SUSY naturalness with implications for LHC, ILC, axion and WIMP detection

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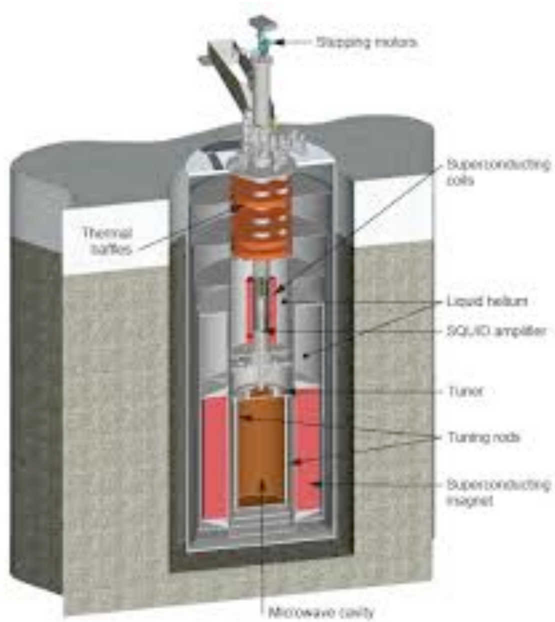

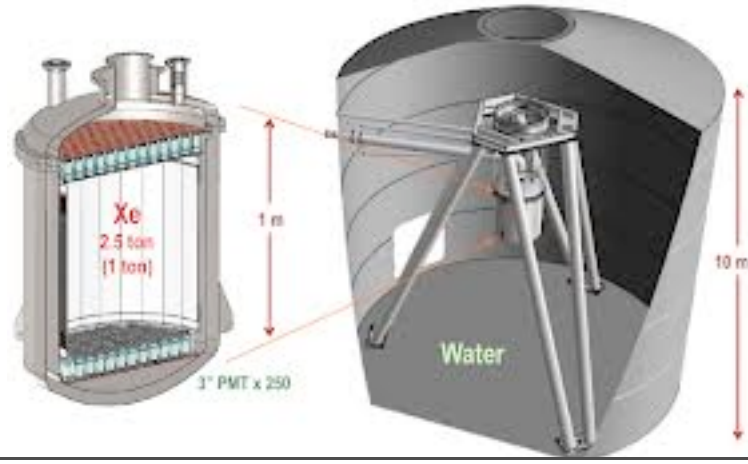

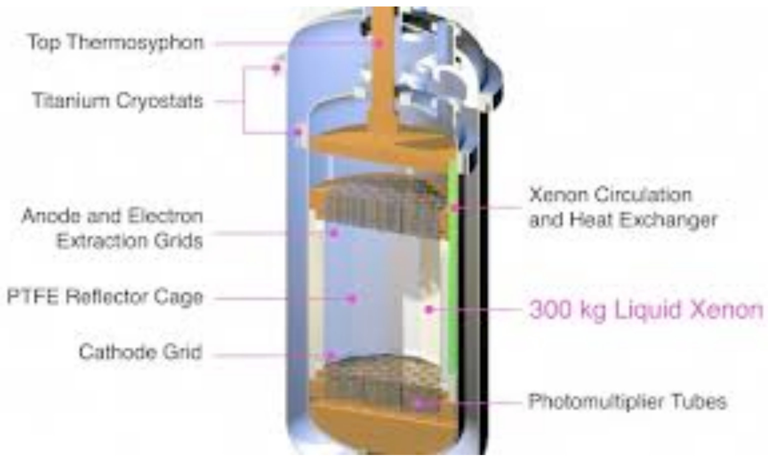

is 2 fine-tuned?

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$$2 = 2 - b + b$$

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$$\lim_{b \to \infty} = ?$$

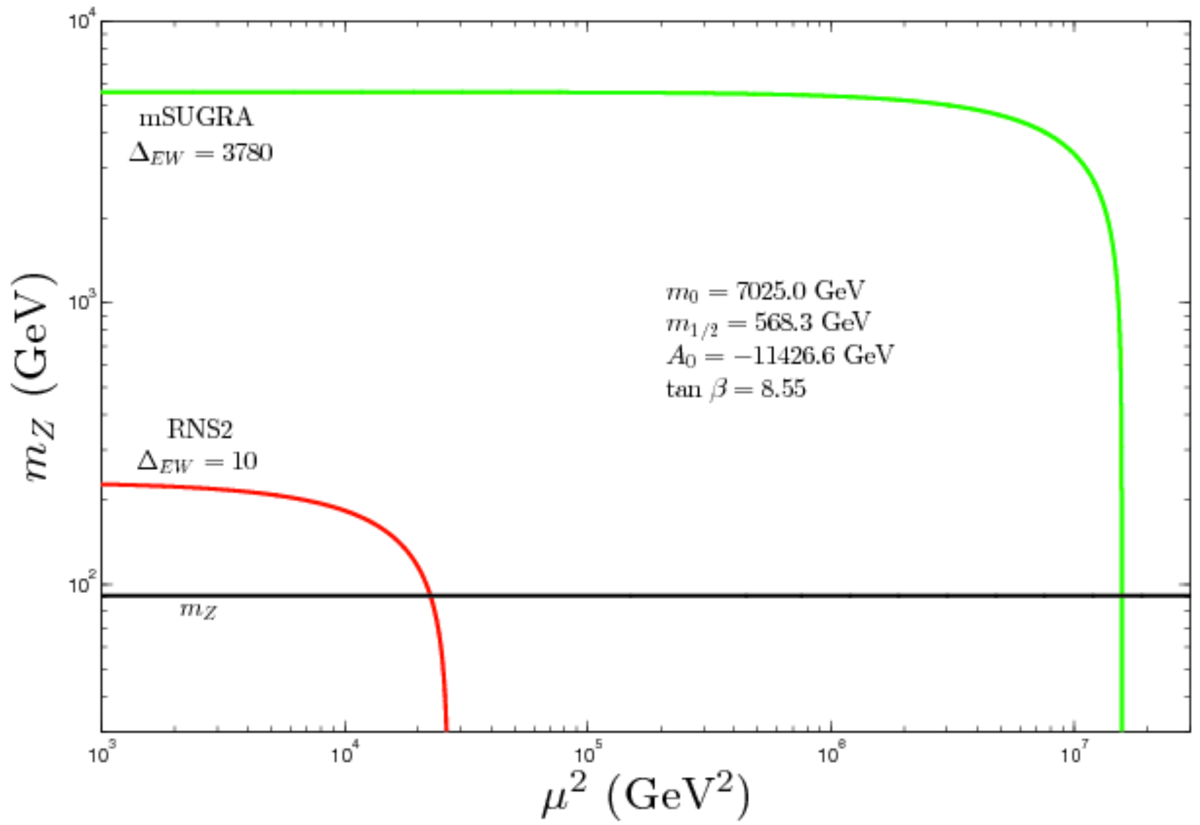
Prime directive on fine-tuning:

``Thou shalt not claim fine-tuning of dependent quantities one against another!"

