Axion, WIMP, LHC and ILC complementarity

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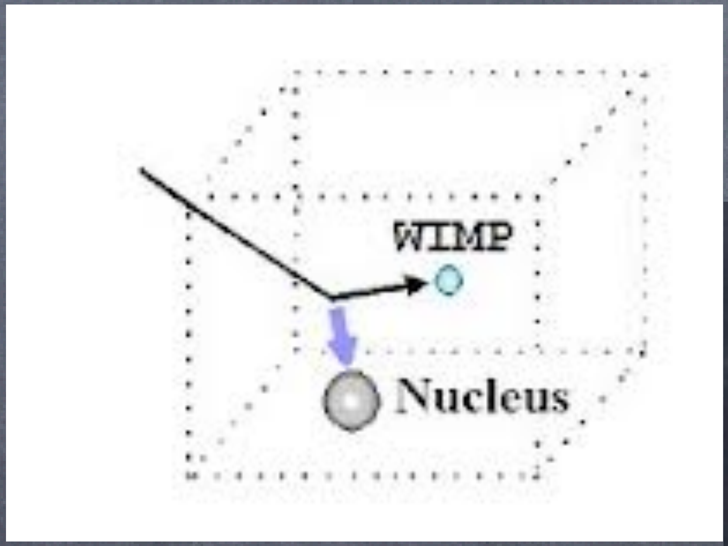
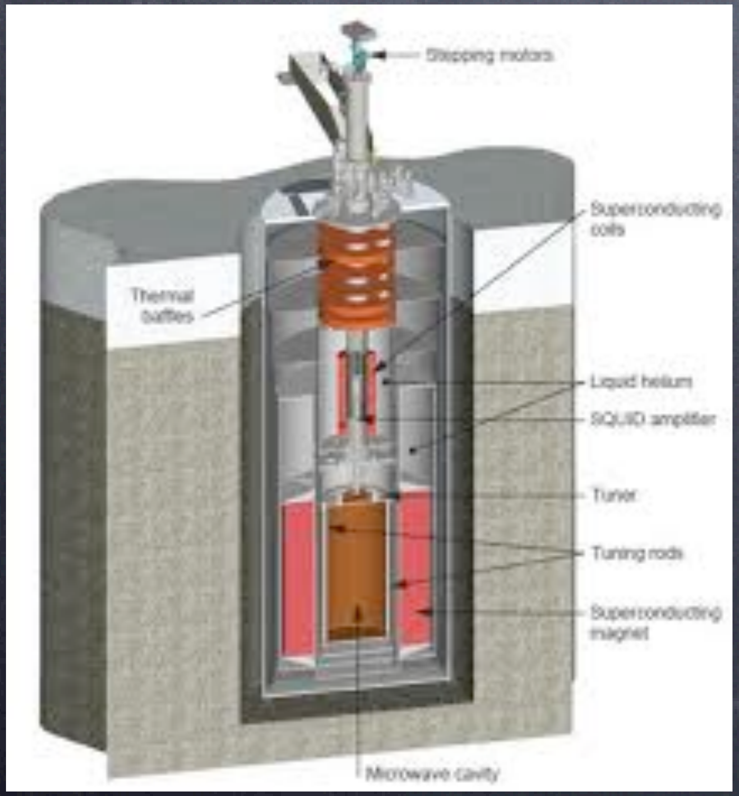
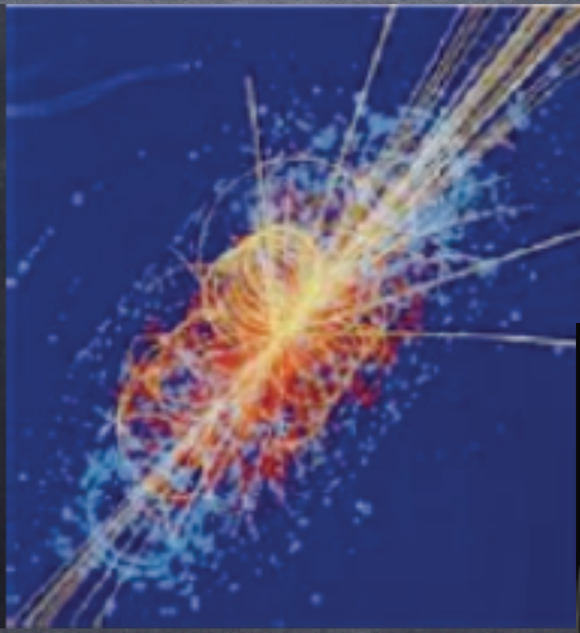
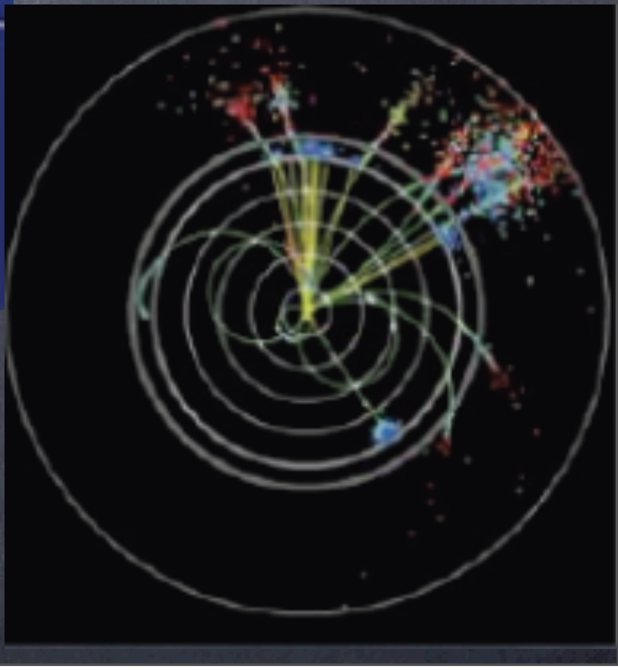




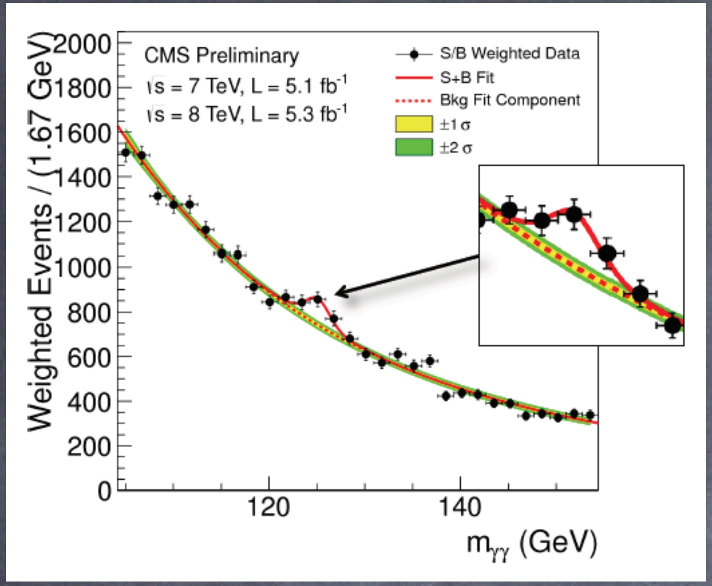




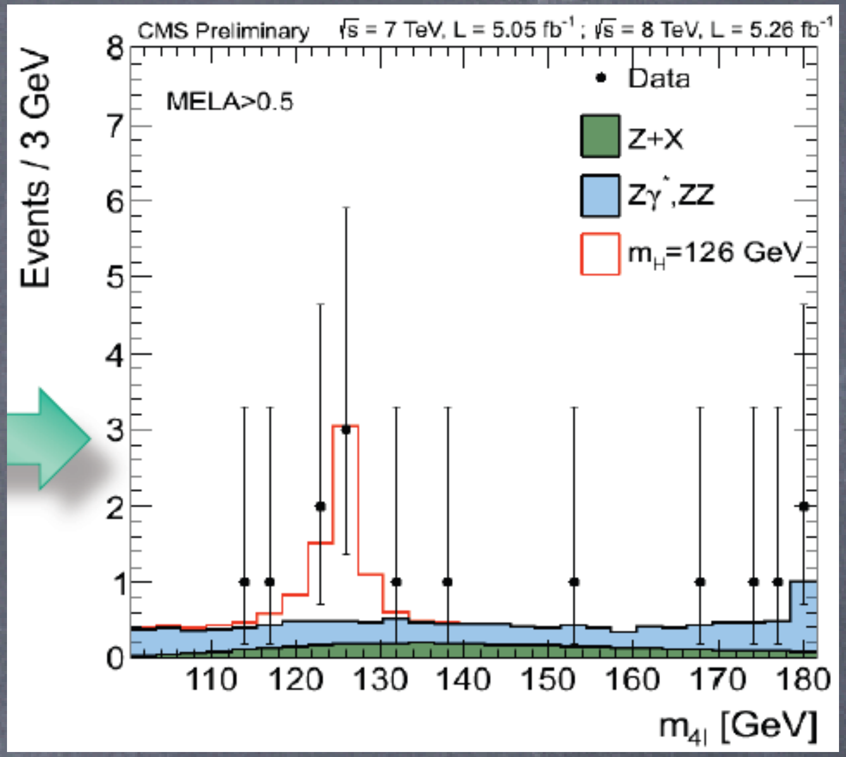
Some great ideas which stand a good chance of being right:

- SUSY
- GUTs
- See-saw neutrino mass
- PQ symmetry, axions
- inflationary cosmology
- superstring

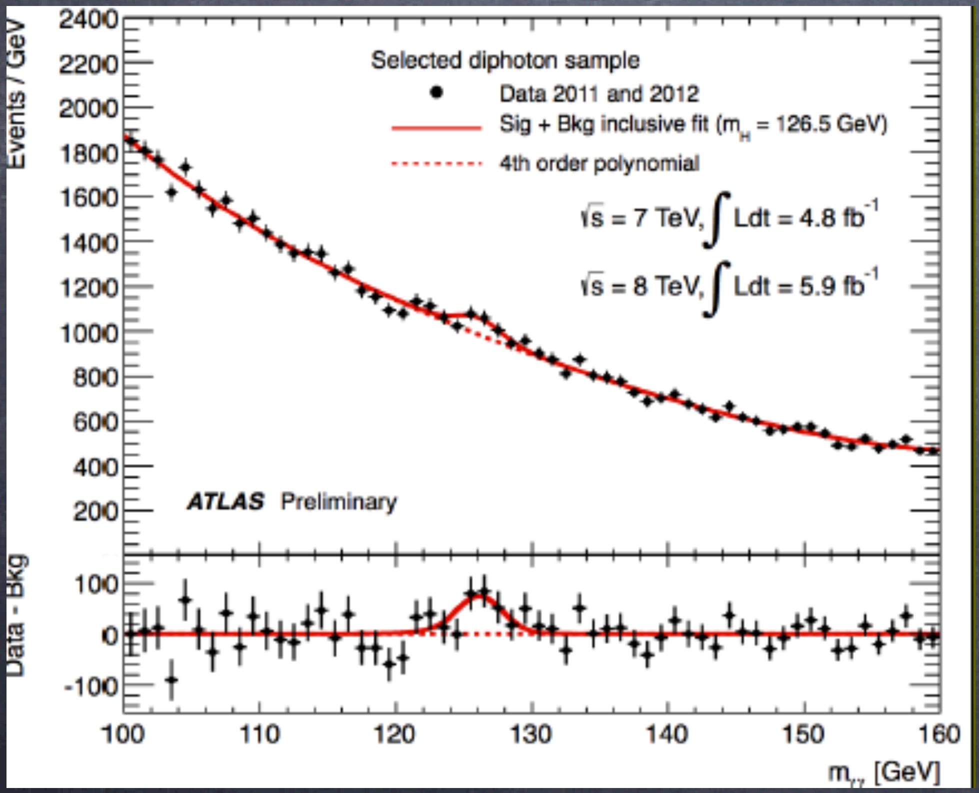
How does LHC impact on these ideas?

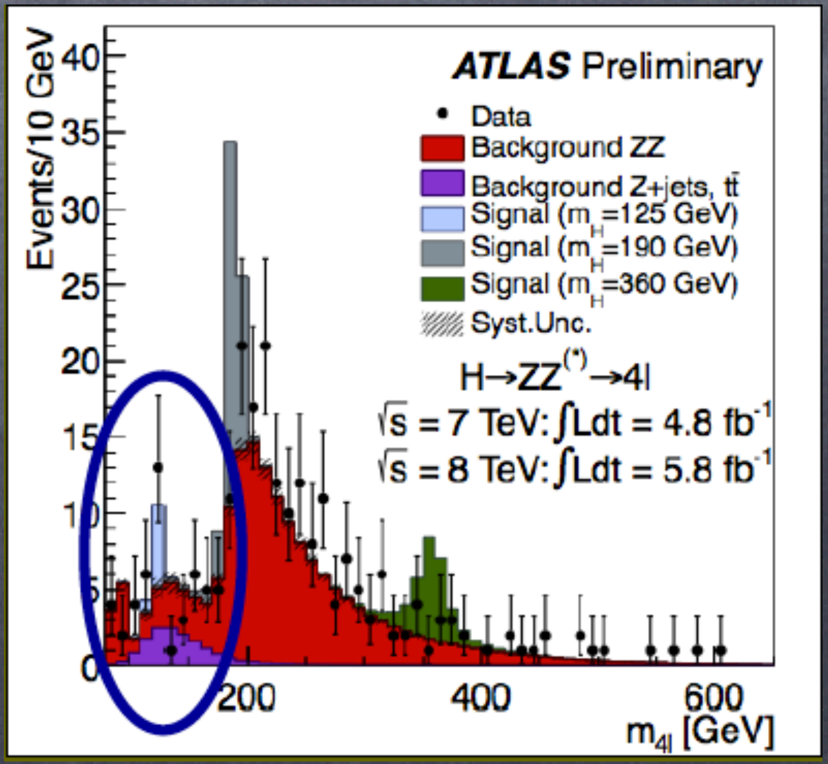


Atlas/CMS
Higgs discovery!



$$m_h \sim 125\ \mathrm{GeV}$$



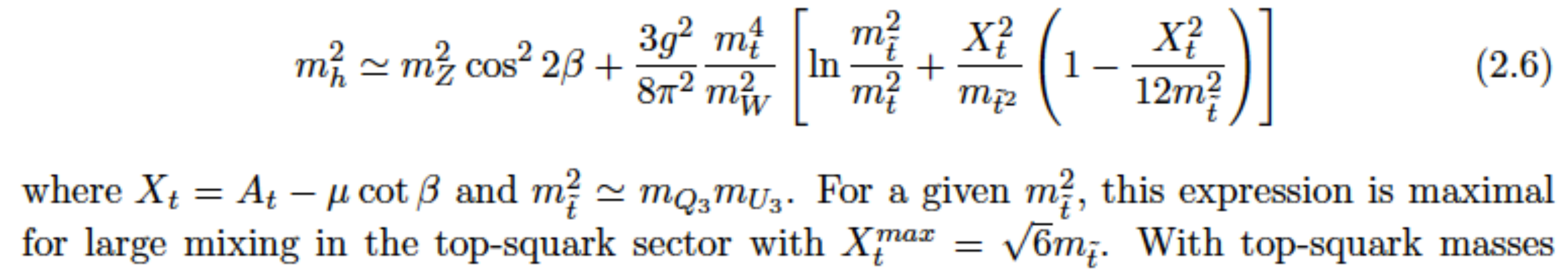


Excess of events also reported from CDF/D0

Higgs mass in SM:

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

Higgs in MSSM: $h,\ H,\ A,\ H^{\pm}$



$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3g^2}{8\pi^2}\frac{m_t^4}{m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}^2}}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right] \qquad (2.6)$$

