Natural SUSY from the string theory landscape

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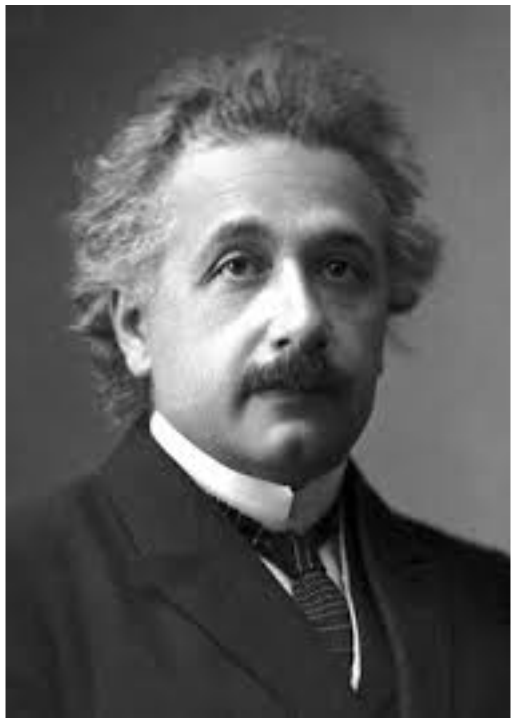

twin pillars of guidance:
simplicity & naturalness

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

A. Einstein

``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

Following Einstein:
be as simple as possible, not simpler

- weak scale effective theory=SM (including Higgs)
- mass instability of fundamental Higgs field duly noted as we proceed beyond the weak scale

Following Weinberg: must be natural to be plausible

- invoke SUSY: SM-> MSSM
- solves Big Hierarchy problem
- softly broken as expected from SUGRA
- might expect m(h)-> LHC scale (multi-TeV)
- require no Little Hierarchy as well

First: avoid unambiguous fine-tunings arising at the weak scale

Scalar potential minimization conditions relate m(W,Z,h)~100 GeV to SUSY Lagrangian

No large uncorrelated cancellations in m(Z) or m(h)

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

$\Delta_{EW}\equiv max_i\left|C_i\right|/(m_Z^2/2)$ 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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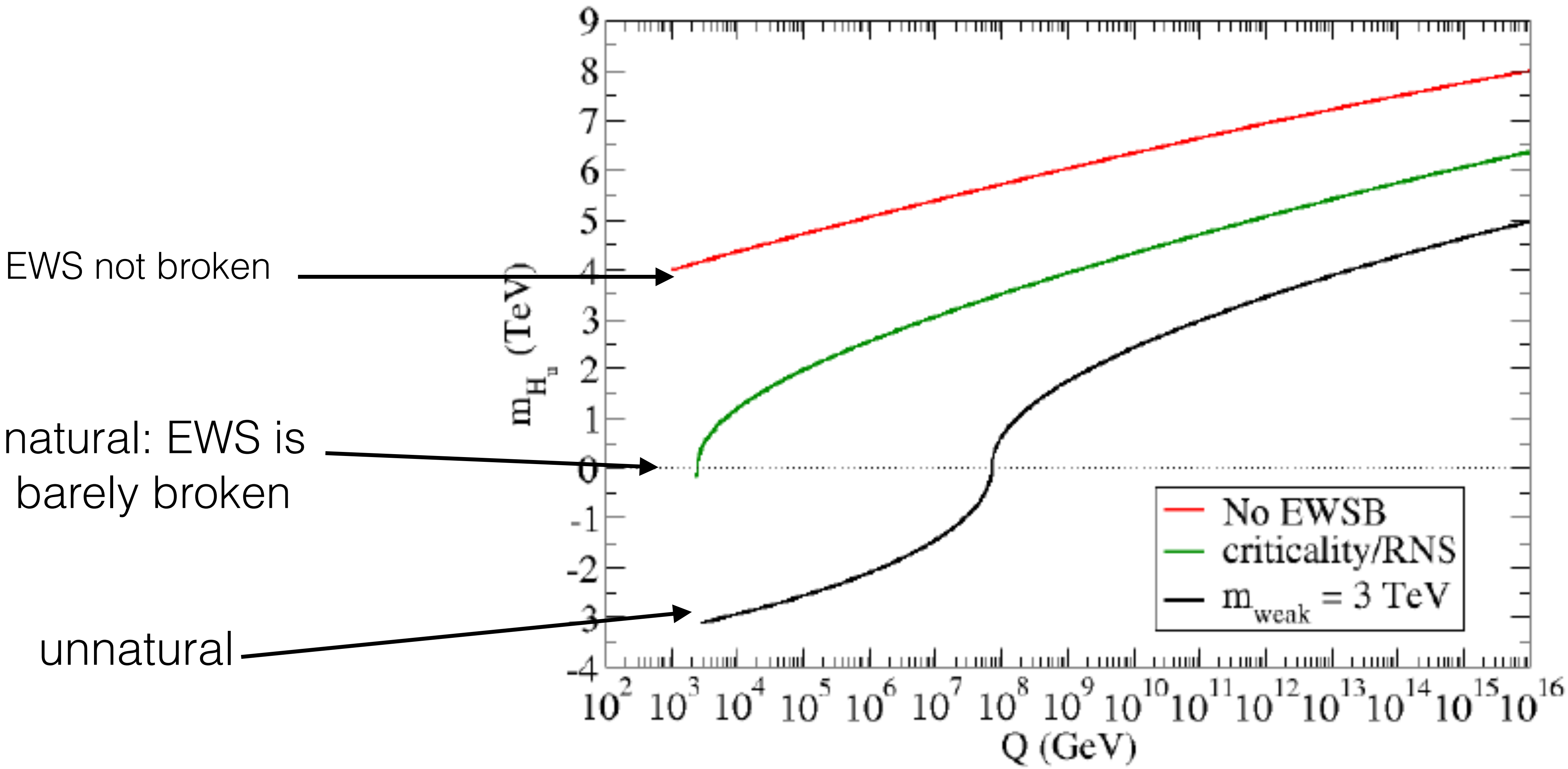
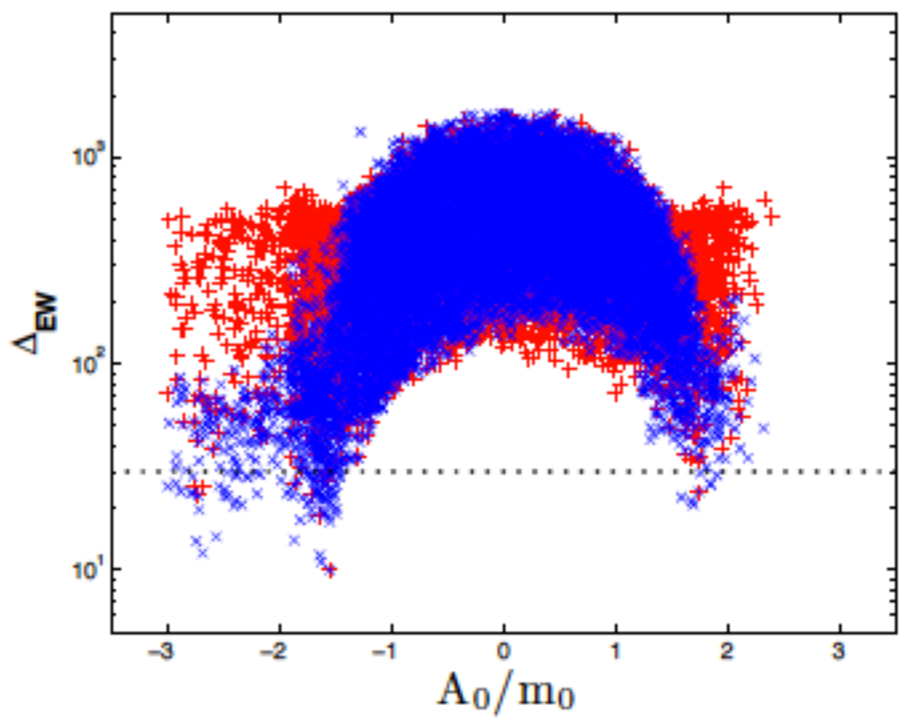
PRL109 (2012) 161802

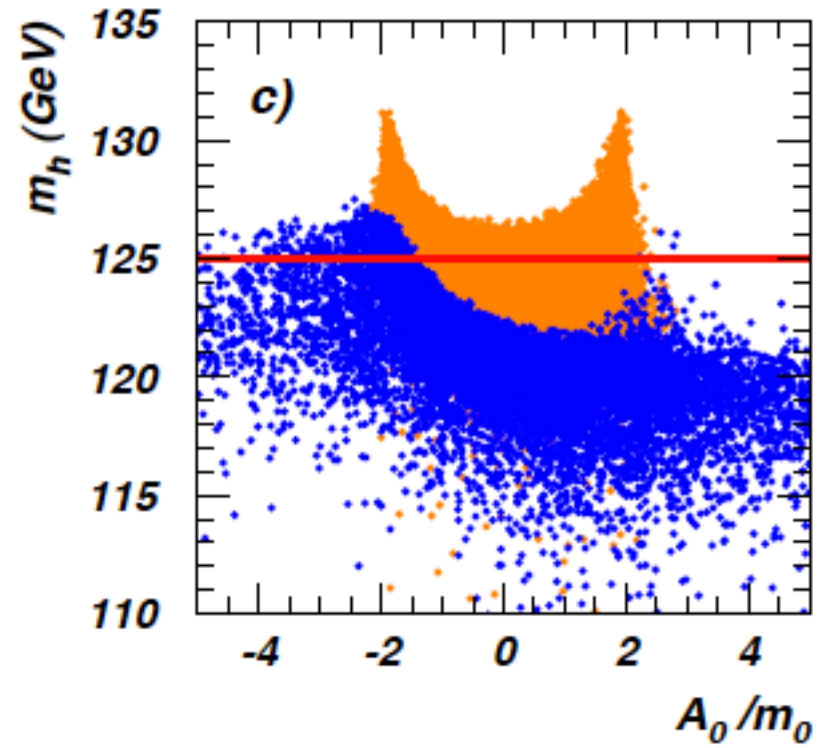
radiative corrections drive $m^2_{H_u}$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness



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

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





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

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

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

Is that all there is to EW naturalness in SUSY?

- What about UV fine-tuning measures?
- What about BG/KN etc. bounds m(C1)<100 GeV, m(glno)<400 GeV, m(t1,t2,b1)<500 GeV?

UV fine-tuning depends on what you take as fundamental soft terms

$$m_h^2 = \mu^2 + m_{H_u}^2(weak) + (mixings < m_Z^2) + (rad.corr. < m_Z^2)$$

expand $m_{H_u}^2$ in terms of GUT scale soft param's using quasi-analytic solutions to RGEs for $\tan\beta = 10$

$$\begin{aligned}
m_h^2 &\simeq 1.09\mu^2(\Lambda) + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \\
&\simeq 1.09\mu^2 + m_{H_u}^2 - 1.92M_3^2 - 0.16M_3M_2 - 0.024M_1M_3 + 0.21M_2^2 \\
&\quad -0.005M_2M_1 + 0.006M_1^2 + 0.33M_3A_t + 0.08M_2A_t \\
&\quad +0.013M_1A_t - 0.11A_t^2 - 0.002M_3A_b \\
&\quad -0.36m_{H_u}^2 + 0.027m_{H_d}^2 \\
&\quad -0.37m_{Q_3}^2 - 0.29m_{U_3}^2 - 0.025m_{D_3}^2 + 0.026m_{L_3}^2 - 0.027m_{E_3}^2 \\
&\quad -0.026m_{Q_2}^2 + 0.06m_{U_2}^2 - 0.026m_{D_2}^2 + 0.026m_{L_2}^2 - 0.027m_{E_2}^2 \\
&\quad -0.026m_{Q_1}^2 + 0.06m_{U_1}^2 - 0.026m_{D_1}^2 + 0.026m_{L_1}^2 - 0.027m_{E_1}^2
\end{aligned}$$

if all high scale soft terms independent then

$$e.g.\ 0.37m_{Q_3}^2 < 10m_h^2 \Rightarrow m_{Q_3} < 650 \text{ GeV}$$

If we work within CMSSM, get very different answer:

$$m_h^2 \simeq 1.09\mu^2 - 1.893m_{1/2}^2 + 0.421m_{1/2}A_0 - 0.11A_0^2$$
$$-0.019m_0(3)^2 + 0.006m_0(2)^2 + 0.006m_0(1)^2$$

$$0.019m_0(3)^2 < 10m_h^2 \Rightarrow m_0(3) <\sim 3\ \mathrm{TeV}$$

correlations between parameters can lead to large cancellations!

If we work in complete model where hidden sector is specified and all soft terms computed in terms of m(3/2)- (as usual in SUGRA models)

$$m_h^2 \simeq 1.09\mu^2 + a\cdot m_{3/2}^2 \simeq \mu^2(weak) + m_{H_u}^2(weak)$$

model is natural for m(3/2) large if a is small

$a\cdot m_{3/2}^2 \simeq m_{H_u}^2$ so a small

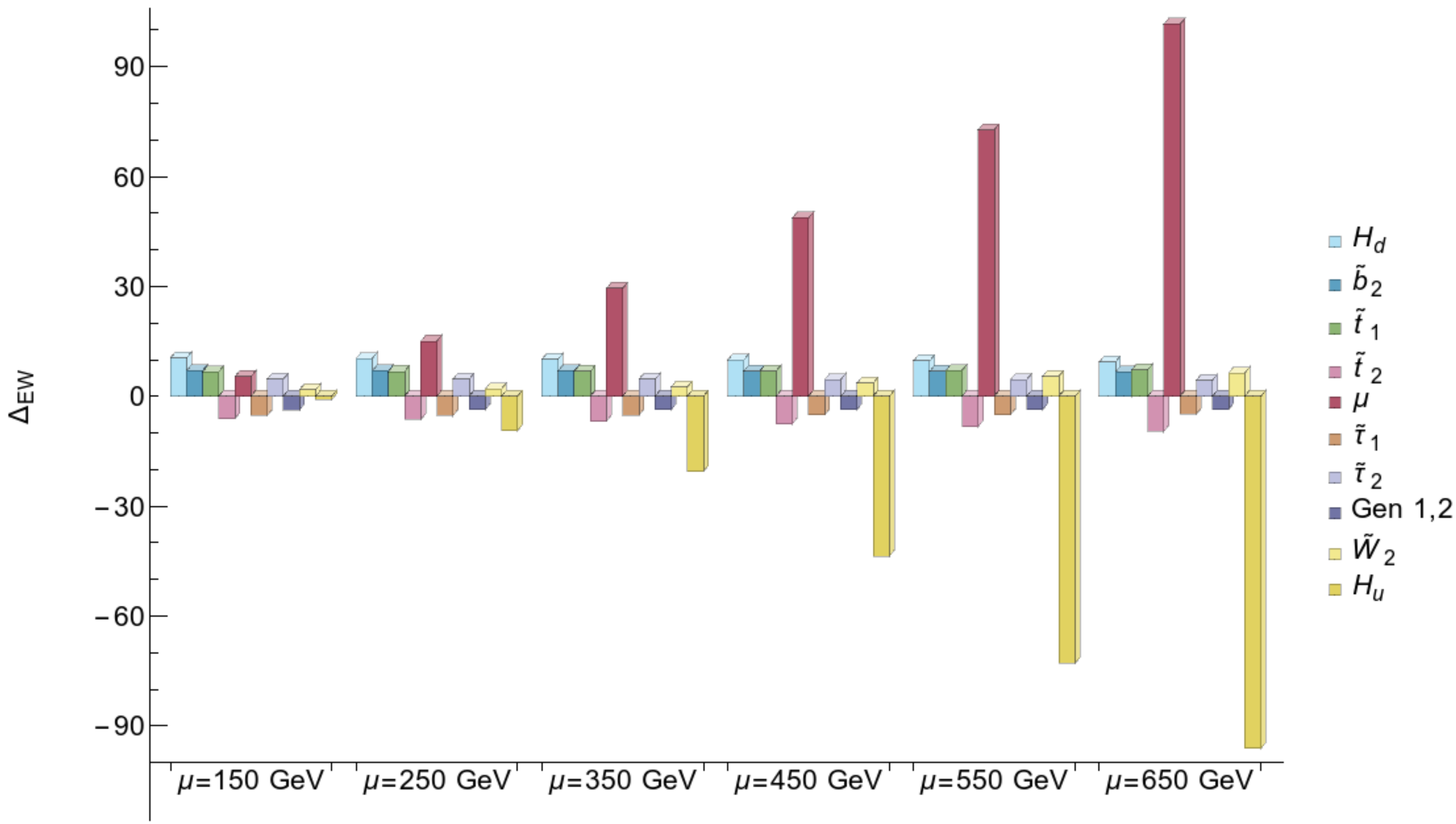
$\Rightarrow m_{H_u}^2$ driven small at weak scale: *same as for* Δ_{EW}!

Δ_{EW} is appropriate fine-tuning measure for either IR or *correlated* UV 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

How much is too much fine-tuning?



HB, Barger, Savoy

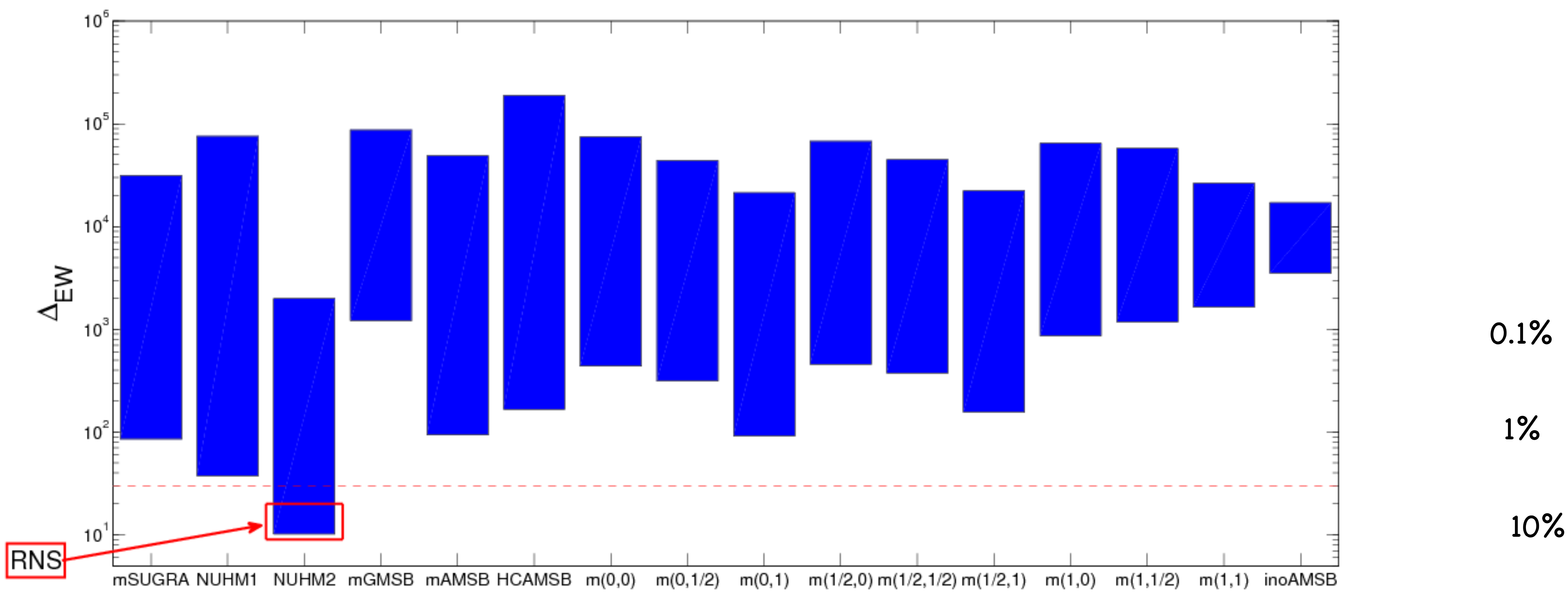
Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

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

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.

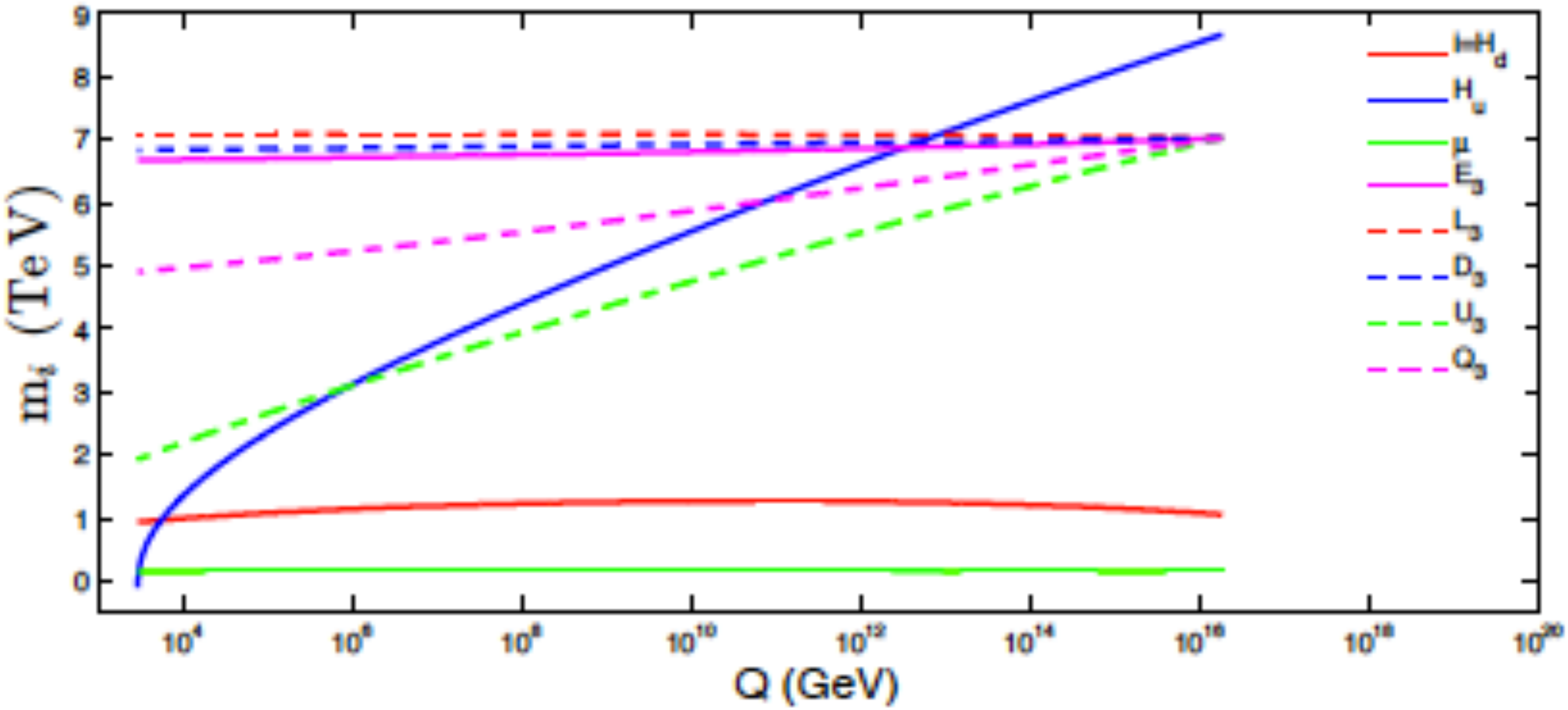
scan over p-space with m(h)=125.5+-2.5 GeV:



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:

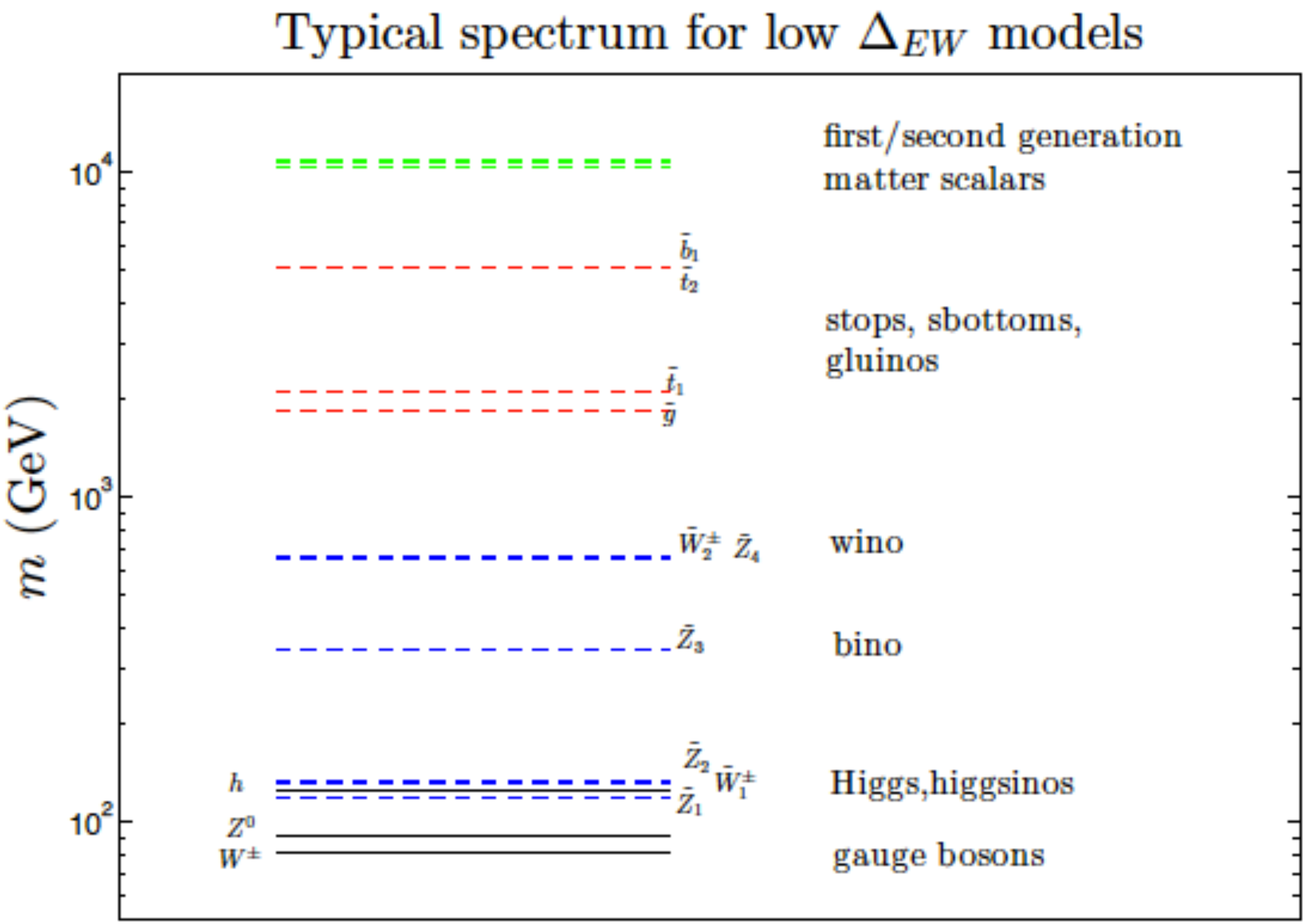
(typically need mHu~25-50% higher than m0)

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

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

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 questions:

1. Why might mu<< m(soft)

2. Why might soft terms be at multi-TeV scale but with m(Hu) driven radiatively to mHu^2(weak)~-(100-200 GeV)^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); 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!

