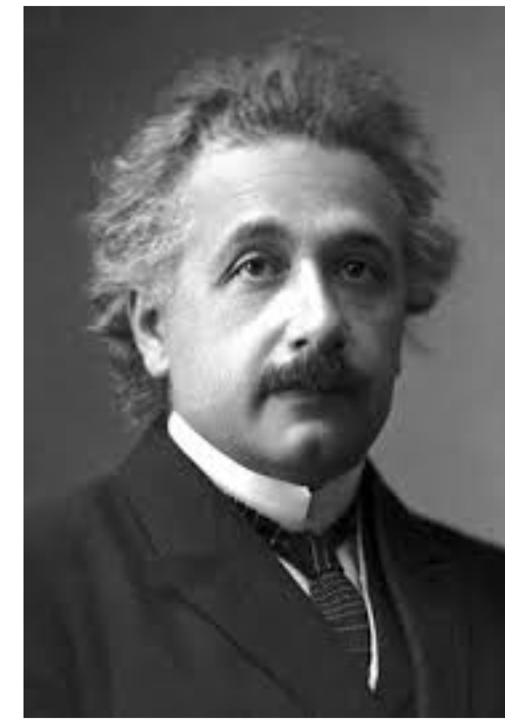
Why SUSY is still natural: with implications for LHC, ILC, WIMP/axion searches

Howard Baer
University of Oklahoma

Bethe Forum,
Bonn, May29, 2017

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

Nature sure looks like SUSY

- stabilize Higgs mass

  Witten, Kaul

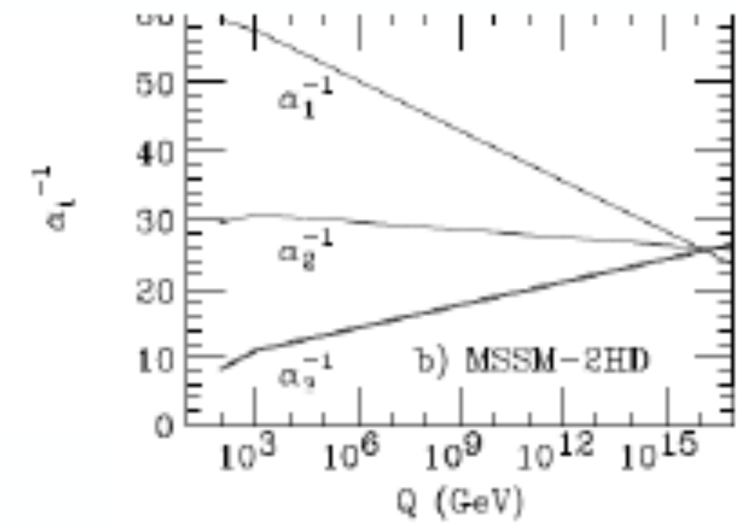
- measured gauge couplings unify

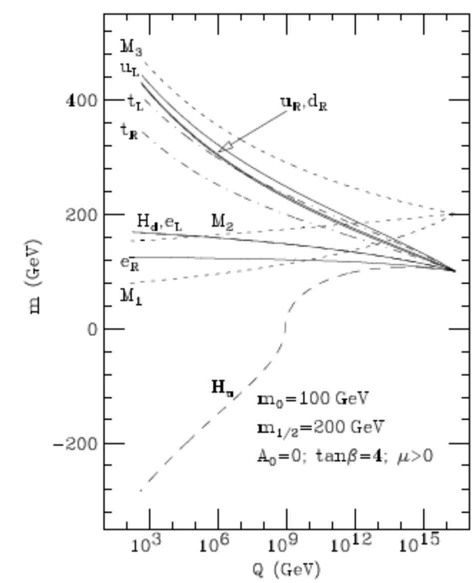
  Dimopoulos, Raby, Wilczek

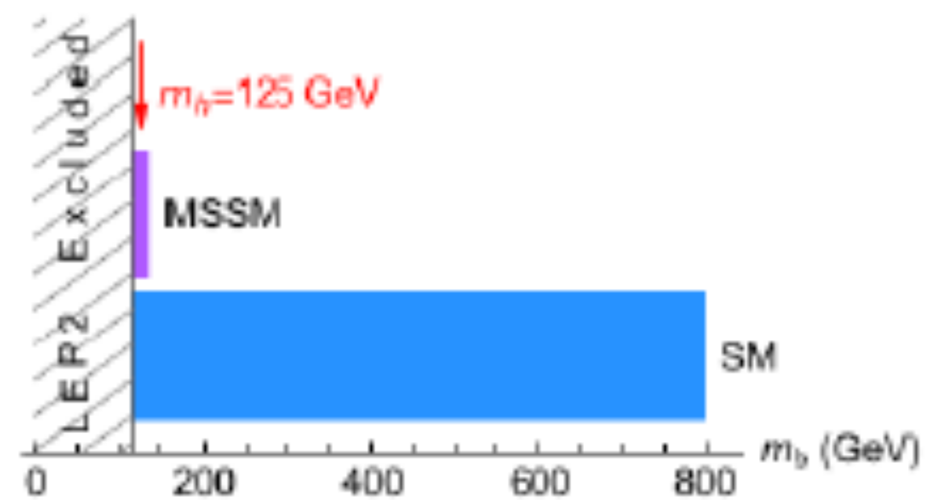
- m(t)~173 GeV for REWSB   Ibanez, Ross

- mh(125): squarely within SUSY window

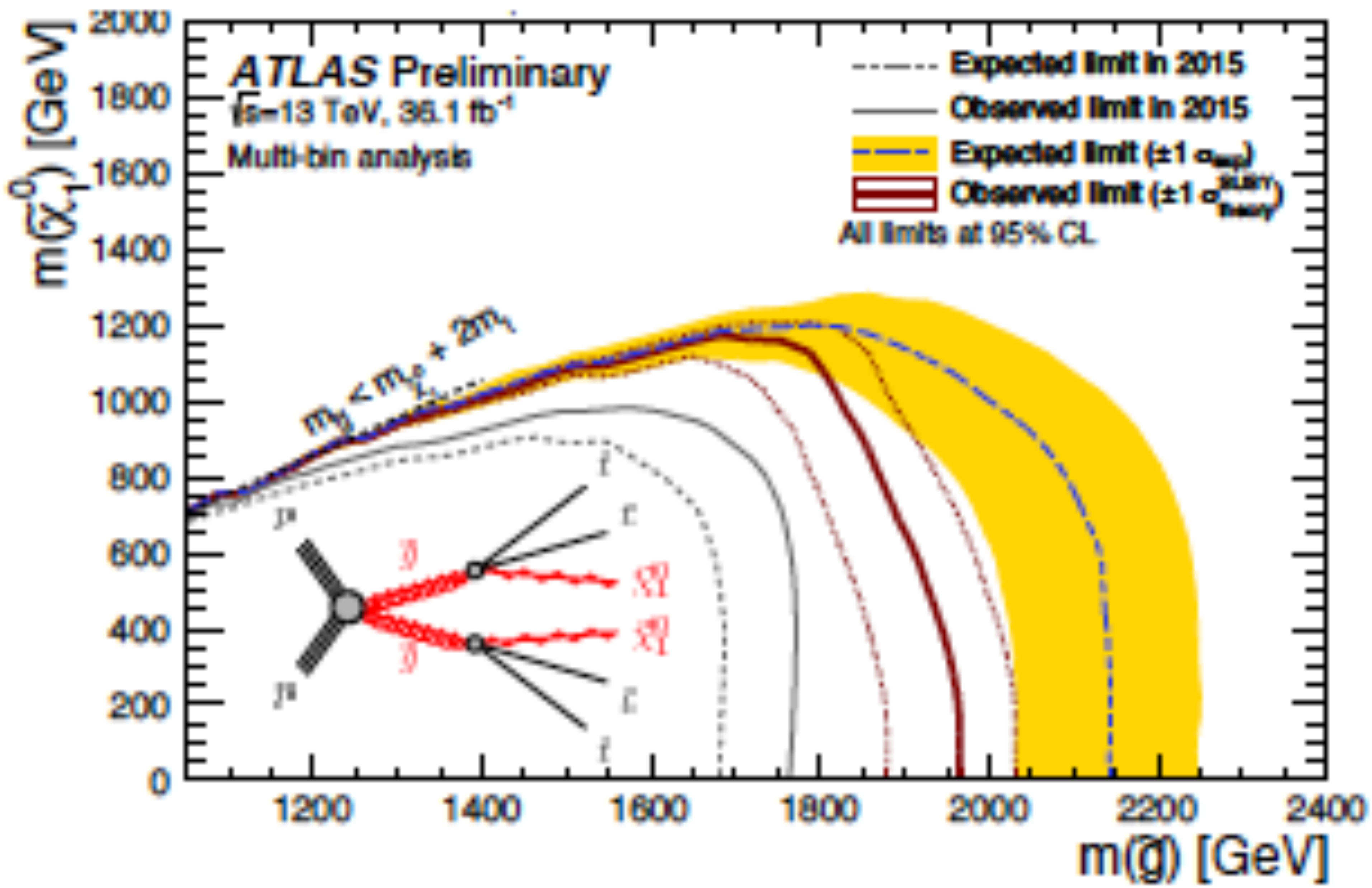
  Haber, Hempfling;
  Okada, Yamaguchi, Yanagida;
  Brignole, Ellis, Zwirner;
  Barbieri, Frigeni;
  Chankowski, Pokorski, Rosiek







recent search results from Atlas run 2 @ 13 TeV:



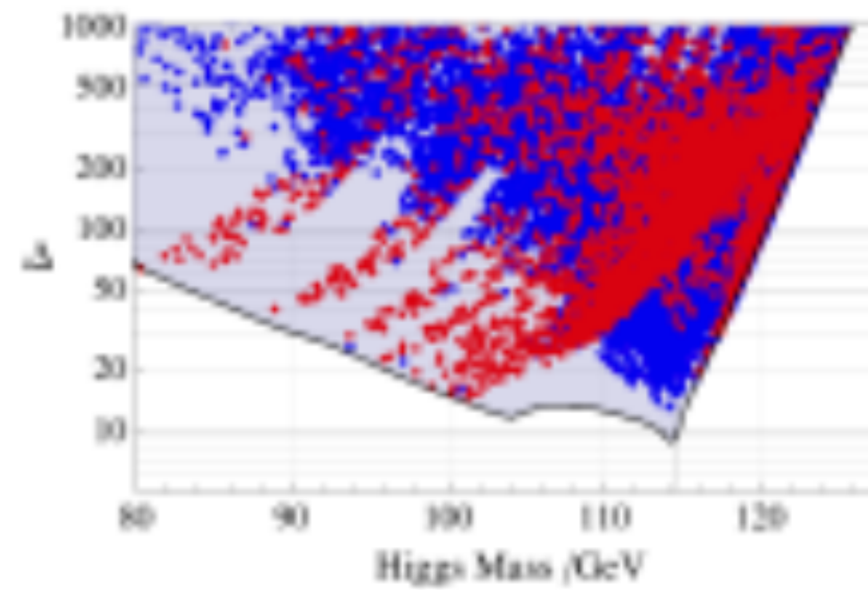
evidently $m_{\tilde{g}} > 1.9$ TeV

compare: BG naturalness (1987): $m_{\tilde{g}} < 0.35$ TeV

These bounds appear in sharp conflict with EW ``naturalness''

	mass
gluino	400 GeV
uR	400 GeV
eR	350 GeV
chargino	100 GeV
neutralino	50 GeV

Barbieri-Giudice 10% bounds, 1987



Cassel, Ghilencea, Ross,2009

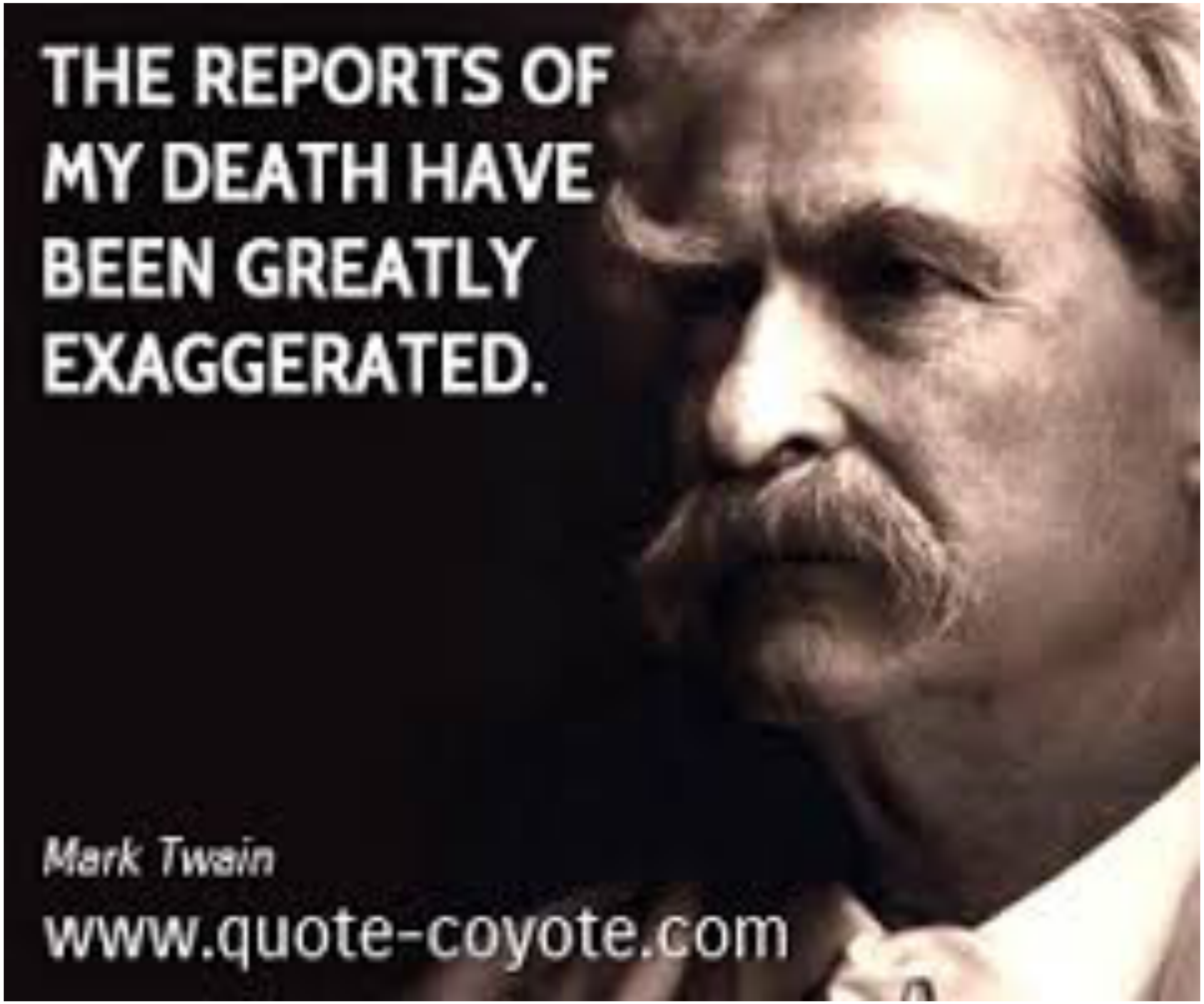
$\Delta \to 1000$

as $m_h \to 125$ GeV

0.1% tuning!?

or is SUSY dead?
how to disprove SUSY?
when it becomes ``unnatural''?
this brings up naturalness issue

Mark Twain, 1835-1910 (or SUSY)



1897

``...settling the ultimate fate of naturalness is perhaps the most profound theoretical question of our time''

Arkani-Hamed et al., arXiv:1511.06495

``Given the magnitude of the stakes involved, it is vital to get a clear verdict on naturalness from experiment''

This should be matched by theoretical scrutiny of what we mean by 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!"

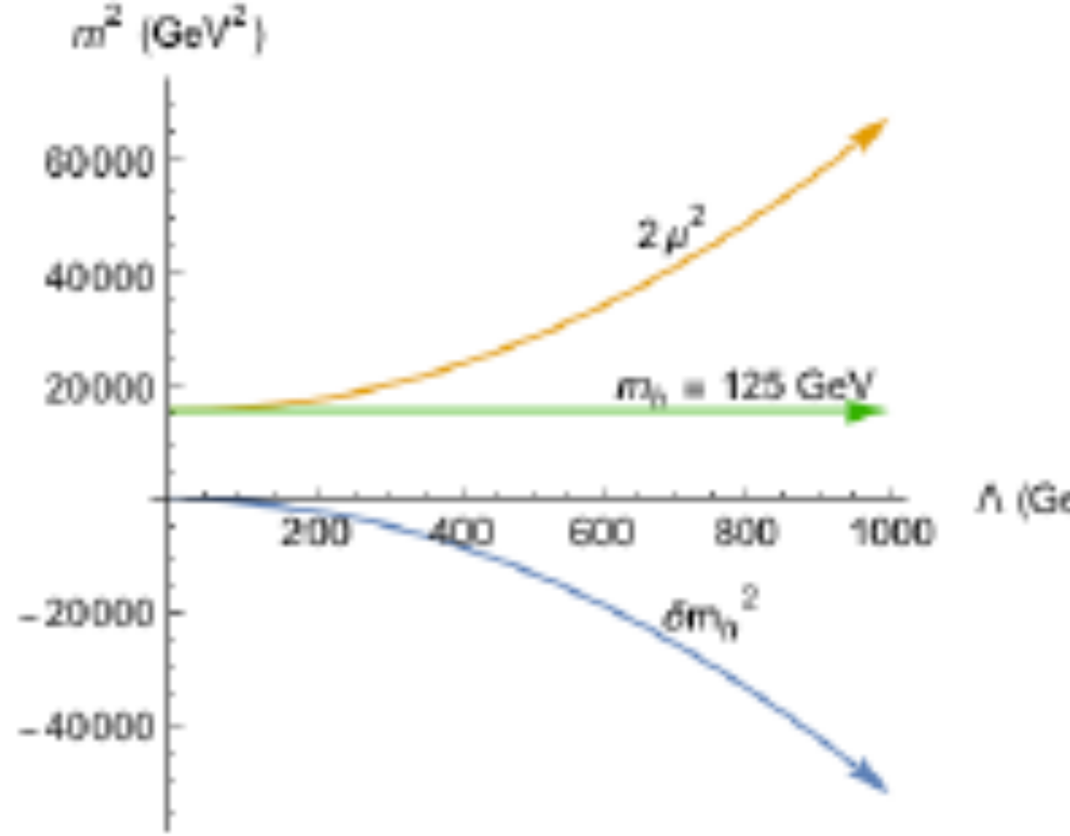
HB, Barger, Mickelson, Padeffke-Kirkland, arXiv:1404.2277

Is observable $\mathcal{O} = \mathcal{O} + a + b - f(b) + c$ fine-tuned for $b > \mathcal{O}$?

Reminder: naturalness in the SM

Higgs sector of SM is ``natural'' only up to cutoff

$$
\begin{aligned}
V &= -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \\
m_h^2 &\simeq 2\mu^2 + \delta m_h^2 \\
\delta m_h^2 &\simeq \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2
\end{aligned}
$$

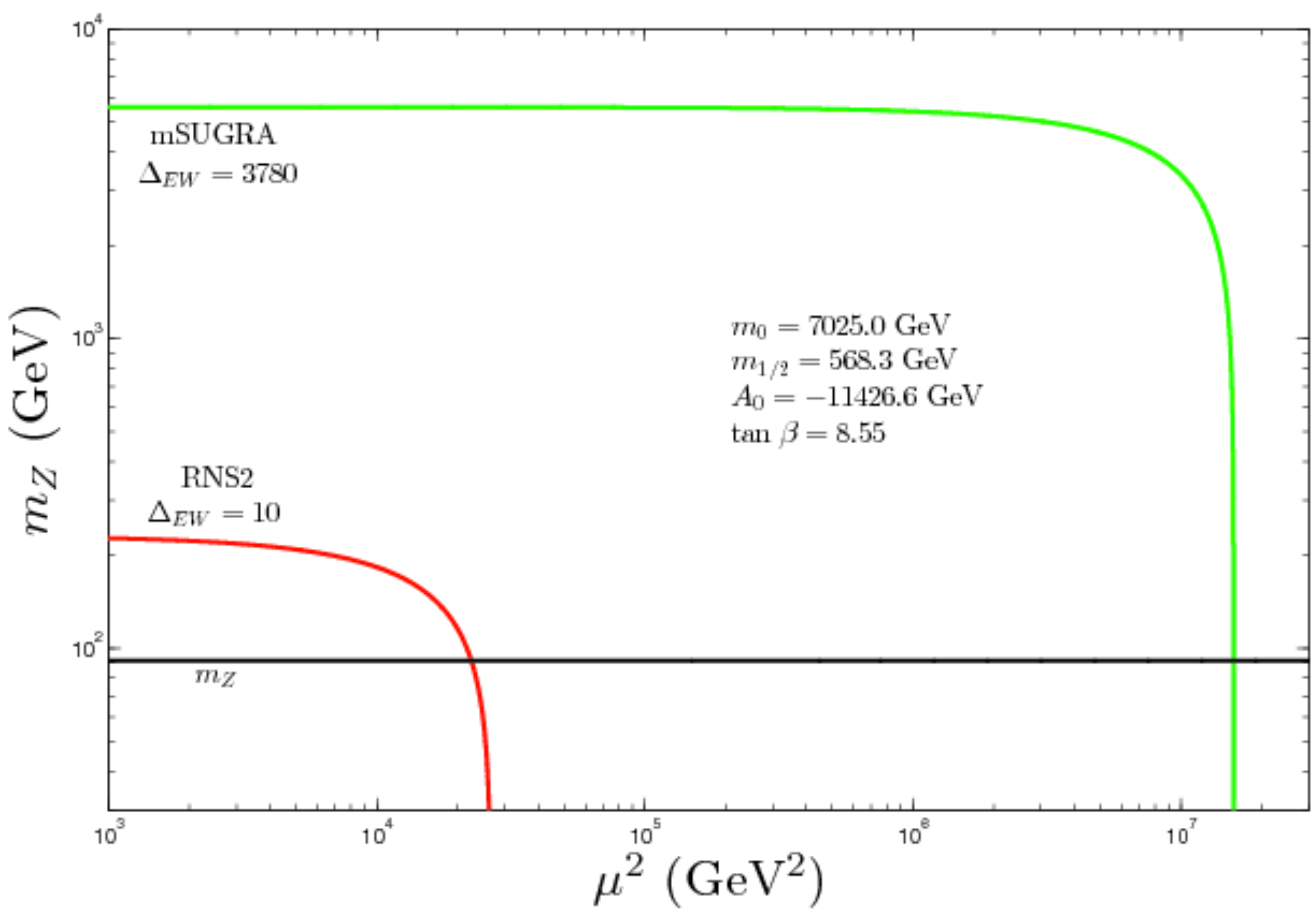


Since δm_h^2 is *independent* of μ^2,
can freely dial (fine-tune) μ^2 to maintain $m_h = 125$ GeV

Naturalness: $\delta m_h^2 < m_h^2 \Rightarrow \Lambda < 1$ TeV!
New physics at or around the TeV scale!

