Supersymmetry and the LHC: An Introduction

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1989 SUSY loop corrections to m_h computed $\Rightarrow$ Surprise! They’re substantial!

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1993 SSC canceled

2001 LEP ends – fails to find Higgs **or** superpartners $\Rightarrow$ Hand-wringing begins in earnest...

Outline

1. Why do we need to look beyond the Standard Model?

2. What is supersymmetry? What is the MSSM?

3. What are the selling points for supersymmetry?

4. SUSY breaking and superpartner masses

5. Minimal supergravity: the simplest SUSY model

6. Signatures of SUSY at hadron colliders

References: S. Martin's *SUSY Primer*,
Chung et al. *Physics Reports **407** (2005) 1* (hep-ph/0312378),
Branson et al. *High p_T-physics at the LHC* (hep-ph/0110021)

The Standard Model in One Page!

$\Rightarrow$ The SM gauge symmetry is $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$g_\mu^{a=1,\ldots,8}, \quad W_\mu^{i=1,2,3}, \quad B_\mu \quad \longrightarrow \mathrm{EWSB} \longrightarrow \quad g_\mu^{a=1,\ldots,8}, \quad W_\mu^+ W_\mu^- Z_\mu, \quad A_\mu$$

$\Rightarrow$ Matter content involves three generations of quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \; u_R, \; d_R; \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \; e_R, \; \nu_R \qquad \longrightarrow \mathbf{16} \text{ of } \mathrm{SO}(10)$$

$\Rightarrow$ The Higgs sector consists of a *single* doublet of $SU(2)_L$ which performs two crucial roles: EWSB and fermion mass generation

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}_L; \qquad \begin{array}{c} \mathcal{L} \ni D_\mu \phi^\dagger D^\mu \phi + Q \phi u_R + Q \phi^\dagger d_R + \ldots \\ D_\mu = \partial_\mu + g A_\mu + \ldots \end{array}$$

$\Rightarrow$ Total SM Lagrangian contains 19 undetermined parameters

$\Rightarrow$ Has (thus far) provided a good-to-excellent description of almost *all* accelerator/particle physics data ever collected!!

So Why Did we Build the LHC?

$\Rightarrow$ Well...we still haven't found the Higgs field

$\Rightarrow$ Even if we did, scalars have problems

$$m_h^2 \simeq m_0^2 + \frac{\lambda^2}{16\pi^2}\Lambda_{\text{UV}}^2 + \dots$$

- Technicolor
- "Little Higgs" Models
- Composite Higgs Models
- Large Extra Dimensions
- Supersymmetry
- ...

$\Rightarrow$ Three things the Standard Model *cannot* explain

- Baryogenesis
- Dark matter
- Dark energy

The Building Blocks of Supersymmetry

$\Rightarrow$ What is meant by a "supermultiplet"?

- Irreducible multiplet of the supersymmetry algebra
- Fields of the same quantum number(s), but different spin
  - $\star$ Chiral supermultiplet: $F = \left\{ \widetilde{f},\ f,\ F_f \right\}$

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- NOT dynamical – no kinetic terms in the component Lagrangian
- Required for SUSY algebra to close "*off-shell*"
- Solve EOM $\partial\mathcal{L}/\partial\Phi = 0$ for auxiliary fields to eliminate them (more later)

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- Solve EOM $\partial\mathcal{L}/\partial\Phi = 0$ for auxiliary fields to eliminate them (more later)
- But important: vevs trigger SUSY breaking (more later)!

The MSSM I: Field Content

$\Rightarrow$ Fields of the MSSM

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
($\times 3$ families)	$\bar{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\ \bar{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
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- One Higgs doublet of *scalars* OK for anomalies
- New fermions create triangle anomalies, e.g. $\mathrm{Tr}\left[Y^3\right] \neq 0$
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  Huh?

From "Superspace" to *Real* Space

$\Rightarrow$ A supersymmetric Lagrangian is defined by a *superpotential* W

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- This is ensured by making it a product of chiral supermultiplets only
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$$u_R^c = \tilde{u}_R^c + \theta u_R^c + \theta^2 F_u \qquad H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} + \theta \begin{pmatrix} \chi_u^+ \\ \chi_u^0 \end{pmatrix} + \theta^2 \begin{pmatrix} F_{H_u}^+ \\ F_{H_u}^0 \end{pmatrix}$$

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- Tensor calculus made simple: every term must have two thetas

$$W \ni \lambda_u Q u_R^c H_u \to \lambda_u \tilde{u}_L u_R^\dagger \chi_u^0 + \lambda_u u_L \tilde{u}_R^c \chi_u^0 + \lambda_u u_L u_R^\dagger h_0 + \lambda_u \tilde{d}_L u_R^\dagger \chi_u^+ + \cdots$$

The MSSM II: Superpotential

$\Rightarrow$ Most general gauge-invariant, renormalizable superpotential

$$W = W_{\rm MSSM} + W_R$$

$$\begin{aligned} W_{\rm MSSM} &= \lambda_u Q u_R^c H_u + \lambda_d Q d_R^c H_d + \lambda_e L e_R^c H_d + \lambda_\nu L \nu_R^c H_u + \mu H_u H_d \\ W_R &= \lambda' Q d_R^c L + \lambda'' d_R^c d_R^c u_R^c + \lambda''' L L e_R^c + \mu' L H_u \end{aligned}$$

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- Higgs states can mix with leptons
- New contributions to FCNC's at loop level $\rightarrow \lambda \sim 0.05$
- Products of operators can allow rapid proton decay ($\tau_p \simeq \tau_n$)

$$\text{e.g. } p \rightarrow \ell^+ \pi^0 \quad \text{via} \quad \widetilde{s}_R, \widetilde{b}_R \quad \text{exchange} \rightarrow \lambda' \lambda'' \sim 10^{-30}$$

The MSSM III: R-Parity

$\Rightarrow$ So we introduce *R-parity* : $R_p = (-1)^{3(B-L)+2s}$

- Without $2s$ we have "matter parity"

$$P_M(Q, u, d, L, e) = -1 \quad P_M(H_u, H_d) = +1$$

- With spin it instead separates SM from superpartners

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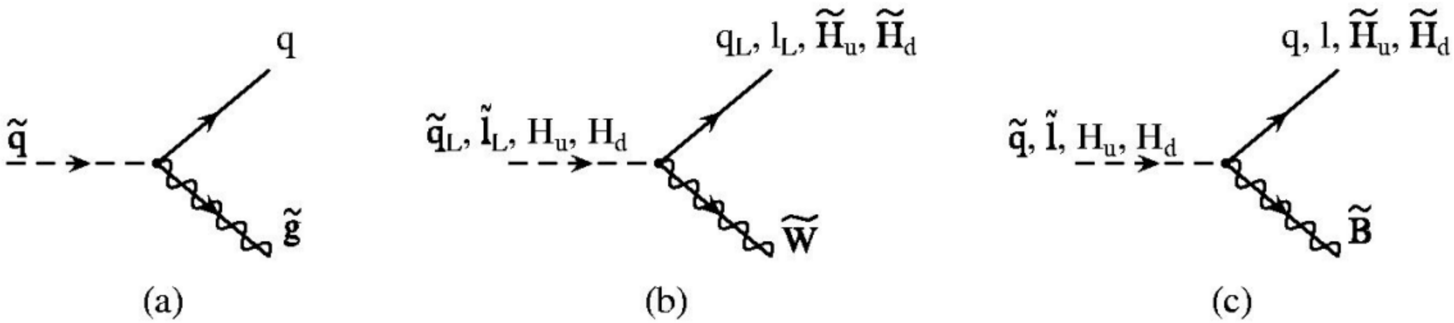
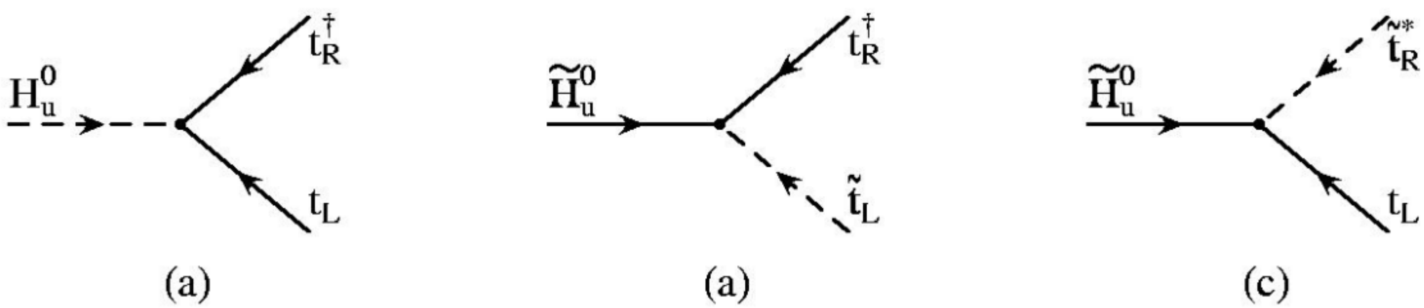
- Immediately forbids all of W_R
- The "two superpartner" rule
- All superpartners must decay into *Lightest Supersymmetric Particle* (LSP)
  - ⋆ Stable
  - ⋆ Neutral and weakly-interacting $\rightarrow$ cold dark matter?
  - ⋆ Signature implication: missing energy

