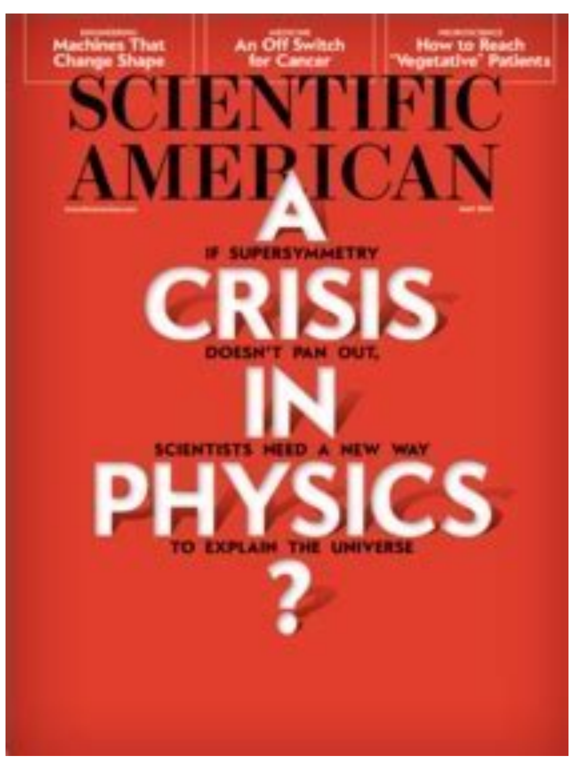
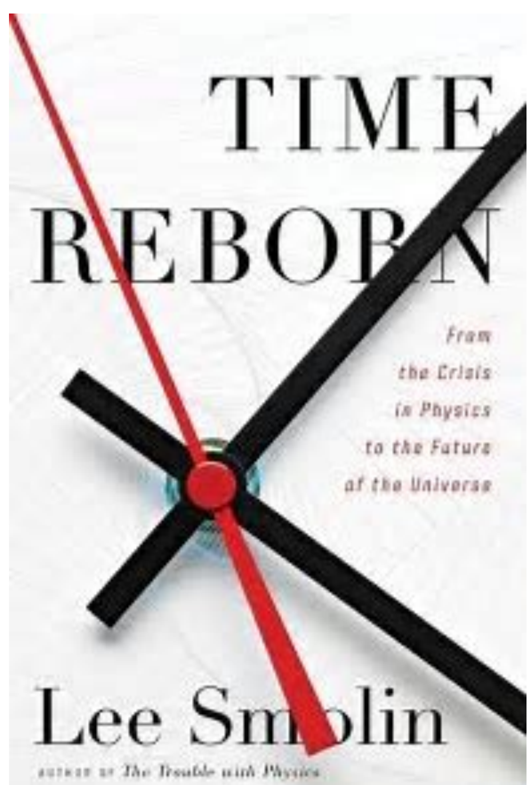
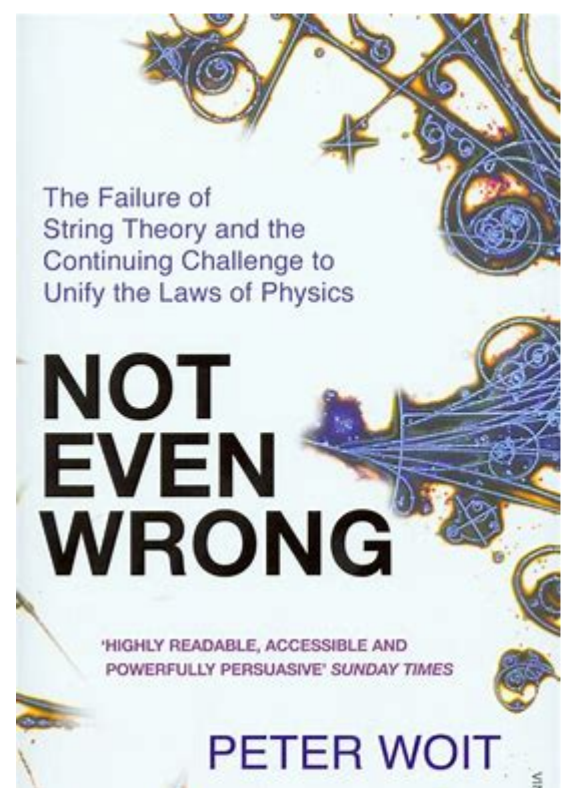
Status of Weak Scale Supersymmetry: is there a crisis from non-appearance of SUSY? is there a crisis in non-predictivity of string theory?)

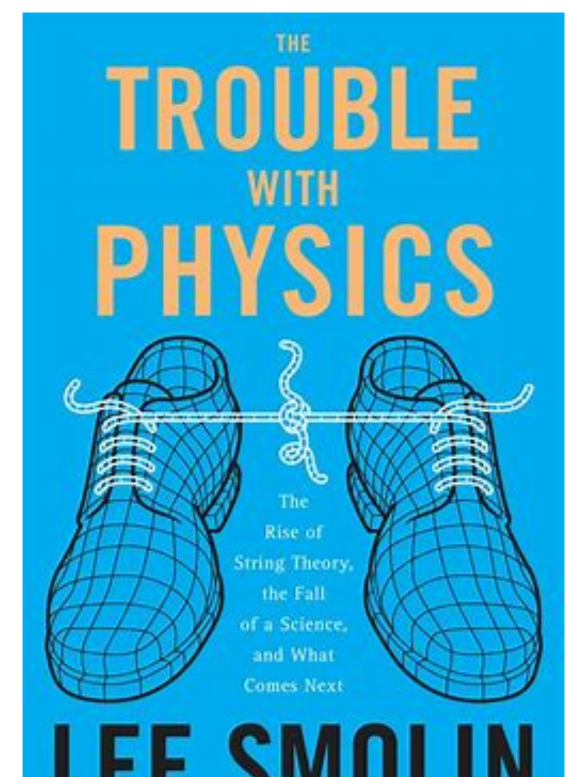
Howard Baer
University of Oklahoma

PaSCos 2018,
CWRU, June 2018









Status of Weak Scale Supersymmetry:
NO- in fact, from some general considerations of string landscape, LHC so far sees exactly what is expected from string theory with MSSM as low energy EFT- but an LHC energy upgrade may be needed to test SUSY!

Howard Baer

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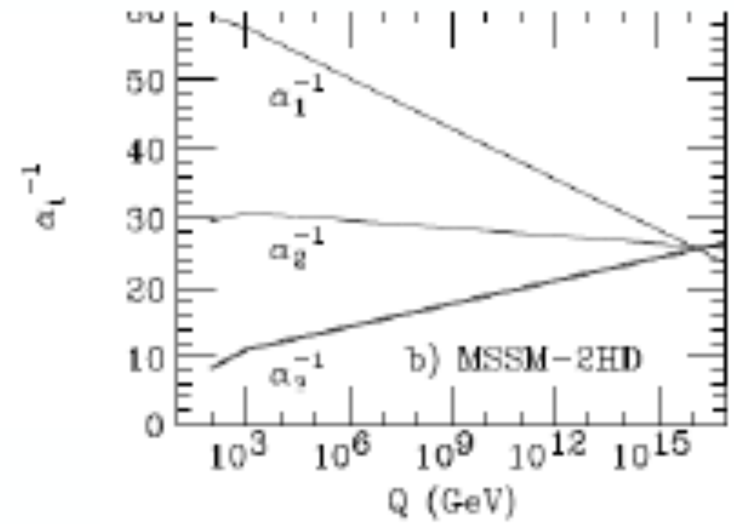
1. Nature sure looks like SUSY

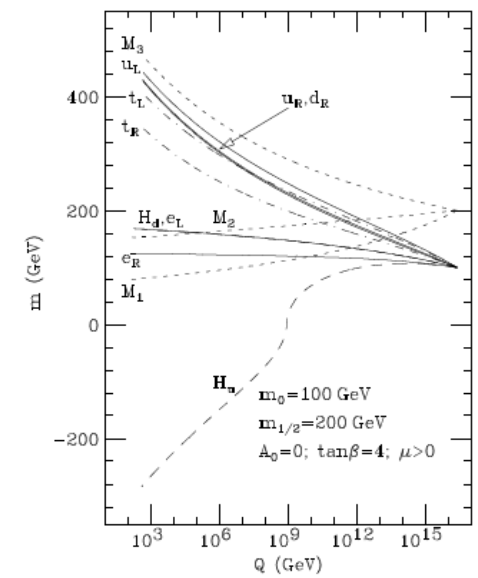
- still simplest, most elegant solution to gauge hierarchy problem
- measured gauge couplings unify
- m(t)~173 GeV for REWSB
- mh(125): squarely within SUSY window

Witten, Kaul

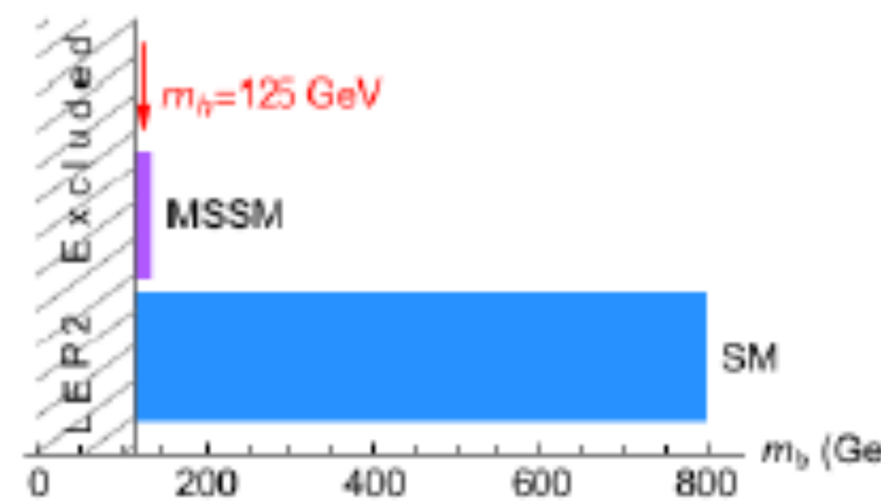


Dimopoulos, Raby, Wilczek

Ibanez, Ross



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



Supersymmetry stabilizes the EW sector of the SM and is actually supported by data via virtual effects: 1. gauge couplings, 2. m(t), 3. m(h)

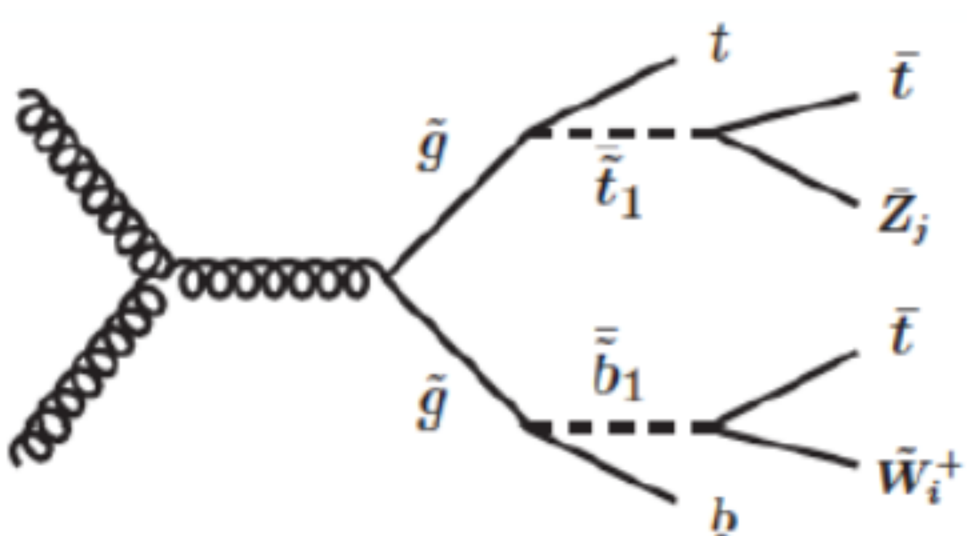
It also improves/adds to solutions of the following

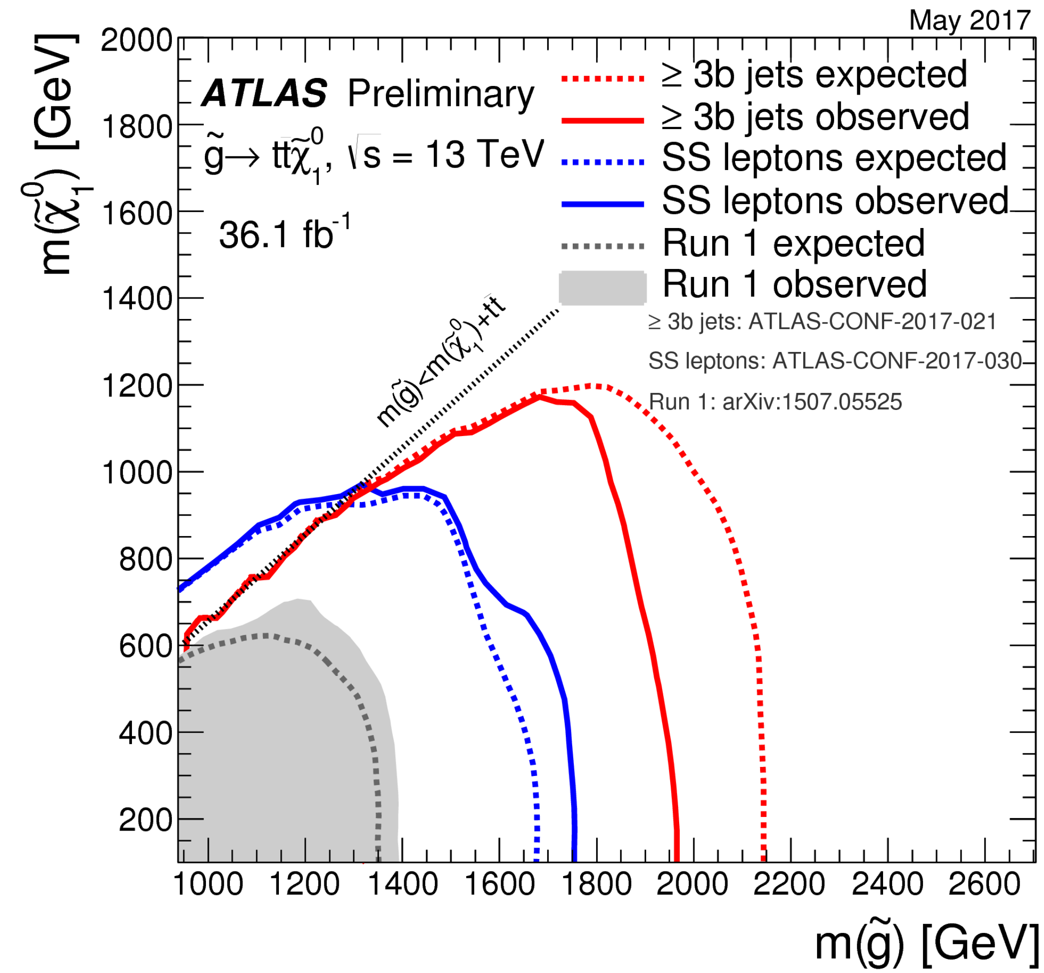
- nu mass and see-saw scale
- QCD, strong CP and PQ scale
- dark matter
- dark energy
- baryogenesis
- quantum gravity via supergravity and string theory

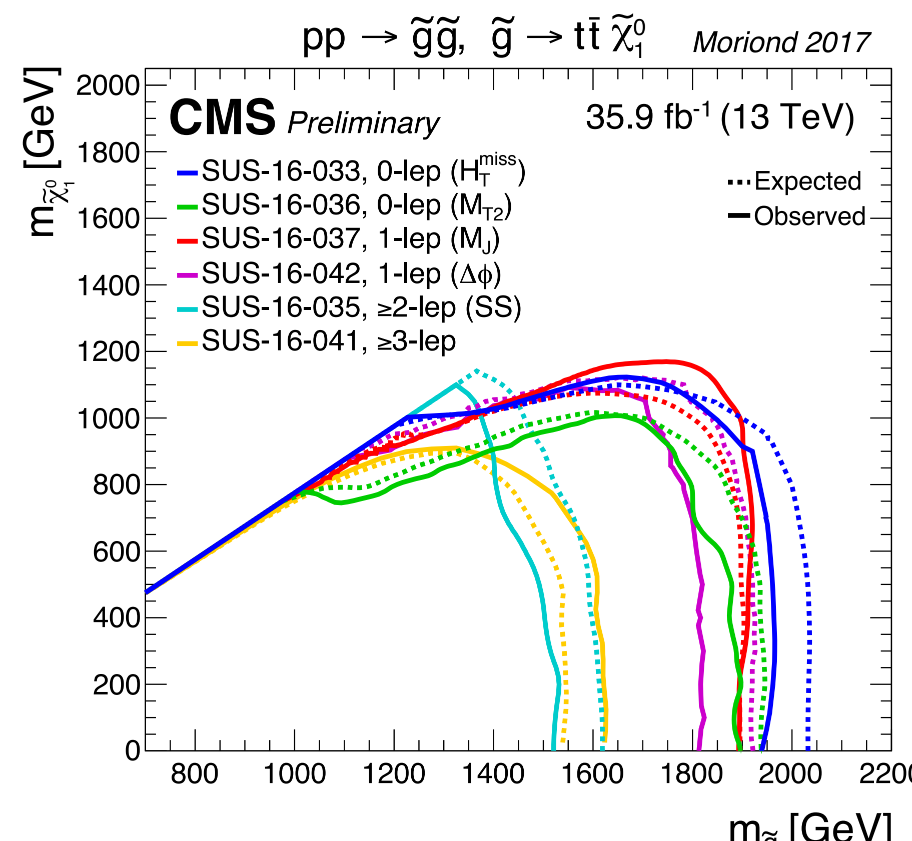
Fundamental prediction: new matter states- the superpartners- should exist not too far from m(weak)~m(W,Z,h)~100 GeV

But where are the sparticles?

gluino pair cascade decay signatures

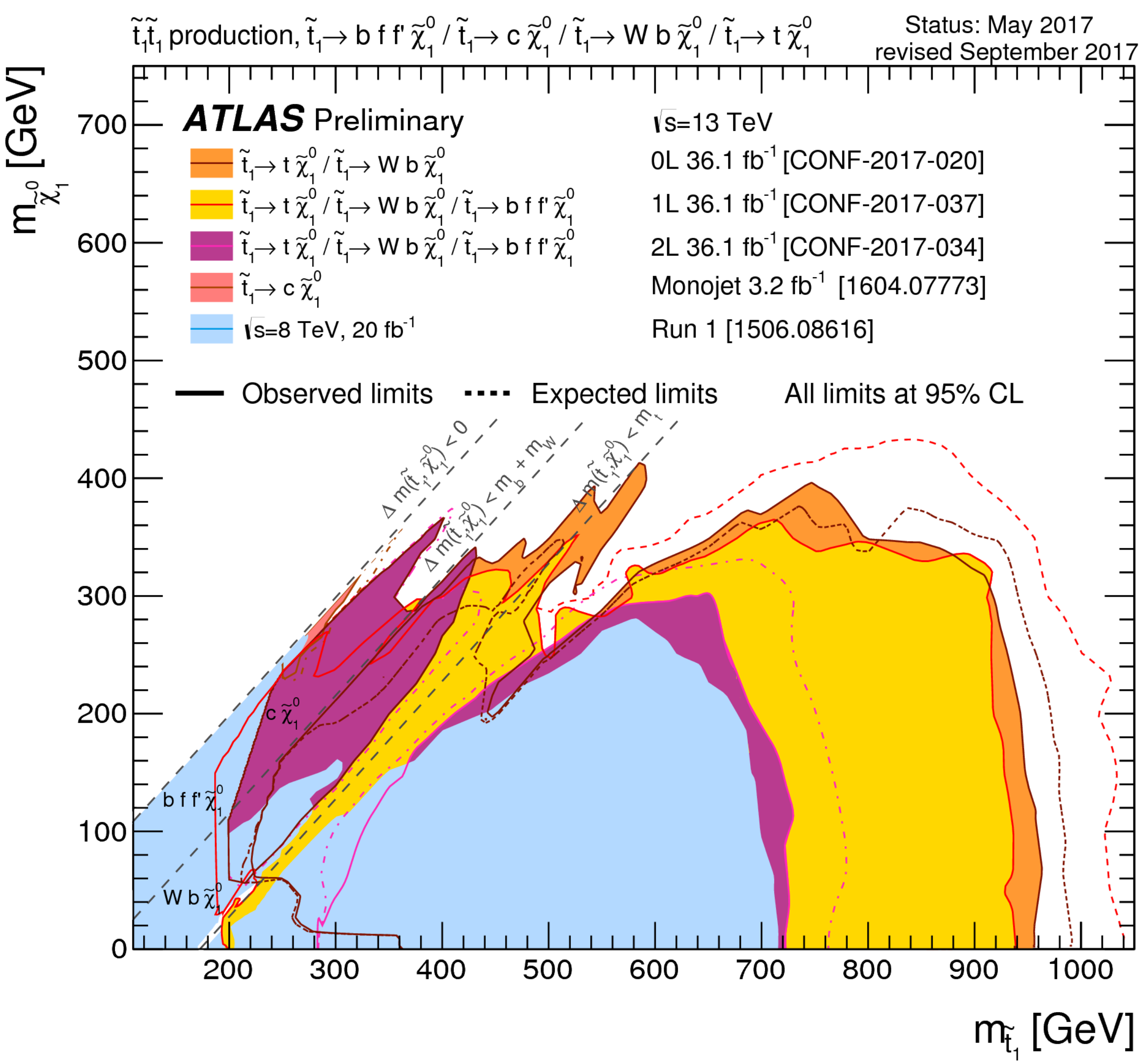


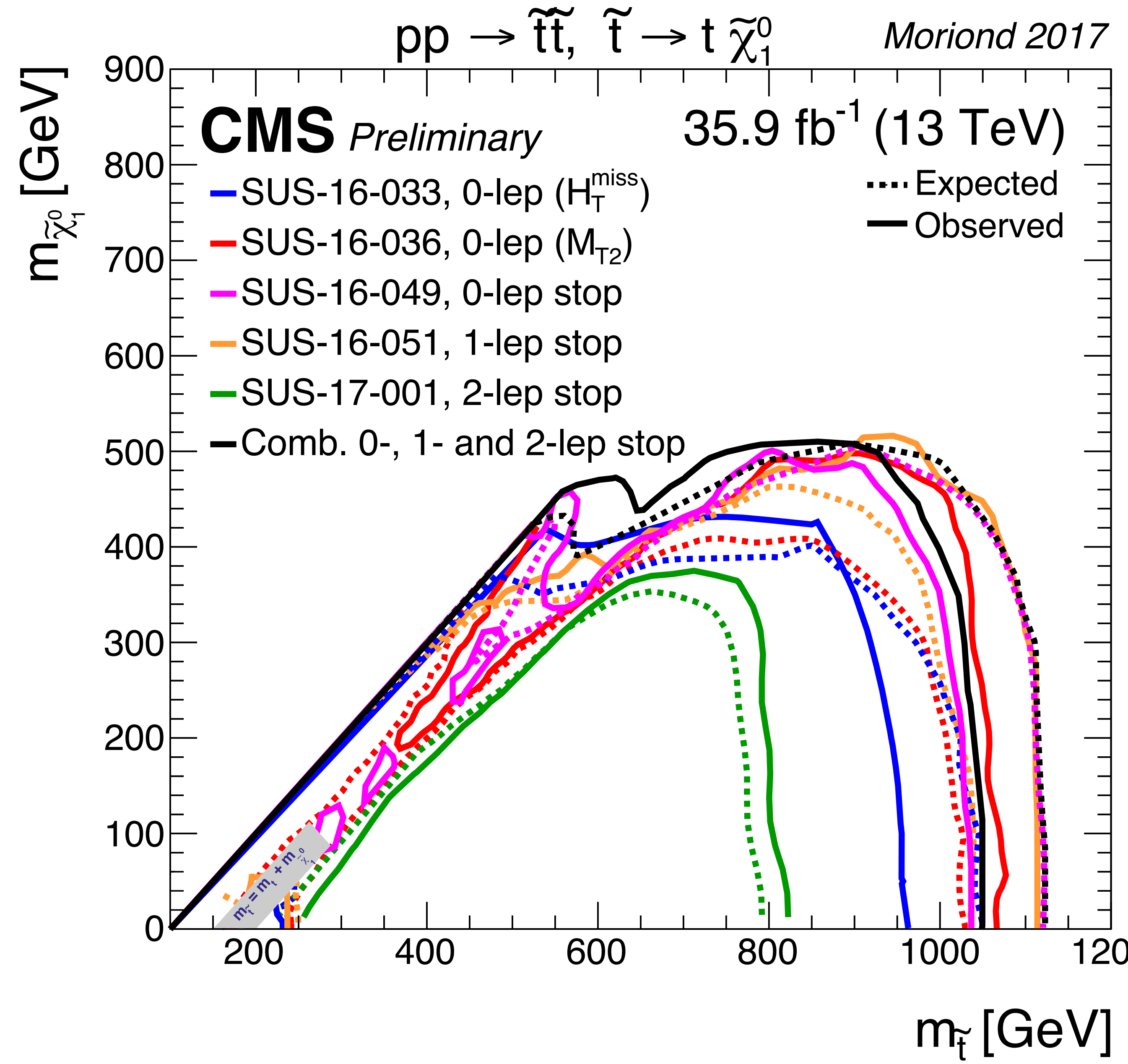




Evidently $m_{\tilde{g}} >\sim 2$ TeV

Present limits on top squarks from LHC

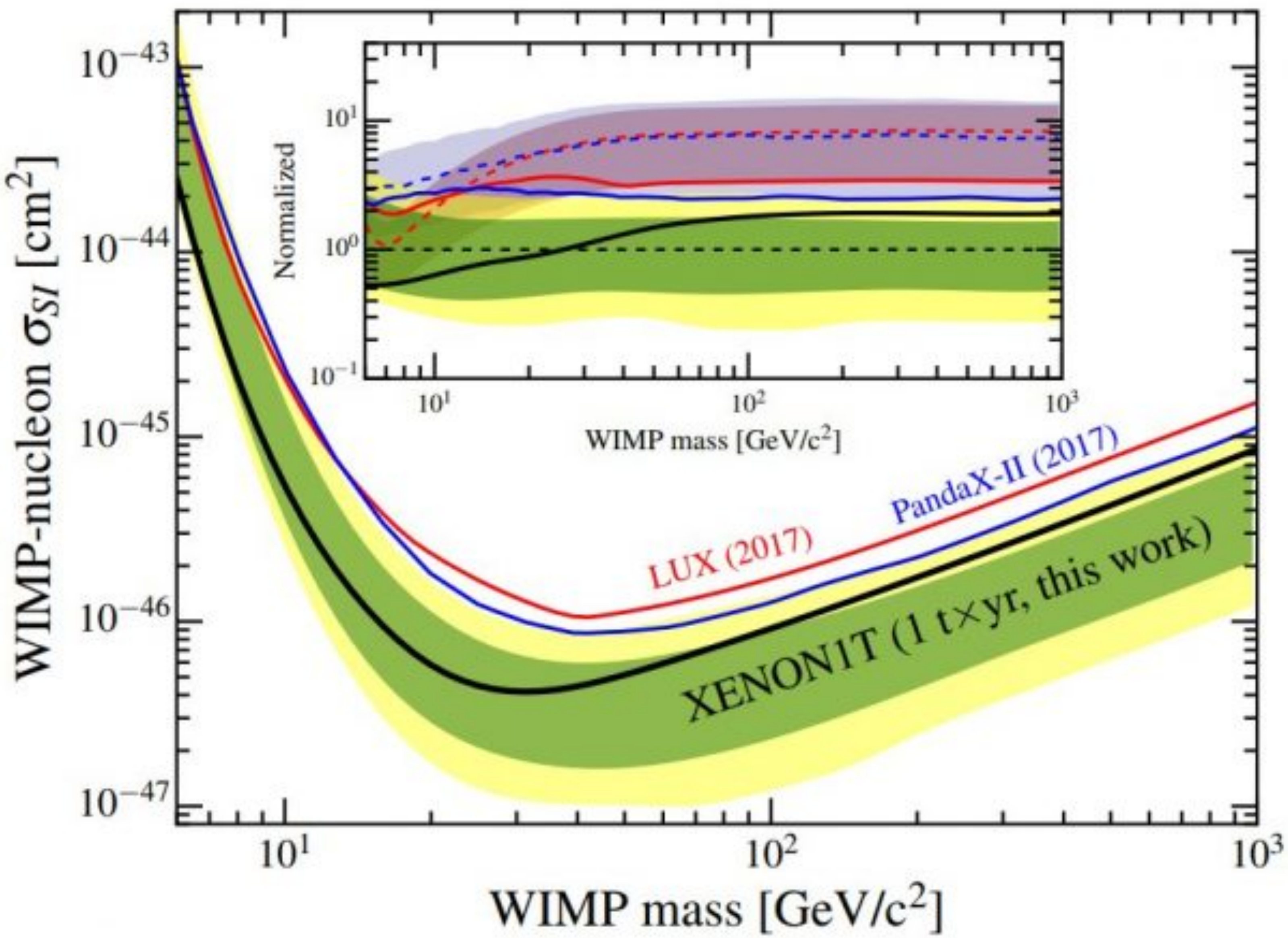




Evidently m(t1)>~1 TeV for m(LSP)~150 GeV

* TeV-scale, highly mixed top squark needed for m(h)~125 GeV
* Also needed for b-> s gamma

Where are the WIMPs?

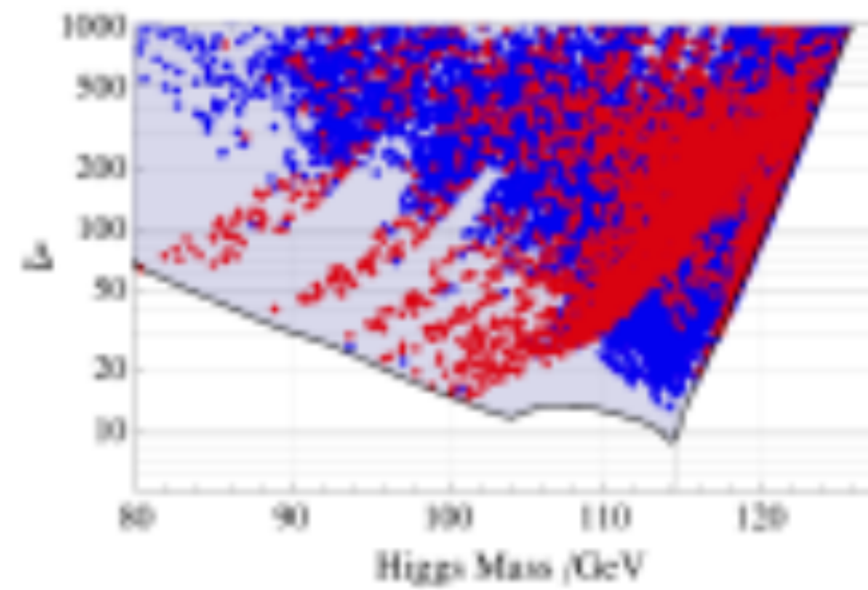


Latest Xe-1ton 279 days of data with 1.3 tons fiducial Xe- reported May 28, 2018 E. Aprile et al.

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

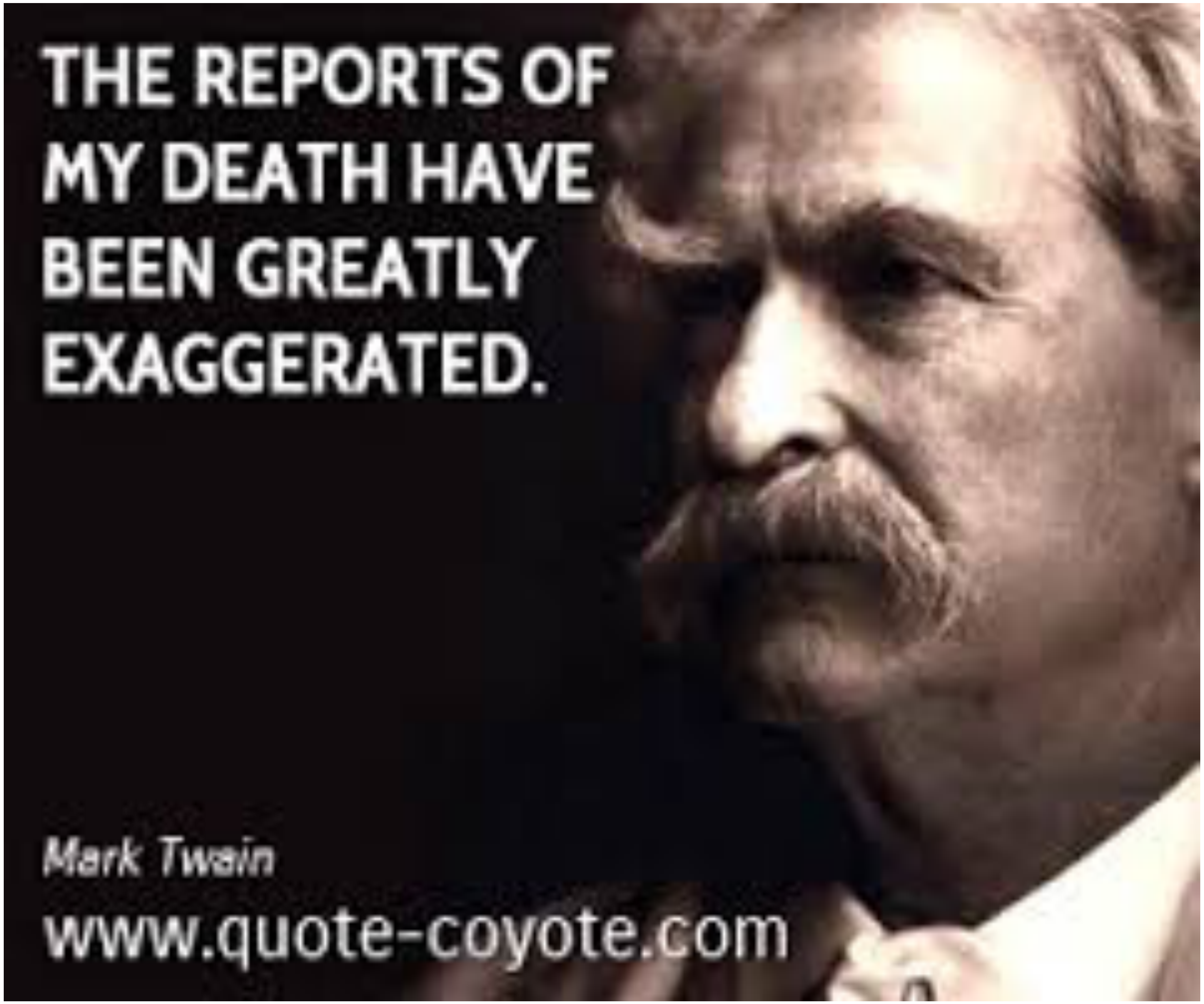


Cassel, Ghilencea, Ross,2009

$\Delta \to 1000$
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

SUSY particles light but hidden?

