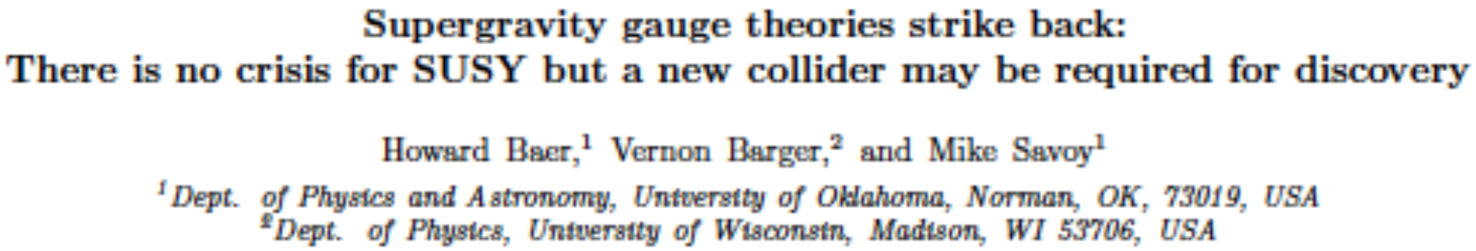
In 1982, Arnowitt, Chamseddine & Nath and others created the supergravity GUT paradigm.

This model has come under heavy criticism especially in recent few years.

However, in regime where data confronts theory, this paradigm emerges as best bet for BSM physics– albeit with some new twists!



Supergravity gauge theories strike back:
There is no crisis for SUSY but a new collider may be required for discovery

Howard Baer,[1] Vernon Barger,[2] and Mike Savoy[1]

[1] *Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019, USA*
[2] *Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA*

Phys. Scripta 90 (2015) 068003

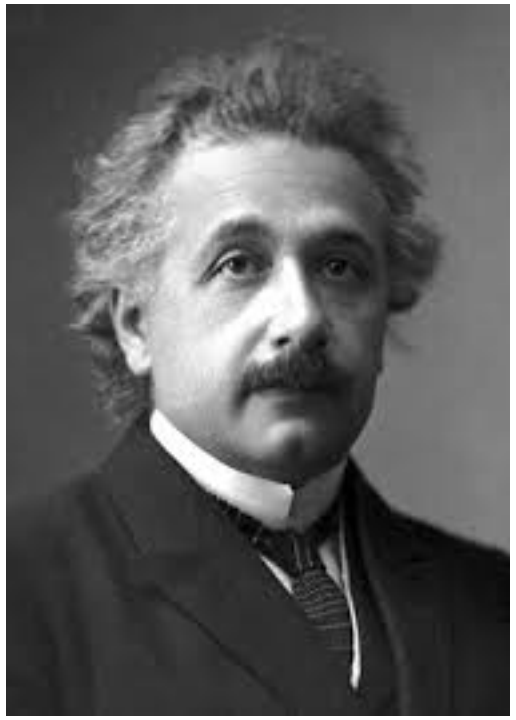
arXiv:1502.04127

SUGRA gauge theories strike back!

there is no crisis for SUSY, but a new collider may be required for discovery

Howard Baer
University of Oklahoma

twin pillars of guidance:
naturalness & simplicity



> ``The appearance of fine-tuning in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained"
>
> S. Weinberg

> ``Everything should be made as simple as possible, but not simpler"
>
> A. Einstein

many venerable papers on SUSY naturalness!

[1] J. R. Ellis, K. Enqvist, D. V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. A **1** (1986) 57.

[2] R. Barbieri and G. Giudice, *Nucl. Phys.* **B 306** (1988) 63.

[3] G. Kane, C. Kolda, L. Roszkowski and J. Wells, *Phys. Rev.* **D 49** (1994) 6173.

[4] G. W. Anderson and D. J. Castano, *Phys. Lett.* **B 347** (1995) 300 and *Phys. Rev.* **D 52** (1995) 1693.

[5] S. Dimopoulos and G. F. Giudice, *Phys. Lett.* **B 357** (1995) 573.

[6] K. L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. D **58** (1998) 096004 [hep-ph/9710473]; S. Akula, M. Liu, P. Nath and G. Peim, Phys. Lett. B **709** (2012) 192; M. Liu and P. Nath, arXiv:1303.7472 [hep-ph].

[7] P. H. Chankowski, J. R. Ellis and S. Pokorski, *Phys. Lett.* **B 423** (1998) 327; P. H. Chankowski, J. R. Ellis, M. Olechowski and S. Pokorski, *Nucl. Phys.* **B 544** (1999) 39.

[8] G. L. Kane and S. F. King, *Phys. Lett.* **B 451** (1999) 113; M. Bastero-Gil, G. L. Kane and S. F. King, *Phys. Lett.* **B 474** (2000) 103.

[30] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, arXiv:1212.2655 [hep-ph].

[31] H. Baer, V. Barger and D. Mickelson, Phys. Rev. D **88** (2013) 095013.

[32] H. Baer, V. Barger, M. Padeffke-Kirkland and X. Tata, Phys. Rev. D **89** (2014) 037701.

[33] S. P. Martin, Phys. Rev. D **89** (2014) 035011.

[34] A. Fowlie, arXiv:1403.3407 [hep-ph].

[35] A. Mustafayev and X. Tata, arXiv:1404.1386 (2014).

[36] R. Barbieri and A. Strumia, Phys. Lett. B **433** (1998) 63.

[42] L. J. Hall, D. Pinner and J. T. Ruderman, JHEP **1204** (2012) 131.

[51] R. Kitano and Y. Nomura, *Phys. Lett.* **B 631** (2005) 58 and *Phys. Rev.* **D 73** (2006) 095004.

[52] M. Papucci, J. T. Ruderman and A. Weiler, *J. High Energy Phys.* **1209** (2012) 035;

[53] C. Brust, A. Katz, S. Lawrence and R. Sundrum, *J. High Energy Phys.* **1203** (2012) 103; R. Essig, E. Izaguirre, J. Kaplan and J. G. Wacker, *J. High Energy Phys.* **1201** (2012) 074.

Ellis, King, Roberts, **JHEP 0804(2008) 099**

Casas,Moreno,Robles, Rolbiecki, Zaldiver, arXiv:1407.6966

[9] J. A. Casas, J. R. Espinosa and I. Hidalgo, JHEP **0401** (2004) 008.

[10] J. L. Feng, K. T. Matchev and T. Moroi, Phys. Rev. D **61** (2000) 075005; J. L. Fe
K. T. Matchev and T. Moroi, hep-ph/0003138; J. L. Feng and D. Sanford, Phys. Rev. D
(2012) 055015.

[11] Y. Nomura and B. Tweedie, Phys. Rev. D **72** (2005) 015006; Y. Nomura, D. Poland a
B. Tweedie, Nucl. Phys. B **745** (2006) 29.

[12] S. Cassel, D. M. Ghilencea and G. G. Ross, *Nucl. Phys.* **B 825** (2010) 203 and *Nucl. Phys.*
835 (2010) 110; S. Cassel, D. M. Ghilencea, S. Kraml, A. Lessa and G. G. Ross, *J. High Ene*
Phys. **1105** (2011) 120; G. G. Ross and K. Schmidt-Hoberg, Nucl. Phys. B **862** (2012) 7
G. G. Ross, K. Schmidt-Hoberg and F. Staub, JHEP **1208** (2012) 074; D. M. Ghilencea a
G. G. Ross, Nucl. Phys. B **868** (2013) 65; A. Kaminska, G. G. Ross and K. Schmidt-Hobe
arXiv:1308.4168 [hep-ph].

[13] R. Dermisek and H. D. Kim, Phys. Rev. Lett. **96** (2006) 211803.

[14] I. Gogoladze, F. Nasir and Q. Shafi, Int. J. Mod. Phys. A **28**, 1350046 (2013) [arXiv:1212.25
[hep-ph]]; I. Gogoladze, F. Nasir and Q. Shafi, arXiv:1306.5699 [hep-ph].

[15] M. Perelstein and B. Shakya, JHEP **1110** (2011) 142; M. Perelstein and B. Shak
arXiv:1208.0833 [hep-ph];

[16] S. Antusch, L. Calibbi, V. Maurer, M. Monaco and M. Spinrath, Phys. Rev. D **85** (2012) 0350
and JHEP **1301** (2013) 187.

[17] E. Hardy, arXiv:1306.1534 [hep-ph].

[18] H. Baer, V. Barger and M. Padeffke-Kirkland, Phys. Rev. D **88** (2013) 055026.

[19] S. Fichet, Phys. Rev. D **86** (2012) 125029 [arXiv:1204.4940 [hep-ph]].

[20] J. E. Younkin and S. P. Martin, Phys. Rev. D **85** (2012) 055028.

[21] K. Kowalska and E. M. Sessolo, arXiv:1307.5790 [hep-ph].

[22] C. Han, K. -i. Hikasa, L. Wu, J. M. Yang and Y. Zhang, arXiv:1308.5307 [hep-ph].

[23] E. Dudas, G. von Gersdorff, S. Pokorski and R. Ziegler, arXiv:1308.1090 [hep-ph].

[24] A. Arvanitaki, M. Baryakhtar, X. Huang, K. Van Tilburg and G. Villadoro, arXiv:1309.35
[hep-ph].

[25] J. Fan and M. Reece, arXiv:1401.7671 [hep-ph].

[26] T. Gherghetta, B. von Harling, A. D. Medina and M. A. Schmidt, arXiv:1401.8291 [hep-ph].

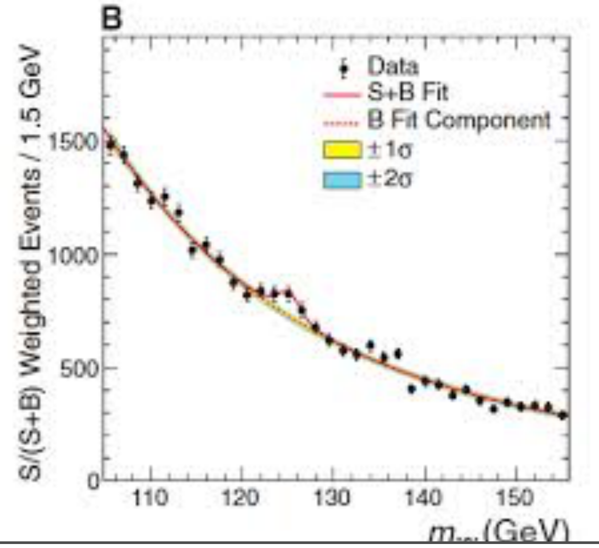
[27] K. Kowalska, L. Roszkowski, E. M. Sessolo and S. Trojanowski, arXiv:1402.1328 [hep-ph].

[28] J. L. Feng, Ann. Rev. Nucl. Part. Sci. **63** (2013) 351.

[29] H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, Phys. Rev. Lett. **109** (2012) 1618

LHC7-8 era a grand success

- Standard Model vigorously confirmed in both QCD and EW sectors
- discovery of Higgs boson m(h)~125.1 GeV: looks highly SM-like: no significant deviations from SM
- Standard Model reigns supreme! Or does it?



But still, critical problems remain

Standard Model

SU(3)xSU(2)xU(1)

Strong CP

Higgs mass
unstable:
Big
Hierarchy

neutrino mass:

astro:
DM,
DE,
baryogenesis

First: the Higgs puzzle:

*scalar fields in QFT:
quadratic divergence causes mass to blow up to
highest scale in theory:
*hard to understand unless
Higgs is composite or protected by some symmetry

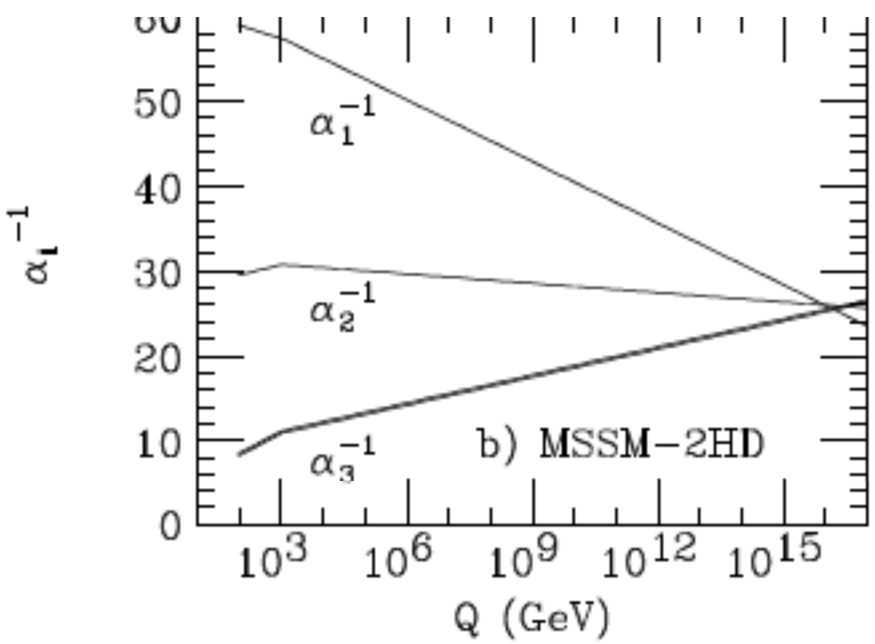
* so far, Higgs looks fundamental

*then SUSY seems likely answer: protects m(h) to
all orders in perturbation theory:
does the job, once-and-for-all!

