Split or Splat Supersymmetry at the LHC

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A little Karl Popper to start with …

"… if we aim, in science, at a high information content … then we have to admit that we also aim at a low probability."

"… only … an improbable theory is worth testing."

Two Improbable Theories

- Split Supersymmetry

  The idea that scalars are very much heavier than the gauginos/higgsinos.

- Splat Supersymmetry

  The idea that scalars have zero mass at some boundary scale and gauginos induce their masses.

SUSY breaking resides in <F> of chiral multiplet

$$X = x + \sqrt{2}\psi\theta + F\theta^2$$

This leads to gravitino mass: $m_{3/2}^2 \sim \dfrac{F^\dagger F}{M_{\rm Pl}^2}$

Gaugino masses: $\int d^2\theta \dfrac{X}{M_{\rm Pl}} \mathcal{W}\mathcal{W} \sim m_{3/2}\lambda\lambda$

Scalar masses: $\int d^2\theta d^2\bar{\theta} \dfrac{X^\dagger X}{M_{\rm Pl}^2} \Phi_i^\dagger \Phi_i \to m_{3/2}^2 \phi_i^* \phi_i$

Everybody $\sim m_{3/2}$, and $m_{3/2} \sim m_W$ for naturalness.

Challenges for Low-Energy SUSY

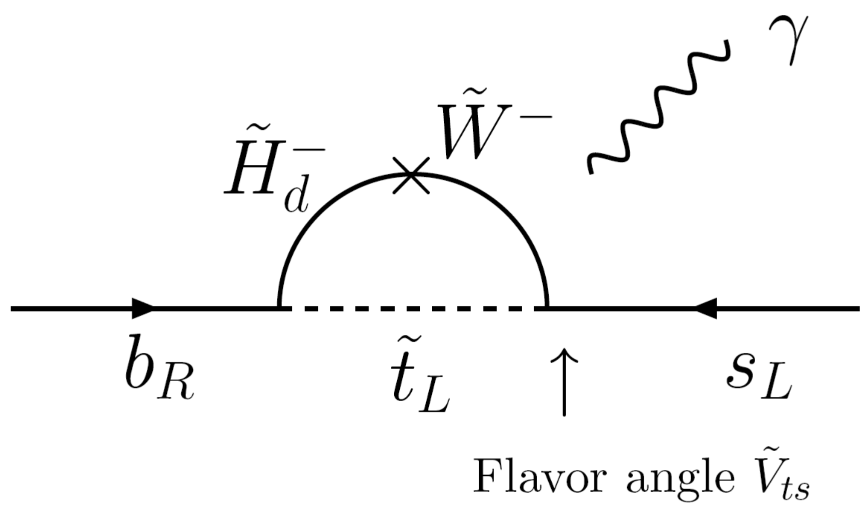
Throw a dart into Minimal SUSY parameter space,
And what do you get?

Observable predictions would be wildly
Incompatible with experiment.

Briefly review these challenges ….

Flavor Changing Neutral Currents

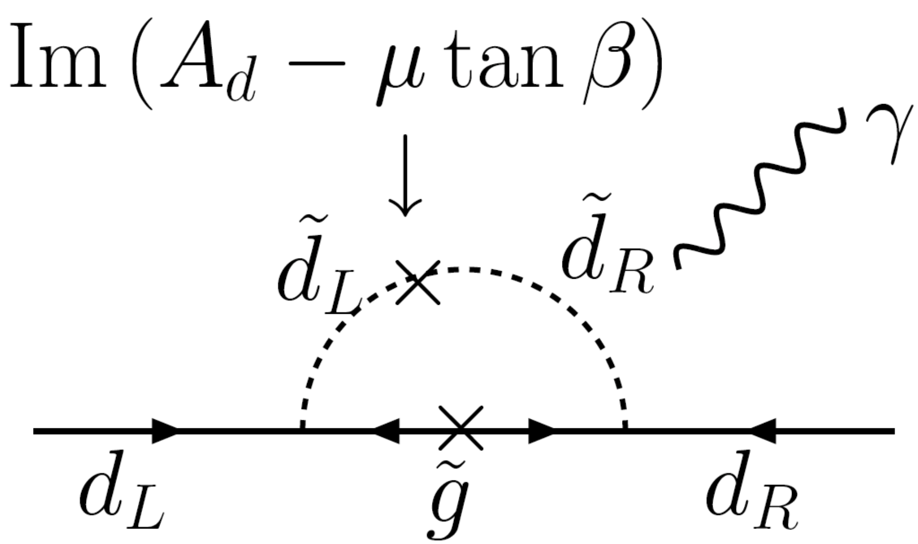
Random superpartner masses and mixing angles would generate FCNC far beyond what is measured:



However: heavy or universal scalars would squash these FCNCs

CP Violation

Supersymmetry has many new sources of CP violation:



Large unless CP angle small or scalar masses heavy.

Higgs boson mass

In minimal supersymmetry the lightest Higgs mass is computable:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{\tilde{m}_t^2}{m_t^2} + \cdots$$

Tree-level value is bounded by $m_Z = 91\,\text{GeV}$. Current lower limit on Higgs boson mass is $114\,\text{GeV}$. Thus, we need $\sim (70\,\text{GeV})^2$ contribution from quantum correction.

Need $\tilde{m}_t \gtrsim 5\,\text{TeV}(0.8\,\text{TeV})$ for $\tan\beta = 2(30)$

Log-sensitivity keeps m_h below the Precision EW bound (~ 200 GeV)

What to do

Supersymmetry

Eliminating bad things:

1. FCNC
2. Proton decay strains
3. CP Violation
4. Too light Higgs mass

Preserving good things:

- SUSY Naturalness
- Light Higgs prediction
- Gauge Coupling Unification
- Dark Matter

Two Approaches:

"Split Supersymmetry":
Scalars are very heavy and solve FCNC, CP violation, and too light Higgs problem, etc. (naturalness issues …)

"Splat Supersymmetry":
Higgs-exempt no-scale susy; 'zero mass' scalars solve FCNC, heavy-enough superpartners for Higgs problem, while DM ok, etc.

