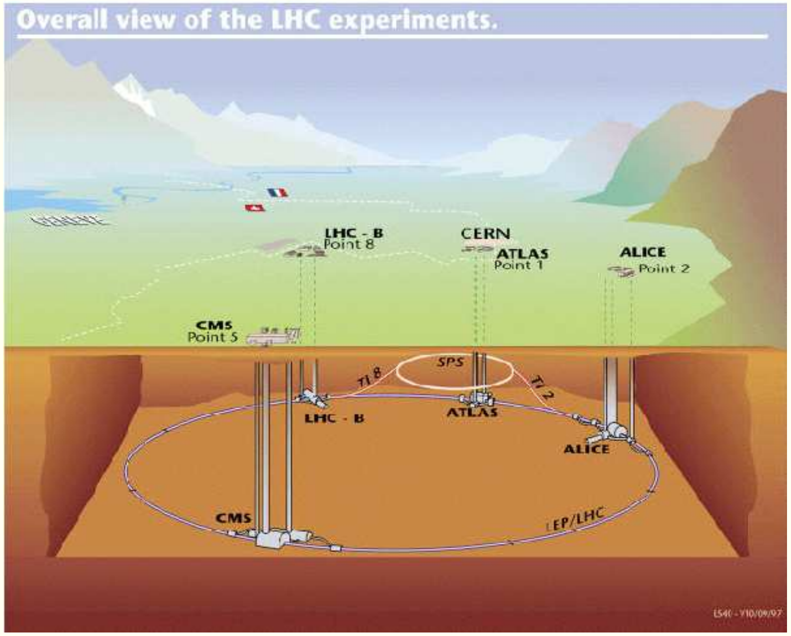
Supersymmetric Dark Matter: Direct, Indirect and Collider Searches

Howard Baer
University of Oklahoma

OUTLINE

- ⋆ The Standard Model
- ⋆ Inconsistencies
- ⋆ Supersymmetry
- ⋆ Dark matter (DM)
  - neutralino, axion/axino, gravitino
- ⋆ The Hunt for DM at LHC
- ⋆ direct DM searches
- ⋆ indirect DM searches



The Standard Model of Particle Physics

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g,\ W^\pm,\ Z^0,\ \gamma$
- ⋆ matter content: 3 generations quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_R,\ d_R;\ \begin{pmatrix} \nu \\ e \end{pmatrix}_L,\ e_R \tag{1}$$

- ⋆ Higgs sector $\Rightarrow$ spontaneous electroweak symmetry breaking:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{2}$$

- ⋆ $\Rightarrow$ massive $W^\pm$, Z^0, quarks and leptons
- ⋆ $\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Yuk.} + \mathcal{L}_{Higgs}$: 19 parameters
- ⋆ good-to-excellent description of (almost) *all* accelerator data!

Shortcomings of SM

Data

- ⋆ neutrino masses and mixing
- ⋆ baryogenesis (matter anti-matter asymmetry)
- ⋆ cold dark matter
- ⋆ dark energy

Theory

- ⋆ quadratic divergences in scalar sector $\Rightarrow$ fine-tuning
- ⋆ origin of generations
- ⋆ explanation of masses/ mixing angles
- ⋆ origin of gauge symmetry/ quantum numbers
- ⋆ unification with gravity

The supersymmetry alternative

Supersymmetry: bosons$\Leftrightarrow$ fermions

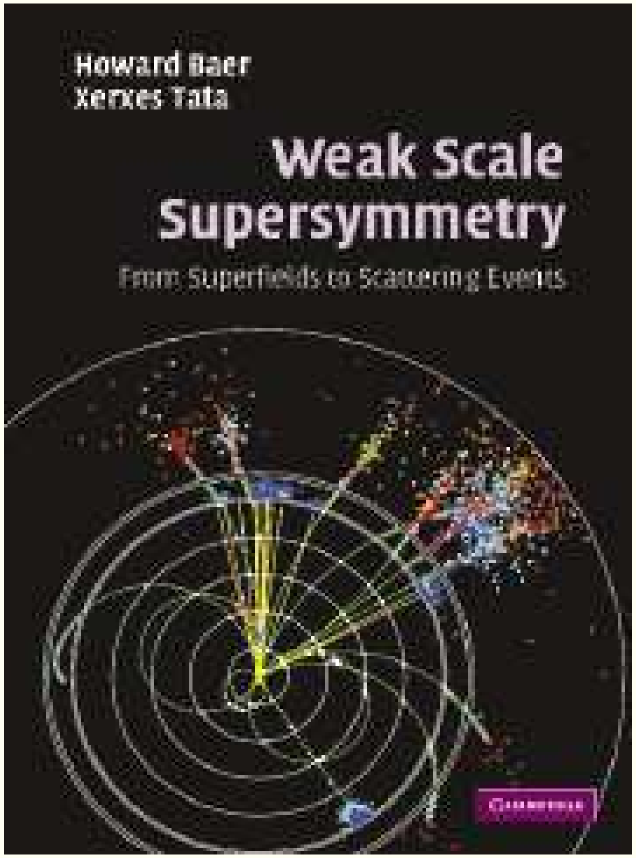
- ⋆ SUSY is a *space-time* symmetry!
- ⋆ space-time $x^\mu \Rightarrow (x^\mu, \theta_i)$ $i = 1, \cdots, 4$ superspace
- ⋆ fields $\psi \Rightarrow \hat{\phi} \ni (\phi,\ \psi)$ superfields
- ⋆ gauge fields $A^\mu \Rightarrow \hat{W} \ni (\lambda,\ A^\mu)$ gauge superfields
- ⋆ superfield formalism $\Rightarrow$ general form for Lagrangian of (globally) supersymmetric gauge theory: quadratic divergences cancel!
- ⋆ SUSY can be broken by *soft* SUSY breaking terms: maintain cancellation of quadratic divergences

Weak Scale Supersymmetry

HB and X. Tata

Spring, 2006; Cambridge University Press

- ⋆ Part 1: superfields/Lagrangians
  - 4-component spinor notation for exp'ts
  - master Lagrangian for SUSY gauge theories
- ⋆ Part 2: models/implications
  - MSSM, SUGRA, GMSB, AMSB, $\cdots$
  - dark matter density/detection
- ⋆ Part 3: SUSY at colliders
  - production/decay/event generation
  - collider signatures
  - R-parity violation



Minimal Supersymmetric Standard Model (MSSM)

- ⋆ Adopt gauge symmetry of Standard Model
  - spin $\frac{1}{2}$ gaugino for each SM gauge boson
- ⋆ SM fermions $\in$ chiral scalar superfields: $\Rightarrow$ scalar partner for each SM fermion helicity state
  - electron $\Leftrightarrow$ $\tilde{e}_L$ and $\tilde{e}_R$
- ⋆ *two* Higgs doublets to cancel triangle anomalies
- ⋆ add all admissible soft SUSY breaking terms
- ⋆ resultant Lagrangian has 124 parameters!
- ⋆ Lagrangian yields mass eigenstates, mixings, Feynman rules for scattering and decay processes
- ⋆ predictive model!

Supergravity (SUGRA)

★ $e^{i\bar{\alpha}Q}$ with $\alpha(x)$: *local* SUSY transformation

- forces introduction of spin 2 graviton and spin $\frac{3}{2}$ gravitino
- resultant theory $\Rightarrow$ General Relativity in classical limit!

★ rules for Lagrangian in supergravity gauge theory: Cremmer et al. (1983)

★ fertile ground: supergravity $\cup$ grand unification: LE limit of superstring?

★ minimal supergravity model (mSUGRA)

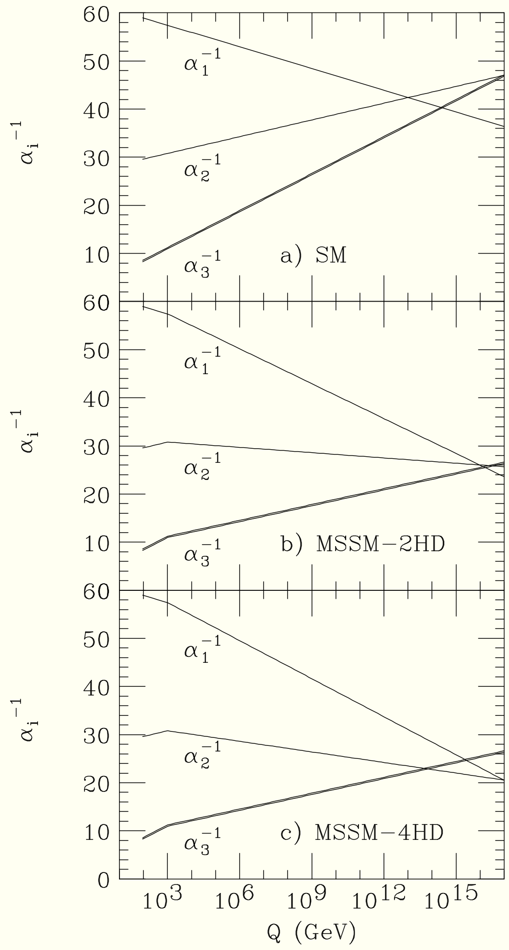
★ $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$

- $m_0 =$ mass of all scalars at $Q = M_{GUT}$
- $m_{1/2} =$ mass of all gauginos at $Q = M_{GUT}$
- $A_0 =$ trilinear soft breaking parameter at $Q = M_{GUT}$
- $\tan\beta =$ ratio of Higgs vevs
- $\mu =$ SUSY Higgs mass term; magnitude determined by REWSB!

Some successes of SUSY GUT theories

- ⋆ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!