- R-parity violation?
- Compressed SUSY?
- Stealth SUSY?

scenarios increasingly implausible:
signals should emerge!

SUSY particles heavy?

Perhaps, but then the naturalness question arises

Should we care?

some attitudes

- SUSY solves Big Hierarchy- so Little Hierarchy is small price to pay
- In fundamental theory, all parameters calculable so who cares about naturalness?
- Nature is natural: resolution of the problem provides a fundamental clue to how nature is constructed

``…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

Let us attempt a working definition of naturalness:

- An observable O is natural if all independent contributions to O are comparable to or less than O

$\mathcal{O} = a_1 p_1 + a_2 p_2 + \cdots + a_n p_n$ for $i = 1 - n$ parameters p_i with coefficients a_i

- Because if one contribution, say $|a_1 p_1| \gg \mathcal{O}$ then some other contribution will have to be large opposite sign such that there is near perfect cancellation

- This is considered highly implausible, hence unnatural

- Something is lacking in the theory- the theory *as is* is likely wrong- needs some added feature or should discard

- Nature is natural!

Naturalness linked to predictivity in physical theory:
e.g. expect perturbation series to converge:
cancel divergences before evaluating terms

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!"

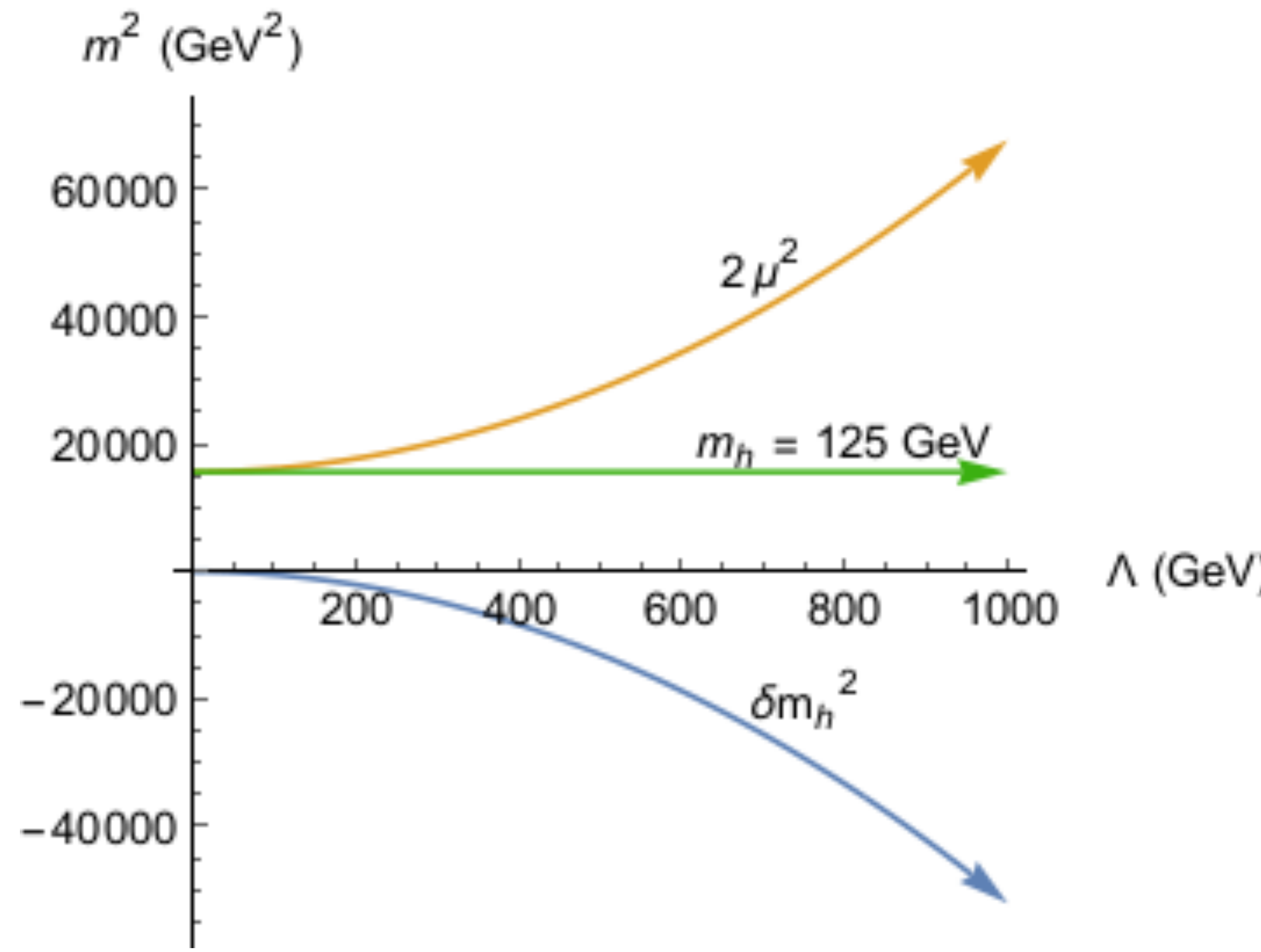
HB, Barger, Mickelson, Padeffke-Kirkland, arXiv:1404.2277

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

Reminder: naturalness in the SM

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

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



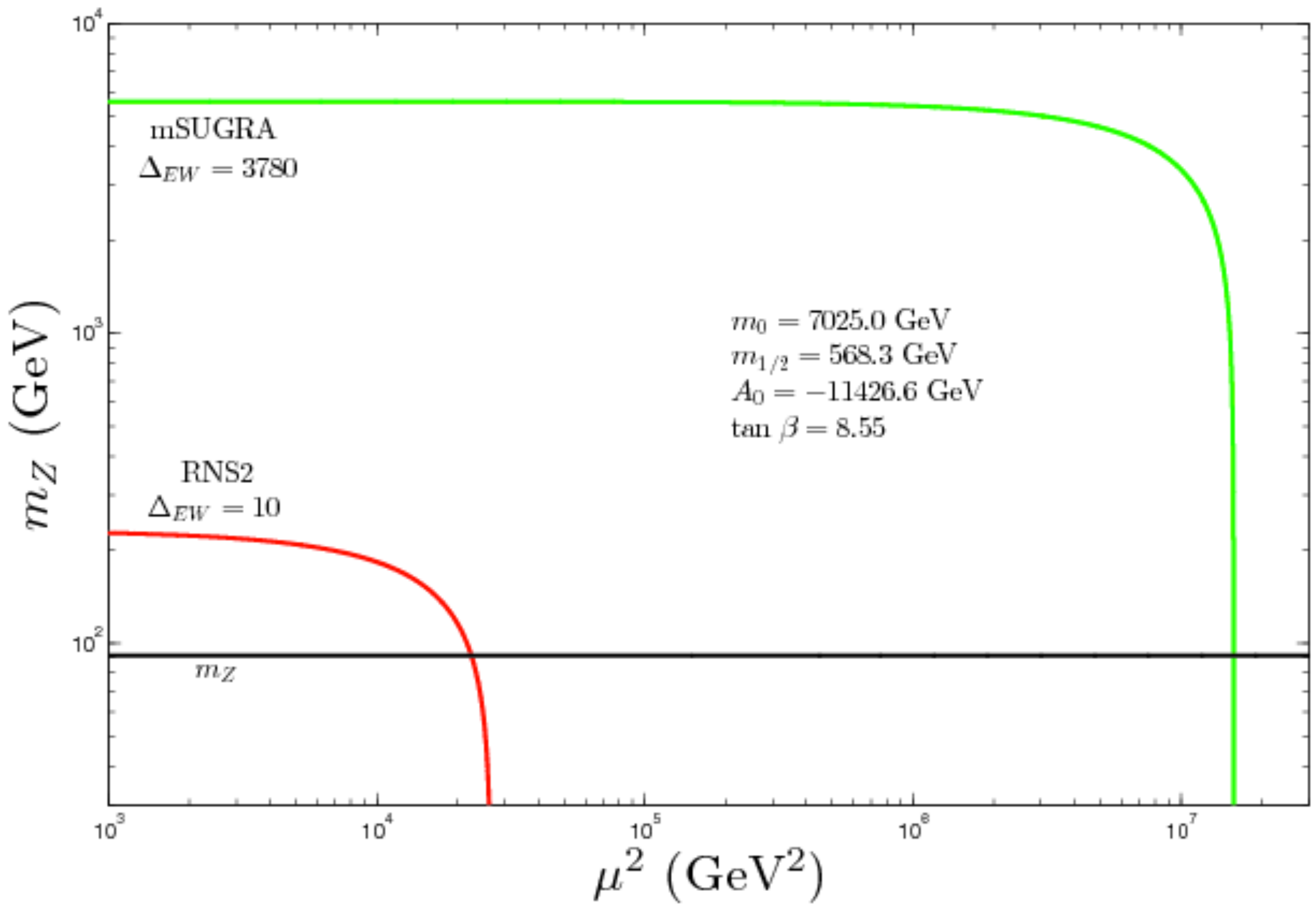
Since δm_h^2 is *independent* of μ^2,
can freely dial (fine-tune) μ^2 to maintain $m_h = 125$ GeV

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

Three measures of fine-tuning:

First: 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:

#1: Simplest, most conservative 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 (Chan, Chatto...,Nath; HB, Barger, Huang)
- $m_{H_u}^2$ 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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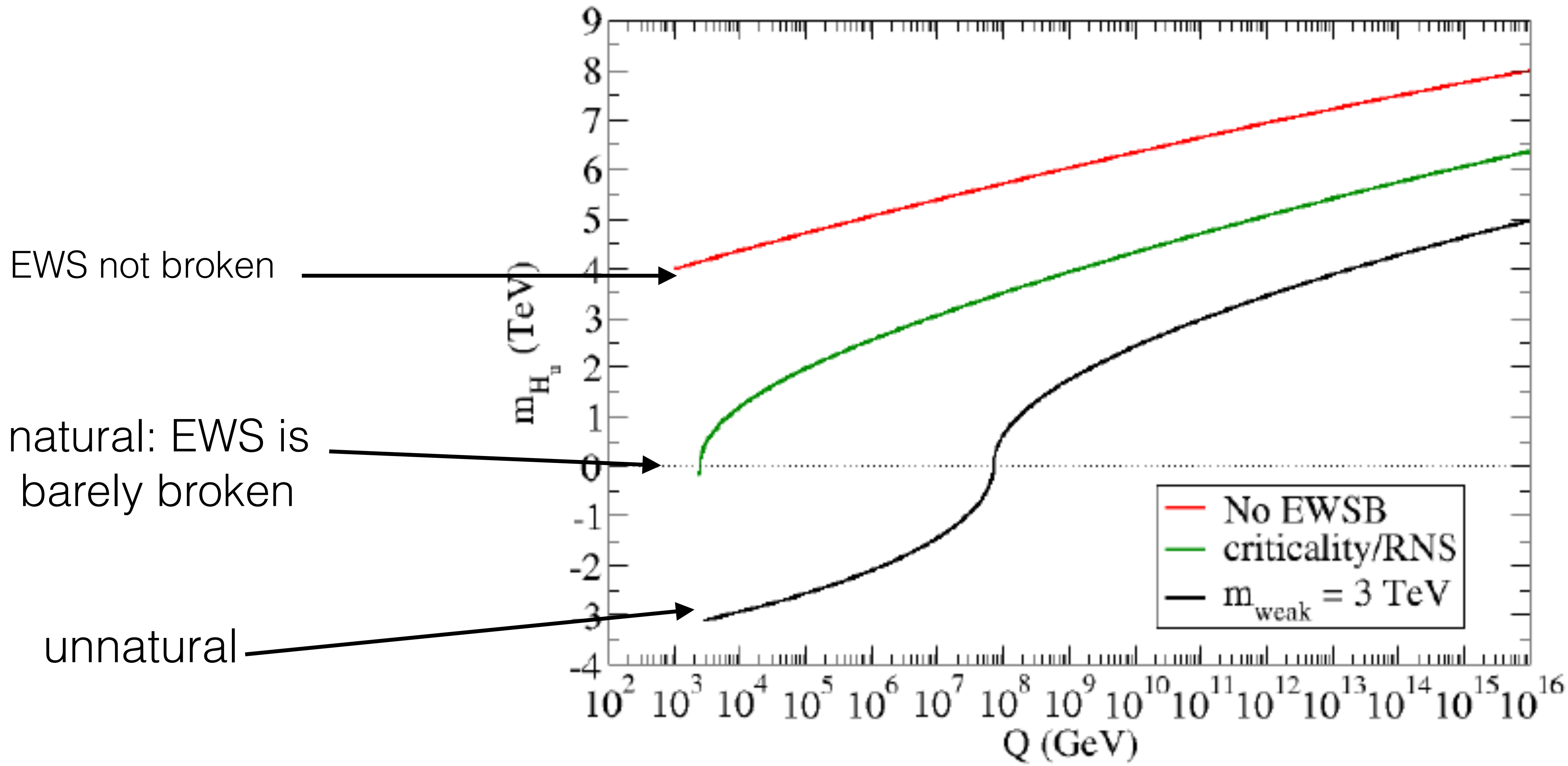
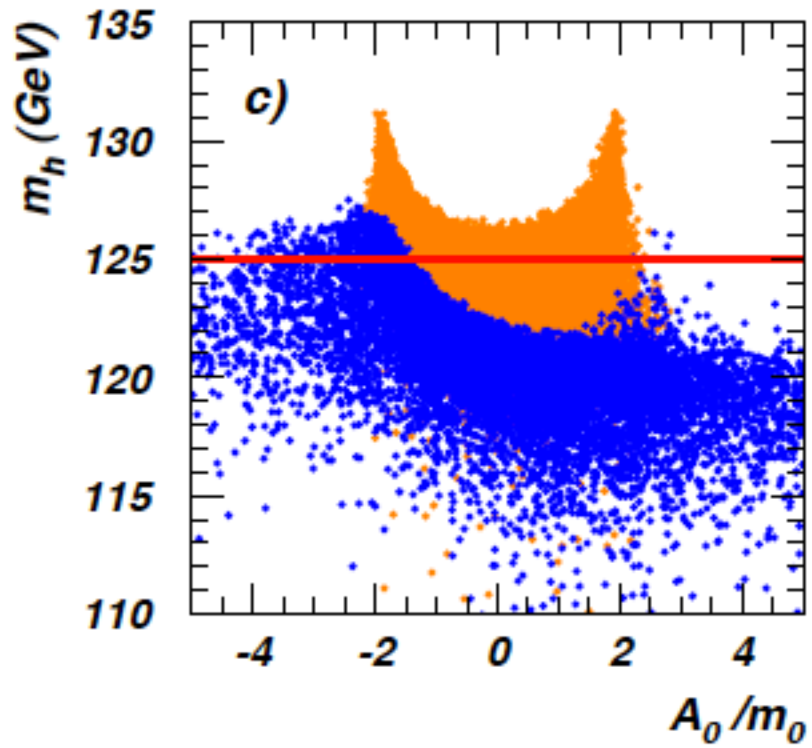
PRL109 (2012) 161802

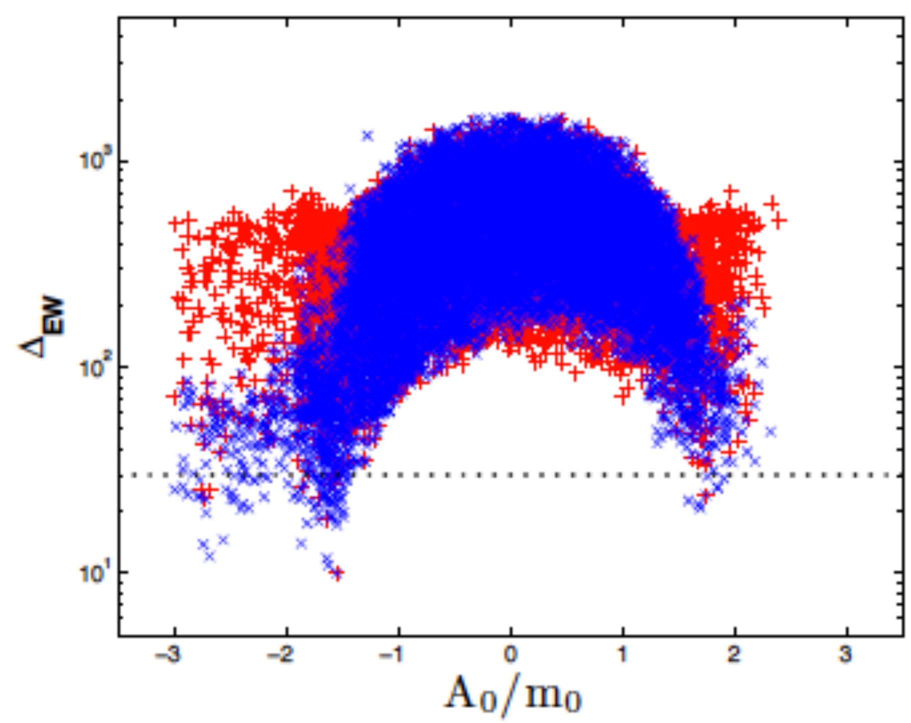
radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness



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





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

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

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

A low value of $\Delta_{EW} <\sim 30$ seems a necessary condition for EW naturalness in the MSSM:

but is it sufficient?

It is common to try an analogous procedure as in SM but for SUSY- this time with dominant log divergences (which are summed via RGEs)

$$
\begin{aligned}
m_h^2 &= \mu^2(weak) + m_{H_u}^2(weak) + mixing + rad.corr. \\
&\simeq \mu^2(\Lambda) + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2
\end{aligned}
$$

$$
\begin{aligned}
\delta m_{H_u}^2 &= \frac{1}{8\pi^2}\int_{Q=\Lambda}^{Q=m(weak)} d\log Q\left[-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2(m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2\right] \\
&\sim -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\log(\Lambda/m(weak))
\end{aligned}
$$

$$
\Delta_{HS} \equiv \delta m_{H_u}^2 / m_h^2
$$

- implies 3 3rd generation squarks <~500 GeV
- stimulated much effort for find stops at LHC
- none found: is SUSY dead?

It is common to try an analogous procedure for SUSY- this time with dominant log divergences (which are summed via RGEs)

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\end{aligned}
$$

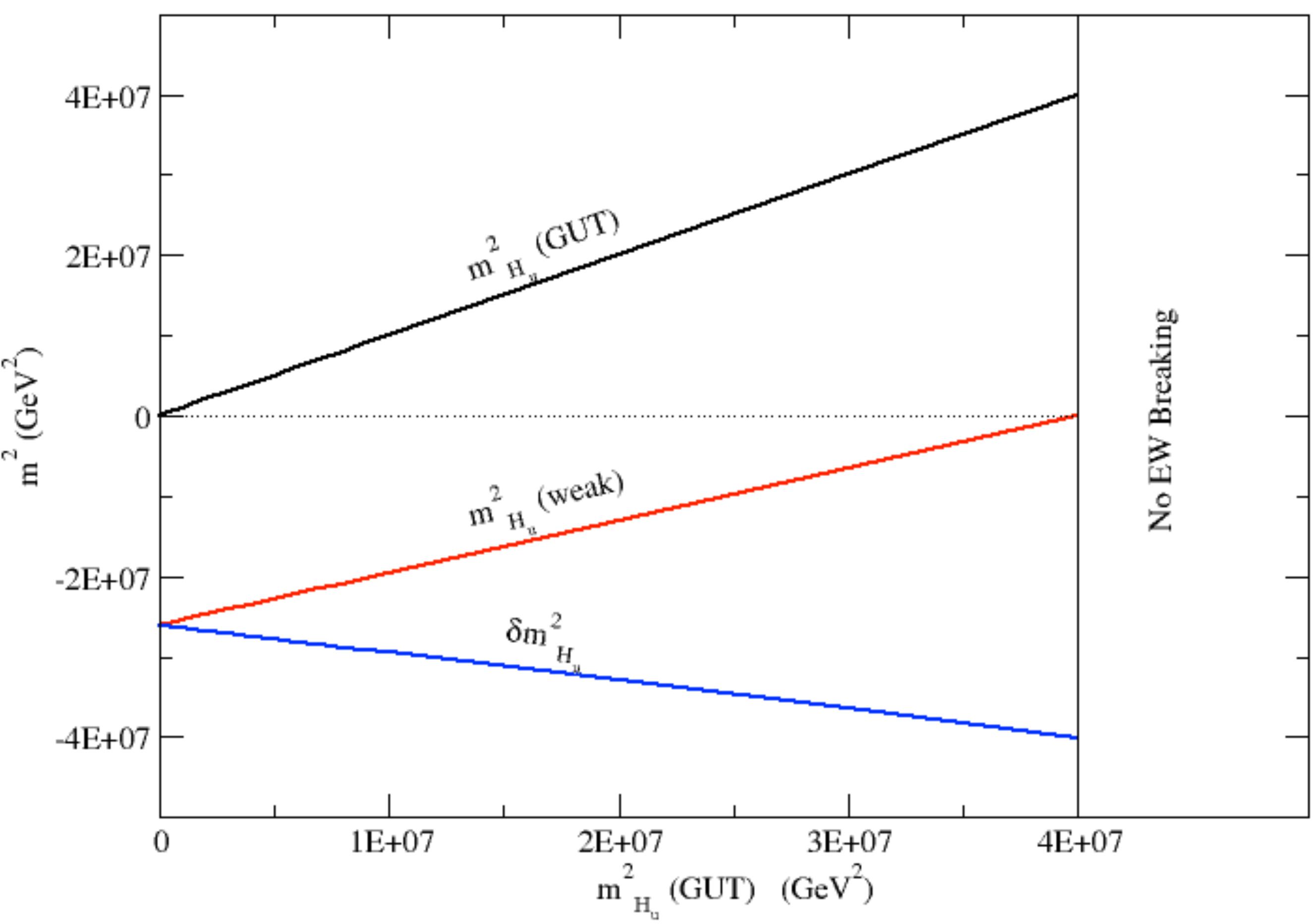
- implies 3 3rd gen squarks <500 GeV
- much effort for find stops at LHC
- but violates prime directive!

What's wrong with this argument?

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

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

violates prime directive!



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

HB, Barger, Savoy, arXiv:1502.04127

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?

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

p_i are the theory parameters

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

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

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

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?

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

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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

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

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

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

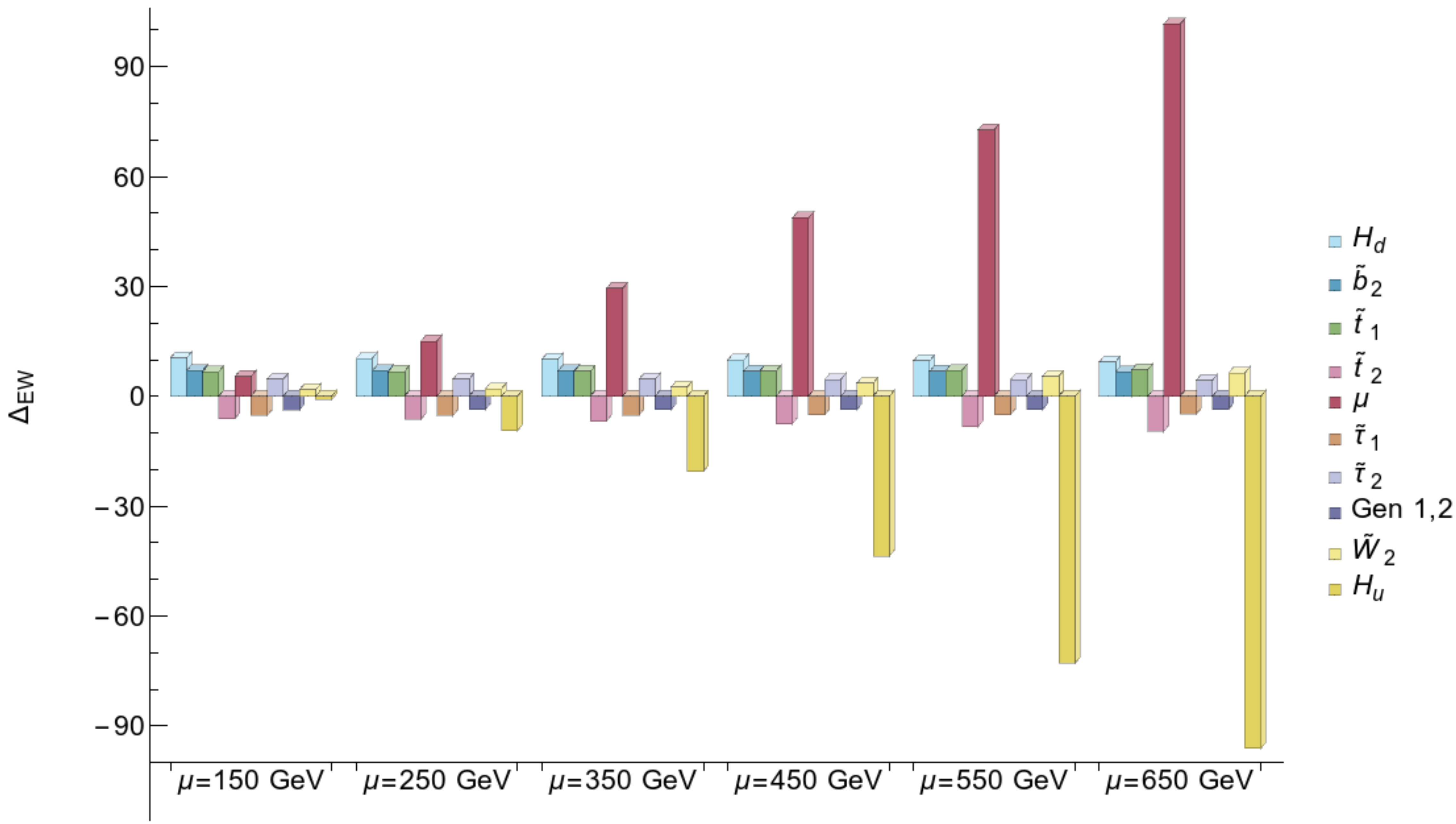
using μ^2 and $m_{3/2}^2$ as fundamental,
then $\Delta_{BG} \simeq \Delta_{EW}$ even using high scale parameters!

On SUSY parameters

- parameters are introduced by theorists to parametrize our ignorance of SUSY breaking
- in any more fundamental theory, soft terms are calculated in terms of single soft breaking parameter
- e.g. $m_{3/2}$ in SUGRA or AMSB, Λ in GMSB
- we think Δ_{EW} is a better measure of whether nature is fine-tuned, rather than our effective theories with artificially-introduced parameters

low Δ_{EW} seems necessary *and* sufficient for naturalness in pMSSM or in high scale models with *correlated* soft terms (as occur in any reasonable UV completion)!

How much is too much fine-tuning?



HB, Barger, Savoy

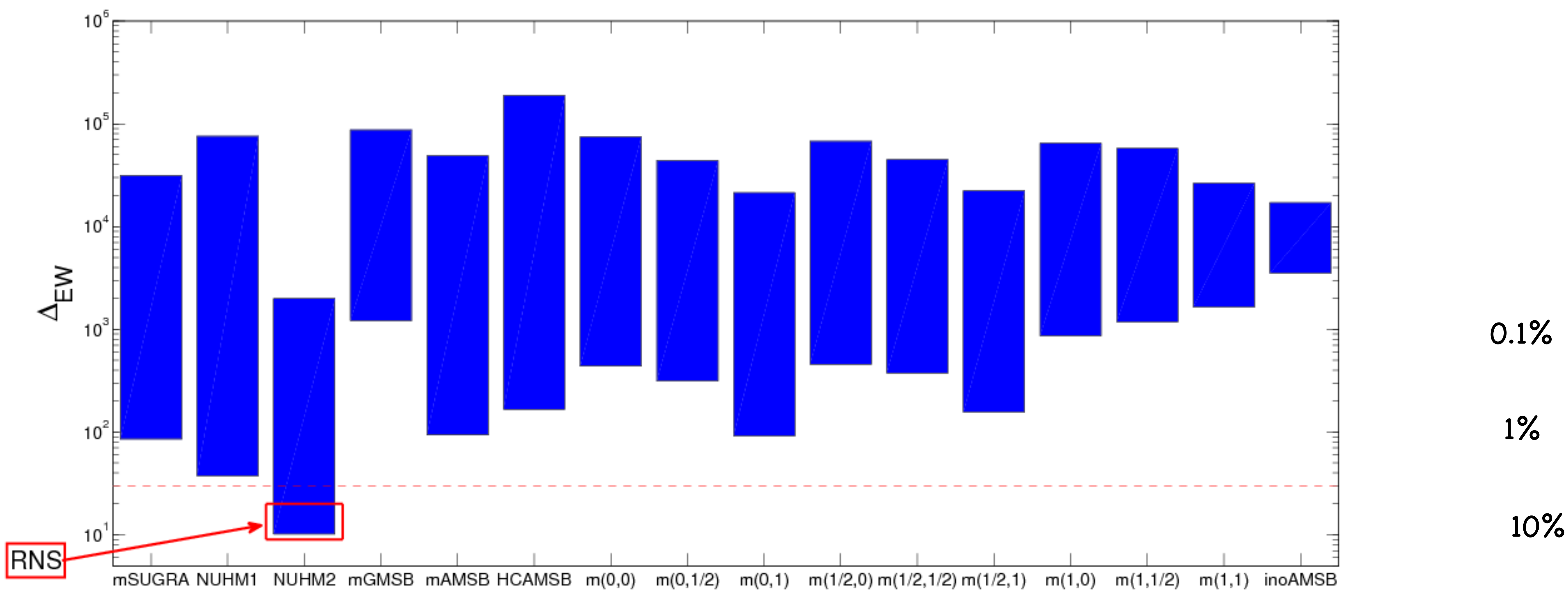
Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

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 natural generalized AMSB and mirage mediation

D. Matalliotakis and H. P. Nilles, Nucl. Phys. B **435** (1995) 115; M. Olechowski and S. Pokorski, Phys. Lett. B **344** (1995) 201; P. Nath and R. L. Arnowitt, Phys. Rev. D **56** (1997) 2820; J. Ellis, K. Olive and Y. Santoso, Phys. Lett. **B539** (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, Nucl. Phys. **B652** (2003) 259; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, JHEP**0507** (2005) 065.

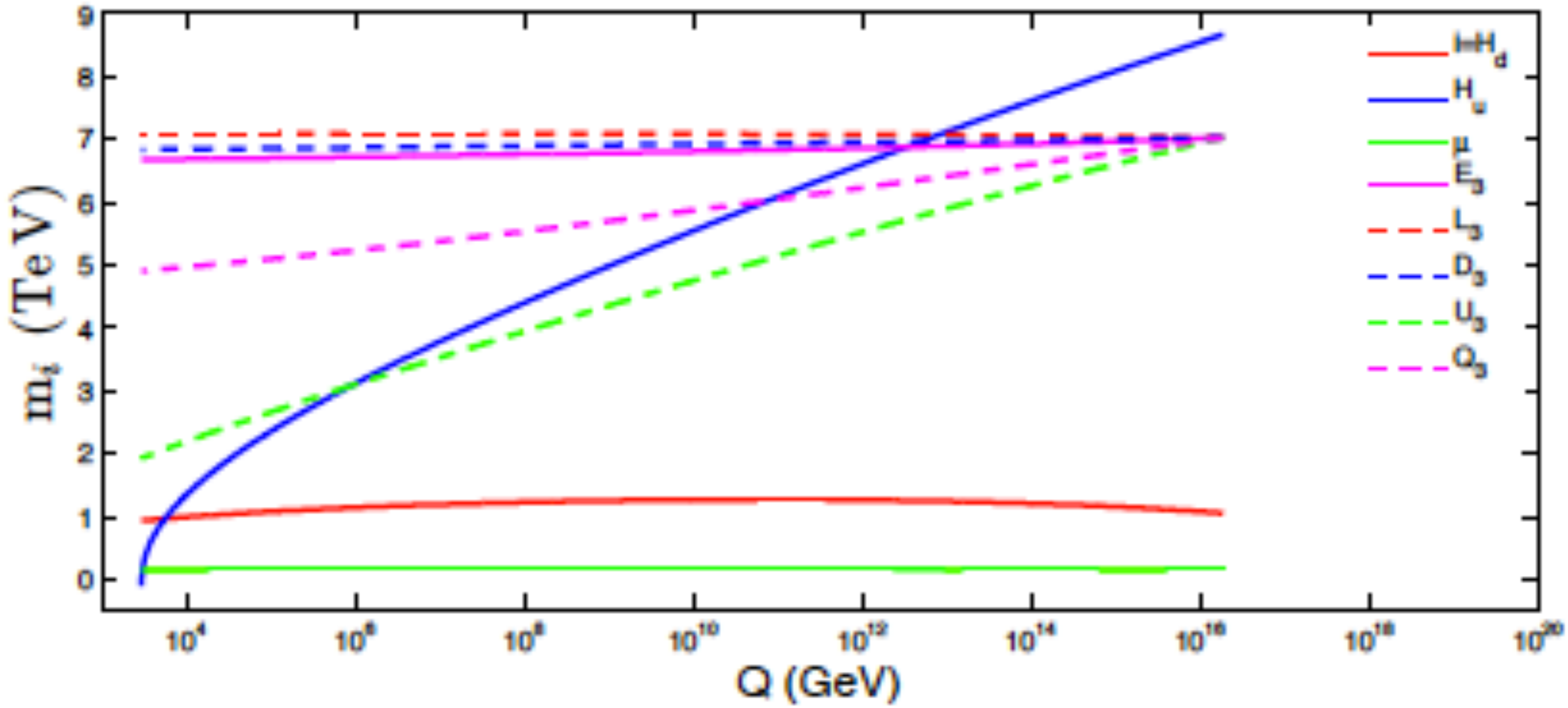
scan over p-space with m(h)=125.5+-2.5 GeV:



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:

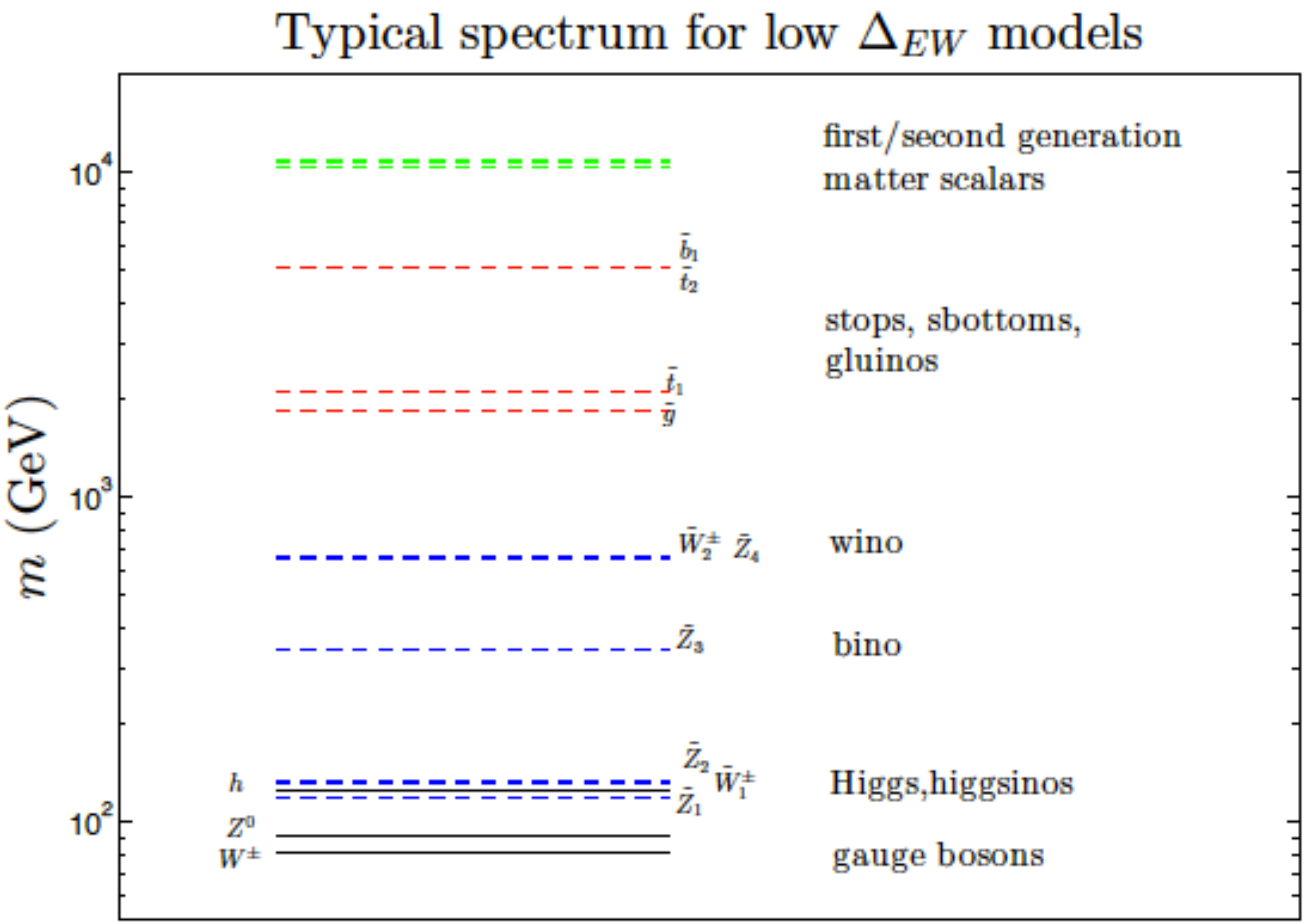
(typically need mHu~25-50% higher than m0)

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

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

Summary so far:

First order question:
why is the weak scale m(W,Z,h)~100 GeV?
Because mu(weak), mHu(weak)~100-200 GeV
and top squarks ~few TeV but highly mixed

Second order question:
Why might mu<< m(SUSY)
and why are soft terms such that
mHu(weak)~100-200 GeV?

