Radiative^* natural SUSY and the ILC

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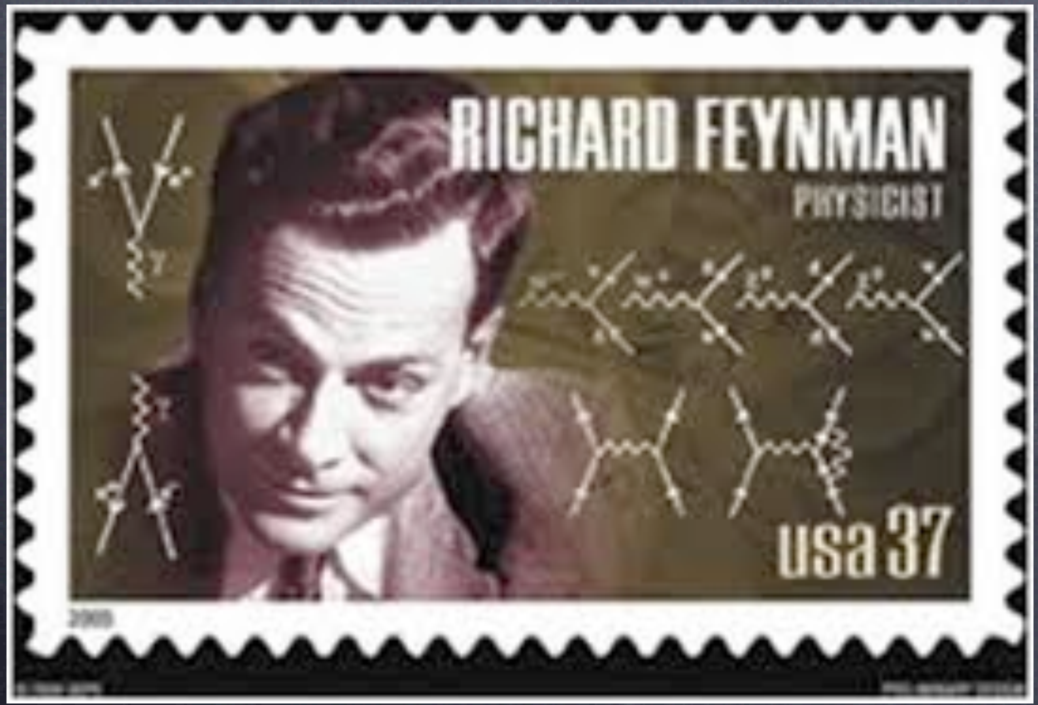
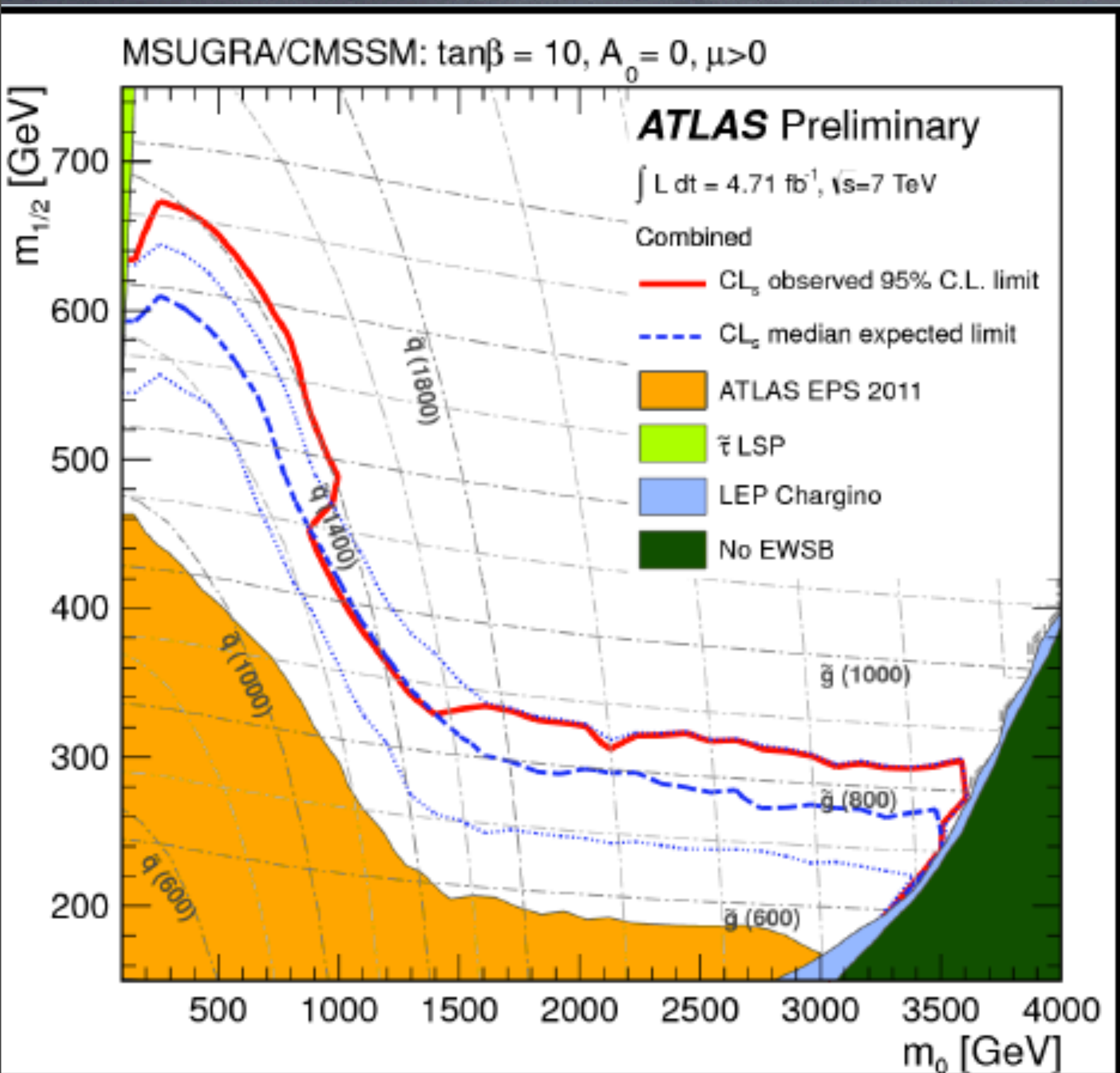
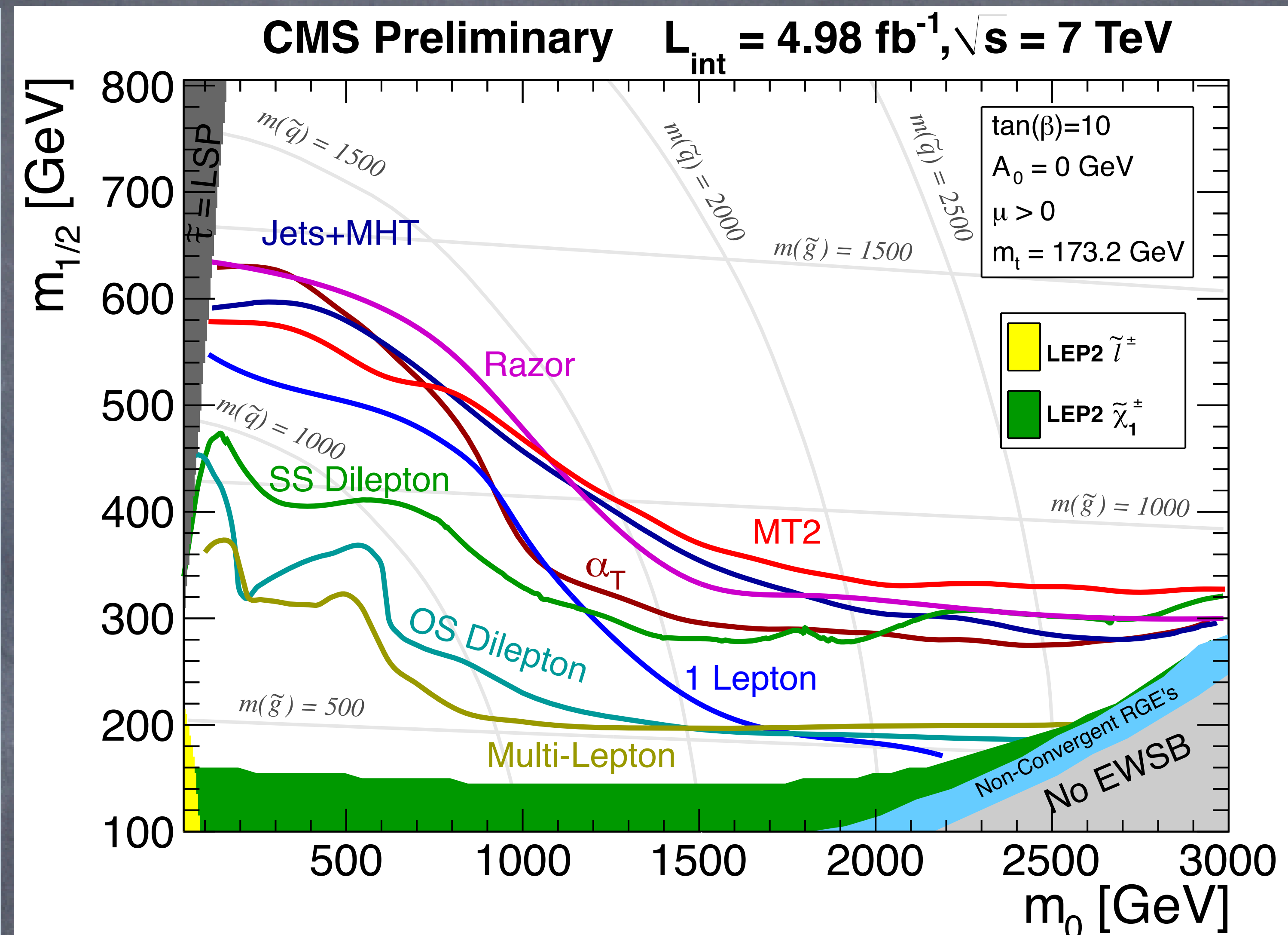
^* (New and improved natural SUSY)



