Lecture 3

Today's topic: Second Extreme of Supersymmetry

The superpartner scalar masses are zero with respect to the gaugino masses at a unification boundary scale.

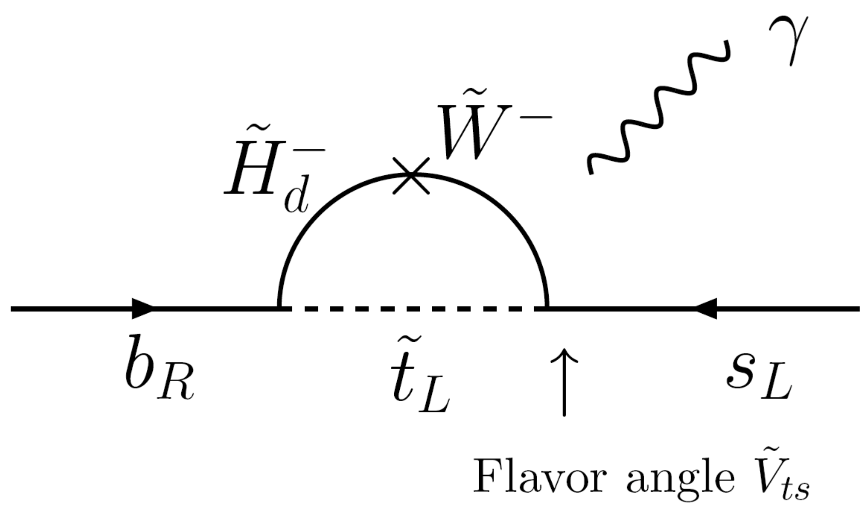
Today we will take very seriously some simple approaches to unification. However, the bigger picture of zero scalar mass boundary conditions are illustrated well.

This goes under the name of 'no-scale supersymmetry', 'gaugino mediation' or 'gauge mediation with logs'.

Recall this earlier slide:

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

1st extreme **2nd extreme**

mSUGRA

$M_{1/2}$ = Common Gaugino mass at GUT scale

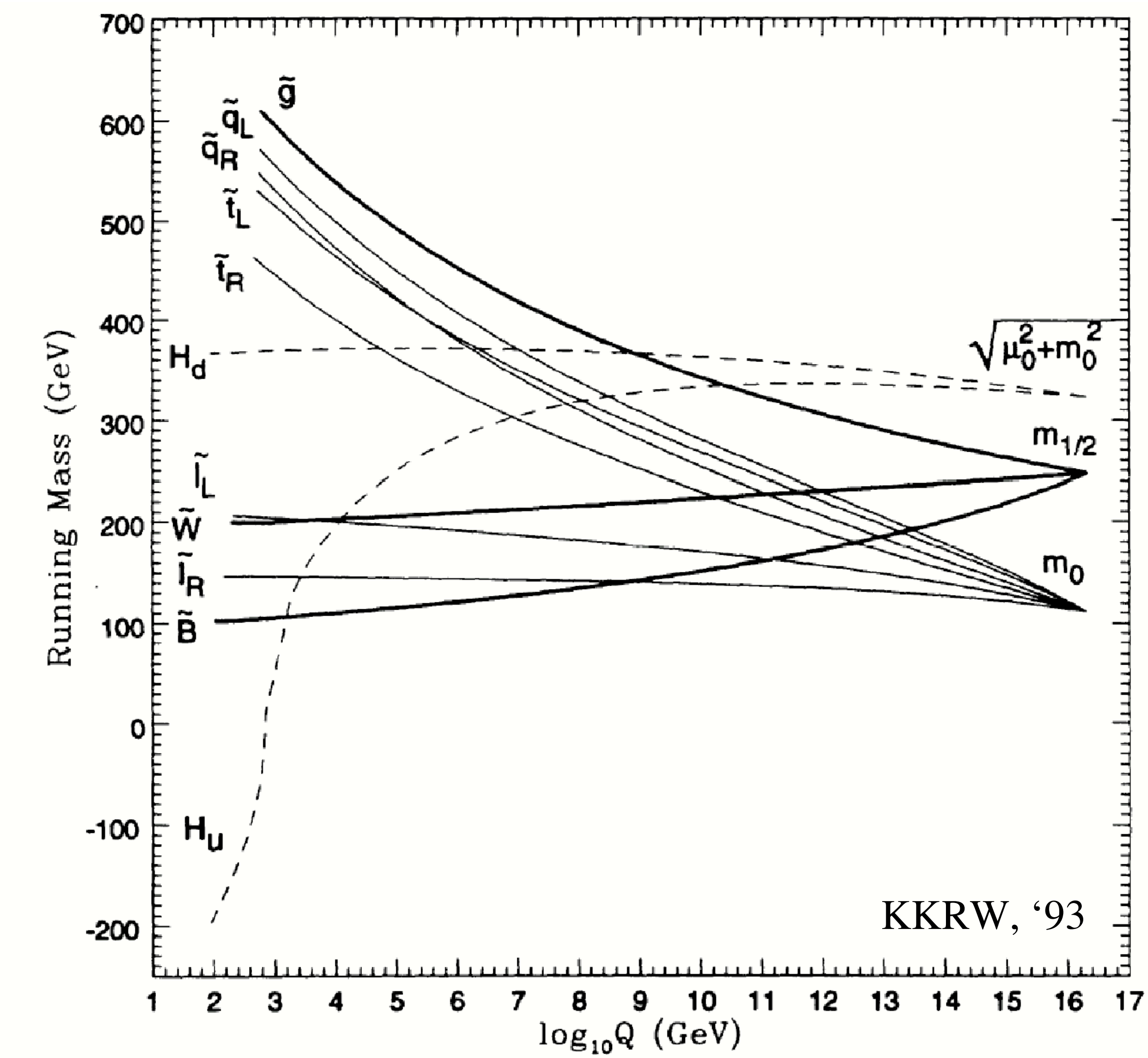
M_0 = Common scalar masses at GUT scale

A_0 = Common tri-scalar interaction mass at GUT scale

Tanβ = Ratio of H_u to H_d vacuum expectation values

Sgn(μ) = Sign of the $H_u H_d$ μ–term in the superpotential

Renormalization Group Flow



No-Scale Supersymmetry

Many studies of this scenario. Great benchmark for studying collider capabilities. But from a theory point of view, somewhat unrealistic.

The most unrealistic part of mSUGRA is that all scalar masses should be the same value at some boundary scale.

Supergravity has no built-in means to dictate that. In fact, arbitrary couplings, and therefore arbitrary flavor violations are to be expected.

Random flavor angles

$\mathbf{m_0}$

mSUGRA assumes this:

$$\tilde{m}^2_{\tilde{Q}_i} = \int d^4\theta \frac{X^\dagger X}{M^2_{Pl}} Q_i^\dagger Q_i \rightarrow \boxed{\frac{F^\dagger F}{M^2_{Pl}}} \tilde{Q}_i^\dagger \tilde{Q}_i$$

But it's more realistic to assume this:

$$\tilde{m}^2_{ij} = \int d^4\theta \lambda_{ij} \frac{X^\dagger X}{M^2_{Pl}} Q_i^\dagger Q_j \rightarrow \lambda_{ij} \frac{F^\dagger F}{M^2_{Pl}} \tilde{Q}_i^\dagger \tilde{Q}_j$$

Induces new super-KM flavor angles

What do we do?

We either make the scalars so heavy that it doesn't matter that there are large flavor angles. That was the first "extreme end" of supersymmetry (split, PeV scale susy) that we've already discussed.

A second possibility is to make the scalar masses so small at the boundary scale that their variability does not matter (no scale, gaugino mediation, etc.).

The majority of the physical scalar masses come from quantum corrections induced by gauginos, which are gauge interactions and thus flavor preserving.

