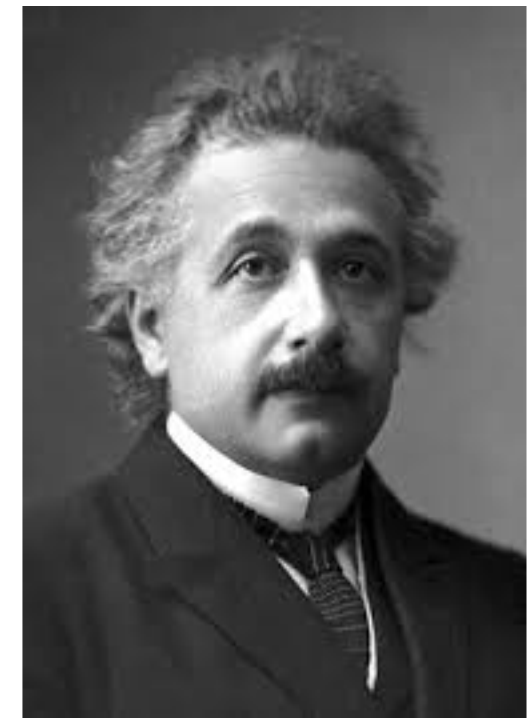
EWinos, natural SUSY and HL-LHC

Howard Baer
University of Oklahoma

LPC@FNAL, April 27, 2016

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"

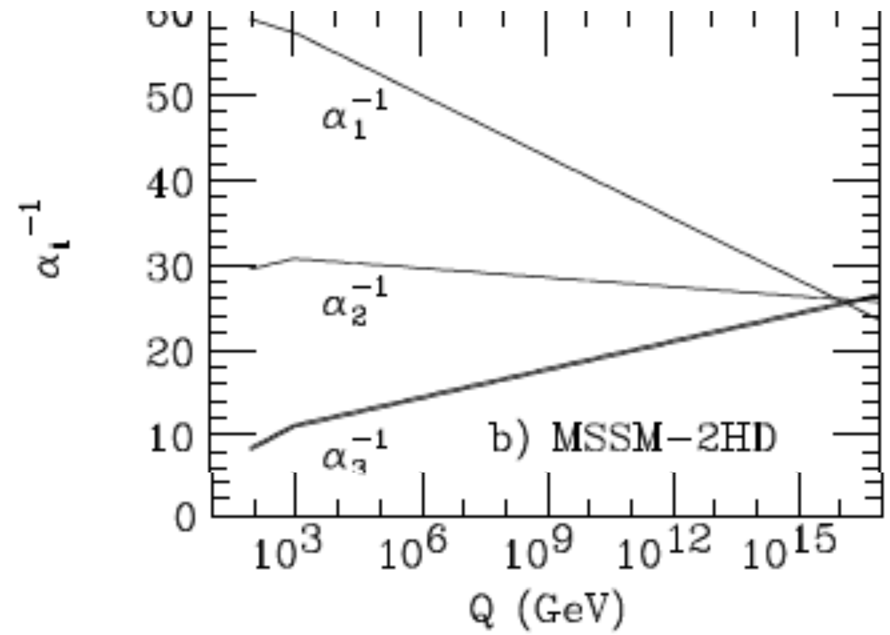
A. Einstein

Status of SUSY

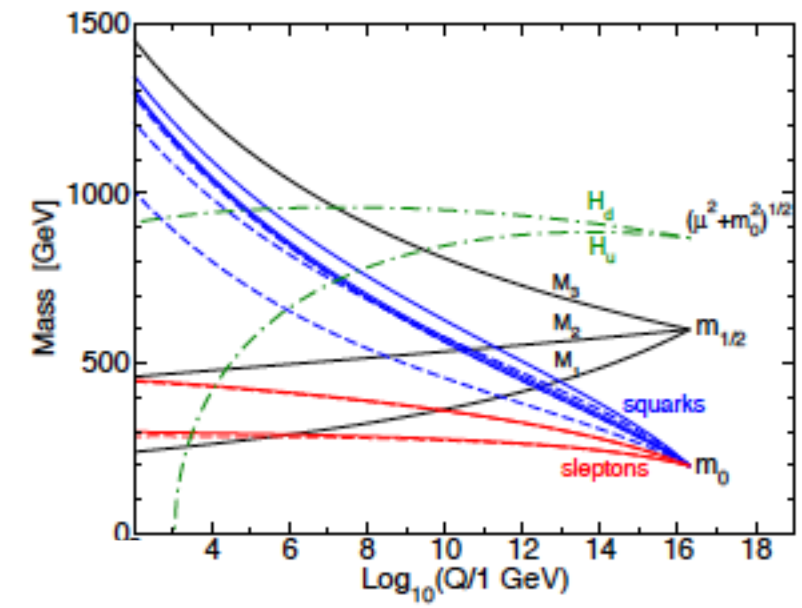
- Still best motivated candidate for physics BSM: solves once-and-for-all gauge hierarchy problem; indirect support from data
- But: sparticle mass limits uncomfortably high?
- But: Higgs mass mh(125) uncomfortably high?
- A seeming conflict between naturalness and data

Reminder: three times data had chance to rule SUSY out

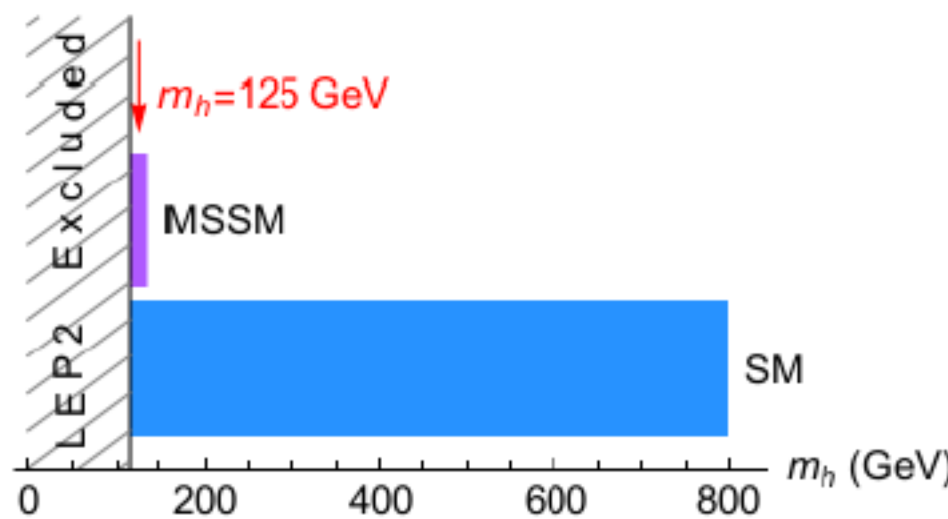
LEP gauge coupling measurements



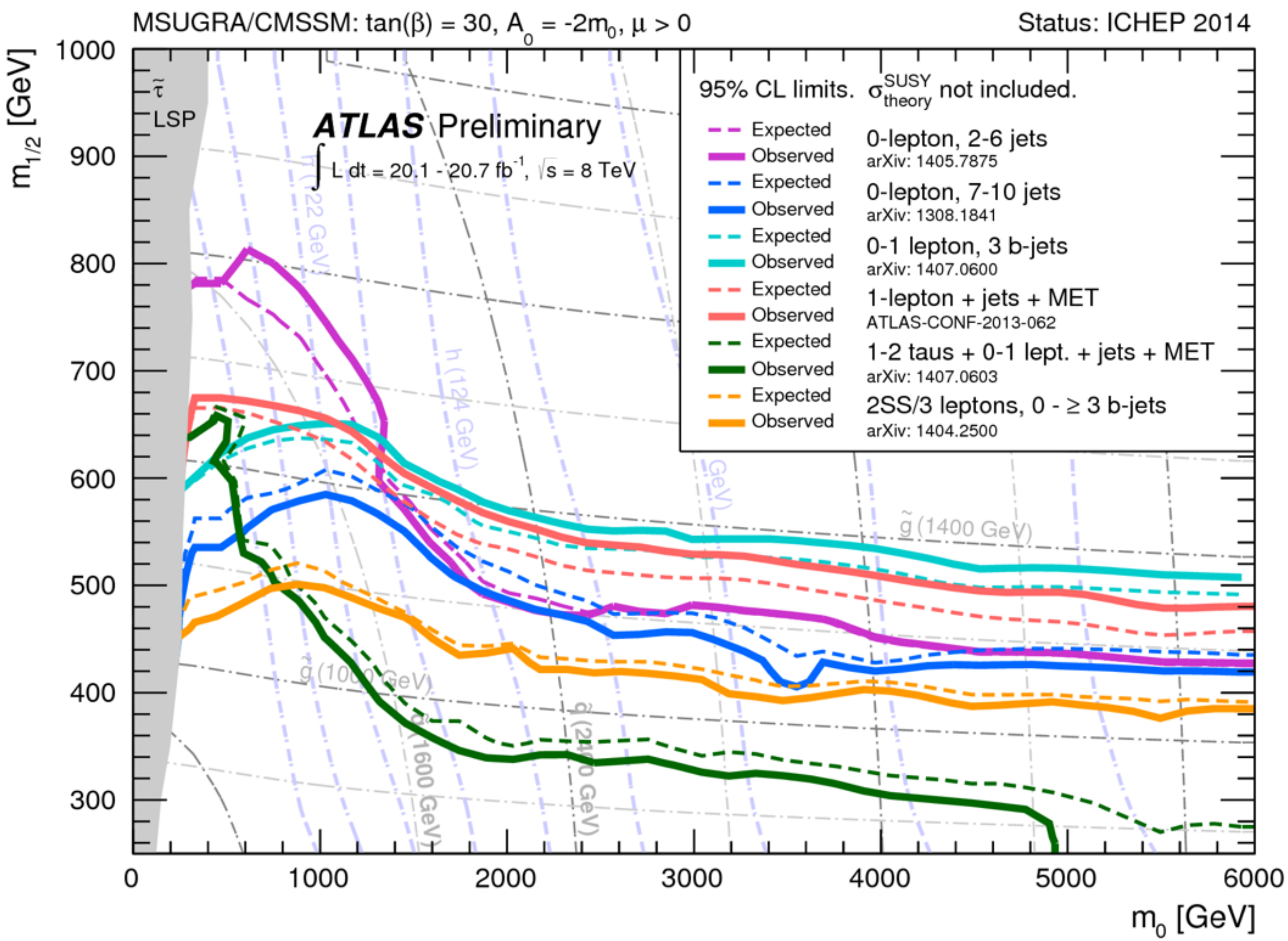
Tevatron: m(t)~173.2 GeV for EWSB



LHC: m(h)~125 GeV



But where are the sparticles?



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

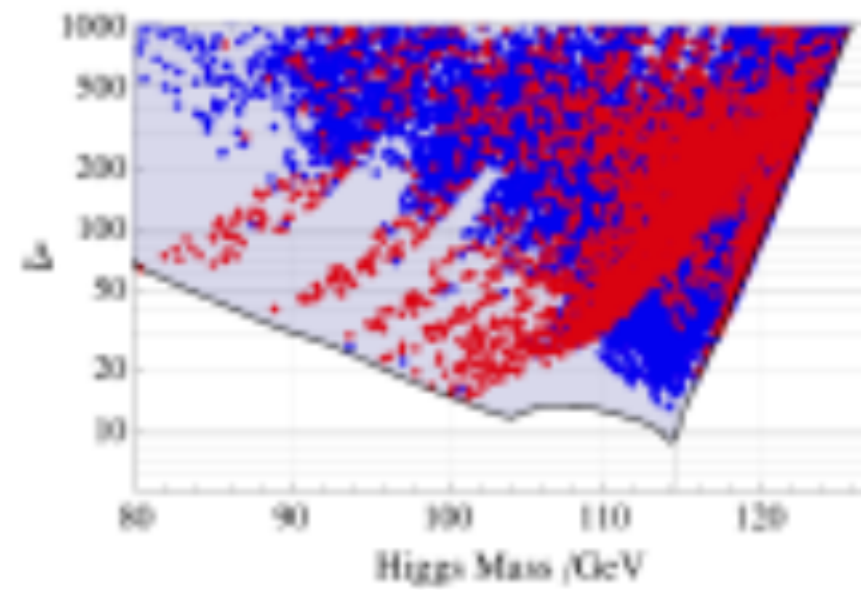
$$m_{\tilde{g}} > 1.8\ TeV \quad (m_{\tilde{q}} \sim m_{\tilde{g}})$$

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

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

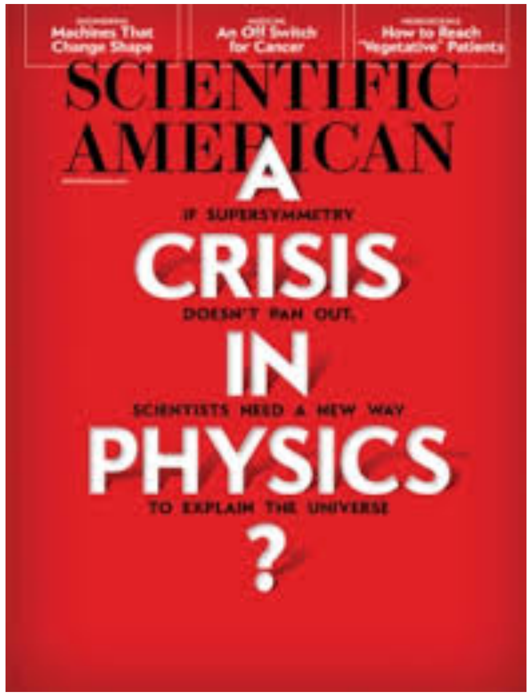


Cassel, Ghilencea, Ross,2009

$\Delta \to 1000$
as $m_h \to 125$ GeV
0.1% tuning!?

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

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

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!

``...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

Oft-repeated myths about naturalness

- 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: Naturalness in the Standard Model

SM case: invoke a single Higgs doublet

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

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

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

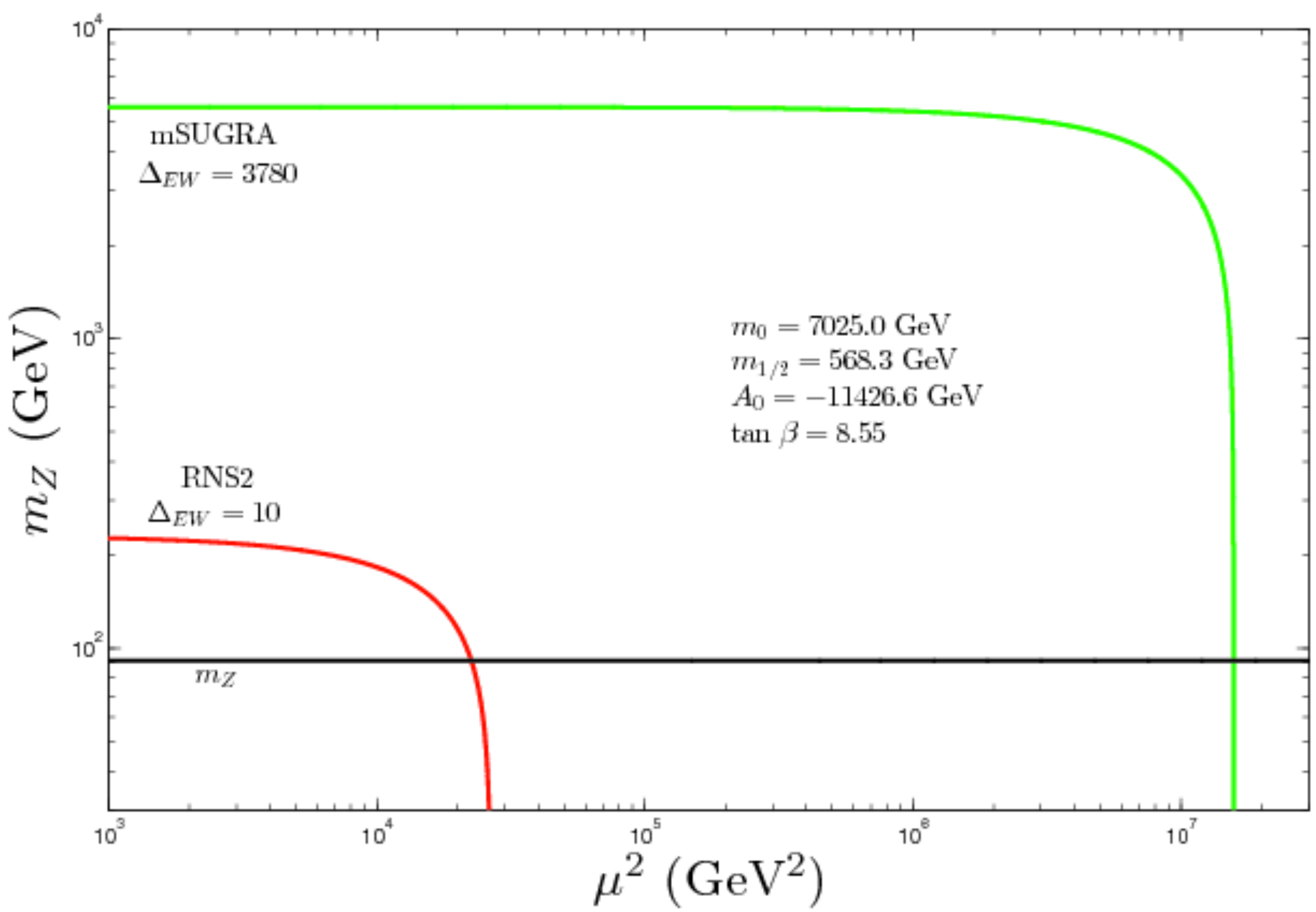
$m_h^2|_{tree}$ and $\delta m_h^2|_{rad}$ are *independent*,

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

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

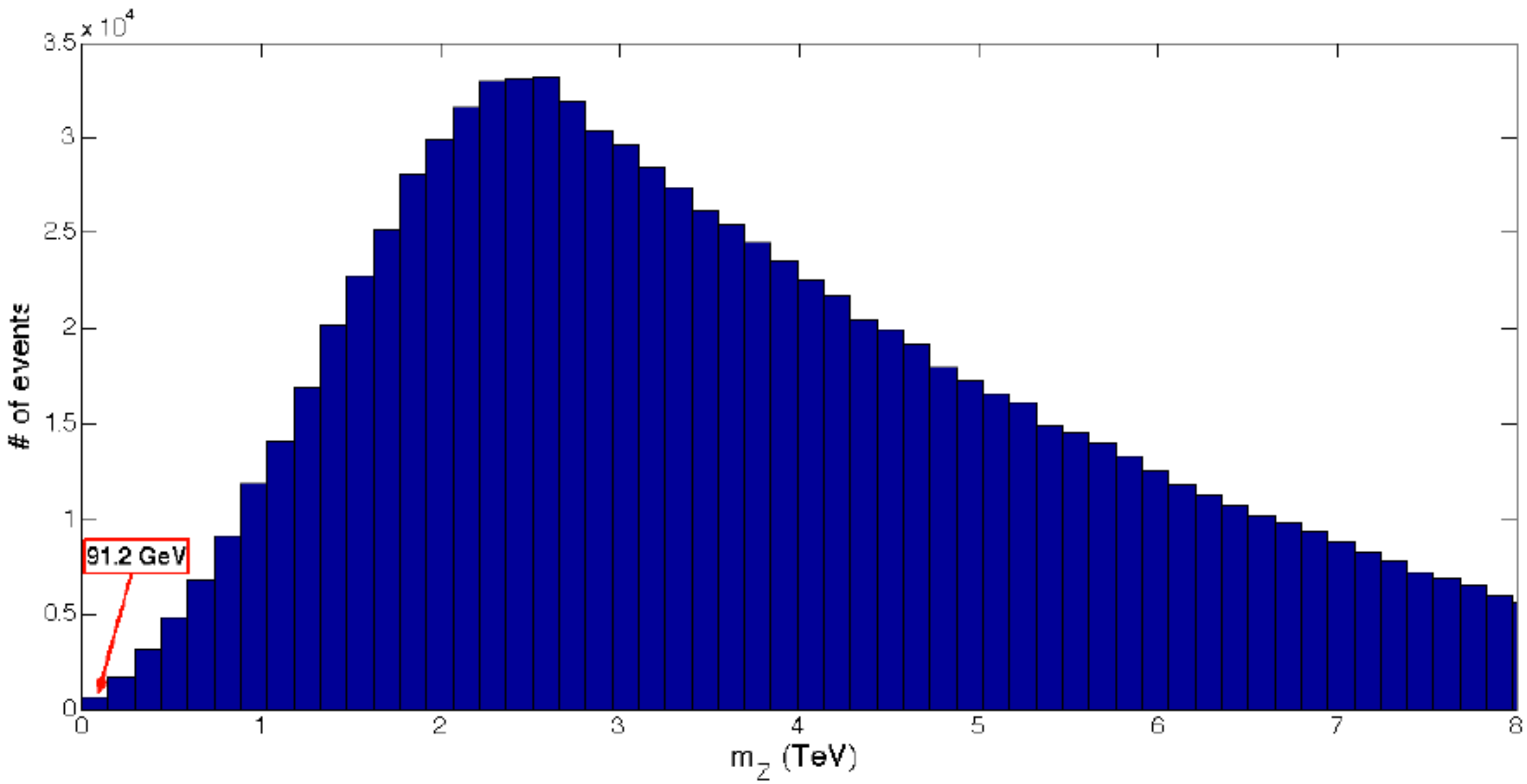
Next: simple electroweak fine-tuning in SUSY:
dial value of mu so that Z mass comes out right:
everybody does it but it is hidden inside spectra codes (Isajet, SuSpect, SoftSUSY, Spheno, SSARD)