E.g., AMSB Gauginos

SUSY breaking accomplished by non-singlet.
Scalars don't care:

$$\int d^4\theta \frac{X^\dagger X}{M_{\rm Pl}^2} Q^\dagger Q \Longrightarrow \frac{F^\dagger F}{M_{Pl}^2} \tilde{Q}^\dagger \tilde{Q} \quad (m_{\tilde{Q}}^2 \simeq F^\dagger F / M_{\rm Pl}^2)$$

Assuming cc = 0
the gravitino mass is

$$m_{\tilde{G}}^2 = \frac{F^\dagger F}{M_{\rm Pl}^2}$$

- Scalars are out of reach
- Binos are not produced
- Higgs mass predicted to be above current limit (but <140 still)
- Wino and gluino production give colliders hope

On the other hand, gauginos do care:

$$\int d^2\theta \frac{X}{M_{\rm Pl}^2} WW \quad \text{not gauge invariant } M_\lambda = 0$$

In this case, leading contribution to gaugino mass is AMSB contribution:

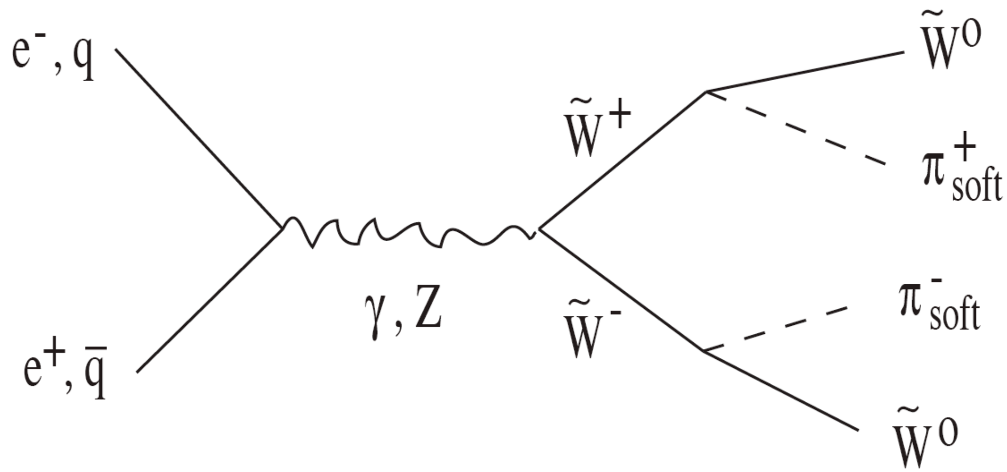
$$M_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} m_{\tilde{G}}$$

M_1:M_2:M_3 ~ 2:1:8

(Randall, Sundrum;
Giudice, Luty, Murayama, Rattazzi)

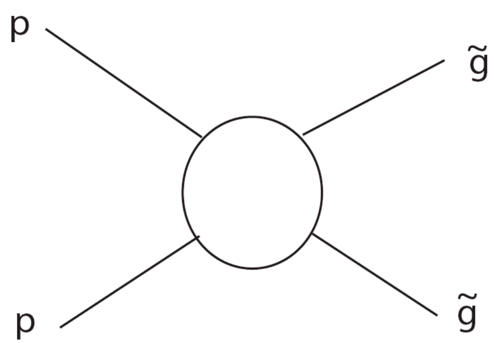
Wino Production and Decays

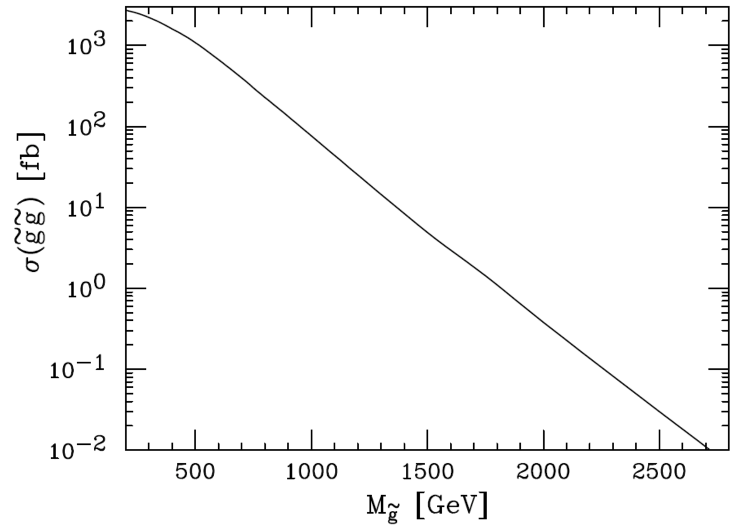
The mass splitting between charged and neutral is tiny.



As it stands, difficult. LEP has limits (~ 90-100 GeV).
Hadron colliders cannot trigger on soft pions.
Trigger on initial state gluon (Tevatron/LHC).
Can this be done?

