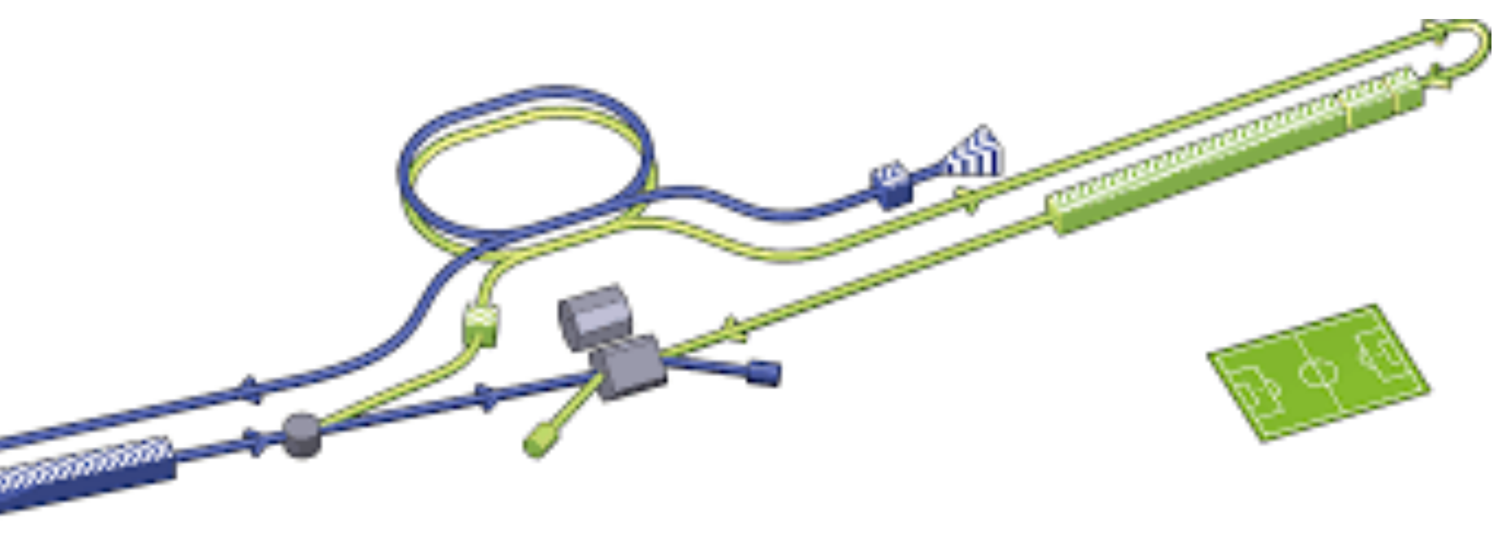
BSM perspective:
why ILC is the right machine for SUSY discovery

Howard Baer (U. of Oklahoma)

SUSY  

The SM has been brilliantly verified by a vast assortment of measurements at LHC and other experiments- but problems remain…

- neutrino mass: how? why so light?
- unification?
- strong CP problem
- Higgs mass: why so light?
- dark matter
- dark energy
- baryogenesis

First problem solved by adding in RHN

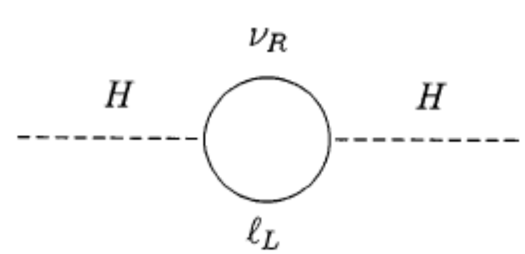
Add in three ν_{Ri} states:

$$\mathcal{L} \ni -\lambda_\nu \bar{L}_a \cdot \tilde{\phi}^a \nu_R + h.c. \qquad \tilde{\phi} = \epsilon^{ab} \phi_b^\dagger$$

ν_{Ri} singlet allows for Majorana mass M_i

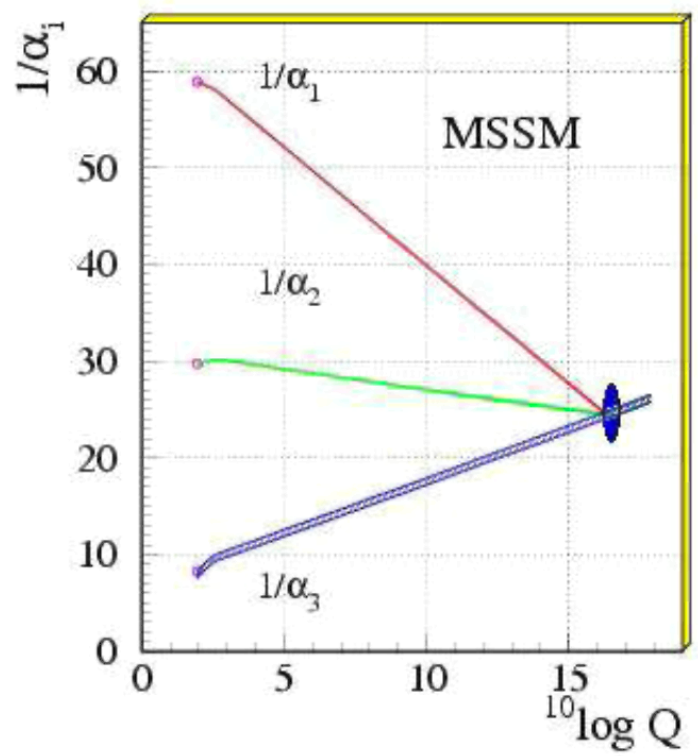
$$\mathcal{M}_\nu \equiv \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix}$$

- see-saw eigenvalues: $m_\nu \sim m_D^2/M$ and M
- for $\lambda_\nu \sim \lambda_t$, get $m_{\nu 3} \sim 0.03$ eV for $M \sim 10^{15}$ GeV
- completes 16-dim spinor of $SO(10)$: unify matter!
- BUT: Higgs mass blows up to see-saw scale!



Grand unified theories

- unify forces
- unify matter
- understand charge assignments
- Higgs mass blows up to GUT scale



Grand Unification − SO(10)			
State	Y $= \frac{2}{3}\Sigma(\mathrm{C}) - \Sigma(\mathrm{W})$	Color C spins	Weak W spins
$\bar{\nu}$	0	+ + +	+ +
$\bar{\mathbf{e}}$	2	+ + +	− −
$\mathbf{u_r}$	$\frac{1}{3}$	− + +	+ −
$\mathbf{d_r}$		− + +	− +
$\mathbf{u_b}$		+ − +	+ −
$\mathbf{d_b}$		+ − +	− +
$\mathbf{u_y}$		+ + −	+ −
$\mathbf{d_y}$		+ + −	− +
$\bar{\mathbf{u}}_\mathbf{r}$	$-\frac{4}{3}$	+ − −	+ +
$\bar{\mathbf{u}}_\mathbf{b}$		− + −	+ +
$\bar{\mathbf{u}}_\mathbf{y}$		− − +	+ +
$\bar{\mathbf{d}}_\mathbf{r}$	$\frac{2}{3}$	+ − −	− −
$\bar{\mathbf{d}}_\mathbf{b}$		− + −	− −
$\bar{\mathbf{d}}_\mathbf{y}$		− − +	− −
ν	−1	− − −	+ −
$\mathbf{e}$		− − −	− +

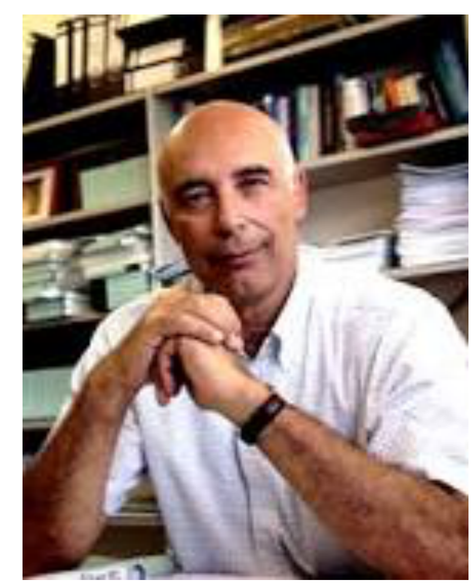
strong CP problem

- QCD: U(2)xU(2) chiral symmetry: isospin, baryon# and 4 light pions?
- ‘tHooft: theta vacuum=> 3 pions but $\mathcal{L} \ni \frac{\alpha_s \bar{\theta}}{8\pi} G_{\mu\nu A} \tilde{G}^{\mu\nu}_A$
- but neutron EDM: $\bar{\theta} < 10^{-10}$
- PQ symmetry: solves but get PQWW axion
- invisible axion (KSVZ/DFSZ): PQ scale $f_a \sim 10^{10} - 10^{12}\ \mathrm{GeV}$
- models like DFSZ: improved by SUSY <=> PQ !

Tame m(Higgs) via SUSY

- extend spacetime symmetries: Poincare -> superPoincare
- fields -> superfields
- SM -> MSSM
- local SUSY: gravity -> supergravity
- soft SUSY breaking terms arise e.g. from SUGRA breaking
- SUSY preserving mu parameter
- SM particles -> superpartners

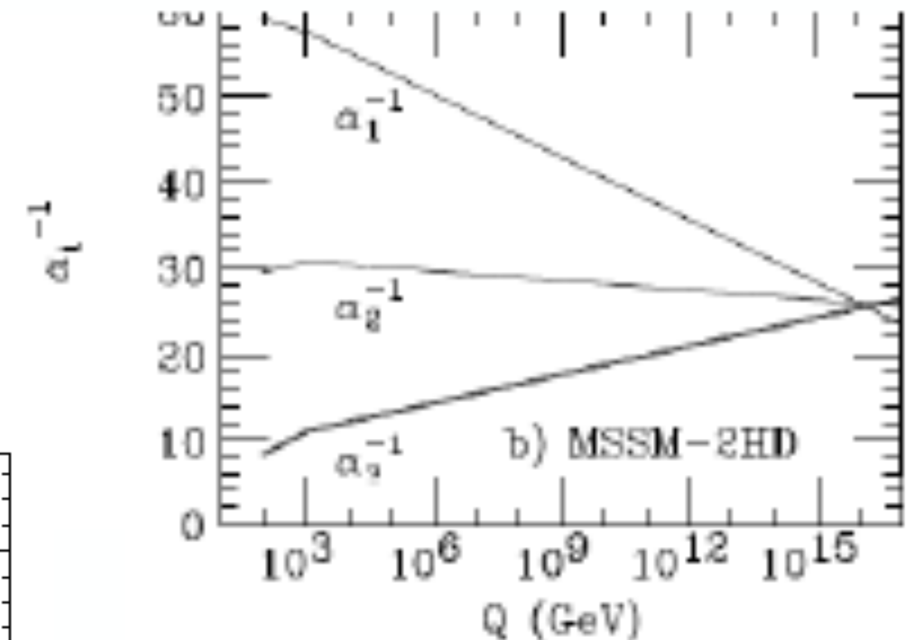
All we know about neutrino masses is well in harmony with the idea and the mass scale of GUT's. As a consequence neutrino masses have added phenomenological support to this beautiful idea and to the models of physics beyond the Standard Model that are compatible with it. In particular, if we consider the main classes of new physics that are currently contemplated, like supersymmetry, technicolour, large extra dimensions at the TeV scale, little Higgs models etc, it is clear that the first one is the most directly related to GUT's. SUSY offers a well defined model computable up to the GUT scale and is actually supported by the quantitative success of coupling unification in SUSY GUT's. For the other examples quoted all contact with GUT's is lost or at least is much more remote. In this sense neutrino masses fit particularly well in the SUSY picture that sofar remains the standard way beyond the Standard Model.

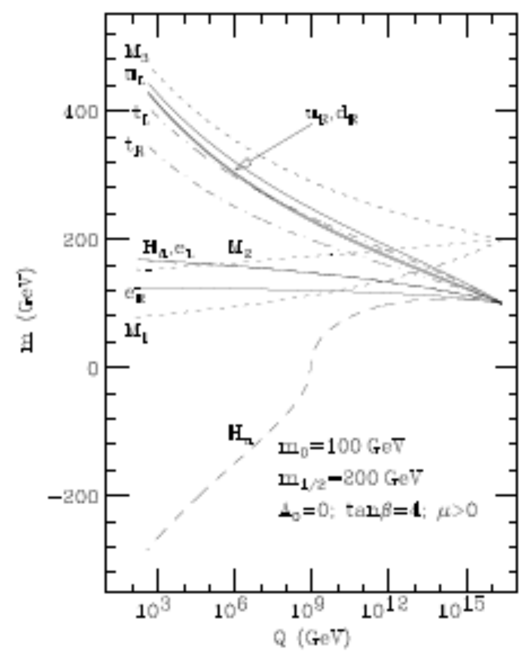


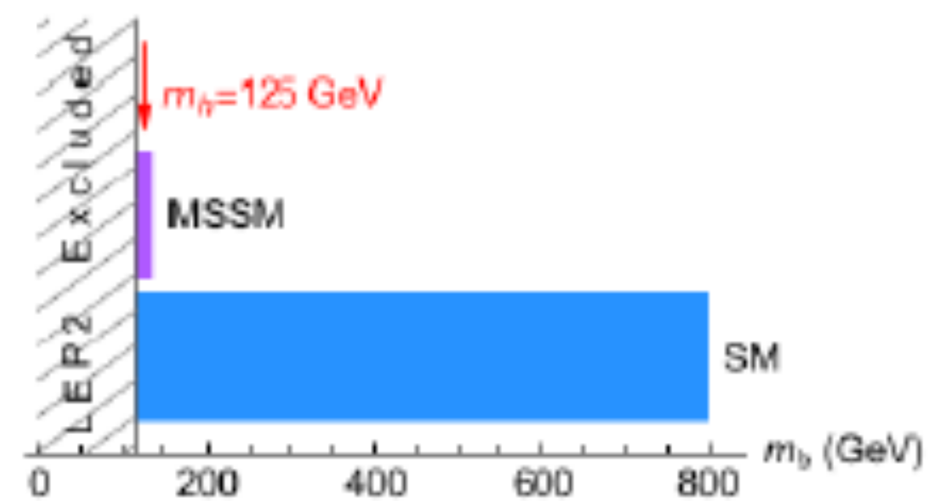
Guido Altarelli
1941-2015

MSSM actually supported (indirectly) via data!

