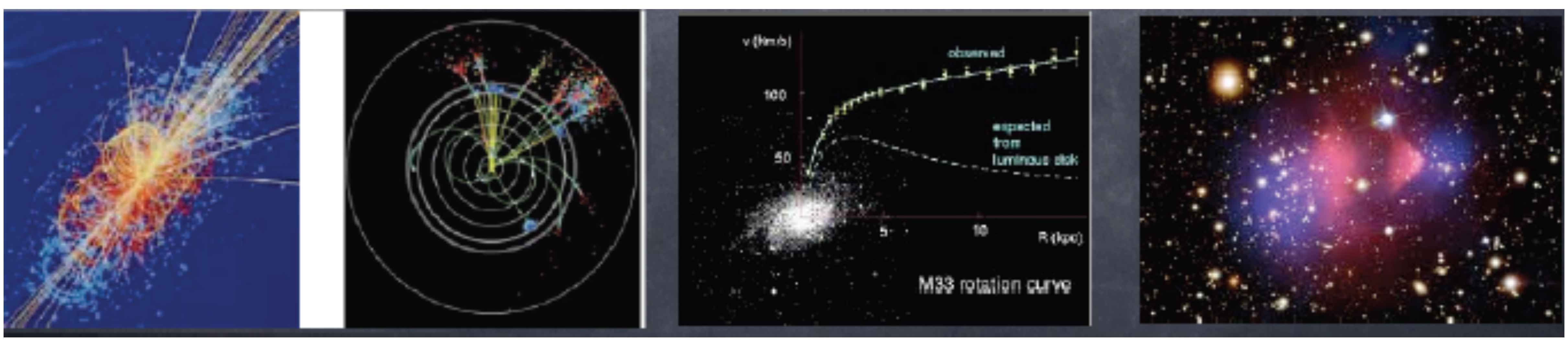
Radiatively-driven natural supersymmetry with implications for LHC, ILC, wimp and axion searches

Howard Baer
University of Oklahoma

with Bae, Barger, Chun, Huang, Lessa, Mickelson, Mustafayev,
Padeffke-Kirkland, Sreethawong, Tata



- h(125.5+-0.5 GeV) at LHC: highly SM-like
- scalars need protective symmetry: SUSY
- m(h)~125.5 GeV falls within narrow MSSM expectation
- m(h) requires highly mixed TeV-scale stops
- LHC: no SUSY: m(glno)>1.3 TeV, m(sqrk)>1.7 TeV, t1 limits
- impression: then MSSM EW fine-tuned at .1% ?
- SUSY as expected likely wrong?
- needs new features or new model?

- How does this perception arise?
- Why is it wrong?
- Overestimate of EWFT
- What does SUSY look like?
- How can we tell?
- Distinct LHC signatures
- Need ILC for definitive check
- Expect axion/wimp signal as well

Naturalness in the Standard Model

SM case: invoke a single Higgs doublet

$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$m_h^2 = m_h^2|_{tree} + \delta m_h^2|_{rad}$$

$$m_h^2|_{tree} = \sqrt{2}\mu^2 \qquad \delta m_h^2|_{rad} = \frac{c}{16\pi^2}\Lambda^2$$

$m_h^2|_{tree}$ and $\delta m_h^2|_{rad}$ are *independent*,

If one term is huge, then the other must be dialed to huge negative values to enforce that m(h) is just 125.5 GeV: this is known as EW fine-tuning

Alternatively, if $m_h^2|_{tree}$ and δm_h^2 are both $\sim m_h^2|_{phys} \simeq 125.5$ GeV, then we say the model is *natural*!

create fine-tuning measure $\longrightarrow$ $\Delta_{SM} \equiv \delta m_h^2|_{rad}/(m_h^2/2)$

$$\Delta_{SM} < 1 \Rightarrow \Lambda \sim 1\ TeV$$

New physics intervenes at 1 TeV!

Bullet point, or large-log fine-tuning, in MSSM:

$$m_h^2 \simeq \mu^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{rad}$$

Since we have SUSY, now $\delta m_{H_u}^2$ only log divergent.
But now cutoff Λ may be as high as m_{GUT}

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right) \qquad X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$$

neglect gauge pieces, S, mHu and running;
then we can integrate from mSUSY to Lambda

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

$\Delta \equiv \delta m_{H_u}^2/(m_h^2/2) \lesssim 10$ then $m_{\tilde{t}_{1,2}}, m_{\tilde{b}_1} \lesssim 200$ GeV and $m_{\tilde{g}} \lesssim 600$ GeV

almost certainly in violation of LHC constraints!

Conclusion: SUSY is EW fine-tuned, and EWFTd
SUSY is most likely wrong SUSY!

What's wrong with this argument?

In zeal for simplicity, have neglected that, unlike case of SM, for SUSY

$m_{H_u}^2$ and $\delta m_{H_u}^2|_{rad}$ are not independent

the larger the value of $m_{H_u}^2(\Lambda)$, then the larger is the cancelling correction $\delta m_{H_u}^2|_{rad}$

The dependent terms should be grouped together

$$m_h^2|_{phys} = \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$$

where instead both μ^2 and $(m_{H_u}^2 + \delta m_{H_u}^2)$ should be comparable to $m_h^2|_{phys}$.

This is just $m_{H_u}^2(m_{weak})$

Such a re-grouping is used in EENZ/BG (Barbieri-Giudice) measure:

$$\Delta_{BG} \equiv max_i\,[c_i] \quad \text{where} \quad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln a_i}\right| = \left|\frac{a_i}{m_Z^2}\frac{\partial m_Z^2}{\partial a_i}\right|$$

Here, the a_i are the various parameters of the theory

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

$\uparrow$

express weak scale value in terms of high scale parameters;
no artificial split between $m_{H_u}^2(\Lambda)$ and $\delta m_{H_u}^2$

Express m(Z) in terms of high scale parameters:

$$
\begin{aligned}
m_Z^2 \simeq\ & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
& +0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
& -0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\
& -1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
& +0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
& +0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
& +0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2
\end{aligned}
$$

Abe, Kobayashi, Omura;
S. P. Martin

For generic parameter choices, Δ_{BG} *is large*

$e.g.\ c_{Q_3} = |0.73m_{Q_3}^2|/m_Z^2 = 351$ for $m_{Q_3} = 2$ TeV

But if: $m_{Q_{1,2}} = m_{U_{1,2}} = m_{D_{1,2}} = m_{L_{1,2}} = m_{E_{1,2}} \equiv m_{16}(1,2)$ then $\sim 0.007m_{16}^2(1,2)$

Even better: $m_{H_u}^2 = m_{H_d}^2 = m_{16}^2(3) \equiv m_0^2$ => $-0.017m_0^2$

For correlated parameters, EWFT collapses in 3rd gen. sector!

model	c_{m_0}	$c_{m_{1/2}}$	c_{A_0}	c_μ	c_{H_u}	c_{H_d}	Δ_{BG}
mSUGRA	156	762	1540	-25.1	−−	−−	1540
NUHM2	16041	762	1540	-25.1	-15208	-643.6	16041

Table 1: Sensitivity coefficients and Δ_{BG} for mSUGRA and NUHM2 model with $m_0 = 9993.4$ GeV, $m_{1/2} = 691.7$ GeV, $A_0 = -4788.6$ GeV and $\tan\beta = 10$. The mSUGRA output values of $\mu = 309.7$ GeV and $m_A = 9859.9$ GeV serve as NUHM2 inputs so that the two models have exactly the same weak scale spectra.

Lesson: the BG measure determines fine-tuning
within various multi-parameter effective theories.
Its value changes from theory to theory
even if the theories give exactly the same spectrum
i.e. it is highly model-dependent,
as it must be since it depends on parameters.

Interpretation of BG in terms of UTH:

- most theorists hypothesize existence of an ultimate theory which describes nature
- perhaps MSSM with all correlated parameters is low E effective theory: UTH
- hope is that UTH is contained within more general multi-parameter effective theories which are popular in literature: mSUGRA, nuhm2,...
- The Δ_{BG} measures EWFT in the multi-parameter effective theories instead of UTH: for large number of parameters, it loses parameter correlations: this leads leads to overestimate
- example: mSUGRA serves as toy UTH for NUHM2 which contains more parameters
-

model	c_{m_0}	$c_{m_{1/2}}$	c_{A_0}	c_μ	c_{H_u}	c_{H_d}	Δ_{BG}
mSUGRA	156	762	1540	-25.1	$--$	$--$	1540
NUHM2	16041	762	1540	-25.1	-15208	-643.6	16041

- need an EWFT measure which gives same value for effective theories as for UTH (i.e. model-independent)

What we really want to know is:
is nature fine-tuned,
(and by implication the UTH which describes it),
and not whether-or-not
the more general effective theories
(which might contain the UTH)
are fine-tuned

Are we then to give up on naturalness
as a guide to SUSY models?

Model-independent EWFT measure: Δ_{EW}

No large uncorrelated cancellations in m(Z) or m(h)

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

$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$ with $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$ etc.

Since Δ_{EW} is model-independent (within MSSM),

expect same value for Eff. theory as for UTH!

Δ_{EW} is very explicit about what is required for low EWFT

In order to achieve low Δ_{EW}, it is necessary that $-m_{H_u}^2$, μ^2 and $-\Sigma_u^u$ all be nearby to $m_Z^2/2$ to within a factor of a few[12, 13]:

1. μ is required to lie in the $100 - 300$ GeV range,
2. a value of $m_{H_u}^2(m_{GUT}) \sim (1.3 - 2.5)m_0$ may be chosen so that $m_{H_u}^2$ is driven radiatively to slightly negative at the weak scale, leading to $m_{H_u}^2(weak) \sim -m_Z^2/2$, and
3. with large stop mixing from $A_0 \sim \pm 1.6 m_0$, the top-squark radiative corrections are softened while m_h is raised to the ~ 125 GeV level.

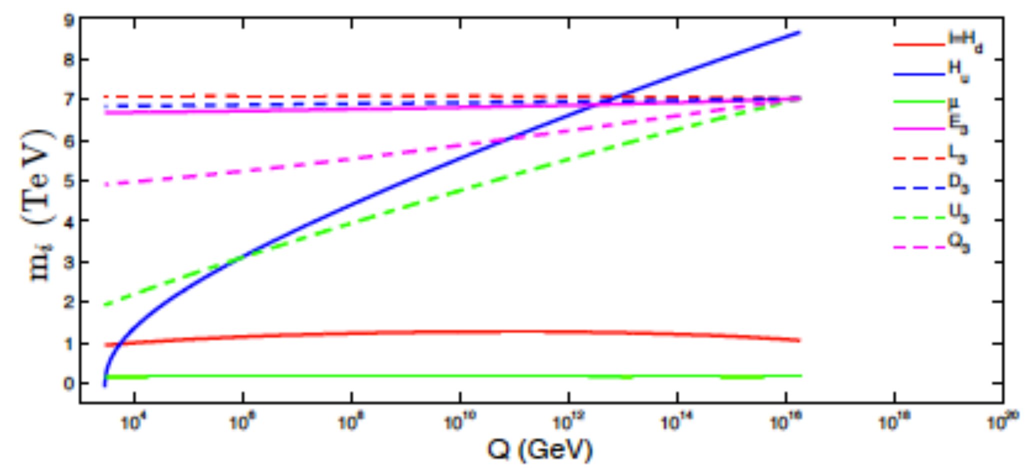
Model-independent EWFT measure: Δ_{EW}

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

For the top squark contributions, we find

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

where $\Delta_t = (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)/2 + M_Z^2\cos 2\beta(\frac{1}{4} - \frac{2}{3}x_W)$ and $x_W \equiv \sin^2\theta_W$



where

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

with the optimized scale choice $Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$.

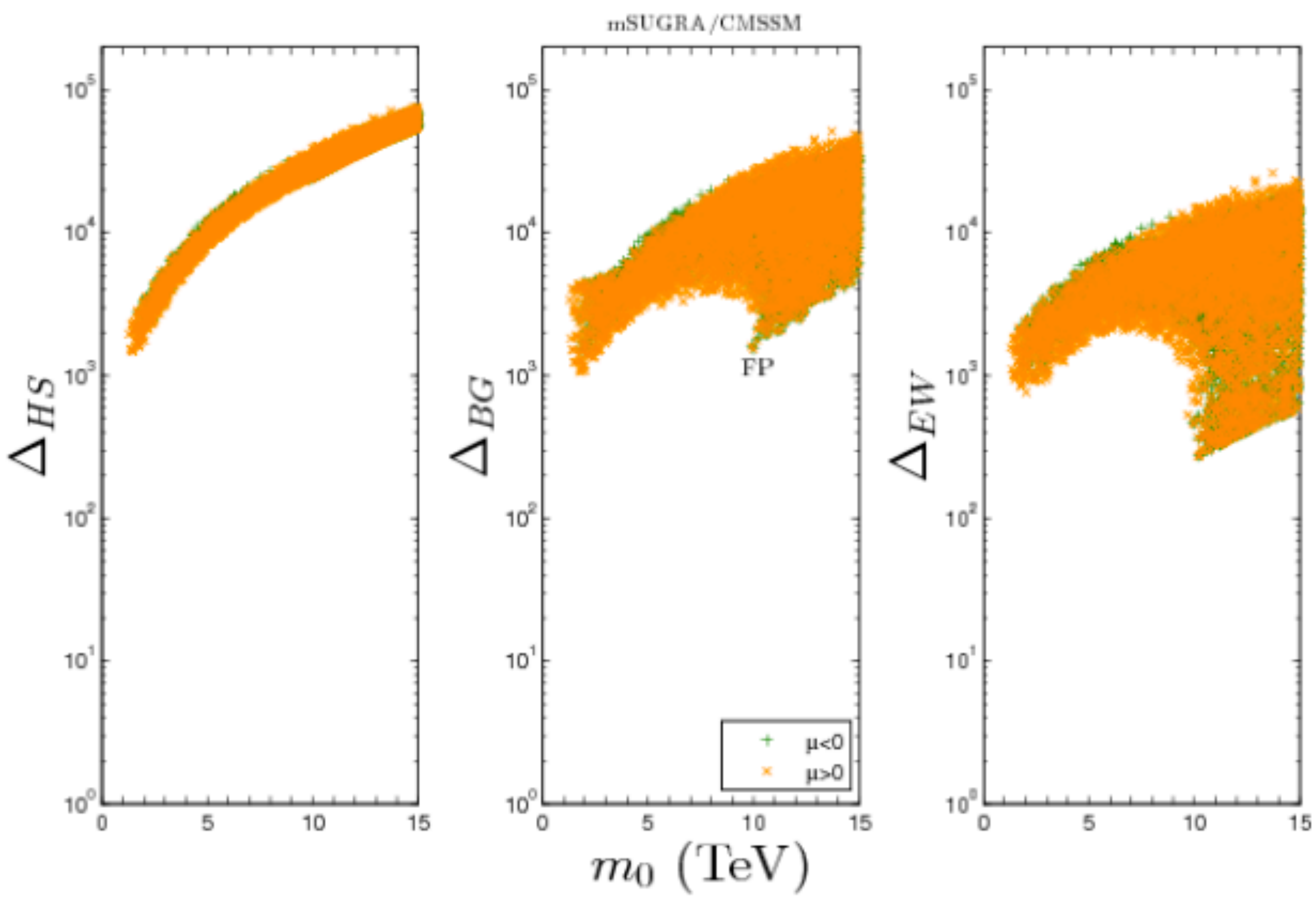
Large At drives down $\Sigma_u^u(\tilde{t}_{1,2})$ while lifting m(h) to 125 GeV!