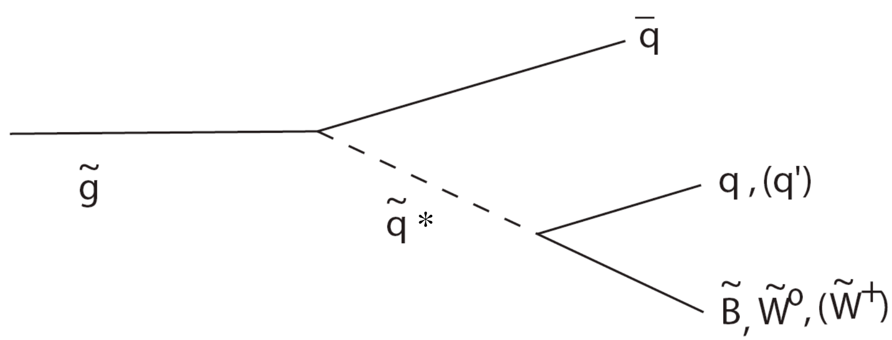
Gluino Production and Decays





Pythia output

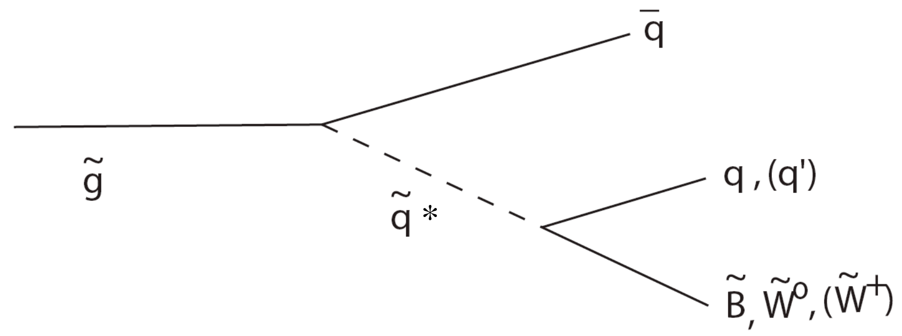
Main decay is three-body through off-shell squark



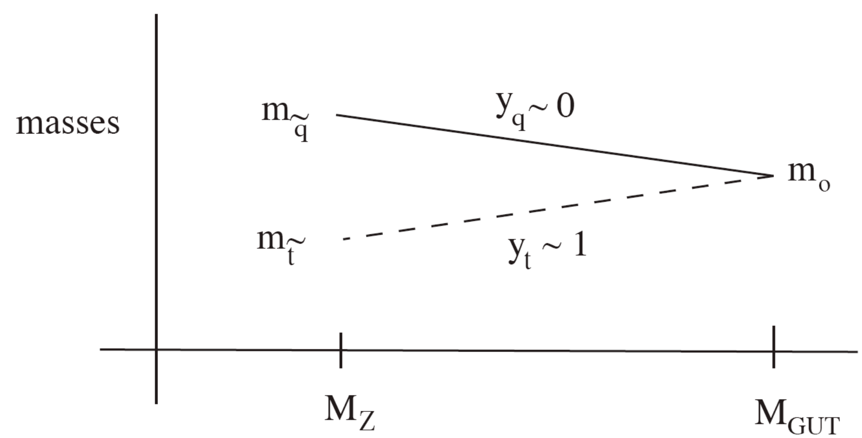
(Toharia, JW & Gambino, Giudice, Slavich for more details on gluino decays within this scenario)

Preference for 3rd generation

The lighter the squark
the higher the BR to
its corresponding quark



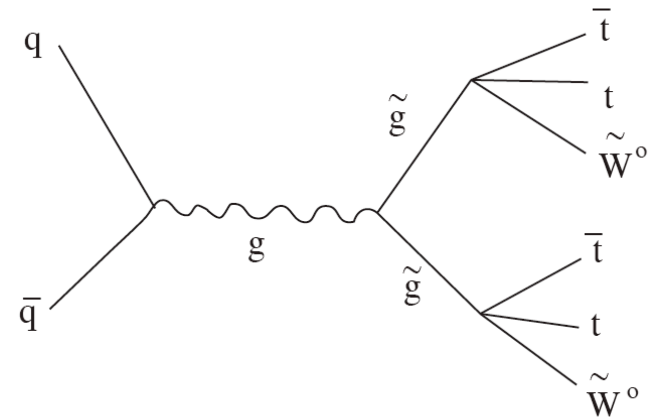
$$\frac{d\tilde{m}^2_{q_i}}{d\log Q} = -\frac{32}{3}M_3^2 + a_i y_{q_i}^2 \tilde{m}^2_{q_i} + \cdots \quad (a_i \text{ is positive})$$

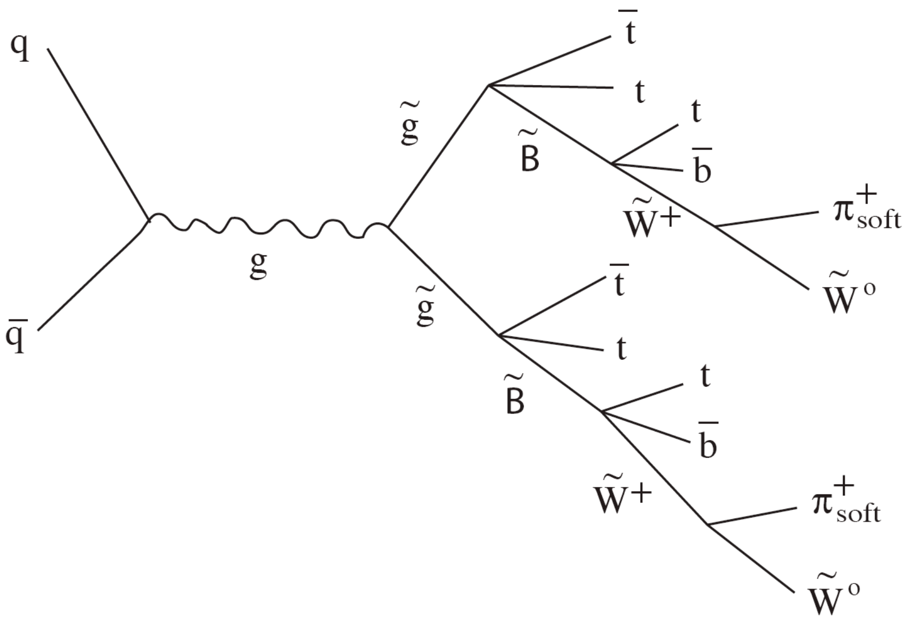


There is a generic preference for decays into 3rd generation quarks.

High multiplicity tops+MET events

Simplest event type: 4 top quarks plus missing energy. Can the missing energy be measured?