Feynman Diagrams with Superpartners

⇒ Example: scalar field decays



⇒ Example: Top Yukawa (superpotential) interactions



OK... So *Why* Supersymmetry? (I)

$\Rightarrow$ It provides a solution to the so-called “hierarchy problem”

- Consider corrections to SM m_H^2 via $\Delta V = -\lambda_S |H|^2 |s|^2$

$$
\begin{aligned}
\delta m_H^2\Big|_{\mathrm{f}} &= \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{\mathrm{UV}}^2 + 6m_f^2 \ln(\lambda_{\mathrm{UV}}/m_f)\right] \\
\delta m_H^2\Big|_{\mathrm{s}} &= \frac{\lambda_s}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_s^2 \ln(\lambda_{\mathrm{UV}}/m_s)\right]
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- Scalars will diverge like fermions (logarithmically) provided
  - ⋆ 2 scalars per every (Weyl) fermion ✓
  - ⋆ The couplings satisfy $\lambda_S = |\lambda_F|^2$

OK... So *Why* Supersymmetry? (I)

$\Rightarrow$ It provides a solution to the so-called "hierarchy problem"

- Consider corrections to SM m_H^2 via $\Delta V = -\lambda_S |H|^2 |s|^2$

$$\begin{aligned} \delta m_H^2\big|_{\rm f} &= \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{\rm UV}^2 + 6m_f^2 \ln(\lambda_{\rm UV}/m_f)\right] \\ \delta m_H^2\big|_{\rm s} &= \frac{\lambda_s}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_s^2 \ln(\lambda_{\rm UV}/m_s)\right] \end{aligned}$$

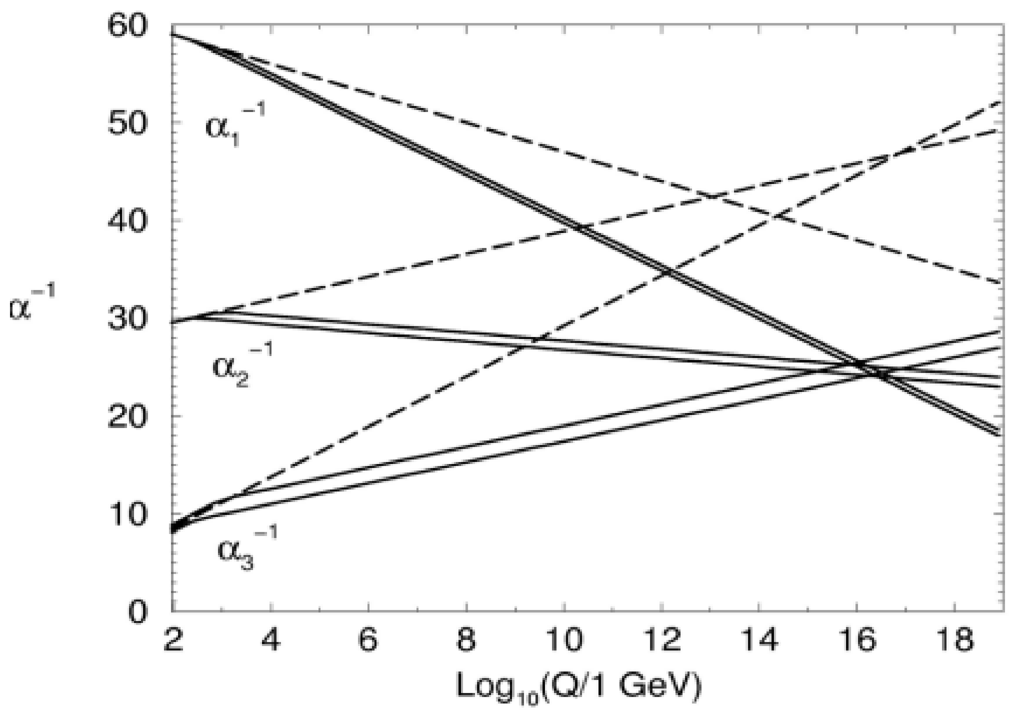
- Scalars will diverge like fermions (logarithmically) provided
  - ⋆ 2 scalars per every (Weyl) fermion ✓
  - ⋆ The couplings satisfy $\lambda_S = |\lambda_F|^2$ ✓
  - ⋆ The scalar and fermion masses are similar

$$\delta m_H^2\big|_{\rm f+s} \sim \frac{\alpha}{16\pi^2}(m_f^2 - m_s^2)\ln\left(\Lambda_{\rm UV}/m\right)$$

- Hence the desire that $(m_f^2 - m_s^2) \lesssim 1\ \mathrm{TeV}$

OK... So *Why* Supersymmetry? (II)

- Dark matter
  - ⋆ LSP is R_p-odd $\rightarrow$ nothing to decay into $\rightarrow$ stable!
  - ⋆ Interacts weakly with itself and with SM $\rightarrow$ perfect CDM candidate!
- Baryogenesis
  - ⋆ SM has only one (small phase); MSSM has 40 of them!
  - ⋆ Phase transition for EWSB strongly first-order in MSSM, but not in SM
- Gauge coupling unification



Gaugino Masses I

$$\mathcal{L}_{\rm soft} \ni -\frac{1}{2} M_a \lambda_a \lambda_a$$

$\Rightarrow$ Gluinos (M_3)

- Only $s = 1/2$, $SU(3)$ adjoint-valued fields $\rightarrow$ no mixing
- Adjoint irrep.'s $\rightarrow$ self-conjugate $\rightarrow$ "LH" and "RH" components identical

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$\Rightarrow$ Charginos (M_2 and μ)

- Four 2-component spinors: Higgsinos (χ_u^+, χ_d^-) and W-inos ($\widetilde{\lambda}_1$, $\widetilde{\lambda}_2$)

$$\psi^{\pm} = \left(\widetilde{W}^+, \chi_u^+, \widetilde{W}^-, \chi_d^-\right)$$

- Charged $\rightarrow$ can be grouped into two Dirac spinors ($\widetilde{C}_1$, $\widetilde{C}_2$)
- Mass terms in 4×4 notation: $\mathcal{L} \ni -\frac{1}{2} \left(\psi^{\pm}\right)^T M_{\widetilde{C}} \left(\psi^{\pm}\right) \;\; + \text{c.c.}$

$$M_{\widetilde{C}} = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \qquad X = \begin{pmatrix} M_2 e^{i\varphi_2} & g_2 v_u \\ g_2 v_d & \mu e^{i\varphi_\mu} \end{pmatrix}$$