``The imagination of nature is far, far greater than that of man'':
a data-driven approach to where SUSY might be hiding

Atlas/CMS search results for SUSY within mSUGRA: no sign of sparticles!





$$m_{\tilde{g}} > 1400 \text{ GeV for } m_{\tilde{q}} \simeq m_{\tilde{g}}; \; m_{\tilde{g}} > 800 \text{ GeV for } m_{\tilde{q}} \gg m_{\tilde{g}}$$

Negative search for SUSY at LHC only exacerbates Little Hierarchy problem:

How do >TeV scale SUSY parameters conspire to yield m(Z)=91.2 GeV?

Naively, would then expect m(Z)~ TeV scale

SUSY must be fine-tuned: time to give up?

not so fast!

"natural SUSY" to the rescue

Minimization of Higgs potential in MSSM leads to famous relation:

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

mu^2 term plausibly small if generated e.g. by Giudice-Masiero:

$$K(\hat{h}, \hat{H}_u, \hat{H}_d) \ni \frac{\lambda \hat{h}^\dagger \hat{H}_u \hat{H}_d}{M_P}$$

$$\mu \sim \lambda \frac{m^2}{M_P} \sim \lambda m_{3/2}$$

What about $m_{H_u}^2$?

$$m_{H_u}^2(m_{SUSY}) = m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$$

$$\delta m_{H_u}^2 \simeq -\frac{3f_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + A_t^2\right)\ln\left(\frac{\Lambda}{m_{SUSY}}\right)$$

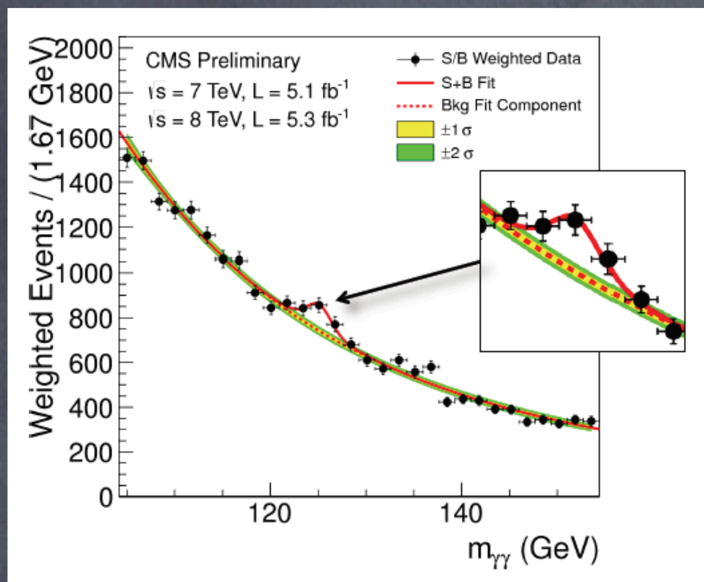
Can be used to create a bound:

- $|\mu| \lesssim 200$ GeV,
- $m_{\tilde{t}_i},\ m_{\tilde{b}_1} \lesssim 500$ GeV,
- $m_{\tilde{g}} \lesssim 1.5$ TeV.

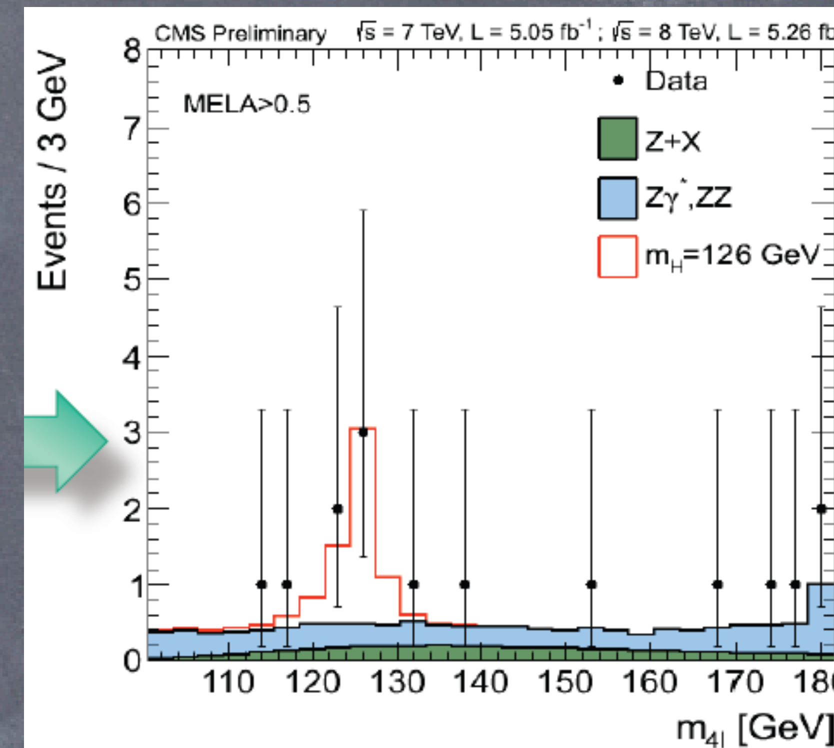
Kitano-Nomura; Papucci et al; Brust et al.

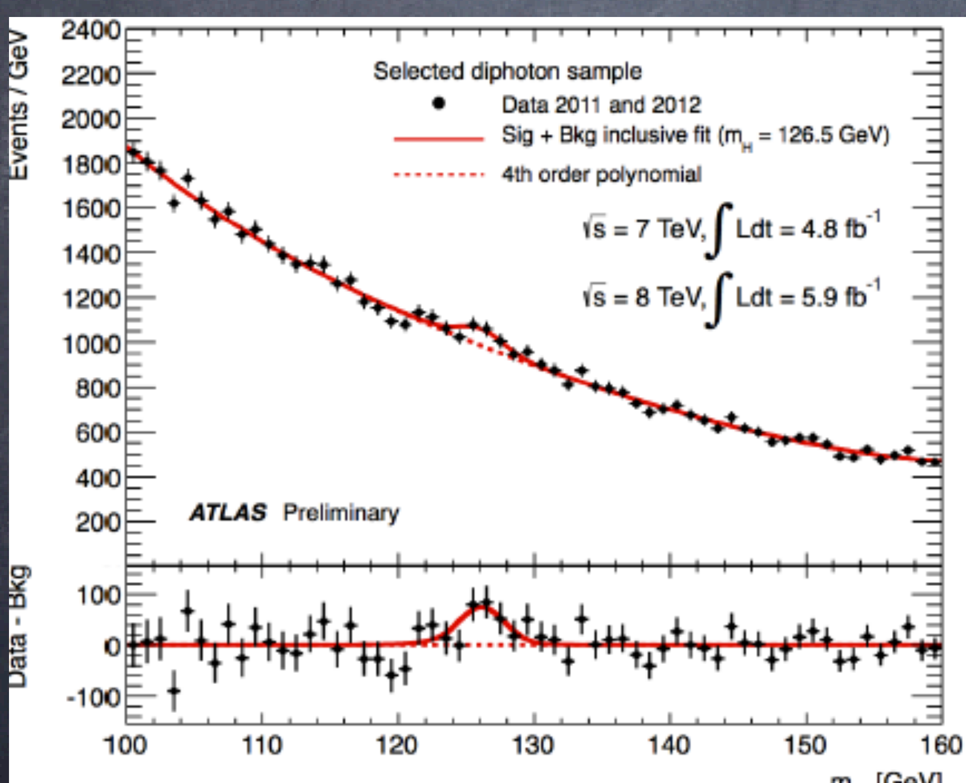
Has motivated earnest search for light 3rd generation squarks at LHC