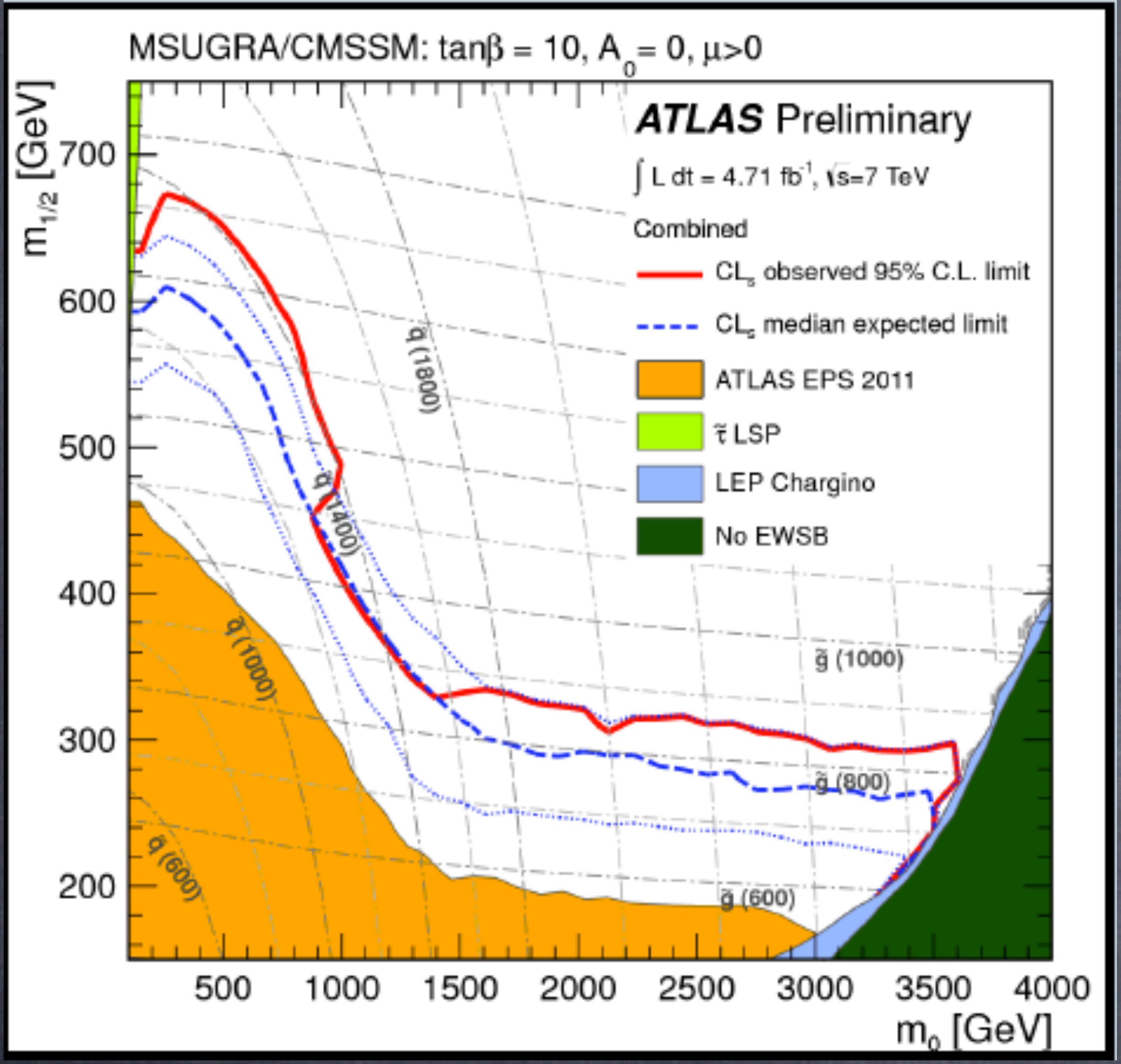
where $X_t = A_t - \mu\cot\beta$ and $m_{\tilde{t}}^2 \simeq m_{Q_3}m_{U_3}$. For a given $m_{\tilde{t}}^2$, this expression is maximal for large mixing in the top-squark sector with $X_t^{max} = \sqrt{6}m_{\tilde{t}}$. With top-squark masses

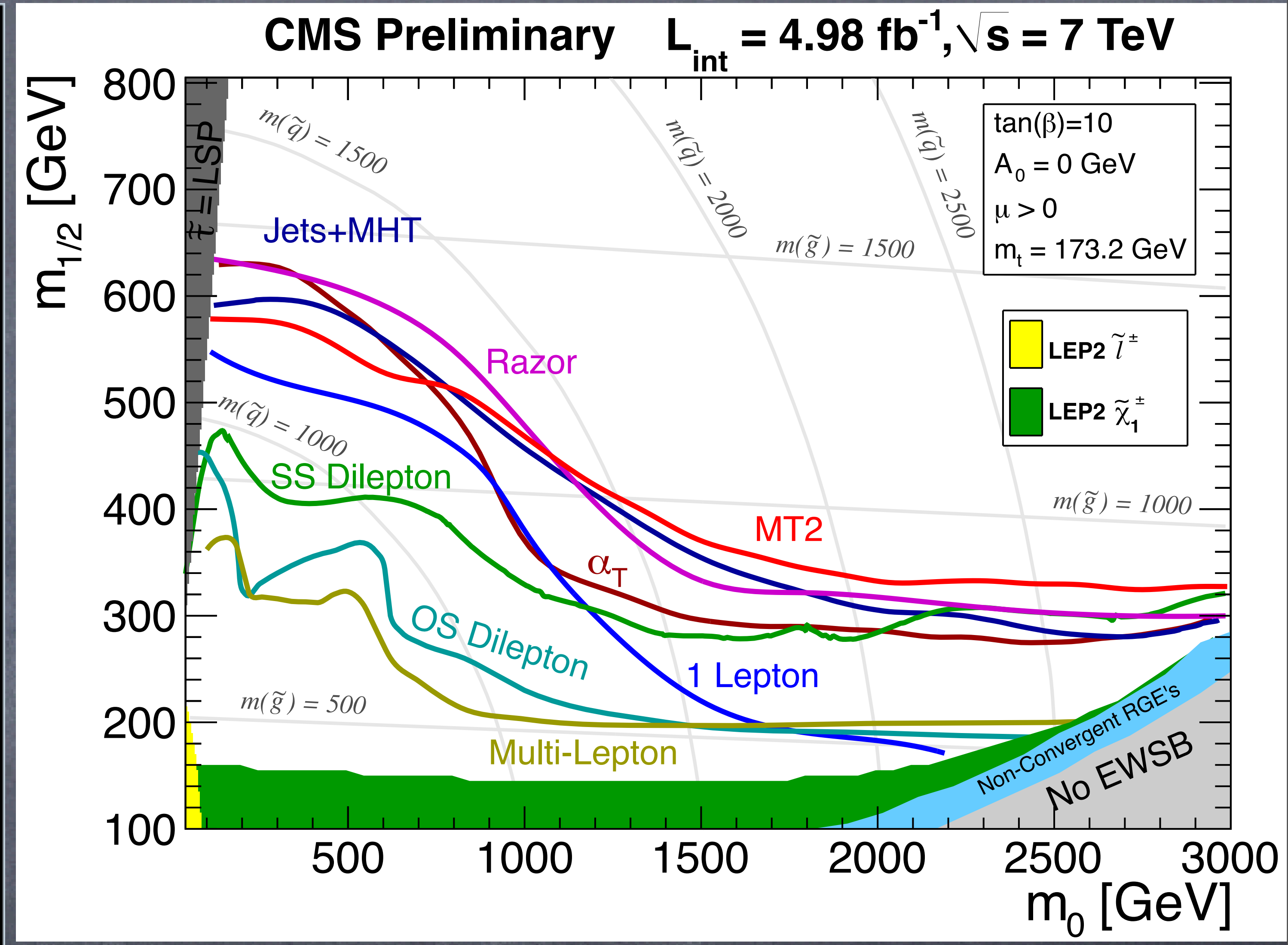
$$m_h \sim 115 - 135 \text{ GeV}$$

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

m(h) falls squarely within narrow range
predicted by MSSM:
confirms SUSY prediction!

What about search for sparticles at LHC?





Atlas/CMS: no sign of mSUGRA at LHC7/LHC8

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

This result seemingly exacerbates the
"Little Hierarchy Problem":
how do TeV-scale SUSY
parameters conspire to give
m(Z) of just 91.2 GeV?

To check: calculate Z mass in SUSY:

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

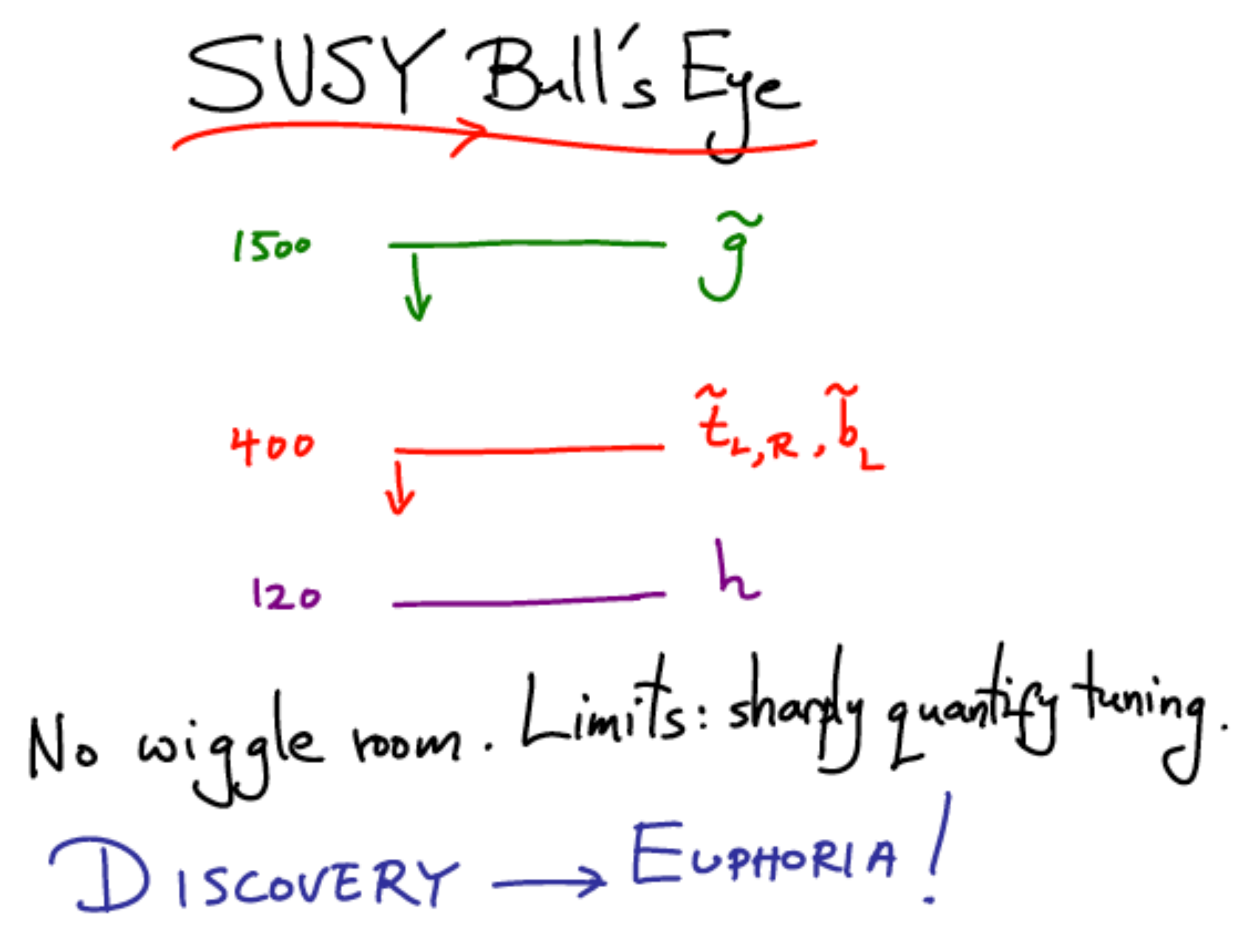
Simplest measure of electroweak finetuning

$$\Delta_{\rm EW} \equiv max(C_i)/(M_Z^2/2)$$

The remaining regions of mSUGRA/CMSSM
have high EWFT: excluded?

Natural SUSY

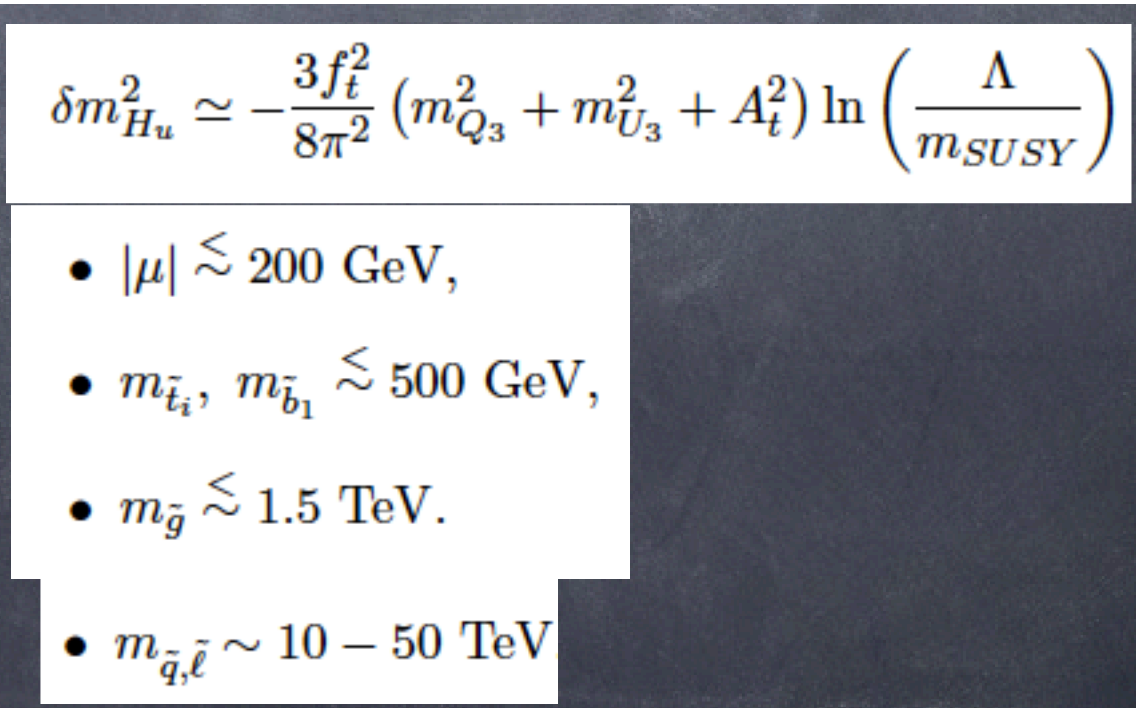
- Ellis, Enqvist, Nanopoulos, Zwirner
- Barbieri-Giudice
- Chan-Chatto-Nath (mu as FT measure)
- Feng-Matchev-Moroi (FP region)
- Kitano-Nomura (natural SUSY)
- HB, Barger, Huang (only mu is small)
- Arkani-Hamed; Brust et al.; Pappucci et al. (Fall 2011)



SUSY Bull's Eye

No wiggle room. Limits: sharply quantify tuning.

