SUSY at LHC

- SUSY models
- sparticle production
- sparticle decay
- event generation
- searches at LHC
- precision measurements
Models of SUSY breaking

★ Spontaneous breaking of SUSY phen. inconsistent within MSSM
★ Hidden sector models (HS)
★ HS is arena for SUSY breaking; how to communicate SUSY breaking to visible sector (VS)?
  – gravity mediation: supergravity (SUGRA) and local SUSY: minimal messenger sector: $m_{3/2} \sim \text{TeV}$: LSP=bino/higgsino/wino/gravitino?
  – gauge mediation (GMSB): introduce messenger sector fields as intermediary between HS and VS: $m_{3/2} \ll \text{TeV}$: LSP=gravitino
  – anomaly mediation (AMSB): $m_{3/2} > \text{TeV}$: LSP=wino
★ role of extra dimensions? compactification? sequestered sector and AMSB; gaugino mediation; GUTs; ···
Calculate spectra using Isajet/Isasugra

- MSSM: weak scale inputs (no RGE running)
- mSUGRA
  - $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$
  - non-universal SUGRA
- gauge mediated SUSY breaking (GMSB)
  - $\Lambda$, $M$, $n_5$, $\tan \beta$, $\text{sign}(\mu)$, $C_{grav}$
  - non-minimal GMSB
- anomaly-mediated SUSY breaking (AMSB)
  - $m_0$, $m_{3/2}$, $\tan \beta$, $\text{sign}(\mu)$
  - non-minimal AMSB
- mixed modulus-AMSB
  - $\alpha$, $m_{3/2}$, $\tan \beta$, $\text{sign}(\mu)$, modular weights
Sparticle mass spectra

★ Mass spectra codes
★ RGE running: $M_{GUT} \rightarrow M_{weak}$
  • Isajet (HB, Paige, Protopopescu, Tata)
    * ≥7.72: Isatools
  • SuSpect (Djouadi, Kneur, Moultaka)
  • SoftSUSY (Allanach)
  • Spheno (Porod)
★ Comparison (Belanger, Kraml, Pukhov)
★ Website: http://kraml.home.cern.ch/kraml/comparison/
Results of $\chi^2$ fit using $\tau$ data for $a_\mu$:

$m_{\mathrm{Sugra}}$ with $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

$m_{\mathrm{Sugra}}$ with $\tan\beta = 54$, $A_0 = 0$, $\mu > 0$

For a hadronic reaction,

\[ A + B \rightarrow c + d + X, \]

where \( c \) and \( d \) are superpartners and \( X \) represents assorted hadronic debris, we have an associated subprocess reaction

\[ a + b \rightarrow c + d, \]

whose cross section can be computed using the Lagrangian for the MSSM. To obtain the final cross section, we must convolute the appropriate subprocess production cross section \( d\hat{\sigma} \) with the parton distribution functions:

\[ d\sigma(AB \rightarrow cdX) = \sum_{a,b} \int_{0}^{1} dx_a \int_{0}^{1} dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) d\hat{\sigma}(ab \rightarrow cd). \]

where the sum extends over all initial partons \( a, b \) whose collisions produce the final state \( c + d \).
Parton Distribution Functions (PDFs)
The fundamental calculable object in QM is the *amplitude* $\mathcal{M}$ for a process to occur.

A pictorial representation of $\mathcal{M}$ is given by a *Feynman diagram*.

Feynman rules for many theories can be found in standard texts: e.g. Peskin& Schroeder, *Introduction to Quantum Field Theory*.

In the MSSM, an additional complication occurs due to presence of *Majorana* spinors.

Methods for handling these given *e.g.* in *Weak Scale Supersymmetry* (HB, X. Tata), or book by M. Drees, Godbole& Roy.

Total amplitude $\mathcal{M}$ is sum of all different ways a process can occur.

$\mathcal{M}$ is a complex number; $|\mathcal{M}|^2$ gives probability.