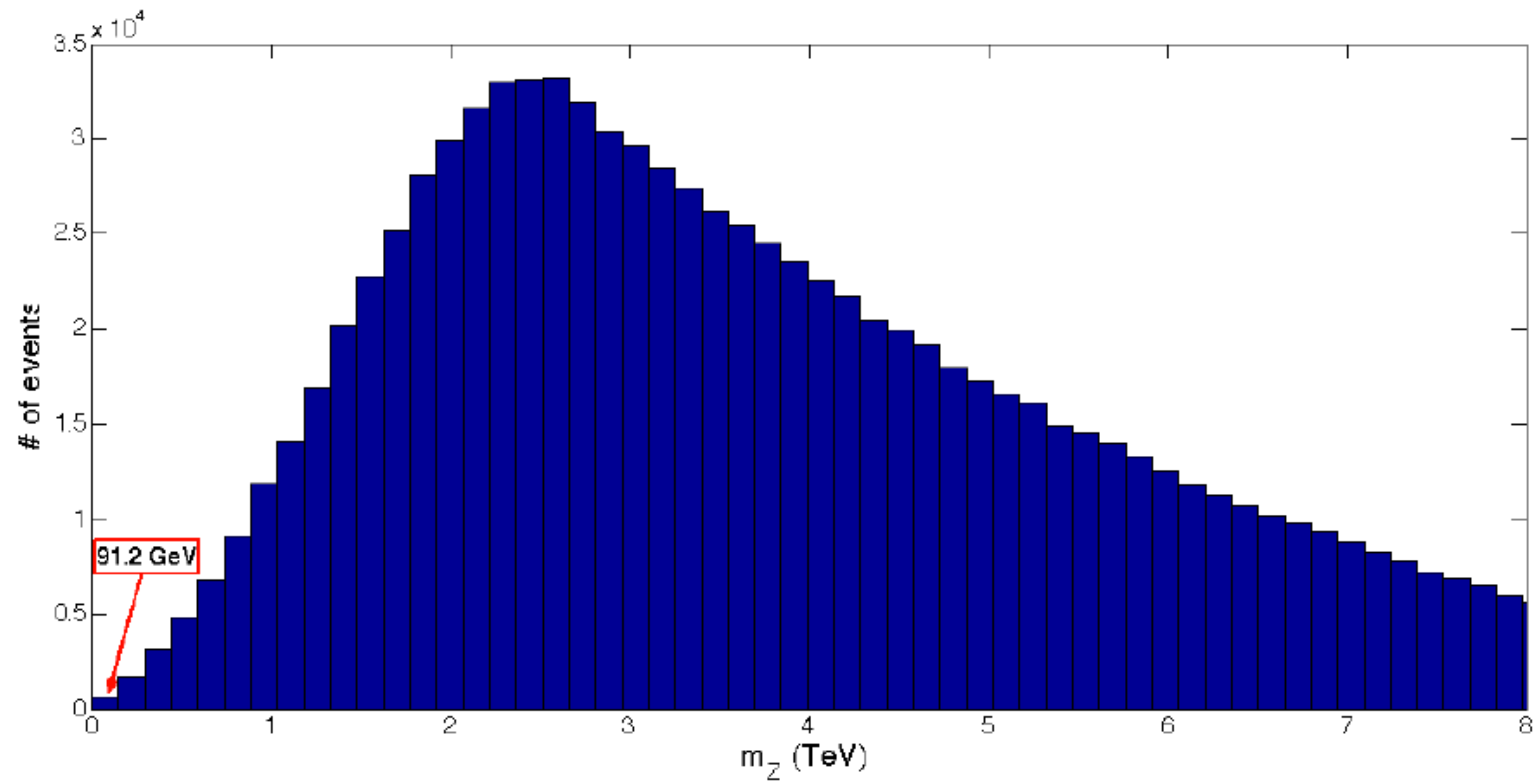
Simple electroweak fine-tuning:
everybody does it but it is hidden inside spectra codes
(Isajet, SuSpect, SoftSUSY, Spheno)

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

e.g. in CMSSM/mSUGRA:



If you didn't fine-tuned, then here is m(Z)



The 20 dimensional pMSSM parameter space then includes

$$
\begin{aligned}
M_1,\ M_2,\ M_3,\\
m_{Q_1},\ m_{U_1},\ m_{D_1},\ m_{L_1},\ m_{E_1},\\
m_{Q_3},\ m_{U_3},\ m_{D_3},\ m_{L_3},\ m_{E_3},\\
A_t,\ A_b,\ A_\tau,\\
m^2_{H_u},\ m^2_{H_d},\ \mu,\ B.
\end{aligned}
$$

scan over parameters

Natural value of m(Z) from pMSSM is ~2-4 TeV

#1: Simplest SUSY measure: Δ_{EW}

Working only at the weak scale, minimize scalar potential: calculate m(Z) or m(h)

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

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

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

simple, direct, unambiguous interpretation:

- $|\mu| \sim m_Z \sim 100 - 200$ GeV — Arnowitt, Nath; Chan, Chattopadyaya, Nath
- $m_{H_u}^2$ should be driven to small negative values such that $-m_{H_u}^2 \sim 100 - 200$ GeV at the weak scale and
- that the radiative corrections are not too large: $\Sigma_u^u \lesssim 100 - 200$ GeV

Large A_t reduces $\Sigma_u^u(\tilde{t}_{1,2})$ whilst lifting m_h to 125.5 GeV

Radiative natural SUSY with a 125 GeV Higgs boson (with V. Barger, P. Huang, A. Mustafayev and X. Tata), Phys. Rev. Letters **109** 161802 (2012).

#2: Higgs mass or large-log fine-tuning Δ_{HS}

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

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right) \qquad X_t = m_{Q3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$$

neglect gauge pieces, S, mHu and running;
then we can integrate from m(SUSY) to Lambda

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

$\Delta_{HS} \sim \delta m_h^2/(m_h^2/2) < 10$ then

$m_{\tilde{t}_{1,2},\tilde{b}_1} < 500$ GeV

$m_{\tilde{g}} < 1.5$ TeV

A_t can't be too big

What's wrong with this argument?