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



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

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

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

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

Radiative natural SUSY with a 125 GeV Higgs boson

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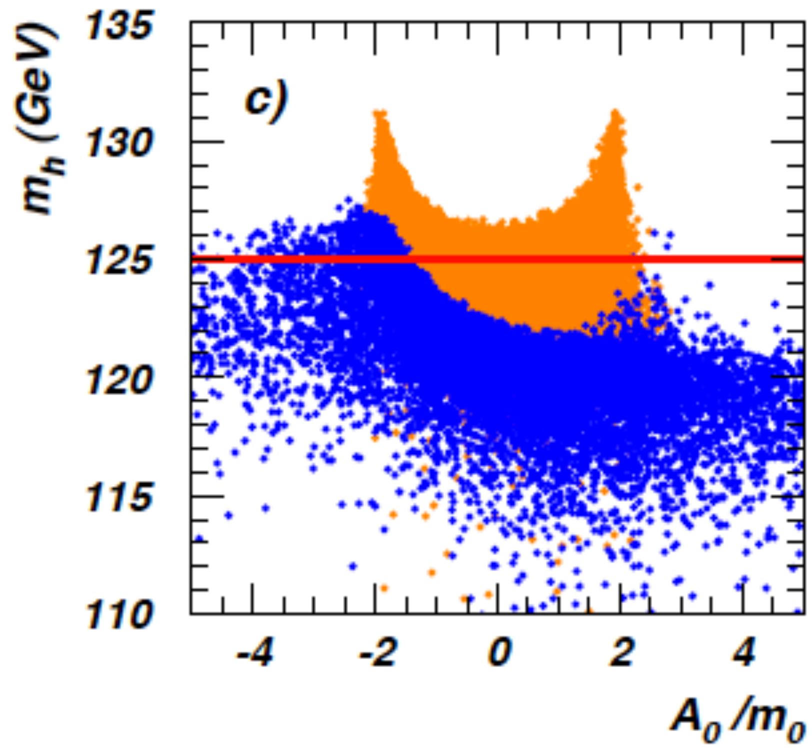
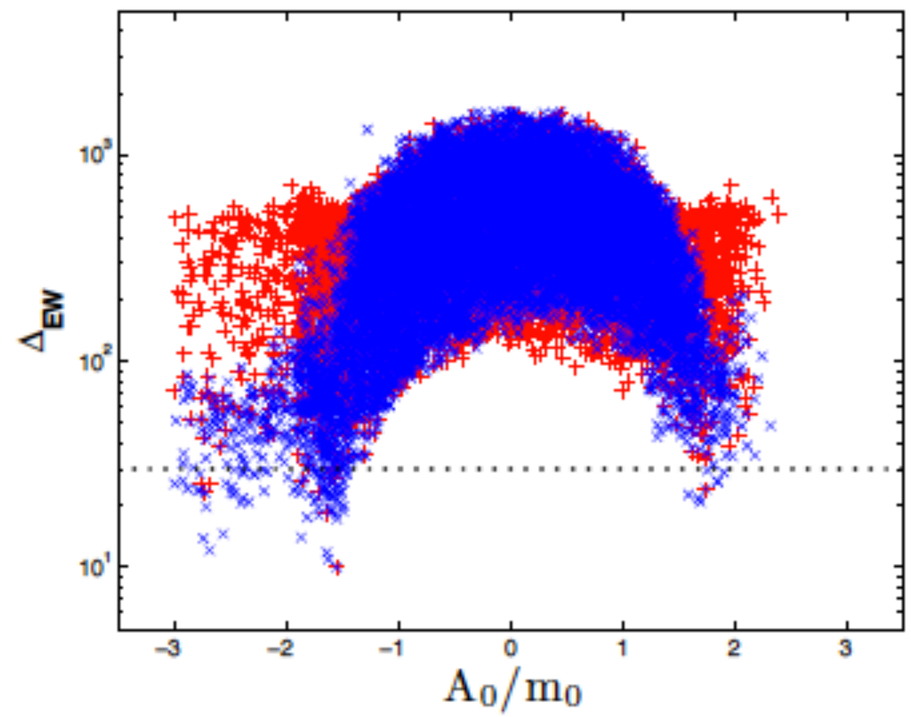
PRL109 (2012) 161802

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





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

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

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

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

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

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

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

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

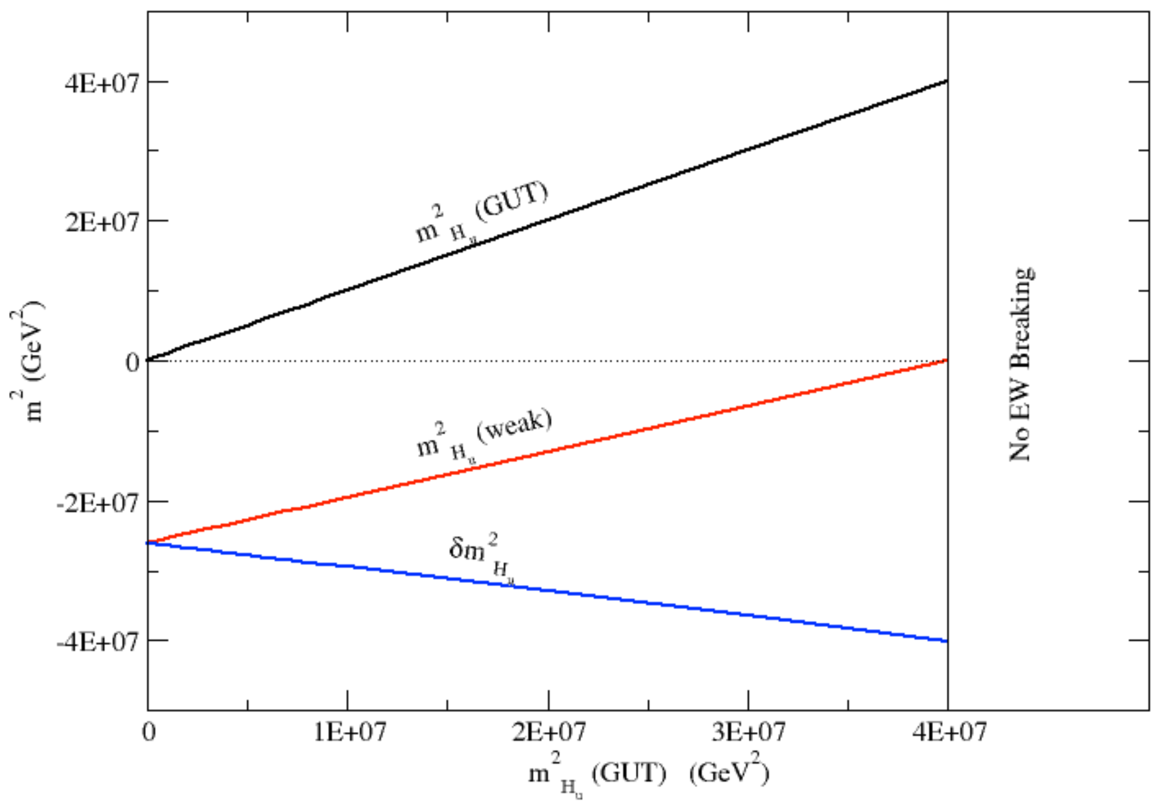
then A_t can't be too big

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

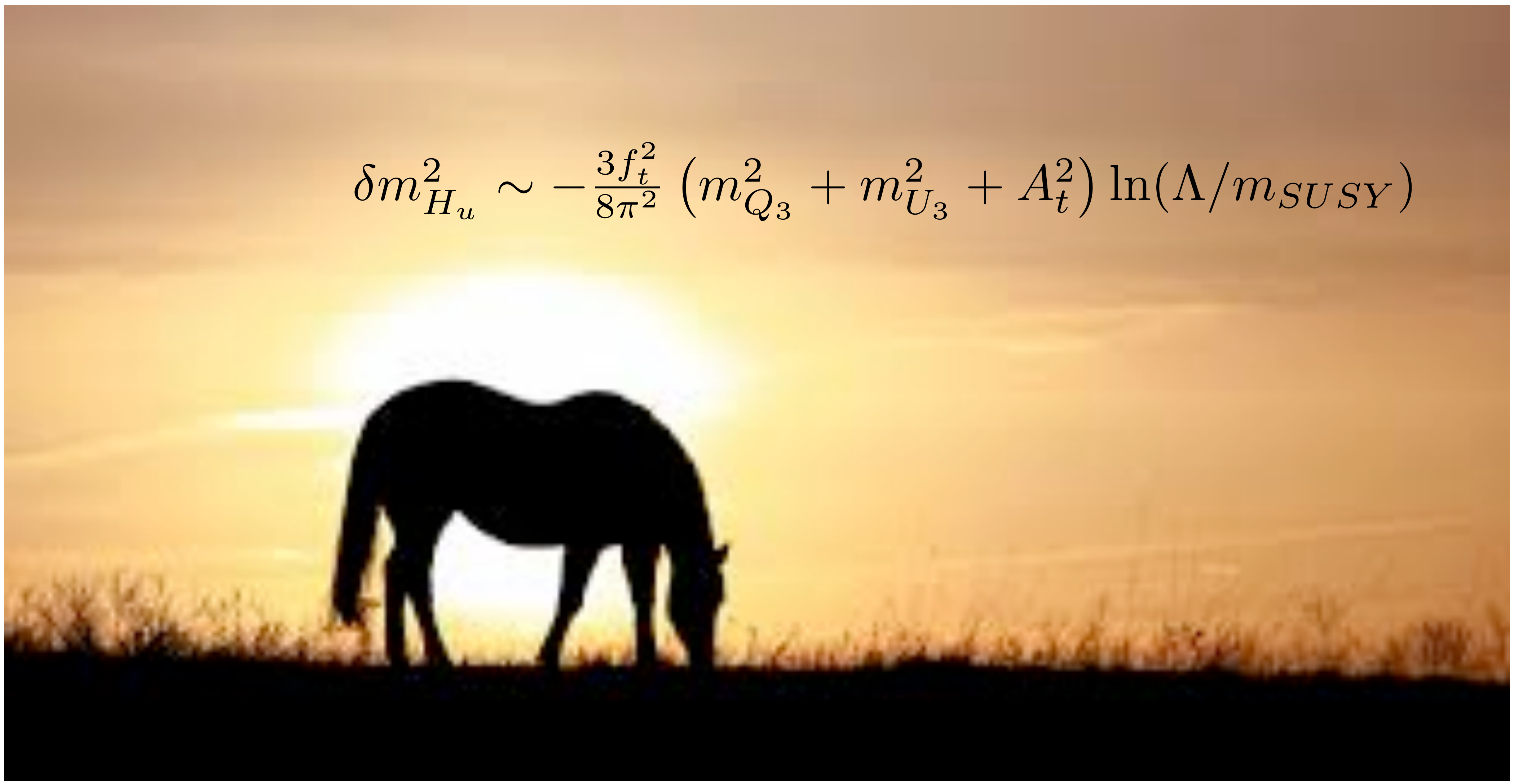
To fix: combine dependent terms:

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

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

↑

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, $\Delta_{BG}\ is\ large$

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

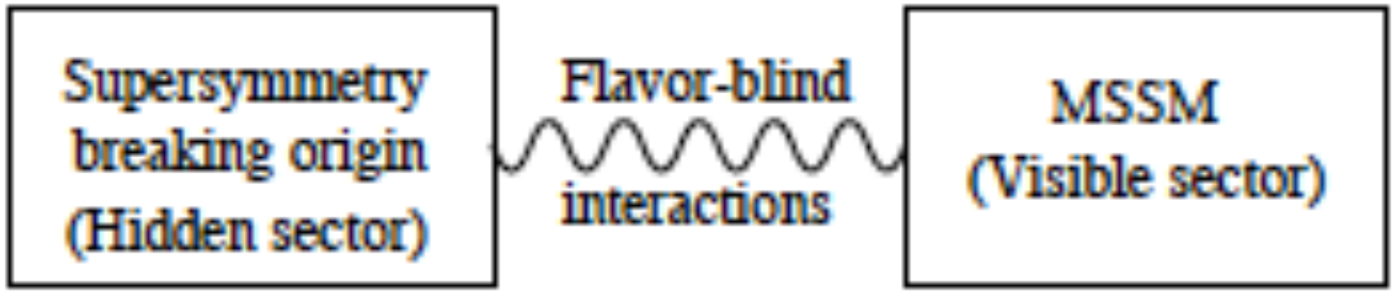
For correlated parameters, EWFT collapses in 3rd gen. sector!

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:

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

GUT scale param's

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

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

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

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

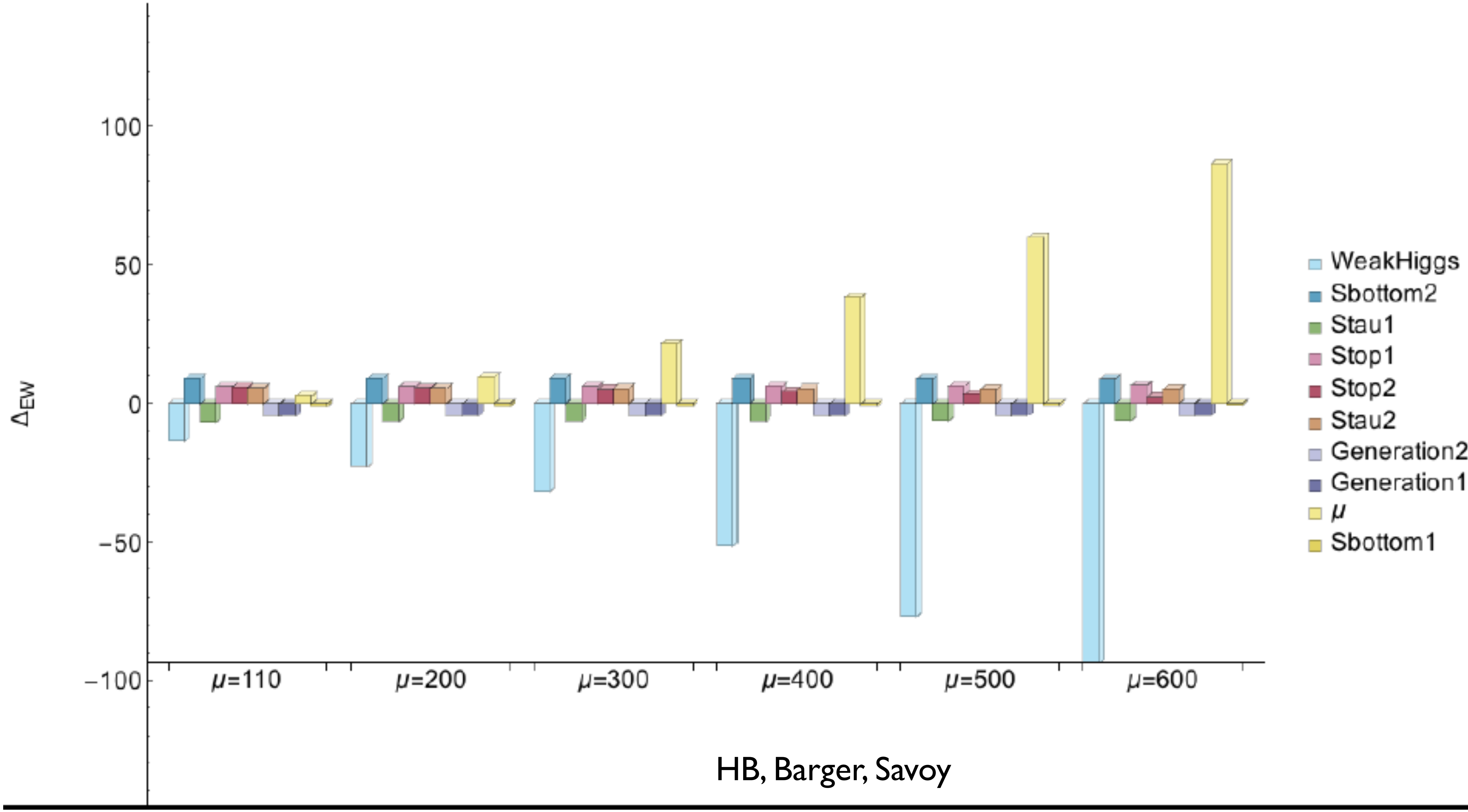
Due to ease of use and including radiative corrections, and due to its explicit model independence, we will use

$$\Delta_{EW}$$

for remainder of talk

hard wired in Isasugra

How much is too much fine-tuning?



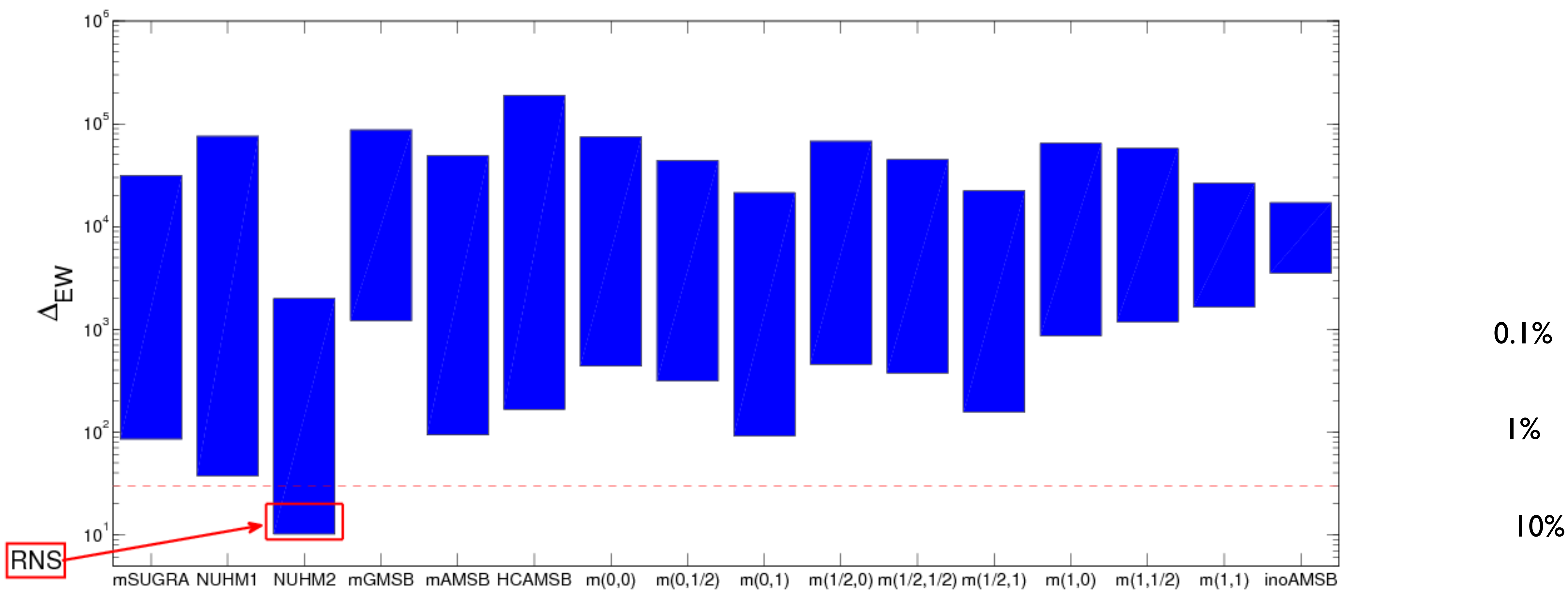
HB, Barger, Savoy

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.