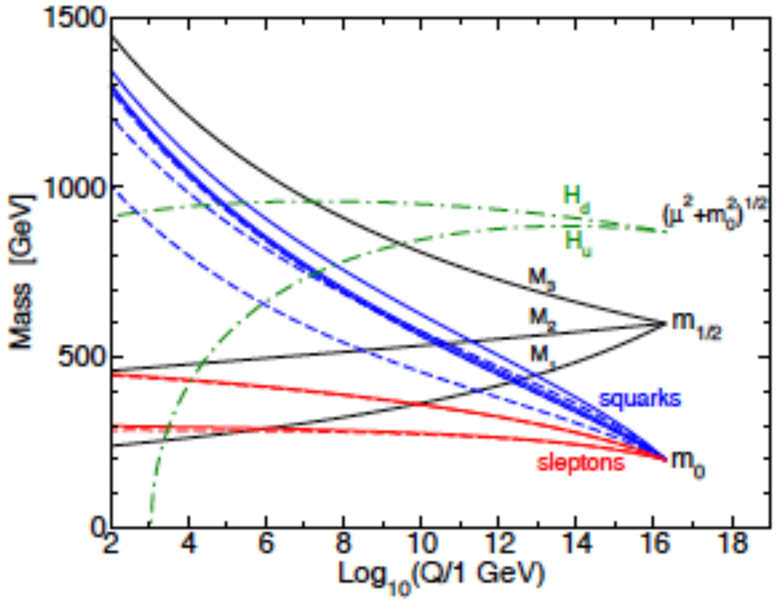
oft repeated mantra:
naturalness requires SUSY at weak scale

Reminder: three times data had chance to rule SUSY out

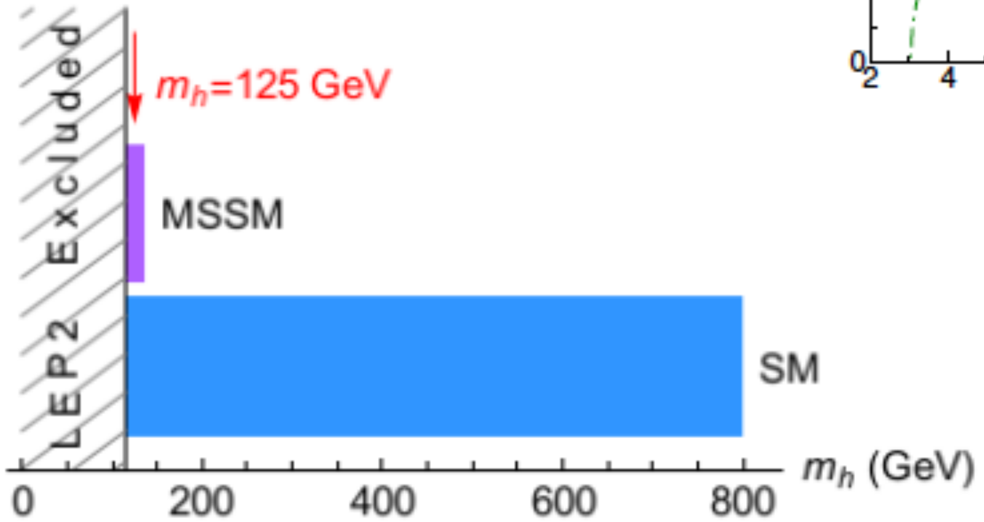
LEP gauge coupling measurements



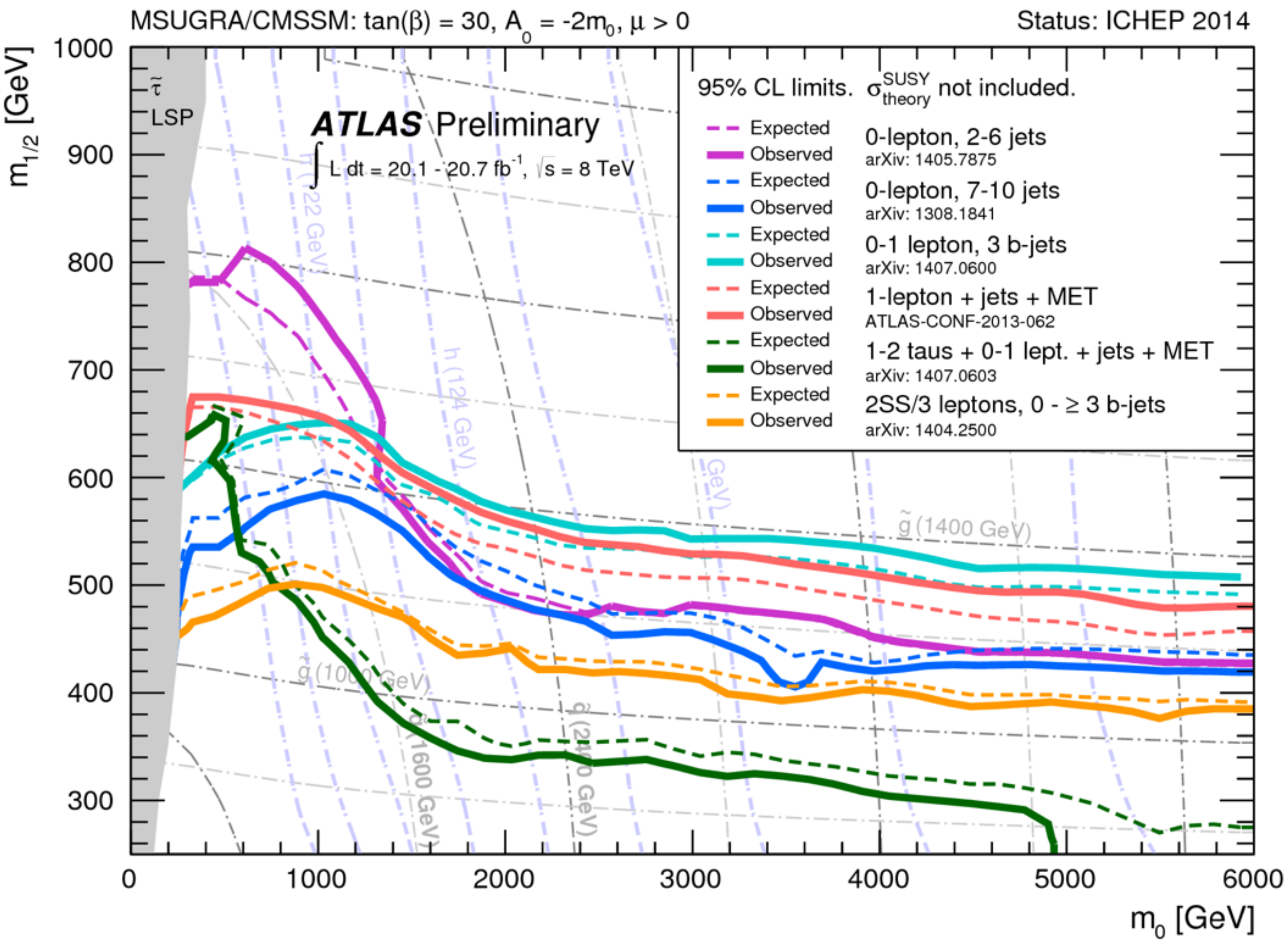
Tevatron: m(t)~173.2 GeV for EWSB



LHC: m(h)<~125 GeV



But where are the sparticles?



$$m_{\tilde g} > 1.3\ TeV \quad (m_{\tilde q} \gg m_{\tilde g})$$

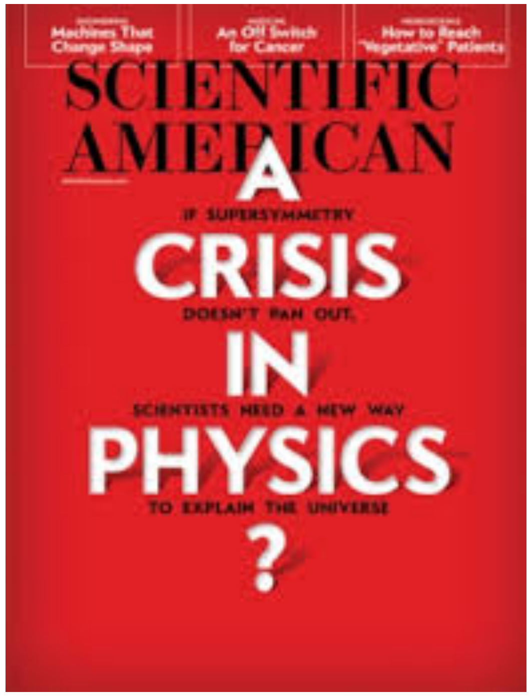
$$m_{\tilde g} > 1.8\ TeV \quad (m_{\tilde q} \sim m_{\tilde g})$$

$$m_h \simeq 125.1\ GeV \Rightarrow m_{\tilde t_{1,2}} \sim TeV$$

Is there a crisis in physics?

We have heard for a long time that (natural) SUSY requires superpartners at the weak scale

Also claim is naturalness requires 3 third generation squarks <600 GeV



Machines That Change Shape
An Off Switch for Cancer
How to Reach "Vegetative" Patients
SCIENTIFIC AMERICAN
A
IF SUPERSYMMETRY
CRISIS
DOESN'T PAN OUT,
IN
SCIENTISTS NEED A NEW WAY
PHYSICS
TO EXPLAIN THE UNIVERSE
?

Where are the WIMPs ``predicted” by WIMP miracle?

This unshakable fidelity to supersymmetry is widely shared. Particle theorists do admit, however, that the idea of natural supersymmetry is already in trouble and is headed for the dustbin of history unless superpartners are discovered soon…

Lykken & Spiropolu

It’s great to see such a high-profile public discussion of the implications of the collapse of the paradigm long-dominant in some circles which sees SUSY extensions of the Standard Model as the way forward for the field.

Peter Woit blog,
April 15, 2014

Sensational claims deserve scrutiny!

Oft-repeated myths about naturalness

see e.g. recent
FNAL workshop

- requires m(t1,t2,b1)<500 GeV
- requires small At parameter
- requires m(gluino)<1500 GeV
- MSSM is fine-tuned to .1% - needs modification
- naturalness is subjective/ non-predictive
- different measures predict different things

This talk will refute all these points!

HB, Barger, Savoy, arXiv:1502.04127

And present a beautiful alternative:
radiatively-driven naturalness

Most claims against SUSY stem from overestimates of EW fine-tuning. These arise from violations of the

Prime directive on fine-tuning:

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

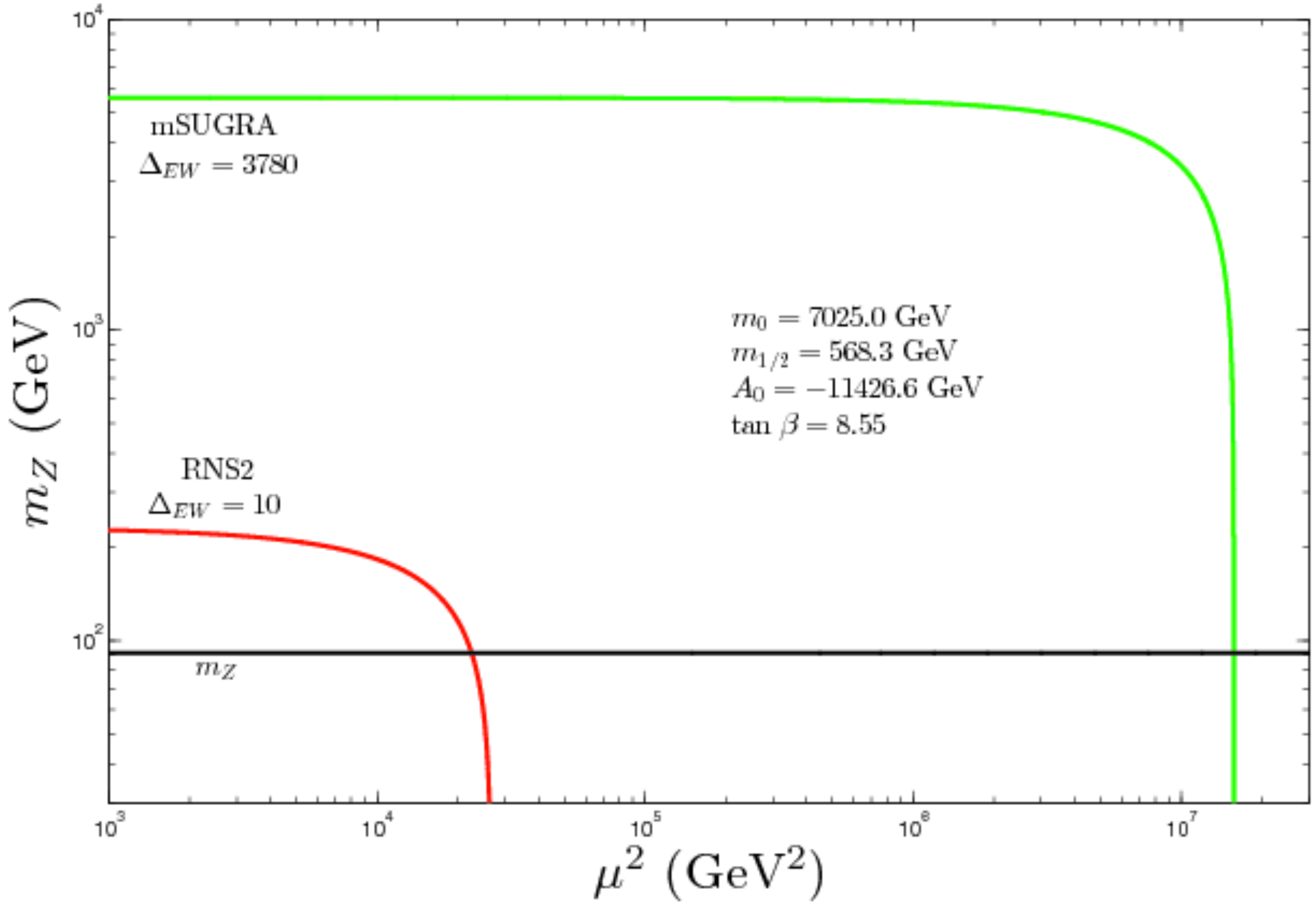
HB, Barger, Mickelson, Padeffke-Kirkland, arXiv:1404.2277

Is $\mathcal{O} = \mathcal{O} + b - b$ fine-tuned for $b > \mathcal{O}$?