In zeal for simplicity, have made several simplifications: most important is that one sets m(Hu)^2=0 at beginning to simplify

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

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

The dependent terms should be grouped together

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

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

After re-grouping: $\Delta_{HS} \simeq \Delta_{EW}$

#3: EENZ/BG traditional measure Δ_{BG}

Such a re-grouping is properly used
in the EENZ/BG measure:

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

Here, the a_i are parameters of the theory

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

↑

express weak scale value in terms of high scale parameters

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

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

$$\begin{aligned}
-2\mu^2(m_{SUSY}) &= -2.18\mu^2 \\
-2m_{H_u}^2(m_{SUSY}) &= 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
&+0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
&-0.025M_1A_t + 0.22A_t^2 + 0.004m_3A_b \\
&-1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
&+0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
&+0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
&+0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2,
\end{aligned}$$

all GUT scale parameters

Abe, Kobayashi, Omura; S. P. Martin

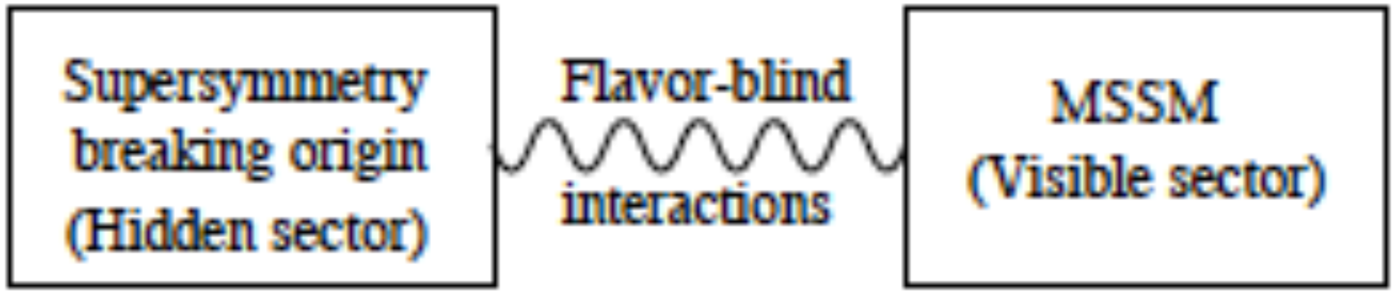
For generic parameter choices, Δ_{BG} *is large*

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!

To properly apply BG measure, need to identify independent soft breaking terms



examine gravity mediation

For any particular SUSY breaking hidden sector, each soft term is some multiple of gravitino mass m(3/2)

$$
\begin{aligned}
m_{H_u}^2 &= a_{H_u} \cdot m_{3/2}^2, \\
m_{Q_3}^2 &= a_{Q_3} \cdot m_{3/2}^2, \\
A_t &= a_{A_t} \cdot m_{3/2}, \\
M_i &= a_i \cdot m_{3/2}, \\
& \cdots .
\end{aligned}
$$

Since we don't know hidden sector, we impose parameters which parameterize our ignorance:

but this doesn't mean each parameter is independent

e.g. dilaton-dominated SUSY breaking: $m_0^2 = m_{3/2}^2$ with $m_{1/2} = -A_0 = \sqrt{3} m_{3/2}$

Writing each soft term as a multiple of m(3/2) then we allow for maximal correlations/cancellations:

GUT scale param's

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

numerical co-efficient which depends on hidden sector

for naturalness, then

$\mu^2 \sim m_Z^2$ and $a \cdot m_{3/2}^2 \sim m_Z^2$

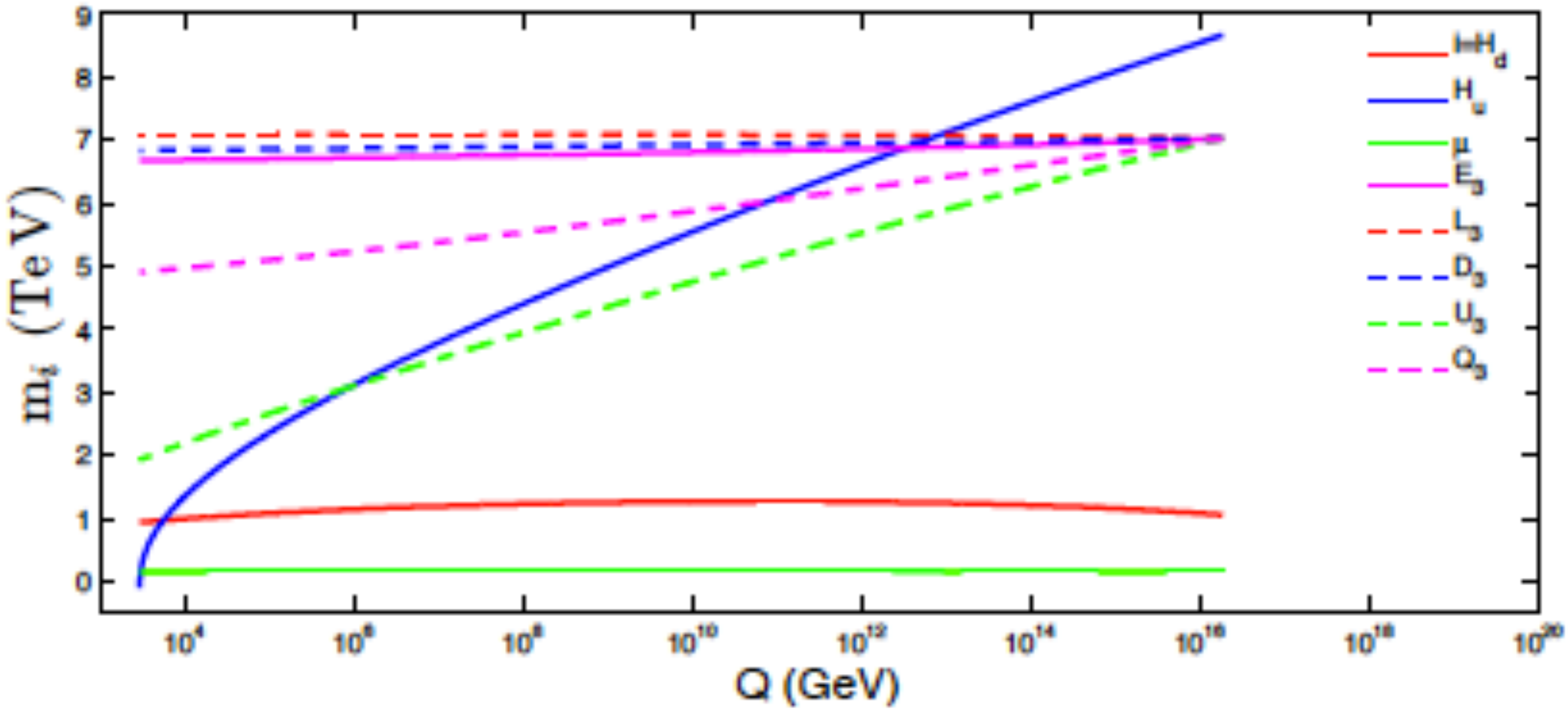
either $m_{3/2} \sim m_Z$ *or* a is small

$$m_Z^2 \simeq -2\mu^2(weak) - 2m_{H_u}^2(weak) \simeq -2.18\mu^2(GUT) + a \cdot m_{3/2}^2$$

then $-m_{H_u}^2(weak) \sim a \cdot m_{3/2}^2 \sim m_Z^2$

$$\lim_{n_{SSB}\to 1} \Delta_{BG} \to \Delta_{EW}$$

Applied properly, all three measures agree: naturalness is unambiguous and highly predictive!