- stabilize Higgs mass
- measured gauge couplings
- m(t)~173 GeV for REWSB
- mh(125): squarely within SUSY window



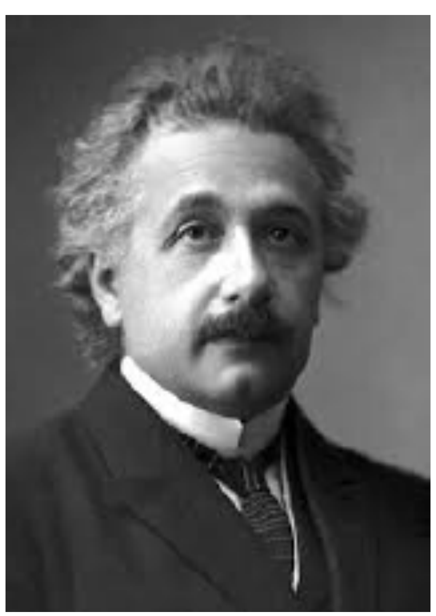




Motivation: simplicity and naturalness

``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

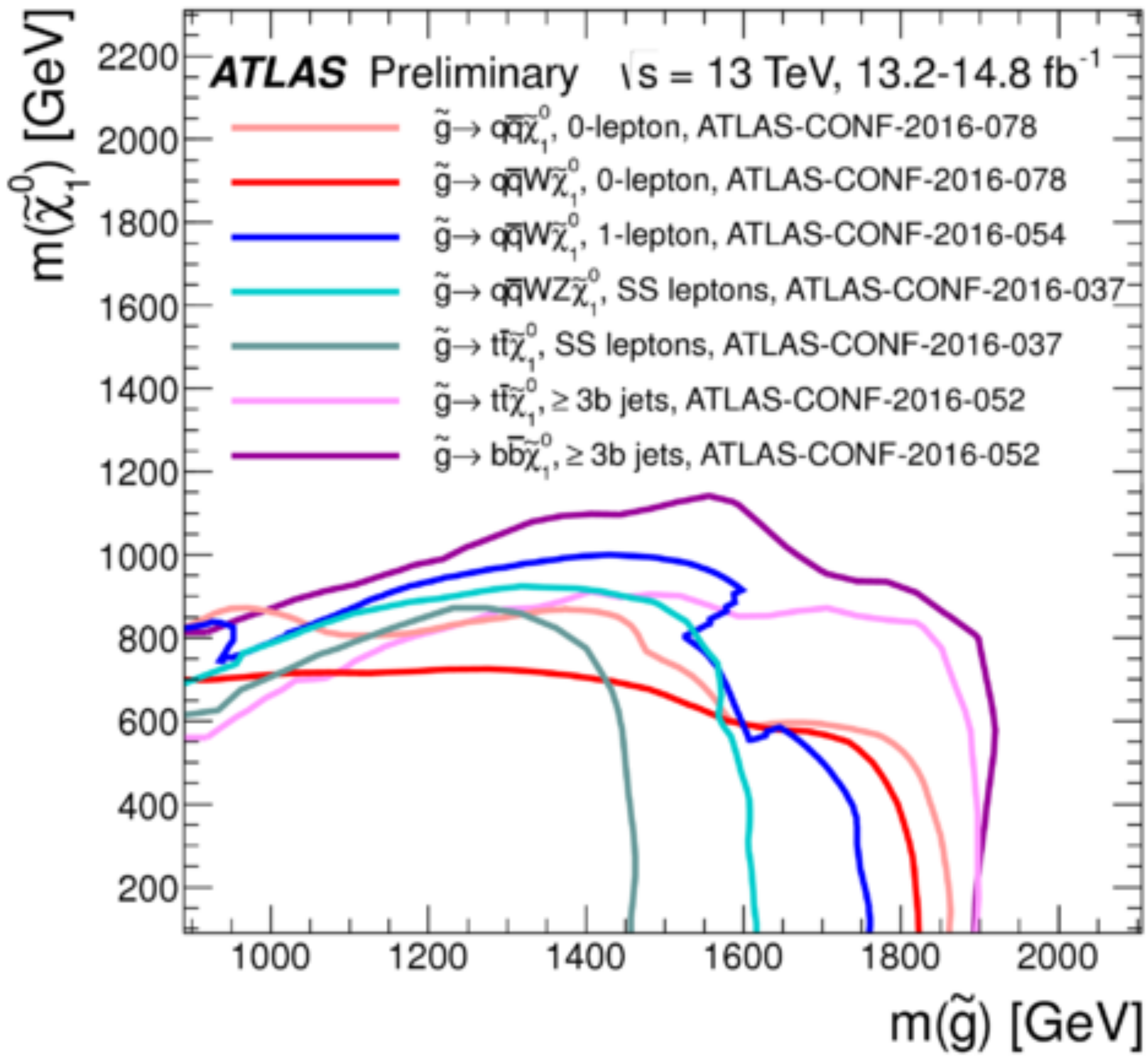


``Everything should be made as simple as possible, but not simpler"

A. Einstein

But where are the sparticles?

recent search results from Atlas run 2 @ 13 TeV:



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

compare BG(1987) $\Delta_{BG} < 10$ bound: $m_{\tilde{g}} < 210$ GeV

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

In the past several years, the notion of electroweak naturalness in SUSY has been clarified:

Most direct expression within MSSM:
minimize scalar potential to determine VeVs:
relate measured value of m(Z) to SUSY Lagrangian

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

weak scale soft term:

radiative corrections: biggest from t1,t2

SUSY conserving mu term

no large unnatural cancellations:
all terms on RHS are <~100-200 GeV

$$\Delta_{\rm EW} \equiv \max|\text{each additive term on RHS}\ |/(m_Z^2/2)$$

Obligatory diatribe on large logs and light stops

It is common to see fine-tuning (wrongly)
expressed in the form

$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2} m_{\tilde{t}_1}^2 \ln\left(\Lambda/m_{SUSY}\right)$$

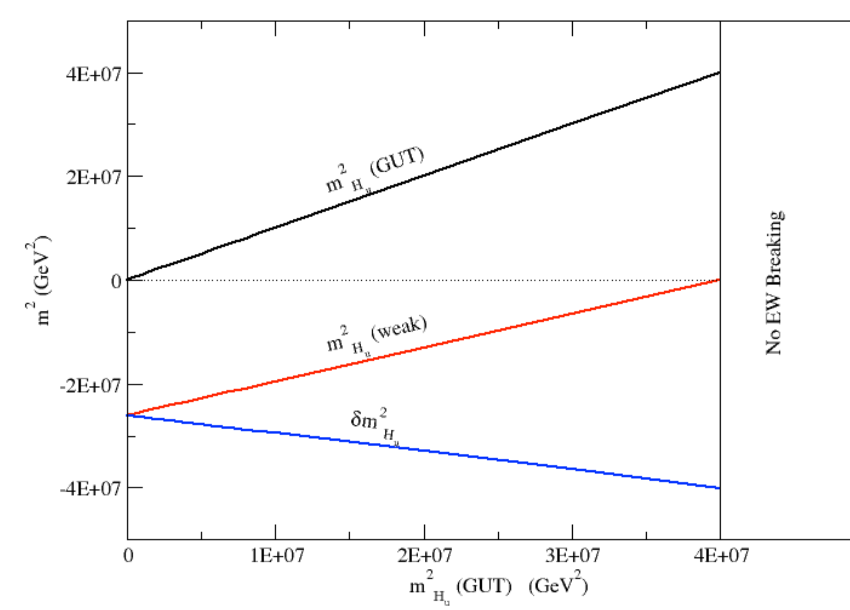
which, if true, would imply light stops required by natural SUSY

In fact, there are a variety of intertwined log divergences contributing to $\delta m_{H_u}^2$ and they should be properly evaluated using the RGE:

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

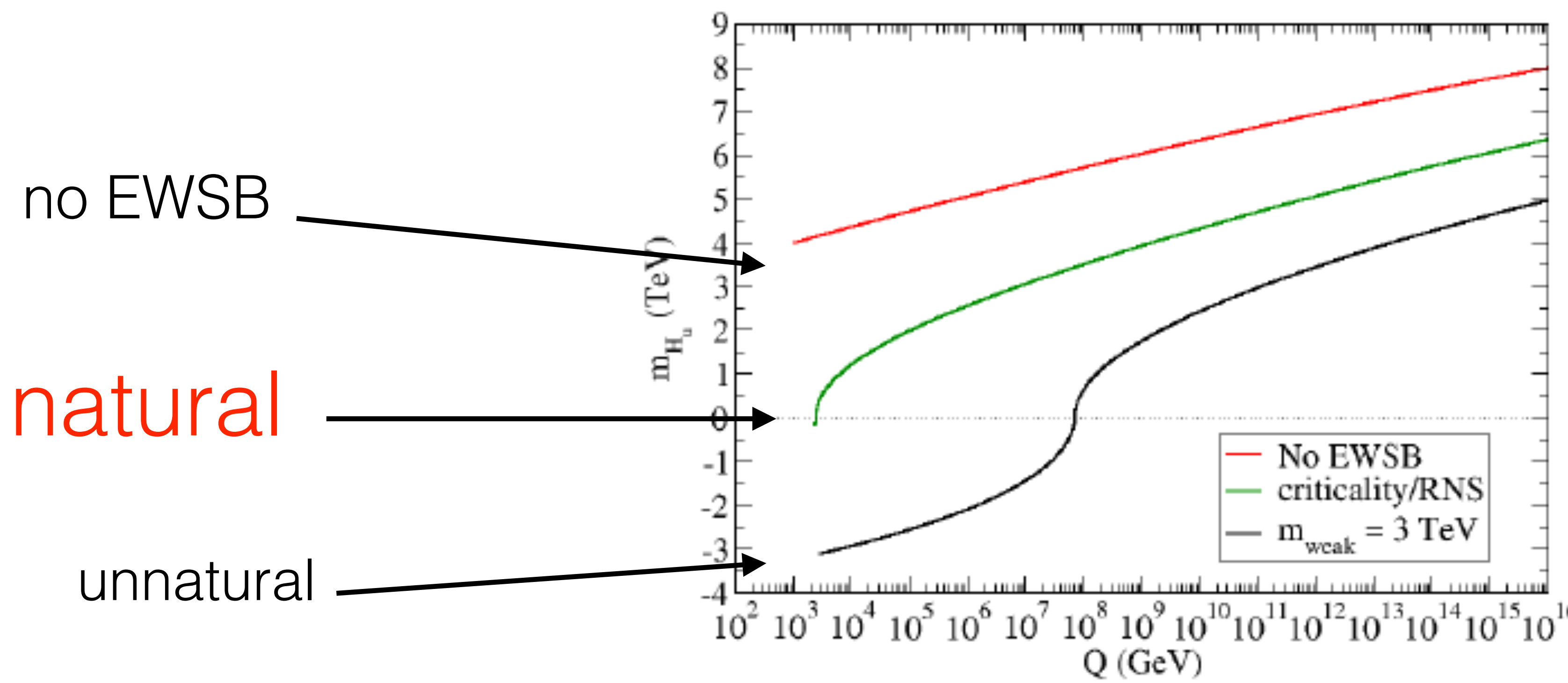
By properly including the self-contribution of $m_{H_u}^2$ to its own running, then one finds that the bigger $m_{H_u}^2(\Lambda)$ becomes, then the bigger is the canceling correction $\delta m_{H_u}^2$.