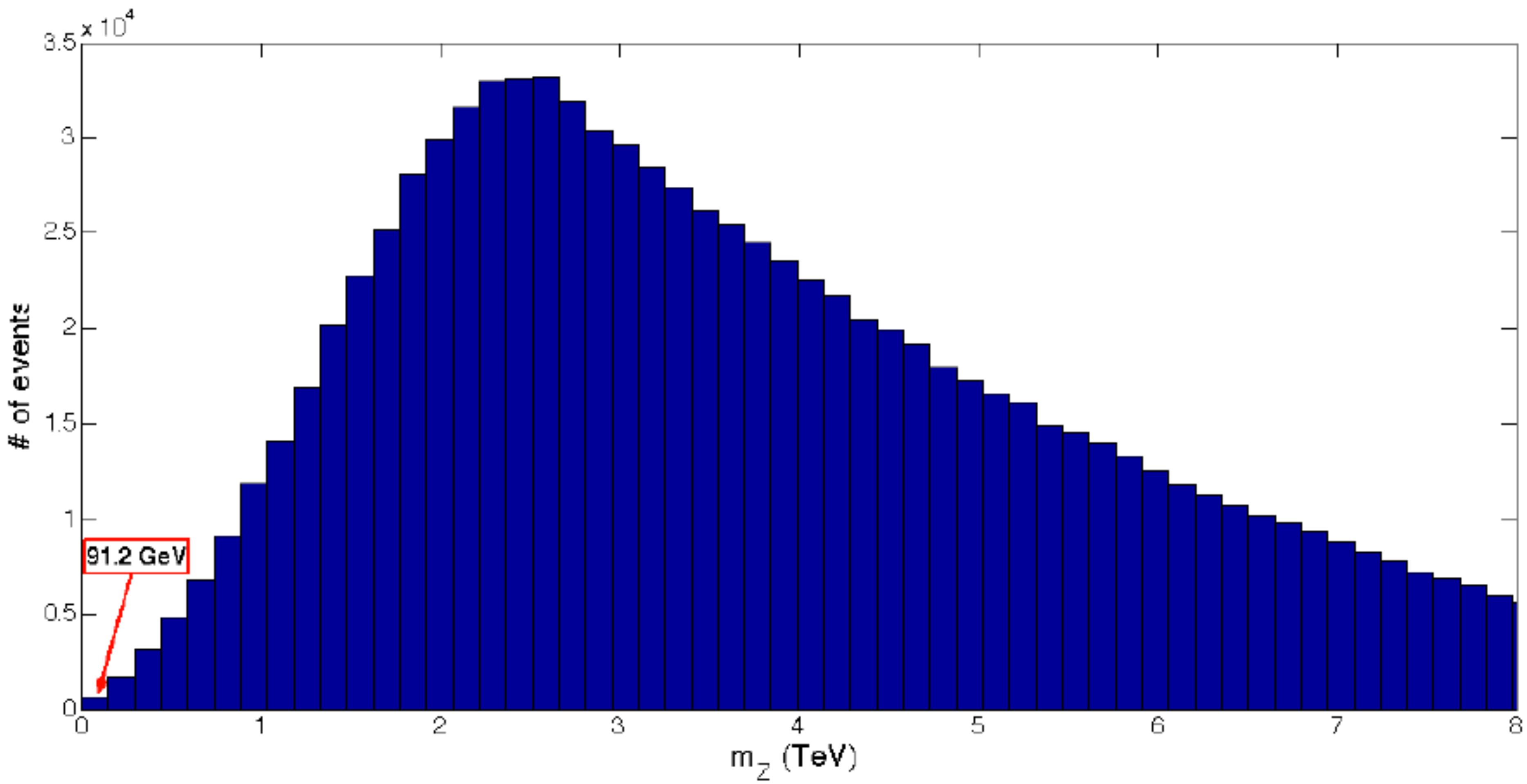
Next: simple electroweak fine-tuning in SUSY:
dial value of mu so that Z mass comes out right:
everybody does it but it is hidden inside spectra codes (Isajet, SuSpect, SoftSUSY, Spheno, SSARD)

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



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

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

scan over parameters

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

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)

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

$\Delta_{EW} \equiv max_i |C_i| / (m_Z^2/2)$ 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 (Chan, Chatto...,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

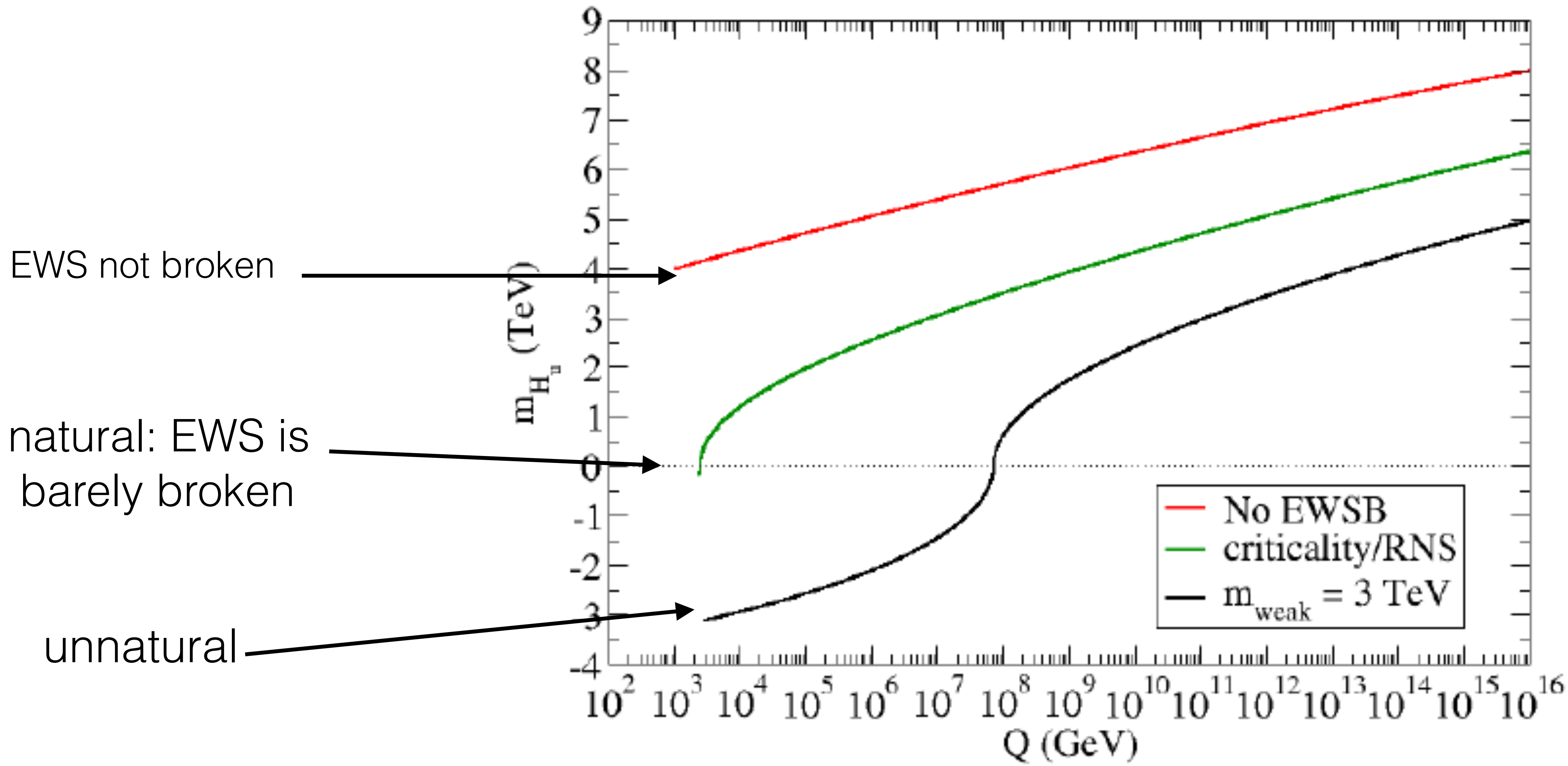
CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

Howard Baer,[1] Vernon Barger, Peisi Huang,[2] Azar Mustafayev,[3] and Xerxes Tata[4]
[1] Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019, USA
[2] Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA
[3] W. I. Fine Institute for Theoretical Physics, University of Minnesota, Minneapolis, MN 55455, USA

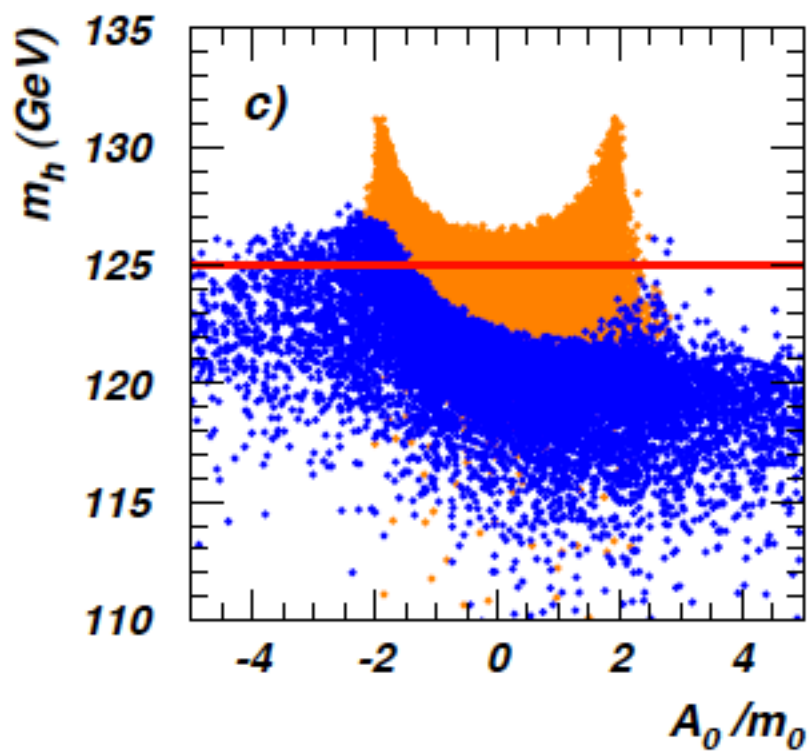
PRL109 (2012) 161802

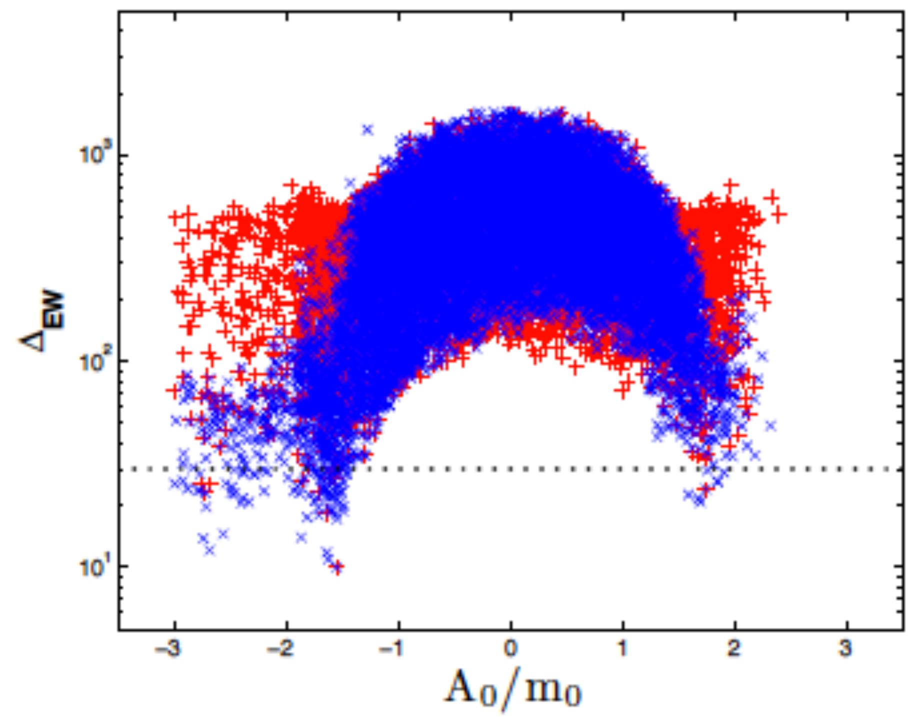
radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness



Evolution of the soft SUSY breaking mass squared term $sign(m_{H_u}^2)\sqrt{|m_{H_u}^2|}$ vs. Q

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





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

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

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

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

It is tempting to pick out one-by-one
quantum fluctuations but must combine log divergences
before taking any limit

$$m_h^2 \simeq \mu^2 + m_{H_u}^2(weak) \simeq \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$$

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

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

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

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

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

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

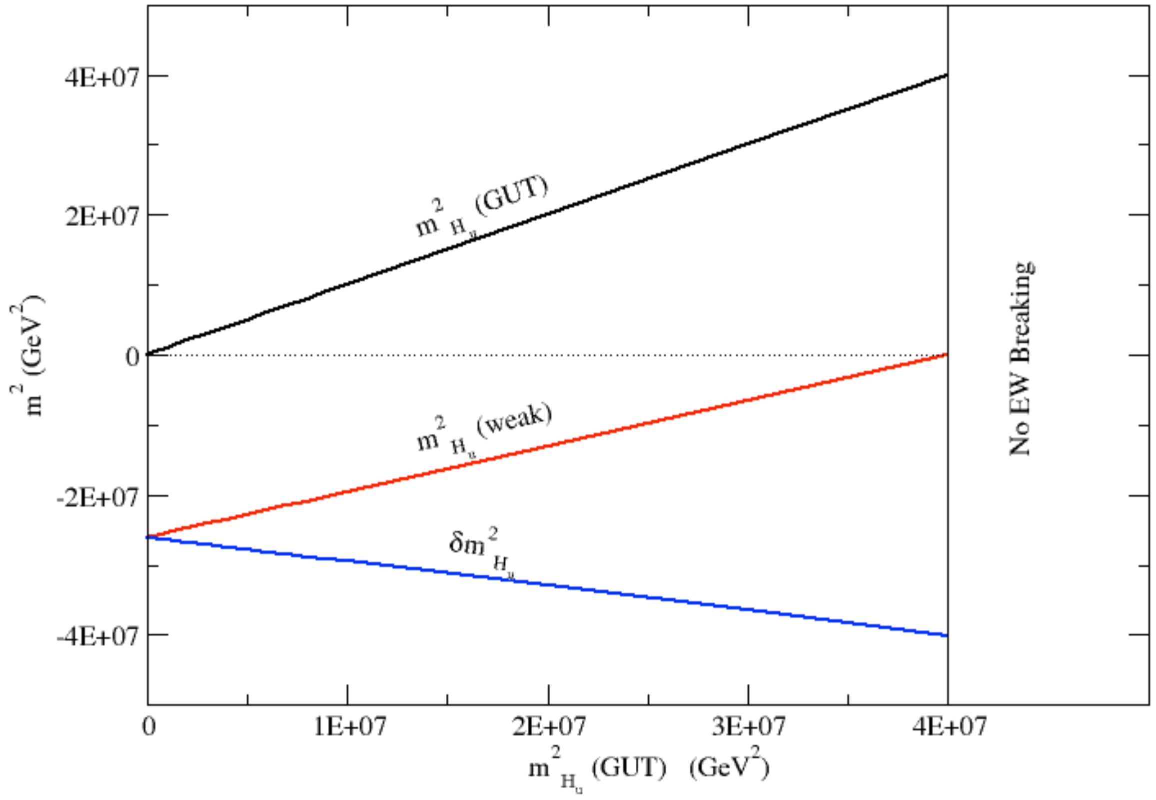
old natural SUSY then A_t can't be too big

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

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

violates prime directive!



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

HB, Barger, Savoy

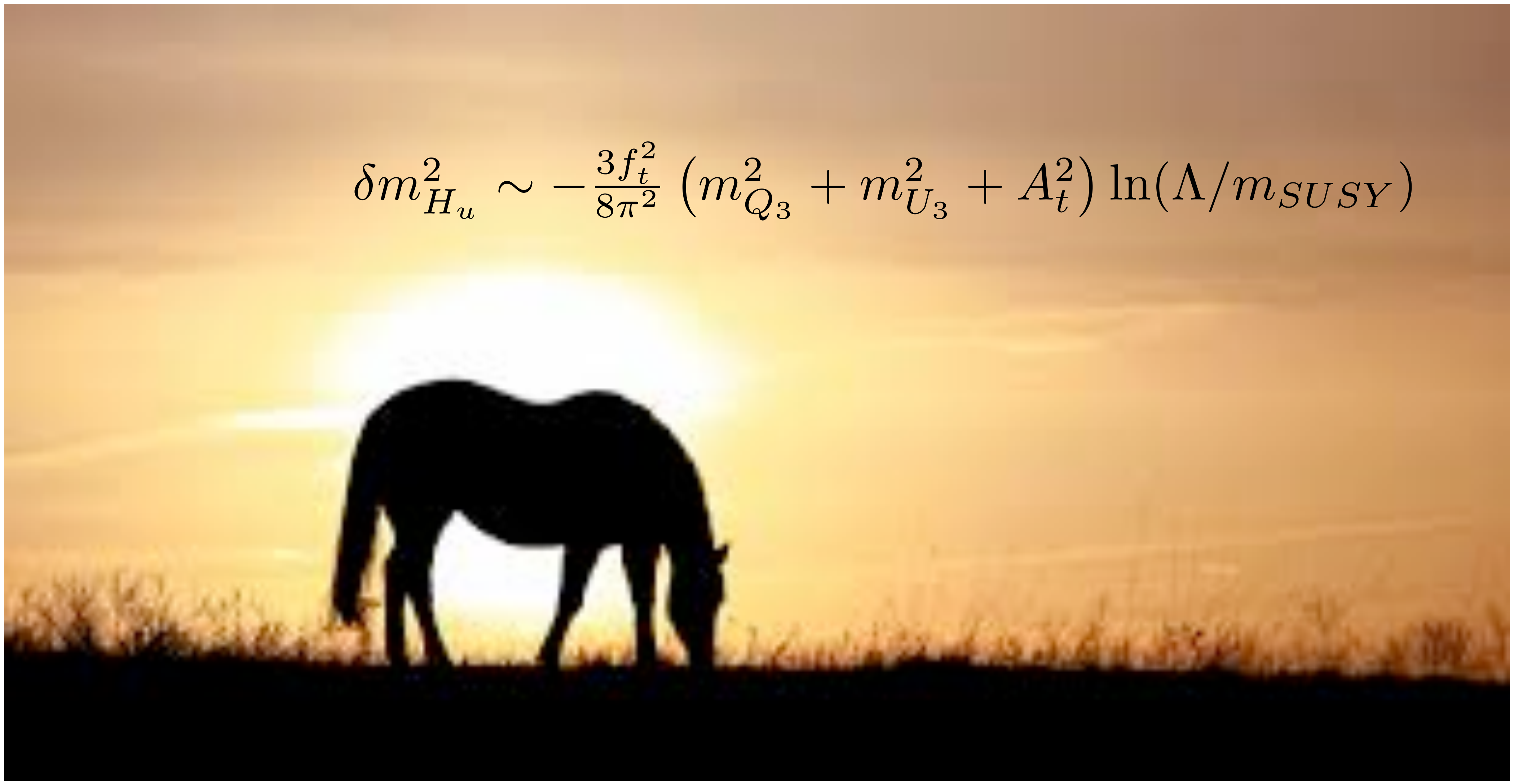
To fix: combine dependent terms:

$m_h^2 \simeq \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ 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



R.I.P.

sub-TeV 3rd generation squarks not required for naturalness

#3. What about EENZ/BG measure?

$$\Delta_{BG} = max_i \left| \frac{\partial \log m_Z^2}{\partial \log p_i} \right| = max_i \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right|$$

p_i are the theory parameters

applied to pMSSM, then $\Delta_{BG} \simeq \Delta_{EW}$

apply to high (e.g. GUT) scale parameters

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

applied to most parameters,

Δ_{BG} large, looks fine-tuned for *e.g.* $m_{\tilde{g}} \simeq M_3 > 1.8$ TeV

$$\Delta_{BG}(M_3^2) = 3.84 \frac{M_3^2}{m_z^2} \simeq 1500$$

#3. What about EENZ/BG measure?

$$\Delta_{BG} = max_i |\frac{\partial \log m_Z^2}{\partial \log p_i}| = max_i |\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}|$$

applied to pMSSM, then $\Delta_{BG} \simeq \Delta_{EW}$

What if we apply to high (e.g. GUT) scale parameters ?

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

For correlated scalar masses $\equiv m_0$,
scalar contribution collapses:
what looks fine-tuned isn't: *focus point SUSY*
multi-TeV scalars are *natural*

Feng, Matchev, Moroi

But wait! in more complete models,
soft terms not independent

violates prime directive!

e.g. in SUGRA, for well-specified hidden sector, each soft term calculated as multiple of m(3/2); soft terms must be combined!

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

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

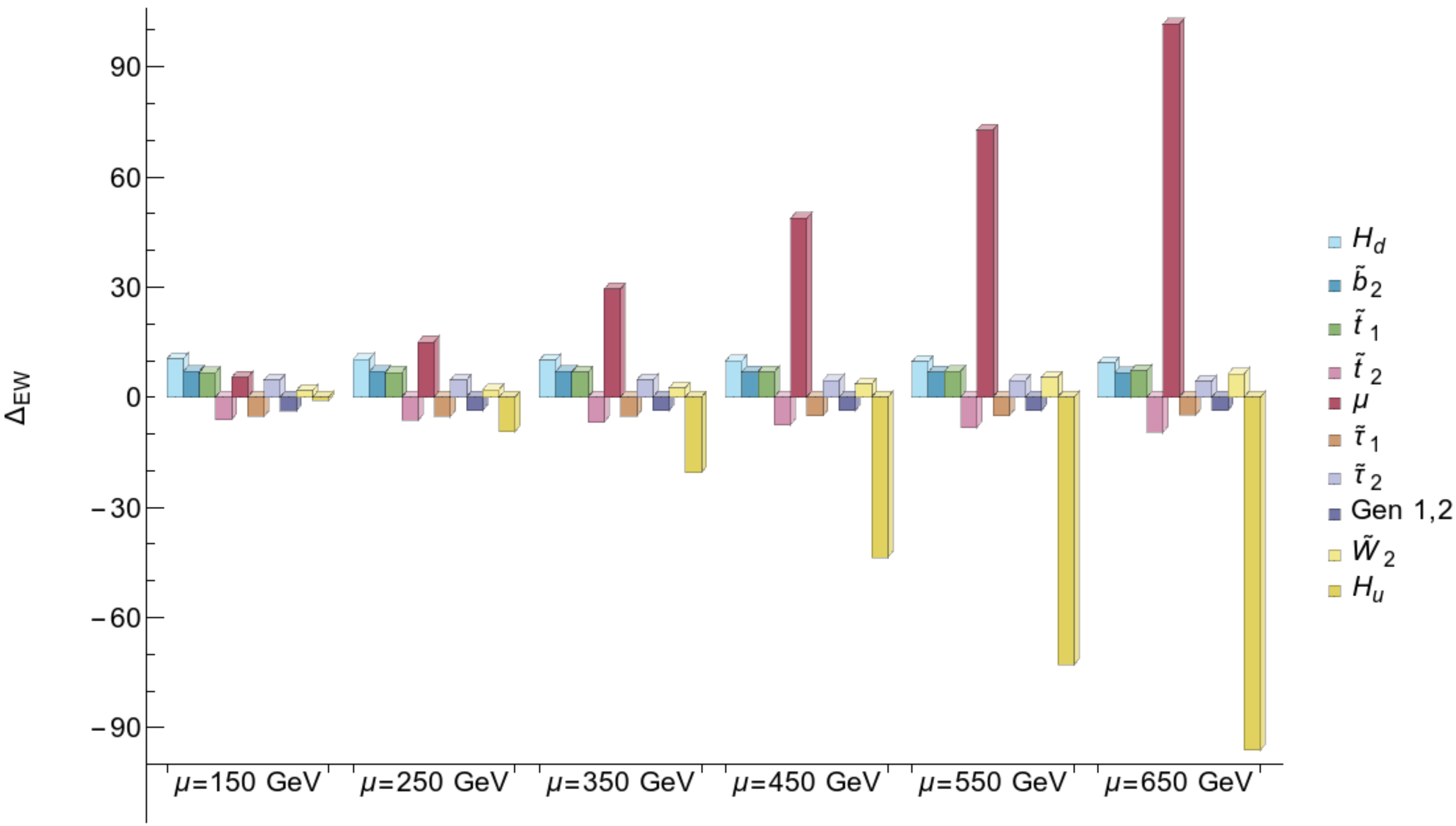
since μ hardly runs, then

$$\begin{aligned} m_Z^2 &\simeq -2\mu^2 + a \cdot m_{3/2}^2 \\ &\simeq -2\mu^2 - 2m_{H_u}^2(weak) \end{aligned}$$

$$m_{H_u}^2(weak) \sim -(100-200)^2 \text{ GeV}^2 \sim -a \cdot m_{3/2}^2/2$$

using μ^2 and $m_{3/2}^2$ as fundamental,
then $\Delta_{BG} \simeq \Delta_{EW}$ even using high scale parameters!

How much is too much fine-tuning?