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); but 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: $W \ni \lambda_\mu S^2 H_u H_d / m_P$

KN: PQ symmetry forbids mu term, but then it is generated via PQ breaking $\mu \sim \lambda_\mu f_a^2 / m_P$

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

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

$f_a \ll m_{hid}$

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/CCK model

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

Choi, Chun, Kim (1996)

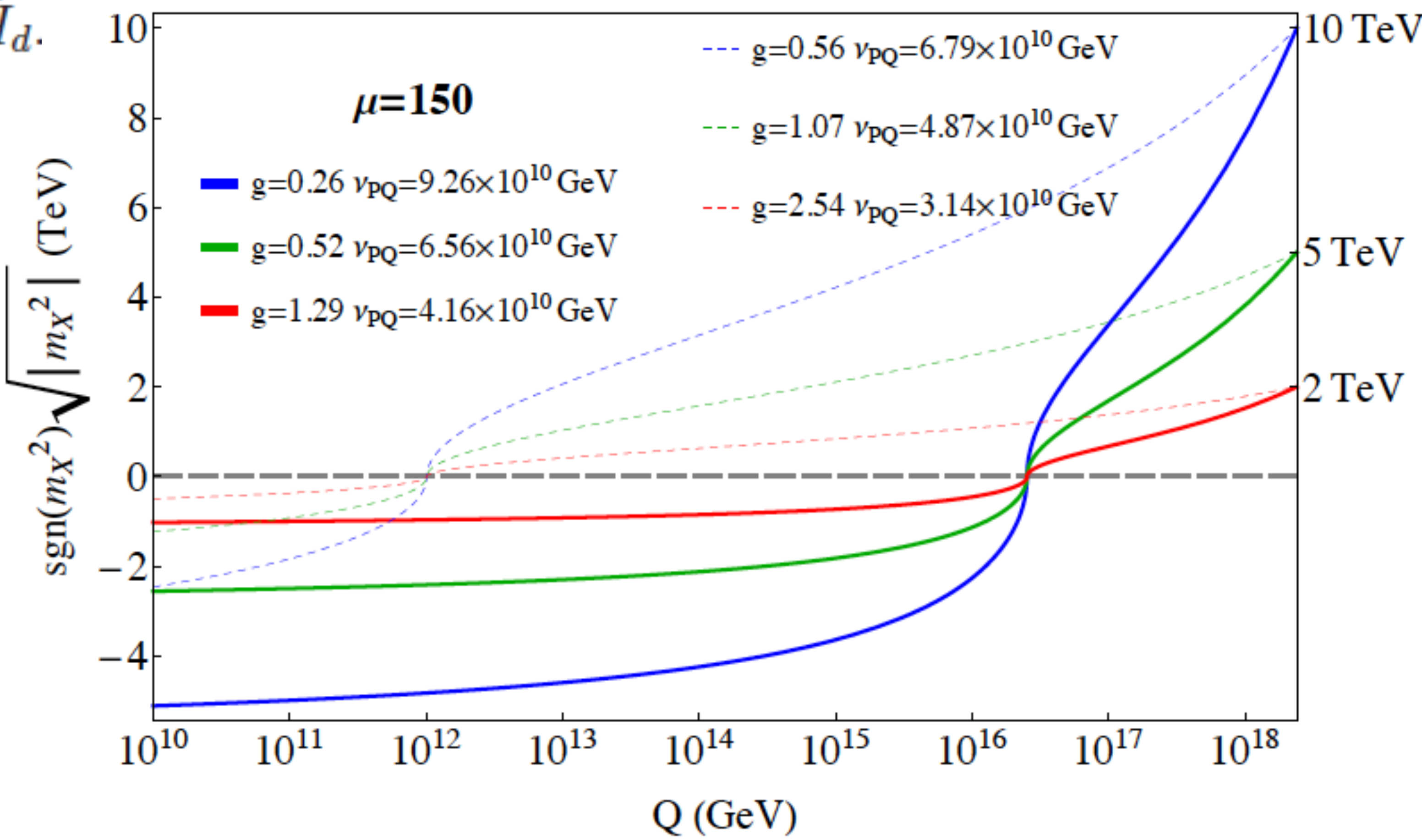
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

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

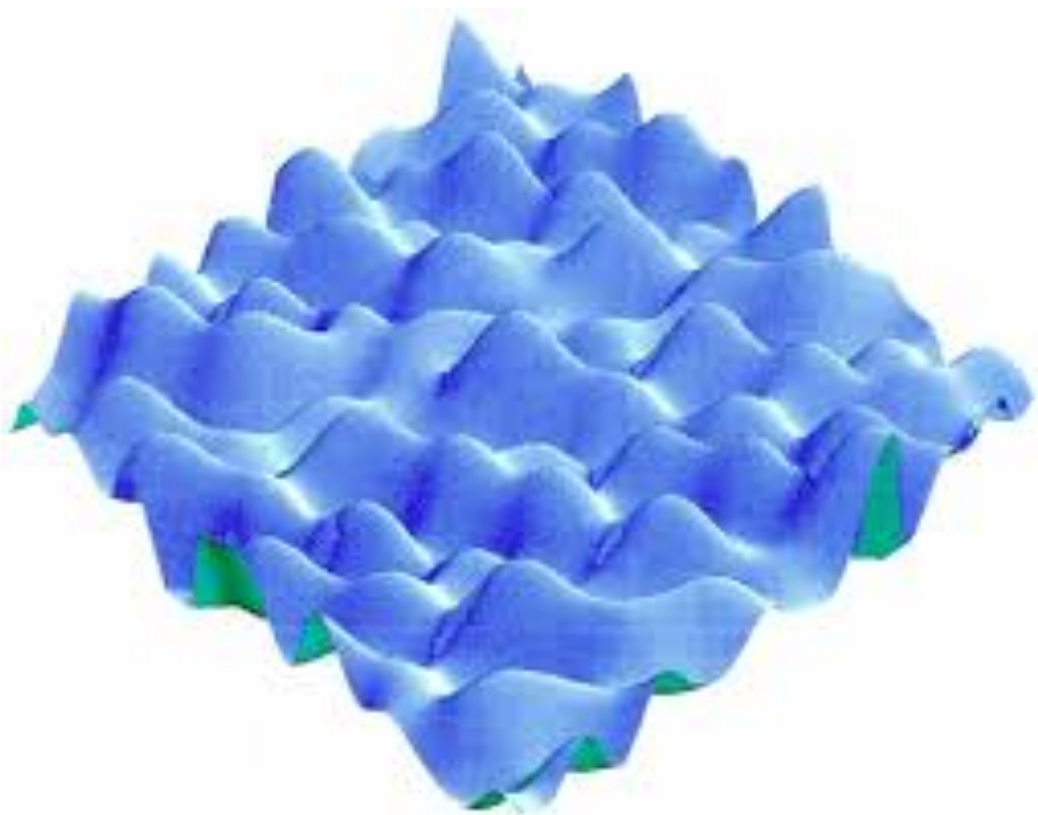
$$\mu = g \frac{v_X v_Y}{M_P} .$$

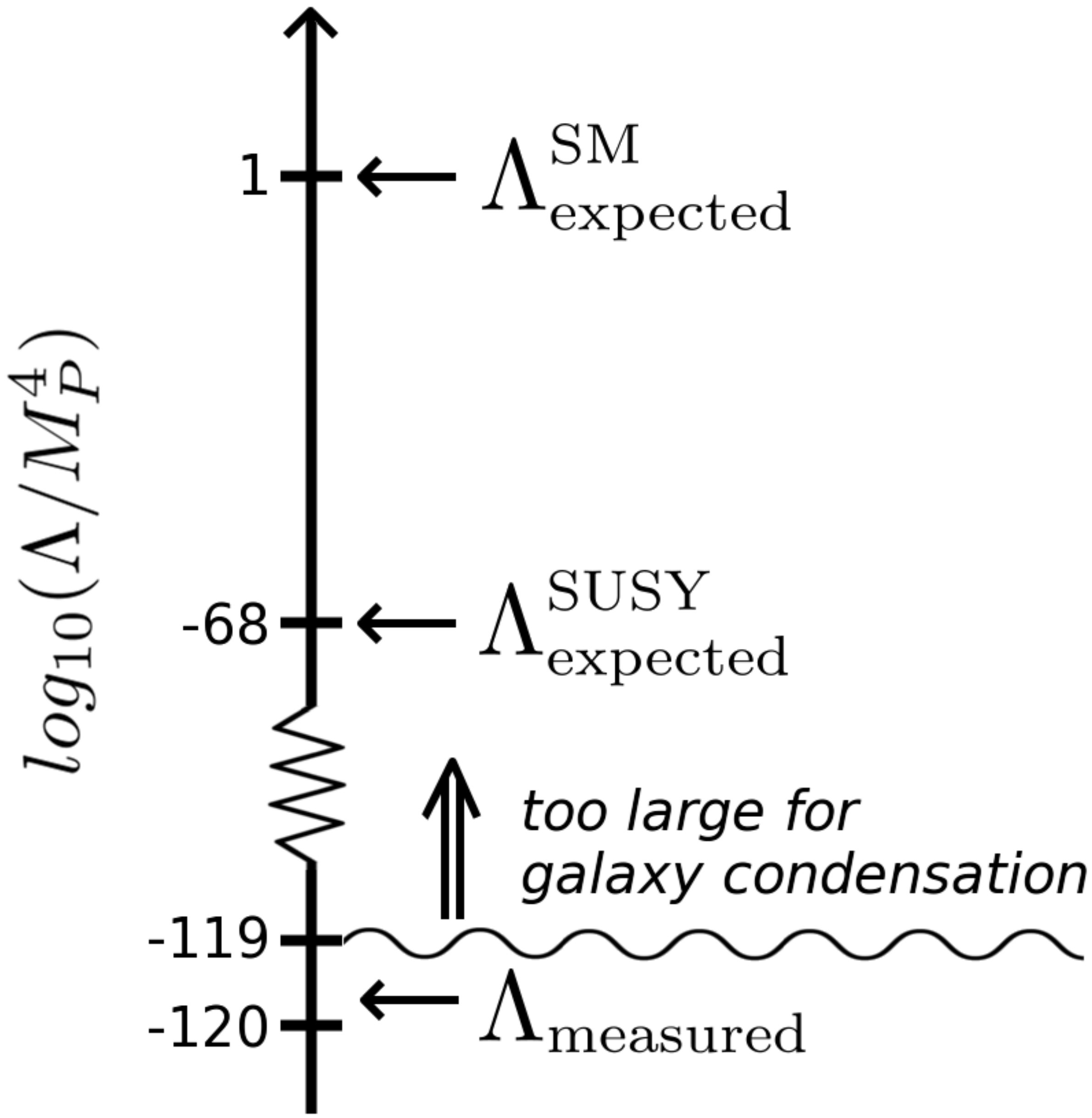


Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

Landscape of string theory vacua provides solution to cosmological constant

$n_{vac} \sim 10^{500}$?





Weinberg; Bousso Polchinski; Denef Douglas;...

Can similar reasoning explain scale of soft SUSY breaking?

Statistical analysis of SUSY breaking scale in IIB theory:

M. Douglas, hep-th/0405279

start with 10^500 string vacua states

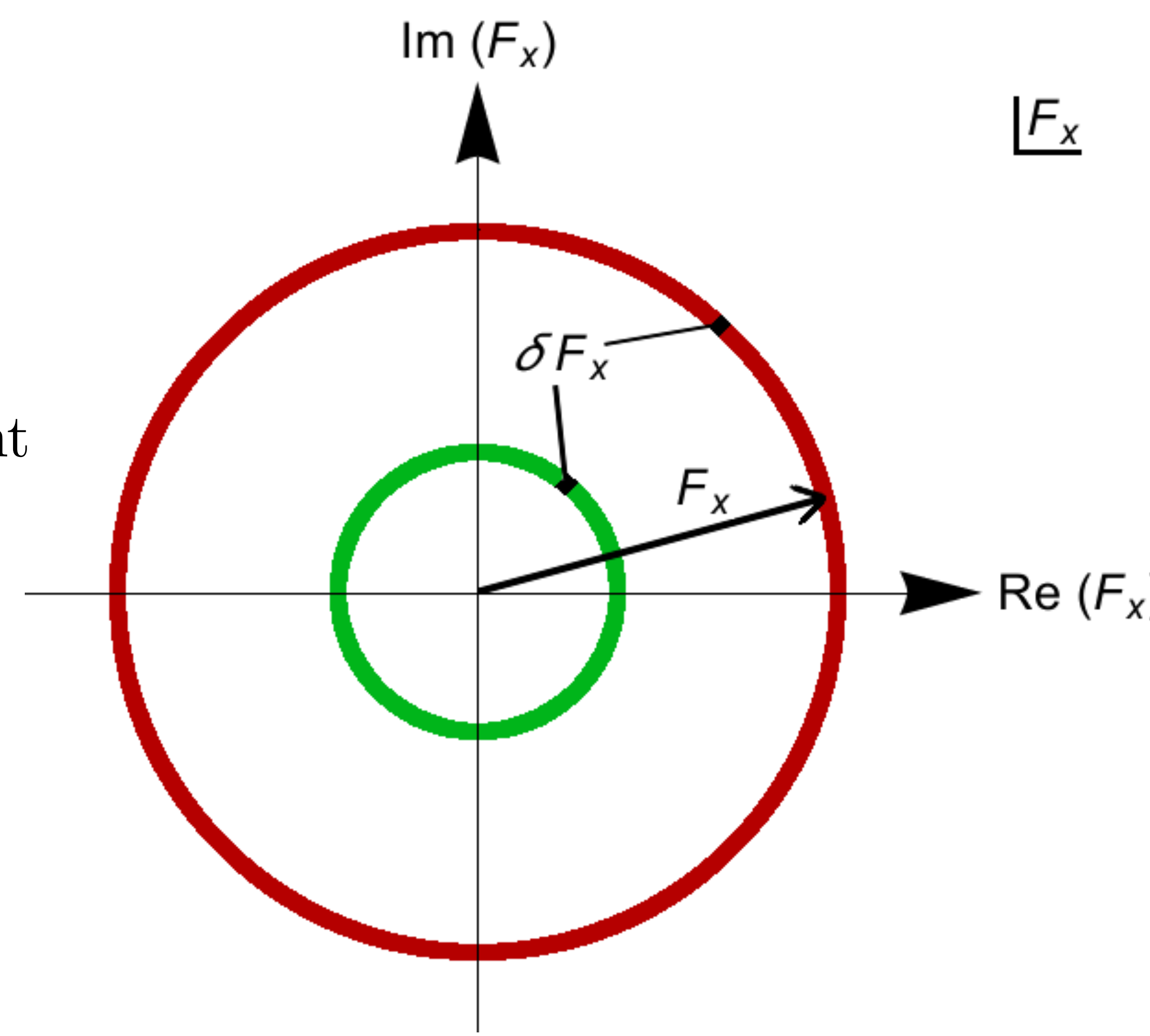
- string theory landscape contains vast ensemble of N=1, d=4 SUGRA EFTs at high scales
- the EFTs contain the SM as weak scale EFT
- the EFTs contain visible sector +potentially large hidden sector
- visible sector contains MSSM plus extra gauge singlets (e.g. a PQ sector, RN neutrinos,...)
- SUGRA is broken spontaneously via superHiggs mechanism via either F- or D- terms or in general a combination

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 $m(weak)^2 \sim |m_{H_u}^2|$
- 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



$m(weak) <\sim 400$ GeV (Agrawal et al.)

V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel, Phys. Rev. D **57** (1998) 5480;
V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel, Phys. Rev. Lett. **80** (1998) 1822.

Denef&Douglas: statistics of SUSY breaking in landscape

DD observation: W_0 distributed uniformly as complex variable allows dynamical neutralization of Λ while not influencing SUSY breaking

Then, number of flux vacua containing spontaneously broken SUGRA with SUSY breaking scale m^2_{hidden} is:

$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$

- $f_{cc} \sim \Lambda/m^4$ where DD maintain $m \sim m_{string}$ and not m_{hidden}
- $f_{SUSY}(m^2_{hidden}) \sim (m^2_{hidden})^{2n_F+n_D-1}$ for uniformly distributed values of F and D breaking fields
- $f_{EWFT} \sim m^2_{weak}/m^2_{soft}$ (?) where $m_{soft} \sim m_{3/2} \sim m^2_{hidden}/m_P$

$$n = 2n_F + n_D - 1$$

$$f_{SUSY} \sim m^n_{soft}$$

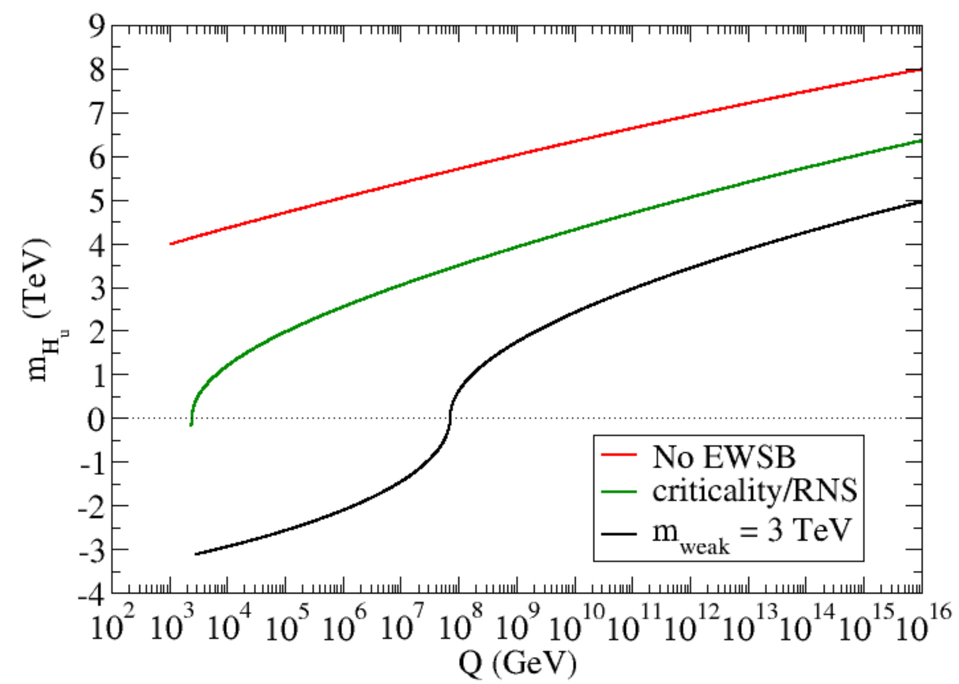
n_F	n_D	n
0	1	0
1	0	1
0	2	1
1	1	2
0	3	2
2	0	3
2	1	4

landscape favors high scale SUSY breaking
tempered by f(EWFT) anthropic penalty!

What about DD/AD anthropic penalty $f_{EWFT} \sim m^2_{weak}/m^2_{soft}$?

This fails in a variety of *practical* cases:

- A-terms get large: $\Rightarrow CCB$ minima
- $m^2_{H_u}$ too large: fail to break EW symmetry



Must require proper EWSB!

Even if EWS properly broken, then

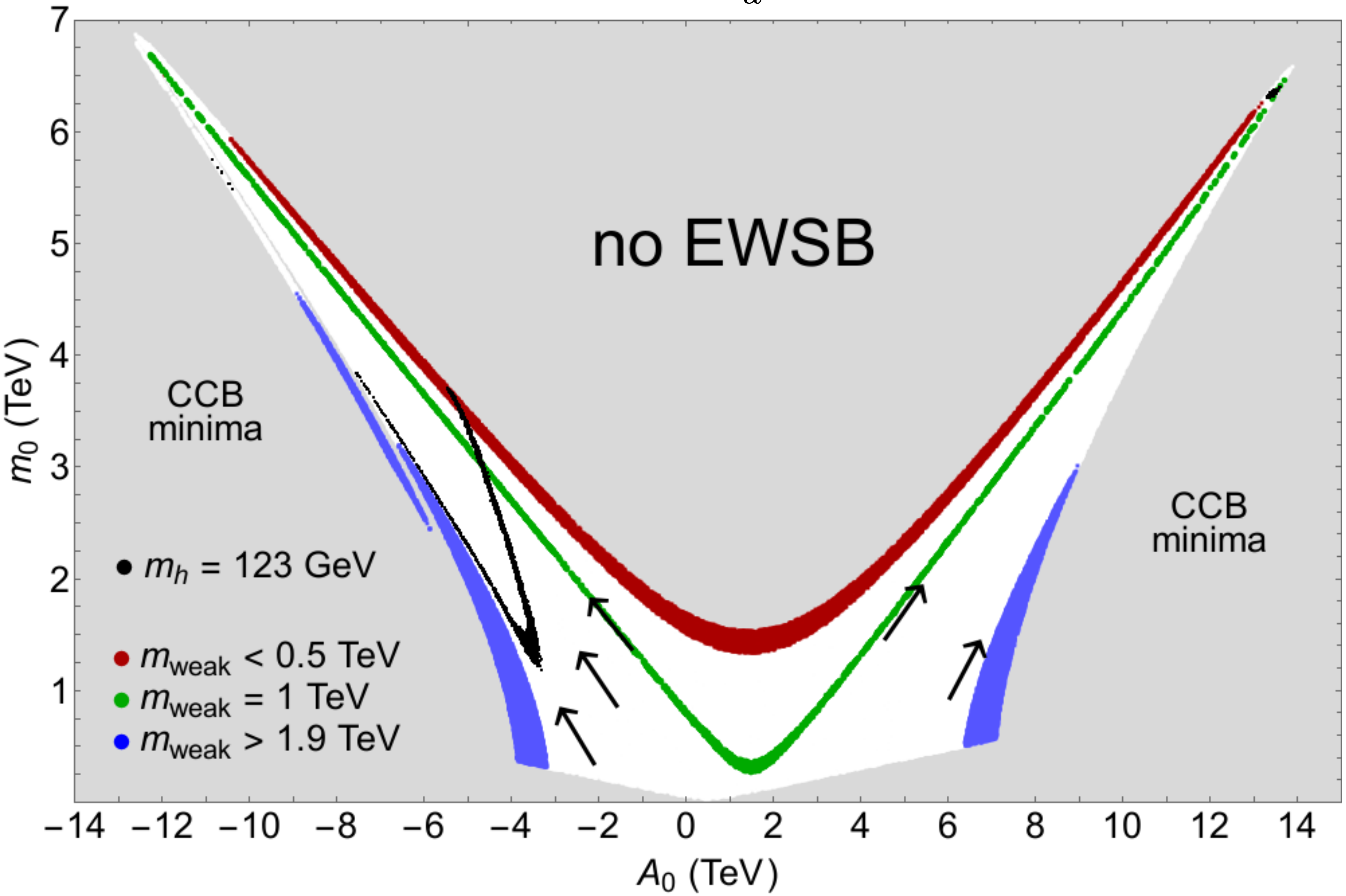
- large A_t *reduces* EWFT in the $\Sigma^u_u(\tilde{t}_{1,2})$
- large $m^2_{H_u}(m_{GUT})$ needed to radiatively drive $m^2_{H_u}$ to natural value at weak scale

Better proposal: $f_{EWFT} \Rightarrow \Theta(30 - \Delta_{EW})$
keeps calculated weak scale within factor ~ 4 of measured weak scale
$m_{weak} \equiv m_{W,Z,h} \sim 100$ GeV

Assume $\mu \sim 100-200$ GeV via *e.g.* rad PW breaking: then m_Z variable and may be large depending on soft terms $m^2_{H_{u,d}}$ and $\Sigma^{u,d}_{u,d}(i)$

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

$$m_{H_u} = 1.3 m_0$$



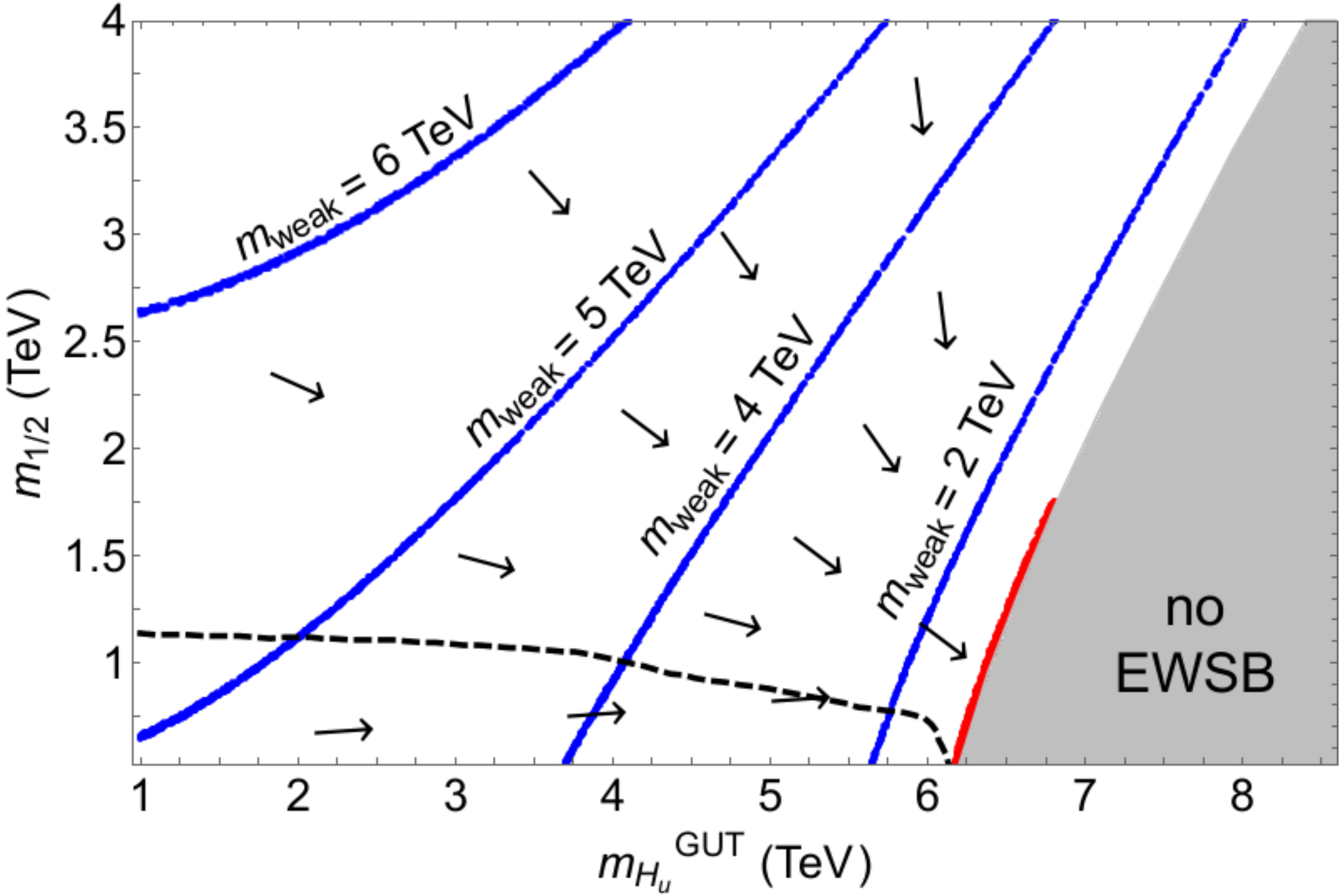
statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Denef, Douglas, JHEP0405 (2004) 072

Giudice, Rattazzi, NPB757 (2006) 19;

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

$m_0 = 5 \text{ TeV}$



statistical/anthropic draw toward FP-like region

Recent work: place on more quantitative footing: scan soft SUSY breaking parameters in NUHM3 model as m(soft)^n along with f(EWFT) penalty

We scan according to m_{soft}^n over:

- $m_0(1,2): \ 0.1 - 40$ TeV,
- $m_0(3): \ 0.1 - 20$ TeV,
- $m_{1/2}: \ 0.5 - 10$ TeV,
- $A_0: \ 0 - \ -60$ TeV,
- $m_A: \ 0.3 - 10$ TeV,

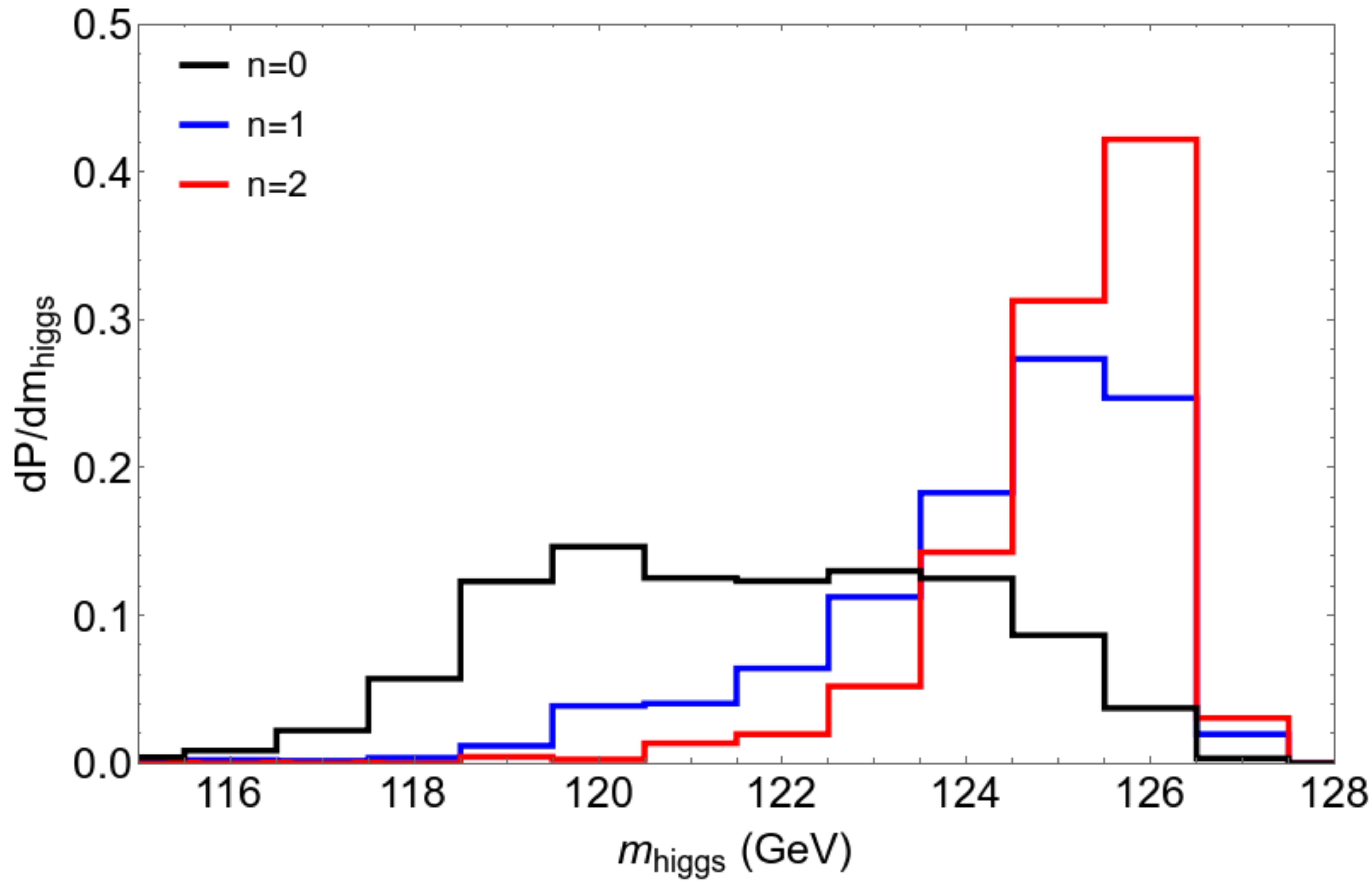
$\tan\beta : 3 - 60$ (flat)

mu=150 GeV (fixed)