Challenges of zero-mass boundary

There are two main challenges to this scenario:

1. Over much of parameter space the lightest superpartner is charged, and thus not a good DM candidate.

2. When the LSP is neutral, the Higgs mass is too light, and in conflict with experiment.

Higgs mass in no scale SUSY

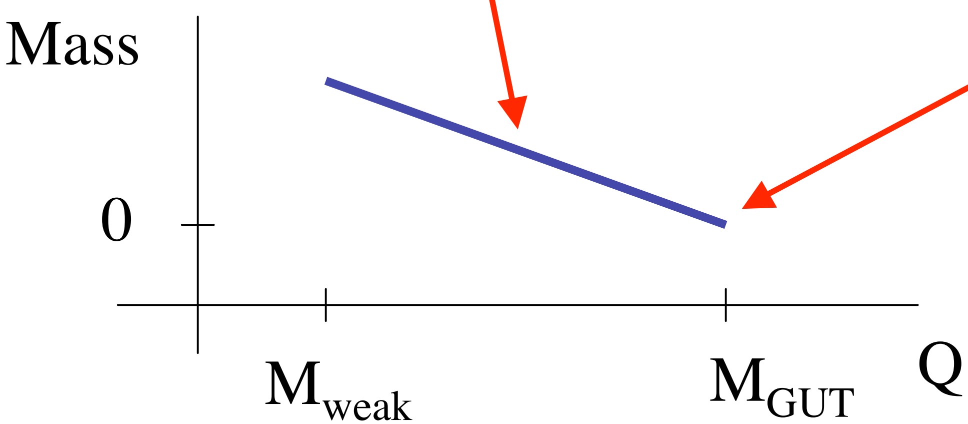
$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{3M_t^4}{\pi^2 v^2} \log \frac{M_{\tilde{t}}}{M_t}$$

Renormalization group flow gives top squark its mass:

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

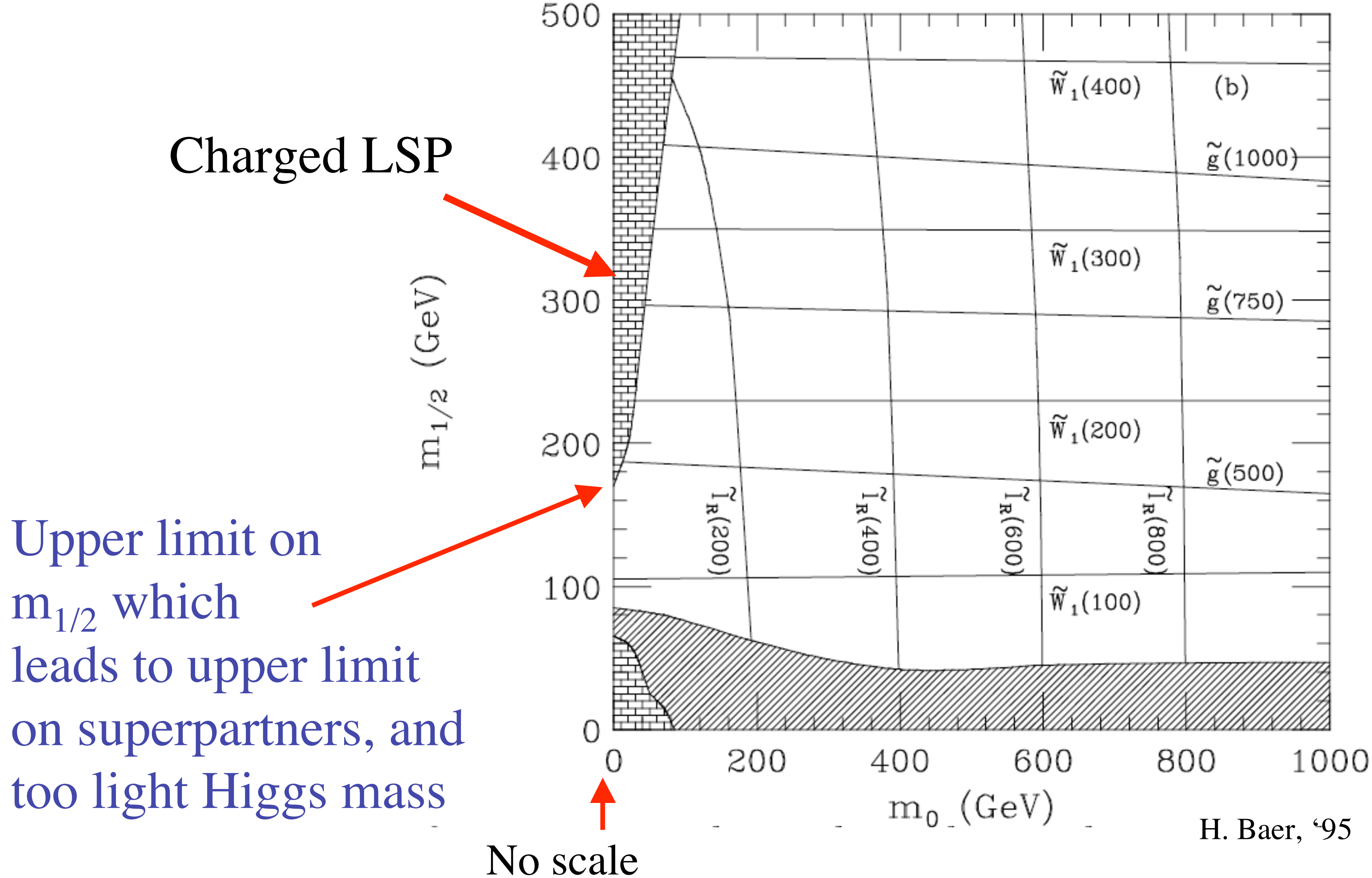
Lifts mass in the IR

Zero at boundary scale



What's wrong with no-scale supersymmetry?

$$M_1 \simeq (0.43) M_{1/2}$$
$$m^2_{\tilde{\tau}_R} \simeq [(0.39) M_{1/2}]^2 + (\sin^2\theta_W |\cos 2\beta|)\, m_Z^2$$



H. Baer, '95

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 the no-scale constraint.

Some Relevant Equations

The scalar RGE equations with non-universal soft masses:

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

Extra factor that is often ignored or not relevant.

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

S=Tr(Ym^2)=0 in mSUGRA & GMSB but not here!

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):

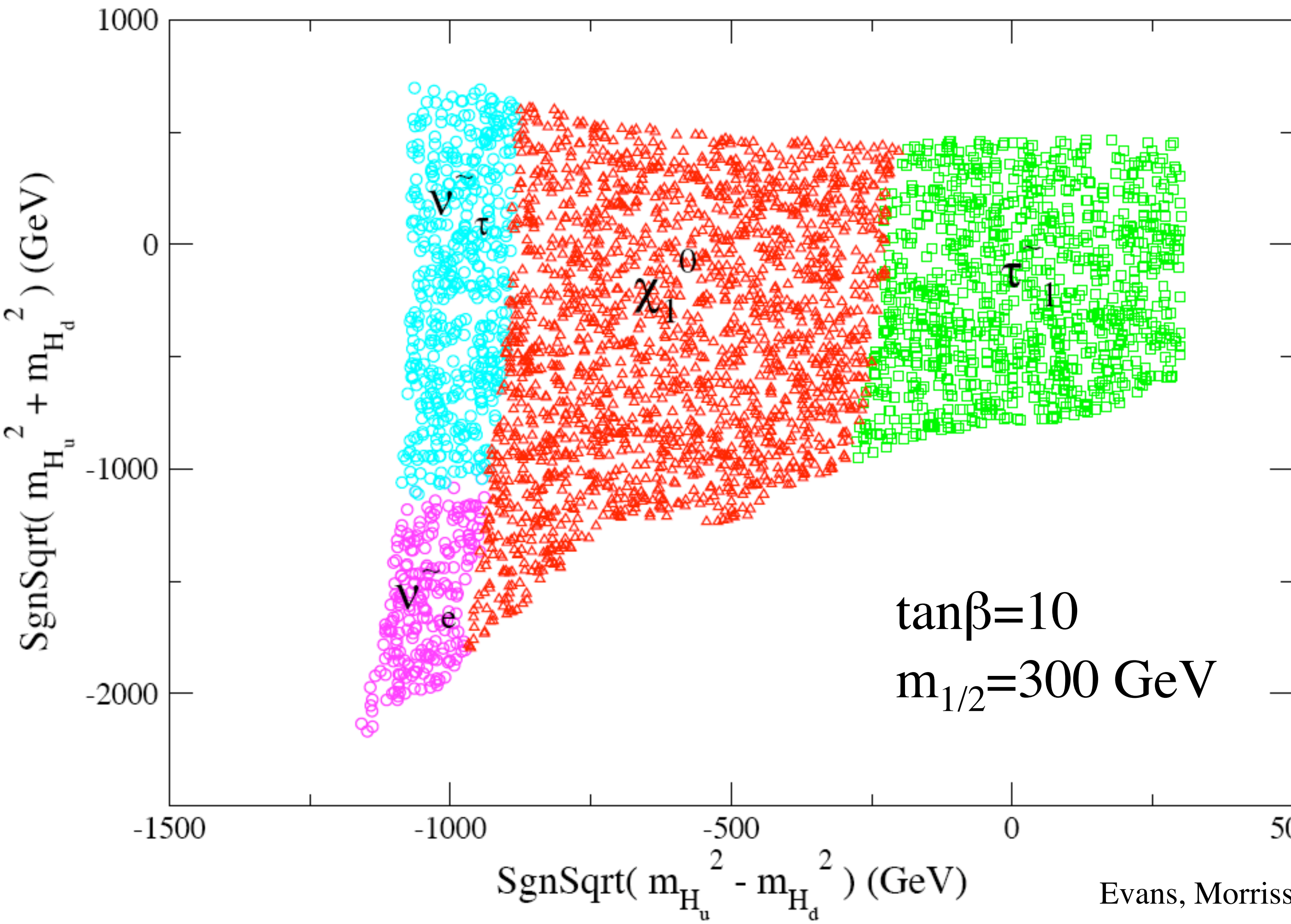
$$m_L^2 \simeq \left[(0.68)\, M_{1/2}\right]^2 + \frac{1}{2}(0.052)\, S_{GUT}$$

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

Need $S_{GUT} < 0$ so that LSP is not charged.