HB, Barger, Savoy

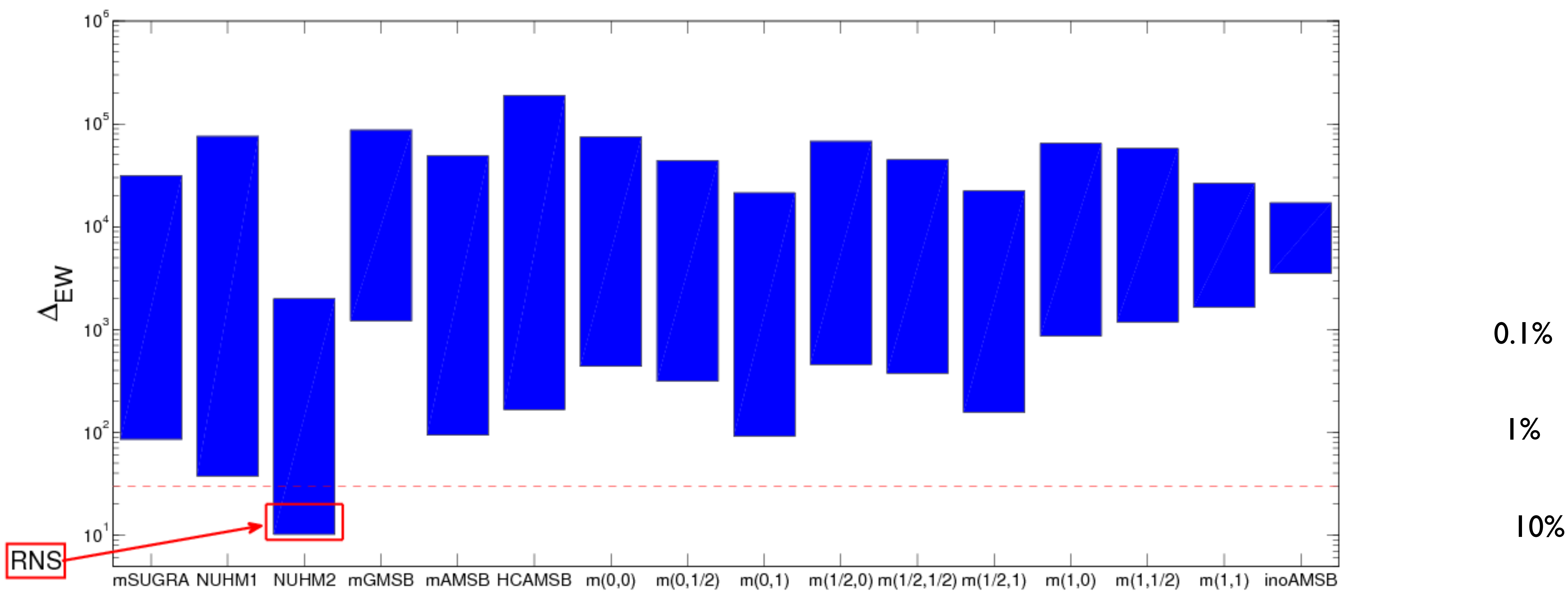
Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

Nature is natural $\Rightarrow \Delta_{EW} < 20 - 30$ (take 30 as conservative)

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

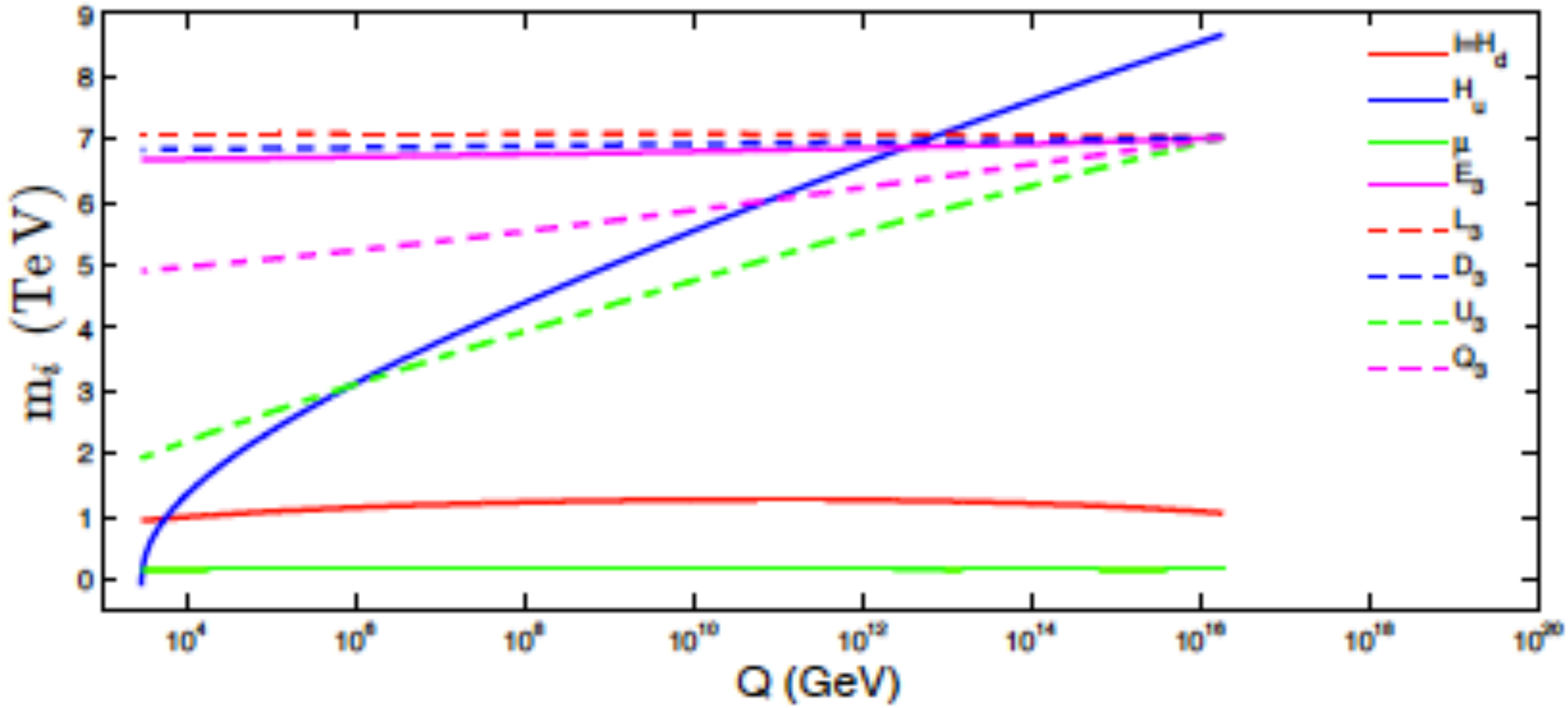
D. Matalliotakis and H. P. Nilles, Nucl. Phys. B **435** (1995) 115; P. Nath and R. L. Arnowitt, Phys. Rev. D **56** (1997) 2820; J. Ellis, K. Olive and Y. Santoso, *Phys. Lett.* **B 539** (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, *Nucl. Phys.* **B 652** (2003) 259; H. Baer, A. Mustafayev, 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:



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:

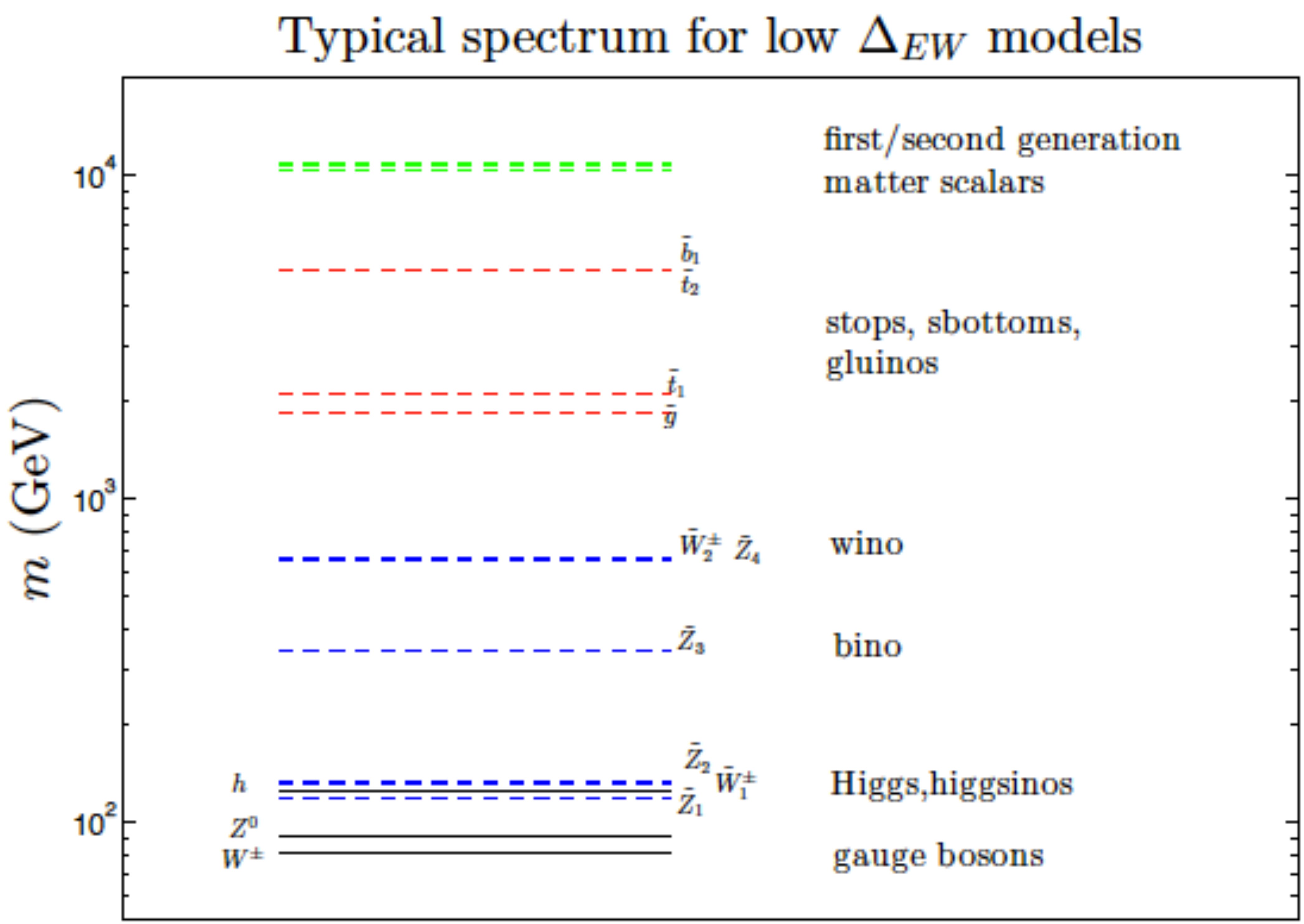
(typically need mHu~25-50% higher than m0)

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]].

bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	0.35 TeV
gluino	400-600 GeV	5-6 TeV
t1	450 GeV	3 TeV
sq/sl	550-700 GeV	10-30 TeV

h(125) and LHC limits are perfectly compatible with 3-10% naturalness: no crisis!



There is a Little Hierarchy, but it is no problem

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

Mirage mediation:
comparable moduli- & anomaly-mediation

Choi, Falkowski, Nilles, Olechowski, Pokorski

Generalized mirage mediation model:

HB, Barger, Serce, Tata: arXiv:1610.06205

$$M_a = \left(\alpha + b_a g_a^2\right) m_{3/2}/16\pi^2, \quad (10)$$

$$A_\tau = \left(-a_3\alpha + \gamma_{L_3} + \gamma_{H_d} + \gamma_{E_3}\right) m_{3/2}/16\pi^2, \quad (11)$$

$$A_b = \left(-a_3\alpha + \gamma_{Q_3} + \gamma_{H_d} + \gamma_{D_3}\right) m_{3/2}/16\pi^2, \quad (12)$$

$$A_t = \left(-a_3\alpha + \gamma_{Q_3} + \gamma_{H_u} + \gamma_{U_3}\right) m_{3/2}/16\pi^2, \quad (13)$$

$$m_i^2(1,2) = \left(c_m\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (14)$$

$$m_j^2(3) = \left(c_{m3}\alpha^2 + 4\alpha\xi_j - \dot{\gamma}_j\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (15)$$

$$m_{H_u}^2 = \left(c_{H_u}\alpha^2 + 4\alpha\xi_{H_u} - \dot{\gamma}_{H_u}\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (16)$$

$$m_{H_d}^2 = \left(c_{H_d}\alpha^2 + 4\alpha\xi_{H_d} - \dot{\gamma}_{H_d}\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (17)$$

elevate a_3, c_m, c_{m3}, c_{H_u}, c_{H_d} from discrete to continuous:
soft terms depend on location of fields in compactified manifold!

p-space:

$$\alpha,\ m_{3/2},\ c_m,\ c_{m3},\ a_3,\ c_{H_u},\ c_{H_d},\ \tan\beta \quad (GMM)$$

$$\alpha,\ m_{3/2},\ c_m,\ c_{m3},\ a_3,\ \tan\beta, \mu,\ m_A \quad (GMM'). \qquad \Leftarrow$$

allows for natural mirage mediation

Allows to generate mini-landscape spectra

Lebedev, Nilles, Raby, Ramos-Sanches, Ratz, Vaudrevange

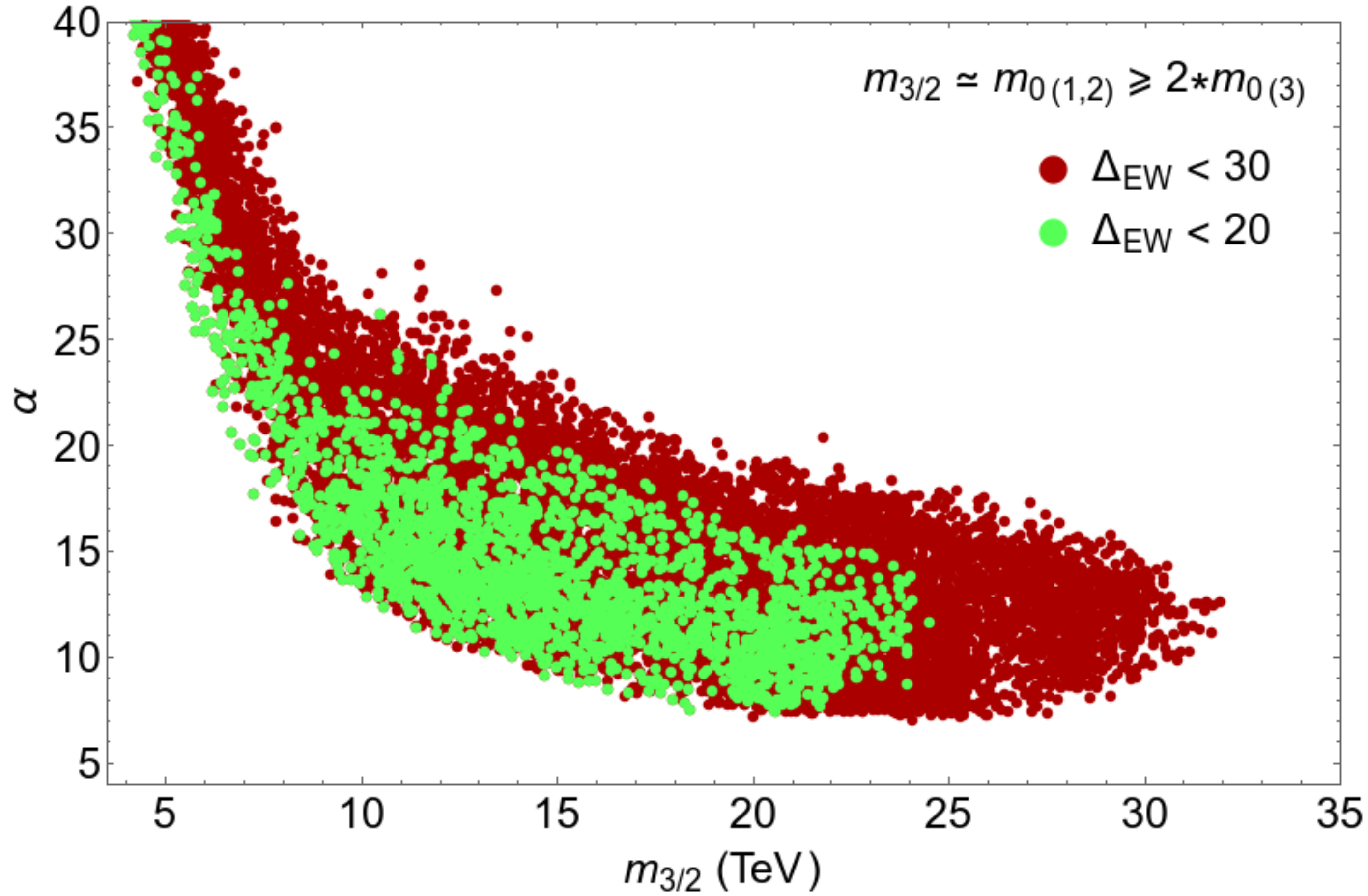
but with radiatively-driven naturalness

HB, Barger, Savoy, Serce, Tata, arXiv:1705.01578

- Look for fertile patch of landscape giving MSSM
- 1,2 gen lives on orbifold fixed points/tori: in 16 of SO(10)
- 3rd gen, Higgs, gauge live more in bulk: split multiplets
- m(1,2)~m(3/2)~10-30 TeV
- m(3)~m(H)~A's~m(inos)~1-3 TeV
- soft terms that of mirage mediation
- programmed Isajet 7.86

To generate minilandscape, take:

$c_m = 16\pi^2/\alpha)^2$ so that $m_0(1,2) \simeq m_{3/2}$

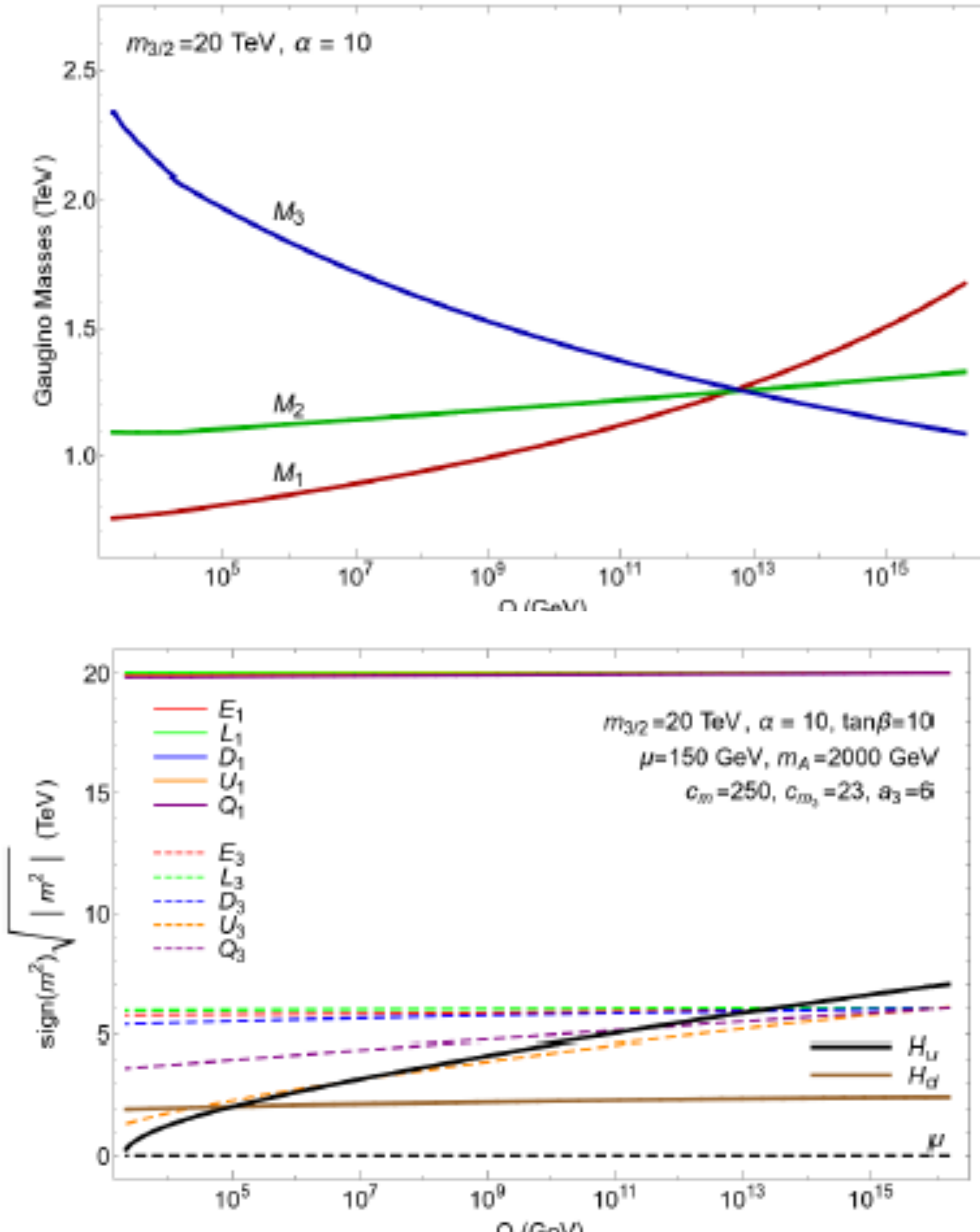


Then get upper bound $m_{3/2} < 25 - 30$ TeV and $\alpha > 7$
else too large $m_0(1,2)$ drives 3rd generation tachyonic

Martin, Vaughn, 2-loop RGEs

Increased upper bound on m(gluino)<6 TeV

Alpha bound => mirage unif scale >10^11 GeV
(not too much compression of inos)



$m_{3/2}$=20 TeV, α = 10
Gaugino Masses (TeV)
M_3
M_2
M_1
Q (GeV)
E_1
L_1
D_1
U_1
Q_1
E_3
L_3
D_3
U_3
Q_3
$m_{3/2}$=20 TeV, α = 10, tanβ=10
μ=150 GeV, m_A=2000 GeV
c_m=250, c_{m_3}=23, a_3=6
$\mathrm{sign}(m^2)\sqrt{|m^2|}$ (TeV)
H_u
H_d
μ
Q (GeV)

$$\Delta_{EW} = 17.6$$

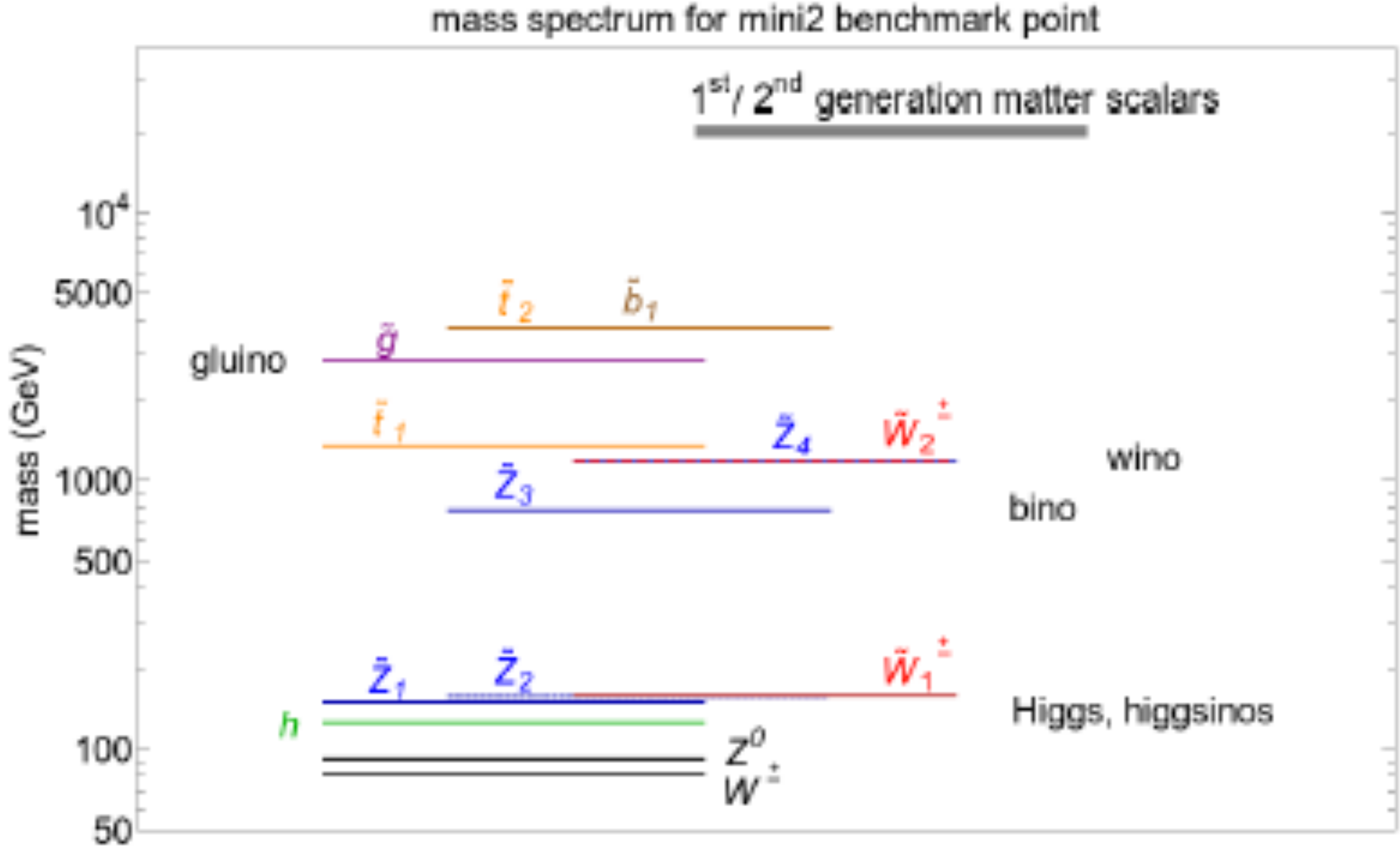


Figure 7: The superparticle mass spectra from the natural mini-landscape point mini2 of Table 1.

