Perspectives on SUSY in the post LHC8 era

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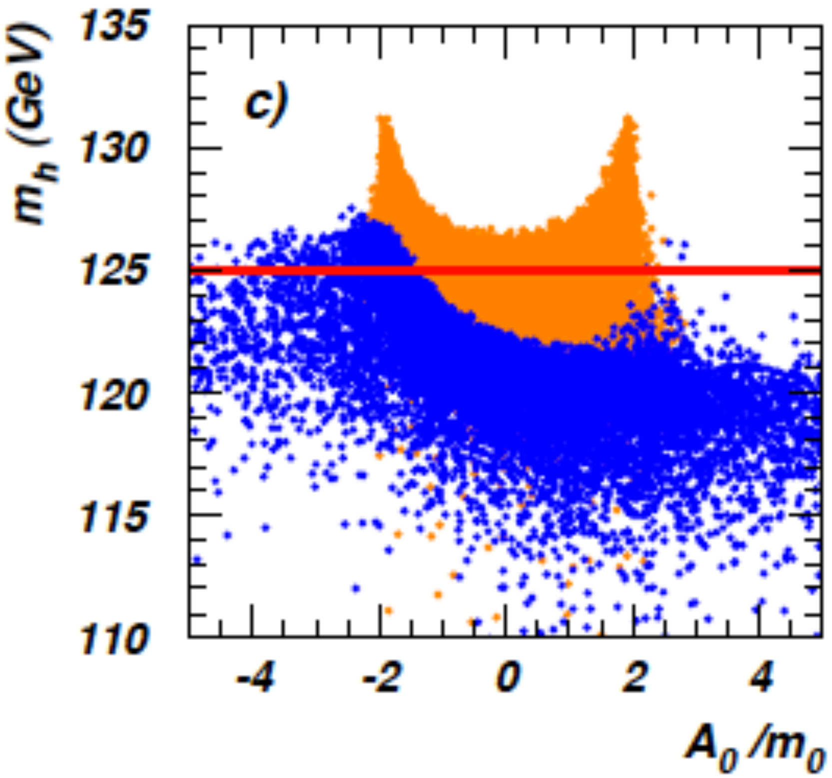
In collaboration with V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong, X. Tata, PRL109(2012)161802, arXiv:1210.3019, arXiv:1212.2655,arXiv:1302.5816; with K. J. Bae and A. Lessa, arXiv:1301.7428

What we learned from LHC7/LHC8

- Higgs-like resonance at ~125 GeV!
- m(h) falls squarely within MSSM window!
- requires: m(t1),m(t2)~ TeV regime
- large mixing
- or else, extra beyond MSSM mass contributions e.g. NMSSM, exotic matter,...



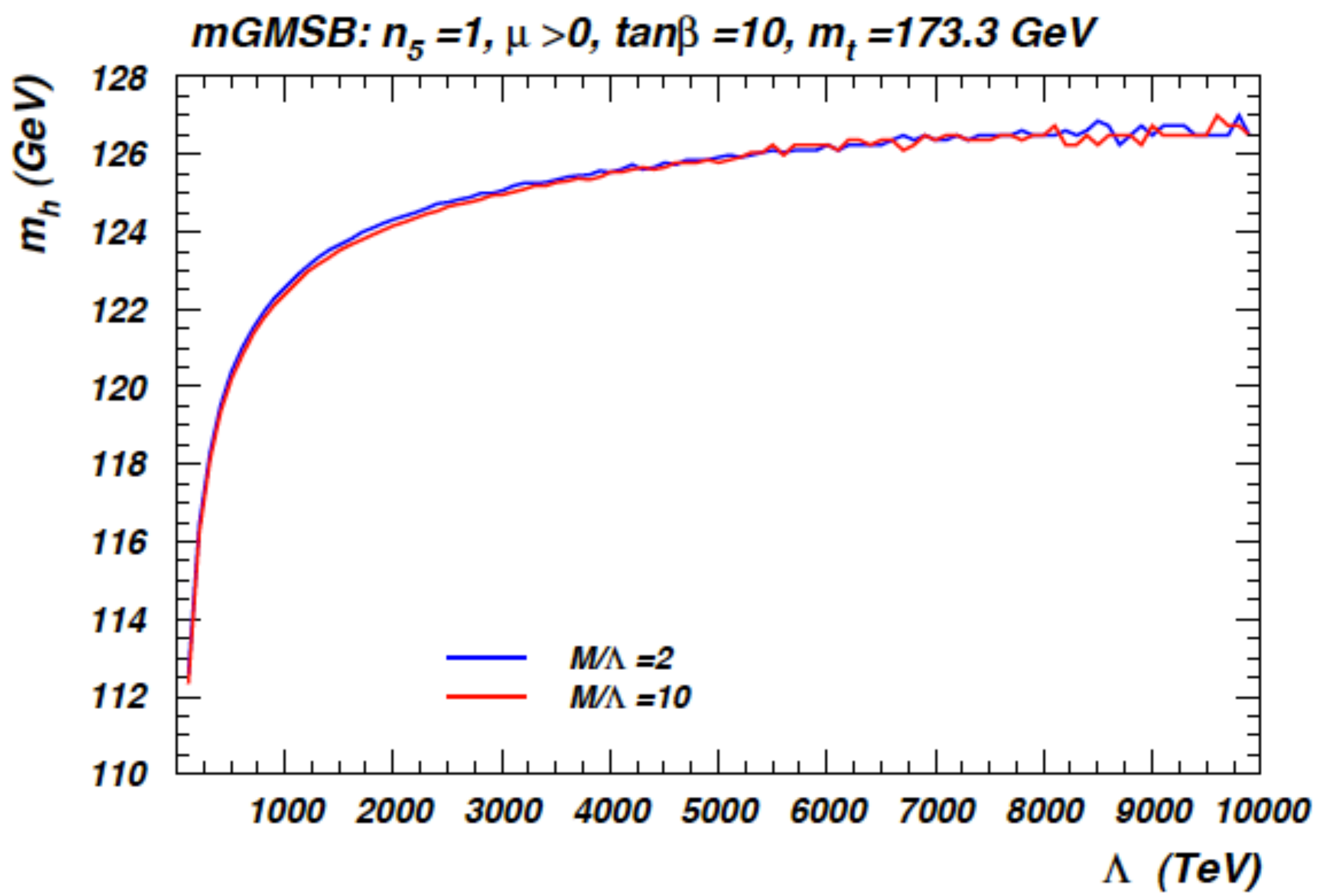
blue:m0<5 TeV
orange: m0<20 TeV

What else?

- No sign of SUSY: in models such as mSUGRA
- $m_{\tilde{q}} \sim m_{\tilde{g}} > 1.4 \text{ TeV or } m_{\tilde{g}} >\sim 1 \text{ TeV if } m_{\tilde{g}} \ll m_{\tilde{q}}$
- Squark mass bound and even more m(h) (which needs m(t1,t2)> TeV) seemingly create tension with naturalness bounds:
- Exacerbates ``little hierarchy problem"
- These results have prompted many groups to reconsider what weak scale SUSY would look like: is it now unlikely or even excluded?

Some old favorites do seem unlikely/excluded

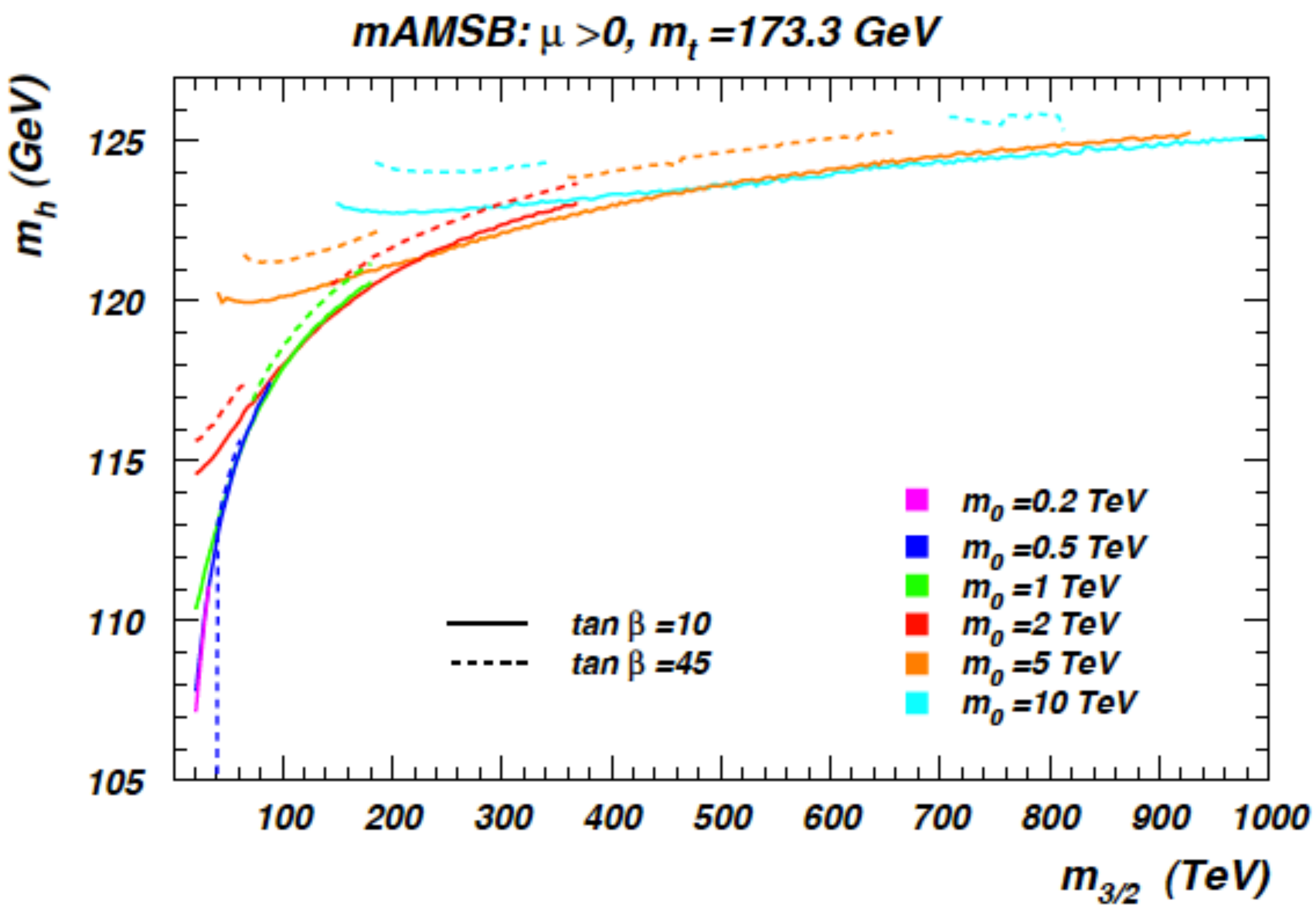
Minimal GMSB:
A~0 makes it difficult to allow m(h)=125 GeV



Need m(gluino)>~ 10 TeV

Go to general GMSB models?