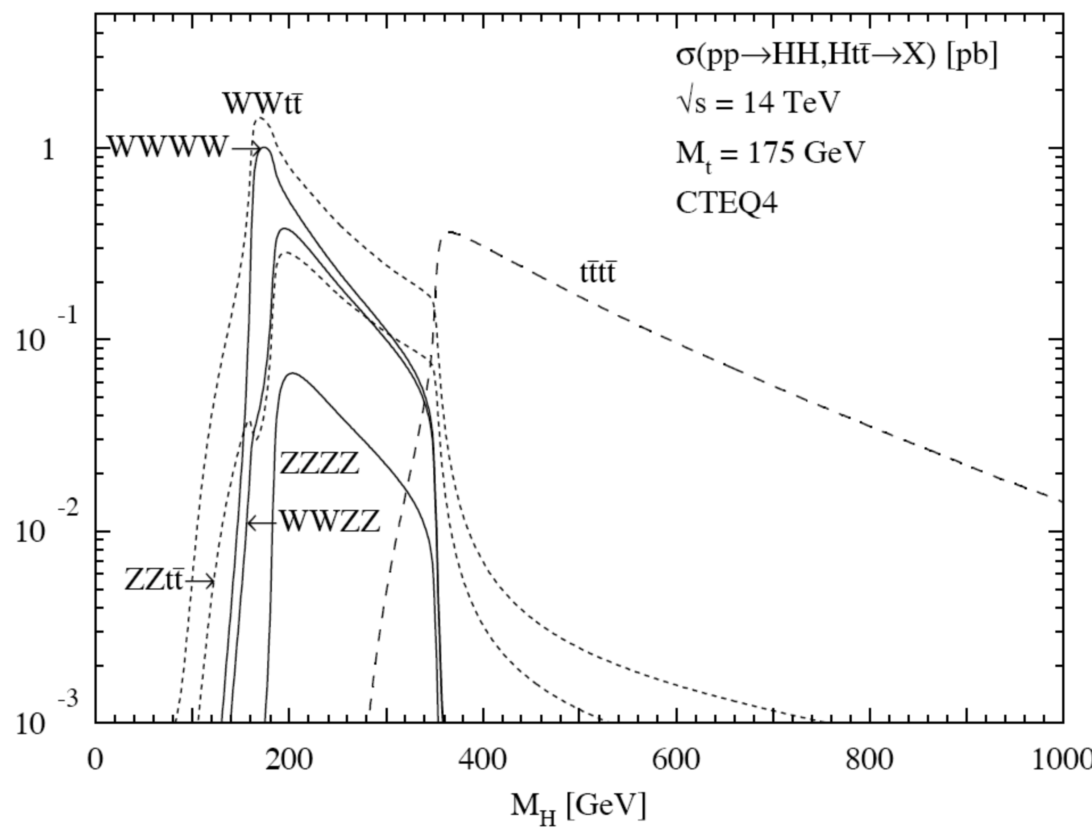
Combinatoric/experimental challenge.

6 tops + 2 b's + 2 pions + MET

Non-SUSY Signature Equivalences

Higgs bosons strongly coupled to the top quark can produce 4-top events copiously.

No missing E_T expected in this case.



Spira, JW, 97

l = e or mu

0l:	37%
1l:	42%
2lOS:	12%
2lSS:	6%
3l:	3%
4l:	0.2%

Higgs-exempt No Scale

Goal is to increase the $m_{1/2}$ which then can increase Superpartner masses, and can increase Higgs mass.

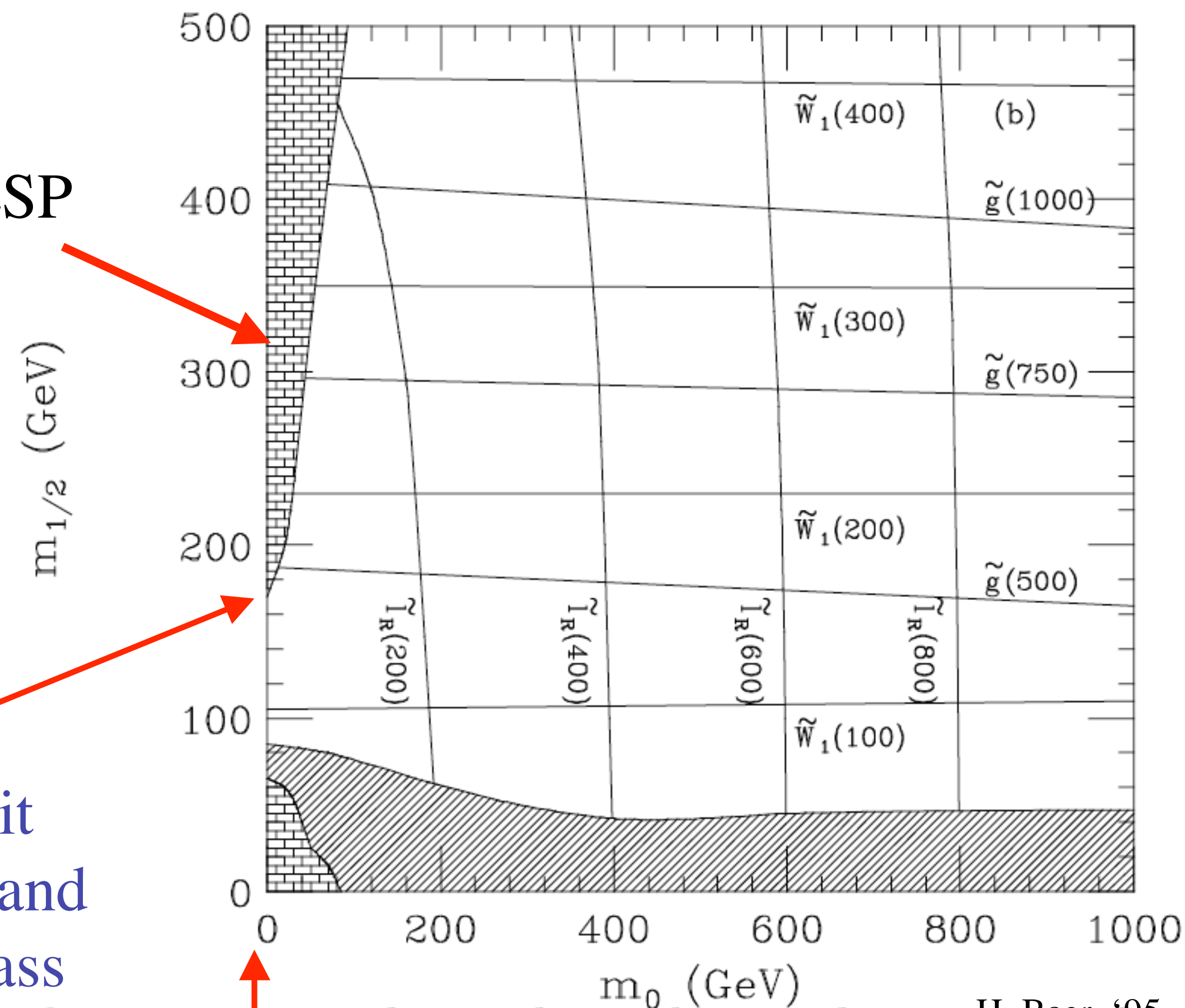
FCNC under control if slepton,squarks mass = 0

