ISAJET 7.88
A Monte Carlo Event Generator for pp, $\bar{p}p$, and e^+e^- Reactions

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1 Introduction

ISAJET is a Monte Carlo program which simulates pp, $\bar{p}p$ and e^+e^- interactions at high energies. ISAJET is based on perturbative QCD plus phenomenological models for parton and beam jet fragmentation. Events are generated in four distinct steps:

- A primary hard scattering is generated according to the appropriate QCD cross section.
- QCD radiative corrections are added for both the initial and the final state.
- Partons are fragmented into hadrons independently, and particles with lifetimes less than about 10^{-12} seconds are decayed.
- Beam jets are added assuming that these are identical to a minimum bias event at the remaining energy.

ISAJET incorporates ISASUSY, which evaluates branching ratios for the minimal supersymmetric extension of the standard model. H. Baer and X. Tata are coauthors of this package, and they have done the original calculations with various collaborators. See the ISASUSY documentation in the patch Section 12.

ISAJET is now mainly developed and tested on Linux and Mac OSX with the `gfortran` compiler. Earlier versions have run on various Unix systems, IBM VM/CMS, DEC VMS, and CDC 7600. ISAJET is written mainly in ANSI standard FORTRAN 77, but it does contain some extensions except in the ANSI version. The code is maintained with a combination of RCS, the Revision Control System, `cpp`, the C Preprocessor; see Section 3 for details. A tar file is available from

`http://www.nhn.ou.edu/~isajet`

ISAPLT contains the skeleton of an HBOOK histogramming job, a trivial calorimeter simulation, and a jet-finding algorithm. These are provided for convenience only and are not supported.

2 Physics

ISAJET is a Monte Carlo program which simulates pp, $\bar{p}p$ and e^+e^- interactions at high energy. The program incorporates perturbative QCD cross sections, initial state and final state QCD radiative corrections in the leading log approximation, independent fragmentation of quarks and gluons into hadrons, and a phenomenological model tuned to minimum bias and hard scattering data for the beam jets.

2.1 Hard Scattering

The first step in simulating an event is to generate a primary hard scattering according to some QCD cross section. This has the general form

$$\sigma = \sigma_0 F(x_1, Q^2) F(x_2, Q^2)$$

where σ_0 is a cross section calculated in QCD perturbation theory, $F(x, Q^2)$ is a structure function incorporating QCD scaling violations, x_1 and x_2 are the usual parton model momentum fractions, and Q^2 is an appropriate momentum transfer scale.

For each of the processes included in ISAJET, the basic cross section σ_0 is a two-body one, and the user can set limits on the kinematic variables and type for each of the two primary jets. For DRELLYAN and WPAIR events the full matrix element for the decay of the W's into leptons or quarks is also included.

The following processes are available:

2.1.1 Minbias

No hard scattering at all, so that the event consists only of beam jets. Note that at high energy the jet cross sections become large. To represent the total cross section it is better to use a sample of TWOJET events with the lower limit on pt chosen to give a cross section equal to the inelastic cross section or to use a mixture of MINBIAS and TWOJET events.

2.1.2 Twojet

All order α_s^2 QCD processes, which give rise in lowest order to two high-p_t jets. Included are, e.g.

$$\begin{aligned} g + g &\to g + g \\ g + q &\to g + q \\ g + g &\to q + \bar{q} \end{aligned}$$

Masses are neglected for c and lighter quarks but are taken into account for b and t quarks. The Q^2 scale is taken to be

$$Q^2 = 2stu/(s^2 + t^2 + u^2)$$

The default parton distributions are those of the CTEQ Collaboration, fit CTEQ5L, using lowest order QCD evolution. A few older sets of parton distributions are included. There is also an interface to the CERN PDFLIB compilation of parton distributions. Note that structure functions for heavy quarks are included, so that processes like

$$g + t \to g + t$$

can be generated. The Duke-Owens parton distributions do not contain b or t quarks.

Since the t is so heavy, it decays before it can hadronize, so instead of t hadrons a t quark appears in the particle list. It is decayed using the $V - A$ matrix element including the W propagator with a nonzero width, so the same decays should be used for $m_t < m_W$ and $m_t > m_W$; the W should *not* be listed as part of the decay mode. The partons are then evolved and fragmented as usual; see below. The real or virtual W and the final partons from the decay, including any radiated gluons, are listed in the particle table, followed by their fragmentation products. Note that for semileptonic decays the leptons appear twice: the lepton parton decays into a single particle of the same type but in general somewhat different momentum. In all cases only particles with `IDCAY` = 0 should be included in the final state.

A fourth generation x, y is also allowed. Fourth generation quarks are produced only by gluon fusion. Decay modes are not included in the decay table; for a sequential fourth generation they would be very similar to the t decays. In decays involving quarks, it is essential that the quarks appear last.

2.1.3 Drellyan

Production of a W in the standard model, including a virtual γ, a W^+, a W^-, or a Z^0, and its decay into quarks or leptons. If the transverse momentum QTW of the W is fixed equal to zero then the process simulated is

$$\begin{aligned} q + \bar{q} \to W &\to q + \bar{q} \\ &\to \ell + \bar{\ell} \end{aligned}$$

Thus the W has zero transverse momentum until initial state QCD corrections are taken into account. If non-zero limits on the transverse momentum q_t for the W are set, then instead the processes

$$\begin{aligned} q + \bar{q} &\to W + g \\ g + q &\to W + q \end{aligned}$$

are simulated, including the full matrix element for the W decay. These are the dominant processes at high q_t, but they are of course singular at $q_t = 0$. A cutoff of the $1/q_t^2$ singularity is made by the replacement

$$1/q_t^2 \to 1/\sqrt{q_t^4 + q_{t0}^4} \quad q_{t0}^2 = (.2\,\mathrm{GeV})M$$

This cutoff is chosen to reproduce approximately the q_t dependence calculated by the summation of soft gluons and to give about the right integrated cross section. Thus this option can be used for low as well as high transverse momenta.

The scale for QCD evolution is taken to be proportional to the mass for lowest order Drell-Yan and to the transverse momentum for high-p_t Drell-Yan. The constant is adjusted to get reasonable agreement with the $W + n$ jet cross sections calculated from the full QCD matrix elements by F.A. Berends, et al., Phys. Lett. B224, 237 (1989).

For the processes $g + b \to W + t$ and $g + t \to Z + t$, cross sections with a non-zero top mass are used for the production and the W/Z decay. These were calculated using FORM 1.1 by J. Vermaseren. The process $g + t \to W + b$ is *not* included. Both $g + b \to W^- + t$ and $g + \bar{t} \to W^- + \bar{b}$ of course give the same $W^- + t + \bar{b}$ final state after QCD evolution. While the latter process is needed to describe the $m_t = 0(!)$ mass singularity for $q_t \gg m_t$, it has a pole in the physical region at low q_t from on-shell $t \to W + b$ decays. There is no obvious way to avoid this without introducing an arbitrary cutoff. Hence, selecting only $W + b$ will produce a zero cross section. The Q^2 scale for the parton distributions in these processes is replaced by $Q^2 + m_t^2$; this seems physically sensible and prevents the cross sections from vanishing at small q_t.

2.1.4 Photon

Single and double photon production through the lowest order QCD processes

$$\begin{aligned} g + q &\to \gamma + q \\ q + \bar{q} &\to \gamma + g \\ q + \bar{q} &\to \gamma + \gamma \end{aligned}$$

Higher order corrections are not included. But γ's, W's, and Z's are radiated from final state quarks in all processes, allowing study of the bremsstrahlung contributions.

2.1.5 Wpair

Production of pairs of W bosons in the standard model through quark-antiquark annihilation,

$$\begin{aligned} q + \bar{q} &\to W^+ + W^- \\ &\to Z^0 + Z^0 \\ &\to W^+ + Z^0, W^- + Z^0 \\ &\to W^+ + \gamma, W^- + \gamma \\ &\to Z^0 + \gamma \end{aligned}$$

The full matrix element for the W decays, calculated in the narrow resonance approximation, is included. However, the higher order processes, e.g.

$$q + q \to q + q + W^+ + W^-$$

are ignored, although they in fact dominate at high enough mass. Specific decay modes can be selected using the WMODEi keywords.

2.1.6 Higgs

Production and decay of the standard model Higgs boson. The production processes are

$$\begin{aligned} g+g &\rightarrow H \quad \text{(through a quark loop)} \\ q+\bar{q} &\rightarrow H \quad \text{(with } t+\bar{t} \text{ dominant)} \\ W^+ + W^- &\rightarrow H \quad \text{(with longitudinally polarized } W\text{)} \\ Z^0 + Z^0 &\rightarrow H \quad \text{(with longitudinally polarized } Z\text{)} \end{aligned}$$

If the (Standard Model) Higgs is lighter than $2M_W$, then it will decay into pairs of fermions with branching ratios proportional to m_f^2. If it is heavier than $2M_W$, then it will decay primarily into W^+W^- and Z^0Z^0 pairs with widths given approximately by

$$\begin{aligned} \Gamma(H \rightarrow W^+W^-) &= \frac{G_F M_H^3}{8\pi\sqrt{2}} \\ \Gamma(H \rightarrow Z^0Z^0) &= \frac{G_F M_H^3}{16\pi\sqrt{2}} \end{aligned}$$

Numerically these give approximately

$$\Gamma_H = 0.5\,\text{TeV}\left(\frac{M_H}{1\,\text{TeV}}\right)^3$$

The width proportional to M_H^3 arises from decays into longitudinal gauge bosons, which like Higgs bosons have couplings proportional to mass.

Since a heavy Higgs is wide, the narrow resonance approximation is not valid. To obtain a cross section with good high energy behavior, it is necessary to include a complete gauge-invariant set of graphs for the processes

$$\begin{aligned} W^+W^- &\rightarrow W^+W^- \\ W^+W^- &\rightarrow Z^0Z^0 \\ Z^0Z^0 &\rightarrow W^+W^- \\ Z^0Z^0 &\rightarrow Z^0Z^0 \end{aligned}$$

with longitudinally polarized W^+, W^-, and Z^0 bosons in the initial state. This set of graphs and the corresponding angular distributions for the W^+, W^-, and Z^0 decays have been calculated in the effective W approximation and included in HIGGS. The W structure functions are obtained by integrating the EHLQ parameterization of the quark ones term by term. The Cabibbo-allowed branchings

$$\begin{aligned} q &\rightarrow W^+ + q' \\ q &\rightarrow W^- + q' \\ q &\rightarrow Z^0 + q \end{aligned}$$

are generated by backwards evolution, and the standard QCD evolution is performed. This correctly describes the W collinear singularity and so contains the same physics as the effective W approximation.

If the Higgs is lighter than $2M_W$, then its decay to $\gamma\gamma$ through W and t loops may be important. This is also included in the HIGGS process and may be selected by choosing `GM` as the jet type for the decay.

If the Higgs has $M_Z < M_H < 2M_Z$, then decays into one real and one virtual Z^0 are generated if the `Z0 Z0` decay mode is selected, using the calculation of Keung and Marciano, Phys. Rev. D30, 248 (1984). Since the calculation assumes that one Z^0 is exactly on shell, it is not reliable within of order the Z^0 width of $M_H = 2M_Z$; Higgs and and Z^0Z^0 masses in this region should be avoided. The analogous Higgs decays into one real and one virtual charged W are not included.

Note that while HIGGS contains the dominant graphs for Higgs production and graphs for W pair production related by gauge invariance, it does not contain the processes

$$
\begin{aligned}
q + \bar{q} &\to W^+W^- \\
q + \bar{q} &\to Z^0Z^0
\end{aligned}
$$

which give primarily transverse gauge bosons. These must be generated with WPAIR.

If the `MSSMi` or `SUGRA` keywords are used with HIGGS, then one of the three MSSM neutral Higgs is generated instead using gluon-gluon and quark-antiquark fusion with the appropriate SUSY couplings. Since heavy CP even SUSY Higgs are weakly coupled to W pairs and CP odd ones are completely decoupled, WW fusion and $WW \to WW$ scattering are not included in the SUSY case. ($WW \to WW$ can be generated using the Standard Model process with a light Higgs mass, say 100 GeV.) The MSSM Higgs decays into both Standard Model and SUSY modes as calculated by ISASUSY are included. For more discussion see the SUSY subsection below and the writeup for ISASUSY. The user must select which Higgs to generate using HTYPE; see Section 6 below. If a mass range is not specified, then the range mass $M_H \pm 5\Gamma_H$ is used by default. (This cannot be done for the Standard Model Higgs because it is so wide for large masses.) Decay modes may be selected in the usual way.

2.1.7 WHiggs

Generates associated production of gauge and Higgs bosons, i.e.,

$$q + \bar{q} \to H + W, H + Z\,,$$

in the narrow resonance approximation. The desired subprocesses can be selected with JETTYPEi, and specific decay modes of the W and/or Z can be selected using the WMODEi keywords. Standard Model couplings are assumed unless SUSY parameters are specified, in which case the SUSY couplings are used.

2.1.8 SUSY

Generates pairs of supersymmetric particles from gluon-quark or quark-antiquark fusion. If the MSSMi or SUGRA parameters defined in Section 6 below are not specified, then only gluinos and squarks are generated:

$$g + g \to \tilde{g} + \tilde{g}$$

$$
\begin{aligned}
q+\bar{q} &\to \tilde{g}+\tilde{g} \\
g+q &\to \tilde{g}+\tilde{q} \\
g+g &\to \tilde{q}+\bar{\tilde{q}} \\
q+\bar{q} &\to \tilde{q}+\bar{\tilde{q}} \\
q+q &\to \tilde{q}+\tilde{q}
\end{aligned}
$$

Left and right squarks are distinguished but assumed to be degenerate. Masses can be specified using the GAUGINO, SQUARK, and SLEPTON parameters described in Section 6. No decay modes are specified, since these depend strongly on the masses. The user can either add new modes to the decay table (see Section 9) or use the FORCE or FORCE1 commands (see Section 6).

If MSSMA, MSSMB, and MSSMC are specified, then the ISASUSY package is used to calculate the masses and decay modes in the minimal supersymmetric extension of the standard model (MSSM), assuming SUSY grand unification constraints in the neutralino and chargino mass matrix but allowing some additional flexibility in the masses. The scalar particle soft masses are input via MSSMi, so that the physical masses will be somewhat different due to D-term contributions and mixings for 3rd generation sparticles. $\tilde{t}_1$ and $\tilde{t}_2$ production and decays are now included. The lightest SUSY particle is assumed to be the lightest neutralino $\tilde{Z}_1$. If the MSSMi parameters are specified, then the following additional processes are included using the MSSM couplings for the production cross sections:

$$
\begin{aligned}
g+q &\to \tilde{Z}_i+\tilde{q}, \quad \tilde{W}_i+\tilde{q} \\
q+\bar{q} &\to \tilde{Z}_i+\tilde{g}, \quad \tilde{W}_i+\tilde{g} \\
q+\bar{q} &\to \tilde{W}_i+\tilde{Z}_j \\
q+\bar{q} &\to \tilde{W}_i^{+}+\tilde{W}_j^{-} \\
q+\bar{q} &\to \tilde{Z}_i+\tilde{Z}_j \\
q+\bar{q} &\to \tilde{\ell}^{+}+\tilde{\ell}^{-}, \quad \tilde{\nu}+\tilde{\nu}
\end{aligned}
$$

Processes can be selected using the optional parameters described in Section 6 below.

Beginning with Version 7.42, matrix elements are taken into account in the event generator as well as in the calculation of decay widths for MSSM three-body decays of the form $\tilde{A} \to \tilde{B} f \bar{f}$, where $\tilde{A}$ and $\tilde{B}$ are gluinos, charginos, or neutralinos. This is implemented by having ISASUSY save the poles and their couplings when calculating the decay width and then using these to reconstruct the matrix element. Other three-body decays may be included in the future. Decays selected with FORCE use the appropriate matrix elements.

An optional keyword MSSMD can be used to specify the second generation masses, which otherwise are assumed degenerate with the first generation. An optional keyword MSSME can be used to specify values of the $U(1)$ and $SU(2)$ gaugino masses at the weak scale rather than using the default grand unification values. The chargino and neutralino masses and mixings are then computed using these values.

2.1.9 SUSY Models

The 24 MSSMi parameters describe the MSSM at the weak scale with the additional assumptions of exact flavor and CP conservation; the general MSSM has 105 parameters. These weak-scale SUSY-breaking parameters presumably arise from spontaneous SUSY breaking in a hidden sector that is communicated to the MSSM at some scale $M \gg M_Z$. There are a number of plausible models in which this symmetry breaking is simple, so that the MSSM at the high scale involves only a small number of parameters. These are then related to those at the weak scale by the renormalization group equations (RGE's).

Isajet therefore implements in subroutine SUGRA the complete 2-loop RGE's for the gauge couplings, Yukawa couplings, and soft breaking terms. Contributions from right-handed neutrinos are optionally included. The RGE's are solved iteratively, running from the weak scale to the high scale M and back using Runge-Kutta integration. After each iteration the SUSY masses are recalculated, and the renormalization group improved 1-loop corrected Higgs potential is calculated and minimized. These results are used to modify the RGE β-functions appropriately as each threshold is crossed during the next iteration. Beginning with Version 7.65, the constant parts as well as the logarithms from these thresholds are included using the results of Pierce *et al.*, Nucl. Phys. **B491**, 3 (1997). The whole process is repeated, increasing the number of Runge-Kutta steps by a factor of 1.2 for each iteration, until all the RGE variables except μ and B differ by less than 0.3%. Since μ and B vary rapidly near the weak scale, they are only required to differ by less than 5%. The requirement of good electroweak symmetry breaking, $\mu^2 > 0$, is only imposed after the iterative solution has converged.

A number of different models for SUSY breaking at the high scale are included in ISAJET. The `SUGRA` parameters must be specified for the minimal supergravity framework. This assumes that the gauge couplings unify at the GUT scale, $M \sim 10^{16}\,\mathrm{GeV}$, defined by $\alpha_2 = \alpha_1$. SUSY breaking occurs at that scale with universal soft breaking terms produced by gravitational interactions with a hidden sector. The parameters of the model are

- m_0: the common scalar mass at the GUT scale;
- $m_{1/2}$: the common gaugino mass at the GUT scale;
- A_0: the common soft trilinear SUSY breaking parameter at the GUT scale;
- $\tan\beta$: the ratio of Higgs vacuum expectation values at the electroweak scale;
- $\mathrm{sgn}\,\mu = \pm 1$: the sign of the Higgsino mass term.

An attractive feature of this model is that the Higgs are unified with the other scalars at the GUT scale but $m_{H_u}^2$ is driven negative by the large top Yukawa coupling f_t. Isajet imposes this radiative symmetry breaking for the SUGRA model but not other possible constraints such as b-τ unification or limits on proton decay.

The SUGRA model with exact compling constant unification produces too large a value of α_s at the weak scale. The default is to use the experimental value, assuming that threshold effects at the GUT scale produce this. Exact unification can also be imposed.

The assumption of universality at the GUT scale is rather restrictive and may not be valid. A variety of non-universal SUGRA (NUSUGRA) models can be generated using the `NUSUG1`, ..., `NUSUG5` keywords. These might be used to study how well one could test the minimal SUGRA model. The keyword `SSBCSC` can be used to specify an alternative scale (i.e., not the coupling constant unification scale) for the RGE boundary conditions. A SUGRA model with non-universal Higgs masses m_{H_u} and m_{H_d} which are determined via input of weak scale parameters μ and m_A can be input using the `NUHM` keyword.

An alternative to the SUGRA model is the Gauge Mediated SUSY Breaking (GMSB) model of Dine, Nelson, and collaborators. In this model SUSY breaking is communicated through gauge interactions with messenger fields at a scale M_m small compared to the Planck scale and are proportional to gauge couplings times Λ_m. Since M_m is small and the masses at it are the same for each generation, there are no flavor changing neutral currents. The messenger fields should form complete $SU(5)$ representations to preserve the unification of the coupling constants. The parameters of the GMSB model, which are specified by the `GMSB` keyword, are

- $\Lambda_m = F_m/M_m$: the scale of SUSY breaking, typically 10–100 TeV;
- $M_m > \Lambda_m$: the messenger mass scale;
- N_5: the equivalent number of $5 + \bar{5}$ messenger fields.
- $\tan\beta$: the ratio of Higgs vacuum expectation values at the electroweak scale;
- $\mathrm{sgn}\,\mu = \pm 1$: the sign of the Higgsino mass term;
- $C_{\mathrm{grav}} \geq 1$: the ratio of the gravitino mass to the value it would have had if the only SUSY breaking scale were F_m.

In GMSB models the lightest SUSY particle is always the nearly massless gravitino $\tilde{G}$. The parameter C_{grav} scales the gravitino mass and hence the lifetime of the next lightest SUSY particle to decay into it. The `NOGRAV` keyword can be used to turn off gravitino decays.

A variety of non-minimal GMSB models can be generated using additional parameters set with the GMSB2 keyword. These additional parameters are

- $\not{R}$, an extra factor multiplying the gaugino masses at the messenger scale. (Models with multiple spurions generally have $\not{R} < 1$.)
- $\delta M_{H_d}^2$, $\delta M_{H_u}^2$, Higgs mass-squared shifts relative to the minimal model at the messenger scale. (These might be expected in models which generate μ realistically.)
- $D_Y(M)$, a $U(1)_Y$ messenger scale mass-squared term (D-term) proportional to the hypercharge Y.
- N_{5_1}, N_{5_2}, and N_{5_3}, independent numbers of gauge group messengers. They can be non-integer in general.

For discussions of these additional parameters, see S. Dimopoulos, S. Thomas, and J.D. Wells, hep-ph/9609434, Nucl. Phys. **B488**, 39 (1997), and S.P. Martin, hep-ph/9608224, Phys. Rev. **D55**, 3177 (1997).

Gravitino decays can be included in the general MSSM framework by specifying a gravitino mass with `MGVTNO`. The default is that such decays do not occur.

Another alternative SUSY model choice allowed is anomaly-mediated SUSY breaking, developed by Randall and Sundrum. In this model, it is assumed that SUSY breaking takes place in other dimensions, and SUSY breaking is communicated to the visible sector via the superconformal anomaly. In this model, the lightest SUSY particle is usually the neutralino which is nearly pure wino-like. The chargino is nearly mass degenerate with the lightest neutralino. It can be very long lived, or decay into a very soft pion plus missing energy. The model incorporated in ISAJET, based on work by Ghergetta, Giudice and Wells (hep-ph/9904378), and by Feng and Moroi (hep-ph/9907319) adds a universal contribution m_0^2 to all scalar masses to avoid problems with tachyonic scalars. The parameters of the model, which can be set via the `AMSB` keyword, are

- m_0: Common scalar mass;
- $m_{3/2}$: Gravitino mass, typically $\gtrsim 10\,\mathrm{TeV}$ since $m_i = (\beta_i/g_i)m_{3/2}$.
- $\tan\beta$: Usual ratio of vev's at weak scale;
- $\mathrm{sgn}\,\mu$: Usual sign of μ, ± 1.

Care should be taken with the chargino decay, since it may have macroscopic decay lengths, or even decay outside the detector. A variety of non-minimal AMSB models can be generated by using the AMSB2 keyword, which allows input of c_f multipliers of the m_0^2 contribution to sfermion masses: $m_{\tilde f}^2 = m_{\tilde f}^2(AMSB) + c_f m_0^2$, for $f = Q, D, U, L, E, H_d$ and H_u.

The mixed modulus-AMSB model, inspired by the KKLT string model of compactification of type IIB strings with fluxes, is also available by stipulating the `MMAMSB` keyword. Inputs consist of the mixing parameter α, $m_{3/2}$, $\tan\beta$ and $sign(\mu)$. Also, the modular weights n_Q, n_D, n_U, n_L, n_E, n_{H_d}, n_{H_u} must be specified, as well as moduli powers ℓ_1, ℓ_2 and ℓ_3 in the gauge kinetic function. These latter quantities are usually all taken equal to 1 for gauge fields on a D7 brane. The matter and Higgs field modular weights can be 0, 1 or 1/2 depending on whether the fields live on a D7 or D3 brane, or their intersection, respectively. The mixing parameter $\sim -20 < \alpha <\sim 20$ while $m_{3/2} : 2 - 50$ TeV. See hep-ph/0604253 for more information.

A more *generalized mirage mediation* model based on arXiv:1610.06205 is also available via the `GNMIRAGE` keyword. This model requires inputs $\alpha, m_{3/2}, c_m, c_{m3}, a_3, \tan\beta, sgn(\mu), c_{H_u}, c_{H_d}$ inputs. Alternatively, the c_{H_u}, c_{H_d} inputs can be overwritten in lieu of μ, m_A inputs by using `NUHM` keyword.

Also, a *generalized anomaly-mediation* model which allows for naturalness in AMSB has been entered in Isajet 7.88 (with keyword input NAMSB). This model allows independent bulk soft term contributions to Higgs multiplets along with bulk A_0 terms (as originally envisioned by Randall and Sundrum). Inclusion of these terms allows for $m_h \sim 125$ GeV and natural AMSB spectra, albeit with light higgsinos as LSP instead of light winos. The parameter space is given as $m_0(1,2), m_0(3), m_{3/2}, A_0, \tan\beta, \mu, m_A$.

Since neutrinos seem to have mass, the effect of a massive right-handed neutrino has been included in ISAJET, when calculating the sparticle mass spectrum. If the keyword `SUGRHN` is used, then the user must input the 3rd generation neutrino mass (at scale M_Z) in units of GeV, and the intermediate scale right handed neutrino Majorana mass M_N, also in GeV. In addition, one must specify the soft SUSY-breaking masses A_n and $m_{\tilde{\nu}_R}$ valid at the GUT scale. Then the neutrino Yukawa coupling is computed in the simple see-saw model, and renormalization group evolution includes these effects between M_{GUT} and M_N. Finally, to facilitate modeling of $SO(10)$ SUSY-GUT models, loop corrections to 3rd generation fermion masses have been included in the ISAJET SUSY models.

The ISASUSY program can also be used independently of the rest of ISAJET, either to produce a listing of decays or in conjunction with another event generator. Its physics assumptions are described in more detail in Section 12. ISASUSY accepts soft SUSY breaking parameters at the weak scale and calculates the masses and decay modes from them. The ISASUGRA program can also be used independently to solve the renormalization group equations with SUGRA, NUSUGRA, GMSB, or AMSB boundary conditions and then to call ISASUSY to calculate the decay modes. The main programs described in Section 5.4 prompt for interactive input and print the results to a file.

Generally the MSSM, SUGRA, or GMSB option should be used to study supersymmetry signatures; the SUGRA or GMSB parameter space is clearly more manageable. The more general option may be useful to study alternative SUSY models. It can also be used, e.g., to generate pointlike color-3 leptoquarks in technicolor models by selecting squark production and setting the gluino mass to be very large. The MSSM or SUGRA option may also be used with top pair production to simulate top decays to SUSY particles.

2.1.10 e^+e^-

An e^+e^- event generator is also included in ISAJET. The Standard Model processes included are e^+e^- annihilation through γ and Z to quarks and leptons, and production of W^+W^- and Z^0Z^0 pairs. In contrast to WPAIR and HIGGS for the hadronic processes, the produced W's and Z's are treated as particles, so their spins are not properly taken into account in their decays. (Because the W's and Z's are treated as particles, their decay modes can be selected using `FORCE` or `FORCE1`, not `WMODEi`. See Section [6] below.) Other Standard Model processes, including $e^+e^- \to e^+e^-$ (t-channel graph) are not included. Once the primary reaction has been generated, QCD radiation and hadronization are done as for hadronic processes.

The e^+e^- generator can be run assuming no initial state radiation (the default), or an initial state electron structure function can be used for bremsstrahlung or the combination bremsstrahlung/beamstrahlung effect. Bremsstrahlung is implemented using the Fadin-Kuraev e^- distribution function, and can be turned on using the `EEBREM` command while stipulating the minimal and maximal subprocess energy. Beamstrahlung is implemented by invoking the `EEBEAM` keyword. In this case, in addition the beamstrahlung parameter Υ and longitudinal beam size σ_z (in mm) must be given. The definition for Υ in terms of other beam parameters can be found in the article Phys. Rev. D49, 3209 (1994) by Chen, Barklow and Peskin. The bremsstrahlung structure function is then convoluted with the beamstrahlung distribution (as calculated by M. Peskin) and a spline fit is created. Since the cross section can contain large spikes, event generation can be slow if a huge range of subprocess energy is selected for light particles; in these scenarios, `NTRIES` must be increased well beyond the default value. In Isajet 7.70 and beyond, $e^+e^- \to \gamma\gamma \to f\bar{f}$ (f is a SM fermion) processes are included, via Peskin's photon structure function from brem- and beamstrahlung. These gamma-gamma induced processes are activated by stipulating the keyword `GAMGAM` to be `.TRUE.`, when running with `EEBEAM`. Since the photon structure function is so highly peaked at low x, it is wise to use `GAMGAM` with only one subprocess at a time, a large number for `NTRIES`, and to use a judicious range of subprocess CM energies in `EEBEAM`.

e^+e^- annihilation to SUSY particles is included as well with complete lowest order diagrams, and cascade decays. The processes include

$$\begin{aligned}
e^+e^- &\to \tilde{q}\tilde{q} \\
e^+e^- &\to \tilde{\ell}\tilde{\ell} \\
e^+e^- &\to \tilde{W}_i\tilde{W}_j \\
e^+e^- &\to \tilde{Z}_i\tilde{Z}_j \\
e^+e^- &\to H_L^0 + Z^0, H_H^0 + Z^0, H_A^0 + H_L^0, H_A^0 + H_H^0, H^+ + H^-
\end{aligned}$$

Note that SUSY Higgs production via WW and ZZ fusion, which can dominate Higgs production processes at $\sqrt{s} > 500\,\mathrm{GeV}$, is not included. Spin correlations are neglected, although 3-body sparticle decay matrix elements are included.

e^+e^- cross sections with polarized beams are included for both Standard Model and SUSY processes. The keyword `EPOL` is used to set $P_L(e^-)$ and $P_L(e^+)$, where

$$P_L(e) = (n_L - n_R)/(n_L + n_R)$$

so that $-1 \leq P_L \leq +1$. Thus, setting `EPOL` to $-.9, 0$ will yield a 95% right polarized electron beam scattering on an unpolarized positron beam.

Isajet 7.84 and beyond include an added subroutine ISASEE which calculates $e^+e^- \to SUSY$ and $HIGGS$ total cross sections depending on collider energy and beam polarization for a given spectrum generated from ISASUSY or ISASUGRA. The cross sections are output to the relevant Les Houches Accord (LHA) file. The PRTEESIG flag in the Makefile must be enabled for this to work.

2.1.11 Technicolor

Production of a technirho of arbitrary mass and width decaying into $W^\pm Z^0$ or W^+W^- pairs. The cross section is based on an elastic resonance in the WW cross section with the effective W approximation plus a W mixing term taken from EHLQ. Additional technicolor processes may be added in the future.

