Effective Supersymmetry Signatures at the LHC

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SUSY stabilizes the EW scale if $M_{\rm SUSY} \stackrel{<}{\sim} \mathcal{O}(1)$ TeV......probe at LHC.

Generic SUSY has flavour problems that are alleviated by:

degeneracy (mSUGRA, GMSB, AMSB) of sparticles with like Q Nos. or by alignment of fermion and sfermion squared mass matrices.

Decoupling of sparticles, $M_{\rm SUSY} \stackrel{>}{\sim} 20-50$ TeV, is also a potential alternative but conflicts with gauge hierarchy constraint

POSSIBLE OUT

Higgsphilic particles (3rd generation scalars, EW inos) at TeV scale, with heavy first/second generation scalars.

Drees (1986); Dimopulos and Giudice (1995); Pomarol and Tomassini (1996); Cohen, Kaplan and Nelson (1996)

Combination of mechanisms $\Longrightarrow$ Higgsphilic guys below 1-2 TeV, $1st$ and $2nd$ generations 5-20 TeV

Effective SUSY or ESUSY

Realizing ESUSY with high scale boundary conditions

Recall Focus Point/Hyperbolic Branch region of mSUGRA.
For fixed $m_{1/2}$, when m_0 becomes too large, μ^2 becomes negative.

- ⋆ With non-universal scalar masses, this just means that for fixed $m_{1/2}$, and $m_0(3) = m_0(H_u) = m_0(H_d)$ become large $\mu^2 < 0$.
- ⋆ If $m_0(1,2) \gg m_0(3)$, two-loop RGE effects pull down 3rd generation squark masses.

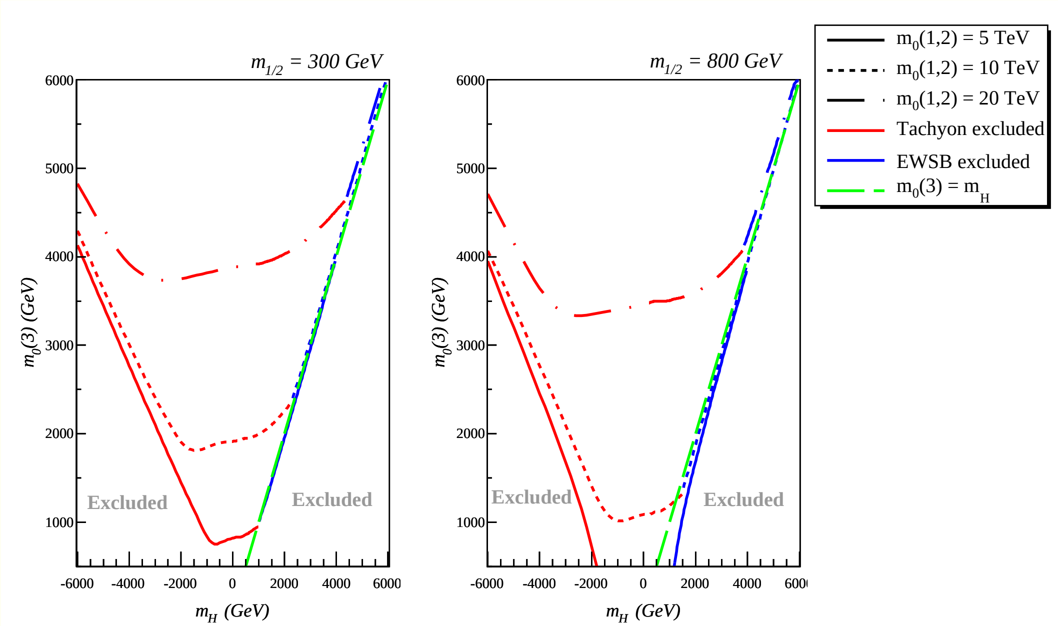
Thus, in ESUSY models, $m_0(3)^2$ bounded from both sides!

No reason for Higgs and matter scalar masses to be related.