Gaugino Masses II – EM Neutral Sector

$\Rightarrow$ Neutralinos (M_1, M_2 and μ)

- Four 2-comp. spinors: Higgsinos (χ_u^0, χ_d^0), W-ino $\widetilde{\lambda}_3 = \widetilde{W}^0$ and B-ino $\widetilde{B}$

$$\psi^0 = \left(\widetilde{B}, \widetilde{W}^0, \chi_d^0, \chi_u^0\right)$$

- Neutral $\rightarrow$ can be organized into four Majorana spinors $\widetilde{N}_i$

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$$M_{\widetilde{N}} = \begin{pmatrix} M_1 e^{i\varphi_1} & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} \\ 0 & M_2 e^{i\varphi_2} & g' v_d/\sqrt{2} & -g' v_u/\sqrt{2} \\ -g' v_d/\sqrt{2} & g' v_d/\sqrt{2} & 0 & -\mu e^{i\varphi_\mu} \\ g' v_u/\sqrt{2} & -g' v_u/\sqrt{2} & -\mu e^{i\varphi_\mu} & 0 \end{pmatrix}$$

⇒ Typical eigenstates if $M_1 \lesssim M_2 \ll \mu$

$$m_{\widetilde{N}_1} \simeq M_1; \quad m_{\widetilde{N}_2} \simeq m_{\widetilde{C}_1} \simeq M_2; \quad m_{\widetilde{N}_3} \simeq m_{\widetilde{N}_4} \simeq m_{\widetilde{C}_1} \simeq \mu$$

$$\widetilde{N}_1 \sim \widetilde{B}; \quad \widetilde{N}_2 \sim \widetilde{W}^0; \quad \widetilde{N}_3, \widetilde{N}_4 \sim \widetilde{H}$$

$$\widetilde{C}_1 \sim \widetilde{W}^\pm; \widetilde{C}_2 \sim \widetilde{H}^\pm$$

The μ parameter

$\Rightarrow$ A *supersymmetric* mass term

$$\begin{aligned} W &\ni \mu H_u H_d = \mu (H_u)_\alpha (H_d)_\beta \epsilon^{\alpha\beta} \\ &\to \mu(\chi_u^+ \chi_d^- - \chi_u^0 \chi_d^0) + |\mu|^2 \left(|h_u^0|^2 + |h_d^0|^2 + |h_u^+|^2 + |h_d^-|^2 \right) \end{aligned}$$

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- Non-vanishing μ needed to give Higgsinos mass
- But if $V_H \sim m_H^2 |h|^2 + \lambda |h|^4$, need $m_H^2 < 0$ if we want $\langle h \rangle \neq 0$
- So we need $|\mu|^2 \lesssim m_{\tilde{f}}^2 \sim (1\ \mathrm{TeV})^2$

$\Rightarrow$ But not tied to SUSY breaking, so no need to be EW scale!

Higgs Sector I: EWSB scalar potential

$\Rightarrow$ Assume that only Higgs fields obtain vevs at minimum

- Minimum can always be found such that $\langle h_u^+ \rangle = \left\langle h_d^- \right\rangle = 0$
- Phase rotations on remaining two Higgs states can make potential real and $\left\langle h_u^0 \right\rangle = v_u$, $\left\langle h_d^0 \right\rangle = v_d$ real and positive

$$\begin{aligned} V &= \left(|\mu|^2 + m_{H_u}^2\right) |h_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right) |h_d^0|^2 \\ &\quad -(b h_u^0 h_d^0 + \text{ c.c.}) + \frac{1}{8}(g^2 + g'^2)(|h_u^0|^2 - |h_d^0|^2)^2 \end{aligned}$$

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\end{aligned}
$$

$\Rightarrow$ Two minimization conditions $\langle \partial V / \partial h_u^0, h_d^0 \rangle = 0$

$$
\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2} M_z^2; \quad 2b = (m_{H_d}^2 + m_{H_u}^2 + 2\mu^2) \sin 2\beta
$$

- Here we have introduced the parameter $\tan\beta = v_u / v_d$
- Note that $v^2 = v_u^2 + v_d^2 \simeq (174 \text{ GeV})^2$ and $M_z^2 = \frac{v^2}{2}(\frac{5}{3}(g')^2 + g_2^2)$

Higgs Sector II: Mass Eigenstates

$\Rightarrow$ Two doublets $\rightarrow$ 8 d.o.f. - 3 d.o.f. (eaten) = 5 Higgs eigenstates

$$\begin{aligned} A &\sim \sin\beta\,\mathrm{Im}(h_d^0) + \cos\beta\,\mathrm{Im}(h_u^0) \\ H^+ &\sim \cos\beta\; h_u^+ + \sin\beta\;(h_d^-)^* \end{aligned}$$

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} \sim \sqrt{2}\begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \mathrm{Re}[h_u^0] - v_u \\ \mathrm{Re}[h_d^0] - v_d \end{pmatrix}$$

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\end{aligned}$$

$\Rightarrow$ Masses of these are given by

$$\begin{aligned}
m_A^2 &= 2b/\sin 2\beta; \quad m_{H^\pm}^2 = m_A^2 + m_W^2 \\
m_{h^0,H^0}^2 &= \frac{1}{2}\left(m_A^2 + M_z^2 \mp \sqrt{(m_A^2 + M_z^2)^2 - 4M_z^2 m_A^2 \cos^2 2\beta}\right)
\end{aligned}$$

$\Rightarrow$ Parameterizing the Higgs sector: minimization conditions allow swap of μ, b for M_z, $\tan\beta$

Breaking SUSY, Generally

$\Rightarrow$ What is a *hidden sector* ?

- No tree-level (renormalizable) interaction of MSSM fields to SUSY breaking order parameters $\langle F \rangle$, $\langle D \rangle$, $\langle M \rangle$
- Thus $\langle D_Y \rangle \neq 0$ and $\left\langle F_{H_u,H_d} \right\rangle \neq 0$ can't be dominant source of SUSY breaking

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- Instead, expect terms like $\langle F_X/M_X \rangle \, \lambda_a \lambda_a$ or $\left\langle |F_X|^2/M_X^2 \right\rangle k_{ij} (\phi^i)^* \phi^j$
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- That is, SUSY breaking is *spontaneous* in the hidden sector, but appears *explicitly* in our sector

$\Rightarrow$ Why must we break SUSY in one?

- If no hidden sector, then at least some scalars lighter than fermions!
- Spontaneous breaking in our sector can only be through $\langle D_Y, D_3 \rangle \neq 0$ and $\left\langle F_{H_u,H_d} \right\rangle \neq 0$

$$m_{\tilde{t}}^2 \sim m_t^2 \pm (a D_Y + b D_3)$$

Gravity Mediation

As a result of putting SUSY breaking in a hidden sector that models are classifed more by how SUSY breaking is transmitted to our sector than how it was actually broken in the first place.