2.1.12 Extra Dimensions

The possibility that there might be more than four space-time dimensions at a distance scale R much larger than $G_N^{1/2}$ has recently attracted interest. In these theories,

$$G_N = \frac{1}{8\pi R^\delta M_D^{2+\delta}} ,$$

where δ is the number of extra dimensions and M_D is the $4+\delta$ Planck scale. Gravity deviates from the standard theory at a distance $R \sim 10^{22/\delta-19}\,\mathrm{m}$, so $\delta \geq 2$ is required. If M_D is of order 1 TeV, then the usual heirarchy problem is solved, although there is then a new heirarchy problem of why R is so large.

In such models the graviton will have many Kaluza-Klein excitations with a mass splitting of order $1/R$. While any individual mode is suppressed by the four-dimensional Planck mass, the large number of modes produces a cross section suppressed only by $1/M_D^2$. The signature is an invisible massive graviton plus a jet, photon, or other Standard Model particle. The `EXTRADIM` process implements this reaction using the cross sections of Giudice, Rattazzi, and Wells, hep-ph/9811291. The number δ of extra dimensions, the mass scale M_D, and the logical flag `UVCUT` are specified using the keyword `EXTRAD`. If `UVCUT` is `TRUE`, the cross section is cut off above the scale M_D; the model is not valid if the results depend on this flag.

2.2 Multiparton Hard Scattering

All the processes listed in Section 2.1 are either $2 \to 2$ processes like `TWOJET` or $2 \to 1$ s-channel resonance processes followed by a 2-body decay like `DRELLYAN`. The QCD parton shower described in Section 2.3 below generates multi-parton final states starting from these, but it relies on an approximation which is valid only if the additional partons are collinear either with the initial or with the final primary ones. Since the QCD shower uses exact non-colliear kinematics, it in fact works pretty well in a larger region of phase space, but it is not exact.

Non-collinear multiparton final states are interesting both in their own right and as backgrounds for other signatures. Both the matrix elements and the phase space for multiparton processes are complicated; they have been incorporated into ISAJET for the first time in Version 7.45. To calculate the matrix elements we have used the MadGraph package by Stelzer and Long, Comput. Phys. Commun. **81**, 357 (1994), hep-ph/9401258. This automatically generates the amplitude using `HELAS`, a formalism by Murayama, Watanabe, and Hagiwarak KEK-91-11, that calculates the amplitude for any Feynman diagram in terms of spinnors, vertices, and propagators. The MadGraph code has been edited to incorporate summations over quark flavors. To do the phase space integration, we have used a simple recursive algorithm to generate n-body phase space. We have included limits on the total mass of the final state using the `MTOT` keyword. Limits on the p_T and rapidity of each final parton can be set via the `PT` and `Y` keyworks, while limits on the mass of any pair of final partons can be set via the `MIJTOT` keyword. These limits are sufficient to shield the infrared and collinear singularities and to render the result finite. However, the parton shower populates all regions of phase space, so careful thought is needed to combine the parton-shower based and multiparton based results.

While the multiparton formalism is rather general, it still takes a substantial amount of effort to implement any particular process. So far only one process has been implemented.

2.2.1 $Z + 2$ jets

The ZJJ process generates a Z boson plus two jets, including the $q\bar{q} \to Zq\bar{q}$, $gg \to Zq\bar{q}$, $q\bar{q} \to Zgg$, $qq \to Zqq$, and $gq \to Zgq$ processes. The Z is defined to be jet 1; it is treated in the narrow resonance approximation and is decayed isotropically. The quarks, antiquarks, and gluons are defined to be jets 2 and 3 and are symmetrized in the usual way.

2.3 QCD Radiative Corrections

After the primary hard scattering is generated, QCD radiative corrections are added to allow the possibility of many jets. This is essential to get the correct event structure, especially at high energy.

Consider the emission of one extra gluon from an initial or a final quark line,

$$q(p) \to q(p_1) + g(p_2)$$

From QCD perturbation theory, for small p^2 the cross section is given by the lowest order cross section multiplied by a factor

$$\sigma = \sigma_0 \alpha_s(p^2)/(2\pi p^2) P(z)$$

where $z = p_1/p$ and $P(z)$ is an Altarelli-Parisi function. The same form holds for the other allowed branchings,

$$\begin{aligned} g(p) &\to g(p_1) + g(p_2) \\ g(p) &\to q(p_1) + \bar{q}(p_2) \end{aligned}$$

These factors represent the collinear singularities of perturbation theory, and they produce the leading log QCD scaling violations for the structure functions and the jet fragmentation functions. They also determine the shape of a QCD jet, since the jet M^2 is of order $\alpha_s p_t^2$ and hence small.

The branching approximation consists of keeping just these factors which dominate in the collinear limit but using exact, non-collinear kinematics. Thus higher order QCD is reduced to a classical cascade process, which is easy to implement in a Monte Carlo program. To avoid infrared and collinear singularities, each parton in the cascade is required to have a mass (spacelike or timelike) greater than some cutoff t_c. The assumption is that all physics at lower scales is incorporated in the nonperturbative model for hadronization. In ISAJET the cutoff is taken to be a rather large value, $(6\,\mathrm{GeV})^2$, because independent fragmentation is used for the jet fragmentation; a low cutoff would give too many hadrons from overlapping partons. It turns out that the branching approximation not only incorporates the correct scaling violations and jet structure but also reproduces the exact three-jet cross section within factors of order 2 over all of phase space.

This approximation was introduced for final state radiation by Fox and Wolfram. The QCD cascade is determined by the probability for going from mass t_0 to mass t_1 emitting no resolvable radiation. For a resolution cutoff $z_c < z < 1 - z_c$, this is given by a simple expression,

$$P(t_0, t_1) = (\alpha_s(t_0)/\alpha_s(t_1))^{2\gamma(z_c)/b_0}$$

where

$$\gamma(z_c) = \int_{z_c}^{1-z_c} dz\, P(z), \qquad b_0 = (33 - 2n_f)/(12\pi)$$

Clearly if $P(t_0, t_1)$ is the integral probability, then dP/dt_1 is the probability for the first radiation to occur at t_1. It is straightforward to generate this distribution and then iteratively to correct it to get a cutoff at fixed t_c rather than at fixed z_c.

For the initial state it is necessary to take account of the spacelike kinematics and of the structure functions. Sjostrand has shown how to do this by starting at the hard scattering and evolving backwards, forcing the ordering of the spacelike masses t. The probability that a given step does not radiate can be derived from the Altarelli-Parisi equations for the structure functions. It has a form somewhat similar to $P(t_0, t_1)$ but involving a ratio of the structure functions for the new and old partons. It is possible to find a bound for this ratio in each case and so to generate a new t and z as for the final state. Then branchings for which the ratio is small are rejected in the usual Monte Carlo fashion. This ratio suppresses the radiation of very energetic partons. It also forces the branching $g \to t + \bar{t}$ for a t quark if the t structure function vanishes at small momentum transfer.

At low energies, the branching of an initial heavy quark into a gluon sometimes fails; these events are discarded and a warning is printed.

Since t_c is quite large, the radiation of soft gluons is cut off. To compensate for this, equal and opposite transverse boosts are made to the jet system and to the beam jets after fragmentation with a mean value

$$\langle p_t^2 \rangle = (.1\,\mathrm{GeV})\sqrt{Q^2}$$

The dependence on Q^2 is the same as the cutoff used for DRELLYAN and the coefficient is adjusted to fit the p_t distribution for the W.

Radiation of gluons from gluinos and scalar quarks is also included in the same approximation, but the production of gluino or scalar quark pairs from gluons is ignored. Very little radiation is expected for heavy particles produced near threshold.

Radiation of photons, W's, and Z's from final state quarks is treated in the same approximation as QCD radiation except that the coupling constant is fixed. Initial state electroweak radiation is not included; it seems rather unimportant. The W^+'s, W^-'s and Z's are decayed into the modes allowed by the `WPMODE`, `WMMODE`, and `Z0MODE` commands respectively. *Warning:* The branching ratios implied by these commands are not included in the cross section because an arbitrary number of W's and Z's can in principle be radiated.

2.4 Jet Fragmentation:

Quarks and gluons are fragmented into hadrons using the independent fragmentation ansatz of Field and Feynman. For a quark q, a new quark-antiquark pair $q_1\bar{q}_1$ is generated with

$$u : d : s = .43 : .43 : .14$$

A meson $q\bar{q}_1$ is formed carrying a fraction z of the momentum,

$$E' + p'_z = z(E + p_z)$$

and having a transverse momentum p_t with $\langle p_t \rangle = 0.35\,\mathrm{GeV}$. Baryons are included by generating a diquark with probability 0.10 instead of a quark; adjacent diquarks are not allowed, so no exotic mesons are formed. For light quarks z is generated with the splitting function

$$f(z) = 1 - a + a(b+1)(1-z)^b, \qquad a = 0.96, b = 3$$

while for heavy quarks the Peterson form

$$f(z) = x(1-x)^2/((1-x)^2 + \epsilon x)^2$$

is used with $\epsilon = .80/m_c^2$ for c and $\epsilon = .50/m_q^2$ for $q = b, t, y, x$. These values of ϵ have been determined by fitting PEP, PETRA, and LEP data with ISAJET and should not be compared with values from other fits. Hadrons with longitudinal momentum less than zero are discarded. The procedure is then iterated for the new quark q_1 until all the momentum is used. A gluon is fragmented like a randomly selected u, d, or s quark or antiquark.

In the fragmentation of gluinos and scalar quarks, supersymmetric hadrons are not distinguished from partons. This should not matter except possibly for very light masses. The Peterson form for $f(x)$ is used with the same value of epsilon as for heavy quarks, $\epsilon = 0.5/m^2$.

Independent fragmentation correctly describes the fast hadrons in a jet, but it fails to conserve energy or flavor exactly. Energy conservation is imposed after the event is generated by boosting the hadrons to the appropriate rest frame, rescaling all of the three-momenta, and recalculating the energies.

2.5 Beam Jets

There is now experimental evidence that beam jets are different in minimum bias events and in hard scattering events. ISAJET therefore uses similar a algorithm but different parameters in the two cases.

The standard models of particle production are based on pulling pairs of particles out of the vacuum by the QCD confining field, leading naturally to only short-range rapidity correlations and to essentially Poisson multiplicity fluctuations. The minimum bias data exhibit KNO scaling and long-range correlations. A natural explanation of this was given by the model of Abramovskii, Kanchelli and Gribov. In their model the basic amplitude is a single cut Pomeron with Poisson fluctuations around an average multiplicity $\langle n \rangle$, but unitarity then produces graphs giving K cut Pomerons with multiplicity $K\langle n \rangle$.

A simplified version of the AKG model is used in ISAJET. The number of cut Pomerons is chosen with a distribution adjusted to fit the data. For a minimum bias event this distribution is

$$P(K) = (1 + 4K^2) \exp -1.8K$$

while for hard scattering

$$P(1) \to 0.1P(1), \quad P(2) \to 0.2P(2), \quad P(3) \to 0.5P(3)$$

For each side of each event an x_0 for the leading baryon is selected with a distribution varying from flat for $K = 1$ to like that for mesons for large K:

$$f(x) = N(K)(1 - x_0)^c(K), \qquad c(K) = 1/K + (1 - 1/K)b(s)$$

The x_i for the cut Pomerons are generated uniformly and then rescaled to $1 - x_0$. Each cut Pomeron is then hadronized in its own center of mass using a modified independent fragmentation model with an energy dependent splitting function to reproduce the rise in dN/dy:

$$f(x) = 1 - a + a(b(s) + 1)^b(s), \qquad b(s) = b_0 + b_1 \log(s)$$

The energy dependence is put into $f(x)$ rather than $P(K)$ because in the AKG scheme the single particle distribution comes only from the single chain. The probabilities for different flavors are taken to be

$$u : d : s = .46 : .46 : .08$$

to reproduce the experimental K/π ratio.

3 Installation

Beginning with Version 7.87, ISAJET is distributed as a single Unix tar file. Unpacking this in an empty directory gives

```
Makefile  isadecay.dat  isainc/  isajet/   isaplt/  isared/  isatex/
runjet.f  sample.inrge  ssrun.f  sugrun.f
```

Directory `isainc/` contains all the include files, primarily COMMON blocks. Directory `isajet/` contains most of the Fortran source code including ISASUSY, which was previously separate. Directory `isaplt/` contains the (obsolete) HBOOK-based simple analysis framework. Directory `isared/` contains the machine-generated code that calculates the relic density of dark matter. Directory `isatex/` contains the LaTeX source for the documentation. There are also Fortran files for the main programs, two data files, and a Unix Makefile.

The C Preprocessor (`cpp`) directive `#include` is used to include COMMON blocks from `isainc/` into the Fortran source code, so `isainc/` must be in the include path. A LaTeX macro handles includes for the documentation. Conditional code is mostly handled using the `#ifdef`...`#endif` and `#define` directives. In a few places slightly more complicated conditional expressions are needed. By convention, all `#define` flags are upper case and end in `_X`.

All Fortran source files include `PILOT.inc` at the beginning. This contains `cpp` directives that define the default:

```
#define DOUBLE_X
#define STDIO_X
#define MOVEFTN_X
#define RANLUX_X
#define NOCERN_X
#define ISATOOLS_X
#define ISAFLAVR_X
#undef  PRTEESIG_X
```

where, for example, `DOUBLE_X` means to use DOUBLE PRECISION where needed. It also defines a number of switches to select options for various operating systems and compilers. The `LINUX_X` switch selects additional features for Linux with the `gfortran` compiler:

```
#ifdef  LINUX_X
#define IMPNONE_X
#define IDATE_X
#define ETIME_X
#endif
```

Thus adding `-DLINUX_X` as a compiler option selects the defaults and enables the date/time features. `MACOS_X` is also provided; currently it is identical. Several obsolete versions are also defined, even the original one for the CDC 7600. There are also additional, more specialized `cpp` flags. The `cpp` directives can be expanded running stand-alone `cpp`, e.g.,

```
cpp -I../isainc -DCDC_X aldata.f | grep -v # > aldata.for
```

But do not expect old versions to be usable.

To compile ISAJET, first edit the top-level Makefile and select (or modify) the compiler `FC`, the compiler options `FFLAGS`, and the loader options `LFLAGS` and `LIBS`. Then run `make` in the top level directory, which will also run it in the subdirectories. That will produce two libraries: `libisajet.a` from the `isajet/` directory files and `libisared.a` from the relic density code in `isared/`. (Both libraries are produced even if `NOISATOOLS_X` is defined but will not be used.) It will produce the event generator executable `isajet.x`; sample jobs for it are given in the following sections. It will also produce executables `isasusy.x` and `isasugra.x` for the SUSY model calculations.

The main programs supplied should work with any modern Unix-based compiler. Other main programs for (very) old systems are discussed in Section 5.

4 Sample Jobs

The simplest ISAJET job reads a user-supplied parameter file and writes a data file and a listing file. The following is an example of a parameter file which generates each type of event:

```
SAMPLE TWOJET JOB
800.,100,2,50/
TWOJET
PT
50,100,50,100/
JETTYPE1
'GL'/
JETTYPE2
'UP','UB','DN','DB','ST','SB'/
END
SAMPLE DRELLYAN JOB
800.,100,2,50/
DRELLYAN
QMW
80,100/
WTYPE
'W+','W-'/
END
SAMPLE MINBIAS JOB
800.,100,2,50/
MINBIAS
END
SAMPLE WPAIR JOB
800.,100,2,50/
WPAIR
PT
50,100,50,100/
JETTYPE1
'W+','W-','Z0'/
JETTYPE2
'W+','W-','Z0'/
WMODE1
'E+','E-','NUS'/
WMODE2
'QUARKS'/
END
SAMPLE HIGGS JOB FOR SSC
40000,100,1,1/
HIGGS
```

```
QMH
400,1600/
HMASS
800/
JETTYPE1
'Z0'/
JETTYPE2
'Z0'/
WMODE1
'MU+','MU-'/
WMODE2
'E+','E-'/
PT
50,20000,50,20000/
END
SAMPLE SUSY JOB
1800,100,1,10/
SUPERSYM
PT
50,100,50,100/
JETTYPE1
'GLSS','SQUARKS'/
JETTYPE2
'GLSS','SQUARKS'/
GAUGINO
60,1,40,40/
SQUARK
80.3,80.3,80.5,81.6,85,110/
FORCE
29,30,1,-1/
FORCE
21,29,1/
FORCE
22,29,2/
FORCE
23,29,3/
FORCE
24,29,4/
FORCE
25,29,5/
FORCE
26,29,6/
END
SAMPLE MSSM JOB FOR TEVATRON
```

```
1800.,100,1,1/
SUPERSYM
BEAMS
'P','AP'/
MSSMA
200,-200,500,2/
MSSMB
200,200,200,200,200/
MSSMC
200,200,200,200,200,0,0,0/
JETTYPE1
'GLSS'/
JETTYPE2
'SQUARKS'/
PT
100,300,100,300/
END
SAMPLE MSSM SUGRA JOB FOR LHC
14000,100,1,10/
SUPERSYM
PT
50,500,50,500/
SUGRA
247,302,-617.5,10,-1/
TMASS
175/
END
SAMPLE SUGRA HIGGS JOB USING DEFAULT QMH RANGE
14000,100,20,50/
HIGGS
SUGRA
200,200,0,2,+1/
HTYPE
'HA0'/
JETTYPE1
'GAUGINOS','SLEPTONS'/
JETTYPE2
'GAUGINOS','SLEPTONS'/
END
SAMPLE E+E- TO SUGRA JOB WITH POLARIZED BEAMS AND BREM/BEAMSTRAHLUNG
500.,100,1,1/
E+E-
SUGRA
125,125,0,3,1/
```

```
TMASS
175,-1,1/
EPOL
-.9,0./
EEBEAM
200.,500.,.1072,.12/
JETTYPE1
'ALL'/
JETTYPE2
'ALL'/
NTRIES
10000/
END
SAMPLE WH JOB
2000,100,0,0/
WHIGGS
BEAMS
'P','AP'/
HMASS
100./
JETTYPE1
'W+','W-','HIGGS'/
JETTYPE2
'W+','W-','HIGGS'/
WMODE1
'ALL'/
WMODE2
'ALL'/
PT
10,300,10,300/
END
SAMPLE EXTRA DIMENSIONS JOB
14000,100,1,100/
EXTRADIM
QMW
5,1000/
QTW
500,1000/
EXTRAD
2,1000,.FALSE./
END
SAMPLE ZJJ JOB AT LHC
14000,100,1,100/
ZJJ
```

```
PT
20,7000,20,7000,20,7000/
MIJLIM
0,0,20,7000/
MTOT
100,500/
NSIGMA
200/
NTRIES
10000/
END
STOP
```

See Section 6 of this manual for a complete list of the possible commands in a parameter file. Note that all input to ISAJET must be in *UPPER* case only.

Subroutine RDTAPE is supplied to read events from an ISAJET data file, which is a machine-dependent binary file. It restores the event data to the FORTRAN common blocks described in Section 7. The skeleton of an analysis job using HBOOK and PAW from the CERN Program Library is provided in patch ISAPLT but is not otherwise supported. A Zebra output format based on code from the D0 Collaboration is also provided in patch ISAZEB; see the separate documentation in patch ISZTEXT.

4.1 DEC VMS

This section is obsolete.

4.2 IBM VM/CMS

This section is obsolete.

4.3 Unix

This section is obsolete; see Section 3.

5 Main Program

A main program for ISAJET for Linux/Unix is supplied in `isajet.tar`. To generate events and write them to disk, the user should provide a main program which opens the files and then calls subroutine ISAJET. In the following sample, i,j,m,n are arbitrary unit numbers.

Main program for VMS:

```
      PROGRAM RUNJET
C
C          MAIN PROGRAM FOR ISAJET ON BNL VAX CLUSTER.
C
      OPEN(UNIT=i,FILE='$2$DUA14:[ISAJET.ISALIBRARY]DECAY.DAT',
     $STATUS='OLD',FORM='FORMATTED',READONLY)
      OPEN(UNIT=j,FILE='myjob.dat',STATUS='NEW',FORM='UNFORMATTED')
      OPEN(UNIT=m,FILE='myjob.par',STATUS='OLD',FORM='FORMATTED')
      OPEN(UNIT=n,FILE='myjob.lis',STATUS='NEW',FORM='FORMATTED')
C
      CALL ISAJET(+-i,+-j,m,n)
C
      STOP
      END
```

Main program for IBM (VM/CMS)

```
      PROGRAM RUNJET
C
C          MAIN PROGRAM FOR ISAJET ON IBM ASSUMING FILES HAVE BEEN
C          OPENED WITH FILEDEF.
C
      CALL ISAJET(+-i,+-j,m,n)
C
      STOP
      END
```

Main program for Unix; this is created by the standard `Makefile`:

```
      PROGRAM RUNJET
C
C          Main program for ISAJET on Unix
C
      CHARACTER*60 FNAME
C
C          Open user files
      READ 1000, FNAME
1000  FORMAT(A)
      PRINT 1020, FNAME
```

```
1020  FORMAT(1X,'Data file      = ',A)
      OPEN(2,FILE=FNAME,STATUS='NEW',FORM='UNFORMATTED')
      READ 1000, FNAME
      PRINT 1030, FNAME
1030  FORMAT(1X,'Parameter file = ',A)
      OPEN(3,FILE=FNAME,STATUS='OLD',FORM='FORMATTED')
      READ 1000, FNAME
      PRINT 1040, FNAME
1040  FORMAT(1X,'Listing file   = ',A)
      OPEN(4,FILE=FNAME,STATUS='NEW',FORM='FORMATTED')
C          Open decay table
      READ 1000, FNAME
      OPEN(1,FILE=FNAME,STATUS='OLD',FORM='FORMATTED')
C
C          Run ISAJET
      CALL ISAJET(-1,2,3,4)
C
      STOP
      END
```

The arguments of ISAJET are tape numbers for files, all of which should be opened by the main program.

`TAPEi`: Decay table (formatted). A positive sign prints the decay table on the output listing. A negative sign suppress printing of the decay table.

`TAPEj`: Output file for events (unformatted). A positive sign writes out both resonances and stable particles. A negative sign writes out only stable particles.

`TAPEm`: Commands as defined in Section 6 (formatted).

`TAPEn`: Output listing (formatted).

In the sample jobs in Section 3, TAPEm is the default Fortran input, and TAPEn is the default Fortran output.

5.1 Interactive Interface

To use the interactive interface, replace the call to ISAJET in the above main program by

```
      CALL ISASET(+-i,+-j,m,n)
      CALL ISAJET(+-i,+-j,m,n)
```

ISASET calls DIALOG, which prompts the user for possible commands, does a limited amount of error checking, and writes a command file on TAPEm. This command file is rewound for execution by ISAJET. A main program is included in patch ISARUN to open the necessary files and to call ISASET and ISAJET.

5.2 User Control of Event Loop

If the user wishes to integrate ISAJET with another program and have control over the event generation, he can call the driving subroutines himself. The driving subroutines are:

`ISAINI(+-i,+-j,m,n)`: initialize ISAJET. The arguments are the same as for subroutine ISAJET.

`ISABEG(IFL)`: begin a run. IFL is a return flag: IFL=0 for a good set of commands; IFL=1001 for a STOP; any other value means an error.

`ISAEVT(I,OK,DONE)` generate event I. Logical flag OK signifies a good event (almost always .TRUE.); logical flag DONE signifies the end of a run.

`ISAEND`: end a run.

There are also subroutines provided to write standard ISAJET records, or Zebra records if the Zebra option is selected:

`ISAWBG` to write a begin-of-run record, should be called immediately after ISABEG

`ISAWEV` to write an event record, should be called immediately after ISAEVT

`ISAWND` to write an end-of-run record, should be called immediately after ISAEND

The control of the event loop is somewhat complicated to accomodate multiple evolution and fragmentation as described in Section 11. Note in particular that after calling ISAEVT one should process or write out the event only if OK=.TRUE. The check on the DONE flag is essential if one is doing multiple evolution and fragmentation. The following example indicates how events might be generated, analyzed, and discarded (replace `&` by `+` everywhere):

```
      PROGRAM SAMPLE
C
&SELF,IF=IMPNONE
      IMPLICIT NONE
&SELF
&CDE,ITAPES
&CDE,IDRUN
&CDE,PRIMAR
&CDE,ISLOOP
C
      INTEGER JTDKY,JTEVT,JTCOM,JTLIS,IFL,ILOOP
      LOGICAL OK,DONE
      SAVE ILOOP
C-----------------------------------------------------------------------
C>         Open files as above
C>         Call user initialization
C-----------------------------------------------------------------------
C
C          Initialize ISAJET
C
      CALL ISAINI(-i,0,m,n)
    1 IFL=0
```

```
      CALL ISABEG(IFL)
      IF(IFL.NE.0) STOP
C
C          Event loop
C
      ILOOP=0
  101 CONTINUE
        ILOOP=ILOOP+1
C          Generate one event - discard if .NOT.OK
        CALL ISAEVT(ILOOP,OK,DONE)
        IF(OK) THEN
C-----------------------------------------------------------------------
C>         Call user analysis for event
C-----------------------------------------------------------------------
        ENDIF
      IF(.NOT.DONE) GO TO 101
C
C          Calculate cross section and luminosity
C
      CALL ISAEND
C-----------------------------------------------------------------------
C>         Call user summary
C-----------------------------------------------------------------------
      GO TO 1
      END
```

5.3 Multiple Event Streams

It may be desirable to generate several different kinds of events simultaneously to study pileup effects. While normally one would want to superimpose minimum bias or low-pt jet events on a signal of interest, other combinations might also be interesting. It would be very inefficient to reinitialize ISAJET for each event. Therefore, a pair of subroutines is provided to save and restore the context, i.e. all of the initialization information, in an array. The syntax is

```
      CALL CTXOUT(NC,VC,MC)
      CALL CTXIN(NC,VC,MC)
```

where VC is a real array of dimension MC and NC is the number of words used, about 20000 in the standard case. If NC exceeds MC, a warning is printed and the job is terminated. The use of these routines is illustrated in the following example, which opens the files with names read from the standard input and then superimposes on each event of the signal sample three events of a pileup sample. It is assumed that a large number of events is specified in the parameter file for the pileup sample so that it does not terminate.

```
      PROGRAM SAMPLE
```

```
C
C          Example of generating two kinds of events.
C
      CHARACTER*60 FNAME
      REAL VC1(20000),VC2(20000)
      LOGICAL OK1,DONE1,OK2,DONE2
      INTEGER NC1,NC2,IFL,ILOOP,I2,ILOOP2
C
C          Open decay table
      READ 1000, FNAME
1000  FORMAT(A)
      OPEN(1,FILE=FNAME,STATUS='OLD',FORM='FORMATTED')
C          Open user files
      READ 1000, FNAME
      OPEN(3,FILE=FNAME,STATUS='OLD',FORM='FORMATTED')
      READ 1000, FNAME
      OPEN(4,FILE=FNAME,STATUS='NEW',FORM='FORMATTED')
      READ 1000,FNAME
      OPEN(13,FILE=FNAME,STATUS='OLD',FORM='FORMATTED')
      READ 1000,FNAME
      OPEN(14,FILE=FNAME,STATUS='NEW',FORM='FORMATTED')
C
C          Initialize ISAJET
      CALL ISAINI(-1,0,3,4)
      CALL CTXOUT(NC1,VC1,20000)
      CALL ISAINI(-1,0,13,14)
      IFL=0
      CALL ISABEG(IFL)
      IF(IFL.NE.0) STOP1
      CALL CTXOUT(NC2,VC2,20000)
      ILOOP2=0
      CALL user_initialization_routine
C
1     IFL=0
      CALL CTXIN(NC1,VC1,20000)
      CALL ISABEG(IFL)
      CALL CTXOUT(NC1,VC1,20000)
      IF(IFL.NE.0) GO TO 999
      ILOOP=0
C
C          Main event
C
101   CONTINUE
        ILOOP=ILOOP+1
```

```
        CALL CTXIN(NC1,VC1,20000)
        CALL ISAEVT(ILOOP,OK1,DONE1)
        CALL CTXOUT(NC1,VC1,20000)
        IF(.NOT.OK1) GO TO 101
        CALL user_analysis_routine
C
C          Pileup
C
        CALL CTXIN(NC2,VC2,20000)
        I2=0
201     CONTINUE
          ILOOP2=ILOOP2+1
          CALL ISAEVT(ILOOP2,OK2,DONE2)
          IF(OK2) I2=I2+1
          IF(DONE2) STOP2
          CALL user_analysis_routine
        IF(I2.LT.3) GO TO 201
        CALL CTXOUT(NC2,VC2,20000)
C
      IF(.NOT.DONE1) GO TO 101
C
C          Calculate cross section and luminosity
C
      CALL CTXIN(NC1,VC1,20000)
      CALL ISAEND
      GO TO 1
C
999   CALL CTXIN(NC2,VC2,20000)
      CALL ISAEND
      CALL user_termination_routine
      STOP
      END
```

It is possible to superimpose arbitrary combinations of events, including events of the same reaction type with different parameters. In general the number of events would be selected randomly based on the cross sections and the luminosity.

At this time CTXOUT and CTXIN cannot be used with the Zebra output routines.

5.4 Main Programs for ISASUSY and ISASUGRA

In addition to the event generator, `isajet.car` contains two programs to calculate SUSY masses and decay modes: ISASUSY, which accepts weak scale parameters, and ISASUGRA, which calculates the weak scale parameters from those at some high scale. The main programs, SSRUN and SUGRUN respectively, are included. They both prompt for interactive input and then call the appropriate ISAJET subroutines. The output is formatted and printed by SSPRT and SUGPRT respectively. Executables for ISASUSY and ISASUGRA are built by the Unix `Makefile` and VMS `isamake.com`.

It is fairly straightforward to modify these routines to scan SUSY parameters, but given the variety of possible scans, no attempt has been made to provide code for this. If only masses are needed, SSMSSM can be modified to remove the calls to the routines that calculate branching ratios.

6 Input

6.1 Input Format

ISAJET is controlled by commands read from the specified input file by subroutine READIN. (In the interactive version, this file is first created by subroutine DIALOG.) Syntax errors will generate a message and stop execution. Based on these commands, subroutine LOGIC will setup limits for all variables and check for inconsistencies. Several runs with different parameters can be combined into one job. The required input format is:

```
Title
Ecm,Nevent,Nprint,Njump/
Reaction
(Optional parameters)
END
(Optional additional runs)
STOP
```

with all lines starting in column 1 and typed in *upper* case. These lines are explained below.

Title line: Up to 80 characters long. If the first four letters are STOP, control is returned to main program. If the first four letters are SAME, the parameters from previous run are used excepting those which are explicitly changed.

Ecm line: This line must always be given even if the title is SAME. It must give the center of mass energy (Ecm) and the number of events (Nevent) to be generated. One may also specify the number of events to be printed (Nprint) and the increment (Njump) for printing. The first event is always printed if Nprint > 0. For example:

```
800.,1000,10,100/
```

generates 1000 events at $E_{\rm cm} = 800\,{\rm GeV}$ and prints 10 events. The events printed are: 1,100,200,.... Note that an event typically takes several pages of output. This line is read with a list directed format (READ*).