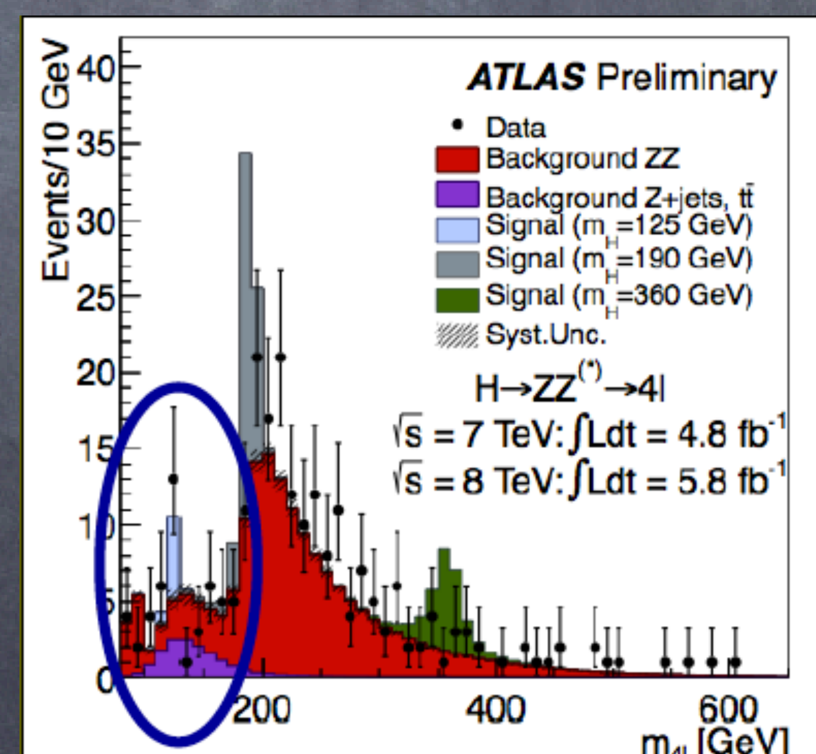
July 4: LHC Higgs signal now 5σ discovery!



$m_h \sim 125 \text{ GeV}$







Excess of events also reported from CDF/D0

Higgs mass in SM:

$$m_{H_{SM}} \sim 115 - 800 \text{ GeV}$$

Higgs in MSSM:

$$h, \; H, \; A, \; H^{\pm}$$

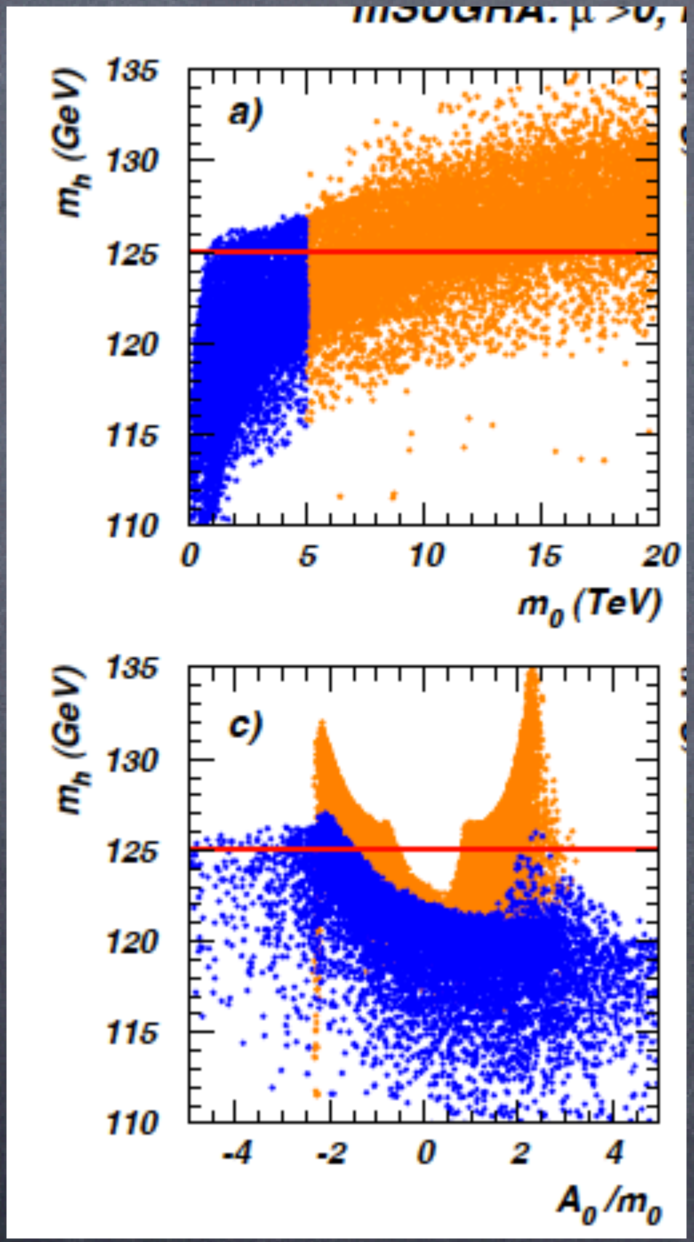
$$m_h \sim 115 - 135 \text{ GeV}$$

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\tilde{X}_t/2 + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right] \quad ($$

where $t = \log(M_{SUSY}^2/m_t^2)$, $\tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{SUSY}^2}\left(1 - \tilde{A}_t^2/12M_{SUSY}^2\right)$ and $\tilde{A}_t = A_t - \mu\cos\beta$.

Data from LHC: Higgs-like resonance @~125 GeV confirms MSSM prediction!

But: m(h)~125 GeV requires m(t1,t2)>~TeV range and large mixing in MSSM ; at odds with natural SUSY



HB, Barger, Mustafayev
PRD85, 075010 (2012)

This conflict has prompted a surge in model building which adds extra matter in order to lift up m(h) while maintaining light stops:

NMSSM^1,

vector like matter^2,

....

^1 extra singlets may destabilize hierarchy:

Bagger, Poppitz, Randall

^2 extra matter at weak scale: where is it?

Better approach: work within MSSM

cancellations may occur:

$$m_Z^2 \simeq \; = \; -1.8\mu^2 + 5.9M_3^2 - 0.4M_2^2 - 1.2m_{H_u}^2 + 0.9m_{Q_3}^2 + 0.7m_{U_3}^2 \\ -0.6A_tM_3 + 0.4M_2M_3 + \cdots$$

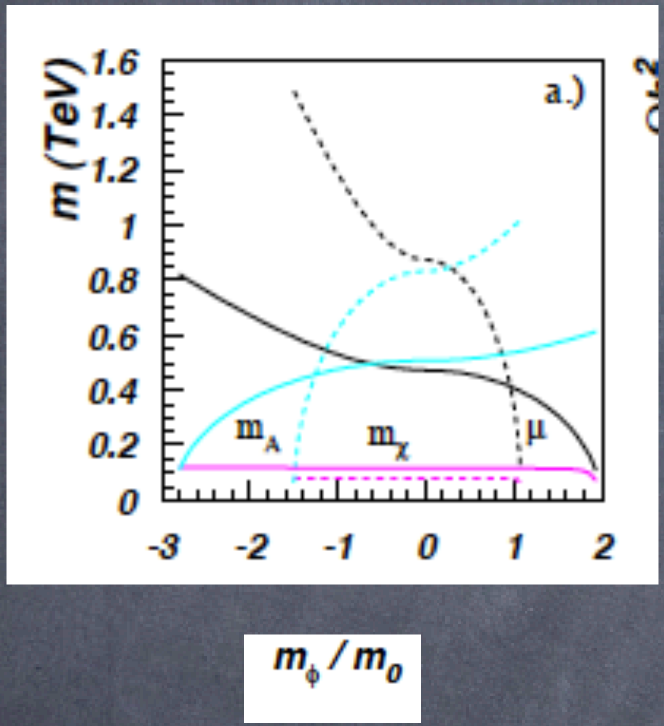
Kane et al.;
Nilles et al.