Exempt the Higgs bosons from no-scale constraint.

What's wrong with no-scale supersymmetry?

Charged LSP

Upper limit on $m_{1/2}$ which leads to upper limit on superpartners, and too light Higgs mass



No scale

H. Baer, '95

Relevant Equations

The scalar RGE equations with non-universal soft masses:

$$(4\pi)^2 \frac{dm_i^2}{dt} \simeq X_i - 8 \sum_a C_i^a \, g_a^2 \, |M_a|^2 + \frac{6}{5} \, g_1^2 \, Y_i \, S$$

$$S = (m_{H_u}^2 - m_{H_d}^2) + tr_F(m_Q^2 - 2m_U^2 + m_E^2 + m_D^2 - m_L^2)$$

This induces a potentially significant shift in masses:

$$\Delta m_i^2 = -\frac{Y_i}{11} \left[1 - \left(\frac{g_1}{g_{GUT}} \right)^2 \right] S_{GUT} \simeq -(0.052) \, Y_i \, S_{GUT}$$

Some numbers

Compare gaugino masses …

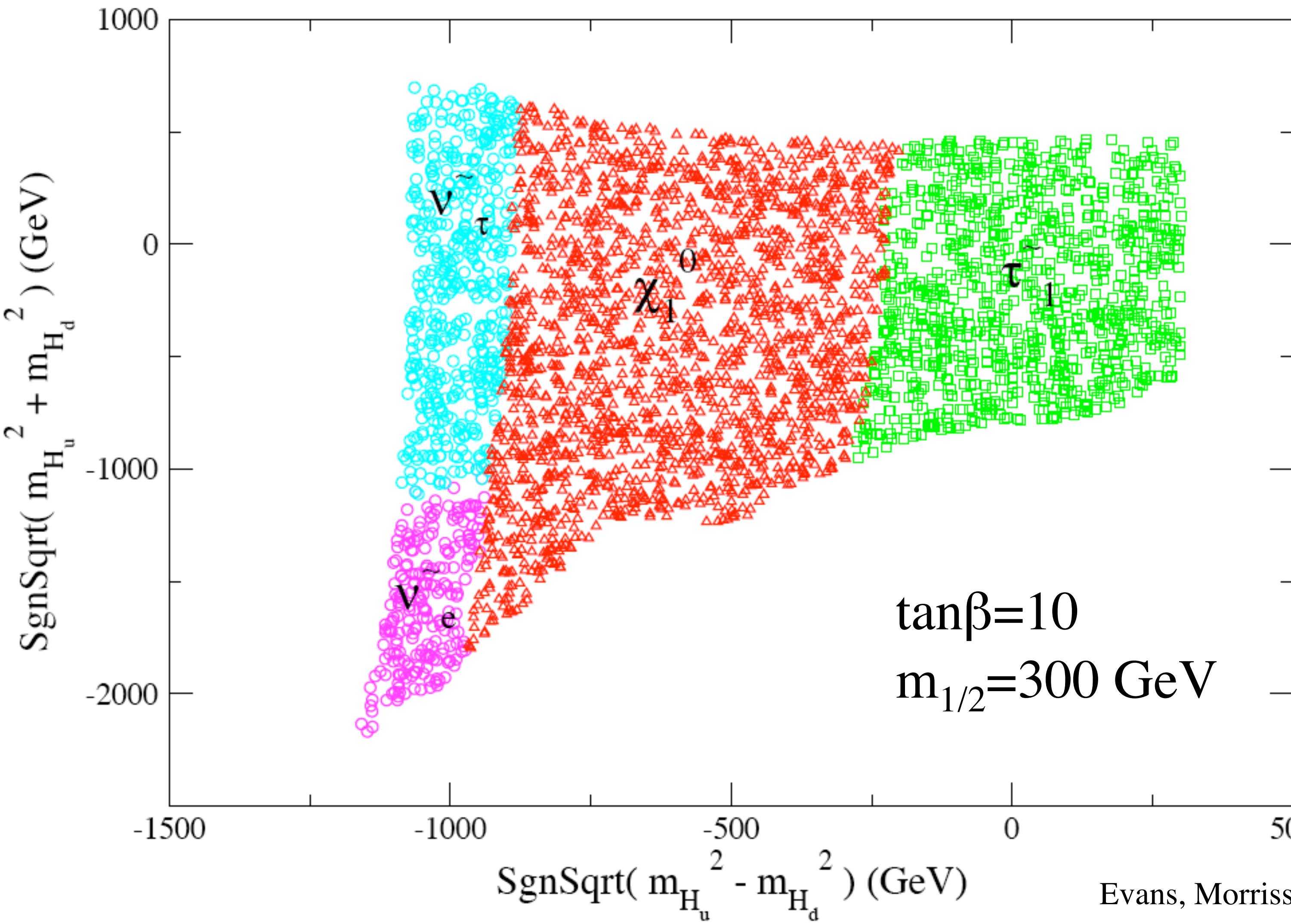
$$M_1 \simeq (0.43)\, M_{1/2}, \quad M_2 \simeq (0.83)\, M_{1/2}, \quad M_3 \simeq (2.6)\, M_{1/2}$$