After Nprint events have been printed, a single line containing the run number, the event number, and the random number seed is printed every Njump events (if Njump is nonzero). This seed can be used to start a new job with the given event if in the new run NSIGMA is set equal to zero:

```
SEED
value/
NSIGMA
0/
```

In general the same events will only be generated on the same type of computer.

Reaction line: This line must be given unless title is SAME, when it must be omitted. It selects the type of events to be generated. The present version can generate TWOJET, E+E-, DRELLYAN, MINBIAS, WPAIR, SUPERSYM, HIGGS, PHOTON, TCOLOR, or WHIGGS events. This line is read with an A8 format.

6.2 Optional Parameters

Each optional parameter requires two lines. The first line is a keyword specifying the parameter and the second line gives the values for the parameter. The parameters can be given in any order. Numerical values are read with a list directed format (READ*), jet and particle types are read with a character format and must be enclosed in quotes, and logical flags with an L1 format. All momenta are in GeV and all angles are in radians.

The parameters can be classified in several groups:

Jet Limits:	W/H Limits:	Decays:	Constants:	Other:
JETTYPE1	HTYPE	FORCE	AMSB	BEAMS
JETTYPE2	PHIW	FORCE1	AMSB2	EPOL
JETTYPE3	QMH	NOB	CUTJET	EEBEAM
MIJLIM	QMW	NODECAY	CUTOFF	EEBREM
MTOT	QTW	NOETA	EXTRAD	GAMGAM
P	THW	NOEVOLVE	GRAGMENT	NPOMERON
PHI	WTYPE	NOFRGMNT	GAUGINO	NSIGMA
PT	XW	NOGRAV	GNMIRAGE	NTRIES
TH	YW	NOPI0	GMSB	PDFLIB
X		NOTAU	GMSB2	SEED
Y			HCAMSB	STRUC
WMODE1			HMASS	WFUDGE
WMODE2			HMASSES	WMMODE
			LAMBDA	WPMODE
			MGVTNO	Z0MODE
			MMAMSB	WRTLHE
			MSSMA	
			MSSMB	
			MSSMC	
			MSSMD	
			MSSME	
			NAMSB	
			NUSUG1	
			NUHM	
			NUHMDT	
			NUSUG2	
			NUSUG3	
			NUSUG4	
			NUSUG5	
			SCLFAC	
			SIGQT	
			SIN2W	
			SLEPTON	
			SQUARK	
			SSBCSC	
			SUGRA	
			SUGRHN	
			TCMASS	
			TMASS	
			WMASS	

It may be helpful to know that the TWOJET, WPAIR, PHOTON, SUPERSYM, and WHIGGS processes use the same controlling routines and so share many of the same variables. In particular, PT limits should normally be set for these processes, and JETTYPE1 and JETTYPE2 are used to select the reactions. Similarly, the DRELLYAN, HIGGS, and TCOLOR processes use the same controlling routines since they all generate s-channel resonances. The mass limits for these processes are set by QMW. Normally the QMW limits will surround the $W^{\pm}$, Z^0, or Higgs mass, but this is not required. (QMH acts like QMW for the Higgs process.) For historical reasons, JETTYPE1 and JETTYPE2 are used to select the W decay modes in DRELLYAN, while WMODE1 and WMODE2 select the W decay modes for WPAIR, HIGGS, and WHIGGS. Also, QTW can be used to generate DRELLYAN events with non-zero transverse momentum, whereas HIGGS automatically fixes QTW to be zero. (Of course, non-zero transverse momentum will be generated by gluon radiation.)

For example the lines

```
P
40.,50.,10.,100./
```

would set limits for the momentum of jet 1 between 40 and 50 GeV, and for jet 2 between 10 and 100 GeV. As another example the lines

```
WTYPE
'W+'/
```

would specify that for DRELLYAN events only W+ events will be generated. If for a kinematic variable only the lower limit is specified then that parameter is fixed to the given value. Thus the lines

```
P
40.,,10./
```

will fix the momentum for jet 1 to be 40 GeV and for jet 2 to be 10 GeV. If only the upper limit is specified then the default value is used for the lower limit. Jet 1 or jet 2 parameters for DRELLYAN events refer to the W decay products and cannot be fixed. If QTW is fixed to 0, then standard Drell-Yan events are generated.

A complete list of keywords and their default values follows.

Keyword Values	Default values	Explanation
AMSB m_0,$m_{3/2}$,tan β,sgn μ	none	Anomaly-mediated SUSY breaking scalar mass, gravitino mass, VEV ratio, sign
AMSB2 $c_Q, c_D, c_U, c_L, c_E, c_{H_d}, c_{H_u}$	1	Non-minimal AMSB multiplies m_0^2 cont'n. to soft SUSY masses
BEAMS type$_1$,type$_2$	'P','P'	Initial beams. Allowed are 'P','AP','N','AN'.
CUTJET μ_c	6.	Cutoff mass for QCD jet evolution.
CUTOFF μ^2, ν	.200,1.0	Cutoff $qt^2 = \mu^2 Q^\nu$ for DRELLYAN events.
EEBEAM $\sqrt{\hat{s}}_{min}$, $\sqrt{\hat{s}}_{max}$, Υ, σ_z	none	impose brem/beamstrahlung min and max subprocess energy, beamstrahlung parameter Υ longitudinal beam size σ_z in mm
EEBREM $\sqrt{\hat{s}}_{min}$, $\sqrt{\hat{s}}_{max}$	none	impose bremsstrahlung for e^+e^- min and max subprocess energy
EPOL $P_L(e^-), P_L(e^+)$	0,0	Polarization of e^- (e^+) beam, $P_L(e) = (n_L - n_R)/(n_L - n_R)$, so that $-1 \leq P_L \leq 1$
EXTRAD δ,M_D,UVCUT	None	Parameters for EXTRADIM process UVCUT is logical flag
FORCE $i, i_1, ..., i_5/$	None	Force decay of particles, $\pm i \to \pm(i1 + ... + i5)$. Can call 20 times. See note for i = quark.
FORCE1 $i, i_1, ..., i_5/$	None	Force decay $i \to i1 + ... + i5$. Can call 40 times. See note for i = quark.

FRAGMENT		Fragmentation parameters.
P_{ud},...	.4,...	See also SIGQT, etc.
GAMGAM		Activate $\gamma\gamma \to f\bar{f}$
TRUE or FALSE	FALSE	in e^+e^- collisions
GAUGINO		Masses for $\tilde{g}$, $\tilde{\gamma}$,
m_1,m_2,m_3, m_4	50,0,100,100	$\tilde{W}^+$, and $\tilde{Z}^0$
GNMIRAGE		Gen. mirage mediation
α,$m_{3/2}$,c_m,c_{m3},a_3,$\tan\beta$,$\mathrm{sgn}\,\mu$,c_{H_u},c_{H_d}	none	mirage-mixing par., gravitino mass, etc.
GMSB		GMSB messenger SUSY breaking,
Λ_m,M_m,N_5	none	mass, number of $5+\bar{5}$, VEV
$\tan\beta$,$\mathrm{sgn}\,\mu$,$C_{\rm gr}$		ratio, sign, gravitino scale
GMSB2		non-minimal GMSB parameters
$\not{R}$,$\delta M^2_{H_d}$,$\delta M^2_{H_u}$,$D_Y(M)$	1,0,0,0	gaugino mass multiplier
N_{5_1},N_{5_2},N_{5_3}	N_5	Higgs mass shifts, D-term mass^2
		indep. gauge group messengers
HCAMSB		Hypercharged AMSB
α,$m_{3/2}$,$\tan\beta$,$\mathrm{sgn}\,\mu$	none	HC-mixing par., gravitino mass,
		VEV ratio, sign
HMASS	0	Mass for standard Higgs.
m		
HMASSES		Higgs meson masses for
m_1,...,m_9	0,...,0	charges 0,0,0,0,0,1,1,2,2.
HTYPE		One MSSM Higgs type ('HL0',
'HL0'/ or...	none	'HH0', or 'HA0')
JETTYPE1		)Select types for jets:
'GL','UP',...	'ALL'	)'ALL'; 'GL'; 'QUARKS'='UP',
		)'UB','DN','DB','ST','SB',
JETTYPE2		)'CH','CB','BT','BB','TP',
'GL','UP',...	'ALL'	)'TB','X','XB','Y','YB';
		)'LEPTONS'='E-','E+','MU-',
JETTYPE3		)'MU+','TAU-','TAU+'; 'NUS';
'GL','UP',...	'ALL'	)'GM','W+','W-','Z0'
		) See note for SUSY types.

LAMBDA		QCD scale
Λ	.2	
MGVTNO		Gravitino mass – ignored for
$M_{\rm gravitino}$	10^{20} GeV	GMSB model
MIJLIM		Multimet mass limits
i,j,$M_{\rm min}$,$M_{\rm max}$	0,0,1 GeV,1 GeV	
MMAMSB		Mixed modulus-AMSB model
α,$m_{3/2}$,$\tan\beta$,sgn μ,	none	mixing par., grav. mass, $\tan\beta$, $sgn(\mu)$
$n_Q, n_D, n_U, n_L, n_E, n_{H_d}, n_{H_u}$	none	modular weights
$\ell_a,\ \ell_s,\ \ell_3$	none	moduli power in GKF
MSSMA		MSSM parameters –
$m(\tilde{g})$,μ,	Required	Gluino mass, μ, A mass,
$m(A)$,$\tan\beta$		$\tan\beta$
MSSMB		MSSM 1st generation –
$m(q_1)$,$m(d_r)$,$m(u_r)$,	Required	Left and right soft squark and
$m(l_1)$,$m(e_r)$		slepton masses
MSSMC		MSSM 3rd generation –
$m(q_3)$,$m(b_r)$,$m(t_r)$,	Required	Soft squark masses, slepton
$m(l_3)$,$m(\tau_r)$,		masses, and squark and slepton
A_t,A_b,A_τ		mixings
MSSMD		MSSM 2nd generation –
$m(q_2)$,$m(s_r)$,$m(c_r)$,	from MSSMB	Left and right soft squark and
$m(l_2)$,$m(mu_r)$		slepton masses
MSSME		MSSM gaugino masses –
M_1,M_2	MSSMA + GUT	Default is to scale from gluino
MTOT		Mass range for multiparton
$M_{\rm min}$,$M_{\rm max}$	None	processes
NAMSB		natural AMSB model
$m_0(1,2)$,$m_0(3)$,$m_{3/2}$,A_0,$\tan\beta$,μ,m_A	none	usual AMSB plus added bulk soft terms
NOB		Suppress B decays to use
TRUE or FALSE	FALSE	external package.
NODECAY		Suppress all decays.
TRUE or FALSE	FALSE	

NOETA TRUE or FALSE	 FALSE	Suppress eta decays.
NOEVOLVE TRUE or FALSE	 FALSE	Suppress QCD evolution and hadronization.
NOGRAV TRUE or FALSE	 FALSE	Suppress gravitino decays in GMSB model
NOHADRON TRUE or FALSE	 FALSE	Suppress hadronization of jets and beam jets.
NONUNU TRUE or FALSE	 FALSE	Suppress Z^0 neutrino decays.
NOPI0 TRUE or FALSE	 FALSE	Suppress π^0 decays.
NOTAU TRUE or FALSE	 FALSE	Suppress tau decays to use external package.
NPOMERON n_1,n_2	 1,20	Allow $n_1 < n < n_2$ cut pomerons. Controls beam jet mult.
NSIGMA n	 20	Generate n unevolved events for SIGF calculation.
NTRIES n	 1000	Stop if after n tries cannot find a good event.
NUHM $\mu(M_{weak})$, $m_A(M_{weak})$	 none	Optional non-universal SUGRA Higgs masses in terms of μ, m_A
NUHMDT $\mu(M_{weak})$, $m_A(M_{weak})$	 none	Optional non-universal soft terms with D-term splitting; input μ, m_A

NUSUG1 M_1,M_2,M_3	 none	Optional non-universal SUGRA gaugino masses
NUSUG2 A_t,A_b,A_τ	 none	Optional non-universal SUGRA A terms
NUSUG3 M_{H_d},M_{H_u}	 none	Optional non-universal SUGRA Higgs masses
NUSUG4 M_{u_L},M_{d_R},M_{u_R}, M_{e_L},M_{e_R}	 none	Optional non-universal SUGRA 1st/2nd generation masses
NUSUG5 M_{t_L},M_{b_R},M_{t_R}, M_{τ_L},M_{τ_R}	 none	Optional non-universal SUGRA 3rd generation masses
P $p_{\rm min}(1)$,. . . ,$p_{\rm max}(3)$	 1.,$0.5E_{\rm cm}$	Momentum limits for jets.
PDFLIB 'name$_1$',val$_1$,. . .	 None	CERN PDFLIB parton distribution parameters. See PDFLIB manual.
PHI $\phi_{\rm min}(1)$,. . . ,$\phi_{\rm max}(3)$	 0,2π	Phi limits for jets.
PHIW $\phi_{\rm min}$,$\phi_{\rm max}$	 0,2π	Phi limits for W.
PT or PPERP $p_{t,\rm min}(1)$,. . . ,$p_{t,\rm max}(3)$	 $.05E_{\rm cm}$,$.2E_{\rm cm}$	p_t limits for jets. Default for TWOJET only.
QMH $q_{\rm min}$,$q_{\rm max}$	 $.05E_{\rm cm}$,$.2E_{\rm cm}$	Mass limits for Higgs. Equivalent to QMW.
QMW $q_{\rm min}$,$q_{\rm max}$	 $.05E_{\rm cm}$,$.2E_{\rm cm}$	Mass limits for W.
QTW $q_{t,\rm min}$,$q_{t,\rm max}$	 .1,$.025E_{\rm cm}$	q_t limits for W. Fix $q_t = 0$ for standard Drell-Yan.
SCLFAC $Q \to nQ$	 $n = 1.0$	Scale factor multiplier in α_s to vary QCD total cross section.

SEED real/integer	0	Seed <281474976710656.D0 for RANF or $<2^{31}$ for RANLUX.
SIGQT σ	.35	Internal k_t parameter for jet fragmentation.
SIN2W $\sin^2(\theta_W)$	.232	Weinberg angle. See WMASS.
SLEPTON m_1,...,m_6	100,...,101.8	Masses for $\tilde{\nu}_e$, $\tilde{e}$, $\tilde{\nu}_\mu$, $\tilde{\mu}$, $\tilde{\nu}_\tau$, $\tilde{\tau}$
SQUARK m_1,...,m_6	100.3,...,240.	Masses for $\tilde{u}$, $\tilde{d}$, $\tilde{s}$, $\tilde{c}$, $\tilde{b}$, $\tilde{t}$
SSBCSC M	M_{GUT}	Alternate mass scale for RGE boundary conditions.
STRUC name	'CTEQ5L'	Structure functions. CTEQ5L, CTEQ3L, CTEQ2L, EHLQ, OR DO
SUGRA m_0,$m_{1/2}$,A_0, $\tan\beta$,sgn μ	none	Minimal supergravity parameters scalar M, gaugino M, trilinear breaking term, vev ratio, +-1
SUGRHN m_{ν_τ},M_N,A_n,$m_{\tilde{\nu}_R}$	$0, 1E20, 0, 0$	SUGRA see-saw ν-effect nu-mass, int. scale, GUT scale nu SSB terms
TH or THETA $\theta_{\min}(1)$,...,$\theta_{\max}(3)$	0,π	Theta limits for jets. Do not also set Y.
THW $\theta_{\min}$,$\theta_{\max}$	0,π	Theta limits for W. Do not also set YW.
TCMASS m,Γ	1000,100	Technicolor mass and width.
TMASS m_t,m_y,m_x	180.,-1.,-1.	t, y, and x quark masses.
WFUDGE factor	1.85	Fudge factor for DRELLYAN evolution scale.

WMASS		W and Z masses. See SIN2W.
M_W,M_Z	80.2, 91.19	
WMMODE		Decay modes for W^- in parton
'UP',...,'TAU+'	'ALL'	cascade. See JETTYPE.
WMODE1		)
'UP','UB',...	'ALL'	)Decay modes for WPAIR.
		)Same code for quarks and
WMODE2		)leptons as JETTYPE.
'UP','UB',...	'ALL'	)
WPMODE		Decay modes for W^+ in parton
'UP',...,'TAU+'	'ALL'	cascade. See JETTYPE.
WRTLHE		
TRUE or FALSE	FALSE	Write events according to Les Houches accord
WTYPE		Select W type: W+,W-,GM,Z0.
type$_1$,type$_2$	'GM','Z0'	Do not mix W+,W- and GM,Z0.
X		Feynman x limits for jets.
$x_{\min}(1)$,...,$x_{\max}(3)$	-1,1	
XGEN		Jet fragmentation, Peterson
a(1),...,a(8)	.96,3,0,.8,.5,...	with $\epsilon = a(n)/m^2$, $n = 4$-8.
XGENSS		Fragmentation of GLSS, UPSS,
a(1),...,a(7)	.5,.5,...	etc. with $\epsilon = a(n)/m**2$
XW		Feynman x limits for W.
$x_{\min}$,$x_{\max}$	-1,1	
Y		Y limits for each jet.
$y_{\min}(1)$,...,$y_{\max}(3)$	from PT	Do not also set TH.
YW		Y limits for W.
$y_{\min}$,$y_{\max}$	from QTW,QMW	Do not set both YW and THW.
Z0MODE		Decay modes for Z^0 in parton
'UP',...,'TAU+'	'ALL'	cascade. See JETTYPE.

6.3 Kinematic and Parton-type Parameters

While the TWOJET PT limits and the DRELLYAN QMW limits are formally optional parameters, they are set by default to be fractions of $\sqrt{s}$. Thus, for example, the parameter file

```
DEFAULT TWOJET JOB
14000,100,1,100/
TWOJET
END
STOP
```

will execute, but it will generate jets between 5% and 20% of $\sqrt{s}$, which is probably not what is wanted. Similarly, the parameter file

```
DEFAULT DRELLYAN JOB
14000,100,1,100/
DRELLYAN
END
STOP
```

will generate $\gamma + Z$ events with masses between 5% and 20% of $\sqrt{s}$, not masses around the Z mass, and transverse momenta between 1 GeV and 2.5% of $\sqrt{s}$.

Normally the user should set PT limits for TWOJET, PHOTON, WPAIR, SUPERSYM, and WHIGGS events and QMW and QTW limits for DRELLYAN, HIGGS, and TCOLOR events. If these limits are not set, they will be selected as fractions of E_{cm}. This can give nonsense. For TWOJET the p_t range should usually be less than about a factor of two except for b and t jets at low p_t to produce uniform statistics. For W^+, W^-, or Z^0 events or for Higgs events the QMW (QMH) range should usually include the mass. But one can select different limits to study, e.g., virtual W production or the effect of a lighter or heavier Higgs on WW scattering. If only t decays are selected, then the lower QMW limit must be above the t threshold. For standard Drell-Yan events QTW should be fixed to zero,

```
QTW
0/
```

Transverse momenta will then be generated by initial state gluon radiation. A range of QTW can also be given. For SUPERSYM either the masses and decay modes should be specified, or the MSSM, SUGRA, GMSB, or AMSB parameters should be given. For fourth generation quarks it is necessary to specify the quark masses.

Note that if the limits given cover too large a kinematic range, the program can become very inefficient, since it makes a fit to the cross section over the specified range. NTRIES has to be increased if narrow limits are set for X, XW or for jet 1 and jet 2 parameters in DRELLYAN events. For larger ranges several runs can be combined together using the integrated cross section per event SIGF/NEVENT as the weight. This cross section is calculated for each run by Monte Carlo integration over the specified kinematic limits and is printed at the end of the run. It is corrected for JETTYPEi, WTYPE, and WMODEi selections; it cannot be corrected for branching ratios of forced decays or for WPMODE, WMMODE, or Z0MODE selections, since these can affect an arbitrary number of particles.

To generate events over a large range, it is much more efficient to combine several runs. This is facilitated by using the special job title SAME as described above. Note that SAME cannot be used to combine standard DRELLYAN events (QTW fixed equal to 0) and DRELLYAN events with nonzero QTW.

The cross sections for multiparton final states in general have infrared and collinear singularities. To obtain sensible results, it is in general essential to set limits both on the p_T of each final parton using PT and on the mass of each pair of partons using MIJLIM. The default lower limits are all 1 GeV. Using these default limits without thought will likely give absurd results.

For TWOJET, DRELLYAN, and most other processes, the JETTYPEi and WTYPEi keywords should be used to select the subprocesses to be included. For $e^+e^- \to W^+W^-$, Z^0Z^0, use FORCE and FORCE1 instead of WMODEi to select the W decay modes. Note that these *do not* change the calculated cross section. (In the E+E- process, the W and Z decays are currently treated as particle decays, whereas in the WPAIR and HIGGS processes they are treated as $2 \to 4$ parton processes.)

For HIGGS with W^+W^- or Z^0Z^0 decays allowed it is generally necessary to set PT limits for the W's, e.g.

```
PT
50,20000,50,20000/
```

If this is not done, then the default lower limit of 1 GeV is used, and the t-channel exchanges will dominate, as they should in the effective W approximation. Depending on the other parameters, the program may fail to generate an event in NTRIES tries.

6.4 SUSY Parameters

SUPERSYM (SUSY) by default generates just gluinos and squarks in pairs. There are no default masses or decay modes. Masses can be set using GAUGINO, SQUARK, SLEPTON, and HMASSES. Decay modes can be specified with FORCE or by modifying the decay table. Left and right squarks are distinguished but assumed to be degenerate, except for stops. Since version 7.11, types must be selected with JETTYPEi using the supersymmetric names, e.g.

```
JETTYPE1
'GLSS','UPSSL','UPSSR'/
```

Use of the corresponding standard model names, e.g.

```
JETTYPE1
'GL','UP'/
```

and generation of pure photinos, winos, and zinos are no longer supported.

If MSSMA, MSSMB and MSSMC are given, then the specified parameters are used to calculate all the masses and decay modes with the ISASUSY package assuming the minimal supersymmetric extension of the standard model (MSSM). There are no default values, so you must specify values for each MSSMi, i=A-C. MSSMD can optionally be used to set the second generation squark and slepton parameters; if it is omitted, then the first generation ones are used. MSSME can optionally be used to set the U(1) and SU(2) gaugino masses; if it is omitted, then the grand unification values are used. The parameters and the use of the MSSM is preserved if the title is SAME. FORCE can be used to override the calculated branching ratios.

The MSSM option also generates charginos and neutralinos with cross sections based on the MSSM mixing angles in addition to squarks and sleptons. These can be selected with JETTYPEi; the complete list of supersymmetric options is:

```
'GLSS',
'UPSSL','UBSSL','DNSSL','DBSSL','STSSL','SBSSL','CHSSL','CBSSL',
'BTSS1','BBSS1','TPSS1','TBSS1',
'UPSSR','UBSSR','DNSSR','DBSSR','STSSR','SBSSR','CHSSR','CBSSR',
'BTSS2','BBSS2','TPSS2','TBSS2',
'W1SS+','W1SS-','W2SS+','W2SS-','Z1SS','Z2SS','Z3SS','Z4SS',
'NUEL','ANUEL','EL-','EL+','NUML','ANUML',MUL-','MUL+','NUTL',
'ANUTL','TAU1-','TAU1+','ER-','ER+','MUR-','MUR+','TAU2-','TAU2+',
'Z0','HL0','HH0','HA0','H+','H-',
'SQUARKS','GAUGINOS','SLEPTONS','ALL'.
```

Note that mixing between L and R stop states results in 1 (light) and 2 (heavy) stop, sbottom and stau eigenstates, which depend on the input parameters of left- and right- scalar masses, plus A terms, μ and $\tan\beta$. The last four JETTYPE's generate respectively all allowed combinations of squarks and antisquarks, all combinations of charginos and neutralinos, all combinations of sleptons and sneutrinos, and all SUSY particles.

For SUSY Higgs pair production or associated production in E+E-, select the appropriate JETTYPE's, e.g.

```
JETTYPE1
'Z0'/
JETTYPE2
'HL0'/
```

As usual, this gives only half the cross section. For single production of neutral SUSY Higgs in pp and $\bar{p}p$ reactions, use the HIGGS process together with the MSSMi, SUGRA, GMSB, or AMSB keywords. You must specify one and only one Higgs type using

```
HTYPE
'HL0' or 'HH0' or 'HA0'/      <<<<< One only!
```

If no QMH range is given, one is calculated using $M \pm 5\Gamma$ for the selected Higgs. Decays into quarks, leptons, gauge bosons, lighter Higgs bosons, and SUSY particles are generated using the on-shell branching ratios from ISASUSY. You can use JETTYPEi to select the allowed Higgs modes and WMODEi to select the allowed decays of W and Z bosons. Since heavy SUSY Higgs bosons couple weakly to W pairs, WW fusion and WW scattering are not included.

SUGRA can be used instead of MSSMi to generate MSSM decays with parameters determined from m_0, $m_{1/2}$, A_0, $\tan\beta$, and $\mathrm{sgn}\,\mu = \pm 1$ in the minimal supergravity framework. The NUSUGi keywords can optionally be used to specify additional parameters for non-universal SUGRA models, while SUGRHN is used to specify the parameterf of an optional right-handed neutrino. Similarly, the GMSB keyword is used to specify the Λ, M_m, N_5, $\tan\beta$, $\mathrm{sgn}\,\mu = \pm 1$, and C_{grav} parameters of the minimal Gauge Mediated SUSY Breaking model. GMSB2 can optionally be used to specify additional parameters of non-minimal GMSB models. The AMSB keyword is used to specify m_0, $m_{3/2}$, $\tan\beta$, and $\mathrm{sgn}\,\mu$ for the minimal Anomaly Mediated SUSY Breaking model. Note that $m_{3/2}$ is much larger than the weak scale, typically 50 TeV.

WHIGGS is used to generate W plus neutral Higgs events. For the Standard Model the JETTYPE is `HIGGS`. If any of the SUSY models is specified, then the appropriate SUSY Higgs type should be used, most likely `HL0`. In either case WMODEi is used to specify the W decay modes. The Higgs is treated as a particle; its decay modes can be set using FORCE.

6.5 Forced Decay Modes

The FORCE keyword requires special care. Its list must contain the numerical particle IDENT codes, e.g.

```
FORCE
140,130,-120/
```

The charge-conjugate mode is also forced for its antiparticle. Thus the above example forces both $\bar{D}^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$. If only a specific decay is wanted one should use the FORCE1 command; e.g.

```
FORCE1
140,130,-120/
```

only forces $\bar{D}^0 \to K^+\pi^-$.

To force a heavy quark decay one must generally separately force each hadron containing it. If the decay is into three leptons or quarks, then the real or virtual W propagator is inserted automatically. Since Version 7.30, top and fourth generation quarks are treated as particles and decayed directly rather than first being made into hadrons. Thus for example

```
FORCE1
6,-12,11,5/
```

forces all top quarks to decay into an positron, neutrino and a b-quark (which will be hadronized). For the physical top mass, the positron and neutrino will come from a real W. Note that forcing $t \to W^+ b$ and $W^+ \to e^+\nu_e$ does *not* give the same result; the first uses the correct $V - A$ matrix element, while the second decays the W according to phase space.

Forced modes included in the decay table or generated by ISASUSY will automatically be put into the correct order and will use the correct matrix element. Modes not listed in the decay table are allowed, but caution is advised because a wrong decay mode can cause an infinite loop or other unexpected effects.

FORCE (FORCE1) can be called at most 20 (40) times in any run plus all subsequent 'SAME' runs. If it is called more than once for a given parent, all calls are listed, and the last call is used. Note that FORCE applies to particles only, but that for gamma, W+, W-, Z0 and supersymmetric particles the same IDENT codes are used both as jet types and as particles.

6.6 Parton Distributions

The default parton distributions are fit CTEQ5L from the CTEQ Collaboration using lowest order QCD. The CTEQ3L, CTEQ2L, and the old EHLQ and Duke-Owens distributions can be selected using the STRUC keyword.

If PDFLIB support is enabled (see Section 4), then any of the distributions in the PDFLIB compilation by H. Plothow-Besch can be selected using the PDFLIB keyword and giving the proper parameters, which are identical to those described in the PDFLIB manual and are simply passed to the routine PDFSET. For example, to select fit 29 (CTEQ3L) by the CTEQ group, leaving all other parameters with their default values, use

```
PDFLIB
'CTEQ',29D0/
```

Note that the fit-number and the other parameters are of type DOUBLE PRECISION (REAL on 64-bit machines). There is no internal passing of parameters except for those which control the printing of messages.

6.7 Multiparton Processes

For multiparton final states one should in general set limits on the total mass `MTOT` of the final state, on the minimum `PT` of each light parton, and on the minimum mass `MIMLIM` of each pair of light partons. Limits for `PT` are set in the ususal way. Limits for the mass M_{ij} of partons i, j are set using

```
MIJLIM
i,j,Mmin,Mmax
```

If $i = j = 0$, the limit is applied to all jet pairs. For example the following parameter file generates `ZJJ` events at the LHC with a mimimum p_T of 20 GeV and a minimum mass of 20 GeV for all jet pairs:

```
GENERATE ZJJ with PTMIN = 20 GEV AND MMIN = 20 GEV
14000,100,1,100/
ZJJ
PT
20,7000,20,7000,20,7000/
MIJLIM
```

```
0,0,20,7000/
MTOT
100,500/
NSIGMA
200/
NTRIES
10000/
END
STOP
```

The default lower limits for `PT` and `MIJLIM` are 1 GeV. While these limits are sufficient to make the cross sections finite, they will in general not give physically sensible results. Thus, *the user must think carefully about what limits should be set.*

7 Output

The output tape or file contains three types of records. A beginning record is written by a call to ISAWBG before generating a set of events; an event record is written by a call to ISAWEV for each event; and an end record is written for each run by a call to ISAWND. These subroutines load the common blocks described below into a single

```
COMMON/ZEVEL/ZEVEL(1024)
```

and write it out when it is full. A subroutine RDTAPE, described in the next section, inverts this process so that the user can analyze the event.

ZEVEL is written out to TAPEj by a call to BUFOUT. For the CDC version IF = PAIRPAK is selected; BUFOUT first packs two words from ZEVEL into one word in

```
COMMON/ZVOUT/ZVOUT(512)
```

using subroutine PAIRPAK and then does a buffer out of ZVOUT to TAPEj. Typically at least two records are written per event. For all other computers IF=STDIO is selected, and ZEVEL is written out with a standard FORTRAN unformatted write.