Then, large soft terms (as required by LHC limits) actually drive $m_{H_u}^2$ from large, unnatural values at high scale Λ to natural values $\sim -m_Z^2$ at the weak scale: radiatively-driven naturalness



light stops NOT required for naturalness;
this folklore has done tremendous damage to the field

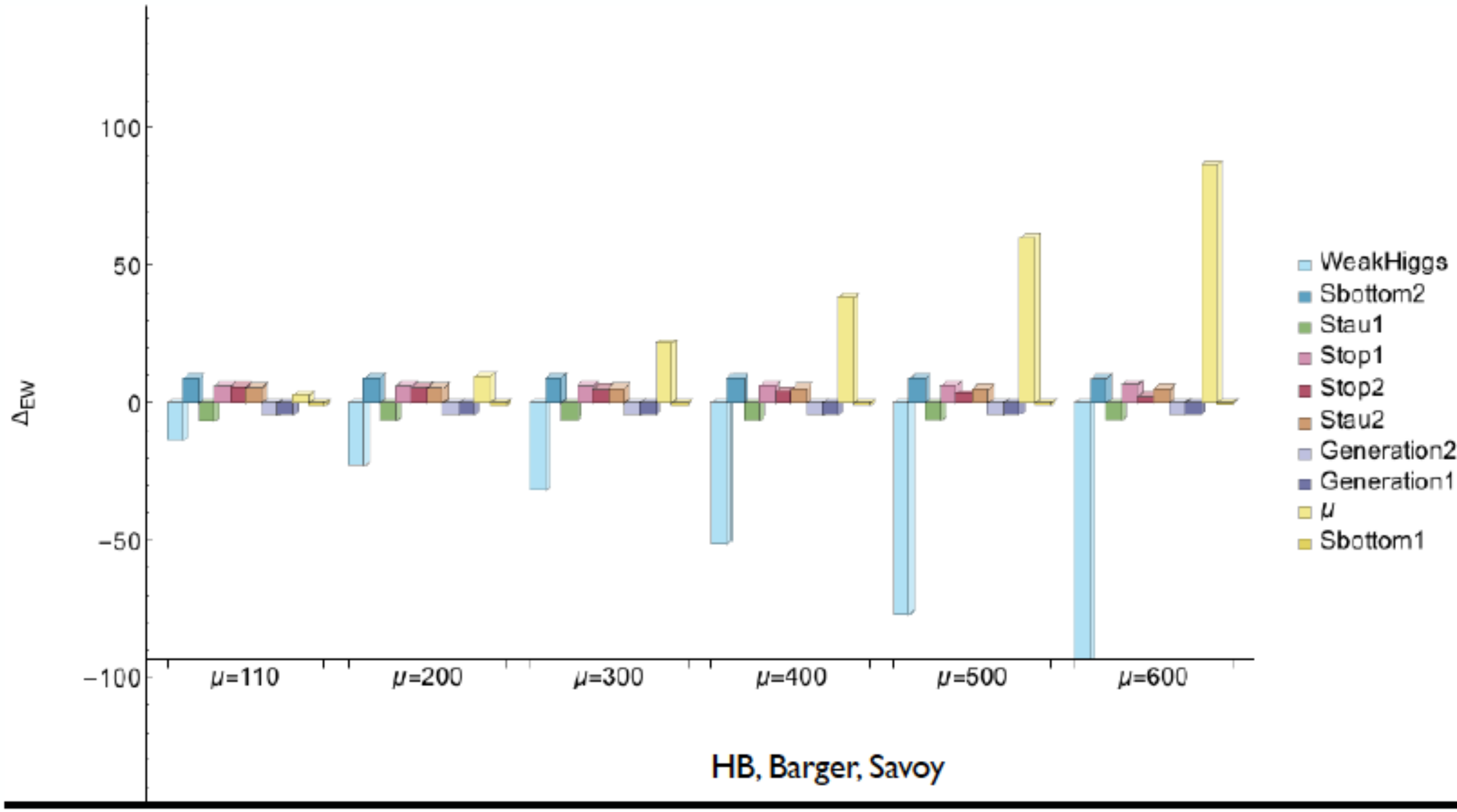
m_{H_u} : may be large ($\sim m_{3/2} \sim$ multi-TeV) at GUT scale but driven to natural values by radiative corrections at weak scale:
radiatively-driven naturalness) or RNS



$\Sigma_u^u(\tilde{t}_{1,2})$: small for TeV-scale highly mixed stops;
$m_{\tilde{g}} <\sim 4$ TeV ($\tilde{g}$ beyond LHC reach?)

SUSY μ term: feeds mass to W, Z, h and higgsinos:
higgsinos $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_{1,2}^0 \sim 100 - 200$ GeV!
soft decay products (due to small mass gaps) hard to see at LHC
but easy to see at ILC with $\sqrt{s} > 2m(higgsino)$

How much is too much fine-tuning?



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

higgsinos should be accessible to ILC!

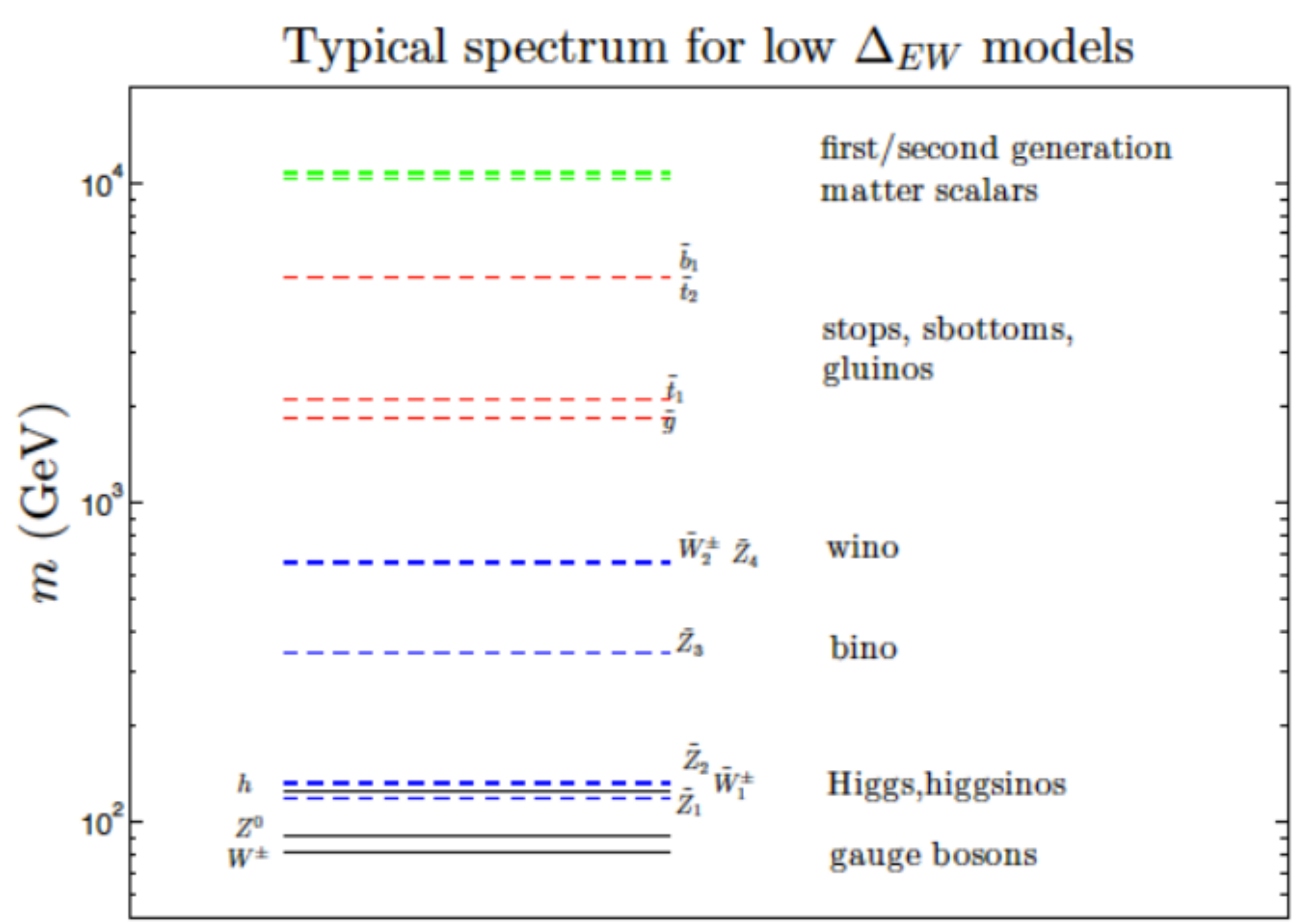
a natural SUSY spectrum

only higgsinos need lie near ~100 GeV scale

stops, gluinos can safely lie ~1-4 TeV scale

at little cost to naturalness:

contributions suppressed by loop factors

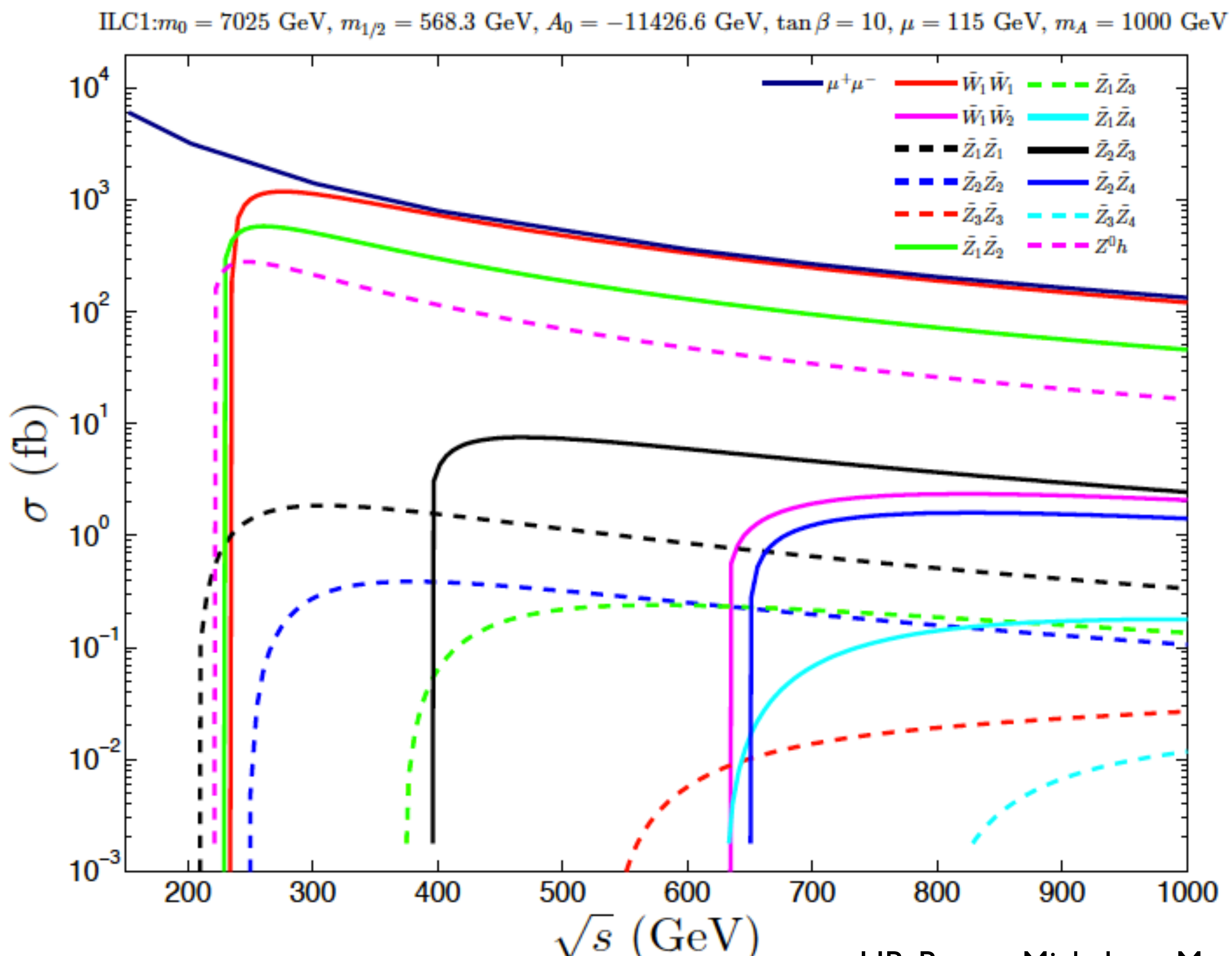


There is a Little Hierarchy, but it is no problem

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

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

see talks Thursday:
Jackie Yan
Suvi-Leena Lehtinen

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

ILC either sees light higgsinos or MSSM dead

What happened to old measures?