Radiatively-driven natural SUSY (RNS):

H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, *Phys. Rev. Lett.* **109** (2012) 161802.

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, *Phys. Rev.* **D 87** (2013) 115028 [arXiv:1212.2655 [hep-ph]].

Scan over mSUGRA/CMSSM model:
is fine-tuned under all three measures:
this effective theory is unlikely to contain the UTH

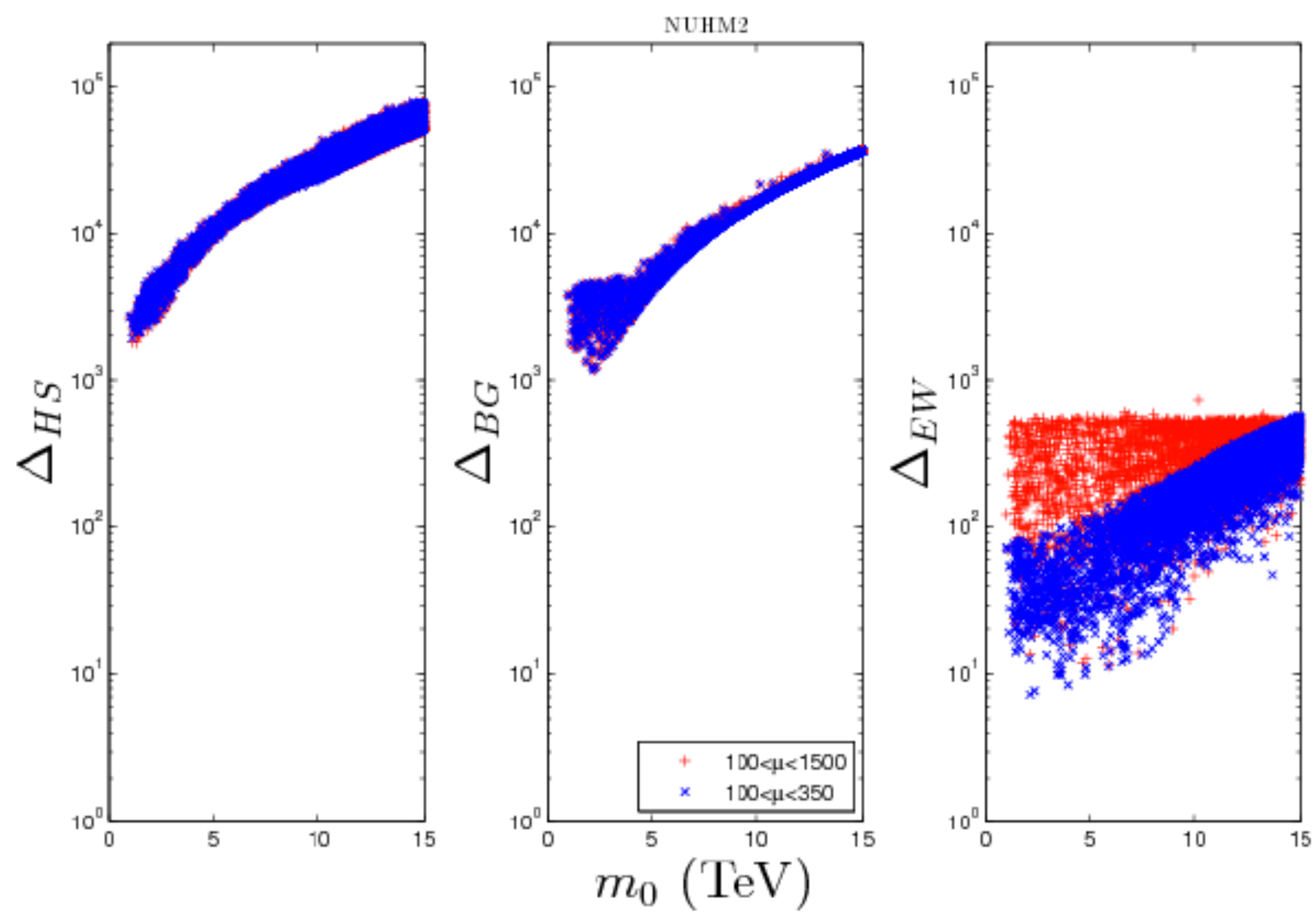


HB, Barger, Mickelson: arXiv:1309.2984

The NUHM2 model allows for not-too-heavy stops at 1-3 TeV with large mixing and m(h)~125 GeV while maintaining low mu~100-200 GeV:

it allows for EWFT at just ~10% level,

thus it may well contain the UTH



$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ m_{H_u},\ m_{H_d}$

can trade for $\mu,\ m_A$

How conventional measures overestimate electroweak fine-tuning in supersymmetric theory (with V. Barger and D. Mickelson), Phys. Rev. D88 (2013) 095013.

When is BG a reliable measure?
For an UTH with correlated soft parameters

Where can we find such a theory?
Actually, most have this property:
e.g. good old supergravity with SUSY
breaking via superHiggs mechanism

All soft terms proportional to gravitino mass $m_{3/2}$

In such a case, then BG and EW
are essentially the same!
Proof:

Expect all soft parameters related to gravitino mass $m_{3/2}$:

- $m_{H_u}^2 = a_{H_u} m_{3/2}^2$
- $m_{Q_3}^2 = a_{Q_3} m_{3/2}^2$
- $A_t = a_{A_t} m_{3/2}$
- $M_3 = a_{M_3} m_{3/2}$, etc.

where the a_i are all just constants.

Then,

$$m_Z^2 = -2.18\mu^2 + a \cdot m_{3/2}^2$$

where a is sum of constants. Then

$$c_{3/2} = \frac{m_{3/2}^2}{m_Z^2} \frac{\partial m_Z^2}{\partial m_{3/2}^2} = a \cdot m_{3/2}^2 / m_Z^2$$

For $\Delta_{BG} \sim 1$, then $a \cdot m_{3/2}^2 \sim m_Z^2$ But also,

$$m_Z^2 \simeq -2\mu^2(weak) - 2m_{H_u}^2(weak)$$

(at weak scale). Relating m_Z^2, we get $-m_{H_u}^2(weak) \simeq m_Z^2$!!!

$$\lim_{n_p \to 1} \Delta_{BG} = \Delta_{EW}!$$

QED

Essential point:

$$a \cdot m_{3/2}^2 \simeq m_Z^2$$

Usually we expect $m_{3/2} \sim m_Z$.
But LHC tells us $m_{3/2} \gg m_Z$
Other possibility:
a is small, *i.e.* there are large cancellations!

Large $m_{H_u}^2(\Lambda)$ is cancelled by large running: $\delta m_{H_u}^2$
so that $m_{H_u}^2 \sim -m_Z^2$ at weak scale:
this is radiatively-driven natural SUSY

An aside on multi-parameter effective SUSY theories:

In high-scale SUGRA models, the Kahler function
superpotential and gauge kinetic function must be specified for hidden sector
to determine the values of soft SUSY breaking terms via superHiggs mechanism
in terms of $m_{3/2}$

Since there is no data on the hidden sector, nobody knows what the model is;
probably it is something as yet unthought of

We introduce variable parameters
in order to cast a wide net, allow for many possibilities for hidden sector

It is important not to confuse parameters with independent degrees of freedom:
they should all be correlated in an ultimate theory

For example, see calculation of soft terms in string theory by Brignole, Ibanez, Munoz

What about mu parameter?
mu term is supersymmetric:
gives mass to particles and sparticles
(W, Z, h, higgsinos)

Expect mu~M(Planck) but
phenomenology -> mu~m(Z)

Several proposed solutions:

- NMSSM (but beware re-introducing divergent tadpoles ala Bagger, Poppitz, Randall)
- Giudice-Masiero (mu~m_{3/2}) :(
- Kim-Nilles: PQ symmetry forbids mu but then generate mu via PQ breaking!

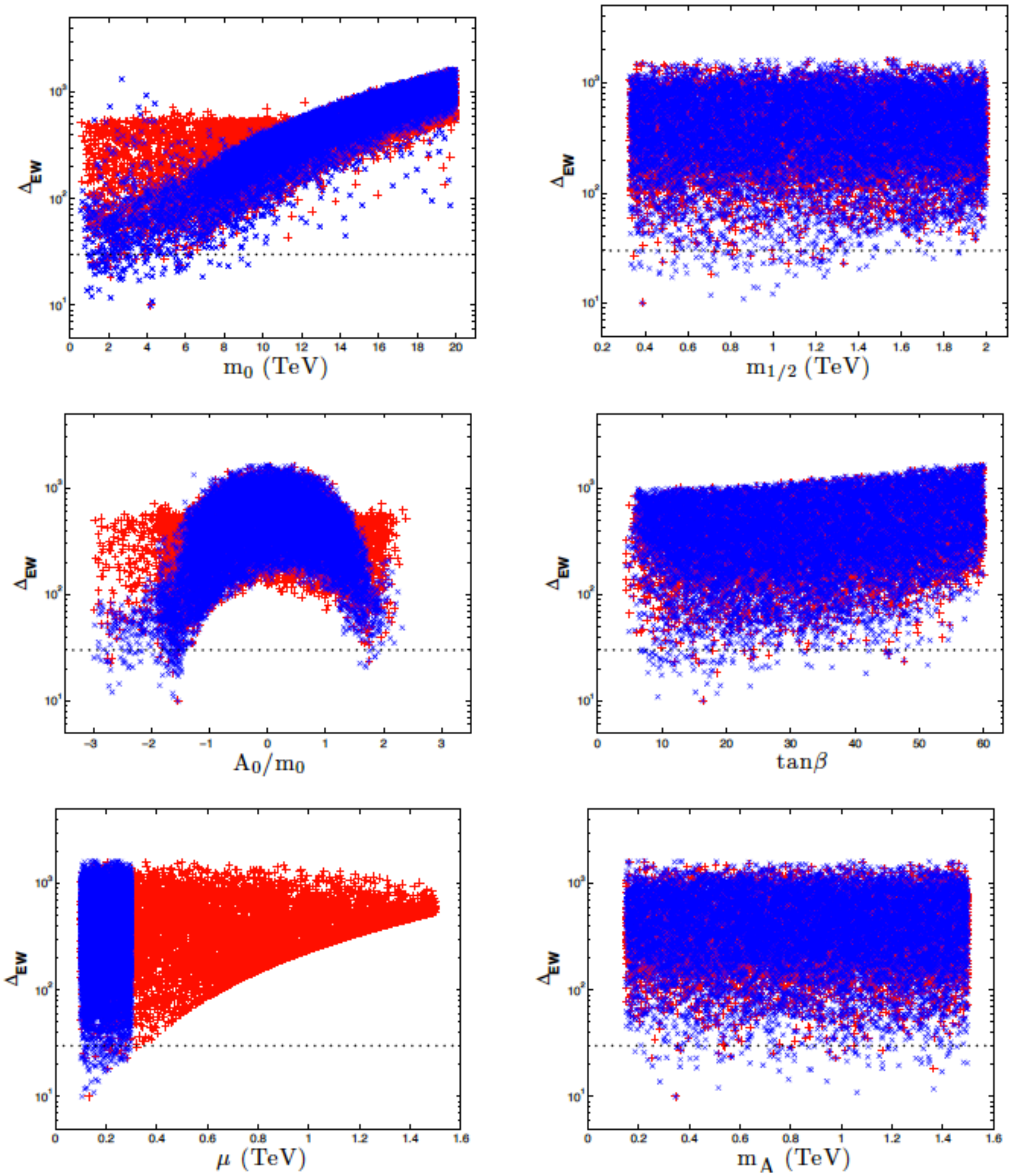
$W \ni \lambda S^2 H_u H_d / M_P$ (the SUSY DFSZ axion model)
$\langle S \rangle \sim f_a \sim 10^{10}$ GeV
$\mu = \lambda f_a^2 / M_P \sim m_Z$
In this case, the Higgs mass tell us where to look for axion!

Here, f_a is the Peccei-Quinn symmetry breaking scale:
astrophysics requires $f_a > 10^9$ GeV

The Little Hierarchy $\mu \ll m_{3/2}$ is a reflection of the mismatch between PQ breaking scale f_a and hidden sector SUSY breaking scale m where $f_a \ll m$. (Originally, Kim-Nilles had sought to relate/equate these two.)