HB, Barger, Serce, Sinha, JHEP1803 (2018) 002

Making the picture more quantitative:

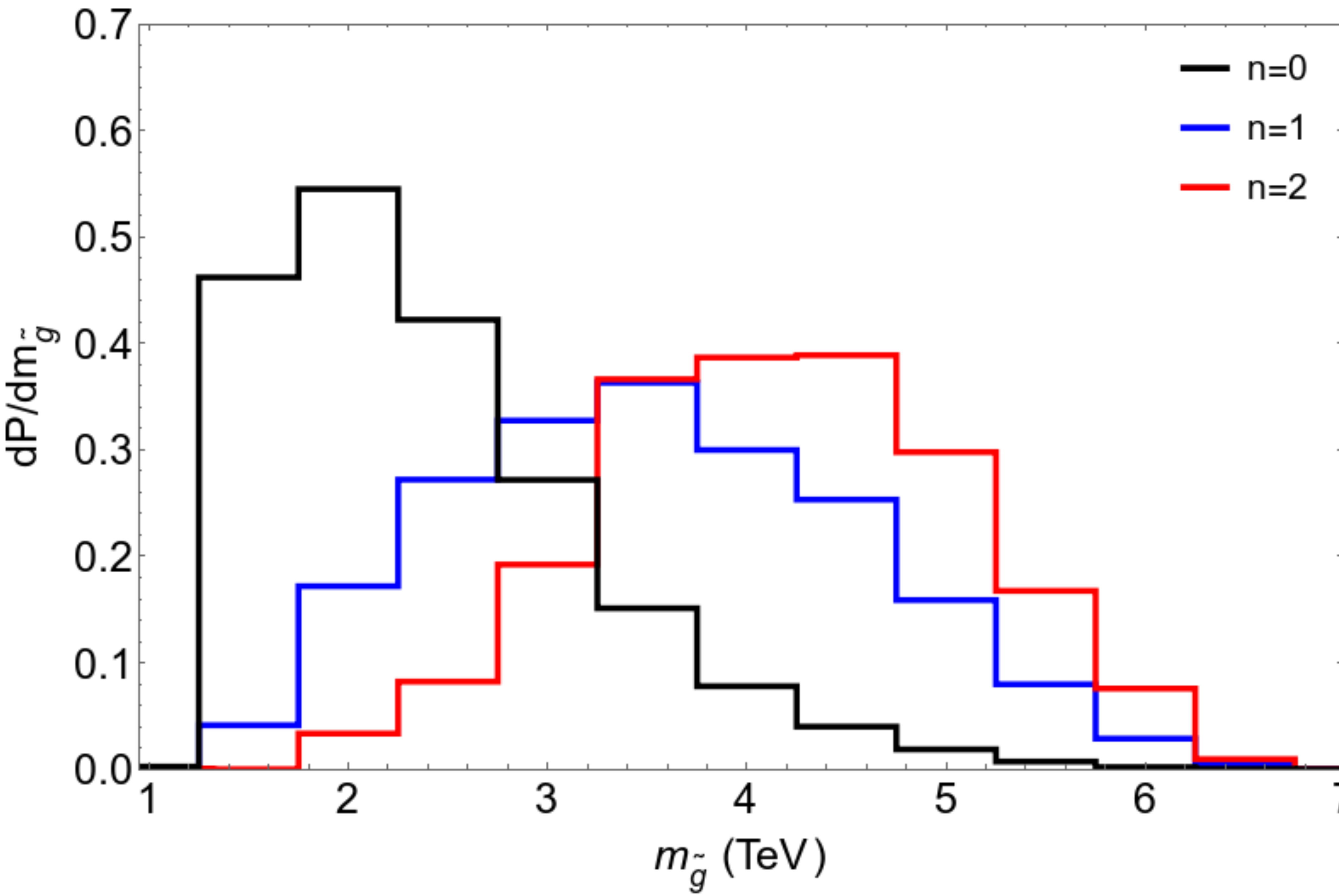
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



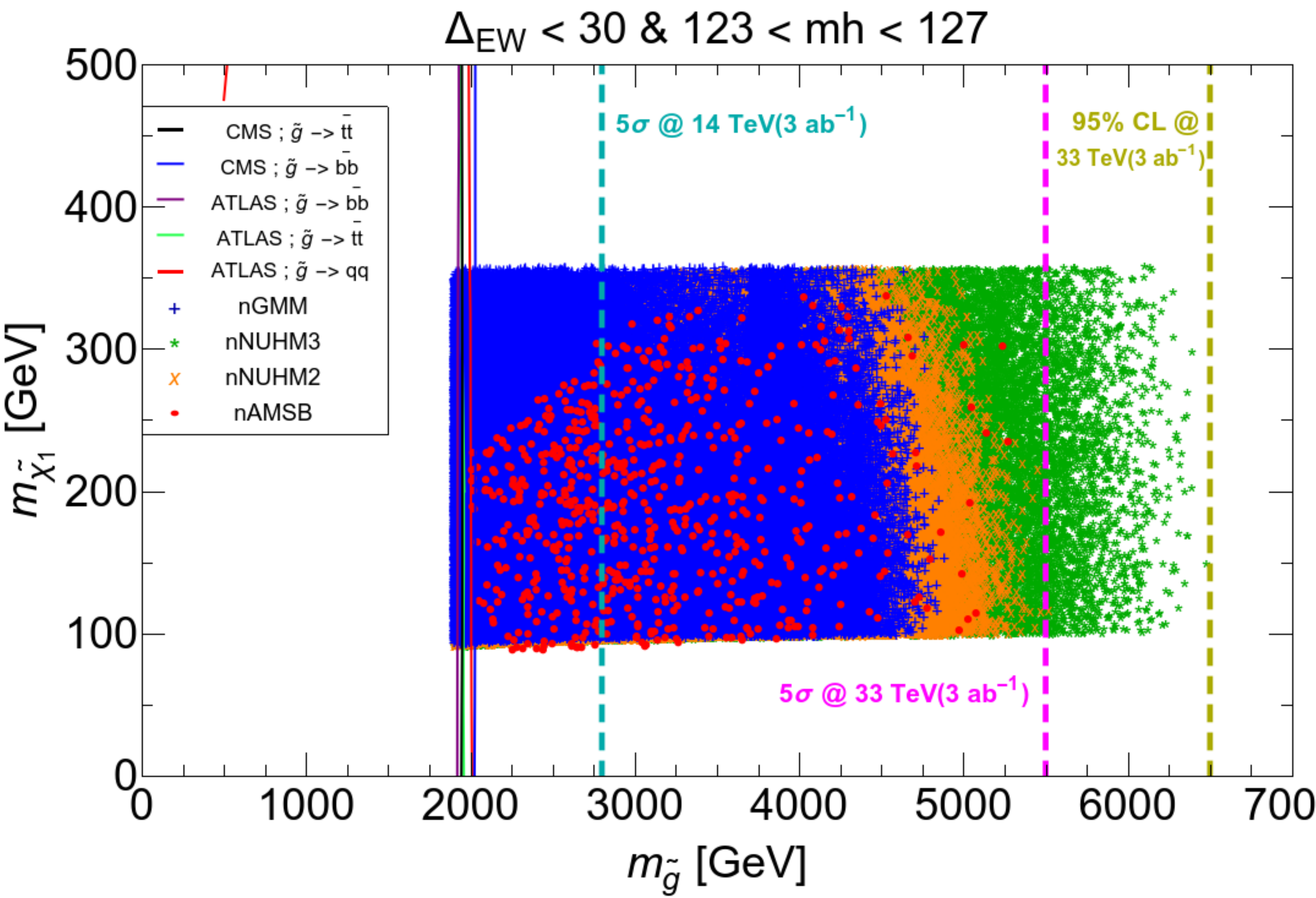
m(h)~125 most favored for n=1,2

HB,Barger, Serce, Sinha

What is corresponding distribution for gluino mass?

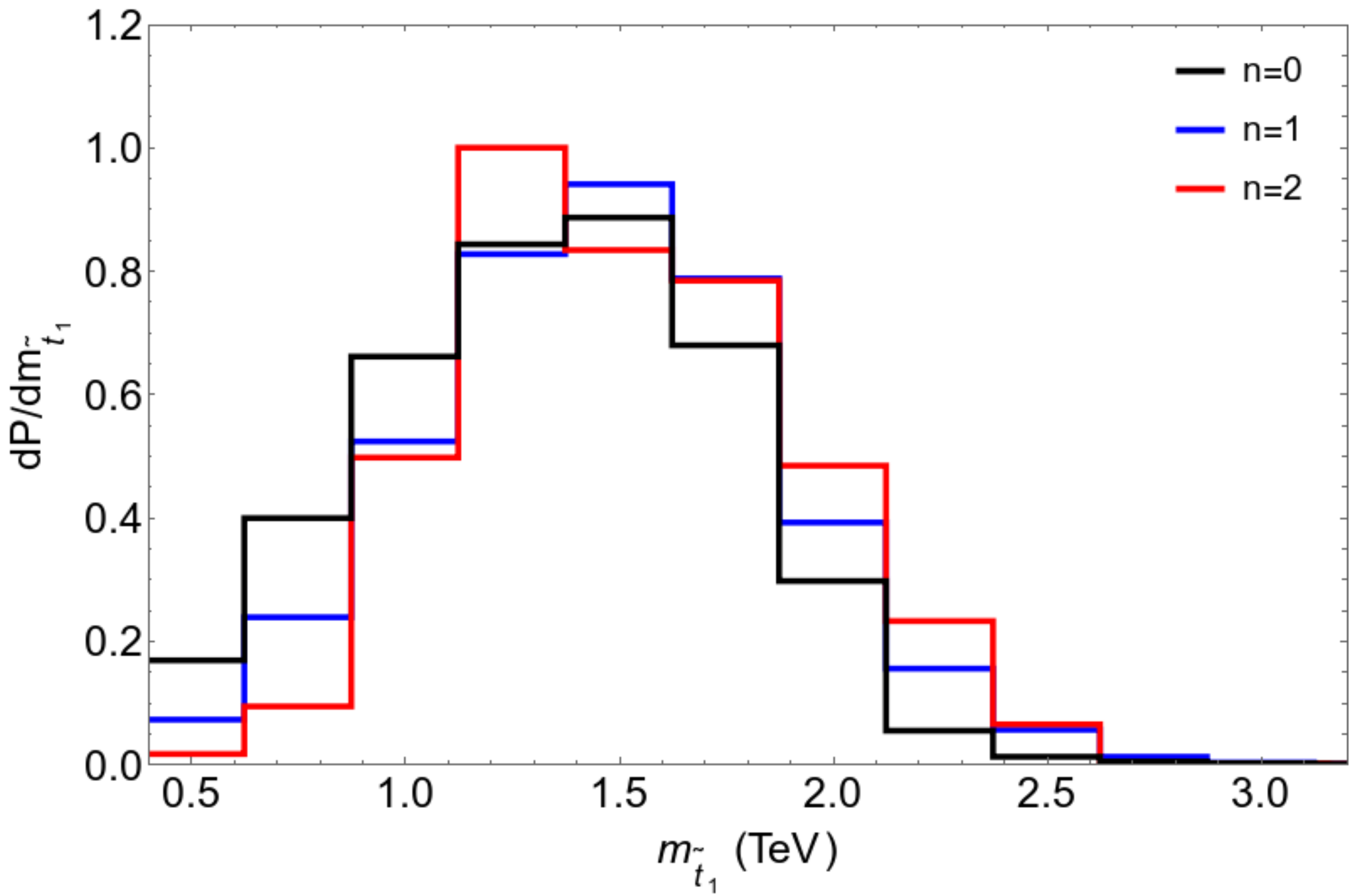


typically beyond LHC 14 reach (may need HE-LHC)



evidently HE-LHC can cover all natural SUSY p-space!

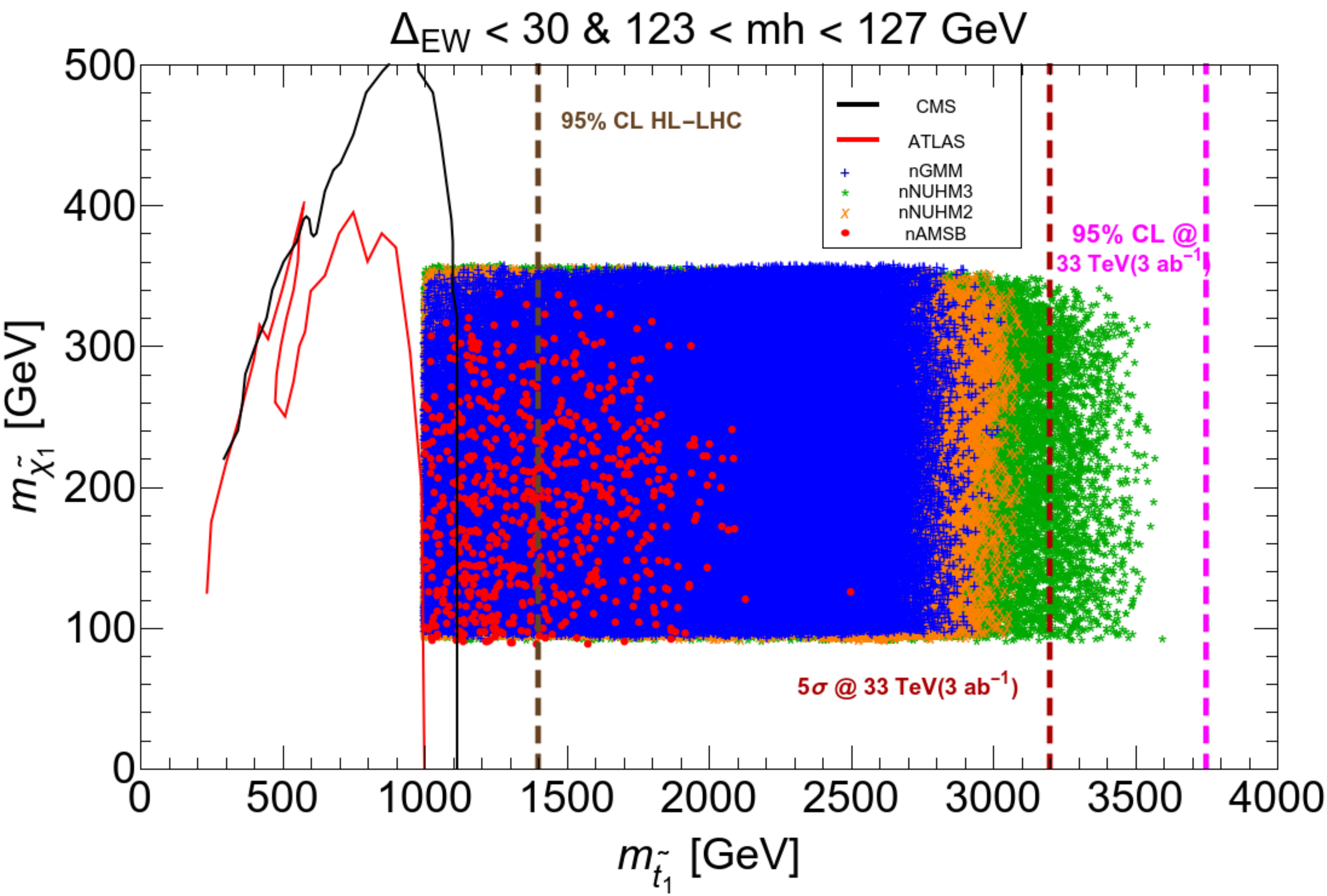
and m(t1)?



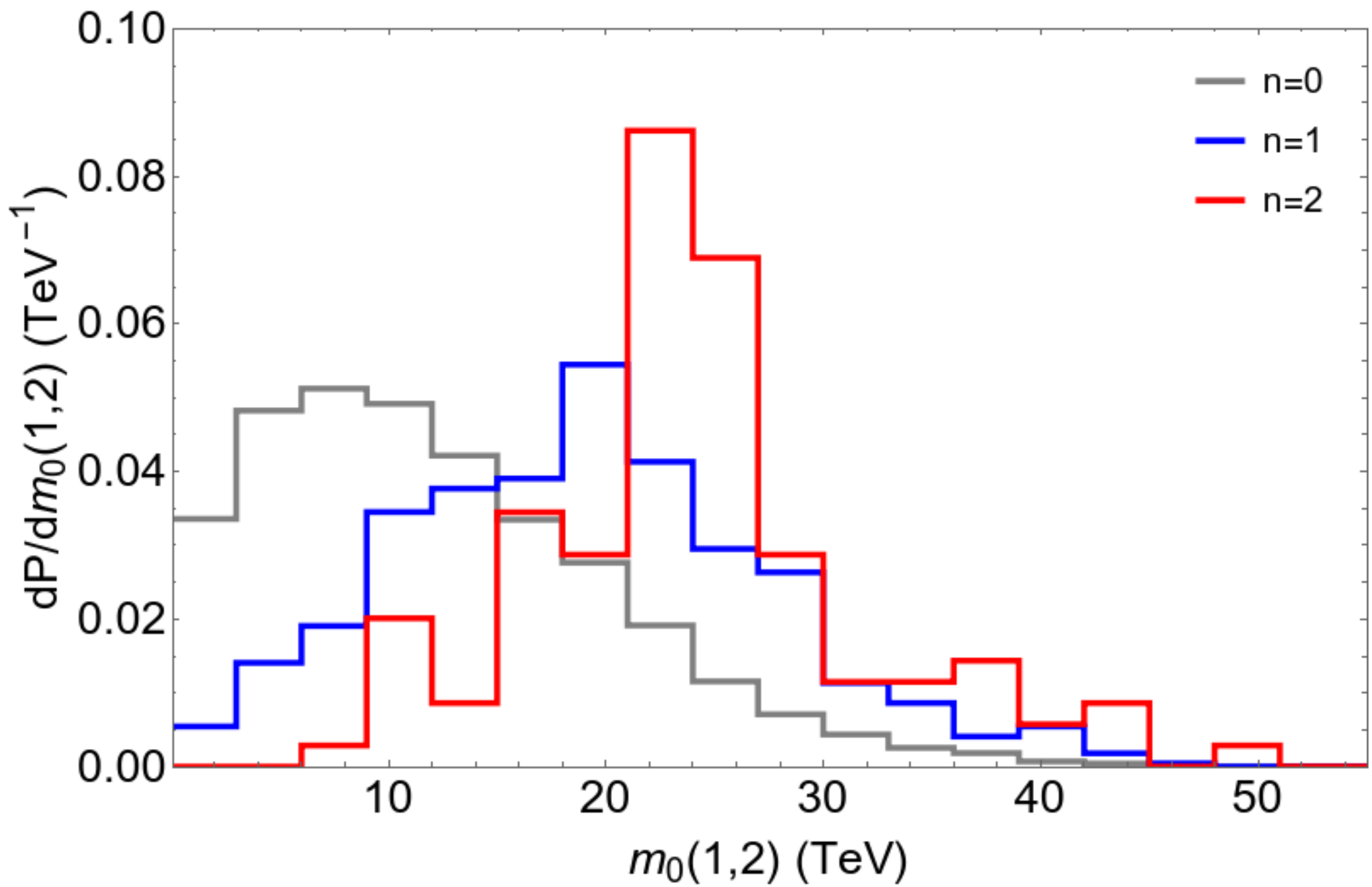
n=0
n=1
n=2
1.2
1.0
0.8
0.6
0.4
0.2
0.0
dP/dm$_{\tilde{t}_1}$
0.5
1.0
1.5
2.0
2.5
3.0
$m_{\tilde{t}_1}$ (TeV)

HL-LHC covers only fraction of p-space

HE-LHC reach for t1 covers all natural SUSY p-space!



first/second generation sfermions pulled to 10-30 TeV thus softening any SUSY flavor/CP problems



Summary n=1,2:

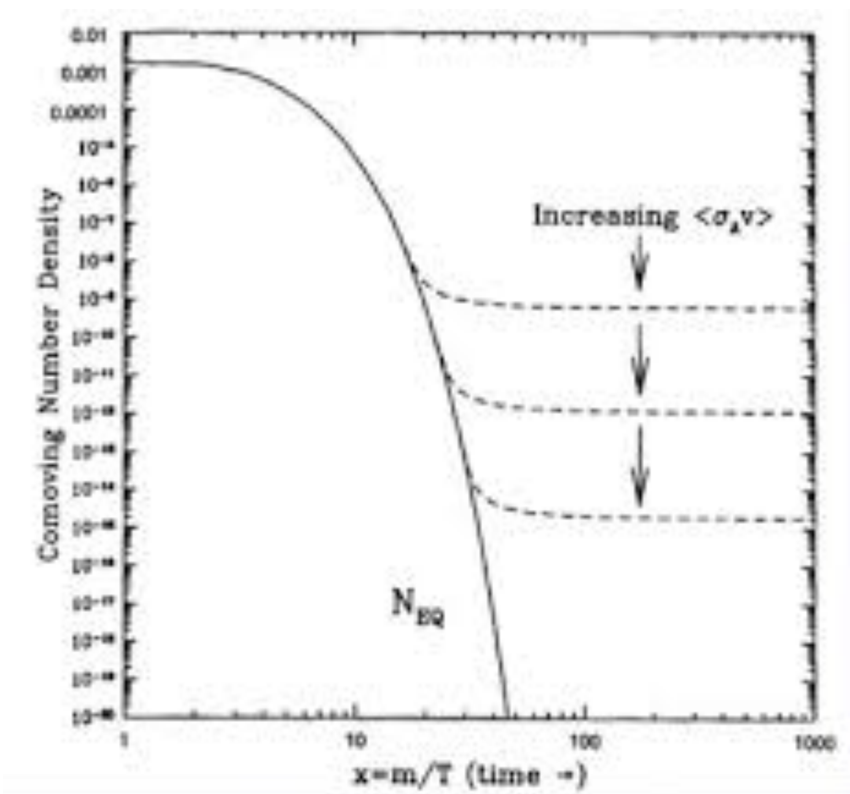
- $m_h \sim 125 \pm 2$ GeV
- $m_{\tilde{g}} \sim 4 \pm 2$ TeV,
- $m_{\tilde{t}_1} \sim 1.5 \pm 0.5$ TeV,
- $m_A \sim 3 \pm 2$ TeV,
- $\tan\beta \sim 13 \pm 7$,
- $m_{\widetilde{W}_1, \widetilde{Z}_{1,2}} \sim 200 \pm 100$ GeV and
- $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 7 \pm 3$ GeV with
- $m_0(1,2) \sim 20 \pm 10$ TeV (for first/second generation matter scalars)

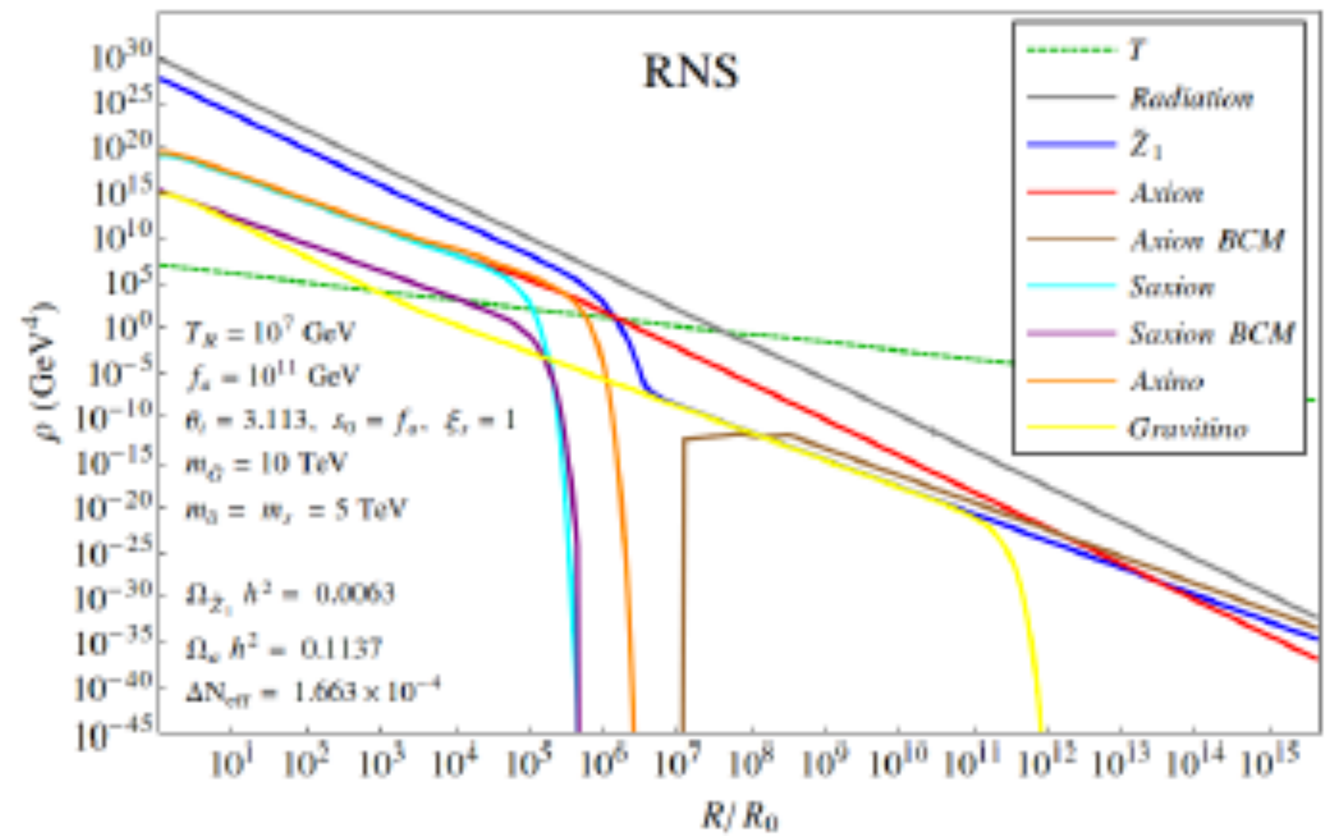
n>=3 case: soft terms pulled so hard usually gives CCB or no EWSB minima in scalar potential or huge value of weak scale >~ TeV

What happens to SUSY WIMP dark matter?

- higgsino-like WIMPs thermally underproduced
- 3 not four light pions => QCD theta vacuum
- F.F~ term should be present but neutron(EDM)=> it is tiny
- strong CP problem => 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

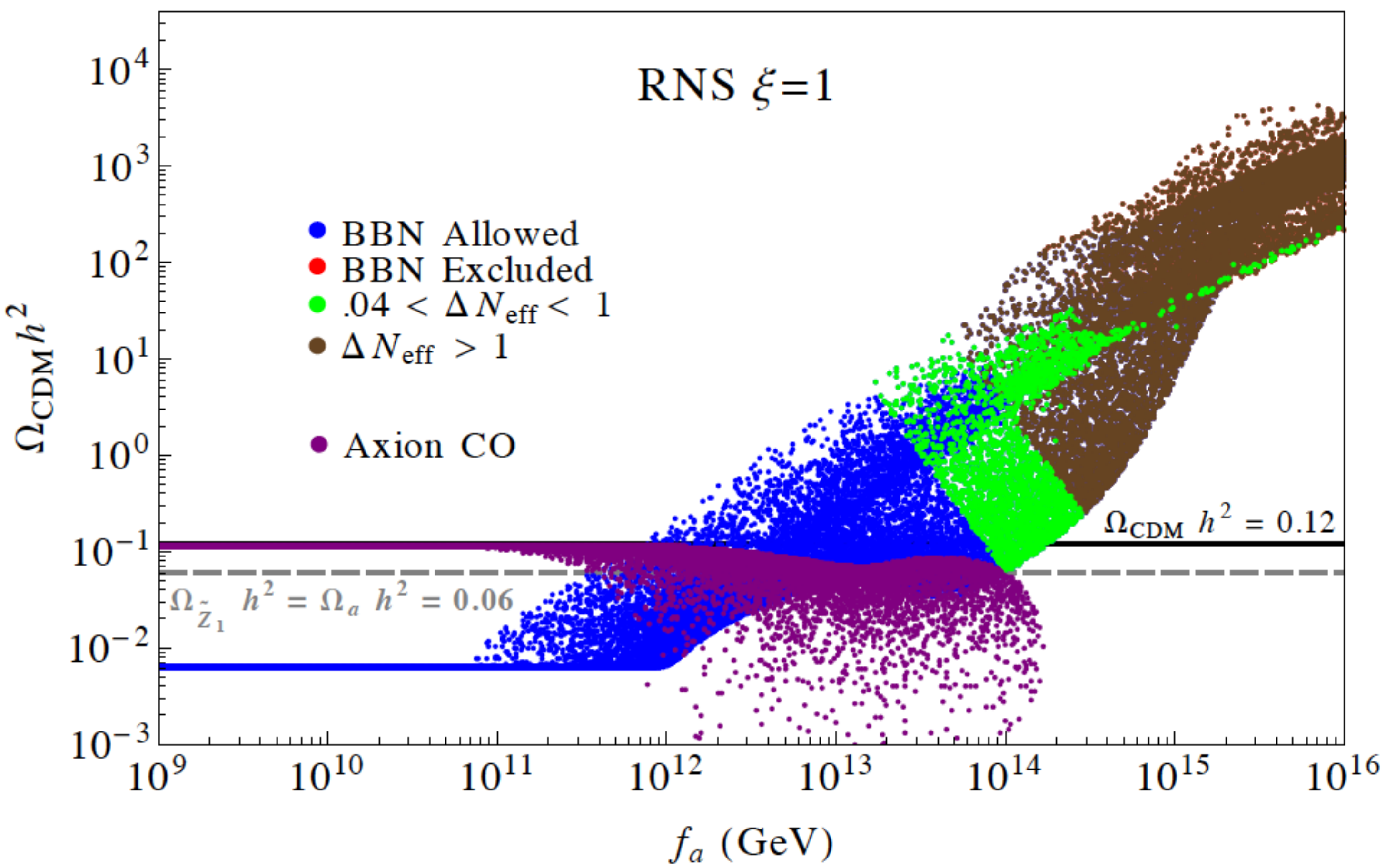




KJ Bae, HB, Lessa, Serce

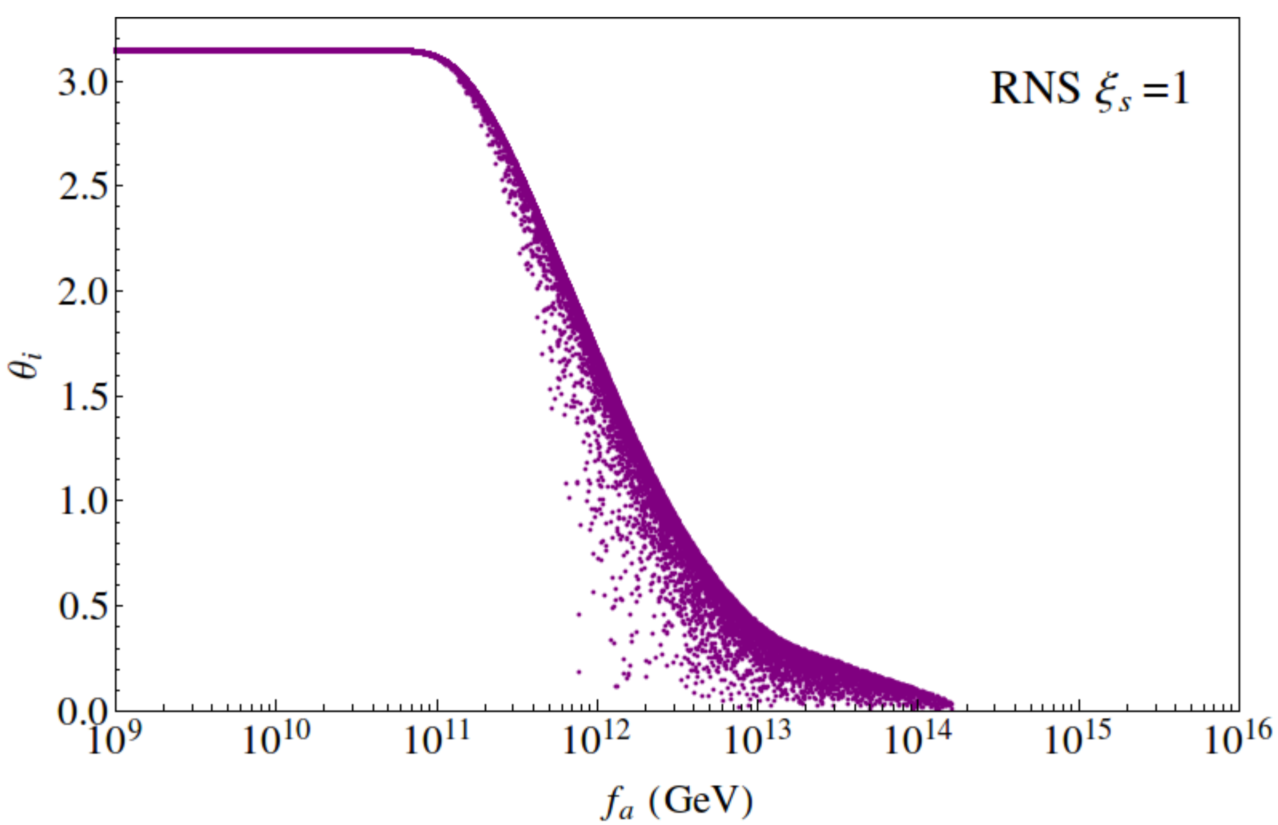
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