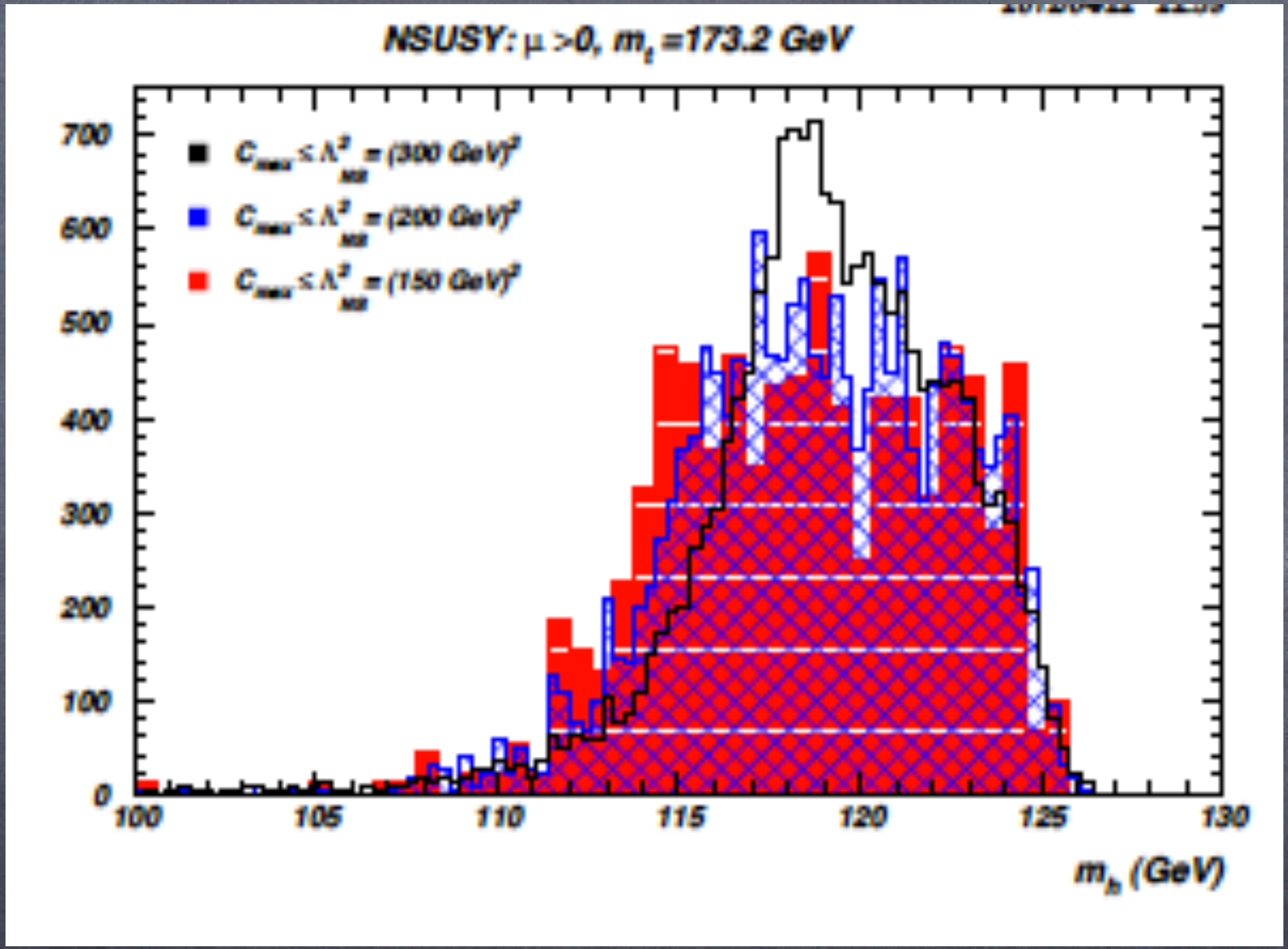
DISCOVERY → EUPHORIA!



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

- $|\mu| \lesssim 200$ GeV,
- $m_{\tilde{t}_i},\ m_{\tilde{b}_1} \lesssim 500$ GeV,
- $m_{\tilde{g}} \lesssim 1.5$ TeV.
- $m_{\tilde{q},\tilde{\ell}} \sim 10 - 50$ TeV

m(h)~125 GeV is problem for natural SUSY:



stops are too light to give m(h)~125 GeV

Further problems for NS:

- large contributions to BF(b->s gamma)
- no signal for t1,t2,b1 at LHC (so far)
- CDM is 10-15 too low for thermally produced lightest higgsinos

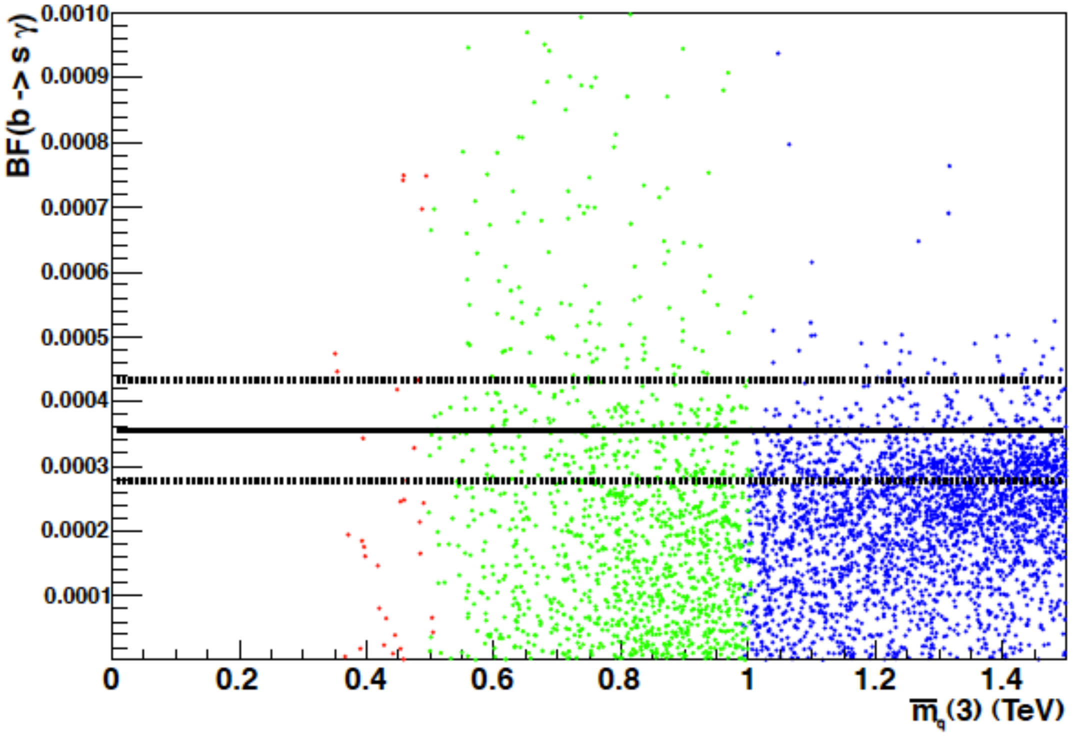


Figure 3: Predicted values of the branching fraction for $b \to s\gamma$ vs. $\overline{m}_{\tilde{q}}(3)$. We also show the experimentally determined central value $\pm 3\sigma$ band for the $BF(b \to s\gamma)$.

Howard Baer[a], Vernon Barger[b], Peisi Huang[b] and Xerxes Tata[c]

Radiative Natural SUSY

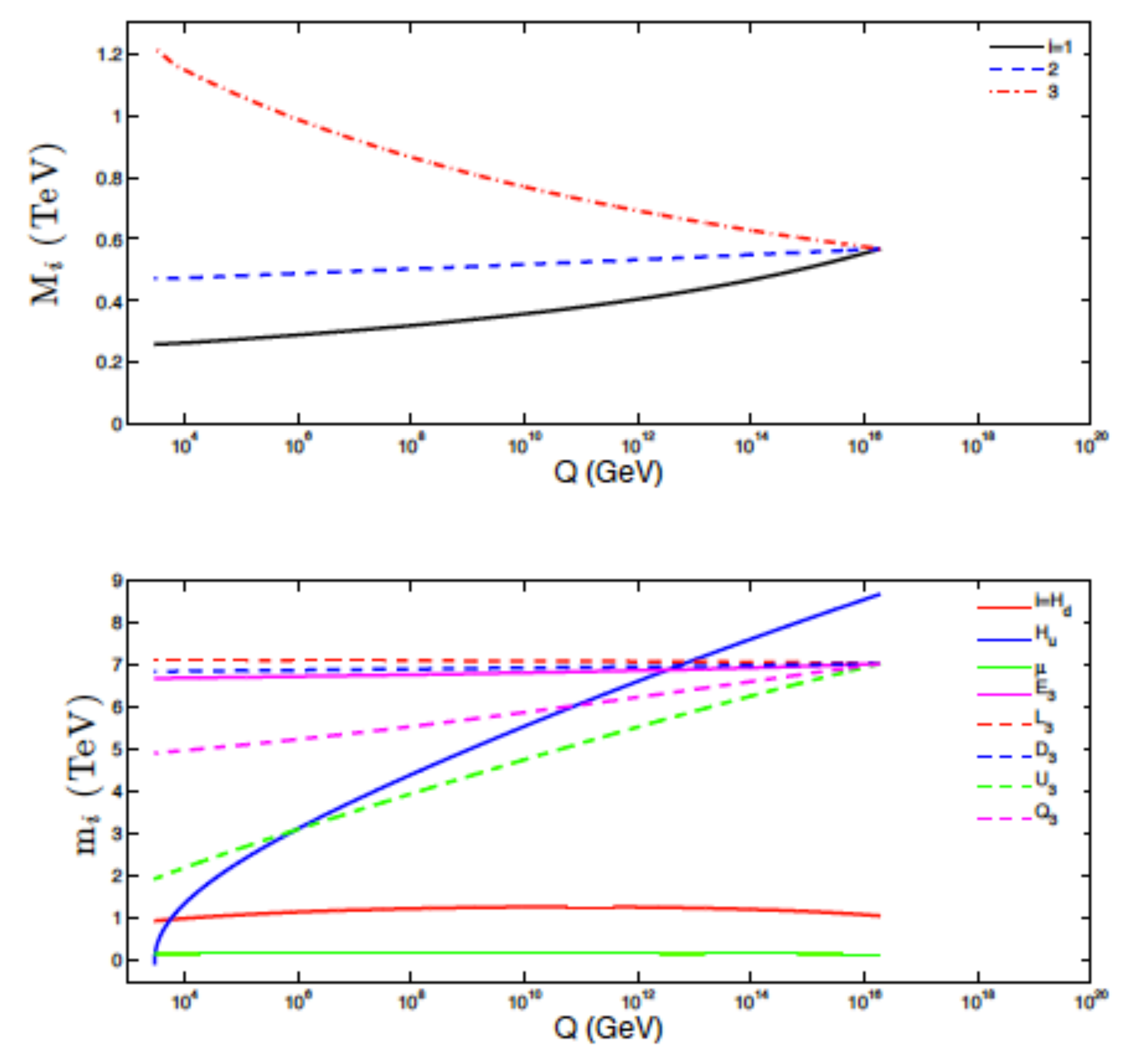
(can be realized in NUHM2 but not mSUGRA)

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A$$

- Step 1: low mu as expected from Giudice-Masiero solution to mu problem

$$\mu \sim \lambda m_{3/2}$$

- Step 2: Allow for small mHu^2 via non-universal Higgs model (NUHM2)
- natural large cancellation in mHu^2 due to large top mass: as in radiative EWSB



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

Next: tamp down radiative corrections

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

The largest of the Σ_u^u almost always come from top squarks, where we find

$$\Sigma_u^u(\tilde t_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde t_{1,2}}^2) \times \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} x_W)\Delta_t}{m_{\tilde t_2}^2 - m_{\tilde t_1}^2} \right]$$

where $\Delta_t = (m_{\tilde t_L}^2 - m_{\tilde t_R}^2)/2 + m_Z^2 \cos 2\beta (\frac{1}{4} - \frac{2}{3} x_W)$, $g_Z^2 = (g^2 + g'^2)/8$, $x_W \equiv \sin^2\theta_W$

$$F(m^2) = m^2 \left(\log(m^2/Q^2) - 1\right)$$

there is a suppression of $\Sigma_u^u(\tilde t_1)$ due to a cancellation between terms

the square brackets of Eq. (3.2). For the $\tilde t_2$ contribution, a large splitting between $m_{\tilde t_2}$ and $m_{\tilde t_1}$ yields a large cancellation within $F(m_{\tilde t_2}^2)$ where $\left(\log(m_{\tilde t_2}^2/Q^2) \to \log(m_{\tilde t_2}/m_{\tilde t_1}) \to 1\right)$ for $Q^2 \simeq m_{\tilde t_1} m_{\tilde t_2}$, leading also to suppression. So while large $|A_t|$ values suppress both top