Move on to describe RNS

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



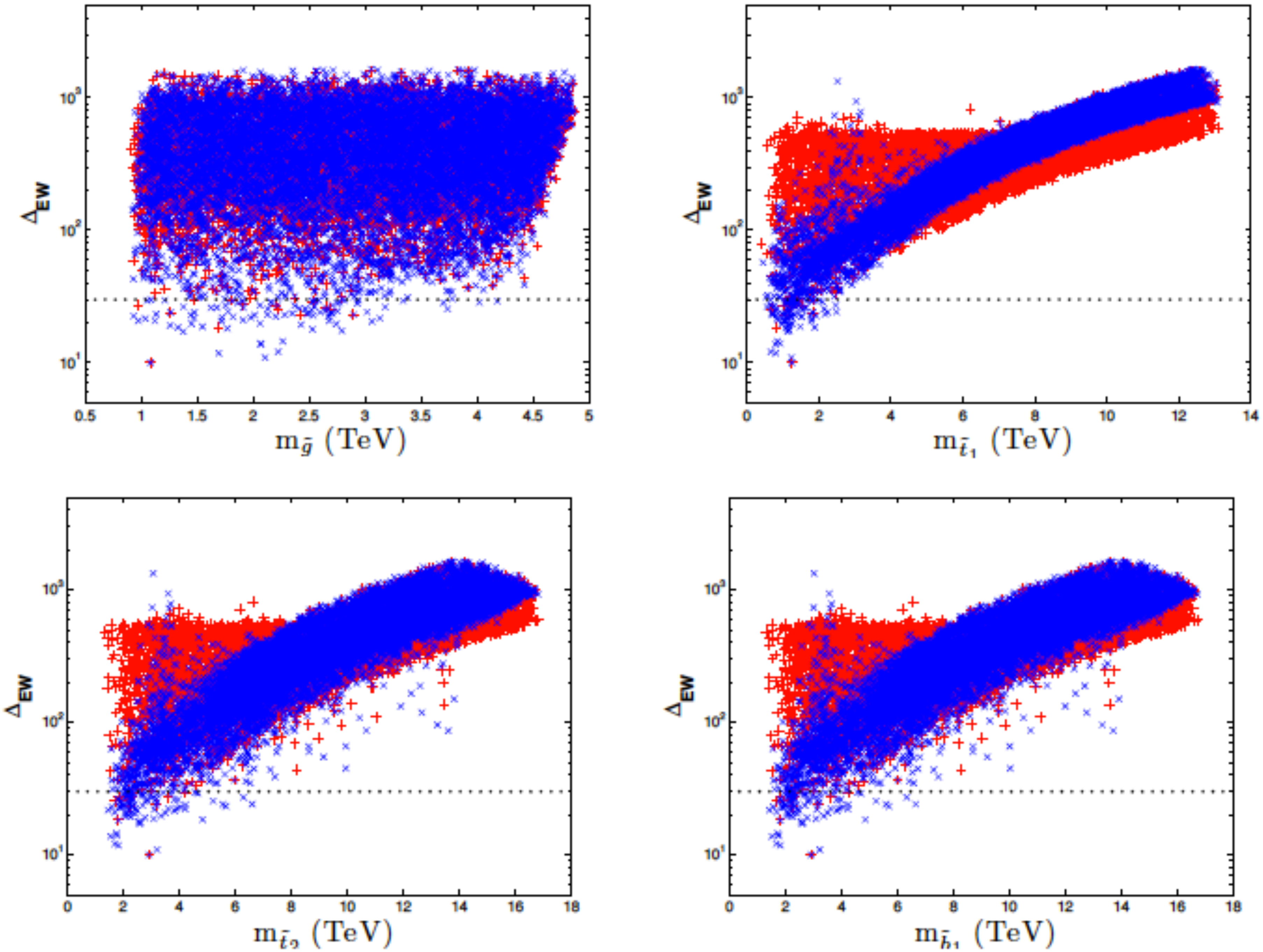
$\Delta_{EW} \sim 10$ or 10% $EWFT$

High-scale models with low Δ_{EW} :

Radiatively-driven natural SUSY, or RNS

HB, Barger, Huang, Mickelson, Mustafayev, Tata, arXiv:1212.2655

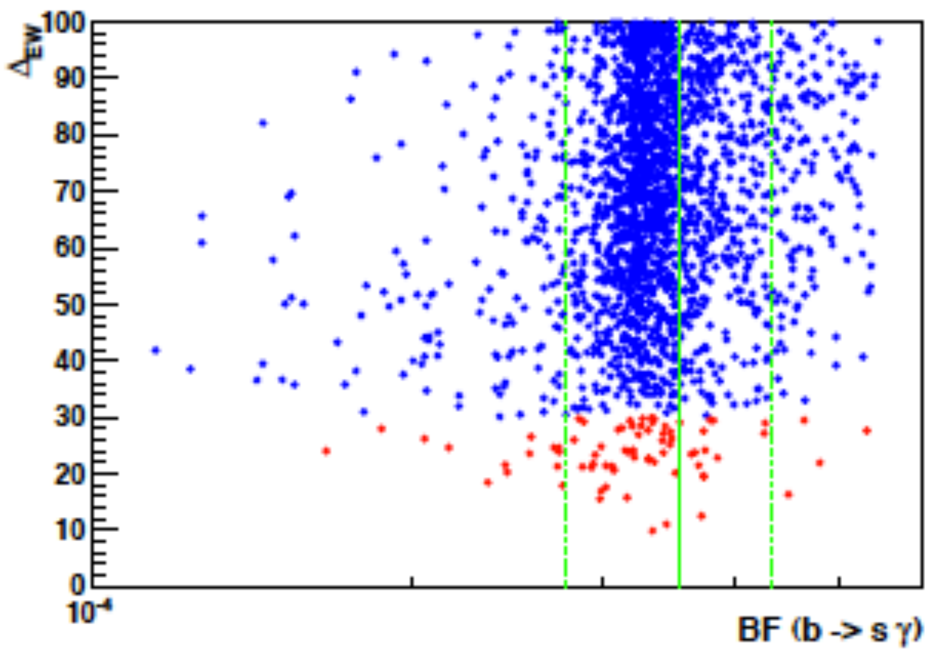
Sparticle masses:

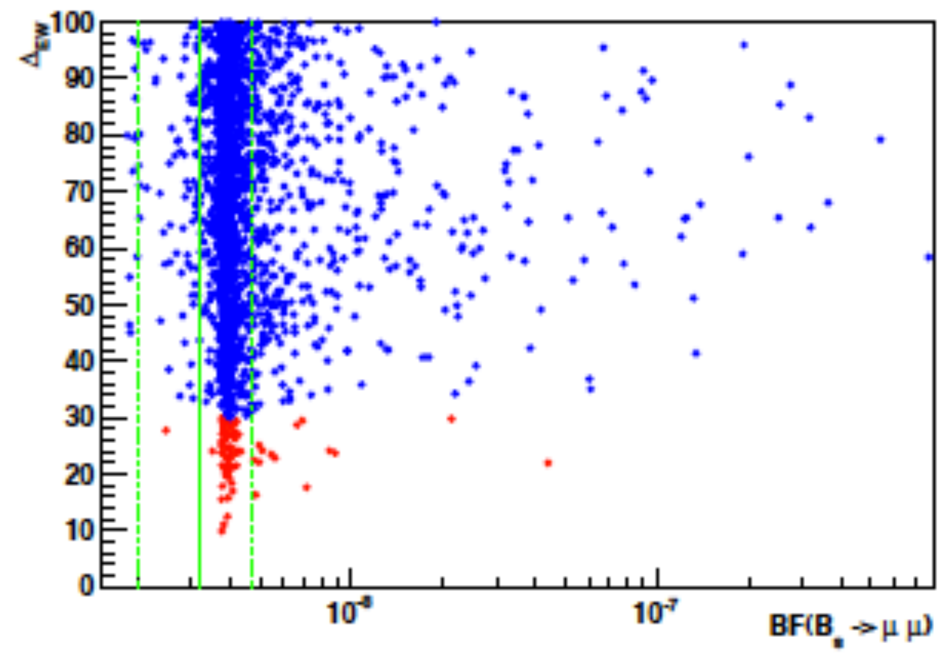


m(t1)~1-3 TeV
m(t2,b1)~2-4 TeV
m(glno)~1-4 TeV

heavier than earlier NS models,
allows for m(h)~125 GeV within MSSM

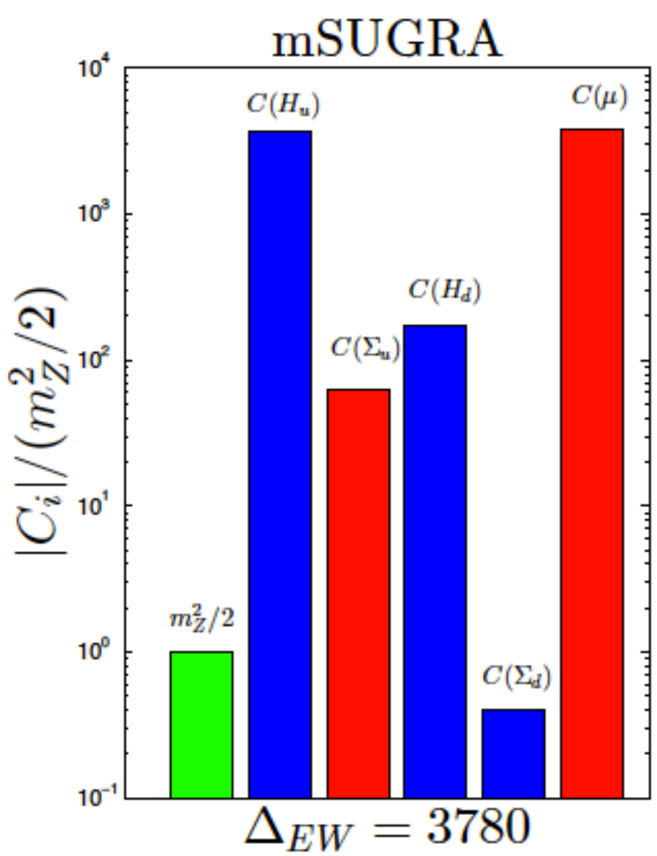
What happens to B constraints?
These are trouble for older Natural SUSY models which required light top/bottom squarks

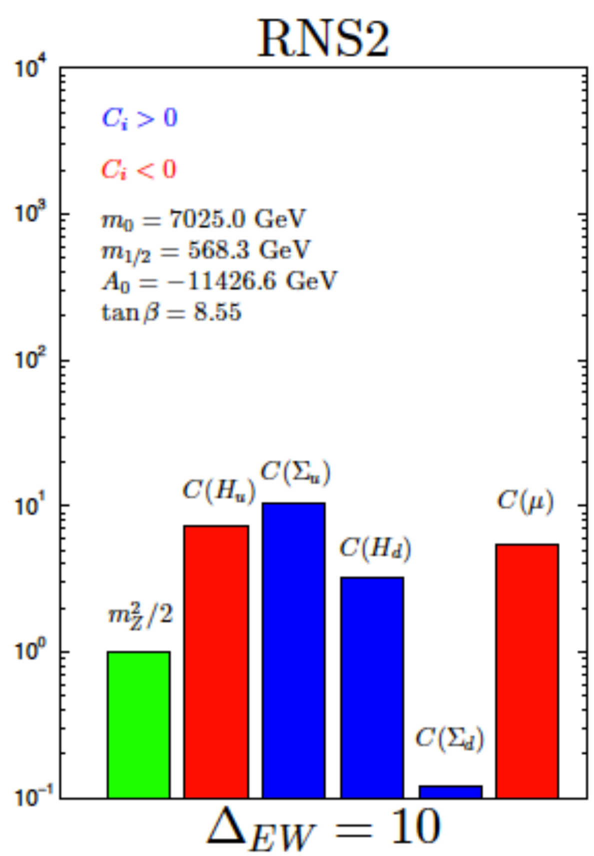


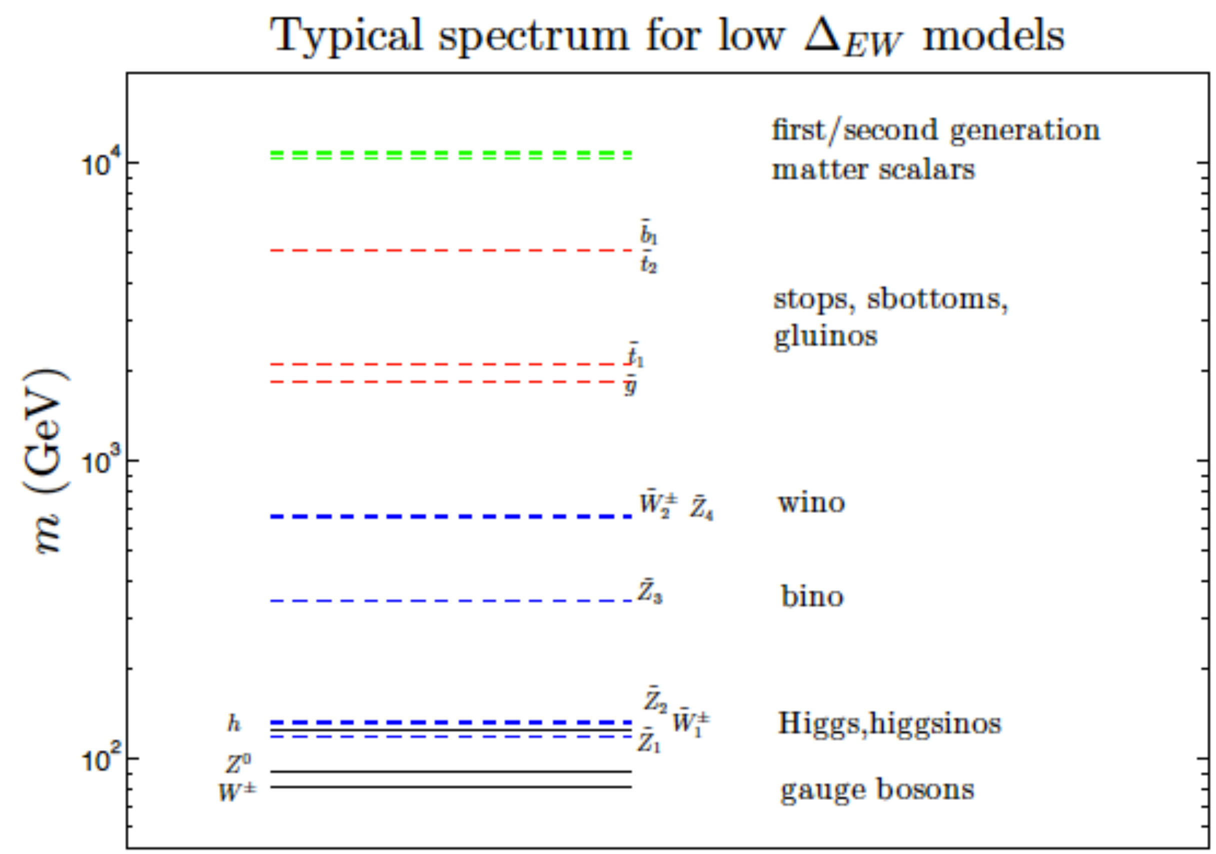


Heavier top squarks, m(A) ameliorate these

All contributions to m(Z) and m(h) are comparable to m(Z) and m(h): model is natural in EW sector!







There is a Little Hierarchy, but it is no problem

Can radiatively-driven natural SUSY be discovered at LHC?