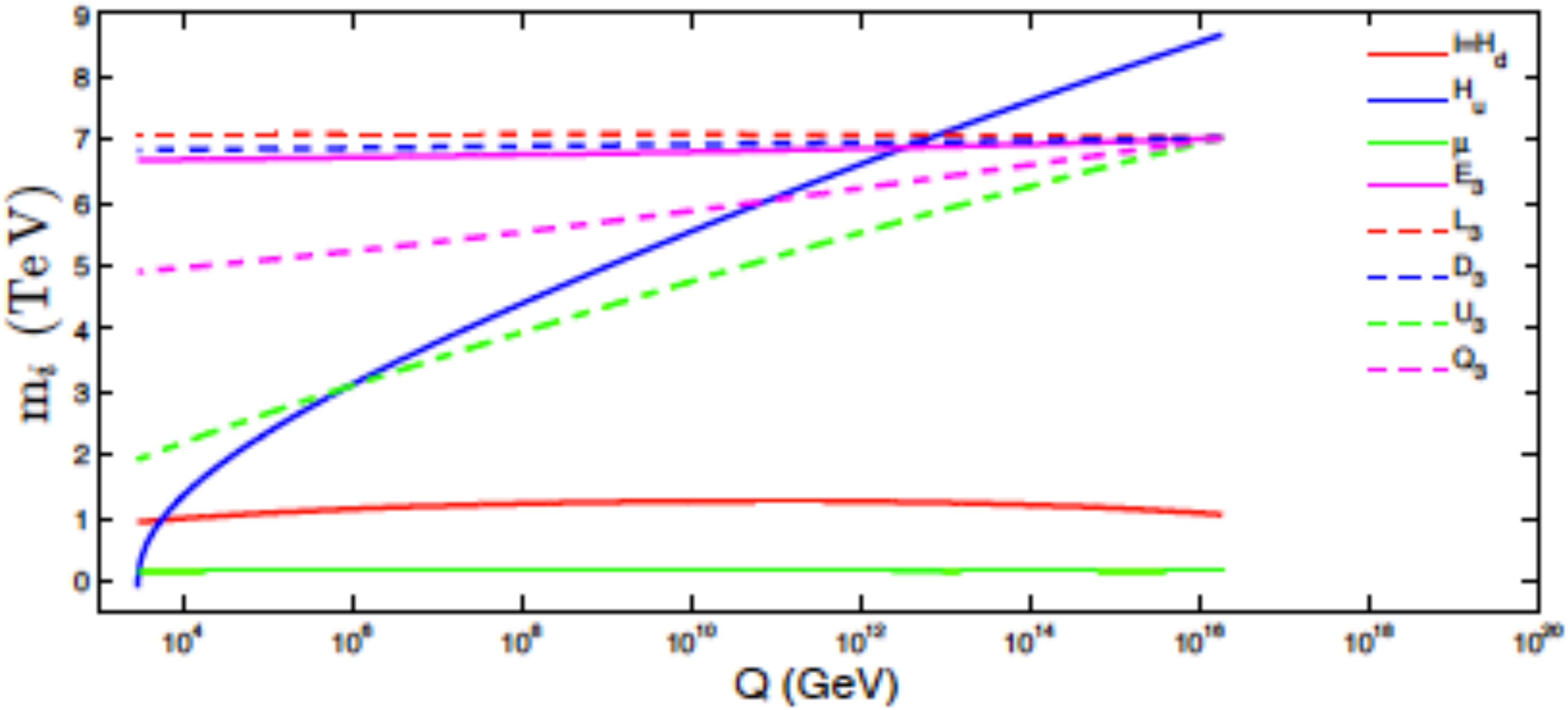
scan over p-space with m(h)=125.5+-2.5 GeV:



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:

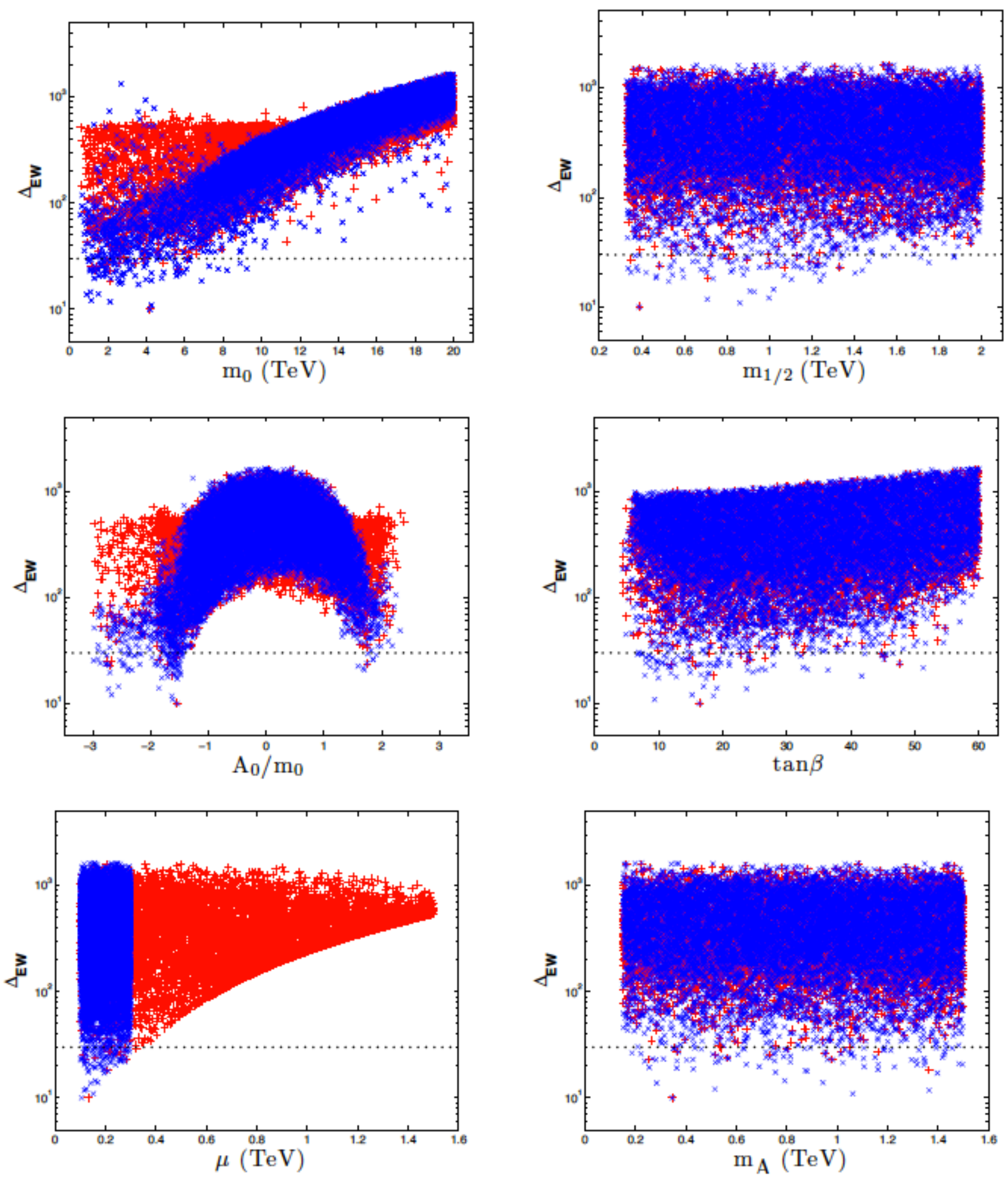
(typically need mHu~25-50% higher than m0)

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!

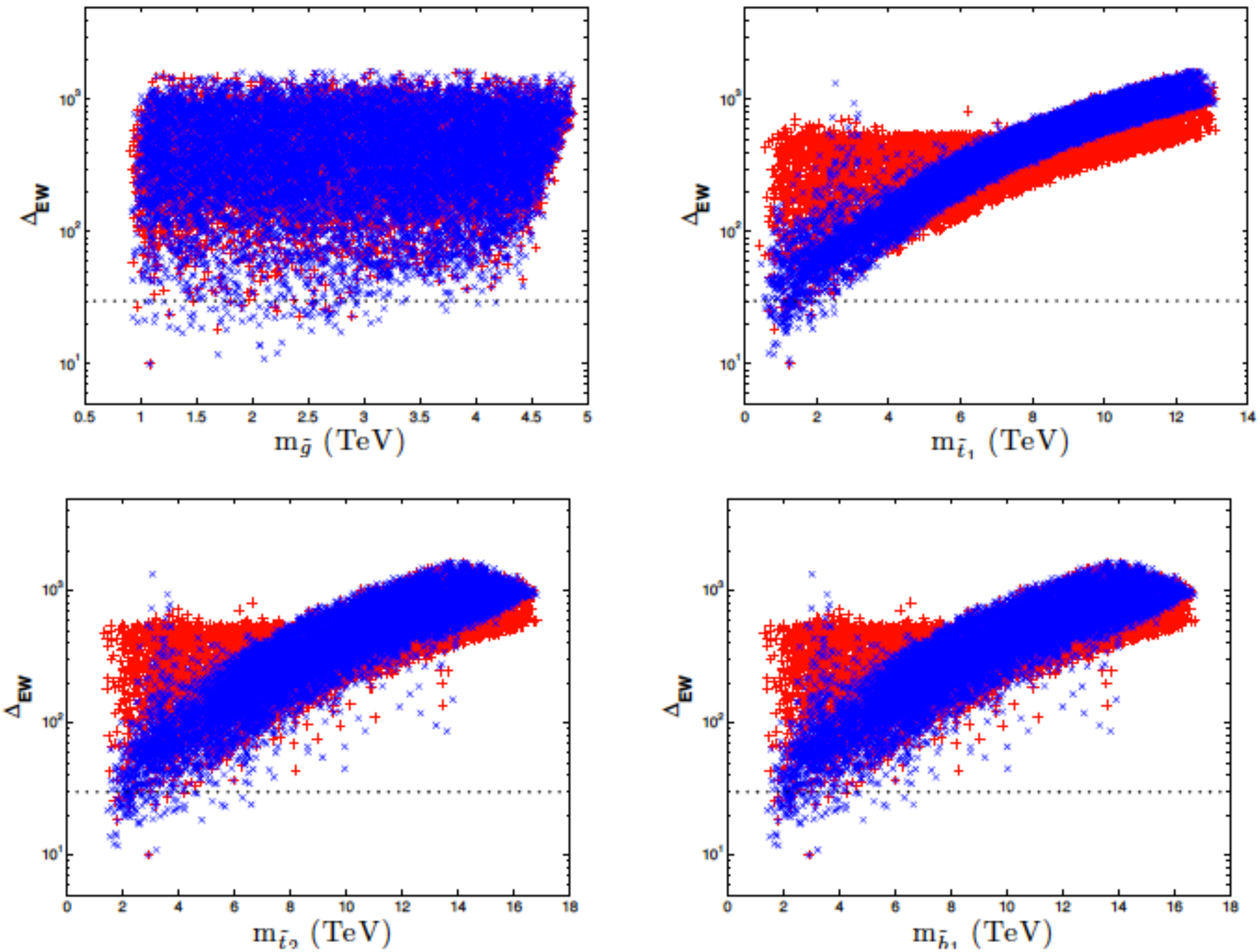


$$\Delta_{EW} \sim 10 \text{ or } 10\% \; EWFT$$

High-scale models with low Δ_{EW} :

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

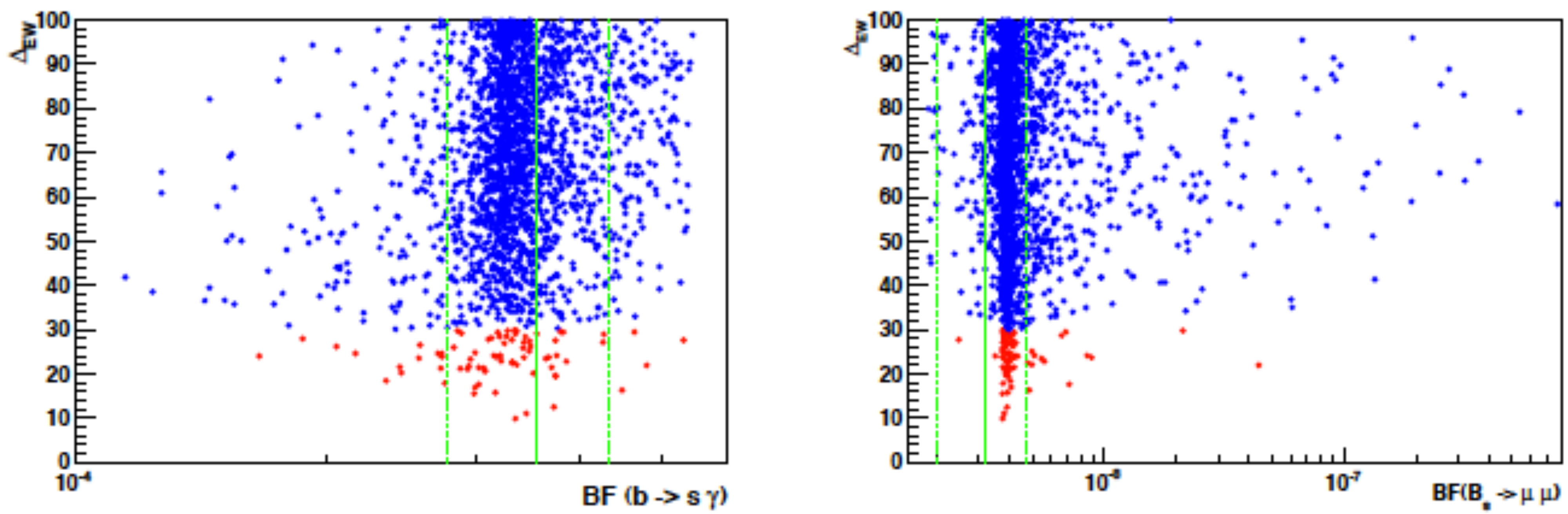
Upper bounds on sparticle masses:



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

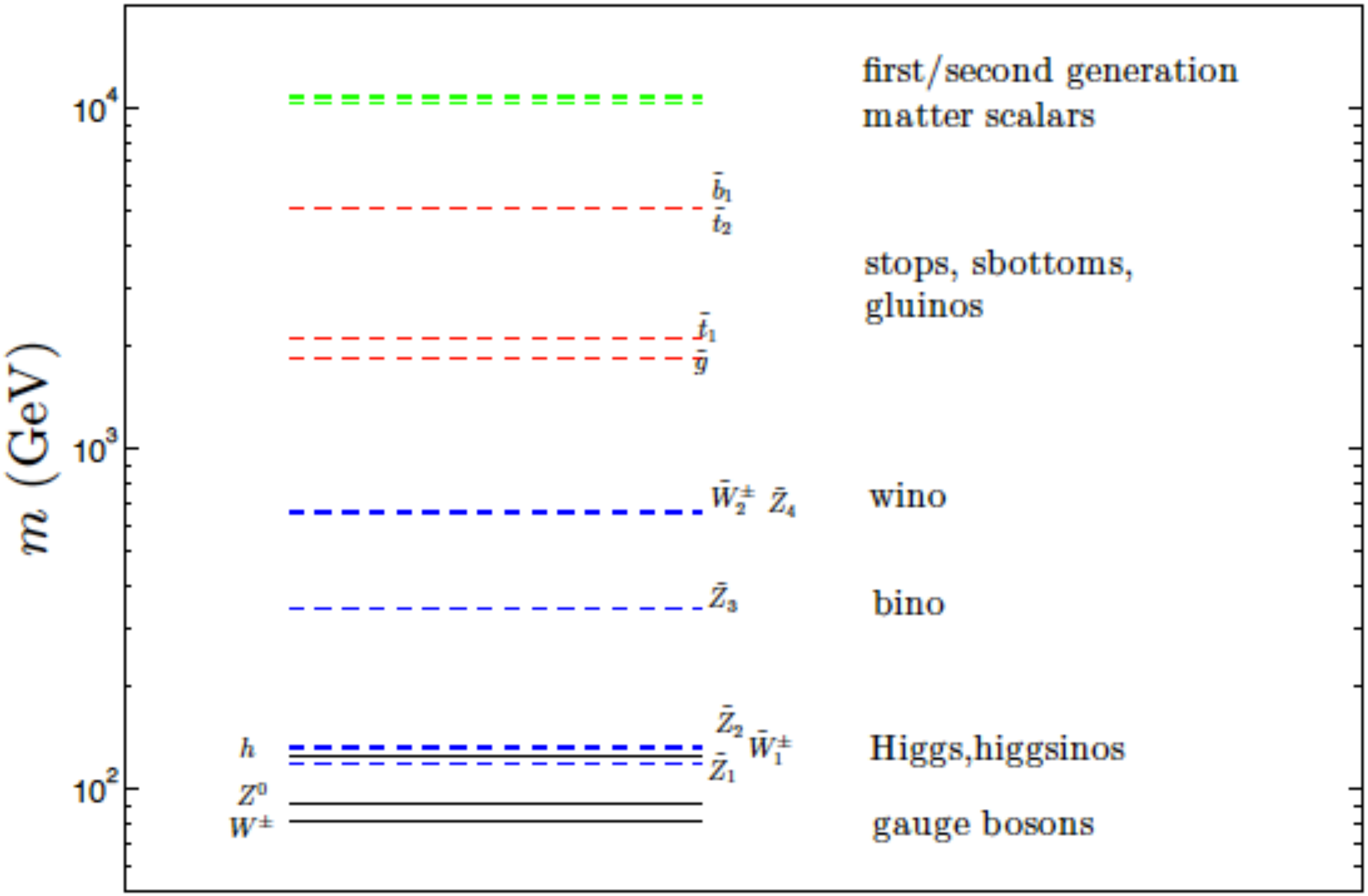
higher than old NS models and
allows for m(h)~125 GeV within MSSM

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!