With slepton masses (negative S helps lift m_E):

$$m_L^2 \simeq \left[(0.68)\, M_{1/2}\right]^2 + \frac{1}{2}(0.052)\, S_{GUT}$$
$$m_E^2 \simeq \left[(0.39)\, M_{1/2}\right]^2 - (0.052)\, S_{GUT}.$$

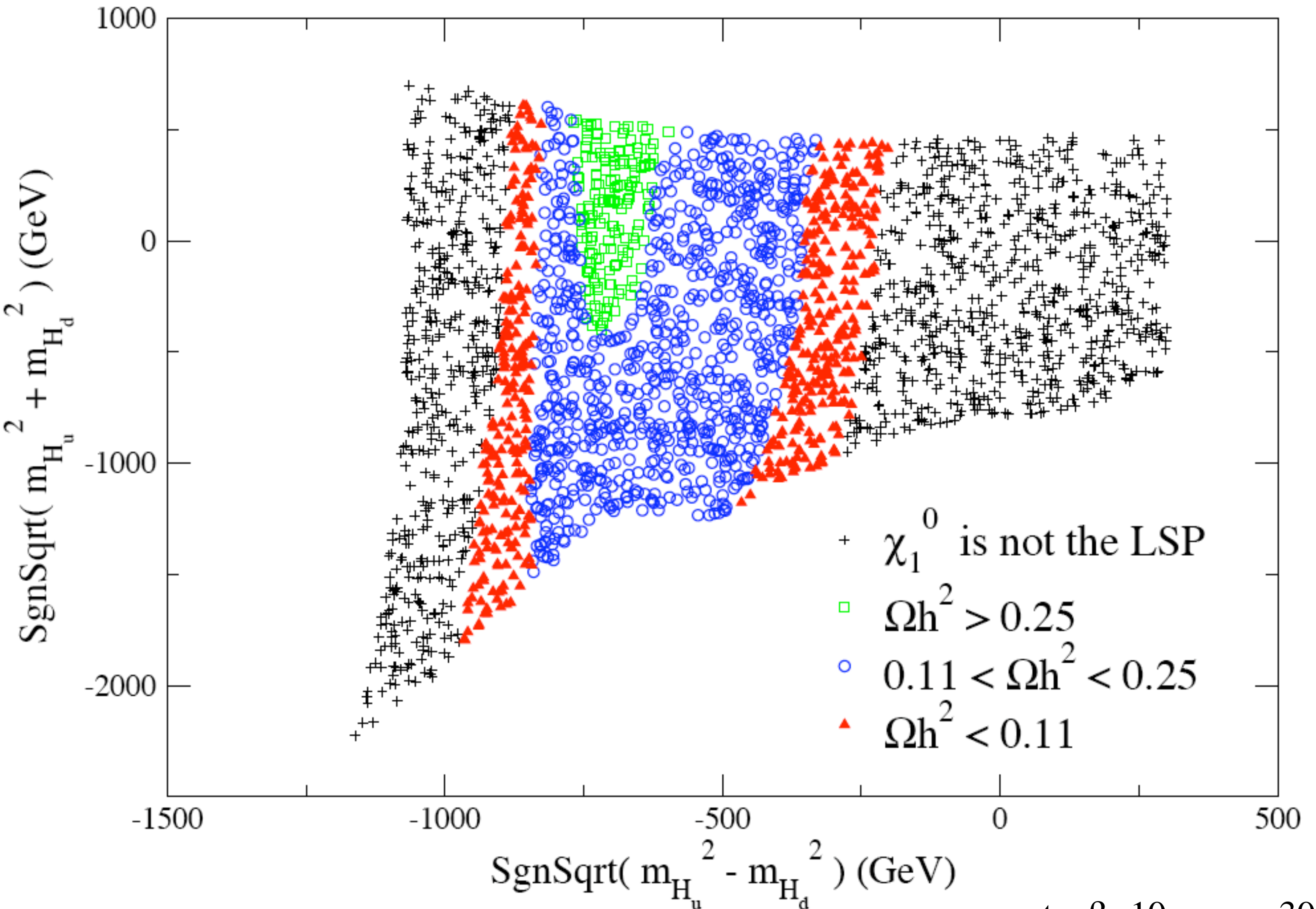
$$S_{GUT} = (m_{H_u}^2 - m_{H_d}^2)$$

LSP in Higgs-exempt No-Scale



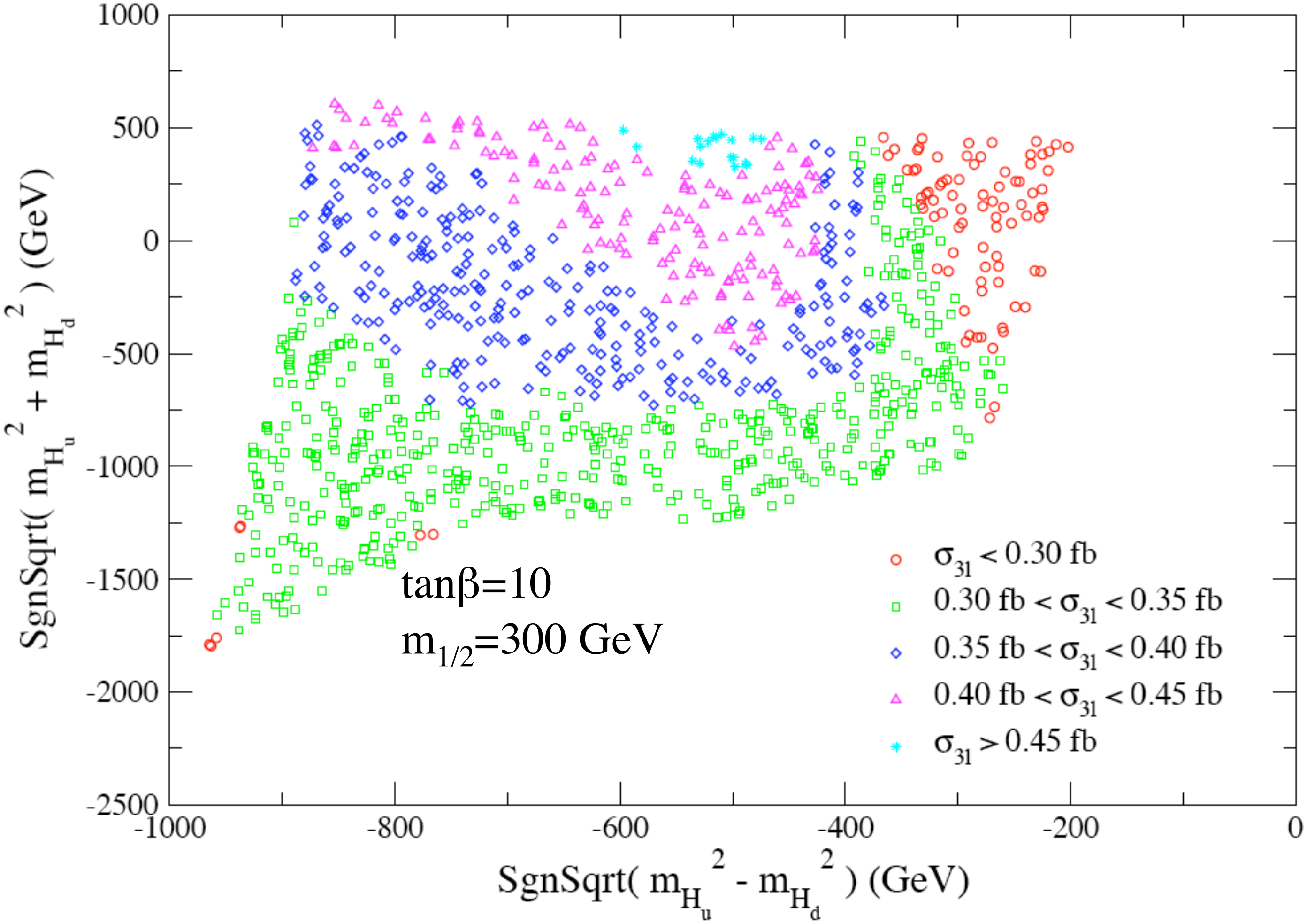
Evans, Morrissey, JW

Dark Matter Relic Abundance



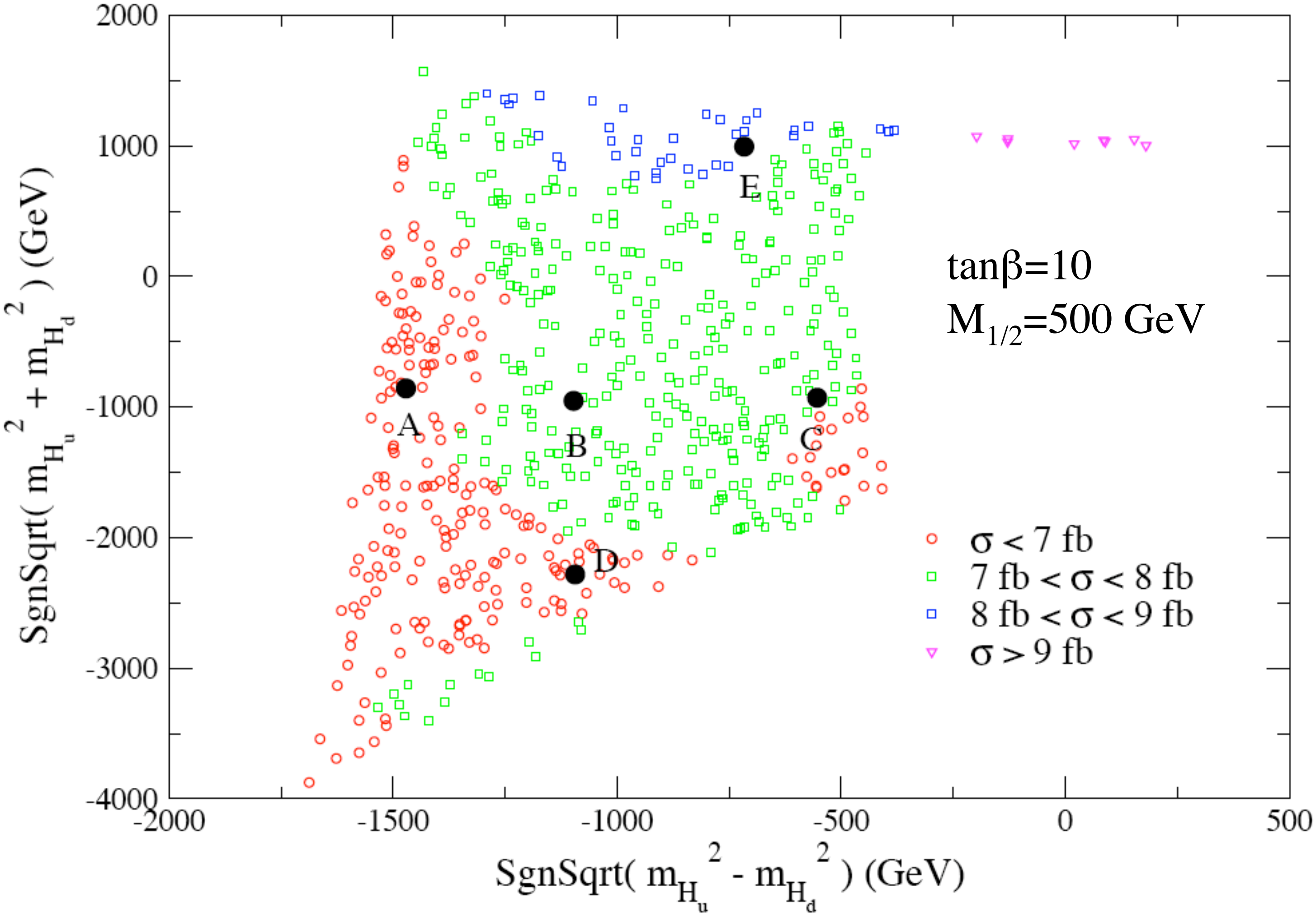
$\tan\beta=10$, $m_{1/2}=300$ GeV

Tevatron 3l Signal



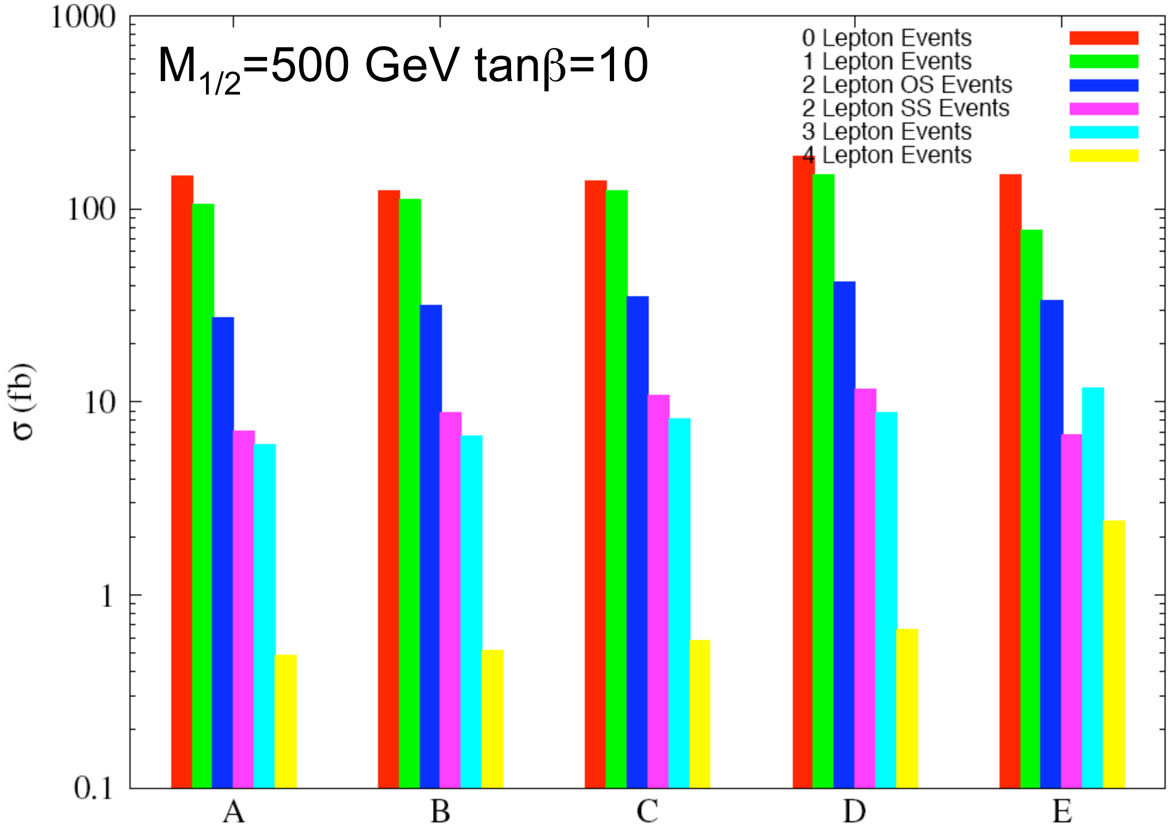
3 leptons plus missing energy. After cuts, 0.49 fb background. Marginal to find HENS scenario at Tevatron with 10 fb^{-1}

LHC 3l Signal