To check, create an RNS model line with variable gluino mass:

$$\begin{aligned} m_0 &= 5 \text{ TeV}, \\ m_{1/2} &: \quad \text{variable between } 0.3 - 2 \text{ TeV}, \\ A_0 &= -1.6 m_0, \\ \tan\beta &= 15, \\ \mu &= 150 \text{ GeV}, \\ m_A &= 1 \text{ TeV}. \end{aligned}$$

10%-2% EWFT

(Split generation model allows m0(1,2)~20-30 TeV)

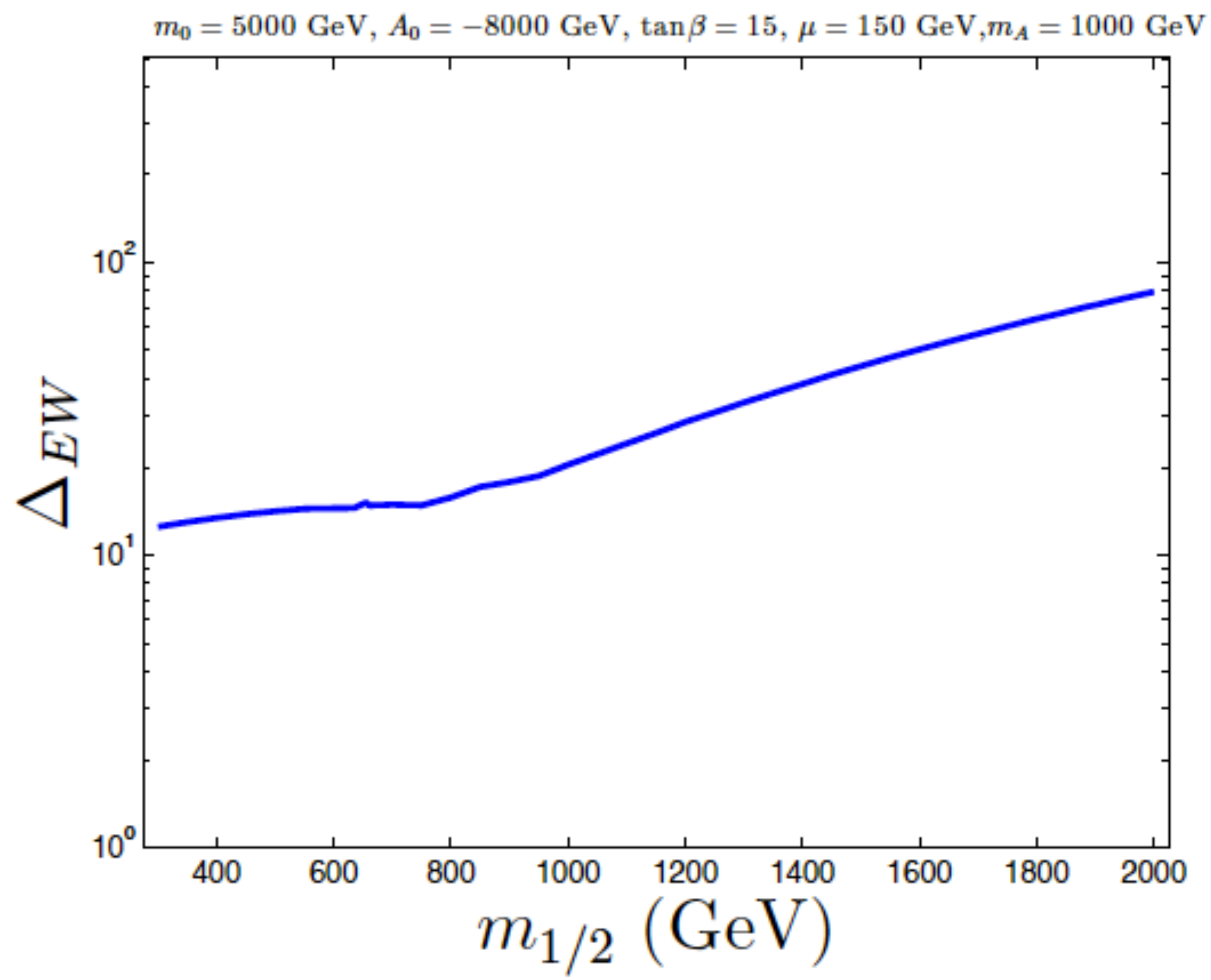
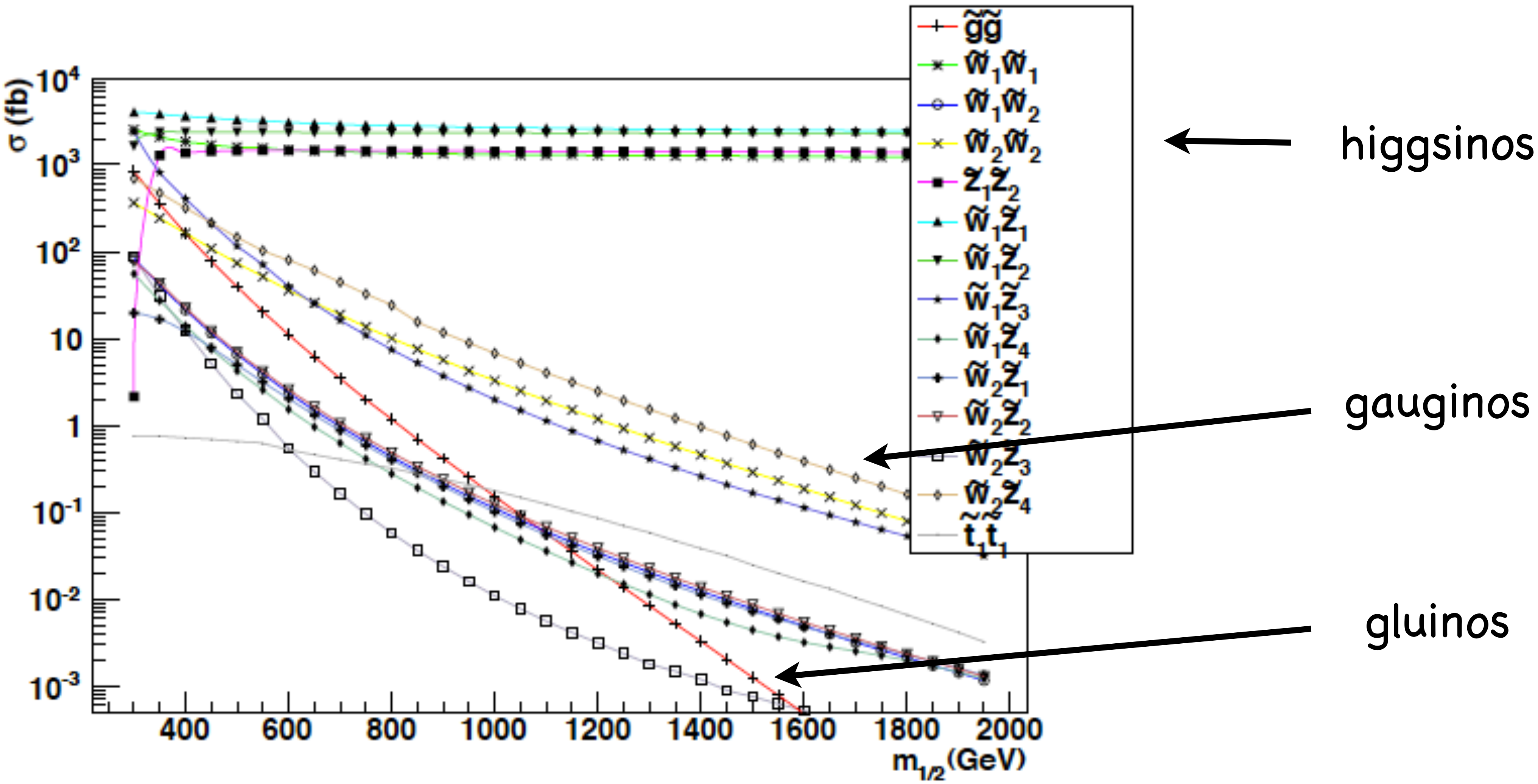


Figure 1: Plot of $\Delta_{\rm EW}$ versus $m_{1/2}$ along the RNS model line.

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, arXiv:1310.4858

Sparticle prod'n along RNS model-line at LHC14:

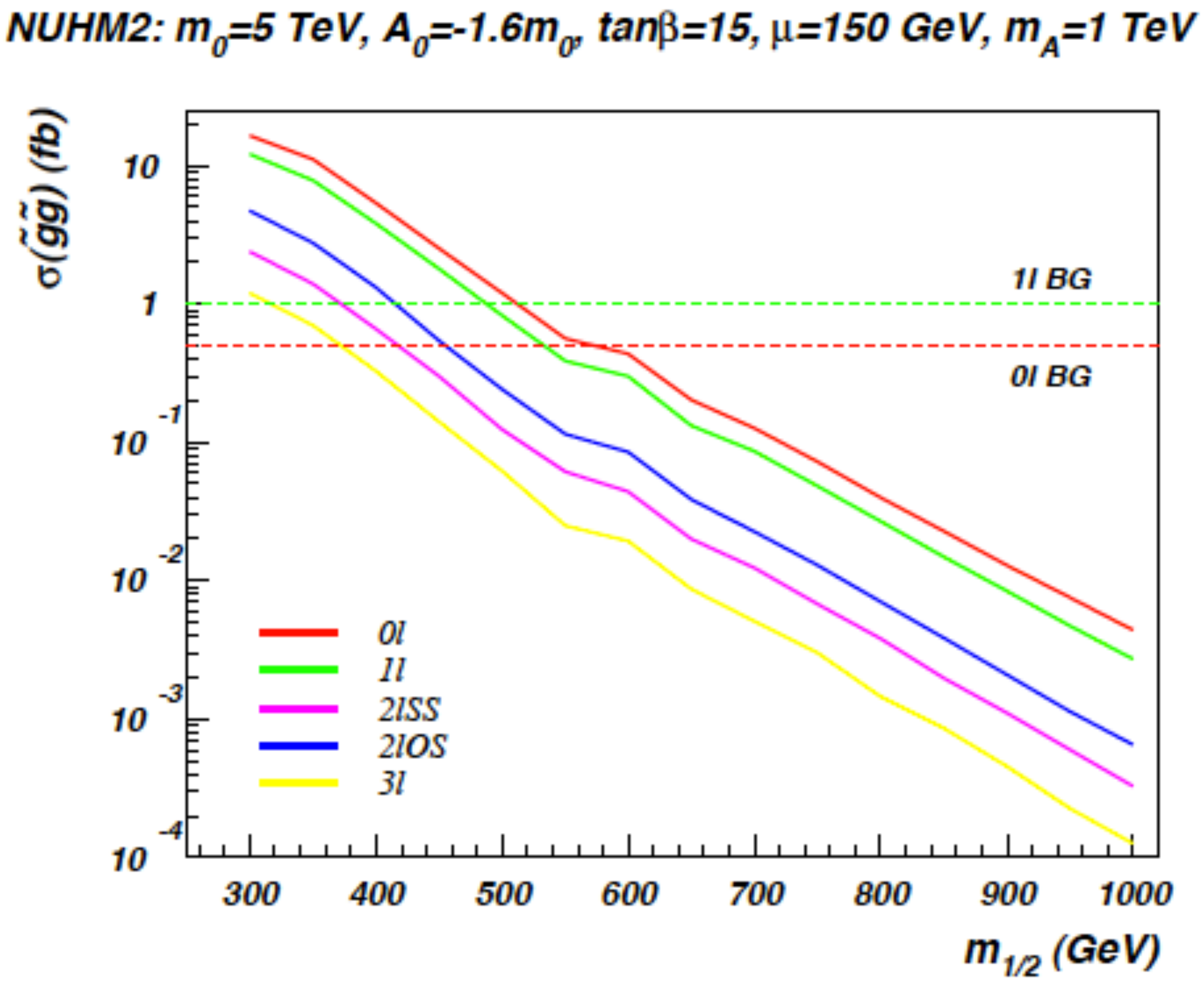


higgsino pair production dominant-but only soft visible energy release from higgsino decays

largest visible cross section: wino pairs

gluino pairs sharply dropping

gluino pair cascade decay signatures



Particle	dom. mode	BF
$\tilde{g}$	$\tilde{t}_1 t$	$\sim 100\%$
$\tilde{t}_1$	$b\widetilde{W}_1$	$\sim 50\%$
$\widetilde{Z}_2$	$\widetilde{Z}_1 f\bar{f}$	$\sim 100\%$
$\widetilde{Z}_3$	$\widetilde{W}_1^{\pm} W^{\mp}$	$\sim 50\%$
$\widetilde{Z}_4$	$\widetilde{W}_1^{\pm} W^{\mp}$	$\sim 50\%$
$\widetilde{W}_1$	$\widetilde{Z}_1 f\bar{f}'$	$\sim 100\%$
$\widetilde{W}_2$	$\widetilde{Z}_i W$	$\sim 50\%$

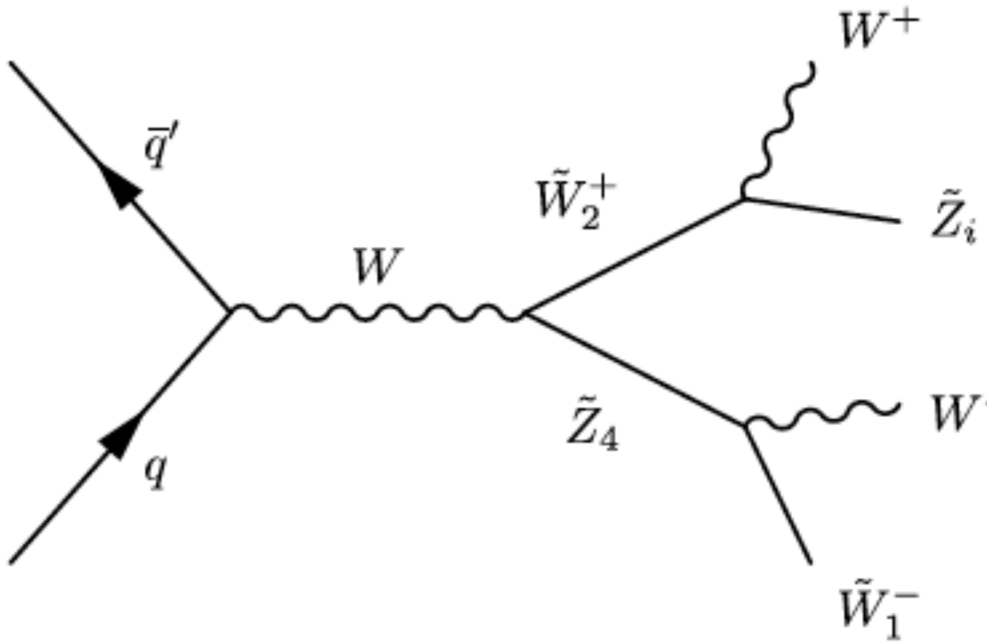
Table 1: Dominant branching fractions of various sparticles along the RNS model line for $m_{1/2} =$ 1 TeV.