7.1 Beginning Record

At the start of each run ISAWBG is called. It writes out the following common blocks:

```
      COMMON/DYLIM/QMIN,QMAX,QTMIN,QTMAX,YWMIN,YWMAX,XWMIN,XWMAX,THWMIN,
     2  THWMAX,PHWMIN,PHWMAX
     3  ,SETLMQ(12)
      SAVE /DYLIM/
      LOGICAL SETLMQ
      EQUIVALENCE(BLIM1(1),QMIN)
      REAL      QMIN,QMAX,QTMIN,QTMAX,YWMIN,YWMAX,XWMIN,XWMAX,THWMIN,
     +          THWMAX,PHWMIN,PHWMAX,BLIM1(12)
```

QMIN,QMAX	=	W mass limits
QTMIN,QTMAX	=	W q_t limits
YWMIN,YWMAX	=	W η rapidity limits
XWMIN,XWMAX	=	W x_F limits
THWMIN,THWMAX	=	W θ limits
PHWMIN,PHWMAX	=	W ϕ limits

```
      COMMON/IDRUN/IDVER,IDG(2),IEVT,IEVGEN
      SAVE /IDRUN/
      INTEGER   IDVER,IDG,IEVT,IEVGEN
```

IDVER = program version
IDG(1) = run date (10000×month+100×day+year)
IDG(2) = run time (10000×hour+100×minute+second)
IEVT = event number

```
C          Jet limits
      INTEGER MXLIM
      PARAMETER (MXLIM=8)
      INTEGER MXLX12
      PARAMETER (MXLX12=12*MXLIM)
      COMMON/JETLIM/PMIN(MXLIM),PMAX(MXLIM),PTMIN(MXLIM),PTMAX(MXLIM),
     $YJMIN(MXLIM),YJMAX(MXLIM),PHIMIN(MXLIM),PHIMAX(MXLIM),
     $XJMIN(MXLIM),XJMAX(MXLIM),THMIN(MXLIM),THMAX(MXLIM),
     $SETLMJ(12*MXLIM)
      SAVE /JETLIM/
      COMMON/FIXPAR/FIXP(MXLIM),FIXPT(MXLIM),FIXYJ(MXLIM),
     $FIXPHI(MXLIM),FIXXJ(MXLIM),FIXQM,FIXQT,FIXYW,FIXXW,FIXPHW
      SAVE /FIXPAR/
      COMMON/SGNPAR/CTHS(2,MXLIM),THS(2,MXLIM),YJS(2,MXLIM),XJS(2,MXLIM)
      SAVE /SGNPAR/
      REAL      PMIN,PMAX,PTMIN,PTMAX,YJMIN,YJMAX,PHIMIN,PHIMAX,XJMIN,
     +          XJMAX,THMIN,THMAX,BLIMS(12*MXLIM),CTHS,THS,YJS,XJS
      LOGICAL SETLMJ
      LOGICAL FIXQM,FIXQT,FIXYW,FIXXW,FIXPHW
      LOGICAL FIXP,FIXPT,FIXYJ,FIXPHI,FIXXJ
      EQUIVALENCE(BLIMS(1),PMIN(1))
```

PMIN,PMAX = jet momentum limits
PTMIN,PTMAX = jet p_t limits
YJMIN,YJMAX = jet η rapidity limits
PHIMIN,PHIMAX = jet ϕ limits
THMIN,THMAX = jet θ limits

```
      INTEGER MXKEYS
      PARAMETER (MXKEYS=20)
      COMMON/KEYS/IKEYS,KEYON,KEYS(MXKEYS)
      COMMON/XKEYS/REAC
      SAVE /KEYS/,/XKEYS/
      LOGICAL KEYS
      LOGICAL KEYON
      CHARACTER*8 REAC
      INTEGER   IKEYS
```

KEYON	=	normally TRUE, FALSE if no good reaction
KEYS	=	TRUE if reaction I is chosen
		1 for TWOJET
		2 for E+E-
		3 for DRELLYAN
		4 for MINBIAS
		5 for SUPERSYM
		6 for WPAIR
REAC	=	character reaction code

```
      COMMON/PRIMAR/NJET,SCM,HALFE,ECM,IDIN(2),NEVENT,NTRIES,NSIGMA,
     $WRTLHE
      SAVE /PRIMAR/
      INTEGER   NJET,IDIN,NEVENT,NTRIES,NSIGMA
      LOGICAL   WRTLHE
      REAL      SCM,HALFE,ECM
```

NJET	=	number of jets per event
SCM	=	square of com energy
HALFE	=	beam energy
ECM	=	com energy
IDIN	=	ident code for initial beams
NEVENT	=	number of events to be generated
NTRIES	=	maximum number of tries for good jet parameters
NSIGMA	=	number of extra events to determine SIGF

```
      INTEGER MXGOQ,MXGOJ
      PARAMETER (MXGOQ=85,MXGOJ=8)
      COMMON/Q1Q2/GOQ(MXGOQ,MXGOJ),GOALL(MXGOJ),GODY(4),STDDY,
     $GOWW(25,2),ALLWW(2),GOWMOD(25,MXGOJ)
      SAVE /Q1Q2/
      LOGICAL GOQ,GOALL,GODY,STDDY,GOWW,ALLWW,GOWMOD
```

GOQ(I,K)	=	TRUE if quark type I allowed for jet k
		I = 1 2 3 4 5 6 7 8 9 10 11 12 13
		$\Rightarrow g\ u\ \bar{u}\ d\ \bar{d}\ s\ \bar{s}\ c\ \bar{c}\ b\ \bar{b}\ t\ \bar{t}$
		I = 14 15 16 17 18 19 20 21 22 23 24 25
		$\Rightarrow \nu_e\ \bar{\nu}_e\ e^-\ e^+\ \nu_\mu\ \bar{\nu}_\mu\ \mu^-\ \mu^+\ \nu_\tau\ \bar{\nu}_\tau\ \tau^-\ \tau^+$
GOALL(K)	=	TRUE if all jet types allowed
GODY(I)	=	TRUE if W type I is allowed.
I= 1 2 3 4		
GM W+ W- Z0		
STDDY	=	TRUE if standard DRELLYAN
GOWW(I,K)	=	TRUE if I is allowed in the decay of K for WPAIR.
ALLWW(K)	=	TRUE if all allowed in the decay of K for WPAIR.

```
      COMMON/QCDPAR/ALAM,ALAM2,CUTJET,SCLFAC,ISTRUC
      SAVE /QCDPAR/
      INTEGER   ISTRUC
      REAL      ALAM,ALAM2,CUTJET,SCLFAC
```

ALAM	=	QCD scale Λ
ALAM2	=	QCD scale Λ^2
CUTJET	=	cutoff for generating secondary partons
ISTRUC	=	3 for Eichten (EHLQ),
	=	4 for Duke (DO)
	=	5 for CTEQ 2L
	=	6 for CTEQ 3L
	=	-999 for PDFLIB

```
      COMMON/QLMASS/AMLEP(100),NQLEP,NMES,NBARY
      SAVE /QLMASS/
      INTEGER   NQLEP,NMES,NBARY
      REAL      AMLEP
```

AMLEP(6:8)	=	t,y,x masses, only elements written

7.2 Event Record

For each event ISAWEV is called. It writes out the following common blocks:

```
      COMMON/FINAL/NKINF,SIGF,ALUM,ACCEPT,NRECS
      SAVE /FINAL/
      INTEGER   NKINF,NRECS
      REAL      SIGF,ALUM,ACCEPT
```

SIGF = integrated cross section, only element written

```
      COMMON/IDRUN/IDVER,IDG(2),IEVT,IEVGEN
      SAVE /IDRUN/
      INTEGER   IDVER,IDG,IEVT,IEVGEN
```

IDVER = program version
IDG = run identification
IEVT = event number

```
      COMMON/JETPAR/P(3),PT(3),YJ(3),PHI(3),XJ(3),TH(3),CTH(3),STH(3)
     1 ,JETTYP(3),SHAT,THAT,UHAT,QSQ,X1,X2,PBEAM(2)
     2 ,QMW,QW,QTW,YW,XW,THW,QTMW,PHIW,SHAT1,THAT1,UHAT1,JWTYP
     3 ,ALFQSQ,CTHW,STHW,Q0W
     4 ,INITYP(2),ISIGS,PBEAMS(5)
      SAVE /JETPAR/
      INTEGER   JETTYP,JWTYP,INITYP,ISIGS
      REAL      P,PT,YJ,PHI,XJ,TH,CTH,STH,SHAT,THAT,UHAT,QSQ,X1,X2,
     +          PBEAM,QMW,QW,QTW,YW,XW,THW,QTMW,PHIW,SHAT1,THAT1,UHAT1,
     +          ALFQSQ,CTHW,STHW,Q0W,PBEAMS
```

P = jet momentum $|\vec{p}|$
PT = jet p_t
YJ = jet η rapidity
PHI = jet ϕ
XJ = jet x_F
TH = jet θ
CTH = jet $\cos(\theta)$
STH = jet $\sin(\theta)$
JETTYP = jet type. The code is listed under /Q1Q2/ above
continued…

SHAT,THAT,UHAT	=	hard scattering $\hat{s}$, $\hat{t}$, $\hat{u}$
QSQ	=	effective Q^2
X1,X2	=	initial parton x_F
PBEAM	=	remaining beam momentum
QMW	=	W mass
QW	=	W momentum
QTW	=	W transverse momentum
YW	=	W rapidity
XW	=	W x_F
THW	=	W θ
QTMW	=	$\sqrt{q_{t,W}^2 + Q^2}$
PHIW	=	W ϕ
SHAT1,THAT1,UHAT1	=	invariants for W decay
JWTYP	=	W type. The code is listed under /Q1Q2/ above.
ALFQSQ	=	QCD coupling $\alpha_s(Q^2)$
CTHW	=	W cos(θ)
STHW	=	W sin(θ)
Q0W	=	W energy

```
      INTEGER   MXJSET,JPACK
      PARAMETER (MXJSET=400,JPACK=1000)
      COMMON/JETSET/NJSET,PJSET(5,MXJSET),JORIG(MXJSET),JTYPE(MXJSET),
     $JDCAY(MXJSET)
      SAVE /JETSET/
      INTEGER   NJSET,JORIG,JTYPE,JDCAY
      REAL      PJSET
#ifdef LEVEL2_X
      LEVEL2,/JETSET/
#endif
```

NJSET	=	number of partons
PJSET(1,I)	=	p_x of parton I
PJSET(2,I)	=	p_y of parton I
PJSET(3,I)	=	p_z of parton I
PJSET(4,I)	=	p_0 of parton I
PJSET(5,I)	=	mass of parton I
JORIG(I)	=	JPACK*JET+K if I is a decay product of K. IF K=0 then I is a primary parton. (JET = 1,2,3 for final jets.) (JET = 11,12 for initial jets.)
JTYPE(I)	=	IDENT code for parton I
JDCAY(I)	=	JPACK*K1+K2 if K1 and K2 are decay products of I. If JDCAY(I)=0 then I is a final parton
MXJSET	=	dimension for /JETSET/ arrays.
JPACK	=	packing integer for /JETSET/ arrays.

```
      INTEGER   MXSIGS,IOPAK
      PARAMETER (MXSIGS=3000,IOPAK=100)
      COMMON/JETSIG/SIGMA,SIGS(MXSIGS),NSIGS,INOUT(MXSIGS),SIGEVT
      SAVE /JETSIG/
      INTEGER   NSIGS,INOUT
      REAL      SIGMA,SIGS,SIGEVT
#ifdef LEVEL2_X
      LEVEL2,/JETSIG/
#endif
```

SIGMA	=	cross section summed over types
SIGS(I)	=	cross section for reaction I (not written)
NSIGS	=	number of nonzero cross sections (not written)
INOUT(I)	=	packed partons for process I (not written)
MXSIGS	=	dimension for JETSIG arrays (not written)
SIGEVT	=	partial cross section for selected channel

```
      INTEGER   MXPTCL,IPACK
      PARAMETER (MXPTCL=4000,IPACK=10000)
      COMMON/PARTCL/NPTCL,PPTCL(5,MXPTCL),IORIG(MXPTCL),IDENT(MXPTCL)
     1,IDCAY(MXPTCL)
      SAVE /PARTCL/
      INTEGER   NPTCL,IORIG,IDENT,IDCAY
      REAL      PPTCL
#ifdef LEVEL2_X
      LEVEL2,/PARTCL/
```

```
#endif
```

NPTCL	=	number of particles
PPTCL(1,I)	=	p_x for particle I
PPTCL(2,I)	=	p_y for particle I
PPTCL(3,I)	=	p_z for particle I
PPTCL(4,I)	=	p_0 for particle I
PPTCL(5,I)	=	mass for particle I
IORIG(I)	=	IPACK*JET+K if I is a decay product of K.
	=	-(IPACK*JET+K) if I is a primary particle from parton K in /JETSET/.
	=	0 if I is a primary beam particle. (JET = 1,2,3 for final jets.) (JET = 11,12 for initial jets.)
IDENT(I)	=	IDENT code for particle I
IDCAY(I)	=	IPACK*K1+K2 if decay products are K1-K2 inclusive. If IDCAY(I)=0 then particle I is stable.
MXPTCL	=	dimension for /PARTCL/ arrays.
IPACK	=	packing integer for /PARTCL/ arrays.

```
      COMMON/PINITS/PINITS(5,2),IDINIT(2)
      SAVE /PINITS/
      INTEGER   IDINIT
      REAL      PINITS
```

PINITS(1,I)	=	p_x for initial parton I
PINITS(2,I)	=	p_y for initial parton I
PINITS(3,I)	=	p_z for initial parton I
PINITS(4,I)	=	p_0 for initial parton I
PINITS(5,I)	=	mass for initial parton I
IDINIT(I)	=	IDENT for initial parton I

```
      INTEGER MXJETS
      PARAMETER (MXJETS=10)
      COMMON/PJETS/PJETS(5,MXJETS),IDJETS(MXJETS),QWJET(5),IDENTW
     $,PPAIR(5,4),IDPAIR(4),JPAIR(4),NPAIR,IFRAME(MXJETS)
      SAVE /PJETS/
      INTEGER   IDJETS,IDENTW,IDPAIR,JPAIR,NPAIR,IFRAME
      REAL      PJETS,QWJET,PPAIR
```

PJETS(1,I) = p_x for jet I
PJETS(2,I) = p_y for jet I
PJETS(3,I) = p_z for jet I
PJETS(4,I) = p_0 for jet I
PJETS(5,I) = mass for jet I
IDJETS(I) = IDENT code for jet I
QWJET(1) = p_x for W
QWJET(2) = p_y for W
QWJET(3) = p_z for W
QWJET(4) = p_0 for W
QWJET(5) = mass for W
IDENTW = IDENT CODE for W
PPAIR(1,I) = p_x for WPAIR decay product I
PPAIR(2,I) = p_y for WPAIR decay product I
PPAIR(3,I) = p_z for WPAIR decay product I
PPAIR(4,I) = p_0 for WPAIR decay product I
PPAIR(5,I) = mass for WPAIR decay product I
IDPAIR(I) = IDENT code for WPAIR product I
JPAIR(I) = JETTYPE code for WPAIR product I
NPAIR = 2 for $W^{\pm}\gamma$ events, 4 for WW events

```
      COMMON/TOTALS/NKINPT,NWGEN,NKEEP,SUMWT,WT
      SAVE /TOTALS/
      INTEGER   NKINPT,NWGEN,NKEEP
      REAL      SUMWT,WT
```

NKINPT = number of kinematic points generated.
NWGEN = number of W+jet events accepted.
NKEEP = number of events kept.
SUMWT = sum of weighted cross sections.
WT = current weight. (SIGMA×WT = event weight.)

```
      COMMON/WSIG/SIGLLQ
      SAVE /WSIG/
      REAL      SIGLLQ
```

SIGLLQ = cross section for W decay.

Of course irrelevant common blocks such as /WSIG/ for TWOJET events are not written out.

7.3 End Record

At the end of a set ISAWND is called. It writes out the following common block:

```
COMMON/FINAL/NKINF,SIGF,ALUM,ACCEPT,NRECS
SAVE /FINAL/
INTEGER   NKINF,NRECS
REAL      SIGF,ALUM,ACCEPT
```

NKINF	=	number of points generated to calculate SIGF
SIGF	=	integrated cross section for this run
ALUM	=	equivalent luminosity for this run
ACCEPT	=	ratio of events kept over events generated
NRECS	=	number of physical records for this run

Events within a given run have uniform weight. Separate runs can be combined together using SIGF/NEVENT as the weight per event. This gives a true cross section in mb units.

The user can replace subroutines ISAWBG, ISAWEV, and ISAWND to write out the events in a different format or to update histograms using HBOOK or any similar package.

7.4 LesHouches Event output

A Les Houches Event accord (LHE) was developed in which any parton level event generator could dump out events in a particular format, which could then be read into a general purpose event generator to add parton showering, hadronization and underlying event structure: see E.Boos *et al.*, hep-ph/0109068. Later, a standard format for Les Houches Events was developed, whereby LHE events would be written out in a standard format, which could then be directly read in to general purpose event generators: see J. Alwall *et al.*, hep-ph/0609017. While Isajet does not allow to read in LHE output, version 7.76 and above do allow one to *write out* LHE events in a format which can be read in by event generators Pythia or Herwig. Since color flow is accounted for in the Isajet LHE events, these can then be showered and hadronized by programs which include color flow in their hadronization schemes.

The Isajet LHE output is enabled by use of the keyword WRTLHE in the input file. By default, WRTLHE is FALSE, but by stipulating it to be TRUE, then showering, hadronization and underlying event is turned off, and the subprocess events followed by (cascade) decays including color flow information are written in standard format to a file called `isajet.lhe`, which in turn should be readable by Pythia or Herwig. If running for ALL SUSY JETYPEs, then Isajet generates well over 1000 subprocesses, which is more than Pythia can input. Thus, the LHE lines containing subprocess listing and cross sections stops at a maximum of 500. However, the events in the LHE file are stll in accord with the complete total cross section and the complete list of all allowed subprocesses. Furthermore, the LHE output XSECUP contains $d\sigma/dp_T^2 dy_1/dy_2$ evaluated at $y_i = 0$ for hadronic interactions and $d\sigma/dz$ for e^+e^-. The LHE listed subprocess differential cross sections are given in mb/GeV^2

or mb, respectively. Also, the subprocess label LPRUP is given using the Isajet internal INOUT code. Presumably these lines are unnecessary for use of LHEs.

If SUSY processes are generated with Isajet and sent to Pythia for showering, hadronization etc., then Pythia will need to know that the lightest neutralino is stable. One can set the `Z1SS` to be stable in the Pythia read-in code by setting `CALL PYGIVE('MDCY(C1000022,1)=0')`. Alternatively, if one includes the `PYDAT3` common block, one can instead set

```
MDCY(PYCOMP(1000022),1)=0
```

8 File Reading

The FORTRAN instruction

```
CALL RDTAPE(IDEV,IFL)
```

will read a beginning record, an end record or an event (which can be more than one record). IDEV is the tape number and

```
IFL=0  for a good read,
IFL=-1 for an end of file.
```

The information is restored to the common blocks described above. The type of record is contained in

```
COMMON/RECTP/IRECTP,IREC
SAVE /RECTP/
INTEGER   IRECTP,IREC
```

IRECTP	=	100 for an event record
IRECTP	=	200 for a beginning record
IRECTP	=	300 for an end record
IREC	=	no. of physical records in event record, 0 otherwise

The parton momenta from the primary hard scattering are contained in /PJETS/. The parton momenta generated by the QCD cascade are contained in /JETSET/. The hadron momenta both from the QCD jets and from the beam jets are contained in /PARTCL/. The final hadron momenta and the associated pointers should be used to calculate the jet momenta, since they are changed both by the QCD cascade and by hadronization. Particles with IDCAY=0 are stable, while the others are resonances.

The weight per event needed to produce a weighted histogram in millibarn units is SIGF/NEVENT. The integrated cross section SIGF is calculated by Monte Carlo integration during the run for the given kinematic limits and JETTYPE, WTYPE, and WMODE selections. Any of three methods can be used to find the value of SIGF:

(1) The current value, which is written out with each event, can be used. To prevent enormous fluctuations at the beginning of a run, NSIGMA extra primary parton events are generated first. The default value, NSIGMA = 20, gives negligible overhead but may not be large enough for good accuracy.

(2) The value SIGF calculated with the full statistics of the run can be obtained by reading through the tape until an end record (IRECTP=300) is found. After SIGF is saved with a different name, the first event record for the run can be found by backspacing the tape NRECS times.

(3) Unweighted histograms can be made for the run and the weight added after the end record is found. An implementation of this using special features of HBOOK is contained in ISAPLT.

The functions AMASS(IDENT), CHARGE(IDENT), and LABEL(IDENT) are available to determine the mass, charge, and character label in A8 format. Subroutine FLAVOR returns the quark content of any hadron and may be useful to convert IDENT codes to other schemes. CALL PRTEVT(0) prints an event.

9 Decay Table

ISAJET uses an external table of decay modes. Particles can be put into the table in arbitrary order, but all modes for each particle must be grouped together. The table is rewound and read in before each run with a READ* format. Beginning with Version 7.41, the decay table must begin with a comment of the form

```
' ISAJET     V7.41   11-JAN-1999 20:41:57'
```

If this does not match the internal version number, a warning is printed. After this initial line, each entry must have the form

```
IDENT,MELEM,CBR,ID1,ID2,ID3,ID4,ID5/
```

where IDENT is the code for the parent particle, MELEM specifies the decay matrix element, CBR is the cumulative branching ratio, and ID1,. . . ,ID5 are the IDENT codes for the decay products. The currently defined values of MELEM are:

MELEM	Matrix Element
0	Phase Space
1	Dalitz decay
2	ω/ϕ decay
3	$V - A$ decay
4	top decay: $V - A$ plus W propagator
5	$\tau \to \ell\nu\bar{\nu}$
6	$\tau \to \nu\pi$, νK
7	$\tau \to \nu\rho$, νa_1

The parent IDENT must be positive; the charge conjugate mode is used for the antiparticle. The values of CBR must of course be positive and monotonically increasing for each mode, with the last value being 1.00 for each parent IDENT. The last parent IDENT code must be zero. Care should be taken in adding new modes, since there is no checking for validity. In some cases order is important; note in particular that quarks and gluons must always appear last so that they can be removed and fragmented into hadrons.

The format of the decay table for Versions 7.41 and later is incompatible with that for Versions 7.40 and earlier. Using an obsolete decay table will produce incorrect results.

The decay table is contained in patch ISADECAY.

10 IDENT Codes

ISAJET uses a numerical ident code for particle types. Quarks and leptons are numbered in order of mass:

```
UP     = 1              NUE    = 11
DN     = 2              E-     = 12
ST     = 3              NUM    = 13
CH     = 4              MU-    = 14
BT     = 5              NUT    = 15
TP     = 6              TAU-   = 16
```

with a negative sign for antiparticles. Arbitrary conventions are:

```
GL     = 9
GM     = 10
KS     = 20
KL     =-20
W+     = 80
Z0     = 90
```

The supersymmetric particle IDENT codes distinguish between the partners of left and right handed fermions and include the Higgs sector of the minimal supersymmetric model:

```
UPSSL ... TPSS1 = 21 ... 26
NUEL ... TAU1-  = 31 ... 36
UPSSR ... TPSS2 = 41 ... 46
NUER ... TAU2-  = 51 ... 56
GLSS  = 29
Z1SS  = 30            Z2SS  = 40
Z3SS  = 50            Z4SS  = 60
W1SS+ = 39            W2SS+ = 49

HL0   = 82            HH0   = 83
HA0   = 84            H+    = 86
```

Finally, the gravitino and graviton are

```
GVSS  = 91            GRAV  = 92
```

The same symbol is used for the graviton and its (possible) Kaluza-Klein excitations.

The code for a meson is a compound integer +-JKL, where J.LE.K are the quarks and L is the spin. The sign is for the J quark. Glueball IDENT codes have not been selected, but the choice GL=9 clearly allows 990, 9990, etc. Flavor singlet mesons are ordered by mass,

```
PI0    = 110
ETA    = 220
ETAP   = 330
ETAC   = 440
```

which is natural for the heavy quarks. Similarly, the code for a baryon is a compound integer +-IJKL formed from the three quarks I,J,K and a spin label L=0,1. The code for a diquark is +-IJ00. Additional states are distinguished by a fifth integer, e.g.,

```
A1+    = 10121
```

These and a few J=2 mesons are used in some of the B decays.

A routine PRTLST is provided to print out a complete list of valid IDENT codes and associated information. The usage is CALL PRTLST(LUN, AMY, AMX) where LUN is the unit number and AMY and AMX are the masses of the Y and X quarks respectively. This routine should be linked with the ISAJET library and with ALDATA.

The complete list of ident codes follows. (Hadrons containing t quarks are defined but are no longer listed since the t quark is treated as a particle.)

IDENT	LABEL	MASS	CHARGE
1	UP	.30000E+00	.67
-1	UB	.30000E+00	-.67
2	DN	.30000E+00	-.33
-2	DB	.30000E+00	.33
3	ST	.50000E+00	-.33
-3	SB	.50000E+00	.33
4	CH	.16000E+01	.67
-4	CB	.16000E+01	-.67
5	BT	.49000E+01	-.33
-5	BB	.49000E+01	.33
6	TP	.17500E+03	.67
-6	TB	.17500E+03	-.67
9	GL	0.	0.00
10	GM	0.	0.00
11	NUE	0.	0.00
-11	ANUE	0.	0.00
12	E-	.51100E-03	-1.00
-12	E+	.51100E-03	1.00
13	NUM	0.	0.00
-13	ANUM	0.	0.00
14	MU-	.10566E+00	-1.00
-14	MU+	.10566E+00	1.00
15	NUT	0.	0.00
-15	ANUT	0.	0.00
16	TAU-	.18070E+01	-1.00
-16	TAU+	.18070E+01	1.00

20	KS	.49767E+00	0.00
-20	KL	.49767E+00	0.00
21	UPSSL	none	0.67
-21	UBSSL	none	-0.67
22	DNSSL	none	-0.33
-22	DBSSL	none	0.33
23	STSSL	none	-0.33
23	SBSSL	none	0.33
24	CHSSL	none	0.67
-24	CBSSL	none	-0.67
25	BTSS1	none	-0.33
-25	BBSS1	none	0.33
26	TPSS1	none	0.67
-26	TBSS1	none	-0.67
29	GLSS	none	0.00
30	Z1SS	none	0.00
31	NUEL	none	0.00
-31	ANUEL	none	0.00
32	EL-	none	-1.00
-32	EL+	none	+1.00
33	NUML	none	0.00
-33	ANUML	none	0.00
34	MUL-	none	-1.00
-34	MUL+	none	+1.00
35	NUTL	none	0.00
-35	ANUTL	none	0.00
36	TAU1-	none	-1.00
-36	TAU1+	none	-1.00
39	W1SS+	none	1.00
-39	W1SS-	none	-1.00
40	Z2SS	none	0.00
41	UPSSR	none	0.67
-41	UBSSR	none	-0.67
42	DNSSR	none	-0.33
-42	DBSSR	none	0.33
43	STSSR	none	-0.33
43	SBSSR	none	0.33
44	CHSSR	none	0.67
-44	CBSSR	none	-0.67

45	BTSS2	none	-0.33
-45	BBSS2	none	0.33
46	TPSS2	none	0.67
-46	TBSS2	none	-0.67
49	W2SS+	none	1.00
-49	W2SS-	none	-1.00
50	Z3SS	none	0.00
51	NUER	none	0.00
-51	ANUER	none	0.00
52	ER-	none	-1.00
-52	ER+	none	+1.00
53	NUMR	none	0.00
-53	ANUMR	none	0.00
54	MUR-	none	-1.00
-54	MUR+	none	+1.00
55	NUTR	none	0.00
-55	ANUTR	none	0.00
56	TAU2-	none	-1.00
-56	TAU2+	none	-1.00
60	Z4SS	none	0.00
80	W+	.80200E+02	1.00
81	HIGGS	.80200E+02	0.00
82	HL0	none	0.00
83	HH0	none	0.00
84	HA0	none	0.00
86	H+	none	1.00
90	Z0	.91190E+02	0.00
91	GVSS	0	0.00
92	GRAV	0	0.00
110	PI0	.13496E+00	0.00
120	PI+	.13957E+00	1.00
-120	PI-	.13957E+00	-1.00
220	ETA	.54745E+00	0.00
130	K+	.49367E+00	1.00
-130	K-	.49367E+00	-1.00
230	K0	.49767E+00	0.00
-230	AK0	.49767E+00	0.00
330	ETAP	.95760E+00	0.00
140	AD0	.18645E+01	0.00

-140	D0	.18645E+01	0.00
240	D-	.18693E+01	-1.00
-240	D+	.18693E+01	1.00
340	F-	.19688E+01	-1.00
-340	F+	.19688E+01	1.00
440	ETAC	.29788E+01	0.00
150	UB.	.51700E+01	1.00
-150	BU.	.51700E+01	-1.00
250	DB.	.51700E+01	0.00
-250	BD.	.51700E+01	0.00
350	SB.	.53700E+01	0.00
-350	BS.	.53700E+01	0.00
450	CB.	.64700E+01	1.00
-450	BC.	.64700E+01	-1.00
550	BB.	.97700E+01	0.00
111	RHO0	.76810E+00	0.00
121	RHO+	.76810E+00	1.00
-121	RHO-	.76810E+00	-1.00
221	OMEG	.78195E+00	0.00
131	K*+	.89159E+00	1.00
-131	K*-	.89159E+00	-1.00
231	K*0	.89610E+00	0.00
-231	AK*0	.89610E+00	0.00
331	PHI	.10194E+01	0.00
141	AD*0	.20071E+01	0.00
-141	D*0	.20071E+01	0.00
241	D*-	.20101E+01	-1.00
-241	D*+	.20101E+01	1.00
341	F*-	.21103E+01	-1.00
-341	F*+	.21103E+01	1.00
441	JPSI	.30969E+01	0.00
151	UB*	.52100E+01	1.00
-151	BU*	.52100E+01	-1.00
251	DB*	.52100E+01	0.00
-251	BD*	.52100E+01	0.00
351	SB*	.54100E+01	0.00
-351	BS*	.54100E+01	0.00
451	CB*	.65100E+01	1.00
-451	BC*	.65100E+01	-1.00
551	UPSL	.98100E+01	0.00
112	F2	.12750E+01	0.00
132	K2*+	.14254E+01	1.00

-132	K2*-	.14254E+01	-1.00
232	K2*0	.14324E+01	0.00
-232	AK2*0	.14324E+01	0.00
10110	F0	.98000E+00	0.00
10111	A10	.12300E+01	0.00
10121	A1+	.12300E+01	1.00
-10121	A1-	.12300E+01	-1.00
10131	K1+	.12730E+01	1.00
-10131	K1-	.12730E+01	-1.00
10231	K10	.12730E+01	0.00
-10231	AK10	.12730E+01	0.00
30131	K1*+	.14120E+01	1.00
-30131	K1*-	.14120E+01	-1.00
30231	K1*0	.14120E+01	0.00
-30231	AK1*0	.14120E+01	0.00
10441	PSI(2S)	.36860E+01	0.00
20440	CHI0	.34151E+01	0.00
20441	CHI1	.35105E+01	0.00
20442	CHI2	.35662E+01	0.00
1120	P	.93828E+00	1.00
-1120	AP	.93828E+00	-1.00
1220	N	.93957E+00	0.00
-1220	AN	.93957E+00	0.00
1130	S+	.11894E+01	1.00
-1130	AS-	.11894E+01	-1.00
1230	S0	.11925E+01	0.00
-1230	AS0	.11925E+01	0.00
2130	L	.11156E+01	0.00
-2130	AL	.11156E+01	0.00
2230	S-	.11974E+01	-1.00
-2230	AS+	.11974E+01	1.00
1330	XI0	.13149E+01	0.00
-1330	AXI0	.13149E+01	0.00
2330	XI-	.13213E+01	-1.00
-2330	AXI+	.13213E+01	1.00
1140	SC++	.24527E+01	2.00
-1140	ASC--	.24527E+01	-2.00
1240	SC+	.24529E+01	1.00