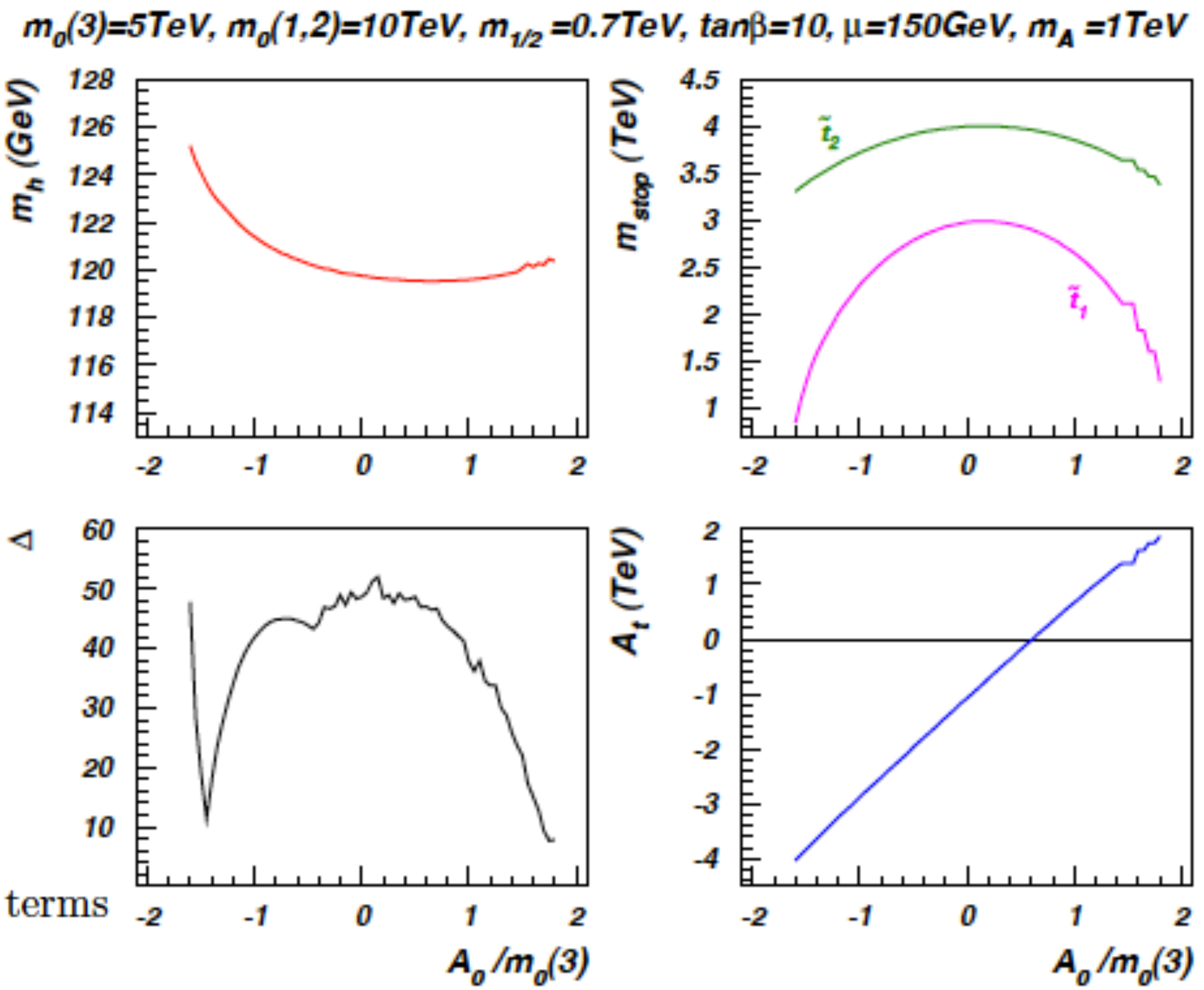
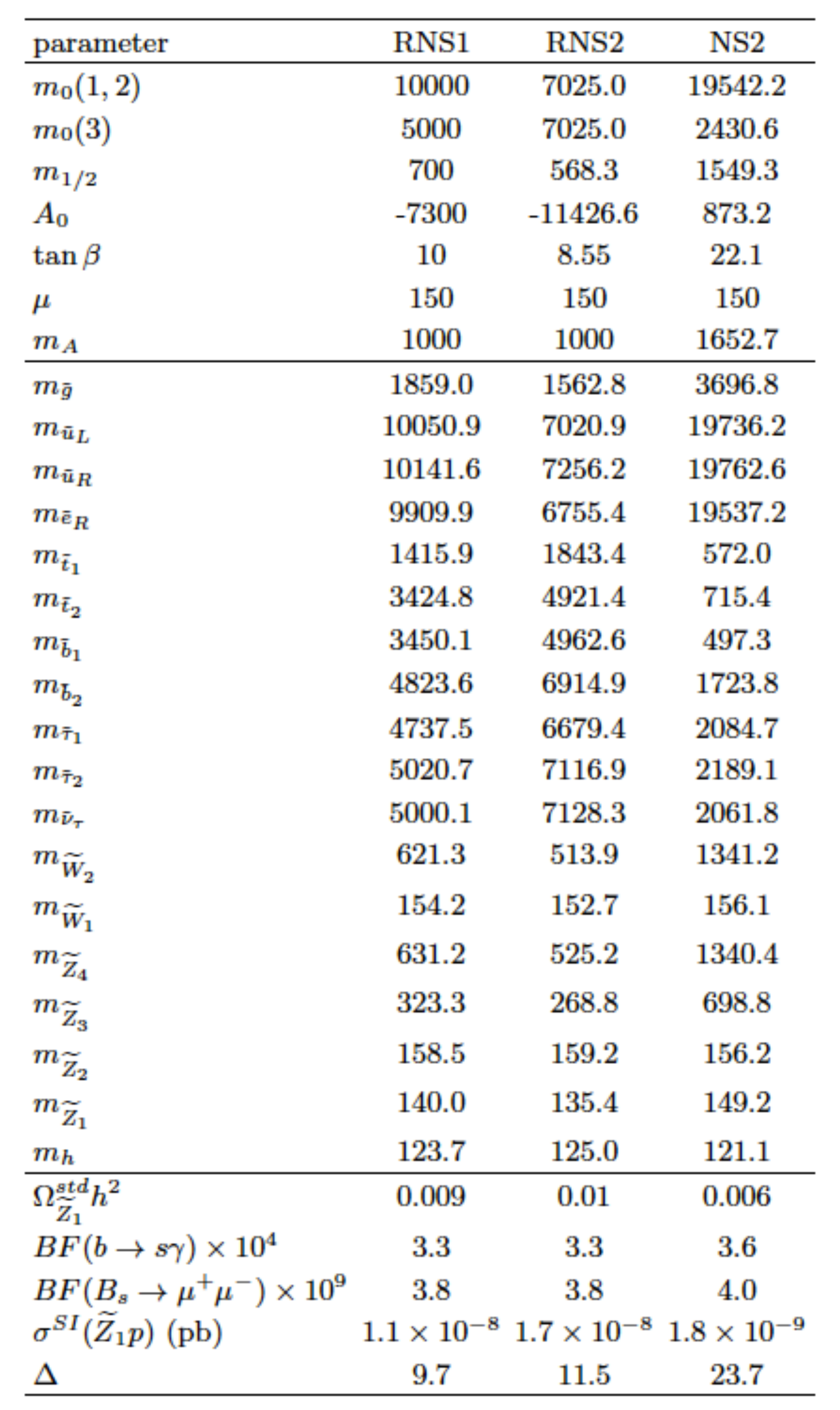


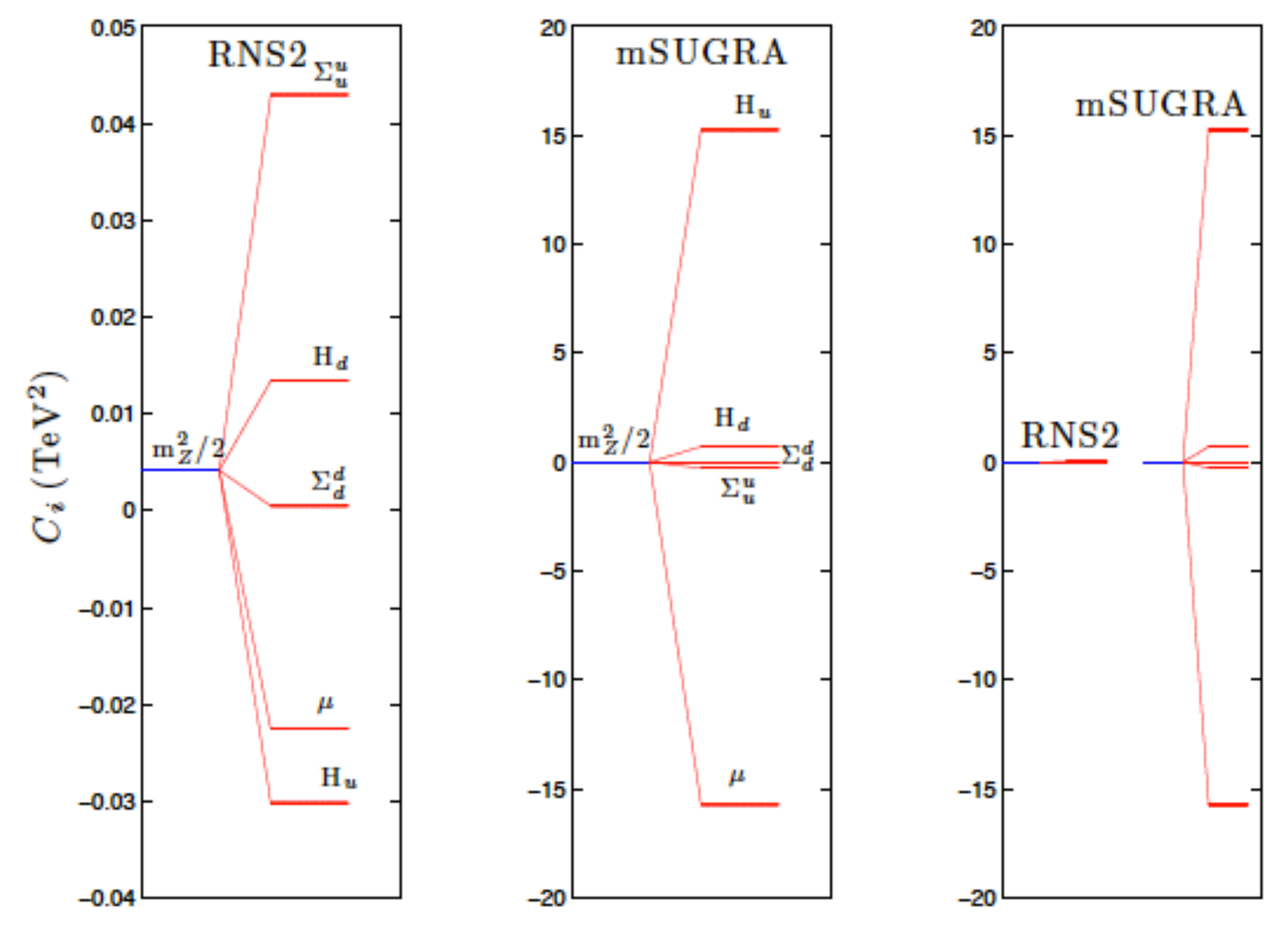
FIG. 1: Plot of *a*). m_h, *b*). $m_{\tilde t_{1,2}}$, *c*). Δ and *d*). A_t versus variation in A_0 for a model with $m_0(1,2) = 10$ TeV, $m_0(3) = 5$ TeV, $m_{1/2} = 700$ GeV, $\tan\beta = 10$ and $\mu = 150$ GeV and $m_A = 1$ TeV.

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

Compulsory 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



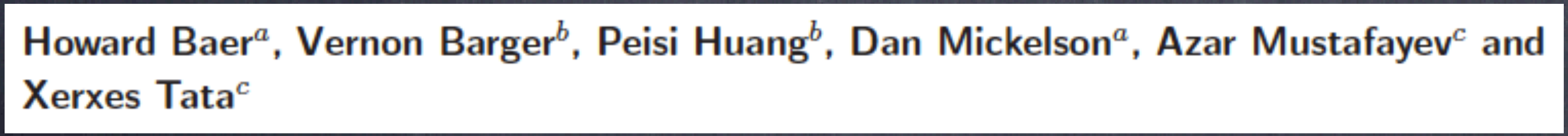
Contributions to EWFT:

RNS vs. mSUGRA

Resolution of Little Hierarchy Problem from Radiative Natural SUSY:

Why are m(Z) and m(h)~100 GeV
when the SUSY breaking scale
m_3/2 is ~10-30 TeV?

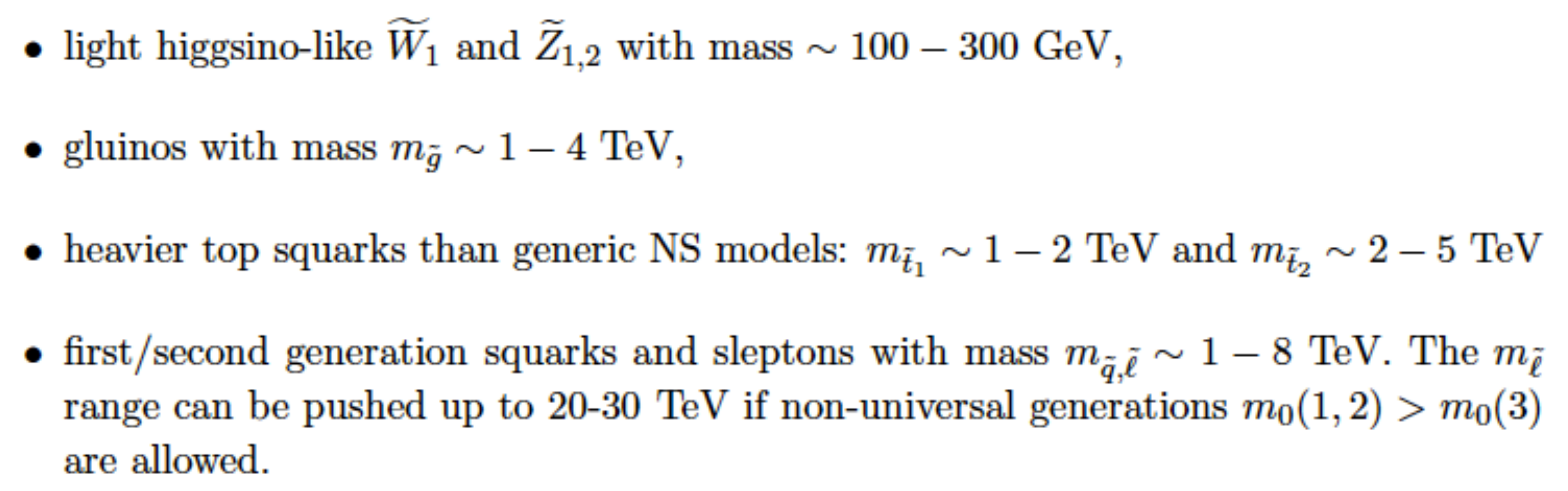
Because the top quark mass
is 173 GeV!



Howard Baer[a], Vernon Barger[b], Peisi Huang[b], Dan Mickelson[a], Azar Mustafayev[c] and Xerxes Tata[c]

PRL109 (2012) 161802 and arXiv:1212.2655

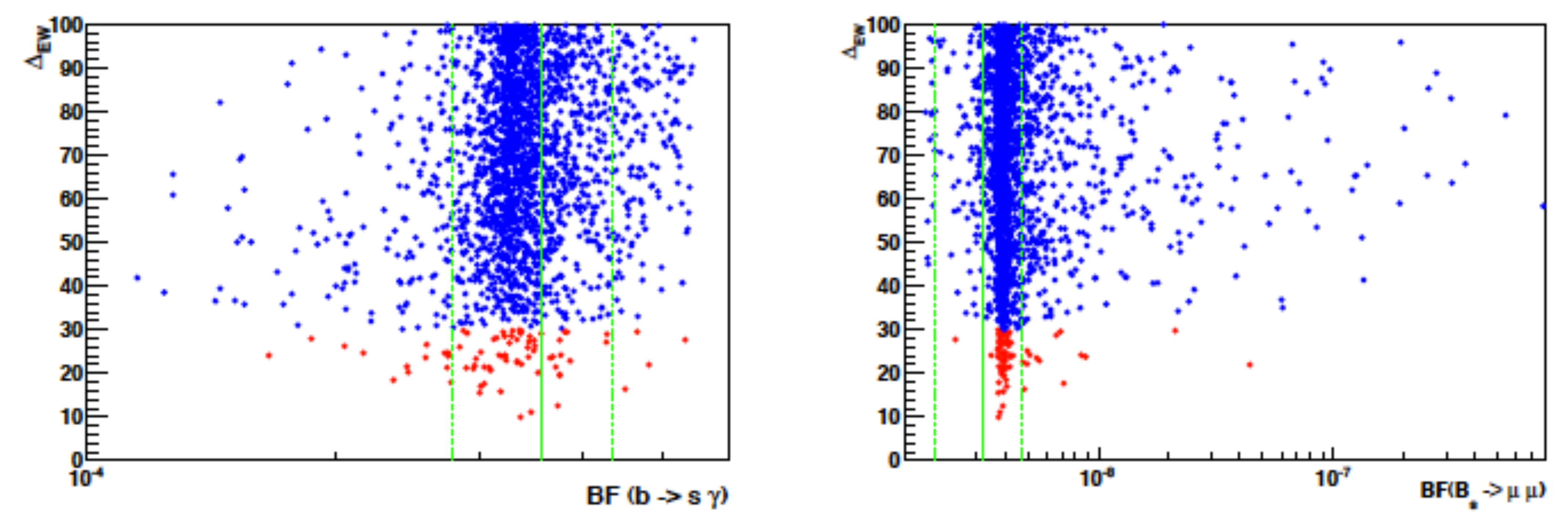
Typical spectra from radiative NS:



- light higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_{1,2}$ with mass $\sim 100 - 300$ GeV,
- gluinos with mass $m_{\tilde{g}} \sim 1 - 4$ TeV,
- heavier top squarks than generic NS models: $m_{\tilde{t}_1} \sim 1 - 2$ TeV and $m_{\tilde{t}_2} \sim 2 - 5$ TeV
- first/second generation squarks and sleptons with mass $m_{\tilde{q},\tilde{\ell}} \sim 1 - 8$ TeV. The $m_{\tilde{\ell}}$ range can be pushed up to 20-30 TeV if non-universal generations $m_0(1,2) > m_0(3)$ are allowed.