Must normalize and sum (integrate) over all momentum configurations to gain cross section, usually in *femtobarns*.
Calculating subprocess cross sections/decay rates in QFT

\[ d\hat{\sigma} = \frac{1}{2\hat{s}} \frac{1}{(2\pi)^2} \int \frac{d^3p_c}{2E_c} \frac{d^3p_d}{2E_d} \delta^4(p_a + p_b - p_c - p_d) \cdot F_{\text{color}}F_{\text{spin}} \sum |\mathcal{M}|^2, \]

- Must sum (integrate) over all final state momentum configurations
- May be done analytically for simple processes \( e.g. \ 2 \rightarrow 2 \)
- Usually done using Monte Carlo method for \( n \geq 3 \)
- Monte Carlo well suited for adding on particle decays so one has really \( 2 \rightarrow n \) processes where \( n \) can be very large
- Convolution of subprocess cross section with PDFs must be done numerically, since PDFs distributed as \textit{subroutines}
Chargino-neutralino production

\[ \begin{align*}
    &d \quad w^- \\
    &\bar{u} \quad \tilde{\nu}_i \\
    &d \\
    &\bar{u} \\
    &d \\
    &\bar{u} \\
    &d \quad \tilde{\nu}_i \\
    &\bar{u} \\
    &d \quad \tilde{\nu}_i \\
    &\bar{u} \\
\end{align*} \]

\( \sigma (fb) \)

\[ \begin{align*}
    &\tilde{\nu}_j \\
    &\tilde{\nu}_i \\
    &\tilde{\nu}_i \\
    &\tilde{\nu}_j \\
    &\tilde{\nu}_i \\
    &\tilde{\nu}_i \\
\end{align*} \]

\[ \begin{align*}
    &\mu = m_{\tilde{g}} = m_{\tilde{q}} \\
    &\text{CTEQ5L PDFs} \\
    &\sqrt{s} = 14 \text{ TeV} \\
\end{align*} \]
Chargino pair production

\[ d \xrightarrow{\gamma,z} \tilde{w}_i \quad \tilde{w}_j \quad d \xrightarrow{\tilde{u}_L} \tilde{w}_i \quad \tilde{w}_j \]

\[ \sigma (fb) \]

\[ m_{\tilde{g}} \ (GeV) \]

\[ \mu = m_{\tilde{g}} = m_{\tilde{q}} \]

CTEQ5L PDFs

\( \sqrt{s} = 14 \text{ TeV} \)
Neutralino pair production

Neutralino pair production diagram with quarks and squarks.

Graphical representation of neutralino pair production with quarks and squarks. The diagram includes processes involving quarks and squarks, with the neutralinos denoted as \( \tilde{z}_i \) and \( \tilde{z}_j \). The diagram also shows the production cross-section \( \sigma \) as a function of the mass of the gaugino \( m_{\tilde{g}} \), with a plot for the process \( pp \rightarrow \tilde{z}_i \tilde{z}_j X \) at \( \sqrt{s} = 14 \text{ TeV} \) using the CTEQ5L PDFs.
Slepton pair production

\begin{align*}
\text{(a)} \quad q & \rightarrow \gamma, z \rightarrow \tilde{\ell}_{L,R} \\
\bar{q} & \rightarrow \tilde{\ell}_{L,R} \\
\text{(b)} \quad q & \rightarrow z \rightarrow \tilde{\nu}_L \\
\bar{q} & \rightarrow \tilde{\nu}_L \\
\text{(c)} \quad q & \rightarrow z \rightarrow \tilde{\tau}_1 \\
\bar{q} & \rightarrow \tilde{\tau}_2 \\
\text{d} & \rightarrow W^- \rightarrow \tilde{\ell}_L \\
\bar{u} & \rightarrow \tilde{\nu}_L
\end{align*}
Slepton pair cross section

$\sigma_{NN}$ (pb)

$\tilde{\tau}_L \tilde{\tau}_L$

$\tilde{\tau}_R \tilde{\tau}_R$

$\tilde{s}_L \tilde{\tau}_L$

$\tilde{\tau}_L \tilde{\tau}_L$

$m_t$ (GeV)

$\sqrt{s} = 2$ TeV

$\sqrt{s} = 14$ TeV
Gluino pair production

\[ g \to \tilde{g} \tilde{g} \]

\[ g \to \tilde{g} \tilde{g} \]

\[ a) \]

\[ q \to \tilde{g} \tilde{g} \] \[ \bar{q} \to \tilde{g} \tilde{g} \]

\[ q \to \tilde{q} \tilde{g} \] \[ \bar{q} \to \tilde{q} \tilde{g} \]

\[ b) \]
Squark pair production

q \rightarrow \tilde{q} \quad q' \rightarrow \tilde{q}'

q \rightarrow \tilde{q} \quad q' \rightarrow \tilde{q} '

a)

q \rightarrow \tilde{q} \quad \tilde{g} \rightarrow \tilde{q}

q \rightarrow \tilde{q} \quad \tilde{g} \rightarrow \tilde{q} '