First: simple electroweak fine-tuning: dial value of mu so that Z mass comes out right:

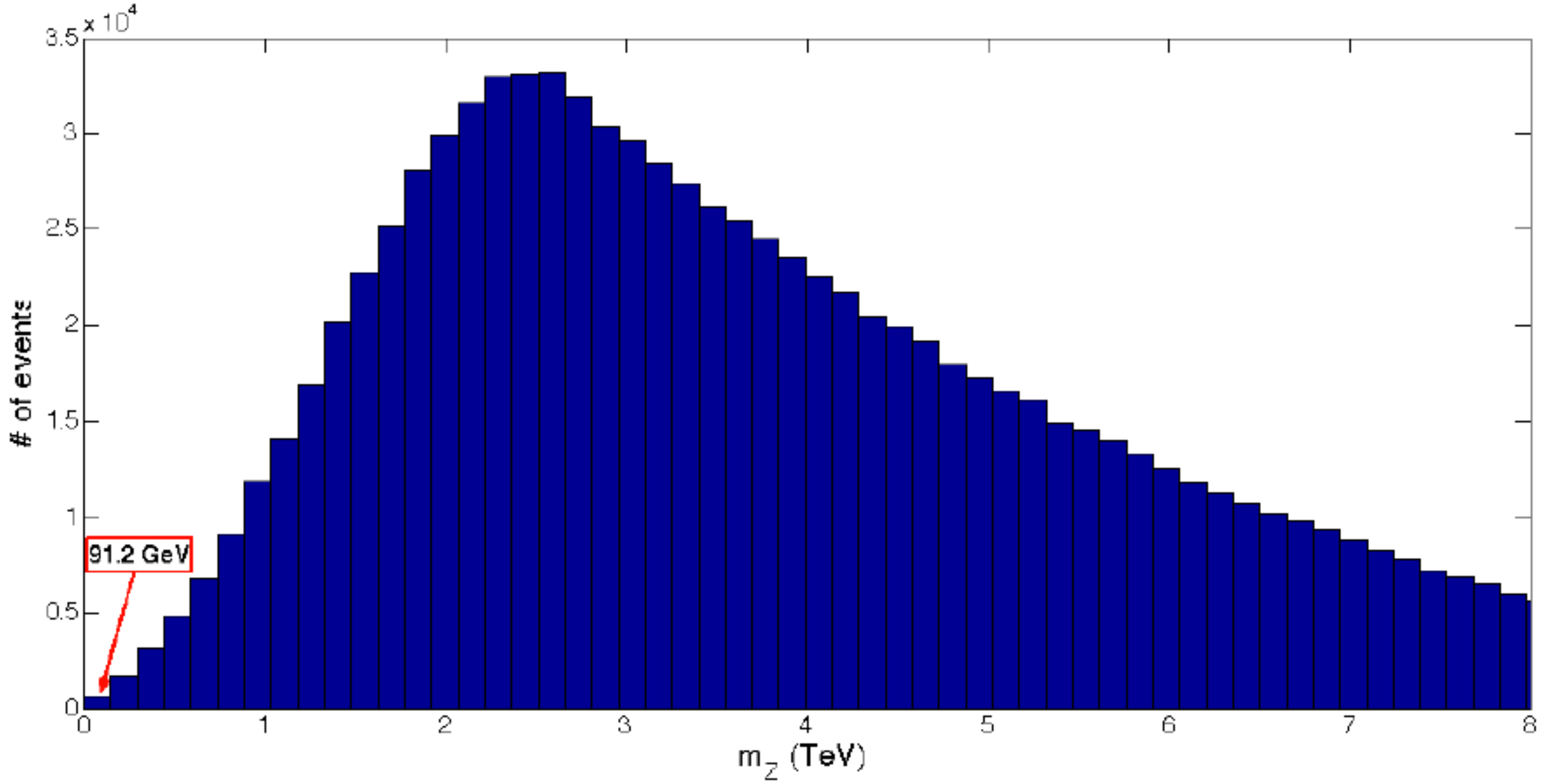
everybody does it but it is hidden inside spectra codes (Isajet, SuSpect, SoftSUSY, Spheno, SSARD)

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



e.g. in CMSSM/ mSUGRA: one then concludes nature gives this:

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



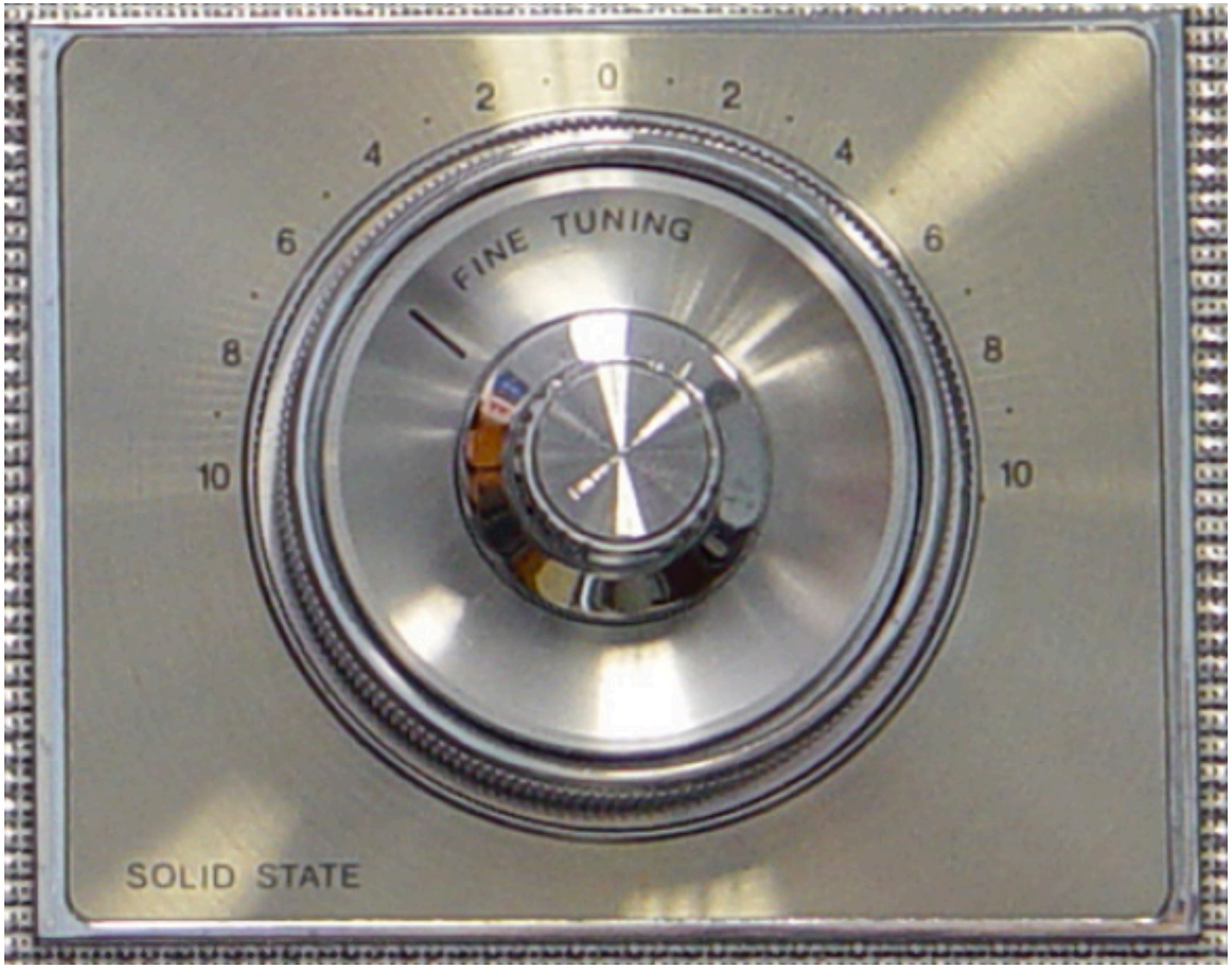
The 20 dimensional pMSSM parameter space then includes

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

scan over parameters

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

Three measures of fine-tuning:



#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)

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

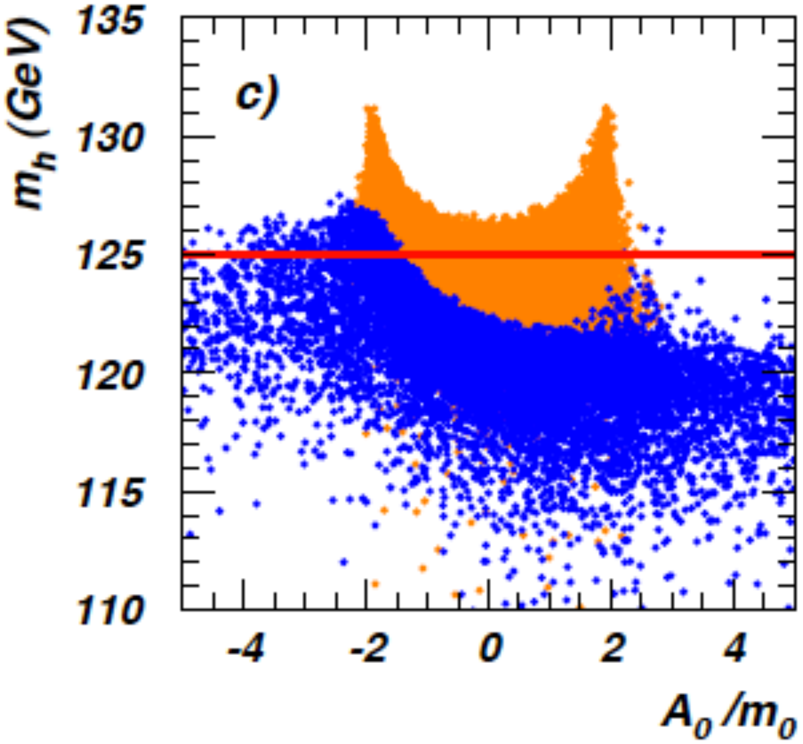
$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$ with $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$ etc.

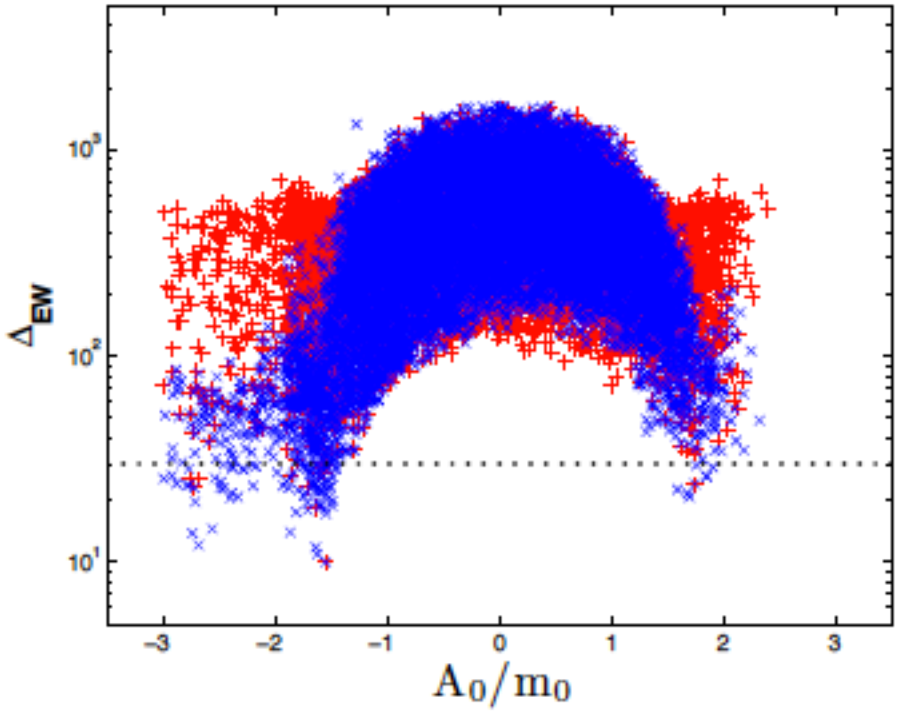
simple, direct, unambiguous interpretation:

- $|\mu| \sim m_Z \sim 100 - 200$ GeV
- $m_{H_u}^2$ 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

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).

Large value of A_t reduces $\Sigma_u^u(\tilde{t}_{1,2})$ contributions to Δ_{EW} while uplifting m_h to ~ 125 GeV





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

$$\Delta_t = (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)/2 + M_Z^2 \cos 2\beta (\tfrac{1}{4} - \tfrac{2}{3} x_W)$$

$$F(m^2) = m^2 \left(\log \frac{m^2}{Q^2} - 1 \right) \qquad Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

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

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

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

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

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

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

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

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

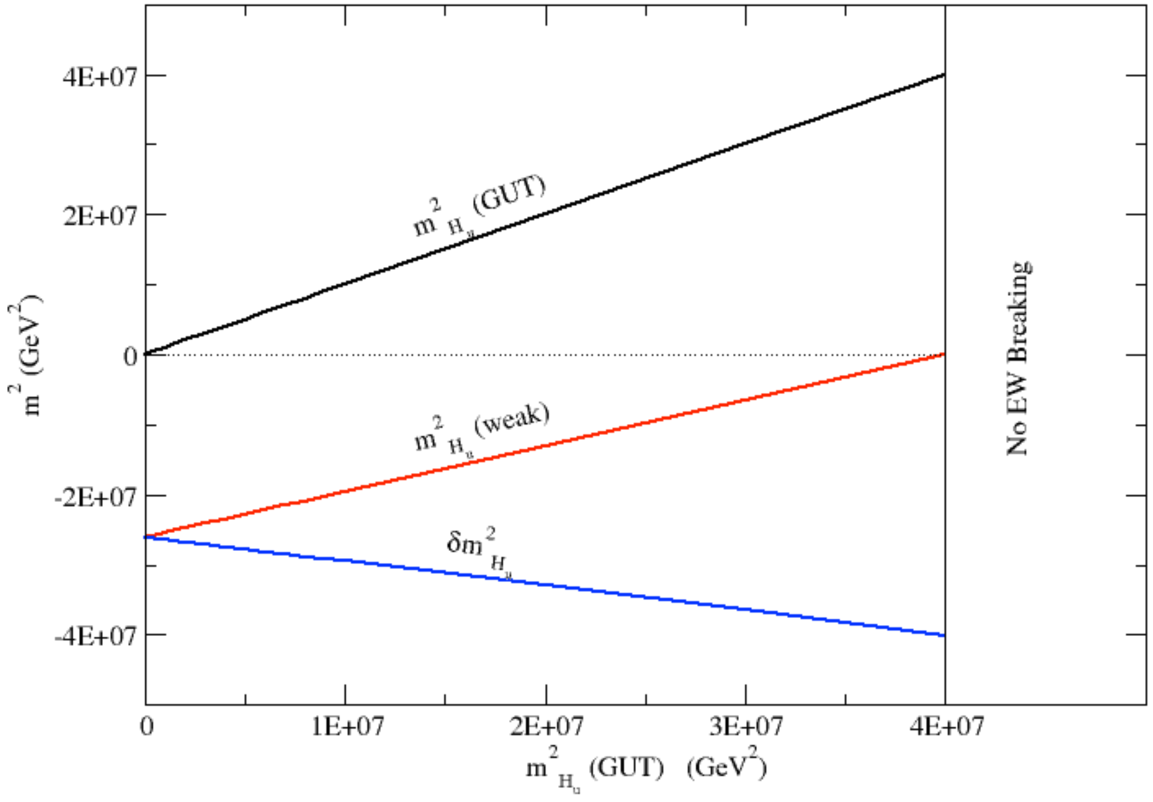
old natural SUSY then A_t can't be too big

What's wrong with this argument?

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

$m^2_{H_u}(\Lambda)$ and $\delta m^2_{H_u}$ are *not* independent!

violates prime directive!



The larger $m^2_{H_u}(\Lambda)$ becomes, then the larger becomes the cancelling correction!