Can stop here or else:

- SUSY mu problem: Kim-Nilles SUSY DFSZ axion solution; radiative PQ breaking => mu<< m(3/2) Little Hierarchy?
- String landscape statistical/anthropic attractor towards natural SUSY soft terms and m(h)~125 GeV
- Dark matter: higgsino-like WIMP + axion admixture? Mainly axions but more likely to see WIMP...
- new signatures for LHC searches
- HL-LHC may not be enough; may need LHC33 for SUSY
- ILC urgently needed!

$$\sqrt{s} > 2m(higgsino) \sim 600 \text{ GeV to discover SUSY}$$

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!

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

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

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

Choi, Chun, Kim (1996)

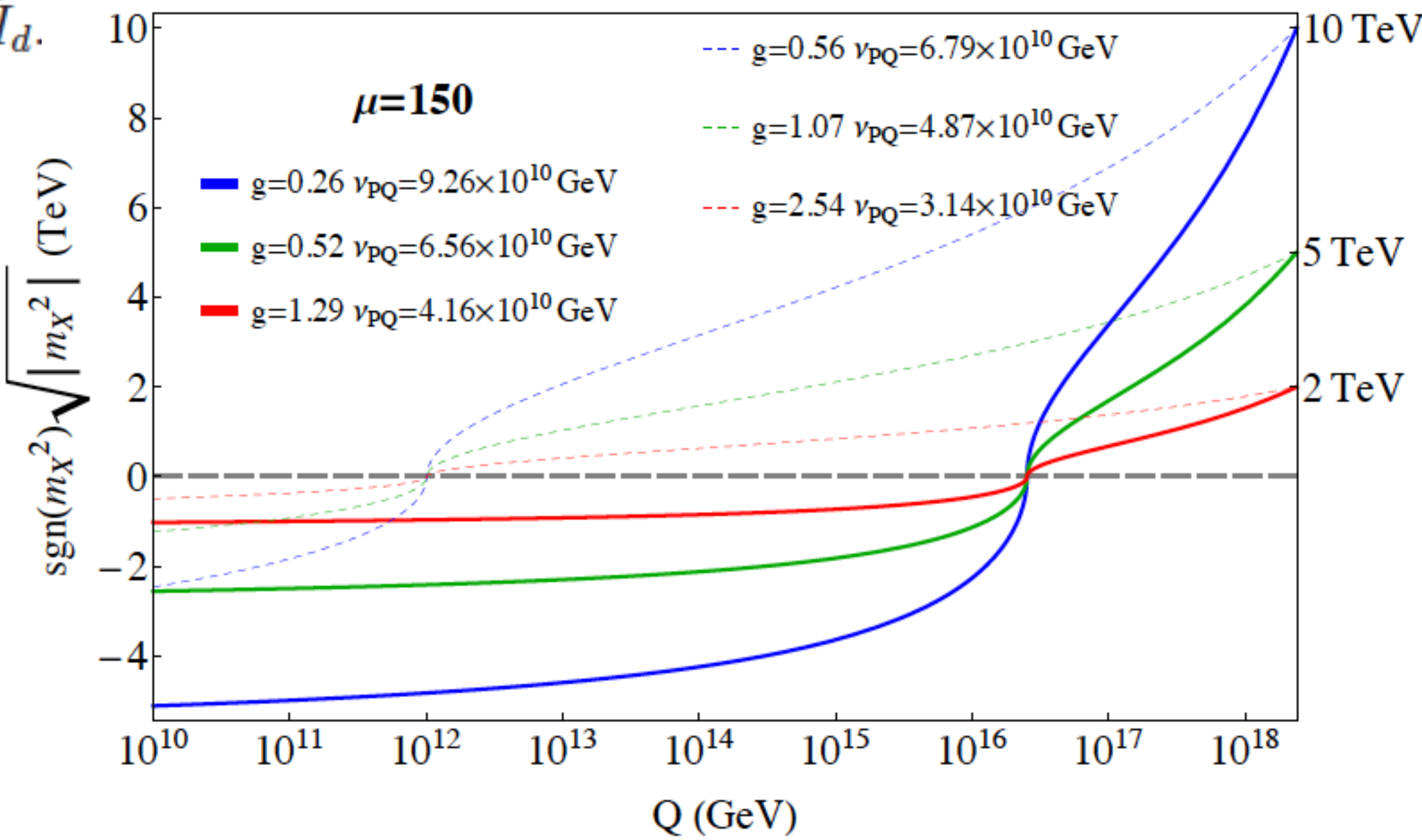
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

$$M_{N^c_i} = v_X \, h_i|_{Q=v_X}$$

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

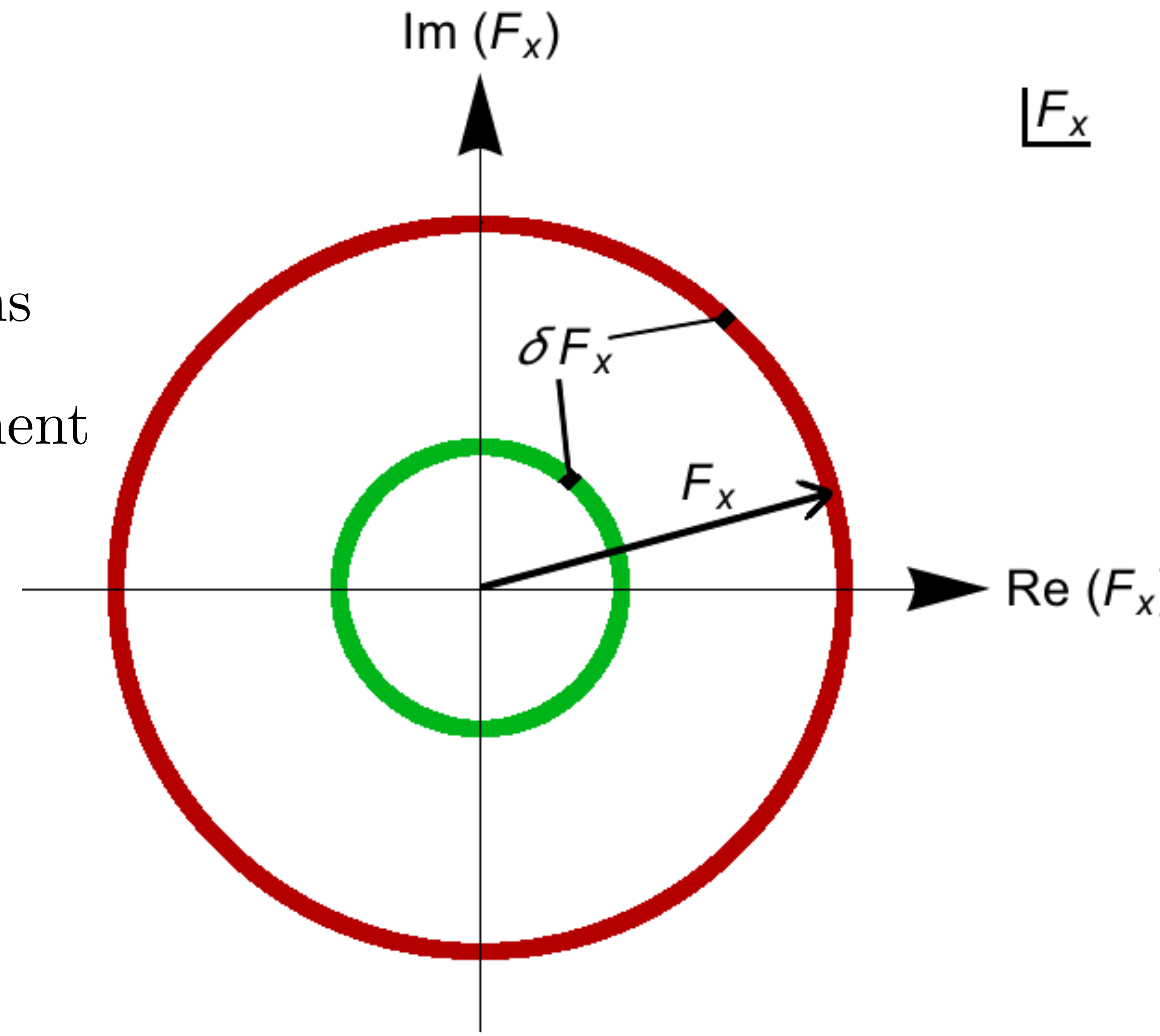


Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

Why do soft terms take on values needed for natural (barely-broken) EWSB?

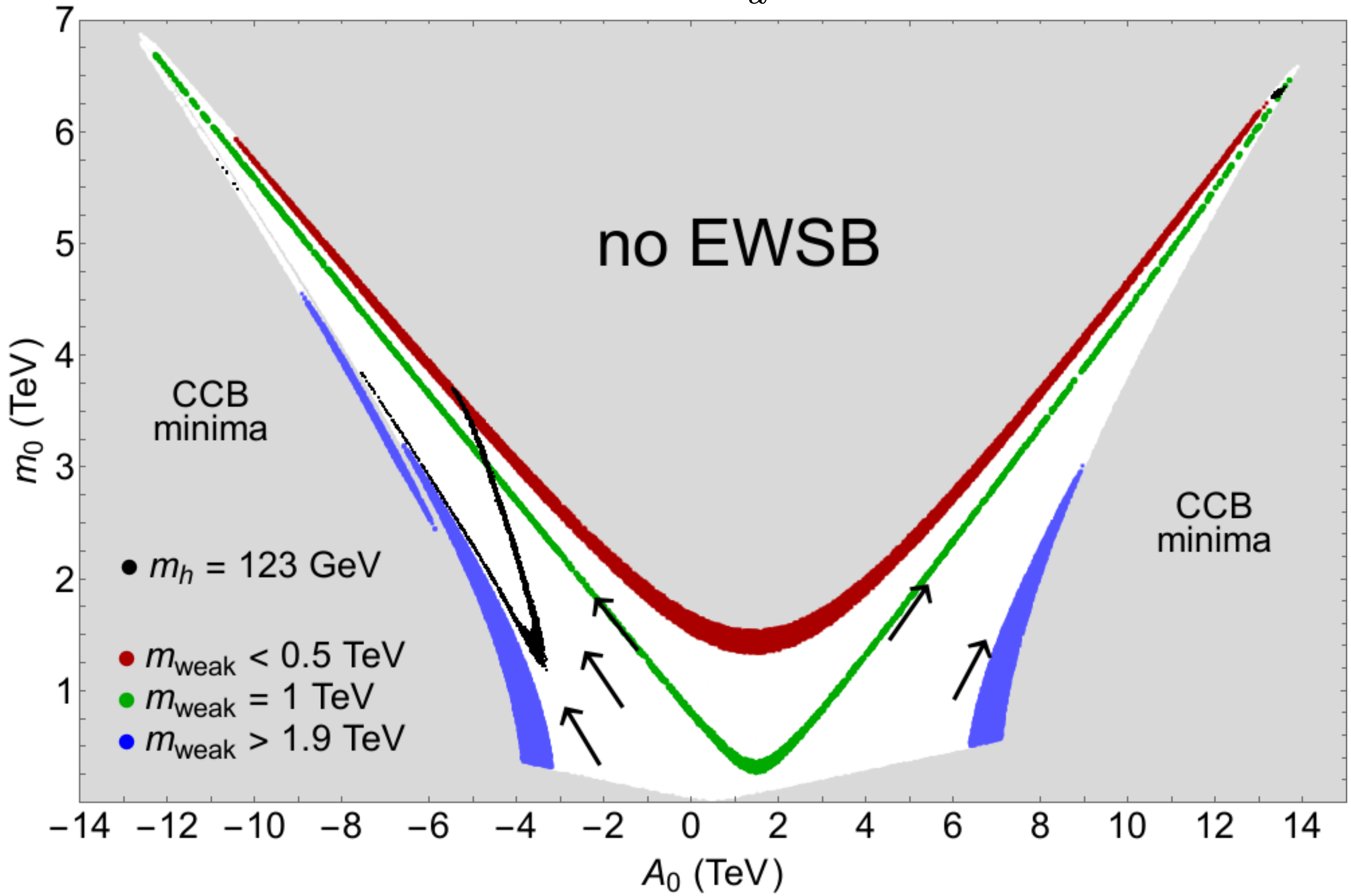
string theory landscape?

- assume model like MSY/CCK where $\mu \sim 100$ GeV
- then $m(weak)^2 \sim |m^2_{H_u}|$
- If all values of SUSY breaking field $\langle F_X \rangle$ equally likely, then mild (linear) statistical draw towards large soft terms
- This is balanced by anthropic requirement of weak scale $m_{weak} \sim 100$ GEV



Anthropic selection of $m_{weak} \sim 100\ GeV$:
If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them

$m_{H_u} = 1.3m_0$

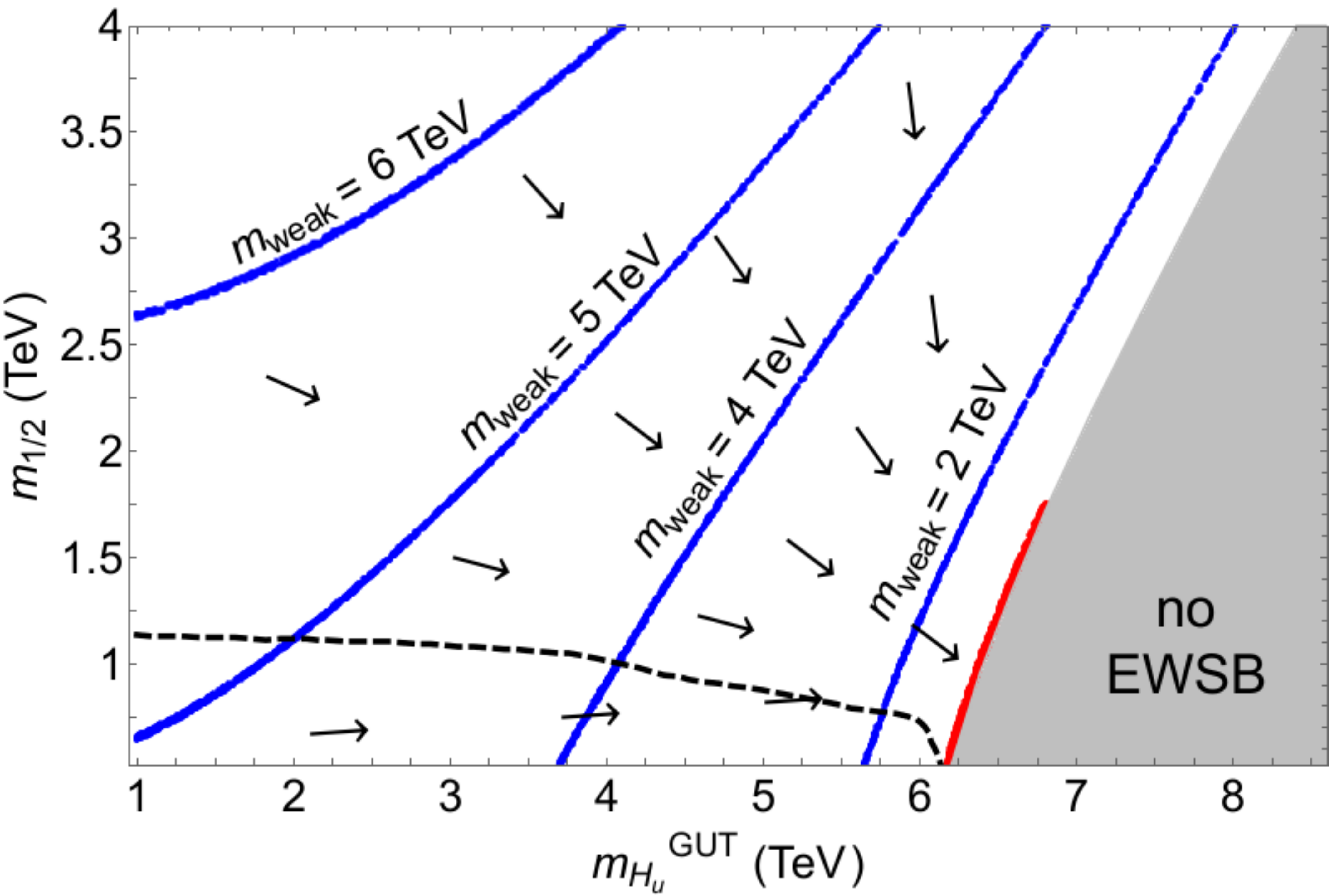


statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Giudice, Rattazzi, 2006

HB, Barger, Savoy, Serce, PLB758 (2016) 113

$m_0 = 5$ TeV

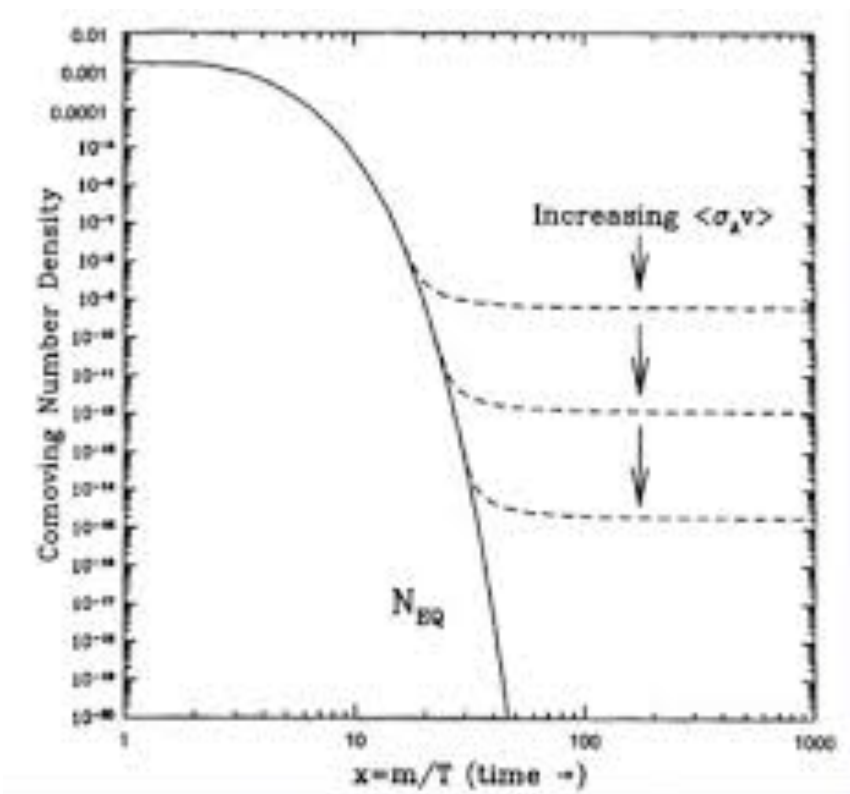


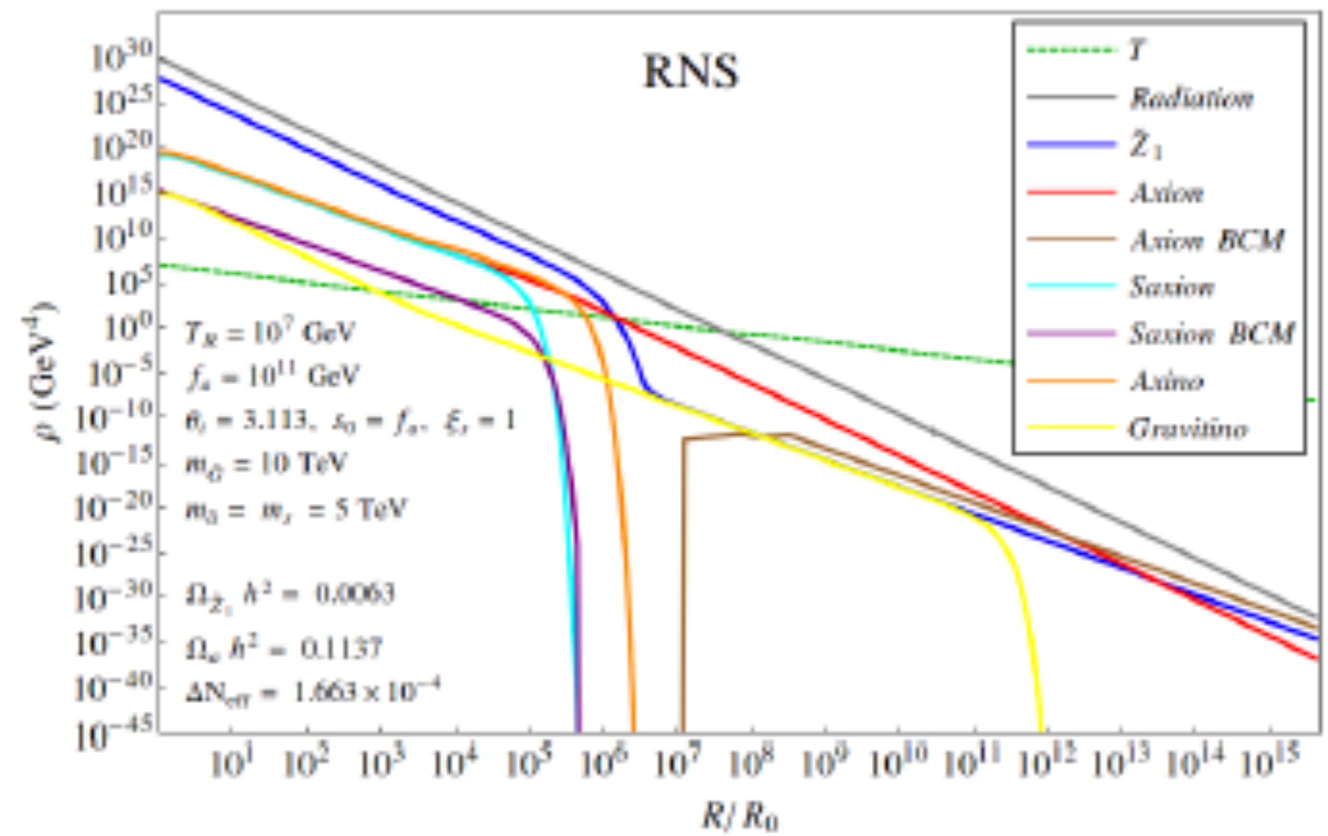
statistical/anthropic draw toward FP-like region

What happens to SUSY WIMP dark matter?