Gauge coupling evolution



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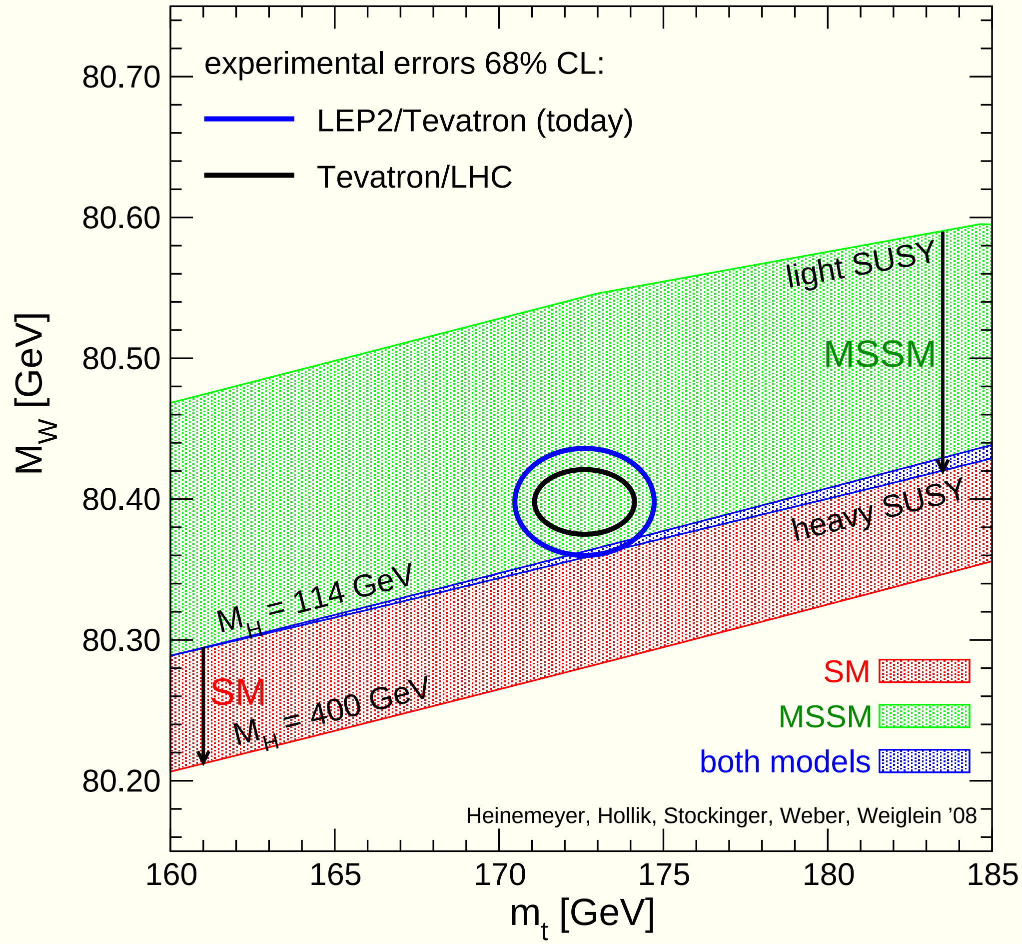
Precision electroweak data and the Higgs mass:



S. Heinemeyer et al.

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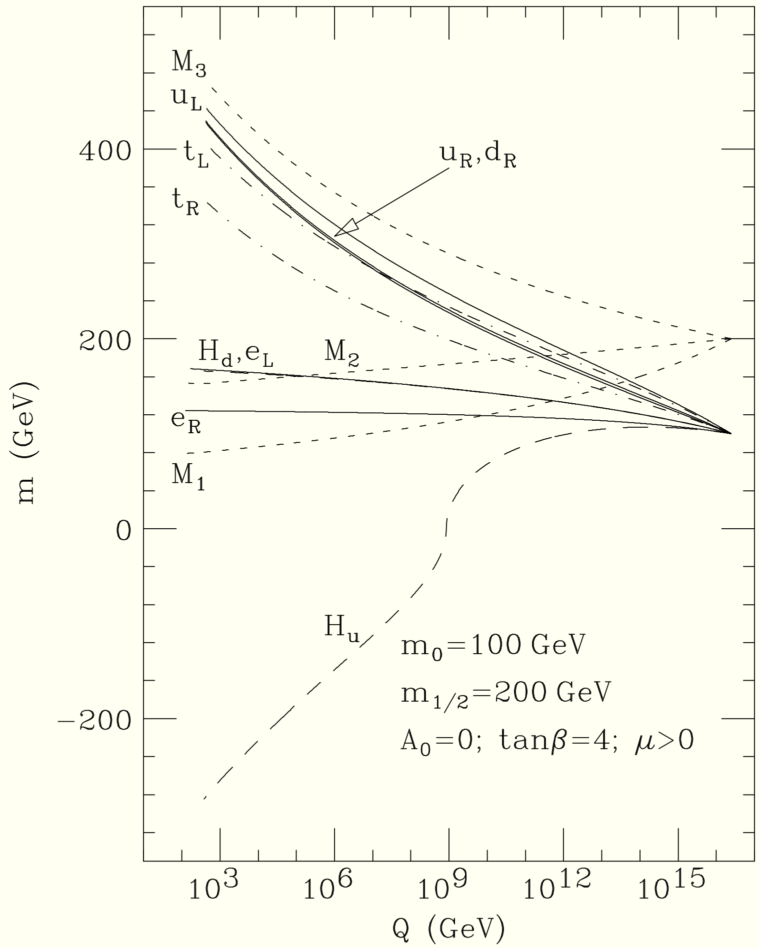
Soft term evolution and radiative EWSB



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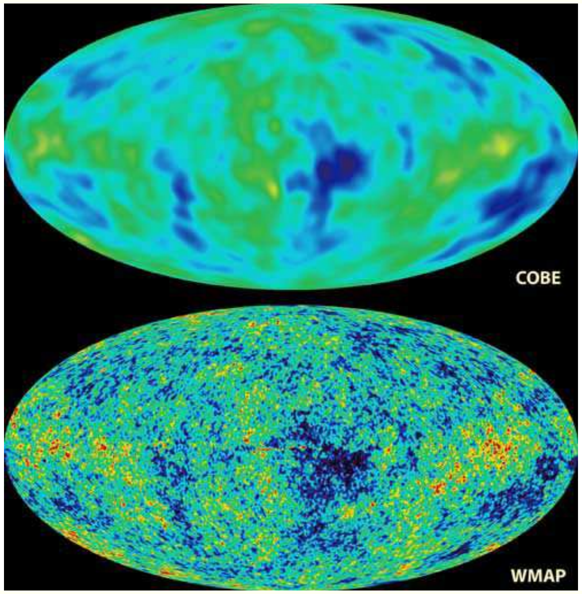
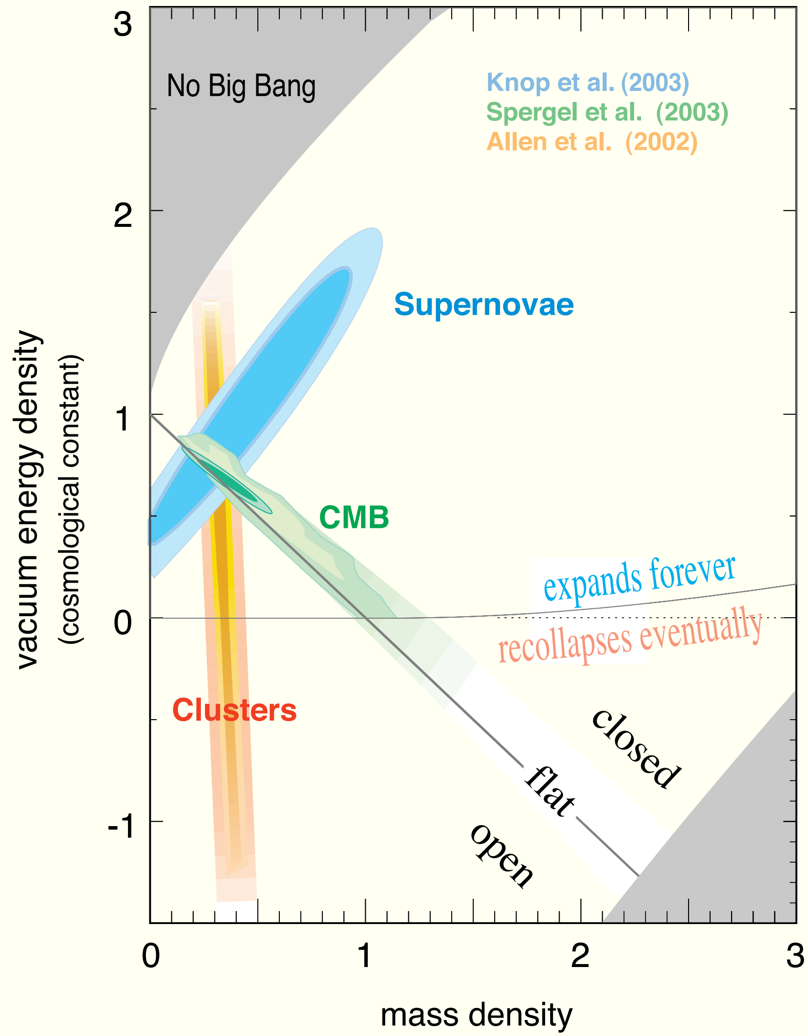
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- ⋆ dark matter candidate: lightest neutralino $\tilde{Z}_1$
- ⋆ stablize neutrino see-saw scale vs. weak scale
- ⋆ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis
- ⋆ can give dark energy via CC Λ (but need huge fine-tuning...)
  - SUGRA $=$ low energy limit of superstring?
  - stringy multiverse: anthropic selection of small CC?

Evidence for dark matter in the universe

- ⋆ binding of galactic clusters (Zwicky, 1930s)
- ⋆ galactic rotation curves
- ⋆ large scale structure formation
- ⋆ inflation $\Rightarrow \Omega = \rho/\rho_c = 1$
- ⋆ gravitational lensing
- ⋆ anisotropies in cosmic MB (WMAP)
- ⋆ surveys of distant galaxies via SN (DE)
- ⋆ Big Bang nucleosynthesis
  - $\Omega_\Lambda \simeq 0.7$
  - $\Omega_{CDM} \simeq 0.25$
  - $\Omega_{baryons} \simeq 0.045$ (dark baryons ~ 0.040
  - $\Omega_\nu \sim 0.005$



Dark matter versus dark energy



SUSY dark matter

- ⋆ R-parity conservation⇒ conserved B and L ⇒ proton stability
  - $R(particle) = 1$; $R(sparticle) = -1$
- ⋆ Naturally occurs in $SO(10)$ SUSY GUT theories
- ⋆ Some consequences:
  - Sparticles are produced in pairs
  - Sparticles decay to other sparticles
  - Lightest SUSY particle (LSP) is absolutely stable (good candidate for dark matter)
- ⋆ LSP must be charge, color neutral (bound on cosmological relics)
- ⋆ Sneutrino would have been detected in direct detection experiments
- ⋆ lightest neutralino $\tilde{Z}_1$ is LSP in wide range of models
- ⋆ $\tilde{Z}_1$ is weakly interacting, massive particle (WIMP)

Calculating the relic density of neutralinos

★ At very high T, neutralinos in thermal equilibrium with cosmic soup

★ As universe expands and cools, expansion rate exceeds interaction rate (freeze-out)