Minimal AMSB: also m(h) problematic



Needs m(gluino)>~10 TeV

successor models: KL, G2MSSM, inoAMSB,MMAMSB

Some reactions from community

- Ignore naturalness: e.g. K-L-O or Kane et al. G2MSSM stringy model with moduli stabilization: scalars ~100 TeV with AMSB-like gauginos and wino=LSP or live far out in mSUGRA plane (note: Kane et al. claim lower mu~.5-1 TeV so maybe not so bad, but still heavy stops)

- natural SUSY ala Kitano-Nomura successor models (Arkani-Hamed, Brust et al., Papucci et al.): these models, couched in MSSM, tend to have m(h)<125 GeV and large deviations to b-> s gamma

- compressed spectra: low energy release from cascade decays to maintain sub-TeV SUSY masses but hide SUSY from LHC

- RPV: similar approach: LSP decays hadronically

- retain naturalness (light stops) but give extra contributions to m(h): NMSSM , vector-like or other exotic matter: model builders delight

- accept some finetuning but try to minimize: HB/FP region of mSUGRA, effective SUSY

- re-examine naturalness

Natural SUSY

Incarnation#1: Kitano-Nomura 2005

$$m_h^2 = |\mu|^2 + m_{H_u}^2|_{\rm tree} + m_{H_u}^2|_{\rm rad},$$

$$m_{H_u}^2|_{\rm rad} \simeq -\frac{3y_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2)\ln\left(\frac{M_{\rm mess}}{m_{\tilde{t}}}\right)$$

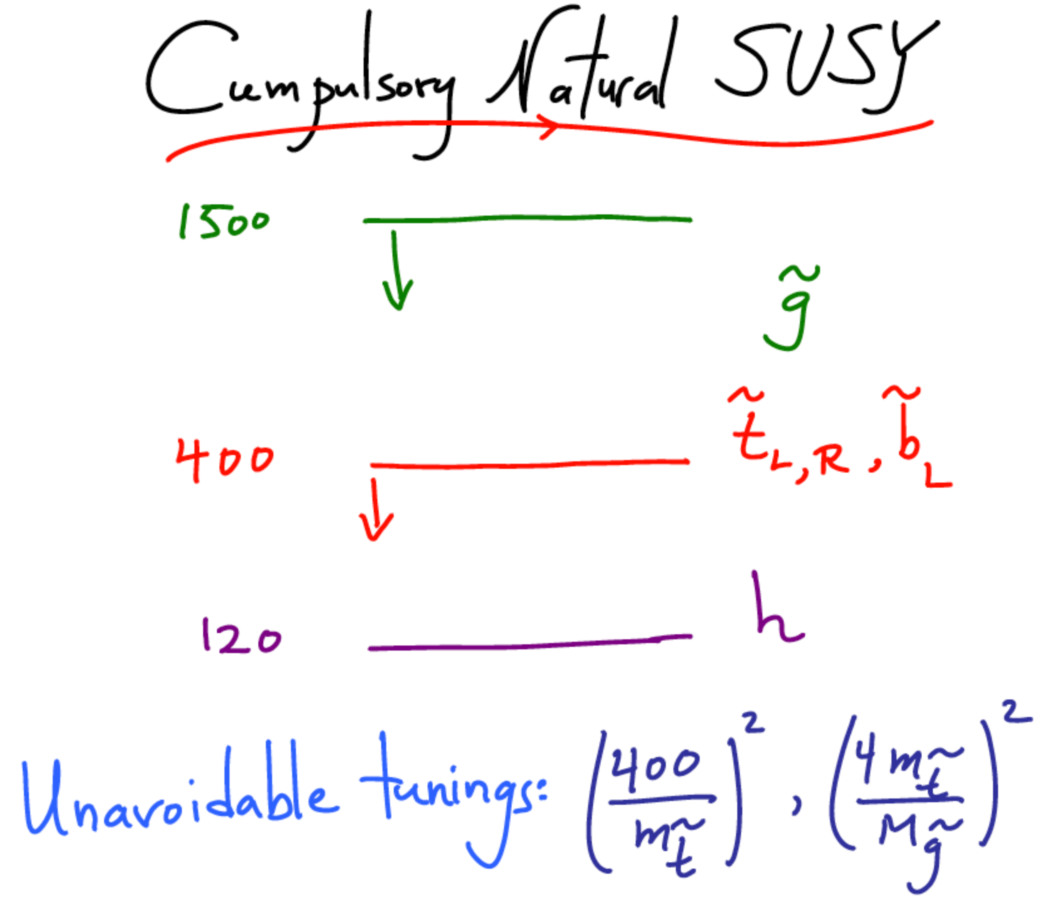
$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$$

$$m_{\tilde{t}}^2 \lesssim \frac{2\pi^2}{3y_t^2}\frac{M_{\rm Higgs}^2}{\left(1+\frac{x^2}{2}\right)\Delta^{-1}\ln\frac{M_{\rm mess}}{m_{\tilde{t}}}} \approx (700\ {\rm GeV})^2\frac{1}{1+\frac{x^2}{2}}\left(\frac{20\%}{\Delta^{-1}}\right)\left(\frac{3}{\ln\frac{M_{\rm mess}}{m_{\tilde{t}}}}\right)\left(\frac{M_{\rm Higgs}}{200\ {\rm GeV}}\right)^2$$

* low mu
* light 3rd generation
* light sub-TeV spectra in pre-LHC era model
* M_mess not too far from TeV; minimize large logs
* sample spectra now highly excluded from LHC/m(h)

NS#2: post LHC7 but pre LHC8/Higgs

- Arkani-Hamed 2011
- Papucci et al.
- Brust et al.
- Essig et al.
- HB, Barger,Huang, Tata
- Wymant
- Arganda et al.



* mu~100-250 GeV

*m(t1,t2,b1)<~500 GeV

* m(gluino<1.5 TeV

m(sq,slep)~10-20 TeV

*m(h)<125 GeV

* BF(b->s gamma) trouble

Re-phase Little Hierarchy problem:

Question: how can it be that
m(Z)=91.2 GeV
while gluino and squark masses sit
at TeV or even
far beyond values?

Simple answer:
the parameters that enter the scalar potential and contribute to m(Z) are all not too far from m(Z)

We shall see that naturally accommodating both m(Z)=91.2 GeV and m(h)=125 GeV are enormously constraining:
SUSY parameter space is not egalitarian but instead these criteria are highly selective!

In MSSM, value of m(Z) determined by combinations of parameters which enter into the scalar potential; minimization leads to a relation between m(Z) and weak scale SUSY parameters:

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

The radiative corrections $\Sigma_u^u,\ \Sigma_d^d$

contain numerous additional terms

minimum and $\tan\beta \equiv v_u/v_d$. At the one-loop level, Σ_u^u contains the contributions $\Sigma_u^u(\tilde{t}_{1,2})$, $\Sigma_u^u(\tilde{b}_{1,2})$, $\Sigma_u^u(\tilde{\tau}_{1,2})$, $\Sigma_u^u(\widetilde{W}_{1,2})$, $\Sigma_u^u(\widetilde{Z}_{1-4})$, $\Sigma_u^u(h,H)$, $\Sigma_u^u(H^\pm)$, $\Sigma_u^u(W^\pm)$, $\Sigma_u^u(Z)$, and $\Sigma_u^u(t)$. Σ_d^d contains similar terms along with $\Sigma_d^d(b)$ and $\Sigma_d^d(\tau)$ while $\Sigma_d^d(t) = 0$ [14].

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

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

Each contribution ~m(Z)

Most important:

low $\Delta_{\rm EW}$ also requires $\mu^2 \sim M_Z^2/2$.

In models such as mSUGRA, mu is determined by m(Z) applied as constraint

here, mu is its own free parameter: NUHM models

Why should mu be so small when m(gl,sq) are so big?

Plausible: in gravity-mediation mu gets its mass differently, e.g. in Giudice-Masiero:

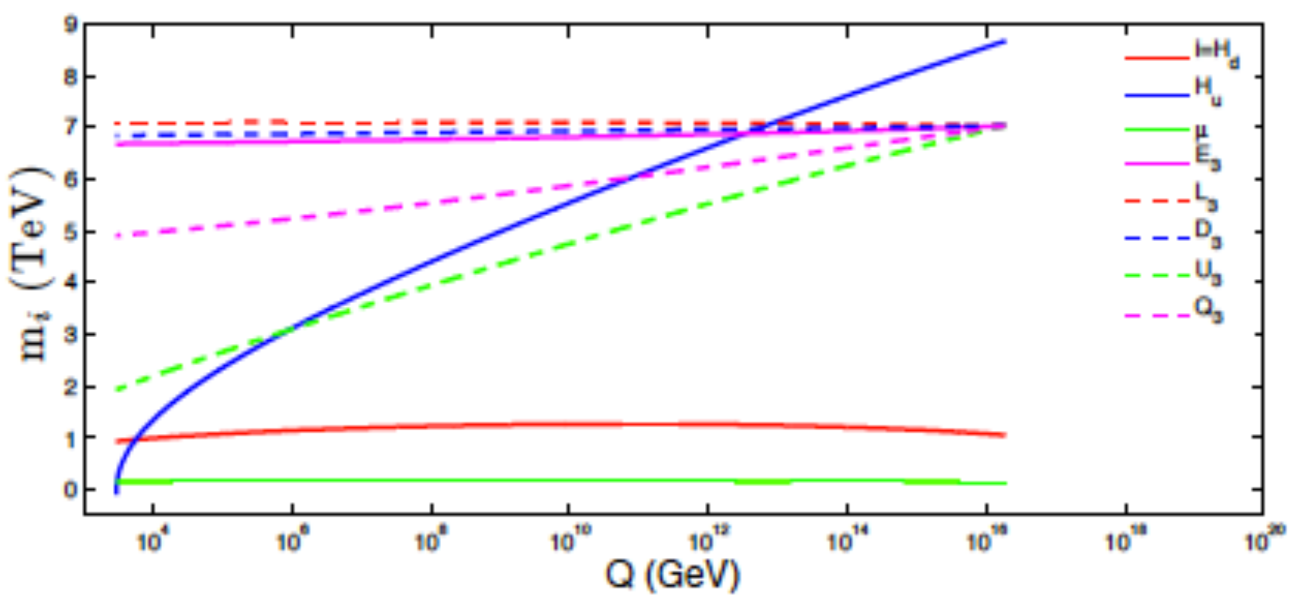
$\mu \sim \lambda m_{3/2}$ so that $|\mu| \ll m_{3/2}$

Next: how can $-m_{H_u}^2(m_{weak}) \sim m_Z^2/2$?

Large top Yukawa radiatively drives $m_{H_u}^2$ to small negative values

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$X_t = m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2$$



Large logs are a feature, not a hindrance; they are large because m(t)=173.2 GeV.

Why is m(t) so large?
I don't know, but I am glad it is.