$m_0(1,2)$, $m_0(3)$, m_{H_u}, m_{H_d}, $m_{1/2}$, A_0, $\tan\beta$, **sign(μ)**

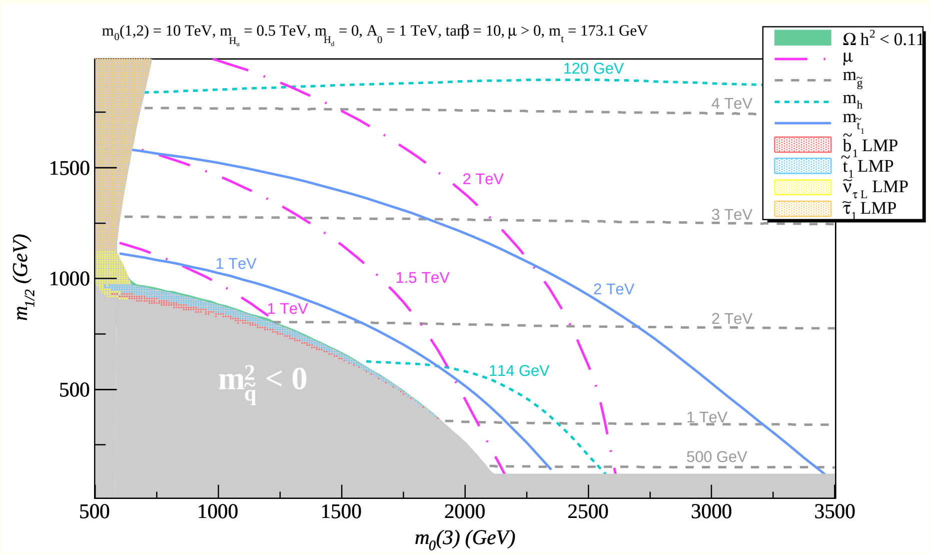
Double-sided bound on $m_0(3)^2$ is true even if the Higgs and 3rd generation scalar mass parameters are free.

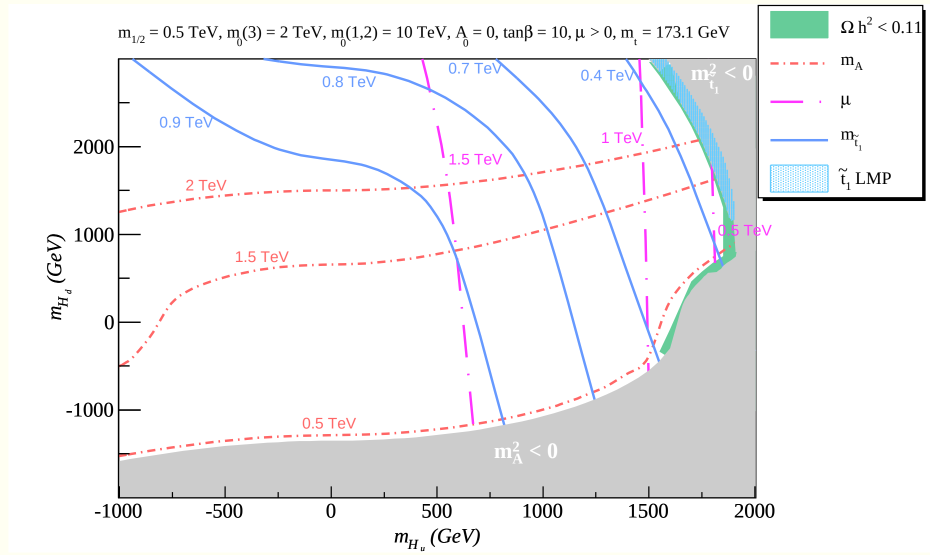
Here, $m_{H_{u,d}} \equiv \mathrm{sign}(m^2_{H_{u,d}})\sqrt{|m^2_{H_{u,d}}|}$



Larger $m_{1/2} \Rightarrow$ heavier squarks $\Rightarrow$ more allowed region.

ESUSY Panoramas





There are viable ESUSY regions.

Lightest MSSM particle may not be a neutralino! May be OK if there is a lighter R-odd particle.

Notice the thermal neutralino relic density allowed region.