-1240	ASC-	.24529E+01	-1.00
2140	LC+	.22849E+01	1.00
-2140	ALC-	.22849E+01	-1.00
2240	SC0	.24525E+01	0.00
-2240	ASC0	.24525E+01	0.00
1340	USC.	.25000E+01	1.00
-1340	AUSC.	.25000E+01	-1.00
3140	SUC.	.24000E+01	1.00
-3140	ASUC.	.24000E+01	-1.00
2340	DSC.	.25000E+01	0.00
-2340	ADSC.	.25000E+01	0.00
3240	SDC.	.24000E+01	0.00
-3240	ASDC.	.24000E+01	0.00
3340	SSC.	.26000E+01	0.00
-3340	ASSC.	.26000E+01	0.00
1440	UCC.	.35500E+01	2.00
-1440	AUCC.	.35500E+01	-2.00
2440	DCC.	.35500E+01	1.00
-2440	ADCC.	.35500E+01	-1.00
3440	SCC.	.37000E+01	1.00
-3440	ASCC.	.37000E+01	-1.00
1150	UUB.	.54700E+01	1.00
-1150	AUUB.	.54700E+01	-1.00
1250	UDB.	.54700E+01	0.00
-1250	AUDB.	.54700E+01	0.00
2150	DUB.	.54700E+01	0.00
-2150	ADUB.	.54700E+01	0.00
2250	DDB.	.54700E+01	-1.00
-2250	ADDB.	.54700E+01	1.00
1350	USB.	.56700E+01	0.00
-1350	AUSB.	.56700E+01	0.00
3150	SUB.	.56700E+01	0.00
-3150	ASUB.	.56700E+01	0.00
2350	DSB.	.56700E+01	-1.00
-2350	ADSB.	.56700E+01	1.00
3250	SDB.	.56700E+01	-1.00
-3250	ASDB.	.56700E+01	1.00
3350	SSB.	.58700E+01	-1.00
-3350	ASSB.	.58700E+01	1.00
1450	UCB.	.67700E+01	1.00
-1450	AUCB.	.67700E+01	-1.00
4150	CUB.	.67700E+01	1.00
-4150	ACUB.	.67700E+01	-1.00
2450	DCB.	.67700E+01	0.00

-2450	ADCB.	.67700E+01	0.00
4250	CDB.	.67700E+01	0.00
-4250	ACDB.	.67700E+01	0.00
3450	SCB.	.69700E+01	0.00
-3450	ASCB.	.69700E+01	0.00
4350	CSB.	.69700E+01	0.00
-4350	ACSB.	.69700E+01	0.00
4450	CCB.	.80700E+01	1.00
-4450	ACCB.	.80700E+01	-1.00
1550	UBB.	.10070E+02	0.00
-1550	AUBB.	.10070E+02	0.00
2550	DBB.	.10070E+02	-1.00
-2550	ADBB.	.10070E+02	1.00
3550	SBB.	.10270E+02	-1.00
-3550	ASBB.	.10270E+02	1.00
4550	CBB.	.11370E+02	0.00
-4550	ACBB.	.11370E+02	0.00

1111	DL++	.12320E+01	2.00
-1111	ADL--	.12320E+01	-2.00
1121	DL+	.12320E+01	1.00
-1121	ADL-	.12320E+01	-1.00
1221	DL0	.12320E+01	0.00
-1221	ADL0	.12320E+01	0.00
2221	DL-	.12320E+01	-1.00
-2221	ADL+	.12320E+01	1.00
1131	S*+	.13823E+01	1.00
-1131	AS*-	.13823E+01	-1.00
1231	S*0	.13820E+01	0.00
-1231	AS*0	.13820E+01	0.00
2231	S*-	.13875E+01	-1.00
-2231	AS*+	.13875E+01	1.00
1331	XI*0	.15318E+01	0.00
-1331	AXI*0	.15318E+01	0.00
2331	XI*-	.15350E+01	-1.00
-2331	AXI*+	.15350E+01	1.00
3331	OM-	.16722E+01	-1.00
-3331	AOM+	.16722E+01	1.00
1141	UUC*	.26300E+01	2.00
-1141	AUUC*	.26300E+01	-2.00
1241	UDC*	.26300E+01	1.00
-1241	AUDC*	.26300E+01	-1.00
2241	DDC*	.26300E+01	0.00
-2241	ADDC*	.26300E+01	0.00

1341	USC*	.27000E+01	1.00
-1341	AUSC*	.27000E+01	-1.00
2341	DSC*	.27000E+01	0.00
-2341	ADSC*	.27000E+01	0.00
3341	SSC*	.28000E+01	0.00
-3341	ASSC*	.28000E+01	0.00
1441	UCC*	.37500E+01	2.00
-1441	AUCC*	.37500E+01	-2.00
2441	DCC*	.37500E+01	1.00
-2441	ADCC*	.37500E+01	-1.00
3441	SCC*	.39000E+01	1.00
-3441	ASCC*	.39000E+01	-1.00
4441	CCC*	.48000E+01	2.00
-4441	ACCC*	.48000E+01	-2.00
1151	UUB*	.55100E+01	1.00
-1151	AUUB*	.55100E+01	-1.00
1251	UDB*	.55100E+01	0.00
-1251	AUDB*	.55100E+01	0.00
2251	DDB*	.55100E+01	-1.00
-2251	ADDB*	.55100E+01	1.00
1351	USB*	.57100E+01	0.00
-1351	AUSB*	.57100E+01	0.00
2351	DSB*	.57100E+01	-1.00
-2351	ADSB*	.57100E+01	1.00
3351	SSB*	.59100E+01	-1.00
-3351	ASSB*	.59100E+01	1.00
1451	UCB*	.68100E+01	1.00
-1451	AUCB*	.68100E+01	-1.00
2451	DCB*	.68100E+01	0.00
-2451	ADCB*	.68100E+01	0.00
3451	SCB*	.70100E+01	0.00
-3451	ASCB*	.70100E+01	0.00
4451	CCB*	.81100E+01	1.00
-4451	ACCB*	.81100E+01	-1.00
1551	UBB*	.10110E+02	0.00
-1551	AUBB*	.10110E+02	0.00
2551	DBB*	.10110E+02	-1.00
-2551	ADBB*	.10110E+02	1.00
3551	SBB*	.10310E+02	-1.00
-3551	ASBB*	.10310E+02	1.00
4551	CBB*	.11410E+02	0.00
-4551	ACBB*	.11410E+02	0.00
5551	BBB*	.14710E+02	-1.00
-5551	ABBB*	.14710E+02	1.00

1100	UU0.	.60000E+00	0.67
-1100	AUU0.	.60000E+00	-0.67
1200	UD0.	.60000E+00	0.33
-1200	AUD0.	.60000E+00	-0.33
2200	DD0.	.60000E+00	-0.67
-2200	ADD0.	.60000E+00	0.67
1300	US0.	.80000E+00	0.33
-1300	AUS0.	.80000E+00	-0.33
2300	DS0.	.80000E+00	-0.67
-2300	ADS0.	.80000E+00	0.67
3300	SS0.	.10000E+01	-0.67
-3300	ASS0.	.10000E+01	0.67
1400	UC0.	.19000E+01	1.33
-1400	AUC0.	.19000E+01	-1.33
2400	DC0.	.19000E+01	0.33
-2400	ADC0.	.19000E+01	-0.33
3400	SC0.	.21000E+01	0.33
-3400	ASC0.	.21000E+01	-0.33
4400	CC0.	.32000E+01	1.33
-4400	ACC0.	.32000E+01	-1.33
1500	UB0.	.49000E+01	0.33
-1500	AUB0.	.49000E+01	-0.33
2500	DB0.	.49000E+01	-0.67
-2500	ADB0.	.49000E+01	0.67
3500	SB0.	.51000E+01	-0.67
-3500	ASB0.	.51000E+01	0.67
4500	CB0.	.65000E+01	0.33
-4500	ACB0.	.65000E+01	-0.33
5500	BB0.	.98000E+01	-0.67
-5500	ABB0.	.98000E+01	0.67

11 Higher Order Processes

Higher order processes can be generated either by the QCD evolution or by supplying partons from an external generator.

Frequently it is interesting to generate higher-order processes with a particular branching in the QCD evolution or with a particular particle or group of particles being produced from the fragmentation. Examples include

1. Branching of jets into heavy quarks (e.g., $g \to b + \bar{b}$);
2. Decay of such a heavy quark into a lepton or neutrino;
3. Radiation of a photon, W, or Z from a jet.

It is important to realize that all of the cross sections and the QCD evolution in ISAJET are based on leading-log QCD, so generating such processes does not give the correct higher order QCD cross sections or "K factors", even though it may produce better agreement with them in some cases.

ISAJET does produce events with particular topologies which in many cases are the most important effect of higher order processes. In the heavy quark example, the lowest order process

$$g + g \to Q + \bar{Q}$$

produces back-to-back heavy quark pairs, whereas the splitting process

$$g + g \to g + g, \quad g \to Q + \bar{Q}$$

produces collinear pairs. Such collinear pairs are essential to obtain agreement with experimental data on $b\bar{b}$ production, and they often are the dominant background for processes of interest.

Branchings such as the emission of a heavy quark pair, a photon, or a $W^{\pm}$ or Z^0 are rare, and since they may occur at any step in the evolution, one cannot force them to occur. Therefore, generation of such events is very slow. M. Della Negra (UA1) suggested first doing n_1 QCD evolutions for each hard scattering and rejecting events without the desired partons, then doing n_2 fragmentations for each successful evolution. This generates the equivalent of $n_1 n_2$ events for each hard scattering, so the cross section must be divided by $n_1 n_2$. This algorithm can speed up the generation of $g \to b + \bar{b}$ splitting by a factor of ten for $n_1 = n_2 = 10$.

Since the evolution and fragmentation steps are executed $n_1 n_2$ times even if good events are found, a single hard scattering can lead to multiple events. This does not change the inclusive cross sections, but it does mean that the fluctuations may be larger than expected. Hence it is important to choose the numbers n_1 and n_2 carefully.

The following entities are used in ISAJET for generating events with multiple evolution and fragmentation:

`NEVENT`: The number of primary hard scatterings to be generated. Set as usual on the input line with the energy.

`SIGF`: The cross section for the selected hard scatterings divided by $n_1 \times n_2$. Hence the correct weight is SIGF/NEVENT, just as for normal running. (The cross section printed at the end of a run does not contain this factor.)

`NEVOLVE`: The number n_1 of evolutions per hard scattering. This should never be set unless you supply a REJJET function. Do not confuse this with NOEVOLVE.

`NHADRON`: The number n_2 of fragmentations for a given evolution. This should never be set unless you supply a REJFRG function. Do not confuse this with NOHADRON.

`REJJET`: A logical function which if true causes the evolution to be rejected. The user must supply one to make the selections which he wants. The default always .FALSE. but includes an example as a comment.

`REJFRG`: A logical function which if true causes the fragmentation to be rejected. The user must supply one to make the selections which he wants. The default always .FALSE. but includes an example as a comment.

Note that one can also use function EDIT to make a final selection of the events. Of course ISAJET must be relinked if EDIT, REJJET or REJFRG is modified.

At the end of a run, the jet cross section, the cross section for the selected events, and the number and fraction of events selected are printed. The cross section SIGF stored internally is divided by $n_1 \times n_2$ so that if the events are used to make histograms, then the correct weight per event is

```
SIGF/NEVENT
```

just as for normal events. Of course NEVENT now has a different meaning; it is in general larger than the number of events in the file but might be smaller if NEVOLVE and NHADRON are badly chosen.

NEVOLVE and NHADRON are set as parameters in the input. One wants to choose them to give better acceptance of the primary hard scatterings but not to give multiple events for one hard scattering. For lepton production from heavy quarks the values

```
NEVOLVE
10/
NHADRON
10/
```

seem appropriate, giving reasonable efficiency. For radiation of photons from jets, NEVOLVE can be somewhat larger but NHADRON should be one, and REJFRG should always return .FALSE., since the selection is just on the parton process, not on the hadronization.

The loops over evolutions and fragmentations are done inside of subroutine ISAEVT and are always executed the same number of times even though ISAEVT returns after each generated event. Logical flag OK signals a good event, and logical flag DONE signals that the run is finished. If you control the event generation loop yourself, you should make use of these flags as in the following extract from subroutine ISAJET:

```
      ILOOP=0
  101 CONTINUE
        ILOOP=ILOOP+1
```

```
     CALL ISAEVT(ILOOP,OK,DONE)
     IF(OK) CALL ISAWEV
   IF(.NOT.DONE) GO TO 101
```

Otherwise you may get the wrong weights.

It is possible to supply to ISAJET events with partons generated by some other program that may have more accurate matrix elements for higher order processes. Because any such calculation must involve cutoffs ISAJET assumes that the partons were generated imposing some R cutoff, where $R = \sqrt{\phi^2 + \eta^2}$, and some E_t cutoff. Given that information ISAJET will generate initial state radiation partons only below the Et cutoff and final state radiation inside the R cutoff. The external partons can be supplied to ISAJET by calls to 2 subroutines. To initialize ISAJET for externally supplied partons, use

```
   CALL INISAP(CMSE,REACTION,BEAMS,WZ,NDCAYS,DCAYS,ETMIN,RCONE,OK)
```

where the inputs are

CMSE	=	center of mass energy
REACTION	=	reaction (only TWOJET and DRELLYAN are implemented so far)
BEAMS(2)	=	chose 'P ' or 'AP'
ETMIN	=	minimum ET of supplied partons
RCONE	=	minimum cone (R) between supplied partons
WZ	=	option 'W', 'Z', or ' ' no W's or Z's
NDCAYS	=	number of decay options (if 0, assume decay has already been done)
DCAYS	=	list of particles W or Z can decay into

and the output is

OK	=	TRUE if initialization is possible

Then for each event use

```
   CALL IPARTNS(NPRTNS,IDS,PRTNS,IDQ,WEIGHT,WZDK)
```

where the inputs are

NPRTNS	=	number of partons, ≤ 10
IDS(NPRTNS)	=	ids of final partons
PRTNS(4,NPRTNS)	=	parton 4 vectors
IDQ(2)	=	ids of initial partons
WEIGHT	=	weight
WZDK	=	if true last 2 partons are from W,Z decay

Further QCD radiation is then generated consistent with ETMIN and RCONE, and the partons are fragmented into hadrons as usual. If RCONE is set to a value greater than 1.5 no cone restriction is applied during parton evolution.

12 ISASUSY: Decay Modes in the Minimal Supersymmetric Model

The code in patch ISASUSY of ISAJET calculates decay modes of supersymmetric particles based on the work of H. Baer, M. Bisset, M. Drees, D. Dzialo (Karatas), X. Tata, J. Woodside, and their collaborators. The calculations assume the minimal supersymmetric extension of the standard model. The user specifies the gluino mass, the pseudoscalar Higgs mass, the Higgsino mass parameter μ, $\tan\beta$, the soft breaking masses for the first and third generation left-handed squark and slepton doublets and right-handed singlets, and the third generation mixing parameters A_t, A_b, and A_τ. Supersymmetric grand unification is assumed by default in the chargino and neutralino mass matrices, although the user can optionally specify arbitrary $U(1)$ and $SU(2)$ gaugino masses at the weak scale. The first and second generations are assumed by default to be degenerate, but the user can optionally specify different values. These inputs are then used to calculate the mass eigenstates, mixings, and decay modes.

Most calculations are done at the tree level, but one-loop results for gluino loop decays, $H \to \gamma\gamma$ and $H \to gg$, loop corrections to the Higgs mass spectrum and couplings, and leading-log QCD corrections to $H \to q\bar{q}$ are included. The Higgs masses have been calculated using the effective potential approximation including both top and bottom Yukawa and mixing effects. Mike Bisset and Xerxes Tata have contributed the Higgs mass, couplings, and decay routines. Manuel Drees has calculated several of the three-body decays including the full Yukawa contribution, which is important for large tan(beta). Note that e+e- annihilation to SUSY particles and SUSY Higgs bosons have been included in ISAJET versions > 7.11. ISAJET versions > 7.22 include the large $\tan\beta$ solution as well as non-degenerate sfermion masses.

Other processes may be added in future versions as the physics interest warrants. Note that the details of the masses and the decay modes can be quite sensitive to choices of standard model parameters such as the QCD coupling ALFA3 and the quark masses. To change these, you must modify subroutine SSMSSM. By default, ALFA3=.12.

All the mass spectrum and branching ratio calculations in ISASUSY are performed by a call to subroutine SSMSSM. Effective with version 7.23, the calling sequence is

```
      SUBROUTINE SSMSSM(XMG,XMU,XMHA,XTANB,XMQ1,XMDR,XMUR,
     $XML1,XMER,XMQ2,XMSR,XMCR,XML2,XMMR,XMQ3,XMBR,XMTR,
     $XML3,XMLR,XAT,XAB,XAL,XM1,XM2,XMT,IALLOW,IMODEL)
```

where the following are taken to be independent parameters:

XMG	=	gluino mass
XMU	=	μ = SUSY Higgs mass
	=	$-2 * m_1$ of Baer et al.
XMHA	=	pseudo-scalar Higgs mass
XTANB	=	$\tan\beta$, ratio of vev's
	=	$1/R$ (of old Baer-Tata notation).

XMQ1	=	$\tilde{q}_l$ soft mass, 1st generation
XMDR	=	$\tilde{d}_r$ mass, 1st generation
XMUR	=	$\tilde{u}_r$ mass, 1st generation
XML1	=	$\tilde{\ell}_l$ mass, 1st generation
XMER	=	$\tilde{e}_r$ mass, 1st generation
XMQ2	=	$\tilde{q}_l$ soft mass, 2nd generation
XMSR	=	$\tilde{s}_r$ mass, 2nd generation
XMCR	=	$\tilde{c}_r$ mass, 2nd generation
XML2	=	$\tilde{\ell}_l$ mass, 2nd generation
XMMR	=	$\tilde{\mu}_r$ mass, 2nd generation
XMQ3	=	$\tilde{q}_l$ soft mass, 3rd generation
XMBR	=	$\tilde{b}_r$ mass, 3rd generation
XMTR	=	$\tilde{t}_r$ mass, 3rd generation
XML3	=	$\tilde{\ell}_l$ mass, 3rd generation
XMTR	=	$\tilde{\tau}_r$ mass, 3rd generation
XAT	=	stop trilinear term A_t
XAB	=	sbottom trilinear term A_b
XAL	=	stau trilinear term A_τ
XM1	=	U(1) gaugino mass
	=	computed from XMG if ¿ 1E19
XM2	=	SU(2) gaugino mass
	=	computed from XMG if ¿ 1E19
XMT	=	top quark mass
IALLOW	=	return flag
IMODEL	=	1 for SUGRA or MSSM
	=	2 for GMSB

The variable IALLOW is returned:

IALLOW	=	1 if Z1SS is not LSP, 0 otherwise

All variables are of type REAL except IALLOW and IMODEL, which are INTEGER, and all masses are in GeV. The notation is taken to correspond to that of Haber and Kane, although the Tata Lagrangian is used internally. All other standard model parameters are hard wired in this subroutine; they are not obtained from the rest of ISAJET. The theoretically favored range of these parameters is

$$100 < M(\tilde{g}) < 2000\,\mathrm{GeV}$$
$$100 < M(\tilde{q}) < 2000\,\mathrm{GeV}$$
$$100 < M(\tilde{\ell}) < 2000\,\mathrm{GeV}$$
$$-1000 < \mu < 1000\,\mathrm{GeV}$$
$$1 < \tan\beta < m_t/m_b$$

$$M(t) \approx 175\,\mathrm{GeV}$$
$$100 < M(A) < 2000\,\mathrm{GeV}$$
$$M(\tilde{t}_l), M(t_r) < M(\tilde{q})$$
$$M(\tilde{b}_r) \sim M(\tilde{q})$$
$$-1000 < A_t < 1000\,\mathrm{GeV}$$
$$-1000 < A_b < 1000\,\mathrm{GeV}$$

It is assumed that the lightest supersymmetric particle is the lightest neutralino $\tilde{Z}_1$, the lighter stau $\tilde{\tau}_1$, or the gravitino $\tilde{G}$ in GMSB models. Some choices of the above parameters may violate this assumption, yielding a light chargino or light stop squark lighter than $\tilde{Z}_1$. In such cases SSMSSM does not compute any branching ratios and returns IALLOW = 1.

SSMSSM does not check the parameters or resulting masses against existing experimental data. SSTEST provides a minimal test. This routine is called after SSMSSM by ISAJET and ISASUSY and prints suitable warning messages.

SSMSSM first calculates the other SUSY masses and mixings and puts them in the common block /SSPAR/:

```
C          SUSY parameters
C          AMGLSS                  = gluino mass
C          AMULSS                  = up-left squark mass
C          AMELSS                  = left-selectron mass
C          AMERSS                  = right-slepton mass
C          AMNiSS                  = sneutrino mass for generation i
C          TWOM1                   = Higgsino mass = - mu
C          RV2V1                   = ratio v2/v1 of vev's
C          AMTLSS,AMTRSS           = left,right stop masses
C          AMT1SS,AMT2SS           = light,heavy stop masses
C          AMBLSS,AMBRSS           = left,right sbottom masses
C          AMB1SS,AMB2SS           = light,heavy sbottom masses
C          AMLLSS,AMLRSS           = left,right stau masses
C          AML1SS,AML2SS           = light,heavy stau masses
C          AMZiSS                  = signed mass of Zi
C          ZMIXSS                  = Zi mixing matrix
C          AMWiSS                  = signed Wi mass
C          GAMMAL,GAMMAR           = Wi left, right mixing angles
C          AMHL,AMHH,AMHA          = neutral Higgs h0, H0, A0 masses
C          AMHC                    = charged Higgs H+ mass
C          ALFAH                   = Higgs mixing angle
C          AAT                     = stop trilinear term
C          THETAT                  = stop mixing angle
C          AAB                     = sbottom trilinear term
C          THETAB                  = sbottom mixing angle
C          AAL                     = stau trilinear term
C          THETAL                  = stau mixing angle
```

```
C          AMGVSS               = gravitino mass
C          MTQ                  = top mass at MSUSY
C          MBQ                  = bottom mass at MSUSY
C          MLQ                  = tau mass at MSUSY
C          FBMA                 = b-Yukawa at mA scale
C          VUQ                  = Hu vev at MSUSY
C          VDQ                  = Hd vev at MSUSY
      COMMON/SSPAR/AMGLSS,AMULSS,AMURSS,AMDLSS,AMDRSS,AMSLSS
     $,AMSRSS,AMCLSS,AMCRSS,AMBLSS,AMBRSS,AMB1SS,AMB2SS
     $,AMTLSS,AMTRSS,AMT1SS,AMT2SS,AMELSS,AMERSS,AMMLSS,AMMRSS
     $,AMLLSS,AMLRSS,AML1SS,AML2SS,AMN1SS,AMN2SS,AMN3SS
     $,TWOM1,RV2V1,AMZ1SS,AMZ2SS,AMZ3SS,AMZ4SS,ZMIXSS(4,4)
     $,AMW1SS,AMW2SS
     $,GAMMAL,GAMMAR,AMHL,AMHH,AMHA,AMHC,ALFAH,AAT,THETAT
     $,AAB,THETAB,AAL,THETAL,AMGVSS,MTQ,MBQ,MLQ,FBMA,
     $VUQ,VDQ
      REAL AMGLSS,AMULSS,AMURSS,AMDLSS,AMDRSS,AMSLSS
     $,AMSRSS,AMCLSS,AMCRSS,AMBLSS,AMBRSS,AMB1SS,AMB2SS
     $,AMTLSS,AMTRSS,AMT1SS,AMT2SS,AMELSS,AMERSS,AMMLSS,AMMRSS
     $,AMLLSS,AMLRSS,AML1SS,AML2SS,AMN1SS,AMN2SS,AMN3SS
     $,TWOM1,RV2V1,AMZ1SS,AMZ2SS,AMZ3SS,AMZ4SS,ZMIXSS
     $,AMW1SS,AMW2SS
     $,GAMMAL,GAMMAR,AMHL,AMHH,AMHA,AMHC,ALFAH,AAT,THETAT
     $,AAB,THETAB,AAL,THETAL,AMGVSS,MTQ,MBQ,MLQ,FBMA,VUQ,VDQ
      REAL AMZISS(4)
      EQUIVALENCE (AMZISS(1),AMZ1SS)
      SAVE /SSPAR/
```

It then calculates the widths and branching ratios and puts them in the common block /SSMODE/:

```
C          MXSS         =  maximum number of modes
C          NSSMOD       = number of modes
C          ISSMOD       = initial particle
C          JSSMOD       = final particles
C          GSSMOD       = width
C          BSSMOD       = branching ratio
C          MSSMOD       = decay matrix element pointer
C          LSSMOD       = logical flag used internally by SSME3
      INTEGER MXSS
      PARAMETER (MXSS=1000)
      COMMON/SSMODE/NSSMOD,ISSMOD(MXSS),JSSMOD(5,MXSS),GSSMOD(MXSS)
     $,BSSMOD(MXSS),MSSMOD(MXSS),LSSMOD
      INTEGER NSSMOD,ISSMOD,JSSMOD,MSSMOD
      REAL GSSMOD,BSSMOD
```

```
      LOGICAL LSSMOD
      SAVE /SSMODE/
```

Decay modes for a given particle are not necessarily adjacent in this common block. Note that the branching ratio calculations use the full matrix elements, which in general will give nonuniform distributions in phase space, but this information is not saved in /SSMODE/. In particular, the decays $H \to Z + Z^* \to Z + f + \bar{f}$ give no indication that the $f\bar{f}$ mass is strongly peaked near the upper limit.

All IDENT codes are defined by parameter statements in the PATCHY keep sequence SSTYPE:

```
C          SM ident code definitions. These are standard ISAJET but
C          can be changed.
      INTEGER IDUP,IDDN,IDST,IDCH,IDBT,IDTP
      INTEGER IDNE,IDE,IDNM,IDMU,IDNT,IDTAU
      INTEGER IDGL,IDGM,IDW,IDZ,IDH
      PARAMETER (IDUP=1,IDDN=2,IDST=3,IDCH=4,IDBT=5,IDTP=6)
      PARAMETER (IDNE=11,IDE=12,IDNM=13,IDMU=14,IDNT=15,IDTAU=16)
      PARAMETER (IDGL=9,IDGM=10,IDW=80,IDZ=90,IDH=81)
C          SUSY ident code definitions. They are chosen to be similar
C          to those in versions < 6.50 but may be changed.
      INTEGER ISUPL,ISDNL,ISSTL,ISCHL,ISBT1,ISTP1
      INTEGER ISNEL,ISEL,ISNML,ISMUL,ISNTL,ISTAU1
      INTEGER ISUPR,ISDNR,ISSTR,ISCHR,ISBT2,ISTP2
      INTEGER ISNER,ISER,ISNMR,ISMUR,ISNTR,ISTAU2
      INTEGER ISZ1,ISZ2,ISZ3,ISZ4,ISW1,ISW2,ISGL
      INTEGER ISHL,ISHH,ISHA,ISHC
      INTEGER ISGRAV
      INTEGER IDTAUL,IDTAUR
      PARAMETER (ISUPL=21,ISDNL=22,ISSTL=23,ISCHL=24,ISBT1=25,ISTP1=26)
      PARAMETER (ISNEL=31,ISEL=32,ISNML=33,ISMUL=34,ISNTL=35,ISTAU1=36)
      PARAMETER (ISUPR=41,ISDNR=42,ISSTR=43,ISCHR=44,ISBT2=45,ISTP2=46)
      PARAMETER (ISNER=51,ISER=52,ISNMR=53,ISMUR=54,ISNTR=55,ISTAU2=56)
      PARAMETER (ISGL=29)
      PARAMETER (ISZ1=30,ISZ2=40,ISZ3=50,ISZ4=60,ISW1=39,ISW2=49)
      PARAMETER (ISHL=82,ISHH=83,ISHA=84,ISHC=86)
      PARAMETER (ISGRAV=91)
      PARAMETER (IDTAUL=10016,IDTAUR=20016)
```

These are based on standard ISAJET but can be changed to interface with other generators. Since masses except the t mass are hard wired, one should check the kinematics for any decay before using it with possibly different masses.

Instead of specifying all the SUSY parameters at the electroweak scale using the MSSMi commands, one can instead use the SUGRA parameter to specify in the minimal supergravity framework the common scalar mass m_0, the common gaugino mass $m_{1/2}$, and the soft trilinear

SUSY breaking parameter A_0 at the GUT scale, the ratio $\tan\beta$ of Higgs vacuum expectation values at the electroweak scale, and $\mathrm{sgn}\,\mu$, the sign of the Higgsino mass term. The `NUSUGi` keywords allow one to break the assumption of universality in various ways. `NUSUG1` sets the gaugino masses; `NUSUG2` sets the A terms; `NUSUG3` sets the Higgs masses; `NUSUG4` sets the first generation squark and slepton masses; and `NUSUG5` sets the third generation masses. The keyword `SSBCSC` can be used to specify an alternative scale (i.e., not the coupling constant unification scale) for the RGE boundary conditions.

The renormalization group equations now include all the two-loop terms for both gauge and Yukawa couplings and the possible contributions from right-handed neutrinos. These equations are solved iteratively using Runge-Kutta numerical integration to determine the weak scale parameters from the GUT scale ones:

1. The 2-loop RGE's for the gauge, Yukawa, and soft breaking terms are run from the weak scale M_Z up to the GUT scale (where $\alpha_1 = \alpha_2$) or other high scale defined by the model, taking all thresholds into account.

2. The GUT scale boundary conditions are imposed, and the RGE's are run back to M_Z, again taking thresholds into account.

3. The masses of the SUSY particles and the values of the soft breaking parameters B and mu needed for radiative symmetry are computed, e.g.

$$\mu^2(M_Z) = \frac{M_{H_1}^2 - M_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - M_Z^2/2$$

   These couplings are frozen out at the scale $\sqrt{M(t_L)M(t_R)}$.

4. The 1-loop radiative corrections are computed.

5. The process is then iterated until stable results are obtained.

This is essentially identical to the procedure used by several other groups. Other possible constraints such as b-τ unification and limits on proton decay have not been included.

An alternative to the SUGRA model is the Gauge Mediated SUSY Breaking (GMSB) model of Dine and Nelson, Phys. Rev. **D48**, 1277 (1973); Dine, Nelson, Nir, and Shirman, Phys. Rev. **D53**, 2658 (1996). In this model SUSY is broken dynamically and communicated to the MSSM through messenger fields at a messenger mass scale M_m much less than the Planck scale. If the messenger fields are in complete representations of $SU(5)$, then the unification of couplings suggested by the LEP data is preserved. The simplest model has a single $5 + \bar{5}$ messenger sector with a mass M_m and and a SUSY-breaking VEV F_m of its auxiliary field F. Gauginos get masses from one-loop graphs proportional to $\Lambda_m = F_m/M_m$ times the appropriate gauge coupling α_i; sfermions get squared-masses from two-loop graphs proportional to Λ_m times the square of the appropriate α_i. If there are N_5 messenger fields, the gaugino masses and sfermion masses-squared each contain a factor of N_5.