In mSUGRA, this only happens in HB/FP region where stops also are heavy;
in NUHM models, this can occur even if lighter stops

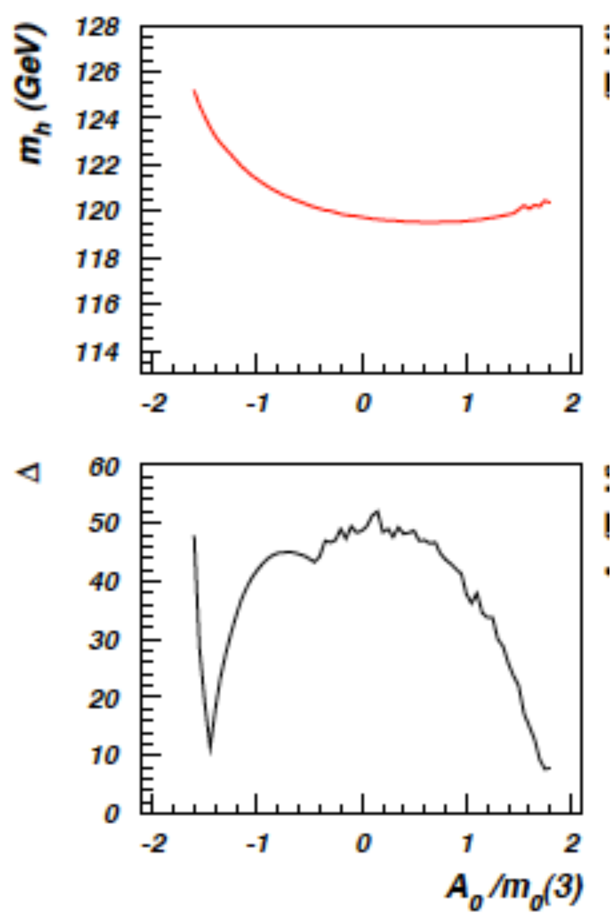
$$m_{H_u}^2(m_{GUT}) \sim (1-2)m_0^2$$

next: radiative corrections

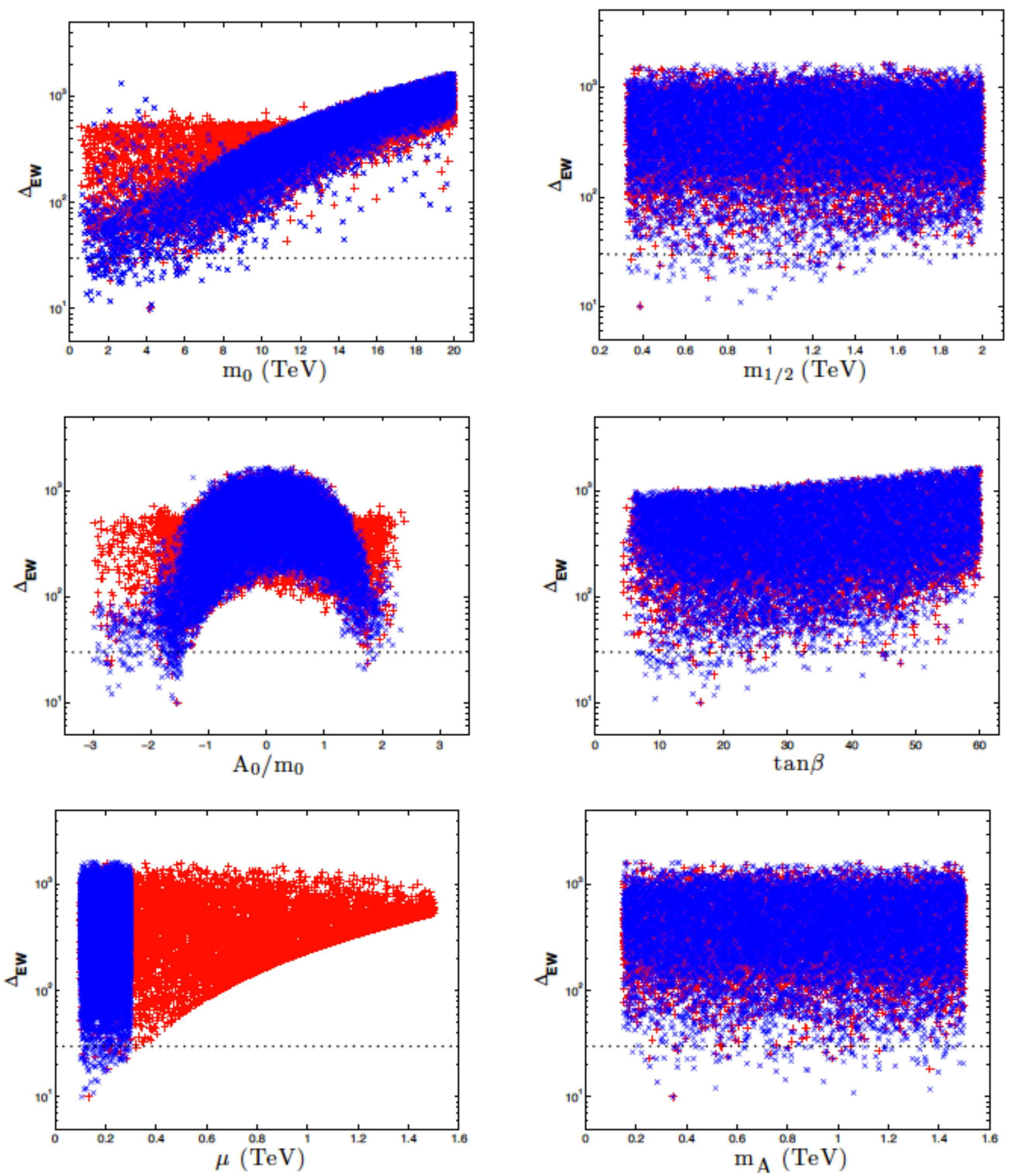
$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2}F(m^2_{\tilde{t}_{1,2}}) \times \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2(\frac{1}{4} - \frac{2}{3}x_W)\Delta_t}{m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}}\right]$$

$$F(m^2) = m^2\left(\log(m^2/Q^2) - 1\right), \text{ with } Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

large stop mixing softens both t1 and t2 radiative corrections while increasing m(h) up to 125 GeV!



Which parameter choices lead to low EWFT and how low can Δ_{EW} be?



$\Delta_{EW} \sim 10$ or 10% $EWFT$

High-scale models with low Δ_{EW} :

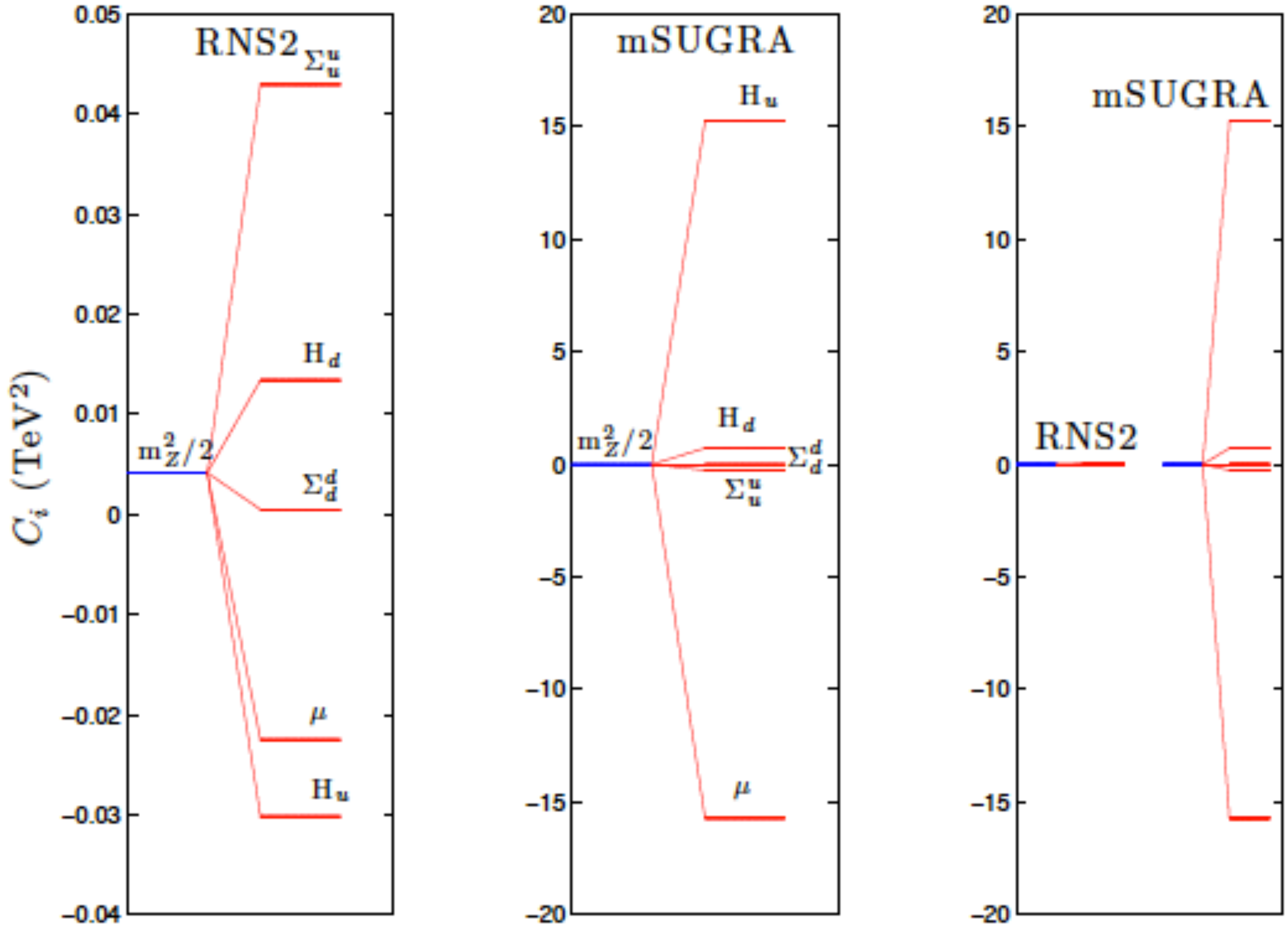
Radiatively-driven natural SUSY, or RNS

What about high scale parameters?
Maybe only small portion of p-space leads to low Delta_EW. What if I vary HS parameters and Delta_EW moves up? Isn't this instability, and hence aren't you really still finetuned?

No. Nature doesn't have any adjustable parameters. We regard the MSSM as an effective theory where the parameters ``parametrize" our ignorance of a more fundamental theory where parameters are fixed. The utility of parameters is that if you find a set which allows for agreement with data, then use those to predict further phenomena. Then devise an experiment to check consistency. If predictions are verified, then model may be a good description of nature.