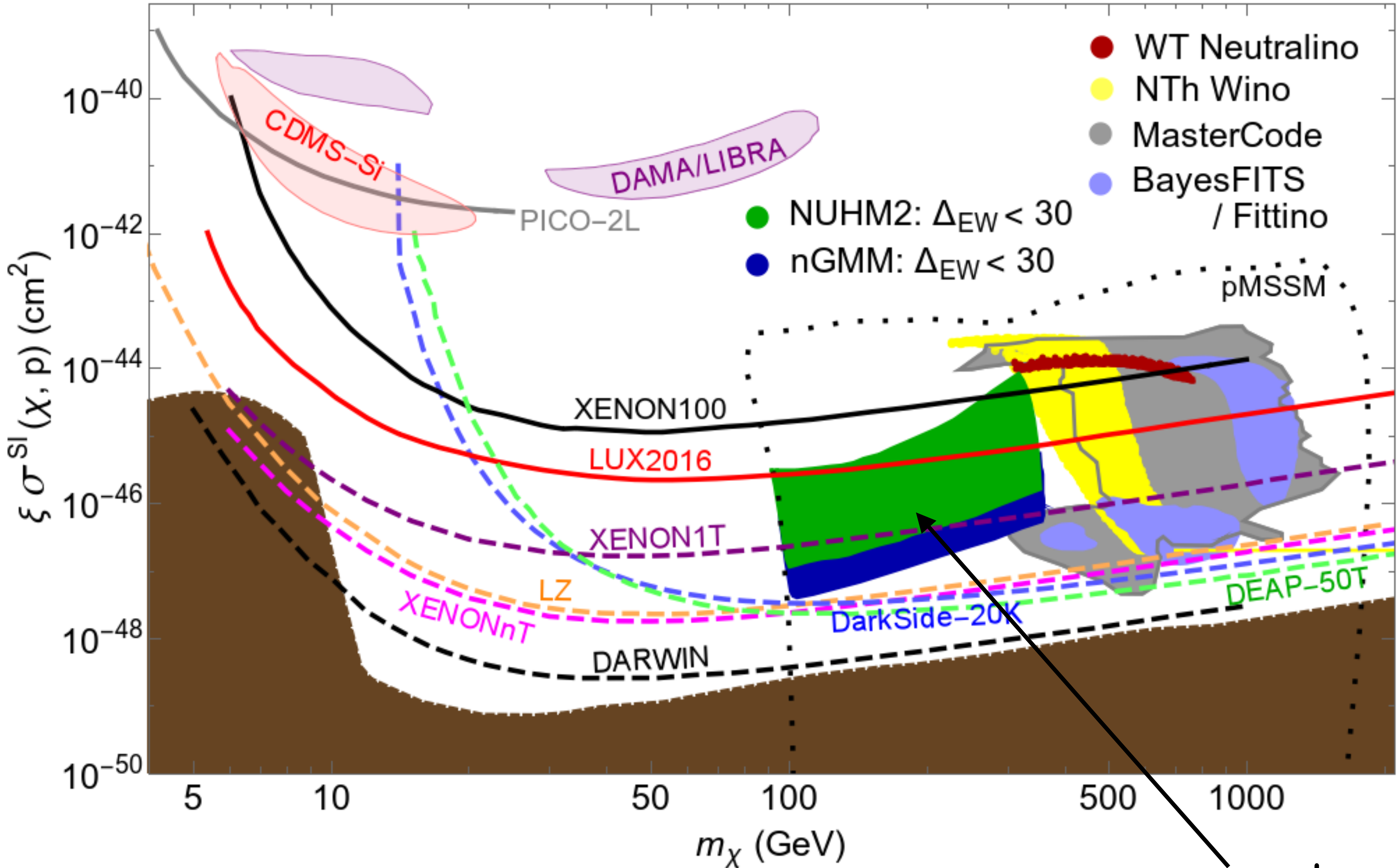
axion abundance



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

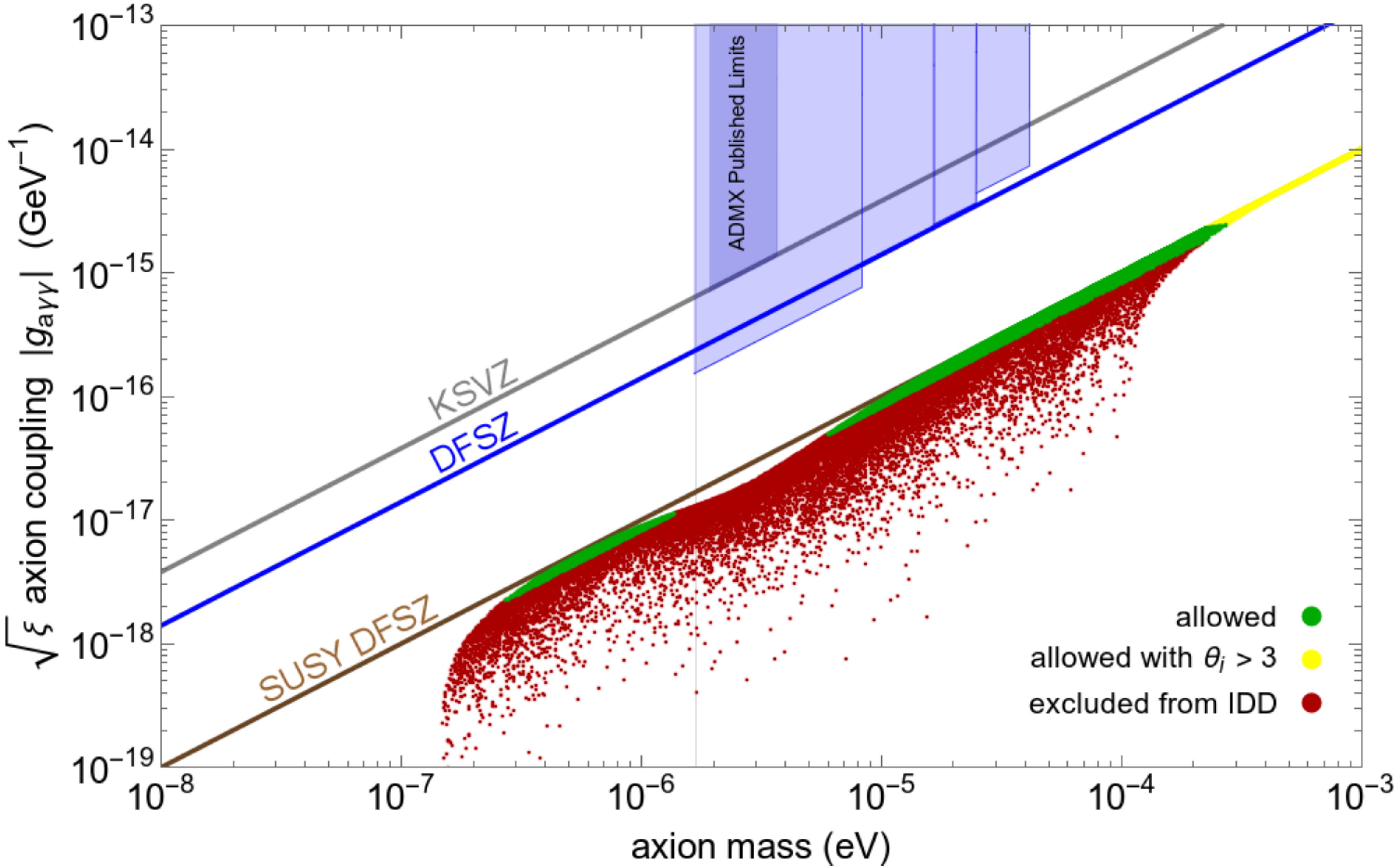
Bae, HB, Barger,Savoy,Serce

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

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

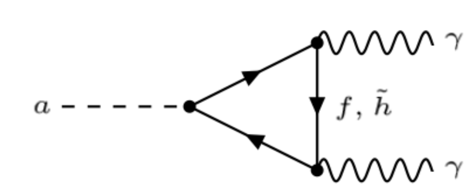
Xe-1-ton now operating!

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



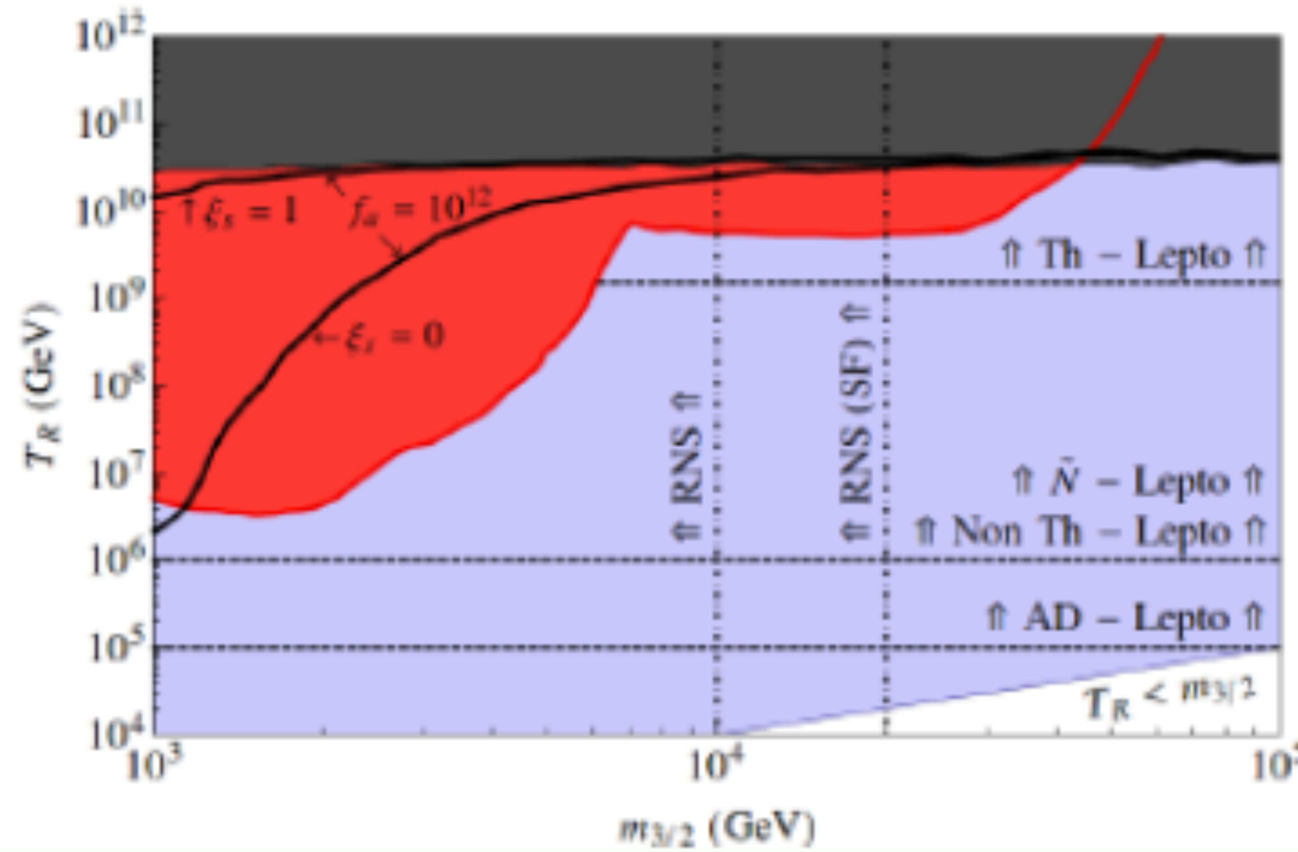
SUSY DFSZ axion: large range in m(a) but coupling reduced

may need to probe broader and deeper!



Baryogenesis scenarios for radiative natural SUSY

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



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

gravitino problem plus axino/saxion problem: still plenty room

Bae,HB, Serce, Zhang, arXiv:1510.00724

some conclusions

- Δ_{EW} provides model-independent naturalness bound valid in IR *and* correlated UV parameters: SUSY still natural mu~100-200 GeV, RNS, m(t1)~TEV but highly mixed!

- mu term linked to axion physics: Kim-Nilles/SUSY DFSZ

- PQ symmetry radiatively broken as consequence of SUSY breaking: unifies 3 intermediate mass scales: SUSY-breaking, PQ, Majorana nu

- A mild statistical draw on soft terms from the string landscape coupled with anthropic pull of weak scale to ~100 GeV -> m(h)~125 GeV

- The same draw provides a decoupling solution to SUSY flavor, CP, gravitino problem (and cosmological moduli problem) and expect m(3/2)~10-30 TeV

- Explains why LHC has so far seen no sign of SUSY

- HL-LHC will probe only a portion of natural SUSY p-space

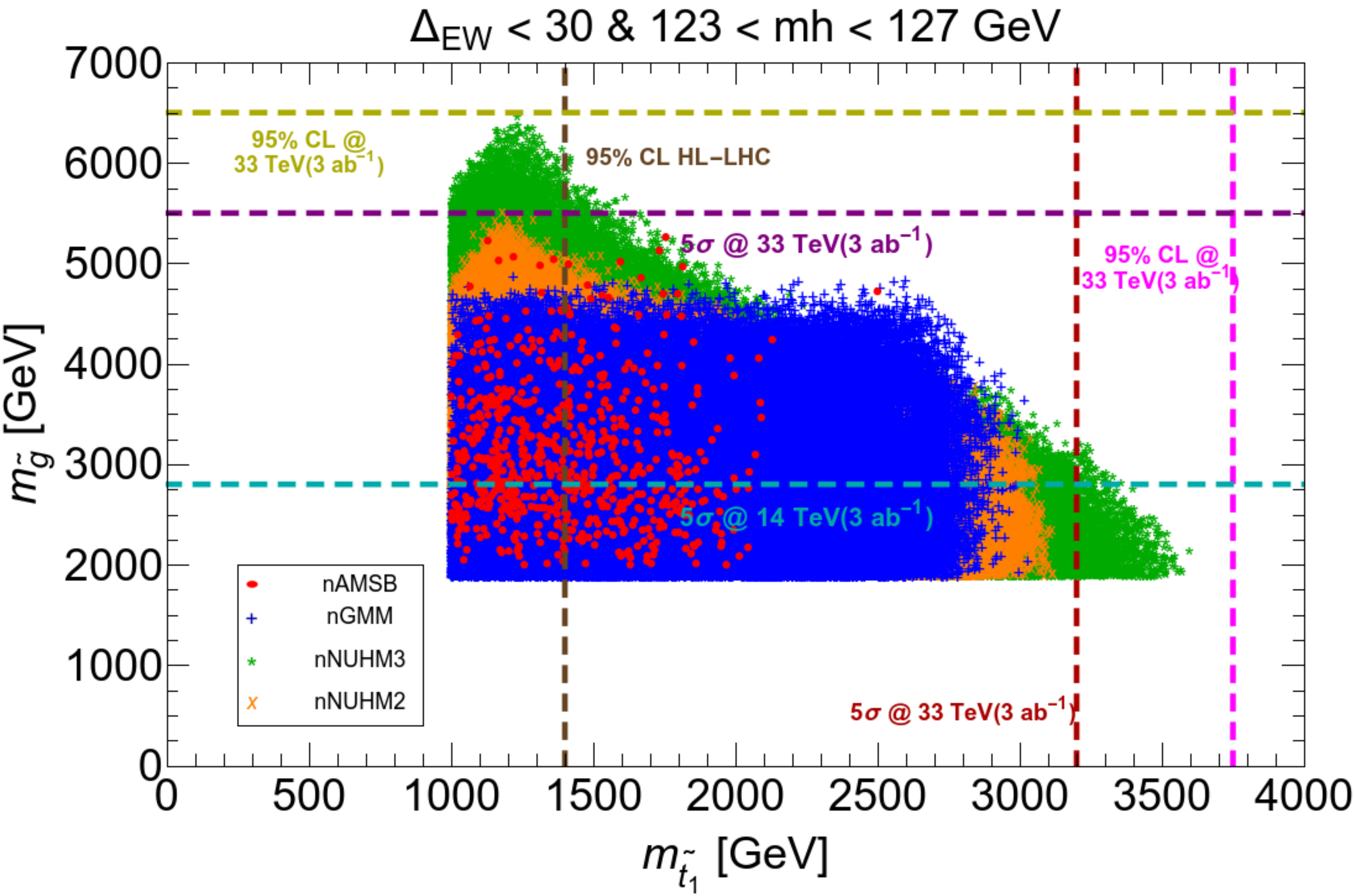
- HE-LHC (rs=27 TeV; 15 ab-1) may be needed for gluino/stop discovery

- dark matter a wimp/axion admixture?

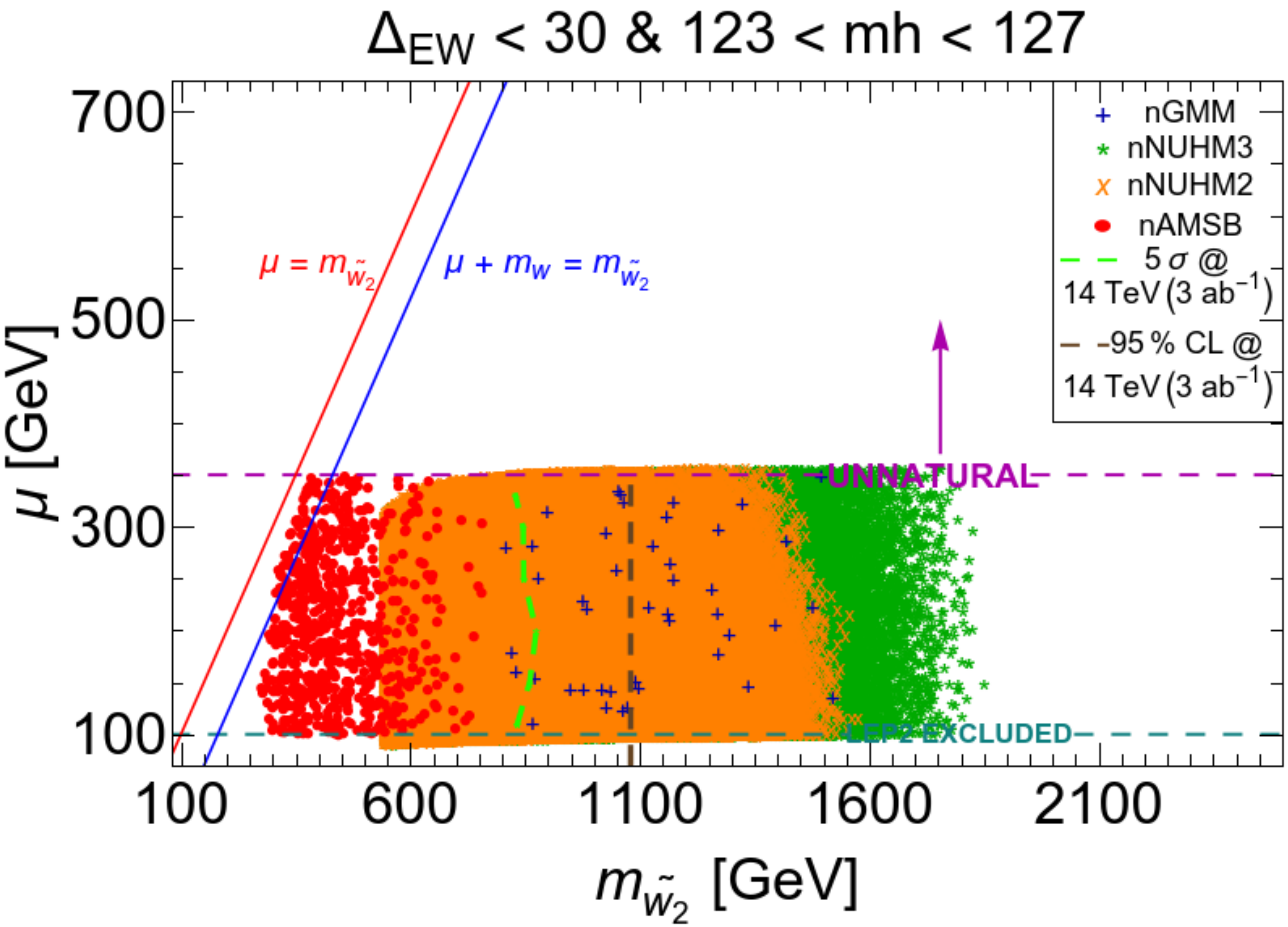
- At ILC250, expect Higgs couplings very SM-like;
  need E(CM)~500-600 GeV>2m(higgsino) to establish SUSY discovery/BSM physics

Backup

HL/HE LHC reach in m(gl) vs. m(t1) plane:

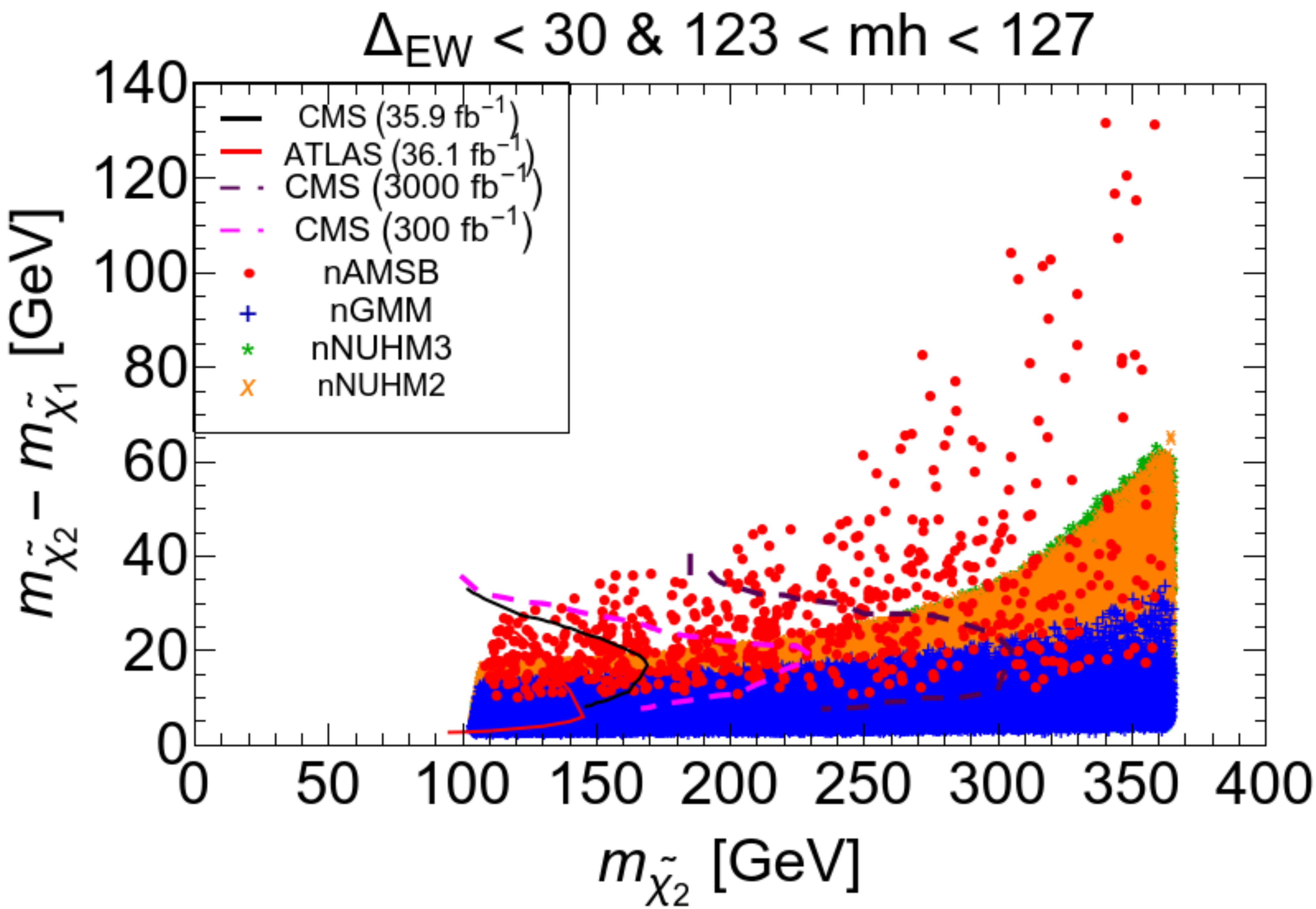


HL-LHC reach for natural SUSY in SSdB channel



- HL-LHC can cover all of nAMSB model; part of nHUM2/nGMM
- not clear if HE-LHC is improvement since QCD backgrounds increase more than EW signal

Status of lljMET searches: new results from Atlas/CMS



compare to CMS projected HL-LHC reach; cover much of p-space;
not clear if HE-LHC helps since again QCD BG increase much more than EW signal

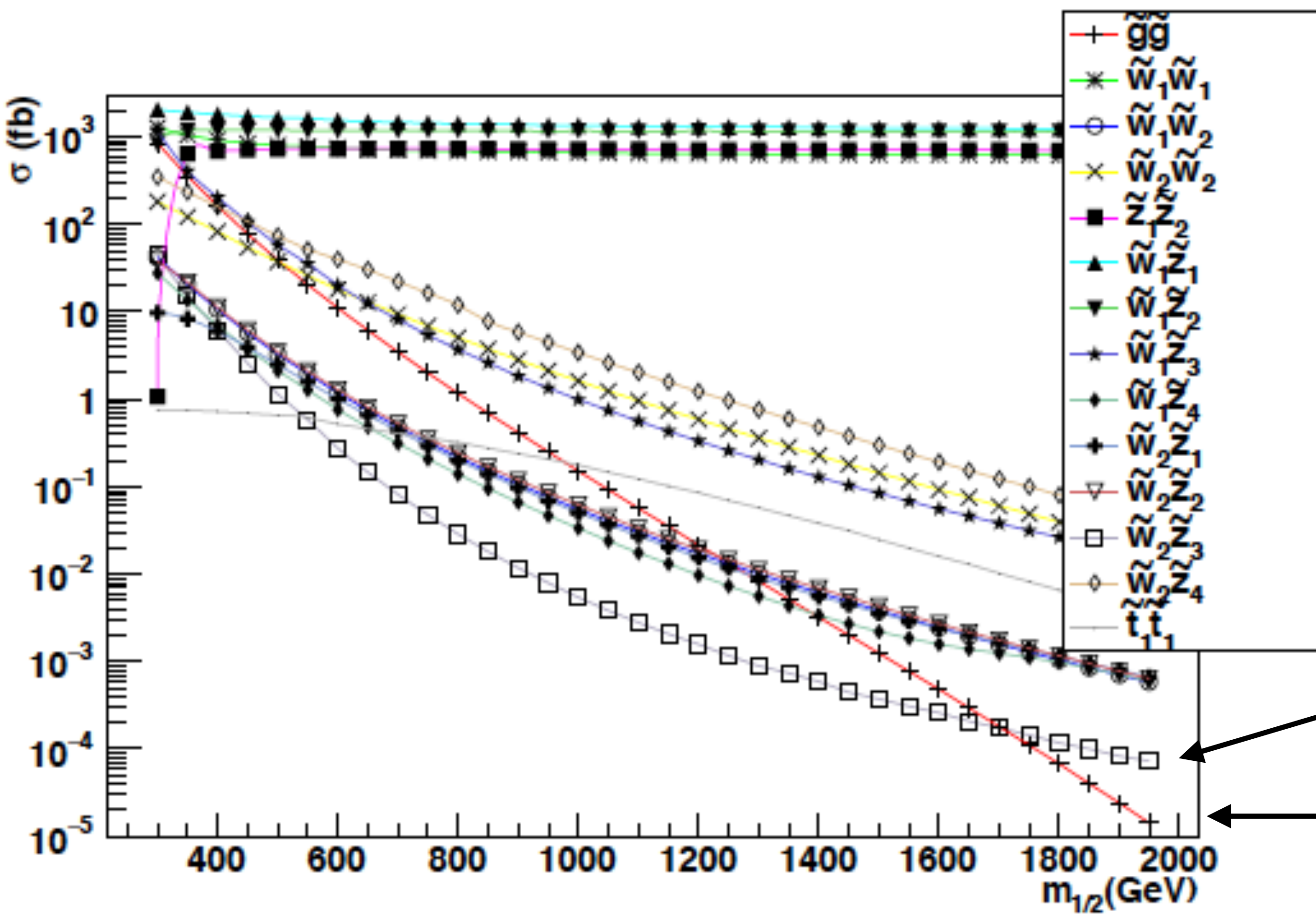
Prospects for SUSY at LHC:

signature list for radiatively-driven natural SUSY:

- $\tilde{g}\tilde{g}$
- $\tilde{t}_1\tilde{t}_1^*$
- $\tilde{Z}_1\tilde{Z}_2$ (higgsino pair production)
- $\tilde{W}_2^{\pm}\tilde{Z}_4$ (wino pair production)

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

mu=150 GeV



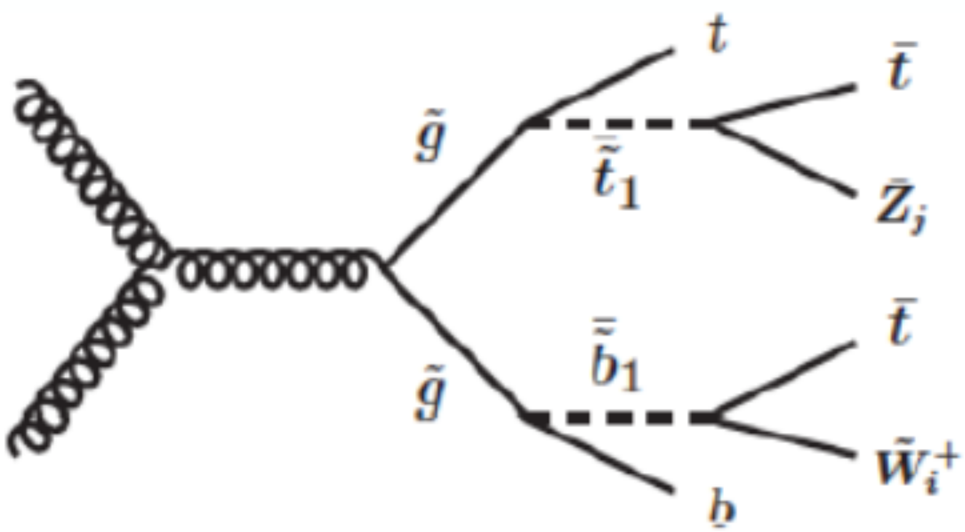
higgsino pair production dominant–but only soft visible energy release from higgsino decays