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

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

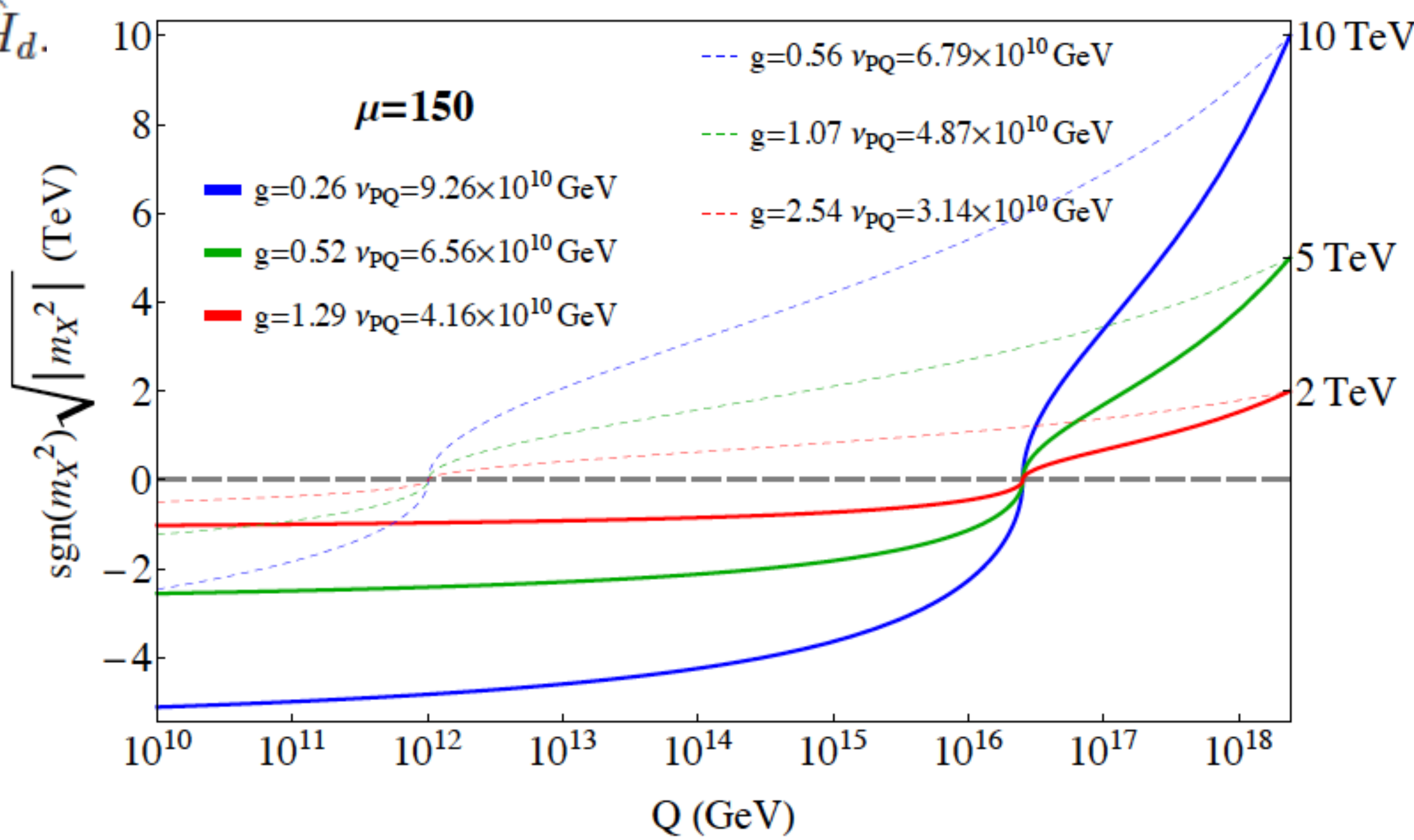
augment MSSM with PQ charges/fields:

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

SUSY breaking triggers PQ breaking: generate fa and MN

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

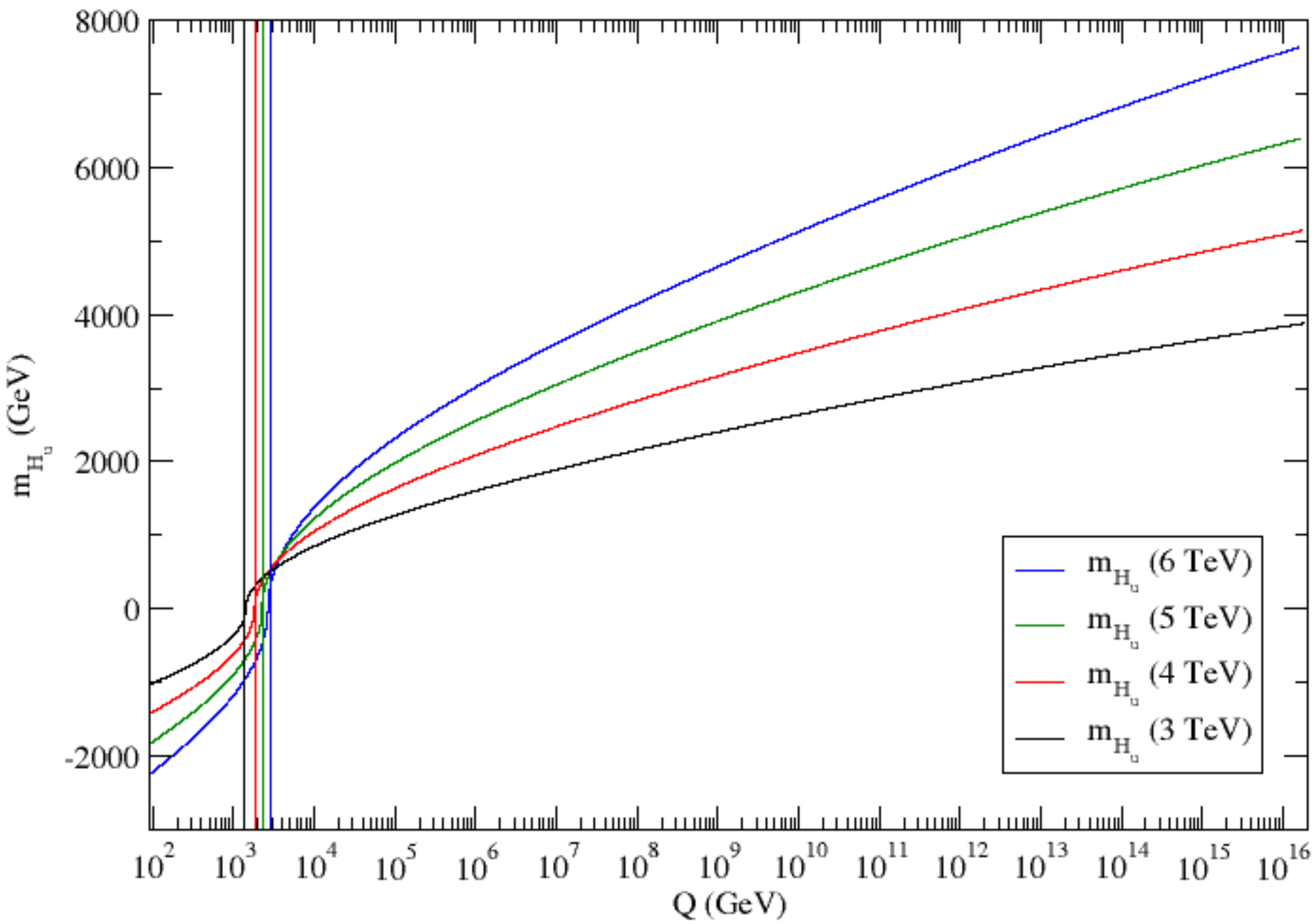
$$\mu = g \frac{v_X v_Y}{M_P} .$$



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

Why might mHu have the value needed to give naturalness at weak scale?

1. For right correlations amongst soft terms, get ``generalized focus point"



e.g.

For $\mu = 150$ GeV, $\tan\beta = 10$ and

$$\begin{aligned} m_0^2 &= m_{3/2}^2 \\ A_0 &= -1.6 m_{3/2} \\ m_{1/2} &= m_{3/2}/5 \\ m_{H_d}^2 &= m_{3/2}^2/2. \end{aligned}$$

$$m_{H_u}^2(GUT) = 1.8 m_{3/2}^2 - (212.52\ \mathrm{GeV})^2.$$

$m_{H_u}^2(weak) \sim a \cdot m_{3/2}^2$ with correlated soft terms such that a is small: generalized focus point behavior

HB, Barger, Savoy, arXiv:1602.06973

Statistical analysis of SUSY breaking scale in II-B string theory landscape of vacua: F. Denef & M. Douglas (for summary, see e.g. hep-th/0405279)

some reasonable assumptions

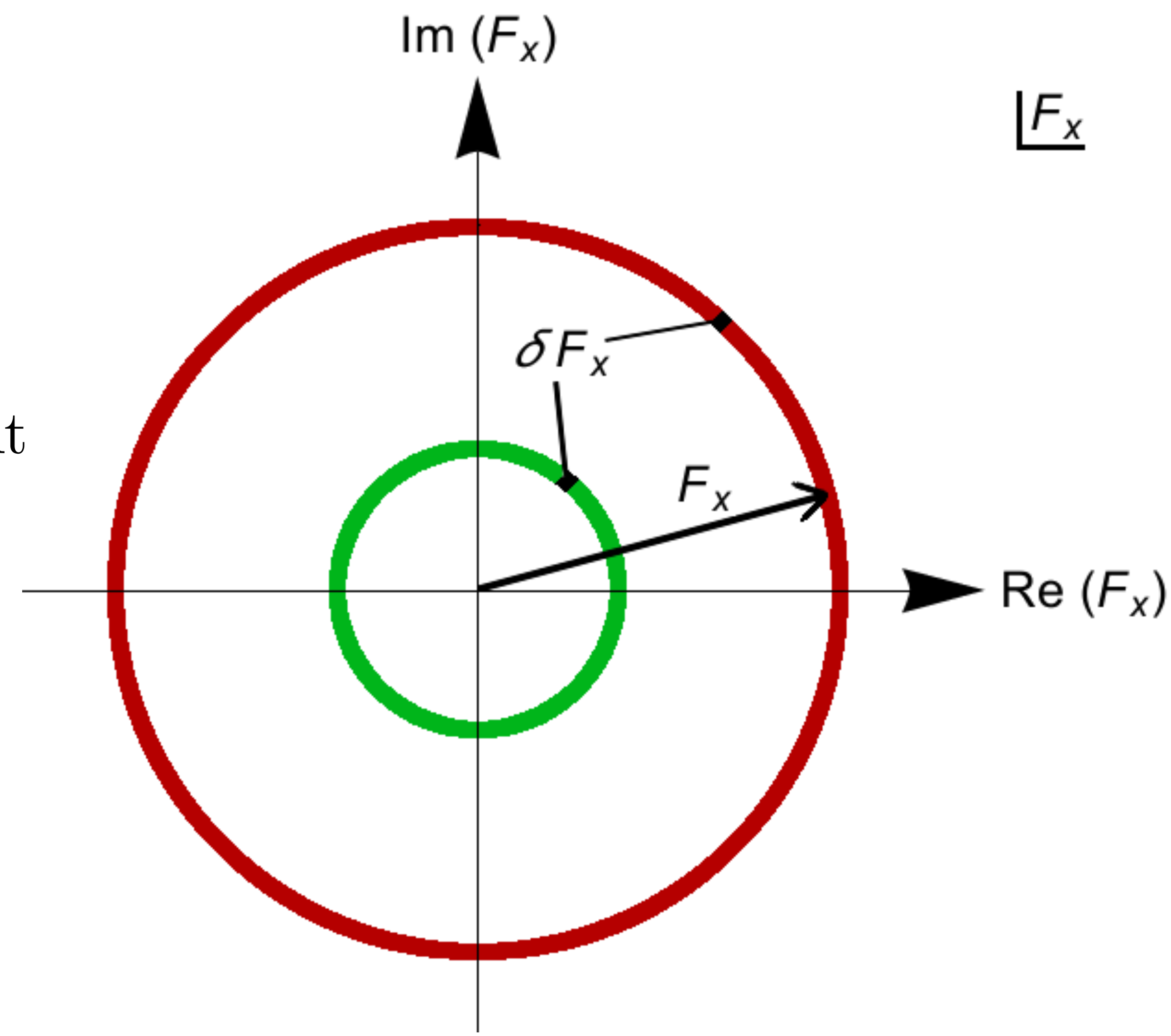
- string theory landscape contains vast ensemble of N=1, d=4 SUGRA EFTs at high scales
- the EFTs contain the SM as weak scale EFT
- the EFTs contain visible sector +potentially large hidden sector
- visible sector contains MSSM plus extra gauge singlets (e.g. a PQ sector, RN neutrinos,...)
- SUGRA is 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?

2. string theory landscape?

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

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



$m(weak) <\sim 400$ 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.

Scalar potential is given by usual SUGRA form:

$$V = e^{K/m_P^2}\left(g^{i\bar{j}} D_i W D_{\bar{j}} W^* - \frac{3}{m_P^2}|W|^2\right) + \frac{1}{2}\sum_\alpha D_\alpha^2$$
$$= e^{K/m_P^2}\left(\sum_i |F_i|^2 - 3\frac{|W|^2}{m_P^2}\right) + \frac{1}{2}\sum_\alpha D_\alpha^2$$

- W = holomorphic superpotential
- K = real Kähler function
- $F_i = D_i W = DW/D\phi^i \equiv \partial W/\partial\phi^i + (1/m_P^2)(\partial K/\partial\phi^i)W$ are F-terms
- $D_\alpha \sim \sum \phi^\dagger g t_\alpha \phi$ are D-terms
- ϕ^i are chiral superfields

minimize V:

- $\partial V/\partial\phi^i = 0$
- $\partial^2 V/\partial\phi^i\partial\phi^j > 0$
- $\Lambda_{cc} = m_{hidden}^4 - 3e^{K/m_P^2}|W|^2/m_P^2$ with
- $m_{hidden}^4 = \sum_i |F_i|^2 + \frac{1}{2}\sum_\alpha D_\alpha^2$ is hidden sector mass scale

gravitino mass $m_{3/2} = e^{K/2m_P^2} m_P \sim m_{hidden}^2/m_P$ with $m_{hidden} \sim 10^{12}$ GeV

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 $m_{soft} \sim m_{3/2} \sim m^2_{hidden}/m_P$

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

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

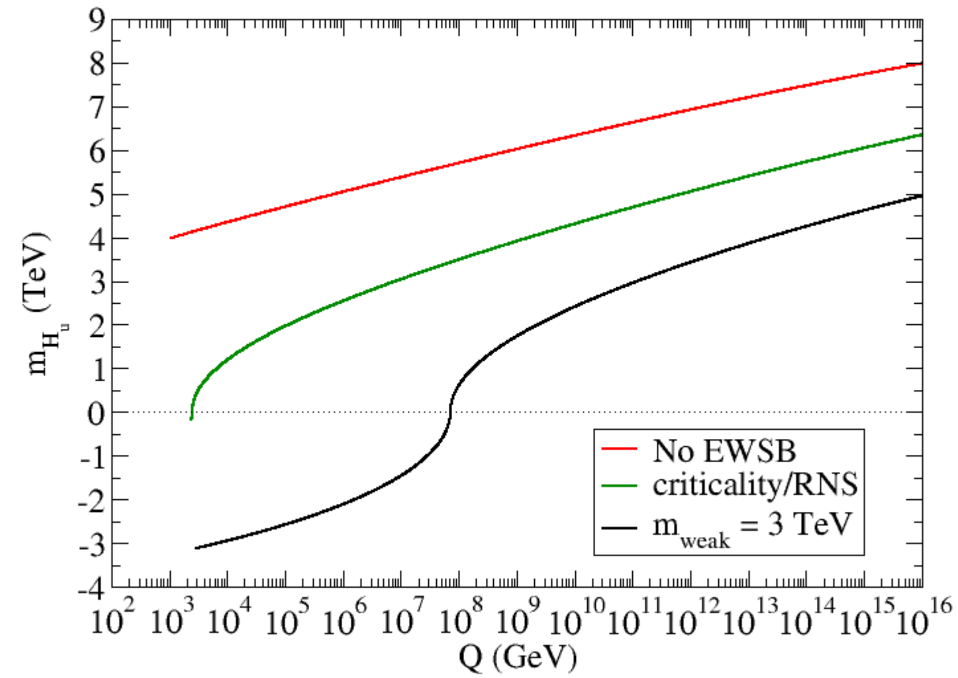
n_F	n_D	n
0	1	0
1	0	1
0	2	1
1	1	2
0	3	2
2	0	3
2	1	4

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

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

This fails in a variety of *practical* cases:

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



Must require proper EWSB!
Even if EWS properly broken, then

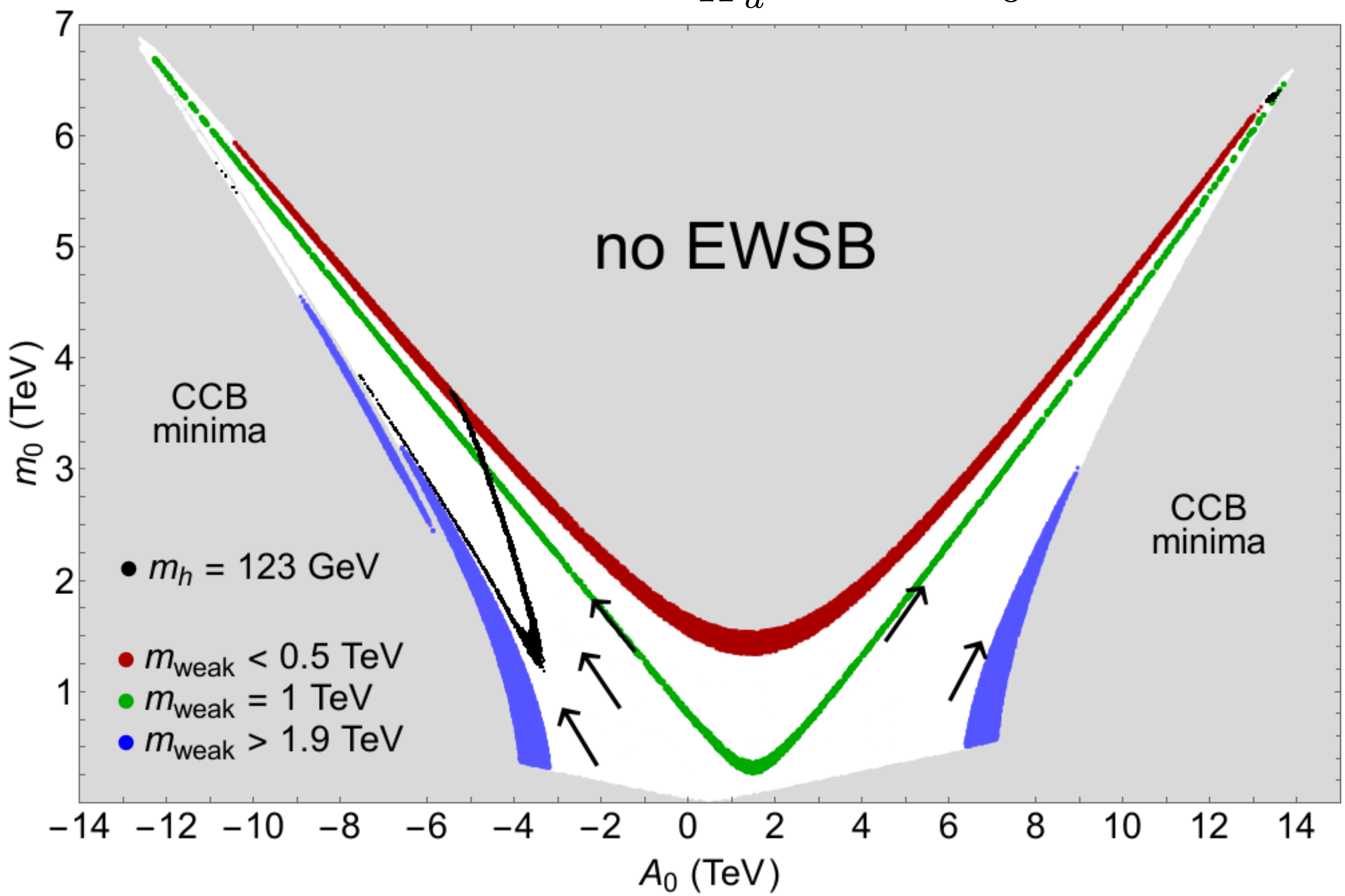
- large A_t *reduces* EWFT in the $\Sigma_u^u(\tilde{t}_{1,2})$
- large $m_{H_u}^2(m_{GUT})$ needed to radiatively drive $m_{H_u}^2$ to natural value at weak scale

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 $m_{H_{u,d}}^2$ and $\Sigma_{u,d}^{u,d}(i)$

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

$m_{H_u} = 1.3 m_0$



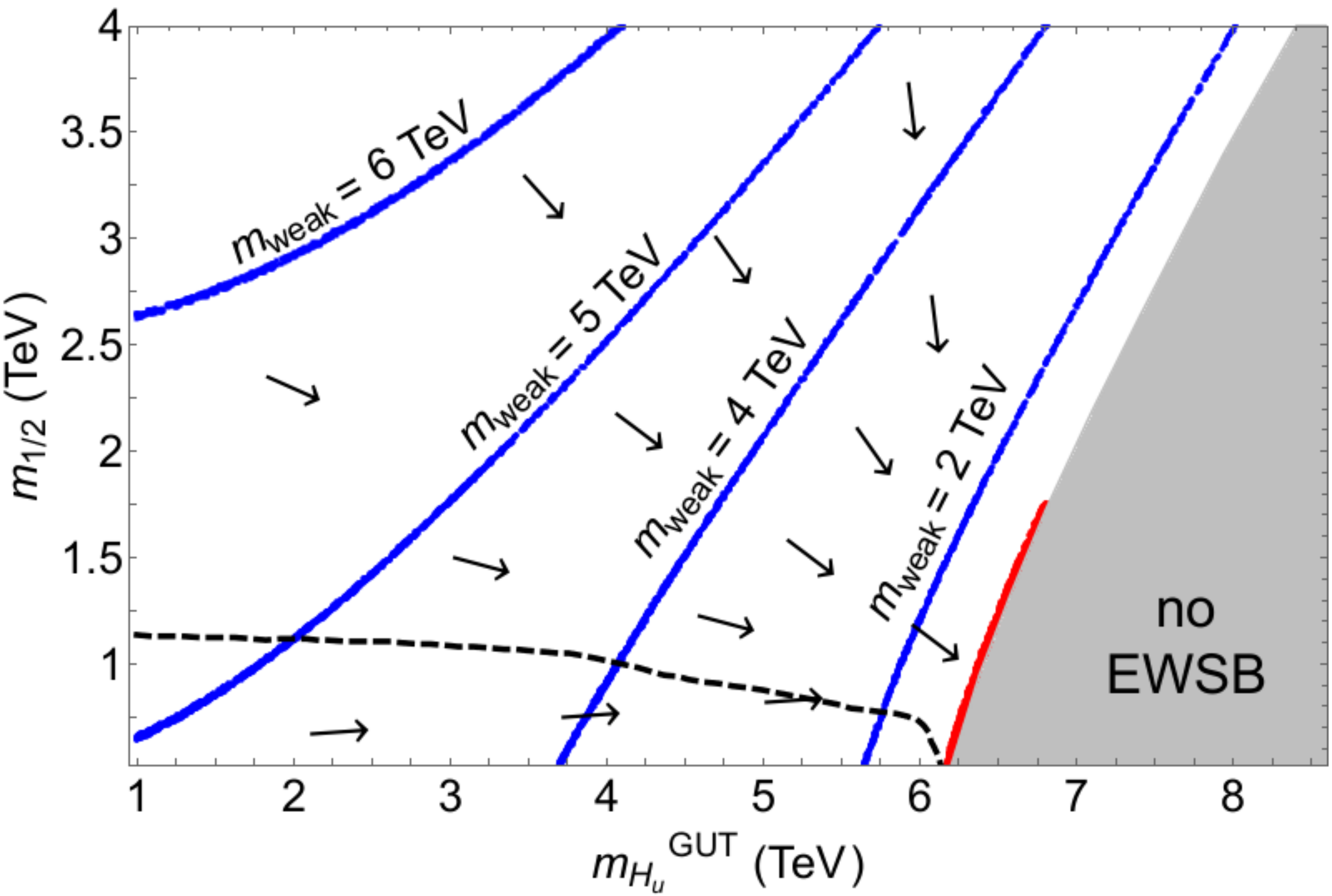
statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Denef, Douglas, JHEP0405 (2004) 072

Giudice, Rattazzi, NPB757 (2006) 19;

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

$m_0 = 5$ TeV



statistical/anthropic draw toward FP-like region

For practical calculations, adopt NUHM3 SUGRA model:

- $m_0(1,2)$ = gen(1,2) common soft mass
- $m_0(3)$ = gen(3) common soft mass
- $m^2_{H_u}$ up-Higgs soft mass
- $m^2_{H_d}$ down-Higgs soft mass
- $m_{1/2}$ = unified gaugino mass
- A_0 = unified trilinear soft term
- $\tan\beta$

Trade $m^2_{H_u},\ m^2_{H_d} \Leftrightarrow \mu,\ m_A$

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A \quad (NUHM3)$$

Recent work: place on more quantitative footing: scan soft SUSY breaking parameters 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,

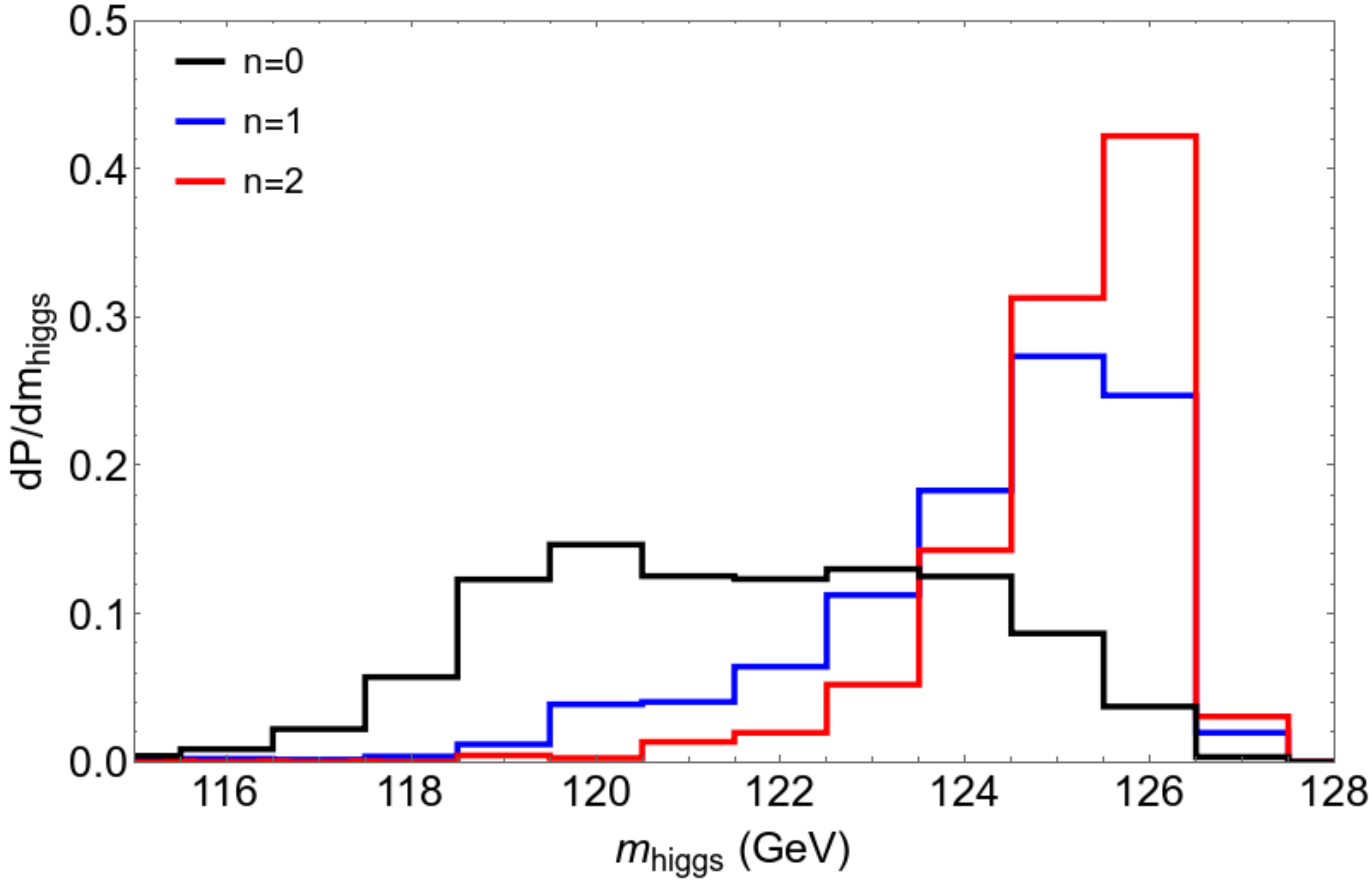
$\tan\beta : 3 - 60$ (flat)

mu=150 GeV (fixed)

HB, Barger, Serce, Sinha (arXiv:1712.01399)