Compare RNS to mSUGRA for similar parameters

$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV, $A_0 = -11426.6$ GeV, $\tan\beta = 8.55$ with $\mu = 150$ GeV and $m_A = 1000$ GeV



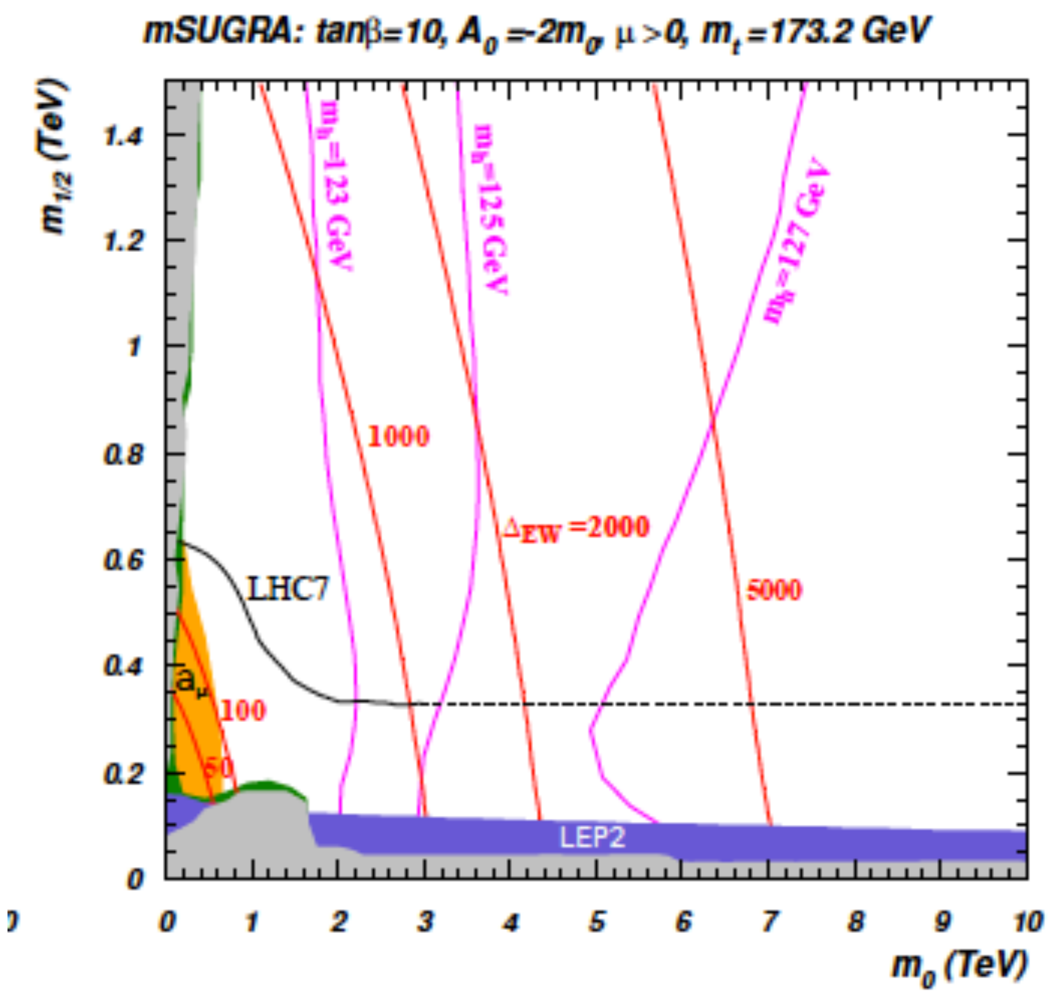
SUSY spectra from radiatively-driven natural SUSY (RNS)

scan NUHM2 space:

- 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-universality of generations with $m_0(1,2) > m_0(3)$ is allowed.

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

What happens to mSUGRA plane?



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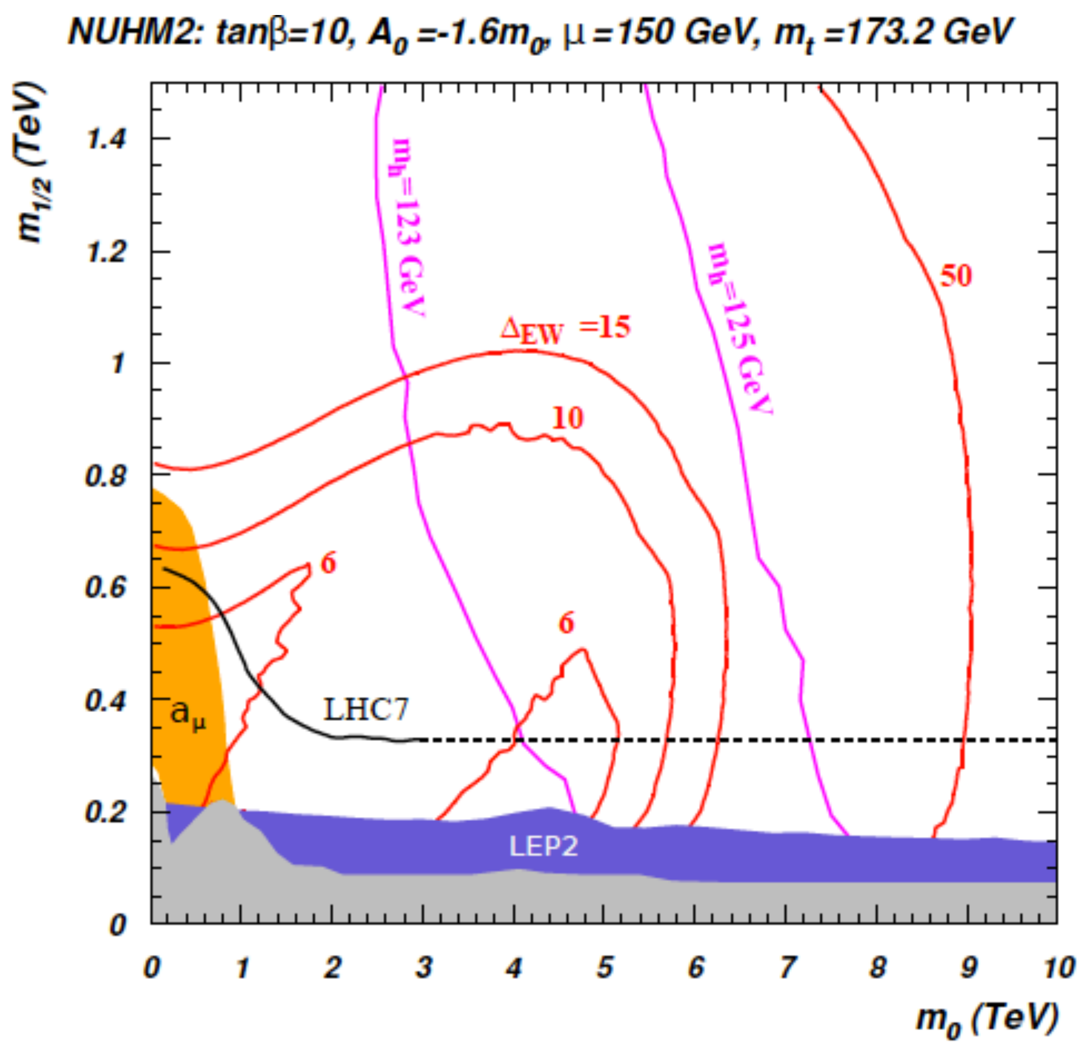
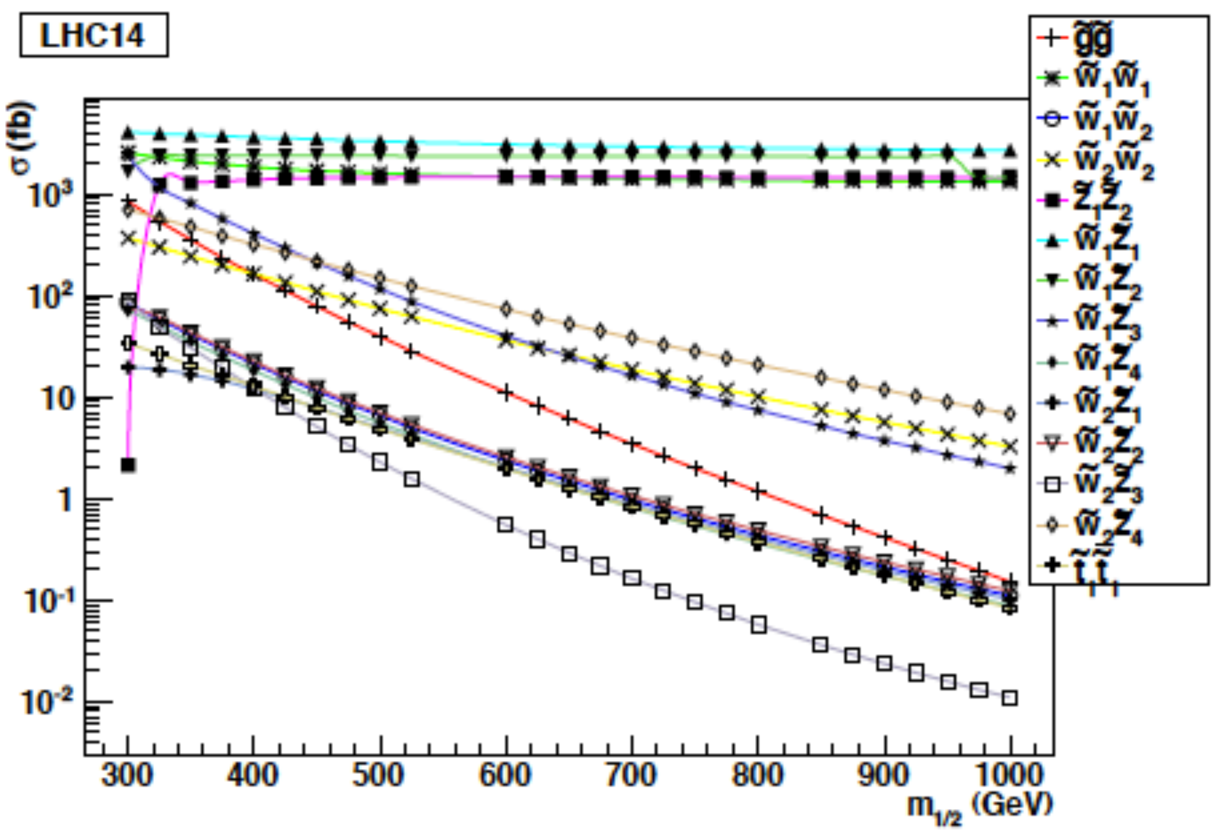
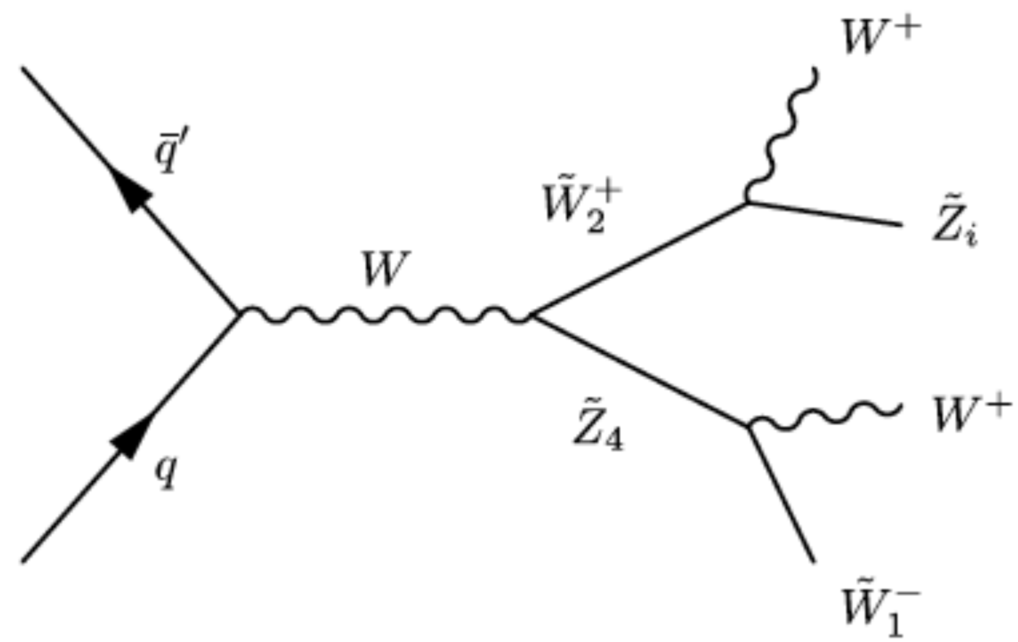