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$\Rightarrow$ Sterile (gauge-singlet) chiral superfield as spurion

- Imagine soft Lagrangian given by

$$-\frac{F_G}{M_G}\sum_a \lambda_a\lambda_a - |\frac{F_S}{M_S}|^2 \sum_f k_{ij}^f(\widetilde{\phi}_f^i)^*\widetilde{\phi}_f^j - \frac{1}{2}\frac{F_B}{M_B}\mu H_u H_d - \frac{F_A}{M_A}\sum_\alpha \lambda_{ijk}^\alpha \widetilde{\phi}^i\widetilde{\phi}^j\widetilde{\phi}^k$$

- M_i are the scales of the mediation fields (what's been integrated out)

- If we take $M_i = M_{\rm PL}$ we have *gravity mediation*

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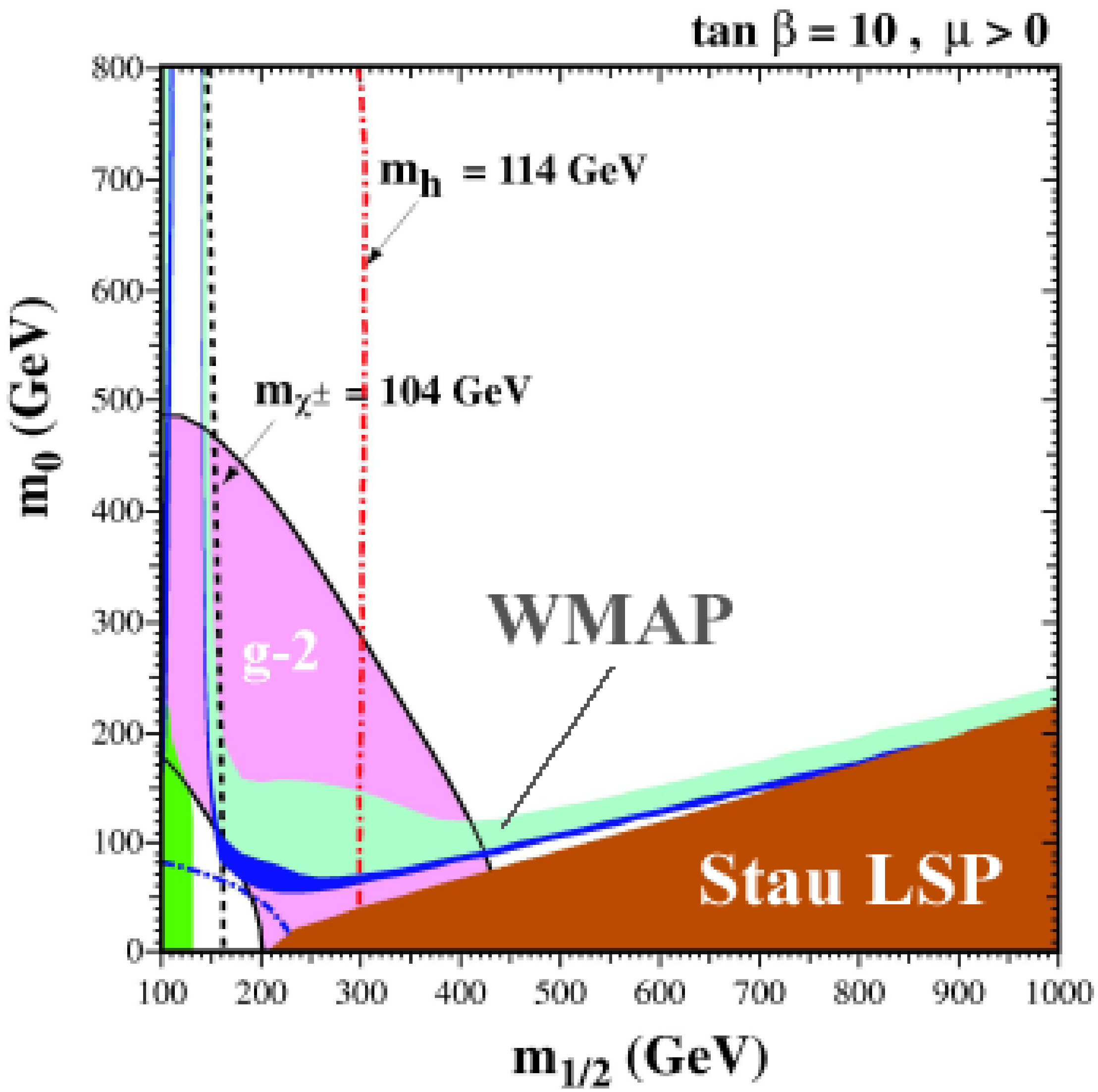
$\Rightarrow$ Resulting soft terms

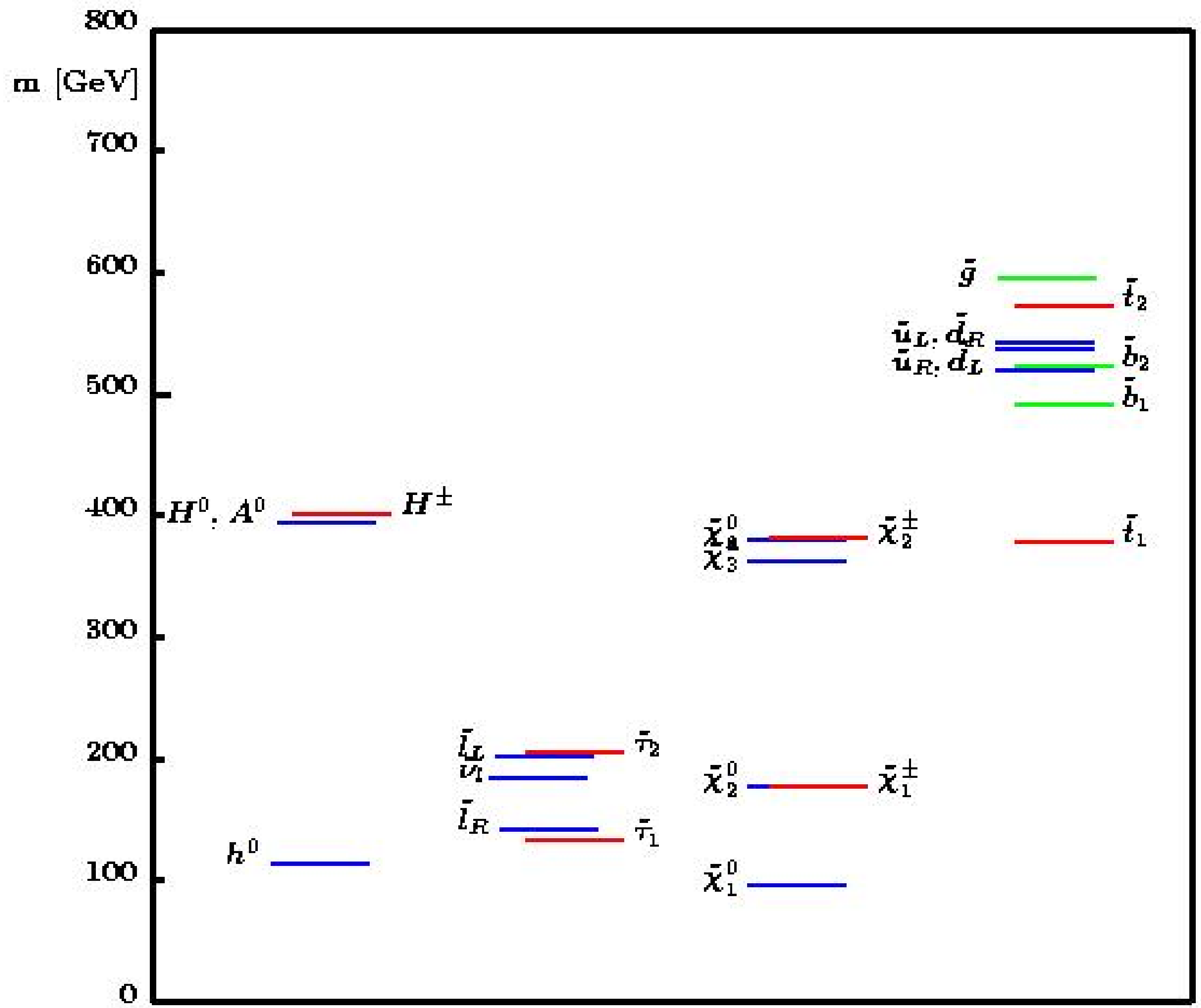
$$m_{1/2} = \frac{F_G}{M_G},\ m_0^2 = |\frac{F_S}{M_S}|^2,\ a^\alpha_{ijk} = \lambda^\alpha_{ijk}\frac{F_A}{M_A},\ b = \mu\frac{F_B}{M_B}$$