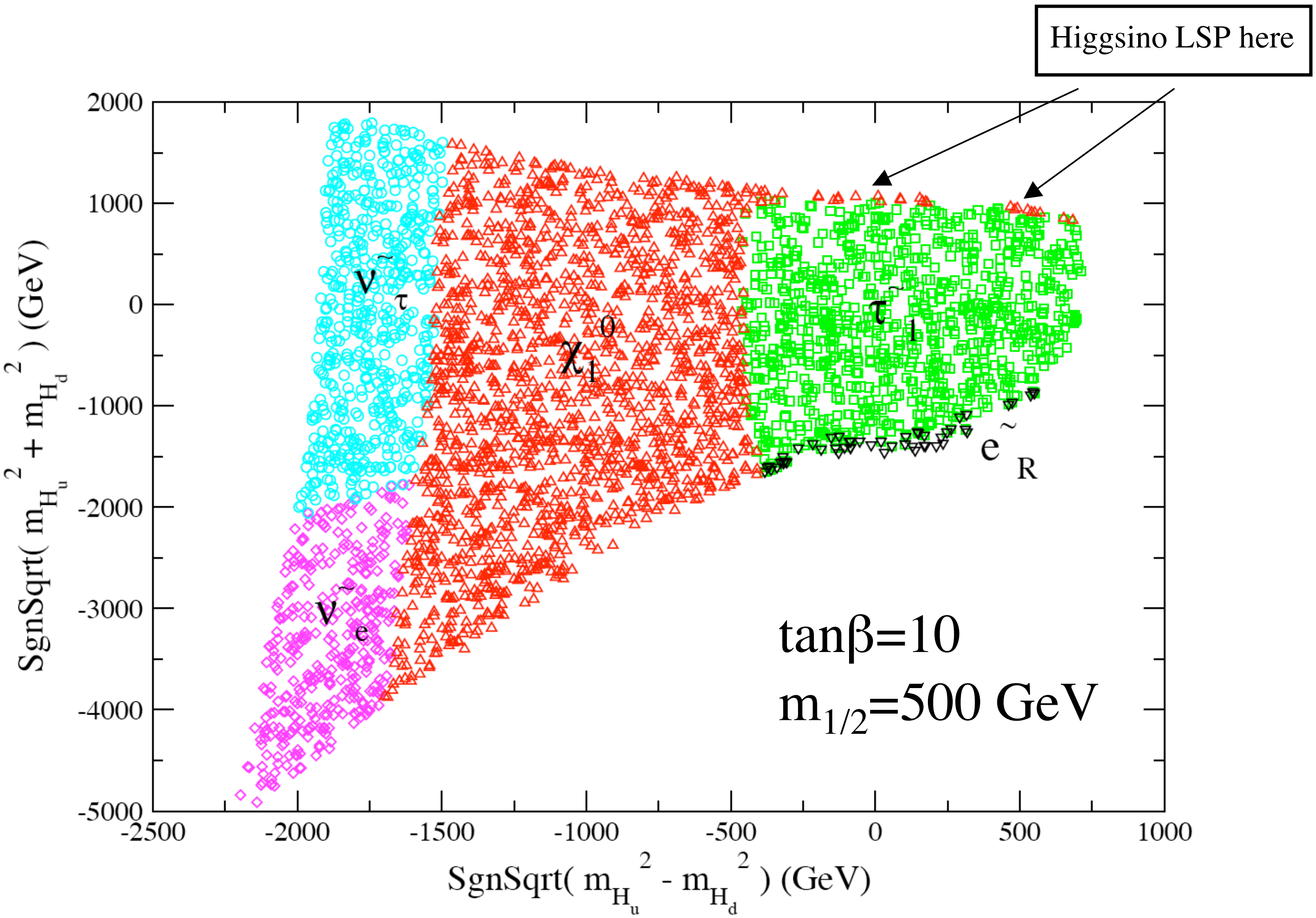
$$S_{GUT} = (m_{H_u}^2 - m_{H_d}^2)$$

LSP in Higgs-exempt No-Scale

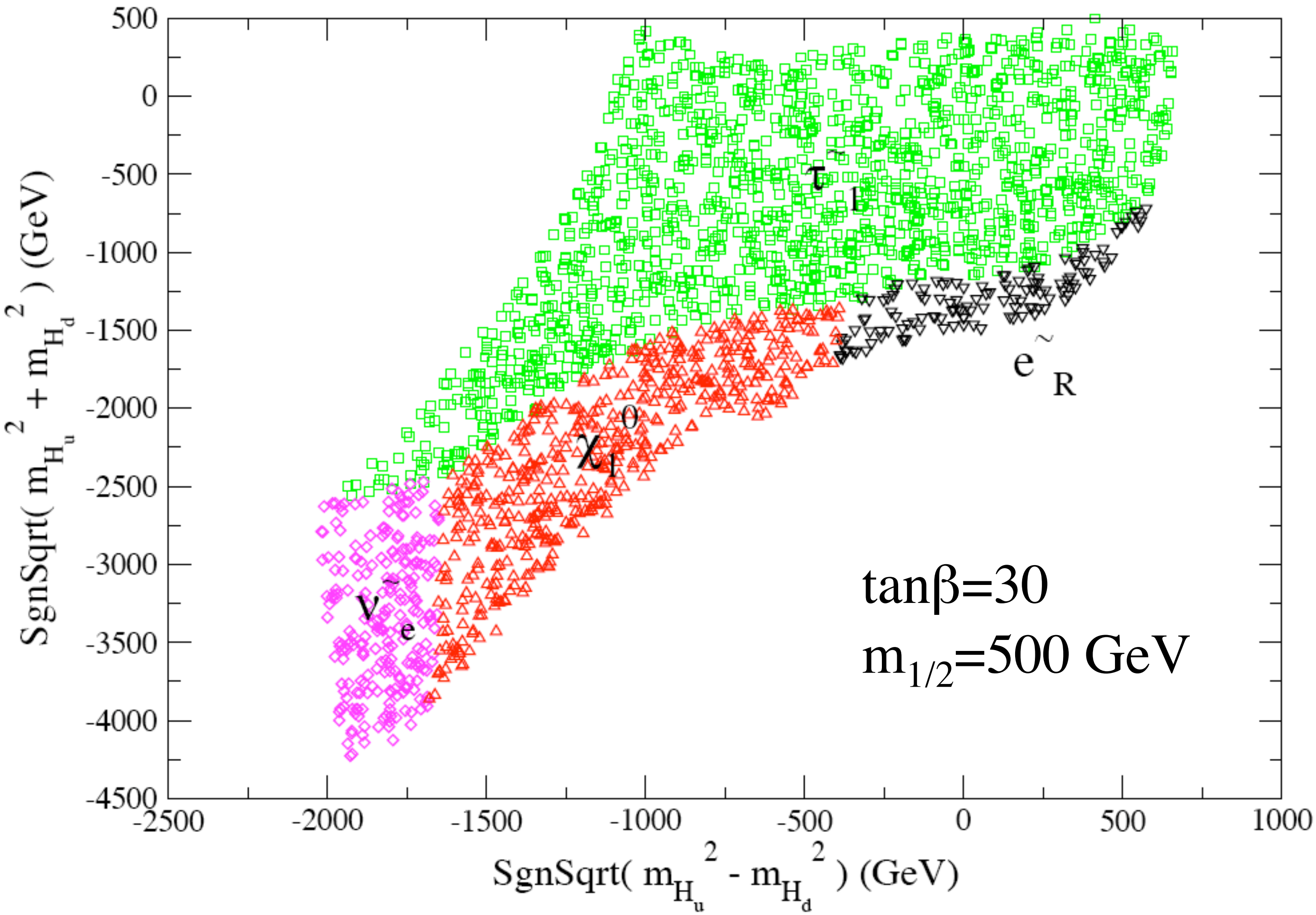


Evans, Morrissey, JW

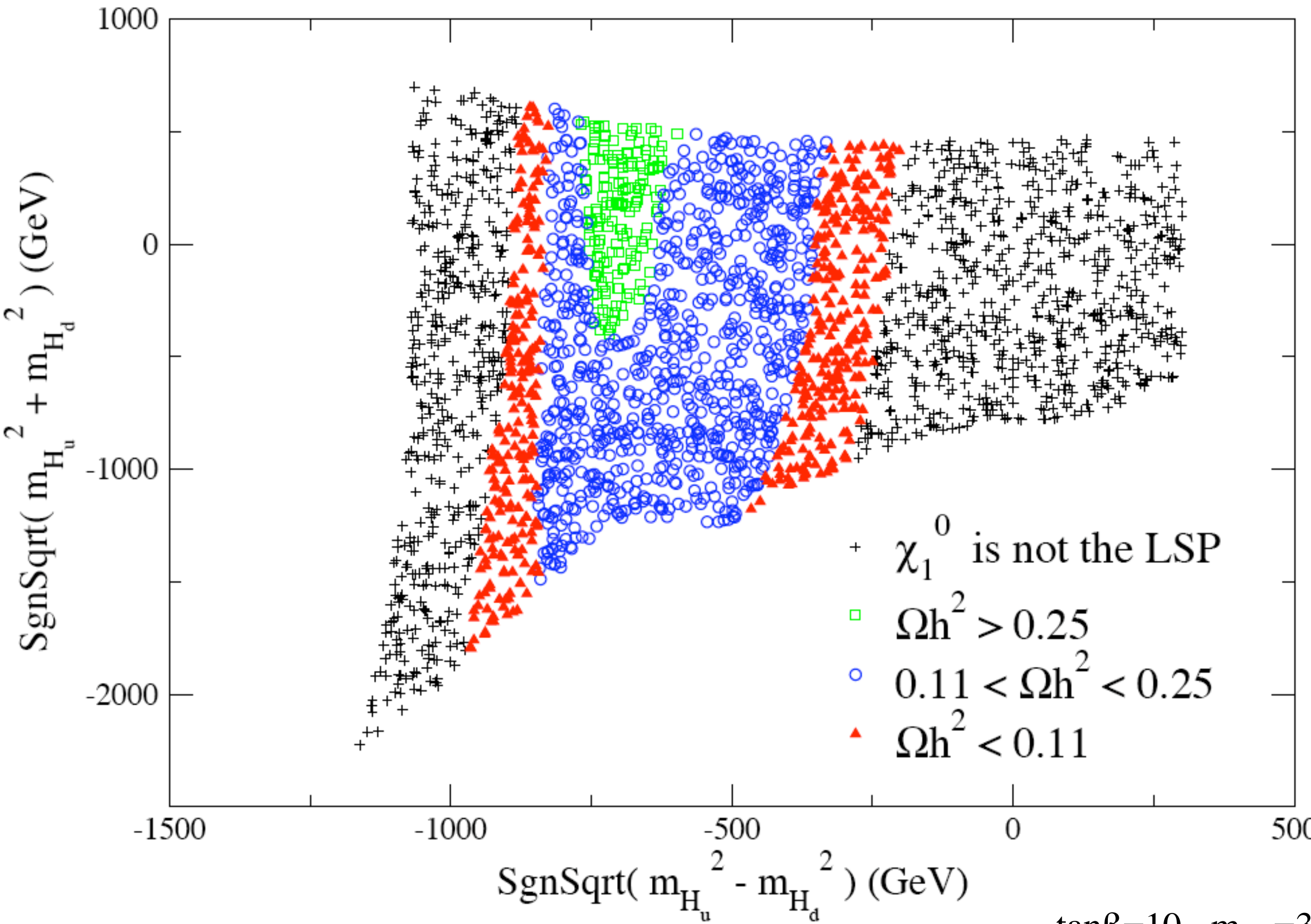
LSP in HENS (higher $m_{1/2}$)