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

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

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

Choi, Chun, Kim (1996)

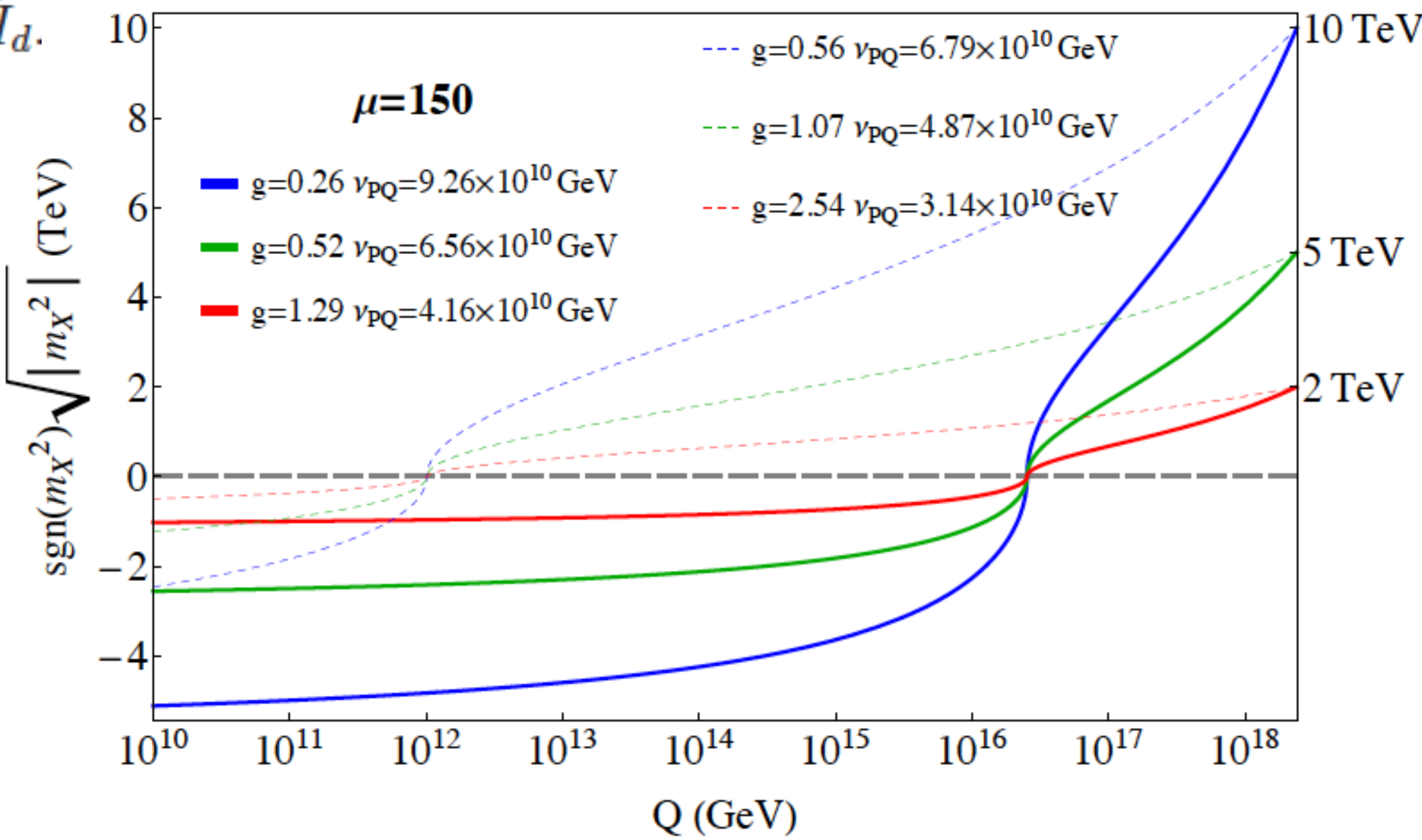
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

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

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



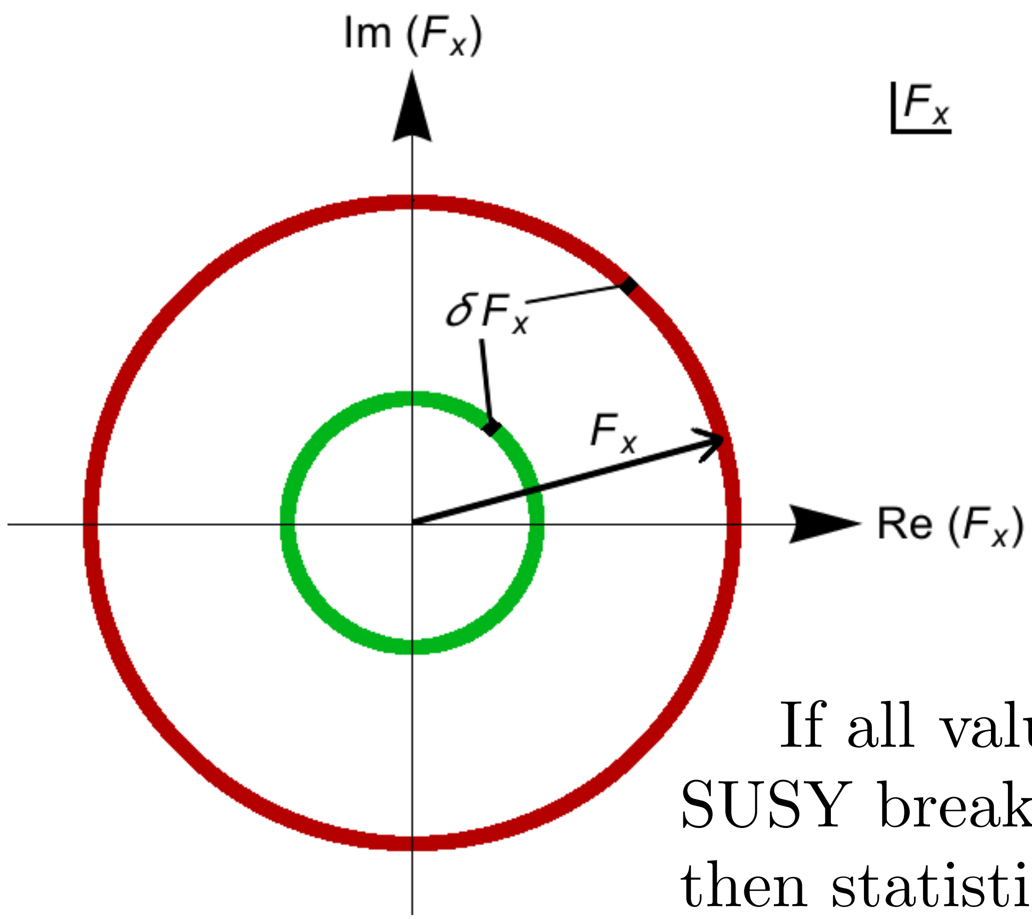
Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

Armed with mechanism to generate mu~100 GeV, then:

Why soft terms that yield naturalness and
barely break EW symmetry?

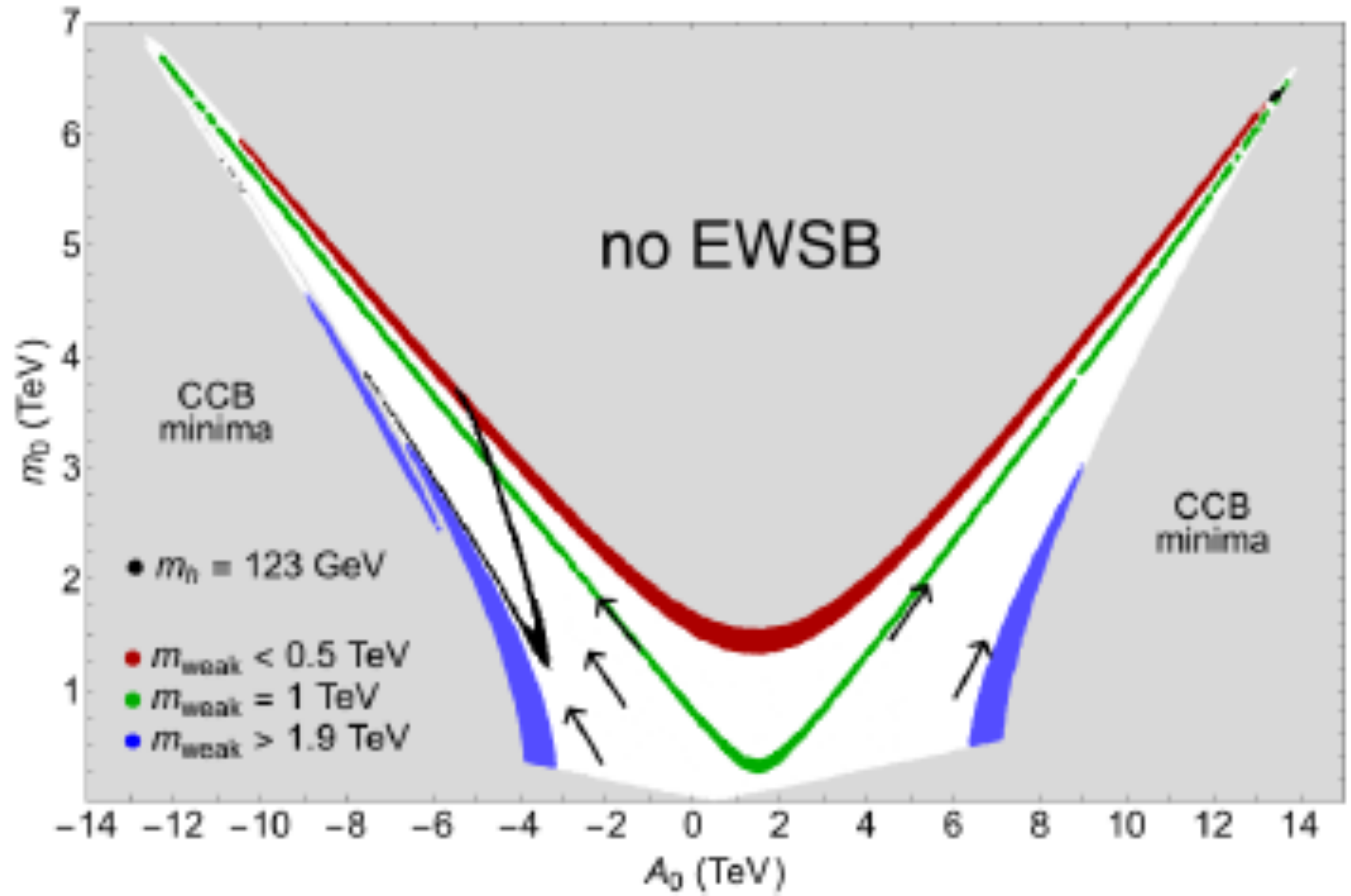
$$m_{H_u}^2 \sim -(100\ \mathrm{GeV})^2 \text{ at weak scale}$$

May appeal to string theory landscape:
statistical draw of soft terms to large
values, subject to generating a universe known
to support life, e.g. a weak scale ~100 GeV

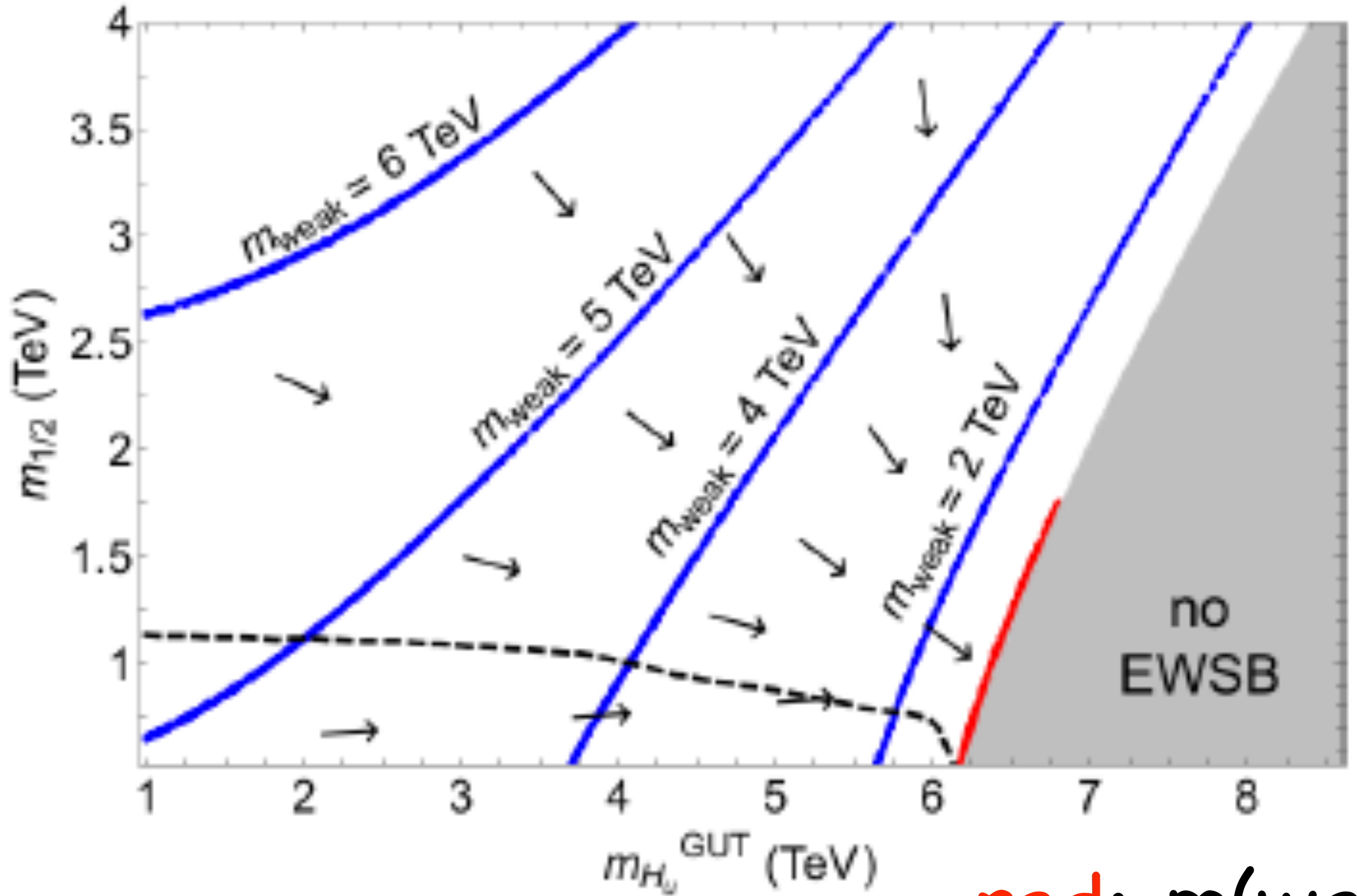


If all values of complex-valued SUSY breaking auxiliary field F_X are equally likely, then statistical draw to large $|\langle F_X \rangle|$

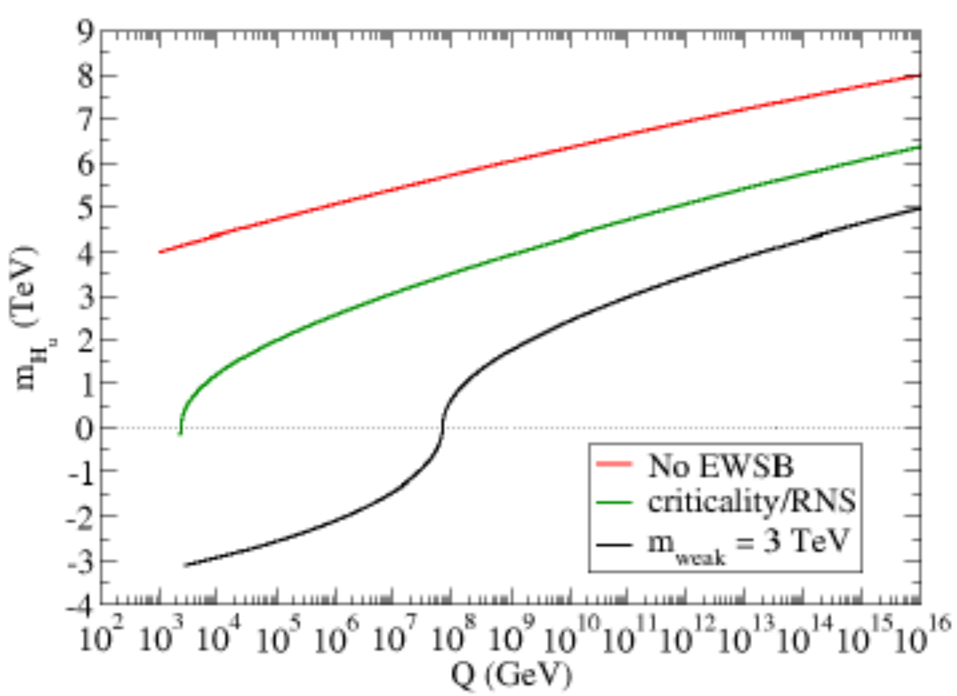
statistical draw to large soft terms
while anthropic constraint that
m(W,Z,h)~100 GeV
(else weak interactions too weak)



pull towards m(h)~125 GeV
and barely -broken (natural) SUSY



red: m(weak)<500 GeV

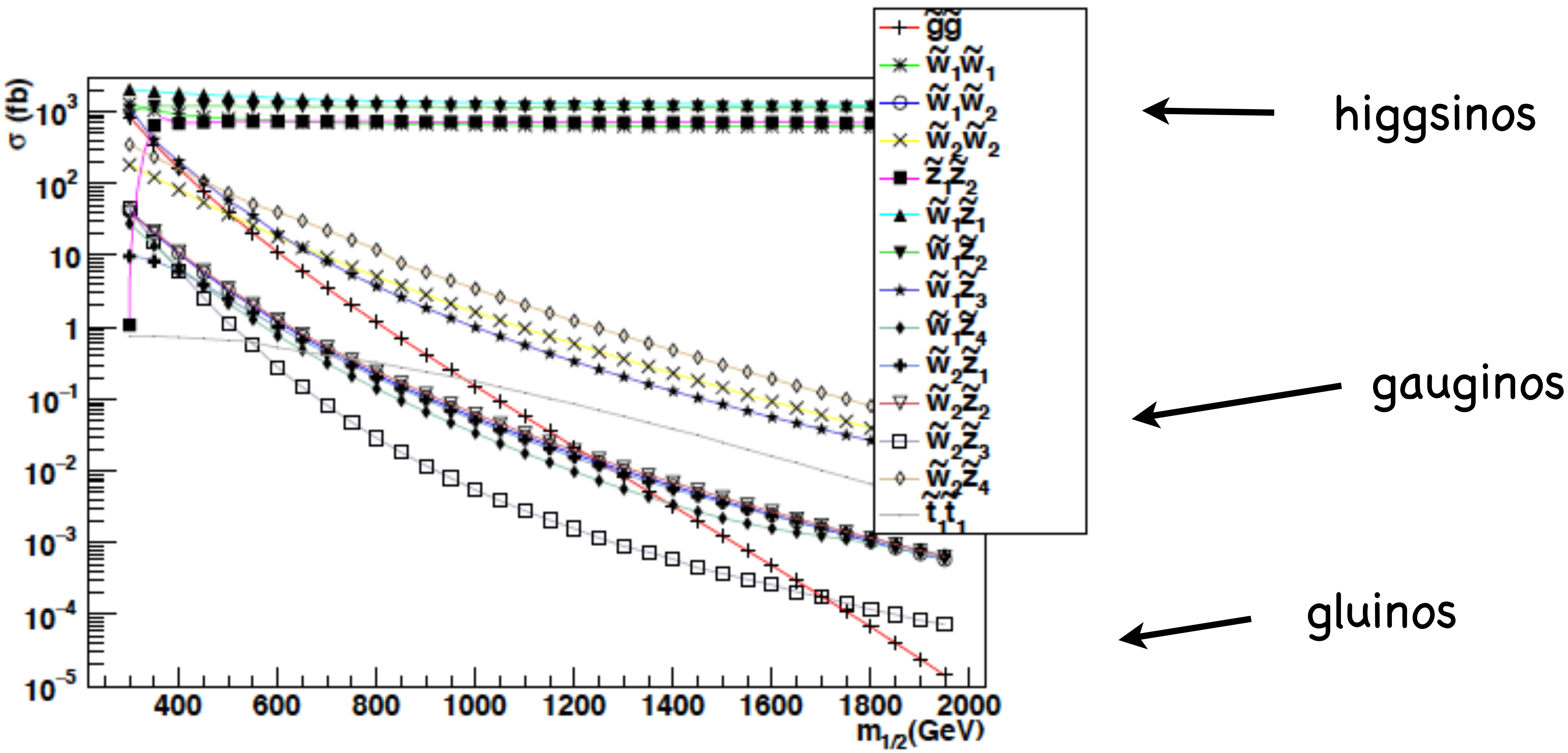


natural SUSY on edge of criticality: barely-broken EW sym.