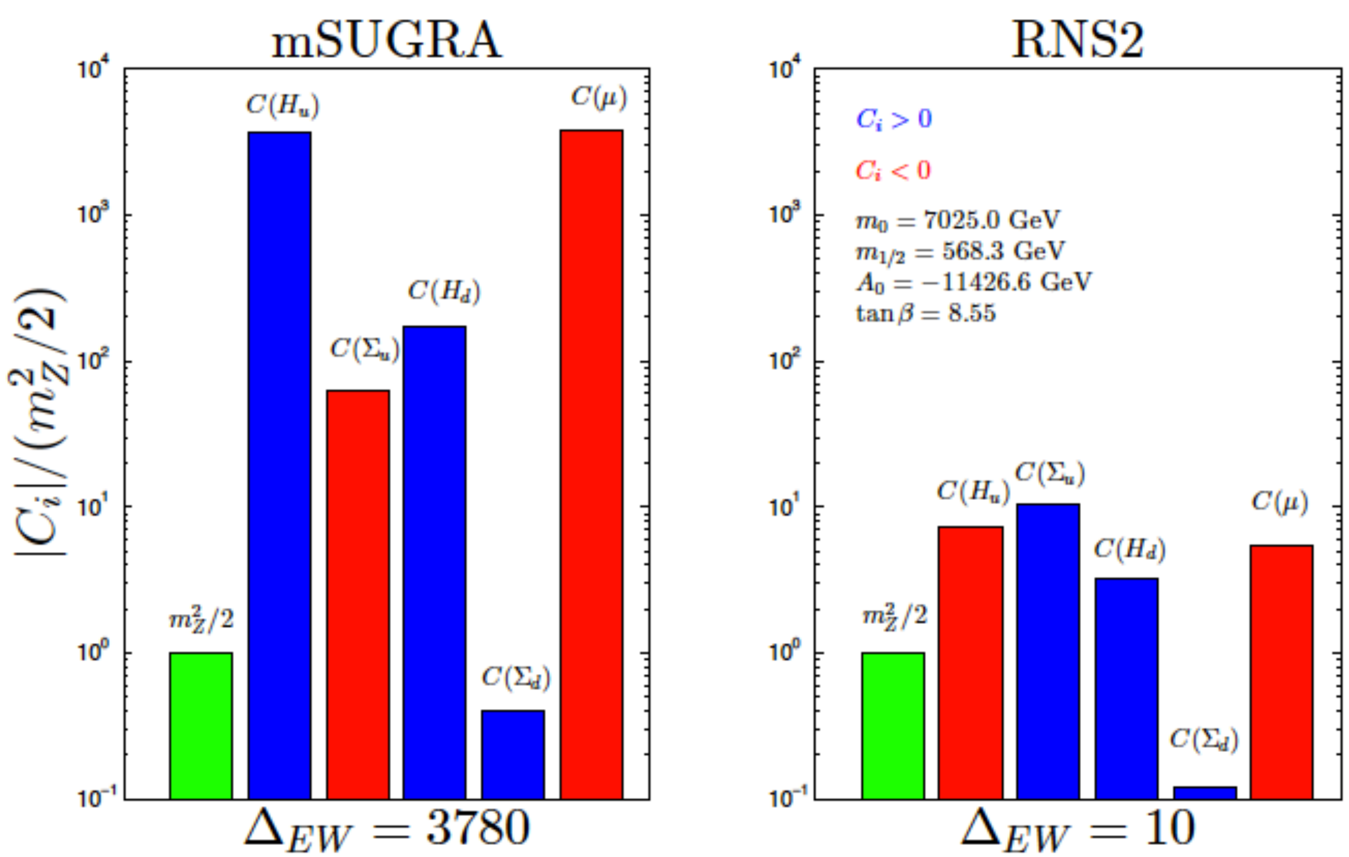


Radiatively-driven natural SUSY, or RNS:

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]].

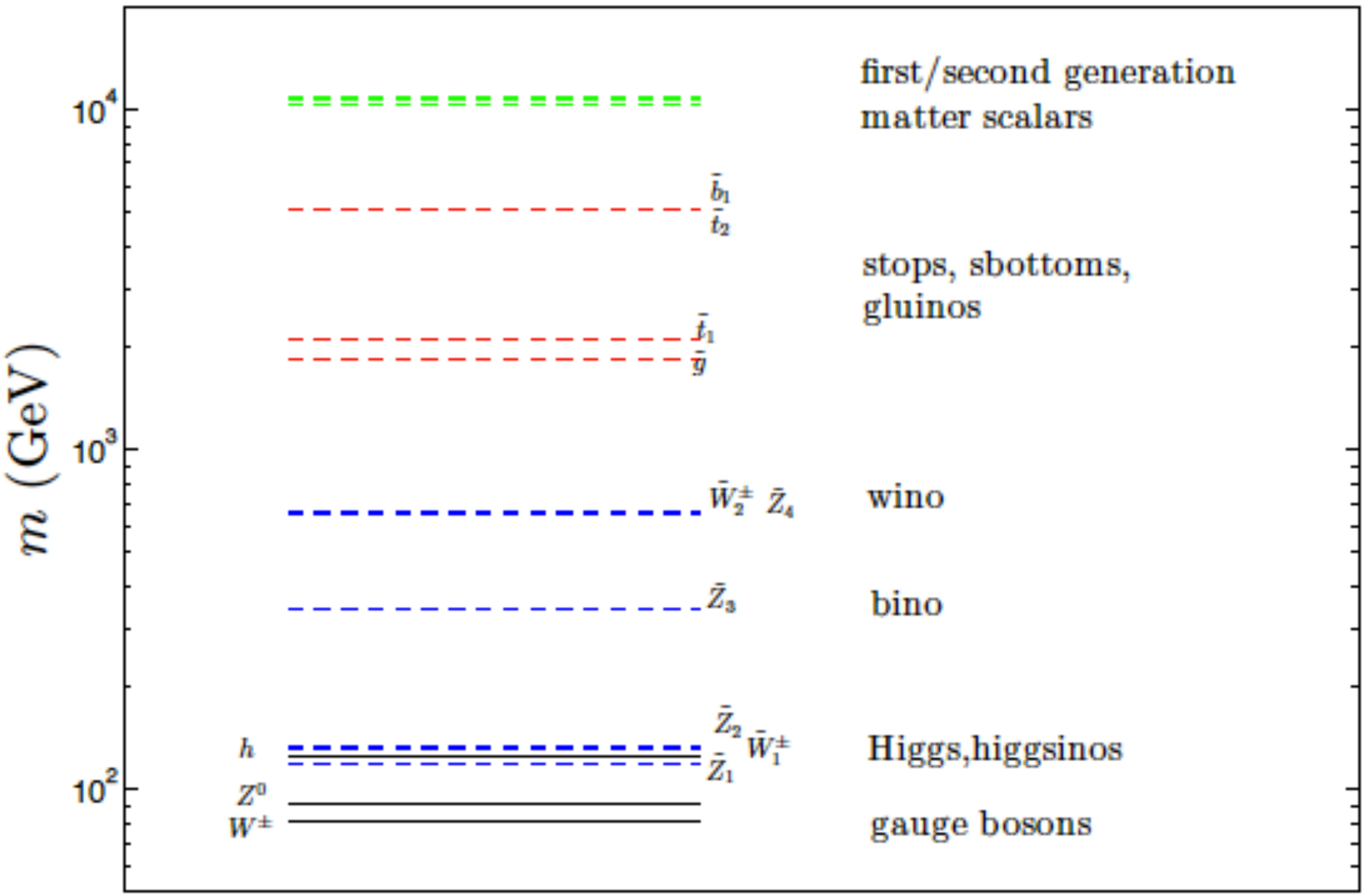
All contributions to m(Z) and m(h) are comparable to m(Z) and m(h):
model is natural in EW sector!