Minimal Supergravity (mSUGRA)

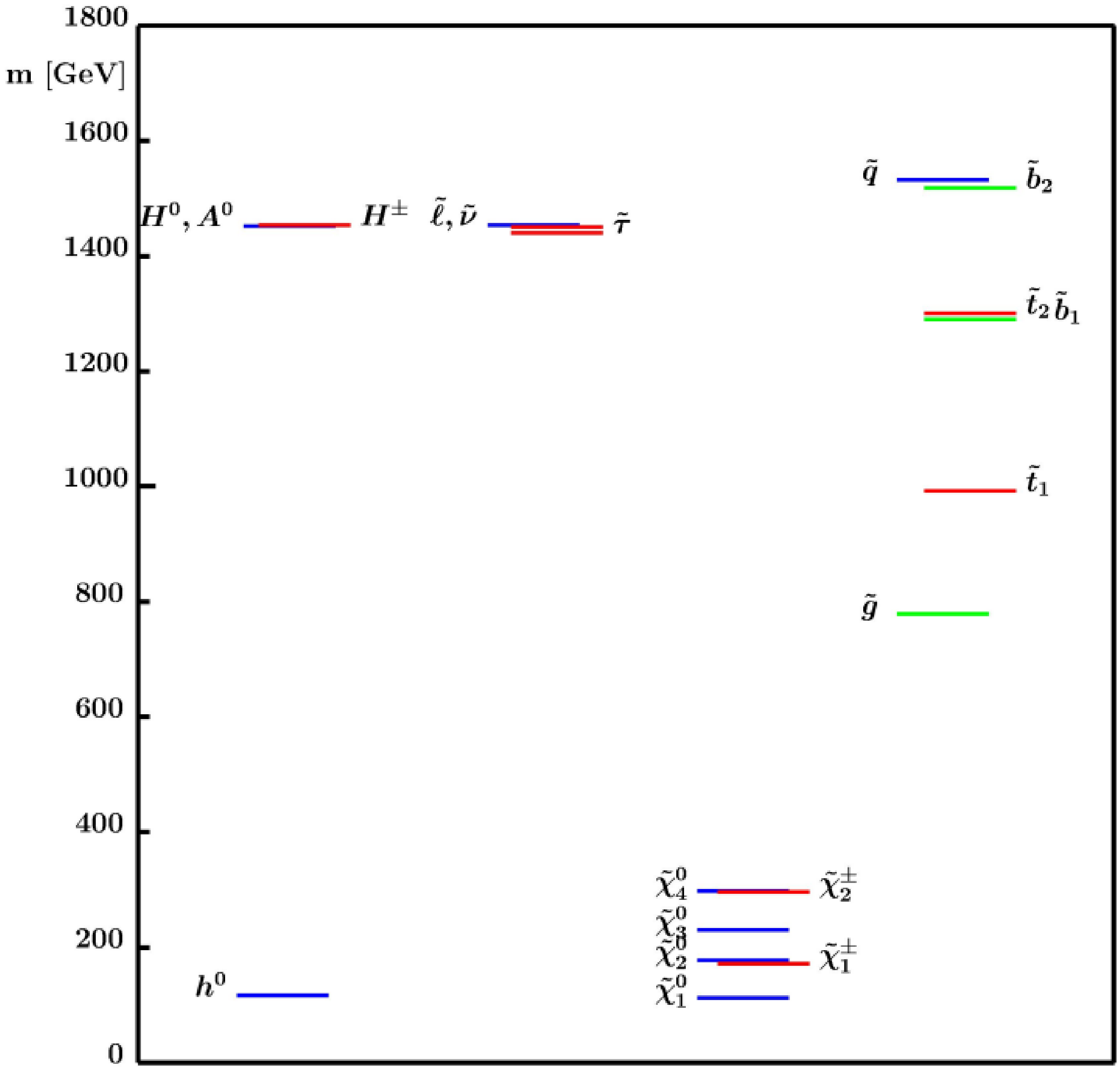
Defined by parameter set: $\{m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)\}$



mSUGRA Sample Spectrum A



mSUGRA Sample Spectrum B



Overview of Classic SUSY Signatures

$\Rightarrow$ Break up into channels by n jets + m leptons + $\not{E}_T$

- 0 leptons + ≥ 2 jets + $\not{E}_T$ ("multijet"channel)
- 1 lepton + ≥ 2 jets + $\not{E}_T$
- 2 leptons + $\not{E}_T$
  - $\star$ Same Sign (SS) vs. Opposite Sign (OS) sub-samples
  - $\star$ Can be "clean"(no jets) or with ≥ 2 jets
- Trilpetons, clean or ≥ 2 jets, + $\not{E}_T$

$\Rightarrow$ Remember: invisible, stable LSP means **no mass peaks**!

Jets plus Missing Energy

$\Rightarrow$ Squark, gluino production rate $\sim$ SM jet production at similar Q^2

$\Rightarrow$ Multijet signal via quark decays

$\widetilde{g} \longrightarrow q\bar{q}\widetilde{N}_i^0$, $\widetilde{g} \longrightarrow t\widetilde{t}$, $\widetilde{q}_L \longrightarrow q\widetilde{C}_i^{\pm}$, etc. [and subsequent cascades]

$\Rightarrow$ The ultimate *inclusive signature*

- Just count events – does not matter what the original particles were
- Look for excess over (known) SM rate

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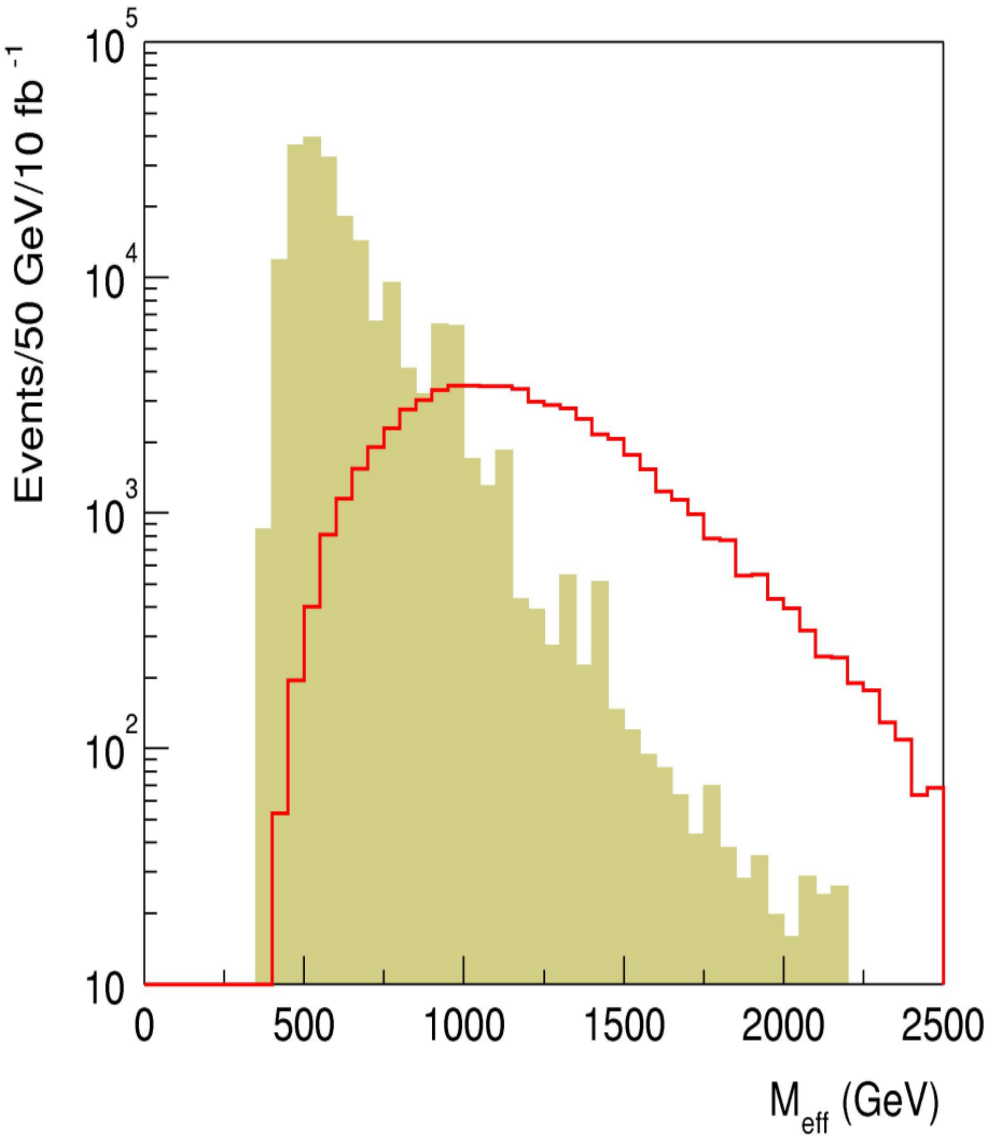
$\Rightarrow$ Kinematic variable $M_{\rm eff} \equiv \not{E}_T + \sum_i (p_T^{\rm jet})_i$ can be useful in SUSY discovery