We scanned the $7\frac{1}{2}$-dimensional parameter space using Markov Chain Monte Carlo.

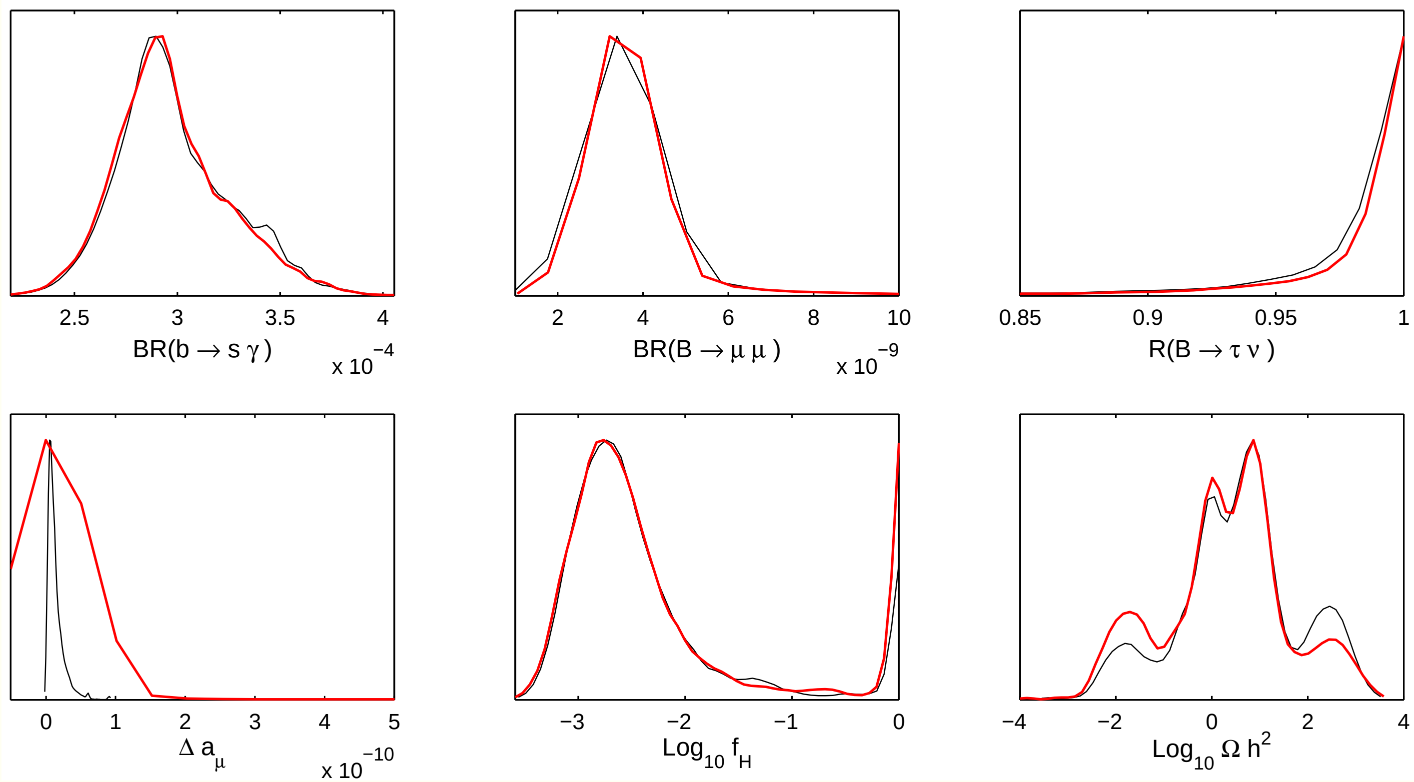
In the scans we incorporated constraints on $B(b \to s\gamma)$, $B(B_s \to \mu\mu)$, $B(B_u \to \tau\nu)$, m_t, m_h and m(sparticles).

We apply a model prior to favour light Higgsphilic particles.