LSP with higher tanβ

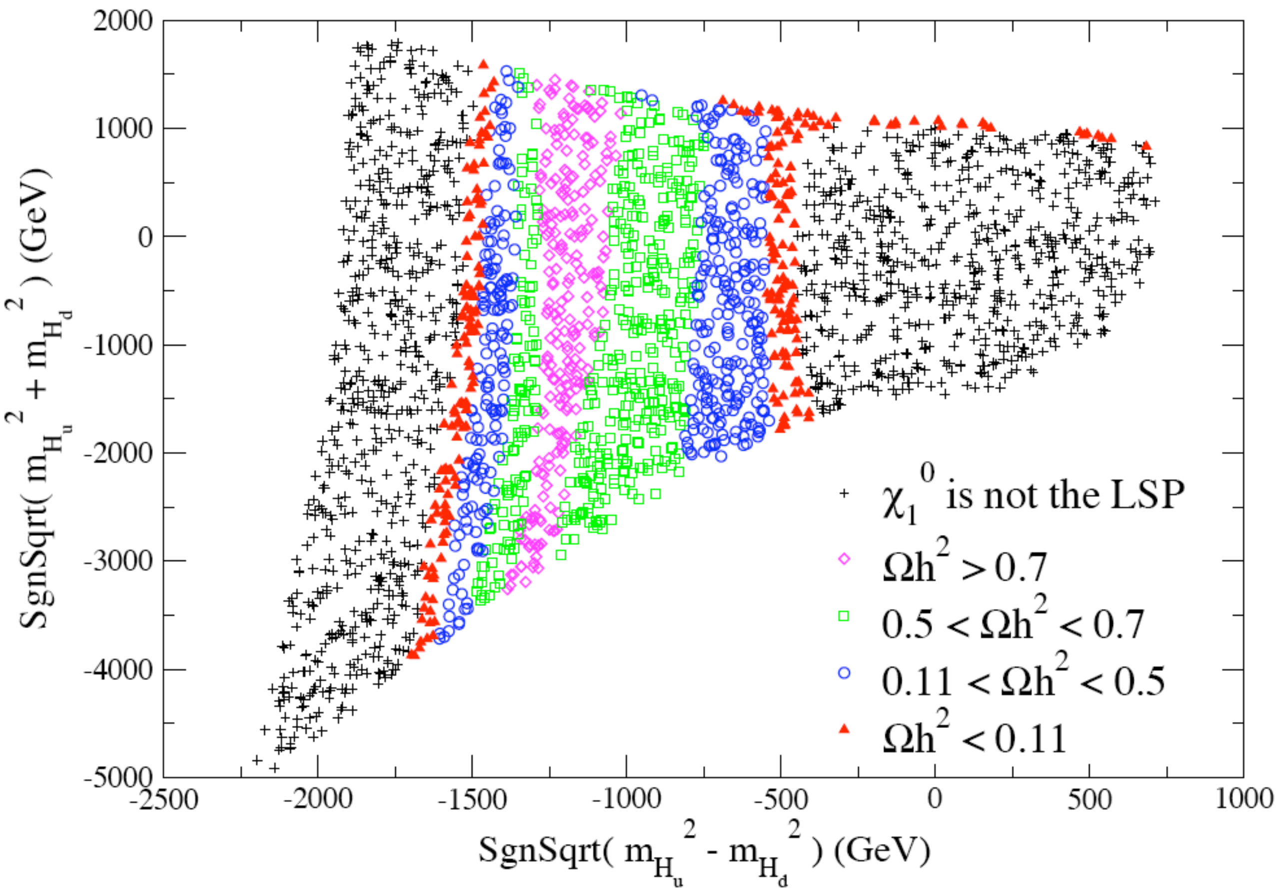


Dark Matter Relic Abundance



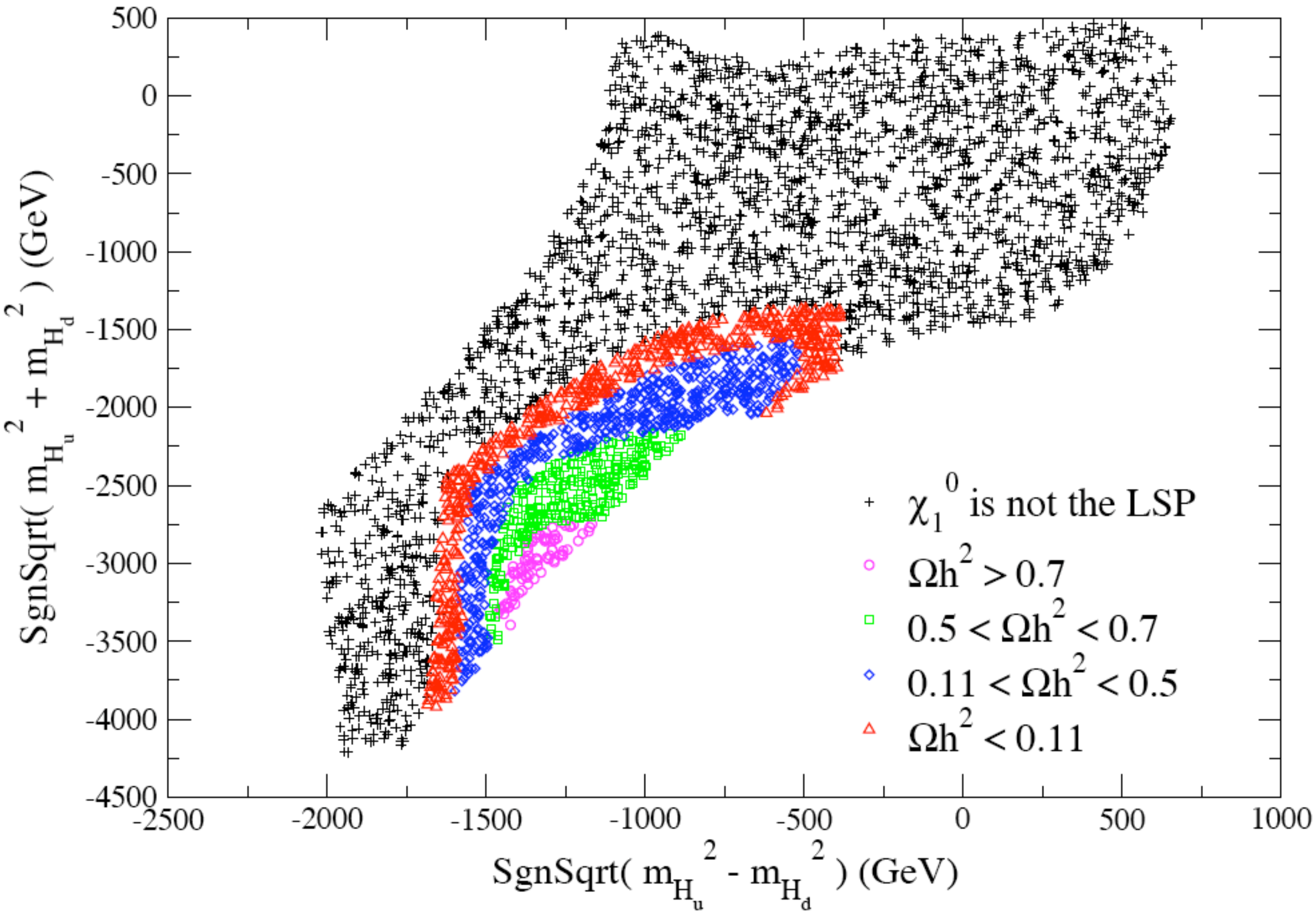
$\tan\beta=10$, $m_{1/2}=300$ GeV

DM Abundance (higher $m_{1/2}$)



Neutralino LSP relic density for $\tan\beta = 10$, $M_{1/2} = 500$ GeV, and $sgn(\mu) > 0$. The region in which the lightest neutralino is not the LSP is denoted by the black plus signs. The red triangles indicate parameter points where the neutralino LSP relic density is less than $\Omega h^2 < 0.11$. In the blue, green, and magenta regions, the neutralino LSP relic density exceeds this value.

DM Abundance (higher tanβ)



Neutralino LSP relic density for $\tan\beta = 30$, $M_{1/2} = 500$ GeV, and $sgn(\mu) > 0$. The region in which the lightest neutralino is not the LSP is denoted by the black plus signs. The red triangles indicate parameter points where