- higgsino-like WIMPs thermally underproduced
- 3 not four light pions => QCD theta vacuum
- EDM(neutron) => axions: no fine-tuning in QCD sector
- SUSY context: axion superfield, axinos and saxions
- DM= axion+higgsino-like WIMP admixture
- DFSZ SUSY axion: solves mu problem with mu<< m_3/2!
- ultimately detect both WIMP and axion?

usual picture => mixed axion/WIMP

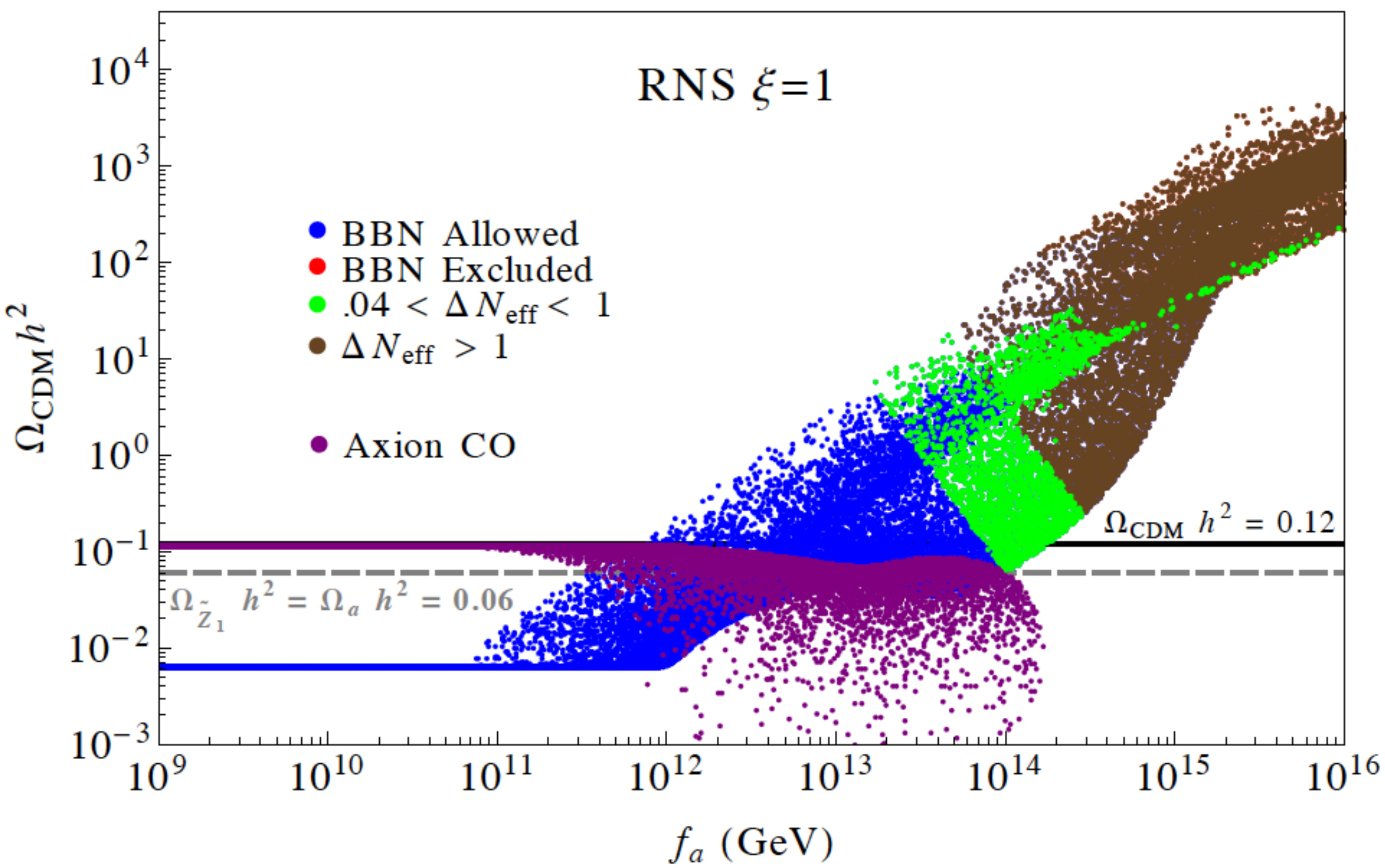




KJ Bae, HB, Lessa, Serce

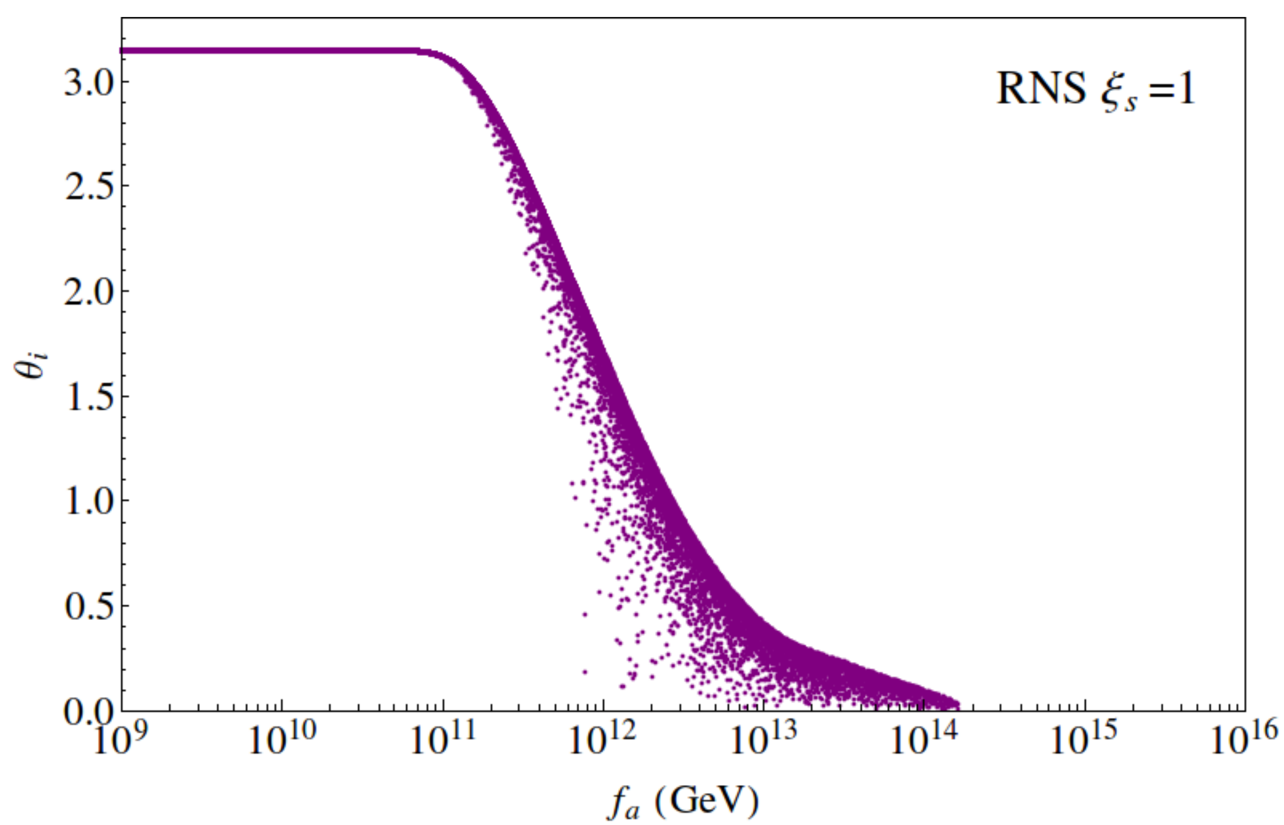
much of parameter space is axion-dominated with 10-15% WIMPs

=>



higgsino abundance

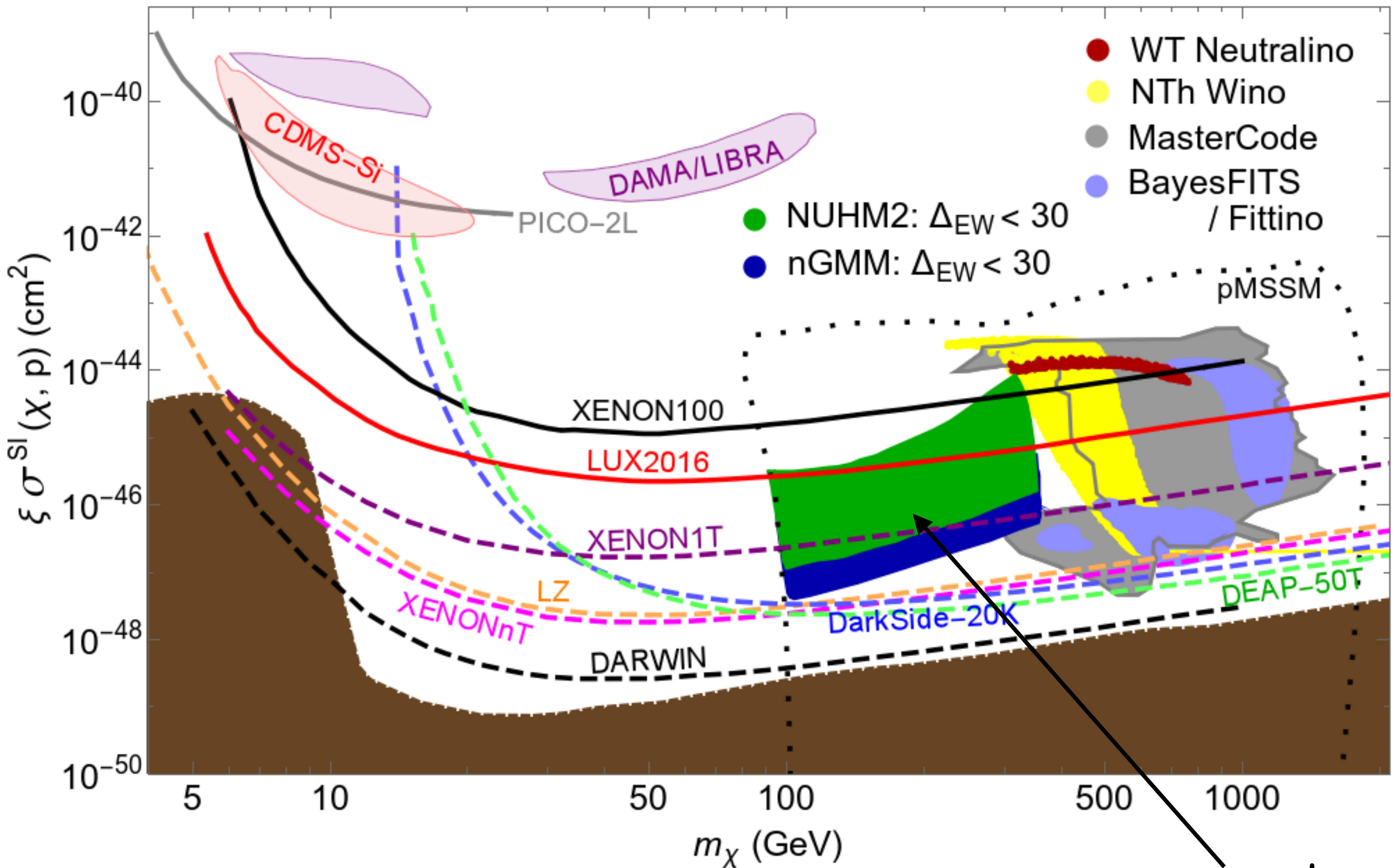
axion abundance



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

Bae, HB,Lessa,Serce

Direct higgsino detection rescaled for minimal local abundance $\xi \equiv \Omega_\chi^{TP} h^2/0.12$



natural SUSY

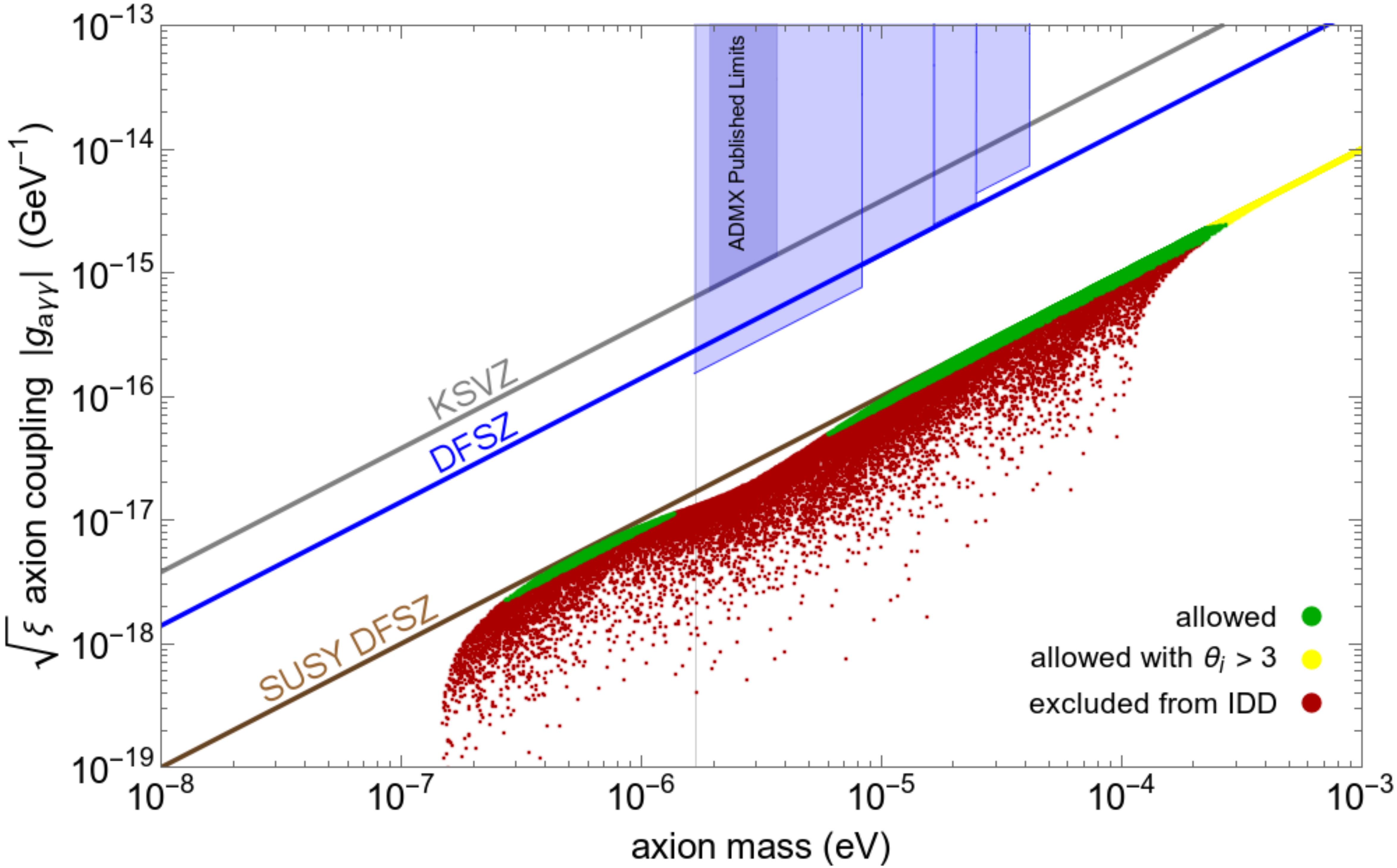
Bae, HB, Barger, Savoy, Serce

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

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

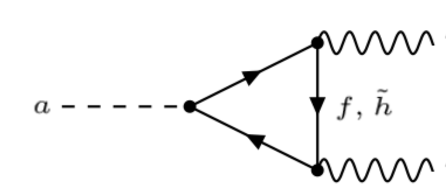
Xe-1-ton now operating!

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



SUSY DFSZ axion: large range in m(a) but coupling reduced

may need to probe broader and deeper!

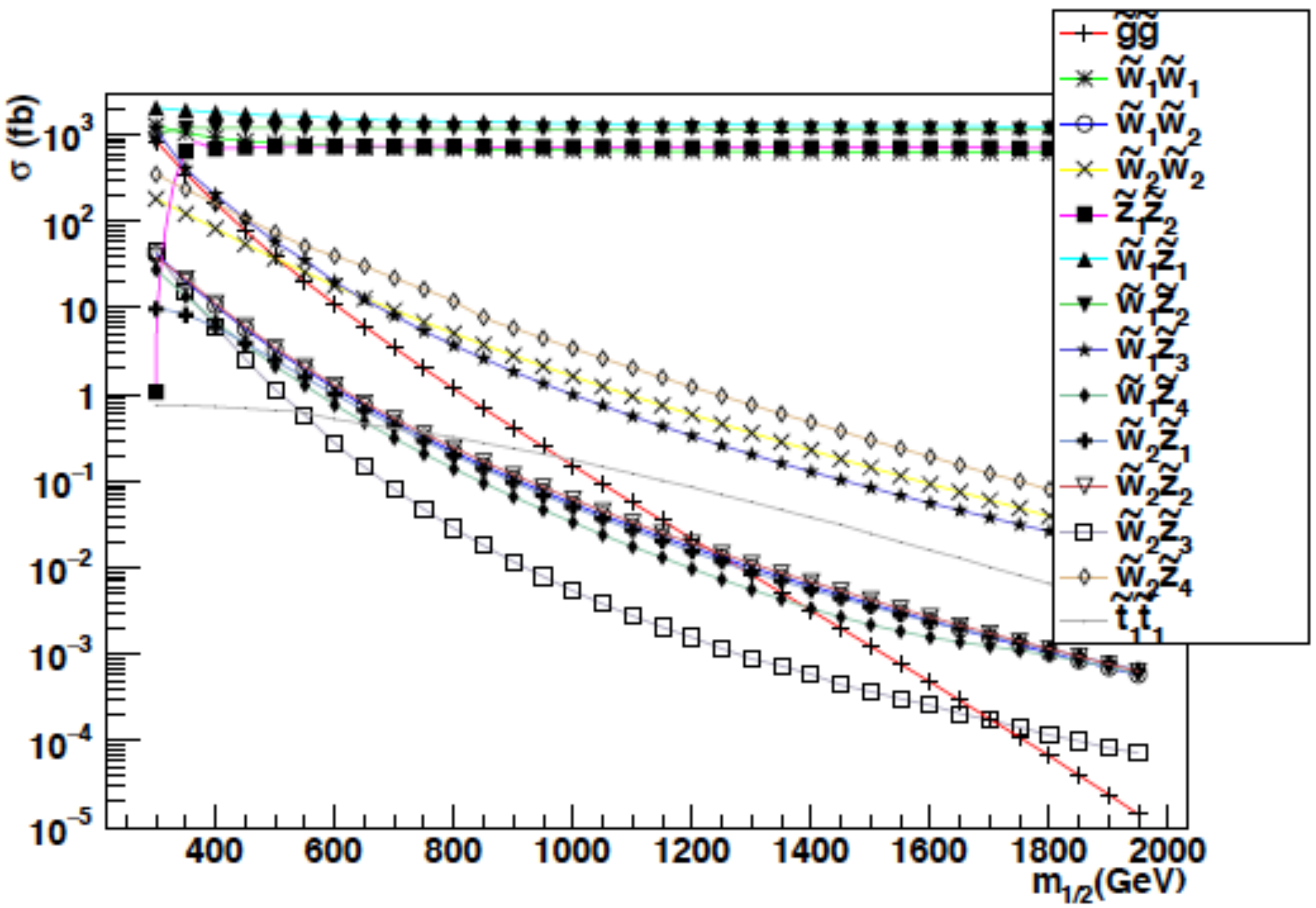


Conclusion: SUSY IS alive and well!

- old calculations of naturalness over-estimate fine-tuning
- naturalness: Little Hierarchy mu<< m(SUSY) allowed
- radiatively-driven naturalness: mu~100-200 GeV, m(t1)<3 TeV, m(gluino)<5-6 TeV
- SUSY DFSZ axion: solve strong CP, solve SUSY mu problem; generate mu<< m(SUSY)
- landscape pull on soft terms towards RNS, m(h)~125 GeV
- natural mirage-mediation/mini-landscape
- natural NUHM2: HL-LHC can cover via SSdB+Z1Z2j channels
- natural mirage/mini-landscape may escape detection at HL-LHC; need LHC33!
- expect ILC as higgsino factory
- DM= axion+higgsino-like WIMP admixture: detect both?
- higgsino-like WIMP detection likely; axion more difficult

Prospects for discovering SUSY with radiatively-driven naturalness at LHC and ILC

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



higgsinos

gauginos

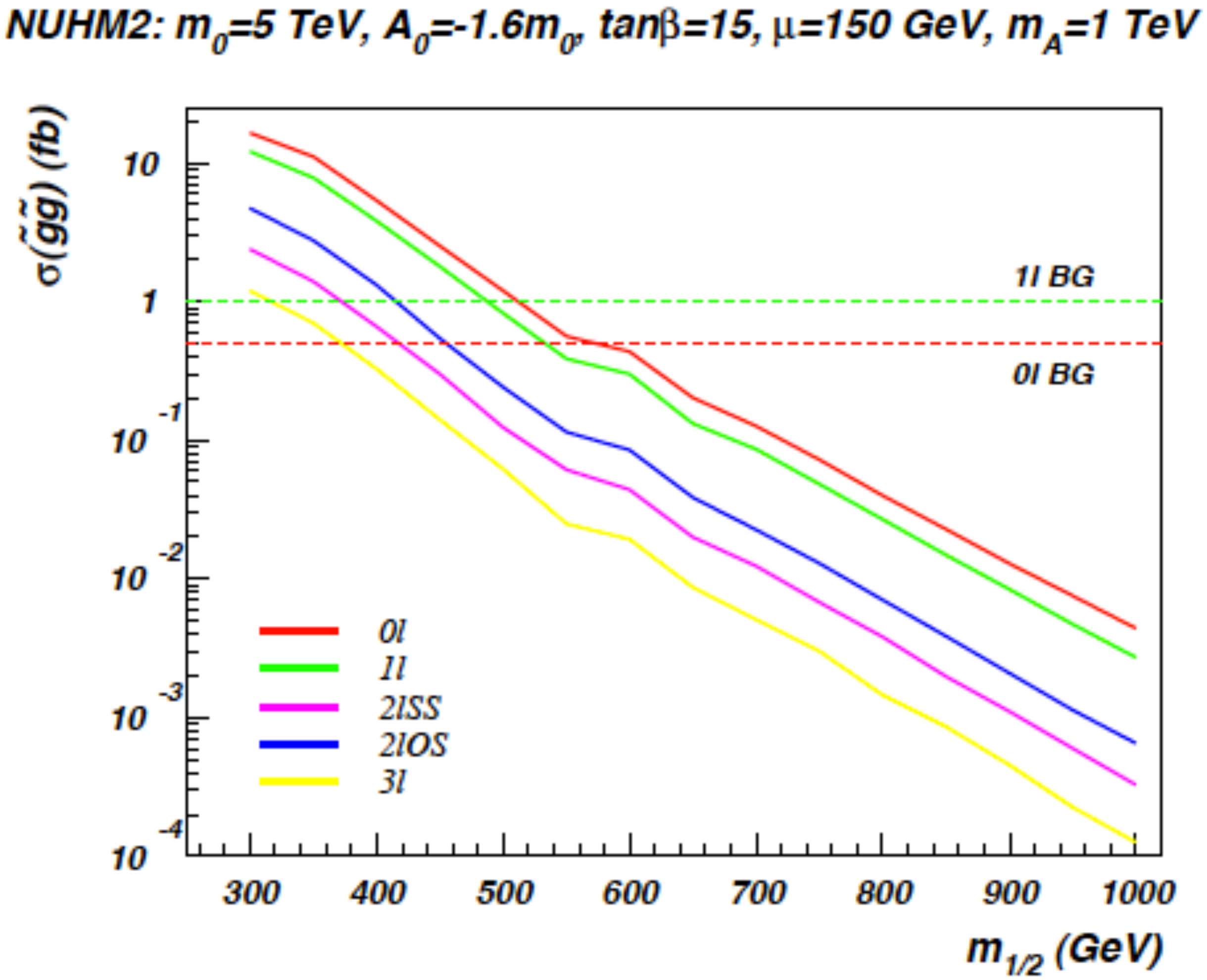
gluinos

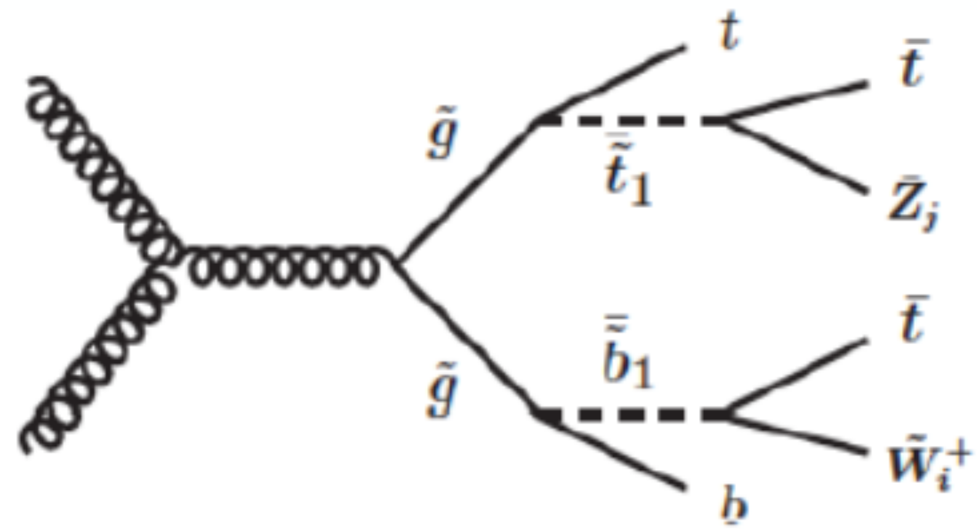
higgsino pair production dominant-but only soft visible energy release from higgsino decays

largest visible cross section: wino pairs

gluino pairs sharply dropping

gluino pair cascade decay signatures





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

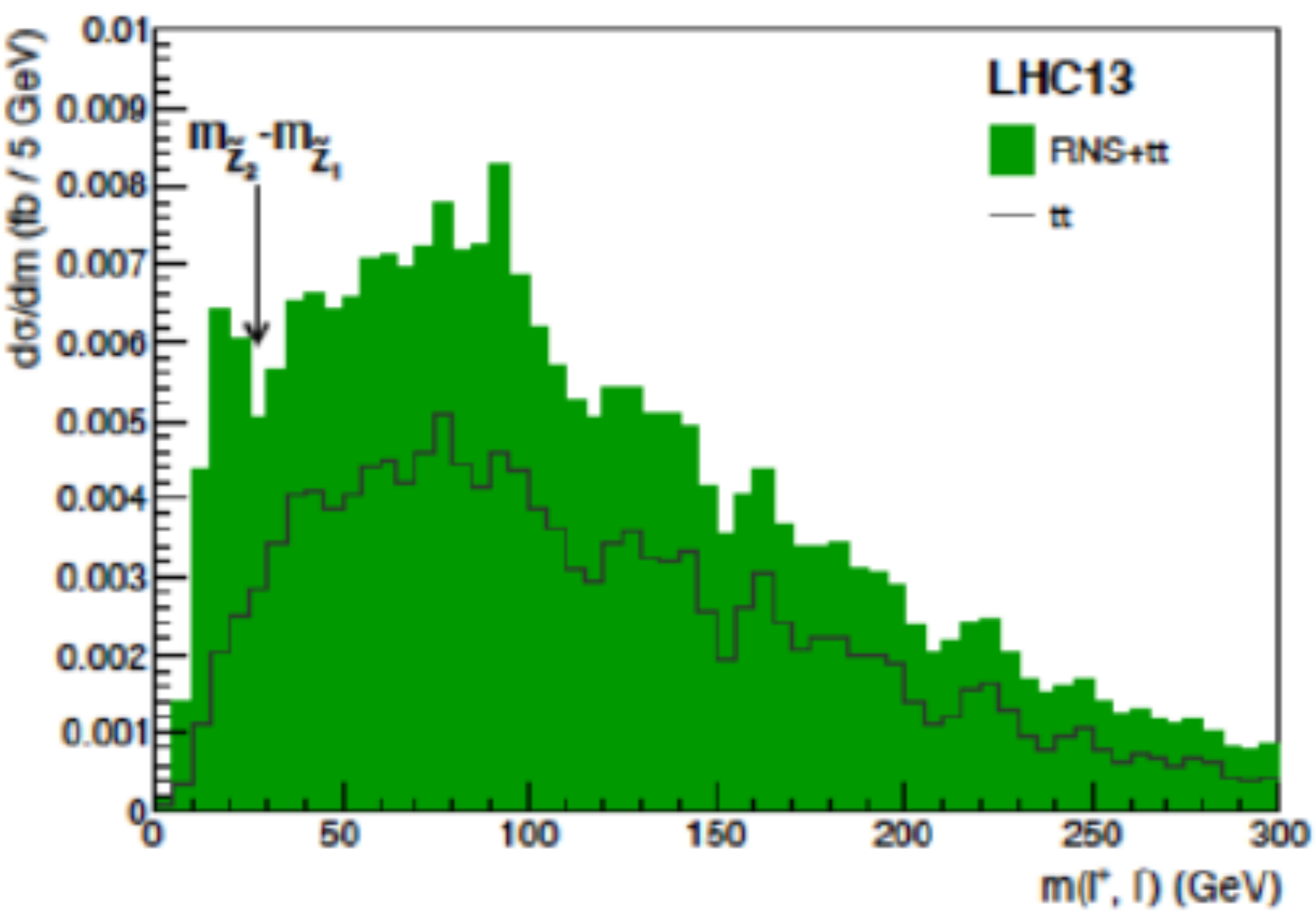
Table 1: Dominant branching fractions of various sparticles along the RNS model line for $m_{1/2} =$ 1 TeV.