unnatural model

natural model: all contributions to m(Z) are comparable to m(Z)

Typical spectrum for low Δ_{EW} models



There is a Little Hierarchy, but it is no problem

$$\mu \ll m_{3/2}$$

SUSY mu problem: mu term is SUSY, not SUSY breaking: expect mu~M(Pl) but phenomenology requires mu~m(Z)

- NMSSM: mu~m(3/2); beware singlets!
- Giudice-Masiero: mu forbidden by some symmetry: generate via Higgs coupling to hidden sector
- Kim-Nilles: invoke SUSY version of DFSZ axion solution to strong CP:

KN: PQ symmetry forbids mu term, but then it is generated via PQ breaking

$$\mu \sim \lambda f_a^2/M_P$$

$$m_{3/2} \sim m_{hid}^2/M_P$$

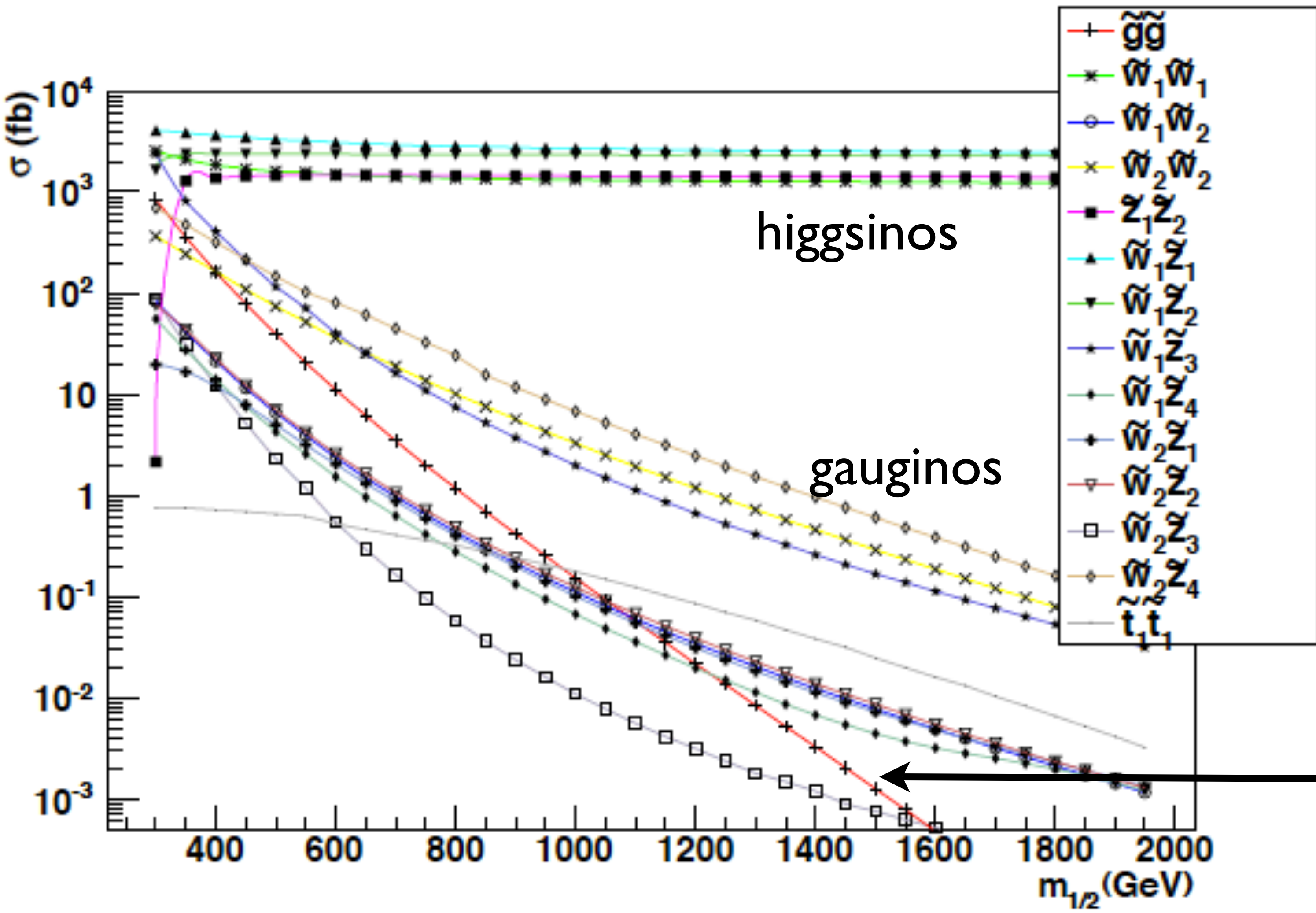
Little Hierarchy due to mismatch between SUSY breaking and PQ breaking scale?

$$f_a \ll m_{hid}$$

Higgs mass tells us where to look for axion!

$$m_a \sim 6.2\mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

Sparticle production along RNS model-line:



LHC14

gluinos

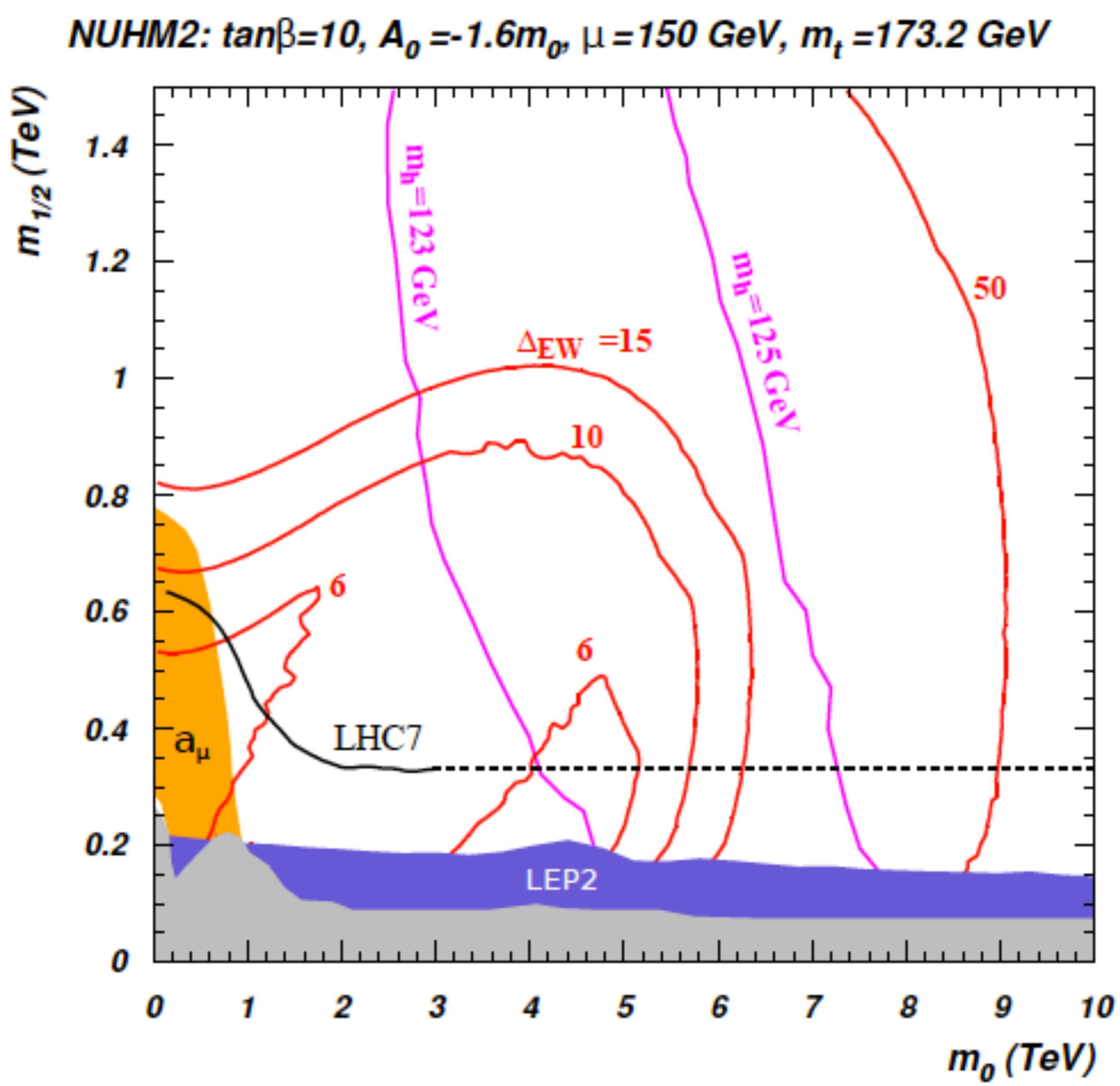
*higgsino pair production dominant-but only soft visible energy release from higgsino decays

*largest visible cross section: wino pairs=> SSdB

*gluino pairs sharply dropping

Radiatively-driven natural supersymmetry at the LHC (with V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata) JHEP**1312** (2013) 013.

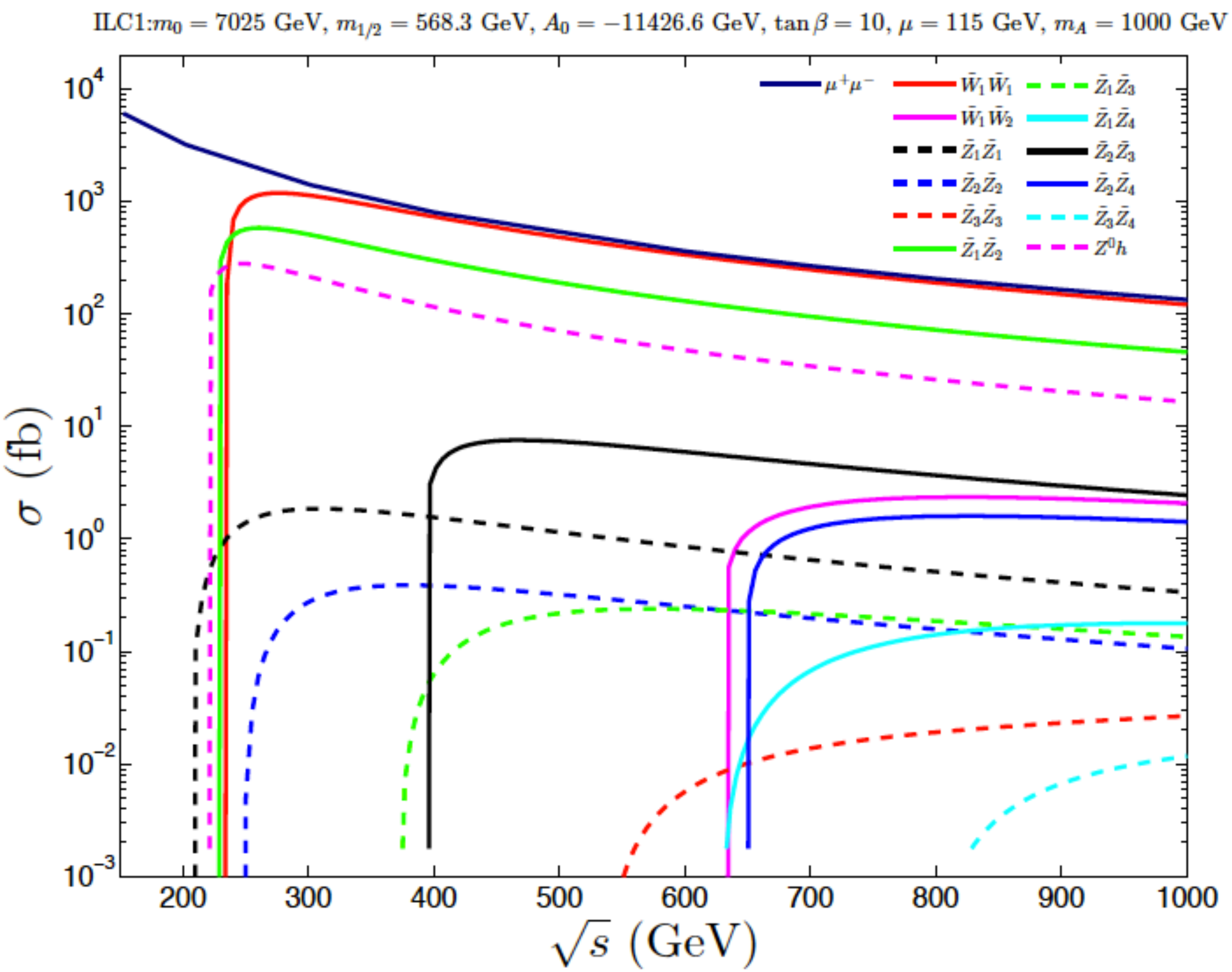
Good old m0 vs. mhf plane still viable, but require low mu (NUHM2)