M3>.4 TeV; raise up $m_{H_u}^2$ to compensate

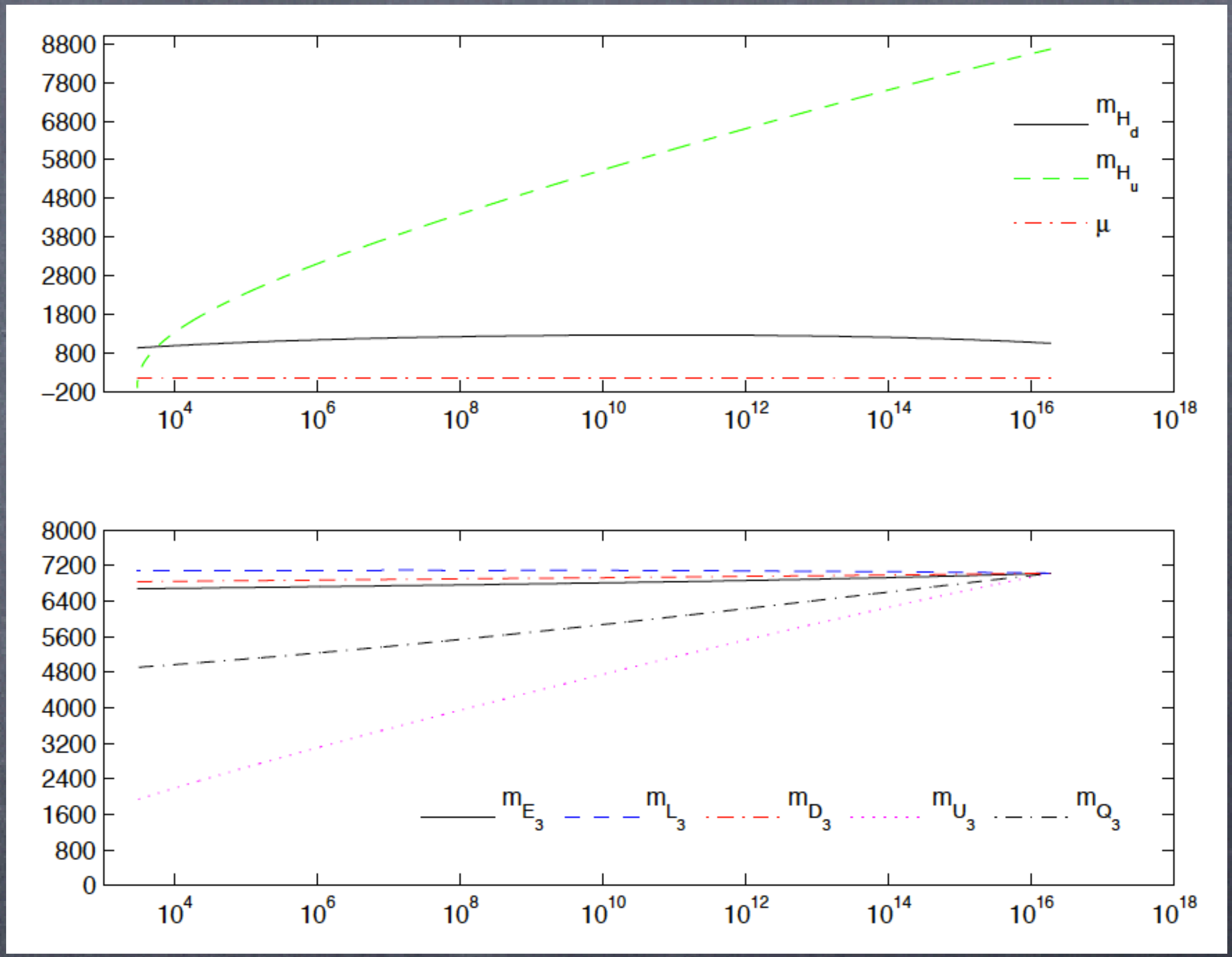
Large cancellation automatically occurs
in SUSY GUTs due
to large top Yukawa coupling:
it is what drives radiative EWSB

This is what occurs in HB/FP region,
(which is now all but excluded)

Non-universal Higgs models (NUHM): lifting $m_{H_u}^2(m_{GUT})$ causes decrease in $m_{H_u}^2(m_{weak})$



HB, Belyaev,Mustafayev, Profumo, Tata
PRD71, 095008 (2005)



NUHM expected in GUT models since Higgs live in different reps than matter

Radiative Natural SUSY

If mHu^2, mu^2 small, then loops may dominate minimization condition

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2,$$

$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \times \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2(\frac{1}{4} - \frac{2}{3}x_W)\Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

$\Delta_t = (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)/2 + m_Z^2 \cos 2\beta(\frac{1}{4} - \frac{2}{3}x_W)$, $g_Z^2 = (g^2 + g'^2)/8$ and $x_W \equiv \sin^2\theta_W$.

$$F(m^2) = m^2(\log\frac{m^2}{Q^2} - 1)$$

- FT measure Δ_{EW}
- Large A_t suppress rad.corr. from t1 while enhance m(h)!
- $m_{\tilde{t}_2}^2/Q^2 \sim e$ suppresses F
- HB, Barger, Huang, Mustafayev, Tata, arXiv:1207.3343 (PRL-in press)

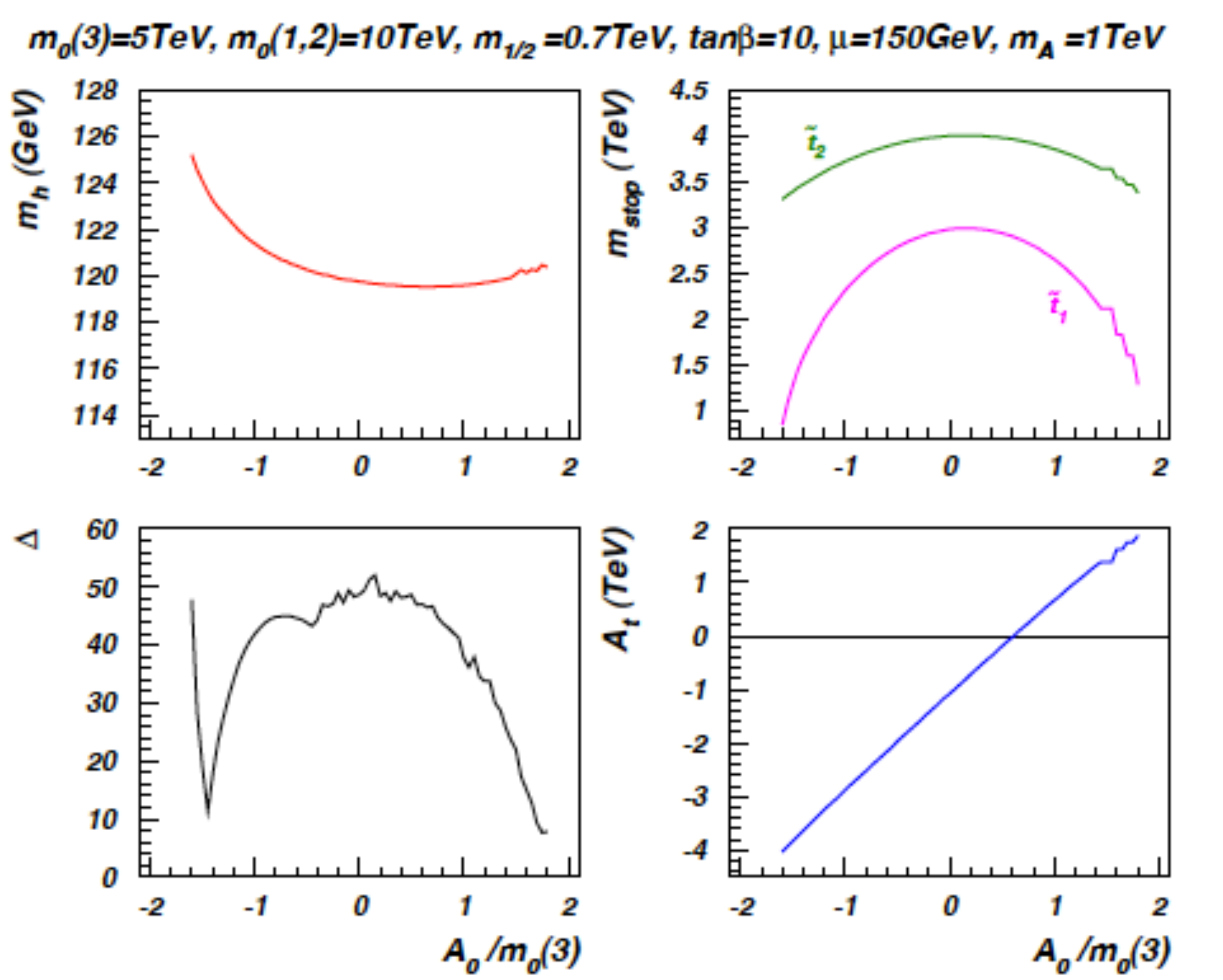


FIG. 1: Plot of a). m_h, b). $m_{\tilde{t}_{1,2}}$, c). Δ and d). A_t versus variation in A_0 for a model with $m_0(1,2) = 10$ TeV, $m_0(3) = 5$ TeV, $m_{1/2} = 700$ GeV, $\tan\beta = 10$ and $\mu = 150$ GeV and $m_A = 1$ TeV.