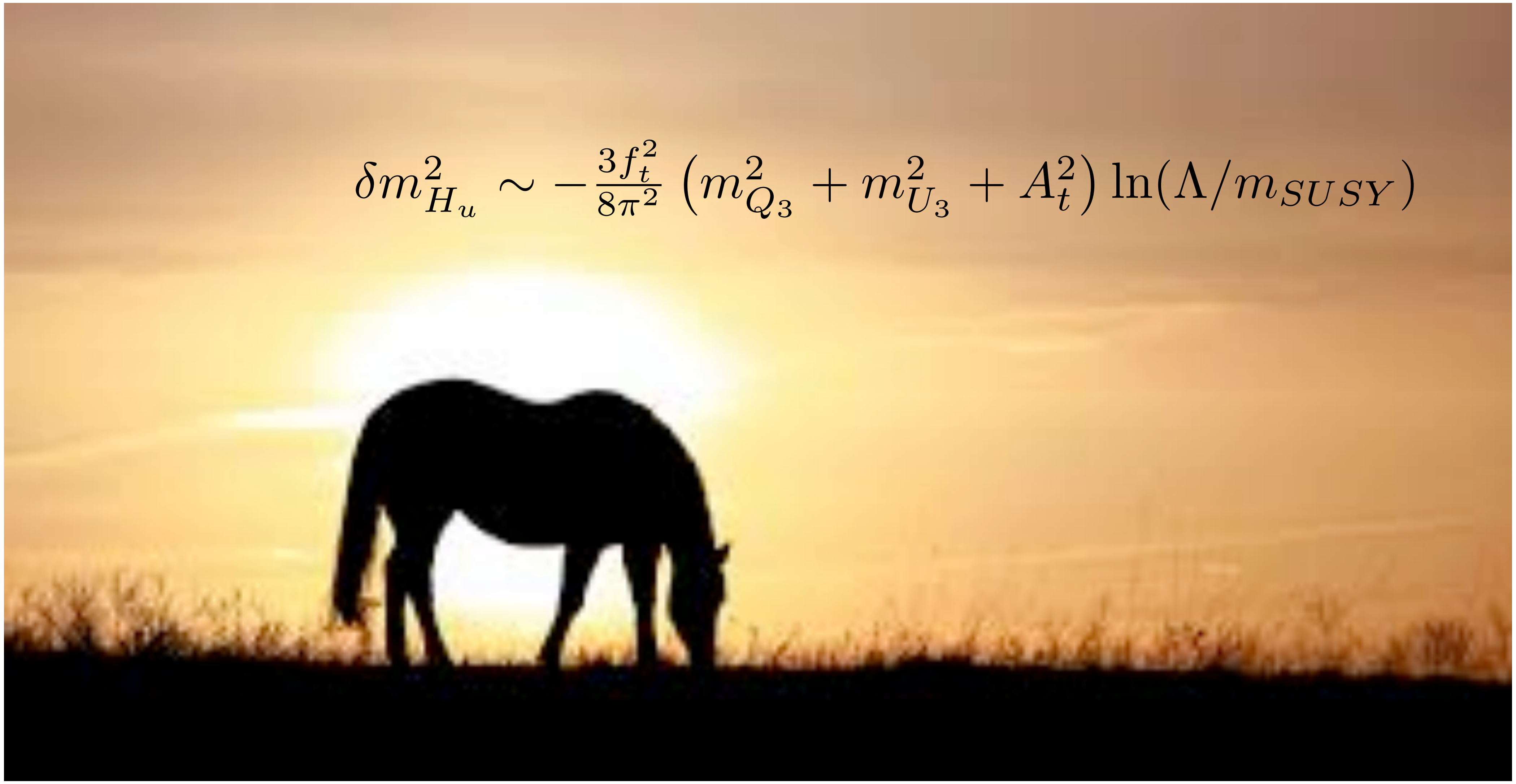
To fix: combine dependent terms:

$m_h^2 \simeq \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ where now both
μ^2 and $\left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ are $\sim m_Z^2$

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

Instead of: the radiative correction $\delta m_{H_u}^2 \sim m_Z^2$
we now have: the radiatively-corrected $m_{H_u}^2 \sim m_Z^2$

Recommendation: put this horse out to pasture



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

R.I.P.

sub-TeV 3rd generation squarks not required for naturalness

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

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

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

the p_i constitute the fundamental parameters of the model.

for pMSSM, obviously $\Delta_{BG} \simeq \Delta_{EW}$

What about models defined at high scale?

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

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

Ibanez, Lopez, Munoz;
Lleyda, Munoz

Kane, King

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

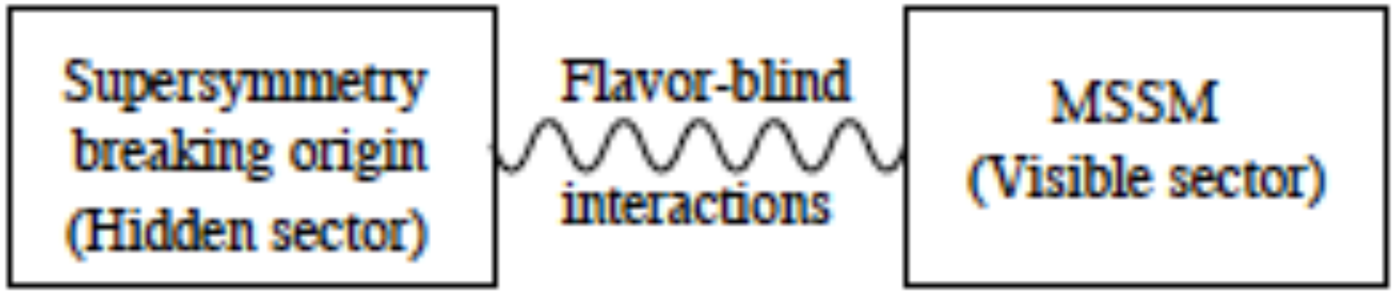
For correlated parameters, EWFT collapses in 3rd gen. sector!

Feng, Matchev, Moroi

- Usually Δ_{BG} is applied to *multi-parameter effective theories* where multiple soft terms are adopted as parameter set.
- For these theories, the multiple soft terms parametrize our ignorance of details of the hidden sector SUSY breaking.
- But in supergravity, for any given hidden sector, soft terms are all *dependent* and can be computed as multiples of $m_{3/2}$.

Thus, the usual evaluation of Δ_{BG} also violates the prime directive!

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)

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

Soni, Weldon (1983);
Kaplunovsky, Louis (1992);
Brignole, Ibanez, Munoz (1993)

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 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

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

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

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

then

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

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

Thus, correctly applying these measures by first collecting dependent quantities, we find that- at tree level- all agree:

$$\Delta_{HS} \simeq \Delta_{BG} \simeq \Delta_{EW}$$

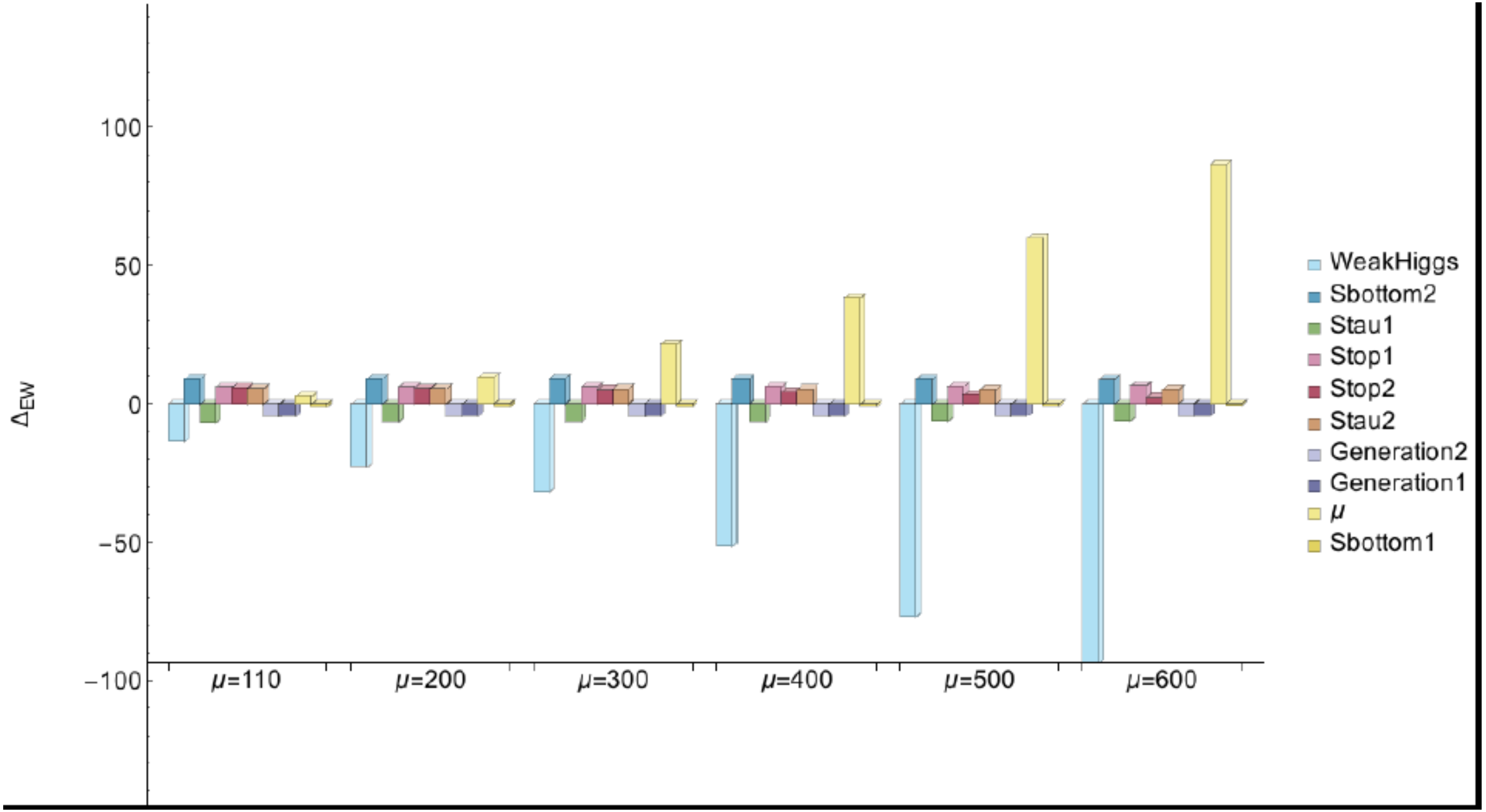
Due to ease of use and including radiative corrections, and due to its explicit model independence, we will use

$$\Delta_{EW}$$

for remainder of talk

hard wired in
Isasugra

How much is too much fine-tuning?

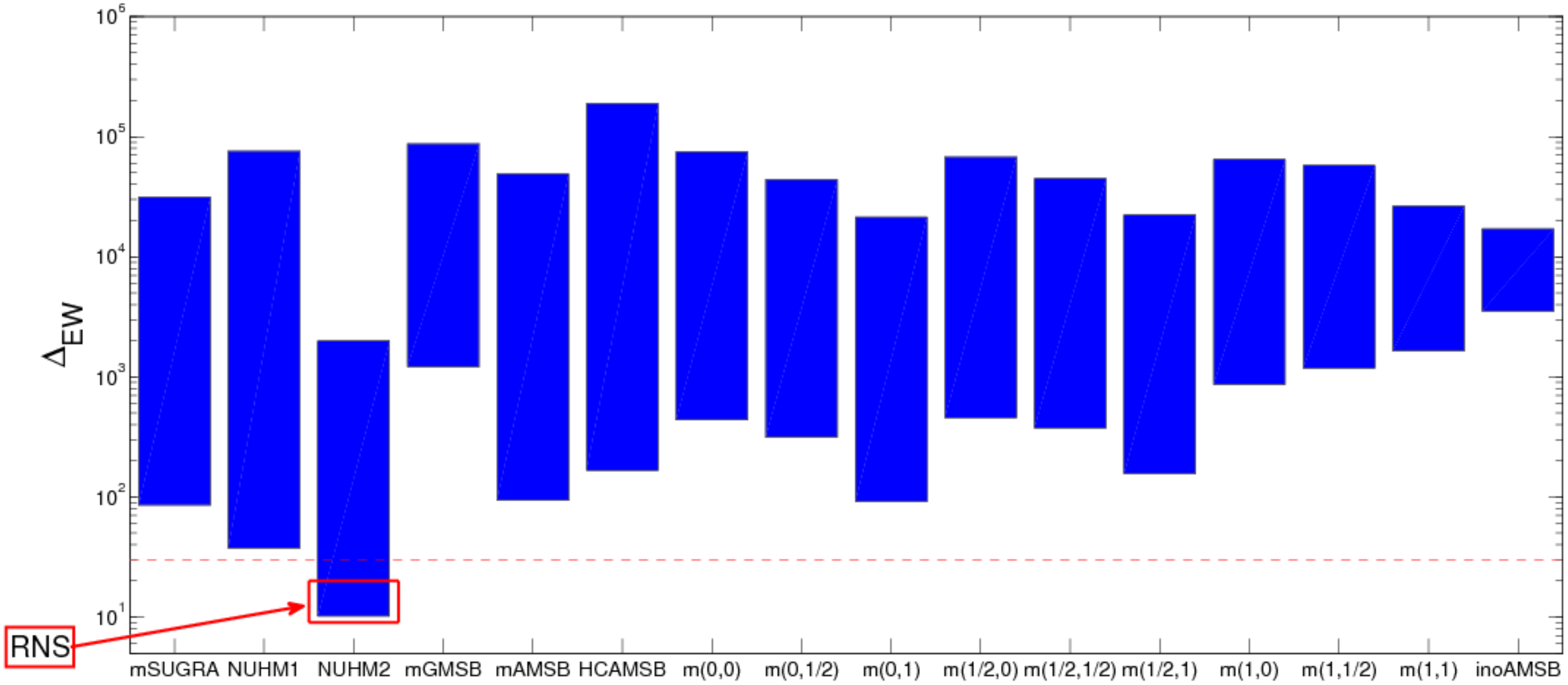


Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

Δ_{EW} is highly selective: most constrained models are ruled out except NUHM2 and its generalizations:

J. Ellis, K. Olive and Y. Santoso, *Phys. Lett.* **B 539** (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, *Nucl. Phys.* B **652** (2003) 259; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *J. High Energy Phys.* 0507 (2005) 065.

scan over p-space with m(h)=125.5+-2.5 GeV:



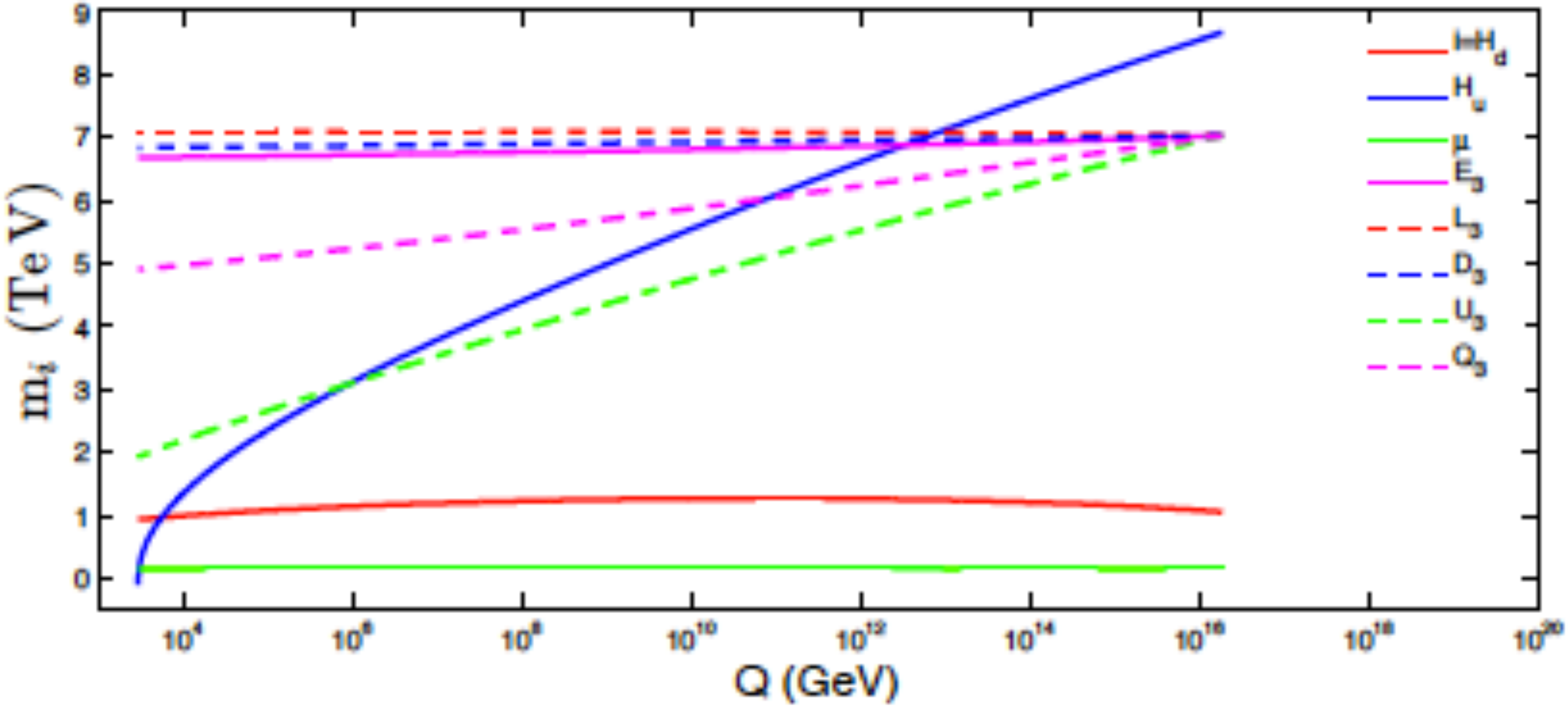
0.1%

1%

10%

HB, Barger, Mickelson,Padeffke-Kirkland, PRD89 (2014) 115019

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



Radiatively-driven natural SUSY, or RNS:

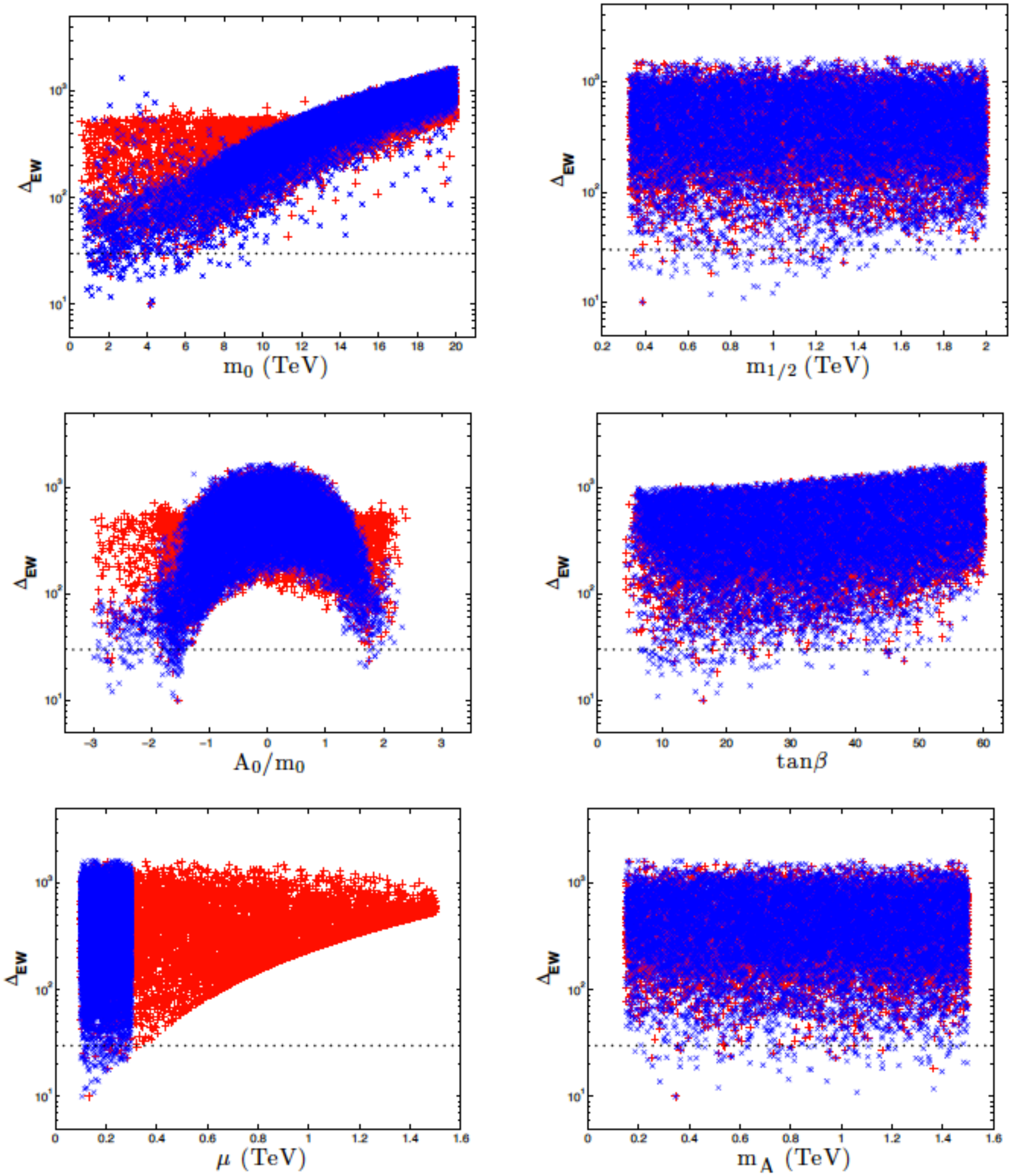
(typically need mHu~25-50% higher than m0)

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]].

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

get upper bounds on parameters and spectra!

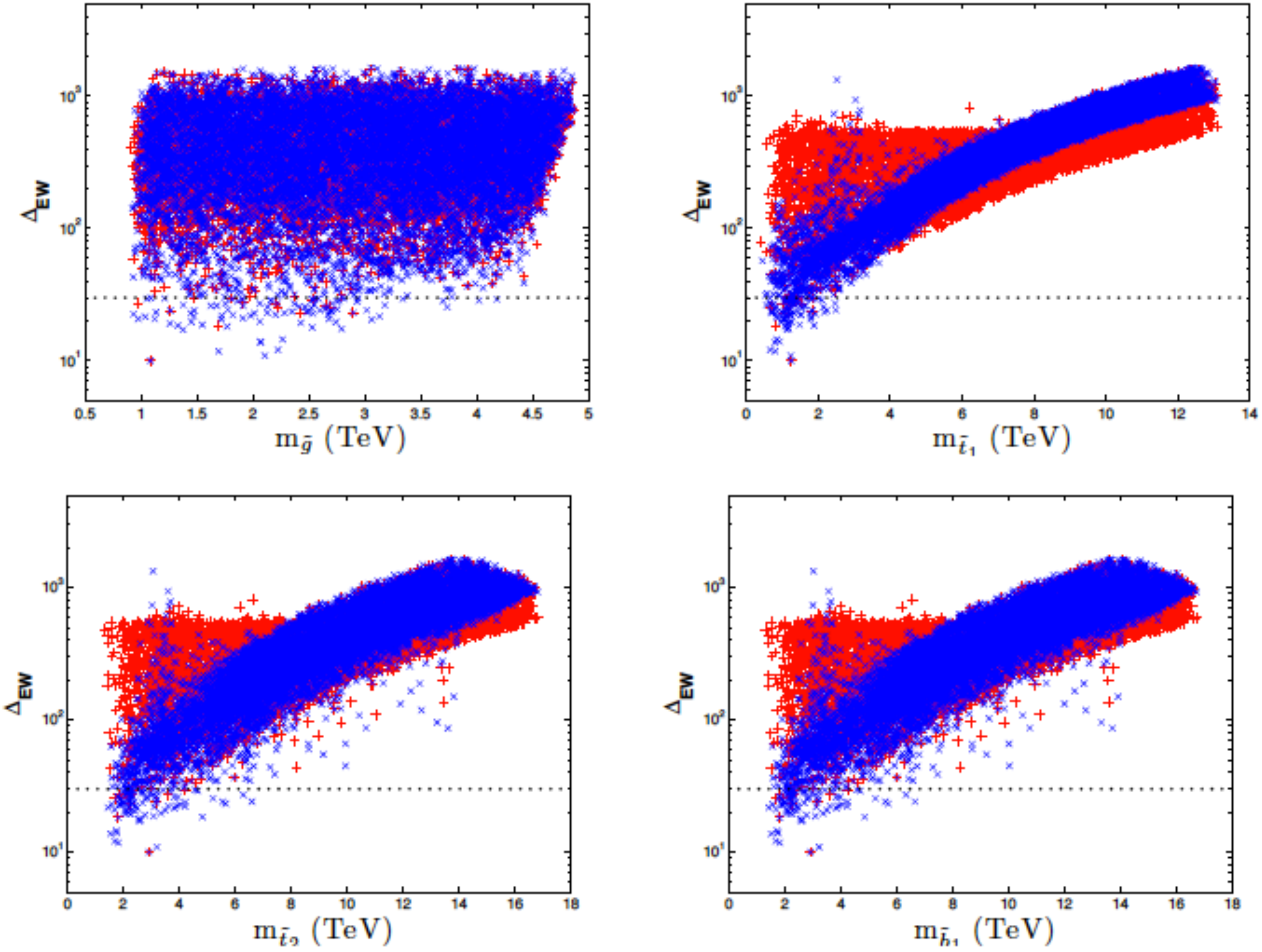


$$\Delta_{EW} \sim 10 \text{ or } 10\% \; EWFT$$

High-scale models with low Δ_{EW} :

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

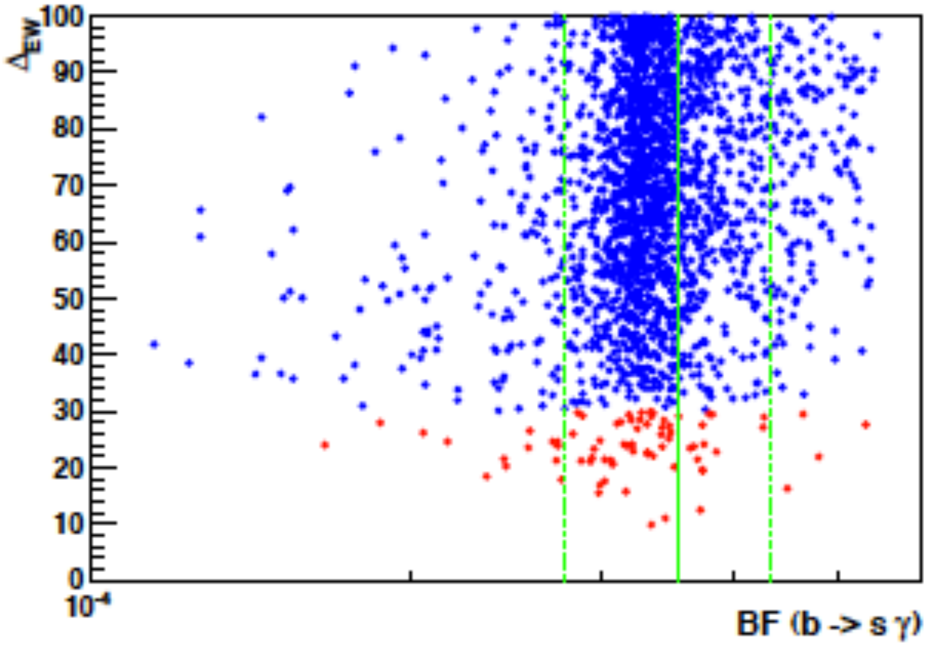
Upper bounds on sparticle masses:

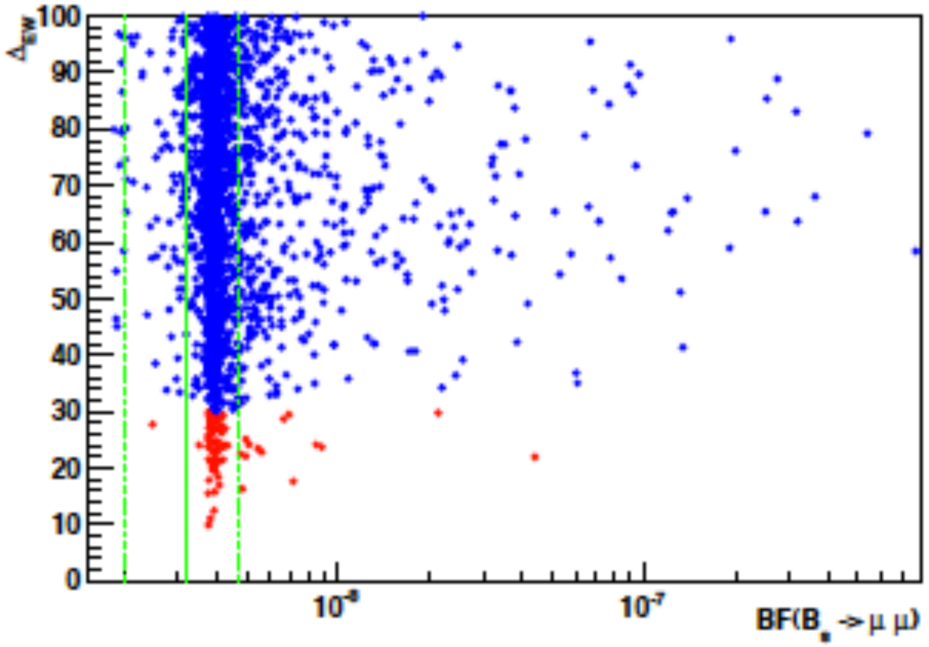


m(t1)~1-3 TeV
m(t2,b1)~2-4 TeV
m(glno)~1-4 TeV

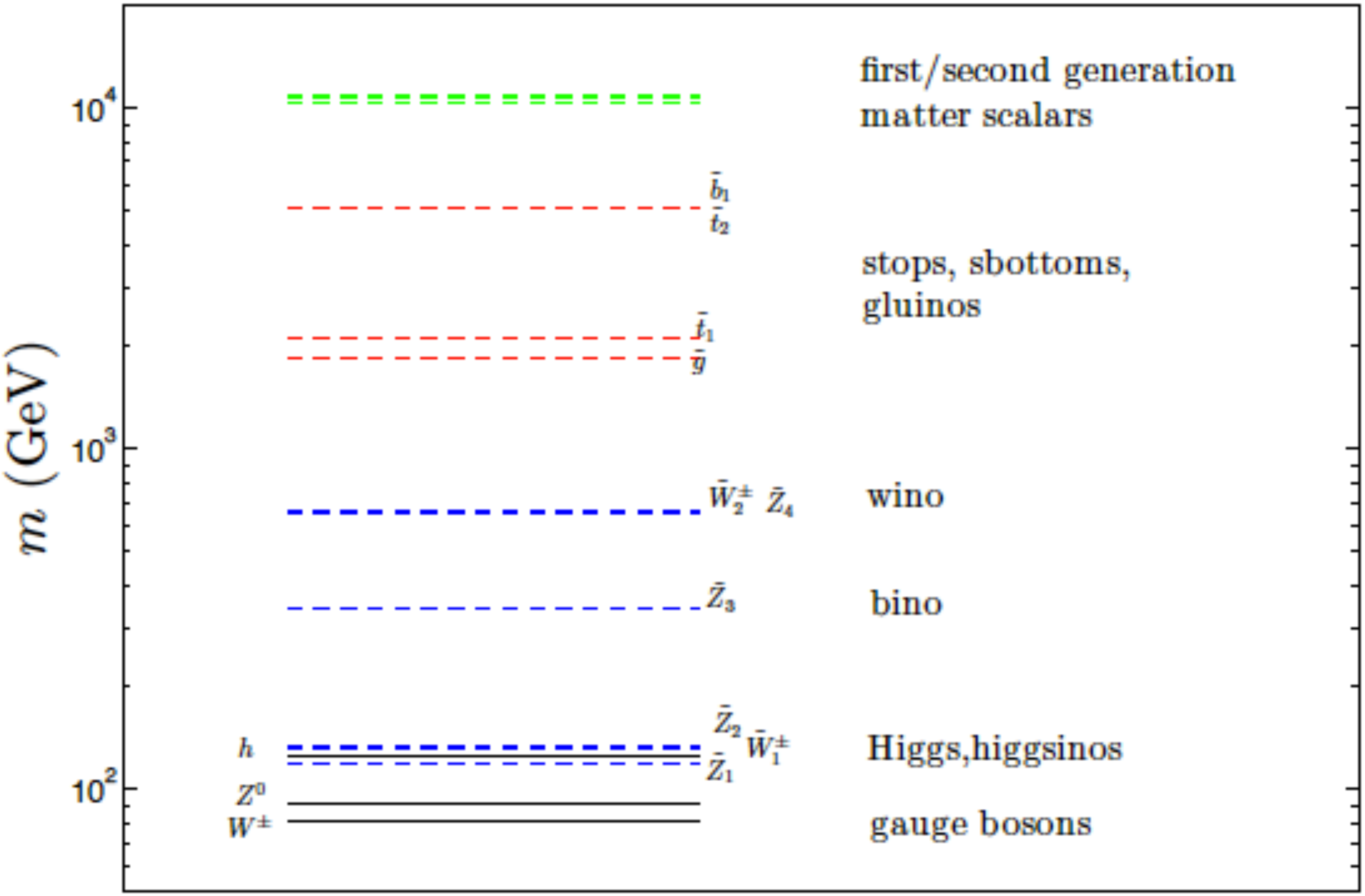
higher than old NS models and
allows for m(h)~125 GeV within MSSM

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



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 PQ breaking and SUSY breaking scales?

$$f_a \ll m_{hid}$$

Higgs mass tells us where to look for axion!

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

Little Hierarchy from radiative PQ breaking? exhibited within context of MSY model

Murayama, Suzuki, Yanagida (1992);
Gherghetta, Kane (1995)

Choi, Chun, Kim (1996)

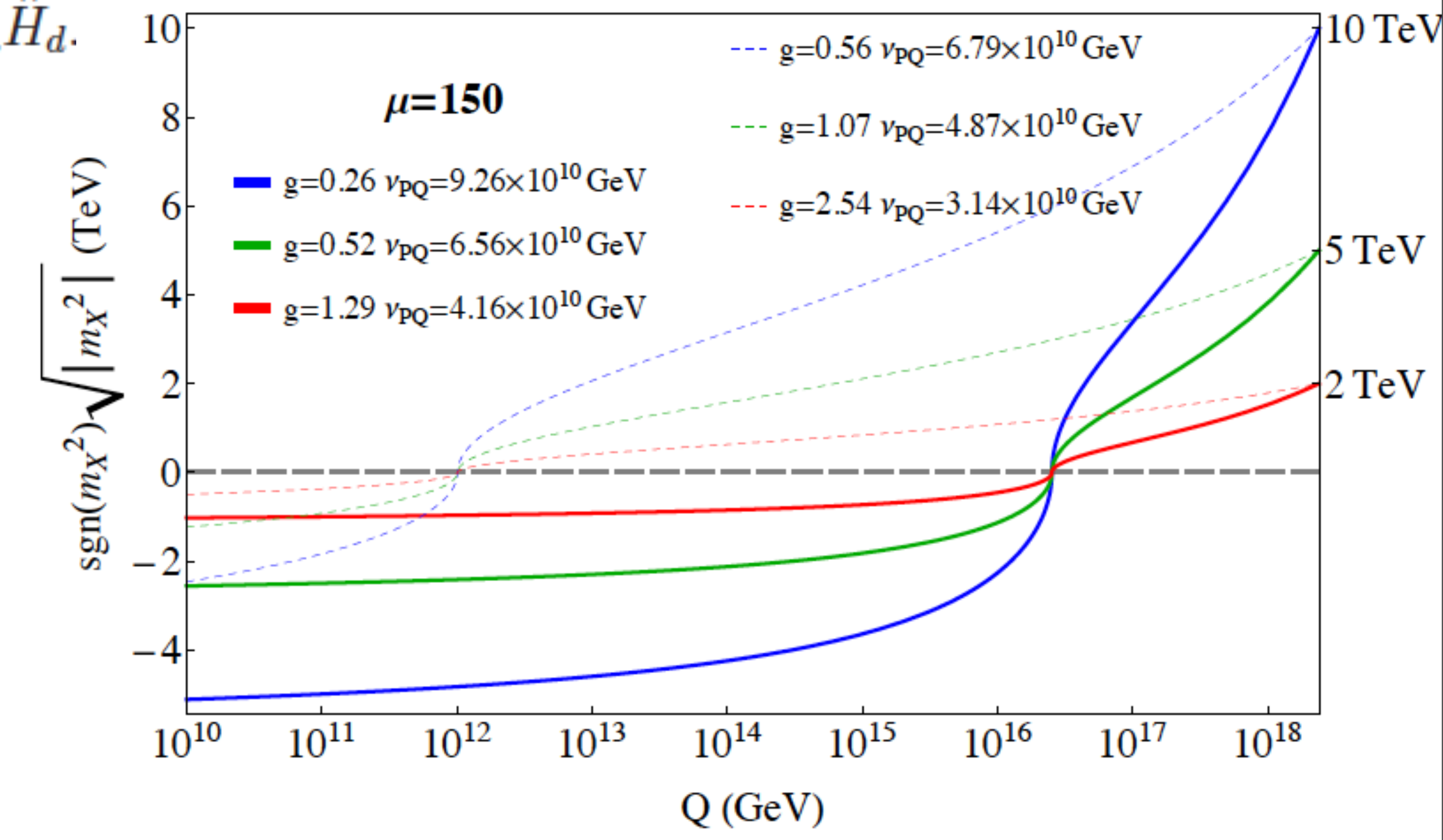
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

$$\hat{f}' = \frac{1}{2} h_{ij} \hat{X} \hat{N}_i^c \hat{N}_j^c + \frac{f}{M_P} \hat{X}^3 \hat{Y} + \frac{g}{M_P} \hat{X} \hat{Y} \hat{H}_u \hat{H}_d .$$

$$M_{N_i^c} = v_X \; h_i|_{Q=v_X}$$

$$\mu = g \frac{v_X v_Y}{M_P} \ .$$



Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

Prospects for discovering RNS at LHC and ILC?

see following talk by X. Tata

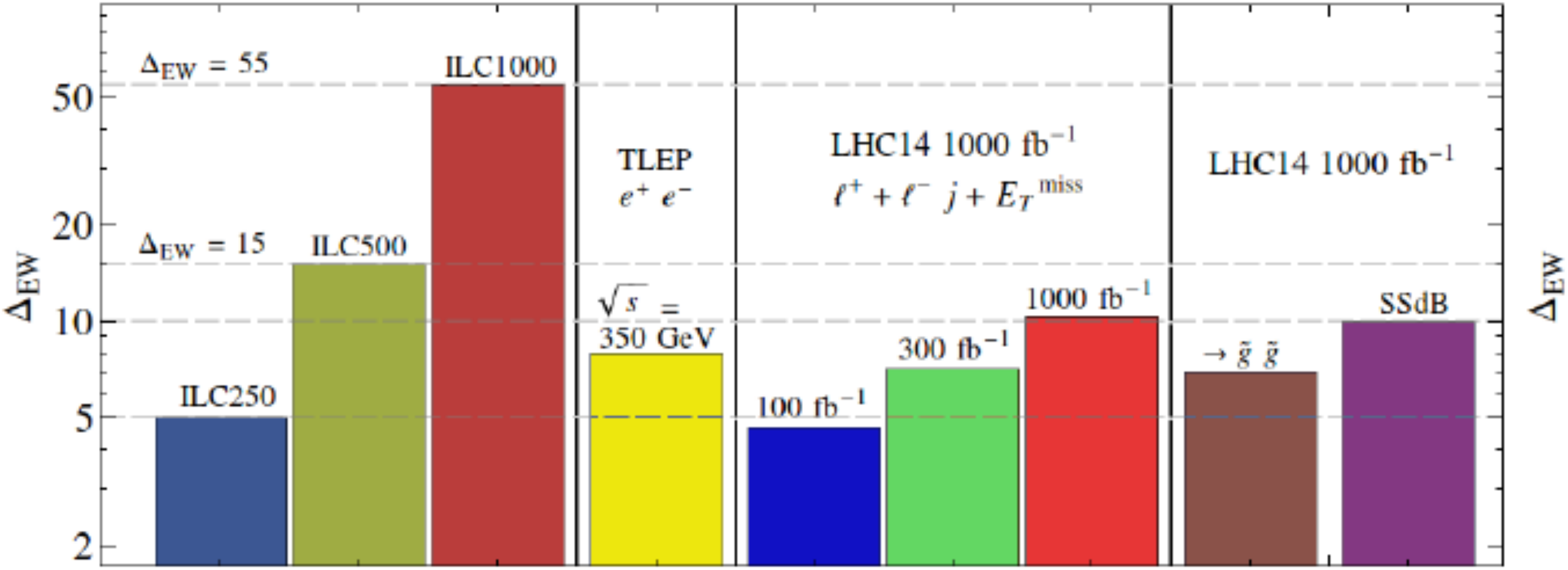
*LHC can see about half of RNS parameter space

*An ILC with $\sqrt{s} > 2\mu$ can completely explore

*Expect higgsino-like WIMPs
at ton-scale WIMP detector

*Expect axion signal at ADMX?

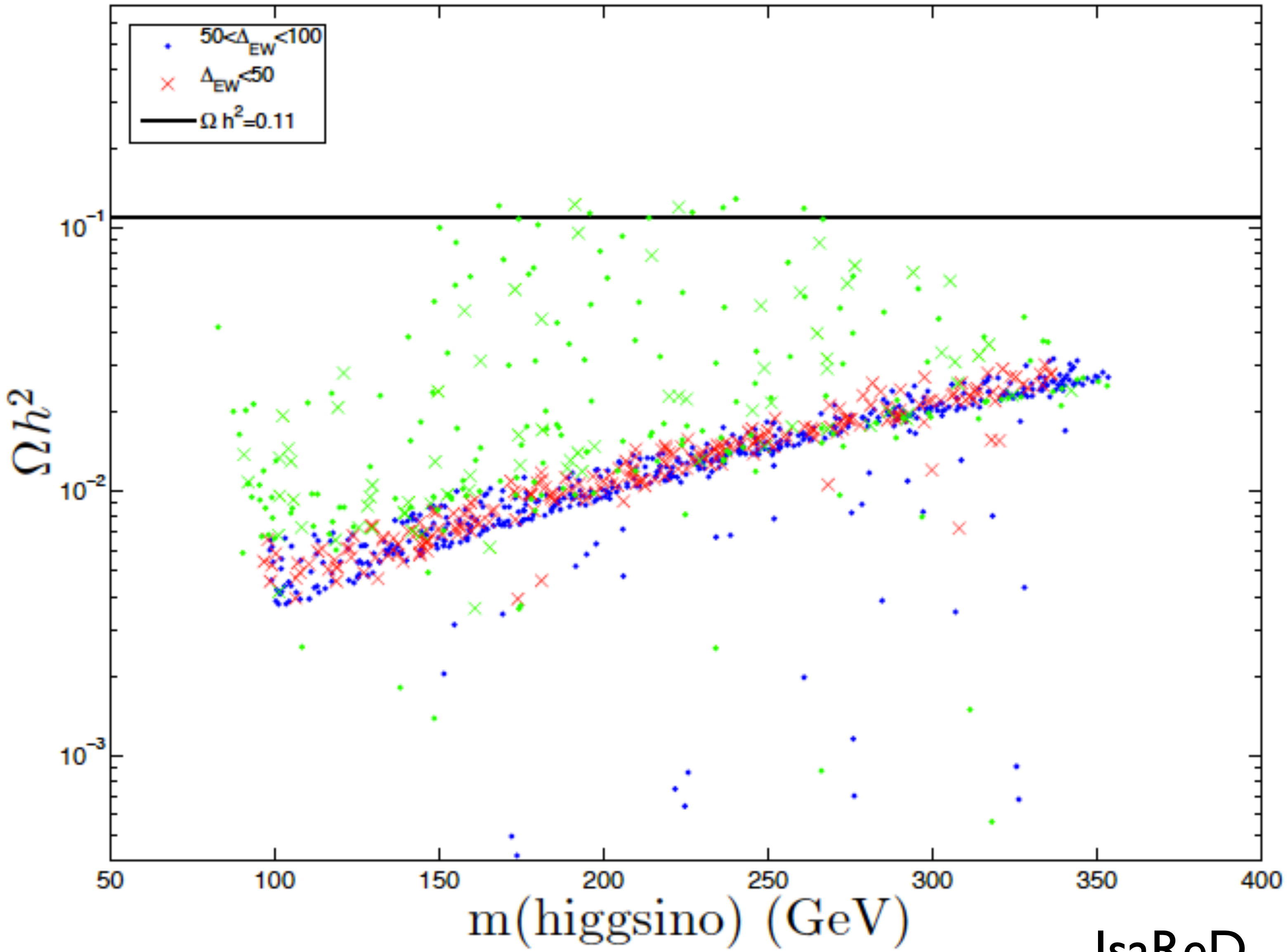
Future collider reach for naturalness



When to give up on naturalness in SUSY?
If ILC(600-700 GeV) sees no light higgsinos