Int. lum. (fb^{-1})	$\tilde{g}\tilde{g}$
10	1.4
100	1.6
300	1.7
1000	1.9

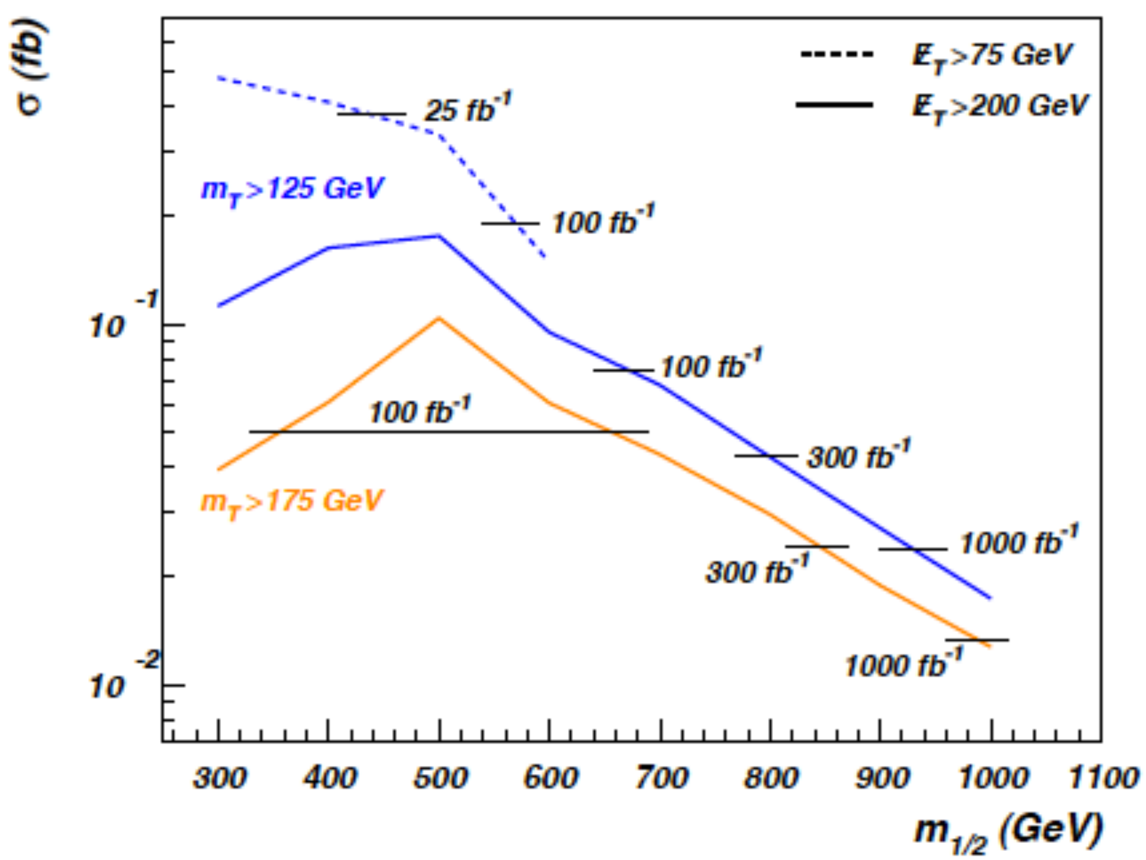
LHC14 reach in m(gluino) (TeV)

since m(gluino) extends to ~5 TeV, LHC14 can see about half the low EWFT parameter space in these modes

Characteristic same-sign diboson (SSdB) signature from SUSY models with light higgsinos:



wino pair production

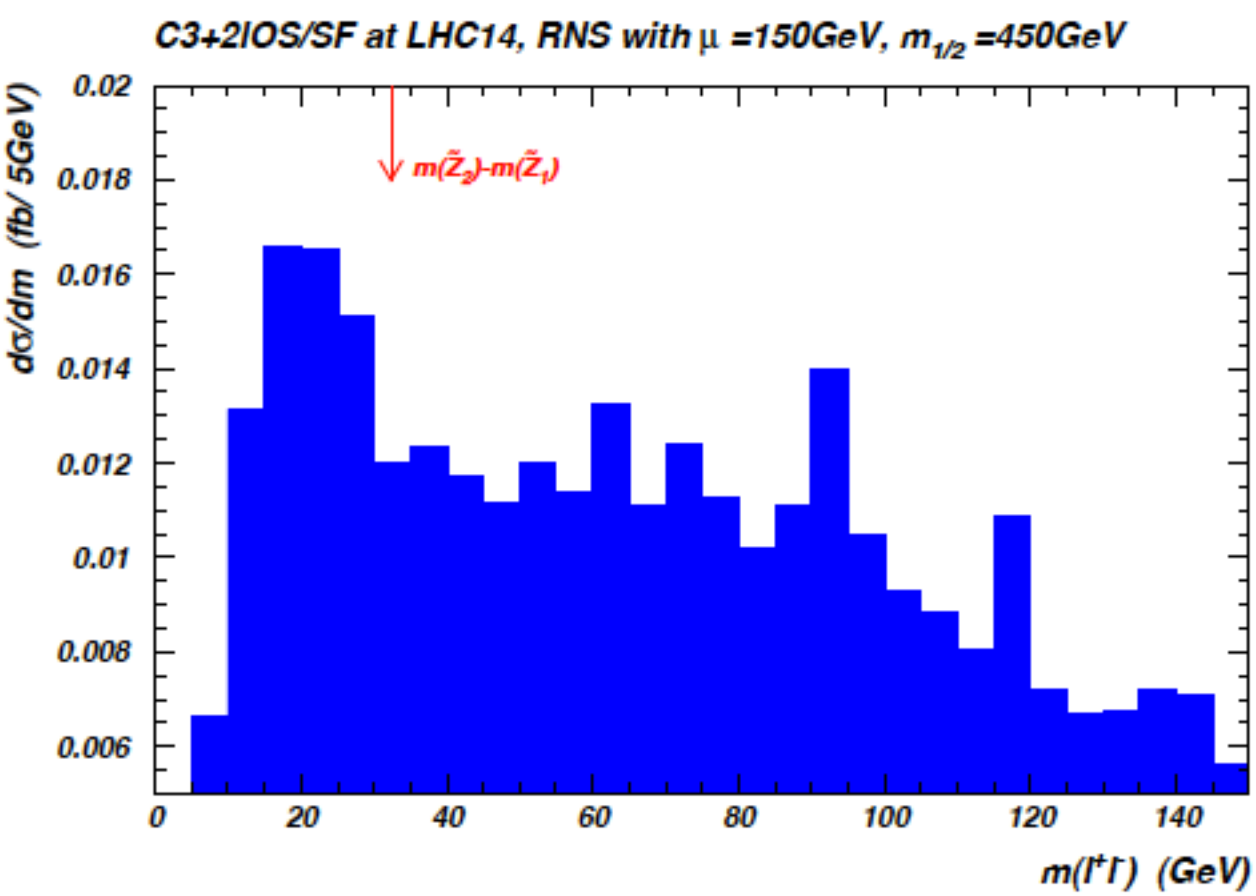


This channel offers best reach of LHC14 for RNS; it is also indicative of wino-pair prod'n followed by decay to higgsinos

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

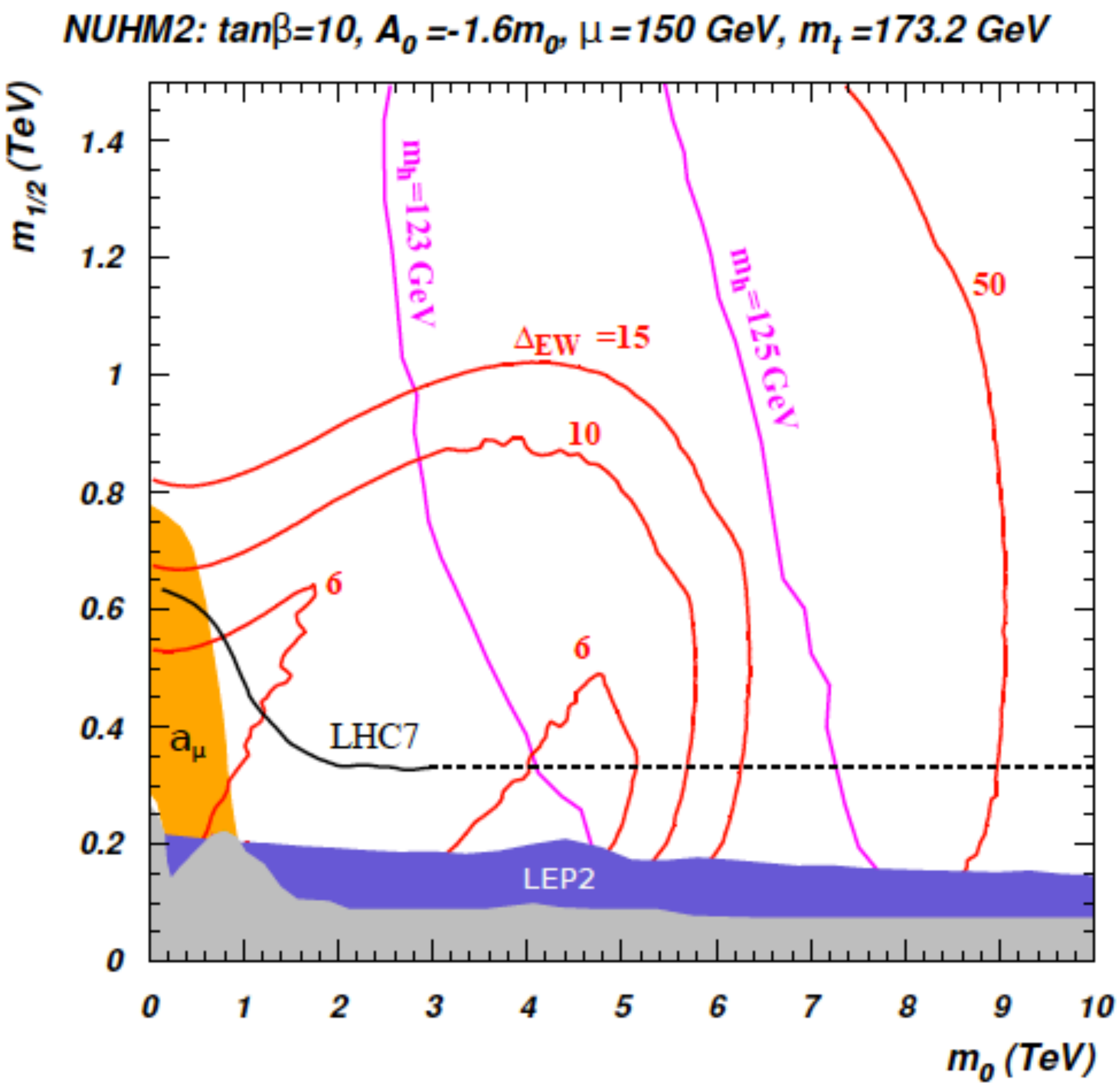
LHC14 has some reach for RNS; if a signal is seen, should be characteristic

Int. lum. (fb^{-1})	$\tilde{g}\tilde{g}$	SSdB	$WZ \to 3\ell$	4ℓ
10	1.4	–	–	–
100	1.6	1.6	–	~ 1.2
300	1.7	2.1	1.4	$\gtrsim 1.4$
1000	1.9	2.4	1.6	$\gtrsim 1.6$



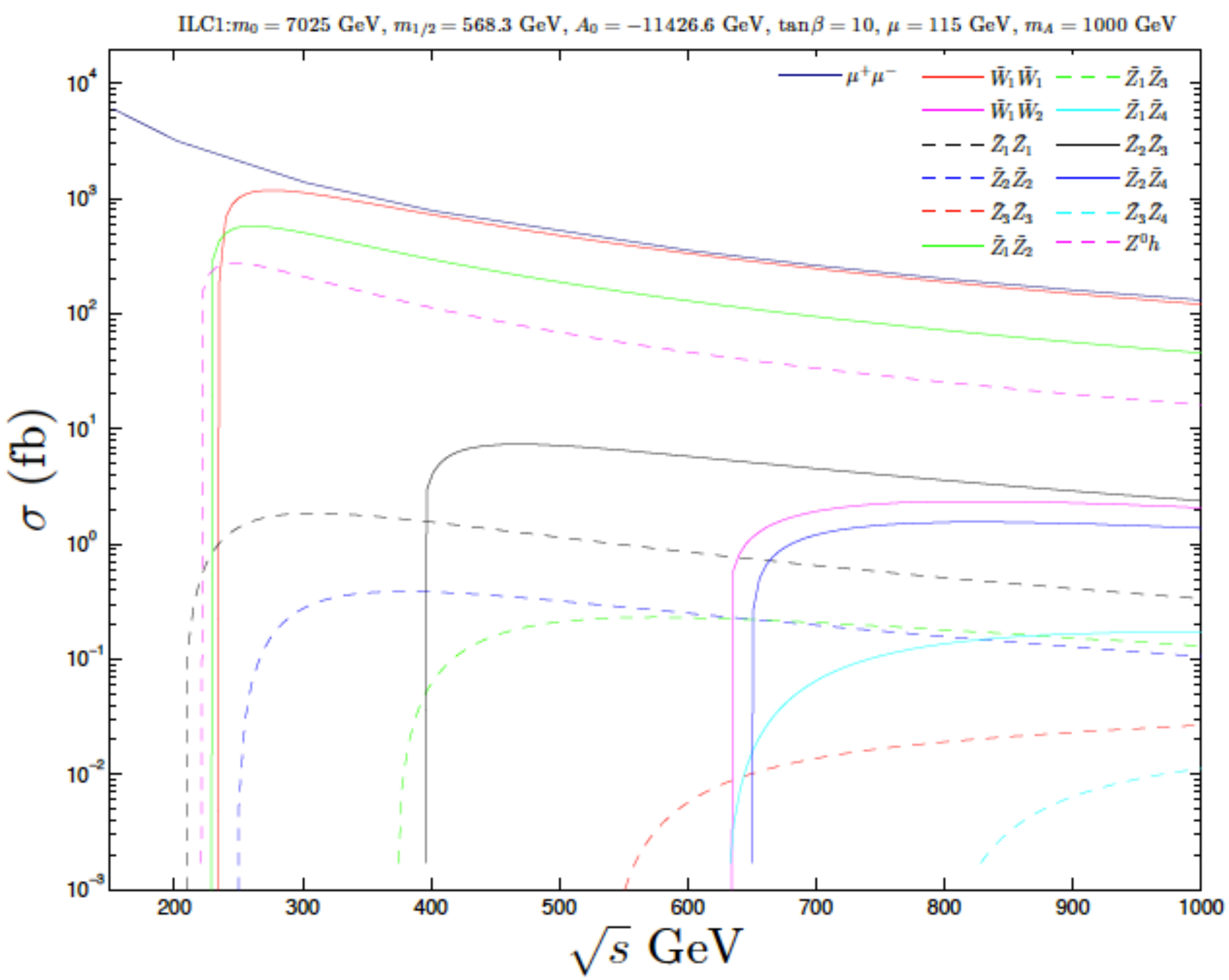
OS/SF dilepton mass edge apparent from cascade decays with z2->z1+l+lbar

Good old m0 vs. mhf plane still viable, but require low mu (NUHM2)



$\mu = 150$ GeV throughout which is allowed for NUHM2

Smoking gun signature: light higgsinos at ILC: ILC is Higgs/higgsino factory and a SUSY discovery machine!