BG/DG measure $\Delta_{BG} \equiv max_i|\frac{\partial \ln m_Z^2}{\partial \ln p_i}|$ evaluated within multi-parameter effective theories which neglect large cancellations due to soft terms being all correlated in more fundamental theory

Large-log measure neglects $m_{H_u}^2$ self-contribution to its own running; by including then large, unnatural $m_{H_u}^2(m_{GUT})$ runs to natural values $\sim -m_Z^2$ at weak scale

By combining dependent contributions to Δ, then both large-log and Δ_{BG} reduce to $\sim \Delta_{EW}$

bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	350 GeV
gluino	400-600 GeV	4000 GeV
t1	450 GeV	3000 GeV
sq/sl	550-700 GeV	10-20 TeV

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

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)

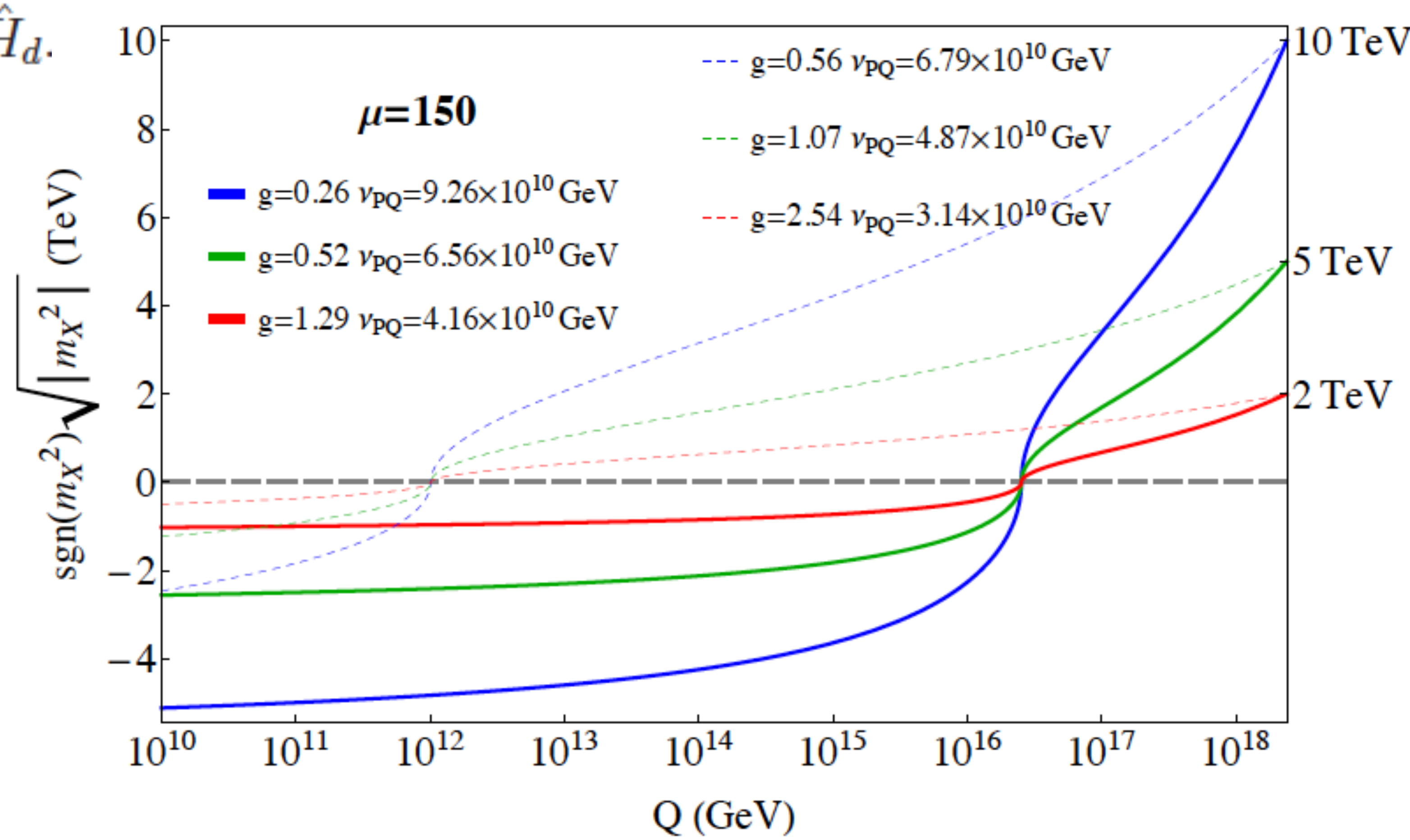
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

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

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

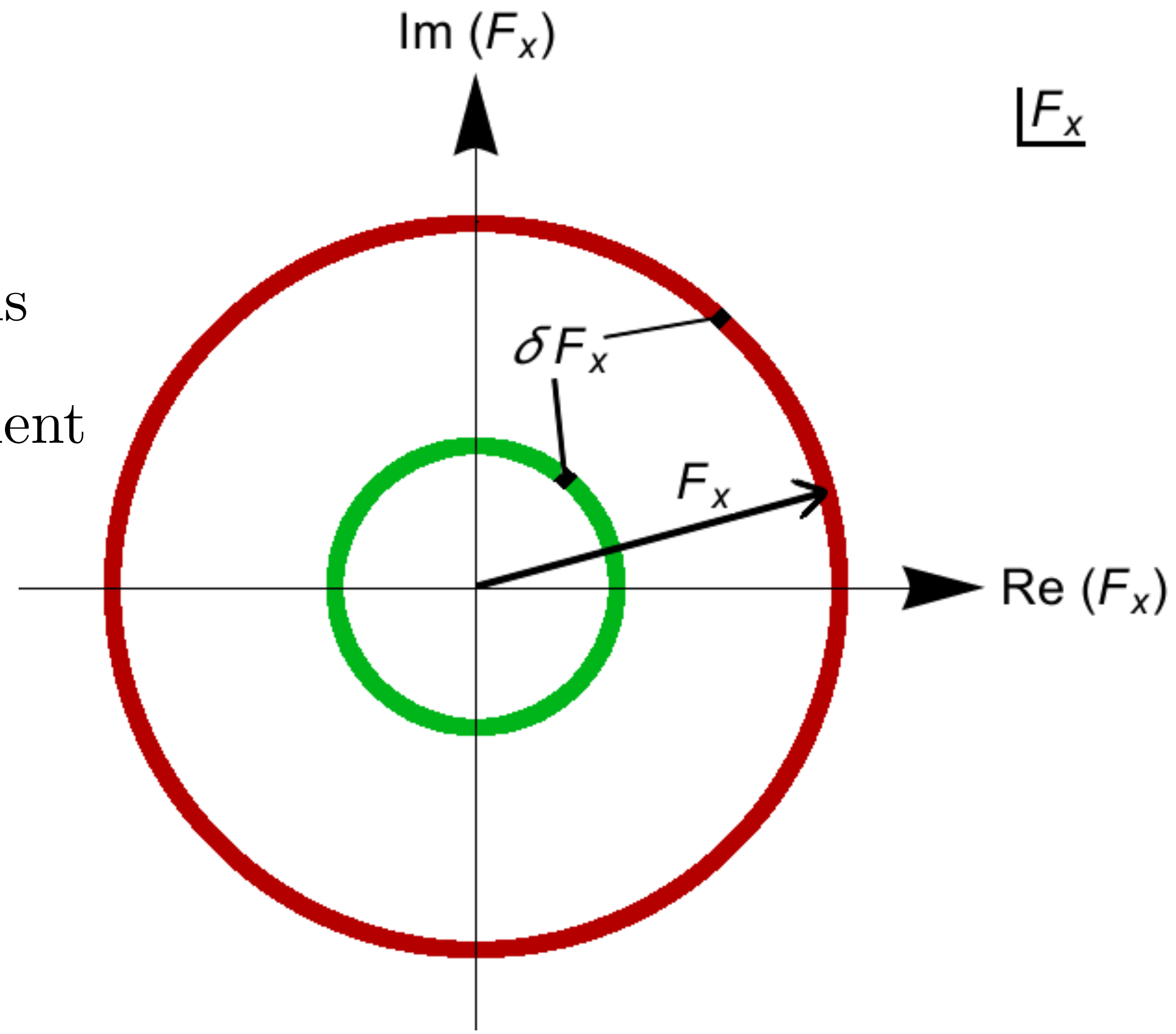


Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

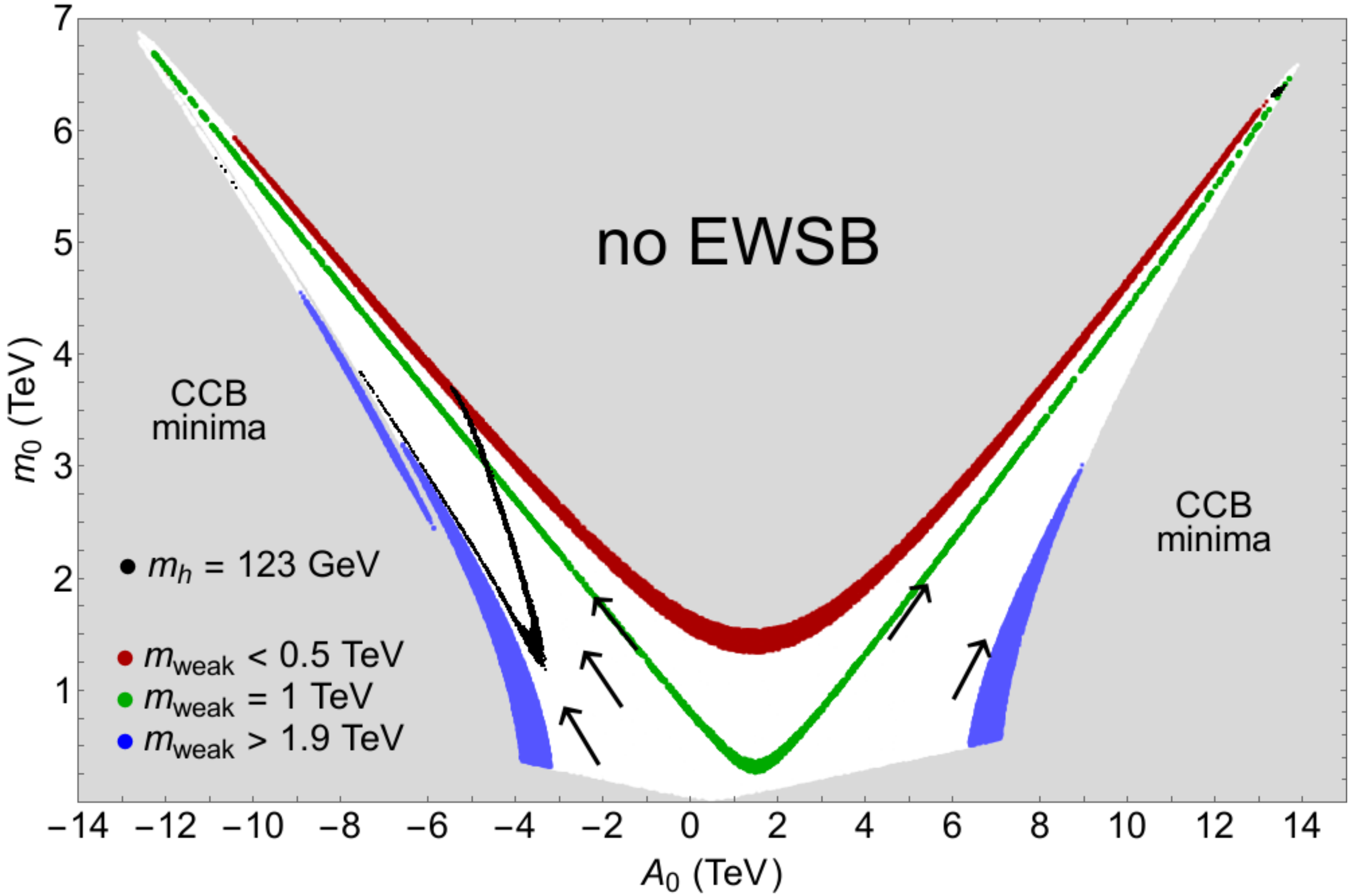
Why do soft terms take on values needed for natural (barely-broken) EWSB?

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



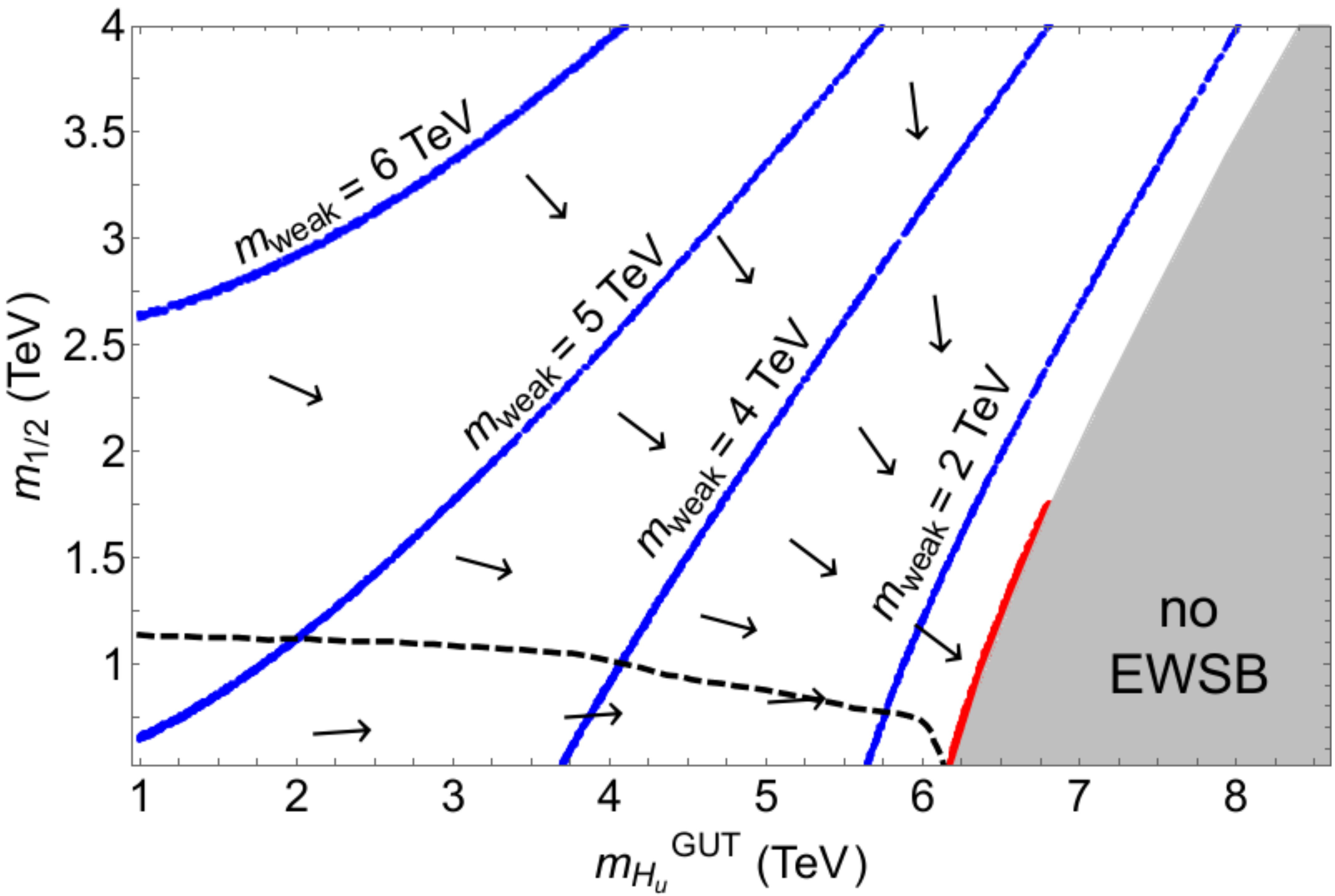
Anthropic selection of $m_{weak} \sim 100\ GeV$:
If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them