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

LHC14 5sigma reach in m(gluino) (TeV)

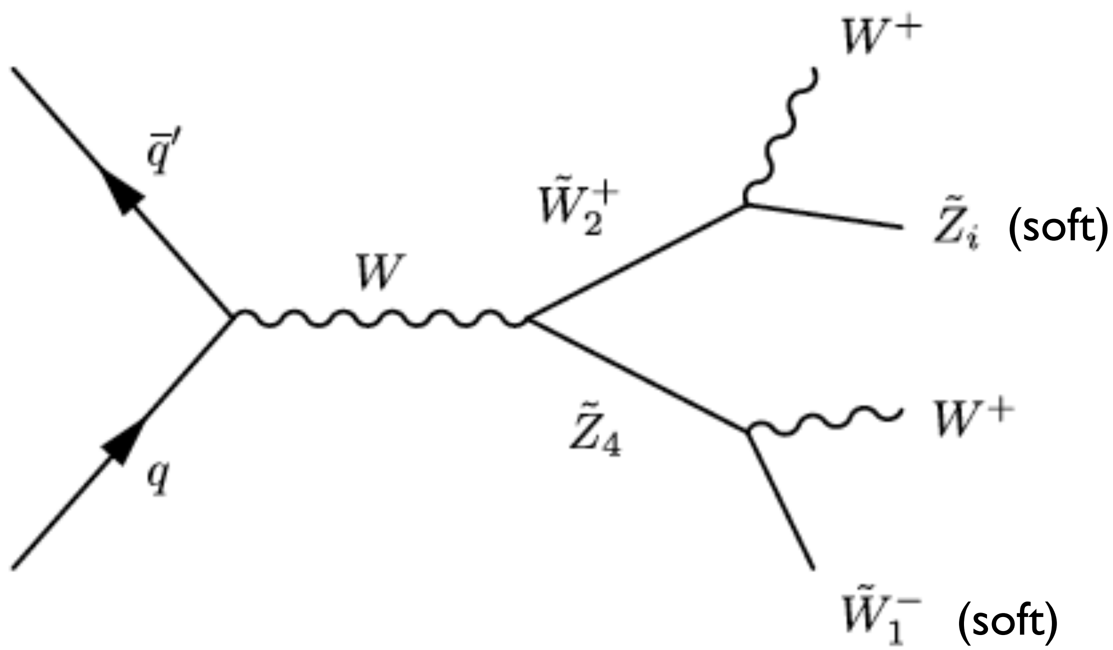
since m(gluino) extends to ~4 TeV, LHC14 can see about half the low EWFT parameter space in these modes

LHC14 has some reach for gluino pair production in RNS; if a signal is seen, should be distinctive

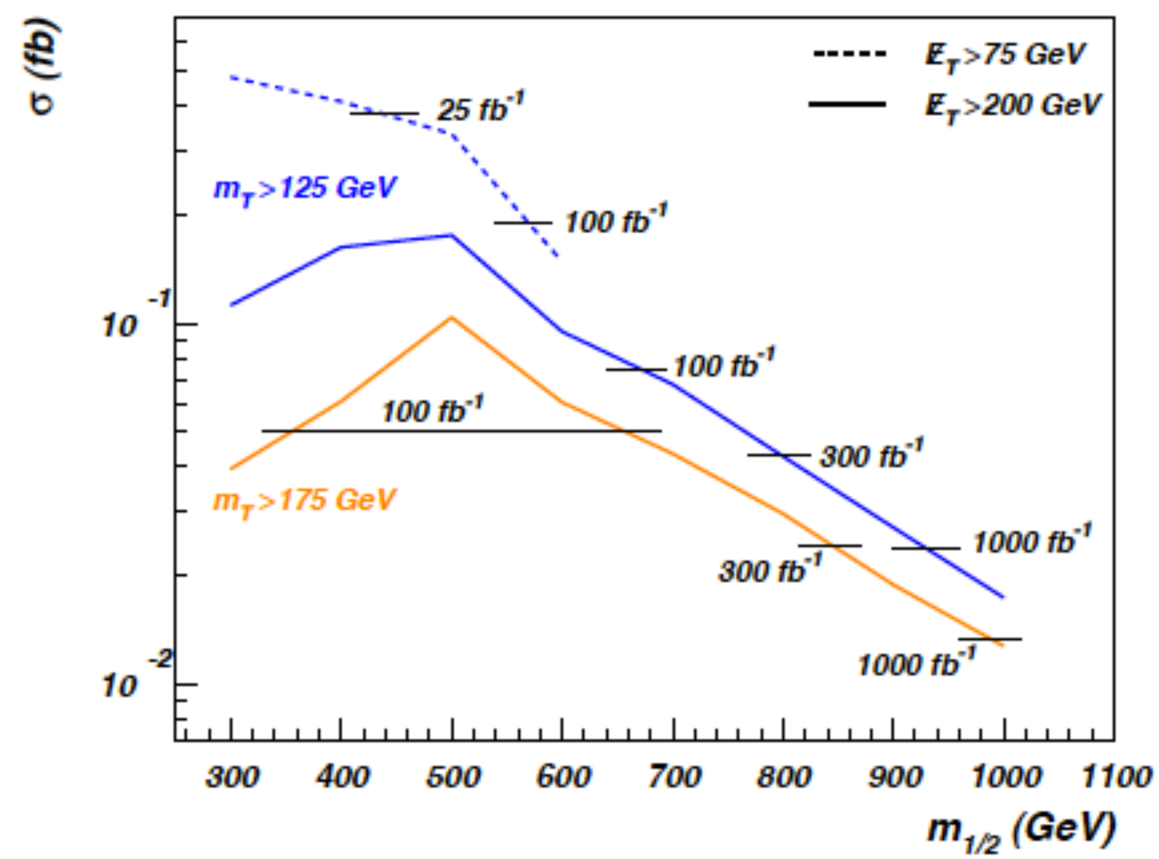


OS/SF dilepton mass edge apparent from cascade decays with z2->z1+l+lbar

Distinctive same-sign diboson (SSdB) signature from SUSY models with light higgsinos!



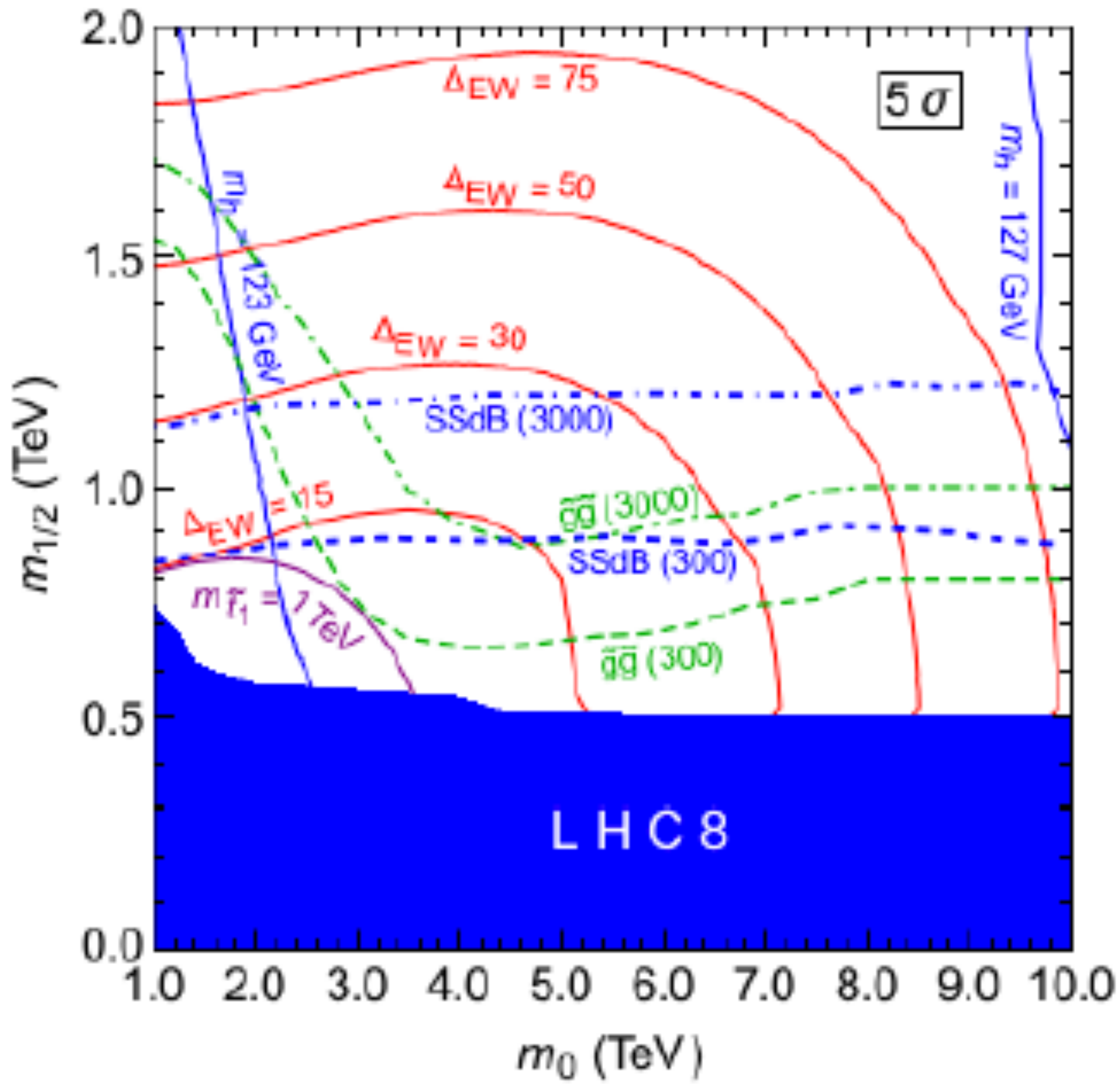
wino pair production



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

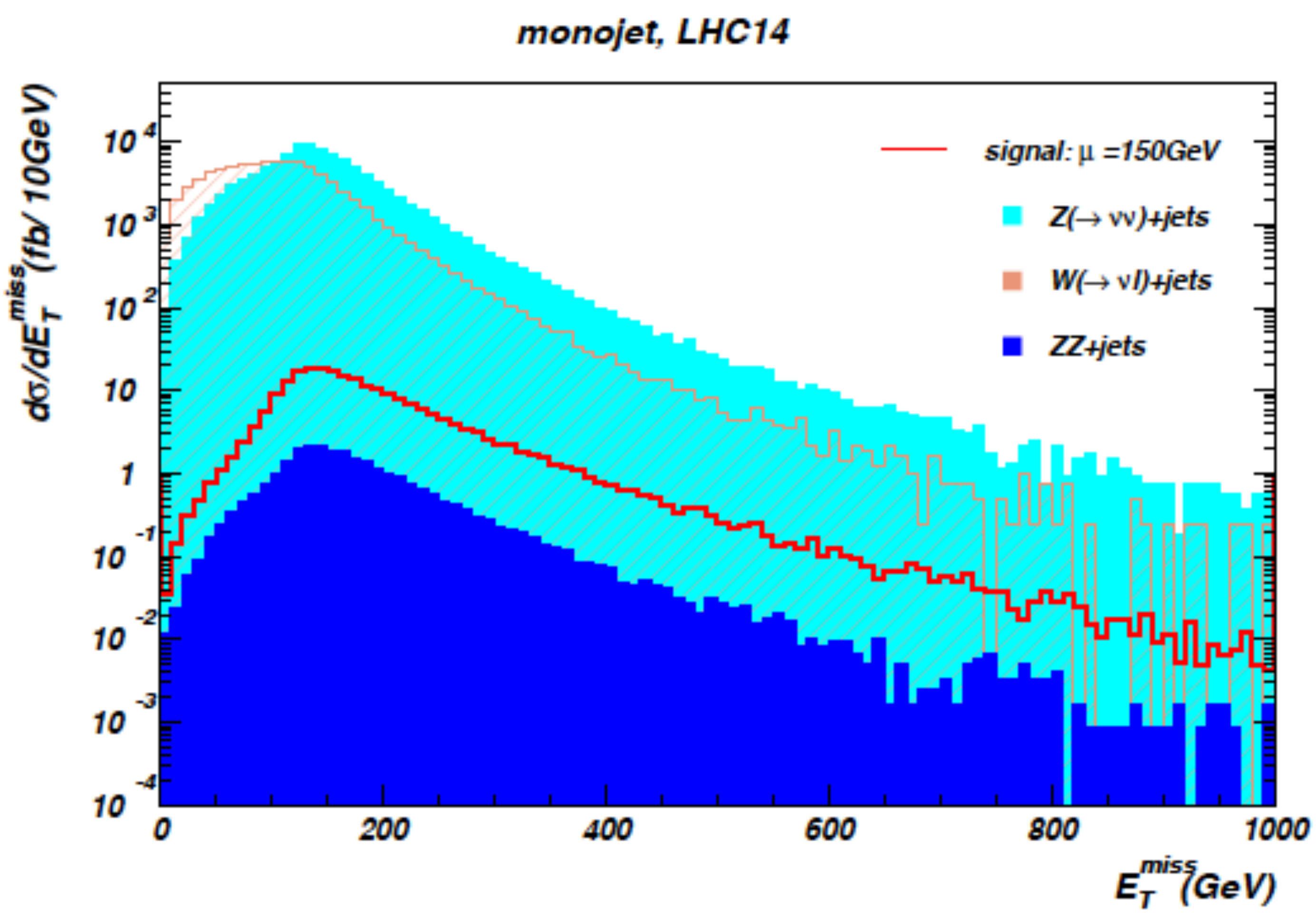
H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

Good old m0 vs. mhf plane still viable, but needs mu~100-200 GeV as possible in NUHM2 instead of CMSSM/mSUGRA



HB,Barger,Savoy, Tata; arXiv:1604.07438

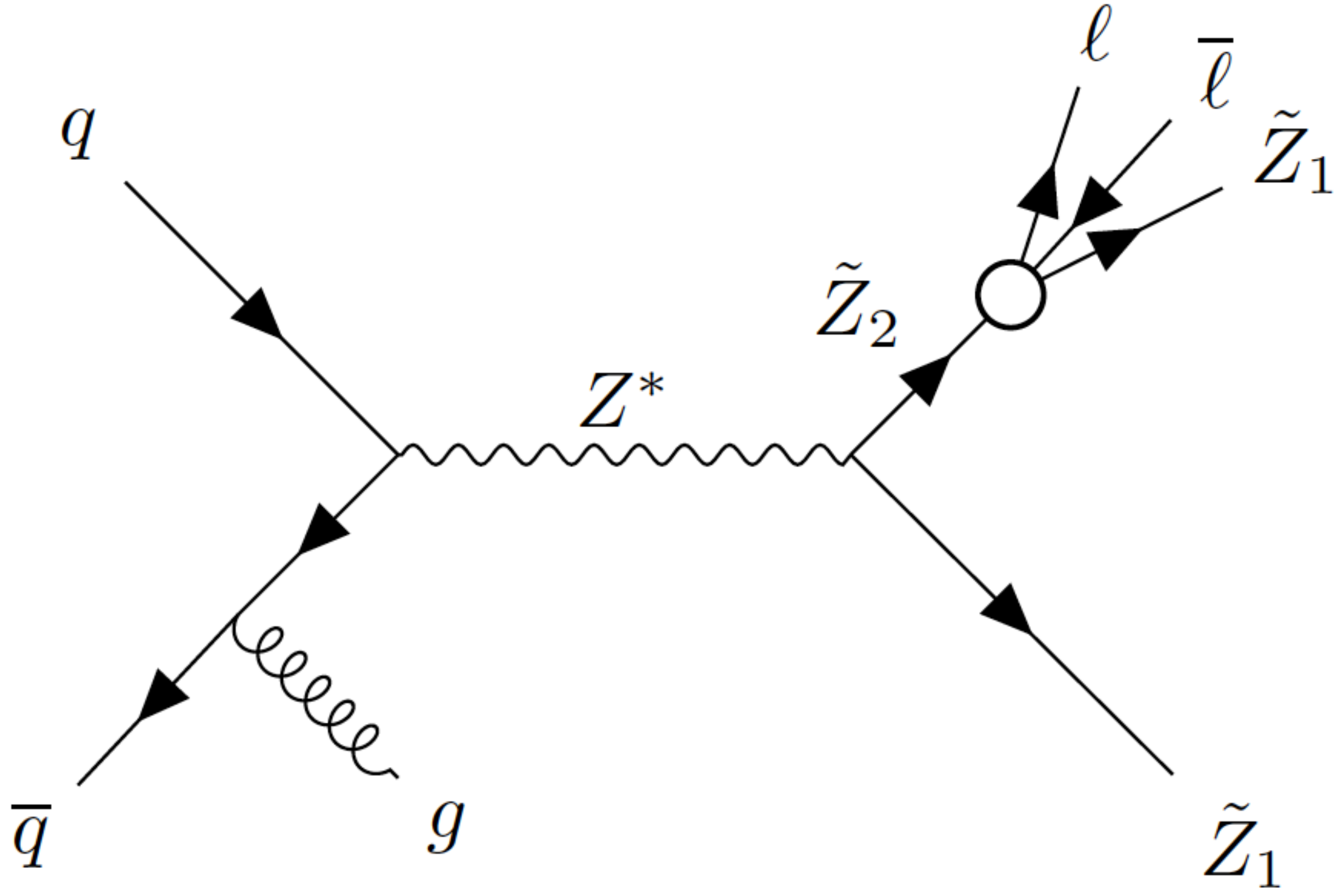
See direct higgsino pair production recoiling from ISR (monojet signal)?

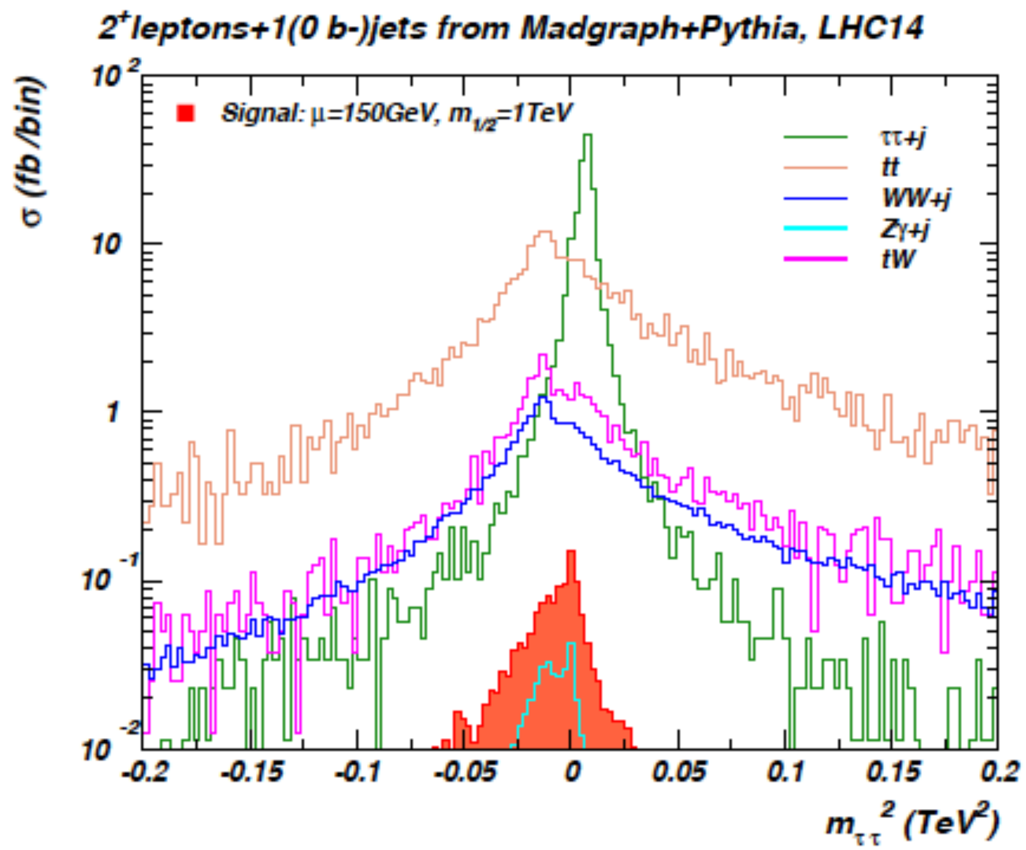


typically 1% S/BG after cuts:
very tough to do!

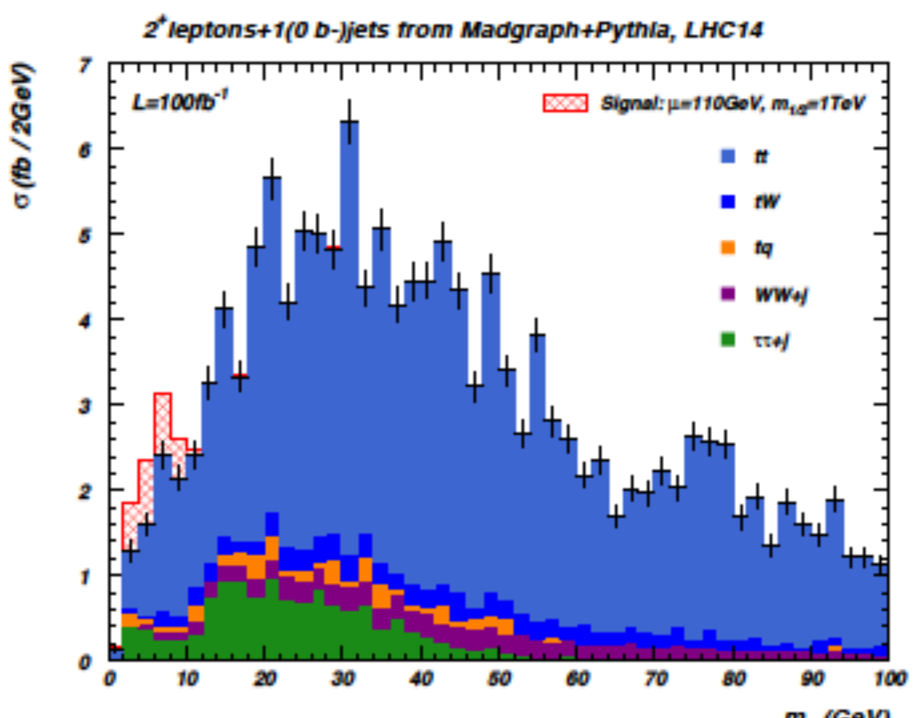
What about $pp \to \tilde{Z}_1 \tilde{Z}_2 j$ with $\tilde{Z}_2 \to \tilde{Z}_1 \ell^+ \ell^-$?