3 leptons plus missing energy. After cuts, 0.1 fb background. For this value of $M_{1/2}$ it is promising at LHC with 10 fb^{-1}

Multi-lepton Signatures



Evans, Morrissey, JW, `07

- ISAJET 7.74 using CALSIM and CALINI
- $|\eta| < 5$ coverage
- Cal cells of size $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$.
- E-Cal: $0.1/\sqrt{E/\mathrm{GeV}} \oplus 0.01$.
- Had-cal with $|\eta| < 3$: $0.5/\sqrt{E/\mathrm{GeV}} \oplus 0.03$
- Had-cal with $|\eta| > 3$: $1.0/\sqrt{E/\mathrm{GeV}} \oplus 0.07$
- jets: $E_T > 100\,\mathrm{GeV}$, $|\eta| < 3$, $\Delta R < 0.7$
- leptons: $p_T > 10\,\mathrm{GeV}$, $|\eta| < 2.5$, $E_T < 5\,\mathrm{GeV}$ within $\Delta R = 0.3$
- events: $n_j \geq 2$ with $E_T, ME_T > 200\,\mathrm{GeV}$, $S_T > 0.2$
- additional cuts for each channel (Baer et al.)

Background
0l : 400 fb
1l : 26 fb
2lOS : 9 fb
2lSS : 0.25 fb
3l : 0.1 fb
4l : 0.002 fb

Conclusions

Many ideas within Supersymmetry. Two specific ideas of interest are Split Supersymmetry and Splat Supersymmetry.

Split Supersymmetry: Naturalness concerns are philosophy (i.e., smart, honest people disagree), but FCNC, DM etc. are data-driven issues. Possibility that only LHC observable is 4 top quarks with missing energy. How well can this be discovered and studied?

Splat Supersymmetry: FCNC + DM + Higgs mass all solved Simultaneously through zeroing out Higgs mass at GUT scale. main LHC challenge is to get full footprint of the many Beyond-SM signatures. Many lepton-rich channels to invert.