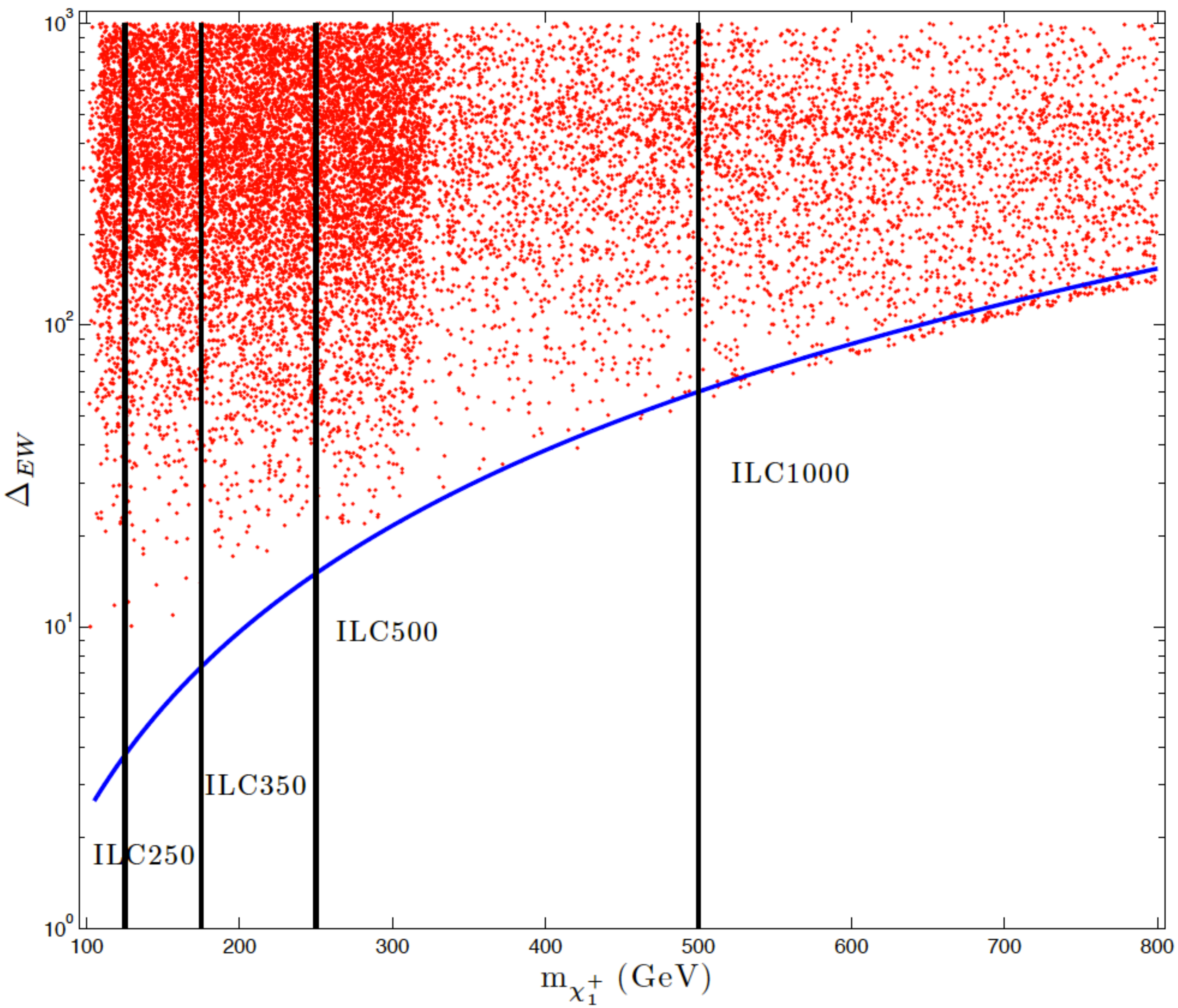
$$\sigma(higgsino) \gg \sigma(Zh)$$

10-15 GeV higgsino mass gaps no problem in clean ILC environment

ILC either sees light higgsinos or natural SUSY dead

Smoking gun signature: 4 light higgsinos at ILC!

$$e^+e^- \to \tilde{W}_1^+\tilde{W}_1^-,\ \tilde{Z}_1\tilde{Z}_2$$



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

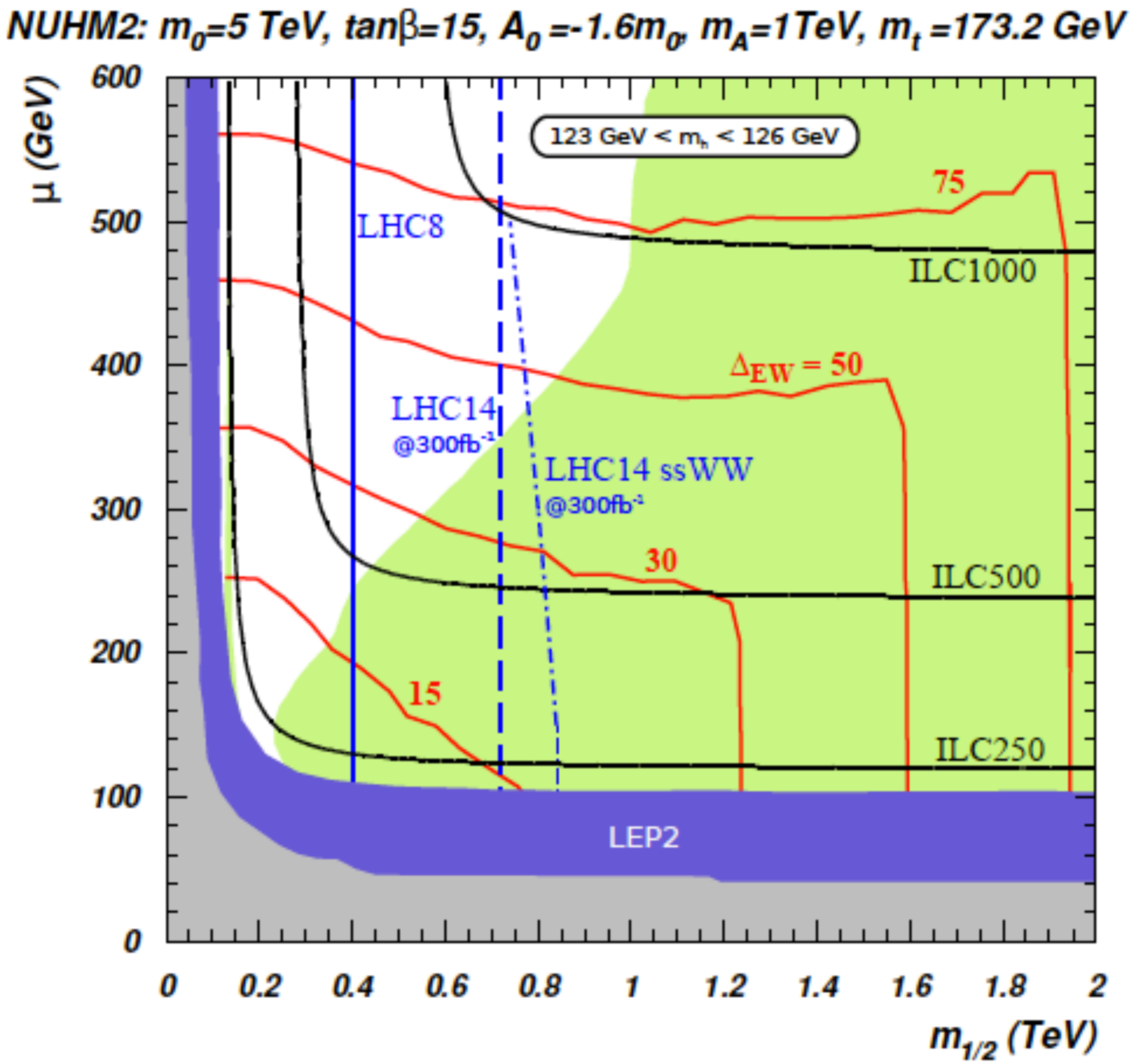
$$\sqrt{s} \sim \sqrt{2\Delta_{EW}}m_Z$$

ILC has capability to measure SUSY parameters and actually reconstruct

$$\Delta_{EW}$$

measure and check if nature is EWFT'd?

LHC/ILC complementarity



When to give up on naturalness in SUSY?
If ILC(500-600 GeV) sees no light higgsinos

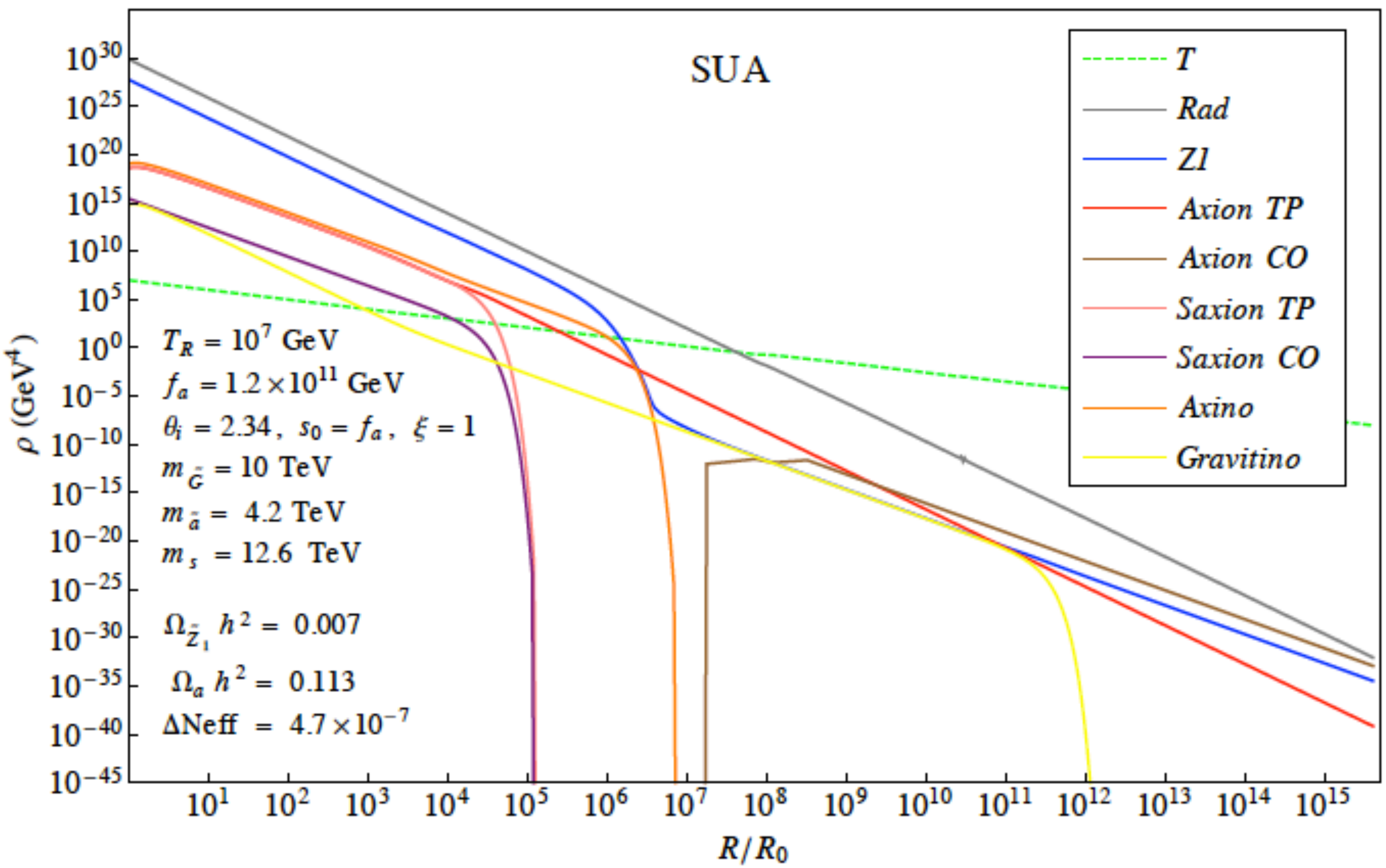
dark matter in natural SUSY

- thermal WIMP (higgsino) abundance low by 10-15
- solve ``strong fine-tuning" via axion
- tame SUSY mu problem via Kim-Nilles/DFSZ
- get 90-95% axion CDM plus 5-10% higgsinos over bulk of parameter space
- reduced abundance of higgsinos still seeable at ton-scale WIMP detectors
- expect axion as well at e.g. ADMX but with DFSZ cplg

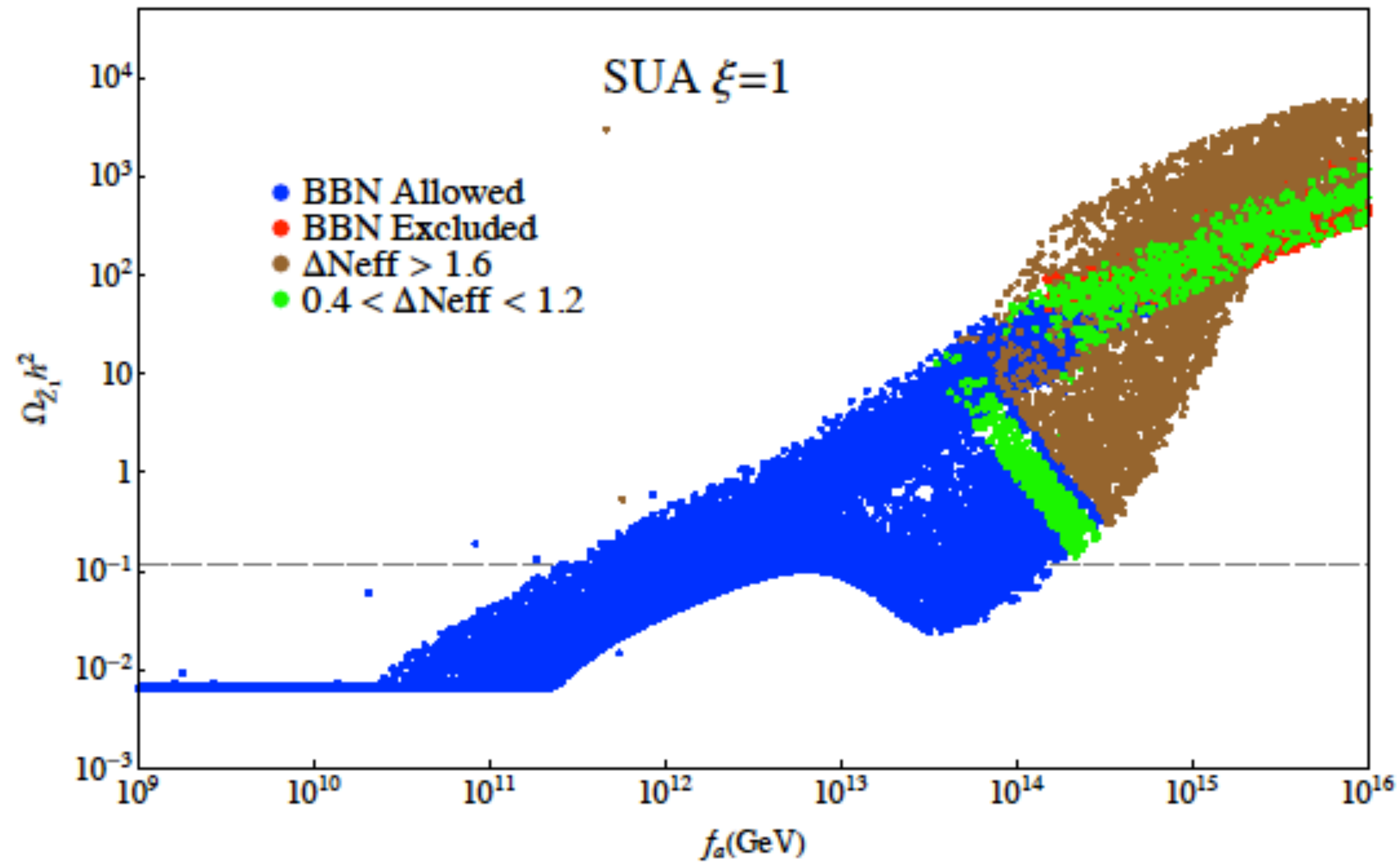
mixed axion-neutralino production in early universe