At the end of the day, for the most part we have:

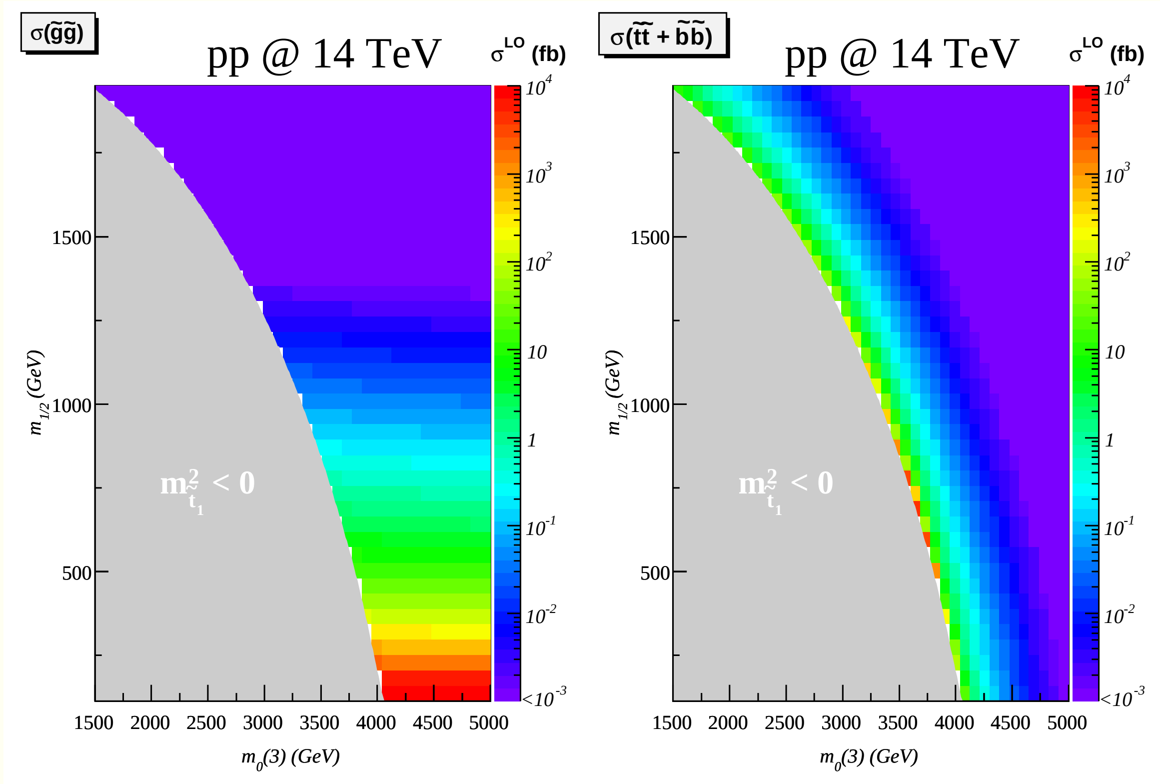
- ⋆ $m_0(1,2) \sim 10$ TeV⇒ Very heavy $1st/2nd$ generations.
- ⋆ $m_0(3) \sim 1-2$ TeV ⇒ $m_{\tilde{t}_1} \sim 400-1000$ GeV, $m_{\tilde{b}_1} \sim 1000 \pm 500$ GeV.
- ⋆ $m_{\tilde{g}} \sim 500-3000$GeV
- ⋆ $\tan\beta \sim 5-30$
- ⋆ $\mu \sim 500-2000$ GeV.

SOME LOW ENERGY OBSERVABLES



- ★ Δa_μ anomaly, if it persists, cannot be due to sparticles.
- ★ Thermal neutralino relic density most likely in 1-10 range but could be lower or higher by a couple of orders of magnitude. Additional dynamics my be needed to get $\Omega_{CDM}h^2$ at its observed value.