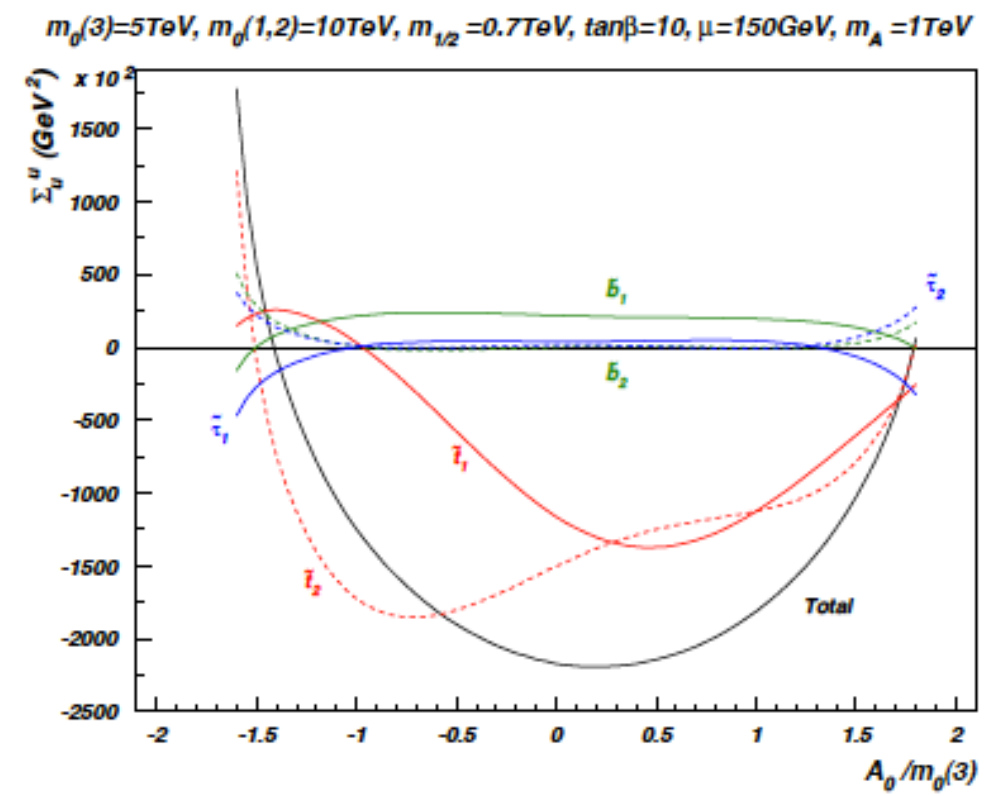
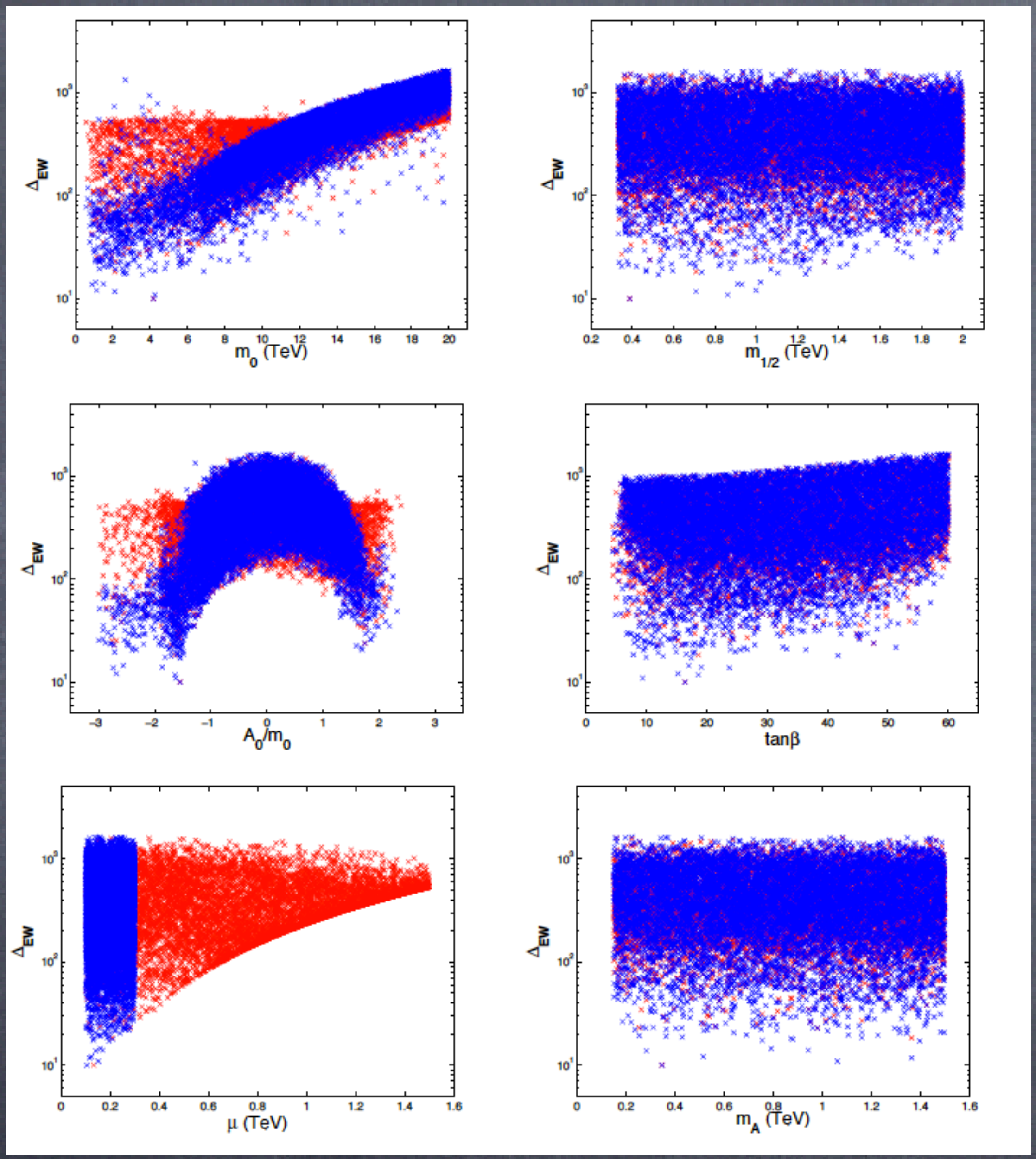


FIG. 2: Plot of third generation contributions to Σ_u^u versus A_0 for benchmark point RNS1 where solid curves come form the lighter mass eigenstate and dashed curves from the heavier. The black solid curve is Σ_u^u which has summed over all contributions.

large stop mixing softens EWFT while raising m(h)!

Detailed scan over RNS p-space:

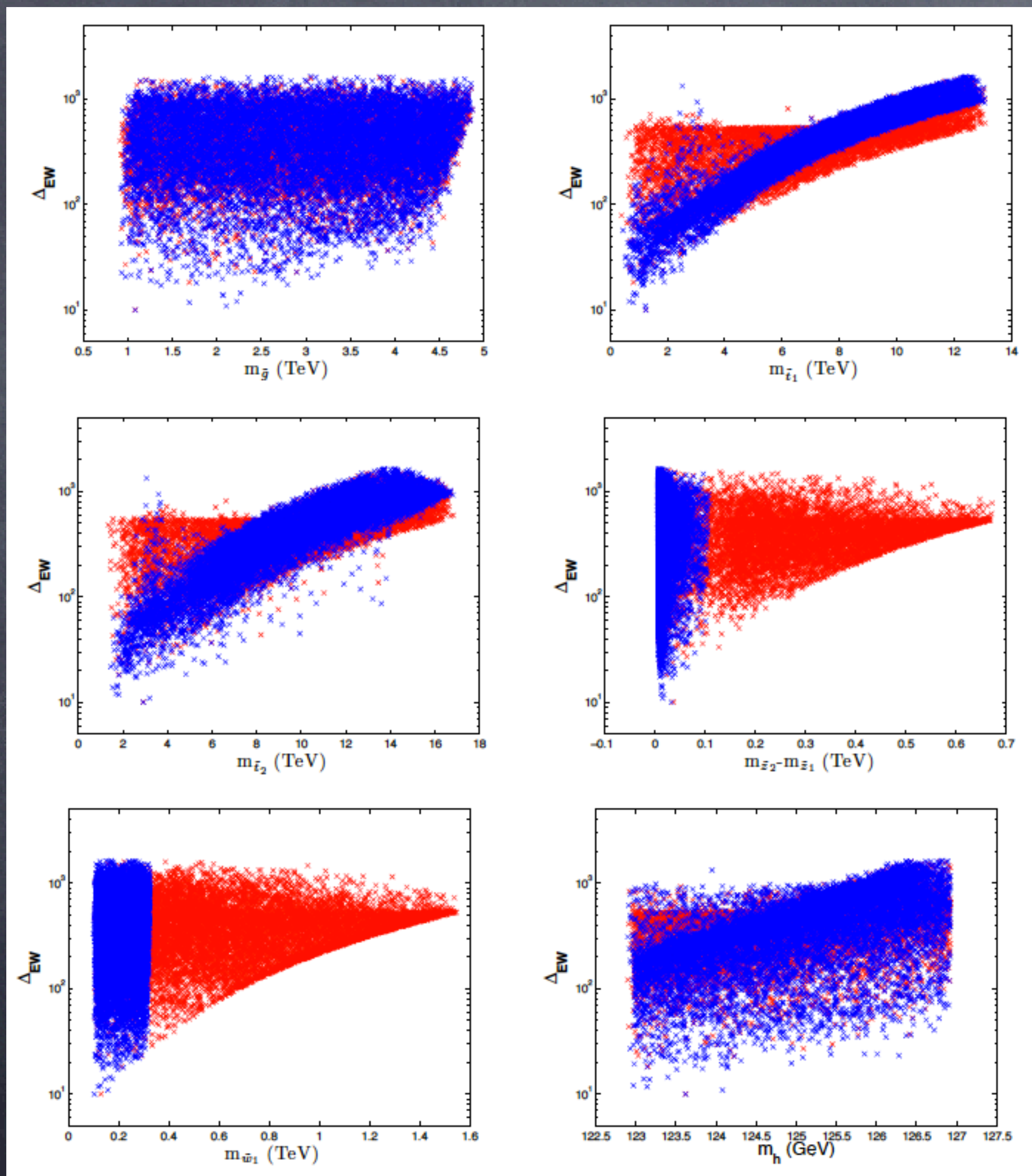


Need low mu,
large A0

EWFT at 3-10%
with m(h)~125 GeV!