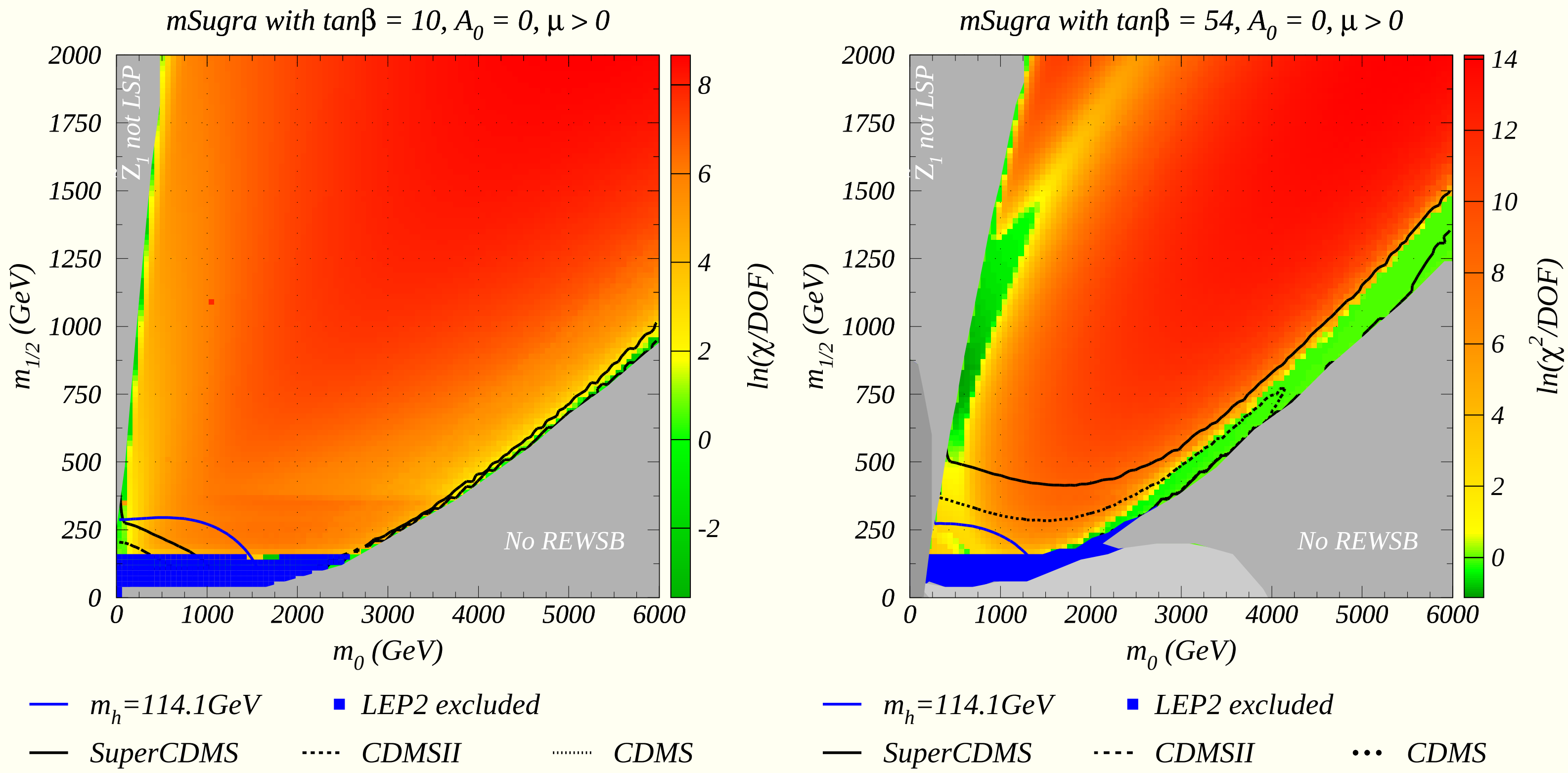
★ number density is governed by Boltzmann eq. for FRW universe

- $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
- $\Omega_{\widetilde{Z}_1} h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{m_{Pl}} \frac{1}{\langle \sigma v \rangle}$
- $\Omega_{CDM} h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 0.9$ pb!
- $\langle \sigma v \rangle = \pi \alpha^2 / 8m^2 \Rightarrow m \sim 100$ GeV
- "The WIMP miracle!": cosmic motivation for new physics at weak scale

★ SUSY: 1722 annihilation/co-annihilation reactions; 7618 Feynman diagrams

★ IsaReD program (HB, A. Belyaev , C. Balazs)

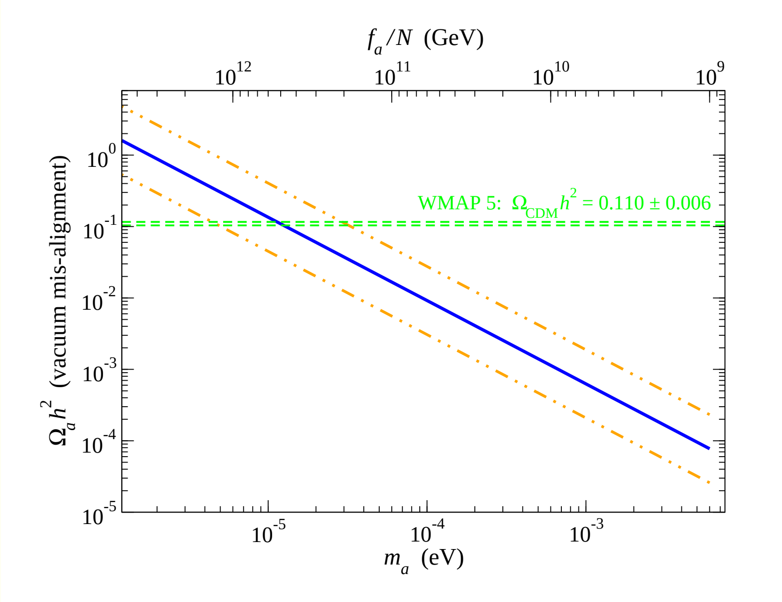
Results of χ^2 fit using τ data for a_μ:



HB, C. Balazs: JCAP 0305, 006 (2003)

Axions

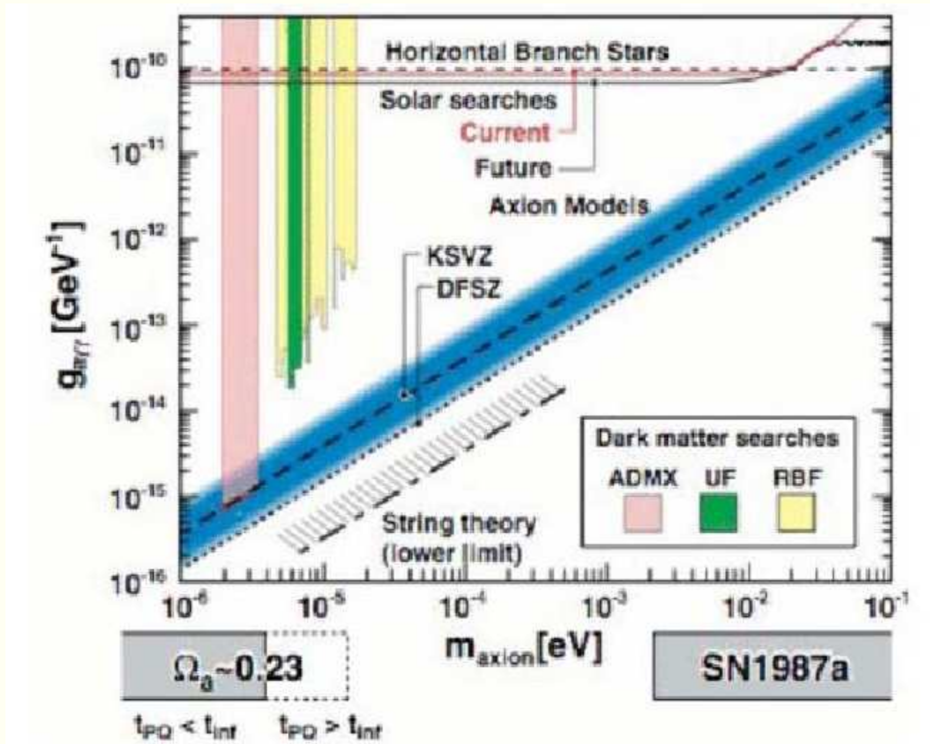
- ⋆ PQ solution to strong CP problem in QCD
- ⋆ pseudo-Goldstone boson from
  PQ breaking at scale $f_a \sim 10^9 - 10^{12}$ GeV
- ⋆ non-thermally produced
  via vacuum mis-alignment as *cold* DM
  - $m_a \sim \Lambda^2_{QCD}/f_a \sim 10^{-6} - 10^{-1} eV$
  - $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1} eV$
  - a couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches



Axion microwave cavity searches

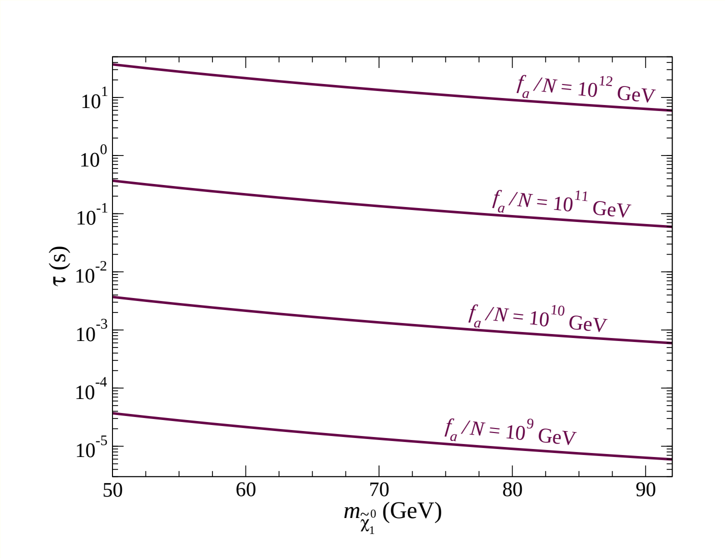
⋆ ongoing searches: ADMX experiment

- Livermore⇒ U Wash.
- Phase I: probe KSVZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- Phase II: probe DFSZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- beyond Phase II:
  probe higher values m_a



Axions + SUSY $\Rightarrow$ Axino $\tilde{a}$ dark matter

- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; can be LSP)
- $m_{\tilde{a}}$ model dependent: keV$\rightarrow$ GeV
- $\widetilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\widetilde{Z}_1$ decay:
- axinos inherit neutralino number density
- $\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}} \Omega_{\widetilde{Z}_1} h^2$:



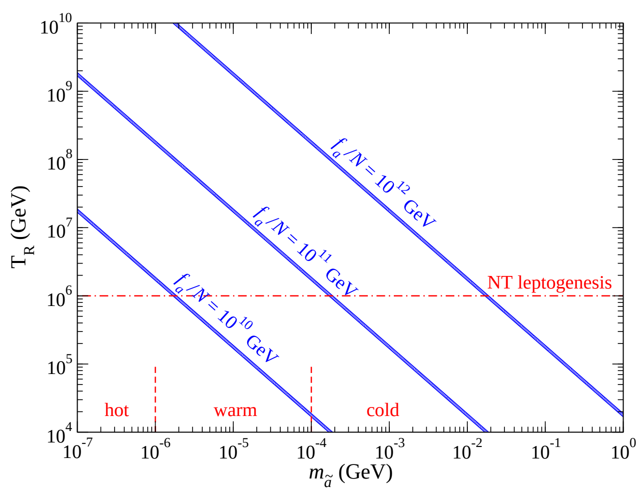
Thermally produced axinos

★ If $T_R < f_a$, then axinos never in thermal equilibrium in early universe

★ Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium

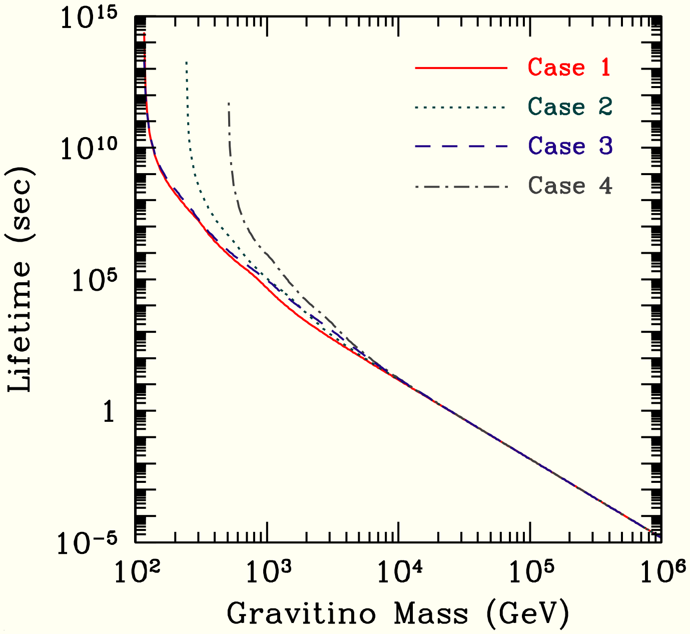
★ Brandenberg-Steffen calculation:

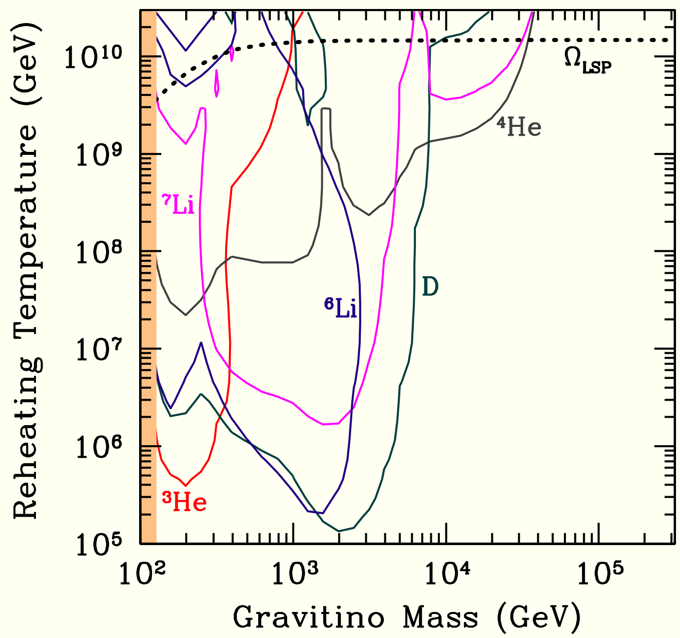
$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right) \qquad (3)$$



Gravitinos: spin-$\frac{3}{2}$ partner of graviton

- gravitino problem in generic SUGRA models: overproduction of $\tilde{G}$ followed by late $\tilde{G}$ decay can destroy successful BBN predictons: upper bound on T_R

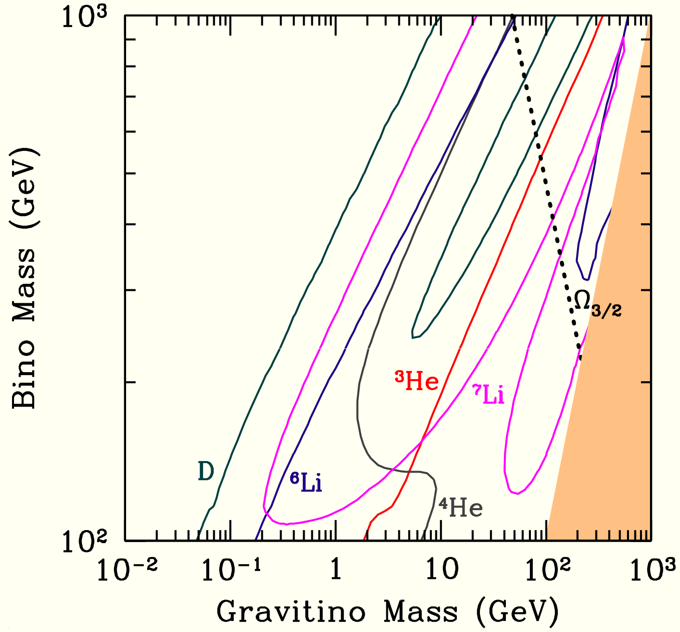




(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive)

Gravitinos as dark matter: again the gravitino problem

- neutralino production in generic SUGRA models: followed by late time $\widetilde{Z}_1 \to \tilde{G} + X$ decays can destroy successful BBN predictons:



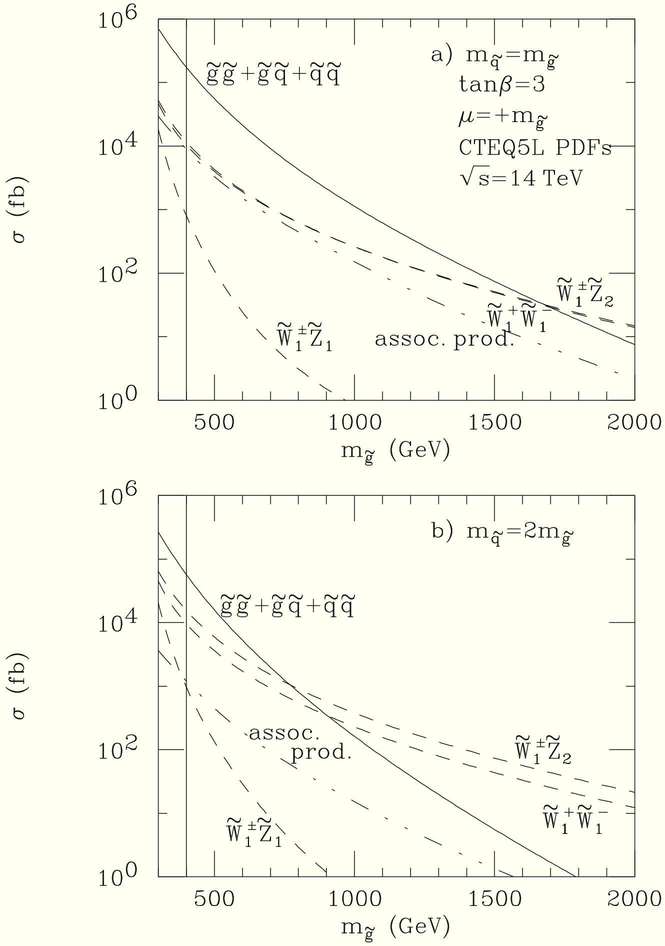
(see Kawasaki, Kohri, Moroi, Yotsuyanagi)

Gravitino dark matter: if one can avoid gravitino problem

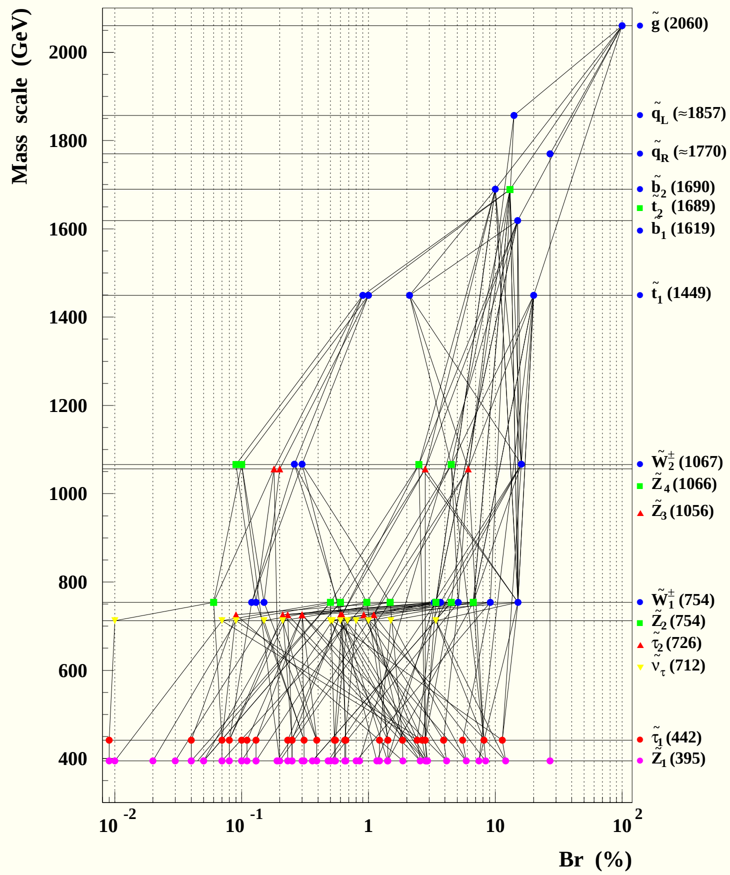
⋆ $m_{\tilde{G}} = F/\sqrt{3}M_* \sim$ TeV in Supergravity models

- if $\tilde{G}$ is LSP, then calculate NLSP abundance as a thermal relic: $\Omega_{NLSP}h^2$
- $\widetilde{Z}_1 \to h\tilde{G},\ Z\tilde{G},\ \gamma\tilde{G}$ or $\tilde{\tau}_1 \to \tau\tilde{G}$ possible
  - lifetime $\tau_{NLSP} \sim 10^4 - 10^8$ sec
  - also produce $\tilde{G}$ thermally (depends on re-heat temp. T_R)
  - DM relic density is then $\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}}\Omega_{NLSP} + \Omega_{\tilde{G}}^{TP}$
  - Feng et al.; Ellis et al.; Brandenberg+Steffen; Buchmuller et al.
- $\tilde{G}$ undetectable via direct/indirect DM searches
- unique collider signatures are possible:
  - $\tilde{\tau}_1$=NLSP: stable charged tracks
  - can collect NLSPs in e.g. water (slepton trapping)
  - monitor for $NLSP \to \tilde{G}$ decays