- Claim: peak in $M_{\rm eff}$ distribution proportional to $M_{\rm SUSY} \equiv \min(M_{\widetilde{g}},\ M_{\widetilde{q}})$
- This channel alone can find SUSY for squarks/gluinos up to 1 TeV with 1 fb^{-1} – 2.5-3 TeV for 300 fb^{-1}

$M_{\rm eff}$ and Kinematic Distributions

- SM backgrounds
  - ⋆ QCD ($gg \to gg$, etc.) with extra jets from parton showers
  - ⋆ Heavy flavor production
  - ⋆ Z + multijets with $Z \to \tau\tau$ or $Z \to \nu\nu$
  - ⋆ W + multijets with $W \to \tau\nu$ or $W \to \ell\nu$
- A typical set of cuts
  - ⋆ $E_T^{\rm jet} \geq$ 100, 50, 50, 50 GeV
  - ⋆ No isolated lepton with $p_T > 20$ GeV
  - ⋆ Transverse sphericity $S_T > 0.2$
  - ⋆ Transverse plane angle $30^o < \Delta\phi(\not{E}_T, j) < 90^o$
  - ⋆ $\not{E}_T > 0.2\ M_{\rm eff}$

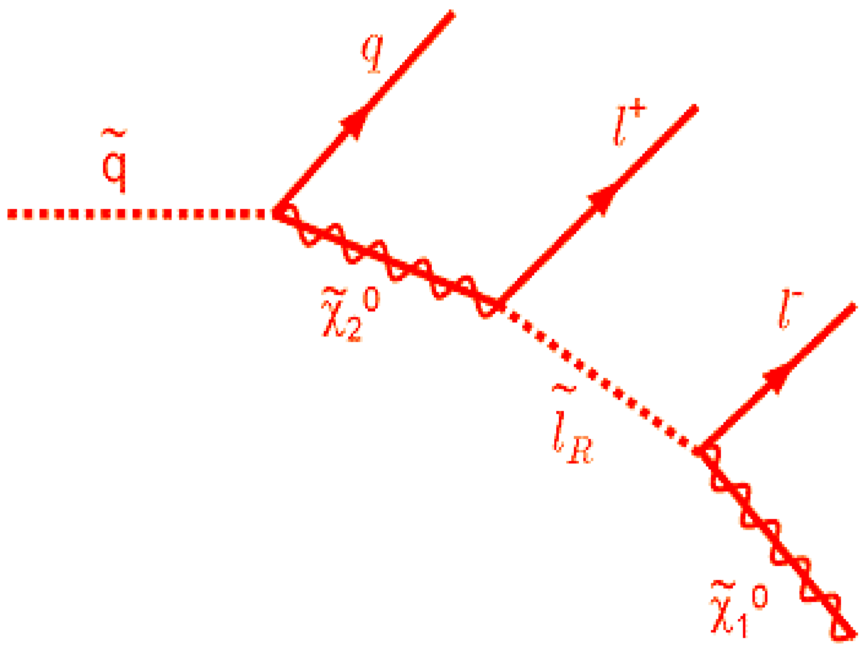


Multilepton Events: OS dileptons

⇒ Multi-lepton signals are comparable in reach/discovery to multijets with $100\,\mathrm{fb}^{-1}$ data

⇒ OS Dilepton events (inclusive)

- Many paths to this signature in SUSY: $\widetilde{C}_1^{\pm}$ pair production, $\widetilde{N}_2^0 \to \widetilde{\ell}^{\pm}\ell^{\mp} \to \widetilde{N}_1^0 \ell^+\ell^-$, $\widetilde{q}_L \to \widetilde{N}_2^0 q \to \widetilde{N}_1^0 \ell^+\ell^- q$, etc.
- Main SM background is $t\bar{t}$ production
- Inclusive OS and *same flavor* can be a SUSY discovery mode