Dark matter in RNS

Mainly higgsino-like WIMPs thermally underproduce DM



IsaReD

green: excluded;
red/blue:allowed

HB, Barger, Mickelson

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/KSVZ/DFSZ invisible axion

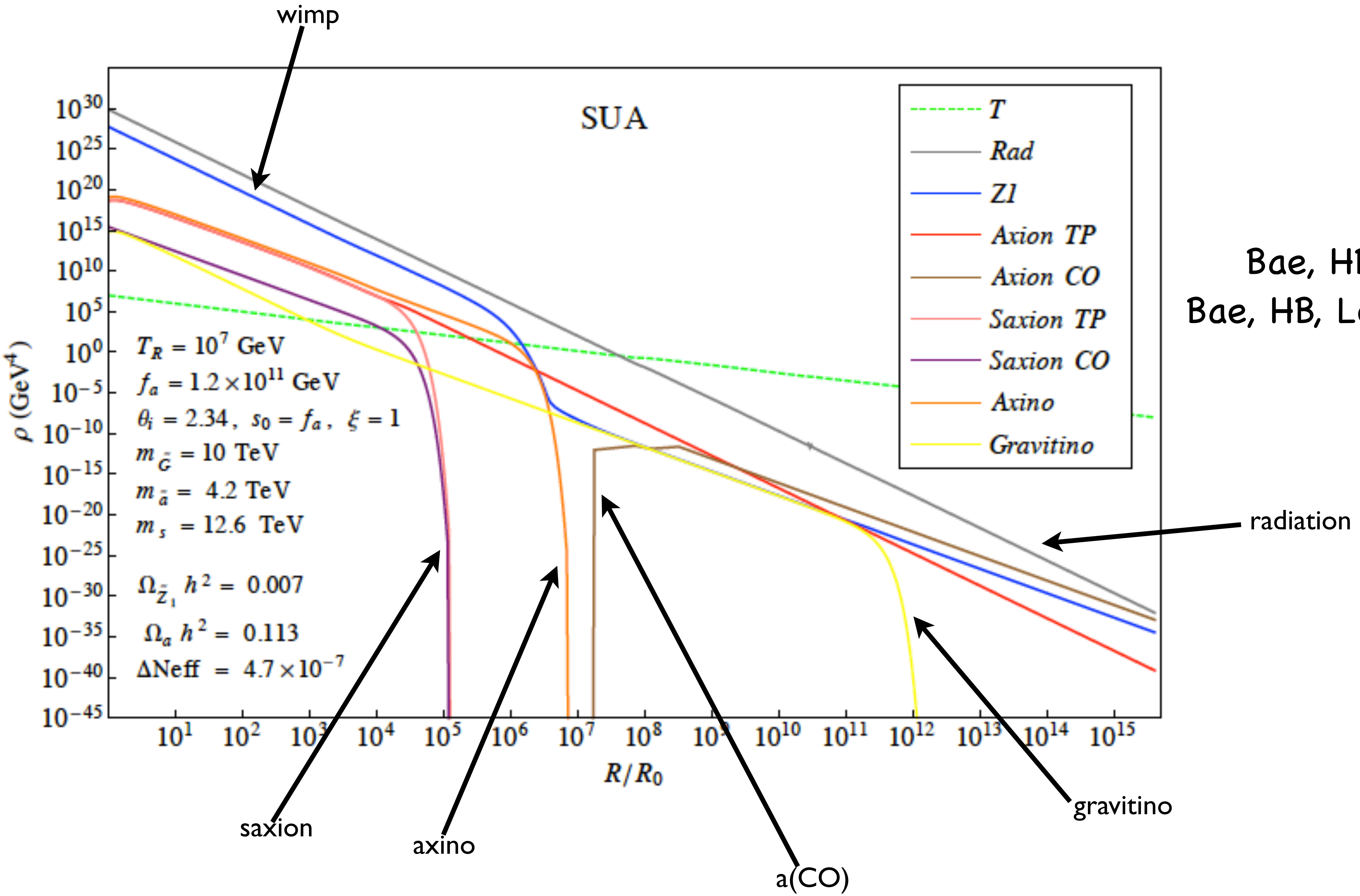
In SUSY, axion accompanied by axino and saxion

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

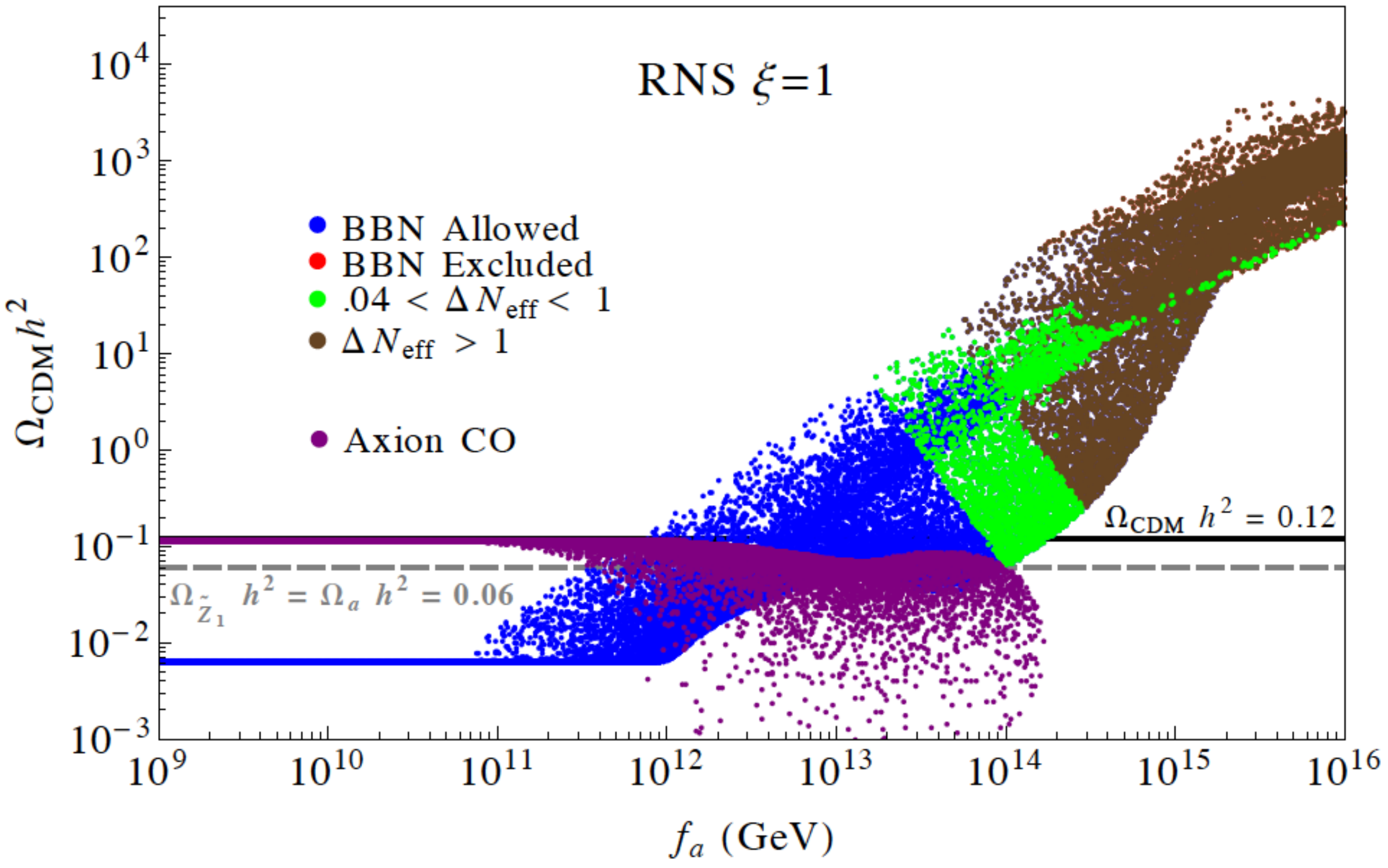
mixed axion-neutralino production in early universe

- 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 in SUSY DFSZ: solve eight coupled Boltzmann equations