HB, Barger, Savoy, Serce: arXiv:1602.07697

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

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

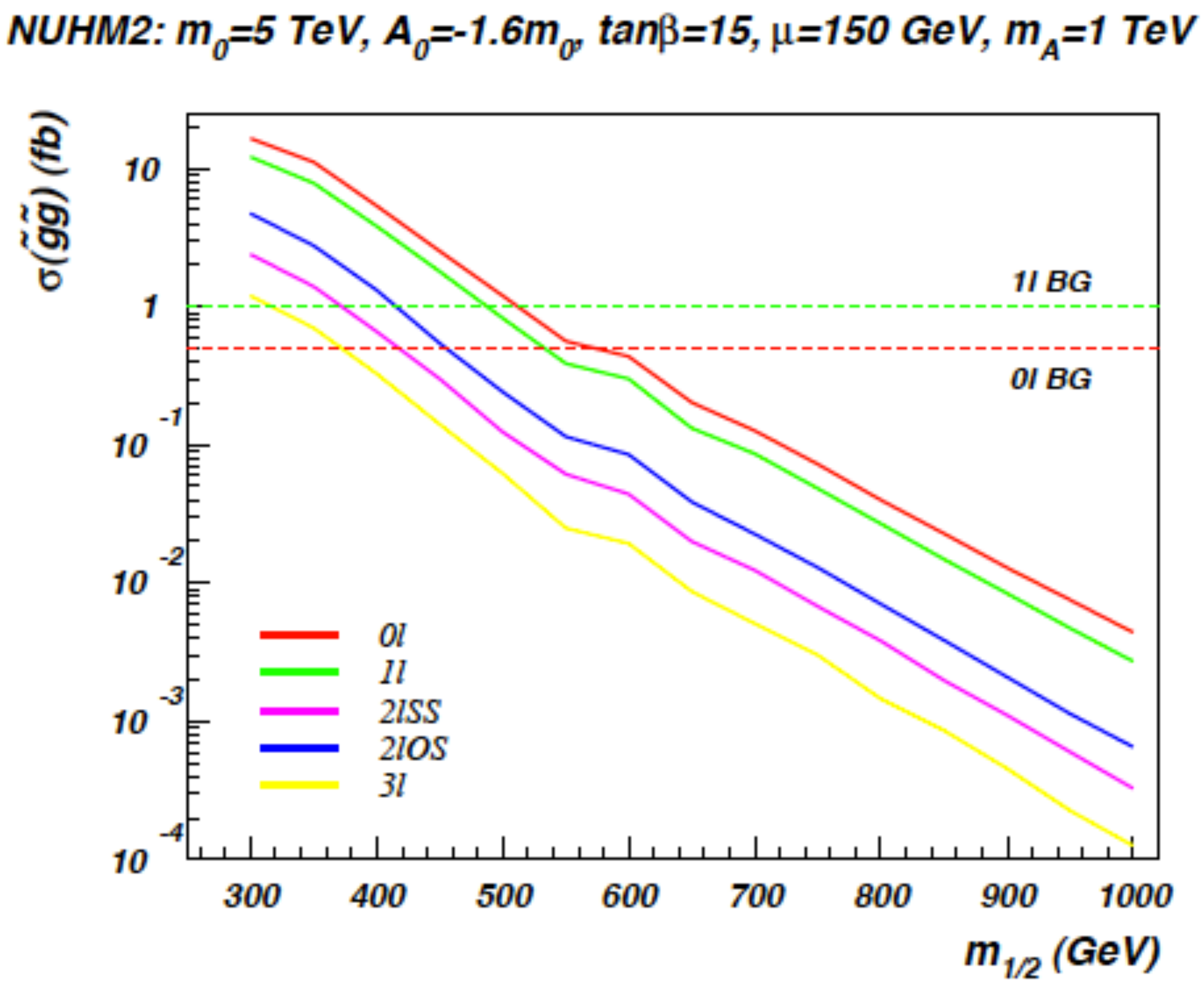


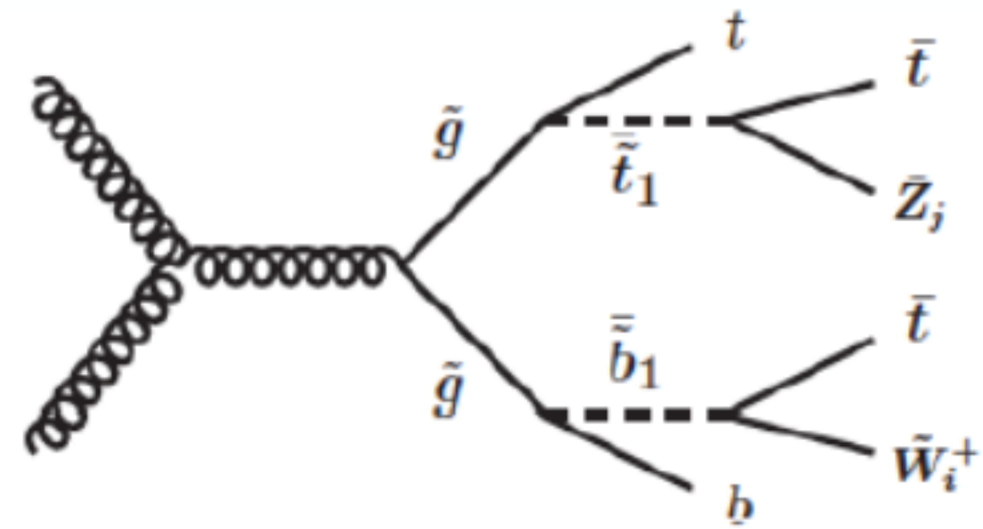
higgsino pair production dominant-but only soft visible energy release from higgsino decays

largest visible cross section: wino pairs

gluino pairs sharply dropping

gluino pair cascade decay signatures





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

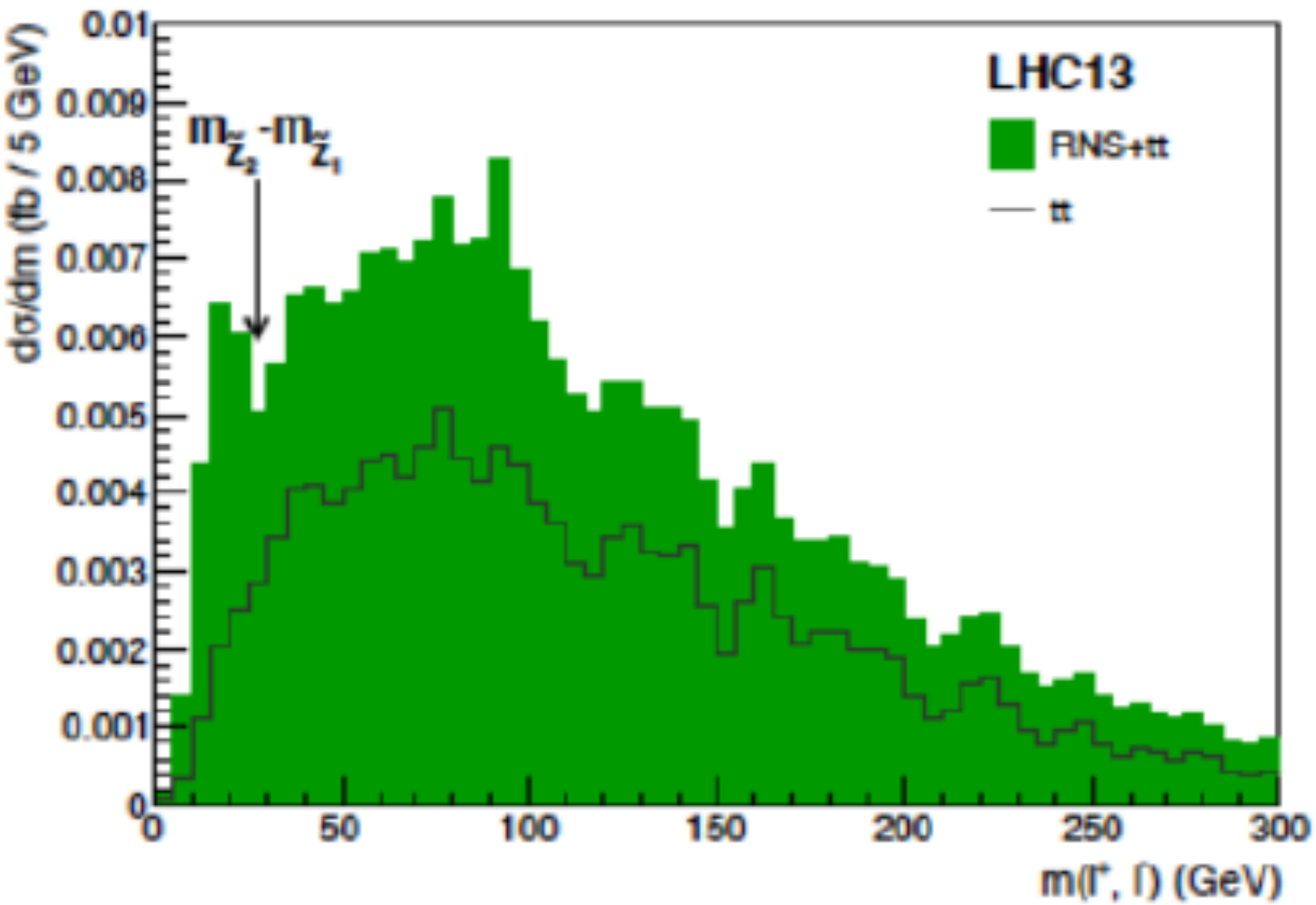
Table 1: Dominant branching fractions of various sparticles along the RNS model line for $m_{1/2}$ = 1 TeV.

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)

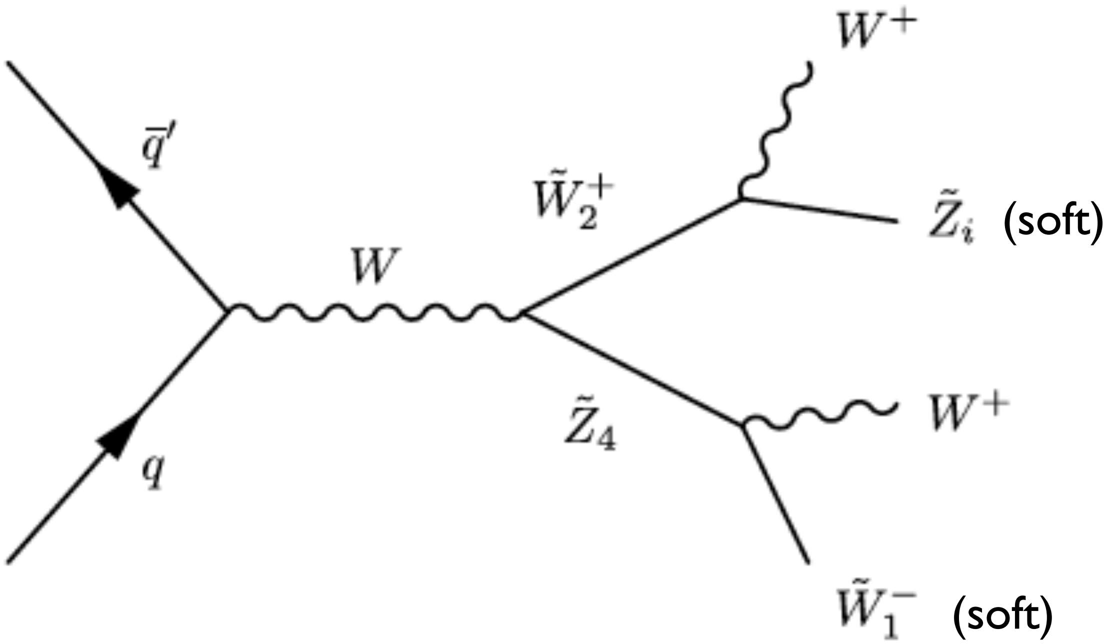
since m(gluino) extends to ~4 TeV, LHC14 can see about half the low EWFT parameter space in these modes

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

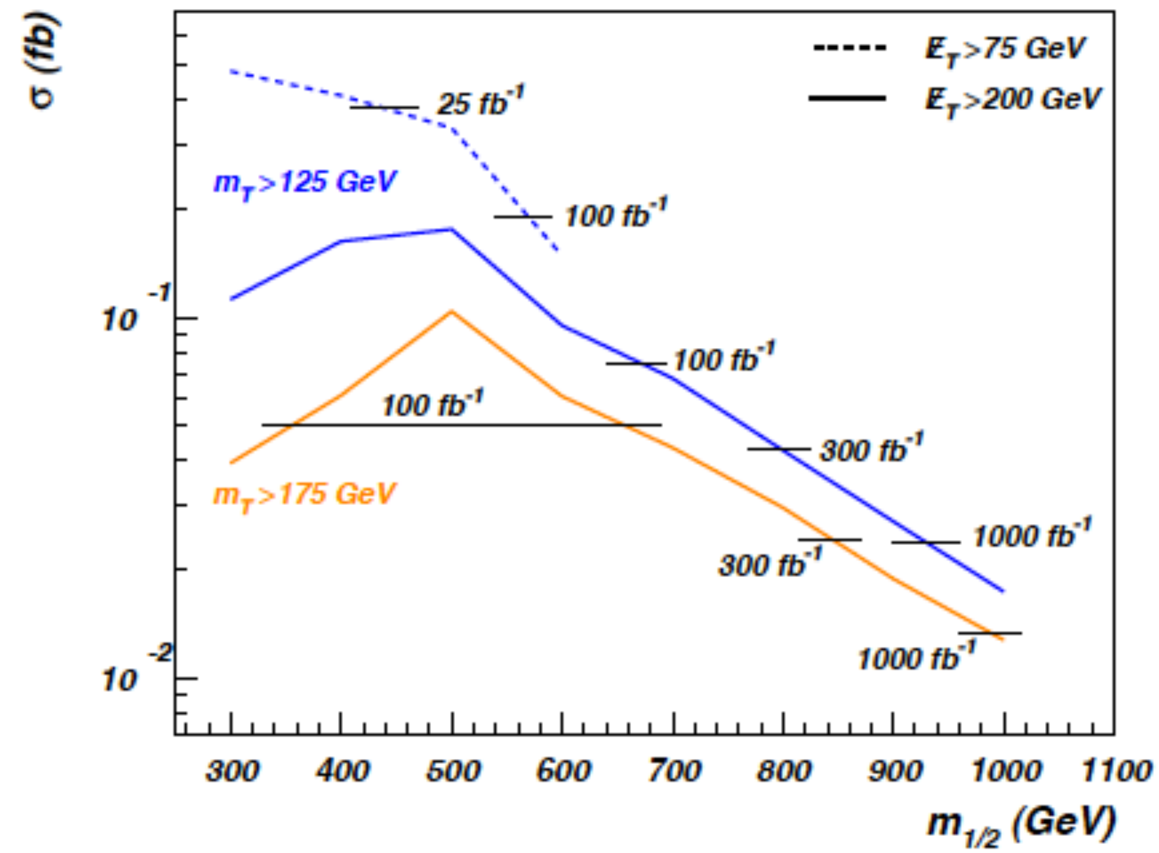


OS/SF dilepton mass edge apparent from cascade decays with z2->z1+l+lbar

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



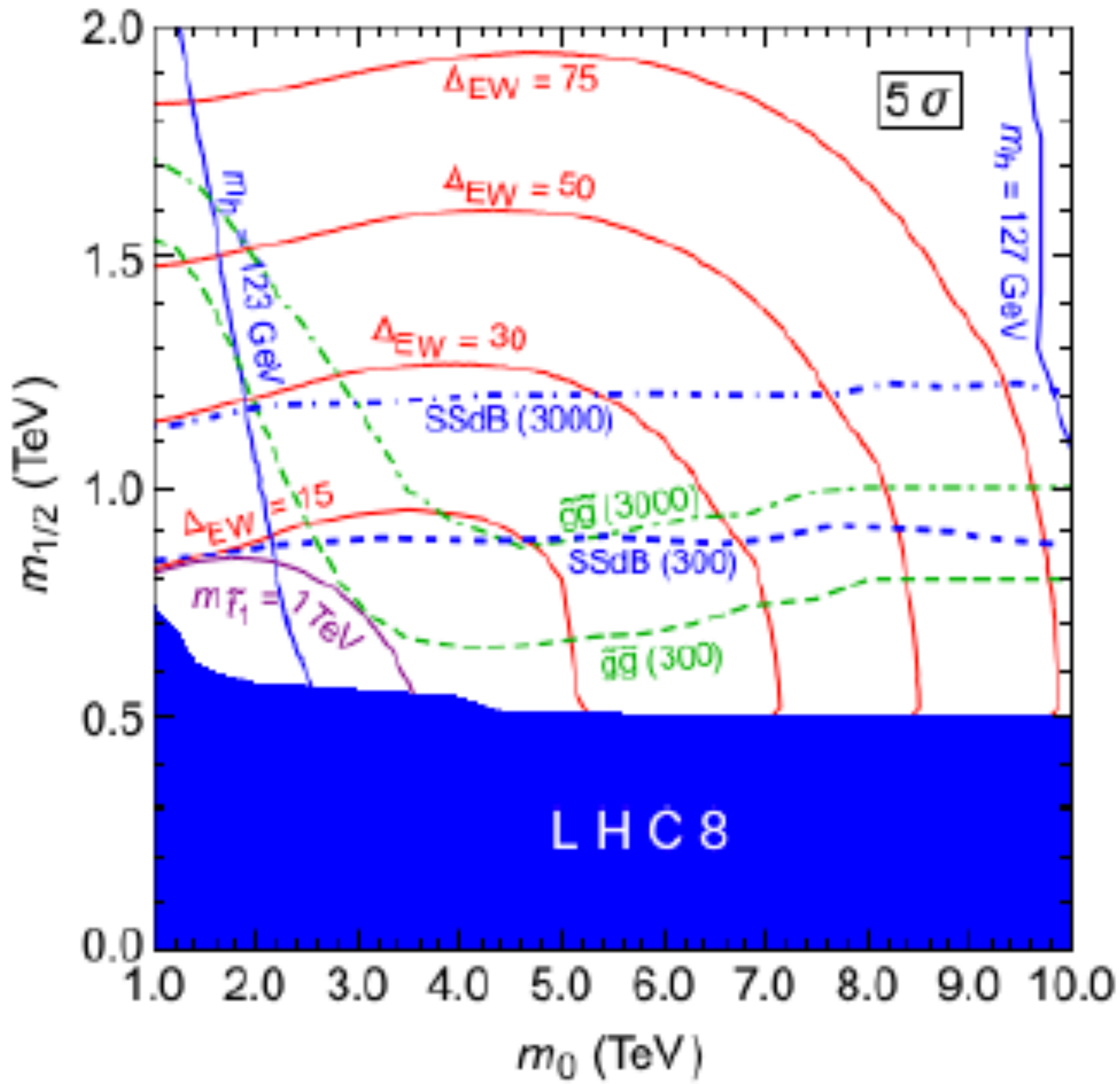
wino pair production



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

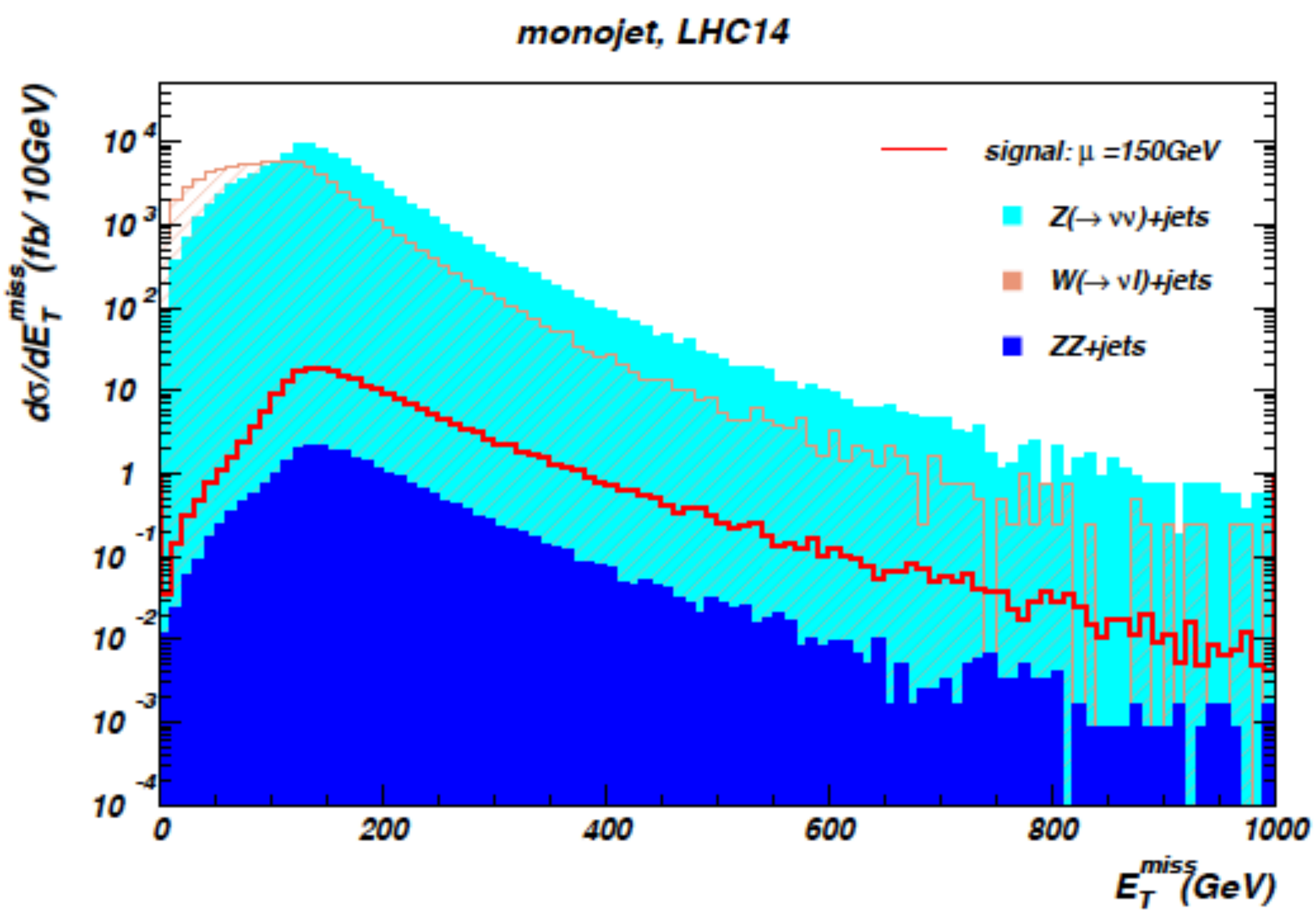
H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