HB, Barger, Huang, Mickelson, Mustafayev, Tata

Sparticle masses from RNS



- mu~100-300 GeV
- m(t1)~1-2 TeV
- m(t2)~2-5 TeV
- m(gl)~1-5 TeV
- m(z2)-m(z1)~10-50 GeV
- m(w1)~100-300 GeV

Sample benchmark points

parameter	RNS1	RNS2	NS2
$m_0(1,2)$	10000	7025.0	19542.2
$m_0(3)$	5000	7025.0	2430.6
$m_{1/2}$	700	568.3	1549.3
A_0	-7300	-11426.6	873.2
$\tan\beta$	10	8.55	22.1
μ	150	150	150
m_A	1000	1000	1652.7
$m_{\tilde{g}}$	1859.0	1562.8	3696.8
$m_{\tilde{u}_L}$	10050.9	7020.9	19736.2
$m_{\tilde{u}_R}$	10141.6	7256.2	19762.6
$m_{\tilde{e}_R}$	9909.9	6755.4	19537.2
$m_{\tilde{t}_1}$	1415.9	1843.4	572.0
$m_{\tilde{t}_2}$	3424.8	4921.4	715.4
$m_{\tilde{b}_1}$	3450.1	4962.6	497.3
$m_{\tilde{b}_2}$	4823.6	6914.9	1723.8
$m_{\tilde{\tau}_1}$	4737.5	6679.4	2084.7
$m_{\tilde{\tau}_2}$	5020.7	7116.9	2189.1
$m_{\tilde{\nu}_\tau}$	5000.1	7128.3	2061.8
$m_{\widetilde{W}_2}$	621.3	513.9	1341.2
$m_{\widetilde{W}_1}$	154.2	152.7	156.1
$m_{\widetilde{Z}_4}$	631.2	525.2	1340.4
$m_{\widetilde{Z}_3}$	323.3	268.8	698.8
$m_{\widetilde{Z}_2}$	158.5	159.2	156.2
$m_{\widetilde{Z}_1}$	140.0	135.4	149.2
m_h	123.7	125.0	121.1
$\Omega^{std}_{\widetilde{Z}_1}h^2$	0.009	0.01	0.006
$BF(b\to s\gamma)\times 10^4$	3.3	3.3	3.6
$BF(B_s\to \mu^+\mu^-)\times 10^9$	3.8	3.8	4.0
$\sigma^{SI}(\widetilde{Z}_1 p)$ (pb)	1.1×10^{-8}	1.7×10^{-8}	1.8×10^{-9}
Δ	9.7	11.5	23.7

m(t1)~1.5 TeV

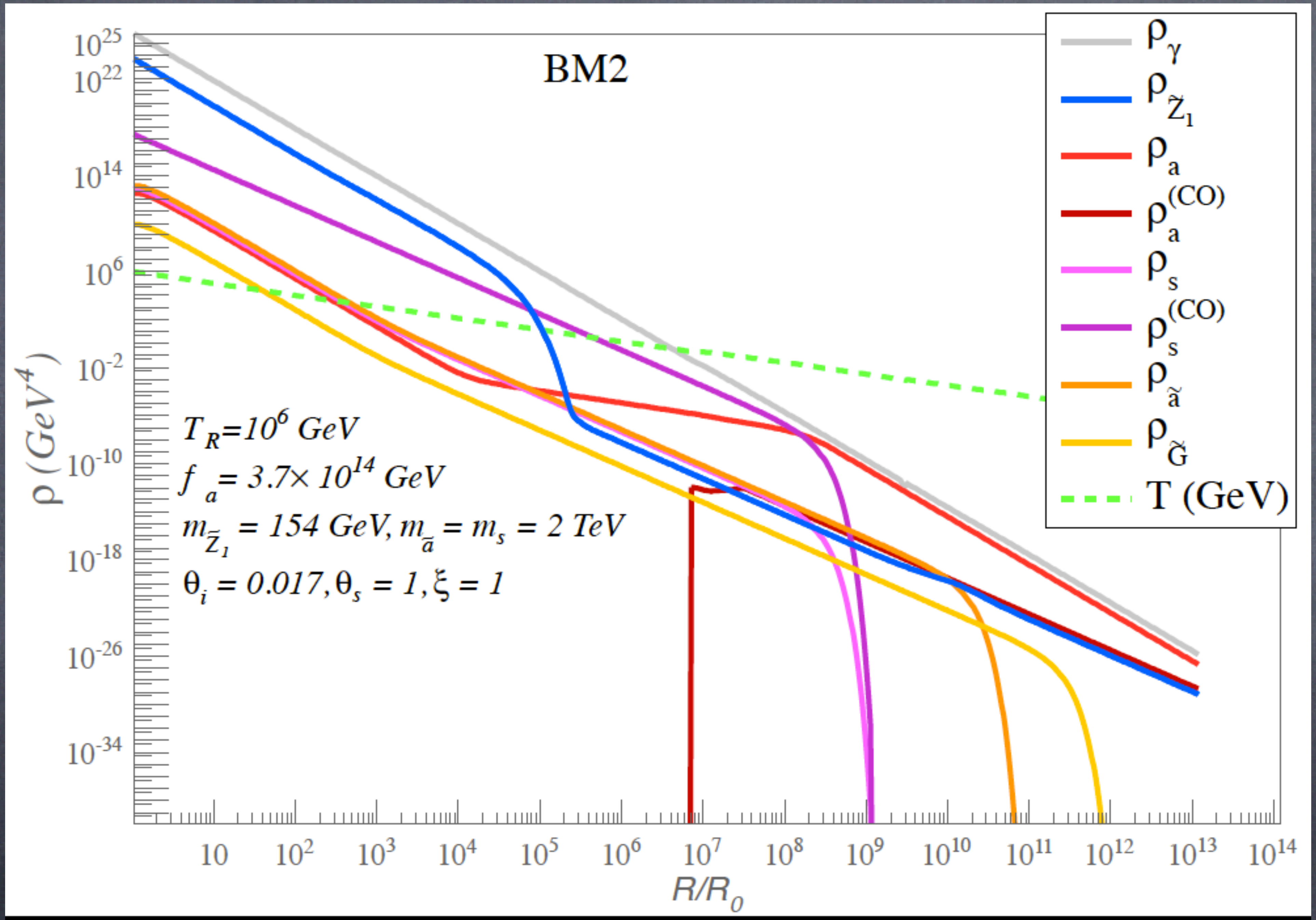
m(t2)~3-5 TeV

But RNS has lower EWFT than generic NS models and also m(h)~125 GeV!

Consequences for colliders

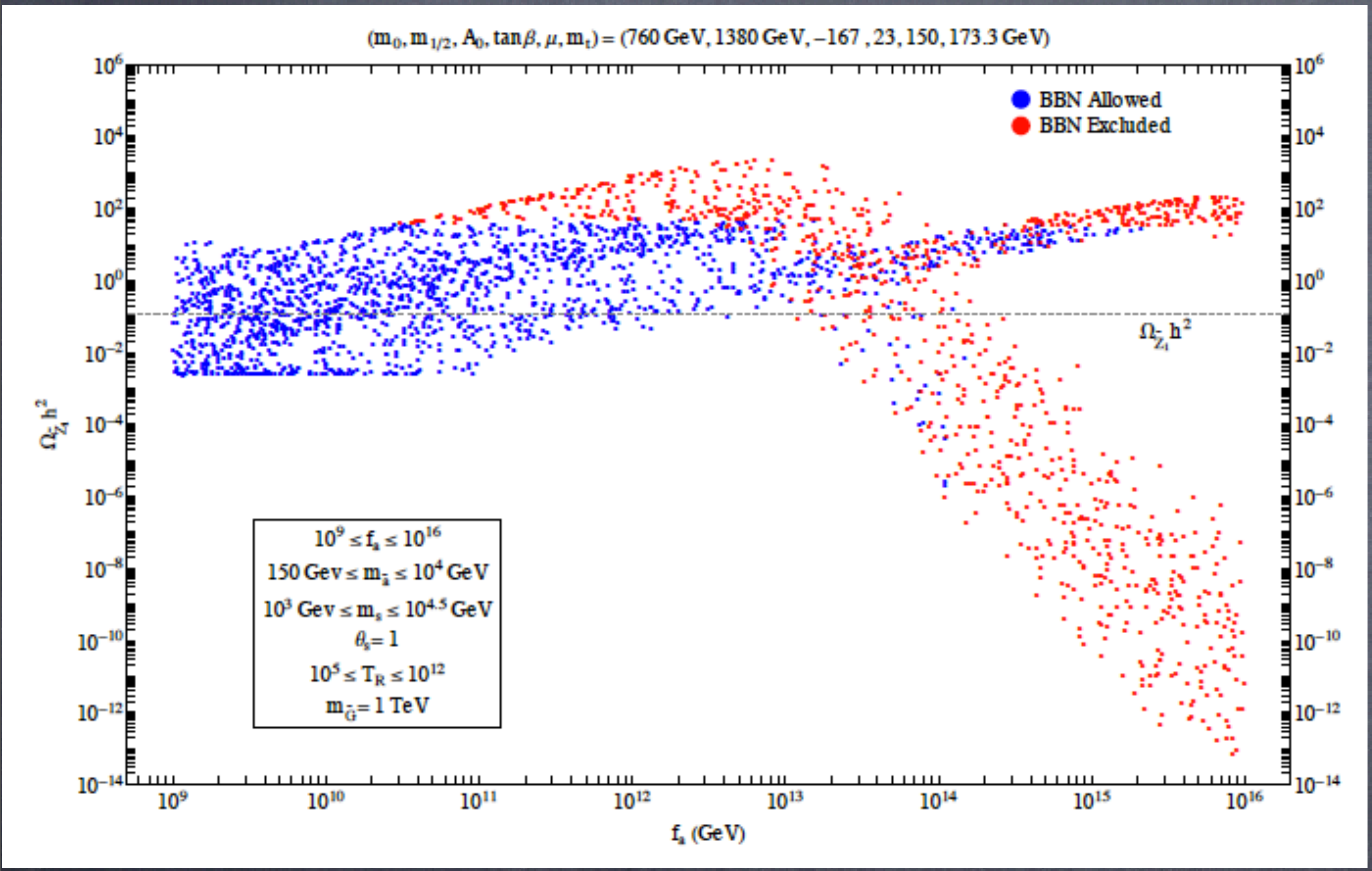
- squarks ~10 TeV but m(gluino)~1-5 TeV: reach of LHC8 to m(gl)~1.1 TeV; LHC14 to m(gl)~2 TeV for >100 fb^-1: maybe see at LHC but maybe not
- low mass OS dilepton pairs from Z2->Z1 e+ e- from gluino pair cascade decays: m(e+e-)<~10-20 GeV; Z2=higgsino-like
- higgsino-like chargino pairs accessible to ILC with $\sqrt{s} \sim 0.3 - 1~\mathrm{TeV}$