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

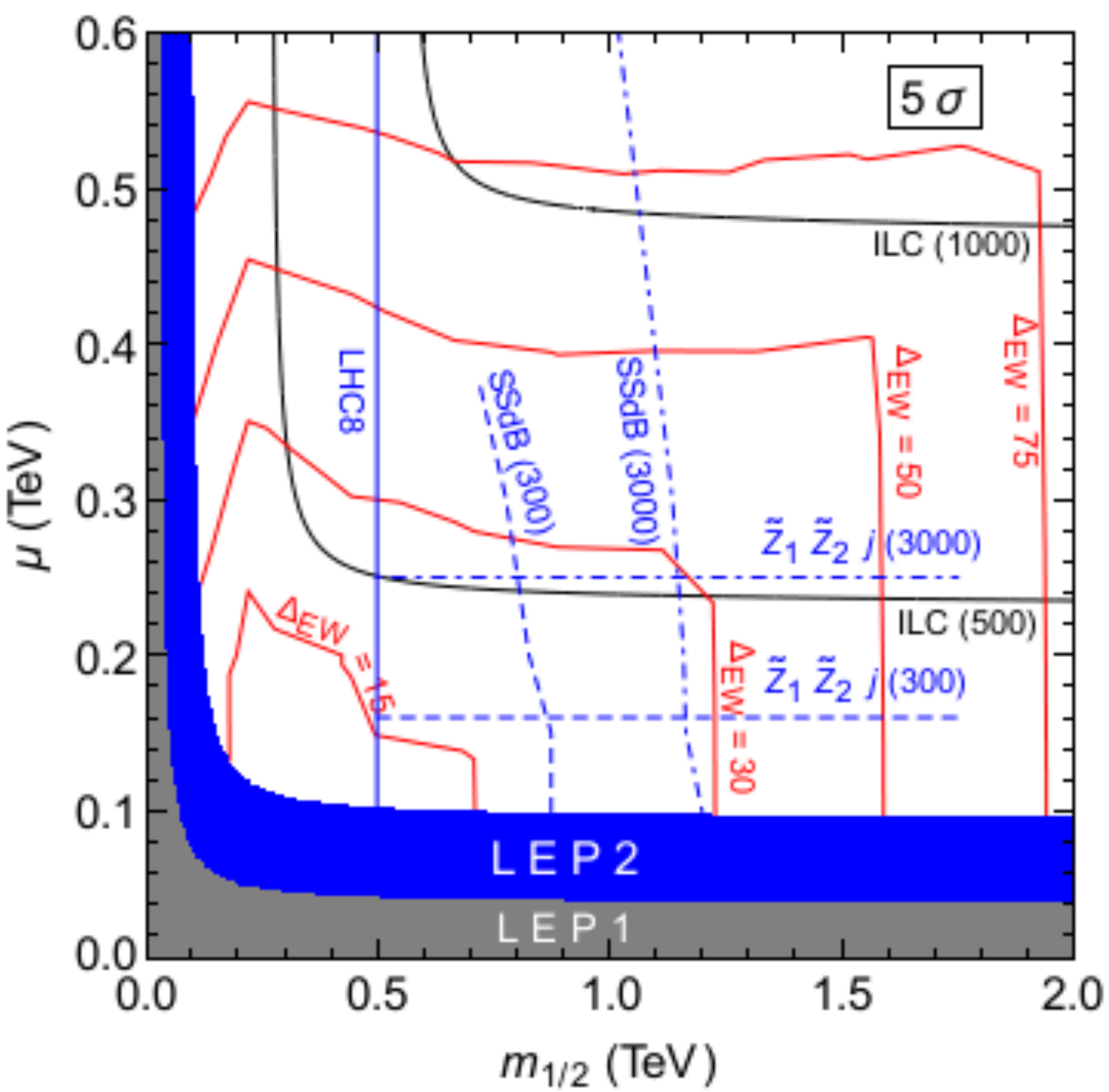


statistical/anthropic draw toward FP-like region prospects for SUSY discovery at LHC and ILC:

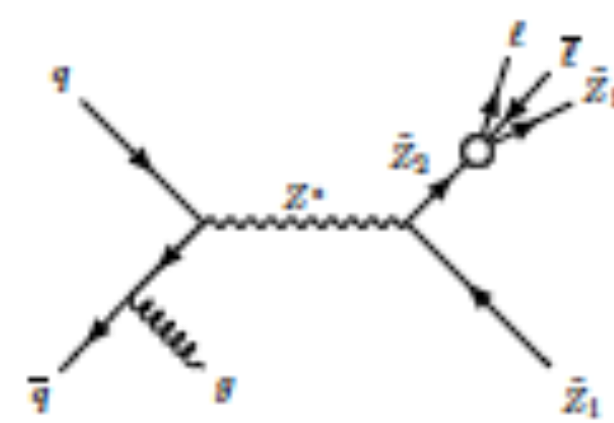
gluino and stops may be too heavy for LHC, even while natural

but for low mu models, new signatures emerge

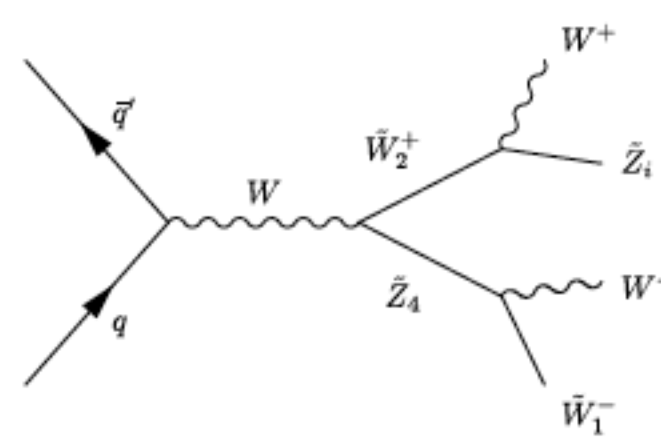
LHC can cover all Delta<30 but may need 3000 fb-1



soft dilepton+ jet+MET



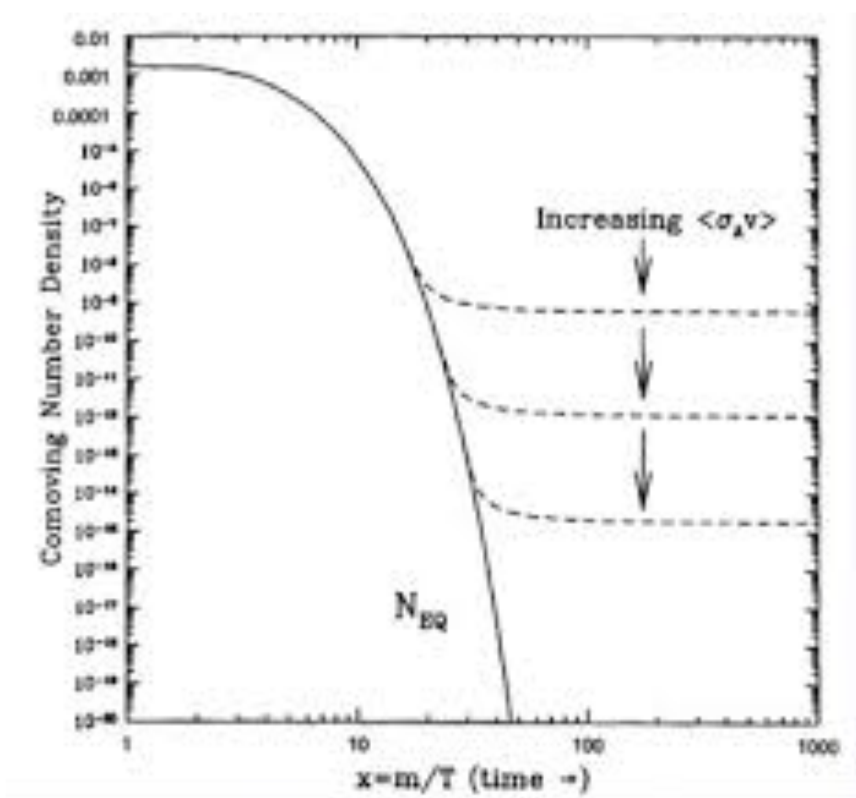
same sign dibosons

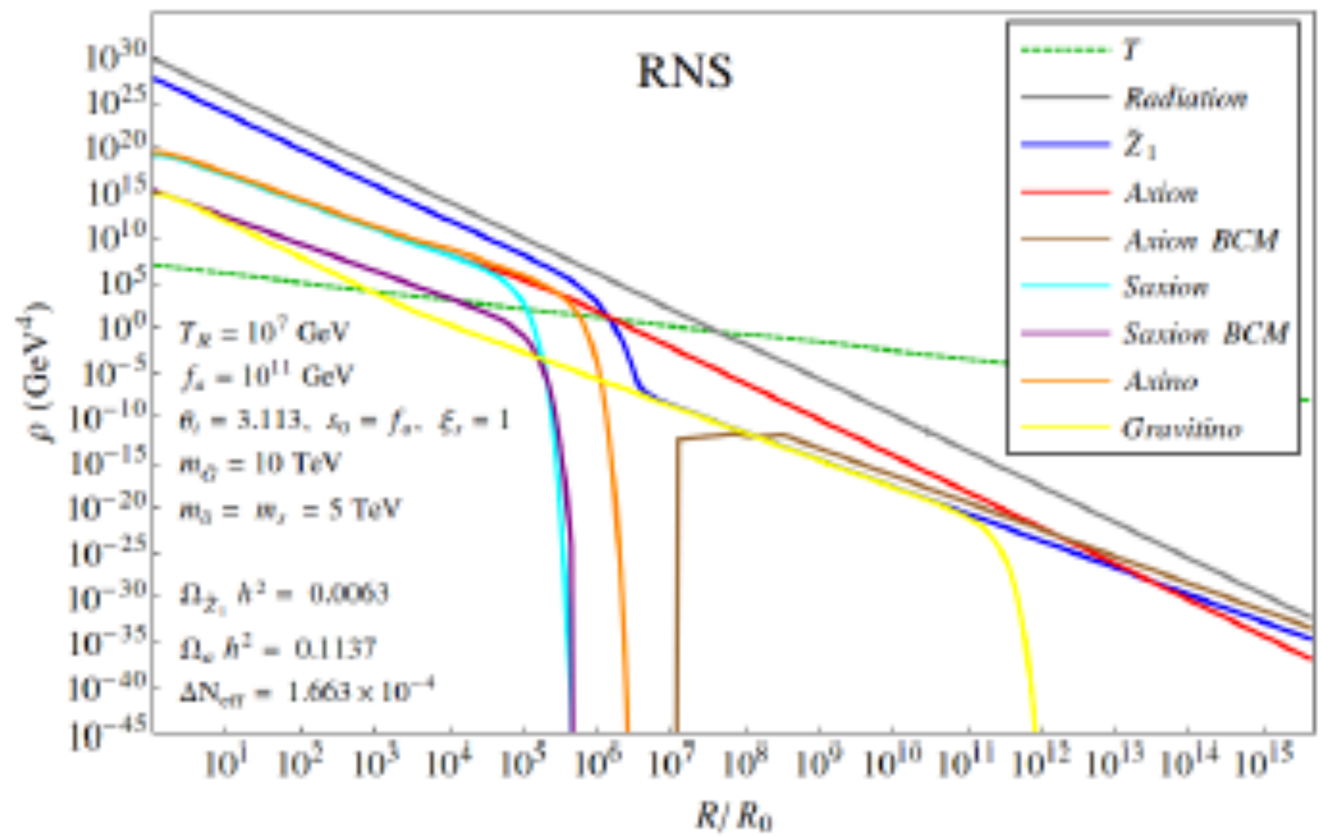


What happens to SUSY WIMP dark matter?