ESUSY Sparticle Production Rates at the LHC



$m_0(1,2) = 20$ TeV; $m_H = 1$ TeV; $A_0 = 0$, $\tan\beta = 10$

ILLUSTRATIVE ESUSY BENCHMARKS

1. Very light gluinos

$m_0(1,2) = 10$ TeV, $m_0(3) = 2.4$ TeV, $m_{1/2} = 160$ GeV

$(\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{\tau}_1, \tilde{\tau}_2) = (646, 1049, 1039, 1711, 2269, 2299)$ GeV

$(\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{W}_1, A) = (69, 139, 139, 1022)$ GeV

$\sigma(\mathrm{SUSY}) = 23.2$ pb ($\tilde{g}\tilde{g}$ 62%; EW-inos 36.6%); $\Omega_{\widetilde{Z}_1} h^2 = 320$.

Huge gluino production rate. Gluinos decay dominantly to 3rd generation quarks, so SUSY events will be rich in b-jets.

Reminiscent of scenarios with unification of t, b, τ Yukawa couplings and light gluino. Determination of $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ along with a rough measure of $m_{\tilde{g}}$ will distinguish these scenarios.

Viability of the scenario requires the neutralino to decay before the onset of BBN. The decay $\widetilde{Z}_1 \to \tilde{a}\gamma$ offers an illustrative possibility. (See Baer's talk.)

2. Heavy gluinos, sub-TeV 3rd Generation

$m_0(1,2) = 12$ TeV, $m_0(3) = 1.5$ TeV, $m_{1/2} = 900$ GeV, $A_0 = 900$ GeV

$(\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{\tau}_1, \tilde{\tau}_2) = (608, 948, 830, 1313, 1341, 1388)$ GeV

$(\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{W}_1, A) = (441, 815, 815, 450)$ GeV

$\sigma(\mathrm{SUSY}) = 158$ fb ($\tilde{t}\tilde{t}$ 83%; $\tilde{b}\tilde{b}$ 12% EW-inos 5%); $\Omega_{\widetilde{Z}_1} h^2 = 0.79$.

- ⋆ Gobs of stop production with $\tilde{t}_1 \to bW\widetilde{Z}_1$. The signal is $bbWW + \not{E}_T$, with limited SUSY contamination and presumably separable from SM backgrounds.
- ⋆ Since $\tilde{b}_1 \to \tilde{t}_1 W$, sbottom pair production yields a $bbWWWW$ final state with $\sigma \sim 18$ fb!

3. An evil cousin of the previous scenario with $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$

$m_0(1,2) = 10$ TeV, $m_0(3) = 1.1$ TeV, $m_{1/2} = 1000$ GeV, $A_0 = 1$ TeV
$(\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{\tau}_1, \tilde{\tau}_2) = (398, 770, 586, 958, 944, 1008)$ GeV
$(\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{W}_1, A) = (372, 708, 708, 398)$ GeV
$\sigma(\mathrm{SUSY}) = 1618$ fb ($\tilde{t}_1\tilde{t}_1$ 87.6%; $\tilde{b}_1\tilde{b}_1$ 9% EW-inos 5%); $\Omega_{\widetilde{Z}_1}h^2 = 0.036$.

★ Bulk of the cross section likely undetectable because of the small $\tilde{t}_1$-LSP mass gap.

★ $\tilde{b}_1\tilde{b}_1$ production, followed by $\tilde{b}_1 \to \tilde{t}_1 W$, yields $WW + \not{E}_T$ events that perhaps may be detectable over SM backgrounds. For comparison, $\sigma_{\mathrm{SM}}(WWZ) \sim 100$ fb.

Lightest MSSM particle may be charged or coloured!

Remember that we have already admitted the possibility that the lightest R-odd particle may not be an MSSM superpartner.

4. The case of the sbottom LMP

$m_0(1,2) = 20$ TeV, $m_0(3) = 3.3$ TeV, $m_{1/2} = 1000$ GeV, $A_0 = 0$ TeV

$(\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{\tau}_1, \tilde{\tau}_2) = (327, 793, \underline{292}, 1885, 2956, 3152)$ GeV

$(\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{W}_1, A) = (452, 881, 878, 2042)$ GeV

$\sigma(\mathrm{SUSY}) = 12.3$ pb ($\tilde{t}_1\tilde{t}_1$ 28.2%; $\tilde{b}_1\tilde{b}_1$ 71.4%)

The sbottom squark is a quasi-stable particle at hadron colliders. Consistency with cosmology again leads us to appeal to the existence of a lighter R-odd particle (axino???).