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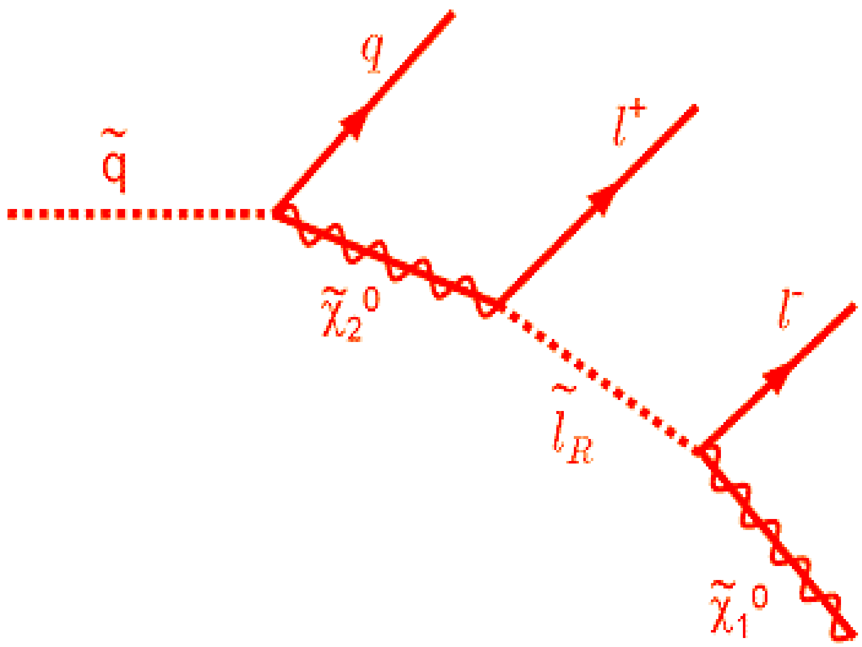
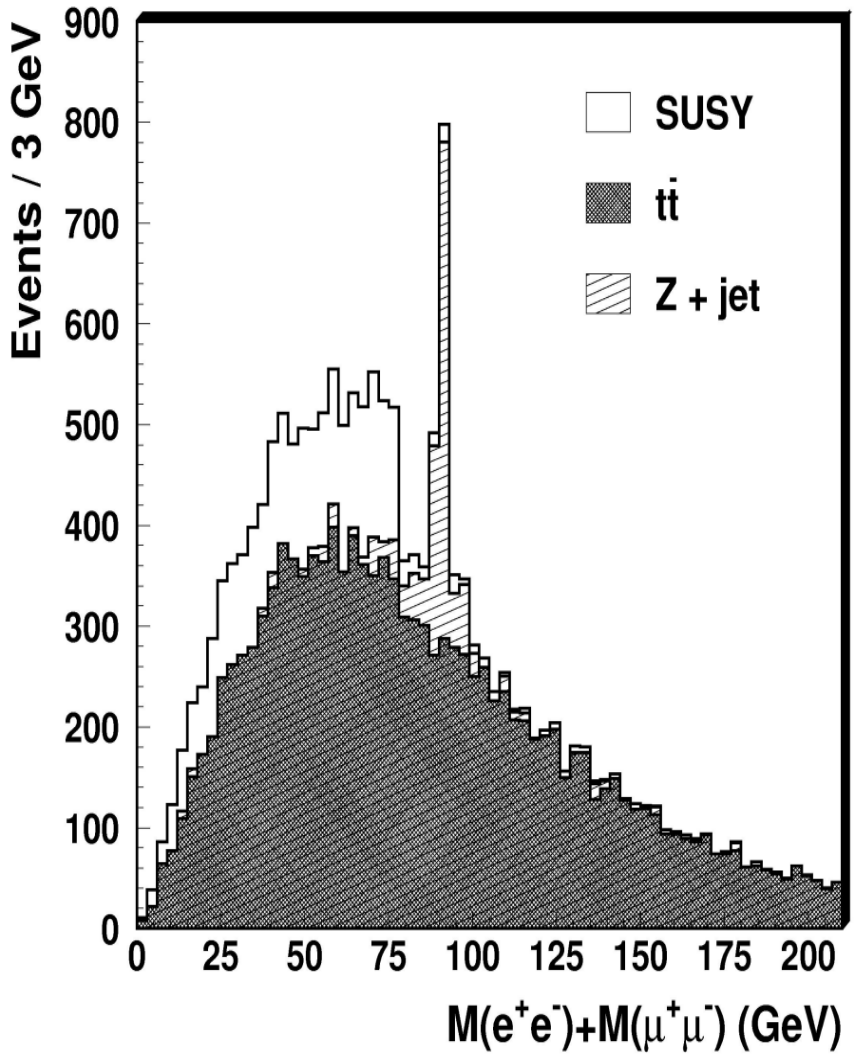
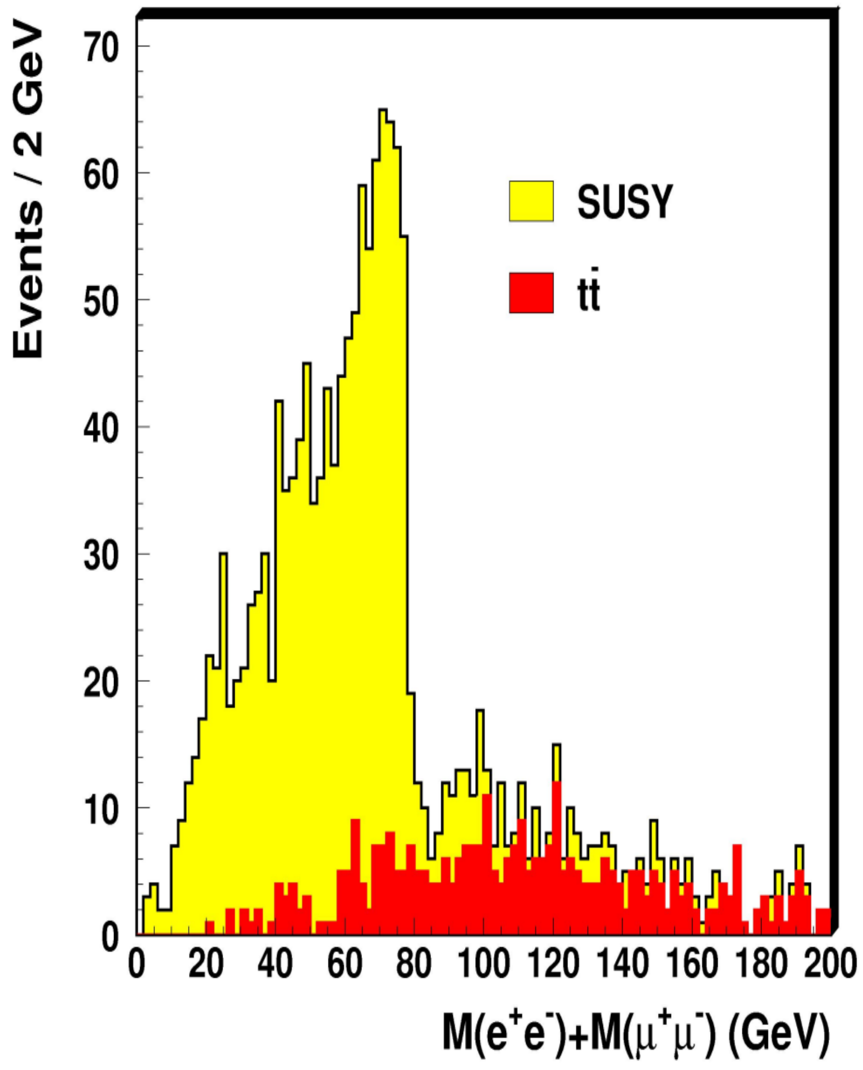


$\Rightarrow$ Reduction of SM background

- Use $e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$ sample to reduce $t\bar{t}$
- Veto $Z \rightarrow \ell\ell$ via invariant mass cut $M_{\ell\ell} \neq M_Z \pm 10\,\mathrm{GeV}$
- Off shell γ and Z decays to taus reduced by $\Delta\phi(\ell\ell) \leq 150^o$

Multilepton Events: OS dileptons





Multilepton Events: SS Dileptons & Trileptons

$\Rightarrow$ SS dilepton events often said to be “truly SUSY” signature

- SS usually seen as gluino-driven; result of Majorana nature

$$\widetilde{g} \to q\widetilde{q} \to qq'\widetilde{C}_1^{\pm} \to qq'W^{\pm}\widetilde{N}_1^0$$

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⇒ "Clean" Trilepton Events: the Gold-Plated Signature

- Lack of jets tends to mean chargino/neutralino production

$$pp \longrightarrow \widetilde{C}_1^{\pm}\widetilde{N}_2^0 \longrightarrow \widetilde{N}_1^0\ell\ell \;\; \widetilde{N}_1^0\ell\nu$$

- Separation of production mechanism (i.e. isolation of $\widetilde{C}_1^{\pm}\widetilde{N}_2^0$ sample) seems possible with cuts
- Various kinematic distributions can be formed $m_{\ell_i\ell_j}$