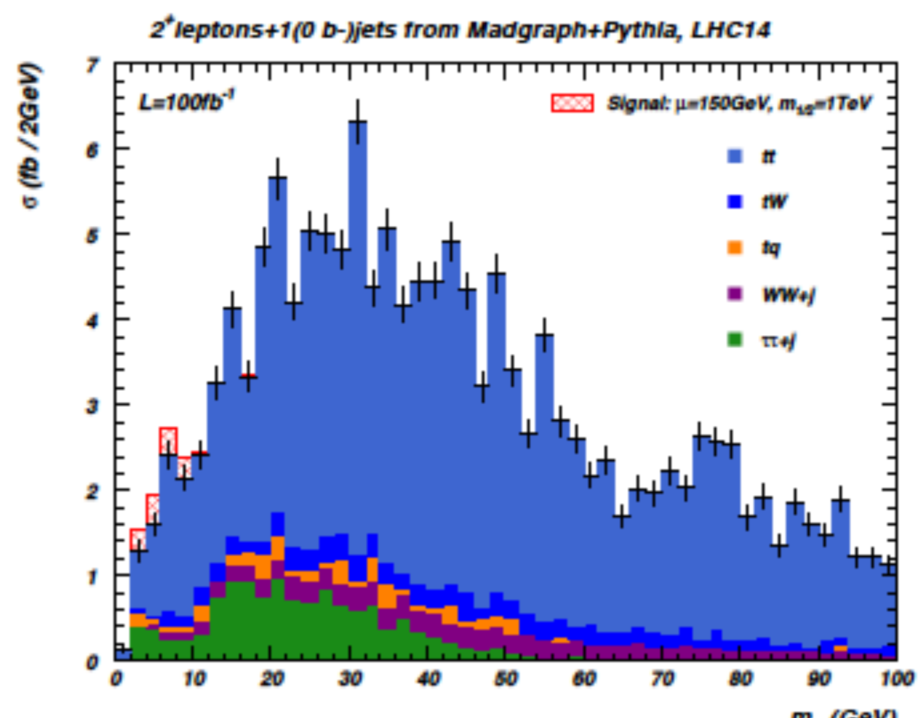
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;



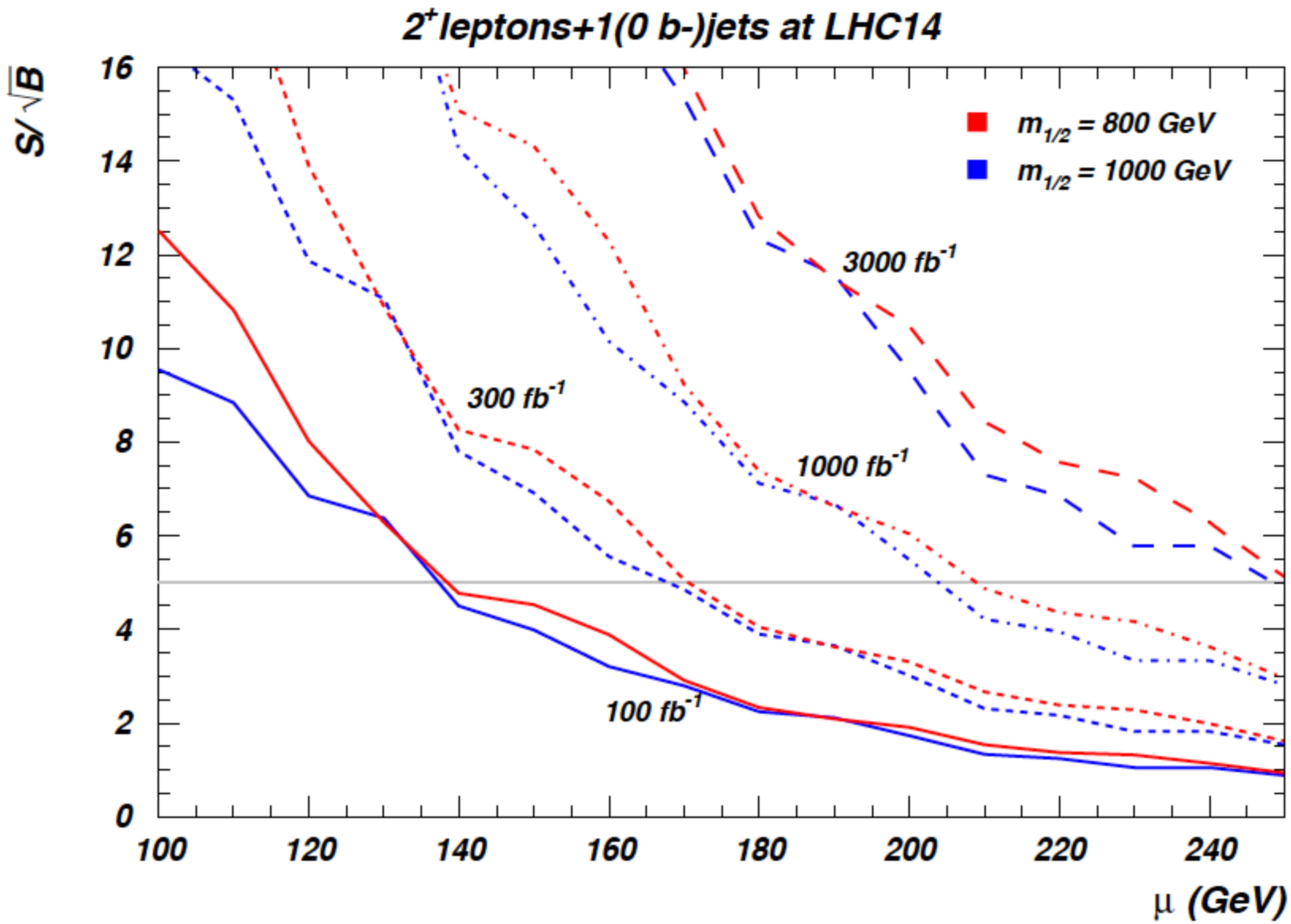


use MET to construct m^2(tau-tau)



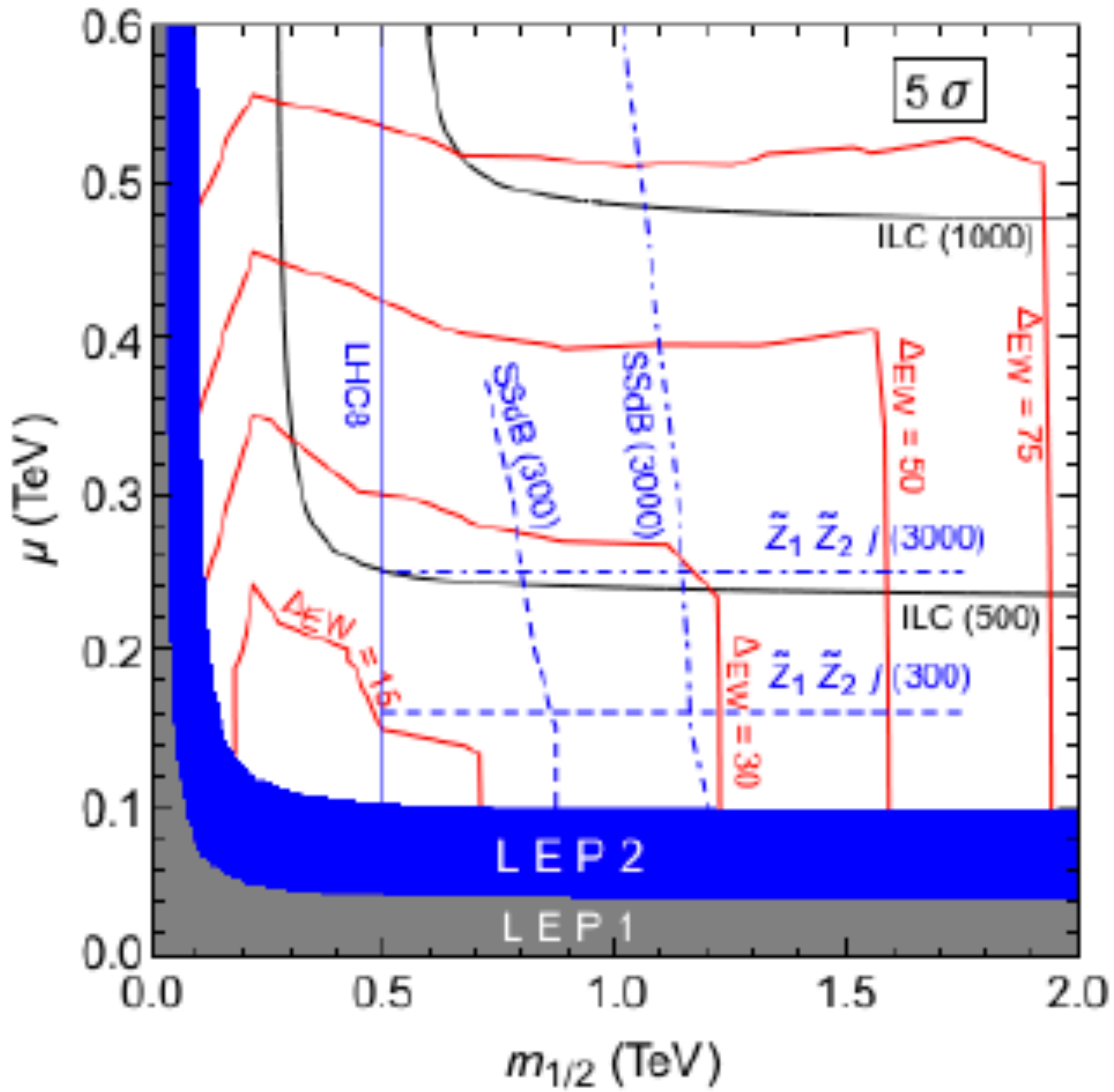


LHC reach for soft dilepton+jet+MET



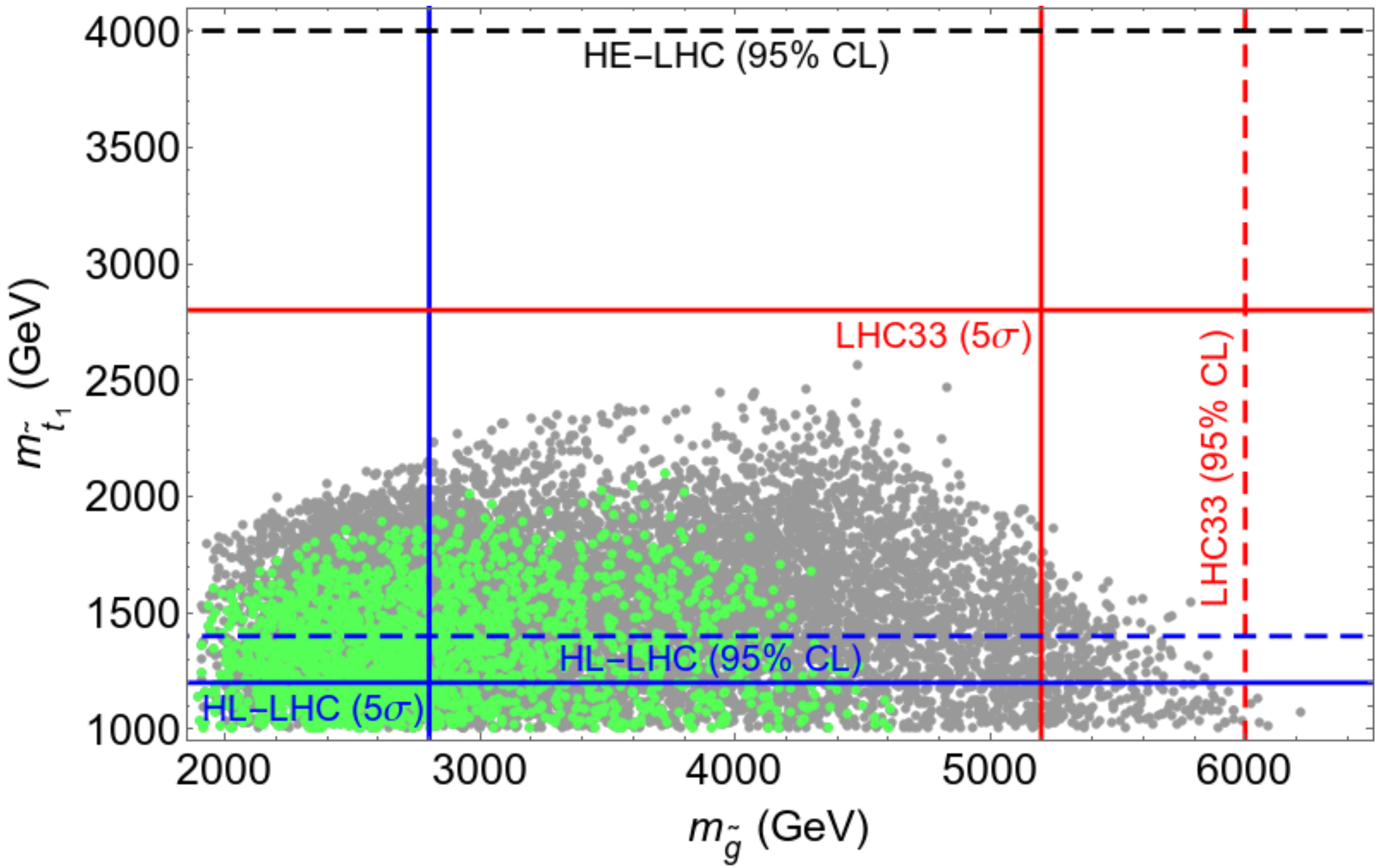
HB, Mustafayev, Tata; PRD90 (2014) 115007

panoramic view of reach of HL-LHC for natural SUSY



LHC14 with 3000 fb¹ can cover essentially all parameter space with $\Delta_{EW} < 30$, usually with 2-3 distinct signals: $\tilde{g}\tilde{g}$, SSdB and $\tilde{Z}_1\tilde{Z}_2 j$

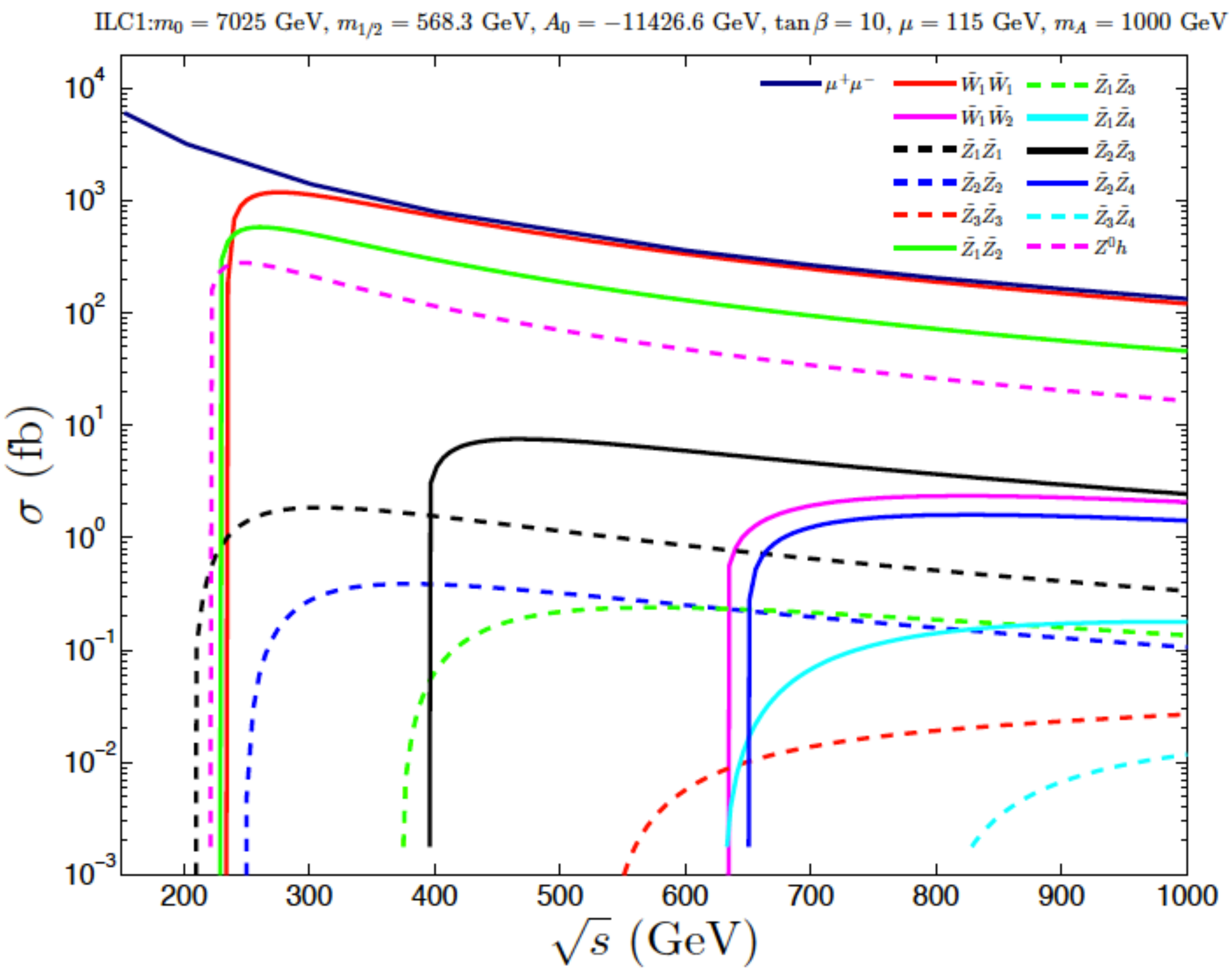
LHC33 will be required to probe all of natural m(t1) vs. m(gluino) plane



natural generalized mirage mediation/ miniLandscape model

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



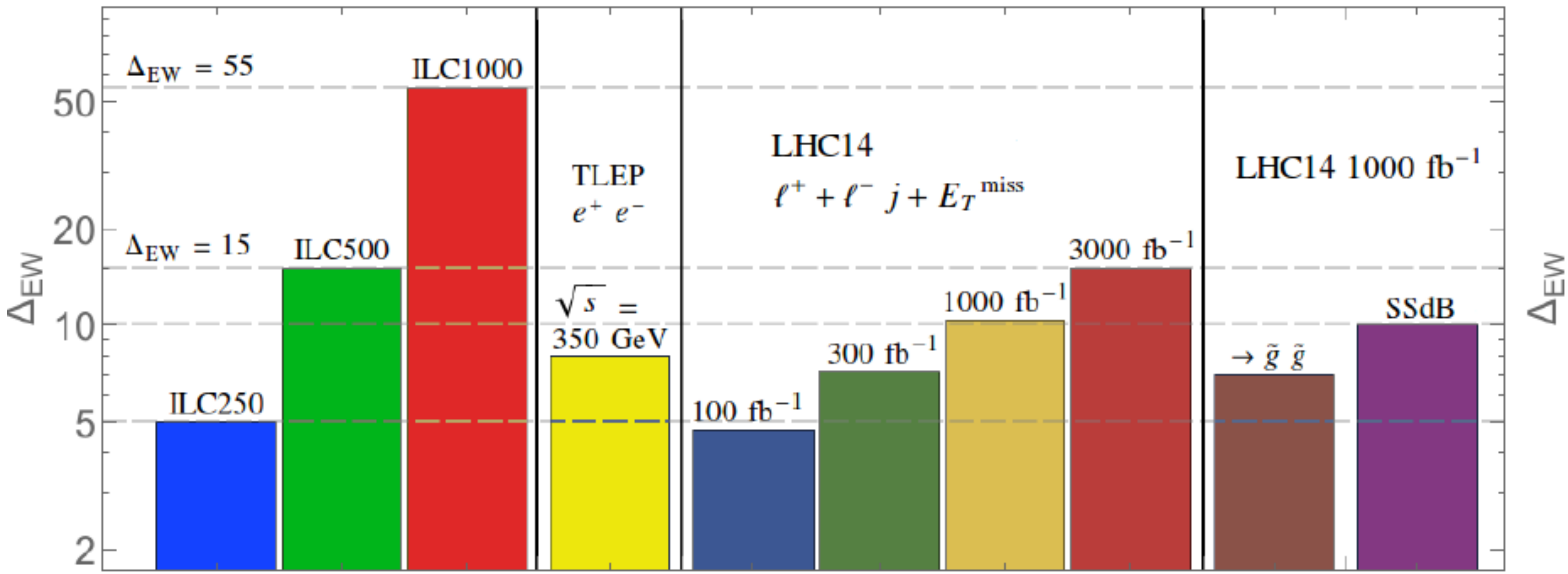
$$\sigma(higgsino) \gg \sigma(Zh)$$

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

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

ILC either sees light higgsinos or MSSM dead

Future collider reach for naturalness

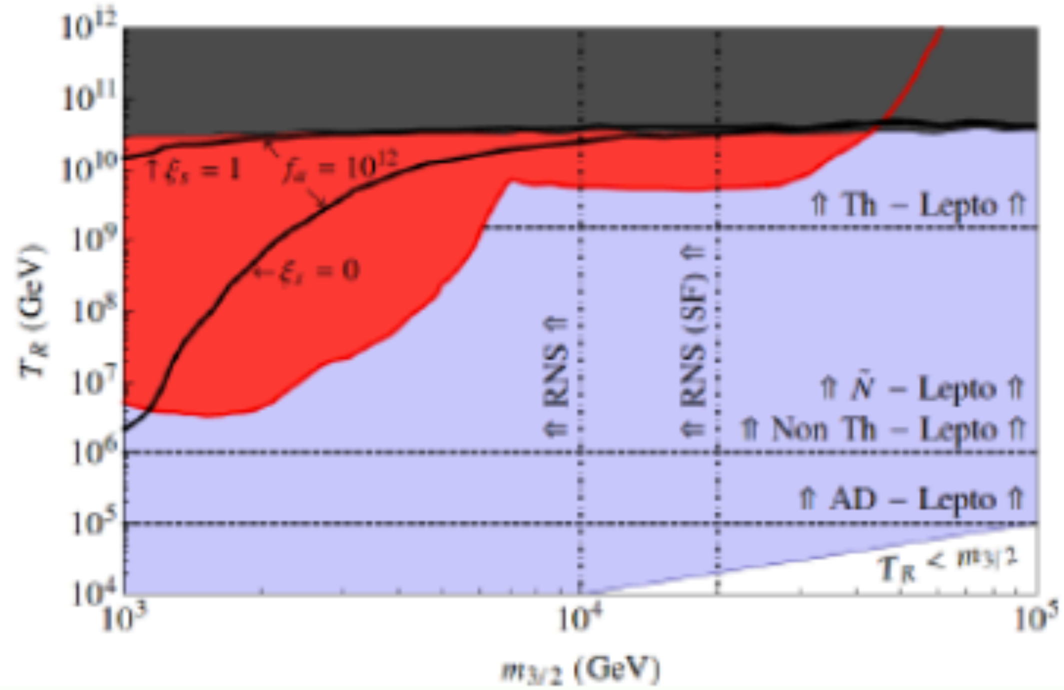


Bae, HB, Nagata, Serce

When to give up on naturalness in MSSM?
If HE-LHC or ILC(600GeV) sees no light higgsinos/SUSY or WIMP at Xe-nton/LZ

Baryogenesis scenarios for radiative natural SUSY

- thermal leptogenesis
- non-thermal (inflaton decay)
- oscillating sneutrino
- Affleck-Dine (AD)