Differences from generic NS models:
heavier t1, t2, b1, gluino, h

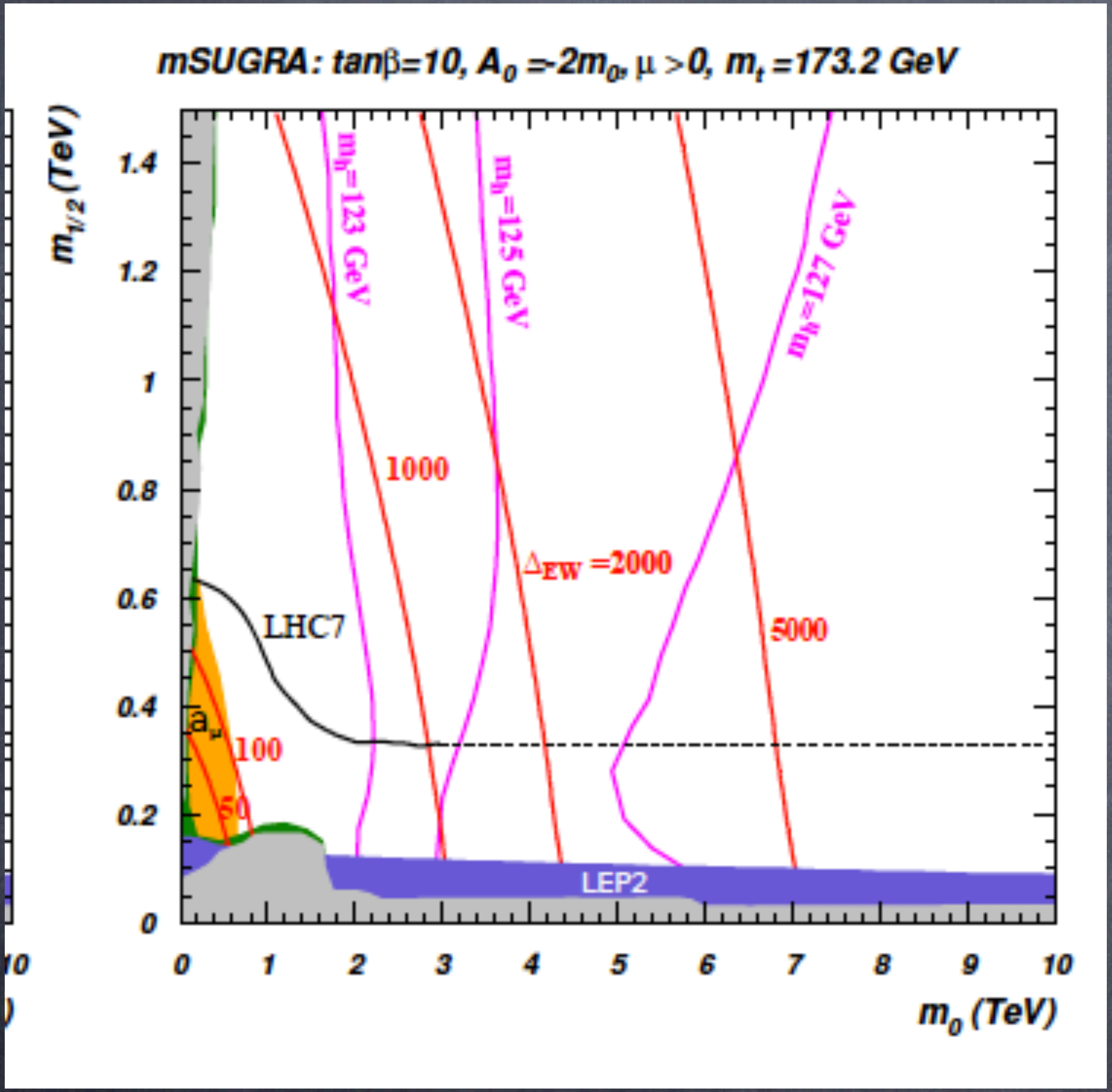
What happens to B-physics constraints?



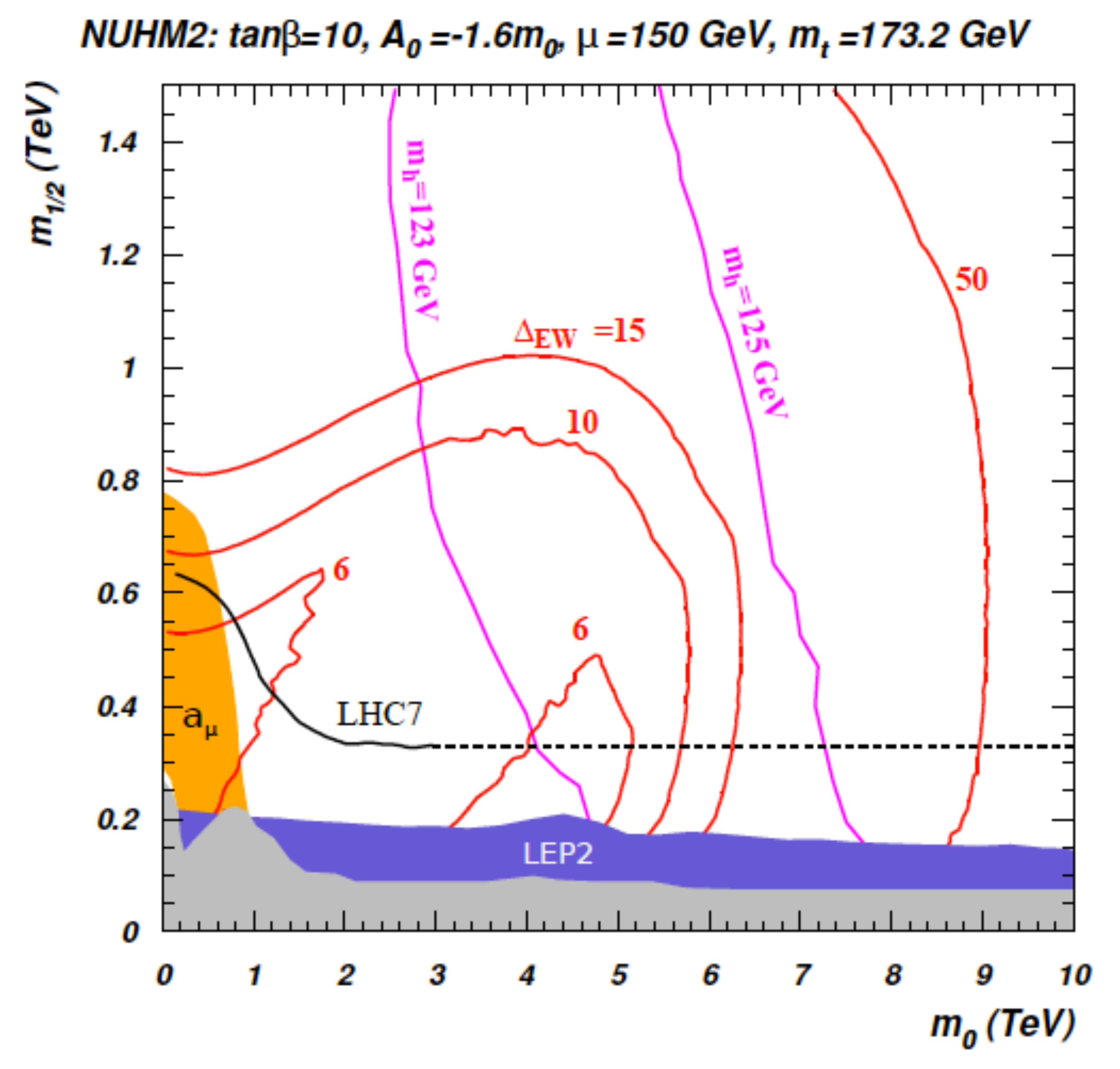
Much better agreement compared to older NS models

Note to LHCb collaboration: SUSY alive and well

What happens to m0 vs. m(1/2) plane?



mSUGRA/CMSSM



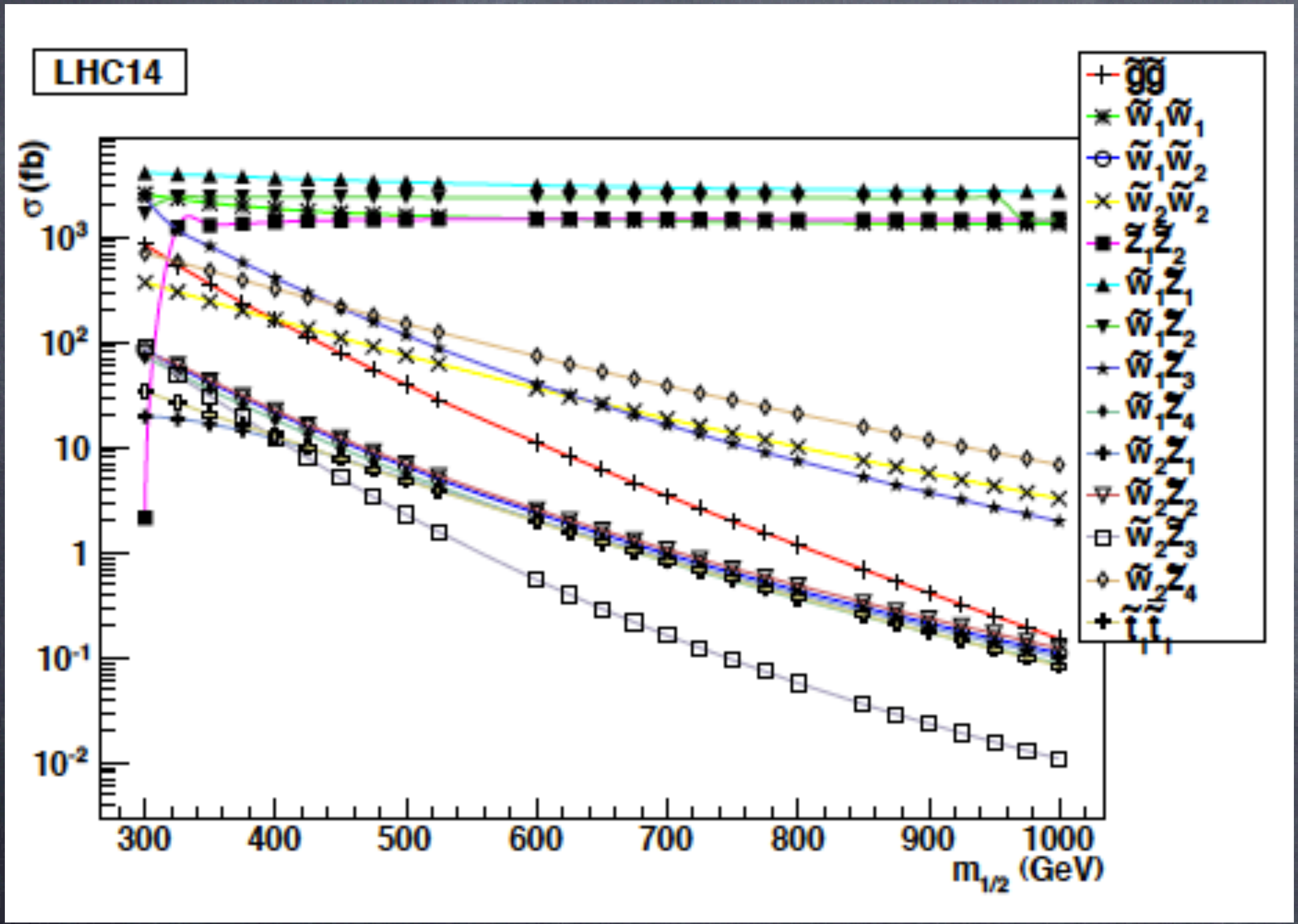
RNS

(no explanation for (g-2)_mu anomaly)

Consequences for LHC

- low mu~100-250 GeV => light higgsinos difficult to see due to small mass gap m(z2)-m(z1), m(w1)-m(z1)~ 10-20 GeV
- squarks ~10-20 TeV but m(gluino)~1-5 TeV: maybe see at LHC but maybe not: reach of LHC14 w/ 100 fb^-1 to m(gl)~1.6 TeV
- new SS diboson signature distinctive of models with light higgsinos: LHC14 reach to m(gl)~2 (2.2) TeV for 100 (300) fb^-1