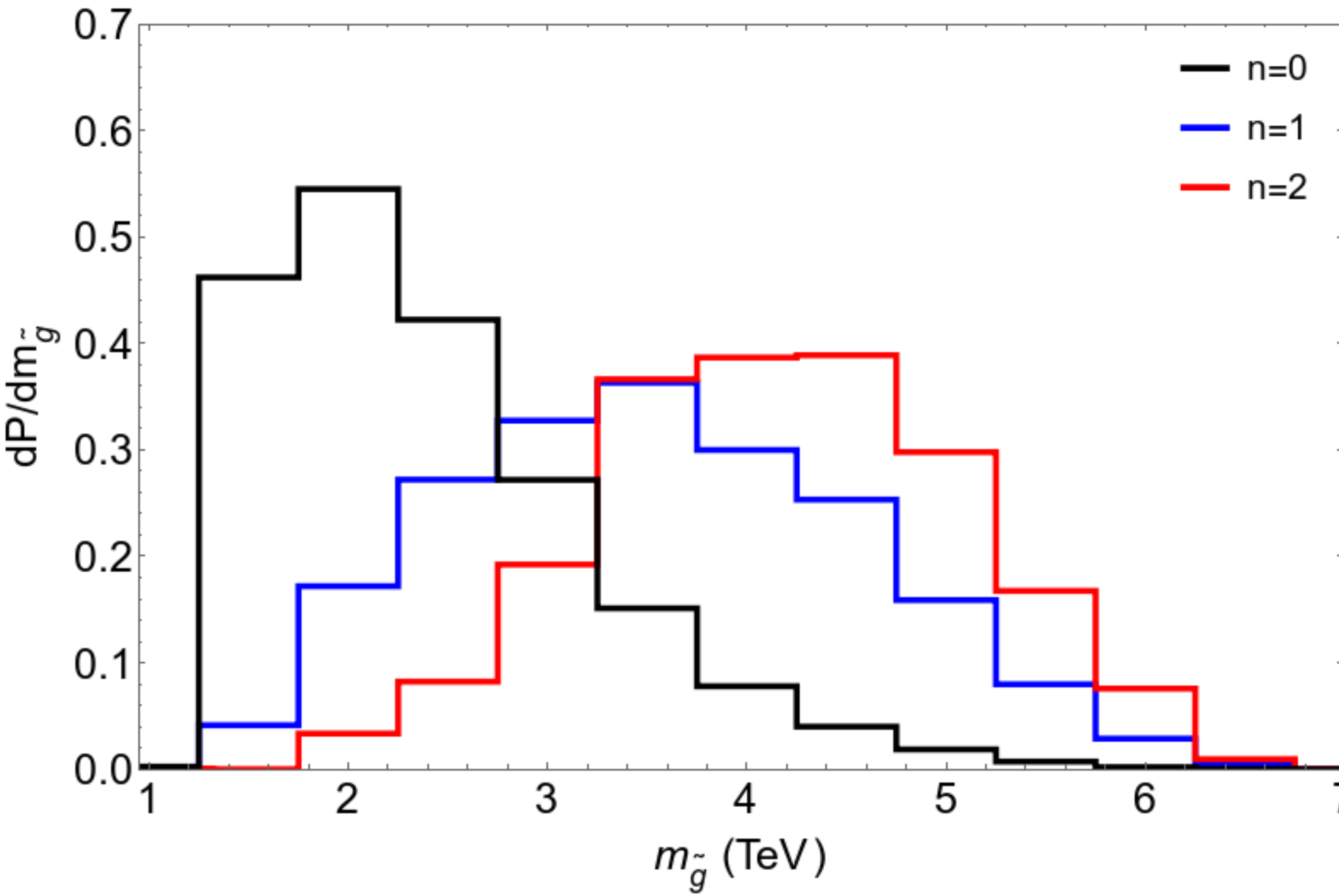
Making the picture more quantitative:

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



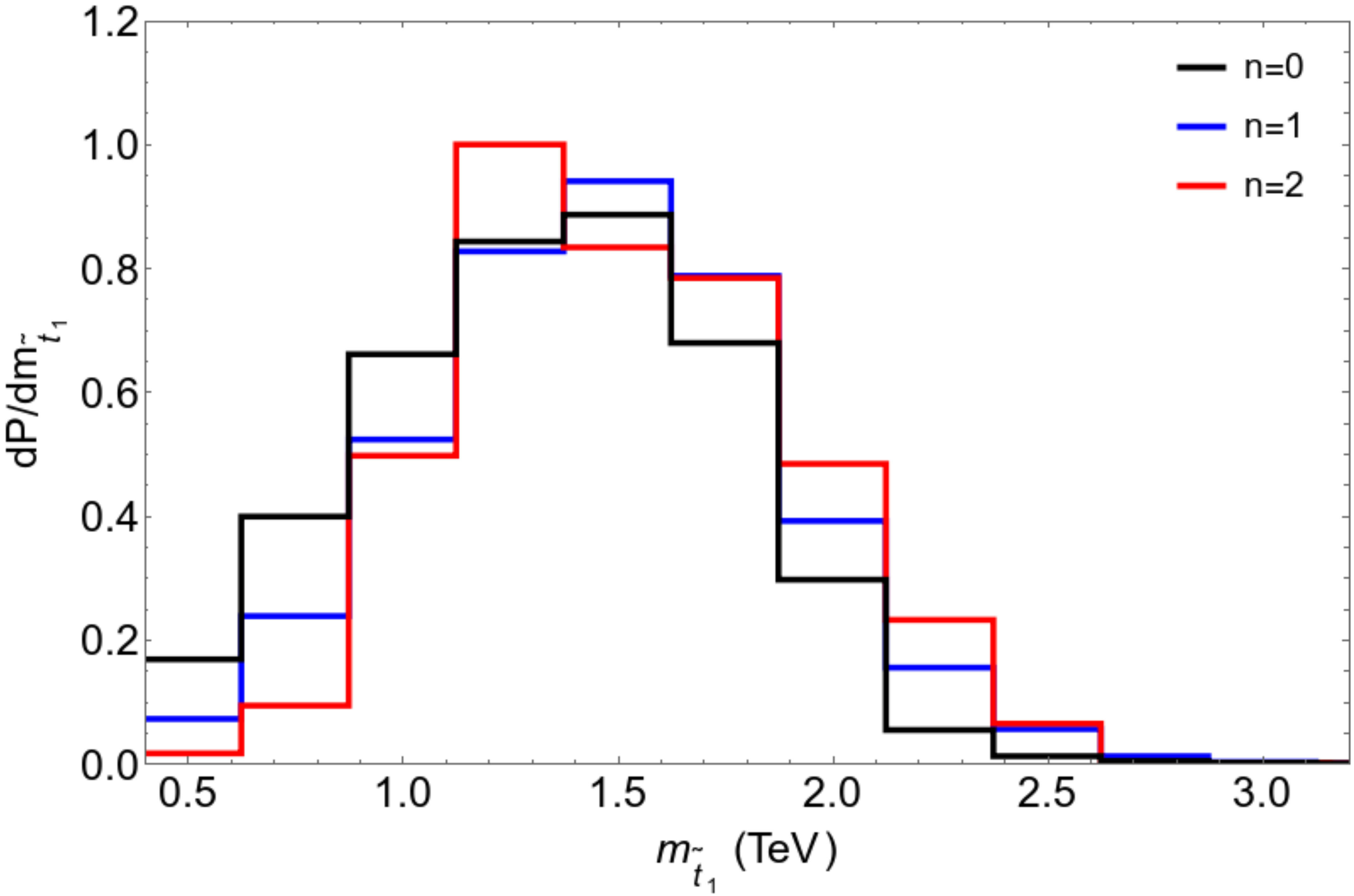
m(h)~125 most favored for n=1,2

What is corresponding distribution for gluino mass?



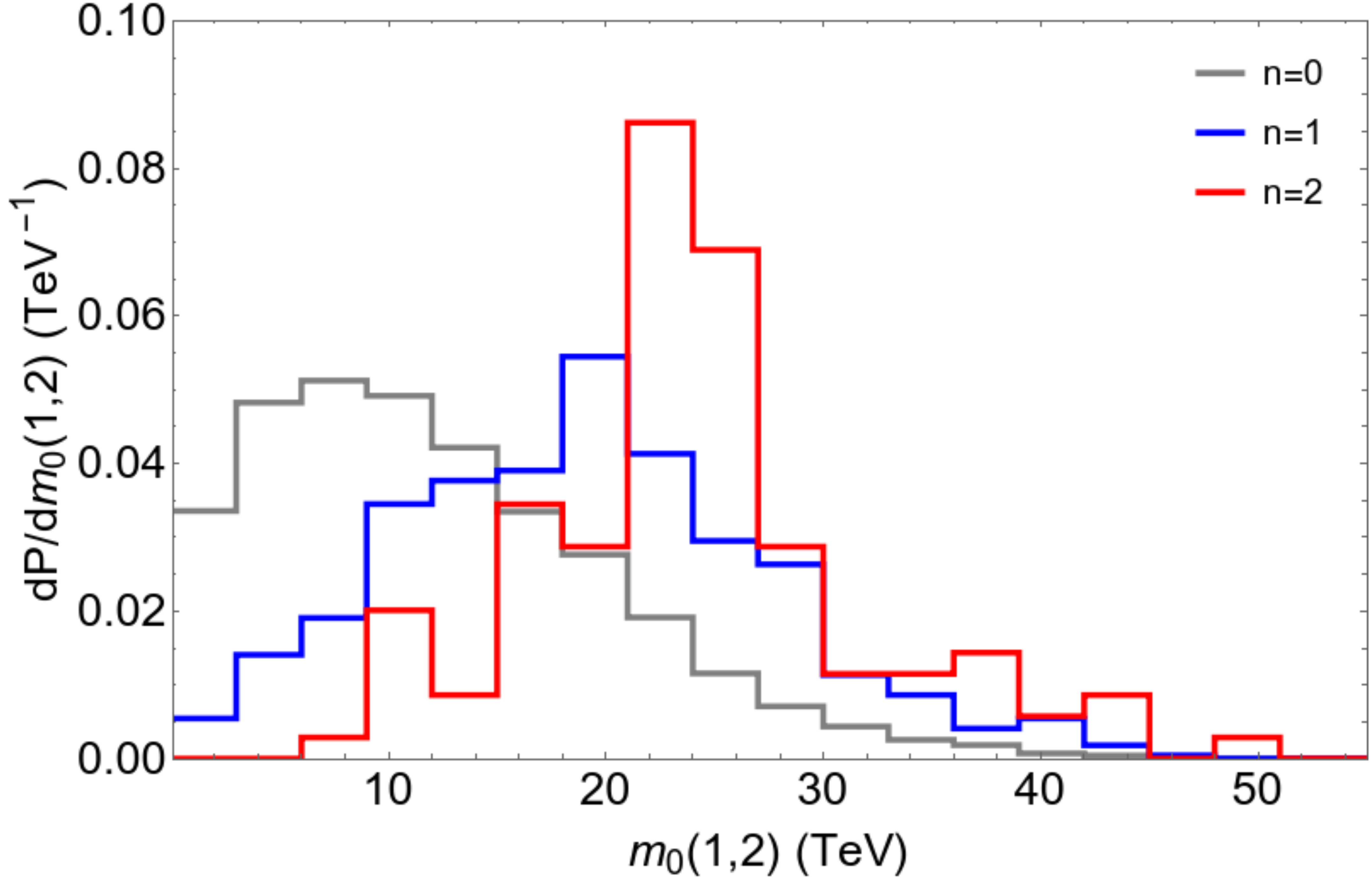
typically beyond LHC 14 reach (may need HE-LHC)

and m(t1)?



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

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

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

Some topics for discussion

- What is correct measure for EW naturalness (in SUSY/other models)? Δ_{HS}?, Δ_{BG} (what are right p_i?) Δ_{EW}? or is naturalness all *subjective*?
- Is naturalness/fine-tuning a path to falsifiability of weak scale SUSY?
- How should contributions to Δ be organized? Factors of 2 etc. (Ross, Schmidt-Hoberg, Staub)
- What about non-holonomic soft terms (NHSTs) $\mu'\tilde{H}_u\tilde{H}_d$:heavy higgsinos while low fine-tuning?
- Are NHSTs large $\sim m_{weak}$ or highly suppressed (Martin, 1999)?
- How much is too much fine-tuning? Important for sparticle mass upper limits/falsifiability
- What about fine-tuning in QCD sector- strong CP and $\bar{\theta}F\tilde{F}$: axions or other solutions?
- Should one insist on naturalness in both EW and QCD sectors? Interplay between axions and SUSY?
- μ problem: $\mu \sim m_{3/2}$ or $\mu \sim m_{weak} \ll m_{soft}$?
- Is there a mechanism behind barely broken EW symmetry in SUSY?
- What does naturalness imply for future accelerators? LHC, HL-LHC, HE-LHC, ILC250, ILC500-600?, FCC, CepC, CppC?
- What does naturalness imply for dark matter? WIMPs? axions? both? other?

Mirage mediation:
comparable moduli- & anomaly-mediation

Choi, Falkowski, Nilles, Olechowski, Pokorski

Generalized mirage mediation model:

HB, Barger, Serce, Tata: arXiv:1610.06205

$$M_a = \left(\alpha + b_a g_a^2\right) m_{3/2}/16\pi^2, \quad (10)$$
$$A_\tau = \left(-a_3\alpha + \gamma_{L_3} + \gamma_{H_d} + \gamma_{E_3}\right) m_{3/2}/16\pi^2, \quad (11)$$
$$A_b = \left(-a_3\alpha + \gamma_{Q_3} + \gamma_{H_d} + \gamma_{D_3}\right) m_{3/2}/16\pi^2, \quad (12)$$
$$A_t = \left(-a_3\alpha + \gamma_{Q_3} + \gamma_{H_u} + \gamma_{U_3}\right) m_{3/2}/16\pi^2, \quad (13)$$
$$m_i^2(1,2) = \left(c_m\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (14)$$
$$m_j^2(3) = \left(c_{m3}\alpha^2 + 4\alpha\xi_j - \dot{\gamma}_j\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (15)$$
$$m_{H_u}^2 = \left(c_{H_u}\alpha^2 + 4\alpha\xi_{H_u} - \dot{\gamma}_{H_u}\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (16)$$
$$m_{H_d}^2 = \left(c_{H_d}\alpha^2 + 4\alpha\xi_{H_d} - \dot{\gamma}_{H_d}\right)\left(m_{3/2}/16\pi^2\right)^2, \quad (17)$$

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

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

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

allows for natural mirage mediation

Allows to generate mini-landscape spectra

Buchmuller, Hamaguchi, Lebedev, Ratz

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

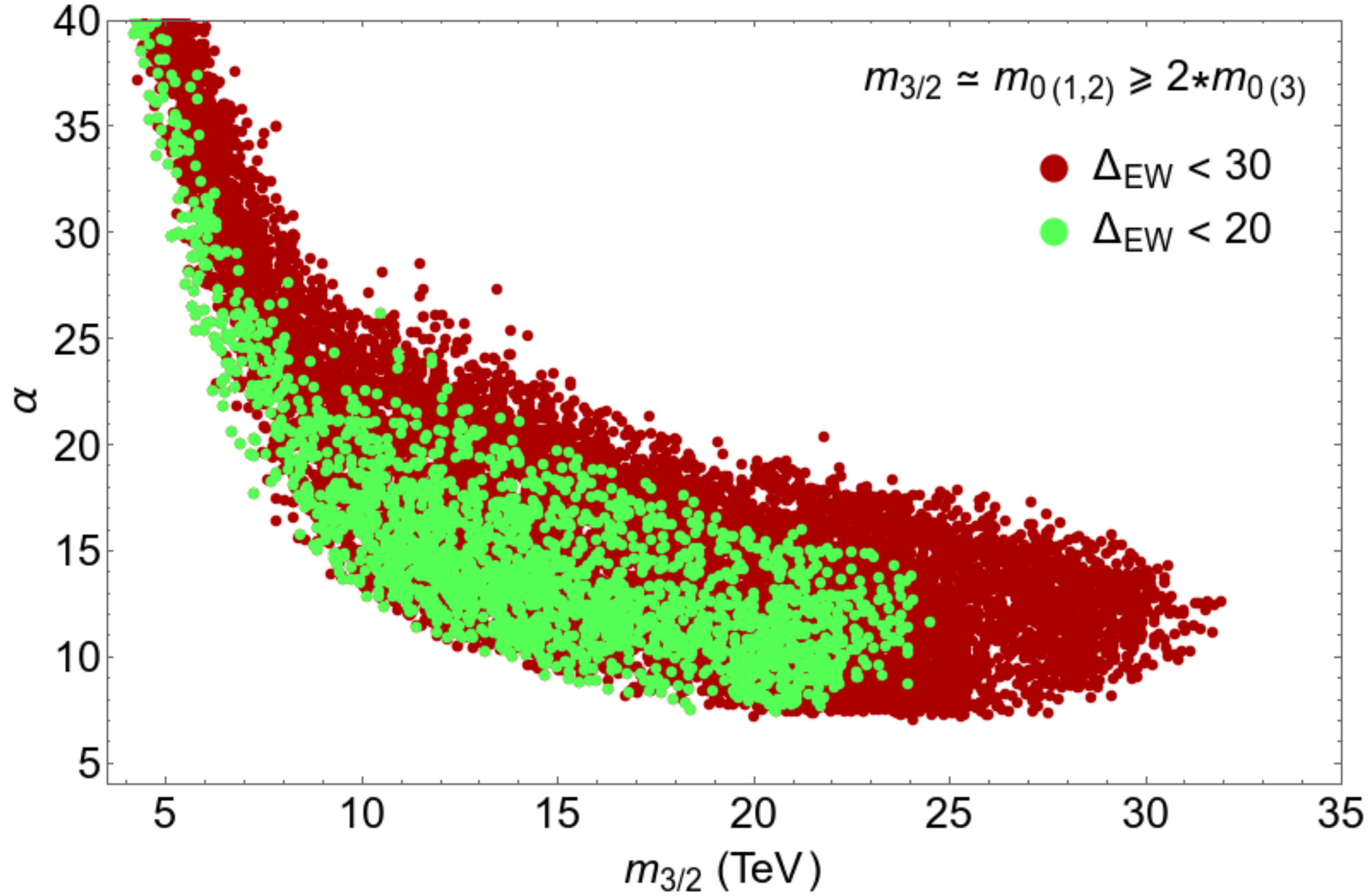
but with radiatively-driven naturalness

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

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

To generate minilandscape, take:

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

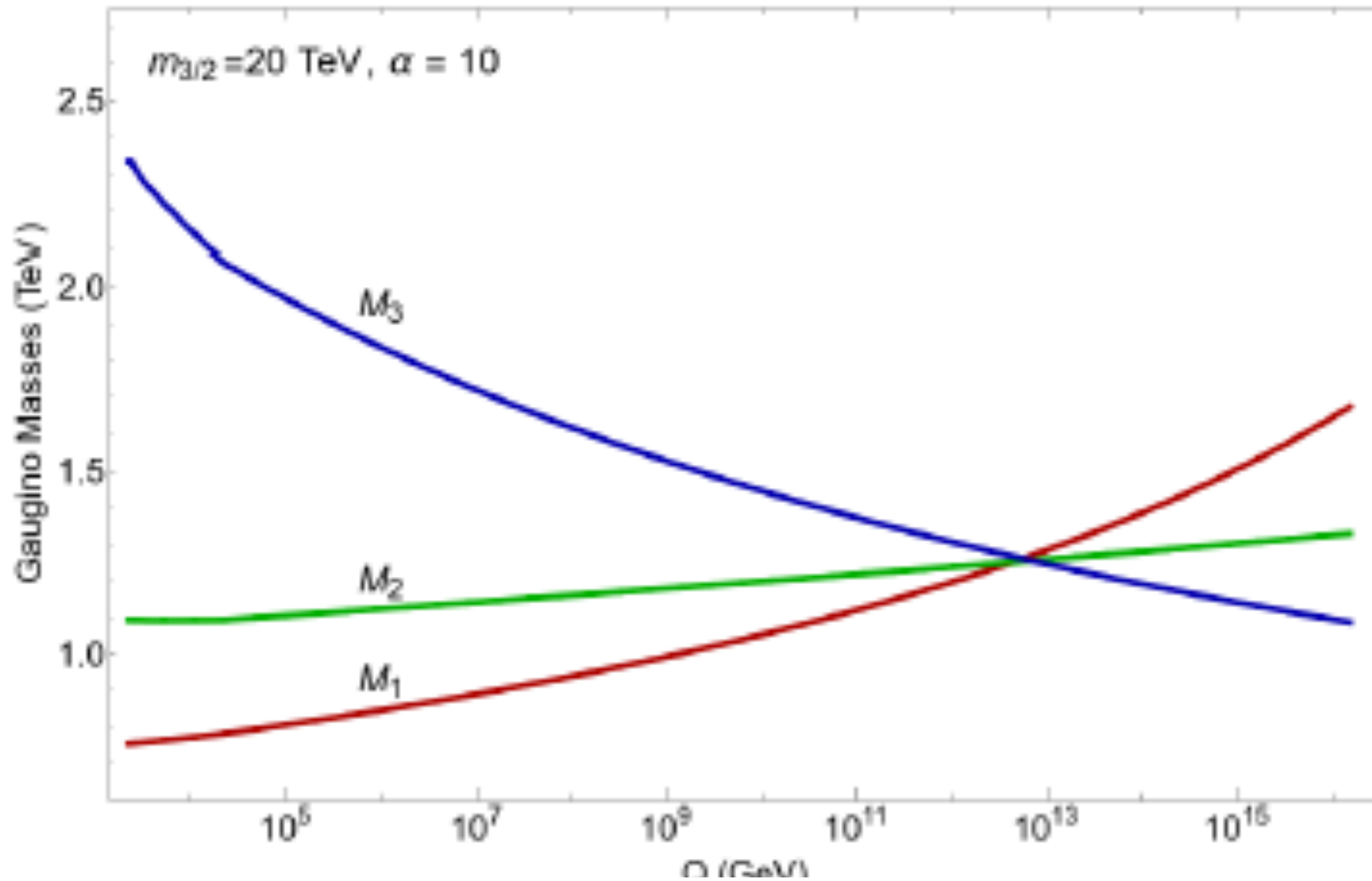


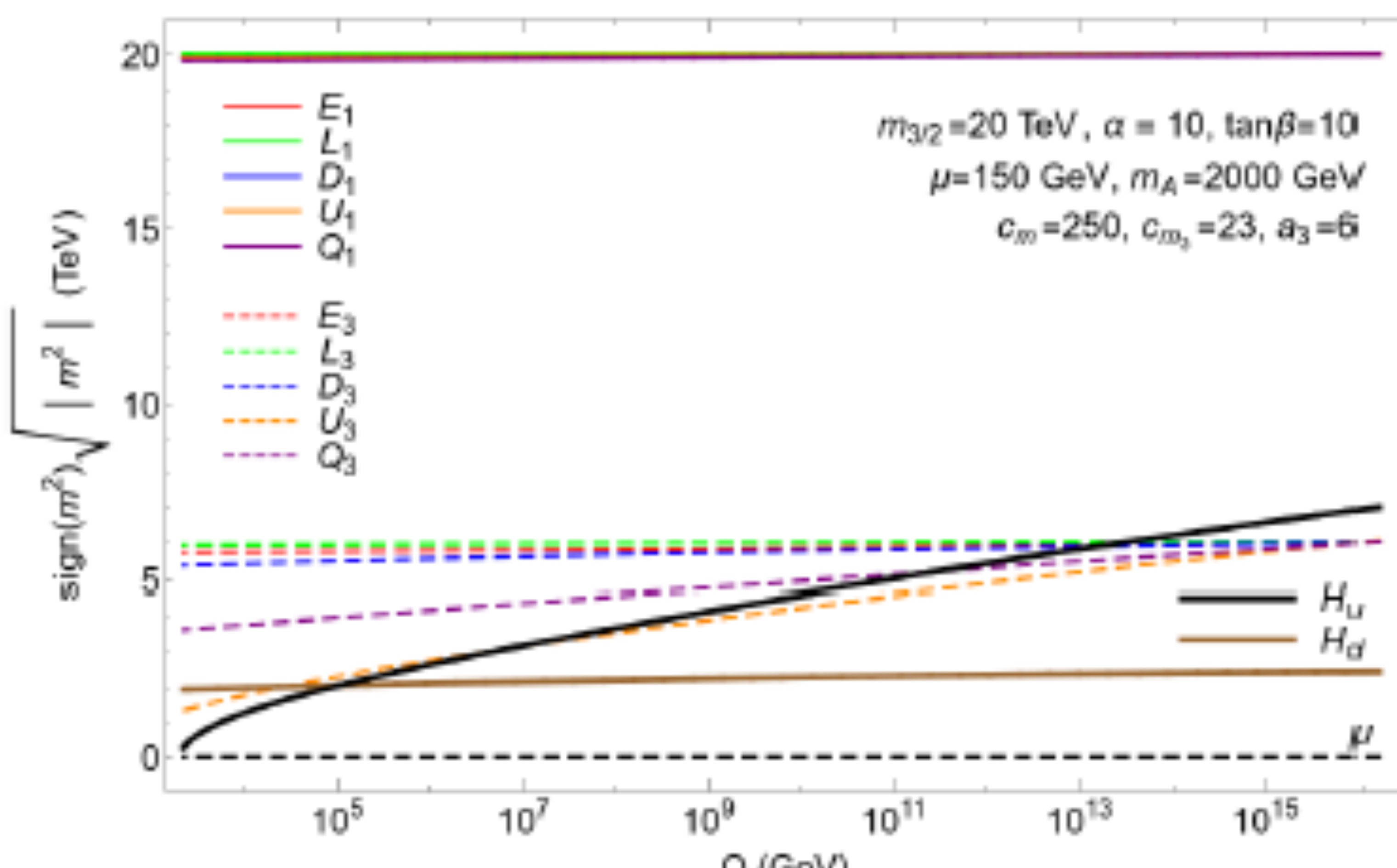
Then get upper bound $m_{3/2} < 25 - 30$ TeV and $\alpha > 7$
else too large $m_0(1,2)$ drives 3rd generation tachyonic

Martin, Vaughn, 2-loop RGEs

Increased upper bound on m(gluino)<6 TeV

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


$m_{3/2}$=20 TeV, α = 10
Gaugino Masses (TeV)
M_3
M_2
M_1
Q (GeV)


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

$$\Delta_{EW} = 17.6$$

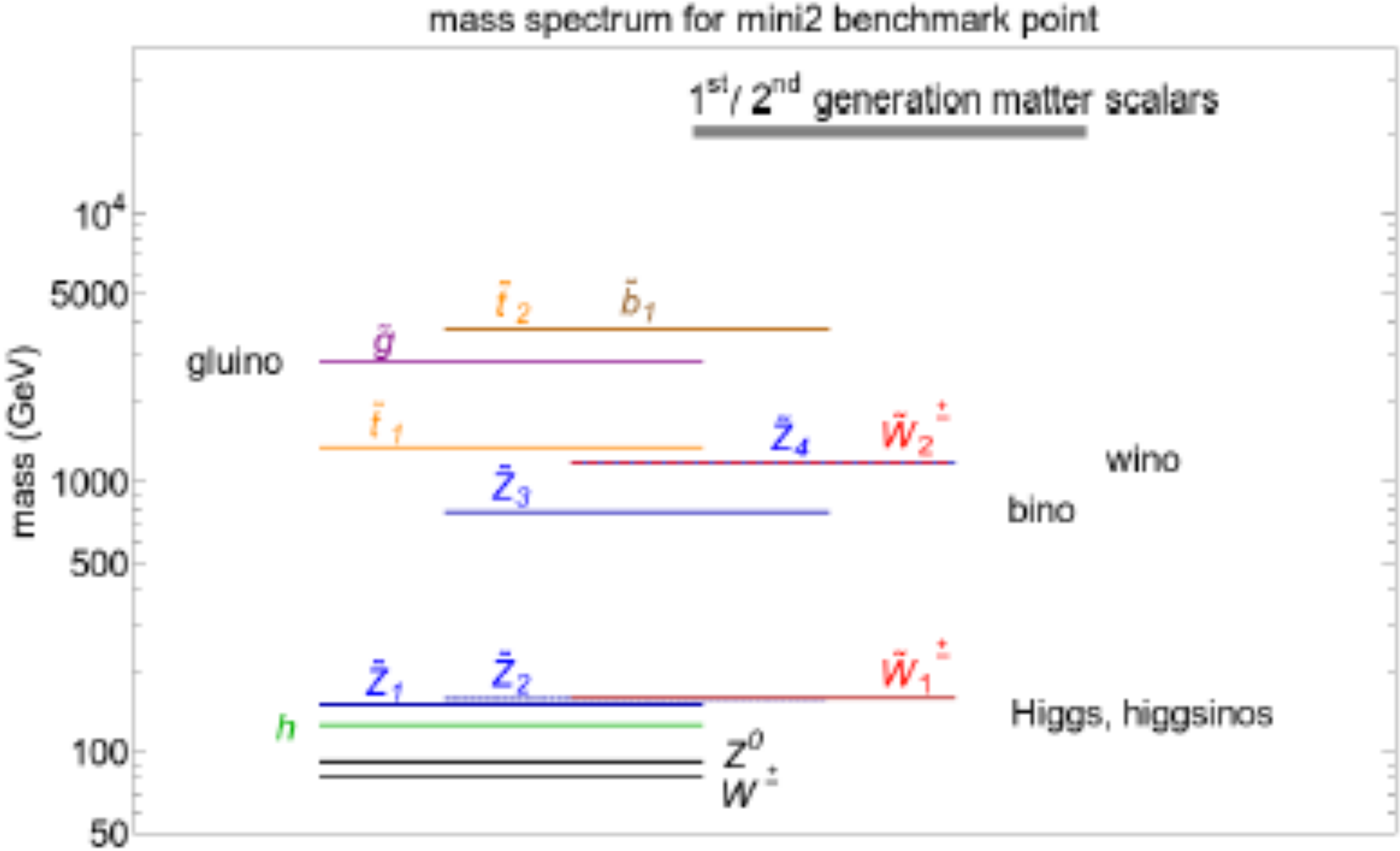


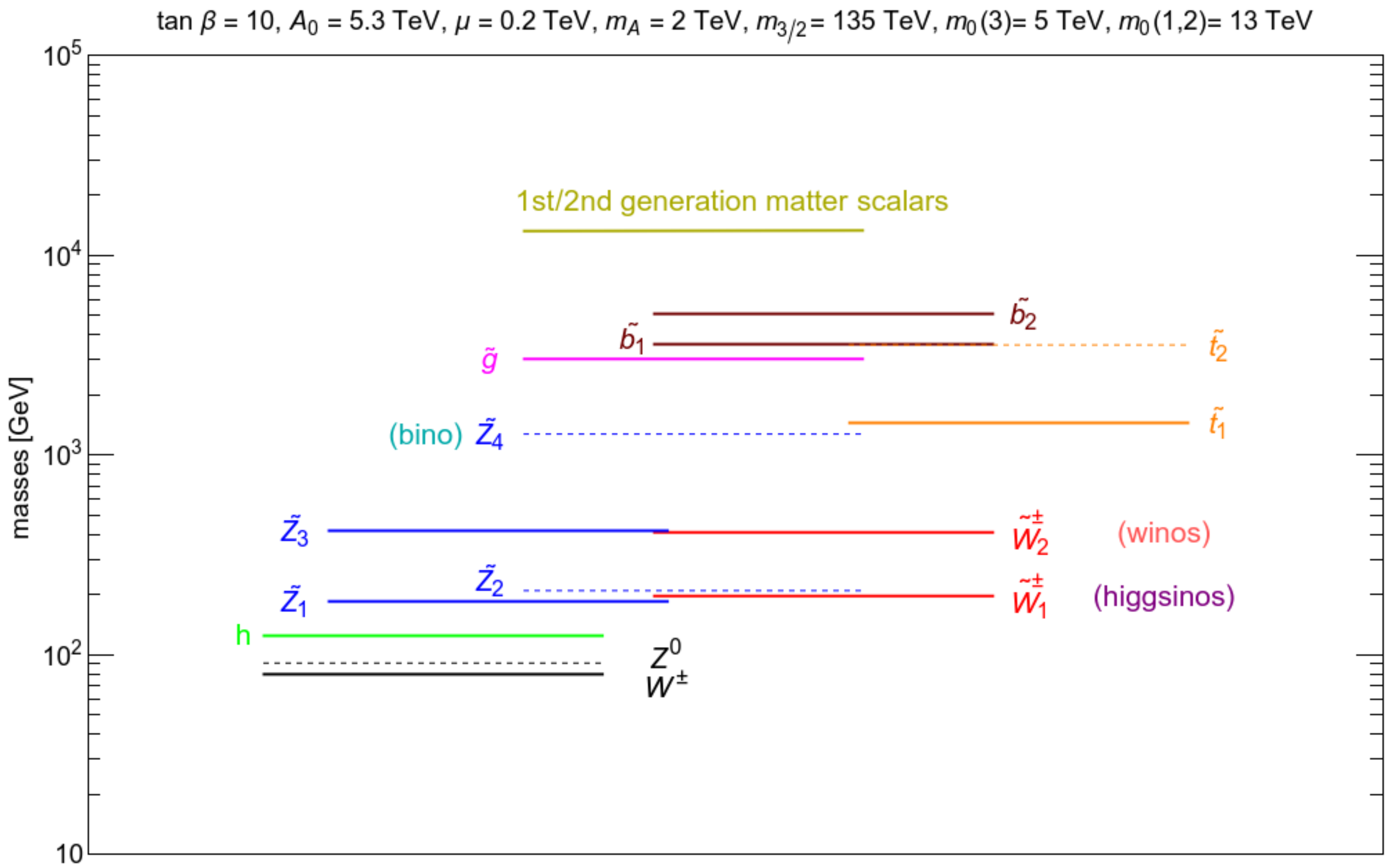
Figure 7: The superparticle mass spectra from the natural mini-landscape point mini2 of Table 1.