- 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

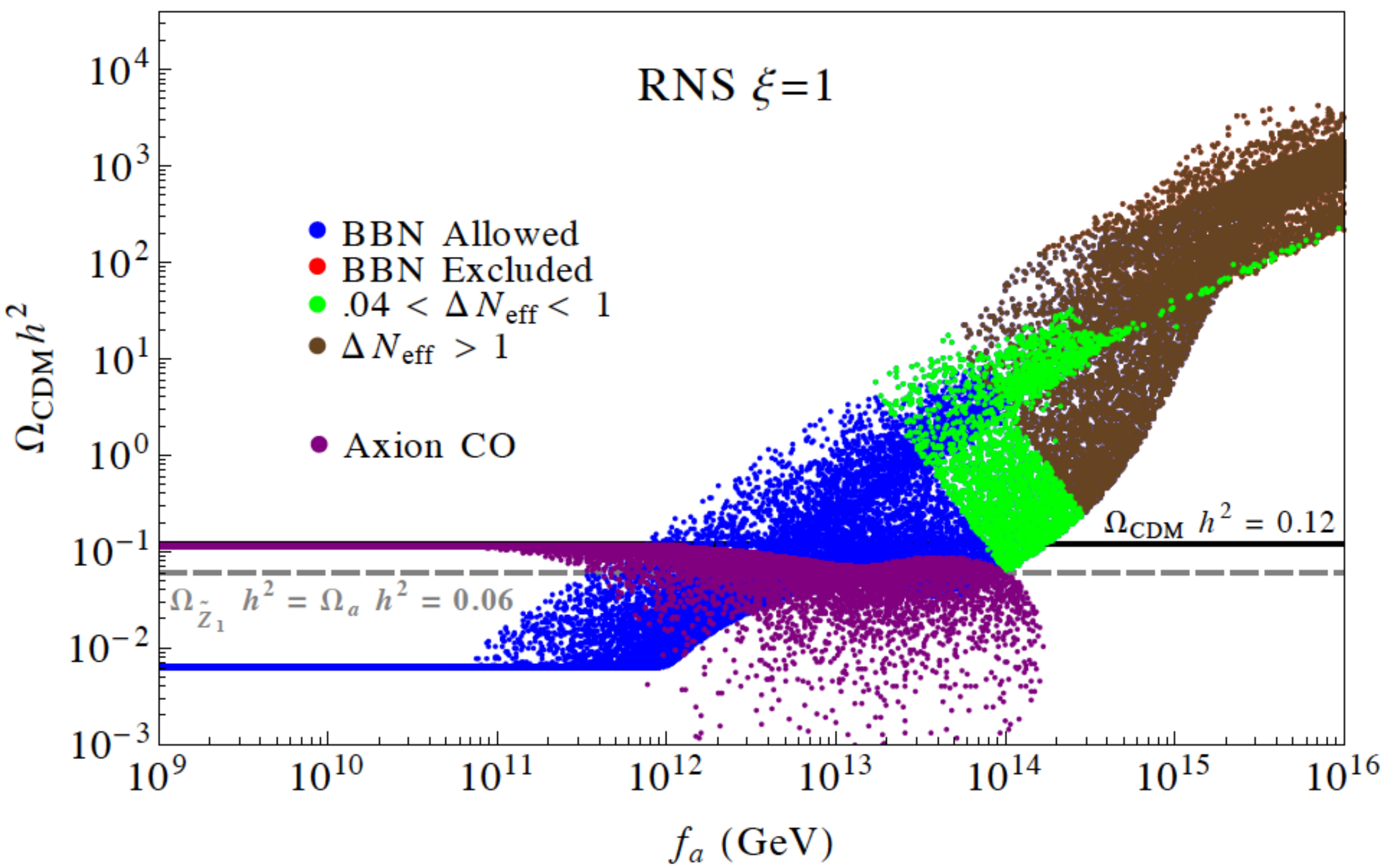




KJ Bae, HB, Lessa, Serce

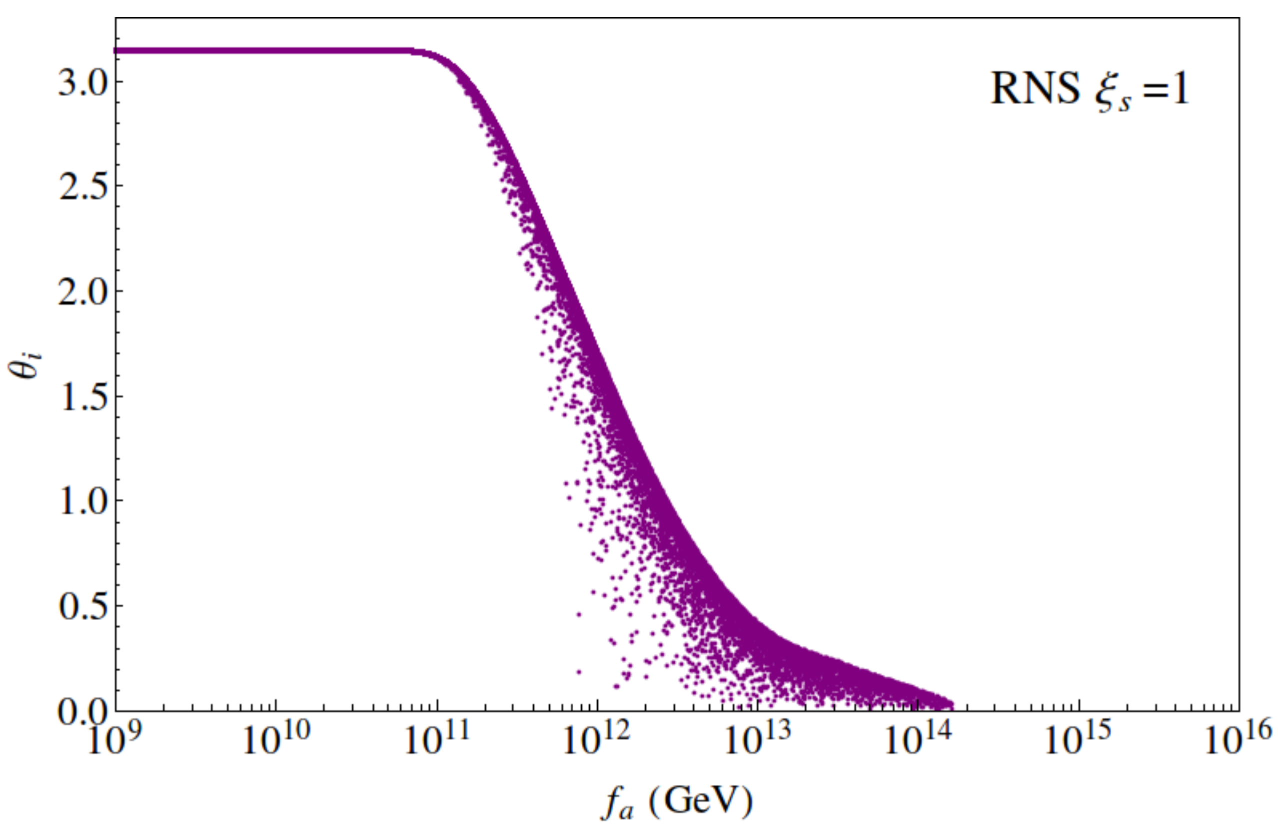
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