RNS production cross sections at LHC14

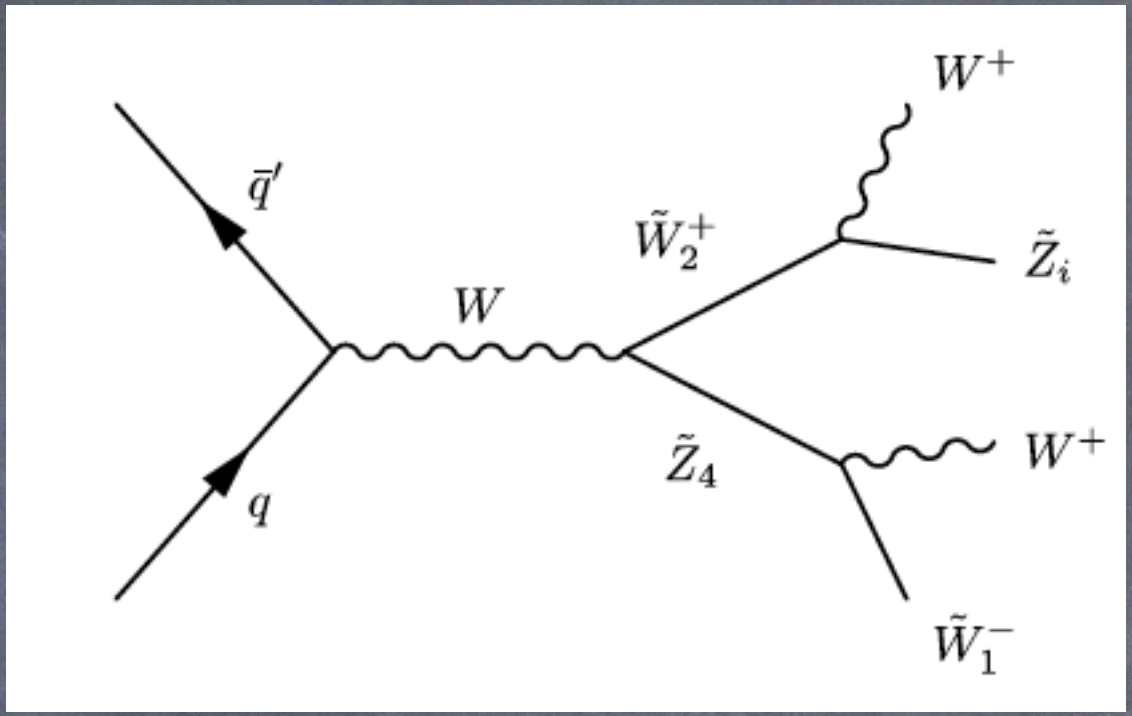


higgsinos

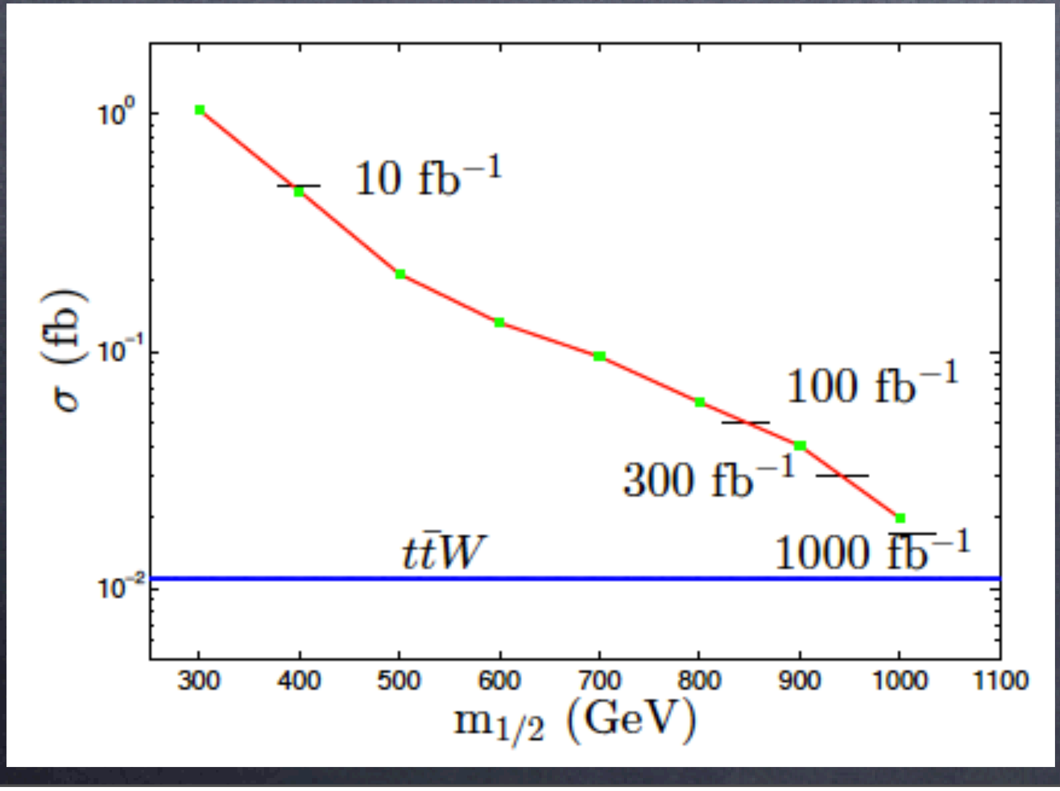
gauginos

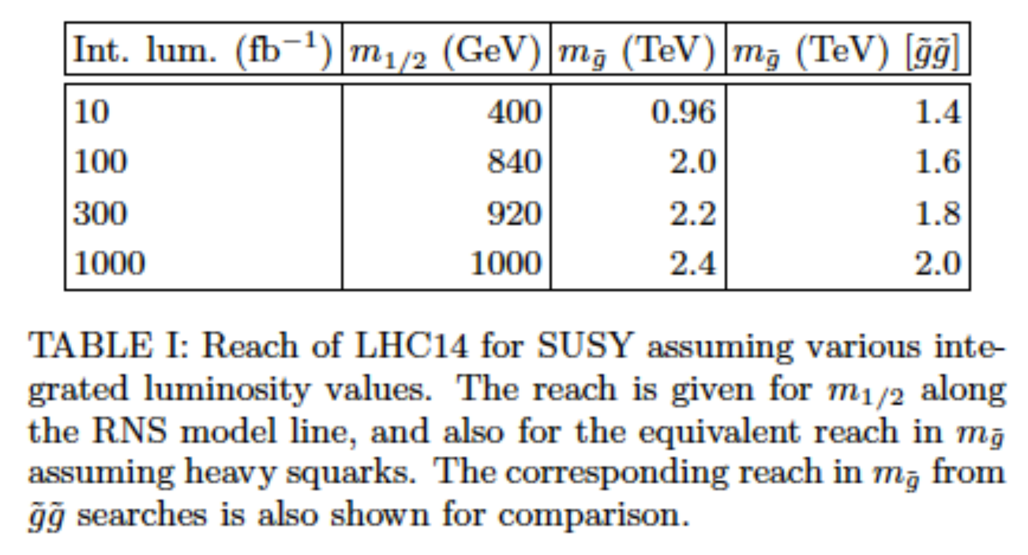
gluinos

SS diboson signature from SUSY with light higgsinos



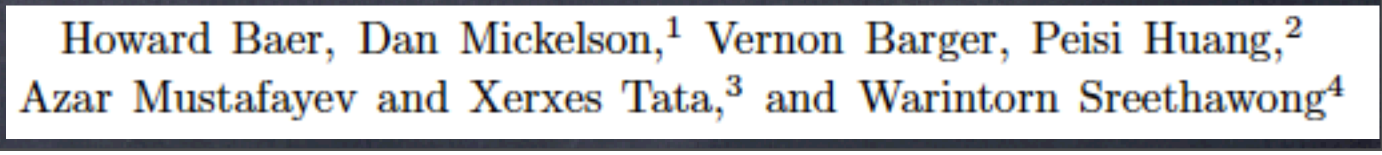
dominant BG: ttW->0.01 fb after cuts





Int. lum. (fb^{-1})	$m_{1/2}$ (GeV)	$m_{\tilde{g}}$ (TeV)	$m_{\tilde{g}}$ (TeV) [$\tilde{g}\tilde{g}$]
10	400	0.96	1.4
100	840	2.0	1.6
300	920	2.2	1.8
1000	1000	2.4	2.0

TABLE I: Reach of LHC14 for SUSY assuming various integrated luminosity values. The reach is given for $m_{1/2}$ along the RNS model line, and also for the equivalent reach in $m_{\tilde{g}}$ assuming heavy squarks. The corresponding reach in $m_{\tilde{g}}$ from $\tilde{g}\tilde{g}$ searches is also shown for comparison.

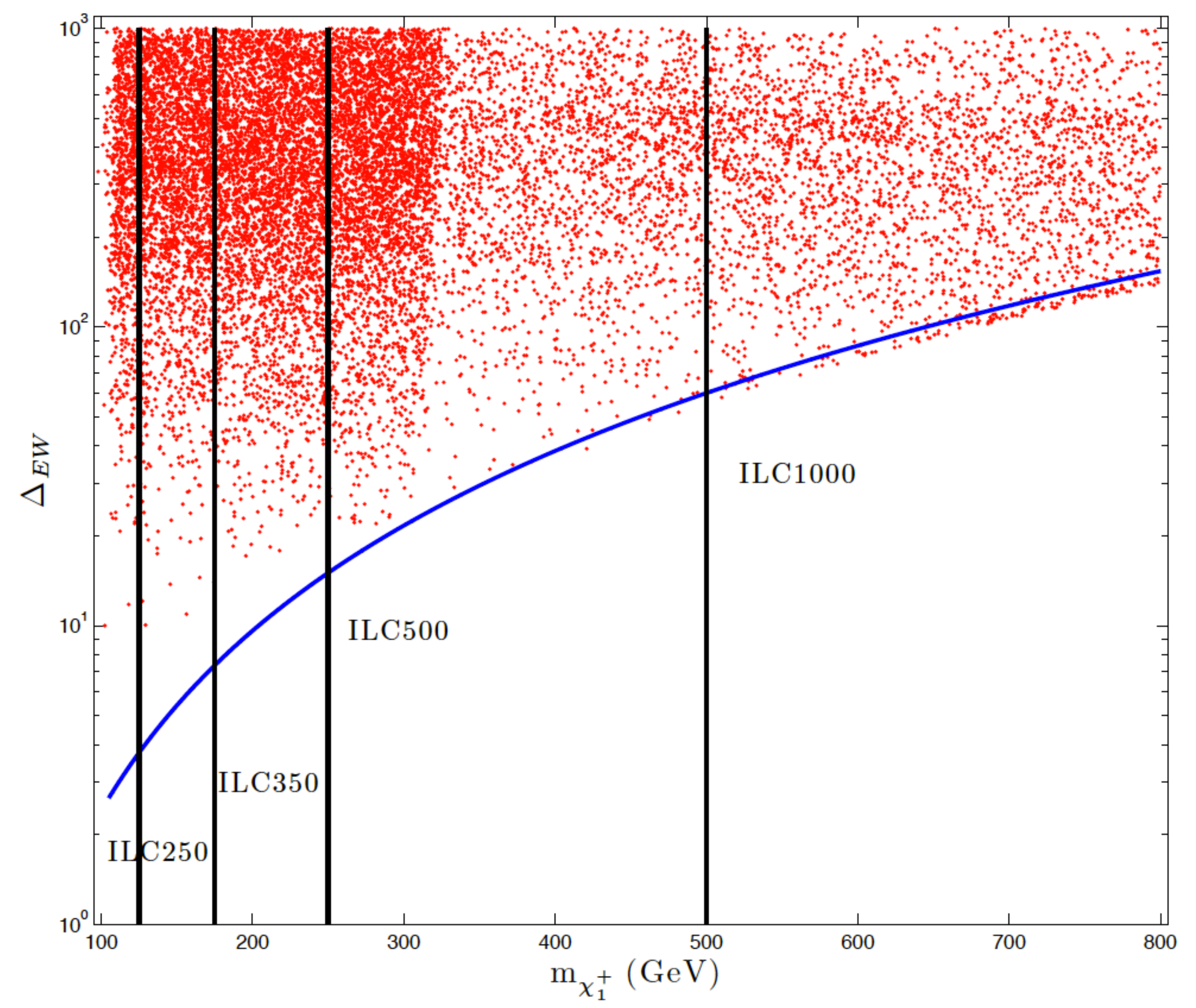


Howard Baer, Dan Mickelson,[1] Vernon Barger, Peisi Huang,[2]
Azar Mustafayev and Xerxes Tata,[3] and Warintorn Sreethawong[4]

Radiative natural SUSY at ILC:

- light higgsinos should be easily visible: directly probe most lucrative parameter space!
- ILC can probe to E=2*mu
- polarization,threshold dependence: detailed characterization of light higgsinos
- ILC would be ``higgsino factory'' in addition to Higgs factory

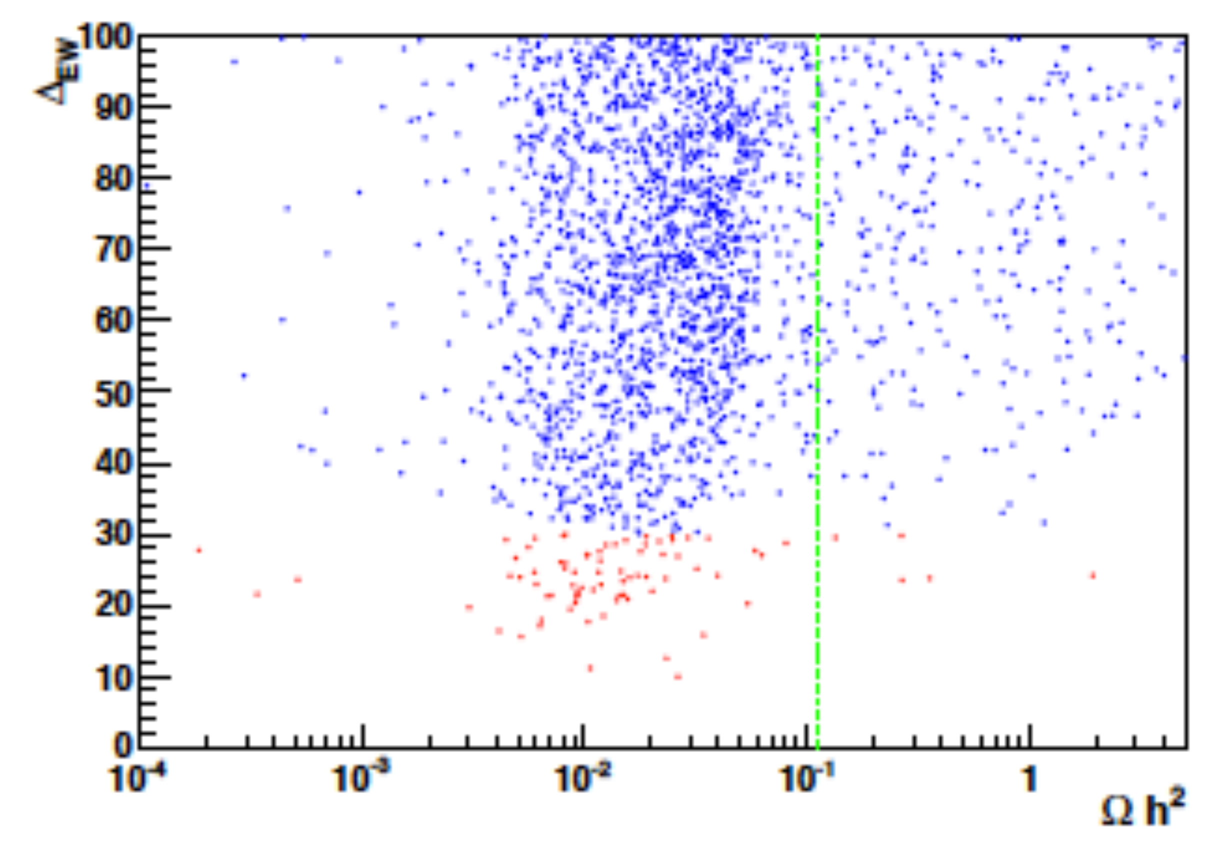
m(higgsino)~m(h)



$$\Delta_{EW} \sim E_{CM}^2/(2m_Z^2)$$

What about higgsinos as cold dark matter?

- Thermal relic abundance usually 10-15 too low
- If we do not ignore strong CP problem, this is a positive result



$$L_{QCD} \supset \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu},$$

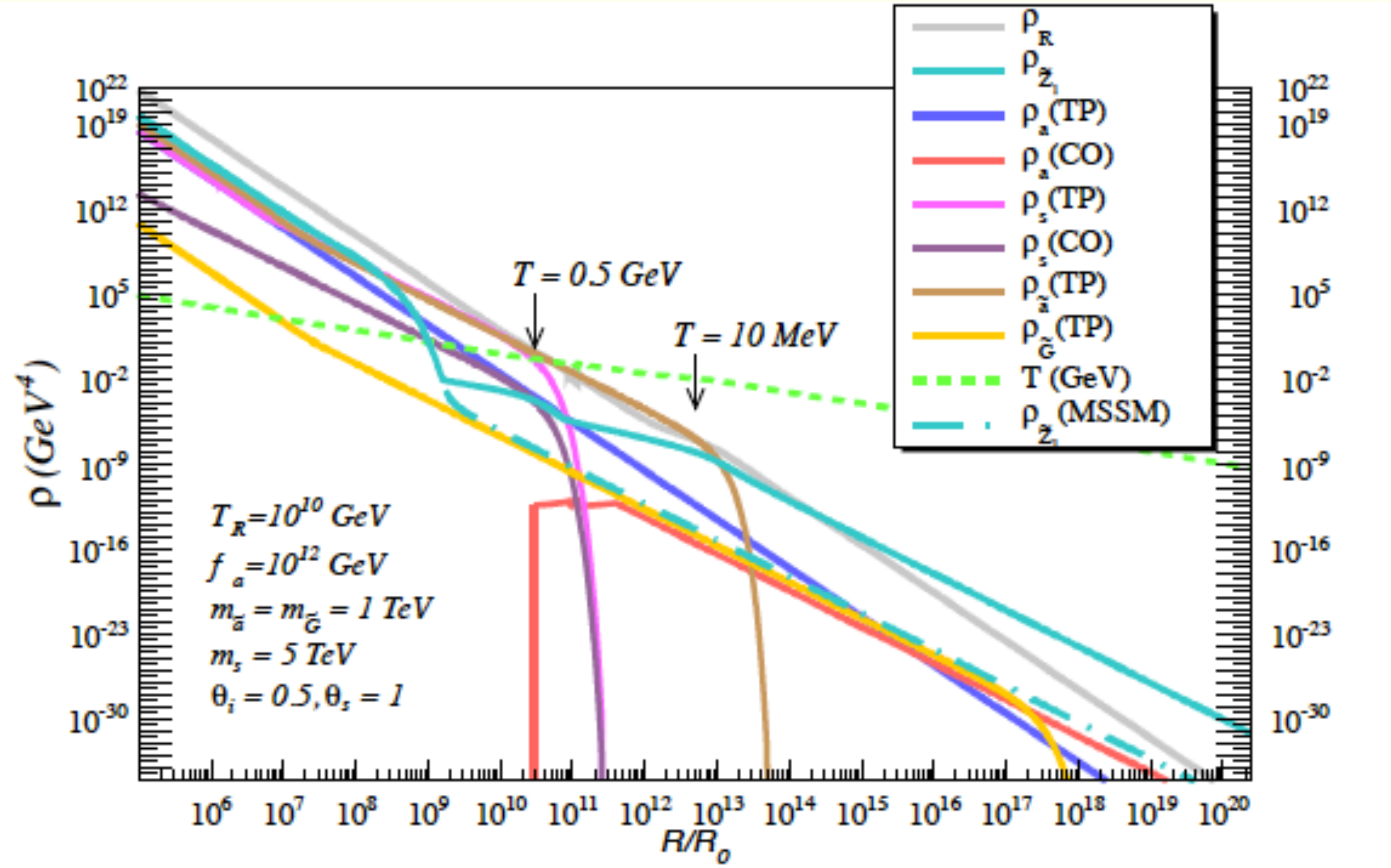
Invoke PQ solution to strong CP: mixed axion-LSP dark matter