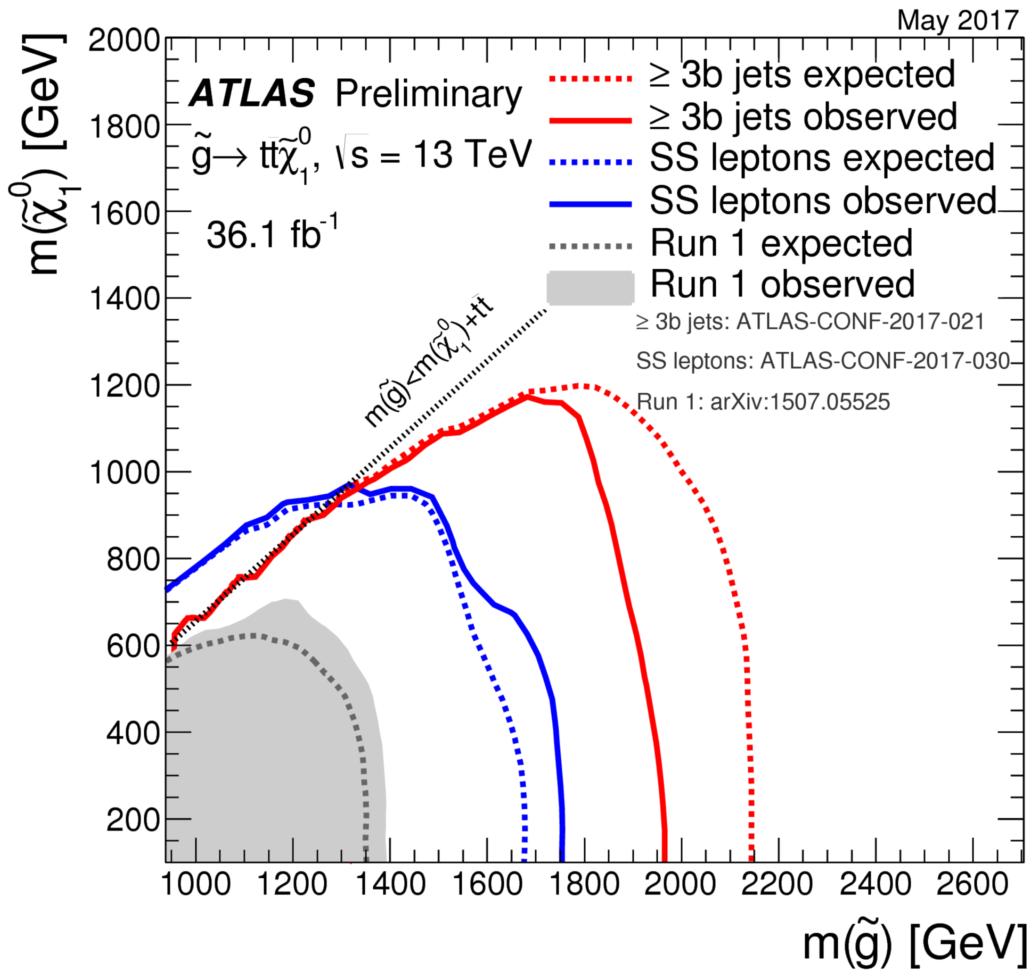
largest visible cross section: wino pairs

gluino pairs sharply dropping

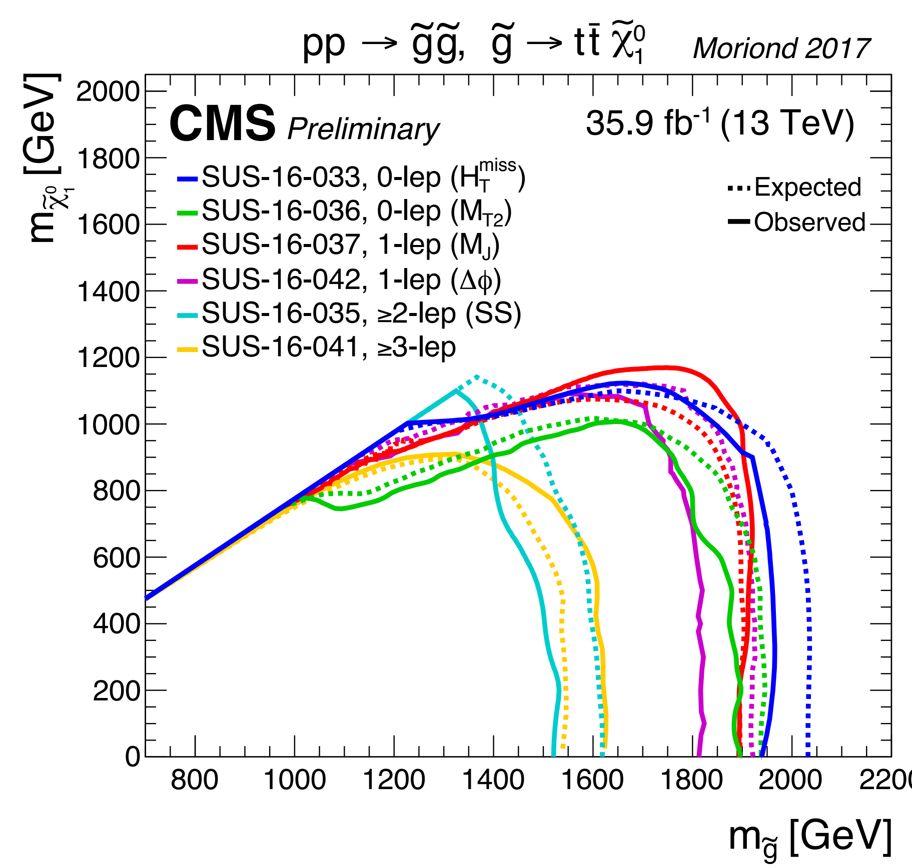
stops at bottom

gluino pair cascade decay signatures

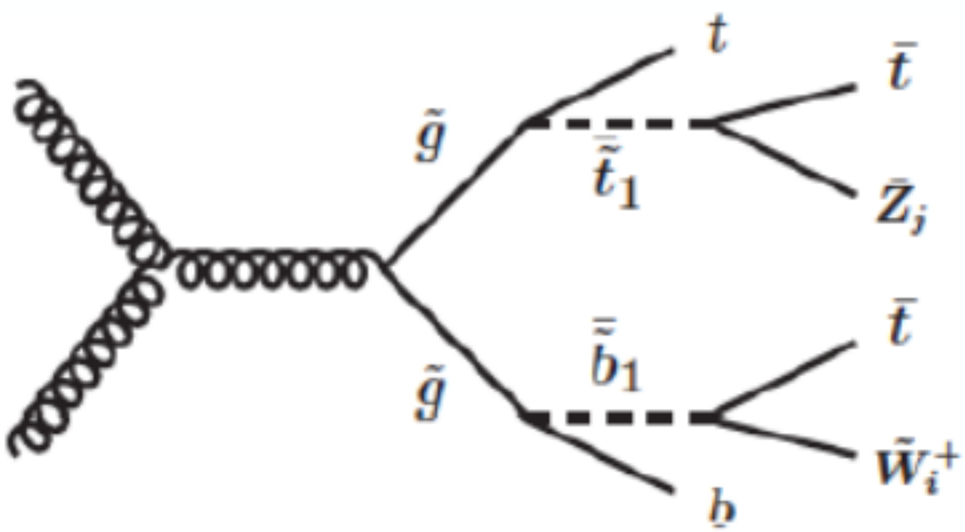




Current limits for m(Z1)~150 GeV:
m(glno)>~2 TeV

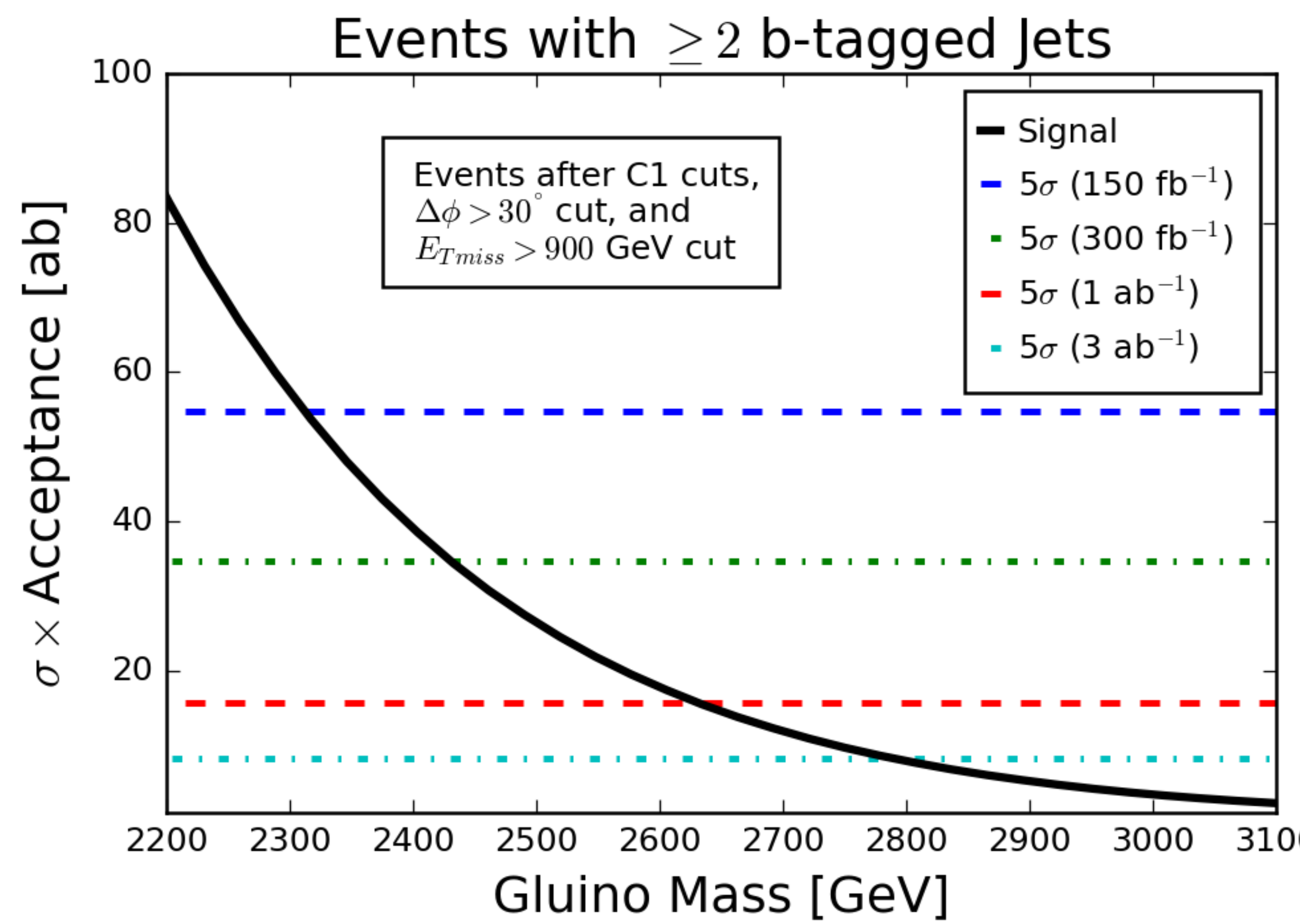


gluino pair cascade decay signatures



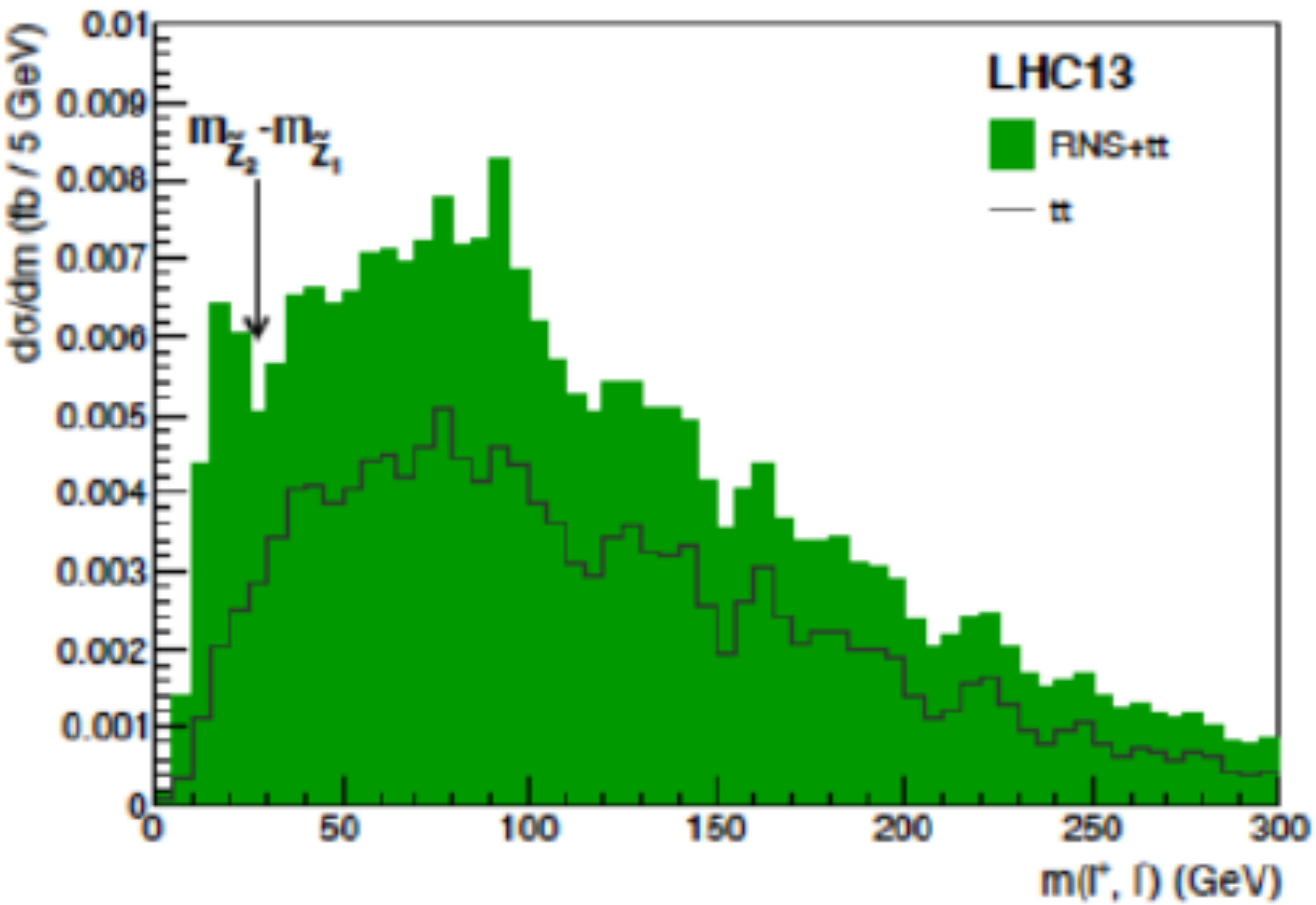
Estimated HL-LHC reach for gluinos

HL-LHC reach to
m(glno)~2.8 TeV;
RNS: m(glno)<~5 TeV



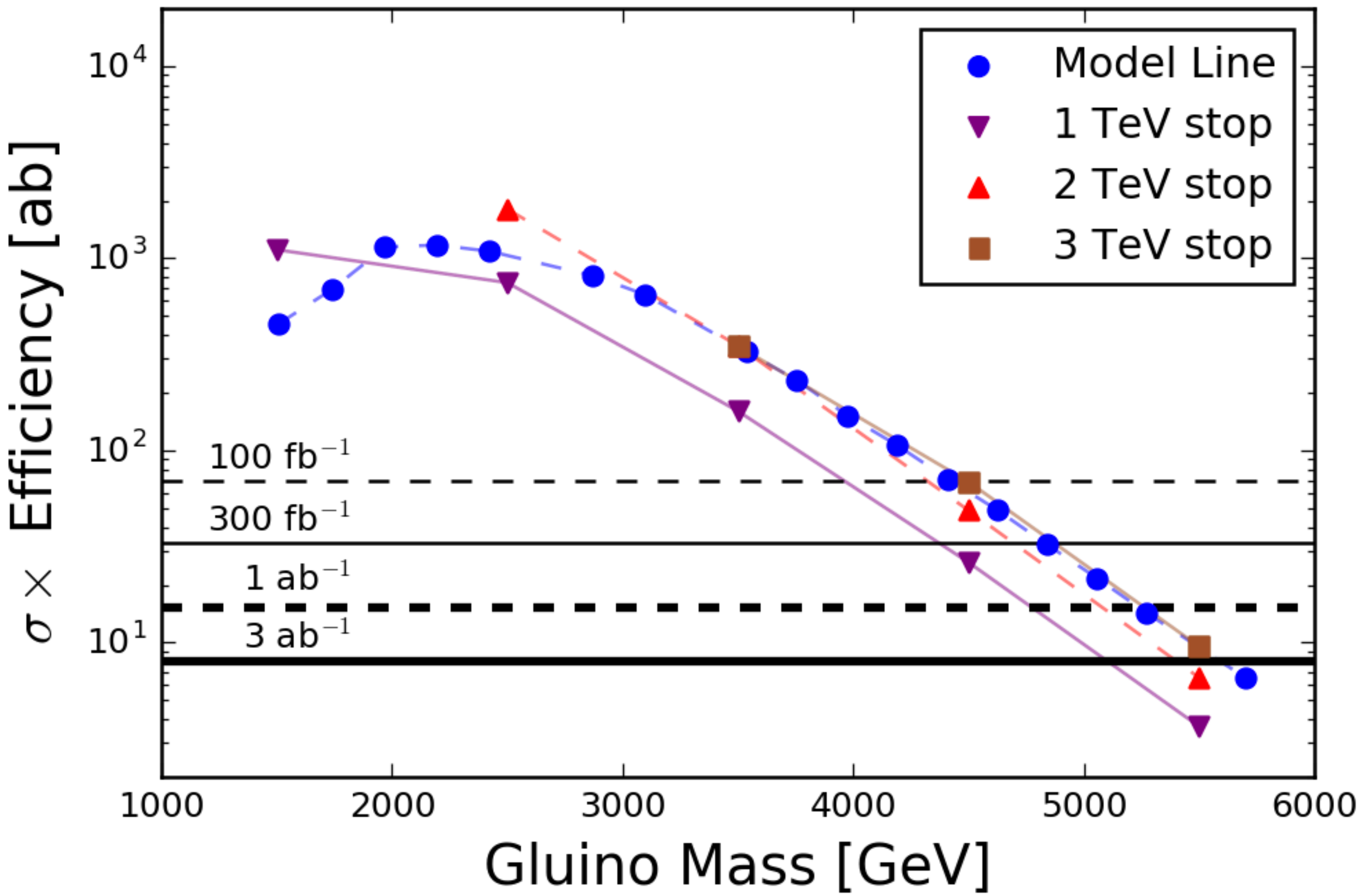
HB, Barger, Huang, Gainer, Savoy, Sengupta, Tata

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

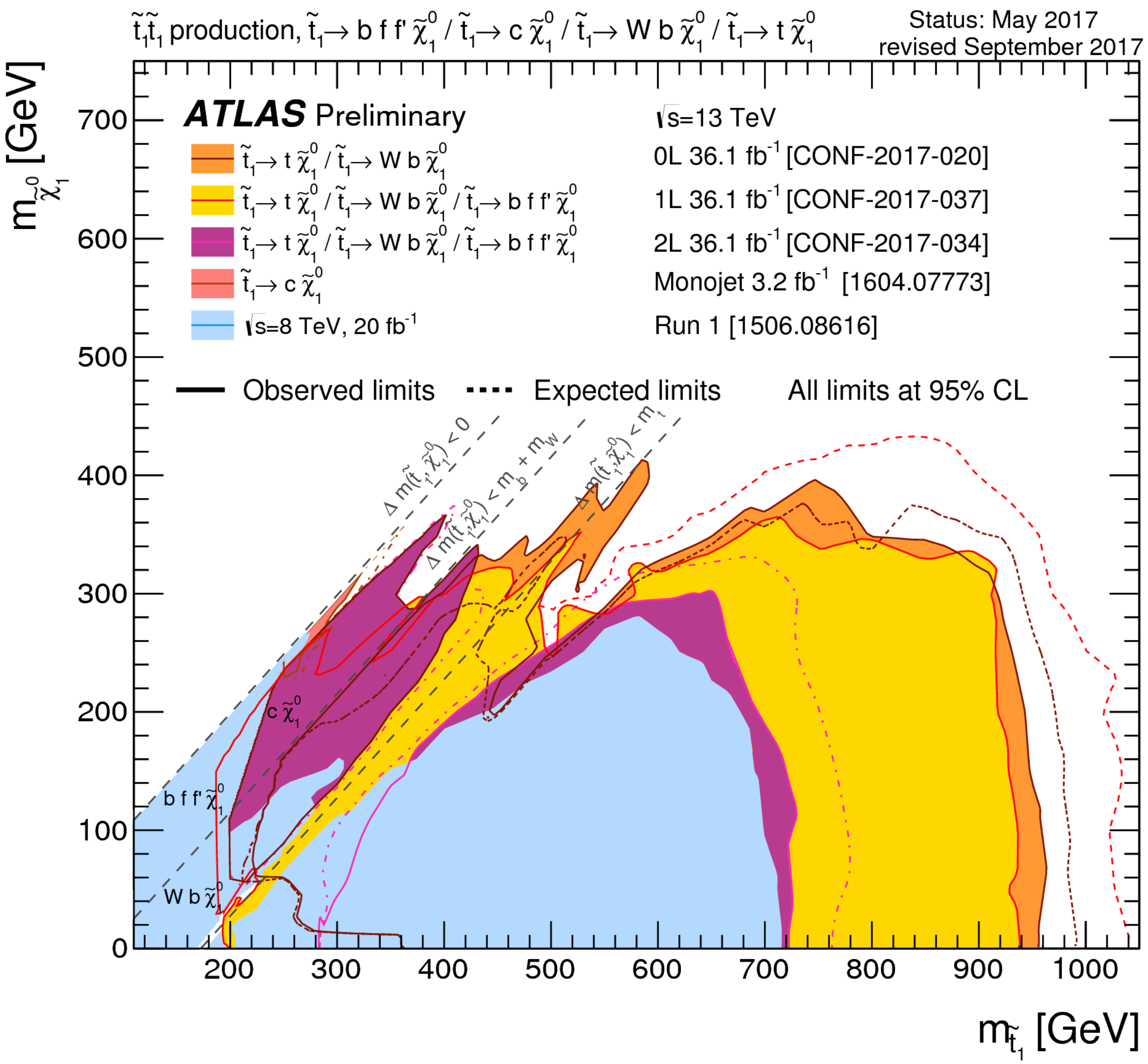
Gluino 5-sigma reach at LHC33: to about m(glno)~5-5.5 TeV

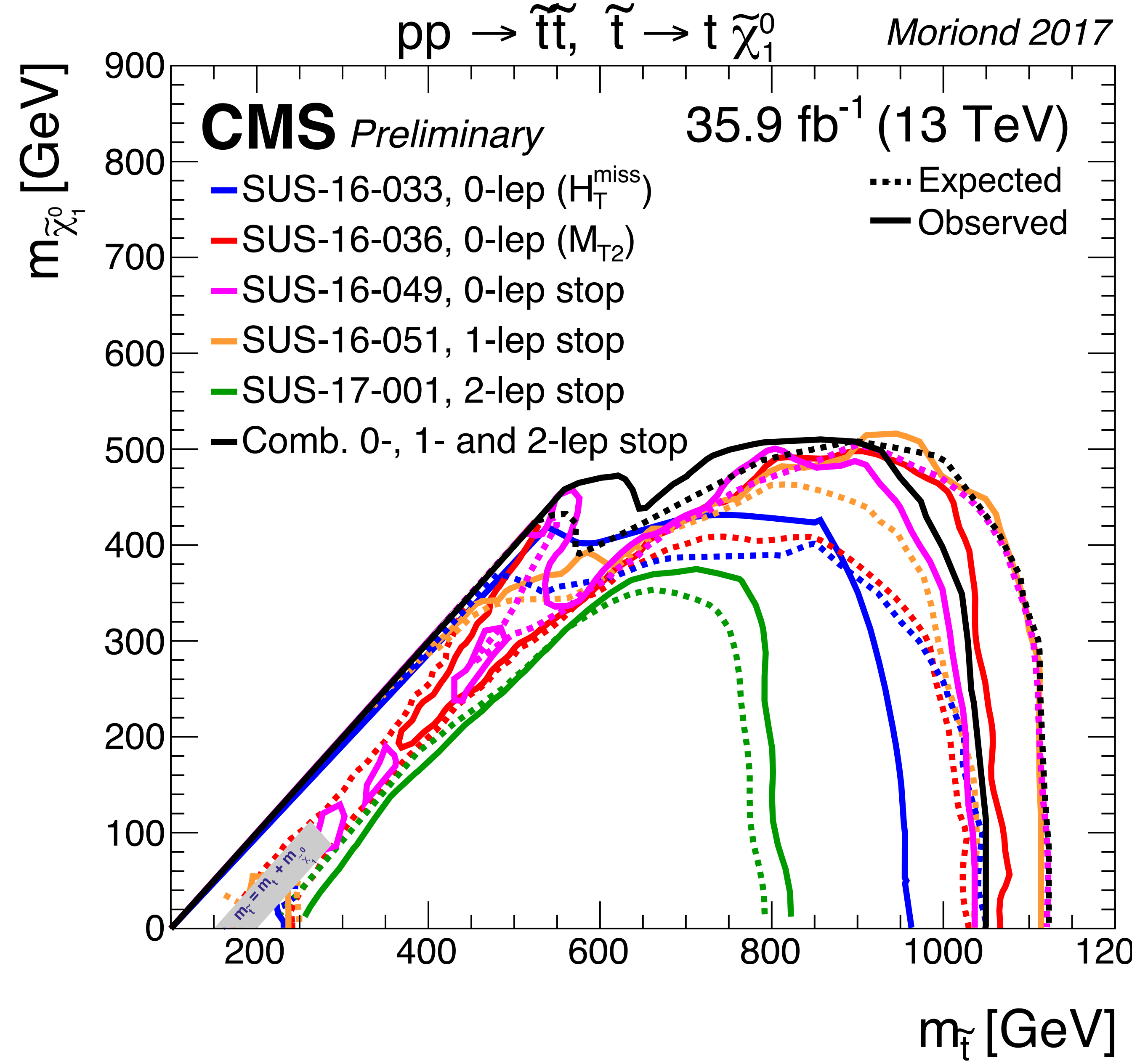


>=4 jets; >=2-b-jets;MET>1500 GeV

HB,Barger, Gainer,Huang, Savoy, Serce, Tata

Present limits on top squarks from LHC

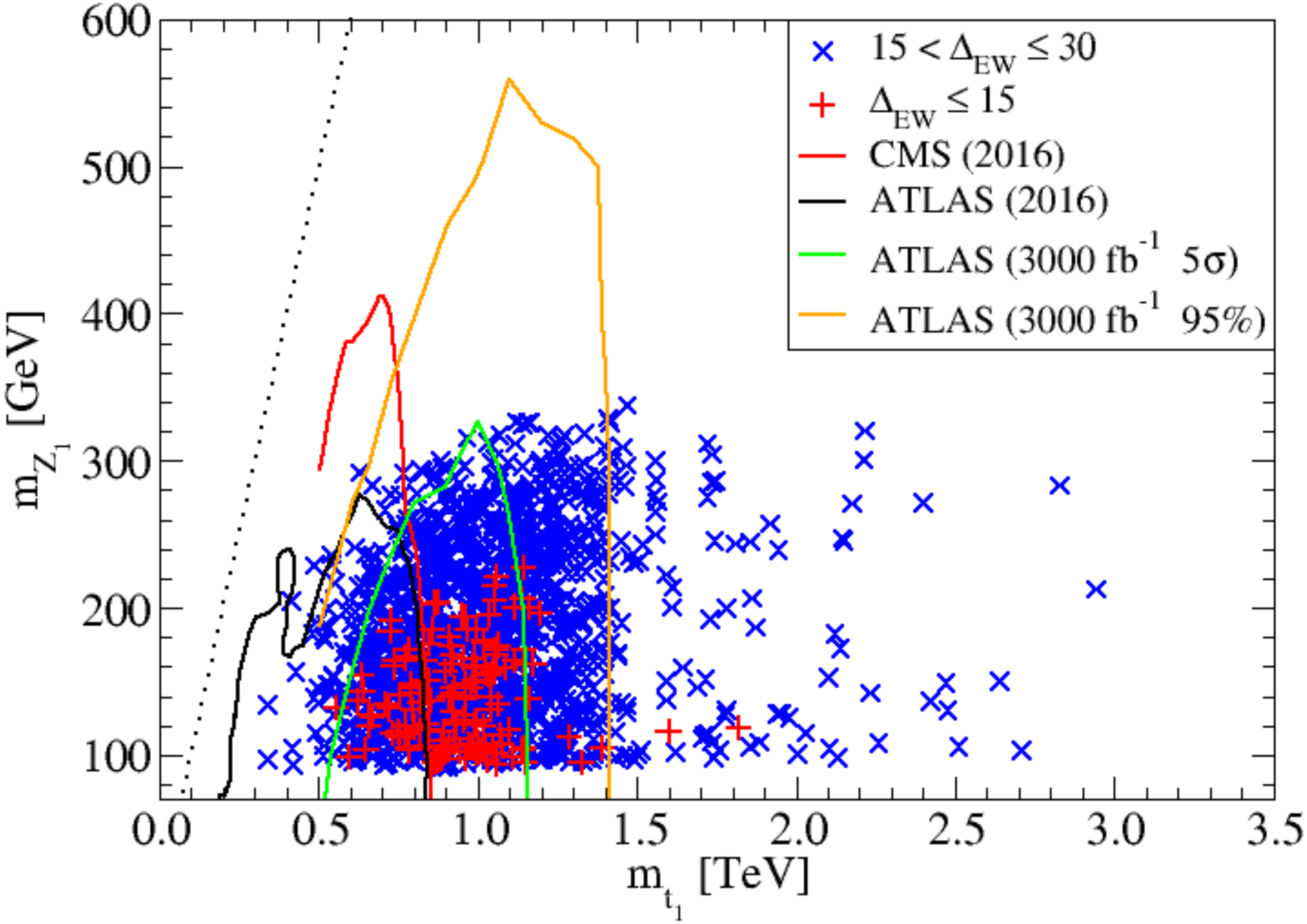




Evidently m(t1)>~1 TeV for m(LSP)~150 GeV

* TeV-scale top squark needed for m(h)~125 GeV
* Also needed for b-> s gamma

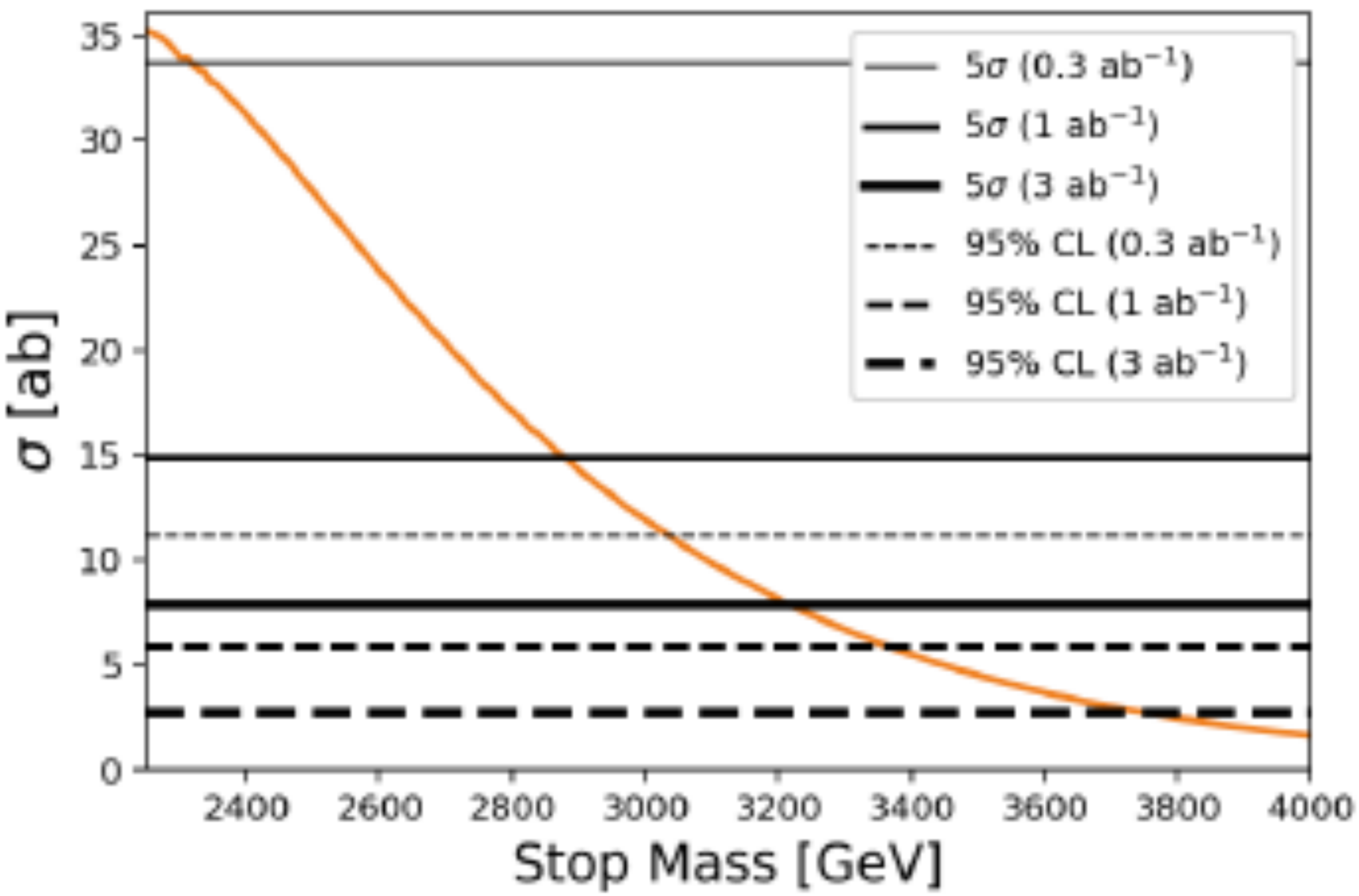
Prospects for top squarks in natural SUSY



m(t1) can range up to 3 TeV with little cost to naturalness;
the hunt for stops has only begun!

HL-LHC reach extends to m(t1)~1.2-1.4 TeV

Reach of LHC33 for top squarks



- $\tilde{t}_1 \to b\tilde{W}_1; \sim 50\%$
- $\tilde{t}_1 \to t\tilde{Z}_1; \sim 25\%$
- $\tilde{t}_1 \to t\tilde{Z}_2; \sim 25\%$

- A. $\tilde{t}_1\tilde{t}_1^* \to b\bar{b} + E_T^{miss}$ $\sim 25\%$,
- B. $\tilde{t}_1\tilde{t}_1^* \to b\bar{t},\ \bar{b}t + E_T^{miss}$ $\sim 50\%$,
- C. $\tilde{t}_1\tilde{t}_1^* \to t\bar{t} + E_T^{miss}$ $\sim 25\%$.

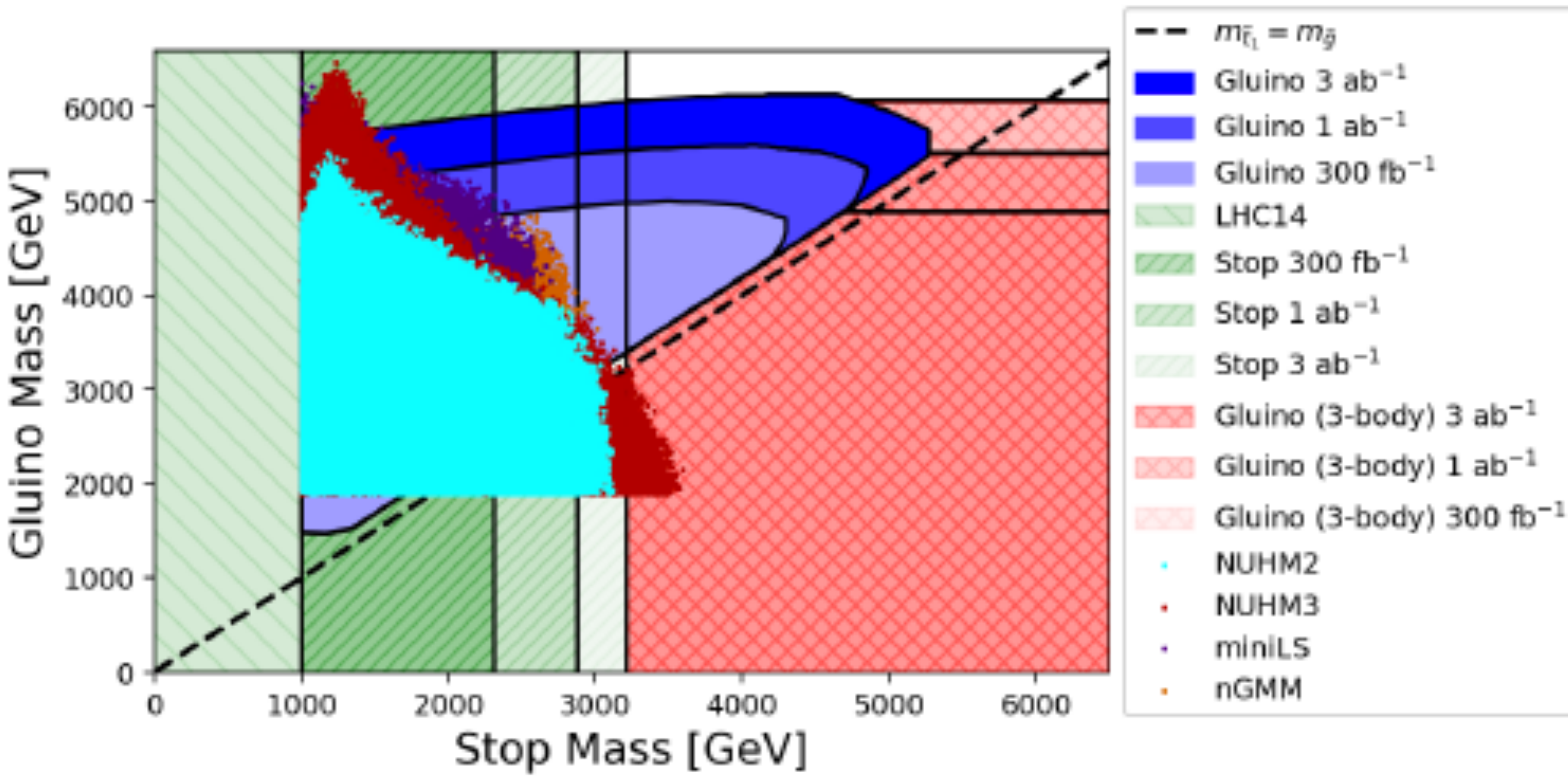
LHC33 reach extends to m(t1)~3-3.8 TeV

n(b-jets)>=2; MET>750 GeV

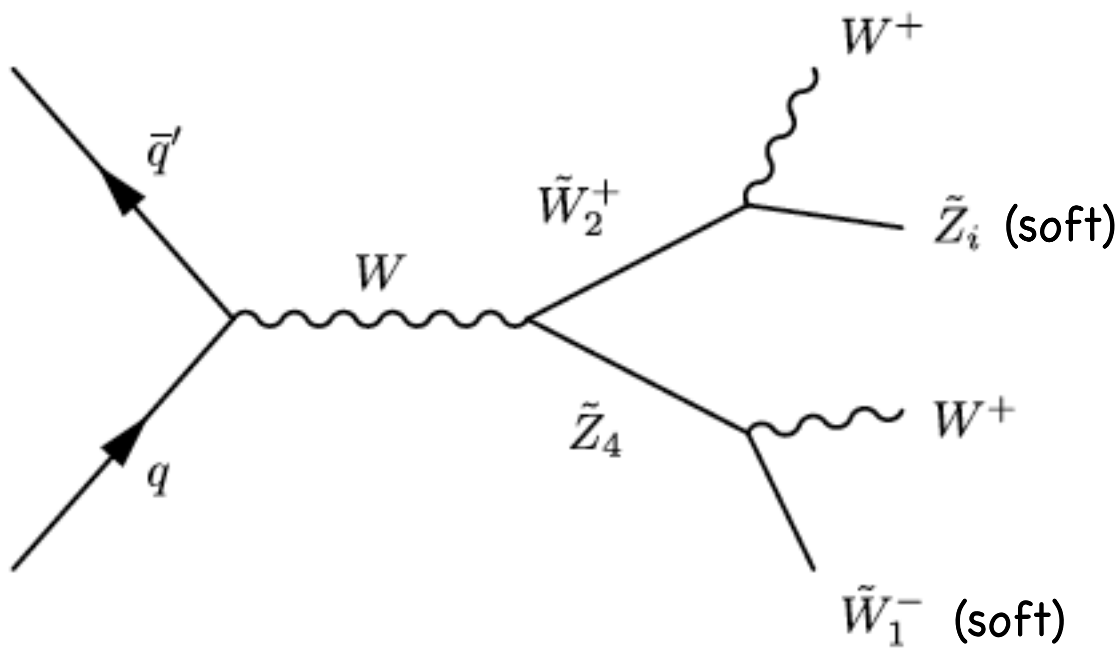
HB, Barger, Gainer, Serce, Tata

Combined LHC33 reach for t1 and glno covers all natural SUSY p-space!