b)

c)
Gluino-squark associated production

\[ q \xrightarrow{\tilde{g}} \tilde{q} \]

\[ g \xrightarrow{\tilde{g}} \tilde{g} \]

\[ q \xrightarrow{\tilde{q}} q \]

\[ g \xrightarrow{\tilde{g}} g \]

\[ q \xrightarrow{\tilde{q}} q \]

\[ q \xrightarrow{\tilde{q}} q \]

\[ q \xrightarrow{\tilde{g}} \tilde{g} \]
Gluino and squark pair production

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = +m_{\tilde{g}} = m_{\tilde{q}} \]

CTEQ5L PDFs

\[ \sigma \text{ (fb)} \]

\[ m_{\tilde{g}} \text{ (GeV)} \]
Production at LHC

Howie Baer, SUSY at LHC, lecture 2: Karlsruhe, July 24, 2007

Diagram showing production rates at the LHC for different particle configurations as a function of the mass of a particular particle. The diagrams illustrate different scenarios for the production of supersymmetric particles, including the production of left-handed and right-handed sleptons, and the interference effects at the LHC for the production of simplified models of supersymmetry. The diagrams also show the impact of varying parameters such as the mass of the gluino, the lightest supersymmetric particle, and the relative production rates for different particle configurations.
Gluino decays: $\tilde{g} \rightarrow q\bar{q}$ or 3-body
Gluino decays: branching fractions

- Left graph:
  - $\mu = 200$ GeV
  - $\tan \beta = 5$
  - $m_{\tilde{q}} = 1$ TeV

- Right graph:
  - $m_0 = 600$ GeV
  - $m_{1/2} = 250$ GeV
  - $A_0 = 0; \mu > 0$
Squark decays

\[ \tilde{u}_L \rightarrow u \tilde{Z}_i, \ d \tilde{W}_j^+, \ u \tilde{g}, \]

\[ \tilde{d}_L \rightarrow d \tilde{Z}_i, \ u \tilde{W}_j^-, \ d \tilde{g}, \]

\[ \tilde{u}_R \rightarrow u \tilde{Z}_i, \ u \tilde{g}, \]

\[ \tilde{d}_R \rightarrow d \tilde{Z}_i, \ d \tilde{g}. \]
Slepton decays

$$\tilde{e}_L \rightarrow e\tilde{Z}_i, \; \nu_e\tilde{W}_j^-,$$

$$\tilde{\nu}_e \rightarrow \nu_e\tilde{Z}_i, \; e\tilde{W}_j^+,$$

$$\tilde{e}_R \rightarrow e\tilde{Z}_i.$$
Chargino decays

\[ \tilde{W}_j \rightarrow W\tilde{Z}_i, \ H^-\tilde{Z}_i, \]
\[ \rightarrow \tilde{u}_L\tilde{d}, \ \tilde{d}_L\tilde{u}, \ \tilde{c}_L\tilde{s}, \ \tilde{s}_L\tilde{c}, \ \tilde{t}_{1,2}\tilde{b}, \ \tilde{b}_{1,2}t, \]
\[ \rightarrow \tilde{\nu}_e\tilde{\nu}_e, \ \tilde{e}_L\nu_e, \ \tilde{\nu}_\mu\tilde{\mu}, \ \tilde{\mu}_L\nu_\mu, \ \tilde{\nu}_\tau\tilde{\tau}, \ \tilde{\tau}_{1,2}\nu_\tau, \] and
\[ \tilde{W}_2 \rightarrow Z\tilde{W}_1, \ h\tilde{W}_1, \ H\tilde{W}_1 \text{ and } A\tilde{W}_1. \]

Charginos may decay to a lighter neutralino via

\[ \tilde{W}_j \rightarrow \tilde{Z}_i + f\tilde{f}', \quad (1) \]
Decay of $\widetilde{W}_1$ versus $\tan\beta$

- $m_0 = 200$ GeV
- $m_{1/2} = 200$ GeV
- $A_0 = 0$
- $\mu > 0$
Neutralino decays

\[ \tilde{Z}_i \rightarrow W\tilde{W}_j, \ H^-\tilde{W}_j, \ Z\tilde{Z}_i', \ h\tilde{Z}_i', \ H\tilde{Z}_i', \ A\tilde{Z}_i' \]
\[ \rightarrow \tilde{q}_{L,R}\bar{q}, \ \tilde{q}_{L,R}q, \ \tilde{\ell}_{L,R}\bar{\ell}, \ \tilde{\ell}_{L,R}\ell, \ \tilde{\nu}_L\bar{\nu}_L, \ \tilde{\nu}_L\nu_L. \]