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

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!

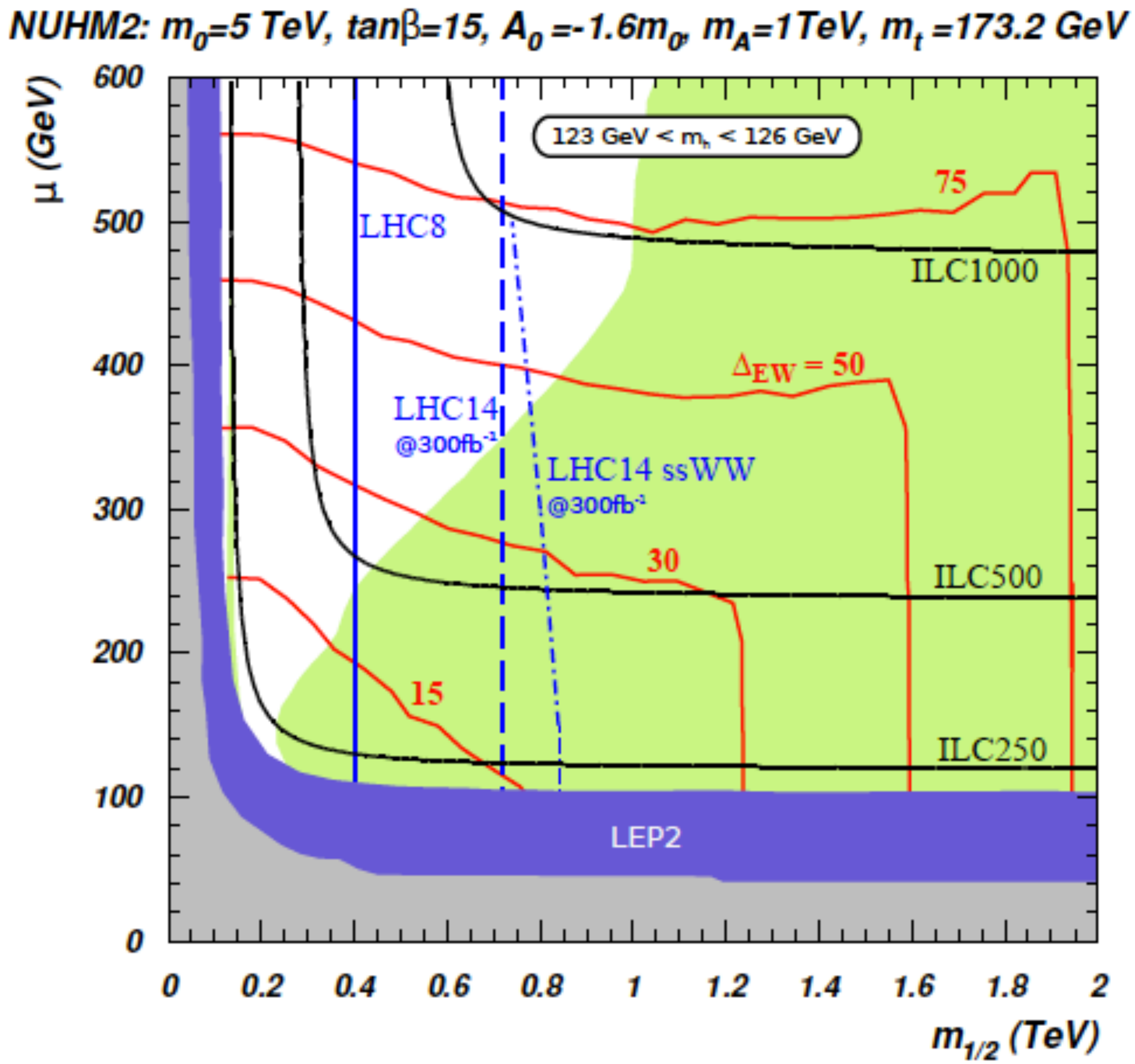


$$\sigma(higgsino) \gg \sigma(Zh)$$

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

ILC either sees light higgsinos or natural SUSY dead

LHC/ILC complementarity



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

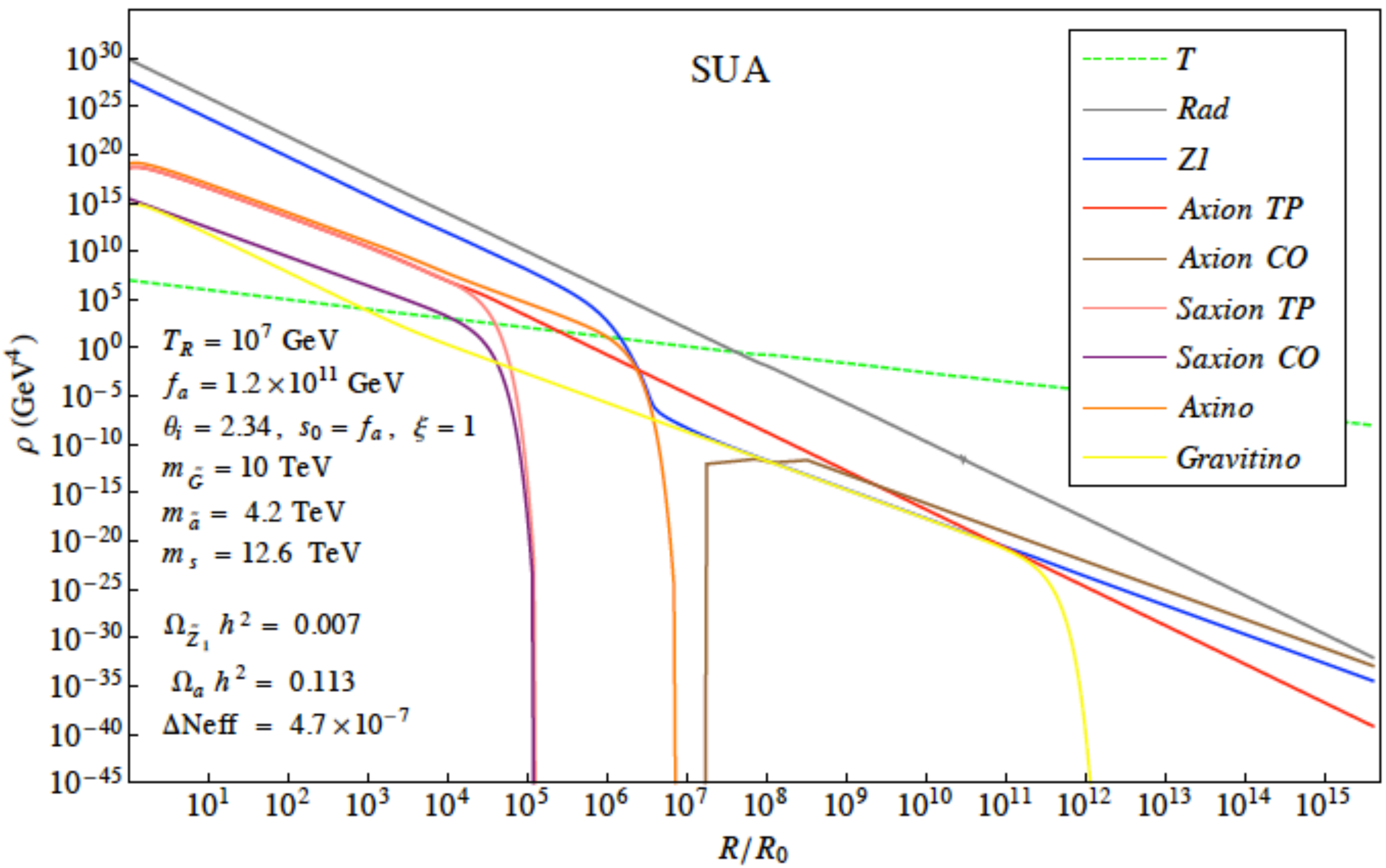
dark matter in natural SUSY

- 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