New signature for LHC: same-sign dibosons from models with light higgsinos

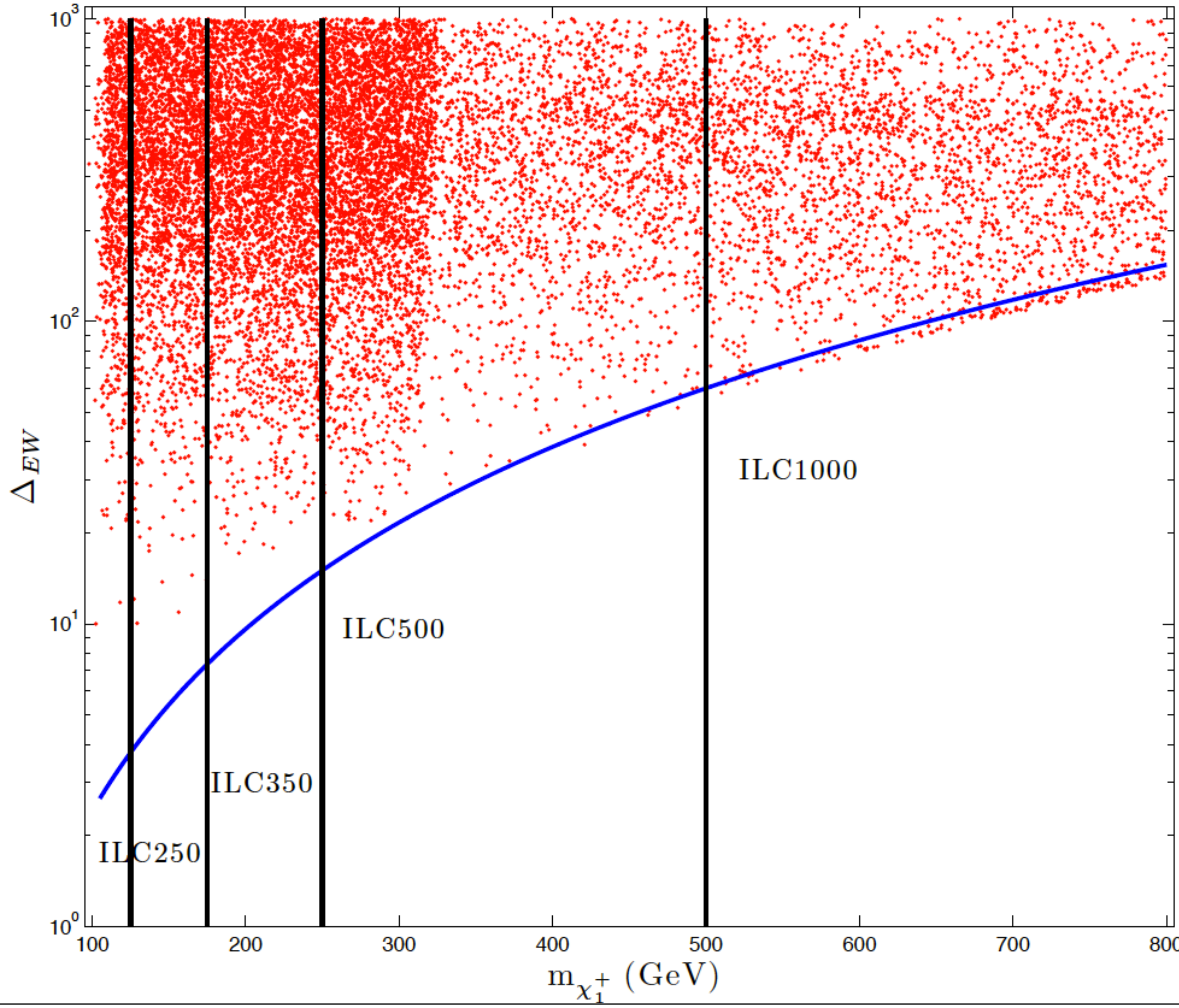




Int. lum. (fb^{-1})	$m_{1/2}$ (GeV)	$m_{\tilde{g}}$ (TeV)	$m_{\tilde{g}}$ (TeV) [$\tilde{g}\tilde{g}$]
10	400	0.96	1.4
100	840	2.0	1.6
300	920	2.2	1.8
1000	1000	2.4	2.0

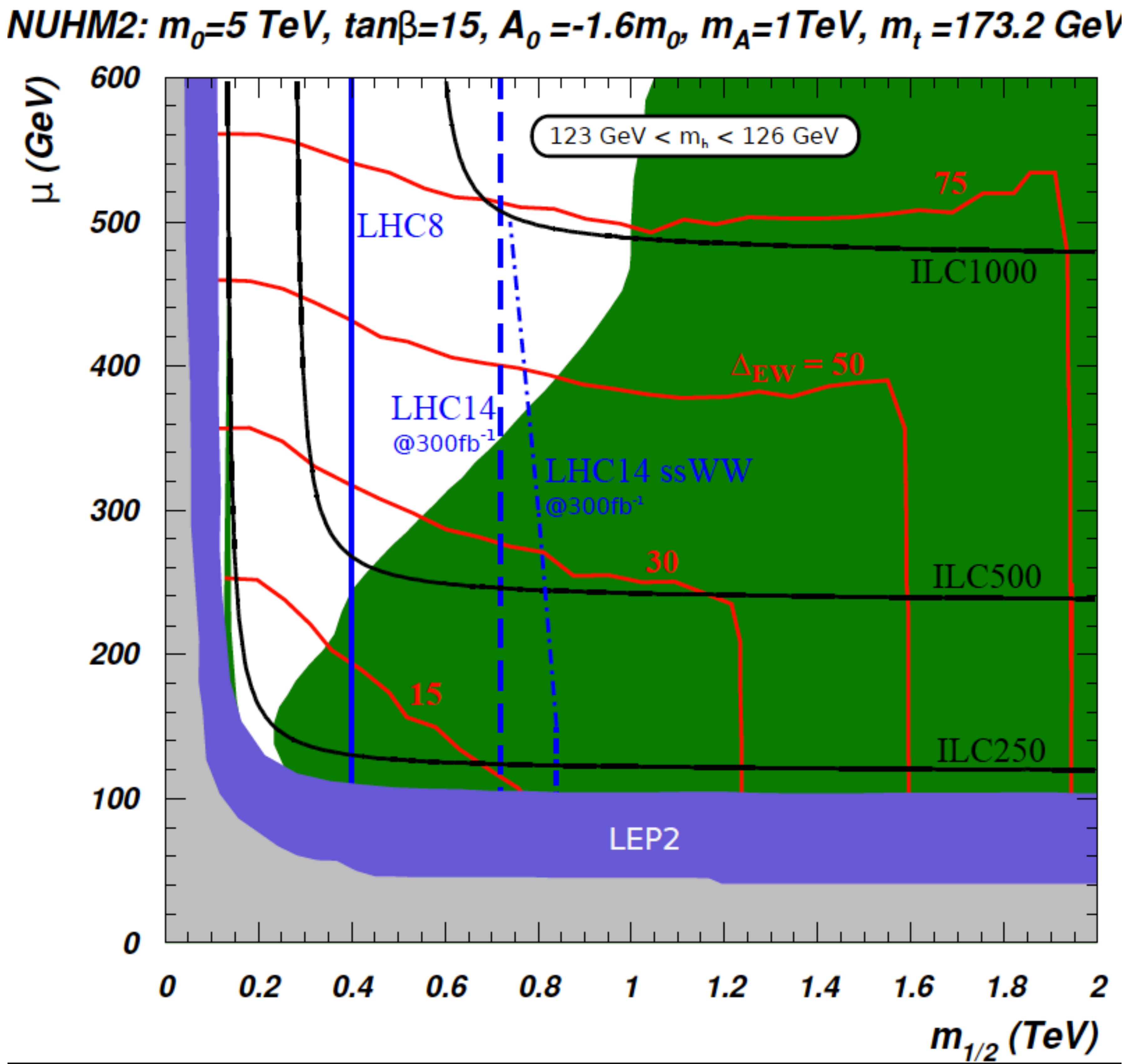
Reach at LHC14 exceeds usual gluino pair search!

Smoking gun signature: 4 light higgsinos at ILC!



$m_{\tilde{W}_1^{\pm}},\ m_{\tilde{Z}_{1,2}}$

LHC/ILC complementarity

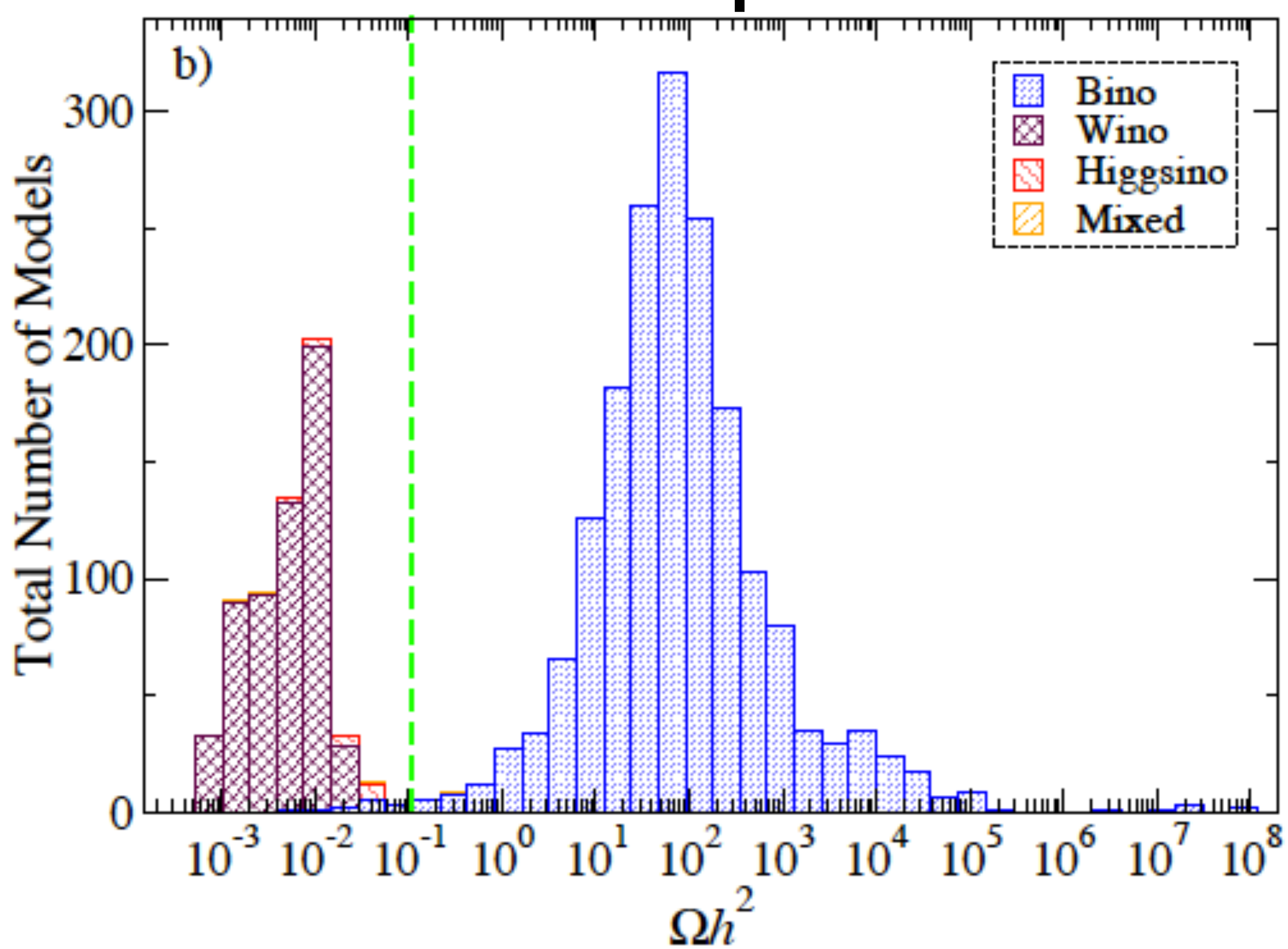


While LHC has some capacity, it will require ILC to draw the story of SUSY electroweak naturalness to a conclusion!