the neutralino LSP relic density is less than $\Omega\, h^2 < 0.11$. In the blue, green, and magenta regions, the neutralino LSP relic density exceeds this value.

Muon g-2 Experiment

The anomalous magnetic moment of the muon

$$\vec{\mu} = g\frac{e\hbar}{2m_\mu c}\vec{s} \equiv (1 + a_\mu)\frac{e\hbar}{m_\mu c}\vec{s}.$$

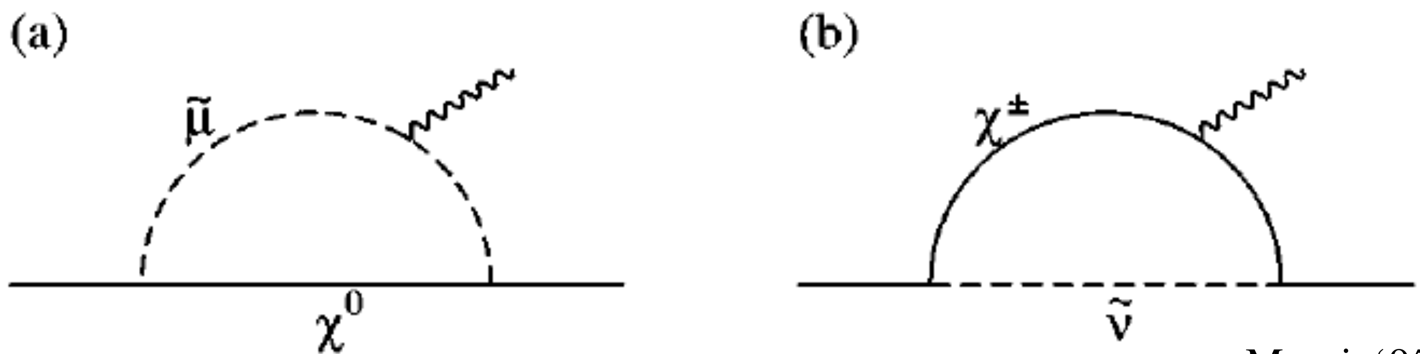
has been measured, and shows signs of possible deviation with respect to the Standard Model:

$$a_\mu^{EXP} - a_\mu^{SM} = (27.7 \pm 9.3) \times 10^{-10}$$

Domingo, Ellwanger, '08

Muon g-2 and Supersymmetry

Light sleptons and charginos can have a large effect:



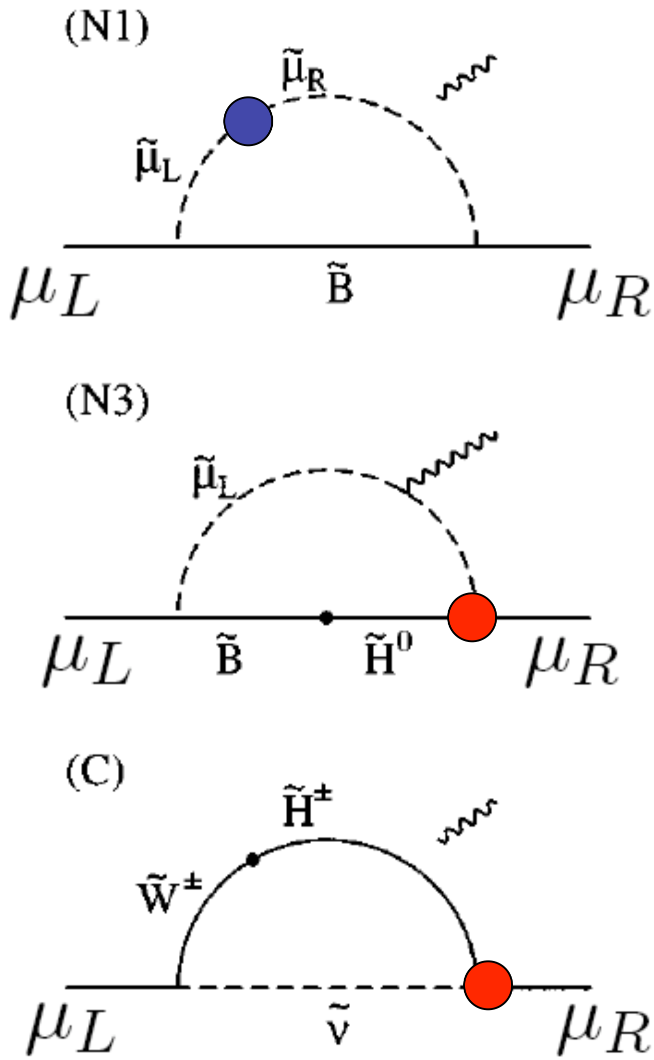
Moroi, '95

If all masses were the same, the result would be:

$$\Delta a_\mu^{\rm MSSM} \approx 130 \times 10^{-11} \tan\beta \, {\rm sign}(\mu) \left(\frac{100 \text{ GeV}}{M_{\rm SUSY}} \right)^2$$