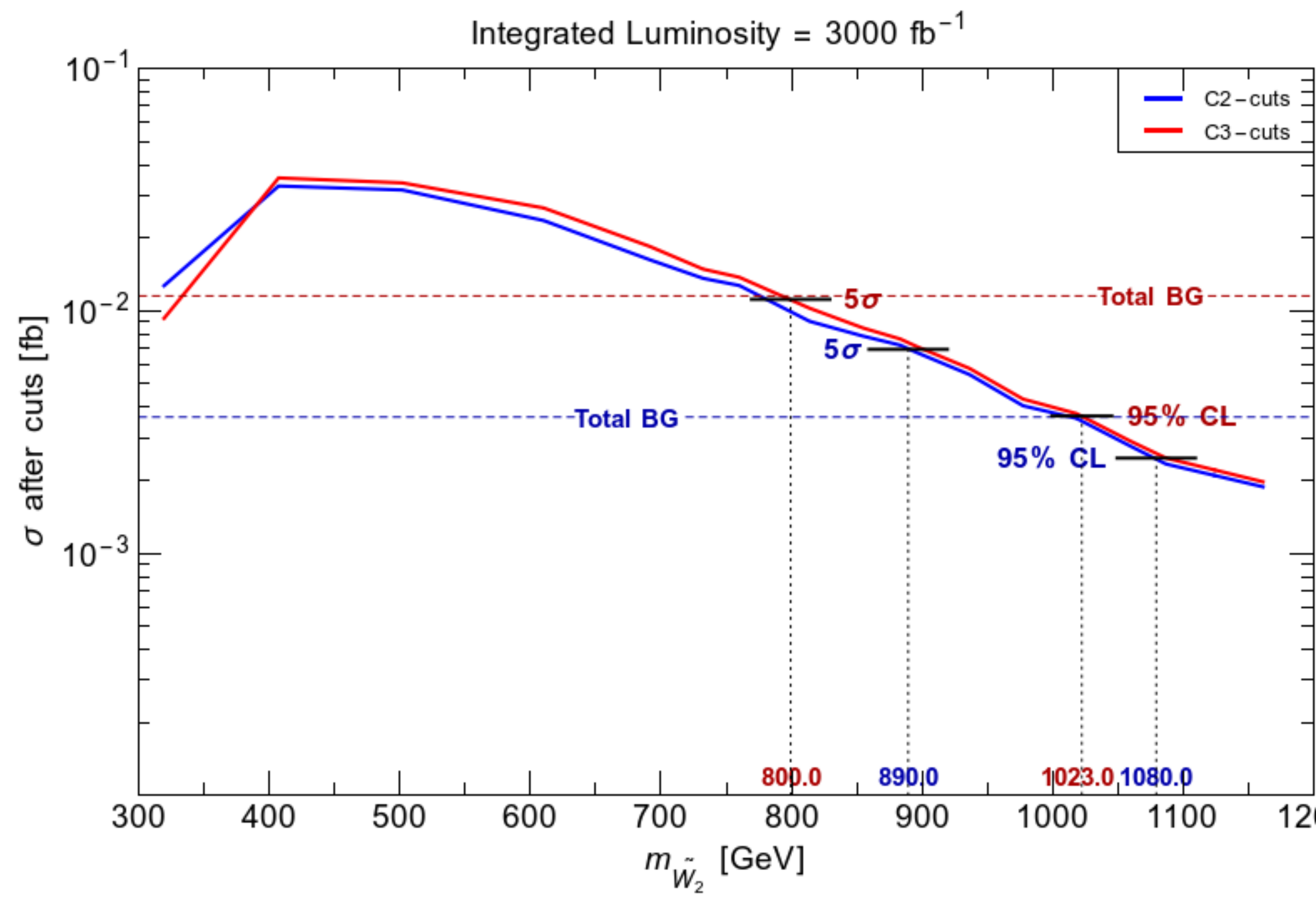
(need to re-do for LHC27)



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



wino pair production

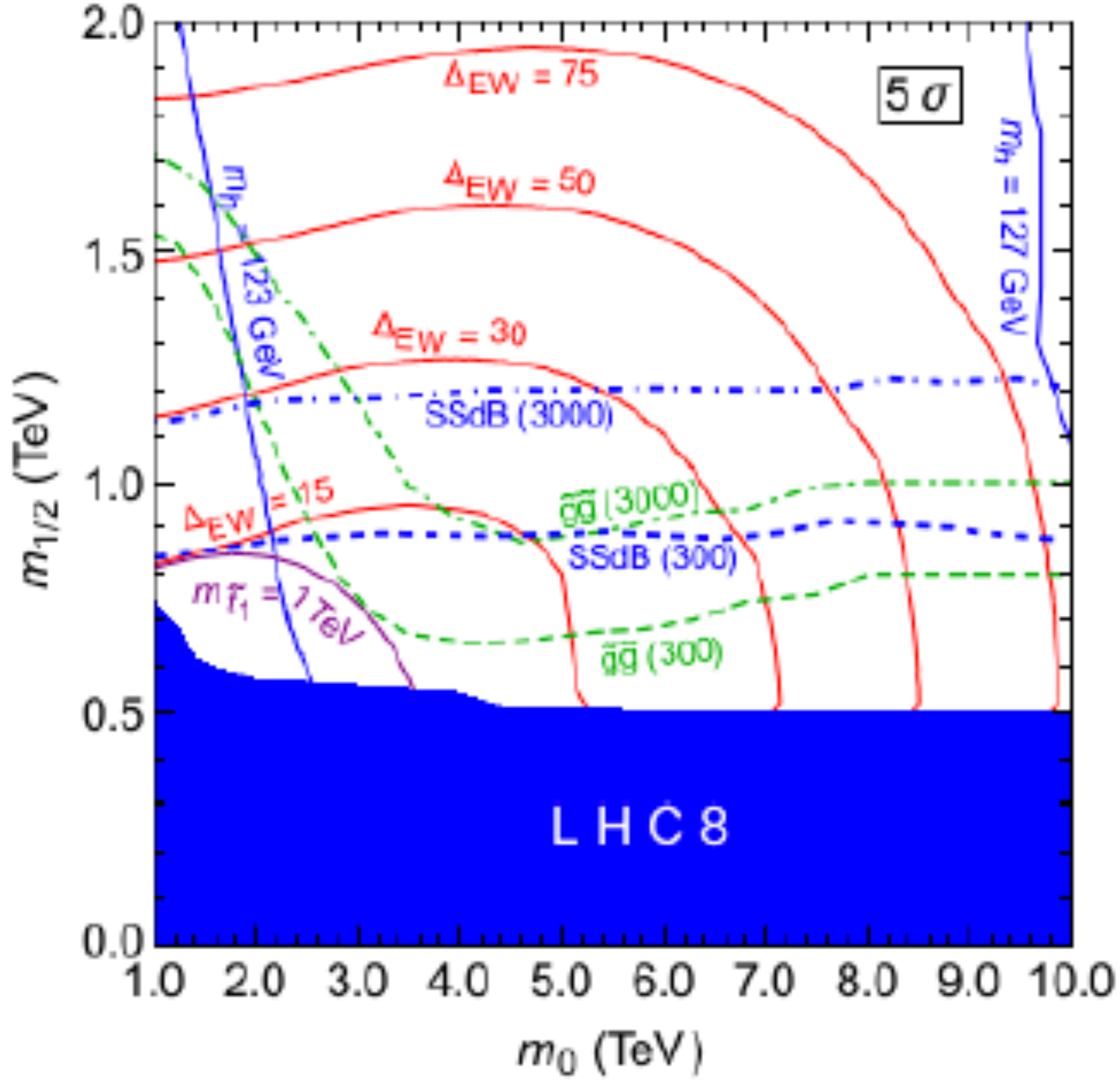


This channel offers good reach of LHC14 for RNS; it is also indicative of wino-pair prod'n followed by decay to higgsinos

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

HB, Barger, Gainer, Sengupta, Tata

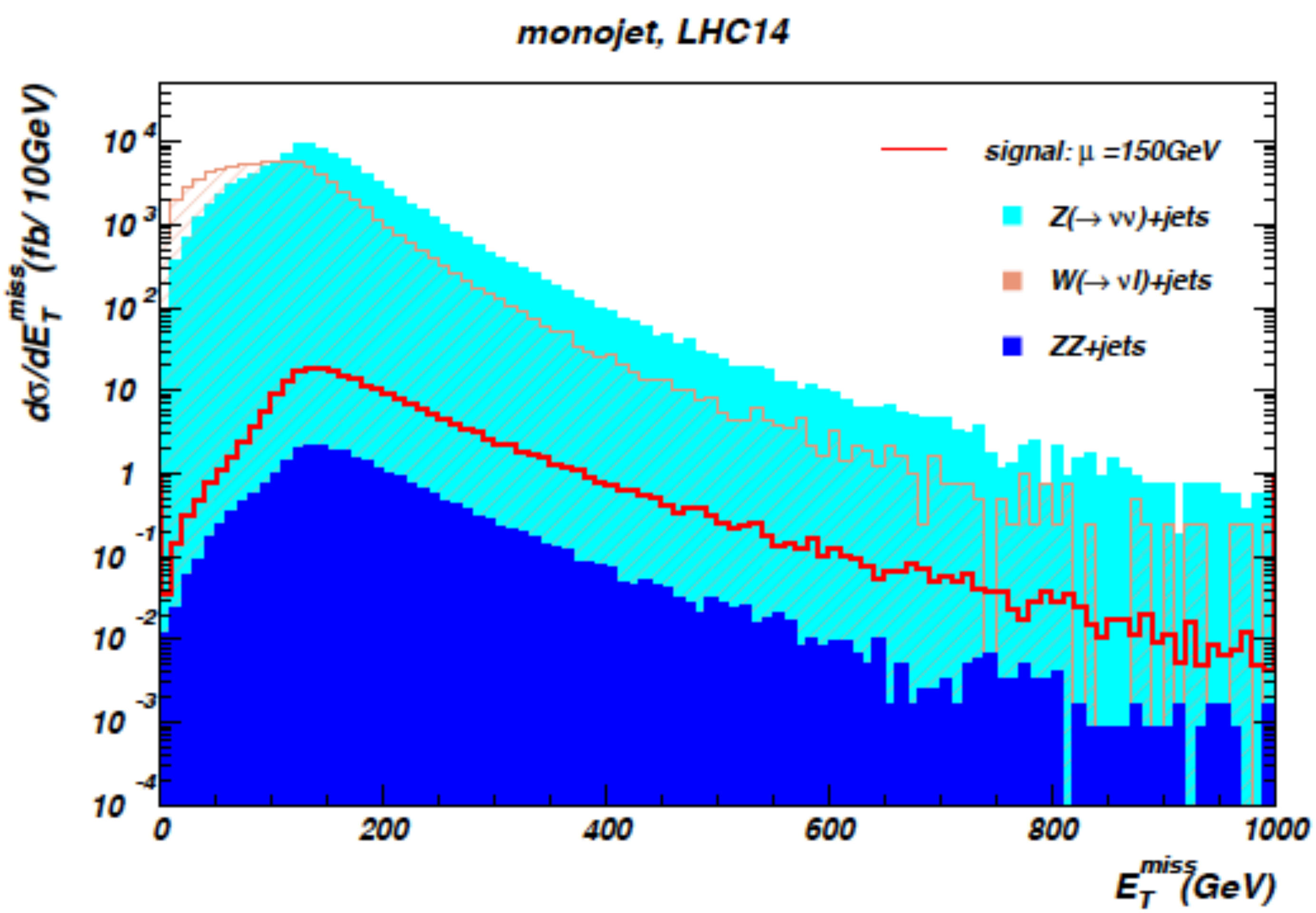
Good old m0 vs. mhf plane still viable, but needs mu~100-200 GeV as possible in NUHM2 instead of CMSSM/mSUGRA



For models with ino mass unif'n, reach via SSdB may exceed glno pairs for high luminosity

HB,Barger,Savoy, Tata; arXiv:1604.07438

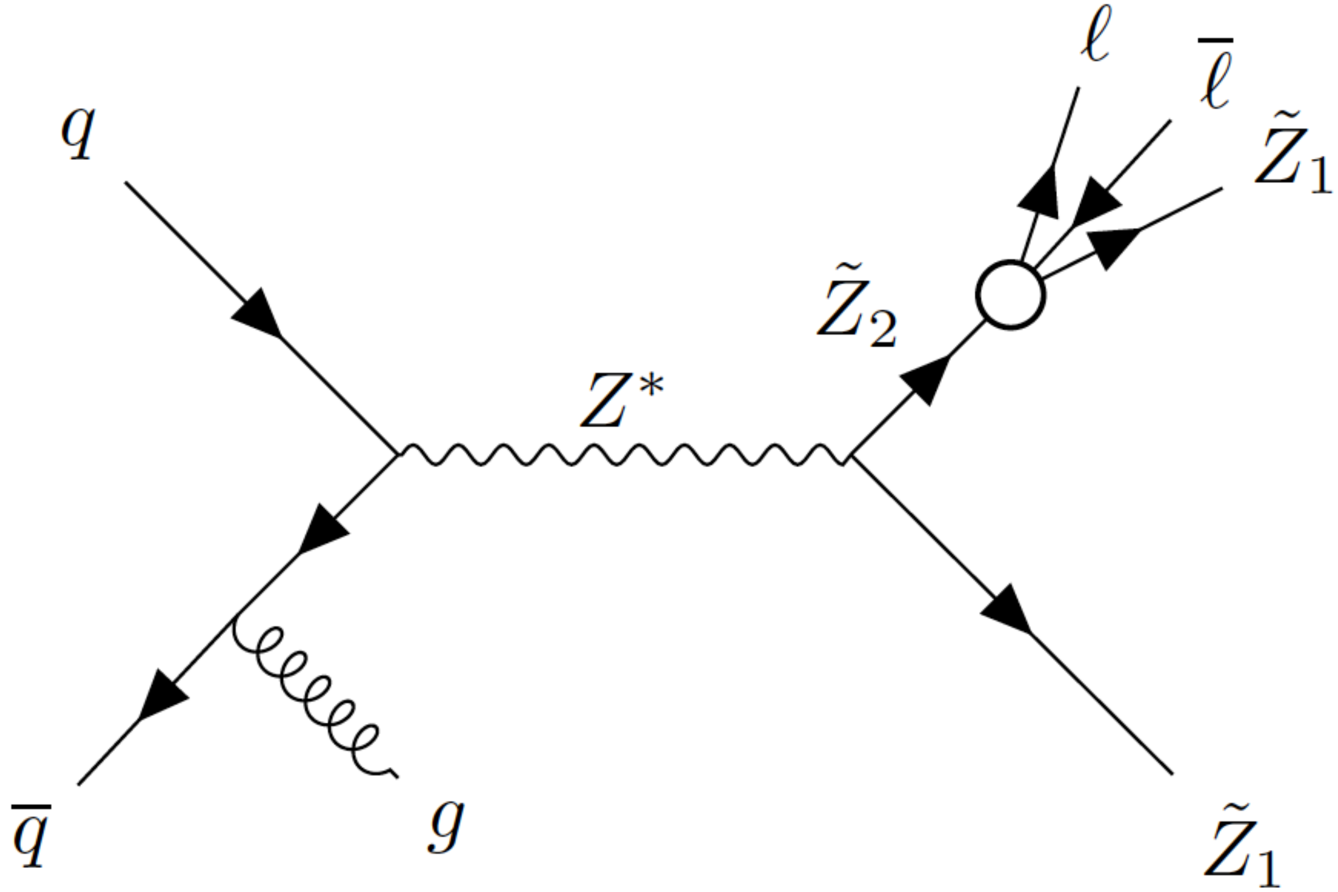
See direct higgsino pair production recoiling from ISR (monojet signal)?



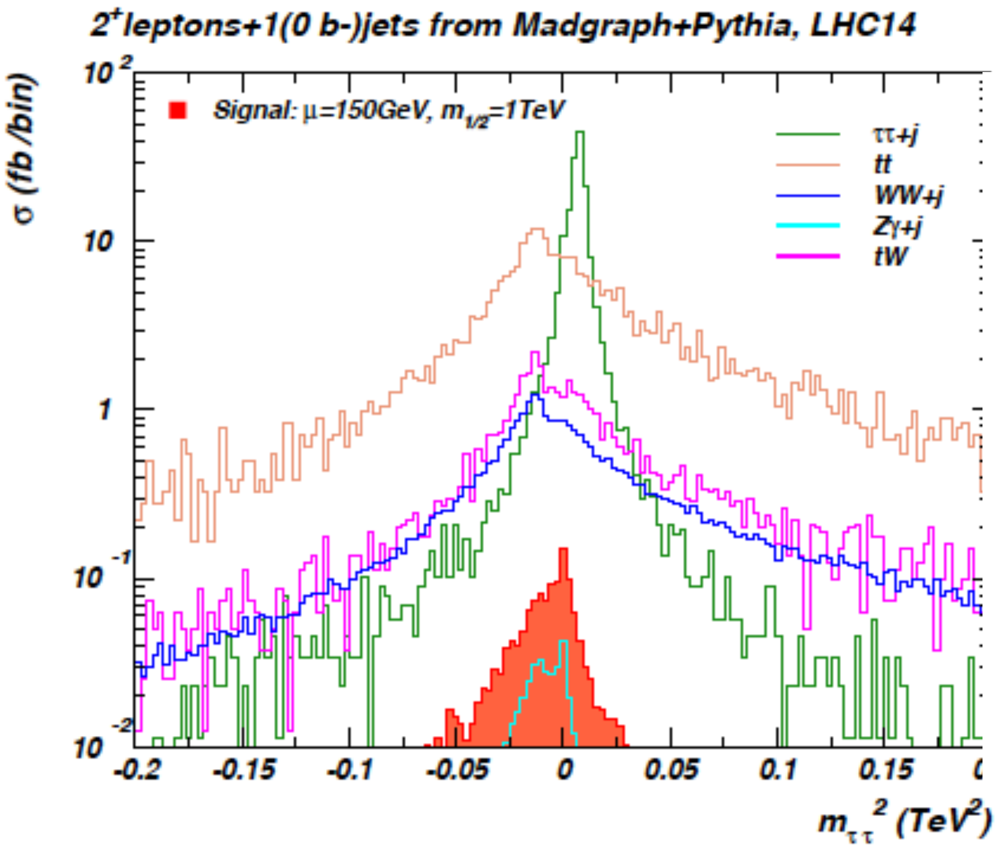
typically 1% S/BG after cuts:
very tough to do!

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

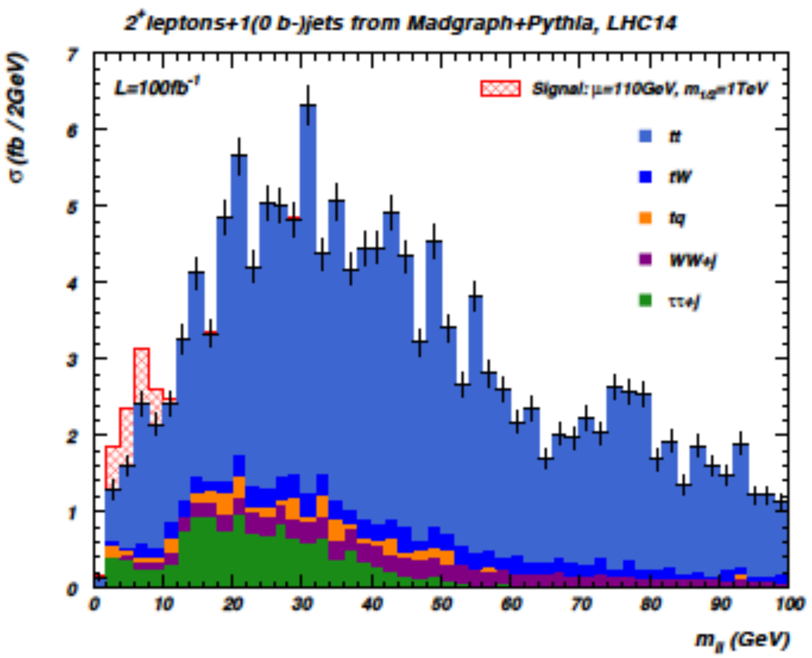
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;

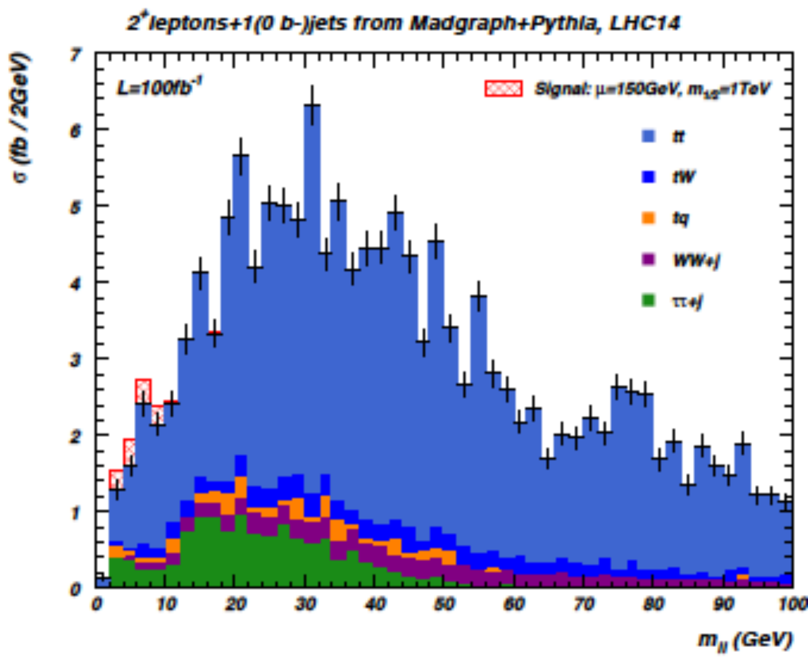


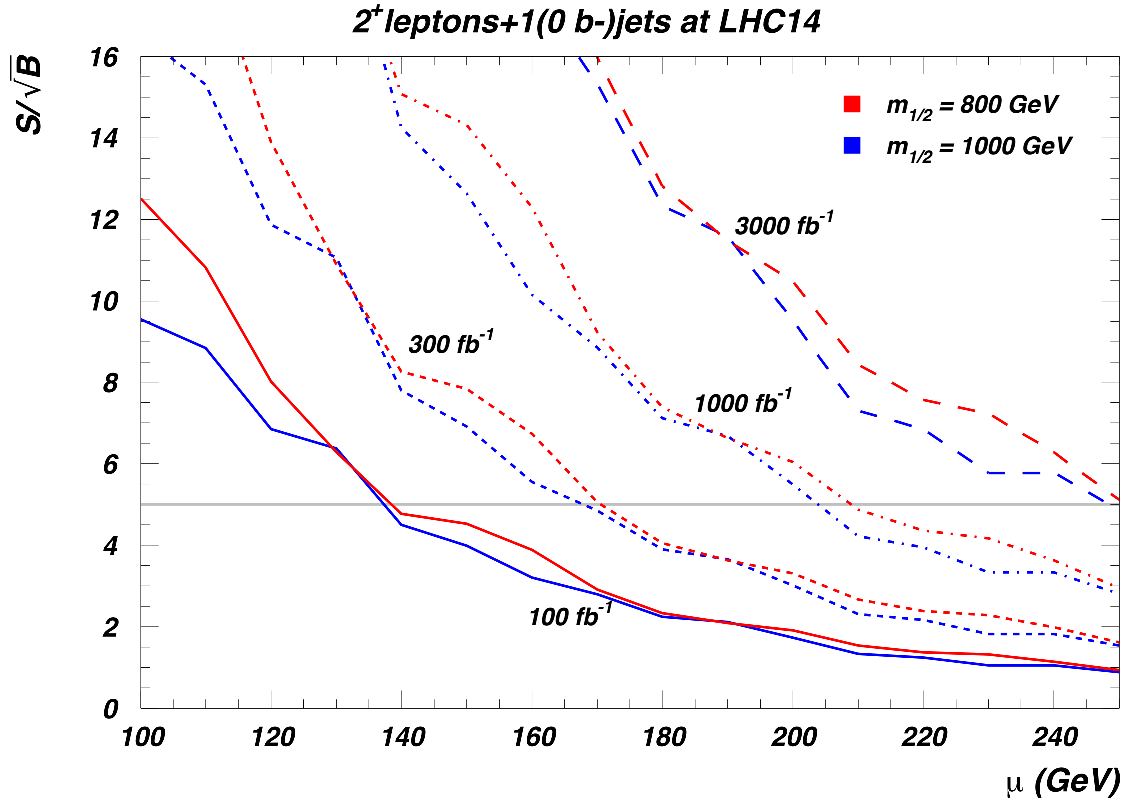
use MET to construct m^2(tau-tau)



cut m(ditau)^2<0







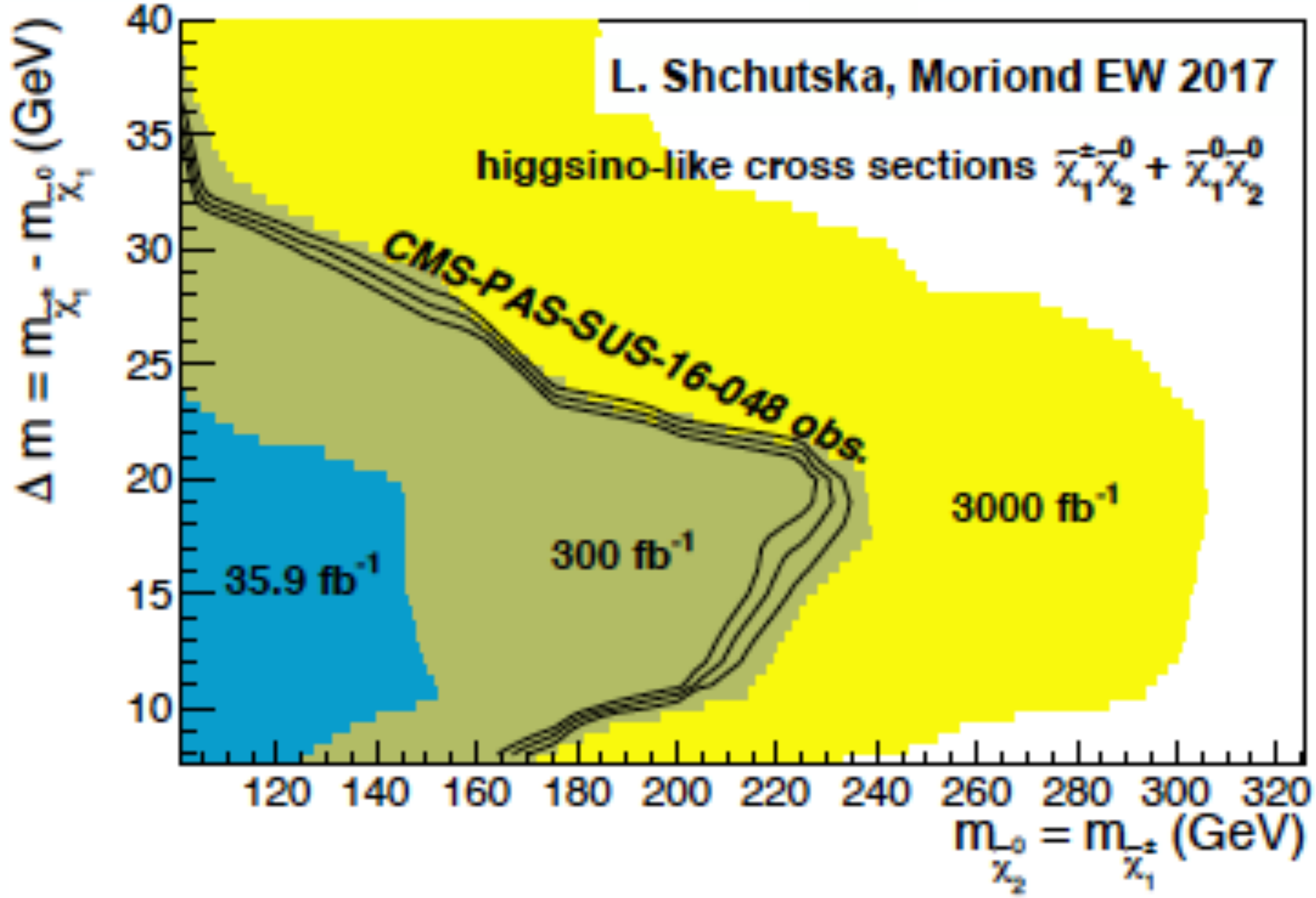
HL-LHC 5-sigma reach
to mu~250 GeV!

HB, Mustafayev, Tata

CMS analysis: this may be the most important SUSY discovery channel at LHC since it directly probes higgsinos which can't be too far from m(W,Z,h)

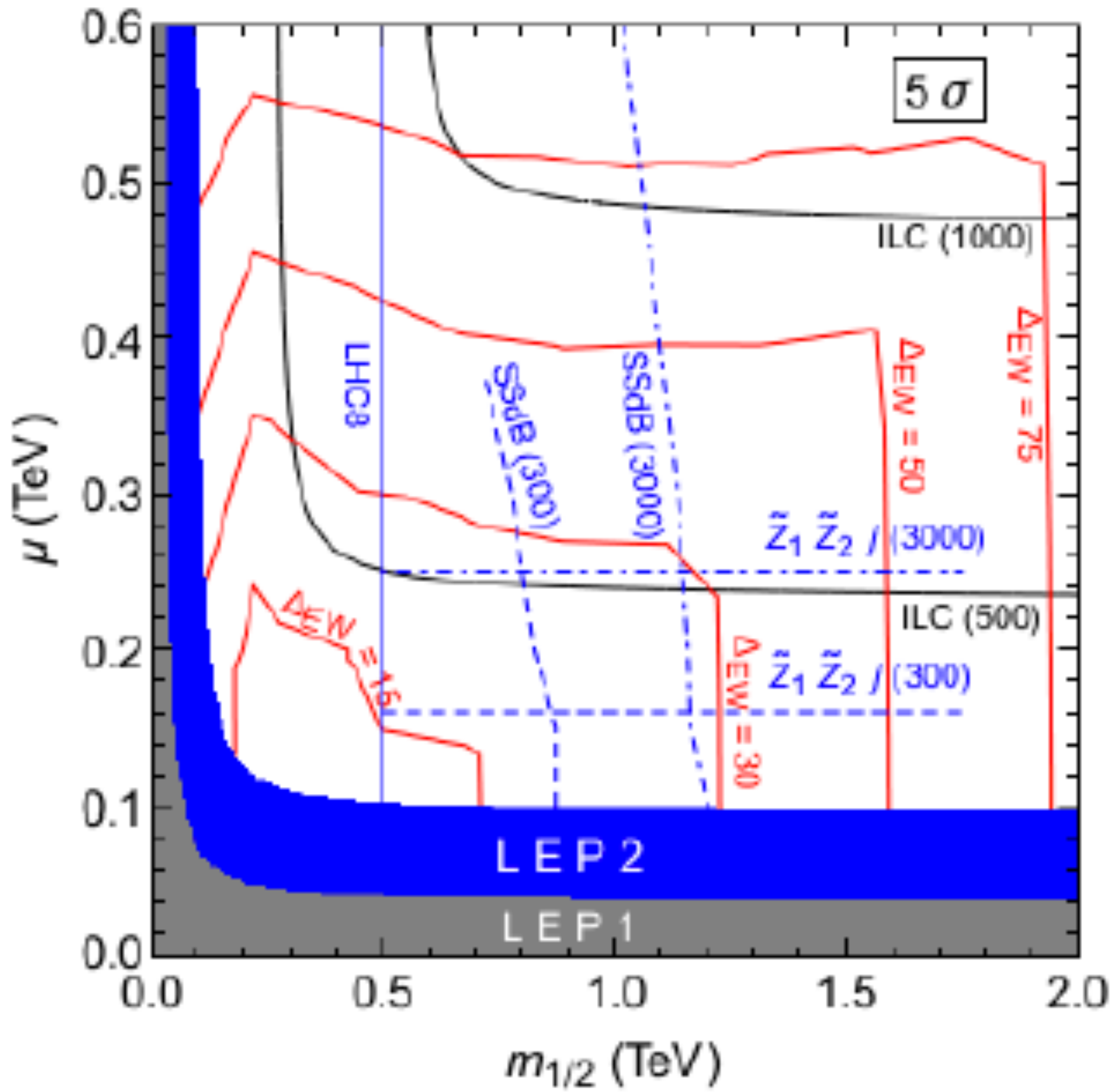
Atlas study underway- results soon?