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

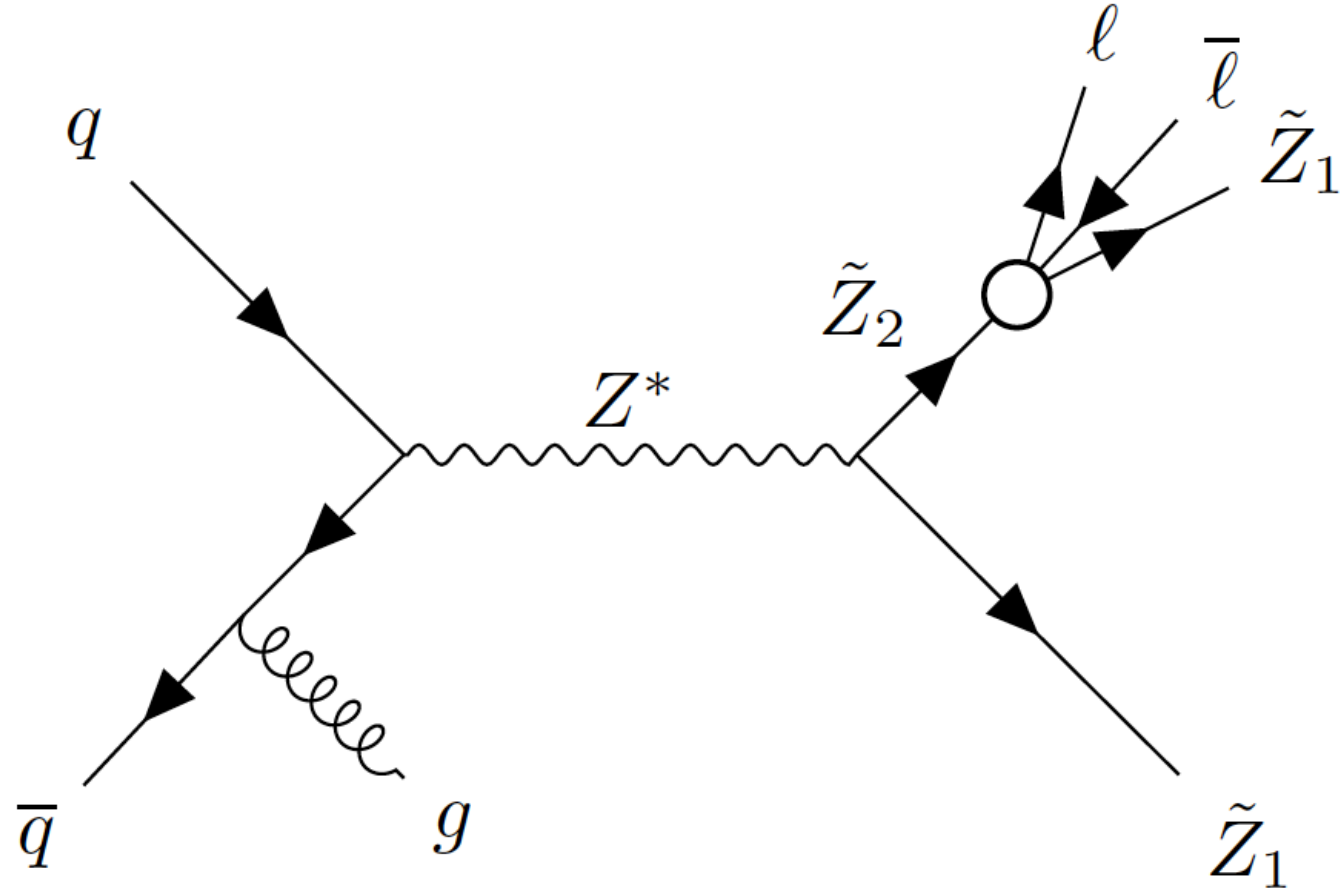
See direct higgsino pair production recoiling from ISR (monojet signal)?

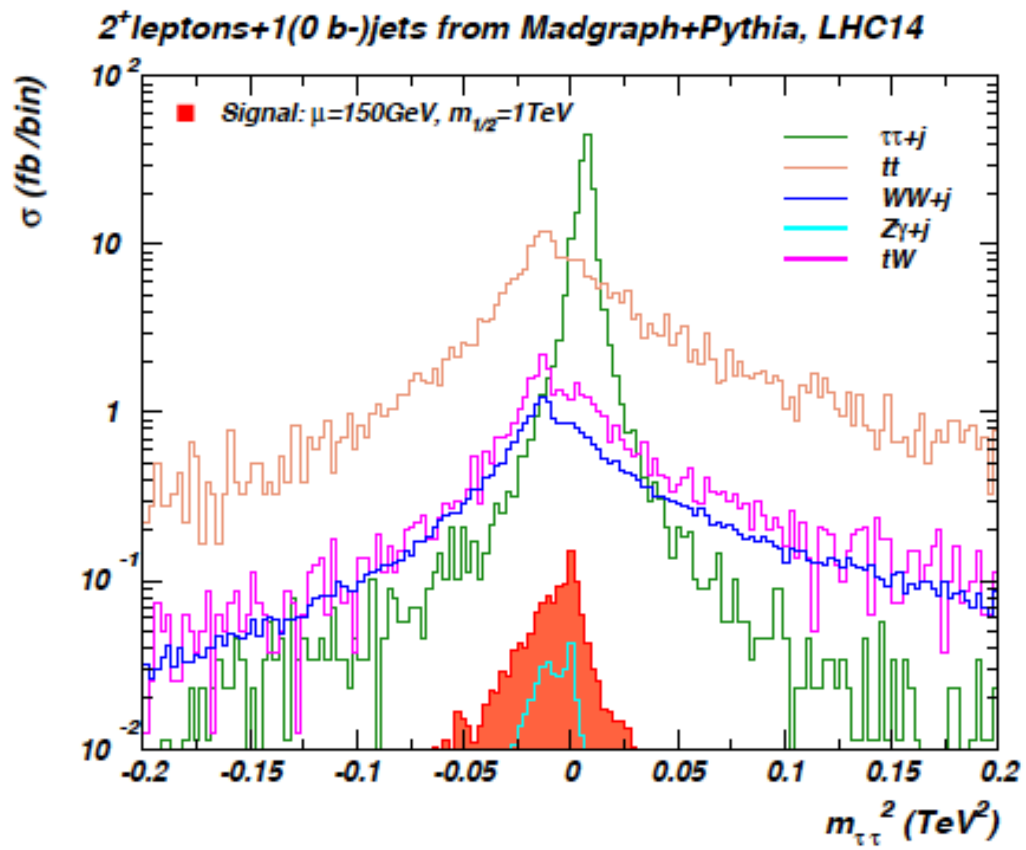


typically 1% S/BG after cuts:
very tough to do!

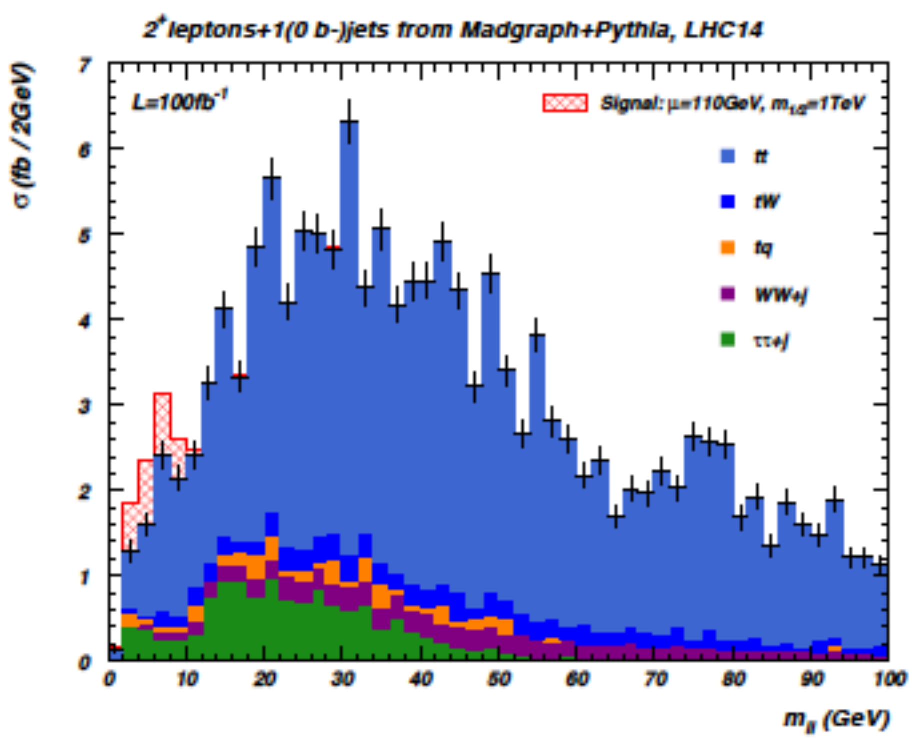
What about $pp \to \tilde{Z}_1 \tilde{Z}_2 j$ with $\tilde{Z}_2 \to \tilde{Z}_1 \ell^+ \ell^-$?

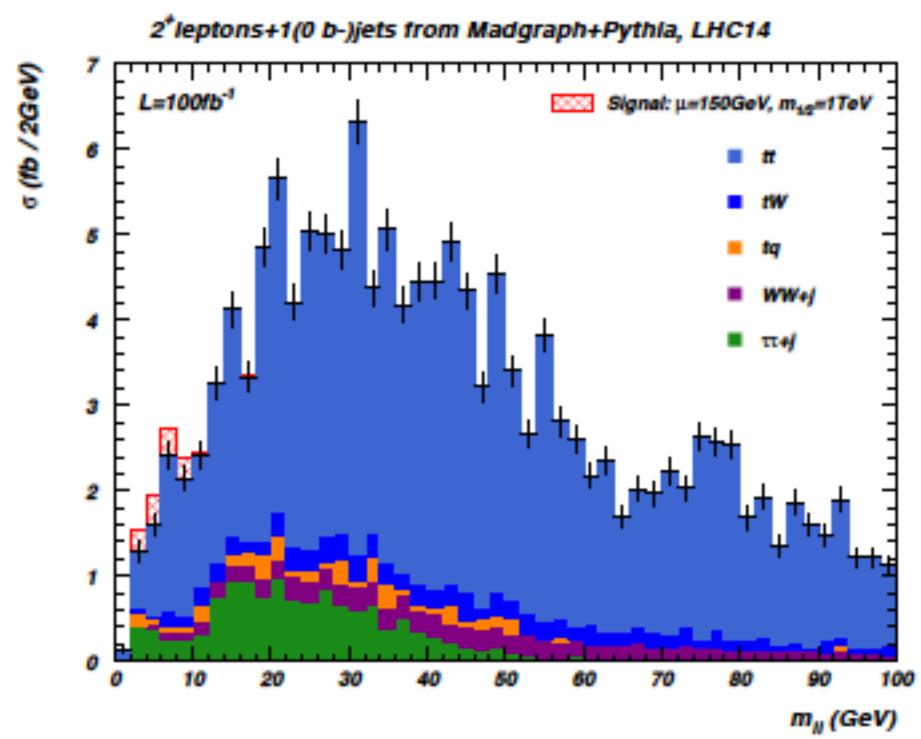
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;



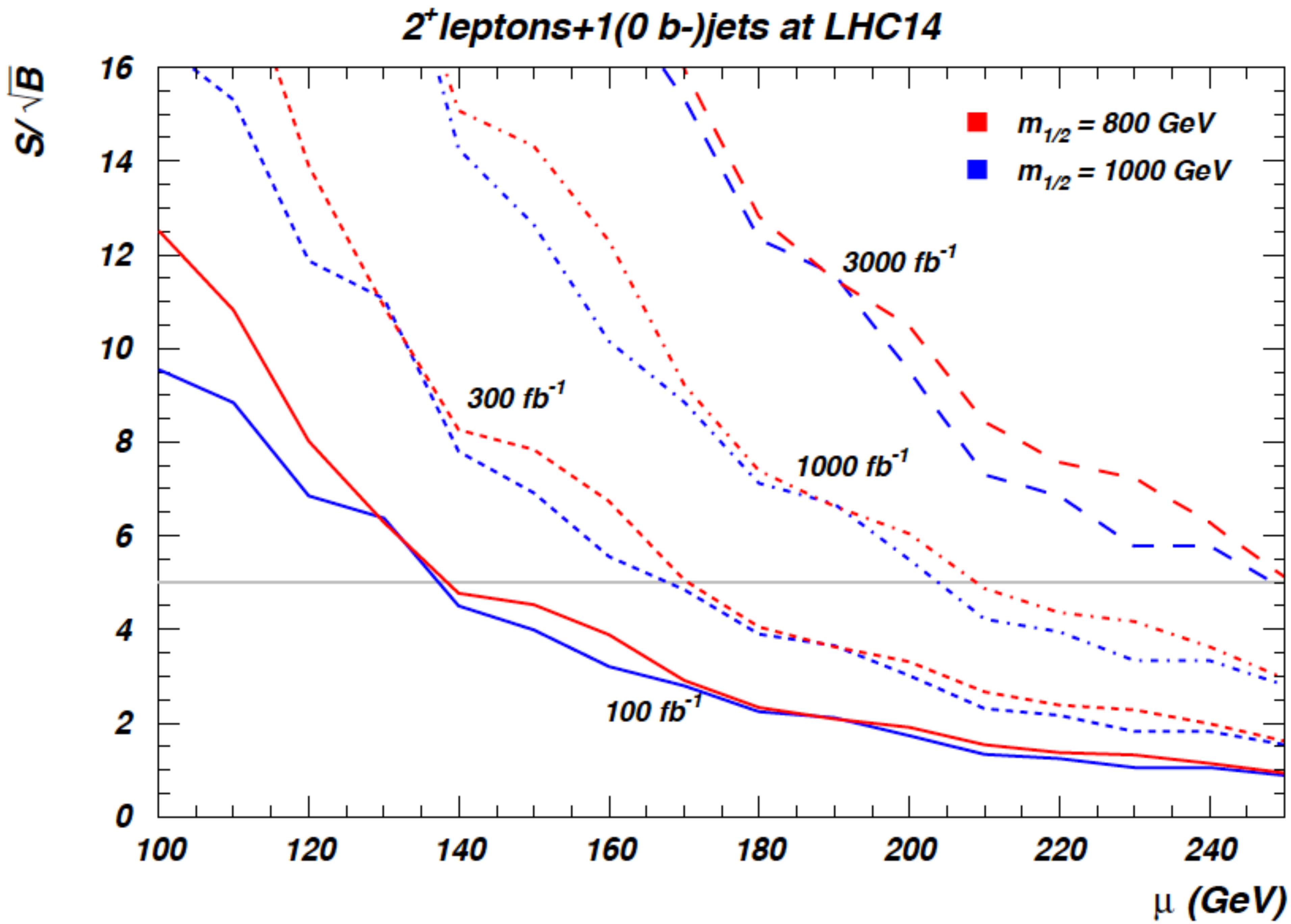


use MET to construct m^2(tau-tau)