Cf., $a_\mu^{EXP} - a_\mu^{SM} = (27.7 \pm 9.3) \times 10^{-10}$

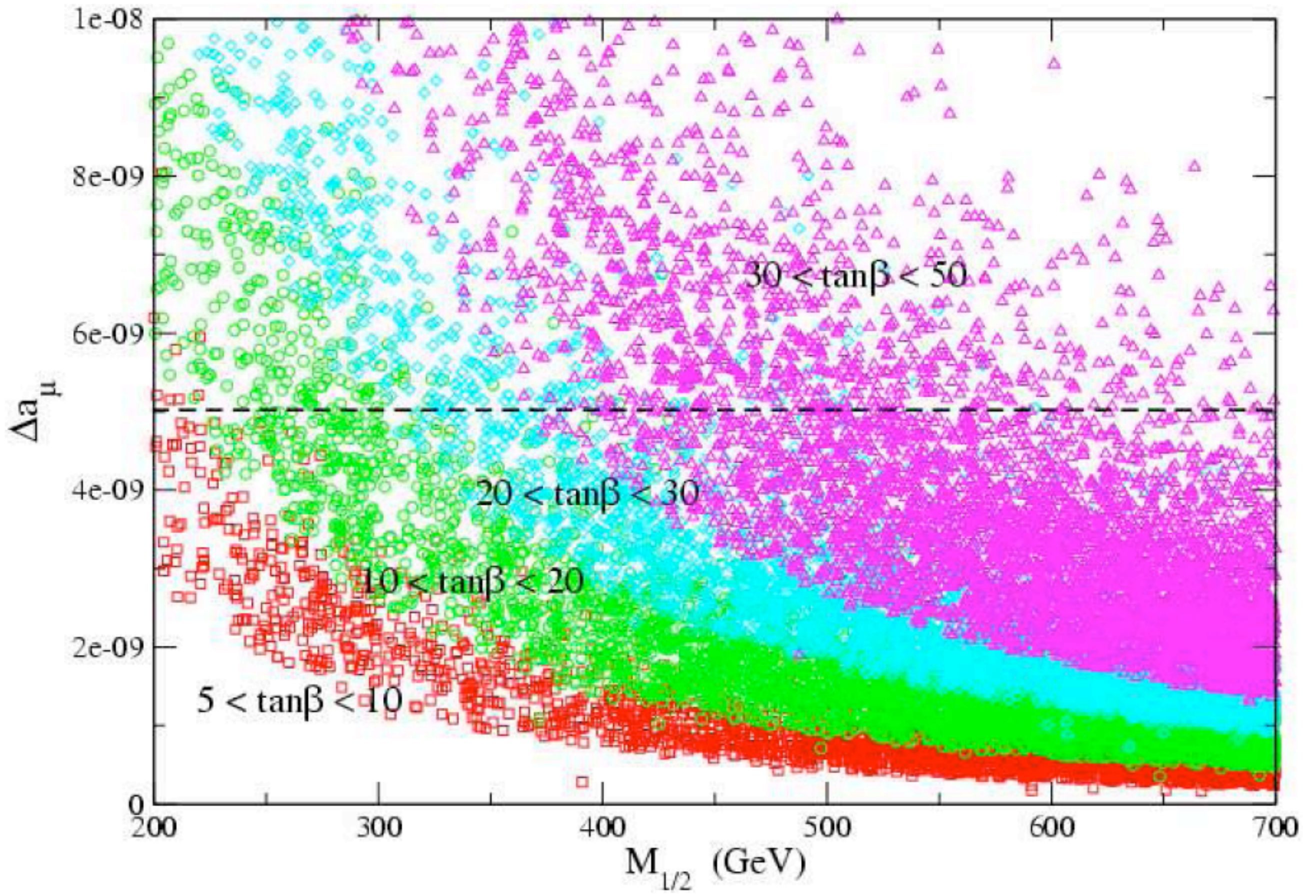
Why large tanβ effect?



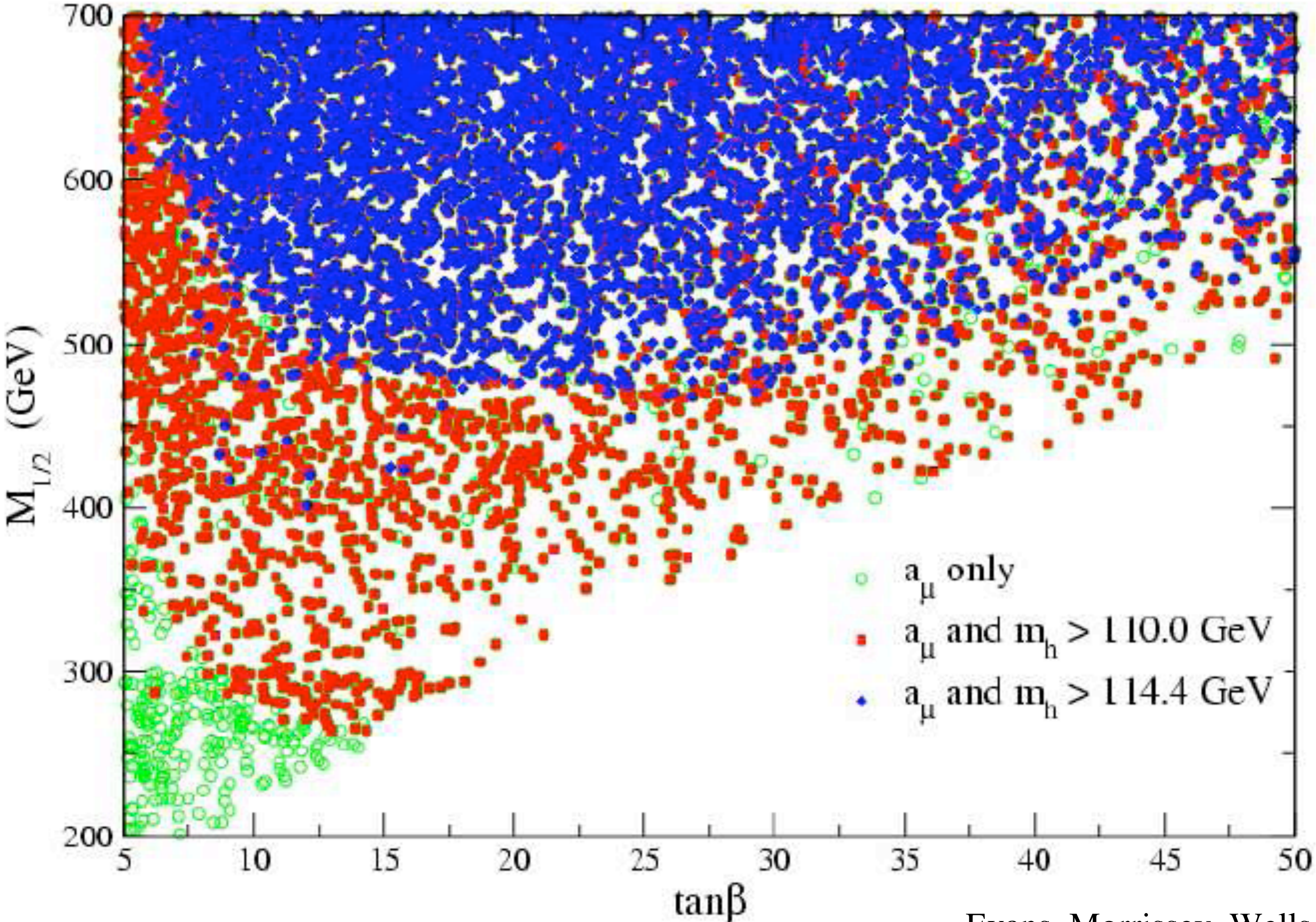
$$y_\mu = \frac{m_\mu}{\langle H_d \rangle} = \frac{m_\mu}{v \cos\beta} \simeq \frac{m_\mu}{v} \tan\beta$$

$$\propto m_\mu \tan\beta$$

g-2 versus $m_{1/2}$ in HENS



Δa_μ^{SUSY} as a function of $M_{1/2}$ for several ranges of $\tan\beta$, and $sgn(\mu) > 0$. The spread of points come from scanning over the acceptable input values of $m^2_{H_u}$ and $m^2_{H_d}$. The red points indicate $\tan\beta \in [5, 10)$, the green points $\tan\beta \in [10, 20)$, the blue points $\tan\beta \in [20, 30)$, and the magenta points $\tan\beta \in [30, 50)$.