Coupled Boltzmann calculation of mixed axion-higgsino CDM



Bae, HB, Lessa

Mixed higgsino-axion CDM in radiative natural SUSY



$f_a \sim 10^{14}$ GeV *allowed*!

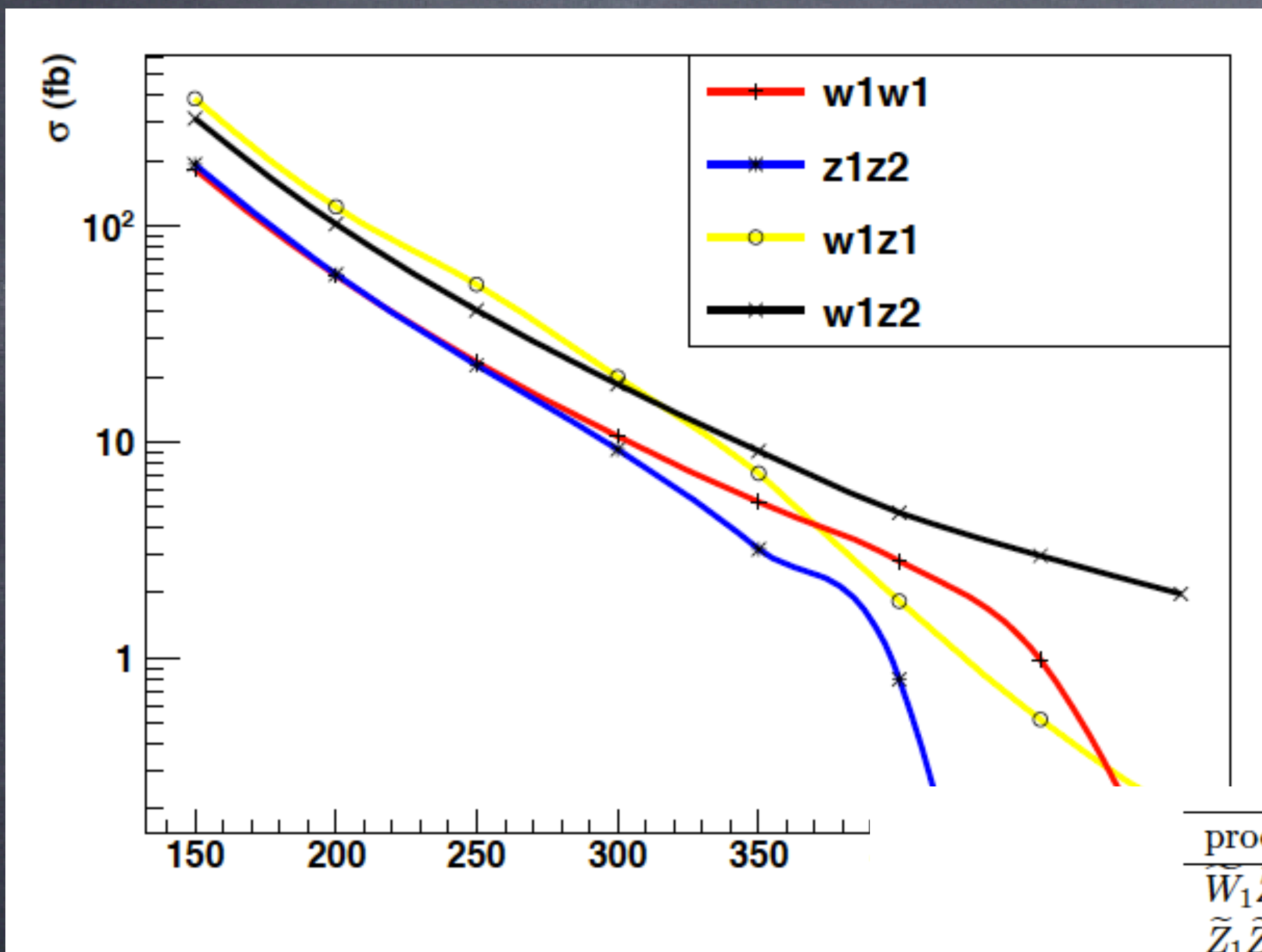
Abundance of higgsinos is boosted due to thermal production and decay of axinos in early universe: the axion saves the day for WIMP direct detection!

Detection of relic axions also possible

Perspective in LHC8 era

- Discovery of h(125) at Atlas, CMS, CDF/D0 compelling and hints at SUSY; further searches are on the way in 2012 at LHC8!
- No sign of SUSY so far; this is to be expected in models where SUSY flavor/CP/p-decay/gravitino problem solved by decoupling
- Naturalness/m(h)~125 GeV reconciled within MSSM by Radiative Natural SUSY with light higgsinos, medium-light gluinos: hard to see at LHC but ILC is higgsino factory!
- Dark matter: preference from theory for axion-higgsino admixture: detect both?

Light higgsinos @ LHC



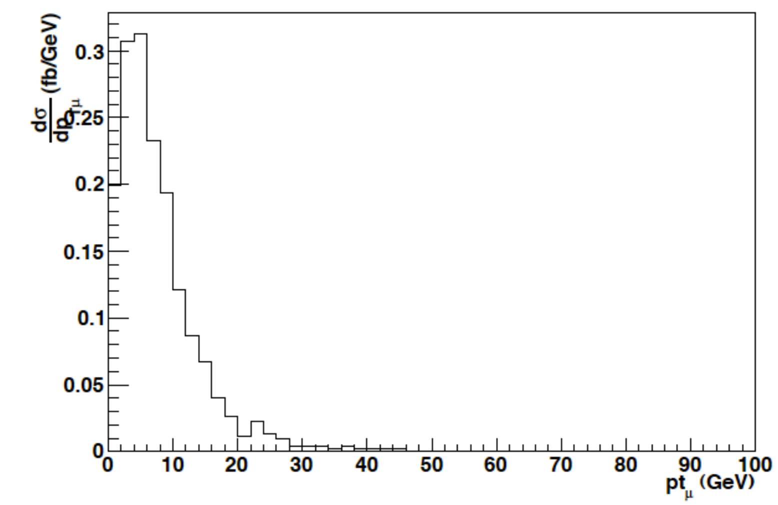


Figure 8: Distribution in $p_T(\mu)$ from $pp \to \widetilde{Z}_1\widetilde{Z}_2 \to \mu^+\mu^- + E_T^{\rm miss}$ events at LHC from higgsino-world benchmark point HW150.

process	σ (fb)	σ (after cuts, fb)
$\widetilde{W}_1\widetilde{Z}_2$	313	0.3
$\widetilde{Z}_1\widetilde{Z}_2$	192	0.13
$\gamma^* \to \mu^+\mu^-$ (DY)	1.1×10^6	4
$W^+W^- \to \mu^+\mu^-$	235.5	2.3
$\gamma^* Z \to \mu^+\mu^-\nu_i\bar{\nu}_i$	6.8	0.3
$\gamma^*, Z \to \tau^+\tau^- \to \mu^+\mu^-$	1.5×10^4	5
$t\bar{t} \to \mu^+\mu^-$	8.9×10^4	< 0.3

Table 2: Signal and BG cross sections in fb before and after cuts at LHC7. The signal rates are for higgsino-world benchmark point HW150. Each background process requires $p_T(\mu) > 5$ GeV.