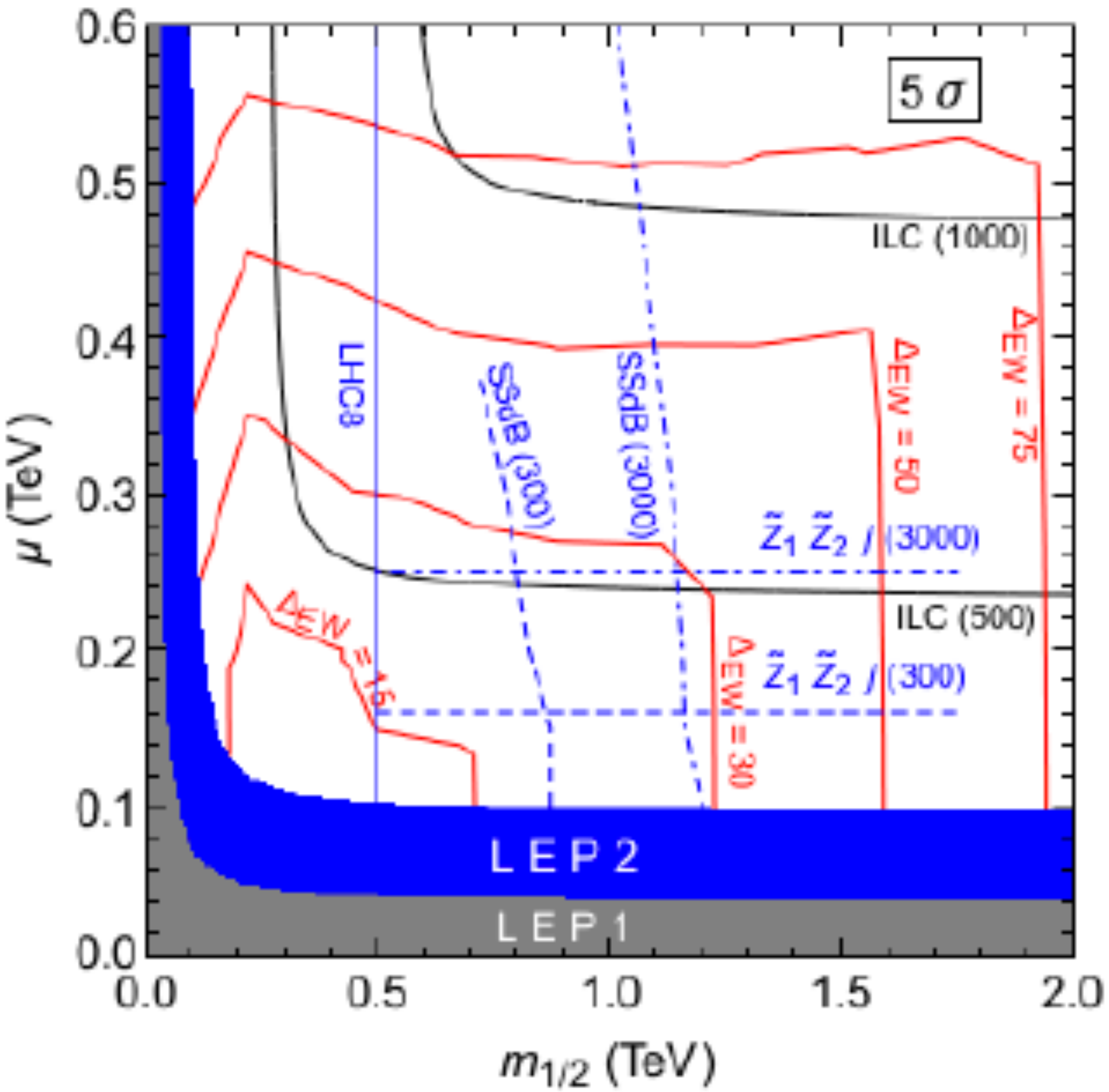


LHC reach for soft dilepton+jet+MET



HB, Mustafayev, Tata; PRD90 (2014) 115007

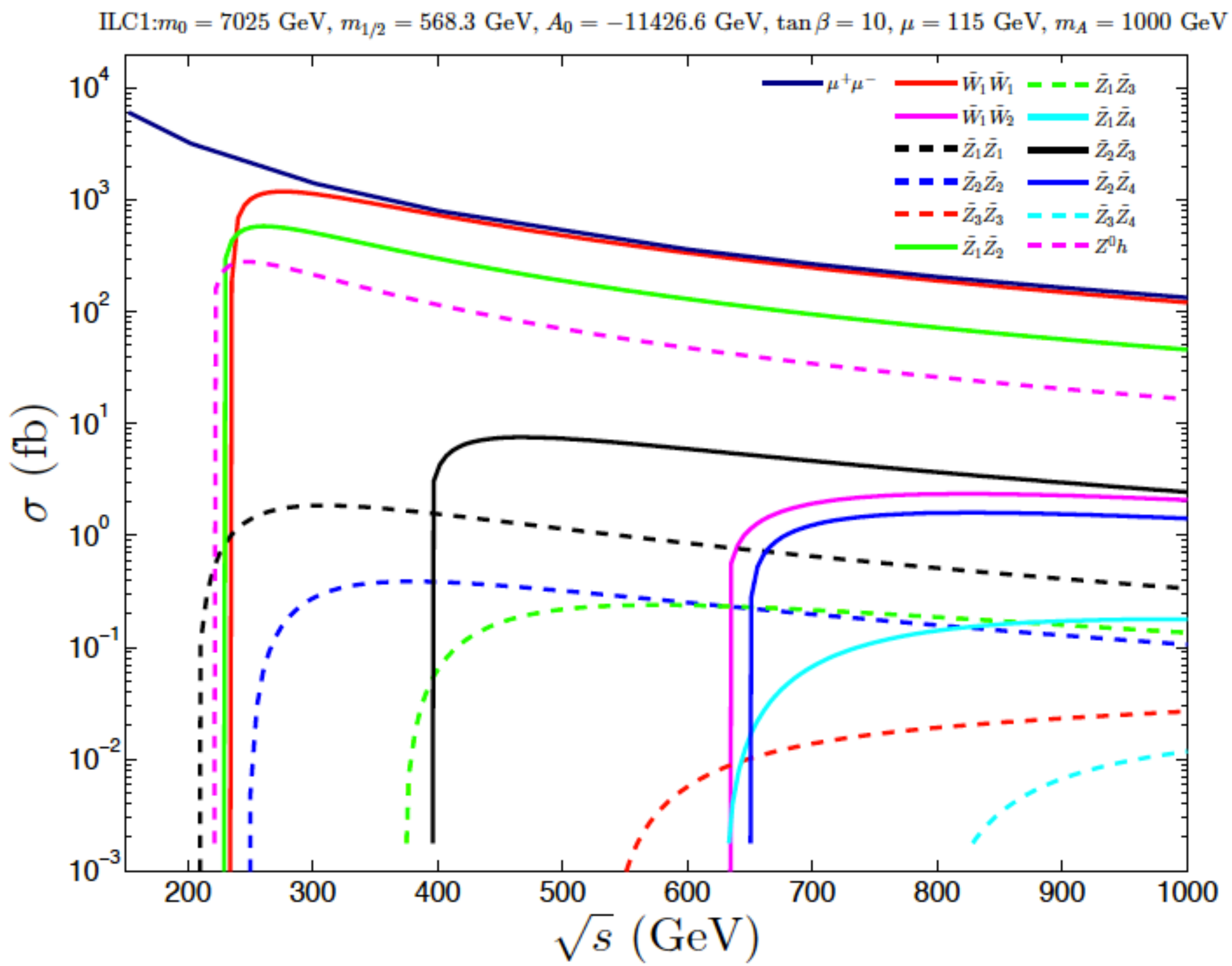
panoramic view of reach of HL-LHC for natural SUSY



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 $\tilde{Z}_1\tilde{Z}_2 j$

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



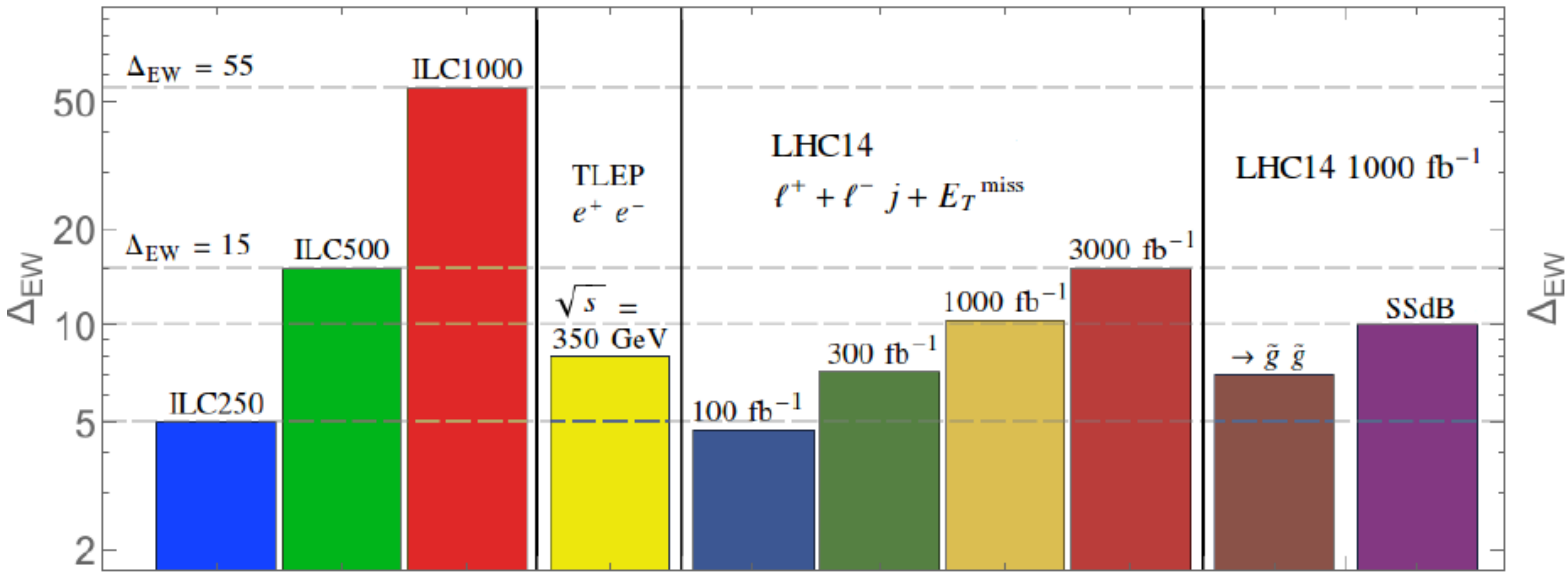
$$\sigma(higgsino) \gg \sigma(Zh)$$

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

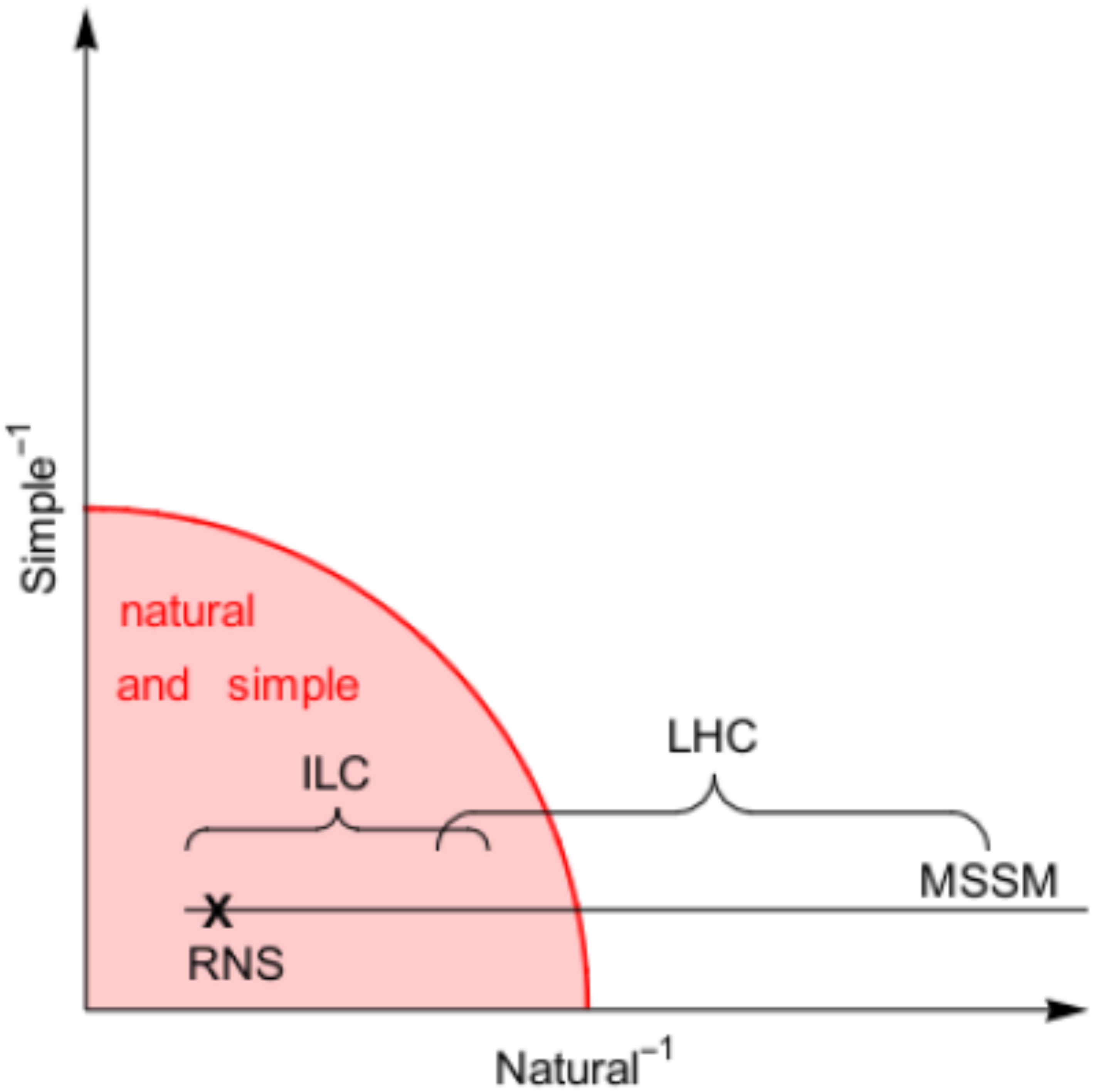


Bae, HB, Nagata, Serce

When to give up on naturalness in MSSM?
If HL-LHC or ILC(600GeV) sees no light higgsinos; WIMP at Xe-1ton/LZ

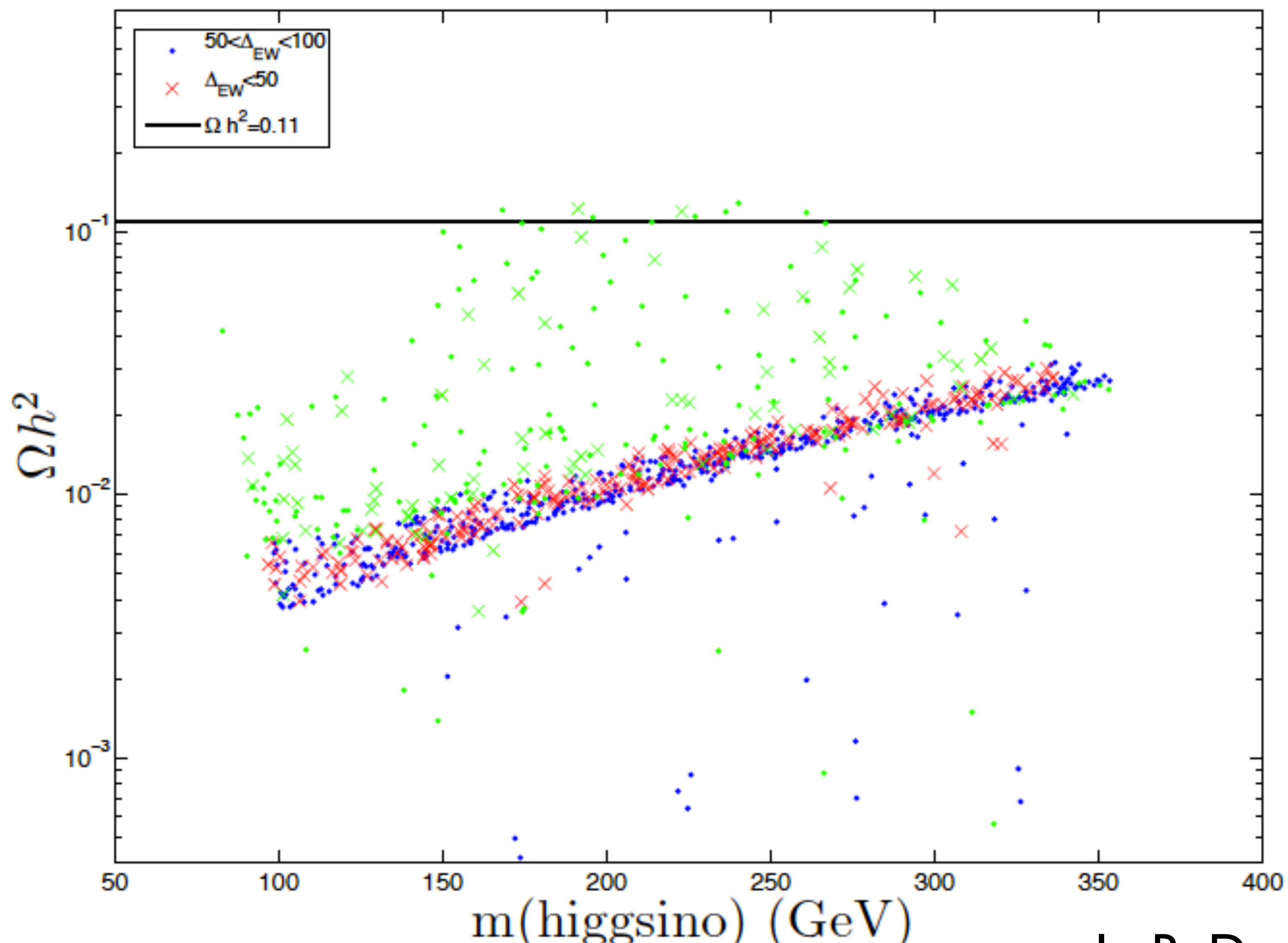
Conclusions: status of SUSY post LHC8

- 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
LHC
ILC
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)

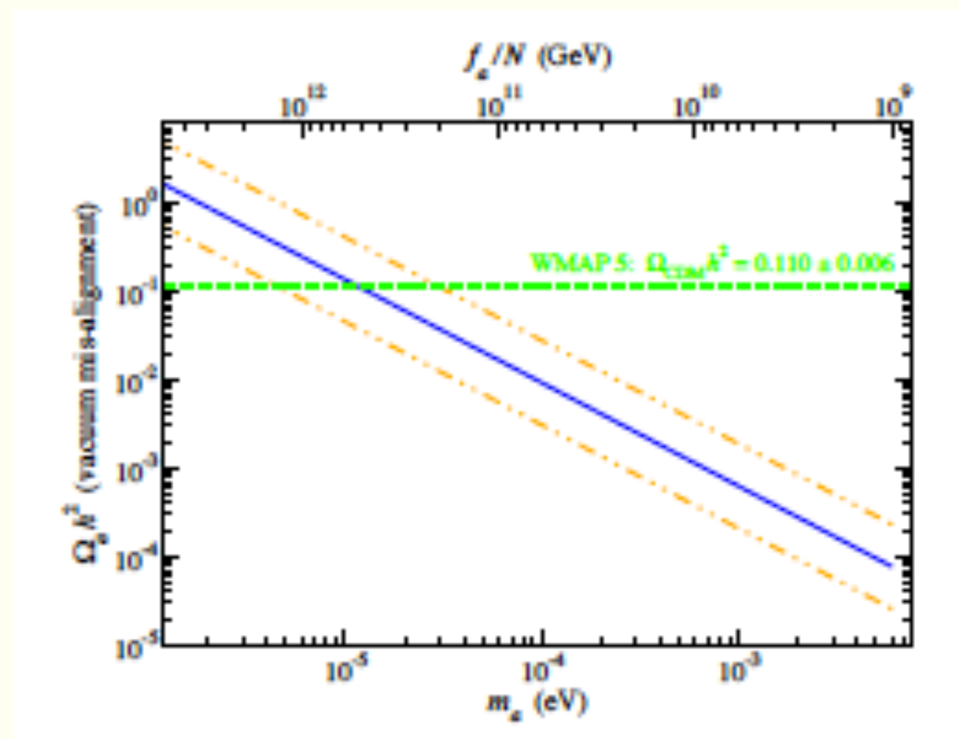
Best solution after 35 years:
PQWW/KSVZ/DFSZ invisible axion