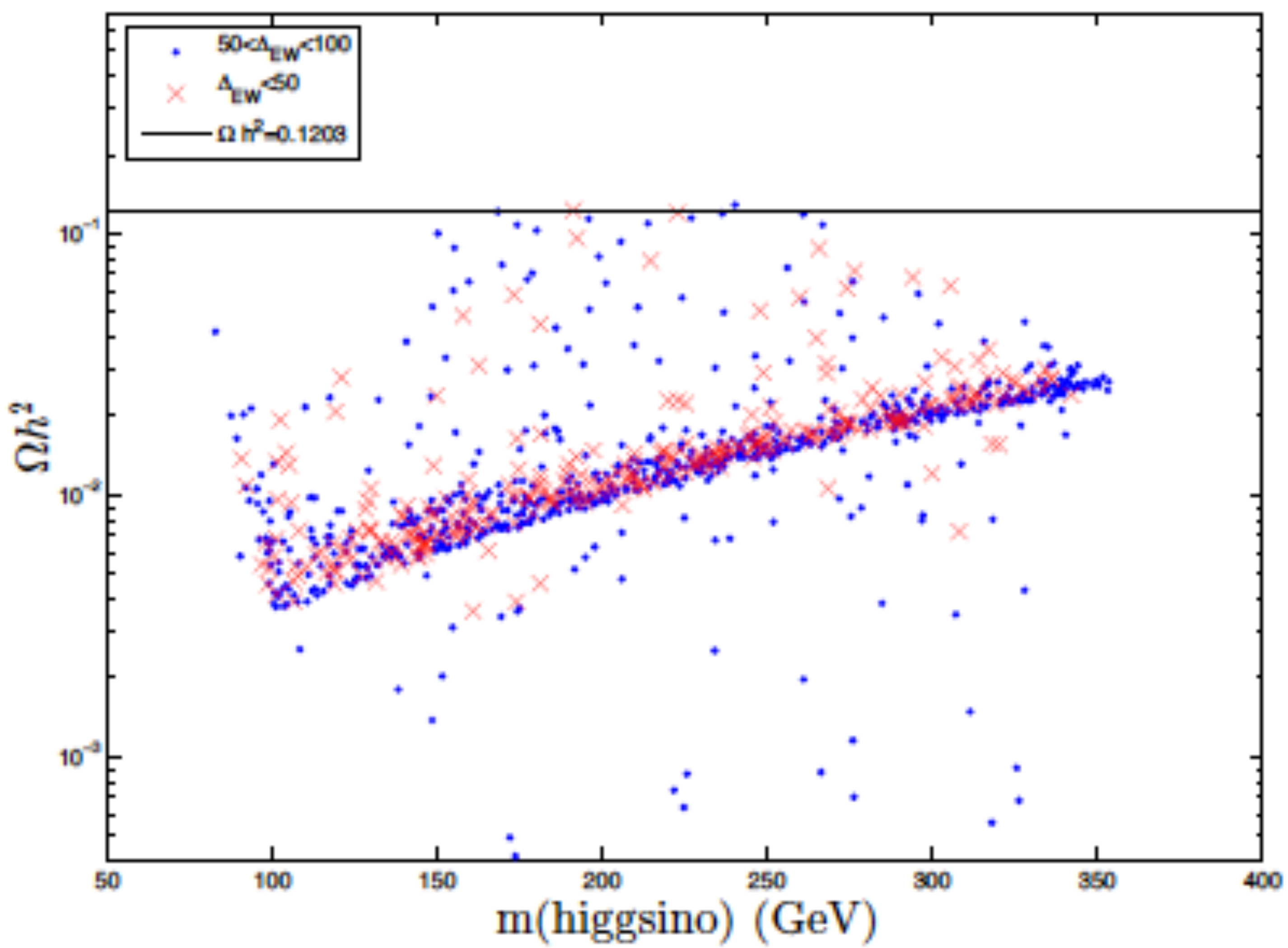
What about DM in RNS? I heard higgsino-like wimp isn't a good DM candidate?

Lightest neutralino all by itself in general not good DM candidate in spite of any hype:

Scan over 19 parameters:



Standard thermal abundance for RNS model



$$\Omega^{std}_{\tilde{Z}_1} h^2 \sim 10 - 15 \text{ low}$$

Invoke Peccei-Quinn sol’n to strong CP problem with SUSY

PQMSSM: Axions + SUSY ⇒ 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$\rightarrow$ 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 axion-neutralino abundance

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

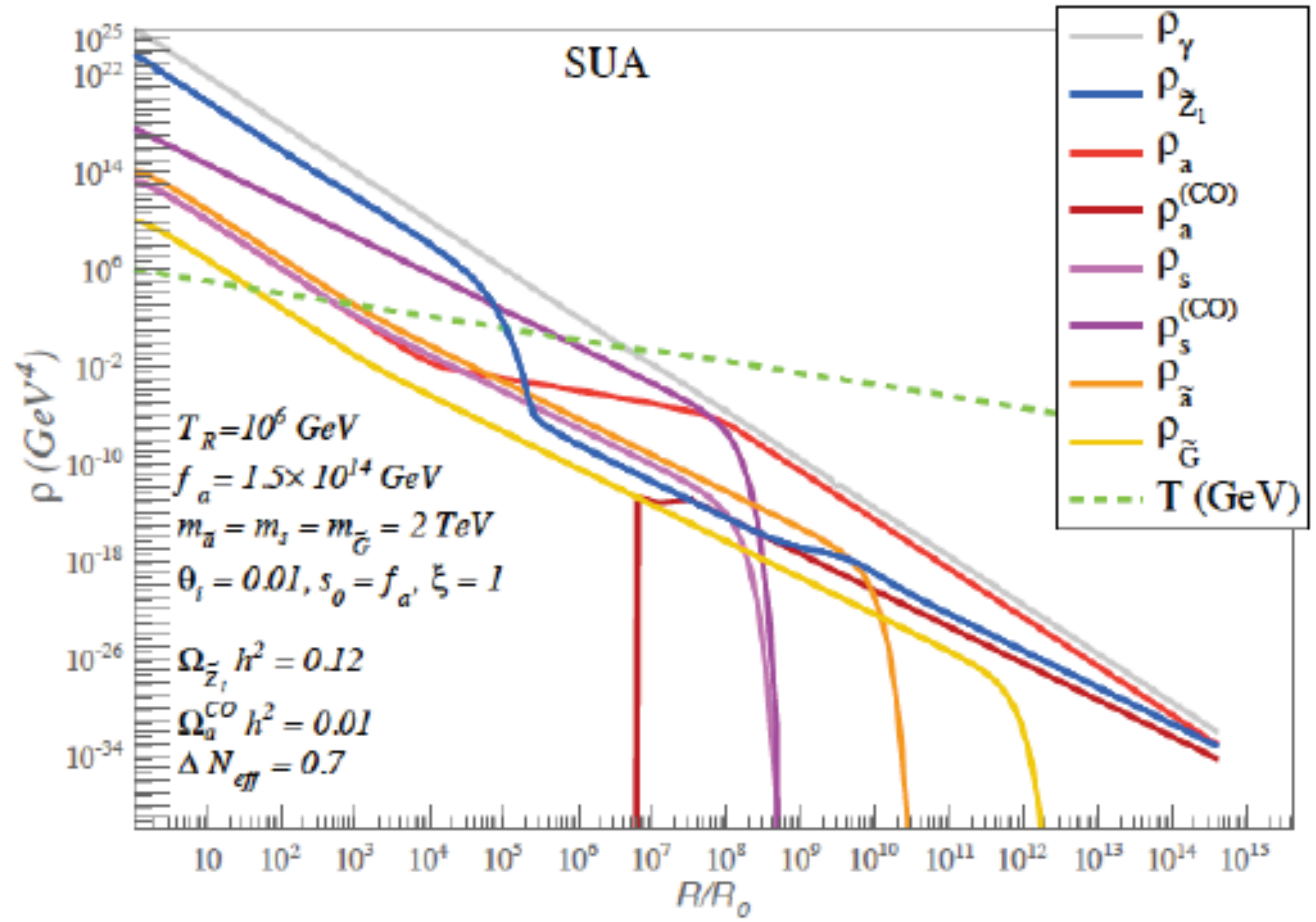
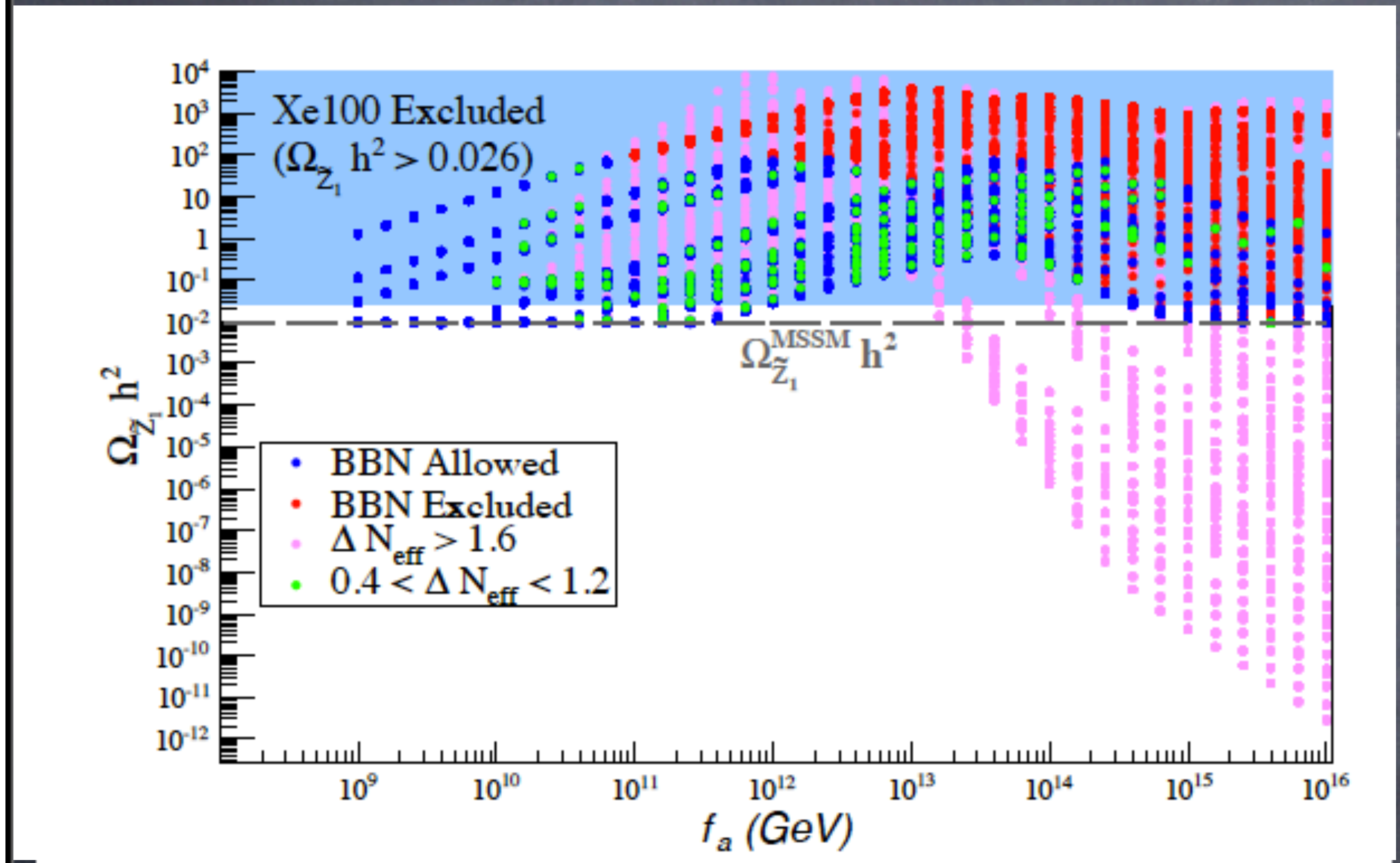


Figure 2: Evolution of various energy densities versus scale parameter R/R_0 for the SUA benchmark.