Can also construct natural AMSB models

- Begin with usual mAMSB: $m_0(bulk), m_{3/2}, \tan\beta$
- Allow Higgs fields to develop independent bulk soft terms: why shouldn't they? They live in different multiplets (RS)
- Allow small (compared to $m_{3/2}$) bulk A_0 terms (RS)
- Added freedom allows for light higgsinos, highly mixed stops
- Natural AMSB with $m_h \sim 125$ GeV!
- gauginos still ordered as usual but: $\mu < M_2 < M_1 < M_3$
- May need ILC with $\sqrt{s} > 2m(higgsino) \sim 500 - 600$ GeV to sort out gaugino hierarchy (unified, mirage or AMSB?) via *Higgsino code*!

HB, Barger, Sengupta

natural AMSB with m(h)~125 GeV



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?

Some answers: see tomorrow talk!

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!

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

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

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

Choi, Chun, Kim (1996)

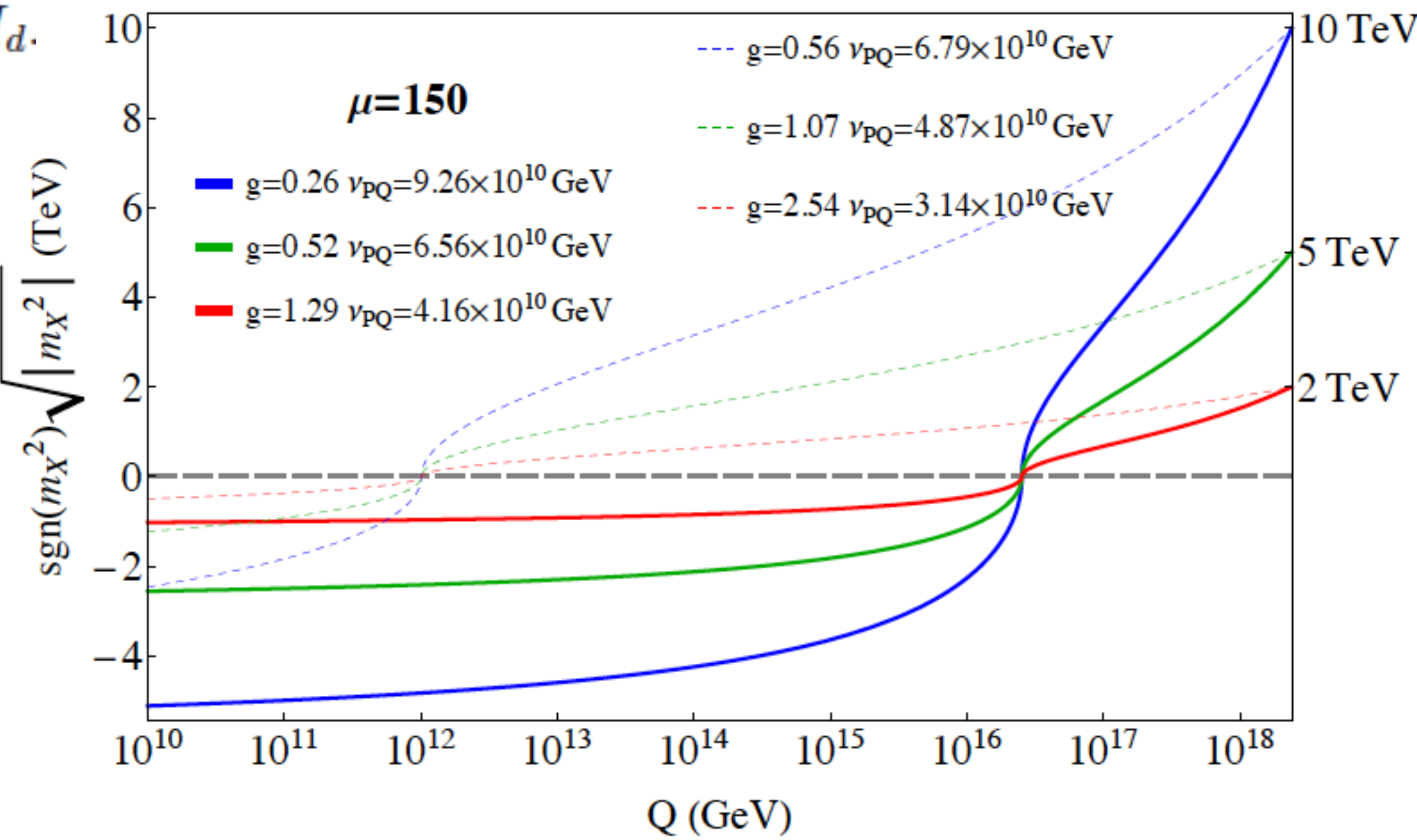
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

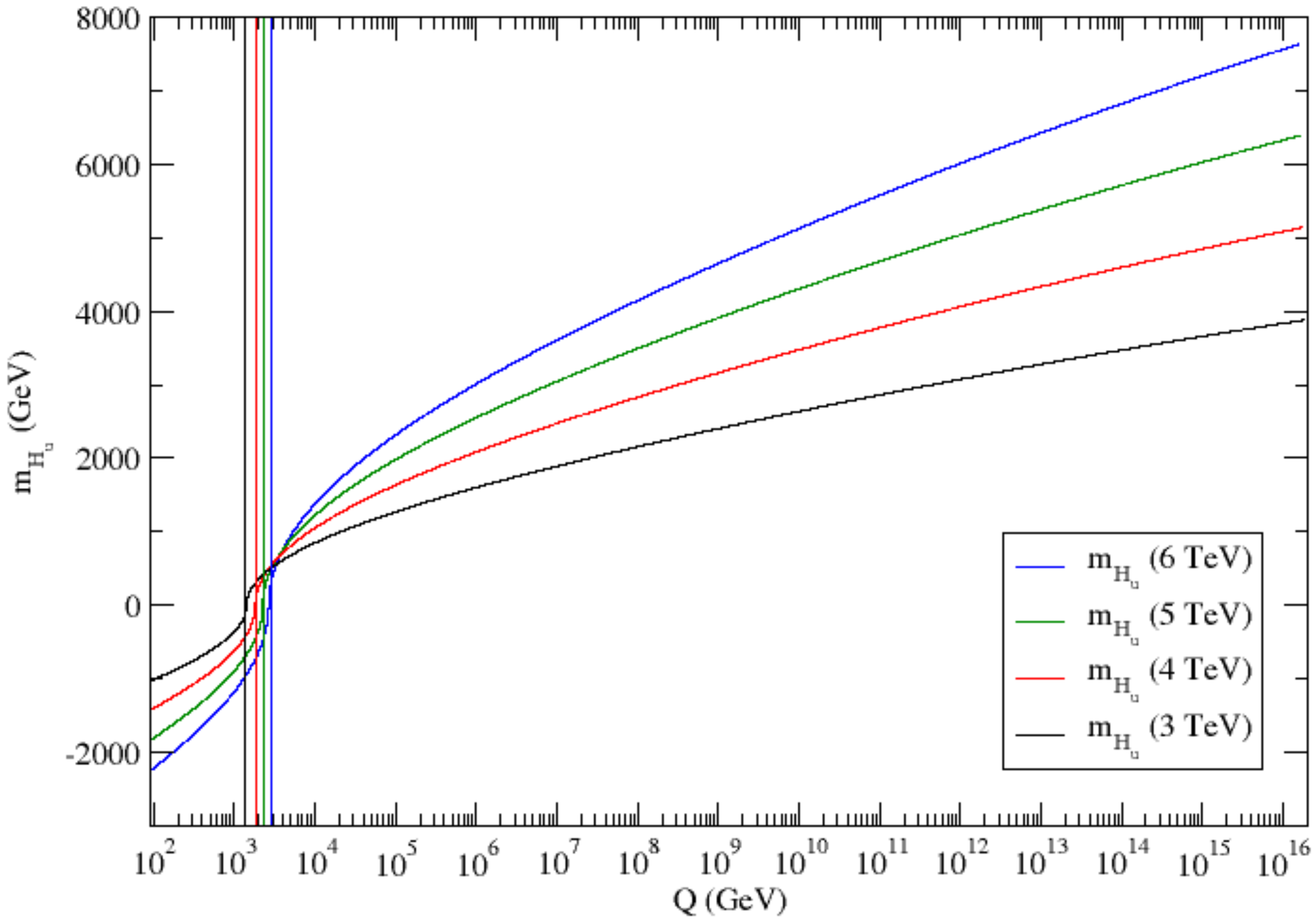
$$M_{N_i^c} = v_X\, h_i|_{Q=v_X}$$

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



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

Why might mHu have the value needed to give naturalness at weak scale?
1. For right correlations amongst soft terms, get ``generalized focus point"



HB, Barger, Savoy

e.g.

For $\mu = 150$ GeV, $\tan\beta = 10$ and

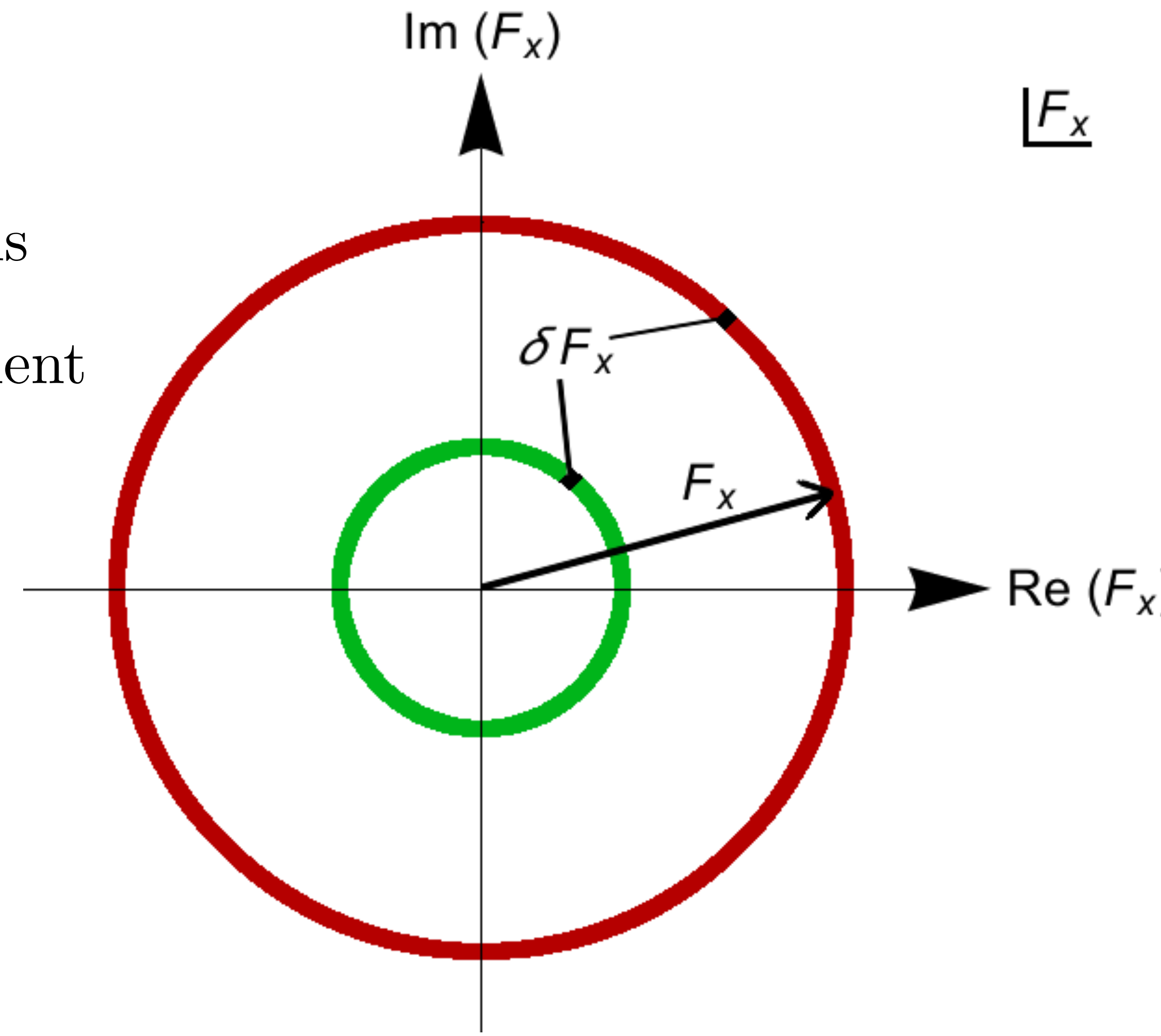
$$\begin{aligned} m_0^2 &= m_{3/2}^2 \\ A_0 &= -1.6 m_{3/2} \\ m_{1/2} &= m_{3/2}/5 \\ m_{H_d}^2 &= m_{3/2}^2/2. \end{aligned}$$

$$m_{H_u}^2(GUT) = 1.8 m_{3/2}^2 - (212.52\ \text{GeV})^2.$$

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

2. string theory landscape?

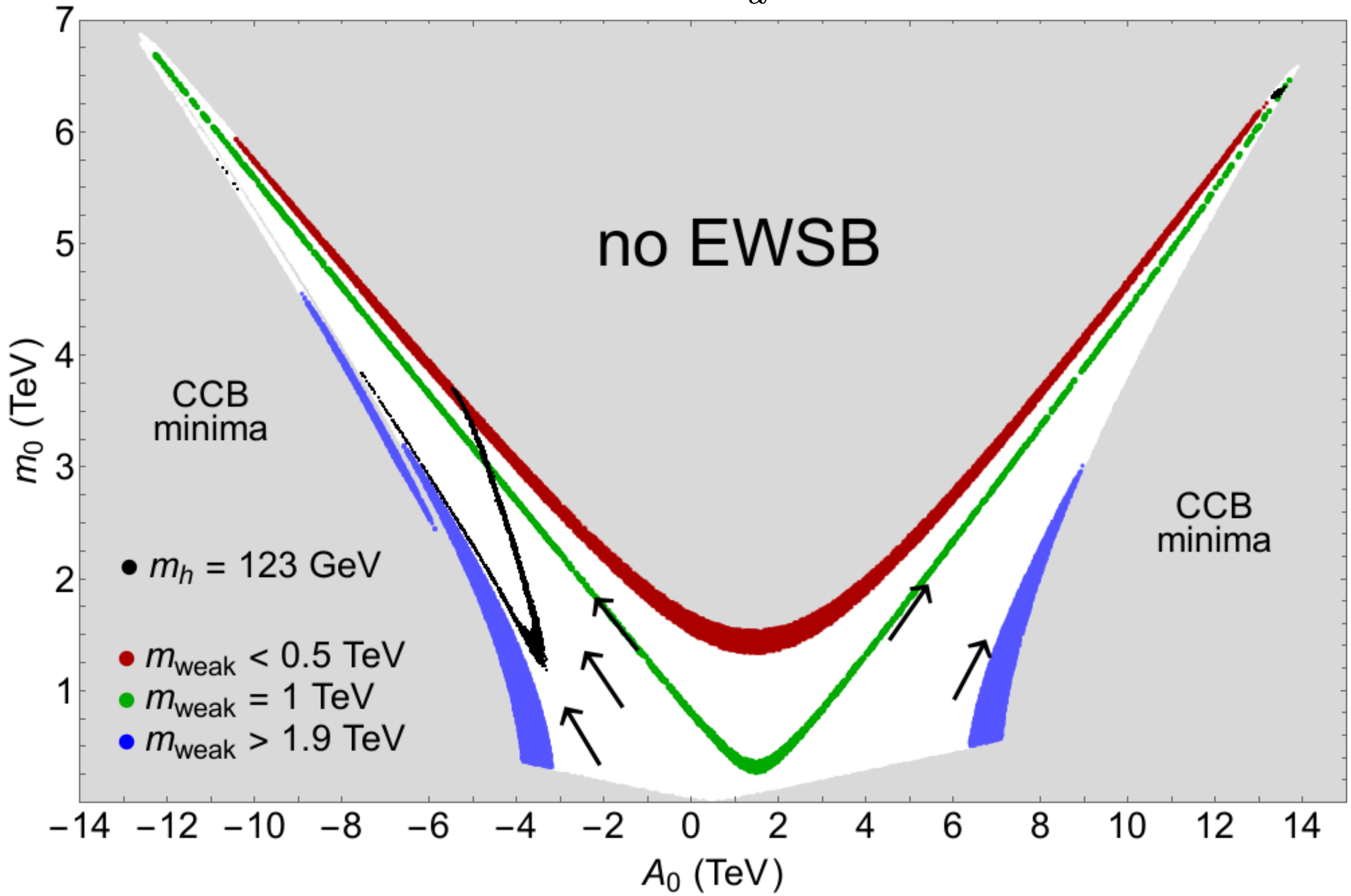
- assume model like MSY/CCK where $\mu \sim 100$ GeV
- then $m(weak)^2 \sim |m^2_{H_u}|$
- If all values of SUSY breaking field $\langle F_X \rangle$ equally likely, then mild (linear) statistical draw towards large soft terms
- This is balanced by anthropic requirement of weak scale $m_{weak} \sim 100$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



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

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

$m_{H_u} = 1.3 m_0$



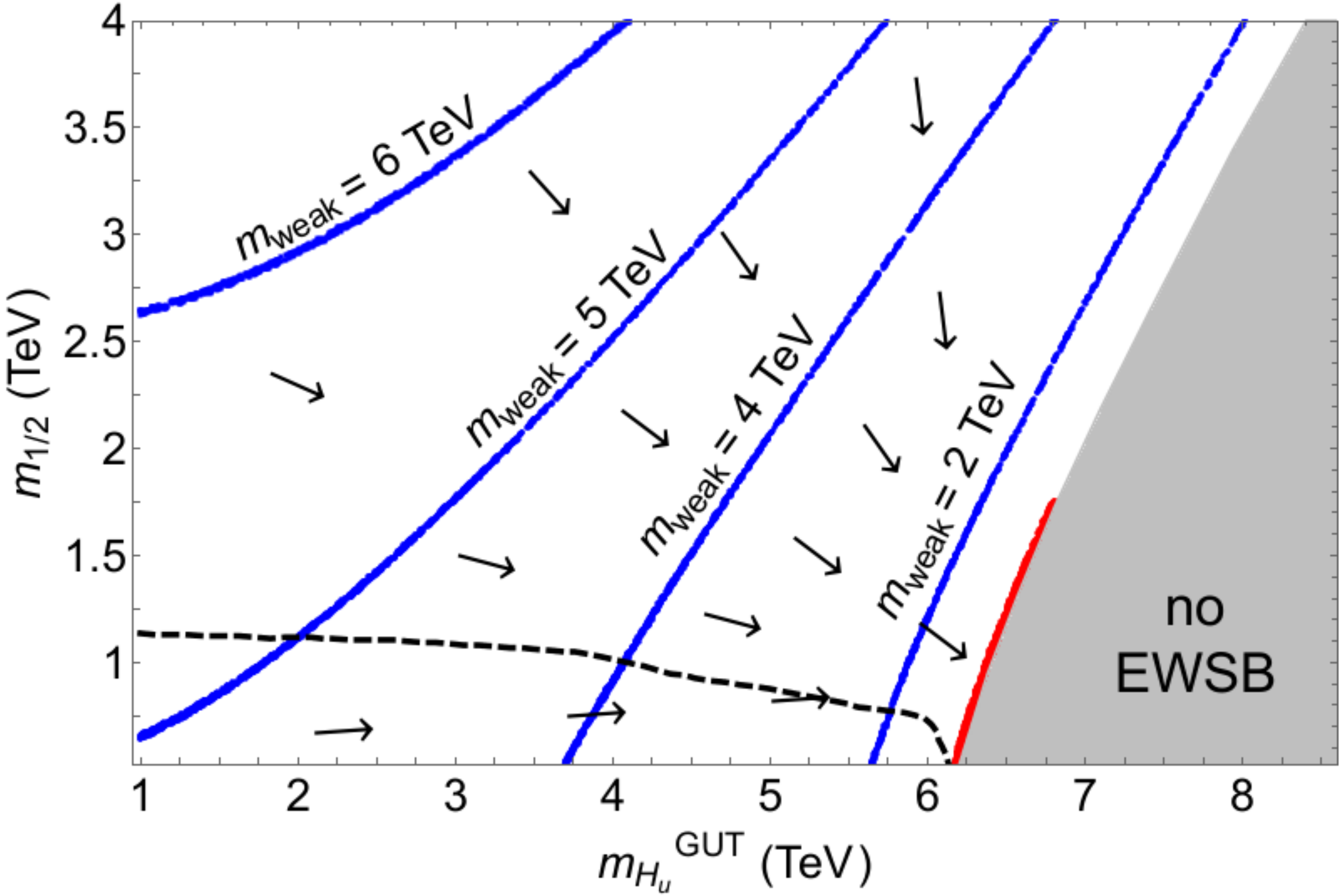
statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Denef, Douglas, JHEP0405 (2004) 072

Giudice, Rattazzi, NPB757 (2006) 19;

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

$m_0 = 5$ TeV



statistical/anthropic draw toward FP-like region

Statistical analysis of SUSY breaking scale:
M. Douglas, hep-th/0405279

some reasonable assumptions

- 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

Scalar potential is given by usual SUGRA form:

$$V = e^{K/m_P^2}\left(g^{i\bar{j}}D_iW D_{\bar{j}}W^* - \frac{3}{m_P^2}|W|^2\right) + \frac{1}{2}\sum_\alpha D_\alpha^2$$
$$= e^{K/m_P^2}\left(\sum_i |F_i|^2 - 3\frac{|W|^2}{m_P^2}\right) + \frac{1}{2}\sum_\alpha D_\alpha^2$$

- W = holomorphic superpotential
- K = real Kähler function
- $F_i = D_iW = DW/D\phi^i \equiv \partial W/\partial\phi^i + (1/m_P^2)(\partial K/\partial\phi^i)W$ are F-terms
- $D_\alpha \sim \sum \phi^\dagger g t_\alpha \phi$ are D-terms
- ϕ^i are chiral superfields

minimize V:

- $\partial V/\partial\phi^i = 0$
- $\partial^2 V/\partial\phi^i\partial\phi^j > 0$
- $\Lambda_{cc} = m_{hidden}^4 - 3e^{K/m_P^2}|W|^2/m_P^2$ with
- $m_{hidden}^4 = \sum_i |F_i|^2 + \frac{1}{2}\sum_\alpha D_\alpha^2$ is hidden sector mass scale

gravitino mass $m_{3/2} = e^{K/2m_P^2} m_P \sim m_{hidden}^2/m_P$ with $m_{hidden} \sim 10^{12}$ GeV

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 $m_{soft} \sim m_{3/2} \sim m^2_{hidden}/m_P$

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

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

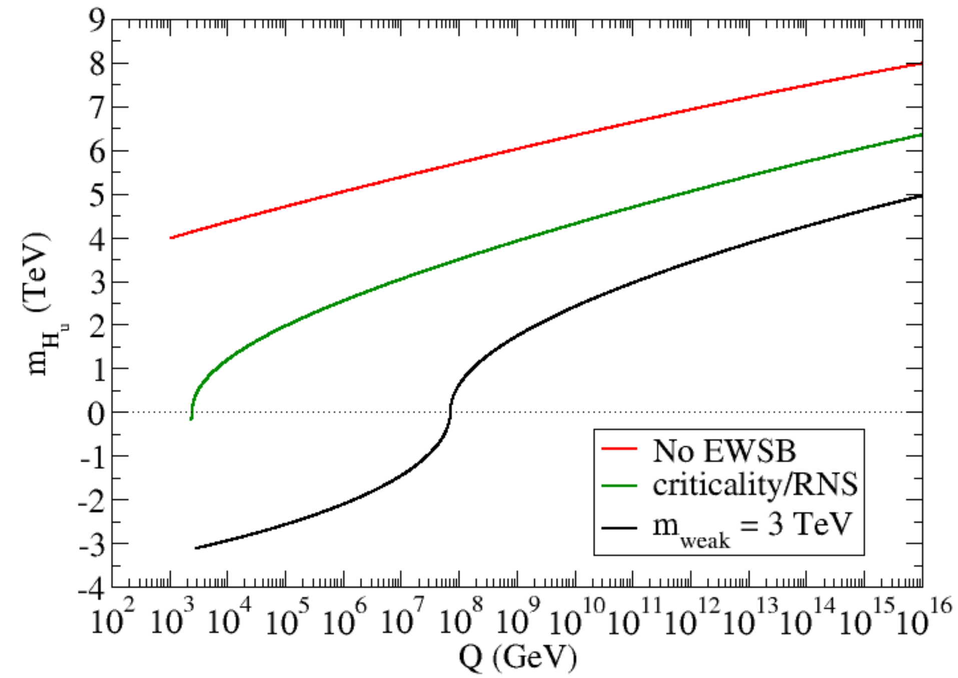
n_F	n_D	n
0	1	0
1	0	1
0	2	1
1	1	2
0	3	2
2	0	3
2	1	4

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 $\Sigma^{u,d}_{u,d}(i)$

$$\frac{m_Z^2}{2} = \frac{m^2_{H_d} + \Sigma^d_d - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

For practical calculations, adopt NUHM3 SUGRA model:

- $m_0(1,2) =$ gen(1,2) common soft mass
- $m_0(3) =$ gen(3) common soft mass
- $m_{H_u}^2$ up-Higgs soft mass
- $m_{H_d}^2$ down-Higgs soft mass
- $m_{1/2} =$ unified gaugino mass
- $A_0 =$ unified trilinear soft term
- $\tan\beta$

Trade $m_{H_u}^2,\ m_{H_d}^2 \Leftrightarrow \mu,\ m_A$

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A \quad (NUHM3)$$

Recent work: place on more quantitative footing: scan soft SUSY breaking parameters 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,