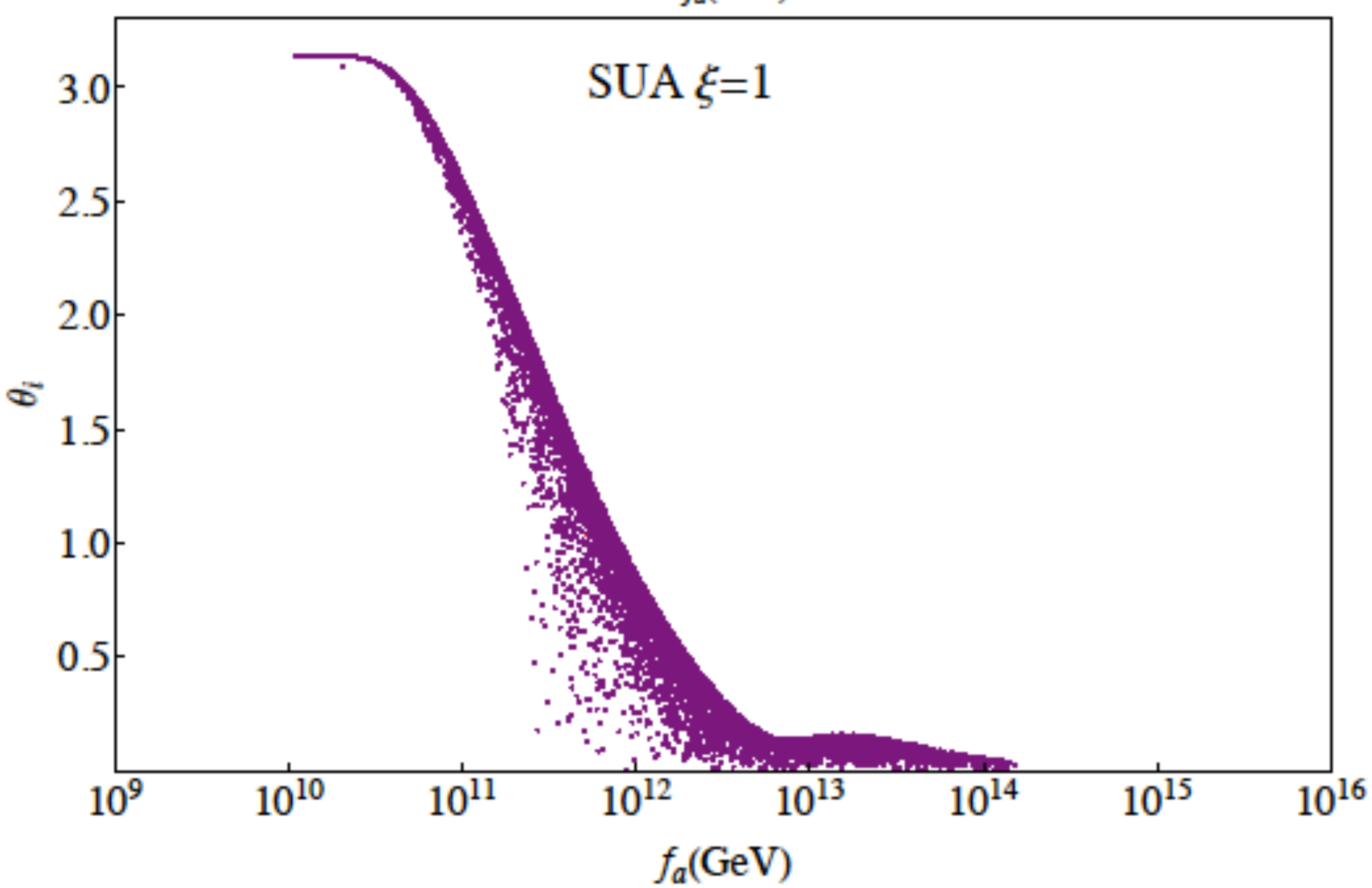
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: dark radiation ($\Delta N_{eff} < 1.6$)
- axinos: TP
  - $\tilde{a} \to SUSY$ augments neutralinos
- gravitinos: TP, decay to SUSY

DM production: solve eight coupled Boltzmann equation



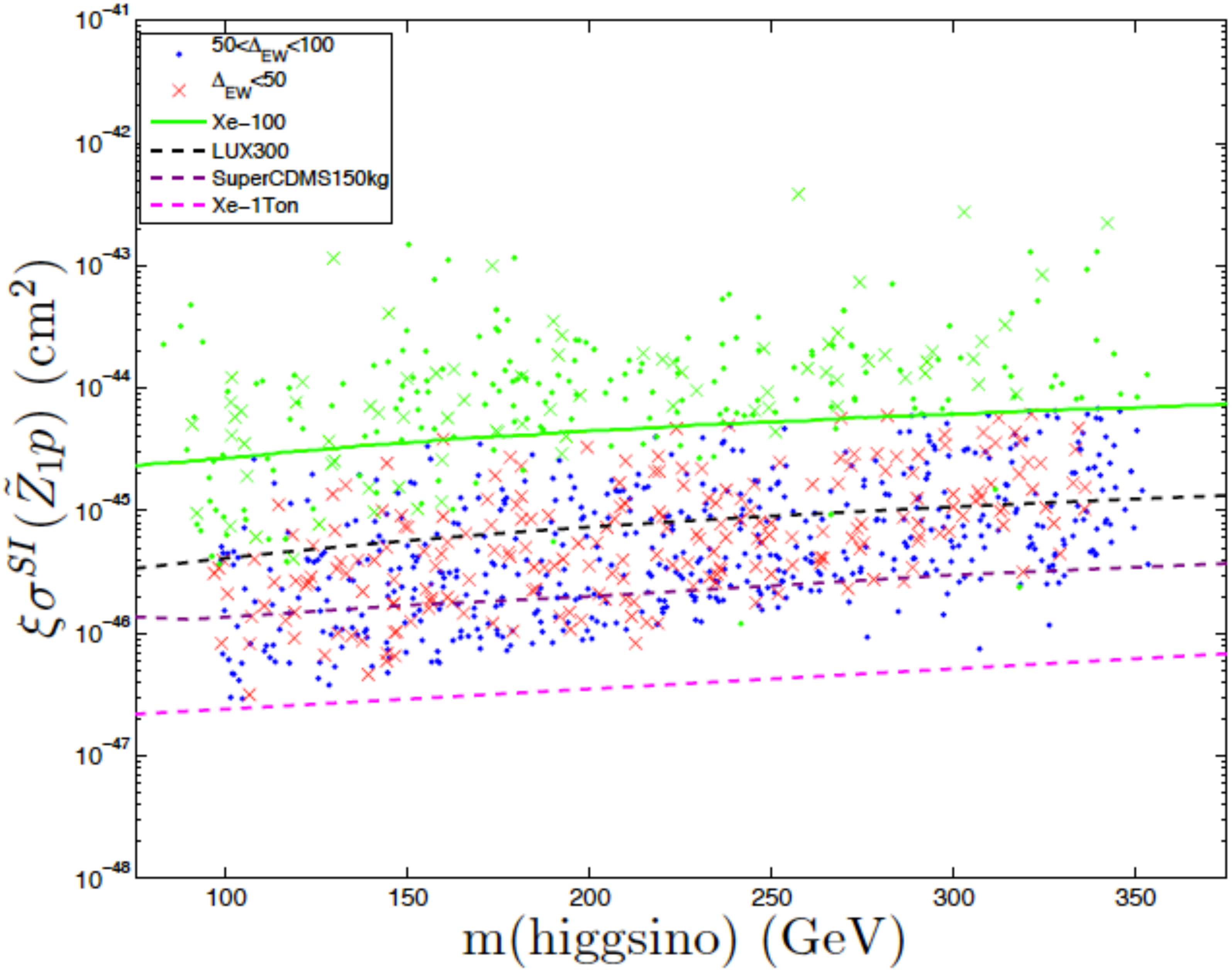
HB, Bae, Chun;
HB,Bae, Lessa, Serce





mainly axion CDM for fa<10^11 GeV; for higher fa, then get increasing wimp abundance

Direct higgsino detection rescaled for minimal local abundance



HB, Barger, Mickelson
arXiv:1303.3816

$$\mathcal{L} \ni -X^h_{11}\overline{\widetilde{Z}}_1\widetilde{Z}_1 h$$

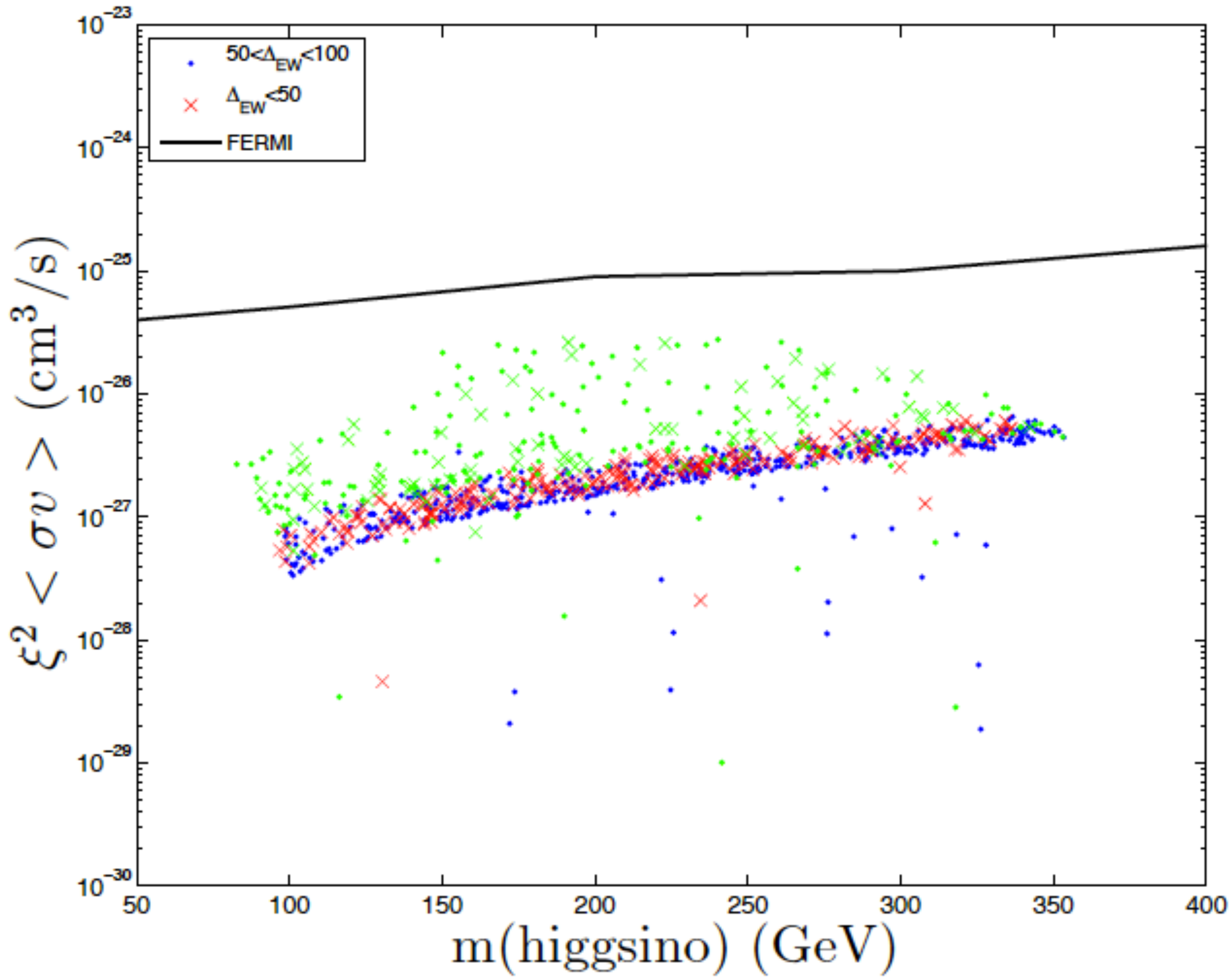
$$X^h_{11} = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

new LUX results

Deployment of Xe-1ton coming soon!