Mixed higgsino-axion CDM in radiative natural SUSY



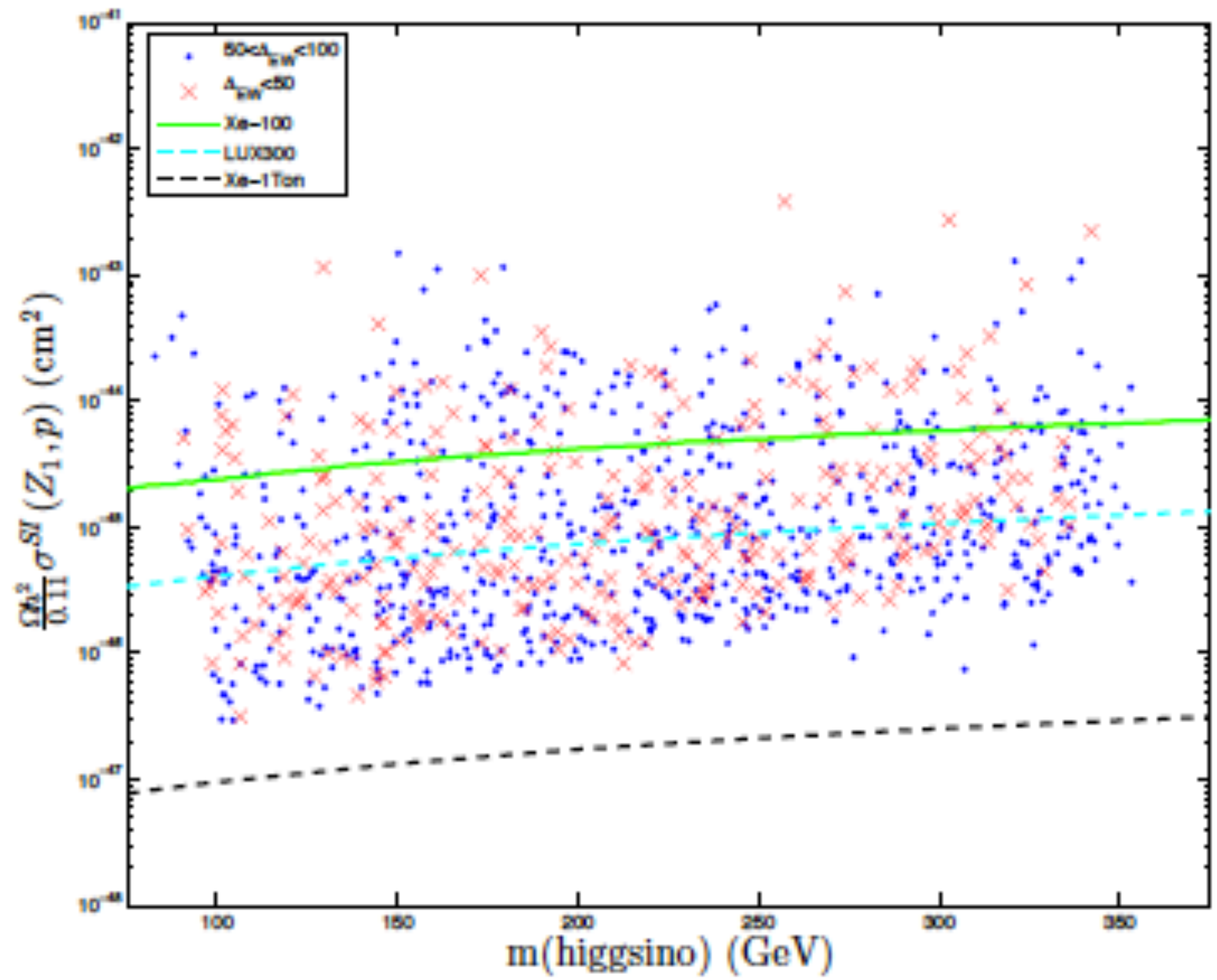
$f_a \sim 10^{14}$ GeV *allowed*!

(string theorists take note)

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!