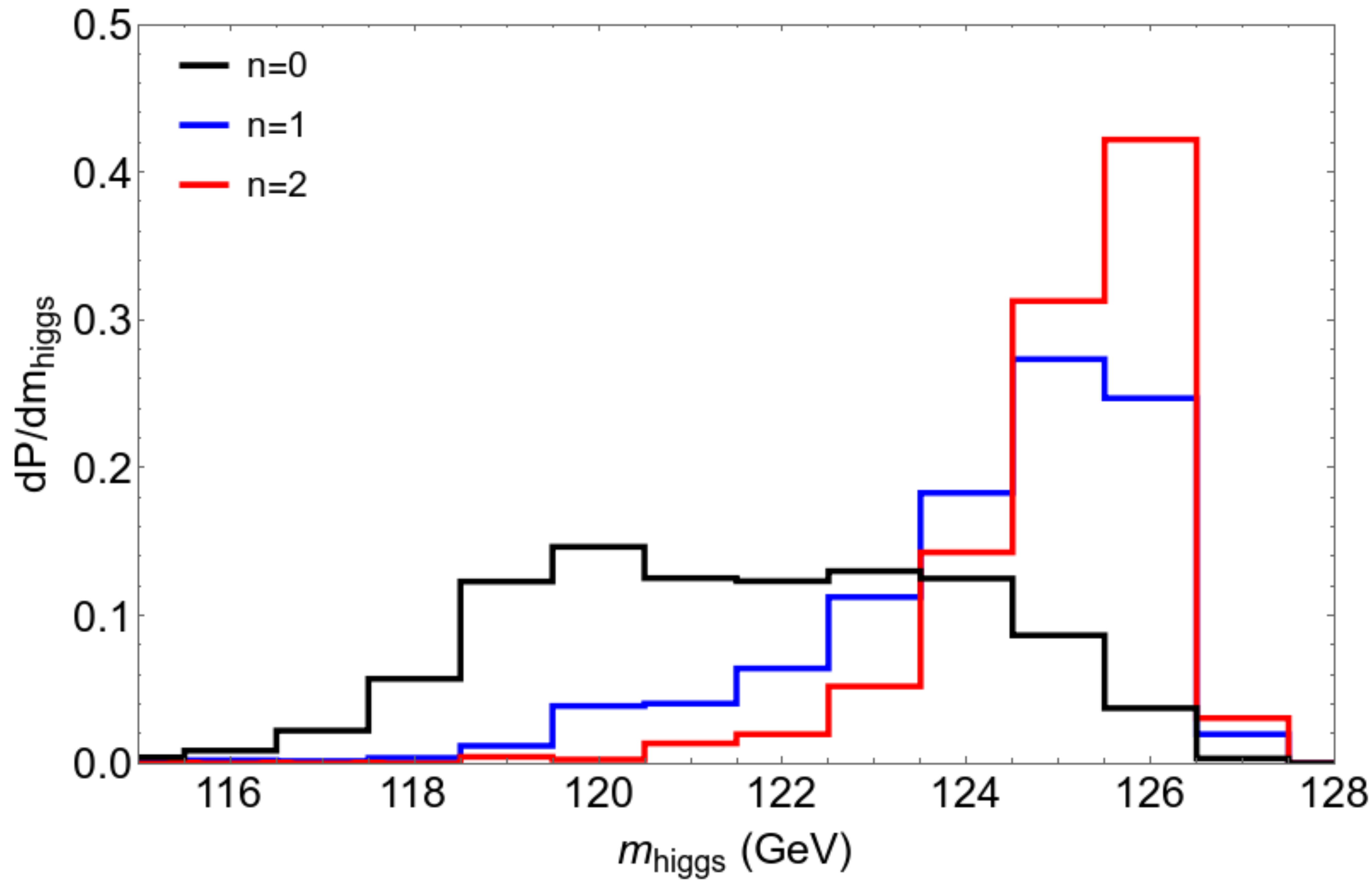
$\tan\beta$: $3 - 60$ (flat)

mu=150 GeV (fixed)

HB, Barger, Serce, Sinha (arXiv:1712.01399)

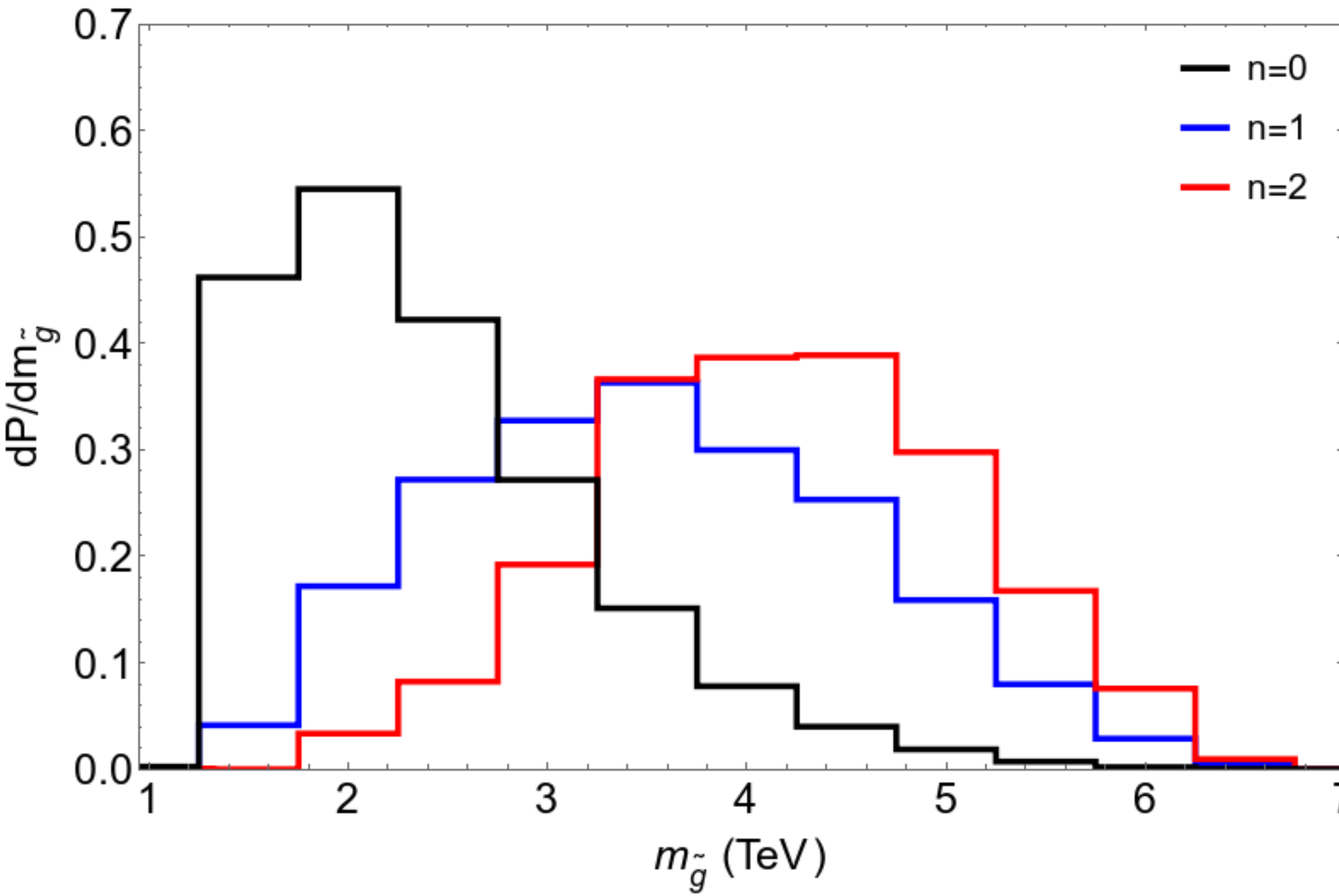
Making the picture more quantitative:

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



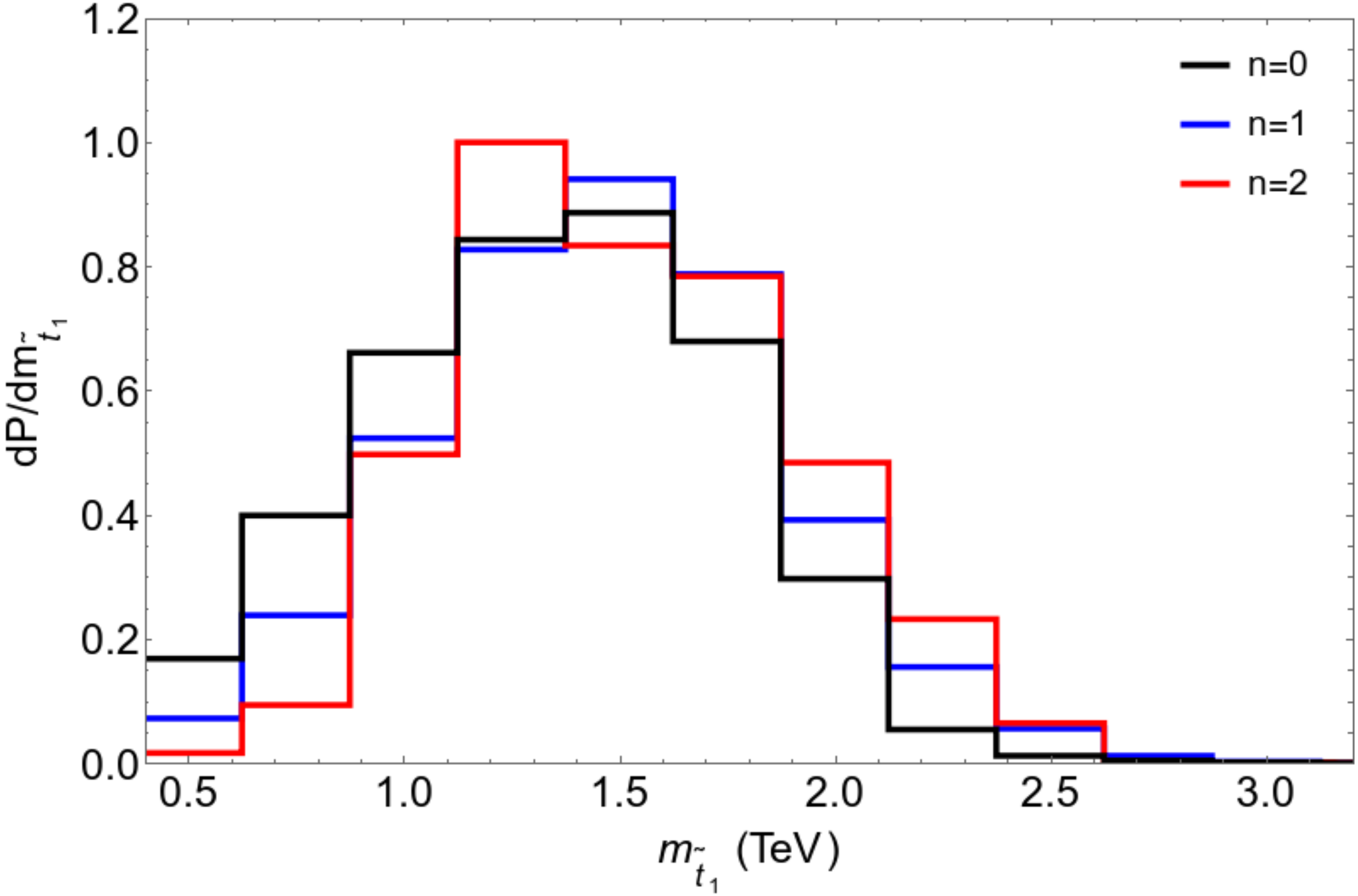
m(h)~125 most favored for n=1,2

What is corresponding distribution for gluino mass?



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

and m(t1)?



Conclusion: SUSY IS alive and well!

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

Backup

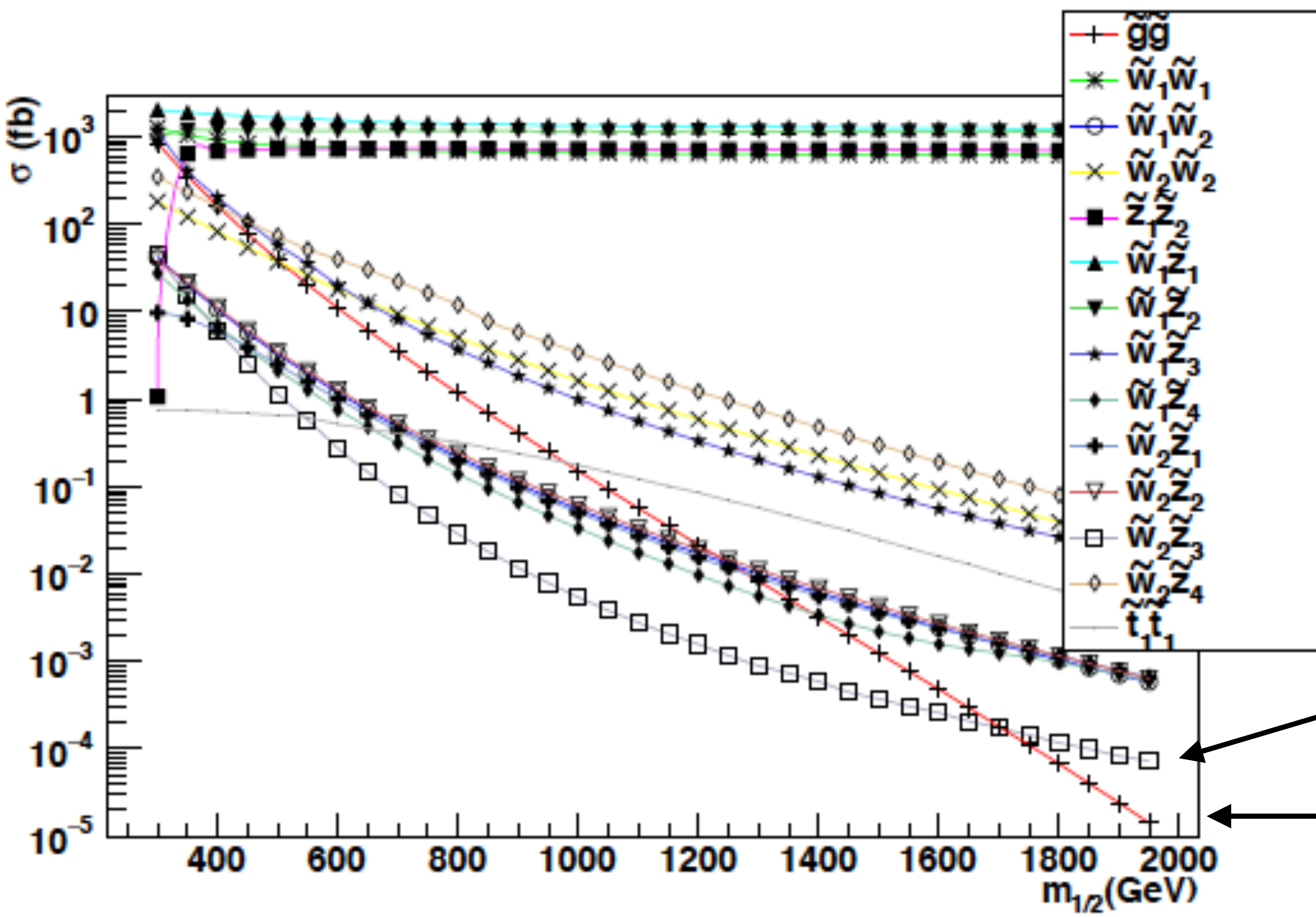
Prospects for SUSY at LHC:

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



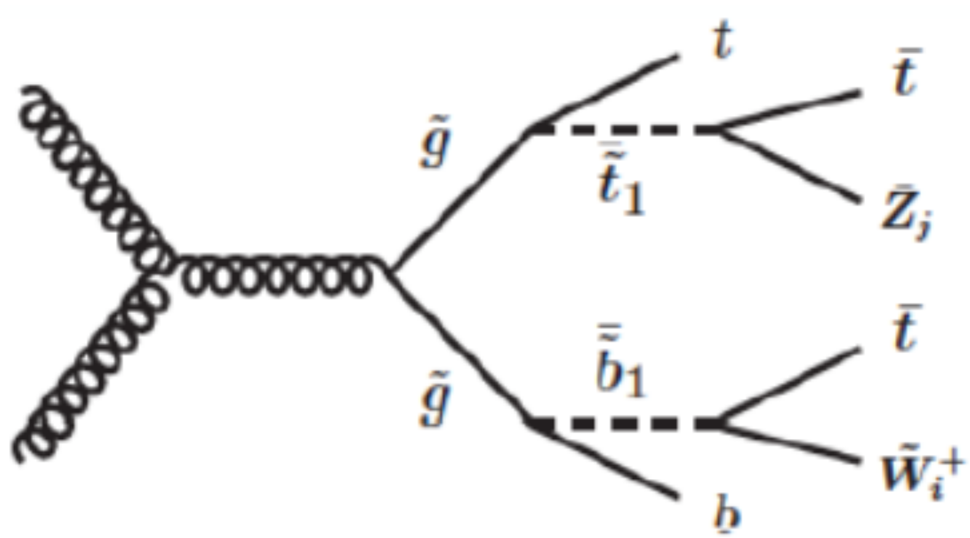
higgsino pair production dominant-but only soft visible energy release from higgsino decays

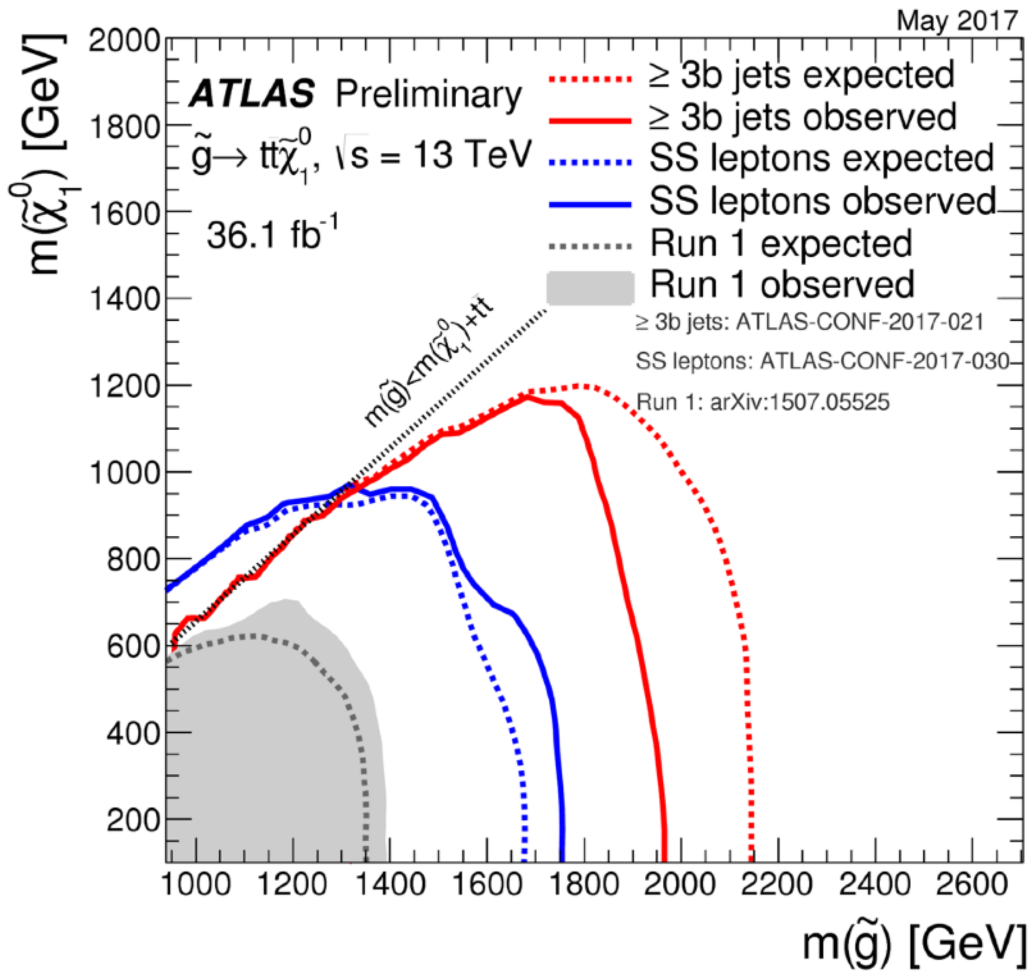
largest visible cross section: wino pairs

gluino pairs sharply dropping

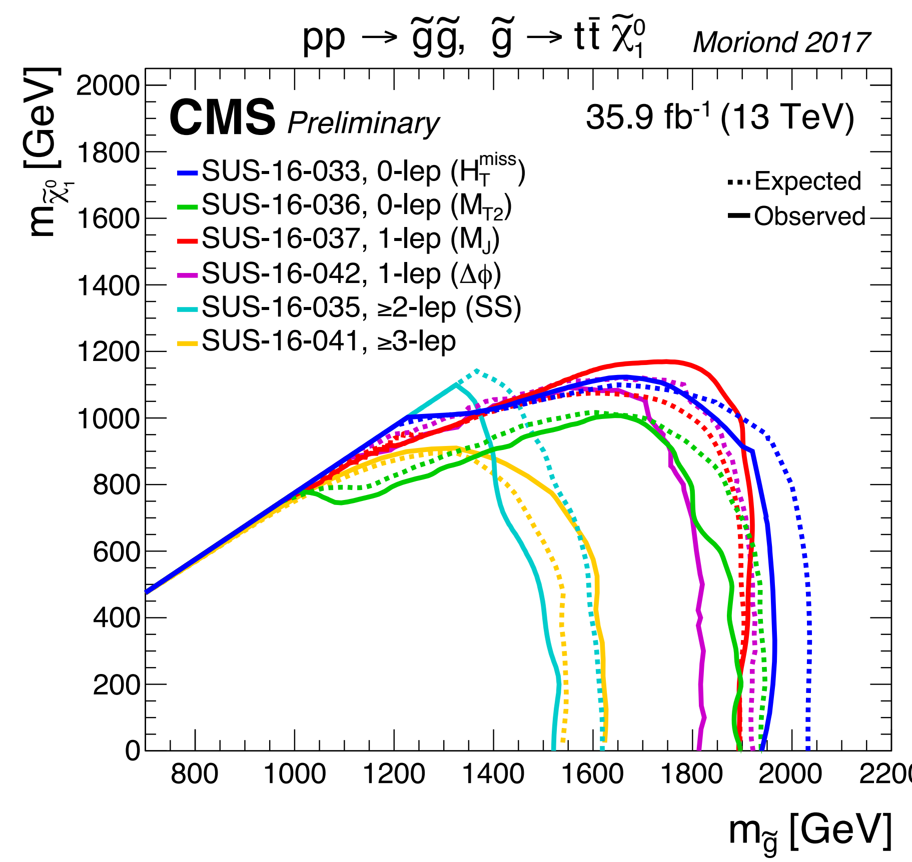
stops at bottom

gluino pair cascade decay signatures

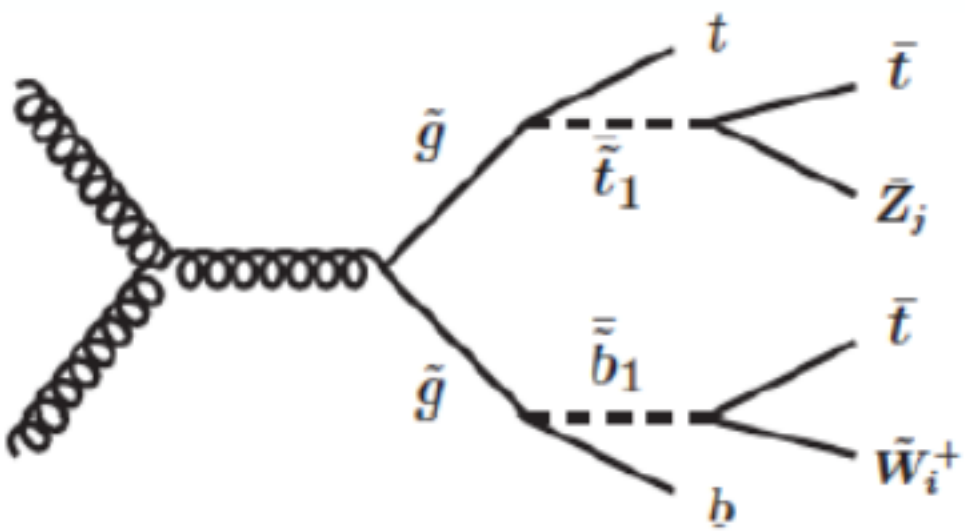




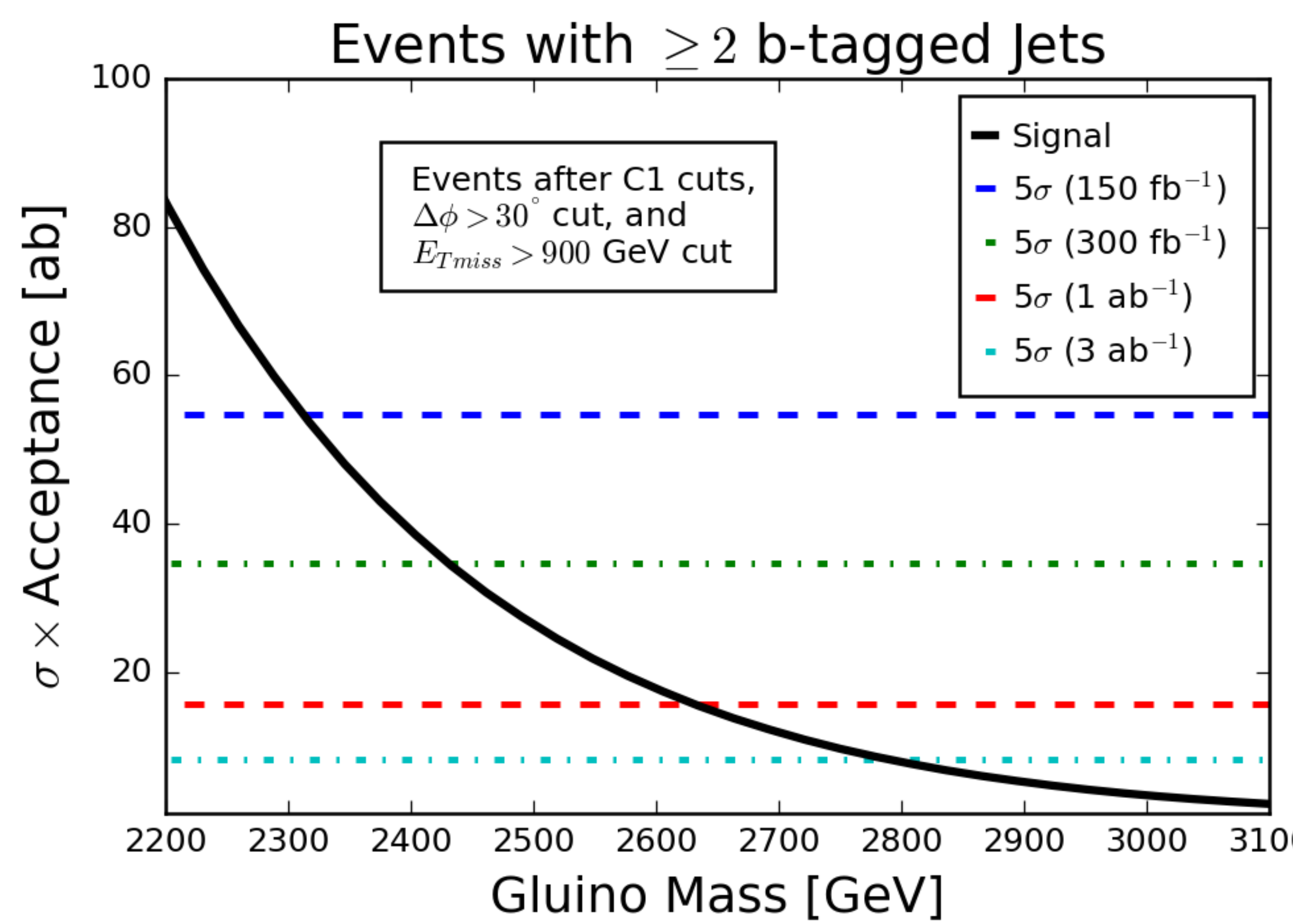
Current limits for m(Z1)~150 GeV:
m(glno)>~2 TeV