Production of sparticles at CERN LHC

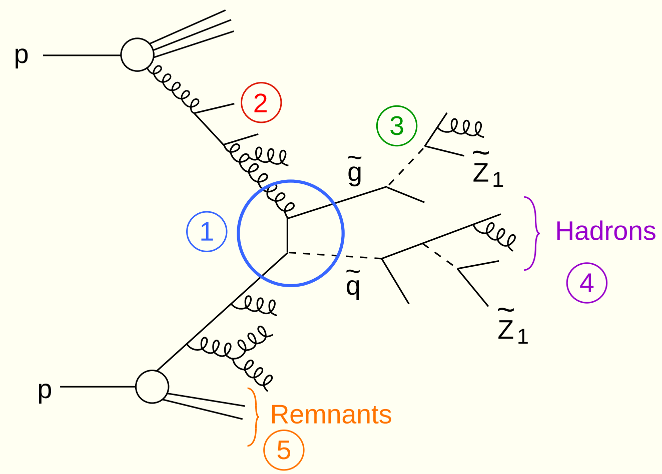


Sparticle cascade decays



$\tilde{Z}_1$ qq (27.0 %)	$\tilde{Z}_1$ τνWWWbb (4.1 %)
$\tilde{Z}_1$ τνWbb (12.1 %)	$\tilde{Z}_1$ ττbb (2.9 %)
$\tilde{Z}_1$ ττWWbb (8.4 %)	$\tilde{Z}_1$ ττqq (2.9 %)
$\tilde{Z}_1$ WWbb (7.4 %)	$\tilde{Z}_1$ τνZWbb (2.8 %)
$\tilde{Z}_1$ τνqq (5.9 %)	$\tilde{Z}_1$ τνhWbb (2.6 %)

Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

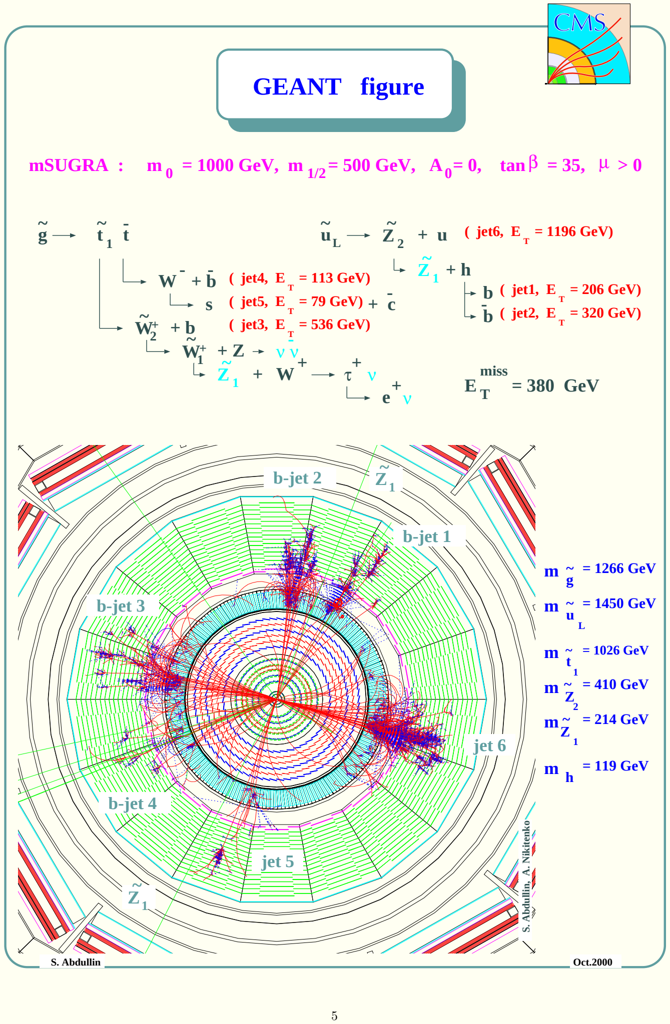
4) Hadronization

5) Beam remnants

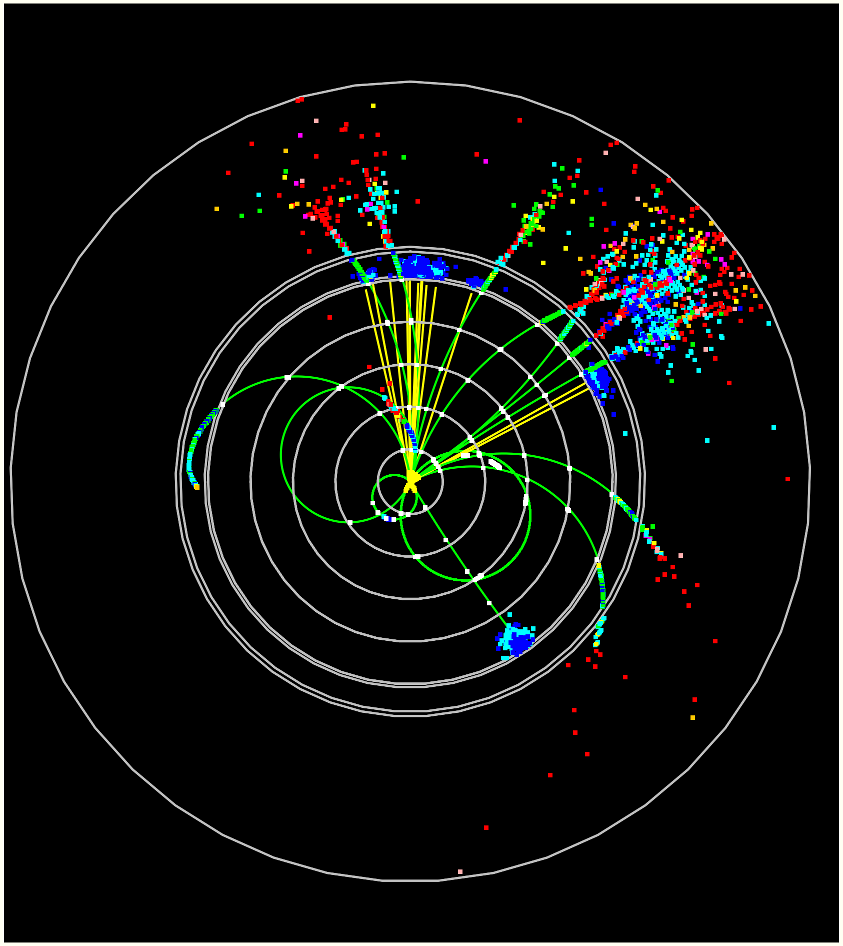
Isajet v7.79 for sparticle event generation

- ⋆ Isajet (1979), by F. Paige and S. Protopopescu
- ⋆ Isajet 7.0 (1993) -7.75: FP, SP, HB and X. Tata
  - Isasugra subprogram: SUGRA models (and others)⇒ sparticle masses, mixings, decay rates
- ⋆ SUSY and SM event generation for hadron colliders
- ⋆ e^+e^- colliders
  - polarized beams
  - bremsstrahlung/ beamstrahlung
- ⋆ IsaTools: $\Omega_{\widetilde{Z}_1}h^2$, $(g-2)_\mu$, $BF(b\to s\gamma)$, $BF(B_s\to\mu^+\mu^-)$, $\sigma(\widetilde{Z}_1 p)$
- ⋆ Les Houches event output: 7.78

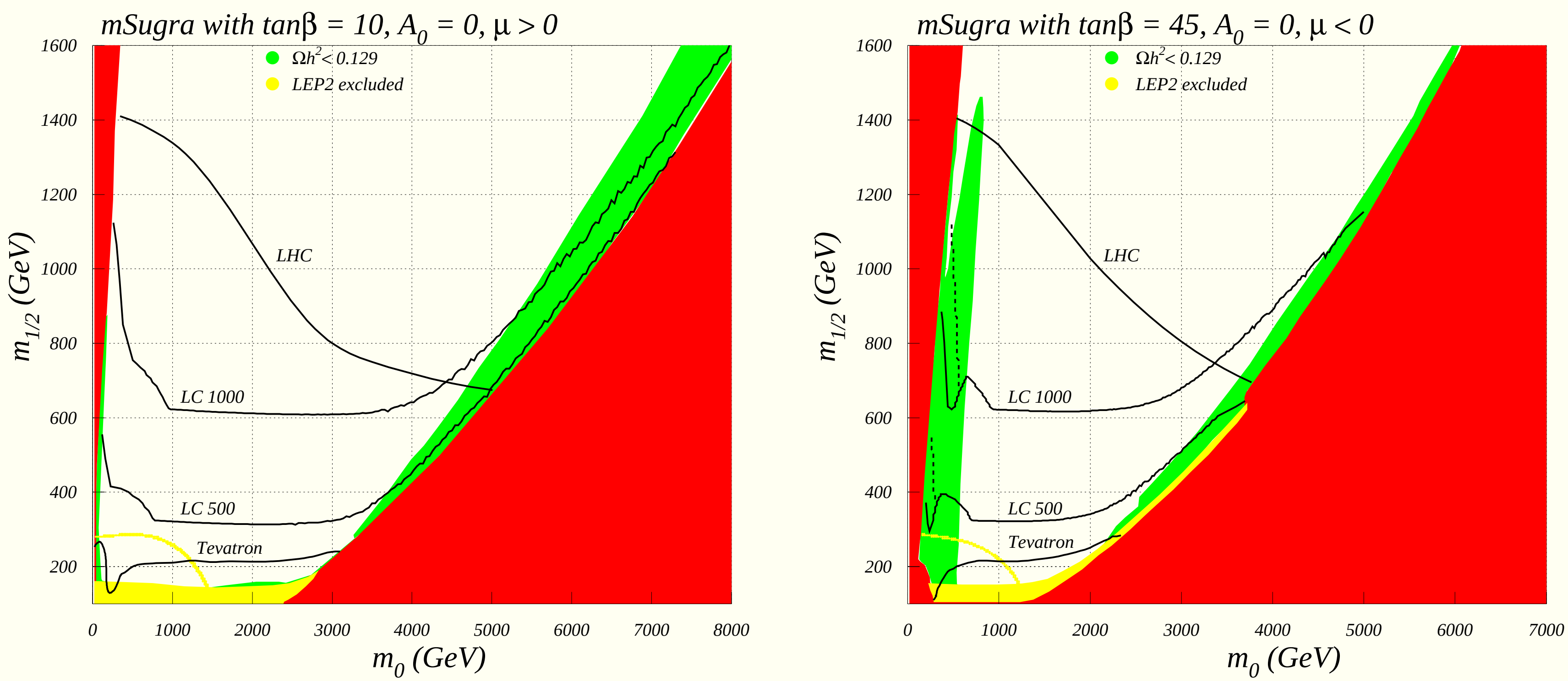
Simulated sparticle production event at LHC