The parameters of the GMSB model implemented in ISAJET are

- $\Lambda_m = F_m/M_m$: the scale of SUSY breaking, typically 10–100 TeV;

- $M_m > \Lambda_m$: the messenger mass scale, at which the boundary conditions for the renormalization group equations are imposed;
- N_5: the equivalent number of $5 + \bar{5}$ messenger fields.
- $\tan\beta$: the ratio of Higgs vacuum expectation values at the electroweak scale;
- $\operatorname{sgn}\mu = \pm 1$: the sign of the Higgsino mass term;
- $C_{\rm grav} \geq 1$: the ratio of the gravitino mass to the value it would have had if the only SUSY breaking scale were F_m.

The solution of the renormalization group equations is essentially the same as for SUGRA; only the boundary conditions are changed. In particular it is assumed that electroweak symmetry is broken radiatively by the top Yukawa coupling.

In GMSB models the lightest SUSY particle is always the nearly massless gravitino $\tilde{G}$. The phenomenology depends on the nature of the next lightest SUSY particle (NLSP) and on its lifetime to decay to a gravitino. The NLSP can be either a neutralino $\tilde{\chi}_1^0$ or a slepton $\tilde{\tau}_1$. Its lifetime depends on the gravitino mass, which is determined by the scale of SUSY breaking not just in the messenger sector but also in any other hidden sector. If this is set by the messenger scale F_m, i.e., if $C_{\rm grav} \approx 1$, then this lifetime is generally short. However, if the messenger SUSY breaking scale F_m is related by a small coupling constant to a much larger SUSY breaking scale F_b, then $C_{\rm grav} \gg 1$ and the NLSP can be long-lived. The correct scale is not known, so $C_{\rm grav}$ should be treated as an arbitrary parameter. More complicated GMSB models may be run by using the GMSB2 keyword.

Patch ISASSRUN of ISAJET provides a main program SSRUN and some utility programs to produce human readable output. These utilities must be rewritten if the IDENT codes in /SSTYPE/ are modified. To create the stand-alone version of ISASUSY with SSRUN, run YPATCHY on isajet.car with the following cradle (with `&` replaced by `+`):

```
&USE,*ISASUSY.                  Select all code
&USE,NOCERN.                    No CERN Library
&USE,IMPNONE.                   Use IMPLICIT NONE
&EXE.                           Write everything to ASM
&PAM,T=C.                       Read PAM file
&QUIT.                          Quit
```

Compile, link, and run the resulting program, and follow the prompts for input. Patch ISASSRUN also contains a main program SUGRUN that reads the minimal SUGRA, non-universal SUGRA, or GMSB parameters, solves the renormalization group equations, and calculates the masses and branching ratios. To create the stand-alone version of ISASUGRA, run YPATCHY with the following cradle:

```
&USE,*ISASUGRA.                 Select all code
&USE,NOCERN.                    No CERN Library
&USE,IMPNONE.                   Use IMPLICIT NONE
&EXE.                           Write everything to ASM
```

```
&PAM.                                   Read PAM file
&QUIT.                                  Quit
```

The documentation for ISASUSY and ISASUGRA is included with that for ISAJET.

ISASUSY is written in ANSI standard Fortran 77 except that IMPLICIT NONE is used if +USE,IMPNONE is selected in the Patchy cradle. All variables are explicitly typed, and variables starting with I,J,K,L,M,N are not necessarily integers. All external names such as the names of subroutines and common blocks start with the letters SS. Most calculations are done in double precision. If +USE,NOCERN is selected in the Patchy cradle, then the Cernlib routines EISRS1 and its auxiliaries to calculate the eigenvalues of a real symmetric matrix and DDILOG to calculate the dilogarithm function are included. Hence it is not necessary to link with Cernlib.

The physics assumptions and details of incorporating the Minimal Supersymmetric Model into ISAJET have appeared in a conference proceedings entitled "Simulating Supersymmetry with ISAJET 7.0/ISASUSY 1.0" by H. Baer, F. Paige, S. Protopopescu and X. Tata; this has appeared in the proceedings of the workshop on *Physics at Current Accelerators and Supercolliders*, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory, 1993). Detailed references may be found therein. Users wishing to cite an appropriate source should, however, cite the most recent ISAJET manual, e.g. hep-ph/0001086 (1999).

13 IsaTools

`IsaTools` is a optional set of subroutines included with Isajet 7.72 and later for the evaluation of various low-energy and cosmological constraints on supersymmetric models using the Isajet supersymmetry code. The package consists of:

1. `IsaRED`, subroutines to evaluate the relic density of (stable) neutralino dark matter in the universe;
2. `IsaBSG`, subroutines to evalue the branching fraction $BF(b \to s\gamma)$;
3. `IsaAMU`, subroutines to evaluate supersymmetric contributions to $\Delta a_\mu \equiv (g-2)_\mu/2$;
4. `IsaBMM`, subroutines to evaluate $BF(B_s \to \mu^+\mu^-)$ and $BF(B_d \to \tau^+\tau^-)$ in the MSSM;
5. `IsaRES`, subroutines to evaluate the spin-independent and spin-dependent neutralino-proton and neutralino-neutron scattering cross sections for direct detection of dark matter.

Below we provide a brief description of each subroutine along with appropriate references. The main code author is indicated by an underline and should be the first choice of contact for any bug related problems.

Details on the application of IsaTools and on the structure of IsaRED, IsaBSG, IsaBMM and IsaRES could be found at the web page
`http://hep.pa.msu.edu/belyaev/proj/dark_matter/isatools_public/`.

13.1 IsaRED (H. Baer, C. Balazs and A. Belyaev)

`IsaRED` evaluates the neutralino relic density in the MSSM. The complete set of tree-level $\tilde{Z}_1\tilde{Z}_1$ annihilation and co-annihilation processes is evaluated. Calculations are based on the matrix element library created using the CompHEP program and interfaced to Isajet. The following SUSY particles in the initial state are taken into account: $\tilde{Z}_1$, $\tilde{Z}_2$, $\tilde{W}_1$, $\tilde{e}_1$, $\tilde{\mu}_1$, $\tilde{\tau}_1$, $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$, $\tilde{u}_1$, $\tilde{d}_1$, $\tilde{c}_1$, $\tilde{s}_1$, $\tilde{t}_1$, $\tilde{b}_1$, $\tilde{g}$.

The fully relativistic thermally averaged cross section times velocity is computed using the Gondolo-Gelmini[1] and Gondolo-Edsjo[2] formalism. The freeze out temperature is solved for iteratively, and then the relic density is computed. To achieve our final result with relativistic thermal averaging, we perform a three-dimensional integral over *i.*) the final state subprocess scattering angle, *ii.*) the subprocess energy parameter, and *iii.*) the temperature from freeze-out to the present day temperature of the universe. We perform the three-dimensional integral using the BASES algorithm[3], which implements sequentially improved sampling in multi-dimensional Monte Carlo integration, generally with good convergence properties. See Ref. [4, 5] for details.

13.2 IsaBSG (H. Baer and M. Brhlik)

This subroutine evaluates the $BF(b \to s\gamma)$ using the effective field theory approach of Anlauf[7], wherein the Wilson co-efficients of various operators are calculated at the relevant scales where various sparticles are integrated out of the theory. This method is used to handle the tW, tH^- and $\tilde{t}_{1,2}\tilde{W}_{1,2}$ loops. The Wilson co-efficients are evolved to scale $Q = M_W$, wherein the effective theory is taken to be the SM. The SM Wilson co-efficients are evolved to $Q = m_b$ using NLO anomalous dimension matrices. Once at scale $Q = m_b$, the complete NLO corrections to the O_2, O_7 and O_8 operators are included[8]. The scale dependence of the final result is of order 10%. In the high scale calculation, the weak scale value of $m_b(M_{SUSY})$ is calculated using two loop RG evolution with full one loop corrections to m_b. This effect is important at large $\tan\beta$. Also, the $\tilde{g}\tilde{q}$ and $\tilde{Z}_i\tilde{q}$ loops are included directly at scale $Q = M_W$, according to the calculation of Masiero et al.[9]. This necessitates an RG computation of well over 100 soft terms and couplings in order to generate the proper off diagonal soft terms at scale $Q = M_W$.

13.3 IsaAMU (H. Baer and C. Balazs)

Supersymmetric contributions to $a_\mu \equiv (g-2)_\mu/2$ come from $\tilde{W}_i\tilde{\nu}_\mu$ and $\tilde{Z}_i\tilde{\mu}_{1,2}$ loops. Complete formulae for these contributions in the MSSM can be found in the article by T. Moroi, Ref. [10]. Numerical analyses based on his result are presented in Ref. [11].

13.4 IsaBMM (J. K. Mizukoshi, X. Tata and Y. Wang)

This subroutine evaluates the branching ratio of the decays $B_s \to \mu^+\mu^-$ and $B_d \to \tau^+\tau^-$, according to formulae given in Ref. [12]:

$$\begin{aligned} B(B_{d'} \to \ell^+\ell^-) &= \frac{G_F^2\alpha^2 m_{B_{d'}}^3 \tau_{B_{d'}} f_{B_{d'}}^2}{64\pi^3}|V_{tb}^* V_{td'}|^2\sqrt{1-\frac{4m_\ell^2}{m_{B_{d'}}^2}} \\ &\times\left[\left(1-\frac{4m_\ell^2}{m_{B_{d'}}^2}\right)\left|\frac{m_{B_{d'}}}{m_b+m_{d'}}c_{Q_1}\right|^2+\left|\frac{2m_\ell}{m_{B_{d'}}}c_{10}-\frac{m_{B_{d'}}}{m_b+m_{d'}}c_{Q_2}\right|^2\right], \end{aligned}$$

where $d' = s, d$ and $\ell = \mu, \tau$. The coefficients of the effective Hamiltonian of the above processes,

$$\begin{aligned} c_{Q_1} &= \frac{2\pi}{\alpha}\chi_{FC}\frac{m_b m_\ell}{\cos^2\beta\sin^2\beta}\left(\frac{\cos(\beta+\alpha)\sin\alpha}{m_h^2}-\frac{\sin(\beta+\alpha)\cos\alpha}{m_H^2}\right), \\ c_{Q_2} &= \frac{2\pi}{\alpha}\chi_{FC}\frac{m_b m_\ell}{\cos^2\beta}\frac{1}{m_A^2} \end{aligned}$$

contain the Higgs-mediated flavor changing neutral currents that arise as a consequence of coupling of Higgs superfield $\hat{h}_u$ with down type fermions at one-loop level. Since this coupling is enhanced for large $\langle h_u\rangle/\langle h_d\rangle \equiv \tan\beta$, the calculations were performed keeping only terms that are most enhanced by powers of $\tan\beta$. Therefore, the χ_{FC} parameter given in Ref. [12] is valid only for $\tan\beta \gtrsim 25-30$. Moreover, in the calculations of one-loop h, Hbd', and Abd' vertex corrections, it has been assumed that the chargino masses are well approximated by $|M_2|$ and $|\mu|$.

13.5 IsaRES (C. Balazs, A. Belyaev and M. Brhlik)

`IsaRES` evaluates the spin-independent and spin-dependent neutralino-proton and neutralino-neutron scattering cross sections according to formulae contained in Refs. [13, 14].

The interactions for elastic scattering of neutralinos on nuclei can be described by the sum of spin-independent ($\mathcal{L}^{eff}_{scalar}$) and spin-dependent ($\mathcal{L}^{eff}_{spin}$) Lagrangian terms:

$$\mathcal{L}^{eff}_{elastic} = \mathcal{L}^{eff}_{scalar} + \mathcal{L}^{eff}_{spin}. \tag{1}$$

σ_{SI} for neutralino scattering off of nuclei is the main experimental observable since σ_{SI} contributions from individual nucleons in the nucleus add coherently and can be expressed via SI nuclear form-factors. The cross section σ_{SI} receives contributions from neutralino-quark interactions via squark, Z and Higgs boson exchanges, and from neutralino-gluon interactions involving quarks, squarks and Higgs bosons at the 1-loop level. The differential σ_{SI} off a nucleus X^A_Z with mass m_A takes the form [15]

$$\frac{d\sigma^{SI}}{d|\vec{q}|^2} = \frac{1}{\pi v^2}[Zf_p + (A-Z)f_n]^2 F^2(Q_r), \tag{2}$$

where $\vec{q} = \frac{m_A m_{\widetilde{Z}_1}}{m_A + m_{\widetilde{Z}_1}}\vec{v}$ is the three-momentum transfer, $Q_r = \frac{|\vec{q}|^2}{2m_A}$ and $F^2(Q_r)$ is the scalar nuclear form factor, $\vec{v}$ is the velocity of the incident neutralino and f_p and f_n are effective neutralino couplings to protons and neutrons respectively. The original calculation has been done in [16] and can be expressed as

$$\frac{f_N}{m_N} = \sum_{q=u,d,s} \frac{f^{(N)}_{Tq}}{m_q}\left[f^{(\tilde{q})}_q + f^{(H)}_q - \frac{1}{2}m_q m_{\tilde{Z}_1} g_q\right] + \frac{2}{27}f^{(N)}_{TG}\sum_{c,b,t}\frac{f^{(H)}_q}{m_q} + \cdots \tag{3}$$

where $N = p,\ n$ for neutron, proton respectively, and $f^{(N)}_{TG} = 1 - \sum_{q=u,d,s} f^{(N)}_{Tq}$. The expressions for the $f^{(H)}_q$ couplings as well as other terms denoted by $\cdots$ are omitted for the sake of brevity but can be found in [16, 17].

The parameters $f^{(p)}_{Tq}$, defined by

$$< N|m_q\bar{q}q|N >= m_N f^{(N)}_{Tq} \qquad (q = u, d, s) \tag{4}$$

contain uncertainties due to errors on the experimental measurements of quark masses. We have adopted values of renormalization-invariant constants $f^{(p)}_{Tq}$ and their uncertainties determined in [18]:

$$f^{(p)}_{Tu} = 0.020 \pm 0.004, \qquad f^{(p)}_{Td} = 0.026 \pm 0.005, \qquad f^{(p)}_{Ts} = 0.118 \pm 0.062 \tag{5}$$

$$f^{(n)}_{Tu} = 0.014 \pm 0.003, \qquad f^{(n)}_{Td} = 0.036 \pm 0.008, \qquad f^{(n)}_{Ts} = 0.118 \pm 0.062. \tag{6}$$

The cross section σ^{SI}_p for neutralino scattering off the proton is calculated in the limit of zero momentum transfer

$$\sigma^{SI} = \frac{4}{\pi} {m^N_r}^2 f^2_N \tag{7}$$

where $m^N_r = m_N m_{\tilde{Z}_1}/(m_N + m_{\tilde{Z}_1})$.

In our calculations we are using the CTEQ5L set of parton density functions [19] evaluated at the QCD scale $Q = \sqrt{M^2_{SUSY} - m^2_{\tilde{Z}_1}}$. The PDF parton density function can be easily updated to any other PDF upon request.

13.6 Compiling and Using IsaTools (F. Paige)

`IsaTools` is so far interfaced only to ISASUGRA, not to ISAJET or ISASUSY. Since `IsaRED` contains about 1.4M lines of Fortran code generated by CompHEP, both compilation and execution are somewhat slow. It was therefore decided to make `IsaTools` optional and to keep keep this code in a separate file, `isared.tar`.

If you *do not* want to use `IsaTools`, edit the `Makefile` and select

```
ISATOOLS =
LIBTOOLS =
```

Then build ISAJET, ISASUSY, and ISASUGRA as described previously. The variable `ISATOOLS` serves as a Patchy flag, and the blank value turns off the calls to `IsaTools` in ISASUGRA.

If you *do* want to use `IsaTools`, edit the `Makefile` and select

```
ISATOOLS = ISATOOLS
LIBTOOLS = -lisared
```

This is the default, and it requires `isared.tar` to be in the same directory as `isajet.car` and `Makefile`. First build `libisared.a` for `IsaTools` and then build the rest of ISAJET, ISASUSY, and ISASUGRA with the commands

```
make isatools
make
```

The outputs from `IsaTools` will appear after the mass spectrum and before the list of decay modes.

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14 Deriving the Weak Scale Couplings from the RGEs: RGEFLAV

A number of subroutines, collectively called RGEFLAV, are made available as part of the ISAJET distribution from ISAJET 7.81 and later. When activated through a choice in ISASUGRA, the RGEFLAV code will recalculate the RGE running of dimensionless and dimensionful parameters in the MSSM, taking into account the full flavor structure of the quarks and squarks [1, 2, 3]. The output consists of all dimensionless and dimensionful parameters (at both high scale and weak scale) with full flavor structure, and both the up- and down-type (6×6) squark mass matrices.

The RGEFLAV code contains threshold corrections to the one-loop RGEs for both the MSSM and SM in addition to the usual two-loop MSSM/SM RGEs in the $\overline{\rm DR}$ scheme. The two-loop RGEs do not contain (numerically higher order) threshold effects, and, for the gauge and Yukawa couplings, we use the MSSM form above $Q = m_H$, the scale of the heavy Higgs scalar mass, and the SM form below $Q = m_H$.

This section aims to provide an overall description of the code and the various issues encountered in the procedure. After outlining the broad approach, we will consider each segment of the code individually, from the input file, through the choice and application of the various boundary conditions, to the final output.

General Outline

RGEFLAV has been designed to be used in combination with ISASUGRA, and is called at the end of the ISASUGRA code. The inputs to ISASUGRA will be used by RGEFLAV as the initial conditions, as will some variables from the main run. The first step to activate RGEFLAV is to input a filename prefix such as `Prefix`. Then, a general outline of the order in which RGEFLAV carries out the various steps is:

1. Read the input file `Prefix.rgein` that contains all the choices available to the user. A user-modifiable sample file called `sample.rgein` is included with the ISAJET distribution.

2. Introduce gauge couplings, light quark Yukawa couplings, third generation Yukawa couplings (from ISASUGRA's main run) and the SM Higgs field VEV all at M_Z.

3. Run the gauge couplings and diagonal Yukawa matrices to m_t. At this scale, insert ISASUGRA's earlier value for $f_t(m_t)$ and rotate the Yukawa coupling matrices into the current basis using user defined rotations.

4. Run up to the high scale using appropriate thresholds, whose values (without taking flavor into account) have already been obtained, to transform SM running into MSSM running.

5. Insert high scale boundary conditions. It is after this step that we begin the iterative loop.

6. Run back down to the weak scale, decoupling particles as their thresholds are passed.

7. At the scale of the heavy Higgs scalar mass, m_H, change over to the new set of RGEs, with restricted Lagrangian terms, as a result of the decoupling of the heavy Higgs boson terms [2]. Save the values of the couplings at m_H for use when running back up.

8. At M_{SUSY}, defined as $\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, apply the electroweak symmetry breaking conditions and radiative corrections to the third generation Yukawa couplings [4].

9. Once the running reaches m_t rotate back to the basis in which the Yukawa matrices are diagonal, reset $f_t(m_t)$ to the value used previously and continue running to M_Z. From now on f_t remains in the theory all the way to M_Z and will therefore change the running of the various couplings from that obtained during the first upwards run.

10. Reset the values of the gauge and all Yukawa couplings other than f_t at M_Z.

11. Run back up to the high scale, applying the rotation (and boundary condition on f_t) at m_t and the thresholds as before.

12. Reset the high scale values of the **a**-parameters and SSB mass matrices and iterate.

13. On the final run, stop at m_H, the heavy Higgs threshold, and output the couplings at this scale.

14. At present, the code then calls `SQSIX`, which is discussed in Subsec. 14.8.

The code cannot be run independently from the `ISAJET` distribution because there are some common blocks which must be filled for `RGEFLAV` to execute properly. These common blocks are:

- `SUGPAS` and `SUGMG`: Contain the initial values of the various thresholds.
- `WKYUK`: Contains the weak scale third generation Yukawa couplings.
- `BSG`: Contains the radiative corrections to the Yukawa couplings.
- `RGEMS`: Contains the value of M_{SUSY} and the value of μ at this scale.

The user may use non-universal GUT scale boundary conditions according to the choices given by `ISASUGRA` and available in the input file (discussed next), but the user must also enter approximate mSUGRA conditions before `RGEFLAV` can begin the iterative process. In the case that running does not continue all the way up to the GUT scale, *e.g.*, in GMSB models, Question 6. of the input file `Prefix.rgein` allows for an optional input of the high scale value at which the boundary conditions are specified.

14.1 The Input File

Once `RGEFLAV` is called at the end of `ISASUGRA`, it reads the input from `Prefix.rgein`, a sample of which is included with the `ISAJET` distribution as file `sample.rgein`. The choices, numbered in the same order as the input file, are:

1. Whether to use the complete two-loop equations. If the following line is '`0`', only one-loop RGEs will be calculated, but threshold effects will still be included. Choosing to only calculate one-loop running speeds up the program by around 15%.

2. This item allows the user to choose between complex inputs and real inputs. If the next line is '`1`', all inputs must be in complex form and the KM matrix will include a phase. If '`0`' is entered, any optional inputs which follow must be single numbers representing one real entry each. Otherwise the program will print an error message and continue no further. Choosing to use a real KM matrix and real boundary conditions dramatically speeds up the running of the RGEs.

3. When the answer to Question 2. is '`1`' the user may wish to enter a phase for μ as opposed to a simple sign. If the user answers yes, the optional setting for `THETA` on the next line is used, otherwise this value is ignored, and a sign for μ consistent with the `ISASUGRA` input is used.

4. If the response to Question 4. is '`1`' the program will not attempt to change the thresholds from those obtained by the main `ISASUGRA` run. Otherwise, thresholds for: the left- and right-handed squarks and sleptons (*i.e.*, the eigenvalues of the SSB sfermion mass matrices), the higgsino (μ), the bino (M_1) and the winos (M_2), will be set during the running of `RGEFLAV`.

5. The mSUGRA GUT scale inputs used by `ISASUGRA` are automatically passed to `RGEFLAV`, but they are only all used if the user sets this entry to '`1`'. If so, reading of the input file moves to Question 17. Otherwise, reading continues to the non-universal inputs, 6. − 16.

Inputs 6. − 16. are the alternative GUT scale inputs. We will deal with these inputs in more detail in Sec. 14.4. After taking care of the GUT scale inputs, the file continues with the choices relating to the weak scale rotations $\mathbf{V}_{L,R}(u,d)$, which are the unitary matrices that diagonalise the Yukawa coupling matrices. For the up-type quarks we use the relation

$$\mathbf{f}_u^{\rm diag} = \mathbf{V}_L^T(u)\mathbf{f}_u\mathbf{V}_R^*(u) \;, \tag{8}$$

and similarly for the down-type quarks. See, *e.g.*, Sec. V. of Ref. [1] for a more detailed discussion.

17. The first choice in the final section is the basis in which to output the results. Since $SU(2)$ is broken in the quark mass basis, we only use this basis for the weak scale inputs. Instead, the output is in a current basis in which either the up- or down-type quarks are diagonal at m_t, thereby retaining $SU(2)$ invariance. Note that when interfacing with `SQSIX`, described in Sec. 14.8, the answer to Question 17. *must* be '`1`' since we wish to associate the $\tilde{c}_{L,R}$ squarks with the c quark mass eigenstate.

18. This question asks whether the user should enter their own choice of general rotation matrices, as described in Sec. 14.2. These matrices will be used to rotate the mass basis quark Yukawa matrices into the current basis and therefore this corresponds to a choice of current basis. Note, however, that the output is always in a current basis where either the up- or down-type quarks are diagonal at m_t. If the user chooses '`1`', the inputs for Question 21. will be read next. If not, the file proceeds to the next question, which allows for more basic choices for the rotation matrices.

19. Here the user chooses the form of $\mathbf{V}_L(u)$. Either they can choose to have $\mathbf{V}_L(u) = \mathbf{K}$, or $\mathbf{V}_L(u) = \mathbb{1}$. The program will ensure that $\mathbf{V}_L(d)$ is fixed so that the appropriate combination of these two matrices is the correct KM matrix, $\mathbf{K}$, according to

$$\mathbf{K} \equiv \mathbf{V}_L^\dagger(u)\mathbf{V}_L(d) \ . \tag{9}$$

20. If the KM matrix is the only source of flavor-violation, the form of the $\mathbf{V}_R(u,d)$ matrices is unimportant. In this entry the user is given a restricted choice for the matrices $\mathbf{V}_R(u,d)$ which serve as default entries if the response to Question 18. is '`0`'. Either both $\mathbf{V}_R(u)$ and $\mathbf{V}_R(d)$ are the unit matrix or $\mathbf{V}_R(u) = \mathbf{K}^\dagger$ and $\mathbf{V}_R(d) = \mathbf{K}$.

21. The final entries are the choice of parameters which will be used to define the rotation matrices if the response to Question 18. is '`1`'. If the user has chosen to have real running in Question 2. the phase in these inputs is ignored. For more detail on the way these inputs are converted into unitary matrices, see Sec. 14.2.

We now move on to consider some of the above inputs in more detail.

14.2 Entering a General Unitary Matrix

As mentioned above, Question 21. of `Prefix.rgein` allows the user to define their own $\mathbf{V}_{L,R}(u,d)$ matrices. Since the KM matrix must still be correct, $\mathbf{V}_L(u)$, $\mathbf{V}_R(u)$, $\mathbf{V}_R(d)$ are taken in as inputs and $\mathbf{V}_L(d)$ is then fixed by requiring that (9) is satisfied.

In order to guarantee the unitary nature of the rotation[1], the input file reads three angles (α, β and γ) and a phase (δ) using a similar parametrisation to that used for the KM matrix. Each unitary matrix, $\mathbf{U}$, is given by

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & s_\gamma \\ 0 & -s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} c_\beta & 0 & s_\beta e^{-i\delta} \\ 0 & 1 & 0 \\ -s_\beta e^{i\delta} & 0 & c_\beta \end{pmatrix} \begin{pmatrix} c_\alpha & s_\alpha & 0 \\ -s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} , \tag{10}$$

$c_\alpha = \cos\alpha$, etc. Note that this is not the most general unitary matrix possible, which would include an additional two phases. However, it is considered that for the time being this choice of inputs will suffice for most practical applications, and the addition of two phases would require only a minor change to the code.

[1] The matrices $\mathbf{V}_{L,R}(u)$ should be numerically unitary to high accuracy.

14.3 Weak Scale Boundary Conditions

Once ISASUGRA calls the main program, and the input file has been read, RGEFLAV fixes the weak scale boundary conditions and runs them up to the GUT scale using the subroutine UPMZMHIGH. For the gauge sector, we take as our input the current PDG values [5]

$$\alpha_{em}^{-1}(M_Z) = 127.925 \pm 0.016 \; ;$$
$$\alpha_s(M_Z, \overline{\mathrm{MS}}) = 0.1176 \pm 0.002 \; ;$$
$$\sin^2\theta_W(M_Z, \overline{\mathrm{MS}}) = 0.23119 \pm 0.00014 \; .$$

theory with the electroweak gauge bosons and the top quark integrated out at $Q = M_Z$. In order to use the SM evolution for $Q > M_Z$, we must match these couplings to those of the full SM, which to two-loop accuracy implies that the SM gauge couplings in the $\overline{\mathrm{MS}}$ scheme are given by [6],

$$\frac{1}{\alpha_1(M_Z)} = \frac{3}{5}\left[\frac{1-\sin^2\theta_W(M_Z)}{\alpha_{em}(M_Z)}\right] + \frac{3}{5}\left[1-\sin^2\theta_W(M_Z)\right] 4\pi\Omega(M_Z) \; , \tag{11}$$

$$\frac{1}{\alpha_2(M_Z)} = \frac{\sin^2\theta_W(M_Z)}{\alpha_{em}(M_Z)} + \sin^2\theta_W(M_Z) 4\pi\Omega(M_Z) \; , \tag{12}$$

$$\frac{1}{\alpha_3(M_Z)} = \frac{1}{\alpha_s(M_Z)} + 4\pi\Omega_3(M_Z) \; , \tag{13}$$

$$\Omega(\mu) = \frac{1}{24\pi^2}\left[1 - 21\ln\left(\frac{M_W}{\mu}\right)\right] + \frac{2}{9\pi^2}\ln\left(\frac{m_t}{\mu}\right) , \tag{14}$$

$$\Omega_3(\mu) = \frac{2}{24\pi^2}\ln\left(\frac{m_t}{\mu}\right) . \tag{15}$$

of the effective theory down to $Q = M_Z$, we have integrated out the top quark at $Q = M_Z$ rather than at its mass as we do for all other particles. This is the origin of the $\ln(m_t/\mu)$ terms in the matching conditions for the gauge couplings above. Since we decouple all SUSY particles as well as the additional Higgs bosons at the scale of their mass, we do not get corresponding jumps in the gauge couplings as these decouple.

Next, we convert the values of these gauge couplings in the $\overline{\mathrm{MS}}$ scheme to their corresponding values in the $\overline{\mathrm{DR}}$ scheme and use the results as boundary conditions at $Q = M_Z$ when solving the RGEs.

For the Yukawa couplings, we begin with the quark masses at $Q = M_Z$ (the masses of the light quarks and leptons at M_Z can be found in Ref. [7]), and convert to SM Yukawa coupling matrices using $v_{SM} = 248.6/\sqrt{2}$ GeV as in Ref. [4]. The masses of the first two generations of quarks have substantial error, which leads to a corresponding error in the Yukawa coupling. The third generation quark masses are more precisely known and in practice the values of the third generation Yukawa couplings are taken from ISASUGRA, with bottom and tau Yukawa couplings at the scale $Q = M_Z$ and the top Yukawa coupling at $Q = m_t$. In extracting these Yukawa couplings we include SUSY radiative corrections [4] at M_{SUSY} obtained by ISASUGRA during its execution, with inter-generation quark mixing neglected.

These diagonal Yukawa couplings, which are in the "quark mass basis" are run to m_t with no flavor structure since it is a good approximation that the running is mainly due to the strong coupling. At m_t all three Yukawa matrices are rotated to the user's choice of current basis using the SM version of (8), replacing $\mathbf{f}_u$ with $\boldsymbol{\lambda}_u = \sin\beta\ \mathbf{f}_u$, and the corresponding relation for $\boldsymbol{\lambda}_d$ ($= \cos\beta\ \mathbf{f}_d$).

Running then continues to the GUT scale with a basic RGE subroutine, `RGE215`, which only contains the RGEs necessary for running the gauge and Yukawa couplings, and implements only rudimentary thresholds. When we reach the scale $Q = m_H$ in the course of running up, we switch from SM Yukawa matrices ($\boldsymbol{\lambda}_{u,d,e}$) to MSSM Yukawa matrices ($\mathbf{f}_{u,d,e}$) and from the SM VEV (v_{SM}) to the VEVs in the two Higgs doublet model:

The subroutine `HIGHIN` takes care of the boundary conditions at the high scale as discussed next.