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

Higgsino detection via halo annihilations:



green: excluded by Xe-100

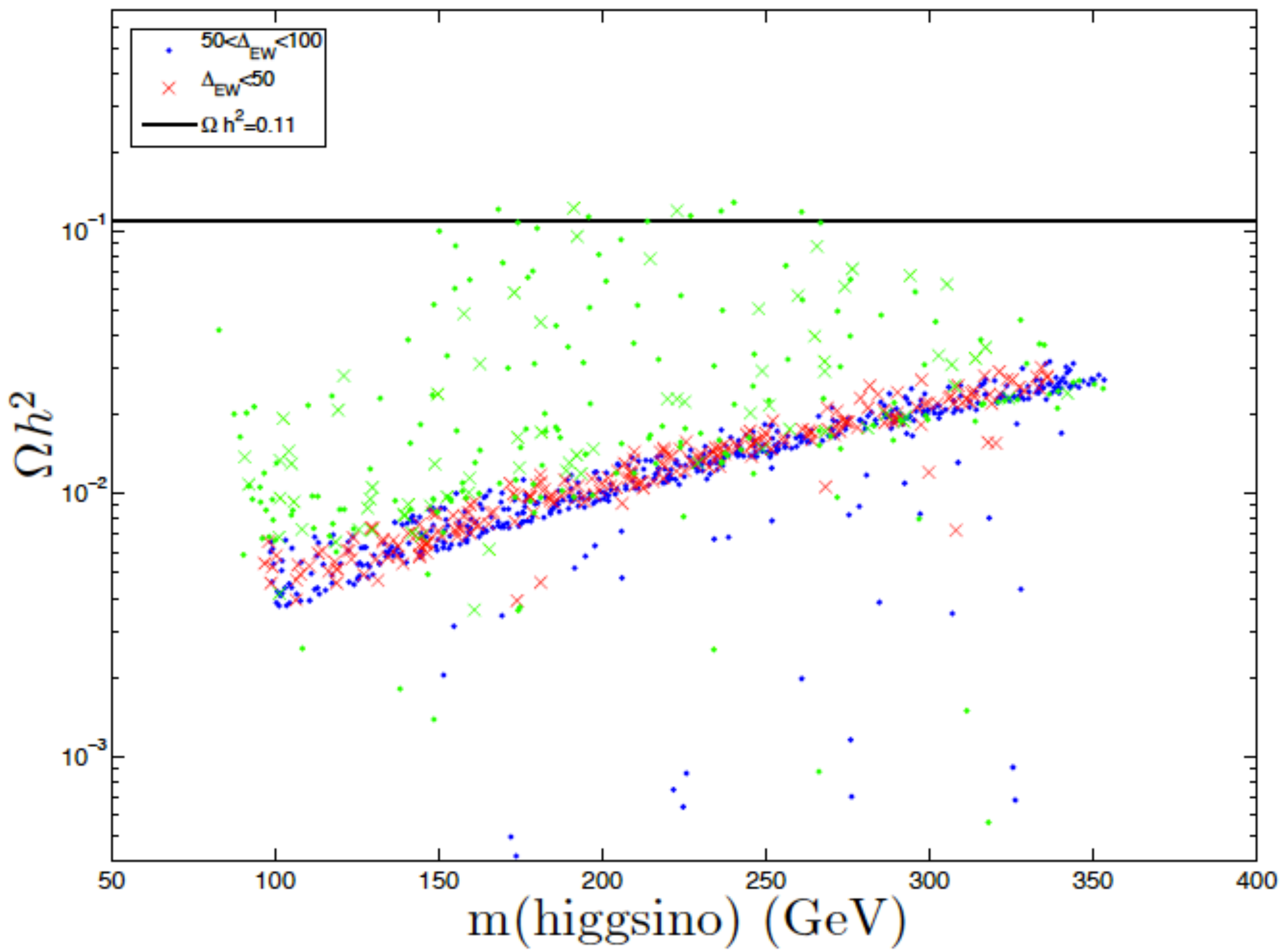
annihilation rate is high but rescaling is squared

Gamma-ray sky signal is factor 10-20 below current limits

Summary

- Radiatively-driven natural SUSY: reconciles naturalness with m(h)~125 GeV and no LHC8 SUSY signal
- light m(higgsino)~100-200 GeV
- light higgsinos: difficult to see at LHC
- Japan ILC is natural SUSY discovery machine
- solve QCD/EW fine-tuning: mixed axion-higgsino dark matter
- SUSY DFSZ: solves mu problem: relate m(h) to m(axion)
- preferred axion range: fa~10^10-10^12 GeV
- WIMP detection also but may need ton-scale detector

Mainly higgsino-like WIMPs thermally underproduce DM



green: excluded;
red/blue:allowed

Factor of 10-15 too low

But so far we have addressed only Part 1
of fine-tuning problem:

In QCD sector, the term $\frac{\bar{\theta}}{32\pi^2}F_{A\mu\nu}\tilde{F}_A^{\mu\nu}$ must occur

But neutron EDM says it is not there: strong CP problem

(frequently ignored by SUSY types)

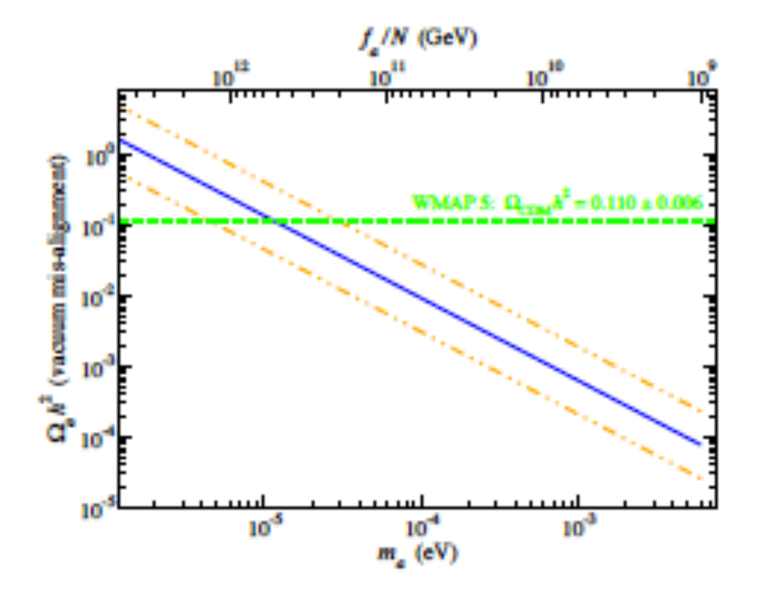
Best solution after 35 years: PQWW invisible axion

In SUSY, axion accompanied by axino and saxion

Changes DM calculus:
expect mixed WIMP/axion DM (2 particles)

Axion cosmology

- ★ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$:
    $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ★ a(x) oscillates,
  creates axions with $\vec{p} \sim 0$:
  production via vacuum mis-alignment
- ★ $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times10^{-6} eV}{m_a}\right]^{7/6} \theta_i^2 h^2$
- ★ astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 GeV$



Axino/saxion decays

Decays very model-dependent;
also depend on KSVZ or DFSZ model

axino-> particle+sparticle: augment LSP abundance but
also provide late-time entropy injection

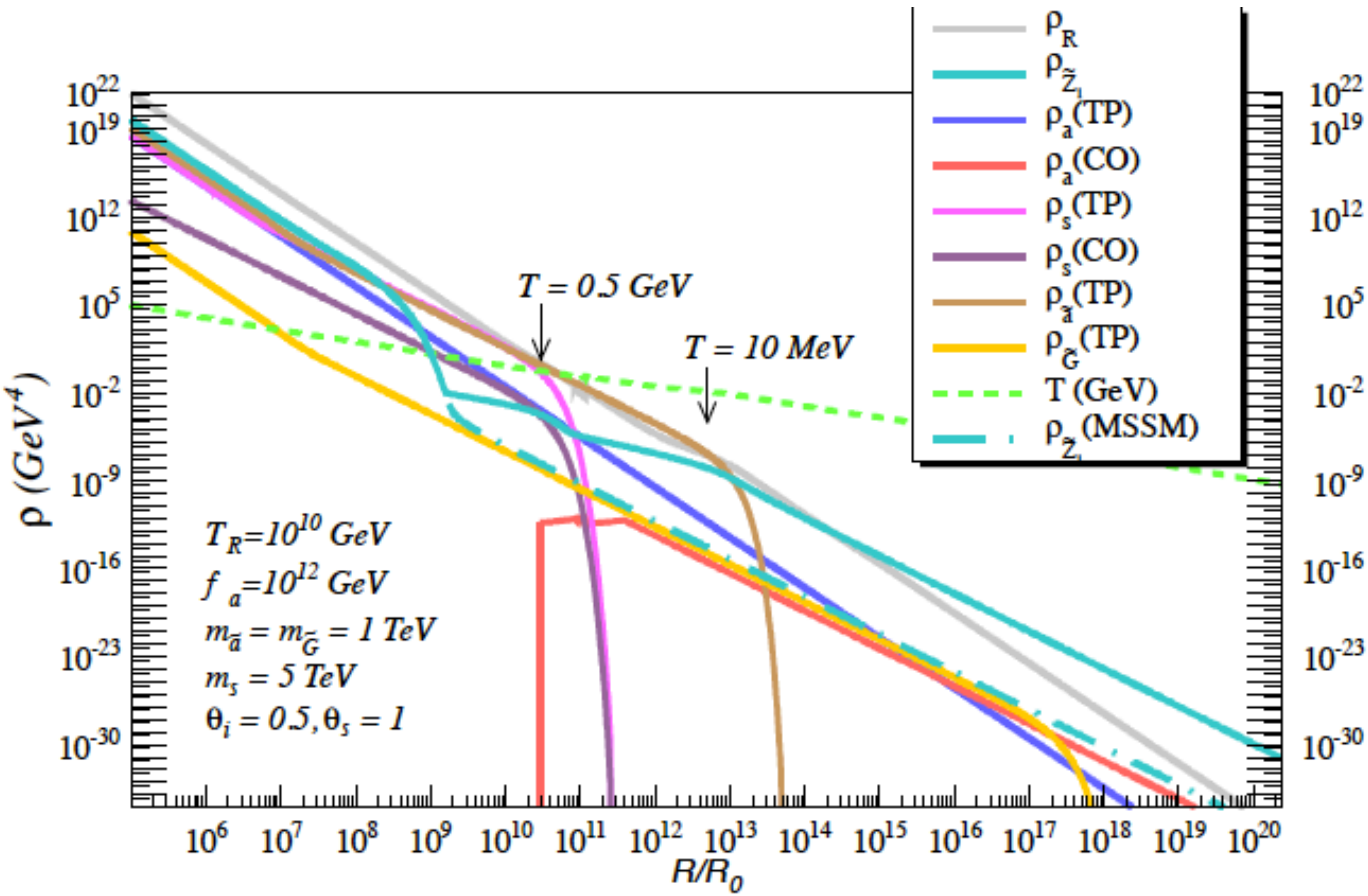
saxion-> gg, hh, etc SM particles (entropy dilution)

saxion-> glno+gno, hgno+hgno, etc (SUSY particles, augment)

saxion->aa, dark radiation, $\Delta N_{eff}\ bounds$

Bae, HB, Lessa, JCAP1304 (2013) 041

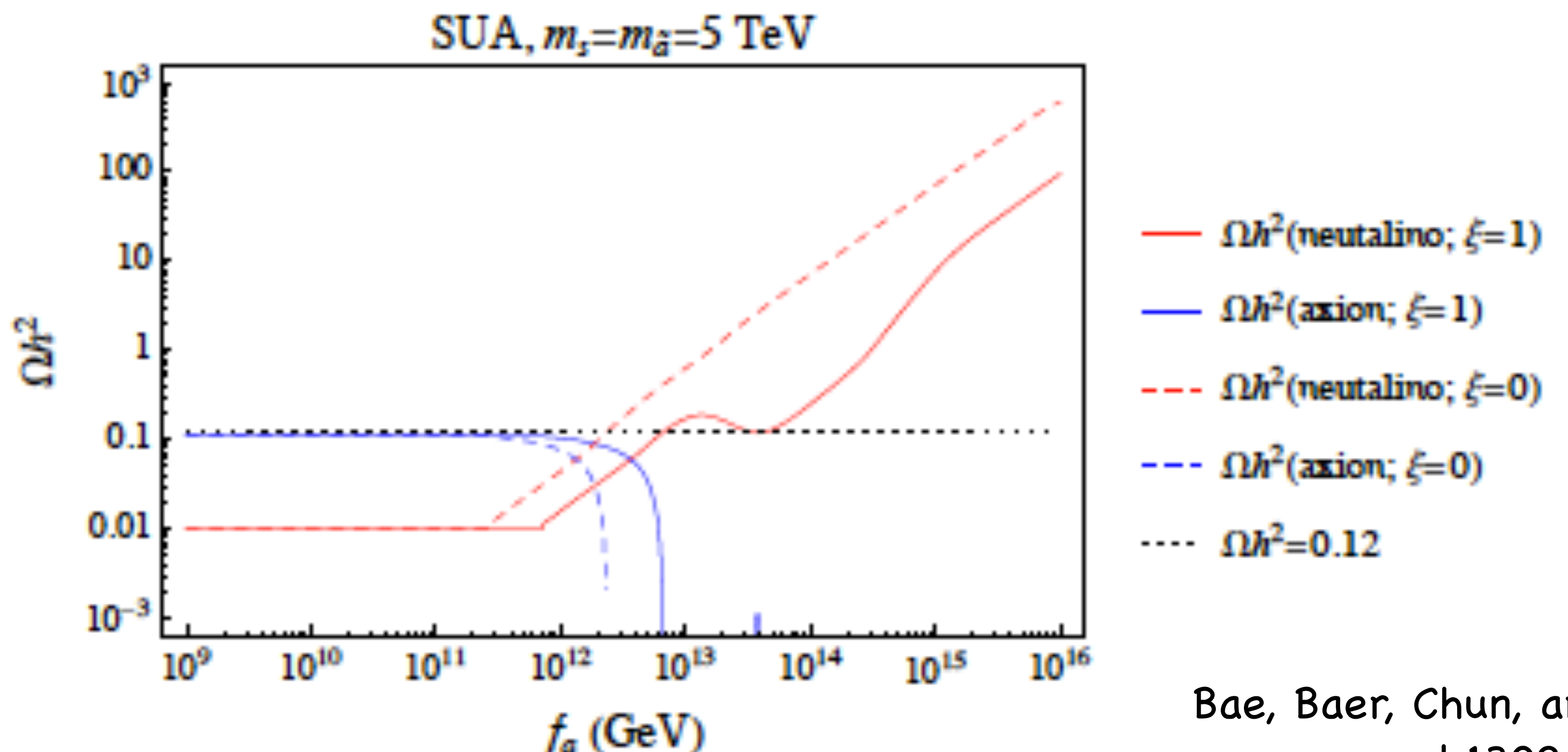
Coupled Boltzmann KSVZ $\xi = 0$



HB, Lessa, Sreethawong

Tree level axion superfield couplings to higgs/higgsinos: axino/saxion decay before WIMP freezeout for f_a<10^12 GeV

Then usual WIMP abundance obtains but supplemented by axion CDM!



Bae, Baer, Chun, arXiv:1309.0519 and 1309.5365

Get 90-95% axion CDM plus 5-10% higgsino-like WIMPs

Detection of mixed a/Z1 DM in natural SUSY with DFSZ axion

detection of axion as usual: range of PQ scale f_a: 10^10-10^11 favored in SUSY DFSZ

detection of WIMPs same as usual but theory projections should be scaled to account for WIMPs making only a fraction of total DM density

use Bottino, Fornengo et al. $\xi \equiv \Omega_\chi h^2/0.12$ rescaling factor