$e^+e^- \to \widetilde{W}_1^+\widetilde{W}_1^- \to (q\bar{q}'\widetilde{Z}_1) + (e\bar{\nu}_e\widetilde{Z}_1)$ at linear collider



Sparticle reach of all colliders with relic density

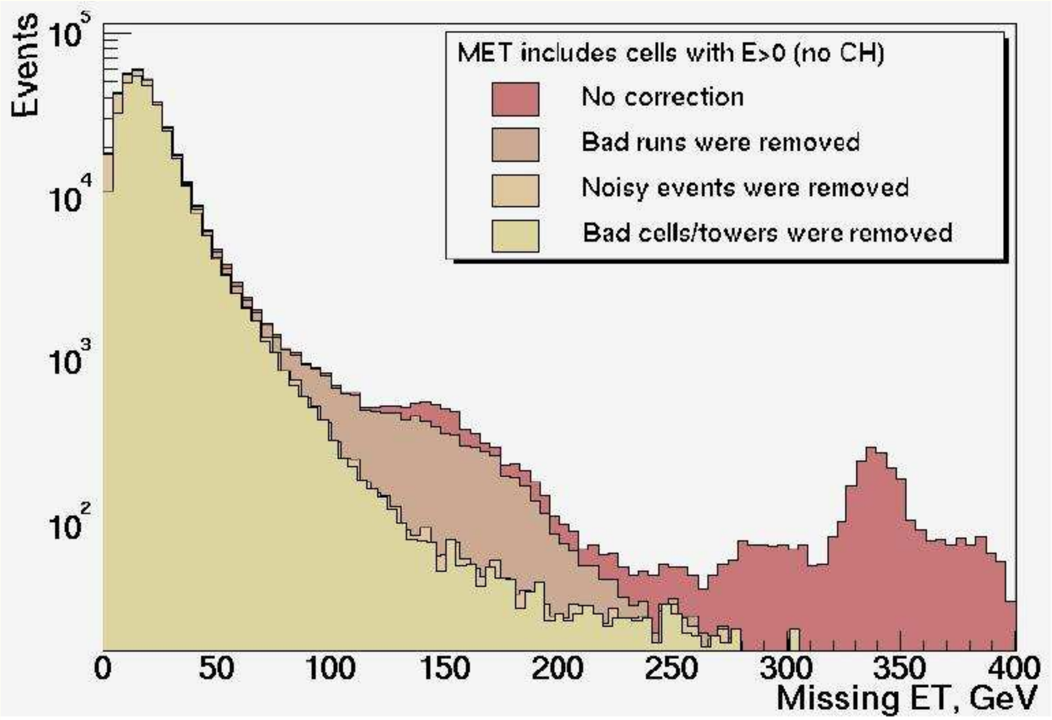


HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

Early SUSY discovery at LHC with just 0.1 fb^{-1}?

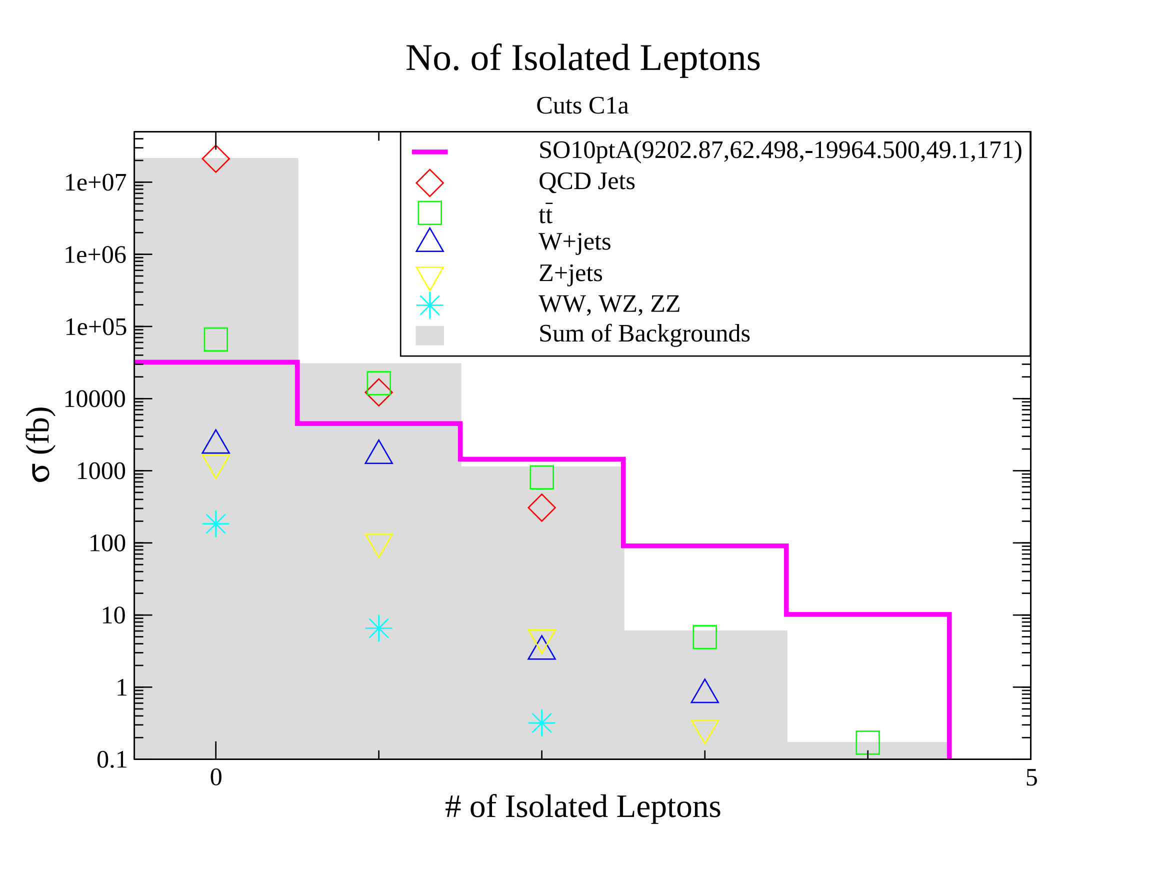
- To make $\not{E}_T$ cut, complete knowledge of detector needed
  - dead regions
  - "hot" cells
  - cosmic rays
  - calorimeter mis-measurement
  - beam-gas events
- Can we make early discovery of SUSY at LHC *without* $\not{E}_T$?
- Expect SUSY events to be rich in jets, b-jets, isolated ℓs, τ-jets,....
- These are *detectable*, rather than inferred objects
- Answer: YES! See HB, Prosper, Summy, arXiv:0801.3799

D0 saga with missing E_T

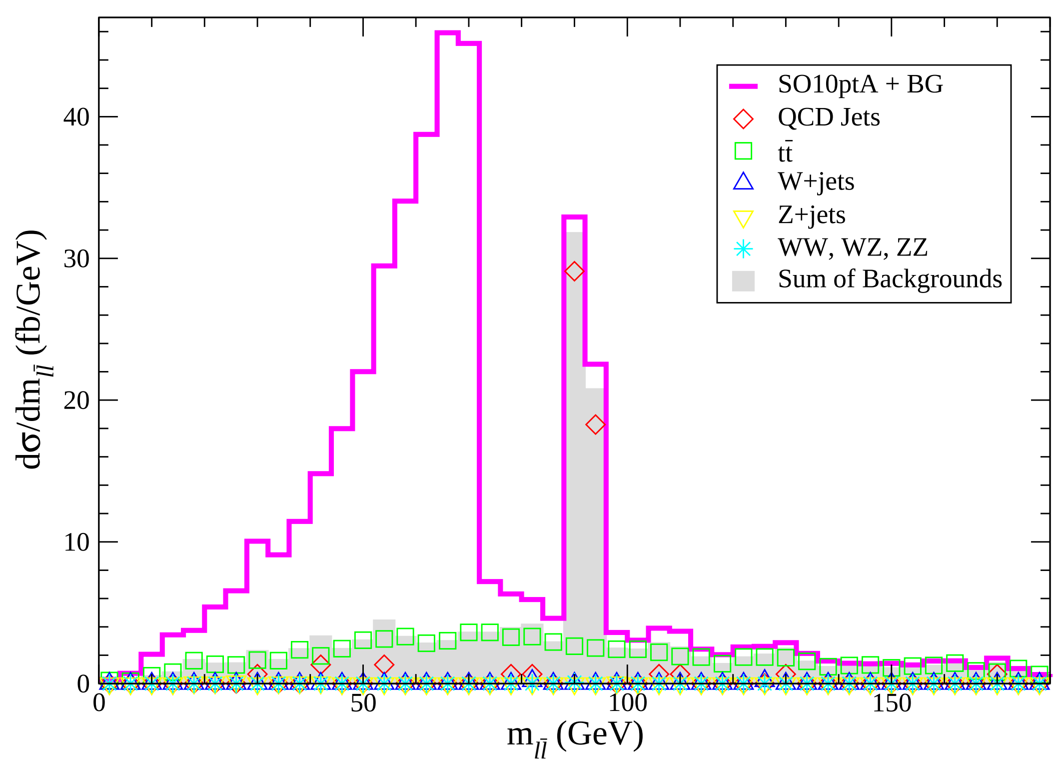


Simple cuts: ≥ 4 jets plus isolated leptons

- $\not\!\!E_T$ not really necessary



Cuts C1′ plus $\geq 2\ OS/SF\ \ell$



Precision measurements at LHC: Atlas and CMS

- $M_{eff} = \not\!\!E_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible $e.g.$ $m(\ell\bar{\ell}jj)$
- Higgs mass bump $h \to b\bar{b}$ likely visible in $\not\!\!E_T + jets$ events
- in favorable cases, may overconstrain system for a given model

⋆ methodology very p-space dependent

⋆ some regions are very difficult $e.g.$ HB/FP

International linear e^+e^- collider (ILC)

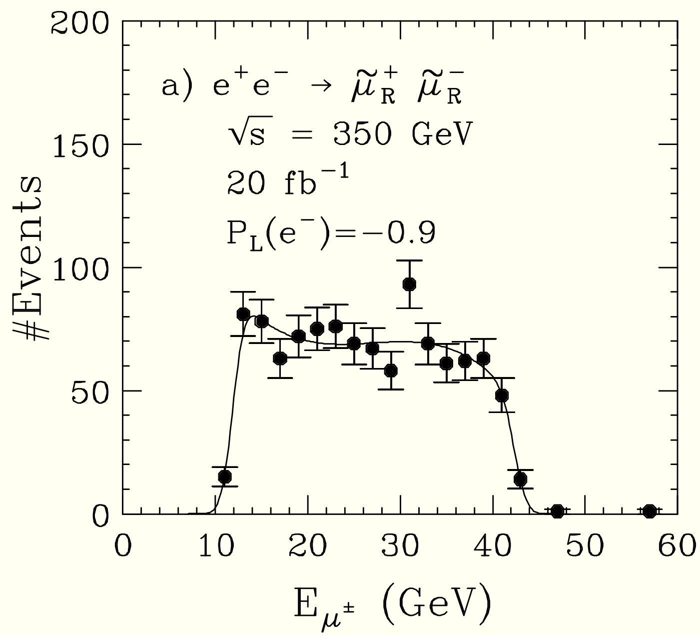
★ A linear e^+e^- collider with $\sqrt{s} = 0.5 - 1$ TeV is highest priority project for HEP beyond LHC! Why?