Higgsino cross section (projection only)



NatSUSY z2-z1 mass gap may range down to 3 GeV so need to ID very soft, low m(ll) leptons

panoramic view of reach of HL-LHC for natural SUSY



Combined SSdB/lljMET searches may cover all Nat SUSY p-space at HL-LHC for models with ino mass unification; in mirage scenario, z2-z1 mass gap can be reduced and M2 can be much higher than in NUHM2

Summary of collider searches

- In light of recent LHC bounds (m(glno)>2 TeV, m(t1)>1 TeV) and m(h) requiring TeV-scale highly mixed top squarks, concern has arisen about an emerging Little Hierarchy problem characterized by m(weak)~100 GeV<< m(SUSY)~multi-TeV rendering perhaps SUSY as ``unnatural"
- We propose an improved naturalness measure based upon scalar potential minimization condition

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

This leads to upper bounds from naturalness:

DM=WIMP/axion mix?

- m(higgsinos)~100-300 GeV (the lighter the better)
- m(t1)<~3 TeV
- m(glno)<~6 TeV

process	current	HL-LHC	HE-LHC
glno-glno	m(glno)>2 TeV	~2.8 TeV	5.5 TeV
t1-t1	m(t1)>1 TeV	1.3 TeV	3.5 TeV
SSdB (winos)	x	m(W2)~1 TeV	?
z1z2j->l+lb+j+MET	barely	mu~250 GeV	?

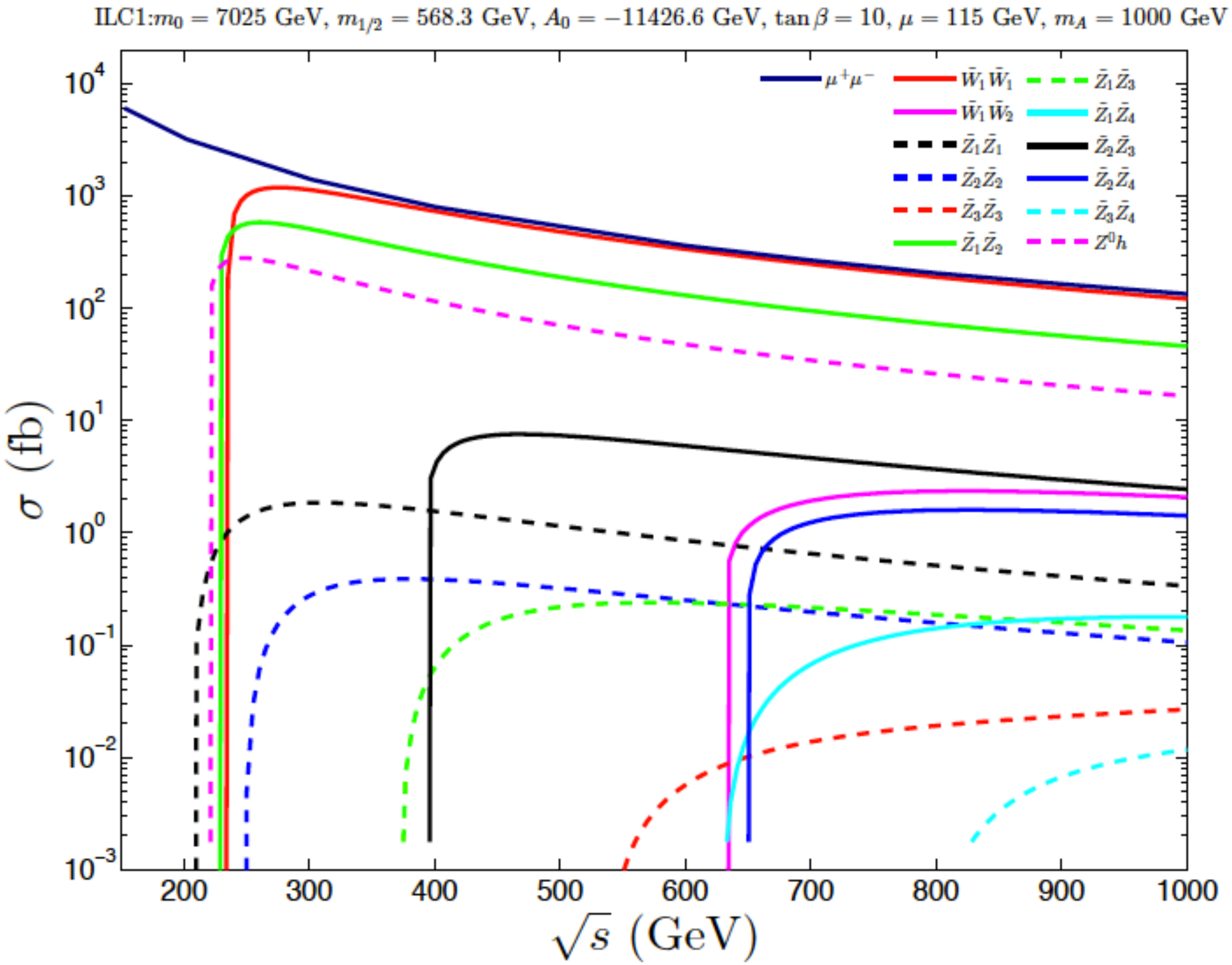
Conclusions:

1. SUSY still natural;
2. hunt for nSUSY has only begun;
3. HL-LHC handle most SUSY with ino-mass unification;
4. other (e.g. mirage) may require HE-LHC to complete search

HB, Barger,Gainer, Huang,Tata
Savoy, Mustafayev
Sengupta,Serce

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!

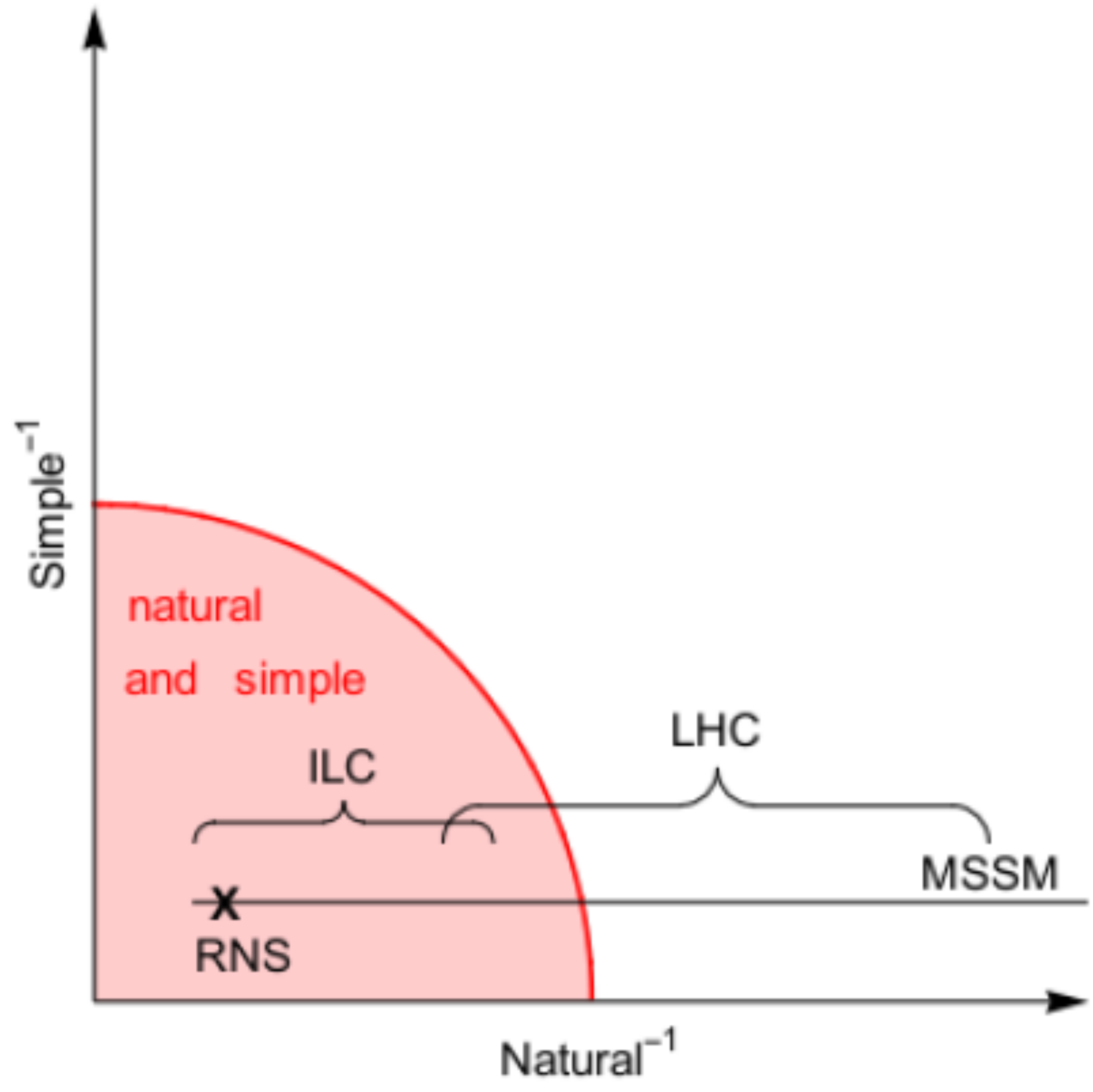


$$\sigma(higgsino) \gg \sigma(Zh)$$

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

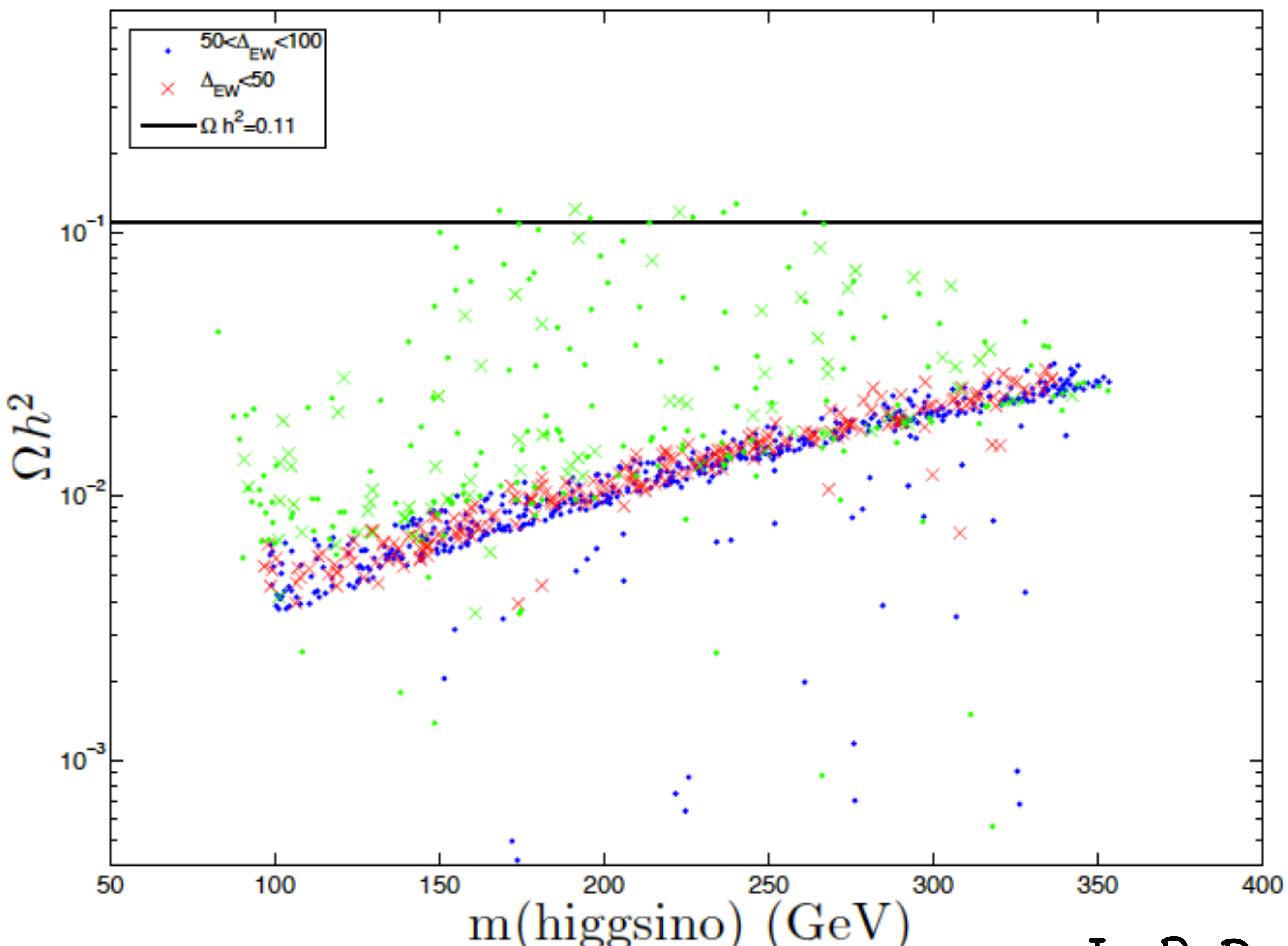
HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

ILC either sees light higgsinos or MSSM dead


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)

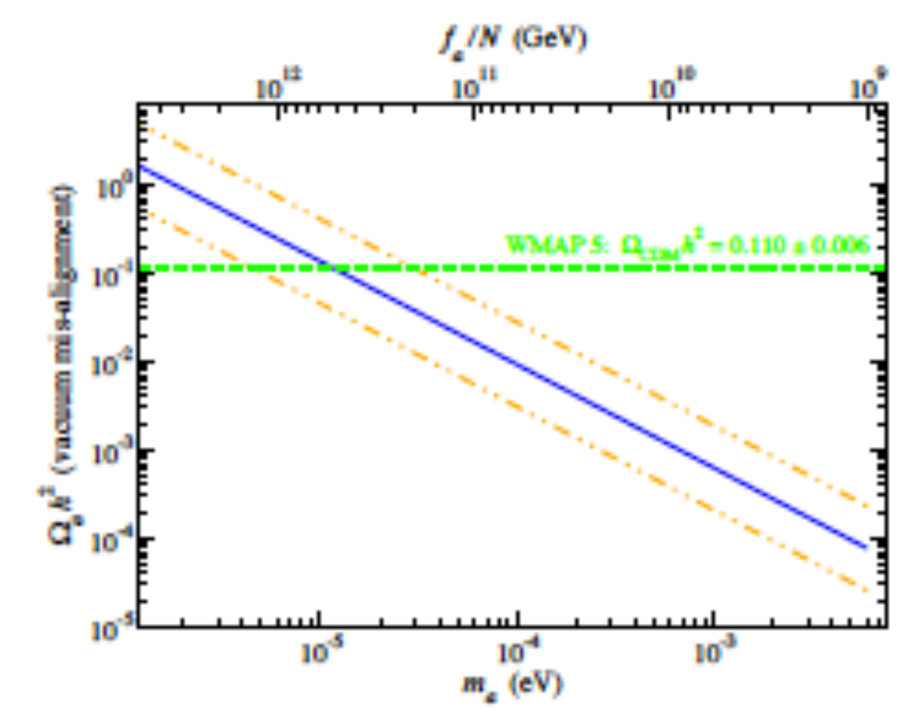
Best solution after 35 years:
PQWW/KSVZ/DFSZ invisible axion

In SUSY, axion accompanied by axino and saxion

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

Axion cosmology

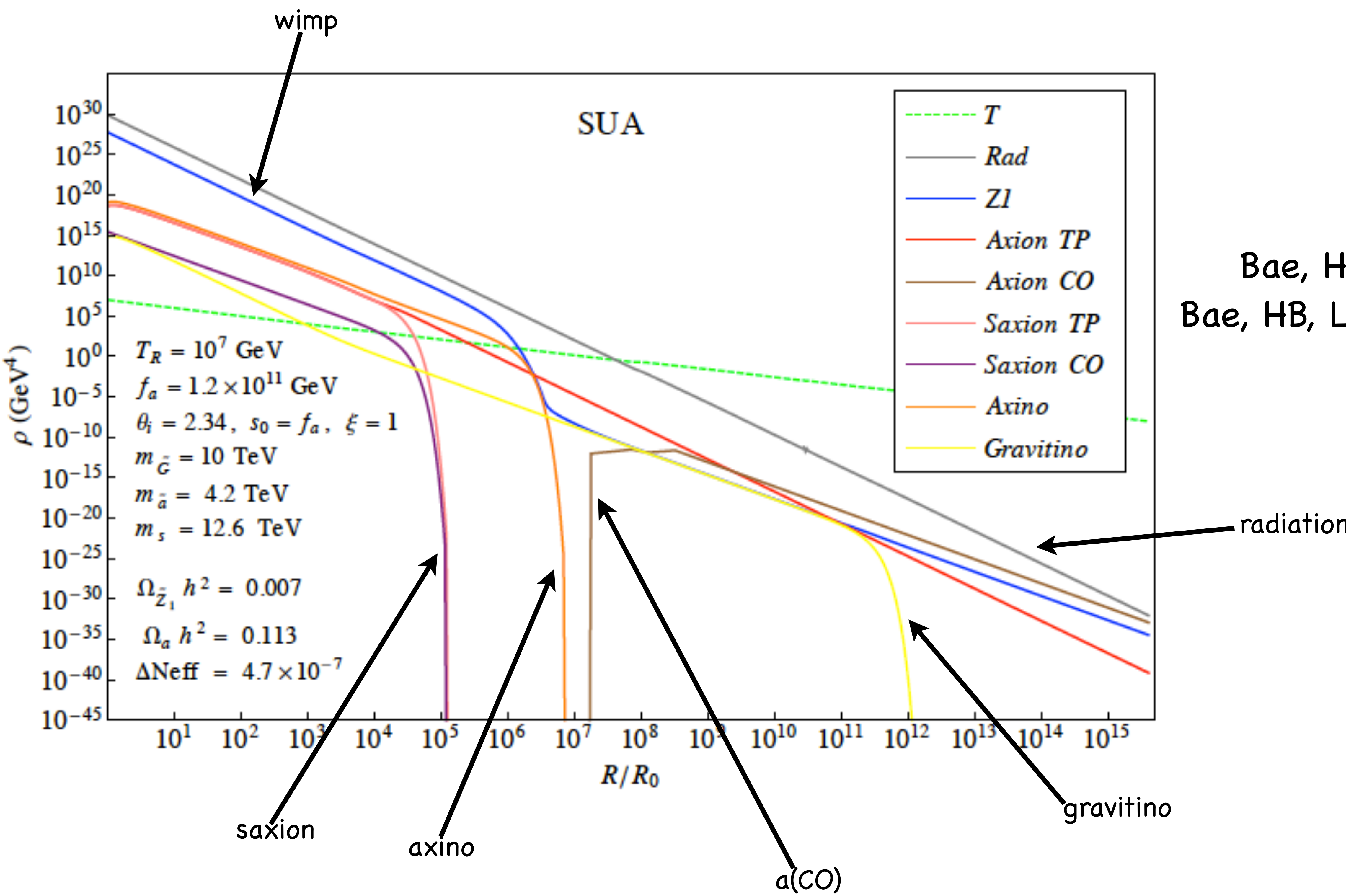
- ★ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial\theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$: $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ★ a(x)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



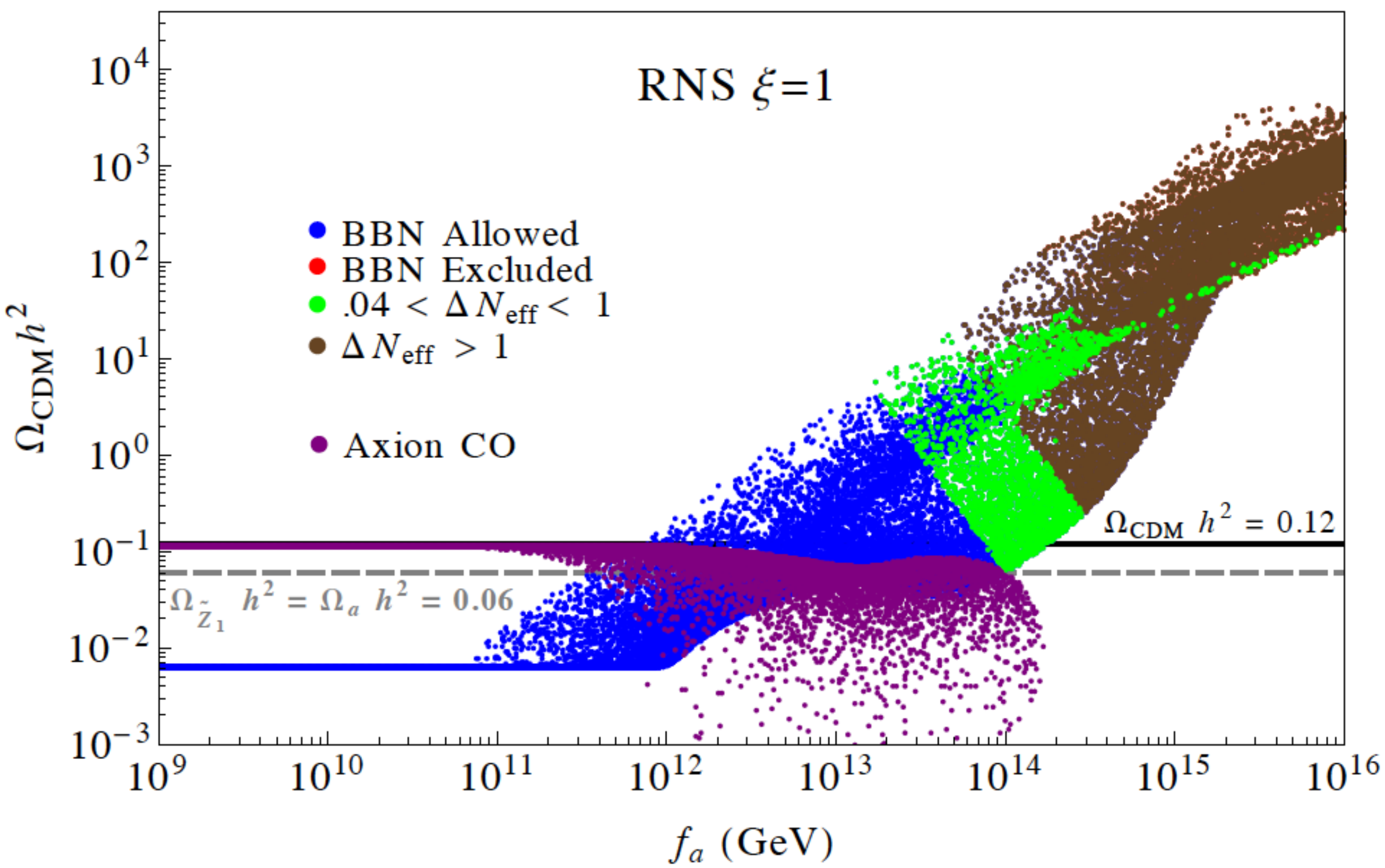
mixed axion-neutralino production in early universe

- 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

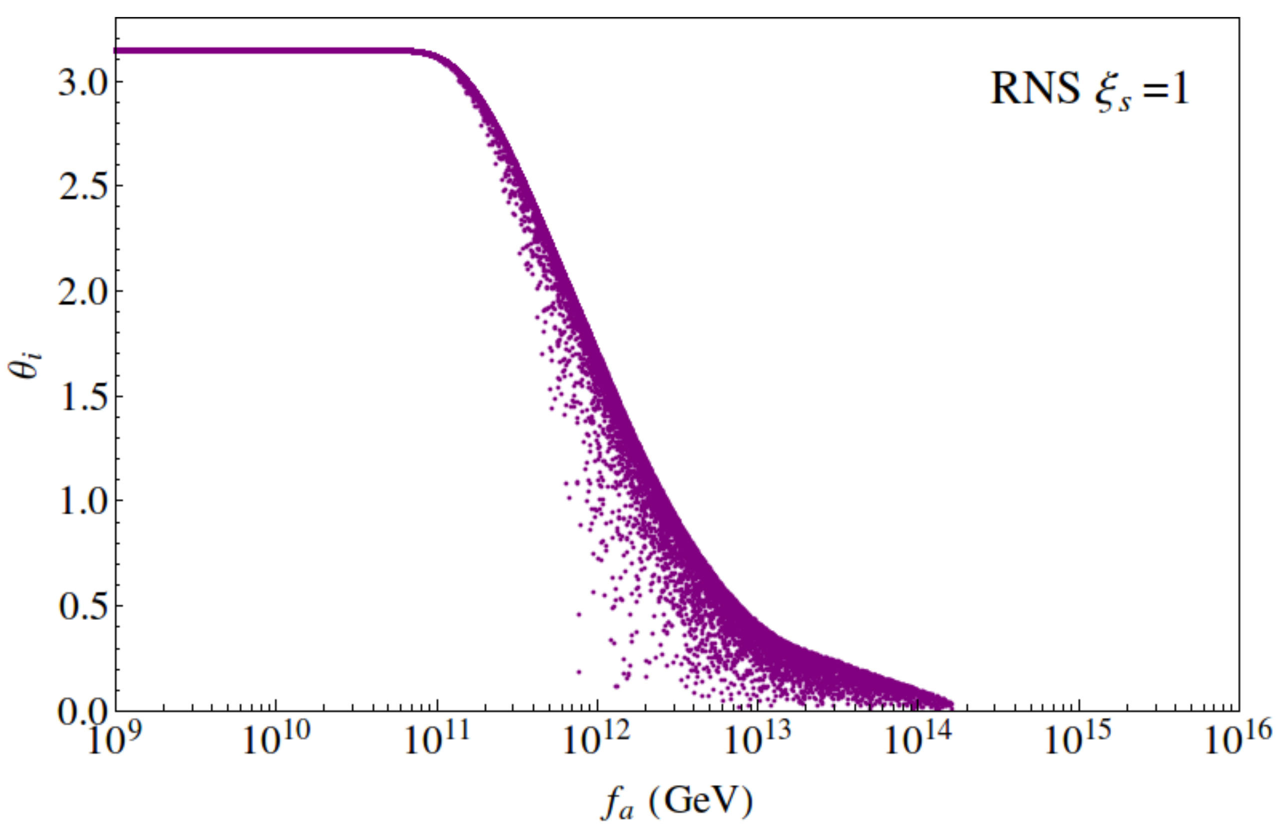


Bae, HB, Chun;
Bae, HB, Lessa, Serce



higgsino abundance

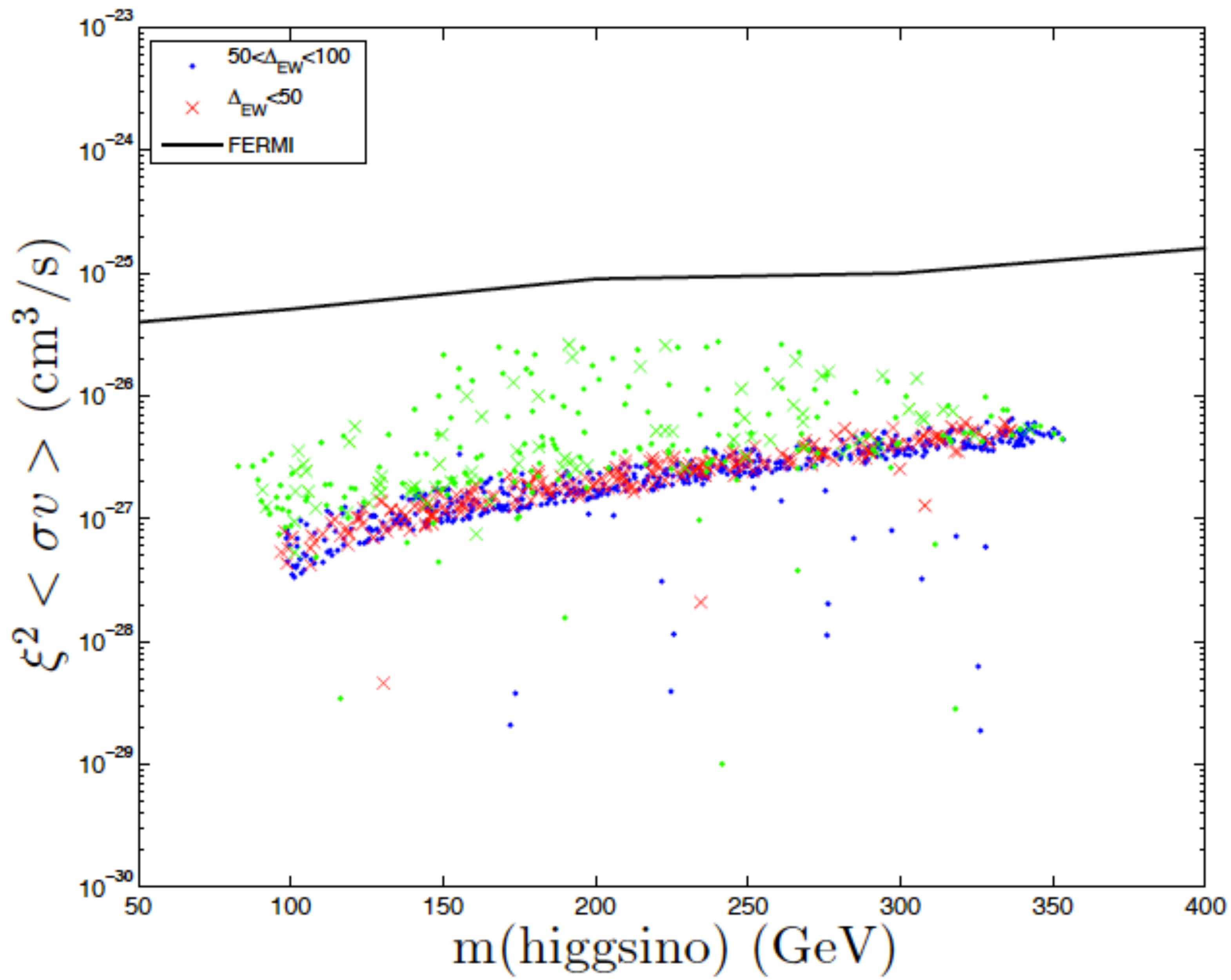
axion abundance



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

Bae, HB,Lessa,Serce

Higgsino detection via halo annihilations:

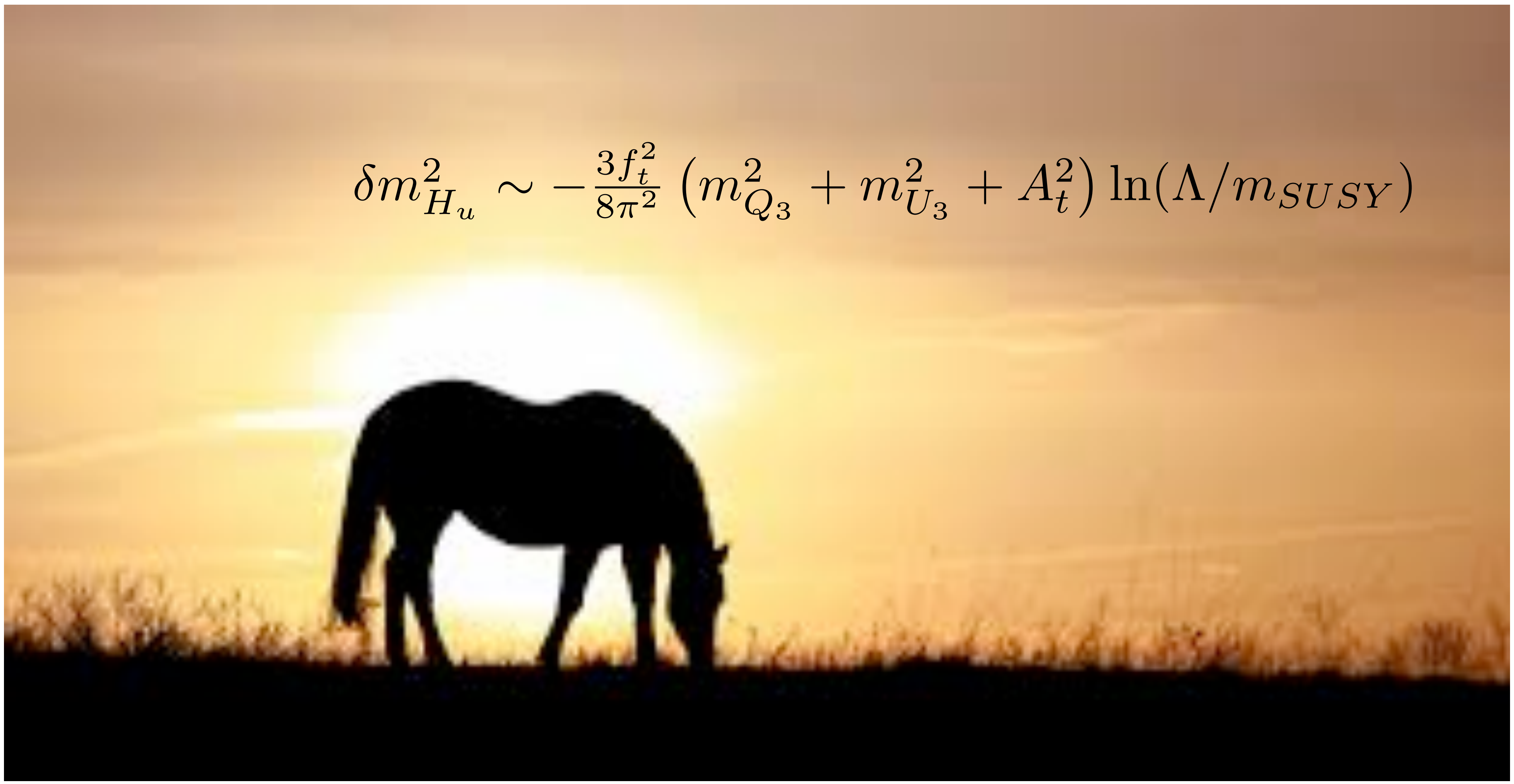


green: excluded by Xe-100

annihilation rate is high but rescaling is squared

Gamma-ray sky signal is factor 10-20 below current limits

Recommendation: put this horse out to pasture



R.I.P.

sub-TeV 3rd generation squarks not required for naturalness