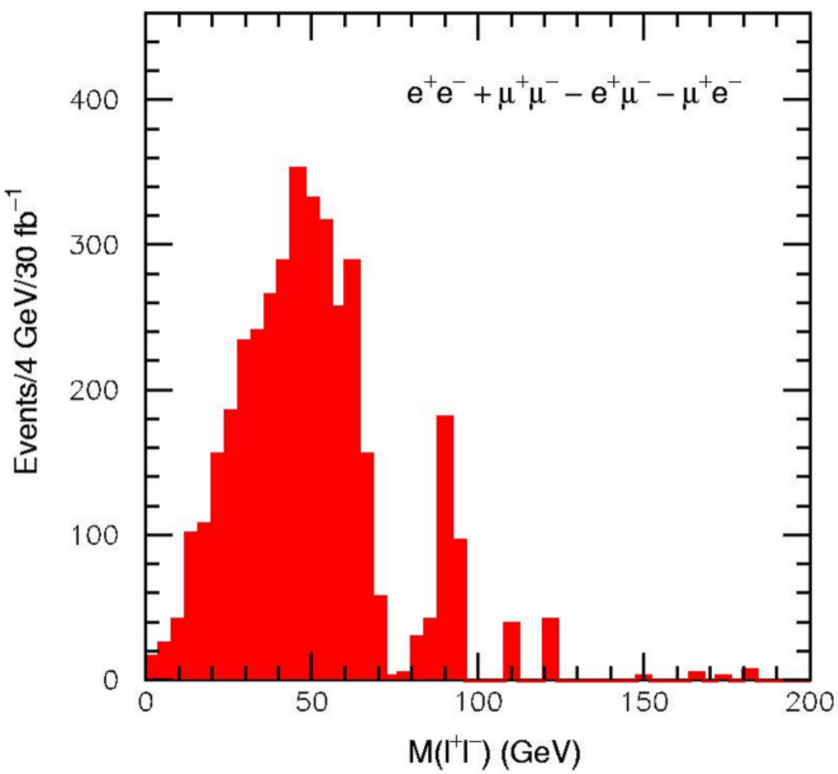
Information from Lepton Distributions

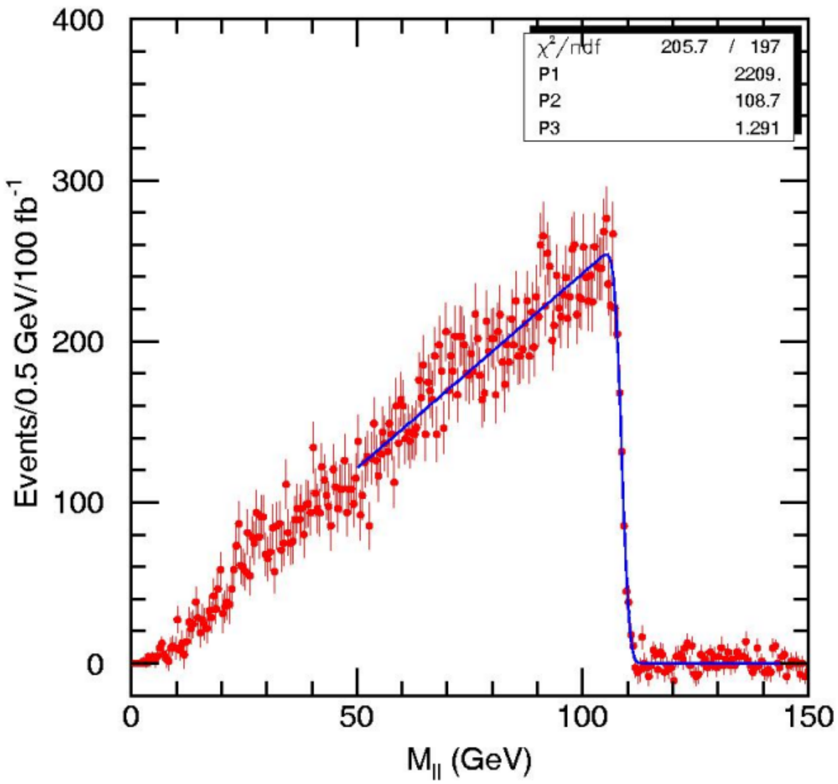
$\Rightarrow$ Endpoint of effective mass distribution of the two leptons carries information.....**but on what?**

$$\widetilde{N}_2^0 \to \widetilde{N}_1^0 \ell^+ \ell^- \text{ then } M_{\ell\ell}^{\max} = M_{\widetilde{N}_2^0} - M_{\widetilde{N}_1^0}$$

$$\widetilde{N}_2^0 \to \widetilde{\ell}^{\pm} \ell^{\mp} \to \widetilde{N}_1^0 \ell^+ \ell^- \text{ then } M_{\ell\ell}^{\max} = \frac{1}{M_{\widetilde{\ell}}} \sqrt{(M^2_{\widetilde{N}_2^0} - M^2_{\widetilde{\ell}})(M_{\widetilde{\ell}^2} - M^2_{\widetilde{N}_1^0})}$$

$\Rightarrow$ Shape of distribution is supposed to tell them apart





Some Words of Caution

Rule of thumb: SUSY "discovery" can be done with **inclusive**, model-independent observations – parameter extraction requires **exclusive**, model-dependent techniques

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⇒ *The background to SUSY is more SUSY!*

Lots of distribution features will be extracted...to what end?

- Example: trilepton + 2 jets allows all sorts of pairings. Do they have information content if you don't know the spectrum? Can you separate chargino/neutralino sources from squark/gluino sources?
- Example: SS dileptons can come from gluinos, but also from

$$pp \to \widetilde{b}_L \bar{\widetilde{b}}_L X \to t \widetilde{C}_1^- t \widetilde{C}_1^+ X$$

Endpoint value measures something different here!

⇒ Need to use strict cuts to separate multiple channels leading to same inclusive topology...*reduction in signal and significance*

Concluding Thoughts

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- Synthesis direction
  - ⋆ Enlarge the set of inclusive signatures
  - ⋆ Improve SM baseline determination
  - ⋆ Study ability to separate regions with a model's parameter space – and models from one another
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  - ⋆ Robustness analysis: from points to lines to footprints

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⇒ Towards a decision tree style strategy

1. Organize analysis tools by needed inputs/model dependence
2. Use least dependent tools with global fits to paradigms
3. Cross check promising paradigms against other analysis measurements
4. Organize flow chart as function of integrated luminosity

Supporting Slides

Some Words of Caution: II

Examples of exclusive analysis: separating contributions to M_{eff} and $m_{\ell\ell}$

In multijet channel, how do you know what fraction of the sample is from production of gluino pairs and what fraction from squark pairs?

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- Jet multiplicity: assume for first/second generation squarks “R” and “L” produced more or less equally
- BR($\widetilde{q}_R \to q\widetilde{N}_1^0$) nearly 100% $\to$ one jet per decay
- $\widetilde{q}_L$ and $\widetilde{g}$ have different decays such as $\widetilde{g} \to q\bar{q}\widetilde{C}_i^{\pm}$ and $\widetilde{g} \to q\bar{q}\widetilde{N}_i^{\pm} \to$ usually more jets per decay

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In SS dilepton + jets sample, how do you separate gluino from squark contributions?

- Charge asymmetry: initial state at LHC is pp
- Cascade decays from $\widetilde{g}\widetilde{q}$ and $\widetilde{q}\widetilde{q}$ events leads to a larger cross section for positive SS pairs than for negative ones
- This asymmetry is sensitive to $m_{\widetilde{g}}/m_{\widetilde{q}}$

Some Words of Caution: III

$\Rightarrow$ Many such algorithms known, but all are devised within limited model regimes (all mSUGRA)

- BR($\widetilde{q}_R \to q\widetilde{N}_1^0$) nearly 100% artifact of LSP being 99% B-ino
- Obtaining $m_{\widetilde{g}}/m_{\widetilde{q}}$ from charge asymmetry in SS dileptons really requires outside knowledge of $m_{\widetilde{g}}$ to work well
- Gluino mass measurement algorithm based on mSUGRA point where $m^2_{\widetilde{\ell}_R} \simeq M_{\widetilde{N}_2^0} M_{\widetilde{N}_1^0}$ – by no means a general result

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$\Rightarrow$ Even once exclusive samples are prepared, information from distributions may be misleading because of **phases**

- Can shift peak of $M_{\rm eff}$ distributions by significant amount
- Can change the **shape** of kinematic distributions and **location** of endpoint
- Can effect cross-sections for gaugino production [clean trilepton signal] by 30-40%
- Relation between mass eigenstates and soft Lagrangian parameters becomes more complicated