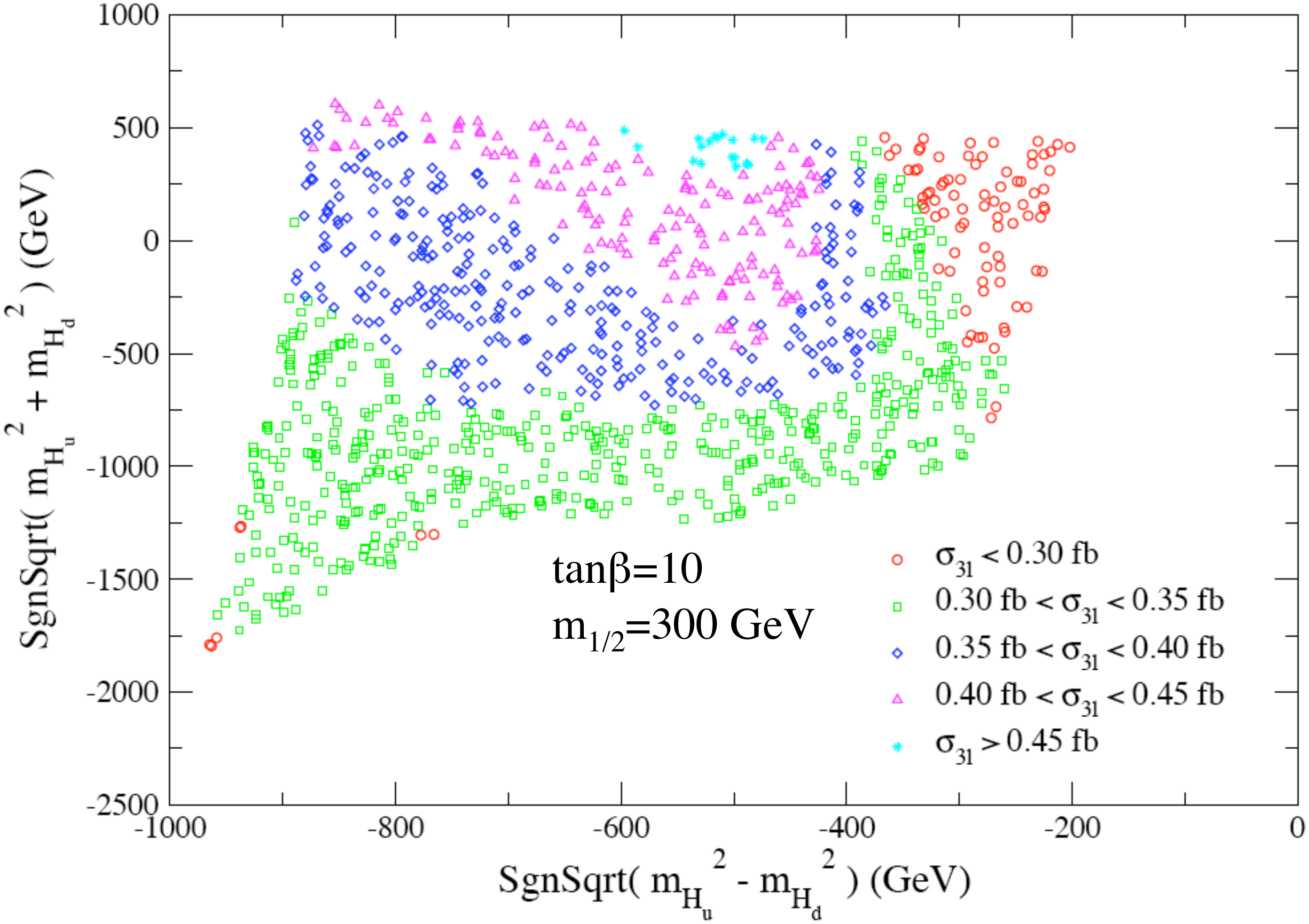


Evans, Morrissey, Wells

Scatter plot in the $M_{1/2} - \tan\beta$ plane of solutions that respect the bounds of $\Delta a_\mu^{SUSY} < 50 \times 10^{-10}$ and $m_h > 114.4\,\mathrm{GeV}$. Due to uncertainty in the top quark mass, and the theoretical uncertainty in the computation of m_h, a more conservative constraint on this theoretically computed value of m_h is $110\,\mathrm{GeV}$, which is also shown in the figure.

Tevatron 3l Signal

$$q\bar{q} \to Z^* \to \chi_1^{\pm}\chi_2^0 \to l^{\pm}\nu\chi_1^0 l^+ l^- \chi_1^0$$



Cuts and BG match Baer et al. '00 analysis:

p_T(leptons) > 30, 15, 10 GeV.

$|\eta$(leptons)$|<2.5$

MET > 25 GeV

Etc.

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

Sample Points in the LHC Scatter Plots

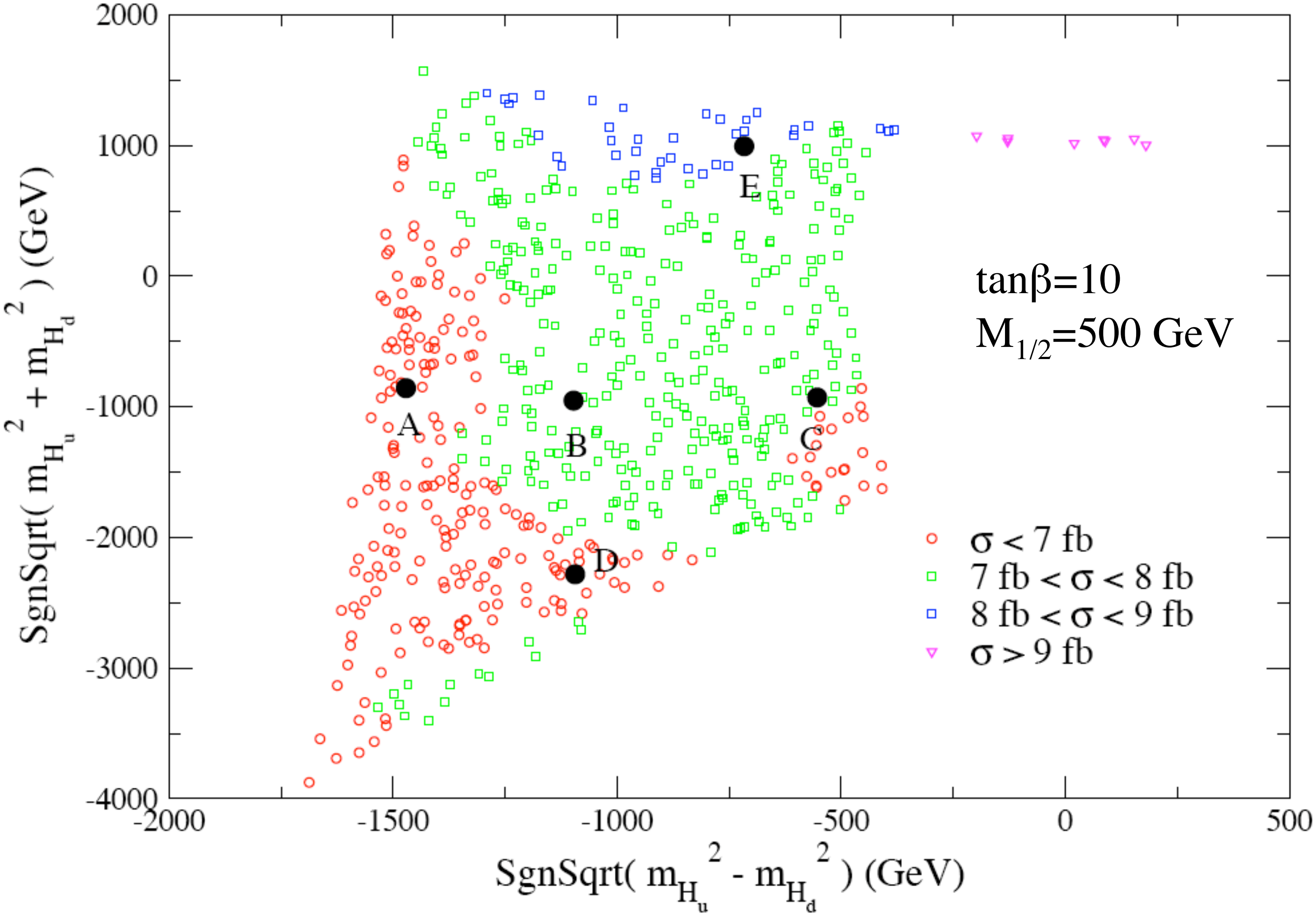
$$SgnSqrt(m_{H_u}^2 \pm m_{H_d}^2)$$

These are four sample points that are identified in subsequent scatter plots.

For all points tanβ=10 and $m_{1/2}$=500 GeV. All masses are in GeV.