If 2-body modes are closed, then the neutralino can decay via

\[ \tilde{Z}_i \rightarrow \tilde{Z}_i' + f \bar{f} \] (2)
Decay of $\tilde{Z}_2$ versus $\tan\beta$
Decays of SUSY Higgs boson $h$

- $h \rightarrow u\bar{u}, \ d\bar{d}, \ s\bar{s}, \ c\bar{c}, \ b\bar{b}, \ e\bar{e}, \ \mu\bar{\mu}, \ \tau\bar{\tau}$
- $h \rightarrow \tilde{Z}_i \tilde{Z}_{i'}, \ \tilde{W}_j^+ \tilde{W}_{j'}^-, \ \tilde{f} \bar{\tilde{f}}$
- $h \rightarrow AA$

where $i, i' = 1 - 4$ and $j, j' = 1, 2$.

Also

- $h \rightarrow W f \bar{f}' / Z f \bar{f}$
- $h \rightarrow gg, \ \gamma\gamma, \ Z\gamma$
Decays of SUSY Higgs boson $H$

- $H \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t}, e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}$
- $H \rightarrow WW, ZZ$
- $H \rightarrow \tilde{Z}_i\tilde{Z}_{i'}, \tilde{W}_j^+\tilde{W}_{j'}, f\bar{f}$
- $H \rightarrow hh, AA, H^+H^-, AZ$
- $H \rightarrow gg, \gamma\gamma, Z\gamma$

where $i, i' = 1 - 4$ and $j, j' = 1, 2$. 
Decays of SUSY Higgs boson $A$

- $A \rightarrow u\bar{u}, \, d\bar{d}, \, s\bar{s}, \, c\bar{c}, \, b\bar{b}, \, t\bar{t}, \, e\bar{e}, \, \mu\bar{\mu}, \, \tau\bar{\tau}$
- $A \rightarrow \tilde{Z}_i\tilde{Z}_{i'}, \, \tilde{W}_j^+\tilde{W}_{j'}^-, \, f\bar{f}$
- $A \rightarrow hZ$
- $A \rightarrow gg, \, \gamma\gamma$

where $i, i' = 1 - 4$ and $j, j' = 1, 2$. 

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Decays of SUSY Higgs boson $H^+$

- $H^+ \rightarrow u\bar{d}, c\bar{s}, t\bar{b}, \nu_e\bar{e}, \nu_\mu\bar{\mu}, \nu_\tau\bar{\tau}$
- $H^+ \rightarrow \widetilde{Z}_i\widetilde{W}_j^+, \widetilde{f}\widetilde{f}'$
- $H^+ \rightarrow hW$

where $i, i' = 1 - 4$ and $j, j' = 1, 2$. 
Decay of top to SUSY?

- $t \rightarrow bW^+$
- $t \rightarrow bH^+$
- $t \rightarrow \tilde{t}_{1,2}\tilde{Z}_i, \tilde{b}_{1,2}\tilde{W}_j$

where $i = 1 - 4$ and $j = 1, 2$. 
Decays to gravitino?

- $\tilde{Z}_1 \rightarrow \gamma \tilde{G}$
- $\tilde{Z}_1 \rightarrow \tilde{G} + (h, H, A \text{ or } Z)$
- $\tilde{f} \rightarrow f \tilde{G}$

Couplings can be extracted from SUGRA Lagrangian:

see e.g. *Weak Scale Supersymmetry*
Sparticle cascade decays

\[ \text{Mass scale (GeV)} \]

\[ \text{Br (\%)} \]

- \( \tilde{g} \) (2060)
- \( \tilde{q}_L \) (~1857)
- \( \tilde{q}_R \) (~1770)
- \( \tilde{b}_L \) (1690)
- \( \tilde{t}_L \) (1689)
- \( \tilde{b}_R \) (1619)
- \( \tilde{t}_R \) (1449)
- \( \tilde{G}_b \) (~2060)
- \( \tilde{G}_t \) (~1857)
- \( \tilde{G}_q \) (~1770)
- \( \tilde{G}_\tau \) (~1690)
- \( \tilde{G}_\nu \) (~1619)