PQMSSM: Axions + SUSY $\Rightarrow$ mixed $a - LSP$ dark matter

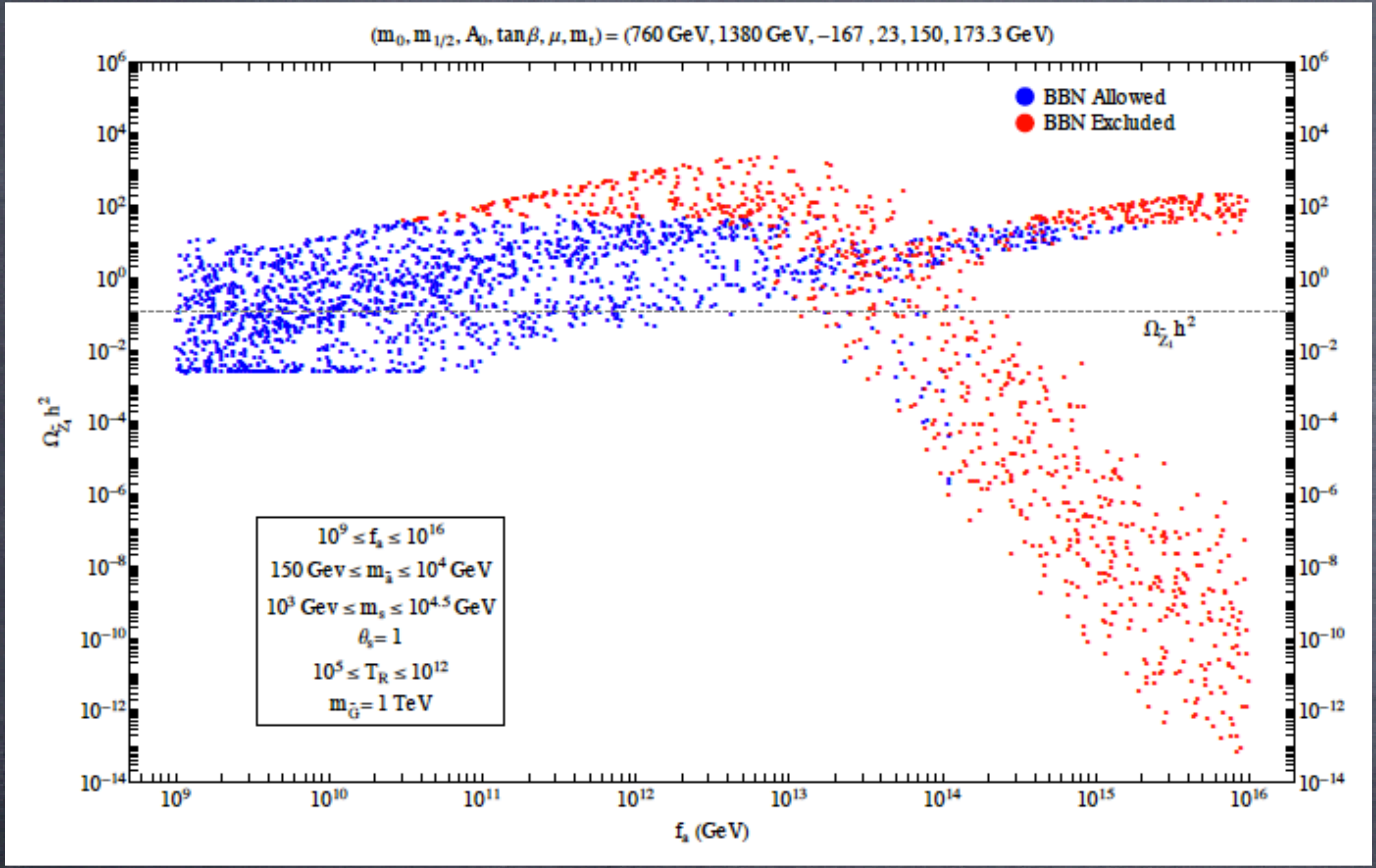
- $\hat{a} = \frac{s+ia}{\sqrt{2}} + i\sqrt{2}\bar{\theta}\tilde{a}_L + i\bar{\theta}\theta_L\mathcal{F}_a$ in 4-comp. notation
- Raby, Nilles, Kim; Rajagopal, Wilczek, Turner
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; possible LSP candidate)
- $m_{\tilde{a}}$ model dependent: keV→ TeV, but $\sim M_{SUSY}$ in gravity mediation
- saxion is spin-0 element: R-even but gets SUSY breaking mass ~ 1 TeV
- axion is usual QCD axion: gets produced via vacuum mis-alignment/ coherent oscillations as usual
- additional PQ parameters: $(f_a,\ m_{\tilde{a}},\ m_s,\ \theta_i,\ \theta_s,\ )$ and T_R

Coupled Boltzmann calculation of mixed $a/bino$ CDM

- Include $\langle\sigma v\rangle(T)$, neutralino production/entropy injection from both axino/saxion decay
- HB, A. Lessa, W. Sreethawong, JCAP**1201**(2012)036
- A. Lessa: Sakurai award 2012 for outstanding theory thesis



Mixed higgsino-axion CDM in radiative natural SUSY



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

(string theorists
take note)

Case for
dominant
s-> gg decay

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

Case for dominant s-> aa decay: contributes to dark radiation

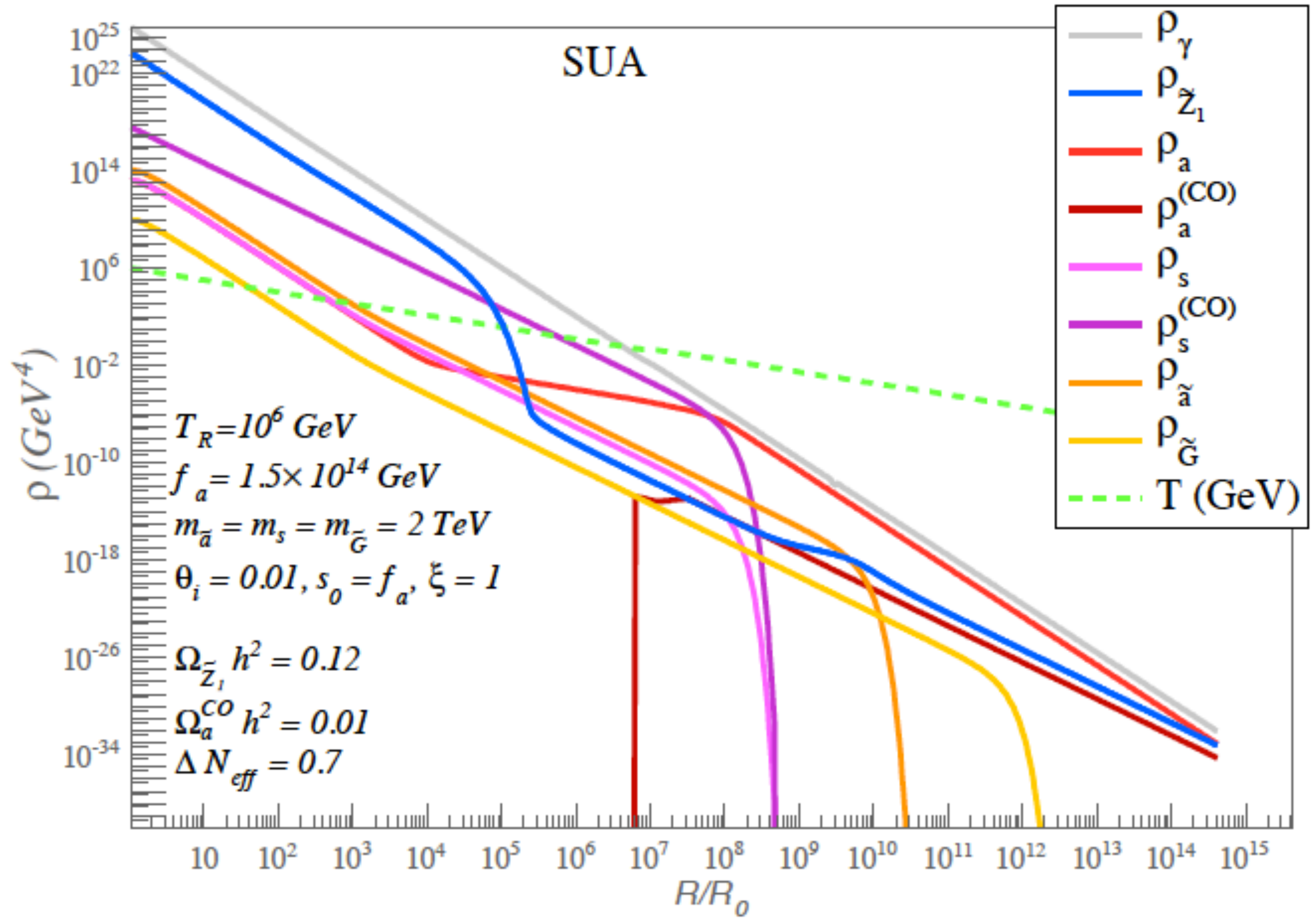
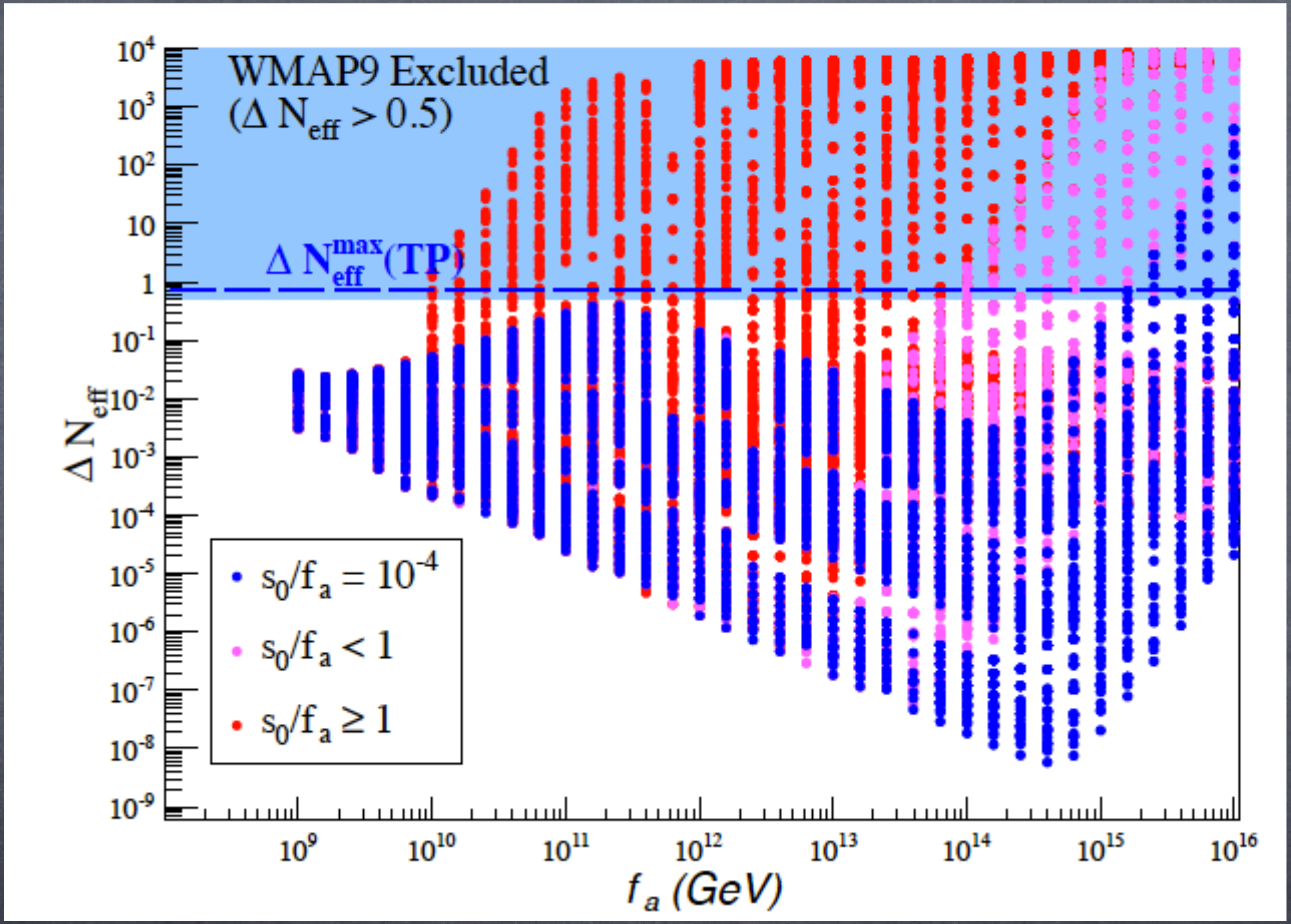


Figure 2: Evolution of various energy densities versus scale parameter R/R_0 for the SUA benchmark.