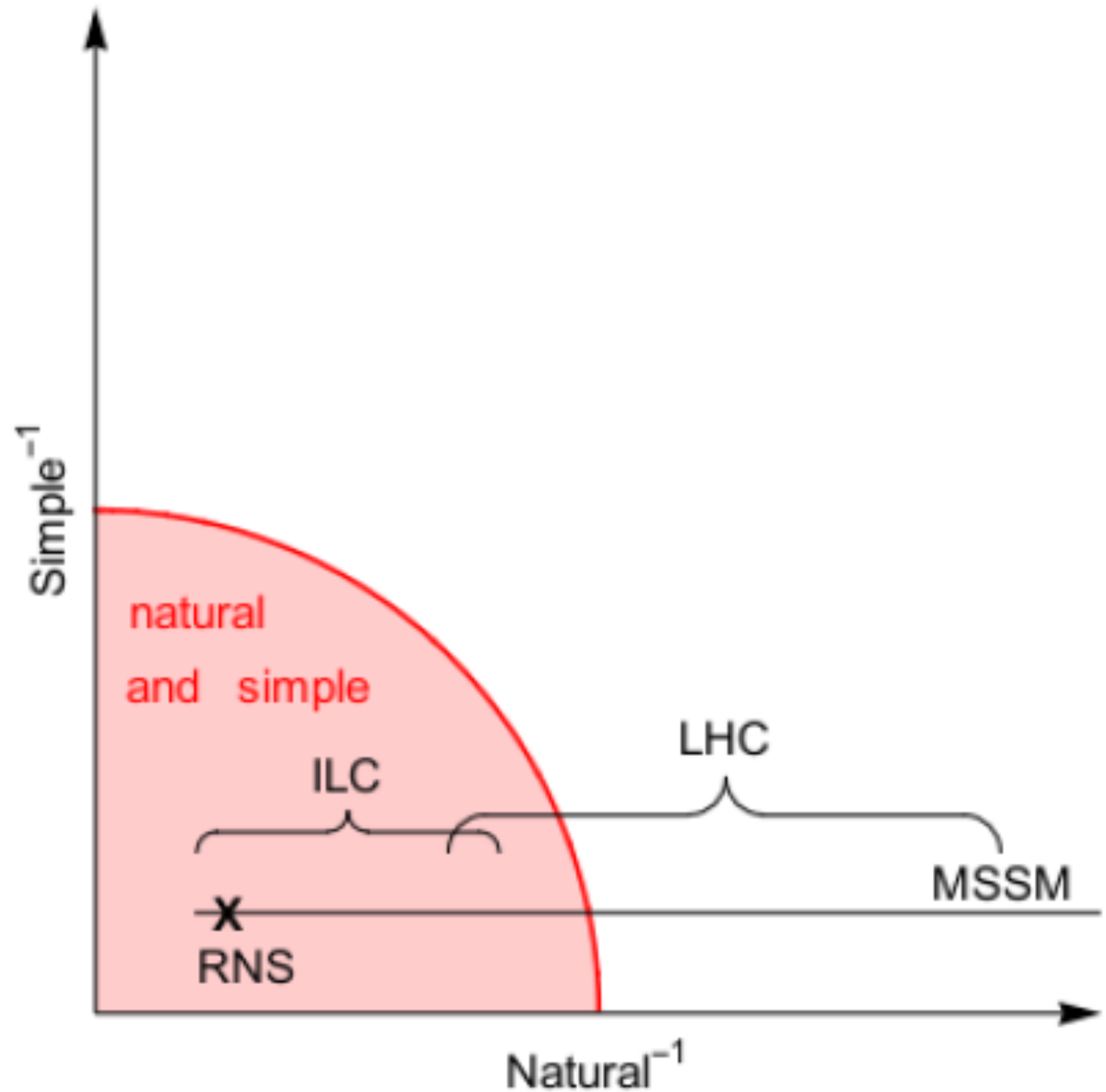
$$f_a = 10^{11},\ 10^{12}\ \mathrm{GeV}$$

Bae,HB, Serce, Zhang, arXiv:1510.00724

gravitino problem plus axino/saxion problem: still plenty room

Conclusions: status of SUSY post LHC8

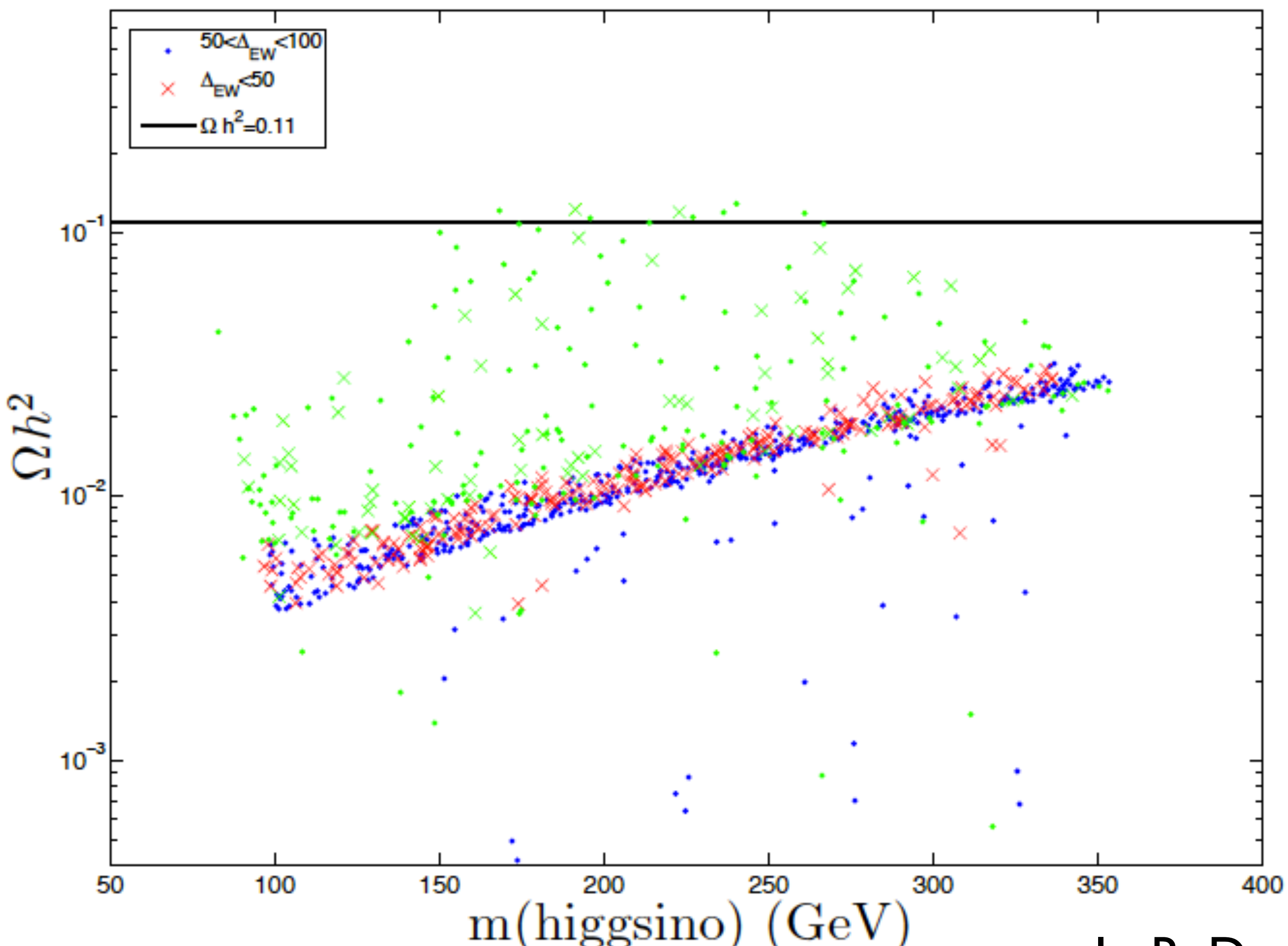
- SUSY EWFT non-crisis: EWFT allowed at 10% level in radiatively-driven natural SUSY: SUGRA GUT paradigm is just fine in NUHM2 but CMSSM/others fine-tuned
- naturalness maintained for mu~100-200 GeV; t1~1-3 TeV, t2~3-8 TeV, highly mixed; m(glno)~1-4 TeV
- LHC14 w/ 3000 fb^-1 can see all DEW<30 RNS parameter 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!
- SUSY DFSZ/MSY invisible axion model: solves strong CP and SUSY mu problems while allowing for mu~m(Z)<<m(SUSY)
- soft terms pulled to natural SUSY/barely broken EWS values, landscape?
- RNS spectra characterized by mainly higgsino-like WIMP: standard relic underabundance
- 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
RNS
Natural^{-1}

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)

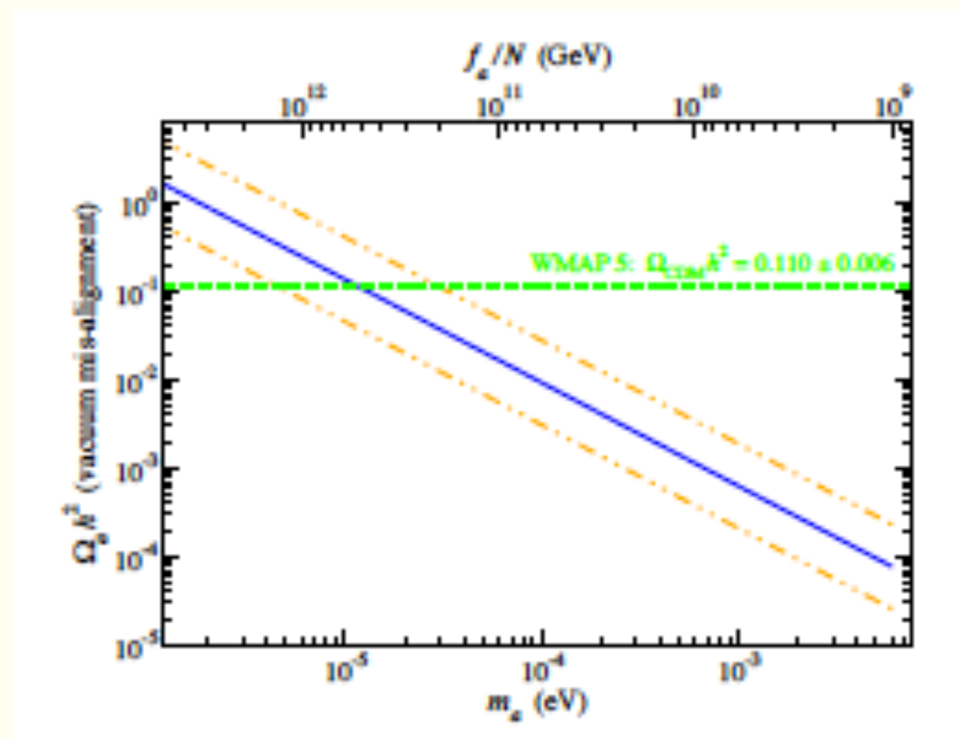
Best solution after 35 years:
PQWW/KSVZ/DFSZ invisible axion

In SUSY, axion accompanied by axino and saxion

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

Axion cosmology

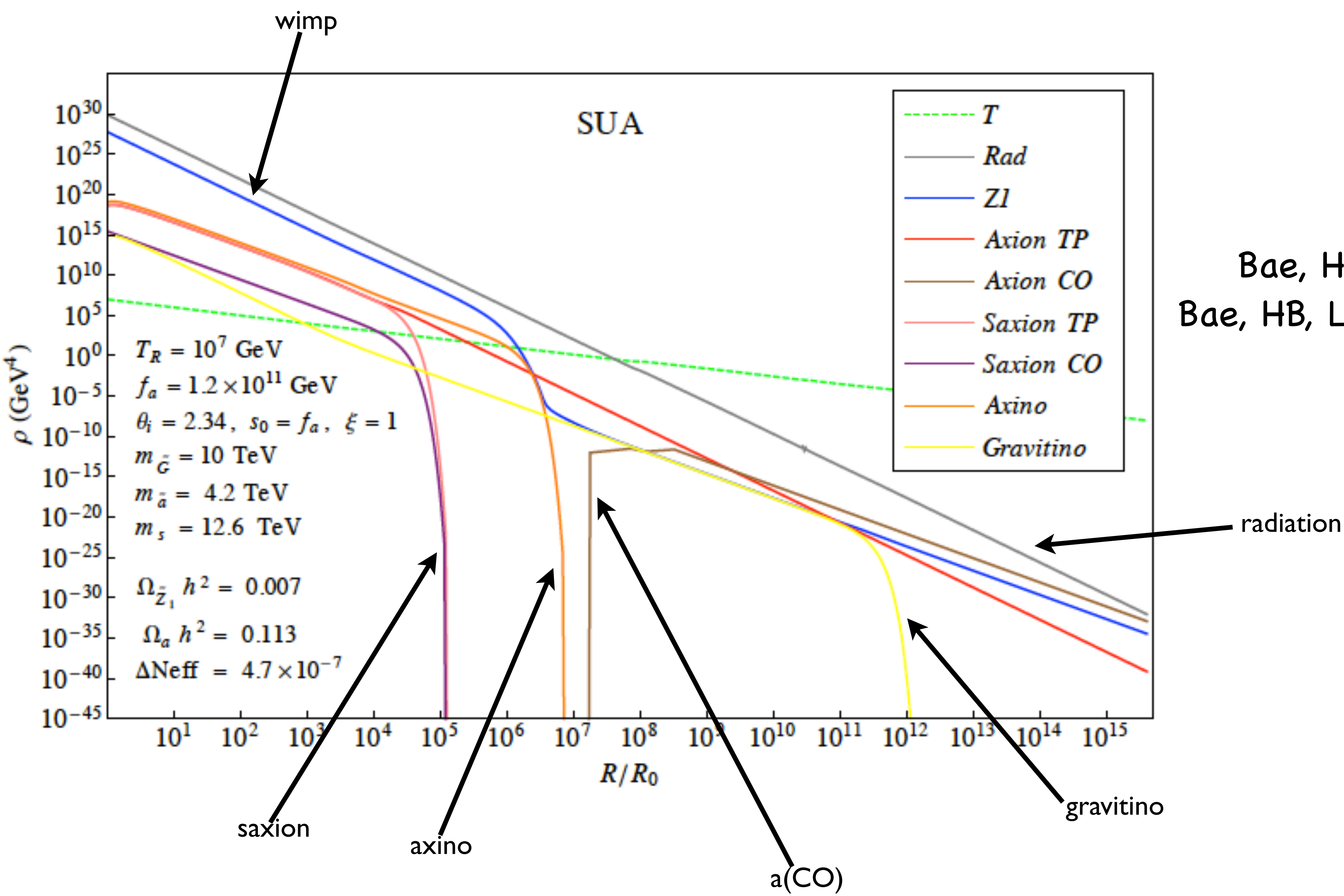
- ★ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial\theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$:
    $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ★ 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 $\Rightarrow f_a \gtrsim 10^9 GeV$



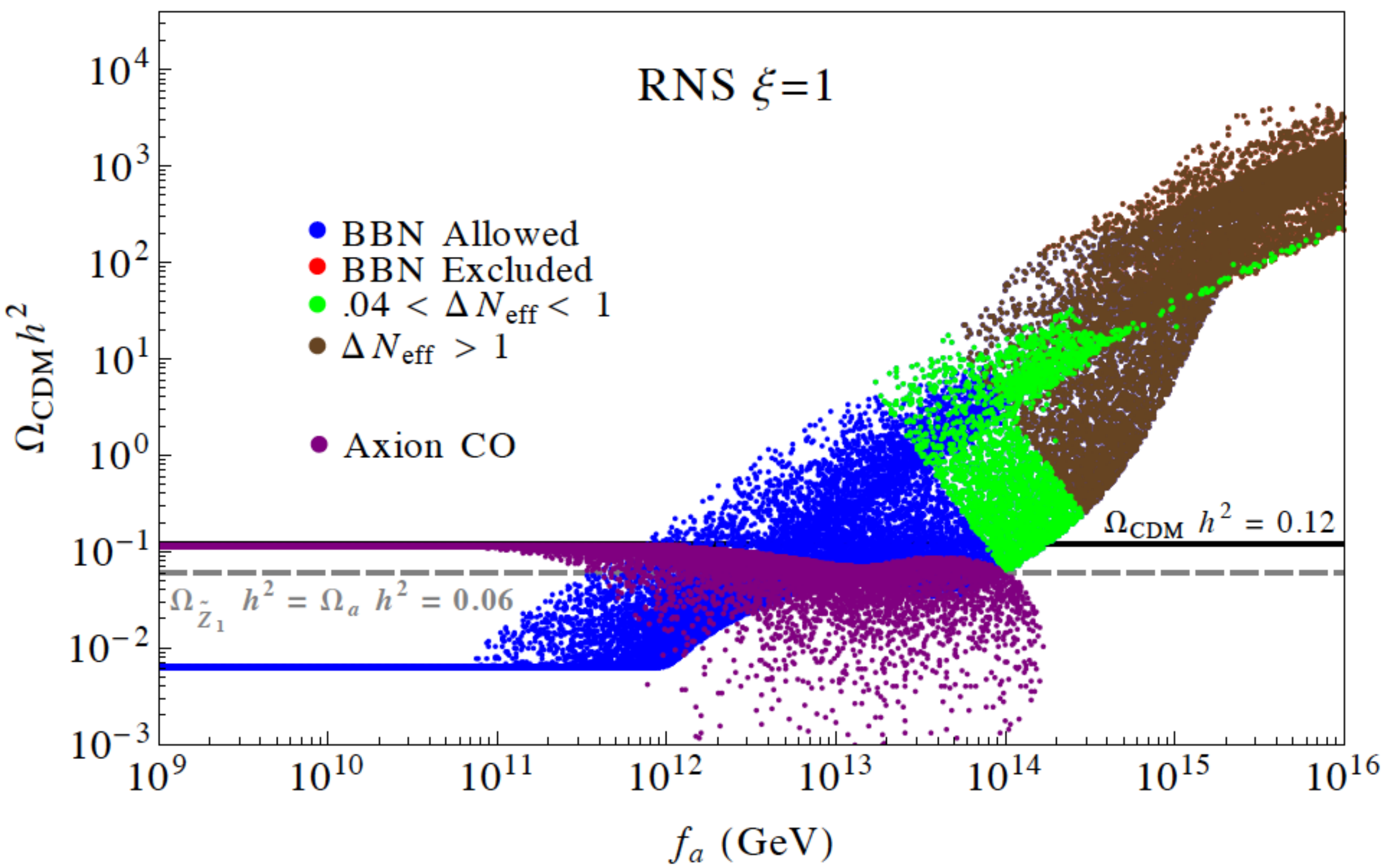
mixed axion-neutralino production in early universe

- 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

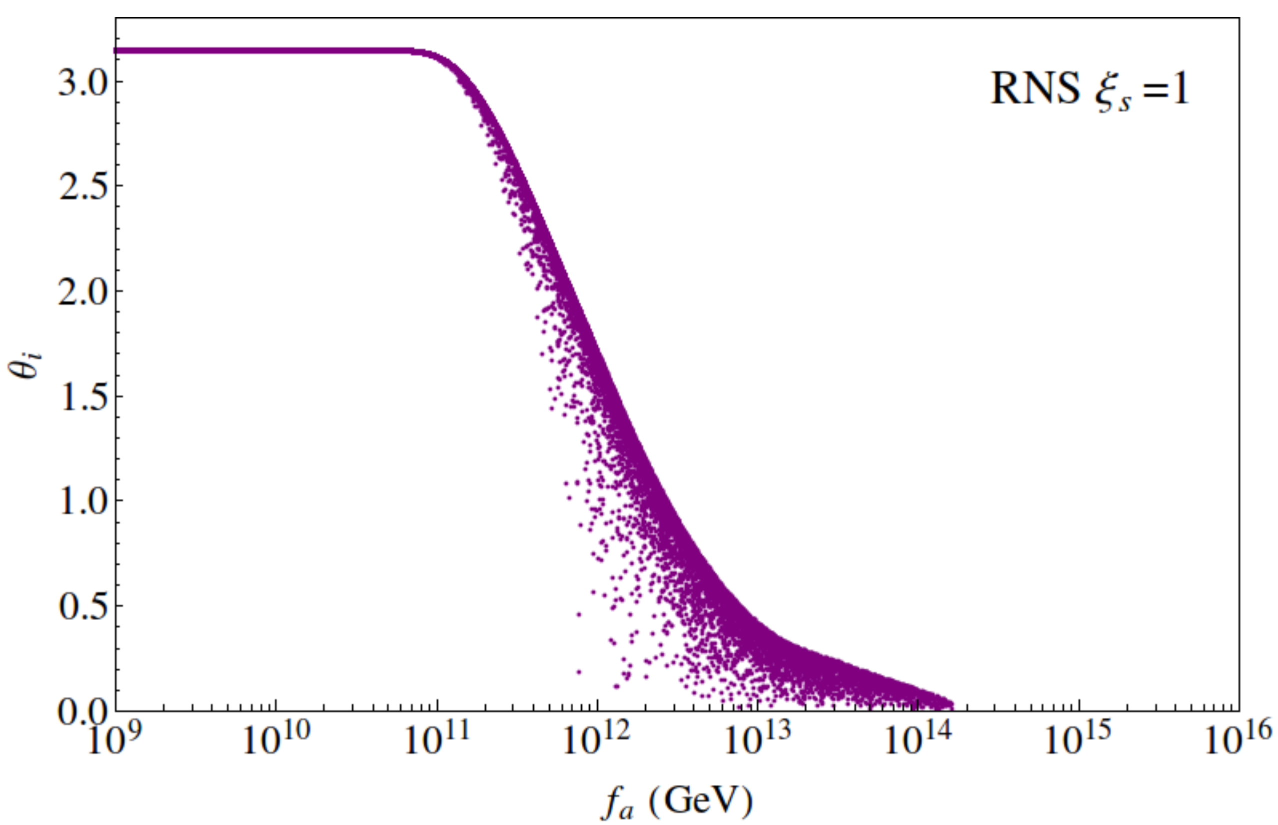


Bae, HB, Chun;
Bae, HB, Lessa, Serce



higgsino abundance

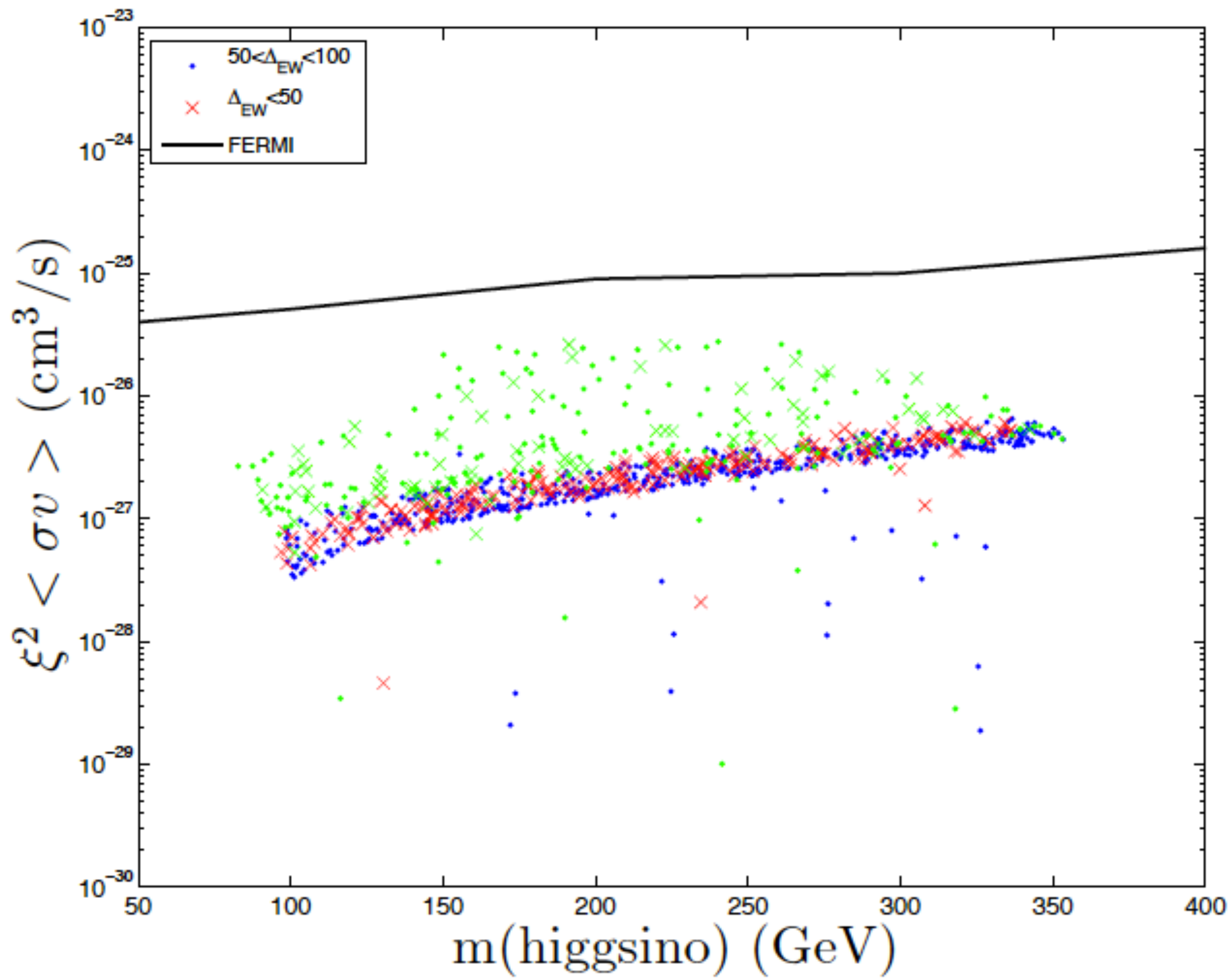
axion abundance



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

Bae, HB,Lessa,Serce

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