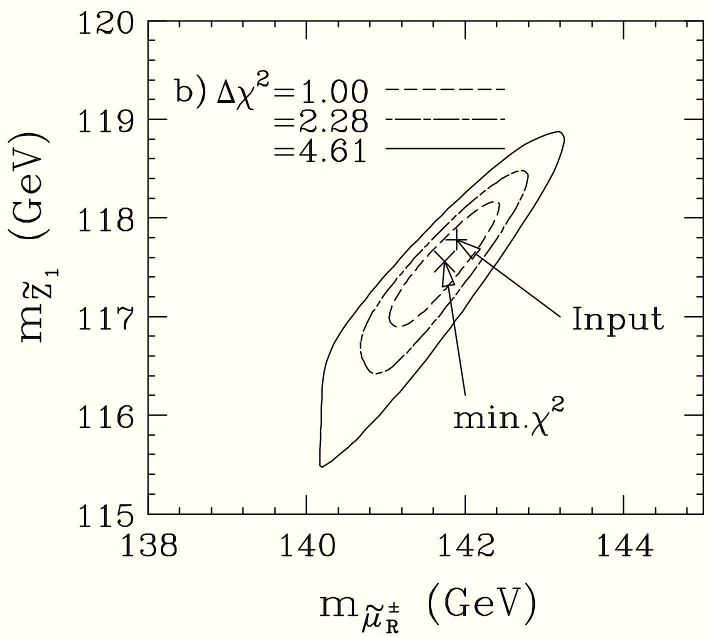
- All beam energy $\Rightarrow$ collision (aside from brem/beamstrahlung losses)
- beam energy known
- clean collision environment
- low (electroweak) background levels
- adjustable beam energy (threshold scans)
- e^- and possibly e^+ beam polarization

★ ILC will be *ideal* machine to perform precision spectroscopy of any new (EW interacting) matter states (provided they are kinematically accessible)!

★ timeline: decision-2012; ready-2025?

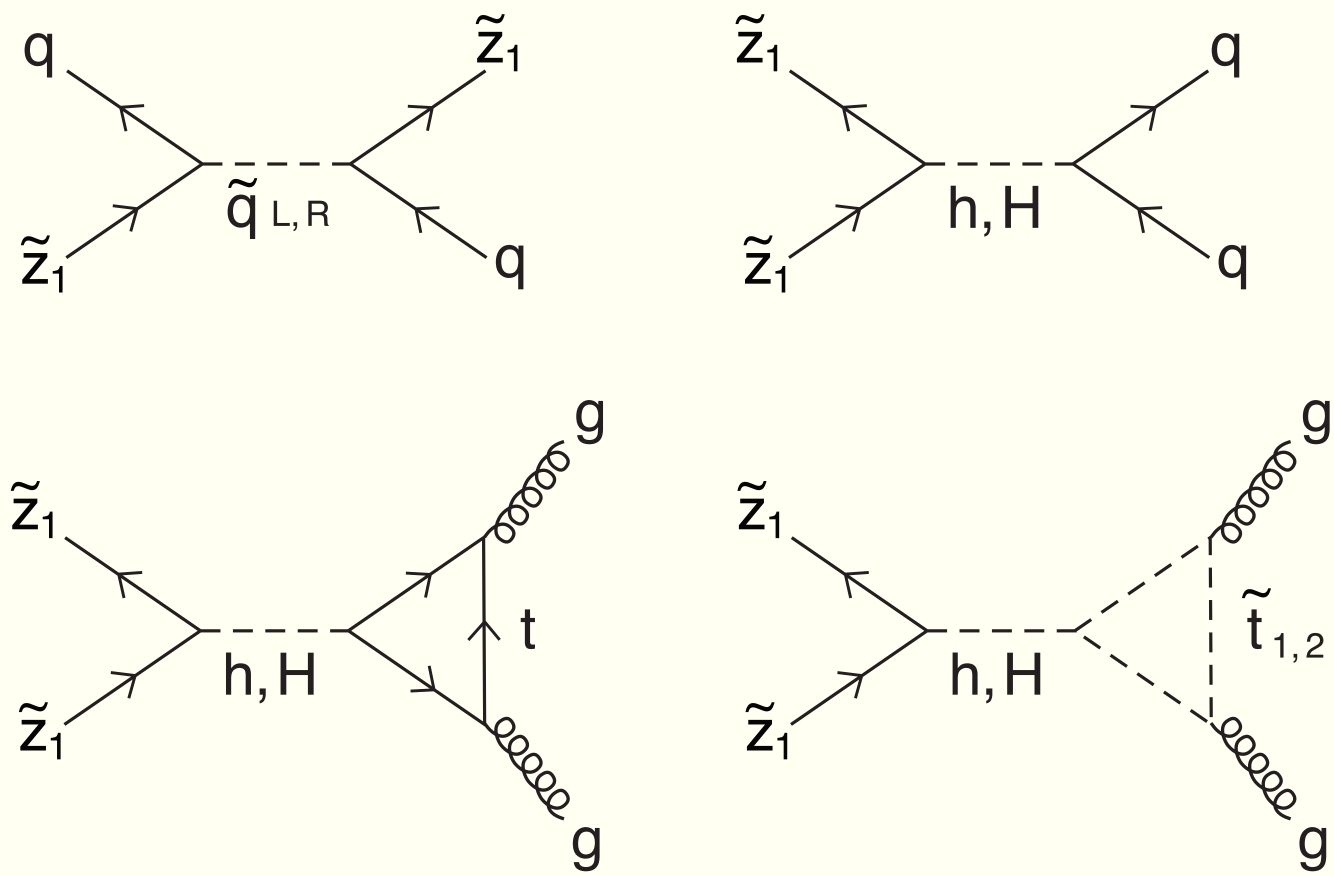
Precision sparticle measurements at a e^+e^- linear collider