- \( \tilde{Z}_L \) (1066)
- \( \tilde{Z}_J \) (1056)
- \( \tilde{Z}_W \) (~1067)
- \( \tilde{Z}_\tau \) (~395)
- \( \tilde{Z}_\nu \) (754)
- \( \tilde{Z}_\tau \) (442)

Decay modes:
- \( \tilde{Z} \) \( \tilde{q} \) (\( \tilde{q} \)) (27.0 %)
- \( \tilde{Z} \) \( \tau \) \( \nu \) (12.1 %)
- \( \tilde{Z} \) \( \tau \) \( \tau \) \( \tau \) (8.4 %)
- \( \tilde{Z} \) \( \tau \) \( W \) \( W \) (7.4 %)
- \( \tilde{Z} \) \( \nu \) \( q \) \( q \) (5.9 %)
- \( \tilde{Z} \) \( \nu \) \( W \) \( W \) (4.1 %)
- \( \tilde{Z} \) \( \tau \) \( W \) \( W \) (2.9 %)
- \( \tilde{Z} \) \( \tau \) \( q \) \( q \) (2.9 %)
- \( \tilde{Z} \) \( \nu \) \( W \) \( W \) (2.8 %)
- \( \tilde{Z} \) \( \tau \) \( q \) \( q \) (2.6 %)

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A realistic picture of what SUSY matter looks like at LHC

- Counting different flavor states (which are potentially measurable), there are well over 1000 subprocess reactions expected at LHC from the MSSM
- On average, each sparticle has 5-20 decay modes
- Rough estimate of distinct SUSY $2 \rightarrow n$ processes:
  - $\sim 100 \times 10 \times 10 \sim 10^5$
  - This is actually a gross underestimate since each daughter of a produced sparticle has multiple decay modes, and so on...
- The way forward: Monte Carlo program
  - Calculate *all* prod’n cross sections: generate according to relative weights
  - Calculate all branching fractions, and generate decays according to them
  - Interface with parton shower, hadronization, underlying event
  - Computer generated events should look something like what we would expect from the MSSM at the LHC
Event generation in LL - QCD

1) Hard scattering / convolution with PDFs
2) Initial / final state showers
3) Cascade decays
4) Hadronization
5) Beam remnants
Event generations for SUSY

★ Isajet (HB, Paige, Protopopsecu, Tata)
  • IH, FW-PS, n-cut Pomeron UE

★ Pythia (Sjöstrand, Lönnblad, Mrenna)
  • SH, FW-PS, multiple scatter UE, SUSY at low $\tan\beta$ only

★ Herwig (Marchesini, Webber, Seymour, Richardson,...)
  • CH, AO-PS, Phen. model UE, Isawig

★ SUSYGEN (Ghodbane, Katsanevas, Morawitz, Perez)
  • mainly for $e^+e^-$; interfaces to Pythia

★ CompHEP, CalcHEP, Madgraph: for automatic Feynman diagram evaluation
Briefly: particle interactions with detector
SUSY scattering event: Isajet simulation

SUSY event with 3 lepton + 2 Jets signature

- $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu < 0$,
- $m(q) = 686$ GeV, $m(\tilde{g}) = 766$ GeV, $m(\tilde{\chi}_0^1) = 257$ GeV,
- $m(\tilde{\chi}_0^0) = 128$ GeV.

Leptons:
- $p_t(\mu^+) = 55.2$ GeV
- $p_t(\mu^-) = 44.3$ GeV
- $p_t(e^-) = 43.9$ GeV

Jets:
- $E_t(Jet1) = 237$ GeV
- $E_t(Jet2) = 339$ GeV

Sparticles:
- $p_t(\tilde{\chi}_1^0) = 95.1$ GeV
- $p_t(\tilde{\chi}_2^0) = 190$ GeV

Charged particles with $p_t > 2$ GeV, $|\eta| < 3$ are shown; neutrons are not shown; no pile up events superimposed.
Conclusions

★ sparticle production
  • generally, $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ $\tilde{q}\tilde{q}$ dominate at LHC if $m_{\tilde{g},\tilde{q}} \lesssim 1$ TeV

★ sparticle decays
  – multi-step cascade decays lead to multi-jets+multi-leptons+$E_T$

★ event generation
  – combine numerous production processes with multi-step sparticle cascade decays, initial/final state parton showering, hadronization and a modeling of underlying event, and hopefully we get a pretty good picture of what production of SUSY matter will look like in the environment of an LHC detector