In SUSY, axion accompanied by axino and saxion

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

Axion cosmology

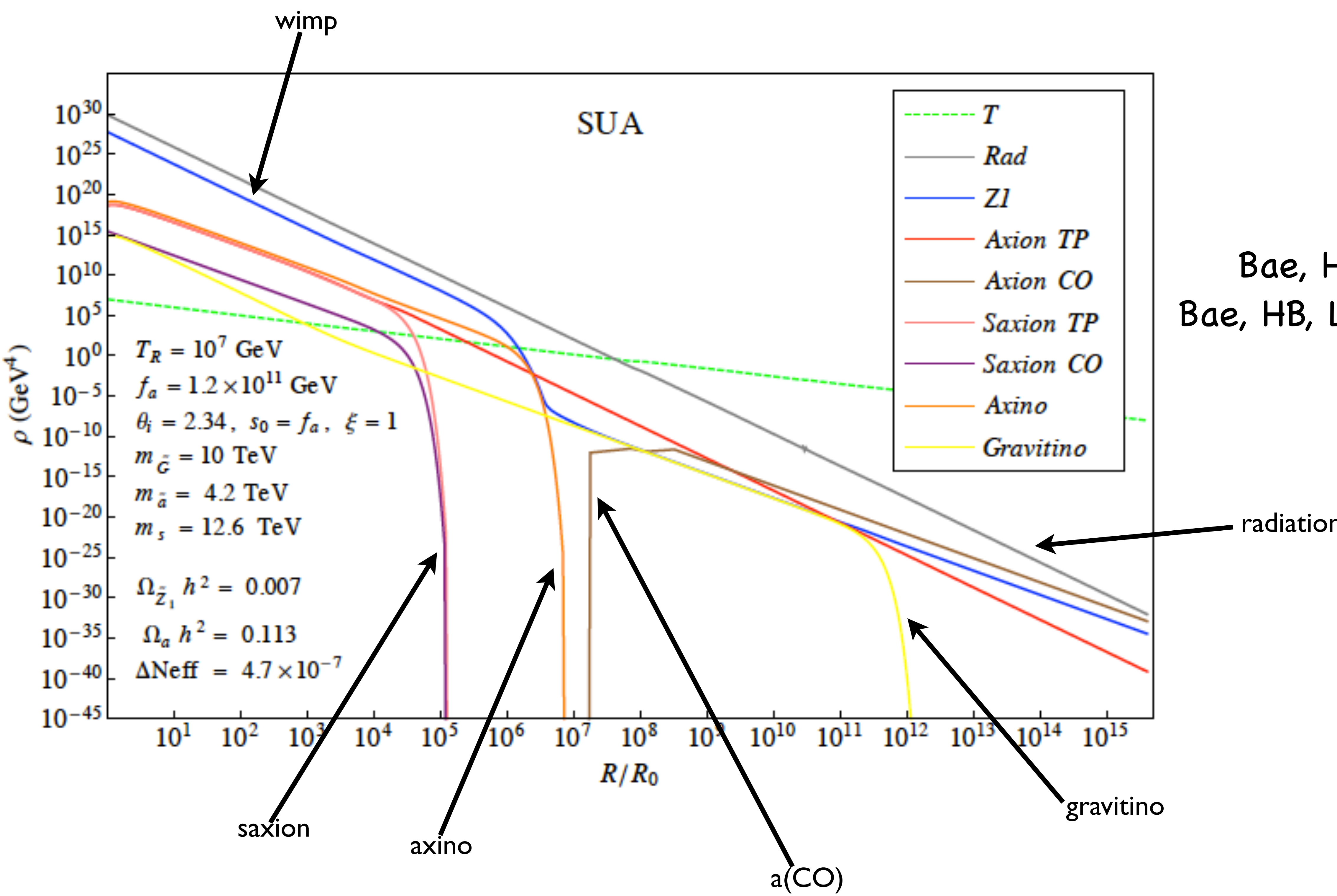
- ⋆ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$: $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ⋆ a(x)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



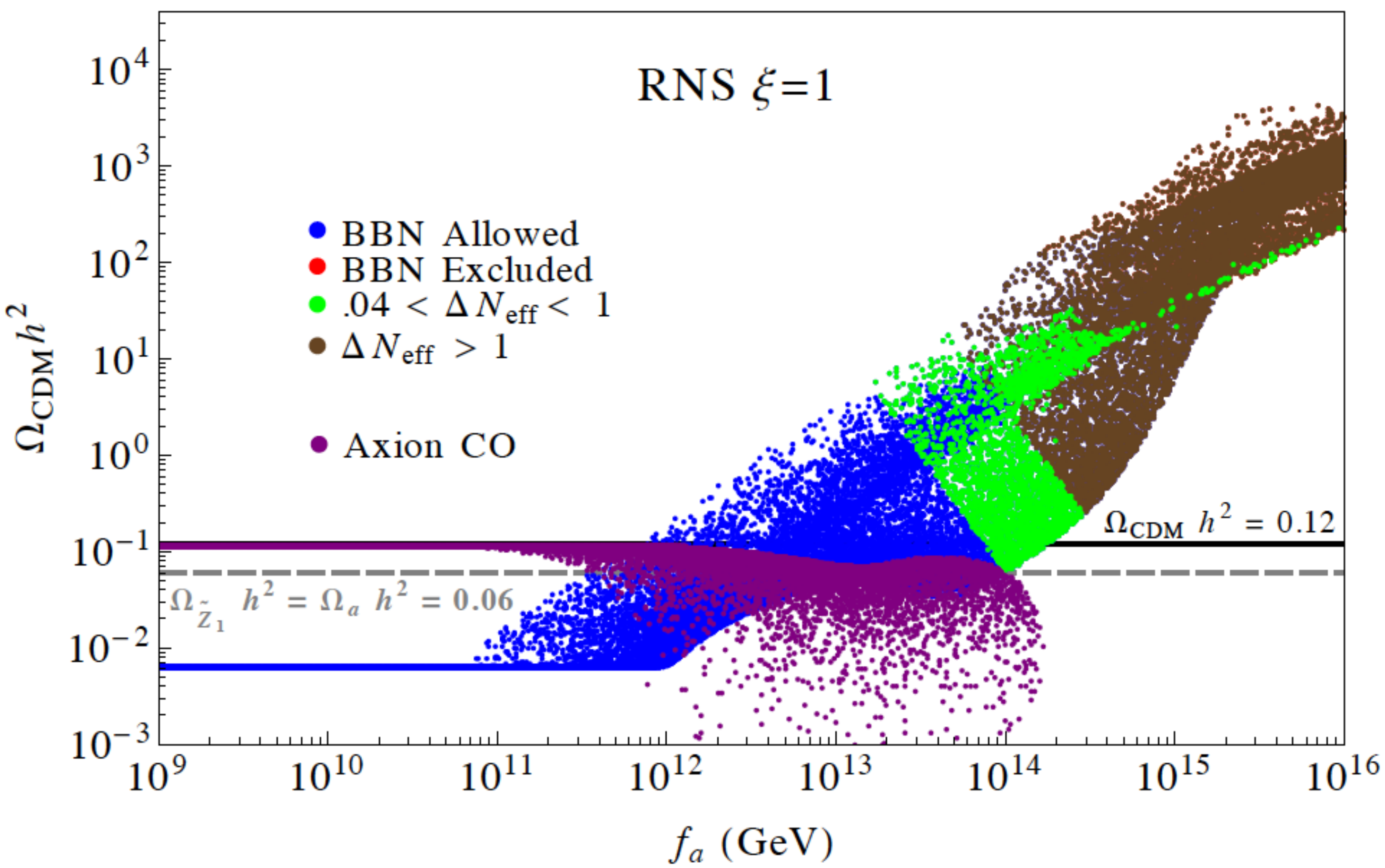
mixed axion-neutralino production in early universe

- 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

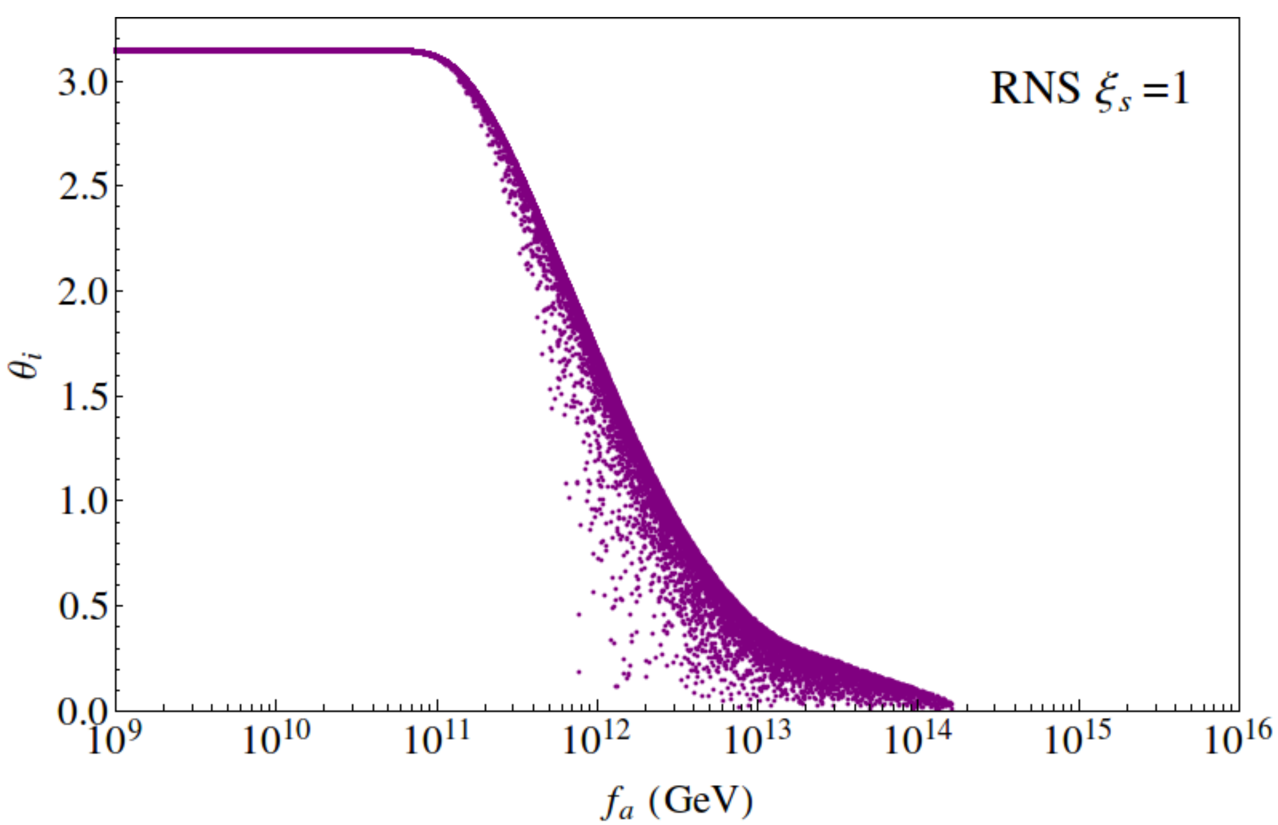


Bae, HB, Chun;
Bae, HB, Lessa, Serce



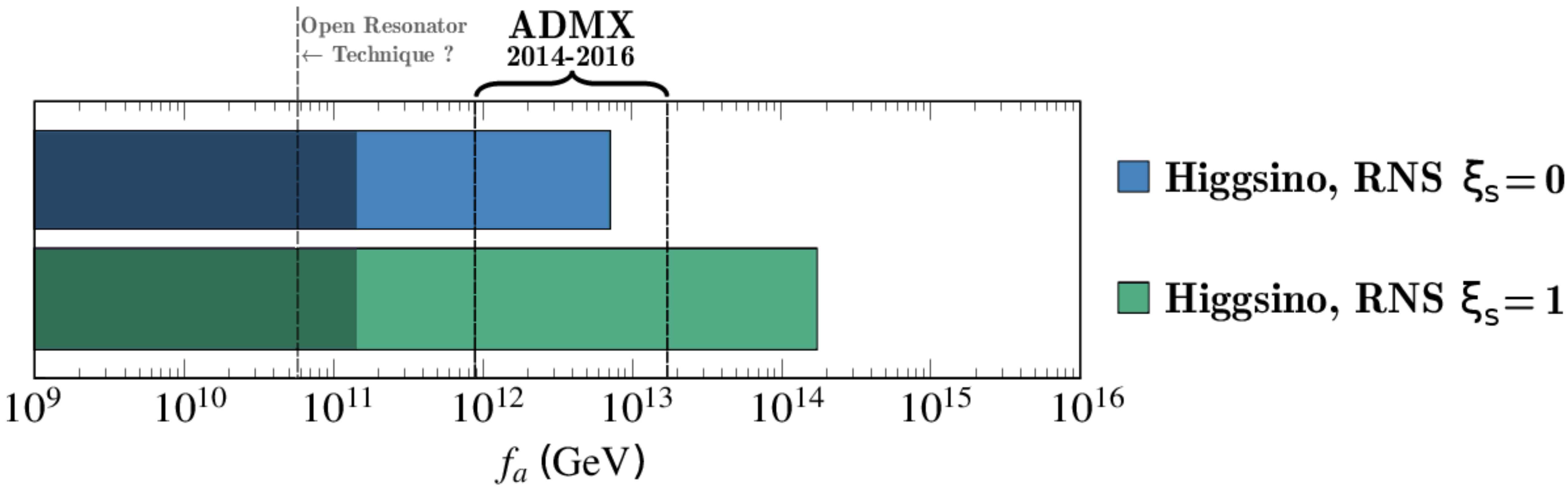
higgsino abundance

axion abundance



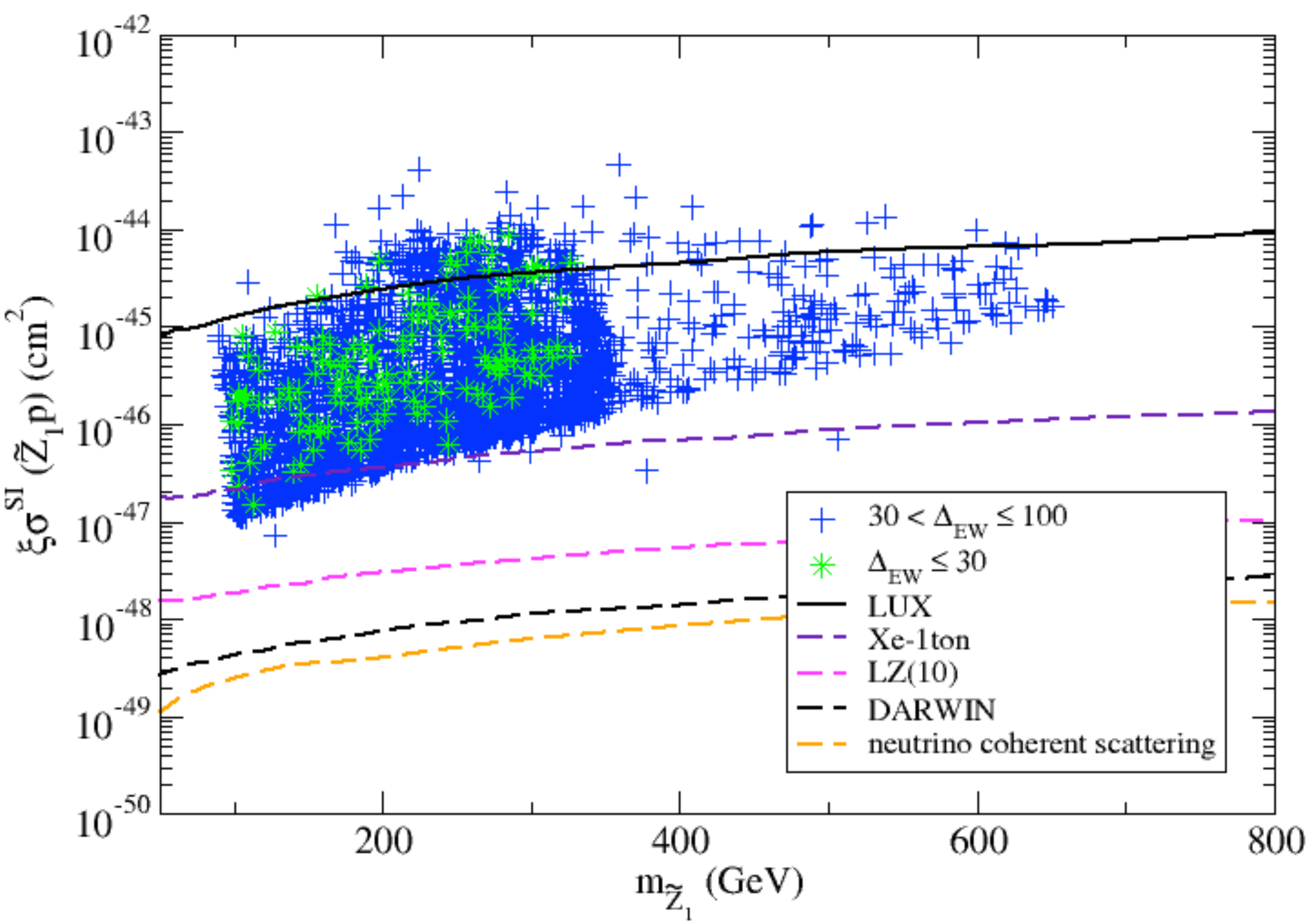
mainly axion CDM
for fa<~10^12 GeV;
for higher fa, then
get increasing wimp
abundance

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

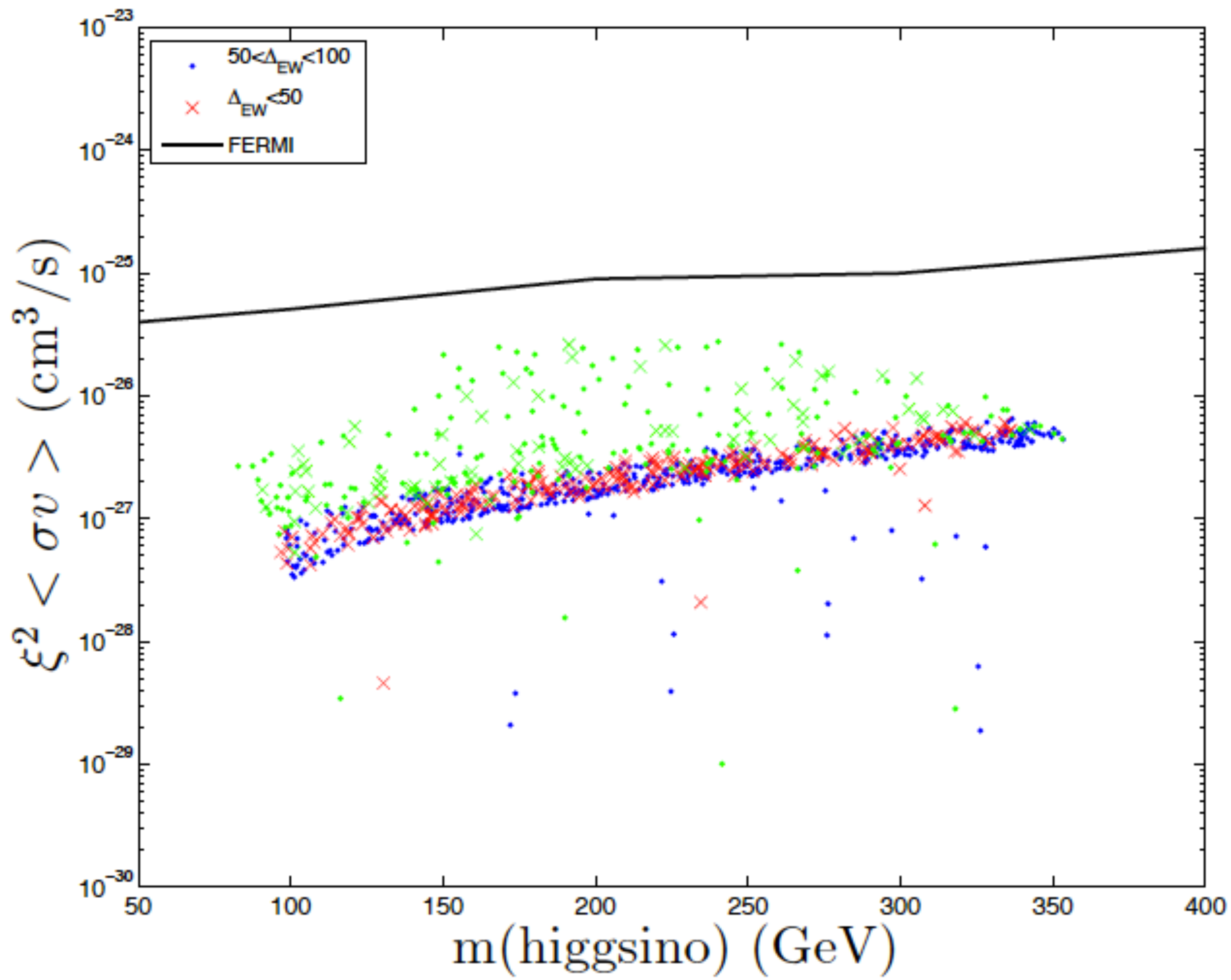
$$\mathcal{L} \ni -X^h_{11}\overline{\tilde{Z}}_1\tilde{Z}_1 h$$

$$X^h_{11} = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(gv_3^{(1)} - g'v_4^{(1)}\right)$$

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

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

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