gluino pair cascade decay signatures



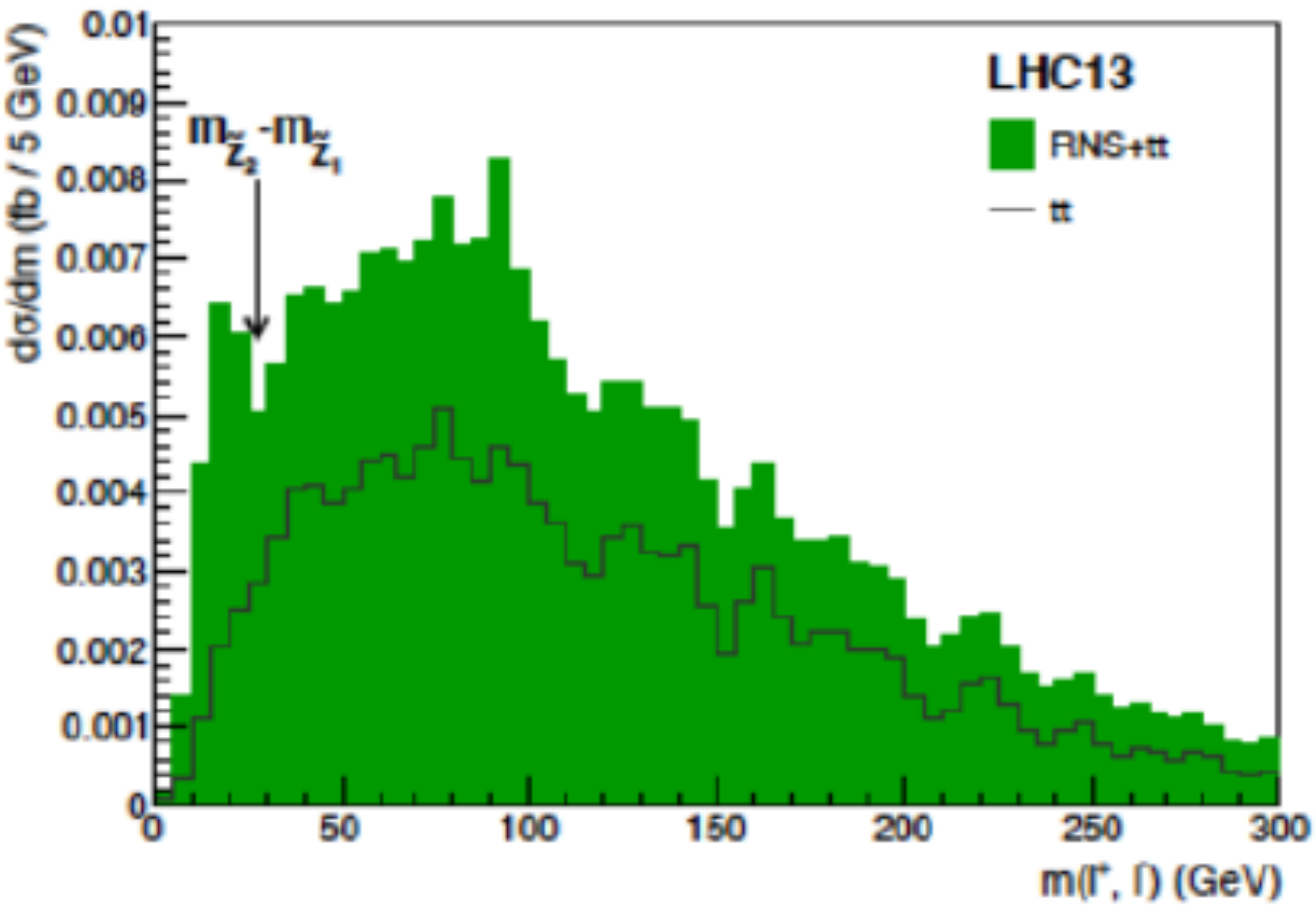
Estimated HL-LHC reach for gluinos



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

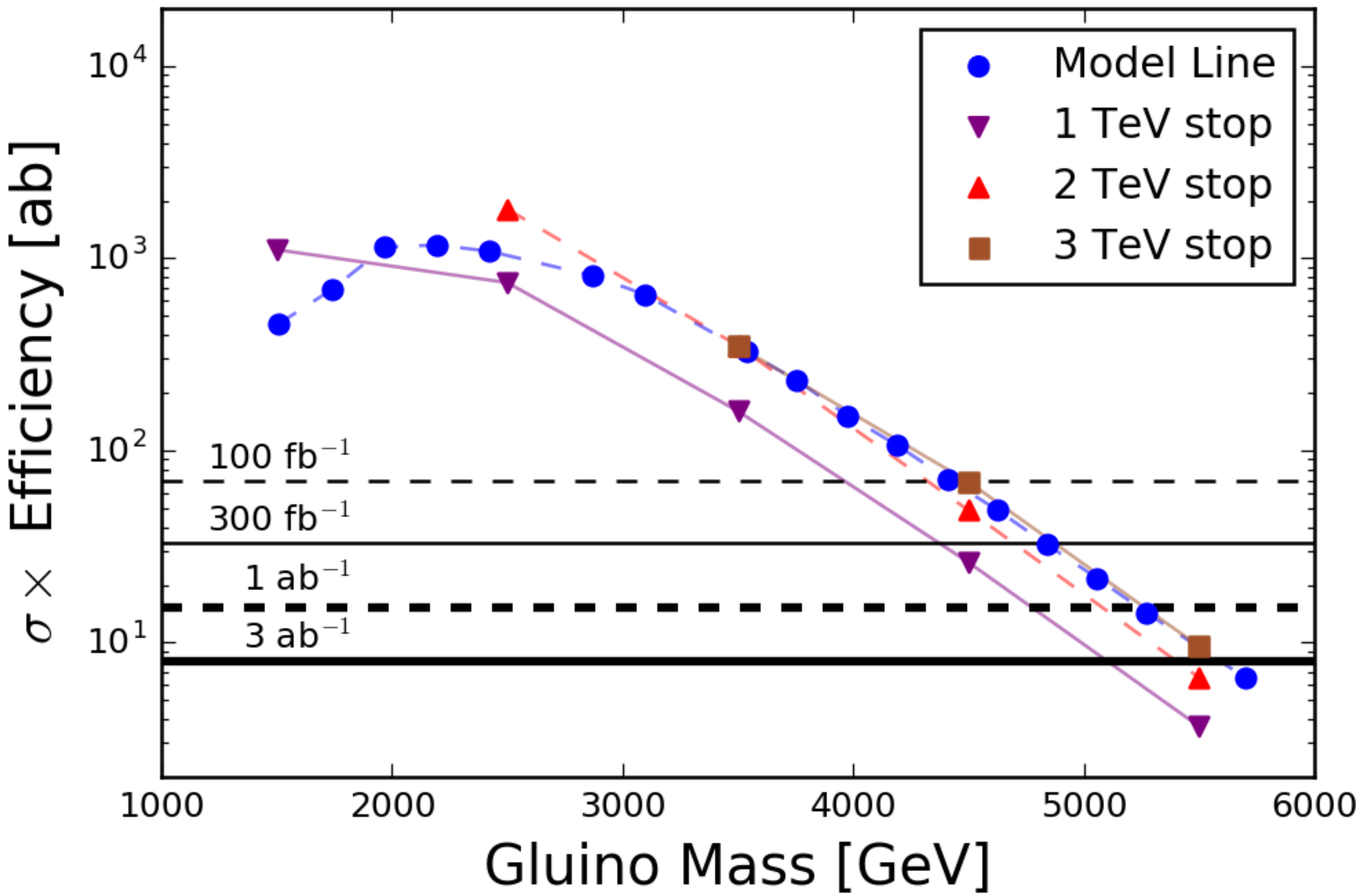
HB, Barger, Huang, Gainer, Savoy, Sengupta, Tata

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

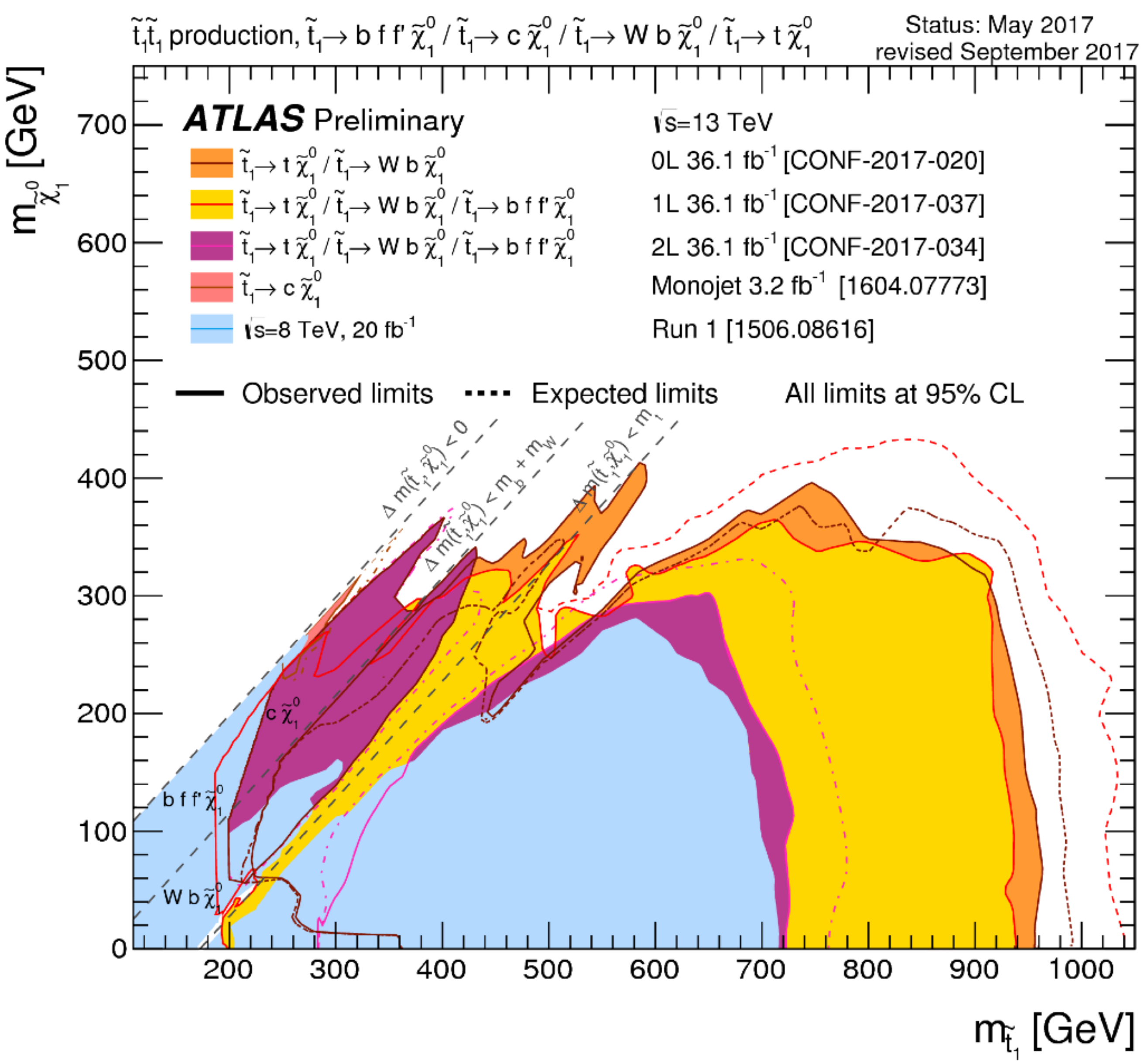
Gluino 5-sigma reach at LHC33: to about m(glno)~5-5.5 TeV

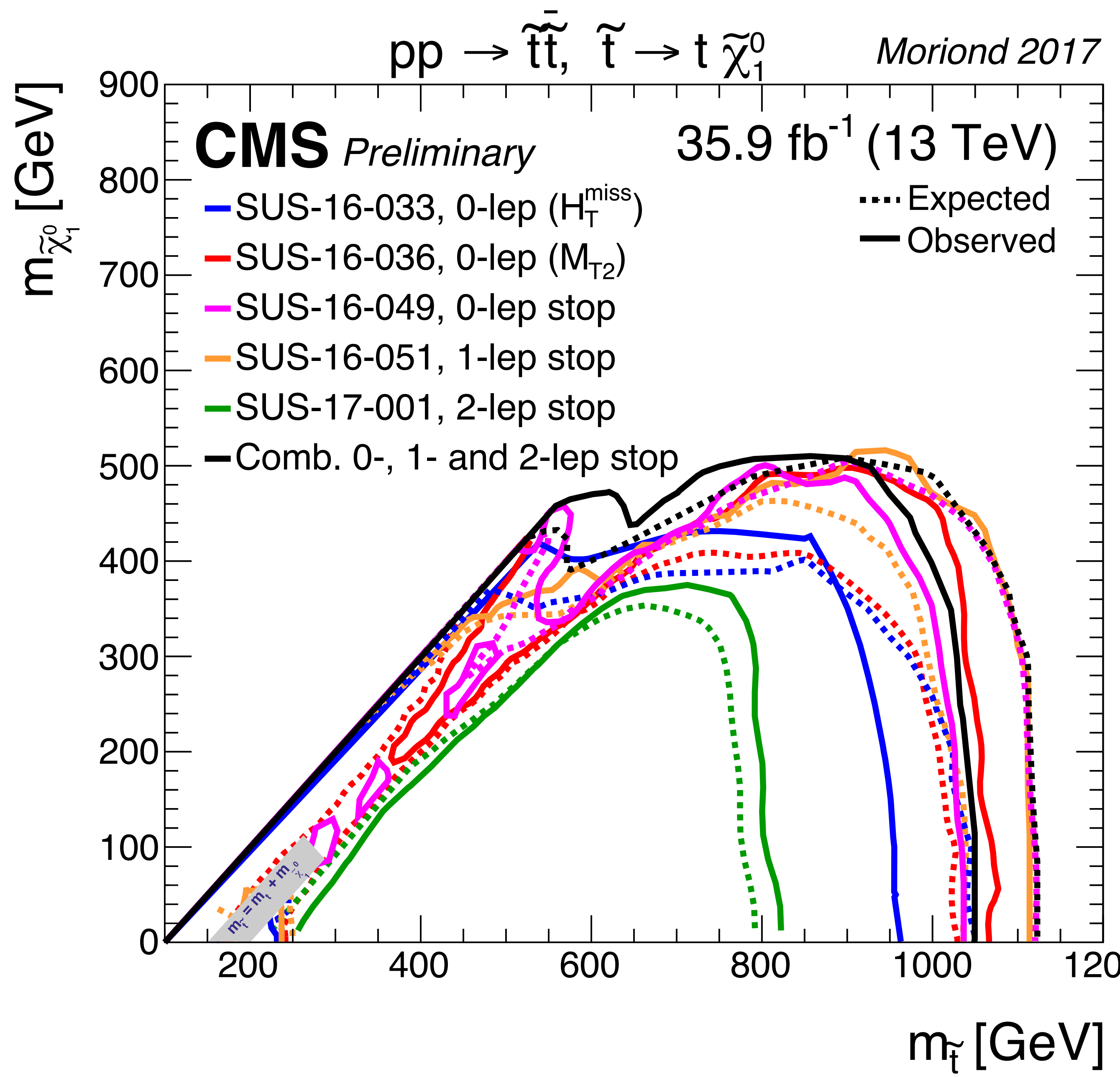


>=4 jets; >=2-b-jets;MET>1500 GeV

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

Present limits on top squarks from LHC

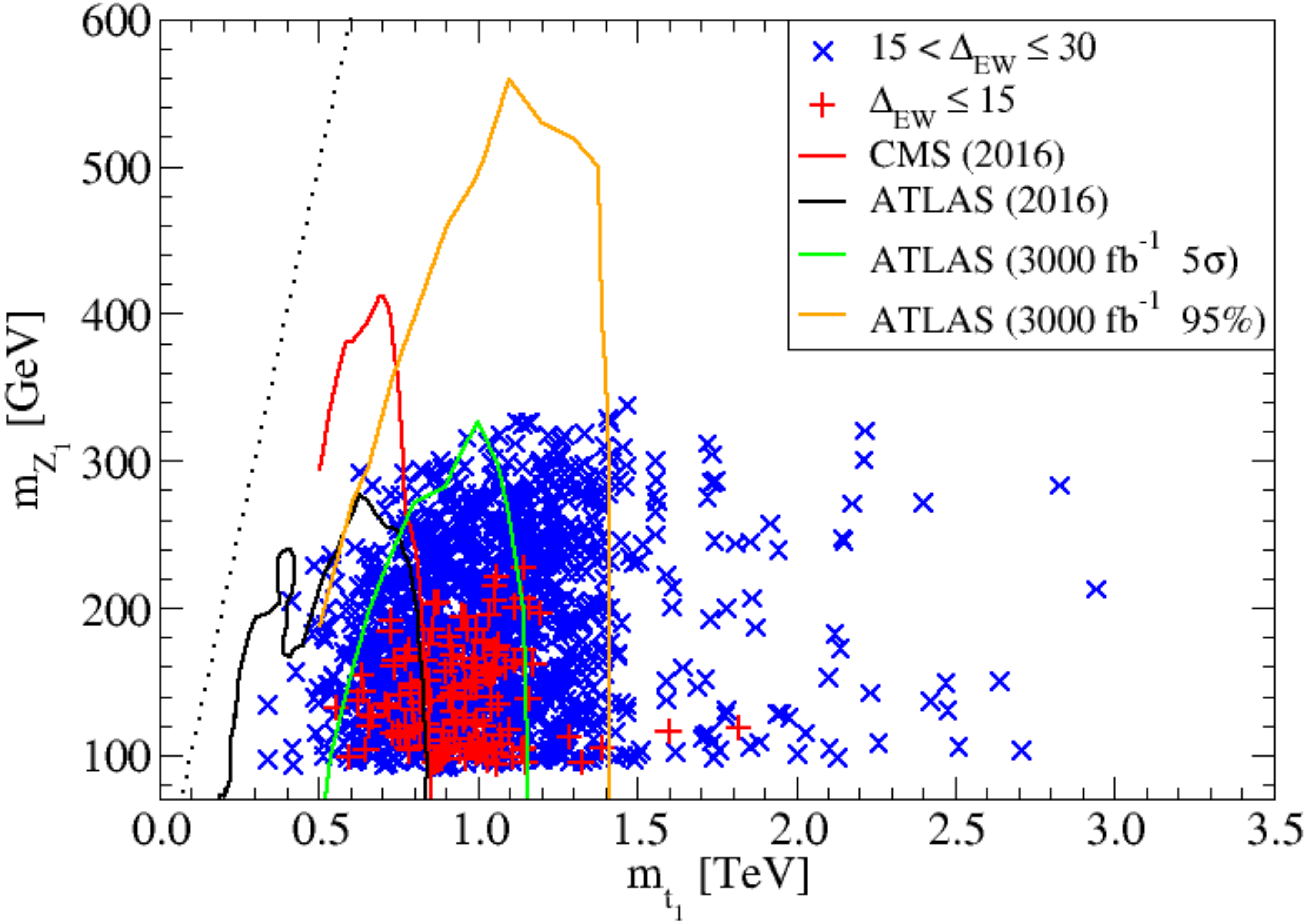




Evidently m(t1)>~1 TeV for m(LSP)~150 GeV

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

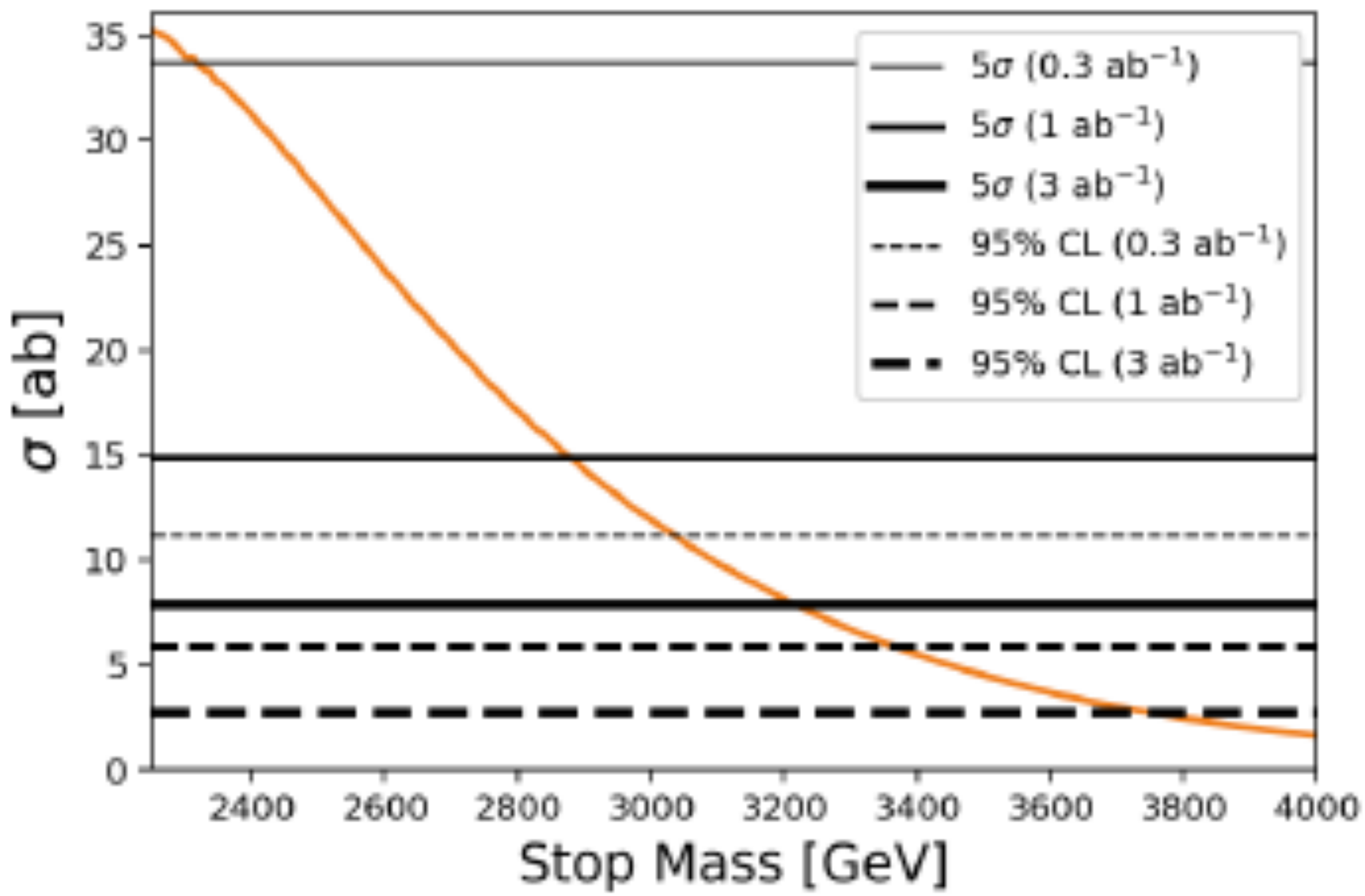
Prospects for top squarks in natural SUSY



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

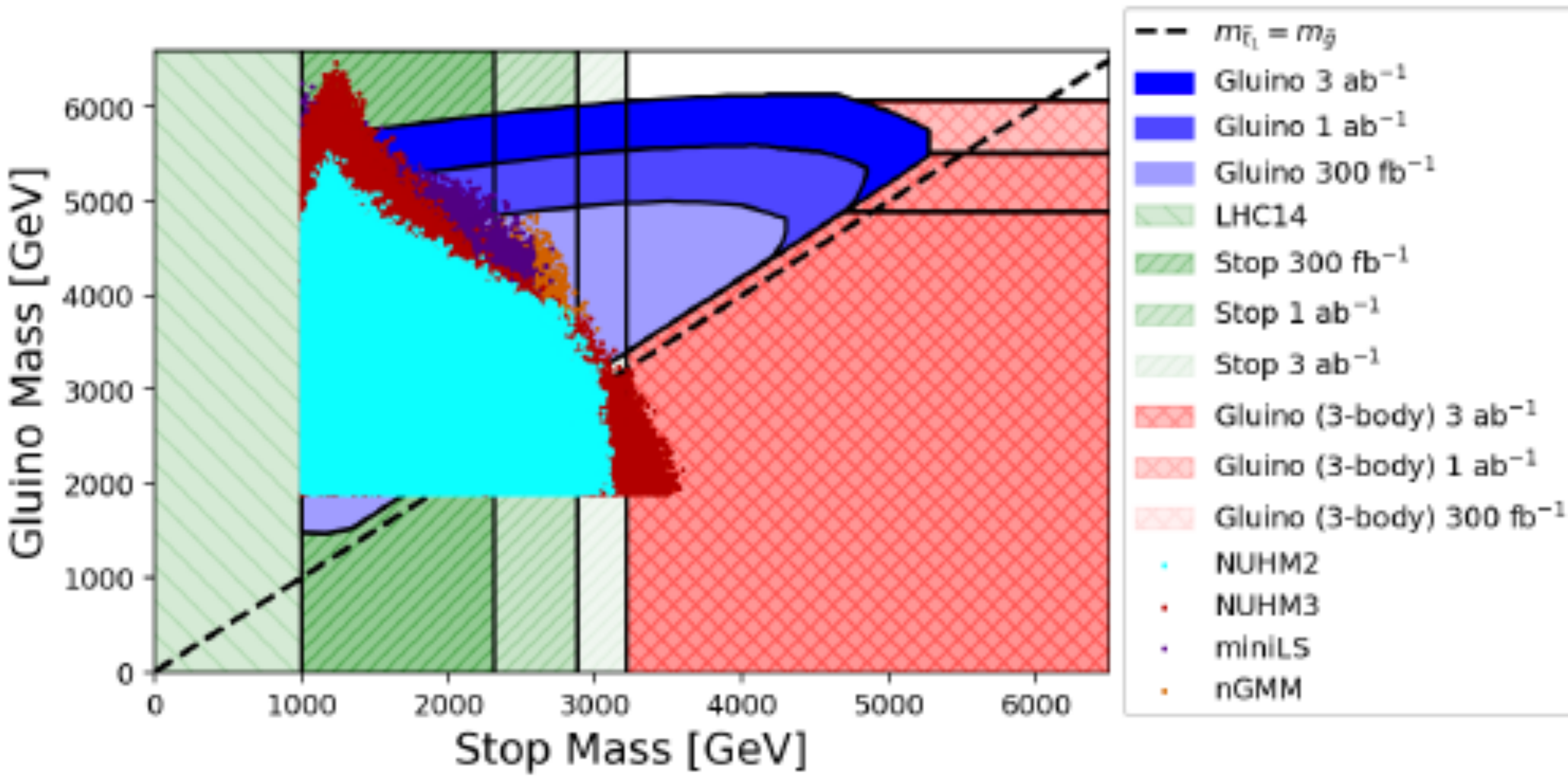
LHC33 reach extends to m(t1)~3-3.8 TeV

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

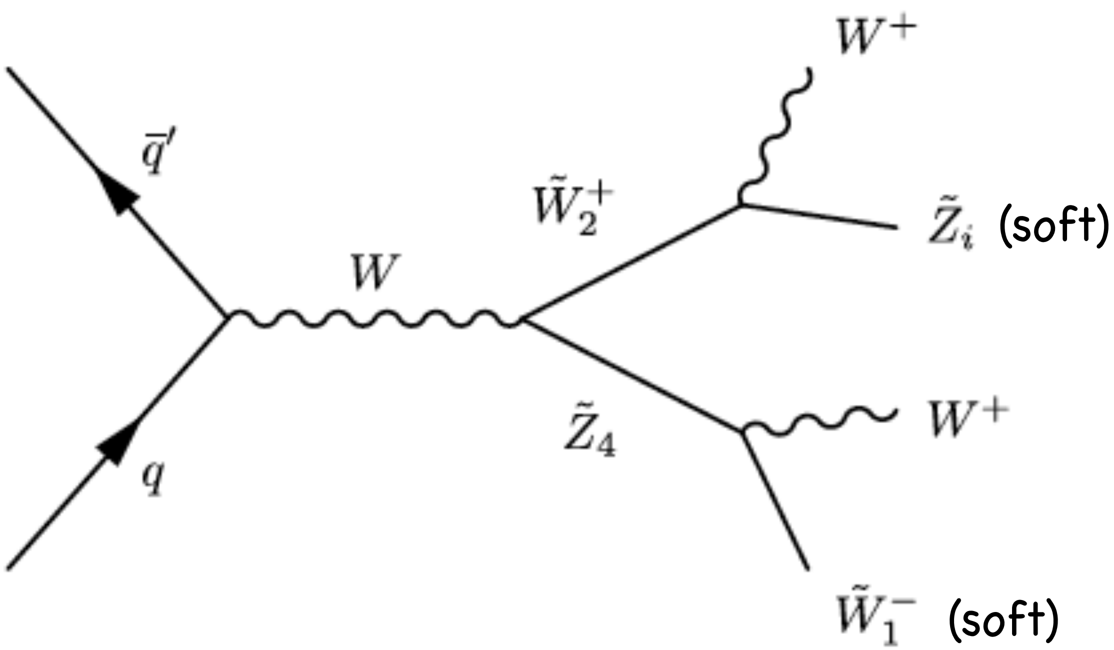
HB, Barger, Gainer, Serce, Tata

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

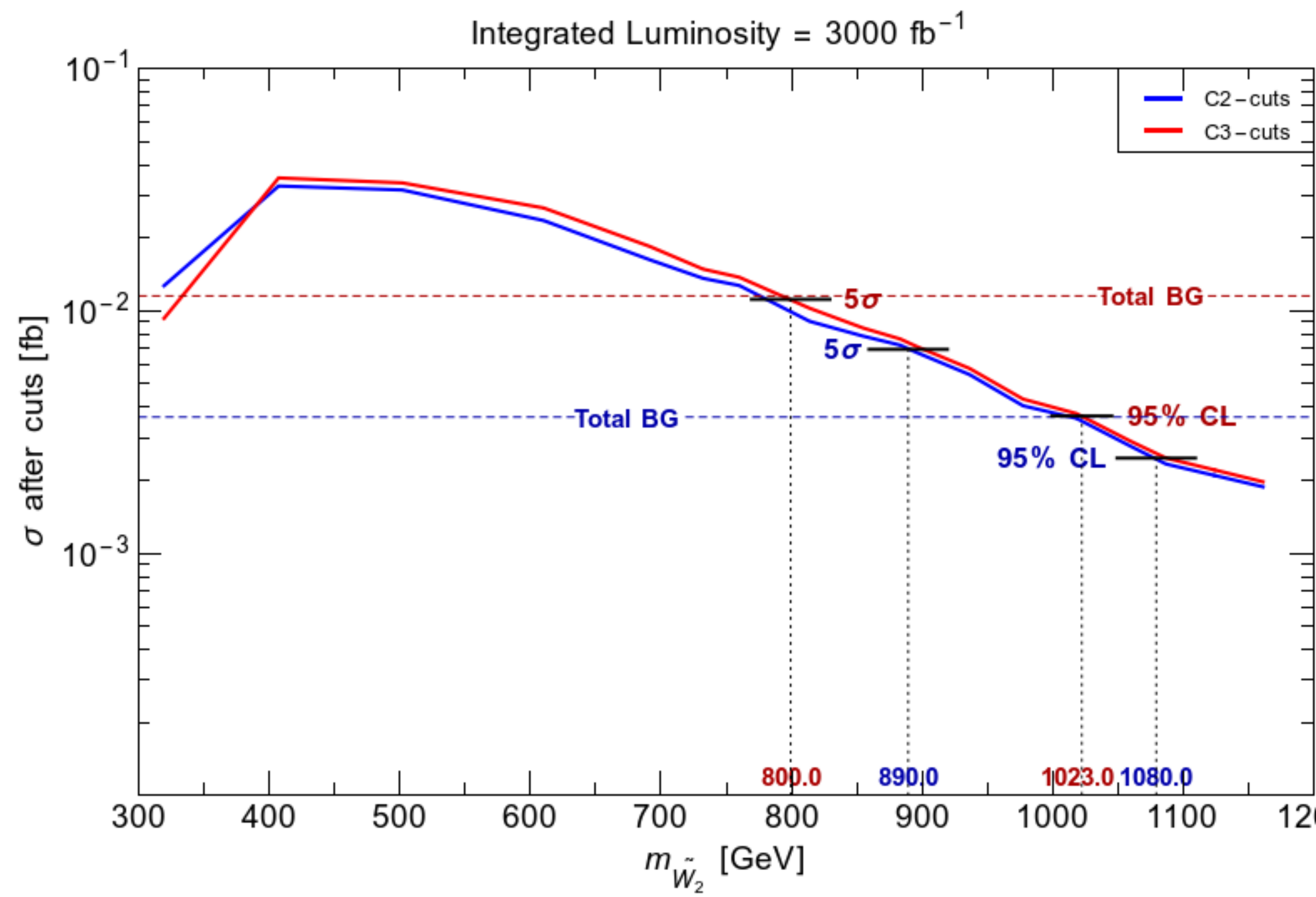
(need to re-do for LHC27)