Light higgsinos @ ILC

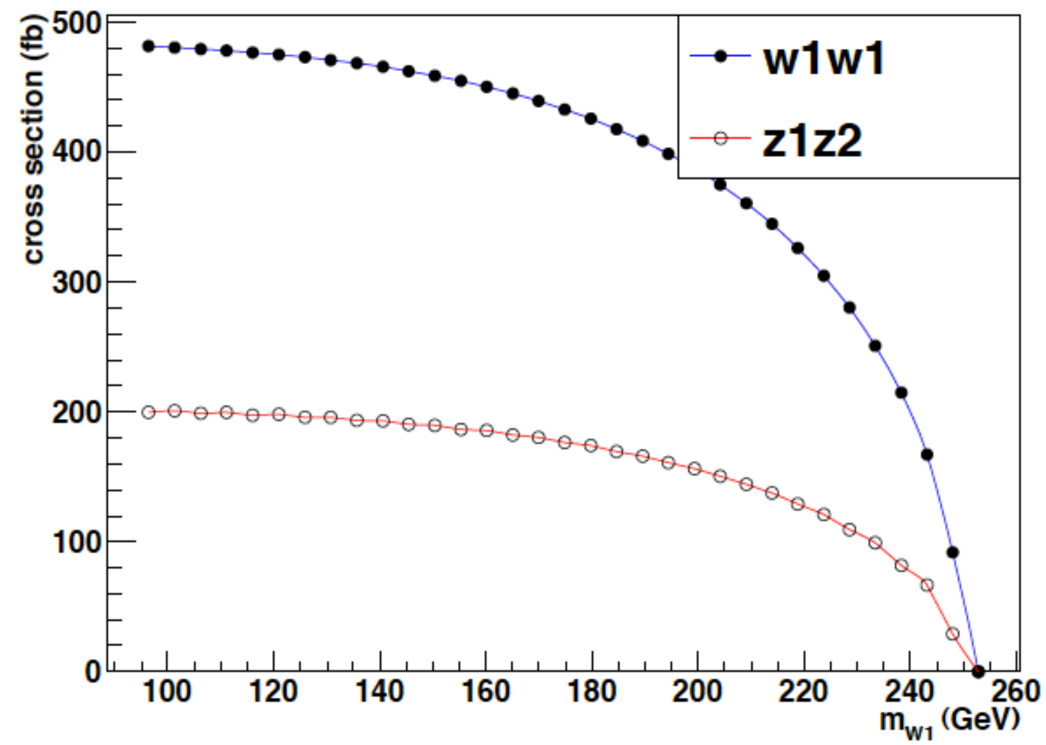


Figure 10: Cross sections for chargino pair production and neutralino pair production v
at a $\sqrt{s} = 500$ GeV ILC or MC collider. We take SUSY parameters as in Fig. 7, and var
variation in $m_{\widetilde{W}_1}$.

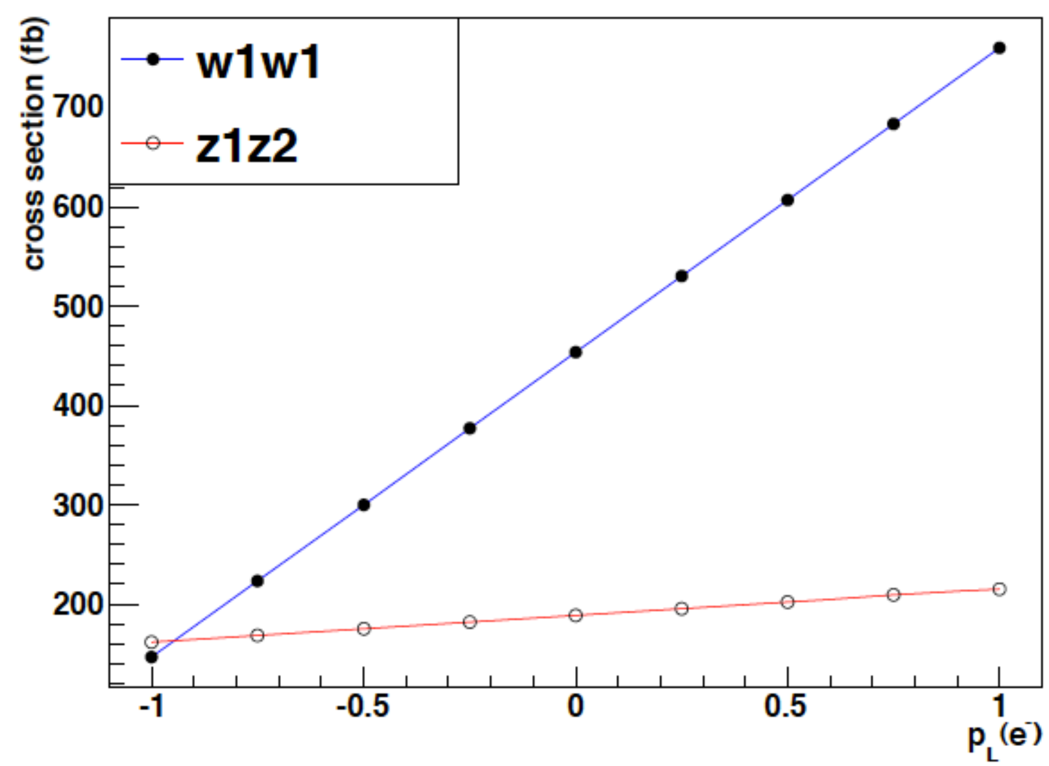
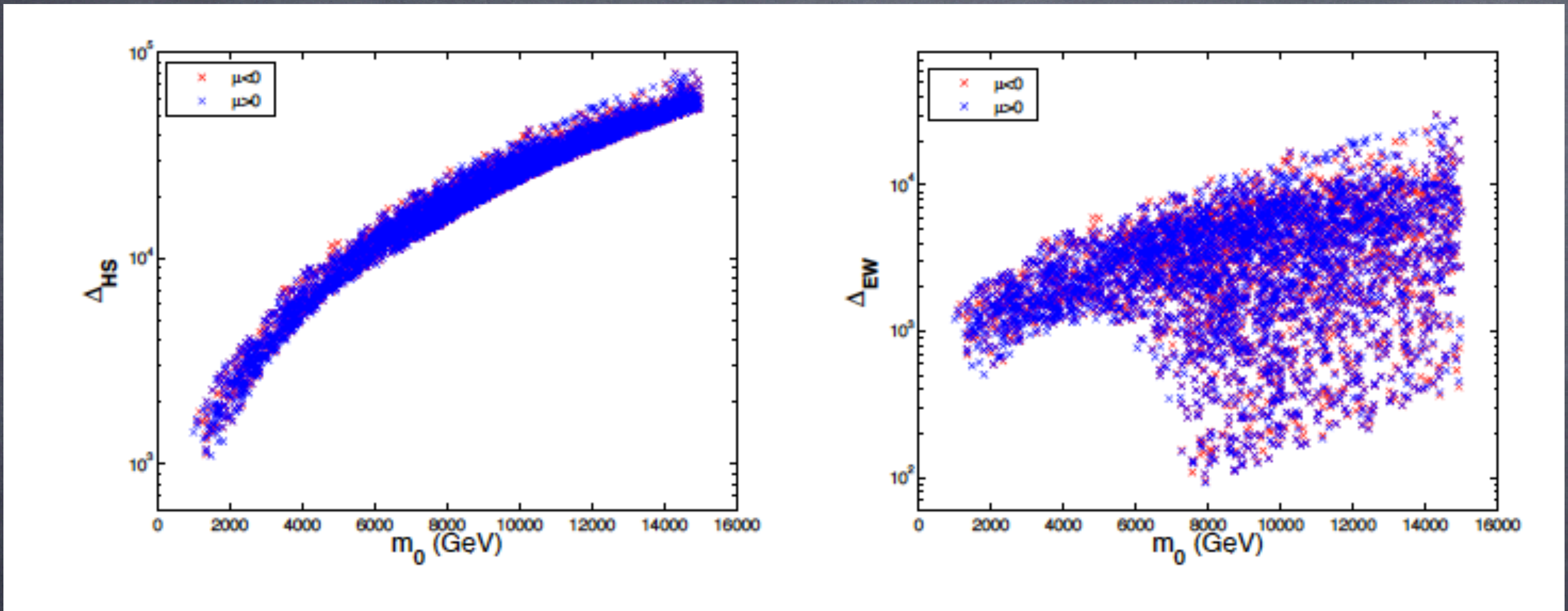


Figure 11: Cross sections for chargino pair production and neutralino pair production versus $P_L(e^-)$ at a $\sqrt{s} = 500$ GeV ILC collider. We take SUSY parameters as in HW1, with $\mu = 150$ GeV.

HB, Barger, Huang;
Hidden SUSY

Finetuning in mSUGRA



$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2(\Lambda) + \delta m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - (\mu^2(\Lambda) + \delta\mu^2)$$

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

HB, Barger, Huang, Mickelson, Mustafayev, Tata