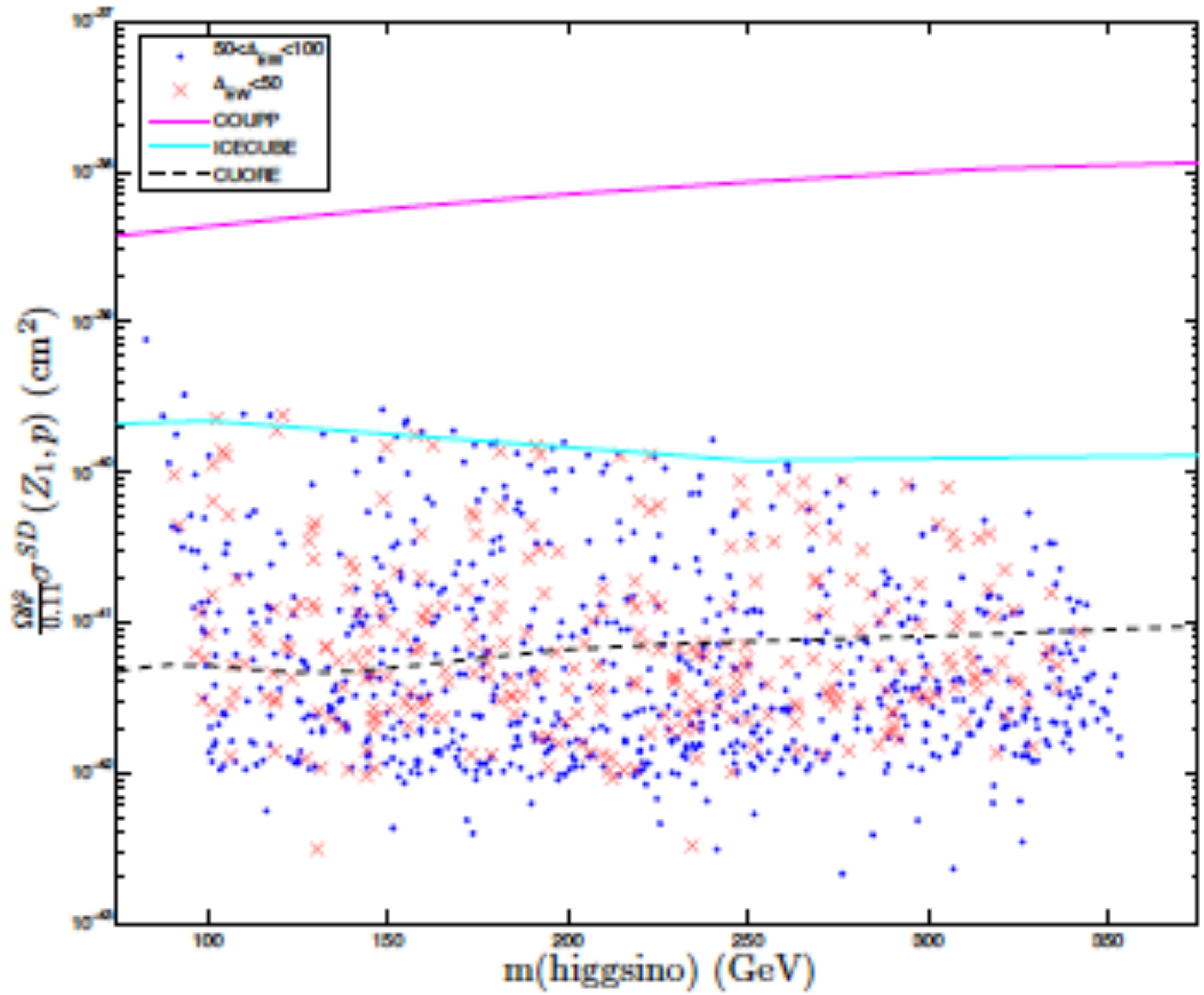
Detection of relic axions also possible

Direct higgsino detection rescaled for minimal local abundance

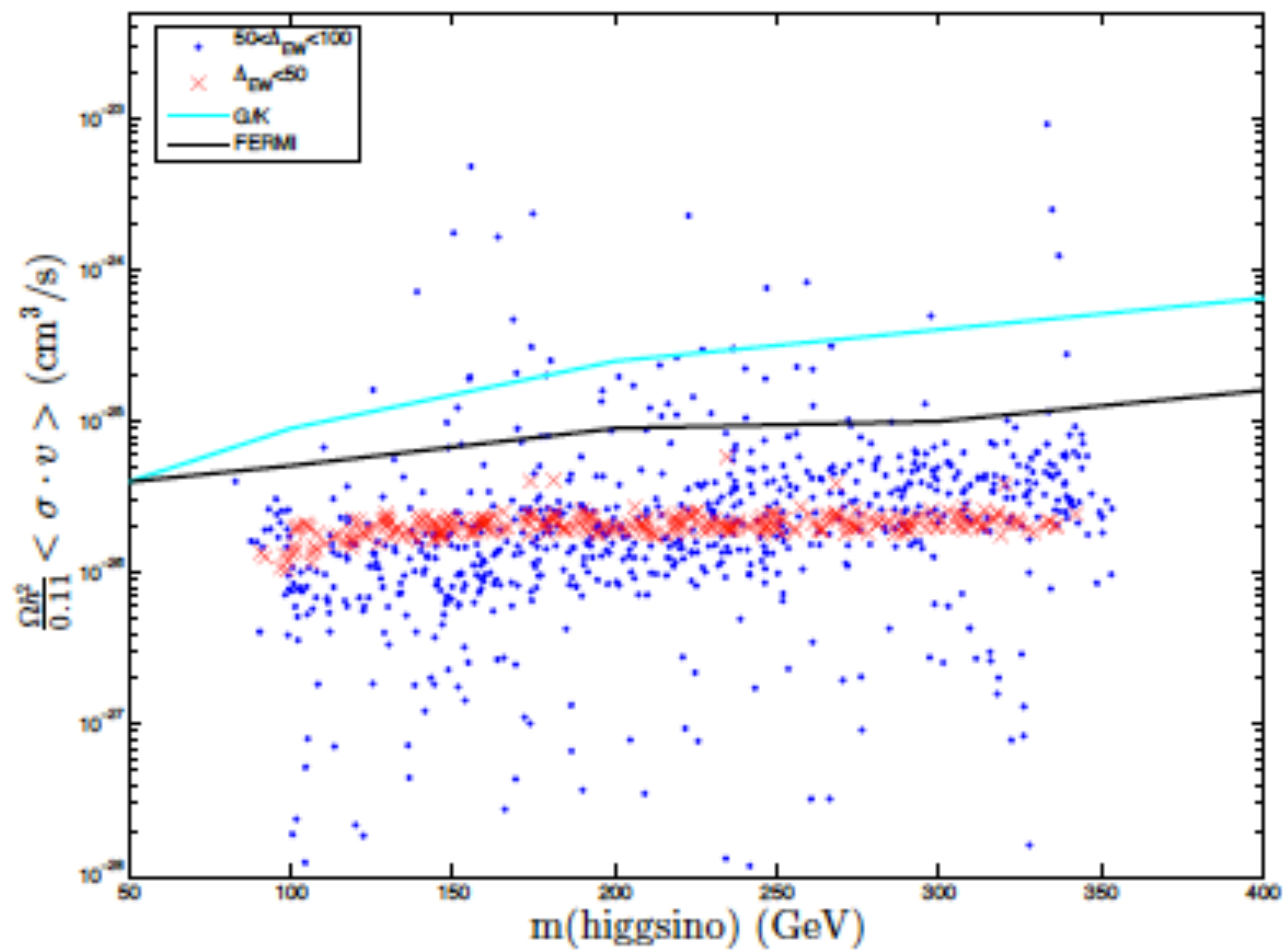


Can test completely with ton scale detector or equivalent (subject to cosmological caveats)

Spin-dependent higgsino detection:



Higgsino detection via halo annihilations:



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

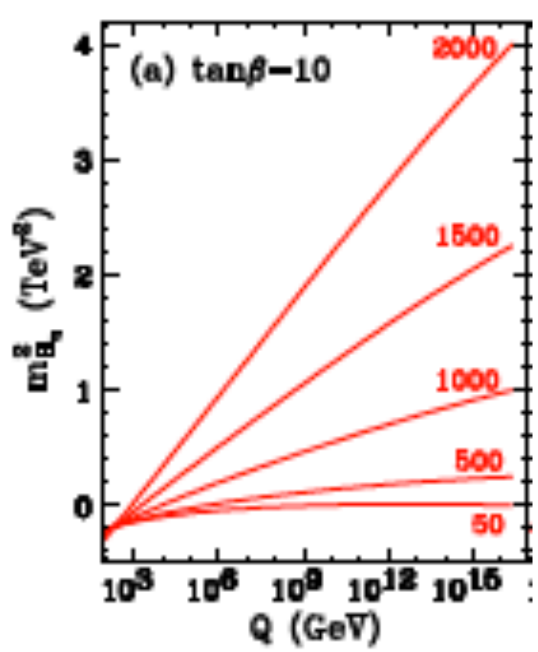
Digression on EW finetuning

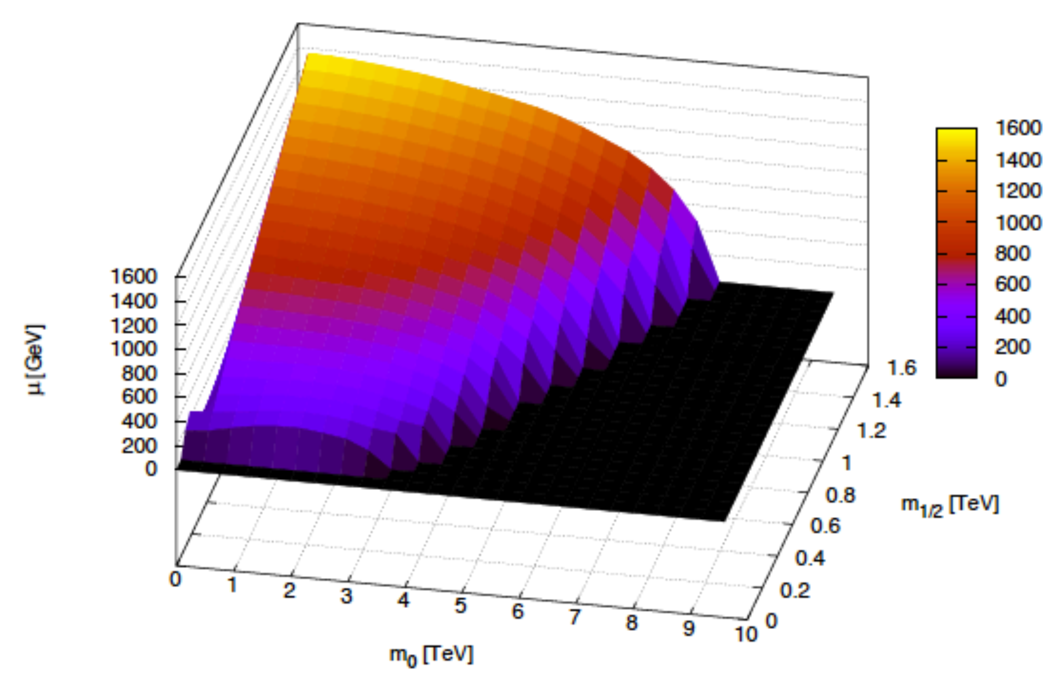
Barbieri-Giudice: how stable is m(Z) against fluctuation in (high scale?) parameters?

$$c_a \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a^2} \right| \qquad\qquad c \equiv \max\{c_a\}$$

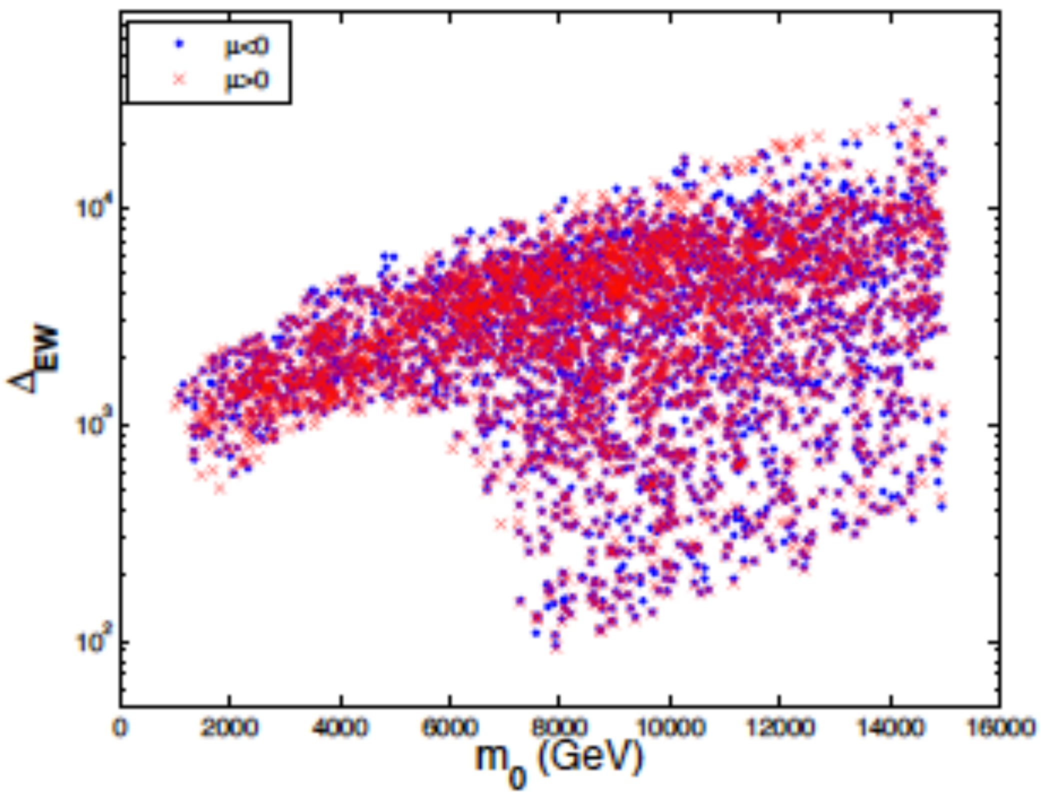
High-scale parameters may be large so long as m(Z) is stable

e.g. reduced finetuning in m0 direction: FP SUSY





While Delta_EW ignores large logs in mHu^2 running, even making use of these to generate low mHu^2 at weak scale, it is nonetheless highly constraining: e.g. mSUGRA at best 1% EWFT and usually much worse



Reason: as we increase m0 into low mu region to reduce EWFT, m(t1,t2) are dragged up and increase EWFT: culprit: mHu=m0

Some virtues of Δ_{EW}

- *Model independent* (within the context of models which reduce to the MSSM at the weak scale): $\Delta_{\rm EW}$ is essentially determined by the sparticle spectrum[27], and – unlike $\Delta_{\rm HS}$ and other measures of fine-tuning – does not depend on the mechanism by which sparticles acquire masses. Since $\Delta_{\rm EW}$ is determined only from weak scale Lagrangian parameters, the phenomenological consequences which may be derived by requiring low Δ_{EW} will apply not only for the NUHM2 model considered here, but also for other possibly more complete (or less complete, such as pMSSM) models which lead to look-alike spectra at the weak scale.

- *Conservative*: $\Delta_{\rm EW}$ captures the minimal fine-tuning that is necessary for any given sparticle spectrum, and so leads to the *most conservative conclusions* regarding fine-tuning considerations.

- *Measureable*: $\Delta_{\rm EW}$ is in principle measurable in that it can be evaluated if the underlying weak scale parameters can be extracted from data.

- *Unambiguous*: Fine-tuning measures which depend on high scale parameter choices, such as the Barbieri-Guidice measure $\Delta_{\rm BG}$ discussed previously, are highly sensitive to exactly which set of model input parameters one adopts: for example, it is well-known that significantly different values of $\Delta_{\rm BG}$ result depending on whether the high scale top-Yukawa coupling is or is not included as an input parameter[37]. There is no such ambiguity in the fine-tuning sensitivity as measured by both $\Delta_{\rm EW}$ and $\Delta_{\rm HS}$.

- *Predictive*: While $\Delta_{\rm EW}$ is less restrictive than Δ_{HS}, it still remains highly restrictive. The requirement of low Δ_{EW} highly disfavors models such as mSUGRA/CMSSM[27], while allowing for very distinct predictions from more general models such as NUHM2.

- *Falsifiable*: The most important prediction from requiring low Δ_{EW} is that $|\mu|$ cannot be too far removed from M_Z. This implies the existence of light higgsinos $\sim 100-300$ GeV which are hard to see at hadron colliders, but which are easily detected at a linear e^+e^- collider with $\sqrt{s} \gtrsim 2|\mu|$. If no higgsinos appear at ILC1000, then the idea of electroweak naturalness in SUSY models is dead.

- *Simple to calculate*: $\Delta_{\rm EW}$ is extremely simple to encode in sparticle mass spectrum programs, even if one adopts models with very large numbers of input parameters.