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



wino pair production

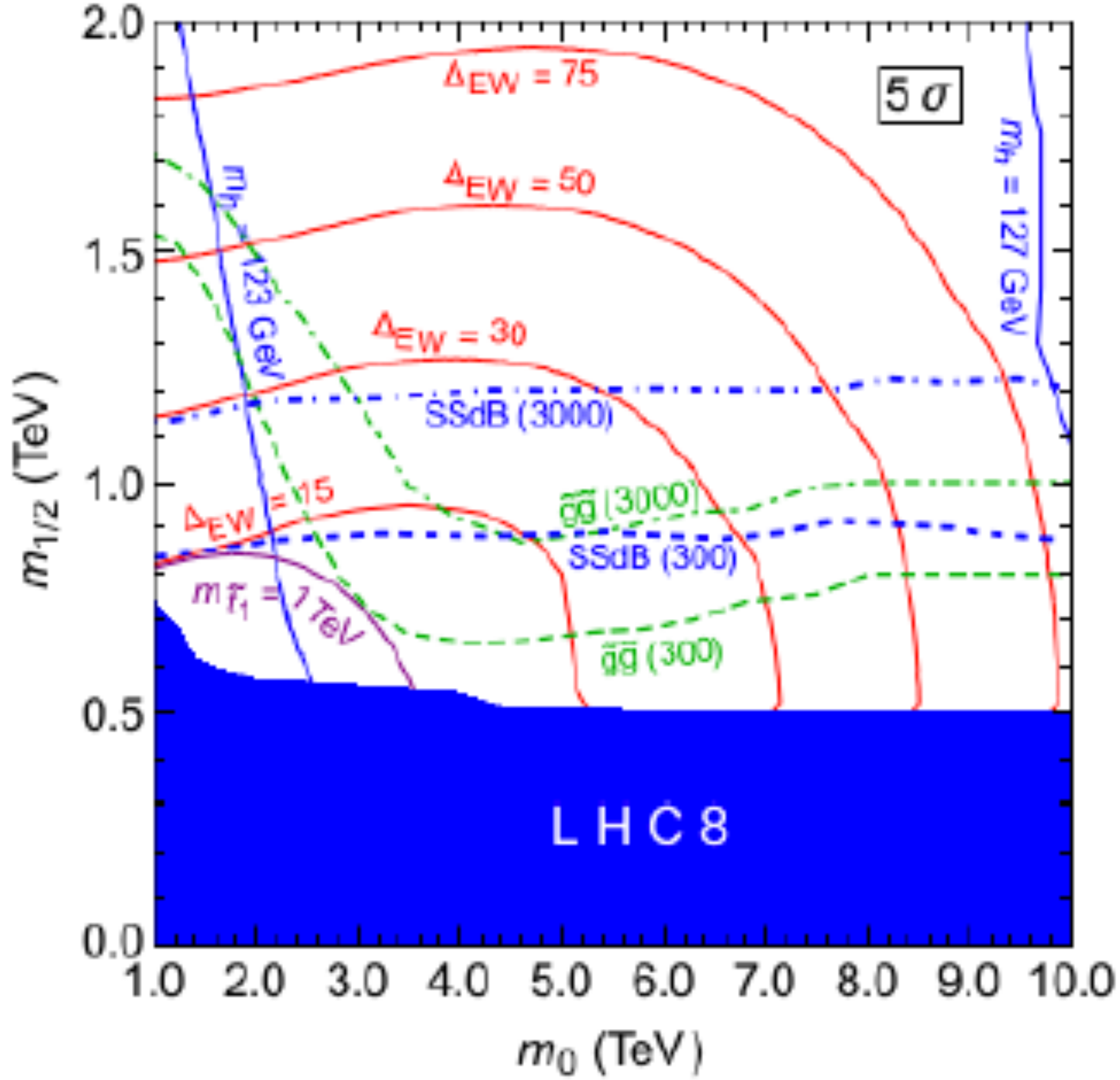


This channel offers good reach of LHC14 for RNS; it is also indicative of wino-pair prod'n followed by decay to higgsinos

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

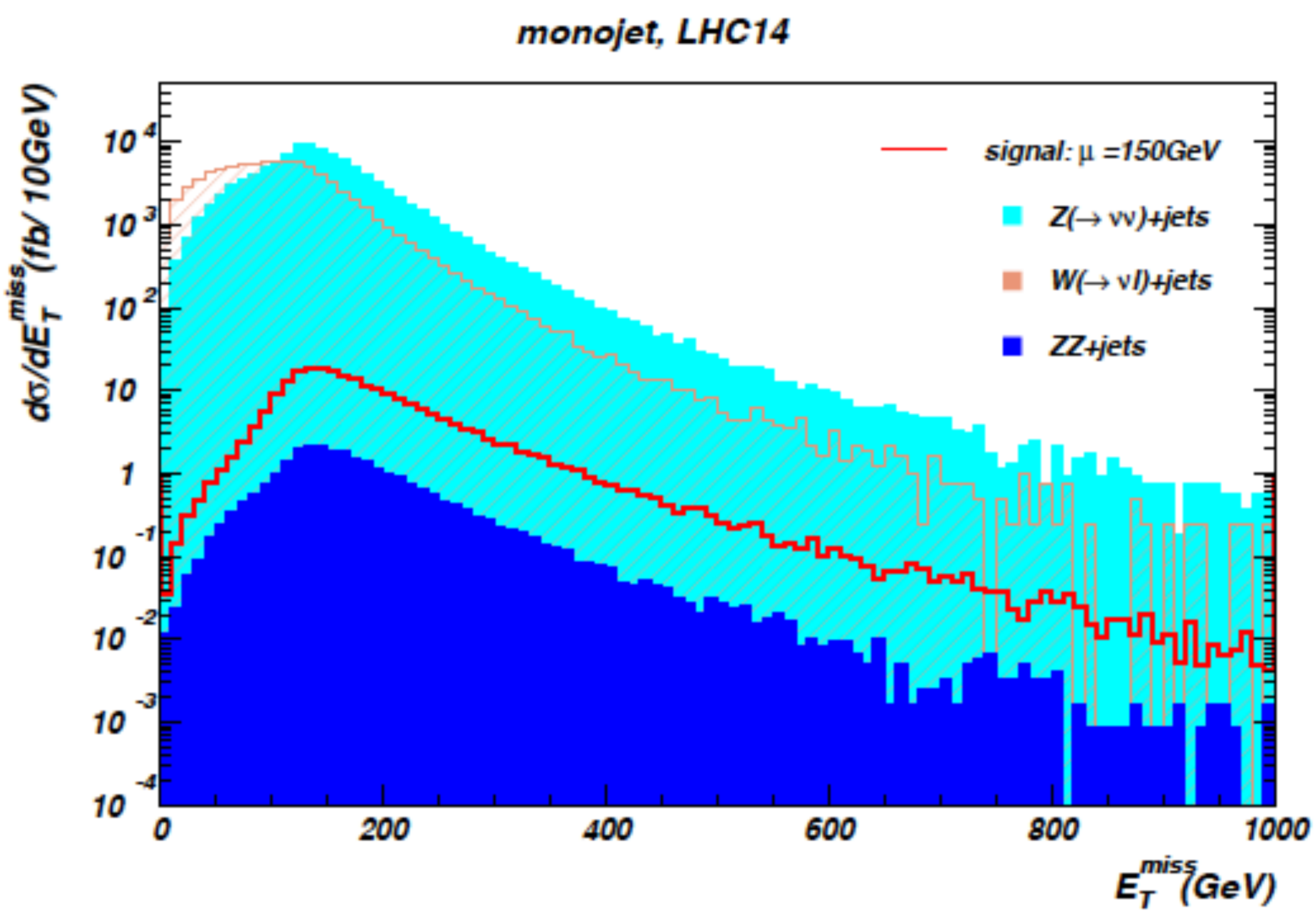
Good old m0 vs. mhf plane still viable, but needs mu~100-200 GeV as possible in NUHM2 instead of CMSSM/mSUGRA



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

HB,Barger,Savoy, Tata; arXiv:1604.07438

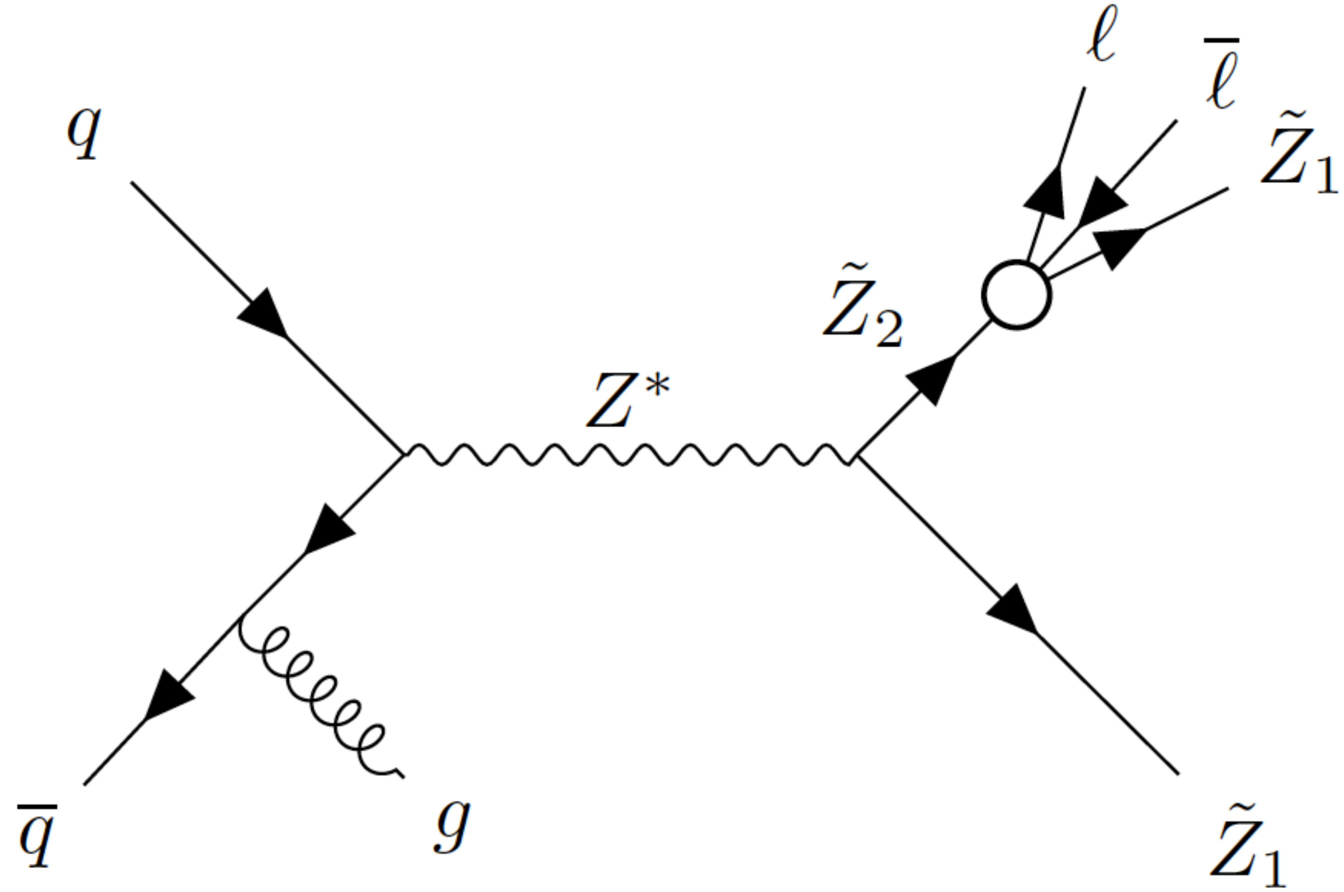
See direct higgsino pair production recoiling from ISR (monojet signal)?



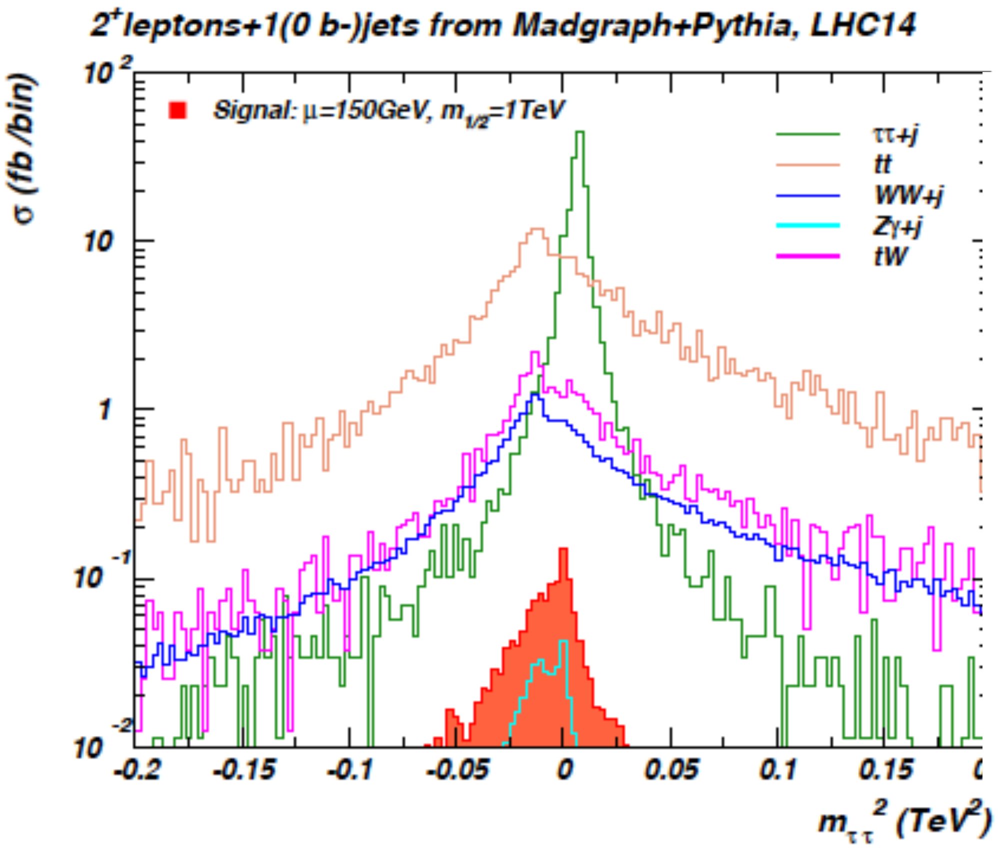
typically 1% S/BG after cuts:
very tough to do!

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

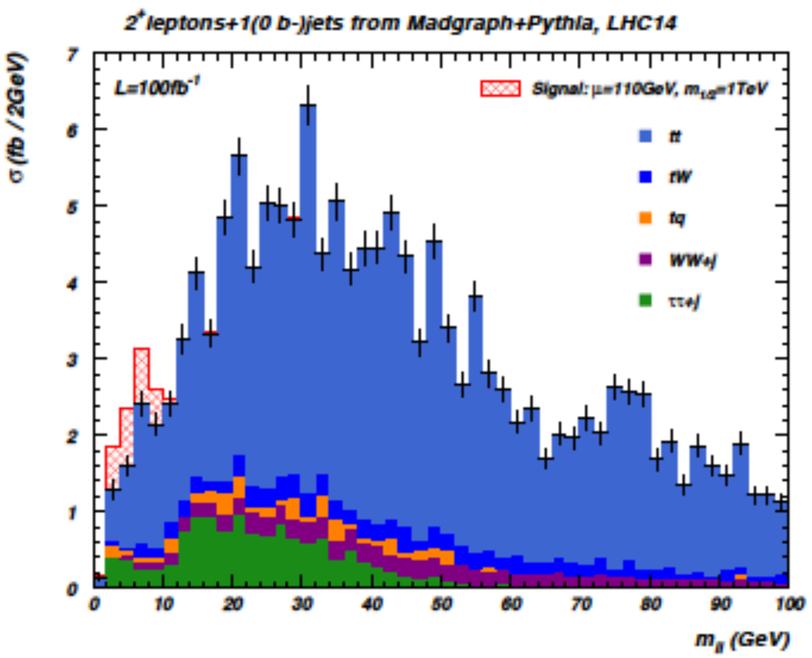
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;

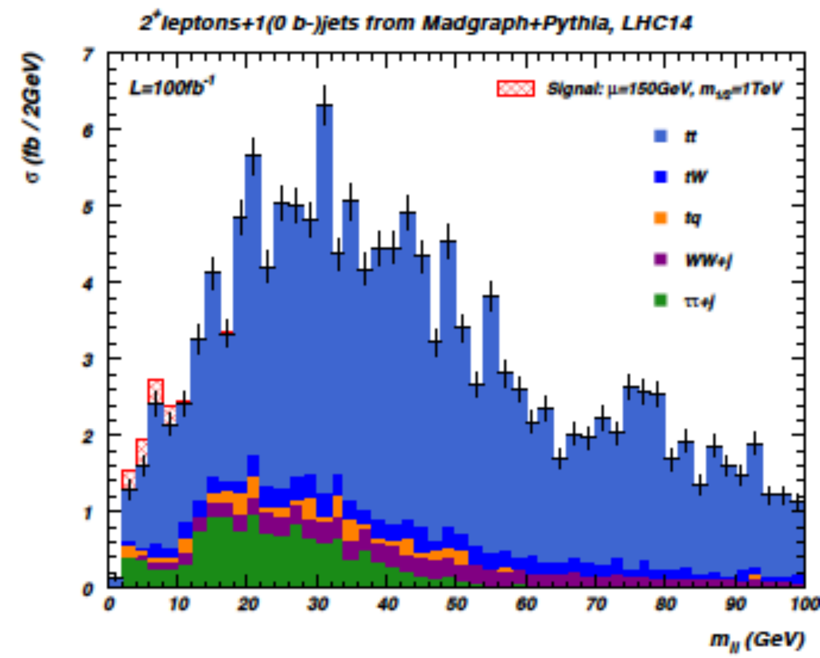


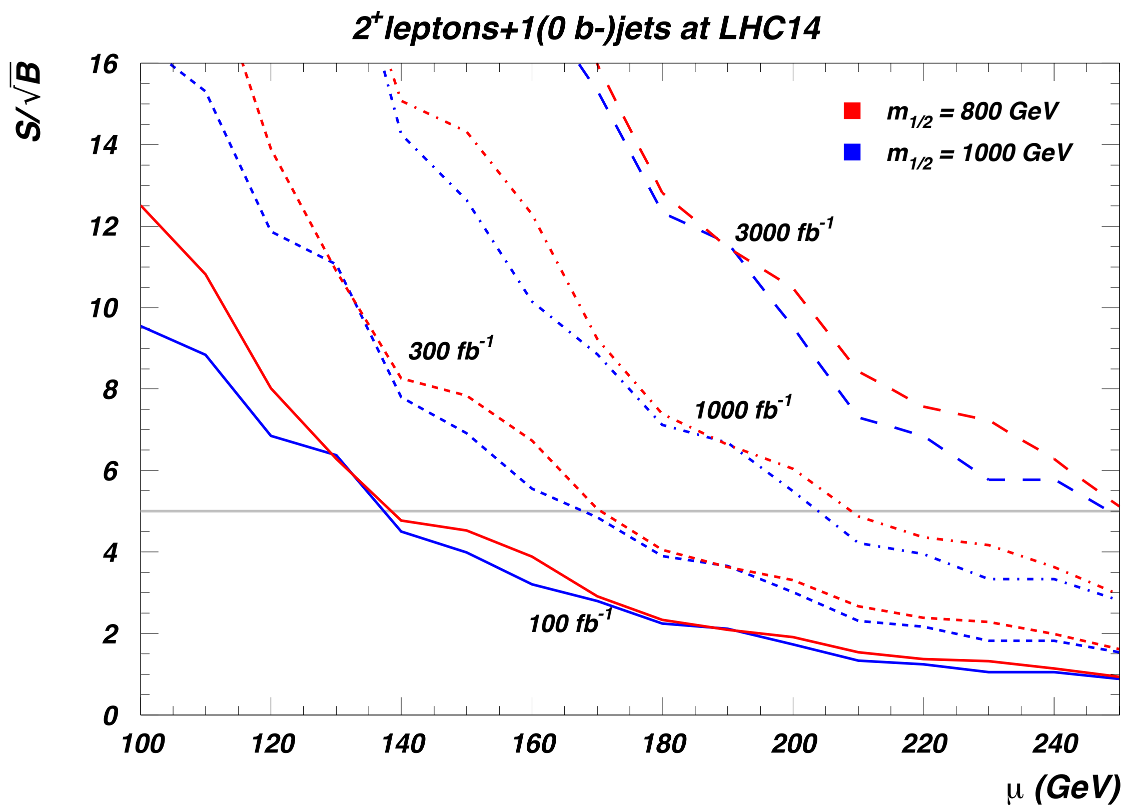
use MET to construct m^2(tau-tau)



cut m(ditau)^2<0







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

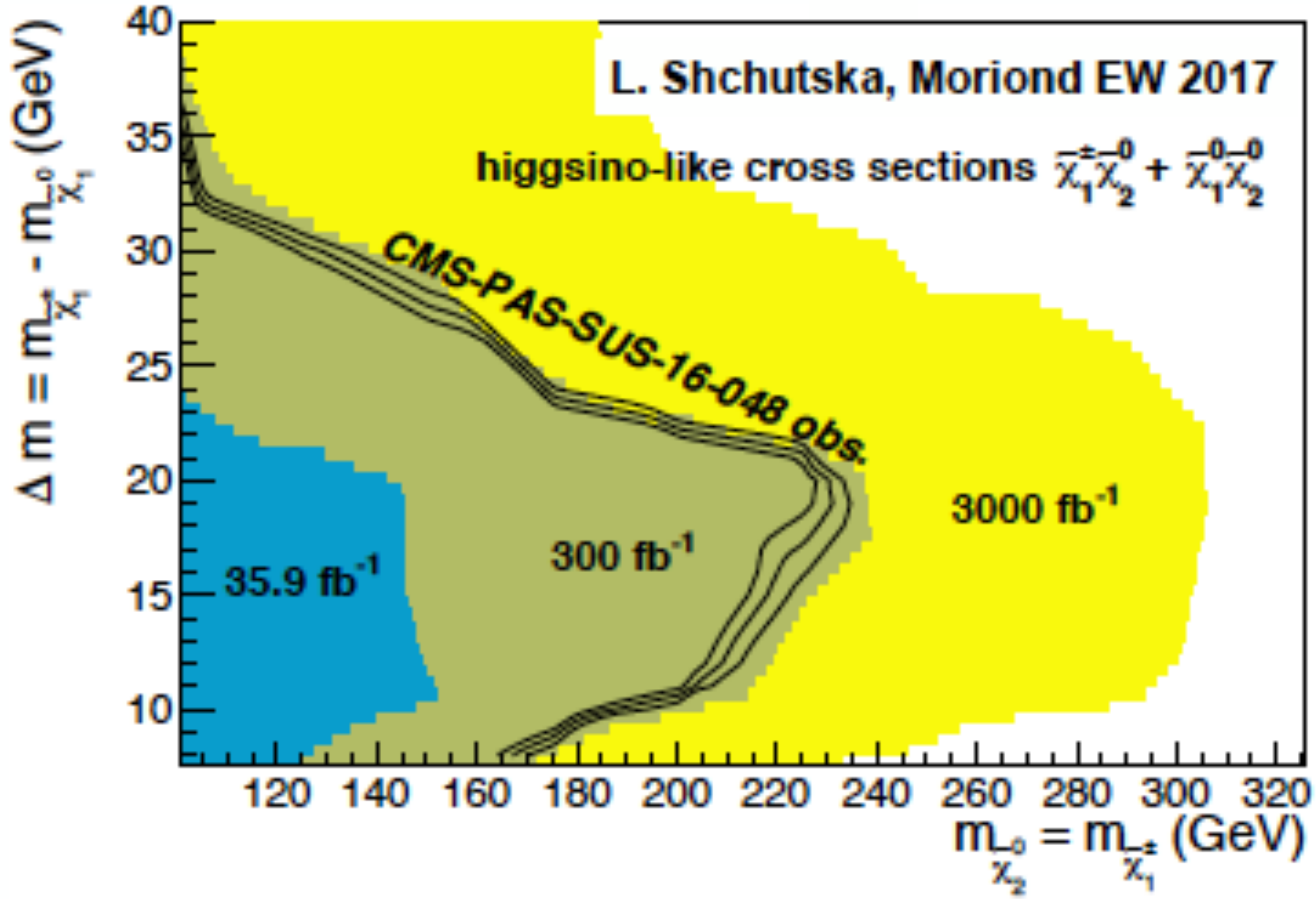
HB, Mustafayev, Tata

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)

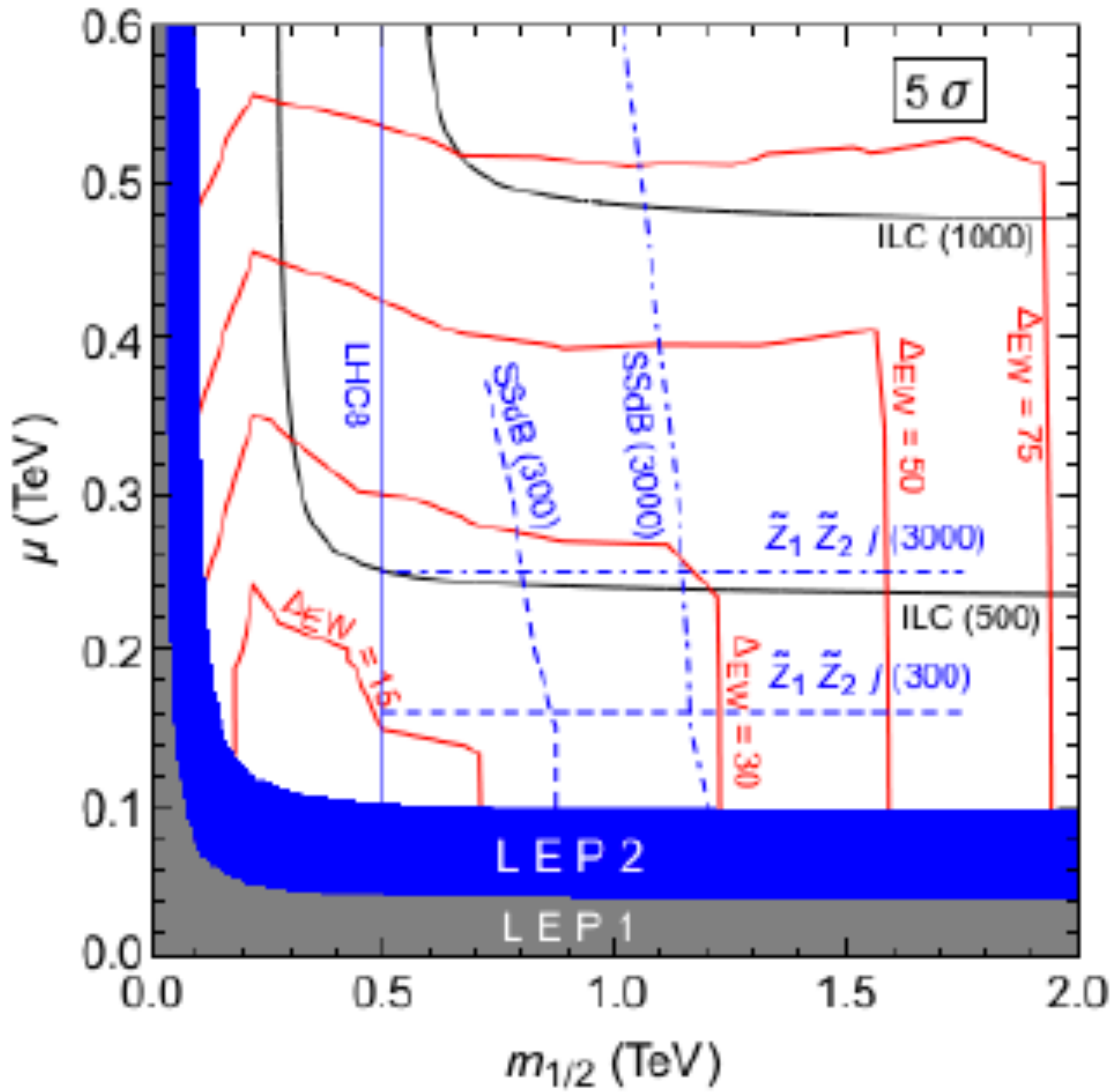
Atlas study underway- results soon?