14.4 Boundary Conditions at the High Scale

The running is deemed to have reached the GUT scale when $\alpha_1(Q)-\alpha_2(Q)$ becomes negative, unless the user responded to Question 6. with a fixed $M_{\rm HIGH}$, in which case the running terminates at the value that was chosen in `Prefix.rgein`.

Since the purpose of `RGEFLAV` is to simulate flavor physics of sparticles in as general a way as possible, subject to experimental constraints that seem to suggest that flavor physics is largely restricted by the structure of the Yukawa coupling matrices, we use a general parametrisation for SSB parameters that does not introduce a new source of flavor-violation, but allows for non-universality of model parameters. A different source of flavor-violation can easily be incorporated by allowing for additional, arbitrary contributions to the SSB mass and trilinear parameter matrices. We parametrize the SSB sfermion mass and **a**-parameter matrices at the high scale as,

$$\mathbf{m}^2_{Q,L} = m^2_{\{Q,L\}0}\mathbb{1} + \mathbf{T}_{Q,L} \qquad (16)$$

$$\mathbf{m}^2_{U,D,E} = m^2_{\{U,D,E\}0}[c_{U,D,E}\mathbb{1} + R_{U,D,E}\mathbf{f}^T_{u,d,e}\mathbf{f}^*_{u,d,e} + S_{U,D,E}(\mathbf{f}^T_{u,d,e}\mathbf{f}^*_{u,d,e})^2] + \mathbf{T}_{U,D,E} \qquad (17)$$

$$\mathbf{a}_{u,d,e} = \mathbf{f}_{u,d,e}[A_{\{u,d,e\}0}\mathbb{1} + W_{u,d,e}\mathbf{f}^\dagger_{u,d,e}\mathbf{f}_{u,d,e} + X_{u,d,e}(\mathbf{f}^\dagger_{u,d,e}\mathbf{f}_{u,d,e})^2] + \mathbf{Z}_{u,d,e}\ , \qquad (18)$$

the superpotential Yukawa coupling matrices *in an arbitrary current basis* at the same scale at which the SSB parameters of the model are specified. The matrices $\mathbf{T}_{Q,L,U,D,E}$ and $\mathbf{Z}_{u,d,e}$ have been introduced only to allow for additional sources of flavor-violation not contained in the Yukawa couplings. Setting $\mathbf{T}_{Q,L,U,D,E} = \mathbf{Z}_{u,d,e} = \mathbf{0}$ gives us the most general parametrisation of the three-generation R-parity conserving MSSM where the Yukawa coupling matrices are the sole source of flavor-violation.

Questions 9. to 16. in `Prefix.rgein` allow the user to choose arbitrary values of all the input coefficients above, subject to the constraint that $\mathbf{T}_{Q,L,U,D,E}$ are Hermitian. The familiar universal mSUGRA boundary conditions are reproduced by setting $c_{U,D,E} = 1$; $m^2_{\{Q,L\}0} = m^2_{\{U,D,E\}0} = m_0^2$; $A_{\{u,d,e\}0} = A_0$; $R_{U,D,E} = S_{U,D,E} = W_{u,d,e} = X_{u,d,e} = 0$; $\mathbf{T}_{Q,L} = \mathbf{T}_{U,D,E} = \mathbf{Z}_{u,d,e} = \mathbf{0}$ in (17)-(18).

The remaining GUT scale inputs — namely, those for the gaugino and Higgs boson scalar masses — are simple numbers, which can be either given by the mSUGRA parameters passed from the ISASUGRA main code, or entered by the user in Questions. 7. and 8. of Prefix.rgein.

14.5 Electroweak Symmetry Breaking

After fixing the high scale parameters, the program proceeds to the subroutine DOWNMHIGHMZ, which runs the entire collection of RGEs contained in the subroutine RGE646. At each step, the code checks to see whether the scale is below $M_{\rm SUSY}$ and, at the point $M_{\rm SUSY}$ is passed, applies the electroweak breaking conditions using the subroutine DOWNMSCOND.

Since $M_{\rm SUSY}$ is at the scale $\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, the electroweak symmetry breaking conditions will always be applied at a scale smaller than the mass of the heaviest SUSY particle. As a result, μ, the higgsino mass parameter, is no longer equal to $\tilde{\mu}$, the parameter that enters the Higgs potential. Moreover, the Higgs potential depends only on $M^2_{H_u} \equiv \left(m^2_{H_u} + |\tilde{\mu}|^2\right)$ and $M^2_{H_d} \equiv \left(m^2_{H_d} + |\tilde{\mu}|^2\right)$, so that it is not possible to separate $|\tilde{\mu}|^2$ from the SSB parameters $m^2_{H_u}$ and $m^2_{H_d}$ that we specify at the high scale. Notice, however, that we can define the relations

$$\left(M^2_{H_u} + M^2_{H_d}\right) \equiv m^2_{H_u} + m^2_{H_d} + 2\,|\tilde{\mu}|^2 \quad \text{and}$$
$$\left(M^2_{H_d} - M^2_{H_u}\right) \equiv m^2_{H_d} - m^2_{H_u} \; .$$

Higgs potential can be written as,

$$b = sc\left(M^2_{H_u} + M^2_{H_d}\right) \tag{19}$$
$$\left(M^2_{H_u} + M^2_{H_d}\right) = -\tfrac{1}{\cos 2\beta}\left(M^2_{H_d} - M^2_{H_u}\right) - \tfrac{1}{2}\left(g'^2 + g^2\right)\left(v_u^2 + v_d^2\right) \; . \tag{20}$$

$(M^2_{H_u}+M^2_{H_d})$ in terms of the difference. Since we know this difference at the high scale, we can evolve this down to $M_{\rm SUSY}$ (along with other SSB parameters) during the iterative process that we use to solve the RGEs. At $Q = M_{\rm SUSY}$ we use (20) to solve for $(M^2_{H_u} + M^2_{H_d})$, which can be evolved back up to the high scale, and during the running we can fix $\tilde{\mu} = \mu$ at the scale of the heaviest SUSY particle. At the high scale we reset the difference, $(M^2_{H_u} - M^2_{H_d})$, to its input value and iterate as per the discussion in Sec. 14.6. The value of the higgsino parameter μ can then be obtained at all scales using the relevant RGE [2].

Finally, the b-parameter can be eliminated in favour of $\tan\beta$ using (19). Although the b-parameter is complex in general, our decision to make v_u and v_d real and positive[2] requires that b also be real and positive at the scale $M_{\rm SUSY}$. Our parameter does, however, retain the ability to develop complex parts as a result of the running, and will not necessarily remain real at all scales.

Up to this point, we have ignored another potential complication that arises if $M_{\rm SUSY} < m_H$. In this case, the heavy particles of the Higgs sector have decoupled by the time we

[2]We can always make a gauge transformation such that just the lower component of H_u has a VEV, and that this VEV is real and positive. Then the minimization of the scalar potential in the Higgs sector requires that the VEV of H_d is aligned; *i.e.*, is also in its lower component. This alignment is a result of dynamics. Finally, we can redefine the phase of the doublet superfield $\hat{H}_d$ so that v_d is real and positive. This is not compulsory, but is the customary practice that allows us to define $\tan\beta$ to be real and positive.

apply the electroweak symmetry breaking conditions, and we only have the light doublet in the effective theory that we use to calculate the RGEs. In this case, the heavy Higgs doublet mass term $\left[c^2\left(m_{H_u}^2+|\tilde{\mu}|^2\right)+s^2\left(m_{H_d}^2+|\tilde{\mu}|^2\right)+sc\left(b+b^*\right)\right]$ and the mixing terms, $\left[sc\left(m_{H_u}^2+|\tilde{\mu}|^2\right)-sc\left(m_{H_d}^2+|\tilde{\mu}|^2\right)+s^2b-c^2b^*\right]$ (and its complex conjugate), together with $\tan\beta$, are frozen at their values at $Q=m_H$, while the light doublet mass parameter, $\left[s^2\left(m_{H_u}^2+|\tilde{\mu}|^2\right)+c^2\left(m_{H_d}^2+|\tilde{\mu}|^2\right)-sc\left(b+b^*\right)\right]$, along with $v_{\rm SM}$, continue to evolve down to $M_{\rm SUSY}$. The three frozen coefficients together with the evolved mass term for the light doublet must therefore be used to solve for $\left(m_{H_d}^2+|\tilde{\mu}|^2\right)$, $\left(m_{H_u}^2+|\tilde{\mu}|^2\right)$ and the complex b-parameter. We can then find a solution in the same manner as for $M_{\rm SUSY}>m_H$.

Before closing this section, we should add that although we have discussed EWSB conditions only at tree-level, in practice we minimize the one-loop effective potential including effects of third generation Yukawa couplings, but ignoring all flavor-mixing effects. These corrections, which effectively shift the Higgs boson SSB mass squared parameters by Σ_u and Σ_d, respectively, are evaluated by replacing $f_{t,b,\tau}$ in the standard relations by the (3,3) element of the corresponding Yukawa matrices in the basis where they are diagonal at m_t, and with the dimensionful parameters also replaced by the (3,3) element of the corresponding matrix (or the appropriate frozen value).

14.6 Iterative Stage

Now that the boundary conditions are defined at each of the three relevant scales, the iteration can begin. The subroutines `DOWNMHIGHMZ` and `UPMZMHIGH2` implement the running in each direction. The iteration takes place a fixed number of times, chosen so that the RGEs reach a stable solution.

Unless the user has answered '`1`' to using fixed thresholds from the main `ISASUGRA` run in Question 4. of `Prefix.rgein`, the program will alter all the thresholds on each downwards run, except those for the gluinos and heavy Higgs fields, which are fixed at the locations obtained earlier by `ISASUGRA`.

The running is carried out as follows:

Downwards running

The subroutine first runs from the GUT scale to the highest threshold with the number of steps given by the variable `NSTEP`. During the ith iteration, this variable has the value $100\times(1.6)^i$, until we reach iteration number 5 at which point it becomes fixed at $100\times(1.6)^5$. If this is the first iteration, the thresholds are taken to be the current `ISASUGRA` thresholds. Running continues between thresholds (inserting the boundary conditions at m_H and $M_{\rm SUSY}$ when necessary) with the number of steps given by

$$\text{Number of Steps}=\frac{|\log\left(Q_1/Q_2\right)|}{\log\left(M_{HIGH}/m_t\right)}\times\left(25\times\texttt{NSTEP}\right)\,, \tag{21}$$

where Q_1 and Q_2 are the scales of the two thresholds between which the running is being carried out. The factor 25 was chosen to ensure enough sampling between the thresholds without unnecessarily slowing down processing time.

At each step, the SSB sfermion mass matrices are diagonalised. If the user has not fixed the thresholds to be the same as those passed from the ISASUGRA main code, the derived eigenvalues are checked to see if any matter sfermions have decoupled. When one of these sparticles does decouple, the subroutine CHDEC carries out the following procedure:

1. Remove the influence of the decoupled particle in the RGE running of the remaining couplings.
2. Store the eigenvectors of the mass matrix so that the rotation between the diagonal basis at the decoupling scale and the original current basis is saved.
3. Store all the entries of the mass matrix itself so that they can be used as a boundary condition when running up.
4. Call the subroutine REMSF so that, in the basis where the mass matrix is diagonal, the entry corresponding to the decoupled particle is set to zero. This ensures that the eigenvector for this particle is removed from the original current basis matrix and cannot influence further downward running.

The subroutine continues to run down until it reaches m_t, where it rotates from the current basis back to the basis in which the Yukawa matrices are diagonal.[3] Running resumes using the SM $\overline{\rm DR}$ RGEs in SMRGEDR, *without decoupling the top quark*, to the scale M_Z.

The integration of the RGEs is carried out by the CERNLIB routine RKSTP. The RGE subroutine, RGE646, contains RGEs for all couplings with and without tildes and with full thresholds for the one-loop running. The quartic couplings are entered separately, but they are set to be equal to their SM counterparts since the RGEs for the quartics are unavailable at this time. In addition, RGE646 contains the two-loop terms from the RGEs, which depend only on the MSSM values of the couplings. In order to obtain an estimate of the two-loop contributions, the pure MSSM RGEs are solved even below all thresholds and these MSSM couplings are used for the two-loop level running of the SUSY couplings. This is acceptable since we are only trying to achieve two-loop level accuracy, and threshold effects in the two-loop terms are numerically much smaller.

Once we have decoupled at least one of the matter sfermions, the right-hand side of the RGEs are calculated in the basis where the squark/slepton matrices are diagonal at the decoupling scale. This is still a current basis, since the quarks and leptons are rotated by the same amount as the squarks and sleptons. RGE646 rotates all couplings into this basis when calculating the right-hand side of the RGEs and, at the end of the subroutine, rotates the result back to the original current basis.

Note that if the location of the thresholds is altered every iteration, the Yukawa couplings are unable to reach a convergent solution. This is because moving the thresholds can disrupt the fine cancellation that is required to obtain vanishing values at m_t for the off-diagonal elements of the Yukawa matrices in their mass basis. We therefore only allow RGEFLAV to change the locations of the thresholds for the first ten iterations. This ensures that the Yukawa couplings converge as closely as allowed by the numerical accuracy of the machine.

[3] Rather than diagonalise the Yukawa matrices at this scale, RGEFLAV uses the rotation matrices, $\mathbf{V}_{L,R}(u,d)$ that were used on the first upwards running. Practically, this means that the rotation matrices are one of the boundary conditions on our iterative running.

Upwards running

Before commencing the run back up to the GUT scale, the boundary conditions at M_Z — the gauge couplings and Yukawa coupling matrices in the quark mass basis — are reset. Running then continues to m_t, where the top quark Yukawa coupling is reset and the Yukawa matrices are rotated into the current basis, and then continues again until the first threshold above m_t is reached.

The upwards running makes no changes to the thresholds. At each step, the subroutine checks whether a threshold has been passed. If so, the influence of the particle in question is removed from the RGEs, and if this is a matter sfermion threshold the soft mass matrix is set to the value which was saved at this point during the downward run.

The RGE subroutine `RGE646` is used just as with downwards running. When we have some but not all matter sfermions present in the theory, we rotate to the basis where the soft mass matrix for the sfermions in question is diagonal at the scale of decoupling. We know what this rotation is since it too was saved in the previous run down.

Once all the thresholds have been passed, the RGEs are equivalent to the standard MSSM RGEs and running continues in a straightforward manner until the high scale is reached. Residual inaccuracies in the running mean that the tilde-couplings are not precisely equal to their non-tilde counterparts once we have passed the highest SUSY threshold. Since these differences can feed back into the other couplings via the RGEs, we set the tilde-couplings equal to the usual SUSY couplings once the highest SUSY threshold has been passed. Also, if the answer to Question 6. is '`0`', since the scale at which the gauge couplings unify may be altered by the location of the thresholds, we allow the running to continue past the unification scale from the previous iteration, and increase the number of steps for this iteration so that the step-size remains constant.

We have checked that if we do not reset the weak scale boundary conditions, and instead use the final values from the previous call to `DOWNMHIGHMZ`, the upwards running is precisely the same as the downwards running.

14.7 `RGEFLAV` Output

The iterative section exits at the high scale after resetting the GUT scale boundary conditions. In order to provide useful output, the code makes one final downward run to m_H. This scale was chosen due to its significance as a point where a number of the operators in the Lagrangian change, however, the output scale could have been chosen to be anywhere between the two extremes of the running. It is expected that m_H will be fairly close to the scale at which the user will be using the couplings for their calculations.

The code writes out two files that contain all the dimensionless and dimensionful couplings of the theory, `Prefix.wkout` and `Prefix.gtout`. The first line of each file contains information on the scale at which the couplings are valid, which in the case of `Prefix.wkout` is $Q = m_H$. Each set of numbers is labelled with the coupling to which they refer, in the order laid out in Table 14.7, arrangement, for example

COUPLINGS	$g_1 \quad g_2 \quad g_3$
f_U	$\mathbf{f}_u$
f_D	$\mathbf{f}_d$
f_E	$\mathbf{f}_e$
GAUGINO MASSES M	$M_1 \quad M_2 \quad M_3$
GAUGINO MASSES M′	$M_1' \quad M_2' \quad M_3'$
a_U	$\mathbf{a}_u$
a_D	$\mathbf{a}_d$
a_E	$\mathbf{a}_e$
SQUARED HIGGS MASSES	$m^2_{H_u} \quad m^2_{H_d}$
M_Q^2	$\mathbf{m}^2_Q$
M_L^2	$\mathbf{m}^2_L$
M_U^2	$\mathbf{m}^2_U$
M_D^2	$\mathbf{m}^2_D$
M_E^2	$\mathbf{m}^2_E$
MU AND B	$\mu \quad b$
V_U AND V_D	$v_u \quad v_d$
Prefix.wkout only	
lambda_U	$\boldsymbol{\lambda}_u$
lambda_D	$\boldsymbol{\lambda}_d$
lambda_E	$\boldsymbol{\lambda}_e$
GTP_Q	$\tilde{\mathbf{g}}'^Q$
GTP_L	$\tilde{\mathbf{g}}'^L$
GTP_U	$\tilde{\mathbf{g}}'^{u_R}$
GTP_D	$\tilde{\mathbf{g}}'^{d_R}$
GTP_E	$\tilde{\mathbf{g}}'^{e_R}$
GTPH_U AND GTPH_D	$\tilde{g}'^{h_u} \quad \tilde{g}'^{h_d}$
GT_Q	$\tilde{\mathbf{g}}^Q$
GT_L	$\tilde{\mathbf{g}}^L$
GTH_U AND GTH_D	$\tilde{g}^{h_u} \quad \tilde{g}^{h_d}$
GTS_Q	$\tilde{\mathbf{g}}^Q_s$
GTS_U	$\tilde{\mathbf{g}}^{u_R}_s$
GTS_D	$\tilde{\mathbf{g}}^{d_R}_s$

FTQ_U	$\tilde{\mathbf{f}}^Q_u$
FTQ_D	$\tilde{\mathbf{f}}^Q_d$
FTL_E	$\tilde{\mathbf{f}}^L_e$
FTU_U	$\tilde{\mathbf{f}}^{u_R}_u$
FTD_D	$\tilde{\mathbf{f}}^{d_R}_d$
FTE_E	$\tilde{\mathbf{f}}^{e_R}_e$
sGTPH_U AND cGTPH_D	$s\tilde{g}'^{h_u} \quad c\tilde{g}'^{h_d}$
sGTH_U AND cGTH_D	$s\tilde{g}^{h_u} \quad c\tilde{g}^{h_d}$
MSSM Section - both files	
COUPLINGS	$g_1 \quad g_2 \quad g_3$
f_U	$\mathbf{f}_u$
f_D	$\mathbf{f}_d$
f_E	$\mathbf{f}_e$
GAUGINO MASSES	$M_1 \quad M_2 \quad M_3$
a_U	$\mathbf{a}_u$
a_D	$\mathbf{a}_d$
a_E	$\mathbf{a}_e$
SQUARED HIGGS MASSES	$m^2_{H_u} \quad m^2_{H_d}$
M_Q^2	$\mathbf{m}^2_Q$
M_L^2	$\mathbf{m}^2_L$
M_U^2	$\mathbf{m}^2_U$
M_D^2	$\mathbf{m}^2_D$
M_E^2	$\mathbf{m}^2_E$
MU AND B	$\mu \quad b$
Prefix.wkout only	
TRI_U	$\left[s\mathbf{a}_u - c(\tilde{\mu}^*\mathbf{f}^{h_u}_u)\right]$
TRI_D	$\left[c\mathbf{a}_d - s(\tilde{\mu}^*\mathbf{f}^{h_d}_d)\right]$
TRI_E	$\left[c\mathbf{a}_e - s(\tilde{\mu}^*\mathbf{f}^{h_d}_e)\right]$
M_HUD	$*$
SM VEV AND LAMBDA_SM	$v_{SM} \quad \lambda$
MTSF_U	$\tilde{\mu}^*\mathbf{f}^{h_u}_u$
MTSF_D	$\tilde{\mu}^*\mathbf{f}^{h_d}_d$
MTSF_E	$\tilde{\mu}^*\mathbf{f}^{h_d}_e$

Table 1: The various dimensionless and dimensionful couplings contained within the output files `Prefix.wkout` and `Prefix.gtout` in the order in which they are printed. Note the two sections that are only printed in `Prefix.wkout`, and the section that contains couplings derived using the MSSM RGEs only. The entry marked with an asterisk is: $\left[s^2\left(m^2_{H_u} + |\tilde{\mu}|^2\right) + c^2\left(m^2_{H_d} + |\tilde{\mu}|^2\right) - sc\,(b + b^*)\right]$.

$$
\begin{array}{lll}
\mathbf{f}_u : & & \\
(\mathbf{f}_u)_{11} & (\mathbf{f}_u)_{12} & (\mathbf{f}_u)_{13} \\
(\mathbf{f}_u)_{21} & (\mathbf{f}_u)_{22} & (\mathbf{f}_u)_{23} \\
(\mathbf{f}_u)_{31} & (\mathbf{f}_u)_{32} & (\mathbf{f}_u)_{33}
\end{array}
$$

$\tilde{\mathbf{f}}_u^Q$, that are equal to their MSSM counterparts at the GUT scale, these are not included in `Prefix.gtout`, which is a much smaller file. The notation used in Table 14.7 is described in full in Refs. [1, 2].

Both `Prefix.wkout` and `Prefix.gtout` are written in the basis chosen by the user in Question 17. of `Prefix.rgein`, where either the up- or the down-type Yukawa couplings are diagonal at m_t. For any specific calculation, the user can then simply evolve these couplings to higher or lower scales as desired, without the need to iterate. The output (in the basis where the up-type Yukawa coupling is diagonal) will be used in the subroutine `SQSIX` to calculate the $\tilde{t}_1$ decay rate, as described next.

14.8 The Decay Subroutine, `SQSIX`

`SQSIX` takes the full list of dimensionless and dimensionful couplings and calculates the two (6×6) squark mass matrices. Having found these in the basis chosen by the user in the input file, it diagonalises one of the two mass matrices. If the user chose for the up-type quark Yukawa coupling matrix to be diagonal at m_t (in the answer to Question 17. of `Prefix.rgein`), the up-type squark mass matrix will be diagonalised. Conversely, if the down-type quark Yukawa coupling matrix was chosen to be diagonal at m_t, then the down-type squark mass matrix will be diagonalised. If the user has chosen for the up-type squark mass matrix to be diagonalised, the final step is a call to `ST1CNEU`, which finds the rate for the decay $\tilde{t}_1 \to c\tilde{Z}_1$. The code carries out this procedure as follows.

1. Since the couplings are received from `RGEFLAV` at $Q = m_H$, `SQSIX` first evolves the couplings to the scale at which the decay is to be calculated, which we choose to be the lightest of the eigenvalues of the left- and right-handed soft mass matrices for the up-type (or down-type) squarks, using the subroutine `DECRUN`.

2. When the program arrives at the required scale, the mass matrices are reconstructed using the saved eigenvalues and eigenvectors from the running procedure. In other words, we recreate the mass matrices in the basis where the squarks are diagonal using the eigenvalues of each squark at its decoupling scale.

3. We then rotate from the squark mass basis to the current basis chosen in the input file, using the known eigenvectors in this basis.

4. Once we have all the couplings at the correct scale in the basis where the quark Yukawa coupling is diagonal at m_t, we construct the (6×6) mass matrix using (52)-(54) of Ref. [2] in the subroutines `UPSQM` and `DOWNSQM` — remembering to use the restricted set of couplings if we are calculating the decay at a scale $Q < m_H$.

5. The mass matrix is then diagonalised in `USMMA` (or `DSMMA` in the case that the down-type squarks are diagonalised), to find the eigenvalues and eigenvectors.

6. Finally, if the up-type squarks were diagonalised (and unless the kinematics forbid this decay from occurring), the decay rate calculation for $\tilde{t}_1 \to c\tilde{Z}_1$ from (60) of Ref. [2] is carried out. To find the rate, we must know $\tilde{\mathbf{g}}'^{Q}$, $\tilde{\mathbf{g}}^{Q}$, $\tilde{\mathbf{g}}'^{u_R}$, $\tilde{\mathbf{f}}_u^{Q}$, and $\tilde{\mathbf{f}}_u^{u_R}$, along with the masses and mixings of the squarks and neutralinos.

The final result for the $\tilde{t}_1 \to c\tilde{Z}_1$ rate is compared to the rate obtained using the single-step estimate in (8.21) of Ref. [3] and these two results are printed to the screen.

References for `RGEFLAV`

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15 Changes in Recent Versions

This section contains a record of changes in recently released versions of ISAJET, taken from the memoranda distributed to users. Note that the released version numbers are not necessarily consecutive.

15.1 Version 7.88, January 2018

We dedicate this version to Frank Paige (who passed away on October 16, 2017). Frank– along with Serban Protopopescu– created the original Isajet code in the late 1970s.

Version 7.88 includes the *natural* anomaly-mediated SUSY breaking model, using keyword input NAMSB. This model includes independent bulk soft term contributions to Higgs scalars $m_{H_u}(bulk)$ and $m_{H_d}(bulk)$ along with small bulk A_0 terms. These added terms can render AMSB as a natural model with $m_h \sim 125$ GeV for appropriate parameter choices. For natural parameter choices, then the LSP is a higgsino rather than a wino. The parameter space is given by $m_0(1,2)$, $m_0(3)$, $m_{3/2}$, A_0, $\tan\beta$, μ and m_A where small $\mu \sim 100-300$ GeV, $A_0 \sim m_0(3)$ and 80 TeV$< m_{3/2} < 150$ TeV lead to natural models.

15.2 Version 7.87, July 2017

Version 7.87 is functionally identical to 7.86. The only change is that the format has been converted from a Patchy .car file to a Unix .tar file with C Preprocessor directives. The conversion was mostly done automatically by changing Patchy `+CDE` to `#include`, Patchy `+SELF,IF=` to `#ifdef`, and Patchy —+SELF— to `#endif`. To facilitate the automatic conversion, the ISAJET and ISASUSY patches have been combined. The ISARED relic density code has not been modified.

15.3 Version 7.86, January 2017

Isajet 7.86 includes several changes.

1. Dominant two loop contributions from Dedes/Slavich to EWSB have been incorporated, which are relevant to the fine-tining calculation in the pMSSM.

2. Some corrections added to bring Higgs widths into closer accord with latest theory.

3. Some minor bugs in SUGEFF found by Peter Ruud are fixed.

4. New generalized mirage mediation model (GMM) based on arXiv:1610.06205 can be run using inputs α, $m_{3/2}$, c_m, c_{m3}, a_3, $\tan\beta$, $sign(\mu)$, c_{H_u} and c_{H_d}. The latter two inputs may be traded for μ and m_A if the $NUHM$ keyword is used.

15.4 Version 7.85, November 2015

Isajet 7.85 includes several changes.

1. Quark and gluon matrix elements for spin-independent neutralino-nucleon scattering rates in ISARES were updated according to Table 1 of Hisano et al., PRD87 (2013) 035020.

2. Light SUSY Higgs boson h coupling strengths are computed for Isasugra and are located in common block KPHGGS: κ_b, κ_t, κ_τ, κ_W, κ_Z, κ_g, κ_γ.

3. New Isasugra model which calculates non-universal soft terms via D-term splittings is programmed as model #11: NUHMDT. The input parameters are m_{16},, $m_{1/2}$, A_0, $\tan\beta$, μ, m_A where $\tan\beta$, μ and m_A are weak scale inputs and m_{10} and $sign(M_D^2)\sqrt{|M_D^2|}$ are output parameters. The D-term splitting model is defined in Eq. 11.18 of *Weak Scale Supersymmetry.*

4. A scale factor multiplier SCLFAC can be input in scattering events which multiplies the QCD coupling scale choice by a numerical factor which can increase or decrease the tree level QCD cross section which is output.

15.5 Version 7.84, June 2014

Isajet 7.84 includes several changes.

1. Minor bug fixes implemented in SUGEFF and the measure Δ_{EW}.
2. The LesHouchesAccord (LHA) file is now output to LesHouchesEvents (LHE) file.
3. The sparticle decay table is now output to LHA output file.
4. The ISAHEP routine was updated to allow for proper conversion of STDHEP labels back to ISAJET labels.
5. Isajet LHE file now prints out all subprocess reactions along with differential cross section $d\sigma/dp_t^2$ at $y = 0$. In the case of SUSY with ALL jettypes, this can add up to over 2500 subprocesses. Earlier versions of Pythia 6.xx allowed up to 500 subprocesses but Pythia 8 can handle arbitrarily many subprocesses.
6. The Isasusy (pMSSM) code will now output a LHA. Also there is the option to list in the LHA file from Isasusy all $e^+e^- \to SUSY/Higgs$ total cross sections depending on collider energy $\sqrt{s}$ and beam polarization $P_L(e^-)$ and $P_L(e^+)$ if the flag PRTEESIG is set in the Makefile.

Thanks to Azar for help with some of the above.

15.6 Version 7.83, June 2012

Isajet 7.83 contains four changes.

1. The branching fraction $BF(B_u \to \tau\nu_\tau)$ calculated at tree level and output in IsaTools.
2. Previous versions could generate negative squared masses for third generation sfermions. The current version stops the calculation and outputs an error message.
3. The percent electroweak fine-tuning is now output from Isasugra. The effective potential calculation includes some small contributions from W, Z and $H^\pm$. Thanks to A. Mustafayev for help.
4. The Isasusy mass spectrum output has been improved so that it is similar to the Isasugra output.

15.7 Version 7.82, June 2011

Isajet 7.82 contains some file name re-labelings needed to sensibly run `RGEFLAV`. It also contains a bug fix needed for reliable event generation in NUHM SUSY models. The gravitino mass is now output in LHA files.

15.8 Version 7.81, April 2011

This version adds an optional package ISAFLAVR for ISASUGRA that calculates the flavor structure in more detail. For detailed description, see Section 14 above and the new Makefile.

The latest version of Isajet provides `RGEFLAV` which is interfaced to ISASUGRA. After running ISASUGRA, the user is prompted if they wish to invoke RGEFLAV by providing a filename `Prefix`. The RGEFLAV run can take of order a minute to run, so should only be used in special cases.

`RGEFLAV` contains the RGEs, including one-loop threshold corrections, for all dimensionless and dimensionful parameters of the MSSM, with full matrix structure and support for complex entries. It therefore includes the complex KM matrix rotation in the quark sector. In addition, there are options in the input file, `Prefix.rgein` (provided by the user; a sample file `sample.rgein` is contained in the release), to allow the user to maintain control over sources of new flavor-violation at the high scale, while still providing the freedom to input general matrices if desired.

After iterating to find a convergent solution, the code writes out a full list of the dimensionless and dimensionful couplings at the scales $Q = m_H$ and $Q = M_{\rm HIGH}$ and both the up-type and down-type squark mass matrices, in a specified current basis. The output files are labeled as `Prefix.gtout`, `Prefix.wkout`, `Prefix.sqm2u`, and `Prefix.sqm2d`. Depending on this choice of basis, one of the two squark mass matrices is diagonalised and the eigenvectors and eigenvalues are also written to a file. More detailed information is available in the Isajet users manual, or in the journal article:

Threshold and Flavour Effects in the Renormalization Group Equations of the MSSM II: Dimensionful couplings. by Andrew D. Box and Xerxes Tata, . Oct 2008. (Published Oct 2008). 96pp. Published in Phys.Rev.D79:035004,2009. e-Print: arXiv:0810.5765 [hep-ph]

In addition, Isajet 7.81 contains some slight modifications of Yukawa coupling thresholds for SUSY RGE running, to gain accord with `RGEFLAV`, and some minor fixes to NUHM models suggested by A. Mustafayev.