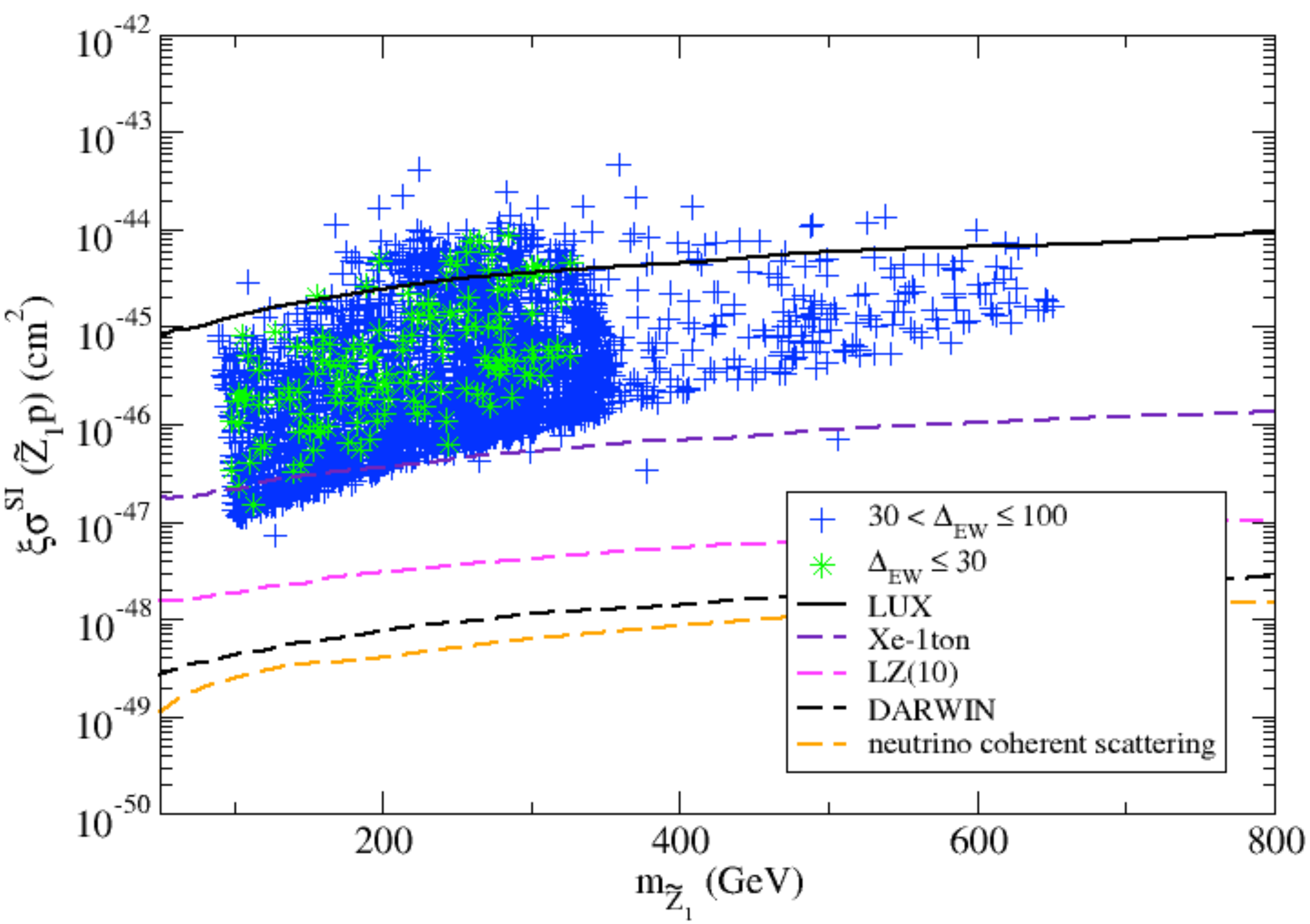
axion abundance



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



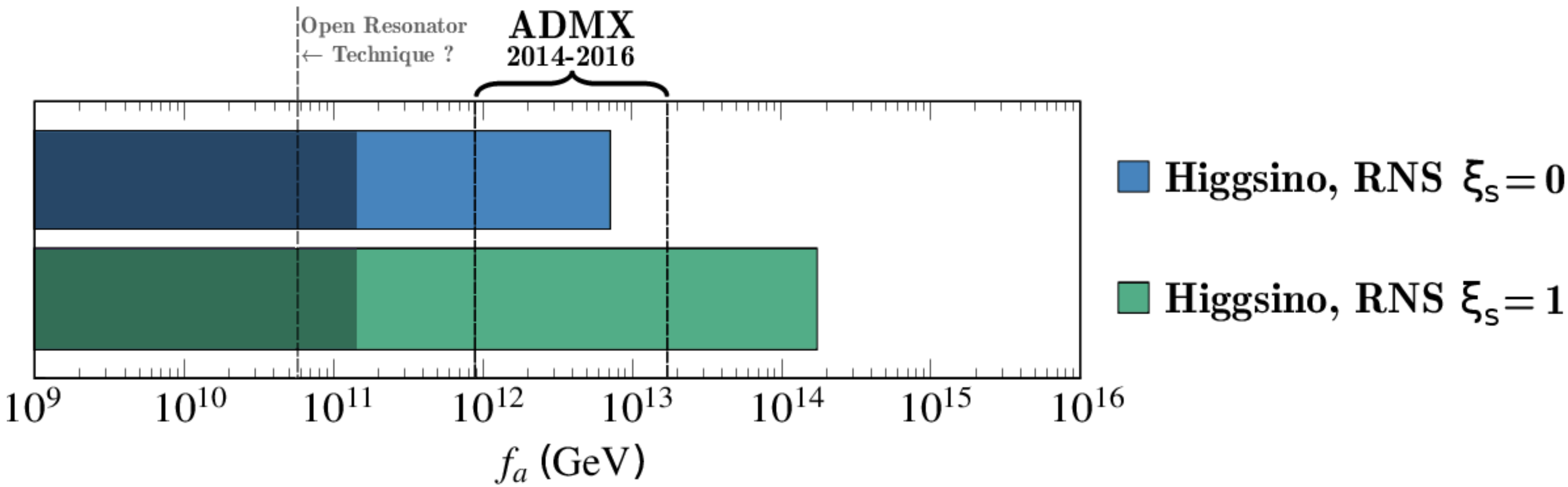
Bae, HB, Barger,Savoy,Serce

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

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

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

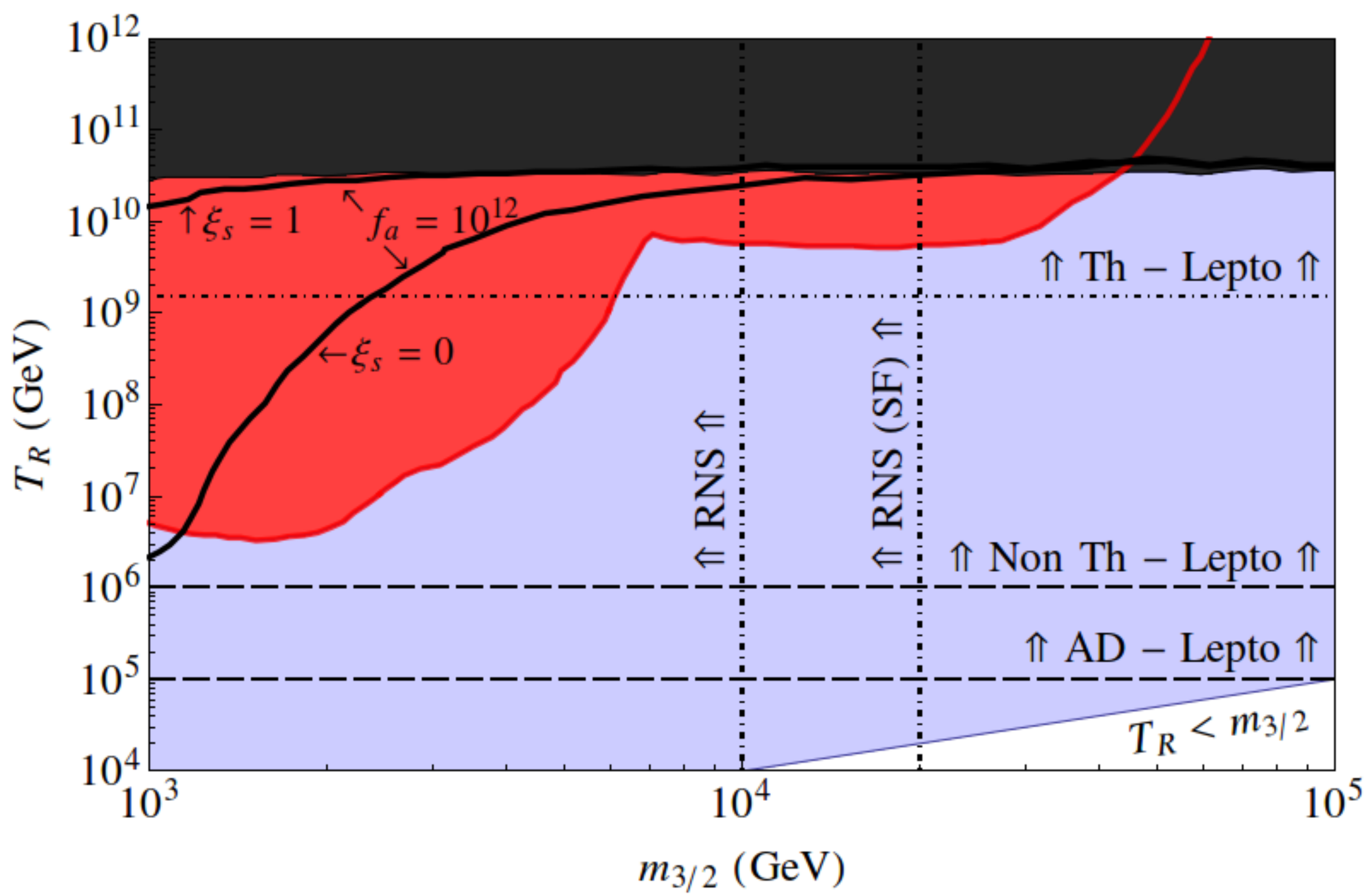
Can test completely with ton scale detector or equivalent (subject to minor caveats)



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

baryogenesis: lots of possibilities in SUSY

* Thermal leptogenesis
* Non-thermal leptogenesis
* Sneutrino leptogenesis
* Affleck-Dine (flat direction) leptogenesis



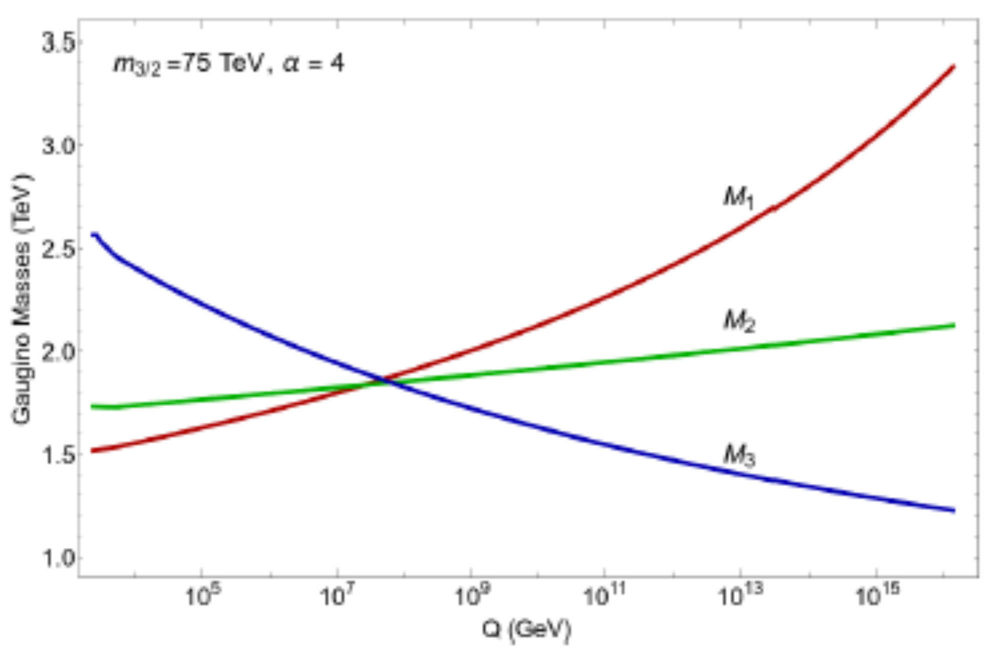
gravitino problem

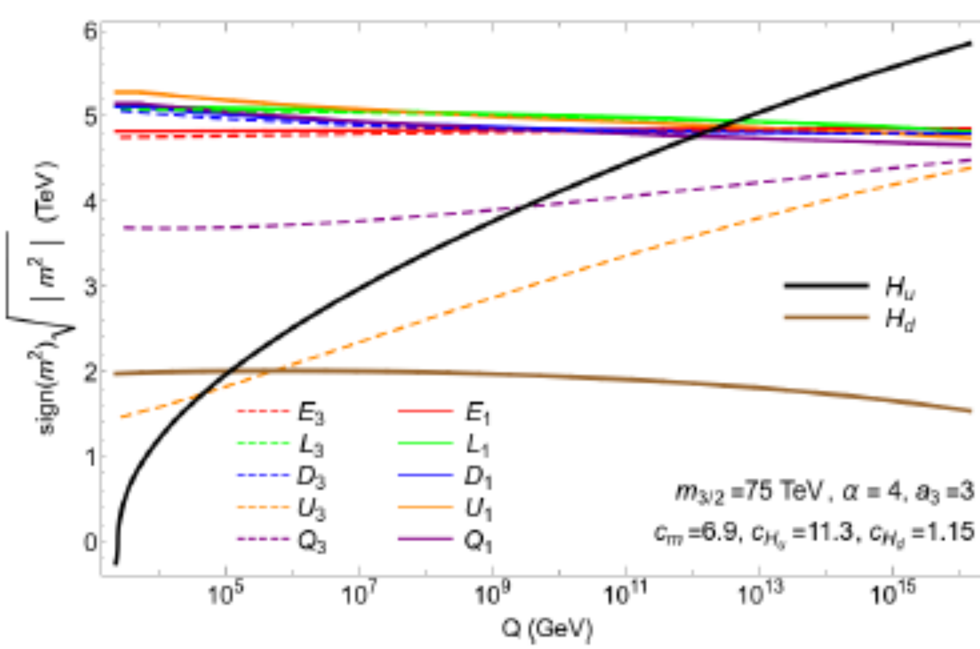
$f_a = 10^{11}$ GeV

Alternative: soft SUSY breaking terms receive comparable gravity-anomaly mediated contributions: mirage mediation

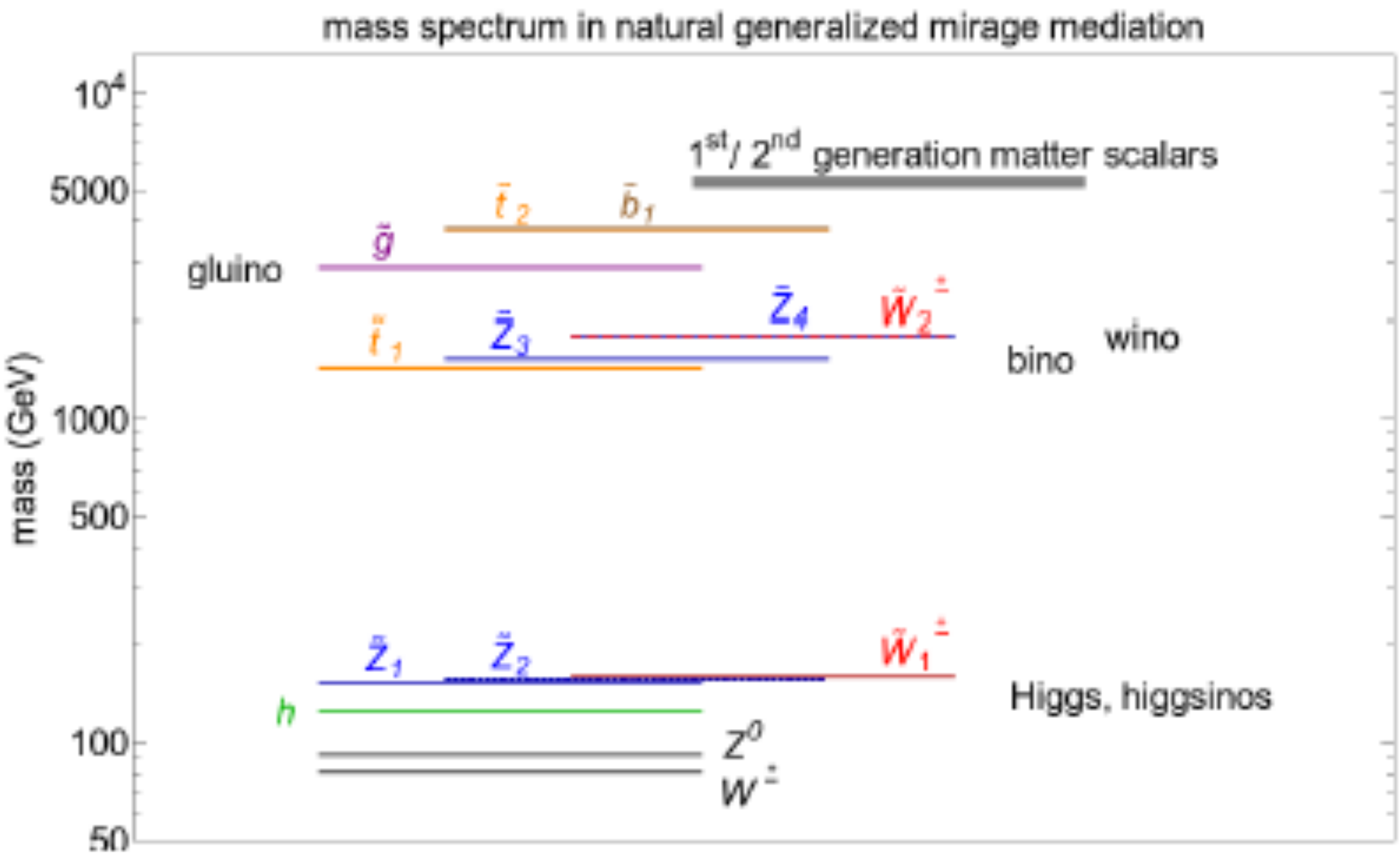
natural generalized mirage mediation

$$
\begin{aligned}
M_a &= M_s\left(l_a\alpha + b_a g_a^2\right),\\
A_{ijk} &= M_s\left(-a_{ijk}\alpha + \gamma_i + \gamma_j + \gamma_k\right),\\
m_i^2 &= M_s^2\left(c_i\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right),
\end{aligned}
$$





mirage mediation: gaugino masses compressed for low mirage unification scale



* spectra beyond reach of even HL-LHC

* yet, model is highly natural

* higgsinos still within discovery reach of ILC!

Conclusion: SUSY is alive and well!

- old calculations of naturalness over-estimate fine-tuning
- naturalness: Little Hierarchy mu<< m(SUSY) allowed
- radiatively-driven naturalness (RNS):
  mu~100-200 GeV, m(t1)<3 TeV, m(gluino)<4 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 NUHM2: HL-LHC can cover via SSdB+Z1Z2j
- expect ILC as higgsino factory
- DM= axion+higgsino-like WIMP admixture: detect both?
- natural mirage mediation: beyond LHC but ILC can discover!

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!”