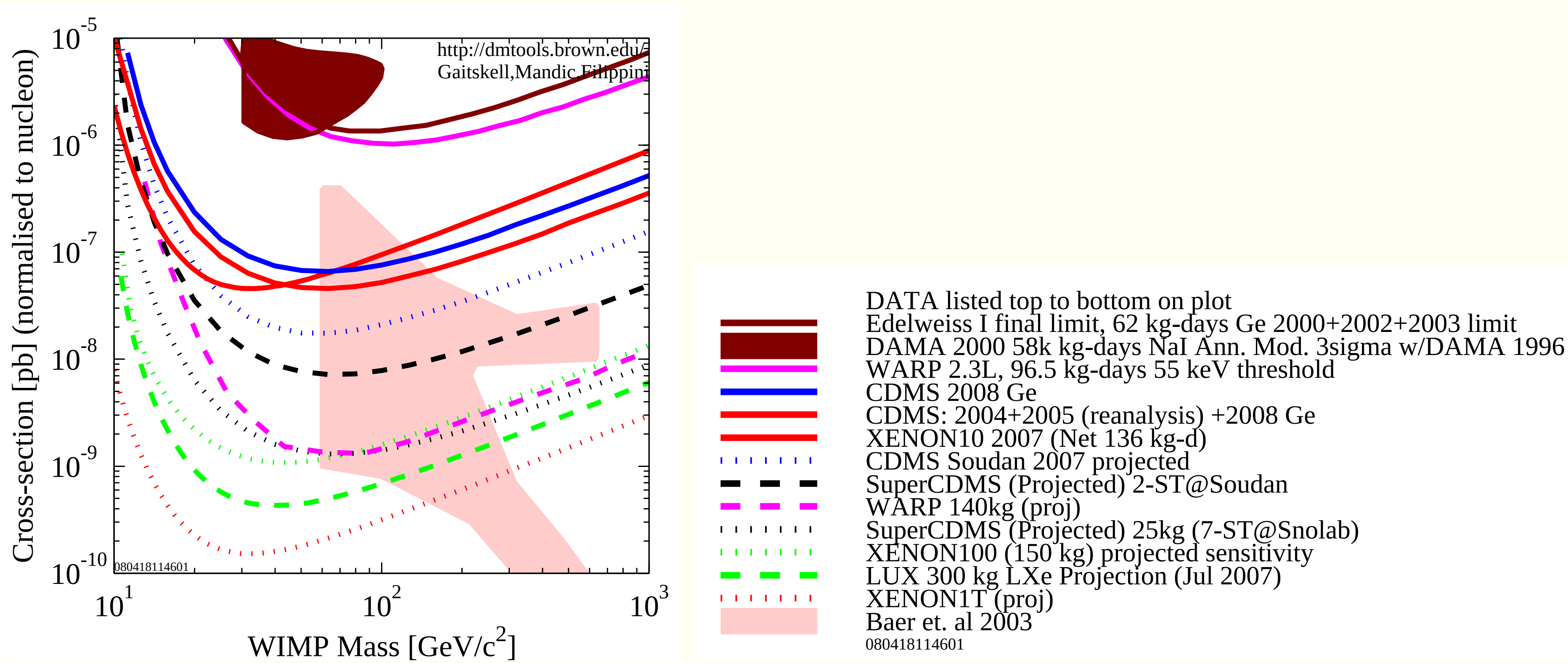


Direct detection of SUSY DM

⋆ Direct search via neutralino-nucleon scattering



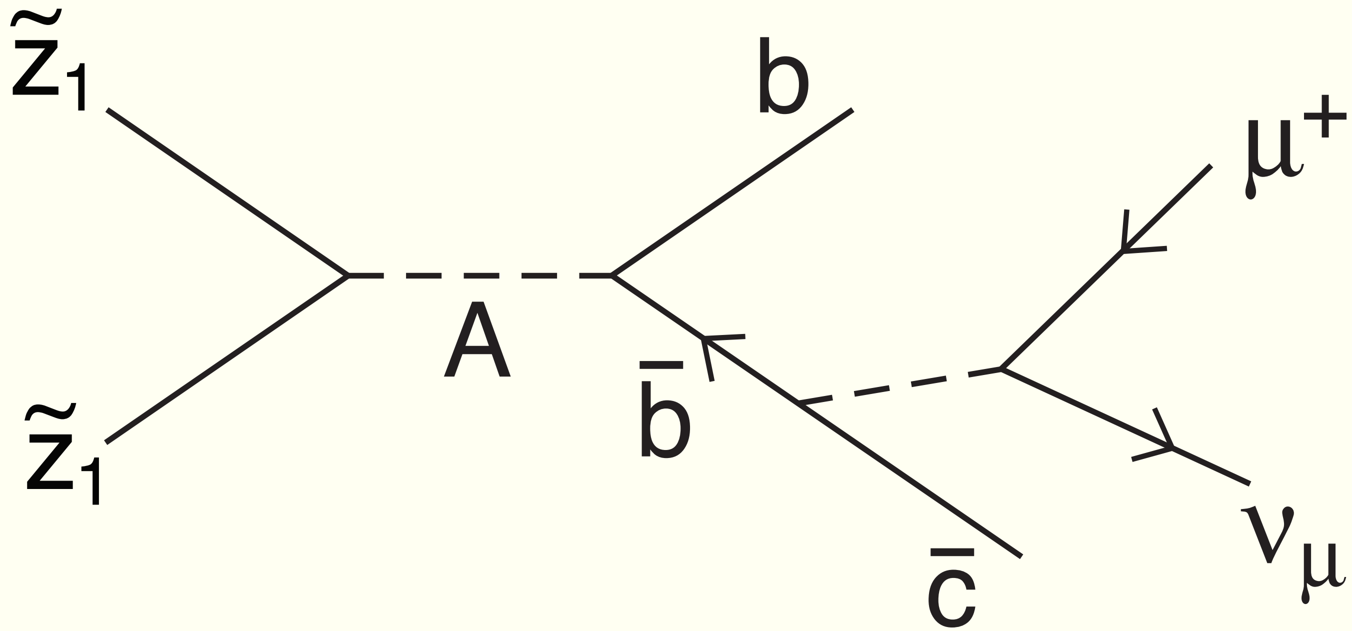
Direct detection of neutralino DM: the race is on!



Indirect detection (ID) of SUSY DM: ν-telescopes

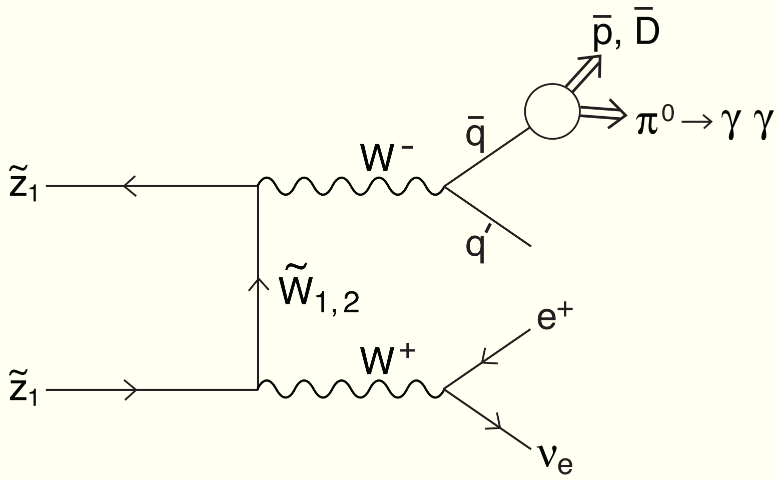
⋆ $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes

- Amanda, Icecube, Antares

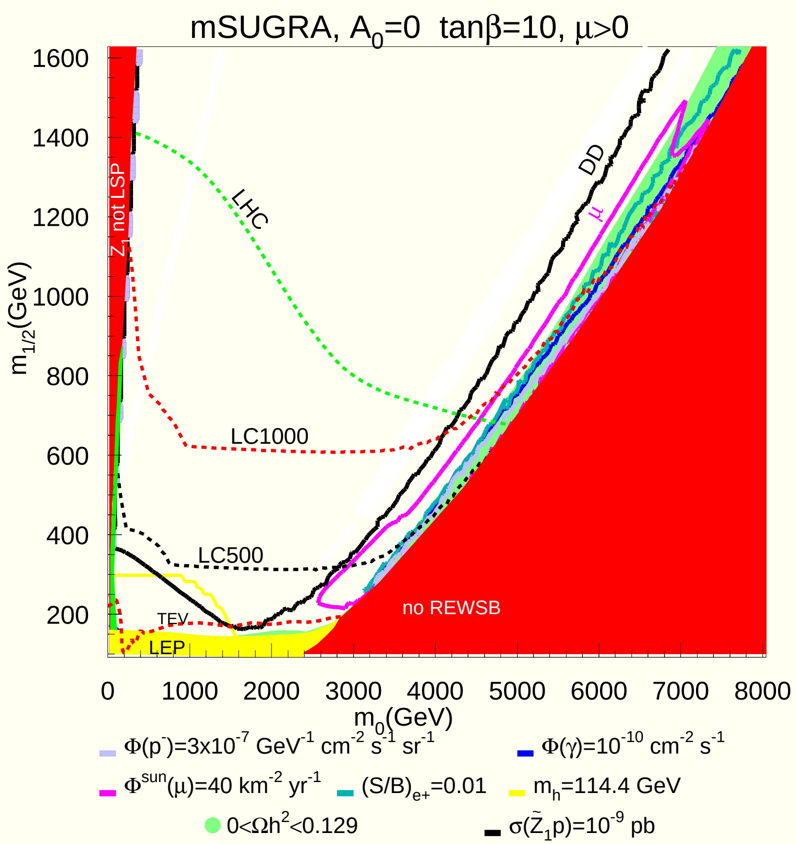


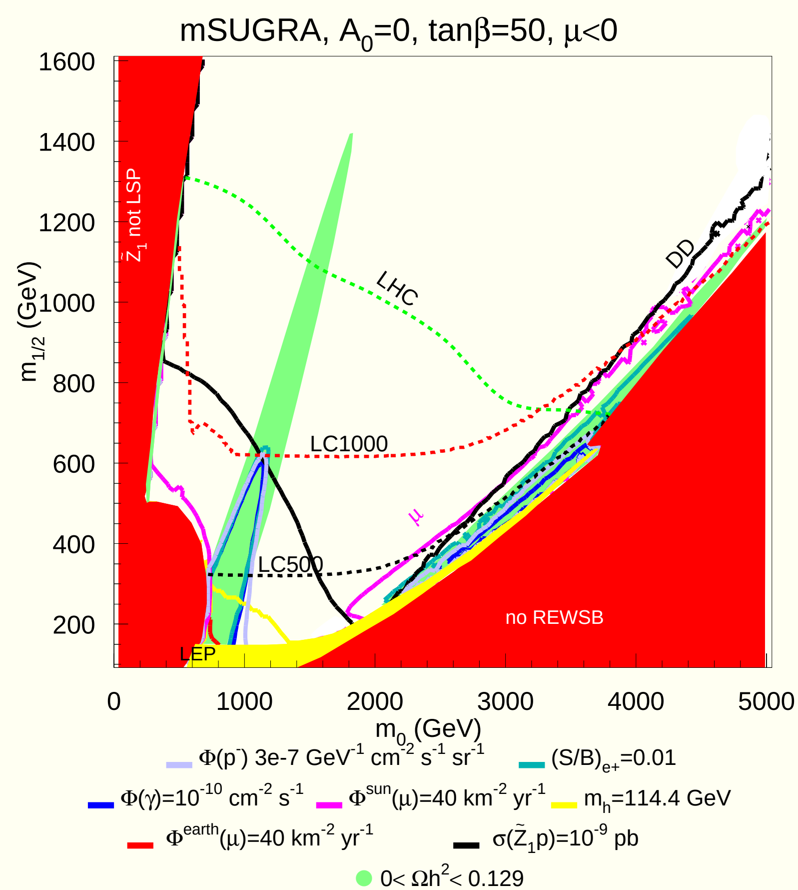
ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo



Direct and indirect detection of neutralino DM





HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

Impact of DM direct/indirect detection on LHC program

- Extend reach in $\sigma_{SI} \sim 10^{-9} - 10^{-10}$ pb
  - explore thoroughly region of MHDM, possibly MWDM
- after discovery, extract m_{wimp}?
  - $m_{\widetilde{Z}_1}$ sets absolute mass scale for SUSY particles-
  - combine with LHC mass edges to gain LHC absolute sparticle masses
  - learn if $\widetilde{Z}_1$ is absolutely stable: R-conservation
- IceCube turn-on can discover/verify especially MHDM
- knowledge of LHC spectra, σ_{SI}, σ_{SD} combined with possible gamma ray signals may allow map of dark matter distribution in the galaxy
- role of $\bar{p}$, e^+, $\bar{D}$ signals

Models beyond mSUGRA

★ Normal scalar mass hierarchy

– split scalar generations $m_0(1) \simeq m_0(2) \ll m_0(3)$

– resolves $BF(b \to s\gamma)$ and $(g-2)_\mu$

★ Non-universal Higgs scalars

– motivated by $SO(10)$ and $SU(5)$ SUSY GUTs

– allow A-funnel at low $\tan\beta$; higgsino DM at low m_0

– enhanced DD/ ID rates

★ DM in models with $t-b-\tau$ Yukawa unification ($SO(10)$)

★ Mixed wino DM

★ Bino-wino co-annihilation (BWCA) DM

★ Low M_3 mixed higgsino DM

★ KKLT mixed moduli/AMSB DM

Conclusions

- ⋆ Supersymmetry is very compelling BSM theory
- ⋆ Irrefragable case for CDM has emerged
- ⋆ Some reach for SUSY at Tevatron
- ⋆ Huge reach for SUSY at CERN LHC
- ⋆ Possible early SUSY discovery at LHC: leptons instead of $\not{E}_T$
- ⋆ e^+e^- LC necessary for precision sparticle spectroscopy
- ⋆ Direct search for WIMP/axion DM is underway
- ⋆ Indirect search for WIMP DM via Icecube ν telescope
- ⋆ Indirect search via γ, $\bar{p}$, e^+, $\bar{D}$ detection from galactic core/halo WIMP annihilations
- ⋆ Solution of mystery of CDM is near if $CDM =$lightest SUSY particle!