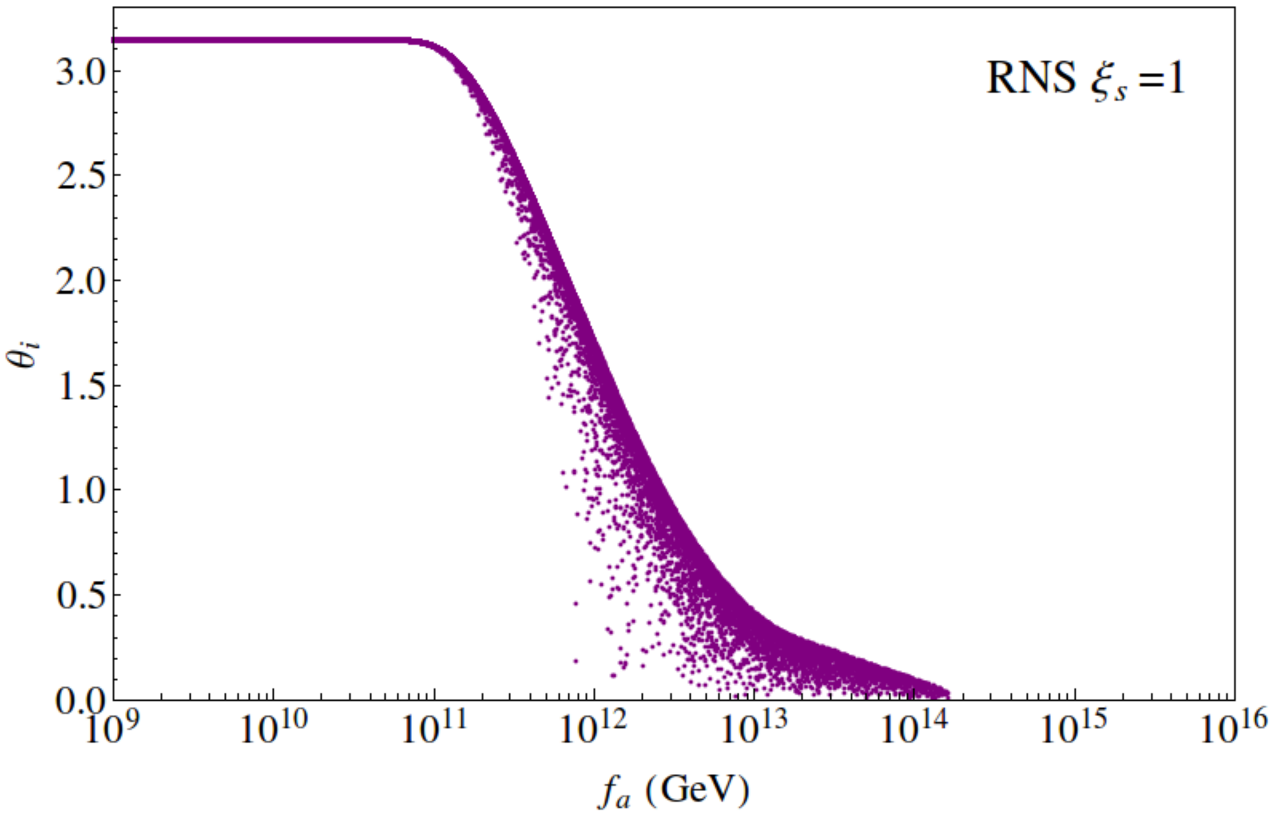


Bae, HB, Chun;
Bae, HB, Lessa, Serce



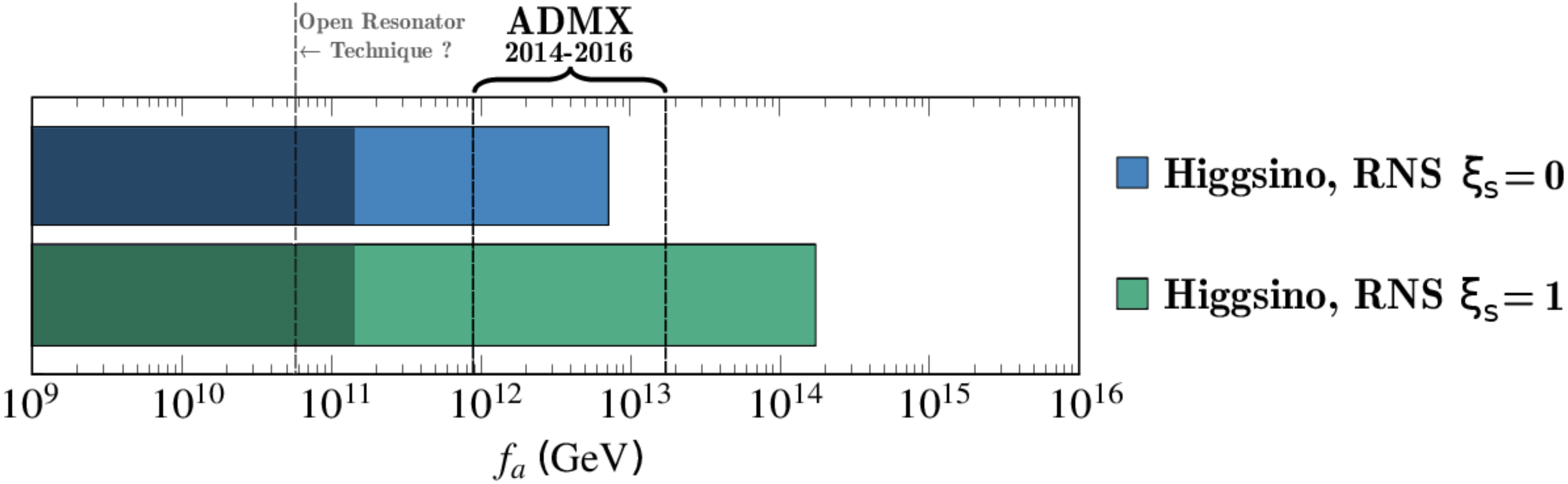
higgsino abundance

axion abundance



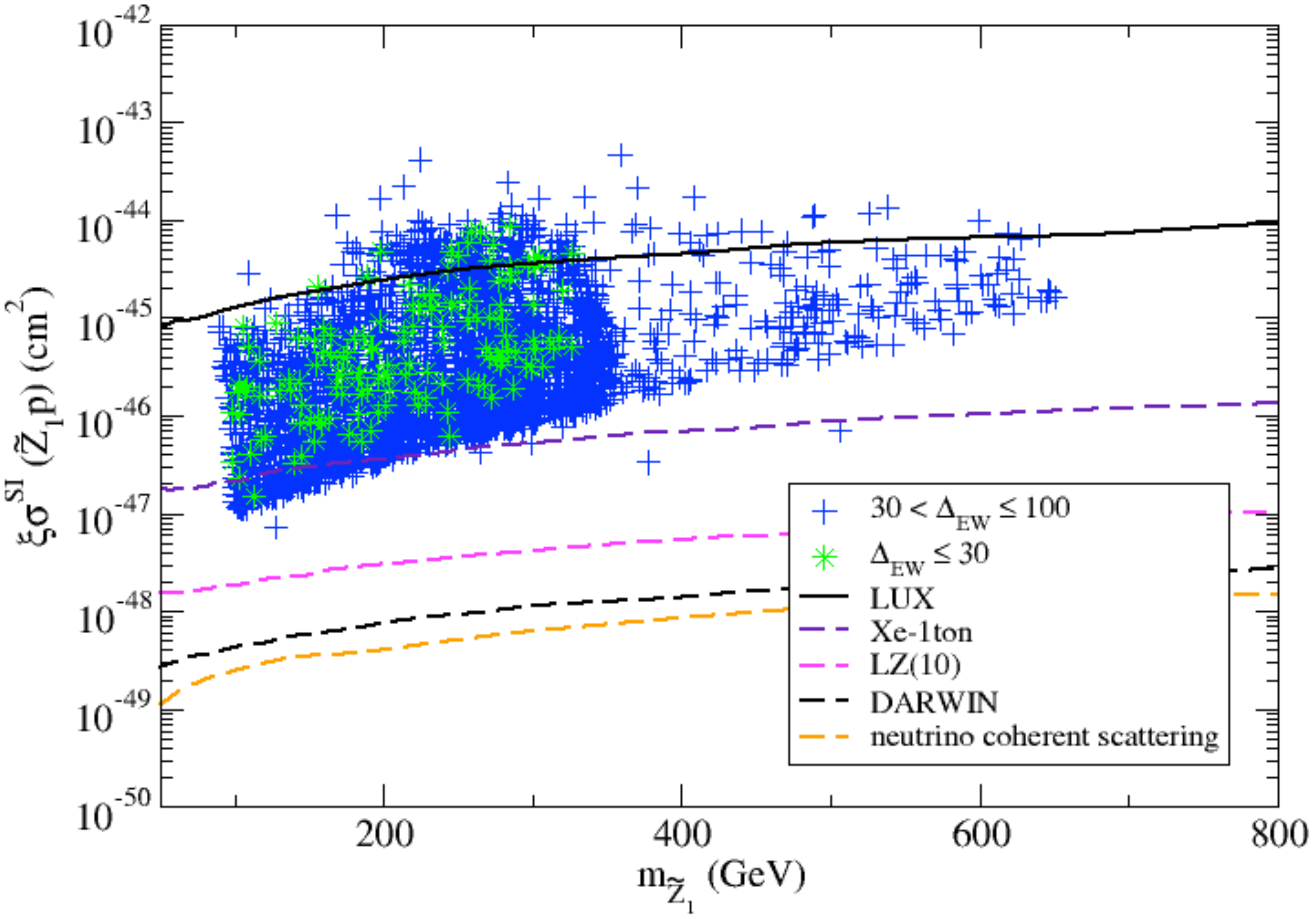
mainly axion CDM for fa<~10^12 GeV; for higher fa, then get increasing wimp abundance

Bae, HB,Lessa,Serce



range of f_a expected from SUSY
with radiatively-driven naturalness
compared to ADMX axion reach

Direct higgsino detection rescaled for minimal local abundance



Bae, HB, Barger,Savoy,Serce

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

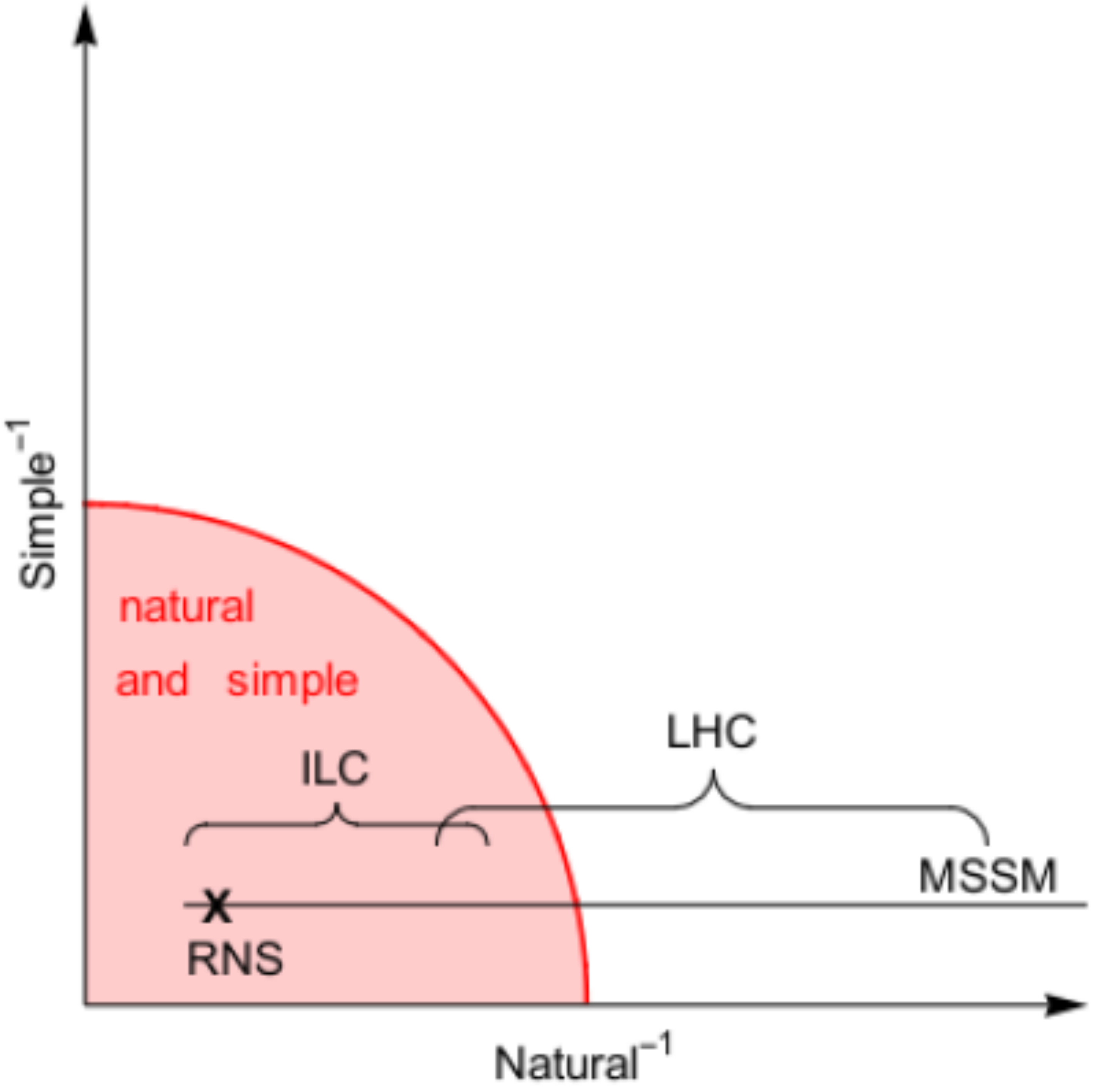
$$X^h_{11} = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

Deployment of Xe-1ton, LZ, SuperCDMS coming soon!

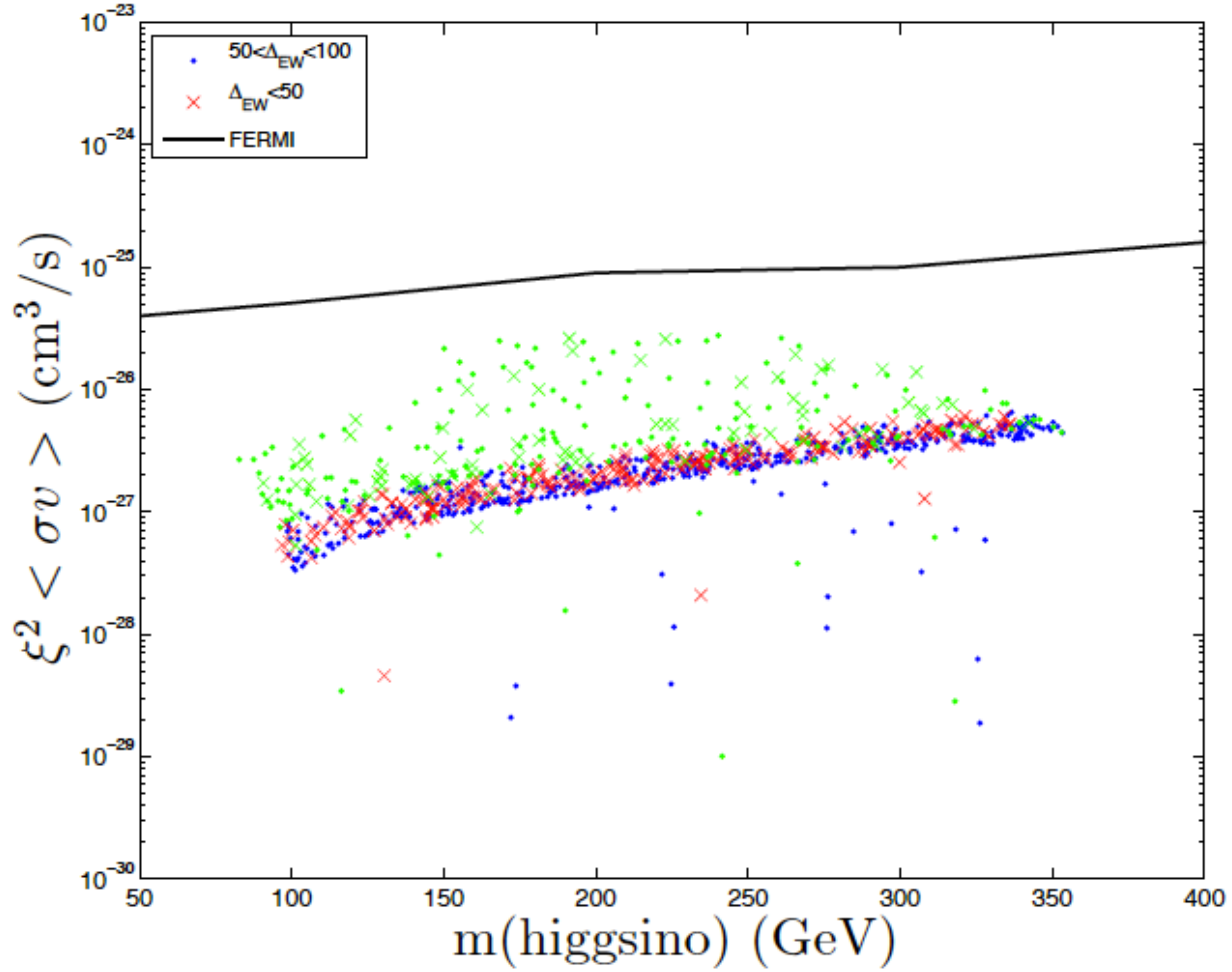
Can test completely with ton scale detector or equivalent (subject to minor caveats)

Conclusions: status of SUSY post LHC8

- SUSY EWFT non-crisis: EWFT allowed at 10% level in radiatively-driven natural SUSY: SUGRA GUT paradigm is just fine in NUHM2 but CMSSM/others fine-tuned
- naturalness maintained for mu~100-200 GeV; t1~1-2 TeV, t2~2-4 TeV, highly mixed; m(glno)~1-5 TeV
- LHC14 w/ 300 fb^-1 can see about half of RNS parameter space
- e+e- collider with sqrt(s)~500-600 GeV needed to find predicted light higgsino states
- Discovery of and precision measurements of light higgsinos at ILC!
- RNS spectra characterized by mainly higgsino-like WIMP: standard relic underabundance
- SUSY DFSZ/MSY invisible axion model:
  solves strong CP and mu problems while allowing for mu~m(Z)
- Expect mainly axion CDM with 5-10% higgsino-like WIMPs over much of p-space
- Ultimately detect both axion and higgsino-like WIMP


Simple^{-1}
natural
and simple
ILC
LHC
MSSM
X
RNS
Natural^{-1}

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

First: Naturalness in the Standard Model

SM case: invoke a single Higgs doublet

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

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

$$m_h^2|_{tree} = 2\mu^2 \qquad \delta m_h^2|_{rad} \simeq \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2$$

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

If δm_h^2 blows up, can freely adjust (tune) $2\mu^2$ to maintain $m_h = 125.5$ GeV

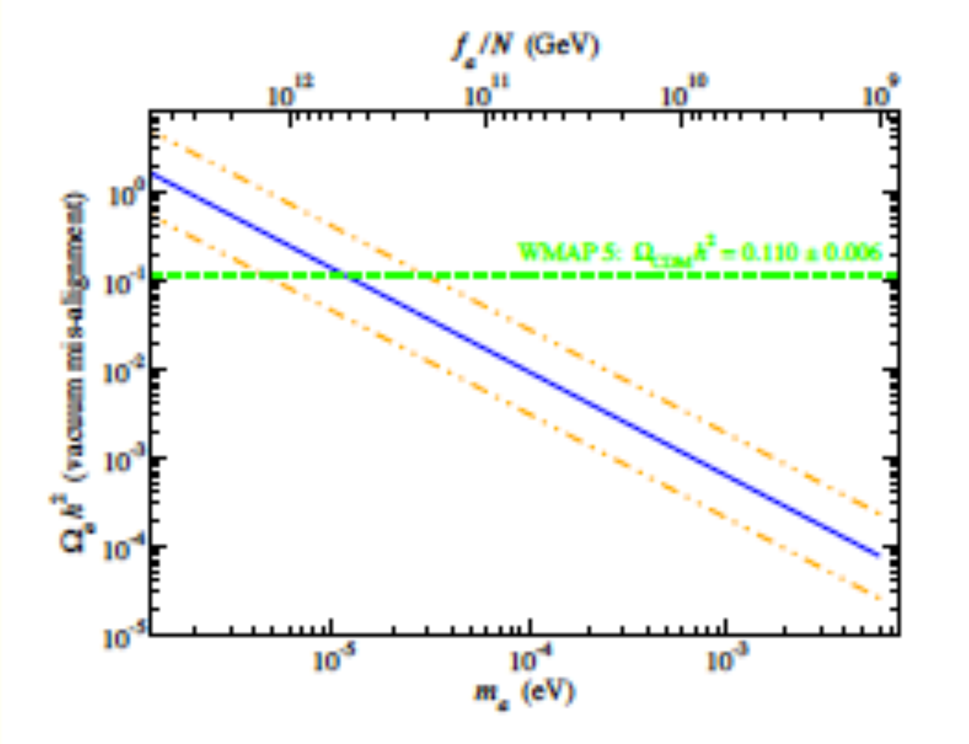
$$\Delta_{SM} \equiv \delta m_h^2|_{rad}/(m_h^2/2) \qquad \Delta_{SM} < 1 \Rightarrow \ \Lambda \sim 1\ TeV$$

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

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
- $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} \theta_i^2 h^2$



- astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 GeV$