	A	B	C	D	E
$SgnSqrt(-)$	-1480	-1103	-530	-1087	-712
$SgnSqrt(+)$	-820	-921	-900	-2138	1197
μ	1150	1033	868	1523	278
M_{A^0}	1465	1156	764	854	1060
M_1	210	210	210	210	209
M_2	389	389	389	389	398
$m_{\chi_1^0}$	209	209	209	210	193
$m_{\chi_2^0}$	385	385	383	387	266
$m_{\chi_3^0}$	1152	1034	871	1525	283
$m_{\chi_4^0}$	1156	1040	878	1527	420
$m_{\chi_1^\pm}$	385	385	383	387	254
$m_{\chi_2^\pm}$	1157	1041	878	1528	419
$m_{\tilde{\nu}_e}$	223	274	315	281	304
$m_{\tilde{e}_L}$	237	285	325	292	314
$m_{\tilde{e}_R}$	384	312	223	308	249
$m_{\tilde{\nu}_\tau}$	217	272	315	288	298
$m_{\tilde{\tau}_1}$	221	261	214	261	233
$m_{\tilde{\tau}_2}$	383	328	331	352	310
$m_{\tilde{g}}$	1156	1155	1152	1161	1151
$m_{\tilde{t}_1}$	901	875	837	1027	719
$m_{\tilde{t}_2}$	1069	1046	1017	1163	955
$m_{\tilde{u}_L}$	1019	1016	1012	1007	1020
$m_{\tilde{u}_R}$	933	952	969	943	972
Ωh^2	0.098	0.687	0.096	0.642	0.134

LHC 3l Signal



Cuts and BG match Baer et al. ‘00 analysis:

p_T(leptons) > 20, 20, 10 GeV

$|\eta$(leptons)$|<2.5$

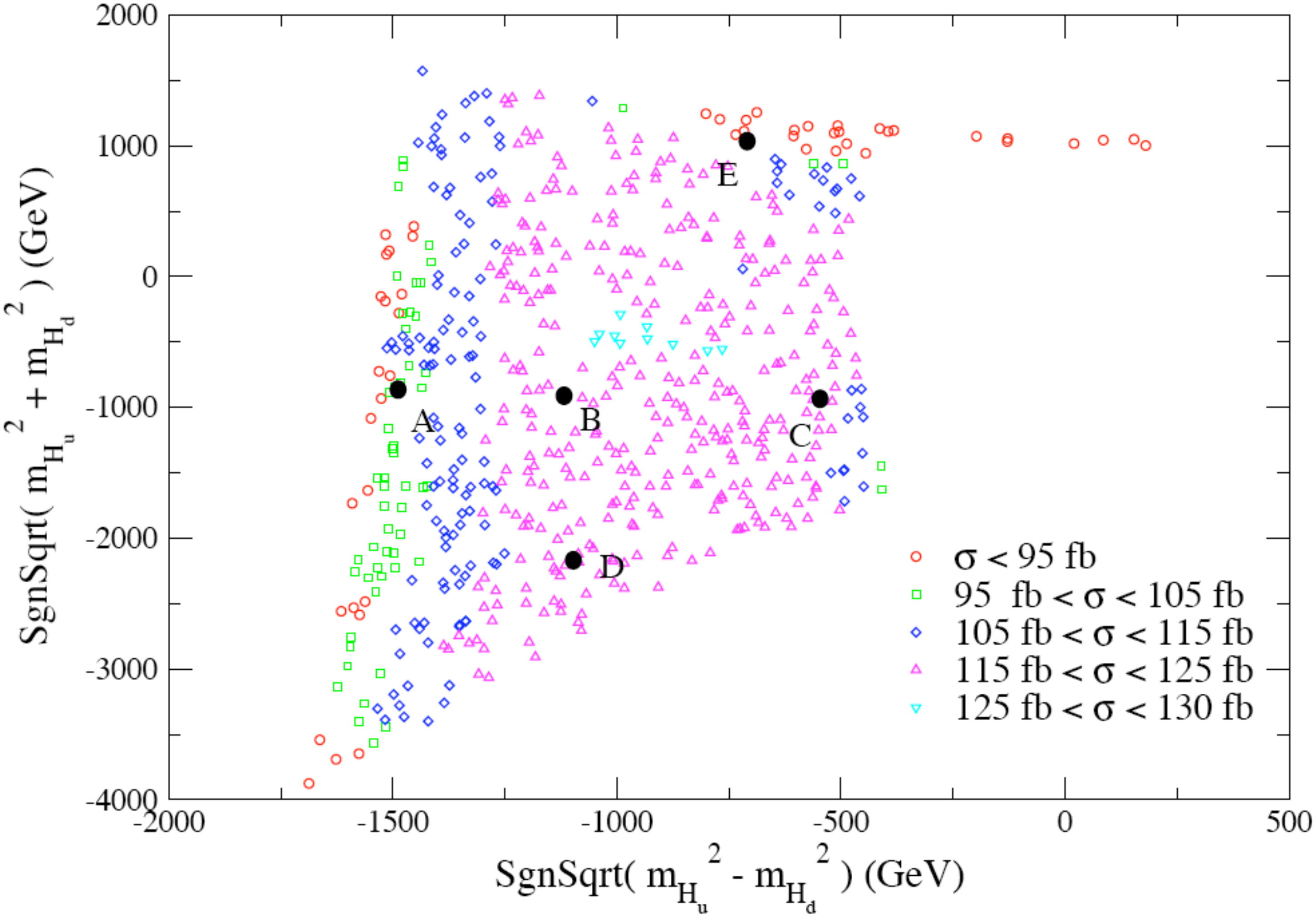
MET > 200 GeV

Etc.

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}

LHC 11 Signal

$$q\bar{q} \to Z^* \to \chi_1^{\pm}\chi_2^0 \to l^{\pm}\nu\chi_1^0\,\nu\bar{\nu}\chi_1^0$$



Cuts and BG match Baer et al. '00 analysis:

$p_T(l) > 20$ GeV

$|\eta(\text{leptons})| < 2.5$

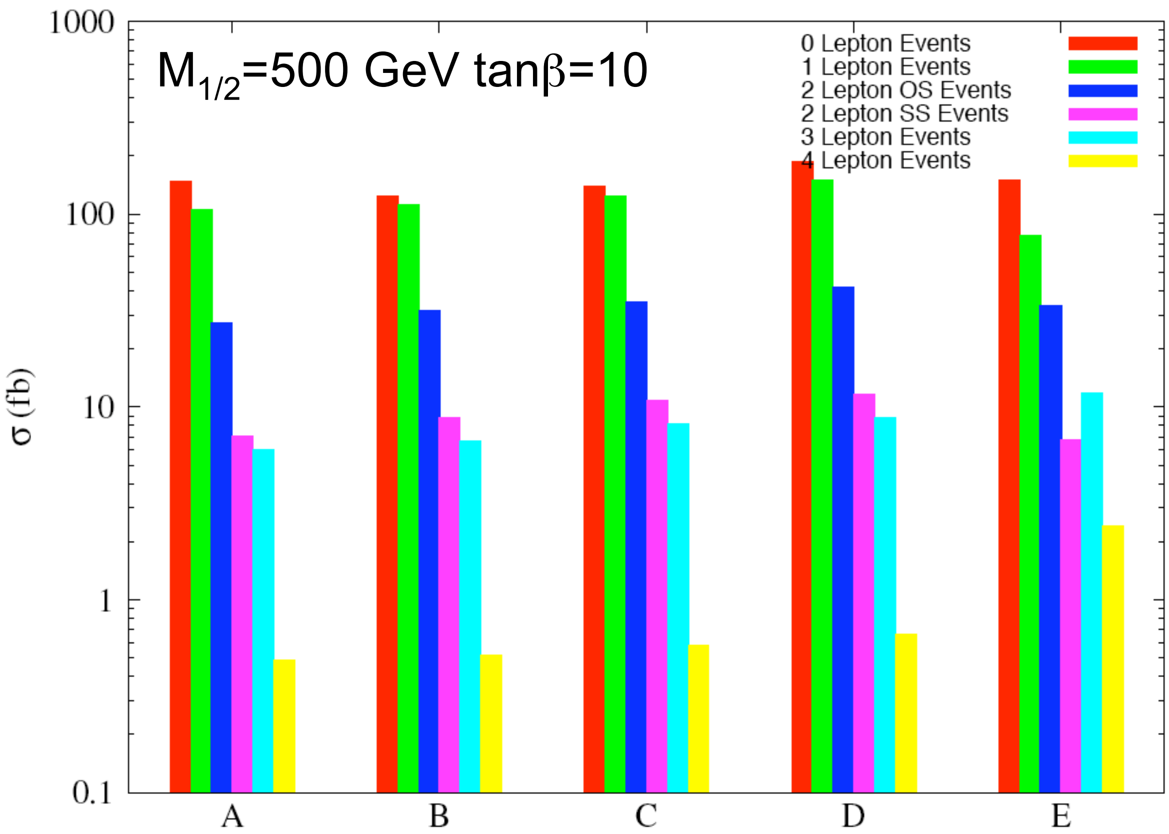
MET > 200 GeV

M_T(l,MET) > 100 GeV

Etc.

1ℓ cross-sections after cuts at the LHC for $M_{1/2} = 500$ GeV and $\tan\beta = 10$. The estimated background is 26 fb.

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

Supersymmetry is a very rich field. Many more ideas abound than I have been able to express here.

We have covered the “opposite ends” of susy: very heavy scalars and zero-mass scalars (at a high-scale boundary). Both ideas have different footprints at the LHC.

In some cases we may need to work hard to pull a signal out (four top quarks plus missing energy), and in some cases the expectations are easier (high multiplicity leptons).

The most generic, important message is that data is discerning, and will lead us to understand nature’s choices.