CDF searches exclude stable quarks lighter than 241 GeV.

ATLAS (arXiv:1103.1984) claims to exclude quasi-stable sbottoms below 294 GeV at 95%CL with just 35 pb^{-1} of data.

$\tilde{t}_1 \to \tilde{b}_1 W^*$ so stop production will only increase the region probed at the LHC, and this specific scenario is probably excluded.

Nonetheless, this example serves to illustrate the variety of SUSY signatures that are possible.

5. The case of the stau LMP

$m_0(1,2) = 6$ TeV, $m_0(3) = 300$ GeV, $m_{1/2} = 800$ GeV, $A_0 = 0$ TeV

$(\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{\tau}_1, \tilde{\tau}_2, \tilde{g}) = (867, 1147, 1083, 1176, \underline{289}, 381, 1941)$ GeV

$(\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{W}_1, A) = (347, 657, 658, 875)$ GeV

$\sigma(\mathrm{SUSY}) = 51.4$ fb ($EW - inos$ 35%; $\tilde{\ell}\tilde{\ell}$ 24% $\tilde{t}_1\tilde{t}_1 + \tilde{b}_1\tilde{b}_1$ 39%)

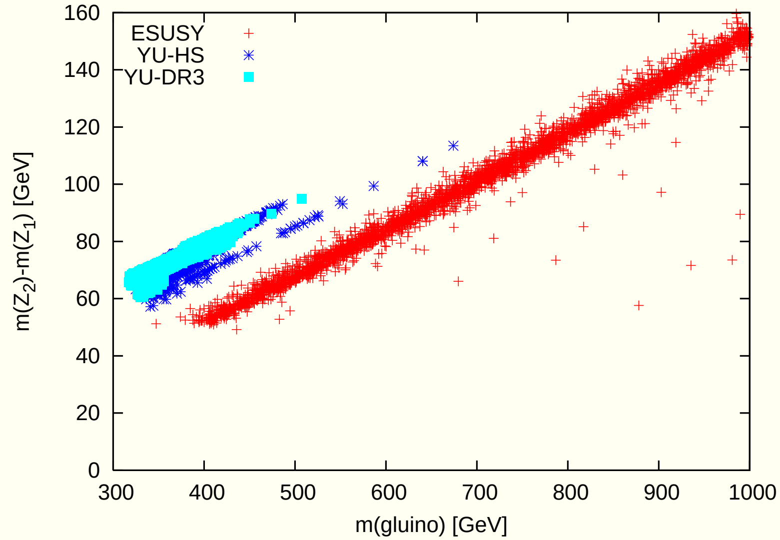
OPAL searches require $m_{\tilde{\tau}_1} > 98.5$ GeV.

The LHC cross section is small, but every SUSY event has at least two $\tilde{\tau}_1$ tracks plus other stuff. *e.g.* $B(\tilde{t}_1 \to t\widetilde{Z}_{1,2}) \sim$ 60%; $B(\tilde{t}_1 \to b\widetilde{W}_1) \sim 40\%$.

Events with tops and bottoms plus two stau tracks and small $\not{E}_T$ if the energy of the LMP can be included.

In summary

- ⋆ Effective Supersymmetry is a viable framework that stabilizes of the electroweak scale and addresses the flavour problem of supersymmetry.
- ⋆ Very wide variety of collider manifestations.
- ⋆ While it is possible that a thermal relic neutralino is the CDM, other scenarios are perfectly viable and potentially lead to collider signals rich in b-jets plus tracks of slow moving ionizing particles.
- ⋆ Despite the fact that the first and second generation sparticles are very heavy, these scenarios are frequently readily testable in experiment. If he muon magnetic moment anomaly is established, ESUSY will be strongly disfavoured.



ESUSY
YU-HS
YU-DR3
m(Z2)-m(Z1) [GeV]
m(gluino) [GeV]
0
20
40
60
80
100
120
140
160
300
400
500
600
700
800
900
1000