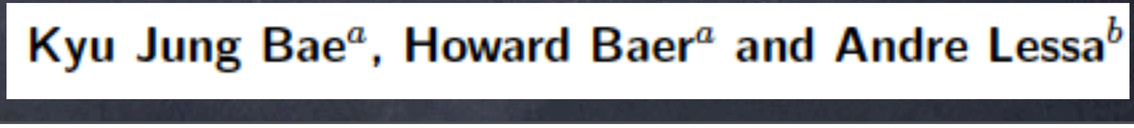
Contribution to ΔN_{eff} from RNS

scan over PQ parameters:

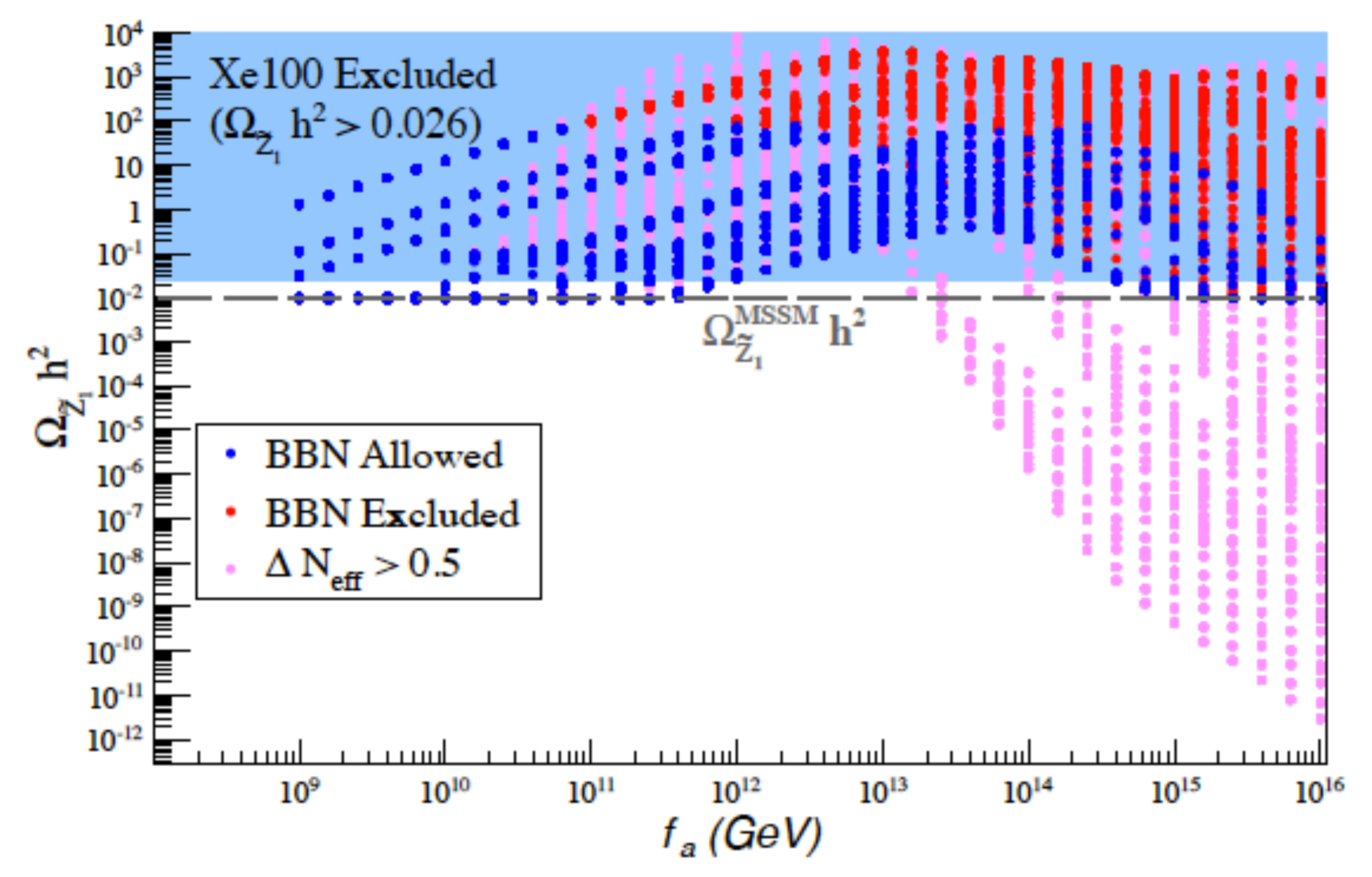


Recent WMAP9 results:
after bug fix 2 days ago

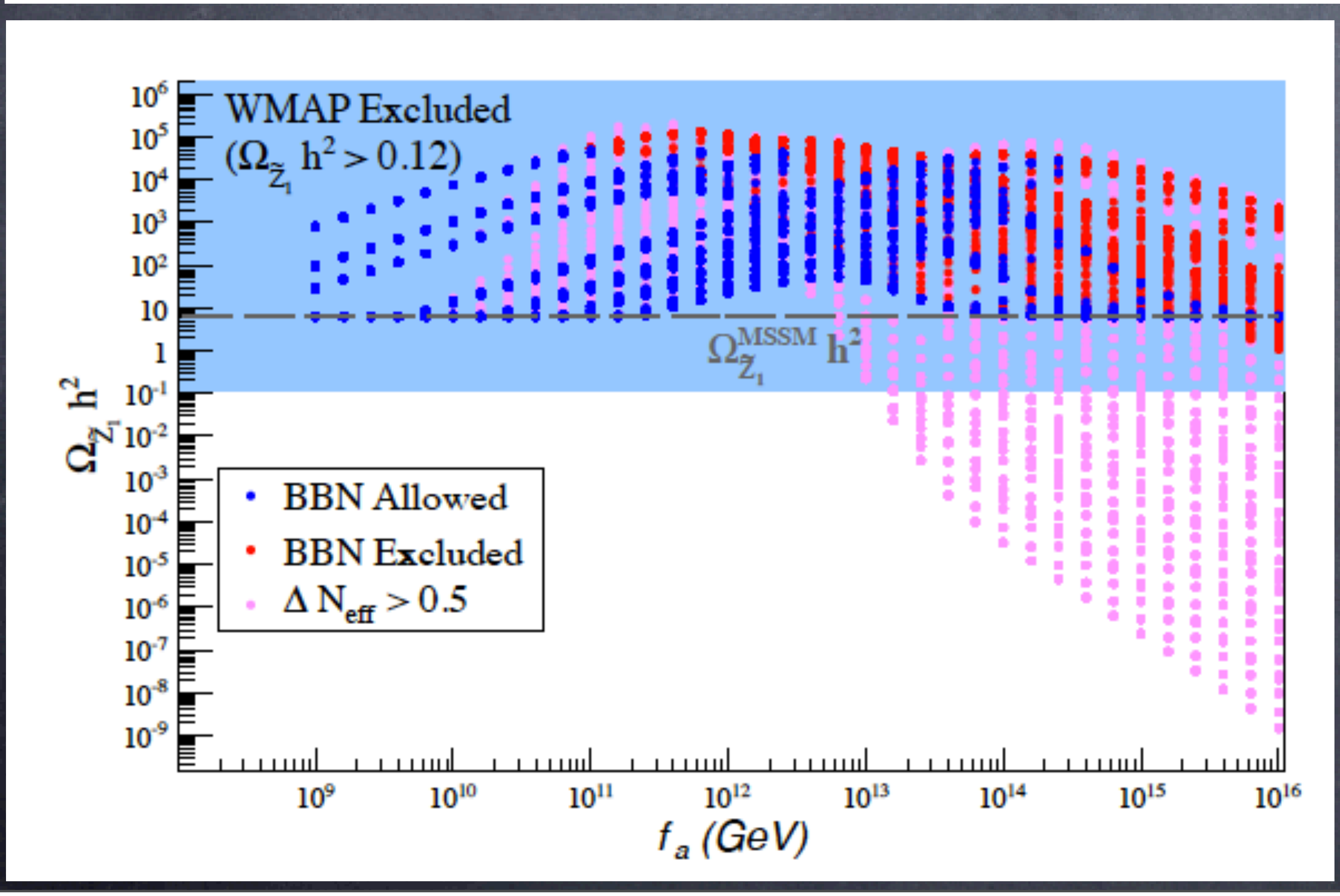
$$N_{eff} = 3.8 \pm 0.4$$



Kyu Jung Bae[a], Howard Baer[a] and Andre Lessa[b]

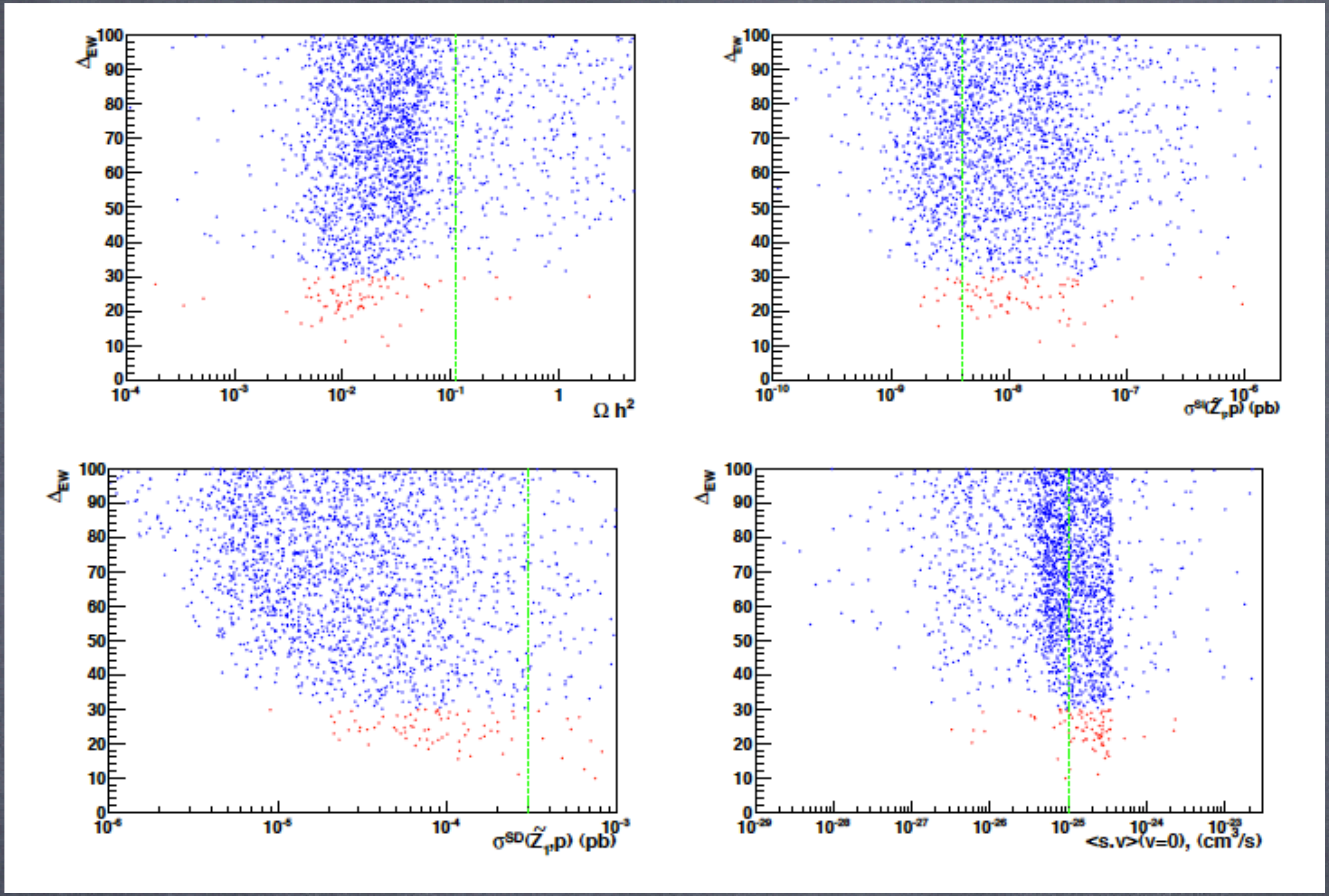


RNS benchmark:
some low/high f_a
survive DM,BBN, DR
constraints:
may find WIMP
and axion!



LHC compatible
overabundance case:
ALL EXCLUDED!

Higgsino-like WIMP searches



Z1 makes up only a fraction of CDM; rest is axions: nonetheless, excellent prospects for WIMP detection; may also detect axion for low f_a but local density may be lower than usually assumed

Example axion-WIMP-collider program of complementarity

(not necessarily time-ordered)

- Discover SUSY @ LHC?: special signatures for higgsino-like LSP: e.g. SS dibosons
- Detailed profile of higgsino-like states determined at ILC: corresponding thermal abundance is Oh2< 0.11
- Discover WIMP: based on direct detection rate for higgsino-like WIMP, determine local WIMP density; lower than expected
- Discover axion if f_a<10^12 GeV; axion local abundance plus WIMP = 0.11

Conclusions:

- SUSY is ``alive and kickin':" better than before
- m(h)=125 and low EWFT-> increase predictivity
- new signals for LHC: SS dibosons
- huge motivation to build ILC/higgsino factory: direct test of SUSY naturalness!
- underabundance of higgsino-like WIMPs just what is needed: room for axions
- test via direct WIMP search: higgsino-like WIMPs not far off, but local abundance < usual
- possibly see axions as well if f_a<10^12 GeV

While bulk of these results were presented
in the case of MSSM with
radiatively driven electroweak naturalness,
the principle phenomenological results are more
general and pertain to almost all SUSY
models with low mu, and light higgsinos which
act as LSP.

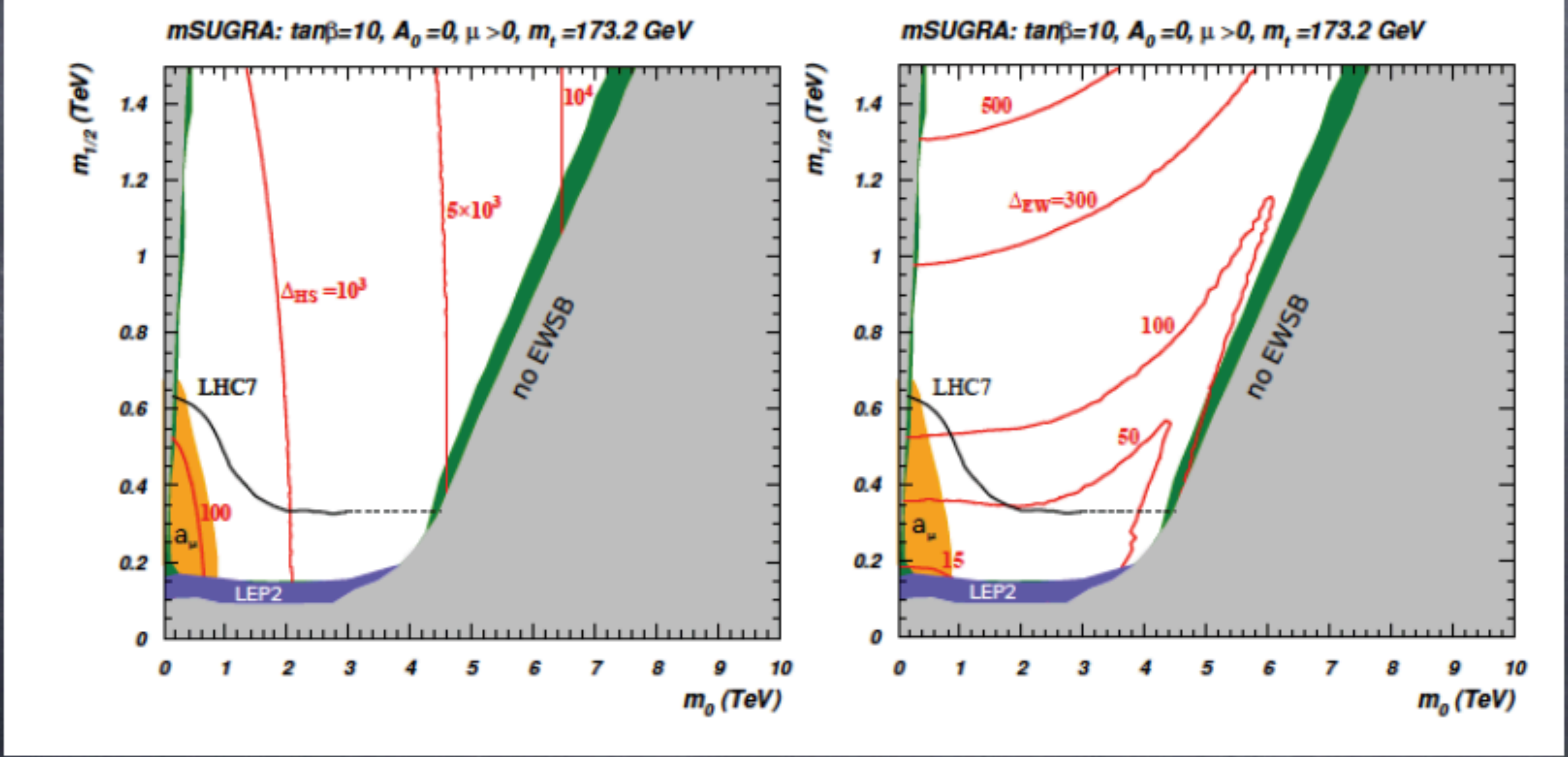
Backup slide

Measure of finetuning:

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

$$\Delta \equiv max_i\,(C_i)\,/(m_Z^2/2) \qquad (2.2)$$

where $C_{H_u} = |-m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)|/$, $C_{H_d} = |m_{H_d}^2/(\tan^2\beta - 1)|/$ and $C_\mu = |-\mu^2|$



weak scale

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

high scale

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