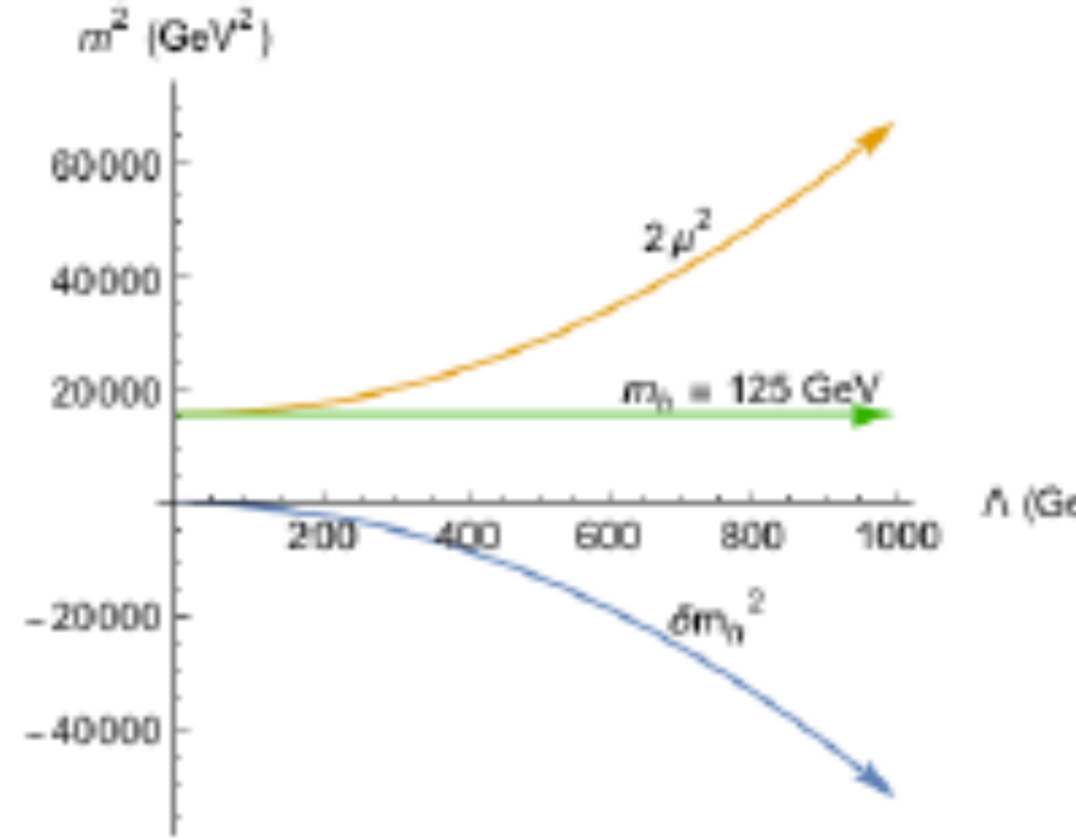
HB, Barger, Mickelson, Padeffke-Kirkland, arXiv:1404.2277

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

Reminder: why we are here

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!

Three measures of fine-tuning:

related work:
Kim, Athron, Balazs, Farmer, Hutchison
PRD90 (2014)055008

#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

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Radiative natural SUSY with a 125 GeV Higgs boson

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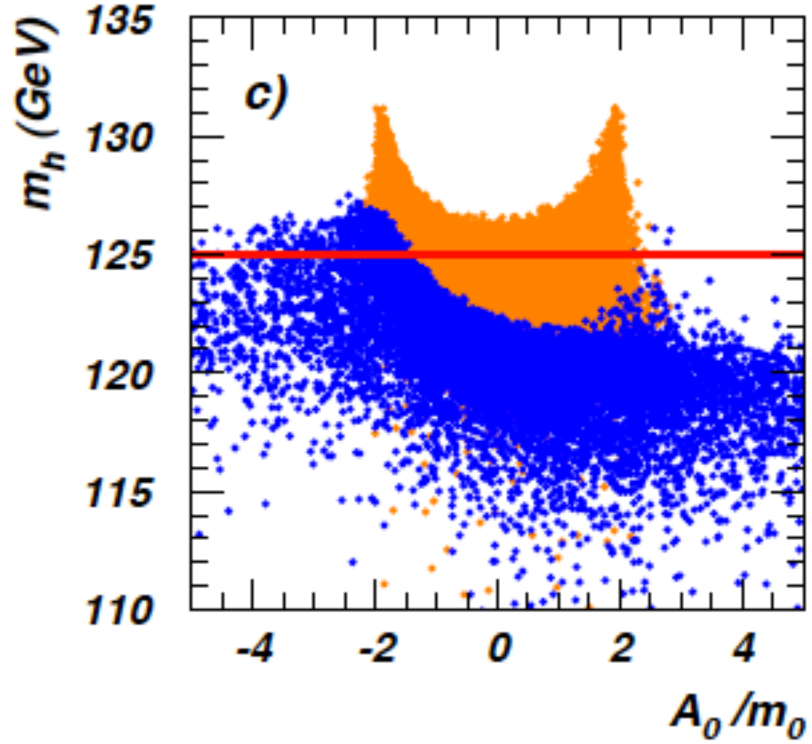
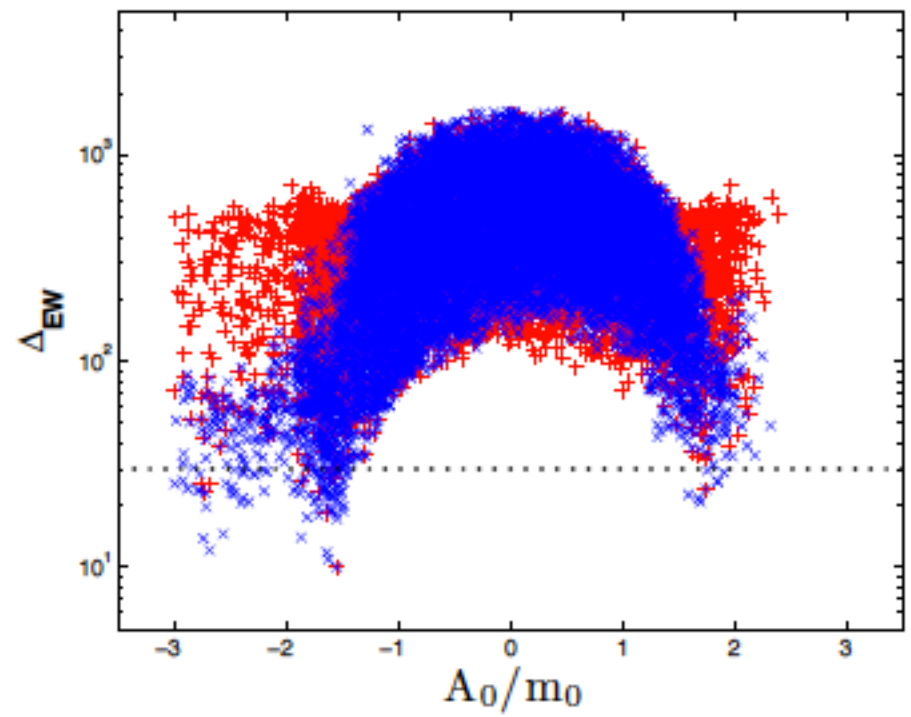
PRL109 (2012) 161802

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



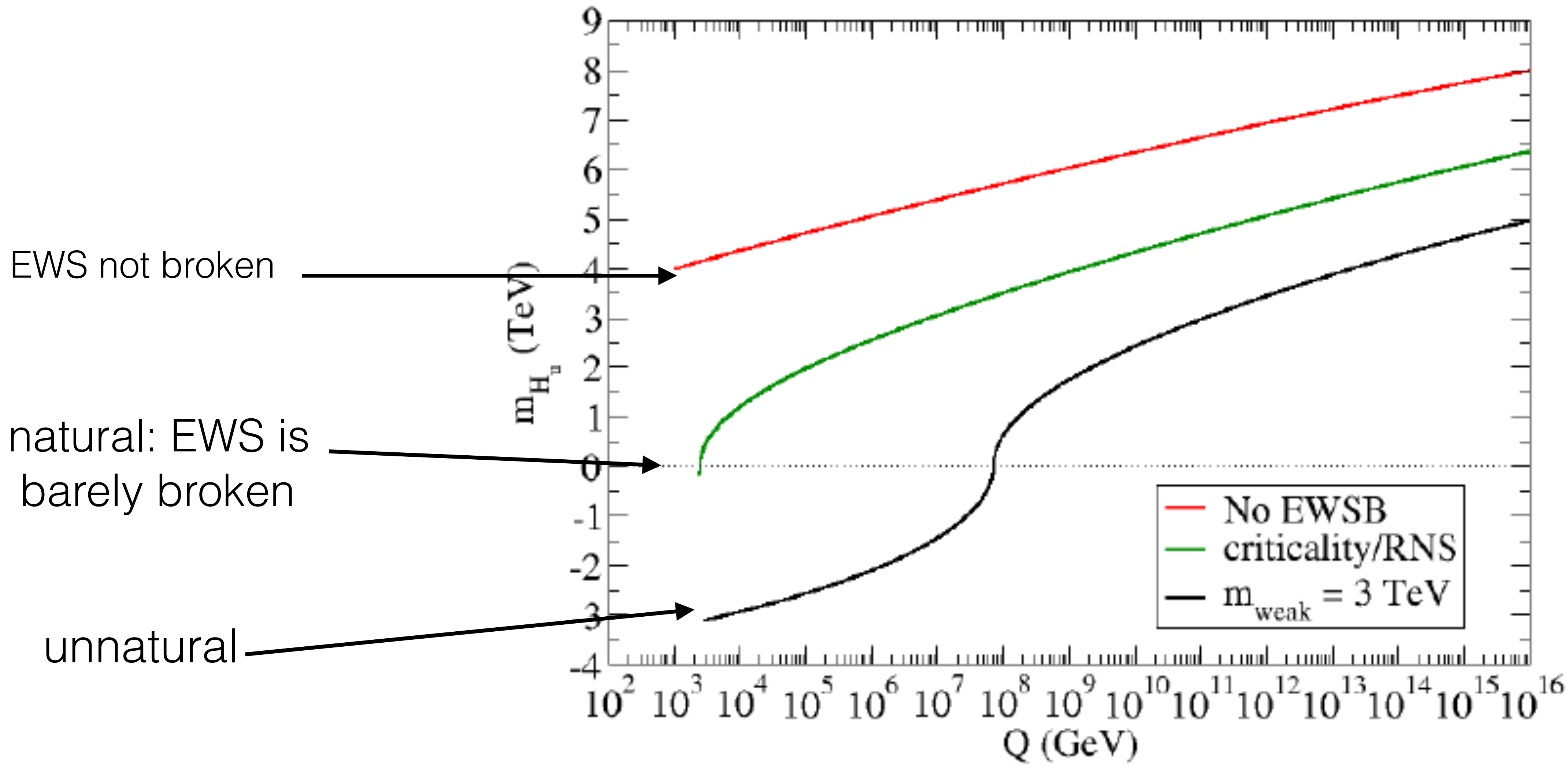


$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2}F(m^2_{\tilde{t}_{1,2}})\left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2(\frac{1}{4} - \frac{2}{3}x_W)\Delta_t}{m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}}\right]$$

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

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

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



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

#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

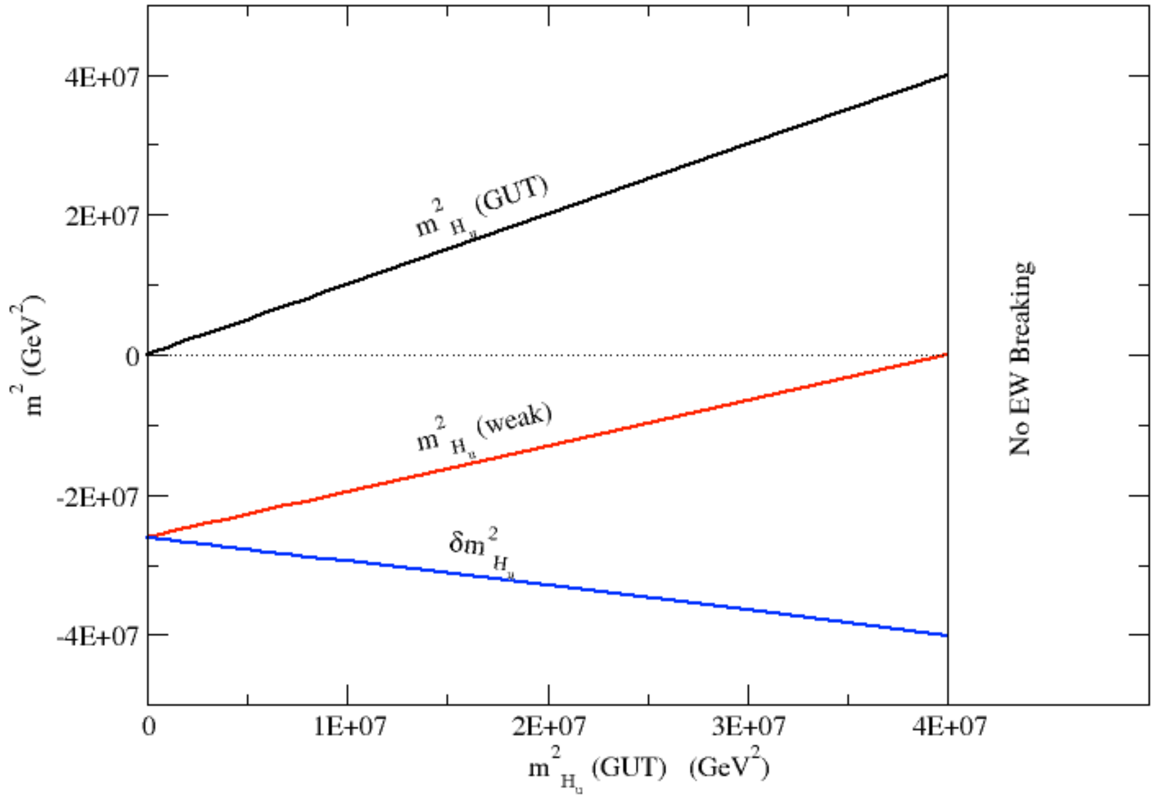
then A_t can't be too big

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 $m_{H_u}^2 \sim m_Z^2$

#3. What about EENZ/BG measure?

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

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

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

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

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

What about EENZ/BG measure?

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

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

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

applied to most parameters,

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

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

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

violates prime directive!

e.g. in SUGRA, for well-specified hidden sector,
<u>each</u> 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

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

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

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