15.9 Version 7.80, October 2009

In Isajet 7.80, we have expanded the ISALHA code to output Les Houches Accord (LHA) files for all varieties of supersymmetric models (earlier, just mSUGRA was enabled). We thank C. Balazs for help with this piece of code.

We have also fixed several bugs in the color flow assignments for subprocesses entering the Isajet Les Houches Event files (LHE).

15.10 Version 7.79, December 2008

We have added the hypercharged anomaly mediation model of Dermisek, Verlinde and Wang (PRL100, 131804 (2008)) to the SUSY model list. This model can be activated via use of the keyword HCAMSB.

In ISASUGRA, we have also adjusted the Yukawa coupling beta-function thresholds in subroutine SURG26. Previously, all squarks decoupled at a common scale set at $m_{\tilde{u}_L}$ and all sleptons decoupled at a common scale $m_{\tilde{e}_L}$. Now, the 1st/2nd and separately the 3rd generation squarks and sleptons decouple at their appropriate soft term values.

In addition, while 2-loop RGE terms were included for MSSM running, no 2-loop RGE terms were included for RGE running between M_Z and M_{SUSY}. Now, the MSSM 2-loop terms are included for running between M_Z and M_{SUSY}. The current version has improved agreement with the exact RGE decoupling solution given by Box and Tata: PRD77, 055007 (2008) and arXiv:0810.5765.

15.11 Version 7.78, March 2008

In Isajet 7.78, several upgraded features have been added.

First, we have added $\tilde{t}_1 \to bW\tilde{Z}_1$ 3-body stop decays, which were previously missing. We have also improved the loop calculation $\tilde{t}_1 \to c\tilde{Z}_1$, which often competes with the 3-body decay (thanks to A. Box for help on this issue).

We have also improved the calculation of $b \to s\gamma$ decay in Isatools. For full flavor structure in the decay, 137 MSSM RGEs must be solved simultaneously. These RGEs have been upgraded to two-loop ones, with double precision runnning (thanks to A. Mustafayev). While $BF(b \to s\gamma)$ is now more accurate, the calculation is slightly slower. Thus, when running Isatools, the user is now prompted as to which calculations are needed, so the slower $b \to s\gamma$ calculation can be avoided if the user is not interested in the result.

We have implemented in 7.76 the Les Houches Event output capability. By setting the keyword WRTLHE to TRUE in the input file, parton showering, hadronization and underlying event are turned off, so just the production subprocess followed by (cascade) decays are allowed, and color flow information is kept. Events are written in standard format to an output file named `isajet.lhe`, which can be read in by programs such as Pythia and Herwig, if alternative showering, hadronization and underlying event algorithms are desired, which may include color flow information. For the Pythia read-in code, it is necessary to set the lightest neutralino as stable by hand. This can be done via `CALL PYGIVE('MDCY(C1000022,1)=0')`. Alternatively, if one has access to the `PYDAT3` common block, one may set `MDCY(PYCOMP(1000022),1)=0`.

We have also fixed some minor bugs in the initialization of the neutralino relic density calculation by Isared, and an initialization bug that affects sparticle spectra coming from successive runs of Isasugra. We fixed a bug in sparticle width assignments going from IsaReD to CalcHEP. Many thanks to Sasha Pukhov and Sasha Belyaev for scrutinization of this code!

We have also changed the scale at which Yukawa couplings are evaluated at in the relic density calculation, from $Q = M_{SUSY}$ to $Q = 2m_{\tilde{Z}_1}$. In Isatools, we now output the thermally averaged neutralino annihilation cross section times velocity evaluated as $v \to 0$, which is useful for indirect detection of dark matter calculations.

15.12 Version 7.75, January 2007

In Isajet 7.75, we have added the mixed modulus-anomaly mediated SUSY breaking model which is inspired by the KKLT construct of type IIB string models compactified with fluxes to stabilize the moduli. This model gives rise to the phenomenon of mirage unification, wherein scalars and gauginos unify at an intermediate scale while gauge couplings still unify at M_{GUT}. The model is implemented as model #9 in Isasugra, and via the `MMAMSB` keyword for event generation. The inputs consist of modulus-AMSB mixing parameter α, gravitino mass $m_{3/2}$, $\tan\beta$, $sign(\mu)$, the matter and Higgs field modular weights n_Q, n_D, n_U, n_L, n_E, n_{H_d} and n_{H_u}, and the modulus powers ℓ_1, ℓ_2 and ℓ_3 that enter the gauge kinetic function. The modular weights can take values of 0, 1, 1/2 for fields on a D7 brane, D3 brane or brane intersection respectively. The modulus power takes values of 1 or 0 for gauge fields on a D7 brane or D3 brane, respectively. See hep-ph/0604253 for more detailed discussion.

We have also fixed a bug in the evaluation of radiatively corrected sbottom mixing angle. The self-energies used in th mixing angle calculation used the radiatively corrected sbottom mass scale, and thus were slightly inconsistent with the mass m(b1), which used the tree-level value of m(b1) in the self energies. The effect was amplified in some regions of parameter space where large cancellations occur in the sbottom mixing angle calculation. The error propagated into the mA calculation via Yukawa couplings, giving at large tan(beta) too large a value of mA.

15.13 Version 7.74, February 2006

In Isajet 7.73, we have modified the ISASUGRA SUSY spectrum calculator to extract all running parameters for mixed sparticles (the -inos, third generation squarks and sleptons) at the common scale `HIGFRZ` $= \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, to gain consistency in implementing the one-loop radiative corrections. Non-mixing soft terms are still extracted at their own scale, to minimize radiative corrections. Squark mixing contributions to the gluino mass radiative correction have also been added. For details, see H. Baer, J. Ferrandis, S. Kraml and W. Porod, hep-ph/0511123. We have also adapted the MSSM Higgs mass calculation to use the running b and t quark masses from the RG code. This typically decreases the light Higgs mass by 2–3 GeV.

We have also generalized the decay routines and radiative corrections to gain validity for either sign of the gaugino mass M_3. Previously, the decay formulae were calculated under the assumption of positive gluino mass, while all along either sign of M_1 and M_2 were allowed.

We have added an `ISALHA` subroutine which outputs a sparticle decay table in Les Houches Accord output format (thanks to C. Balazs for help on this).

Several minor bugs have been corrected in the relic density routine `ISARED` (thanks to A. Belyaev and A. Pukhov).

15.14 Version 7.72, August 2005

Isajet Version 7.72 provides `IsaTools`, including

1. `IsaRED`, subroutines to evaluate the relic density of (stable) neutralino dark matter in the universe;

2. `IsaBSG`, subroutines to evalue the branching fraction $BF(b \to s\gamma)$;

3. `IsaAMU`, subroutines to evaluate supersymmetric contributions to $\Delta a_\mu \equiv (g-2)_\mu/2$;

4. `IsaBMM`, subroutines to evaluate $BF(B_s \to \mu^+\mu^-)$ and $BF(B_d \to \tau^+\tau^-)$ in the MSSM;

5. `IsaRES`, subroutines to evaluate the spin-independent and spin-dependent neutralino-proton and neutralino-neutron scattering cross sections for direct detection of dark matter.

`IsaTools` is so far interfaced only to ISASUGRA, and it it requires `isared.tar` in addition to `isajet.car` and the standard `Makefile` contained therein.

This version also optionally provides from ISASUGRA both an output file compatible with the SUSY LesHouches Accord and an output file compatible with the ISAWIG interface for HERWIG. The ISAWIG interface assumes that R-parity is conserved.

Isajet 7.72 also allows for the entry of negative squared Higgs soft masses in SUGRA models with non-universality using the NUSUG3 keyword. In addition, in models with non-universal Higgs masses, one now has the option to use either GUT scale Higgs soft masses using NUSUG3, or weak scale parameters μ and m_A can be used as inputs using the NUHM keyword.

Various small corrections have been made.

15.15 Version 7.70, October 2004

The solution of the renormalization group equations for SUSY models has been converted to double precision. This gives better numerical stability, especially in difficult regions such as the large m_0 or "focus point" region of minimal SUGRA. The two-loop corrections for the top mass have been included.

Non-minimal AMSB models have been added. The keyword `AMSB2` can be used to set the high-scale s-fermion masses:

$$m_{\tilde{f}}^2 = m_{\tilde{f}}^2(\mathrm{AMSB}) + c_f m_0^2 \,.$$

The processes $e^+e^- \to \gamma\gamma \to f\bar{f}$ (f is a SM fermion) have also been included using Peskin's photon structure function from brem- and beamstrahlung. These gamma-gamma induced processes are activated by setting the keyword `GAMGAM` to be `.TRUE.` when running with `EEBEAM`.

15.16 Version 7.69, August 2003

The complete set of 1-loop radiative corrections to sparticle masses has been included in the ISAJET SUSY spectrum calculation, according to the formulae given by Pierce *et al.*, Nucl. Phys. **B491**, 3 (1997). Previous versions of ISAJET had included the logarithmic 1-loop corrections by freezing out soft mass parameters at a scale equal to their mass. The current calculation includes all finite corrections as well. Crucial contributions to the encoding of these expressions were made by Tadas Krupovnickas. We have also adjusted slightly the input $\overline{DR}$ gauge couplings at M_Z to coincide with measured central values. Logarithmic threshold corrections to gauge and Yukawa couplings are accounted for as in previous ISAJET versions by changing the beta functions in the RGEs as various soft mass thresholds are passed. We have also enlarged the set of SUSY RGEs to include running of the Higgs field vevs. The net effect of these changes is to modify various sparticle masses by typically 1-5% from the predictions of ISAJET 7.64.

The size of the small mass splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ is important for AMSB phenomenology. Rather than extracting this splitting from the general result, for the AMSB model we calculate it from the tree and the 1-loop vector boson loop graphs [taken from Cheng, Dobrescu and Matchev, Nucl. Phys. **B543**, 47, (1999)] and use it to set the $\tilde{\chi}_1^\pm$ mass.

We have modified the RGE solution to use the previous SUSY masses to compute μ before computing the new SUSY masses and from them the loop corrections to μ. This seems to improve the convergence, e.g., in the focus point, or hyperbolic branch region, of the mSUGRA model. The RGE solution still does not converge properly in isolated regions.

We have also corrected a sign mistake in the A-term boundary conditions for the anomaly-mediated SUSY breaking model.

15.17 Version 7.64, September 2002

The talk by Sabine Kraml at SUSY02 stressed the sensitivity of the allowed region of radiative electroweak symmetry breaking to fine details of the calculation. We have reexamined the issue and corrected several problems. A coding error in the Passarino-Veltman function B_1, `SSB1` has been fixed. The requirement $\mu^2 > 0$ is not imposed until after the solution of the renormalization group equations has stabilized. The value of $m_b(m_Z)$ has been updated to 2.83 GeV. A running gluino mass has been used in the top and bottom self-energy, along with α_s evaluated at a higher scale. Since the parameters of the Higgs potential vary rapidly near the weak scale, the convergence requirements on these have been loosened, while the requirements on the other parameters have been somewhat tightened. The combined effect of these changes is to shift the boundary for radiative electroweak symmetry breaking to higher scalar masses.

Stephan Lammel found that the matrix element used to generate $\tilde{g} \to \tilde{\chi}_i^\pm q\bar{q}$ was missing some poles, although the branching ratio was correct. This has been fixed.

The radiative decays $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0\gamma$ have been included.

15.18 Version 7.63, April 2002

The SUSY mass calculations have been improved, especially for M_A in terms of other SUSY parameters, by using the MSSM Yukawa couplings from the renormalization group equations. The numerical precision of the solution to the SUSY renormalization group equations has also been improved; this should give better stability near the boundaries of the allowed regions. The complete 1-loop self-energies for the t, b, and τ have been included from Pierce, Bagger, Matchev, and Zhang, Nucl. Phys. B491, 3 (1997). Finally, a number of bugs have been fixed, including one in the τ decay of t quarks.

15.19 Version 7.58, August 2001

The CTEQ5L parton distributions have been added and made the default.

Keywords NOB and NOTAU have been added to turn off B and τ decays so that an external decay package such as QQ or TAUOLA can be used. To preserve the polarization information for τ's, separate (non-standard) IDENT codes for τ_L and τ_R are used for NOTAU. The user must provide an appropriate interface.

The RANLUX random number generator has been added as a compile time option. It has a very long period, and any 32-bit integer seed gives an independent sequence. If RANLUX is used, the keyword SEED takes the integer seed plus two additional integers that are normally zero but can be used to restart the generator. See the CERN Program Library writeups for more information.

Right-handed neutrinos are now included if the keyword SUGRHN is used. The user must input the 3rd generation neutrino mass (at scale M_Z), the intermediate scale right handed neutrino Majorana mass M_N, and the soft SUSY-breaking masses A_n and $m_{\tilde{\nu}_R}$ at the GUT scale. Then the neutrino Yukawa coupling is computed in the simple see-saw model, and renormalization group evolution includes these effects between M_{GUT} and M_N.

The decays $\tilde{g} \to \tilde{W}_i u \bar{d}$ have been updated to include non-degenerate squark masses. The arbitrary width for $\tilde{t} \to \tilde{Z}_1 c$ used previously has been replaced by the calculated value. $\overline{DR}$ masses are used consistently. Yukawa couplings in the the SUGRA routine are now calculated in the $\overline{DR}$ regularization scheme to be consistent with two loop renormalization group evolution.

In solving the SUSY renormalization group equations, the requirement of good electroweak symmetry breaking is imposed only at the end. Previously a point could be rejected if there was no symmetry breaking even in the initial iteration with a truncated set of equations.

The sign of the A term in the AMSB model has been corrected.

The Standard Model process $e^+e^- \to ZH$ was missing and has been added.

Function ITRANS has been updated to reflect the current PDG particle codes for SUSY particles.

15.20 Version 7.51, May 2000

Several improvements in the SUSY RGE's have been made. All two-loop terms including both gauge and Yukawa couplings and the contributions from right-handed neutrinos are now included. There is a new keyword SSBCSC to specify a scale other than the GUT scale for the RGE boundary conditions.

The process $Z + \gamma$ is now included in WPAIR. (This was omitted because it has no contribution from triple gauge boson couplings.)

An incorrect type declaration produced unphysical results for beamsstrahlung on some computers. This has been fixed. While the bug is serious for e^+e^- with the EEBEAM option, it has no effect on other processes. Some other minor bugs have also been fixed.

15.21 Version 7.47, December 1999

There are several improvements in the treatment of supersymmetry. The Anomaly Mediated SUSY Breaking model of of Randall and Sundrum and of Gherghetta, Giudice, and Wells (hep-ph/9904378) has been added. The parameters of the model are a universal scalar mass m_0 at the GUT scale, a gravitino mass $m_{3/2}$, and the usual $\tan\beta$ and $\operatorname{sgn}\mu$. These are set by the `AMSB` keyword. The renormalization group equations have been extended to include two-loop Yukawa terms and right-handed sneutrinos (with default masses above the Planck scale). The $\tilde{\nu}_R$ play a role in the evolution for the inverted hierarchy models of Bagger, Feng, and Polonsky, hep-ph/9905292. SUSY loop corrections to Yukawa couplings have been incorporated in the SUSY mass calculations.

The Helas library of Murayama, Watanabe, and Hagiwara has been incorporated together with a simple multi-body phase space generator. This makes it possible to use code generated by MadGraph to produce multi-body hard scattering processes. As a first example, a `ZJJ` process that generates $Z+2$ jets has been added, with the Z treated as a narrow resonance. Additional processes may be added in future releases.

A new `EXTRADIM` process has been added to generate Kaluza-Klein graviton production in association with a jet or photon in models with extra dimensions at the TeV scale. The cross sections are from G.F.Giudice et al., hep-ph/9811291. We thank I. Hinchliffe and L. Vacavant for providing this.

A number of bugs have been fixed, including in particular one in the decay $\widetilde{W}_i \to \tilde{Z}_j \tau\nu$.

15.22 Version 7.44, April 1999

A serious bug introduced in Version 7.42 that could lead to matrix elements being stored for the wrong mode has been corrected. Some sign errors in the matrix elements for gaugino decays have also been corrected.

15.23 Version 7.42, January 1999

Beginning with this version, matrix elements are taken into account in the event generator as well as in the calculation of decay widths for MSSM three-body decays of the form $\tilde{A} \to \tilde{B} f \bar{f}$, where $\tilde{A}$ and $\tilde{B}$ are gluinos, charginos, or neutralinos. This is implemented by having ISASUSY save the poles and their couplings when calculating the decay width and then using these to reconstruct the matrix element. Other three-body decays may be included in the future. Decays selected with `FORCE` use the appropriate matrix elements.

As part of the changes to implement these matrix elements, the format of the decay table has changed. It now starts with a header line; if this does not match the internal version, then a warning is printed. The decay table now includes an index MELEM that specifies the matrix element to be used for all processes. This is also used for `FORCE` decays and is printed on the run listing for them. SUSY 3-body decays have internally generated negative values of MELEM.

This version also includes both initial state radiation and beamstrahlung for e^+e^- interactions. For initial state radiation (bremsstrahlung), if the `EEBREM` keyword is selected, an electron structure function will be used. For a convolution of both bremsstrahlung and beamstrahlung, the keyword `EEBEAM` must be used, with appropriate inputs (see documentation).

15.24 Version 7.40, October 1998

A new process WHIGGS generates $W^{\pm} + H$ and $Z + H$ events for both the Standard Model and SUSY models and also Higgs pair production for SUSY models. The types and W decay modes are selected with JETTYPE and WMODE as for WPAIR events. This process is of particular interest for producing fairly light Higgs bosons at the Tevatron. See the documentation for more details.

Some non-minimal GMSB models can be generated using a new keyword GMSB2. The optional parameters are an extra factor between the gaugino and scalar masses, shifts in the Higgs masses, a D-term proportional to hypercharge, and independent numbers of messenger fields for the three gauge groups. The documentation gives more details and references.

The default for SUGRA models has been changed to use $\alpha_s(M_Z) = 0.118$, the experimental value. This means that the couplings do not exactly unify at the GUT scale, presumably because of the effects of heavy particles. The keyword AL3UNI can be used to select exact unification, which produces too large a value for $\alpha_s(M_Z)$.

A number of three-body slepton decays that occur through left-right mixing are now included. These are obviously small but might compete with gravitino decays. In particular, a decay like $\tilde{\mu}_R \to \tilde{\tau}_1 \nu \bar{\nu}$ might lead to a wrong momentum measurement in the muon system. So far we have found no case in which this is probable.

The new release also includes a separate Unix tar file `mcpp.tar` containing C++ code to read a standard ISAJET output file and copy all the information into C++ classes. The tar file contains makefiles for Software Release Tools, documentation, and examples as well as the code.

15.25 Version 7.37, April 1998

Version 7.37 incorporates Gauge Mediated SUSY Breaking models for the first time. In these models, SUSY is broken in a hidden sector at a relatively low scale, and the masses of the MSSM fields are then produced through ordinary gauge interactions with messenger fields. The parameters of the GMSB model in ISAJET are M_m, the messenger mass scale; $\Lambda_m = F_m/M_m$, where F_m is the SUSY breaking scale in the messenger sector; N_5, the number of messenger fields; the usual $\tan\beta$ and $\operatorname{sgn}\mu$; and $C_{\text{grav}} \geq 1$, a factor which scales the gravitino mass and hence the lifetime for the lightest MSSM particle to decay into it.

GMSB models have a light gravitino $\tilde{G}$ as the lightest SUSY particle. The phenomenology of the model depends mainly on the nature of the next lightest SUSY particle, a $\tilde{\chi}_1^0$ or a $\tilde{\tau}_1$, which changes with the number N_5 of messengers. The phenomenology also depends on the lifetime for the $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ or $\tilde{\tau}_1 \to \tilde{G}\tau$ decay; this lifetime can be short or very long. All the relevant decays are included except for $\tilde{\mu} \to \nu\nu\tilde{\tau}_1$, which is very suppressed.

The keyword MGVTNO allows the user to independently input a gravitino gravitino mass for the MSSM option. This allows studies of SUGRA (or other types) of models where the gravitino is the LSP.

Version 7.37 also contains an extension of the SUGRA model with a variety of non-universal gaugino and sfermion masses and A terms at the GUT scale. This makes it possible to study, for example, how well the SUGRA assumptions can be tested.

Two significant bugs have also been corrected. The decay modes for B^* mesons were missing from the decay table since Version 7.29 and have been restored. A sign error in the interference term for chargino production has been corrected, leading to a larger chargino pair cross section at the Tevatron.

15.26 Version 7.32, November 1997

This version makes several corrections in various chargino and neutralino widths, thus changing the branching ratios for large $\tan\beta$. For $\tilde{\chi}_2^0$, for example, the $\tilde{\chi}_1^0 b\bar{b}$ branching ratio is decreased significantly, while the $\tilde{\chi}_1^0\tau^+\tau^-$ one is increased. Thus the SUGRA phenomenology for $\tan\beta \sim 30$ is modified substantially.

The new version also fixes a few bugs, including a possible numerical precision problem in the Drell-Yan process at high mass and q_T. It also includes a missing routine for the Zebra interface.

15.27 Version 7.31, August 1997

Version fixes a couple of bugs in Version 7.29. In particular, the JETTYPE selection did not work correctly for supersymmetric Higgs bosons, and there was an error in the interactive interface for MSSM input. Since these could lead to incorrect results, users should replace the old version. We thank Art Kreymer for finding these problems.

Since top quarks decay before they have time to hadronize, they are now put directly onto the particle list. Top hadrons ($t\bar{u}$, $t\bar{d}$, etc.) no longer appear, and FORCE should be used directly for the top quark, i.e.

```
FORCE
6,11,-12,5/
```

The documentation has been converted to LaTeX. Run either LaTeX 2.09 or LaTeX 2e three times to resolve all the forward references. Either US (8.5x11 inch) or A4 size paper can be used.

15.28 Version 7.30, July 1997

This version fixes a couple of bugs in the previous version. In particular, the JETTYPE selection did not work correctly for supersymmetric Higgs bosons, and there was an error in the interactive interface for MSSM input. Since these could lead to incorrect results, users should replace the old version. We thank Art Kreymer for finding these problems.

Since top quarks decay before they have time to hadronize, they are now put directly onto the particle list. Top hadrons ($t\bar{u}$, tud, etc.) no longer appear, and FORCE should be used directly for the top quark, i.e.

```
FORCE
6,11,-12,5/
```

The documentation has been converted to LaTeX. Run either LaTeX 2.09 or LaTeX 2e three times to resolve all the forward references. Either US (8.5×11 inch) or A4 size paper can be used.

15.29 Version 7.29, May 1997

While the previous version was applicable for large as well as small $\tan\beta$, it did contain approximations for the 3-body decays $\tilde{g} \to t\bar{b}\tilde{W}_i$, $\tilde{Z}_i \to b\bar{b}\tilde{Z}_j, \tau\tau\tilde{Z}_j$, and $\tilde{W}_i \to \tau\nu\tilde{Z}_j$. The complete tree-level calculations for three body decays of the gluino, chargino and neutralino, with all Yukawa couplings and mixings, have now been included (thanks mainly to M. Drees). We have compared our branching ratios with those calculated by A. Bartl and collaborators; the agreement is generally good.

The decay patterns of gluinos, charginos and neutralinos may differ from previous expectations if $\tan\beta$ is large. In particular, decays into τ's and b's are often enhanced, while decays into e's and μ's are reduced. It could be important for experiments to study new types of signatures, since the cross sections for conventional signatures may be considerably reduced.

We have also corrected several bugs, including a fairly serious one in the selection of jet types for SUSY Higgs. We thank A. Kreymer for pointing this out to us.

15.30 Version 7.27, January 1997

The new version contains substantial improvements in the treatment of the Minimal Supersymmetric Standard Model (MSSM) and the SUGRA model. The squarks of the first two generations are no longer assumed to be degenerate. The mass splittings and all the two-body decay modes are now correctly calculated for large $\tan\beta$. While there are still some approximations for three-body modes, ISAJET is now usable for the whole range $1 \lesssim \tan\beta \lesssim M_t/M_b$. The most interesting new feature for large $\tan\beta$ is that third generation modes can be strongly enhanced or even completely dominant.

To accomodate these changes it was necessary to change the MSSM input parameters. To avoid confusion, the MSSM keywords have been renamed MSSM[A-C] instead of MSSM[1-3], and the order of the parameters has been changed. See the input section of the manual for details.

Treatment of the MSSM Higgs sector has also been improved. In the renormalization group equations the Higgs couplings are frozen at a higher scale, $Q = \sqrt{M(\tilde{t}_L)M(\tilde{t}_R)}$. Running t, b and τ masses evaluated at that scale are used to reproduce the dominant 2-loop effects. There is some sensitivity to the choice of Q; our choice seems to give fairly stable results over a wide range of parameters and reasonable agreement with other calculations. In particular, the resulting light Higgs masses are significantly lower than those from Version 7.22.

The default parton distributions have been updated to CTEQ3L. A bug in the PDFLIB interface and other minor bugs have been fixed.

15.31 Version 7.22, July 1996

The new version fixes errors in $\tilde{b} \to \tilde{W}t$ and in some $\tilde{t}$ decays and Higgs decays. It also contains a new decay table with updated τ, c, and b decays, based loosely on the QQ decay package from CLEO. The updated decays are less detailed than the full CLEO QQ program but an improvement over what existed before. The new decays involve a number of additional resonances, including $f_0(980)$, $a_1(1260)$, $f_2(1270)$, $K_1(1270)$, $K_1^*(1400)$, $K_2^*(1430)$, $\chi_{c1,2,3}$, and $\psi(2S)$, so users may have to change their interface routines.

A number of other small bugs have been corrected.

15.32 Version 7.20, June 1996

The new version corrects both errors introduced in Version 7.19 and longstanding errors in the final state QCD shower algorithm. It also includes the top mass in the cross sections for $gb \to Wt$ and $gt \to Zt$. When the t mass is taken into account, the process $gt \to Wb$ can have a pole in the physical region, so it has been removed; see the documentation for more discussion.

Steve Tether recently pointed out to us that the anomalous dimension for the $q \to qg$ branching used in the final state QCD branching algorithm was incorrect. In investigating this we found an additional error, a missing factor of $1/3$ in the $g \to q\bar{q}$ branching. The first error produces a small but non-negligible underestimate of gluon radiation from quarks. The second overestimates quark pair production from gluons by about a factor of 3. In particular, this means that backgrounds from heavy quarks Q coming from $g \to Q\bar{Q}$ have been overestimated.

The new version also allows the user to set arbitrary masses for the $U(1)$ and $SU(2)$ gaugino mases in the MSSM rather than deriving these from the gluino mass using grand unification. This could be useful in studying one of the SUSY interpretations of a CDF $ee\gamma\gamma\not{E}_T$ event recently suggested by Ambrosanio, Kane, Kribs, Martin and Mrenna. Note, however, that radiative decay are *not* included, although the user can force them and multiply by the appropriate branching ratios calculated by Haber and Wyler, Nucl. Phys. B323, 267 (1989). No explicit provision for the decay $\tilde{Z}_1 \to \tilde{G}\gamma$ of the lightest zino into a gravitino or goldstino and a photon has been made, but forcing the decay $\tilde{Z}_1 \to \nu\gamma$ has the same effect for any collider detector.

A number of other minor bugs have also been corrected.

15.33 Version 7.16, October 1995

The new version includes e^+e^- cross sections for both SUSY and Standard Model particles with polarized beams. The e^- and e^+ polarizations are specified with a new keyword EPOL. Polarization appears to be quite useful in studying SUSY particles at an e^+e^- collider.

The new release also includes some bug fixes for *pp* reactions, so you should upgrade even if you do not plan to use the polarized e^+e^- cross sections.

15.34 Version 7.13, September 1994

Version 7.13 of ISAJET fixes a bug that we introduced in the recently released 7.11 and another bug in $\tilde{g} \to \tilde{q}\bar{q}$. We felt it was essential to fix these bugs despite the proliferation of versions.

The new version includes the cross sections for the e^+e^- production of squarks, sleptons, gauginos, and Higgs bosons in Minimal Supersymmetric Standard Model (MSSM) or the minimal supergravity (SUGRA) model, including the effects of cascade decays. To generate such events, select the `E+E-` reaction type and either SUGRA or MSSM, e.g.,

```
SAMPLE E+E- JOB
300.,50000,10,100/
E+E-
SUGRA
100,100,0,2,-1/
TMASS
170,-1,1/
END
STOP
```

The effects of spin correlations in the production and decay, e.g., in $e^+e^- \to \widetilde{W}_1^+\widetilde{W}_1^-$, are not included.

It should be noted that the Standard Model e^+e^- generator in ISAJET does not include Bhabba scattering or W^+W^- and Z^0Z^0 production. Also, its hadronization model is cruder than that available in some other generators.

15.35 Version 7.11, September 1994

The new version includes the cross sections for the e^+e^- production of squarks, sleptons, gauginos, and Higgs bosons in Minimal Supersymmetric Standard Model (MSSM) or the minimal supergravity (SUGRA) model including the effects of cascade decays. To generate such events, select the `E+E-` reaction type and either SUGRA or MSSM, e.g.,

```
SAMPLE E+E- JOB
300.,50000,10,100/
E+E-
SUGRA
100,100,0,2,-1/
TMASS
170,-1,1/
END
STOP
```

The effects of spin correlations in the production and decay, e.g., in $e^+e^- \to \widetilde{W}_1^+\widetilde{W}_1^-$, are not included.

It should be noted that the Standard Model e^+e^- generator in ISAJET does not include Bhabba scattering or W^+W^- and Z^0Z^0 production. Also, its hadronization model is cruder than that available in some other generators.

15.36 Version 7.10, July 1994

This version adds a new option that solves the renormalization group equations to calculate the Minimal Supersymmetric Standard Model (MSSM) parameters in the minimal supergravity (SUGRA) model, assuming only that the low energy theory has the minimal particle content, that electroweak symmetry is radiatively broken, and that R-parity is conserved. The minimal SUGRA model has just four parameters, which are taken to be the common scalar mass m_0, the common gaugino mass $m_{1/2}$, the common trilinear SUSY breaking term A_0, all defined at the GUT scale, and $\tan\beta$; the sign of μ must also be given. The renormalization group equations are solved iteratively using Runge-Kutta integration including the correct thresholds. This program can be used either alone or as part of the event generator. In the latter case, the parameters are specified using

SUGRA
m_0, $m_{1/2}$, A_0, $\tan\beta$, $\operatorname{sgn}\mu$

While the SUGRA option is less general than the MSSM, it is theoretically attractive and provides a much more managable parameter space.

In addition there have been a number of improvements and bug fixes. An occasional infinite loop in the minimum bias generator has been fixed. A few SUSY cross sections and decay modes and the JETTYPE flags for SUSY particles have been corrected. The treatment of B baryons has been improved somewhat.