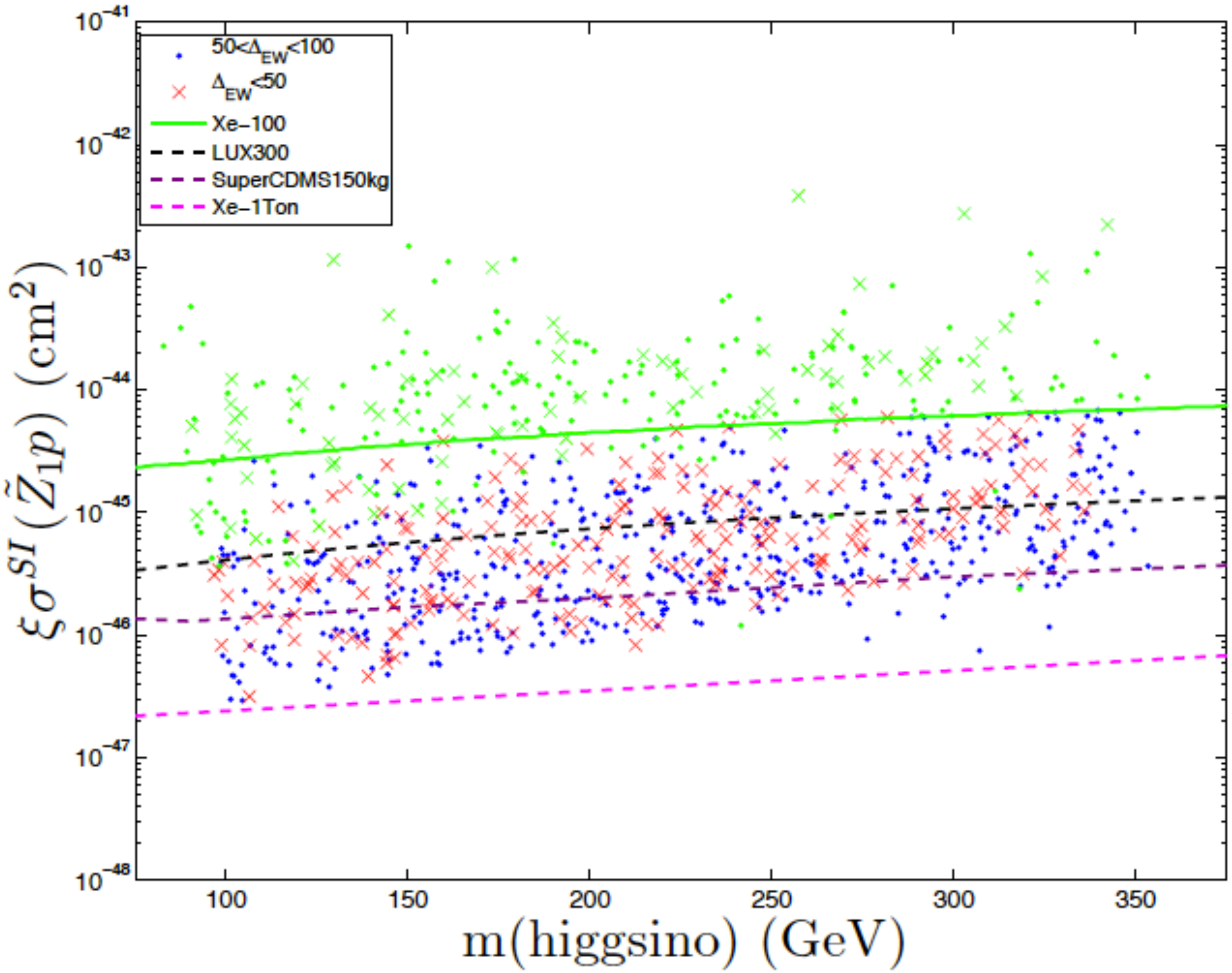
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: 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

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)

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

Oft-repeated myths about naturalness

- requires m(t1,t2,b1)<500 GeV
- requires small At parameter
- MSSM is fine-tuned to .1%
- naturalness is subjective/ non-predictive
- different measures predict different things