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

Higgsino cross section (projection only)



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	?

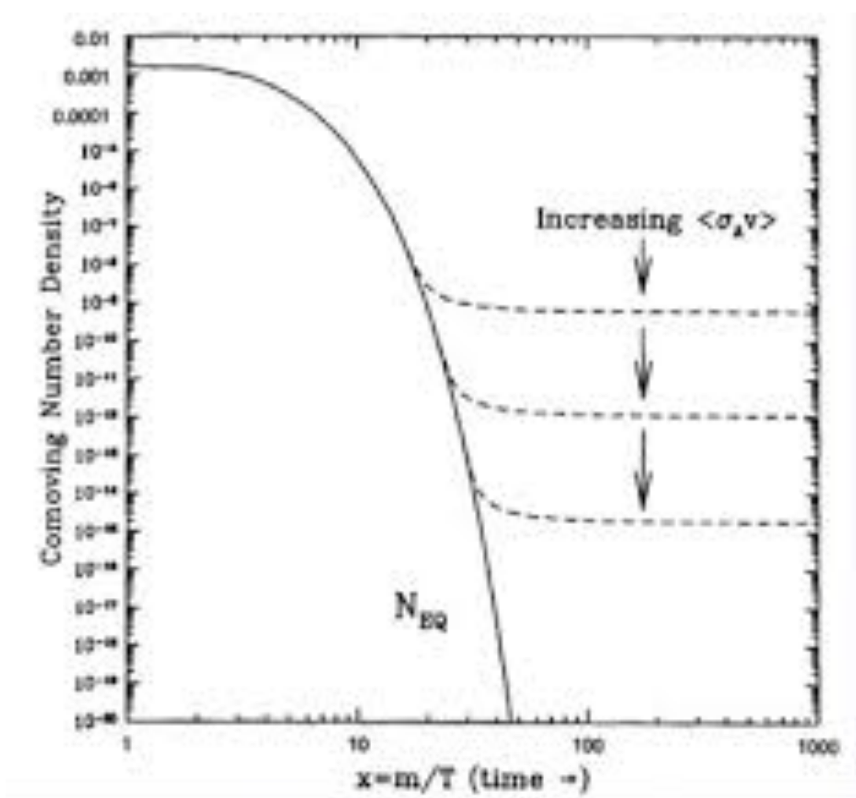
Conclusions:
1. SUSY still natural;
2. hunt for nSUSY has only begun;
3. HL-LHC handle most SUSY with ino-mass unification;
4. other (e.g. mirage) may require HE-LHC to complete search

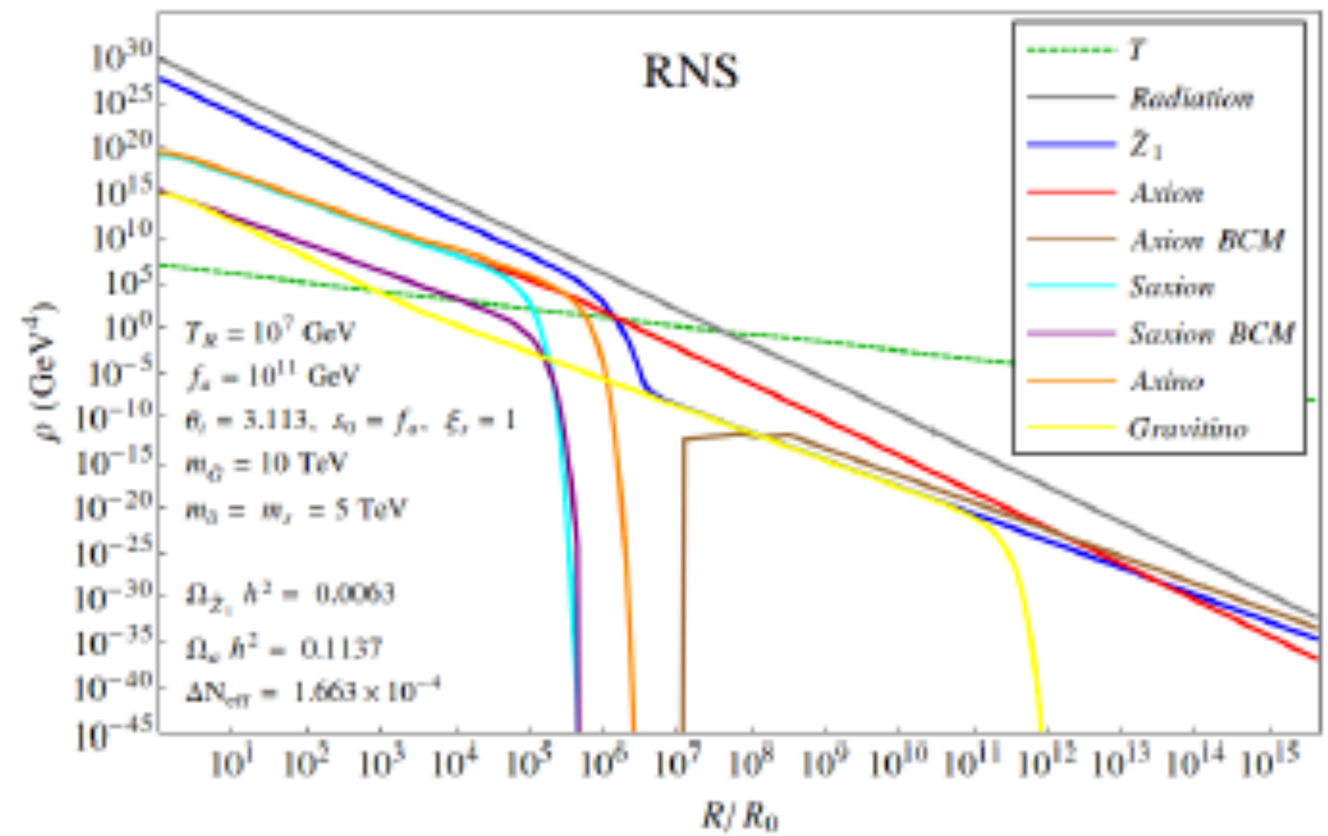
HB, Barger, Gainer, Huang, Tata
Savoy, Mustafayev
Sengupta, Serce

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

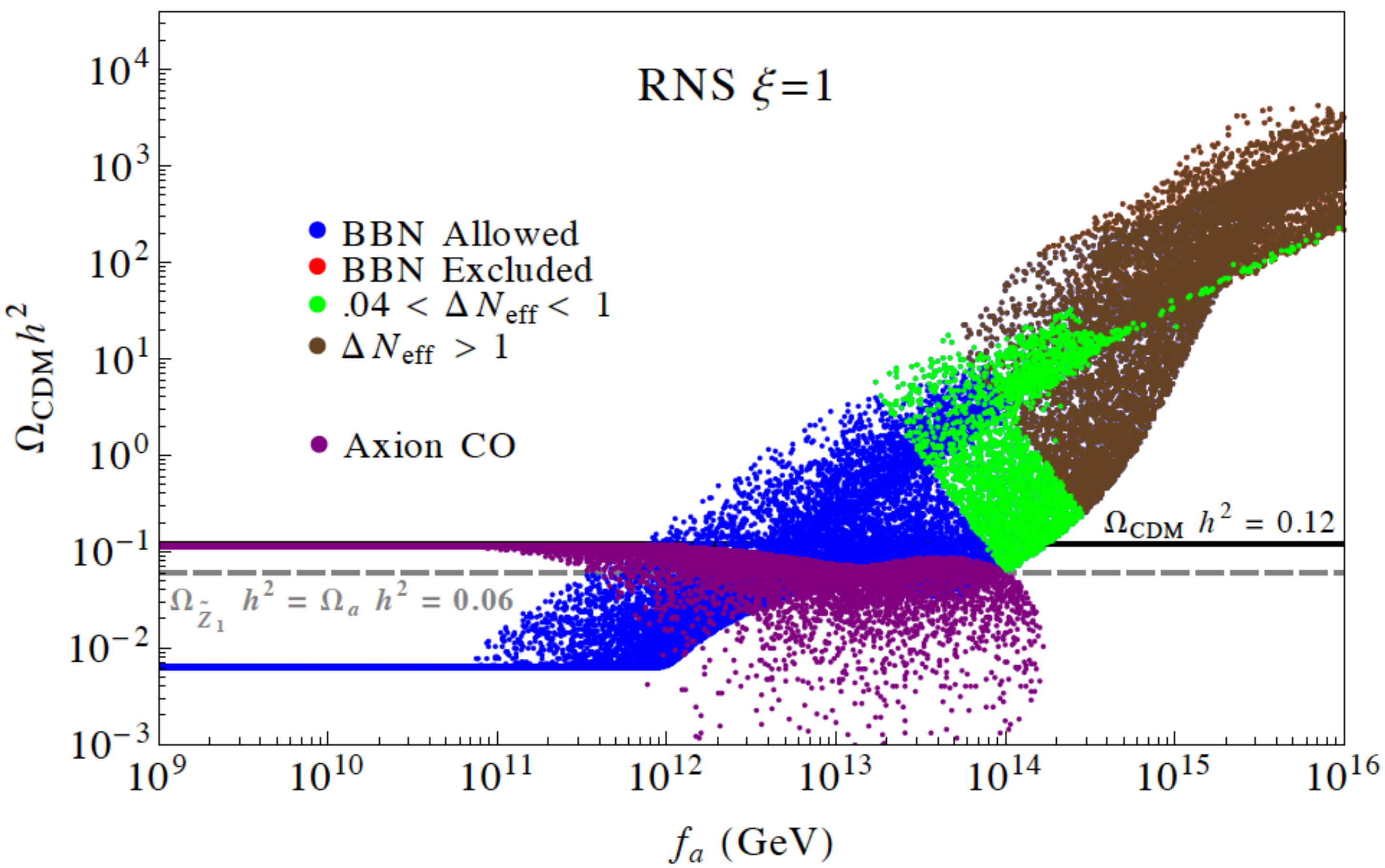




KJ Bae, HB, Lessa, Serce

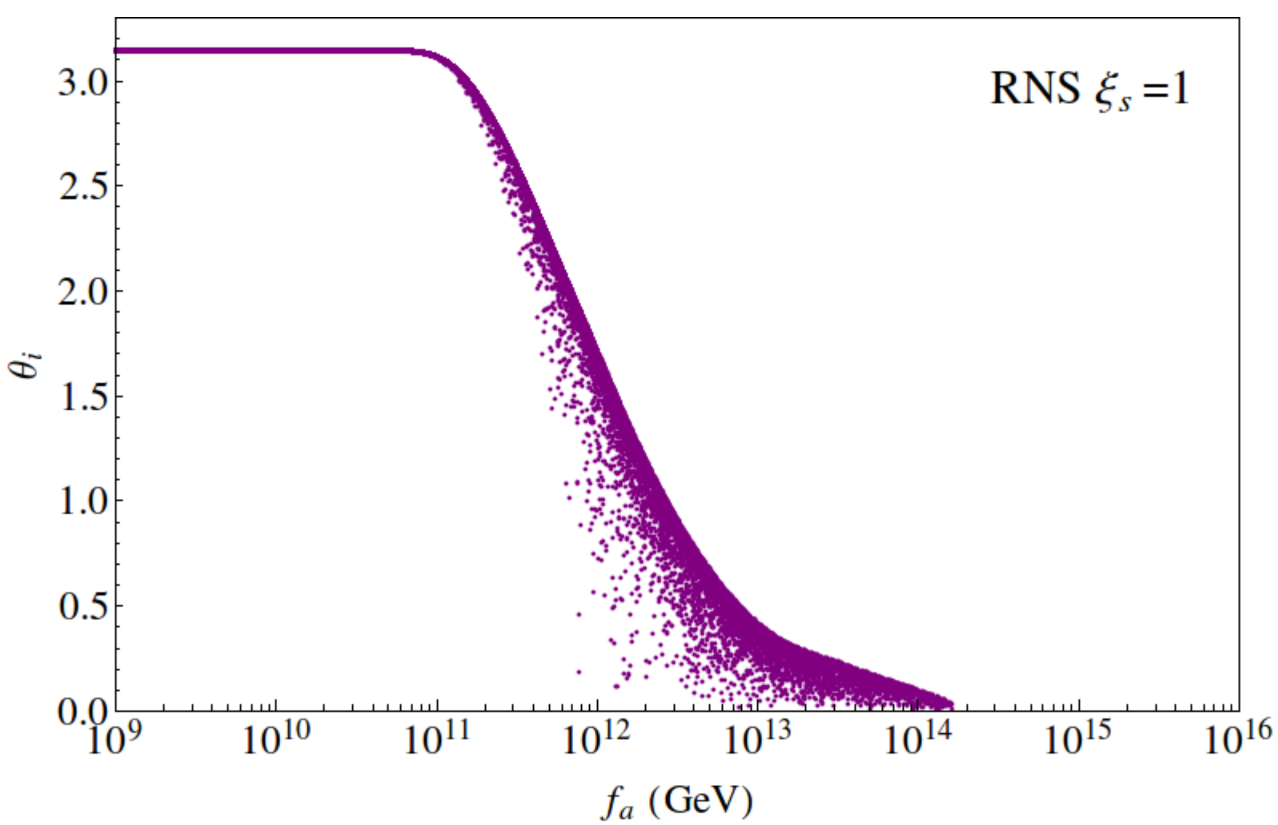
much of parameter space is axion-dominated with 10-15% WIMPs

=>



higgsino abundance

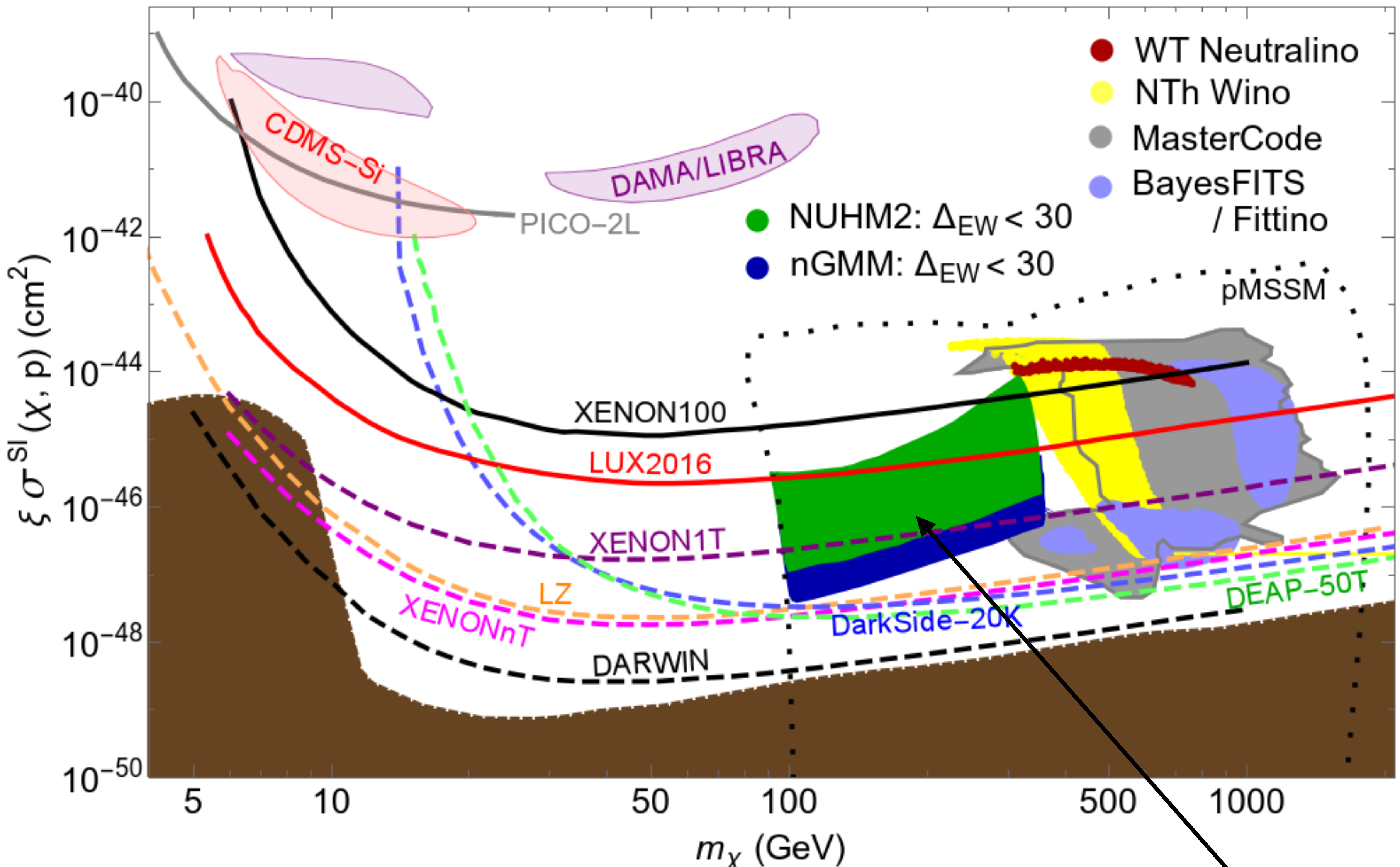
axion abundance



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

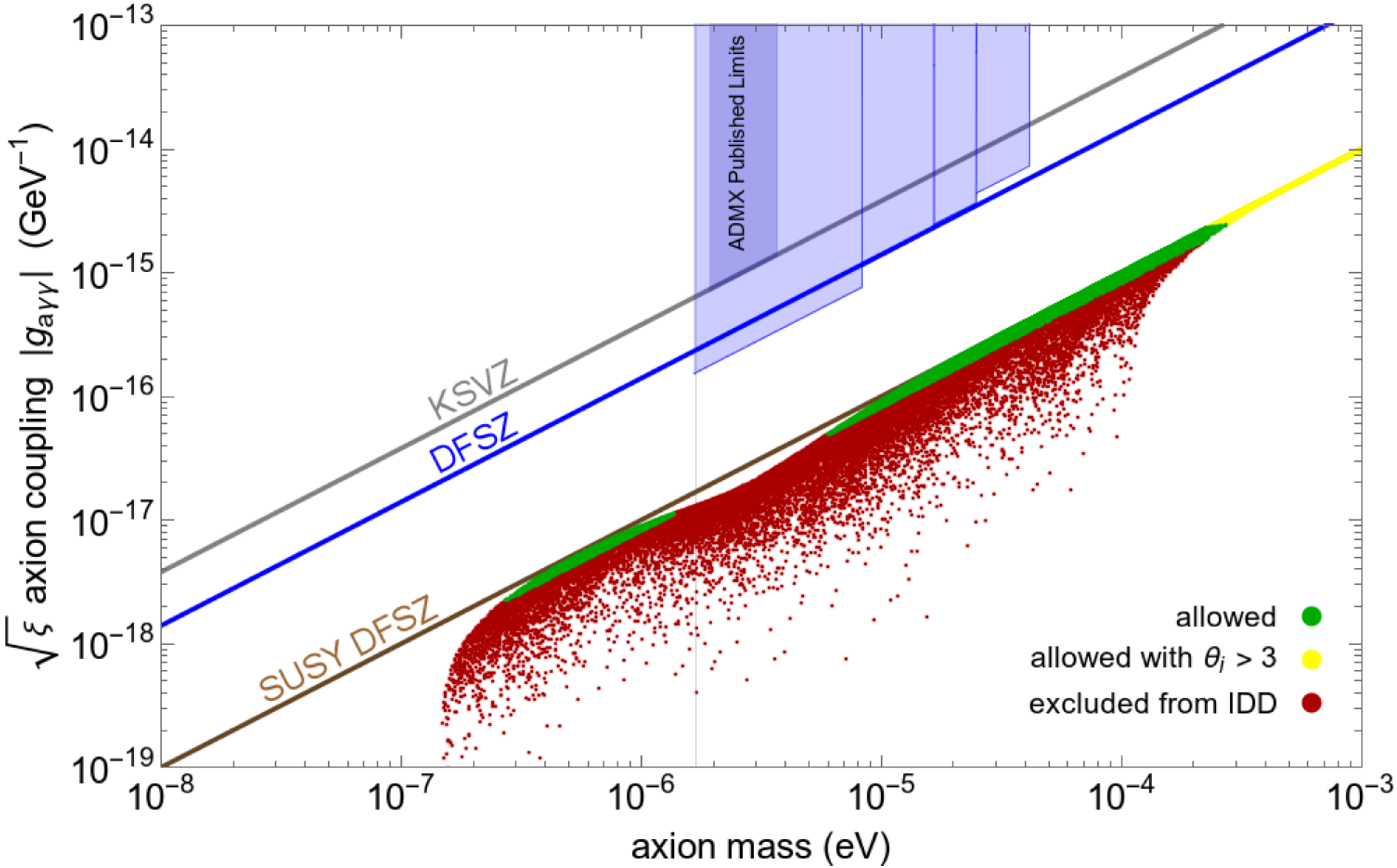
Bae, HB, Barger, Savoy, Serce

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

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

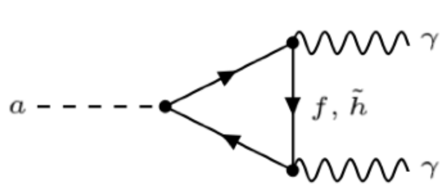
Xe-1-ton now operating!

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



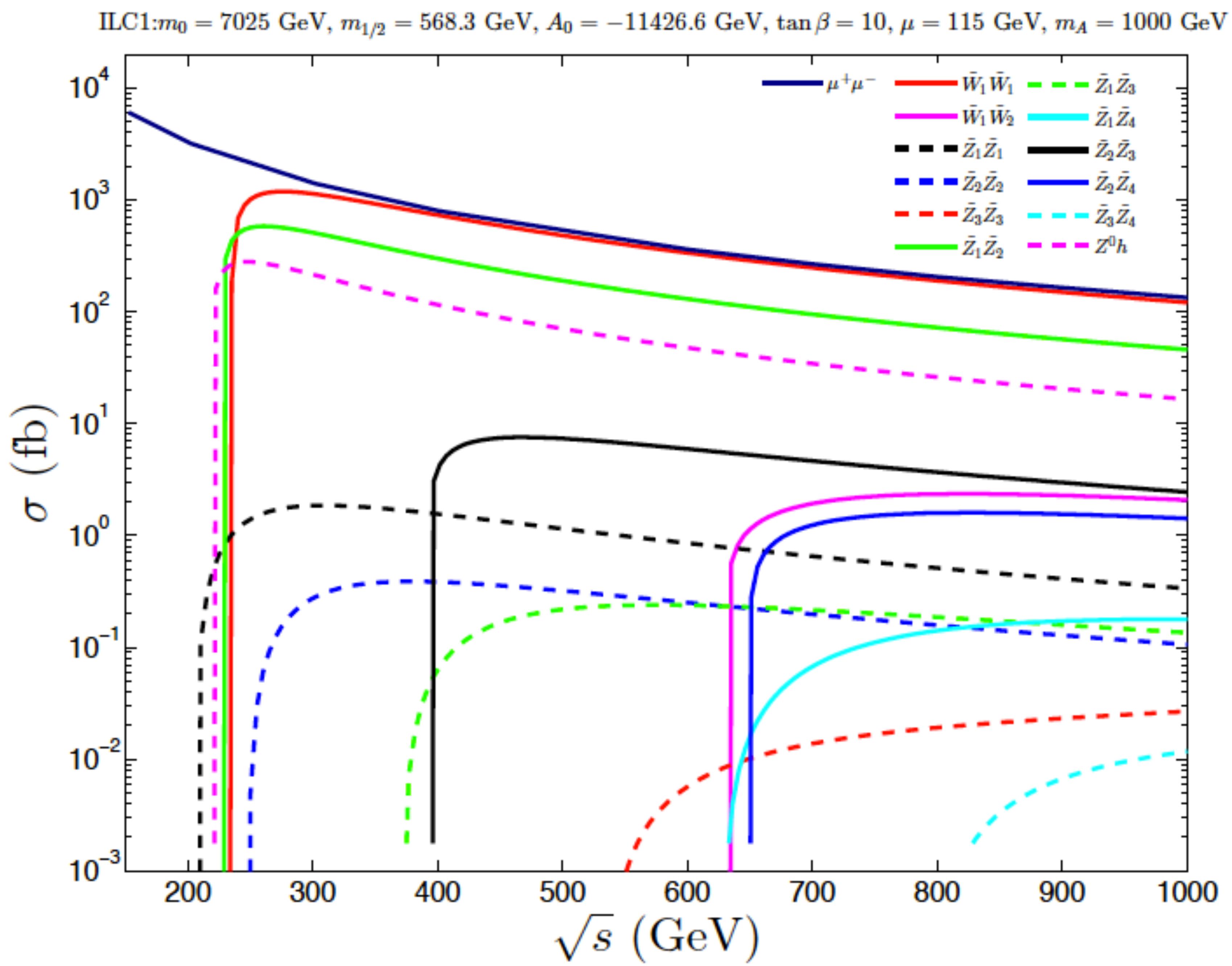
SUSY DFSZ axion: large range in m(a) but coupling reduced

may need to probe broader and deeper!



Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



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

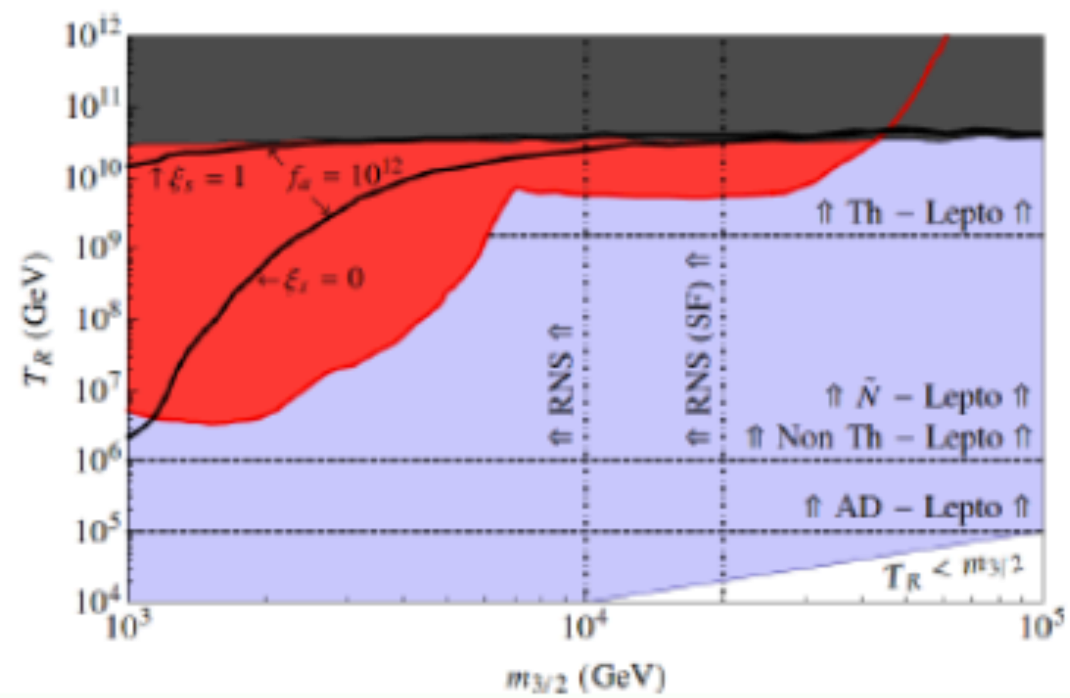
10-15 GeV higgsino mass gaps no problem in clean ILC environment

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

ILC either sees light higgsinos or MSSM dead

Baryogenesis scenarios for radiative natural SUSY

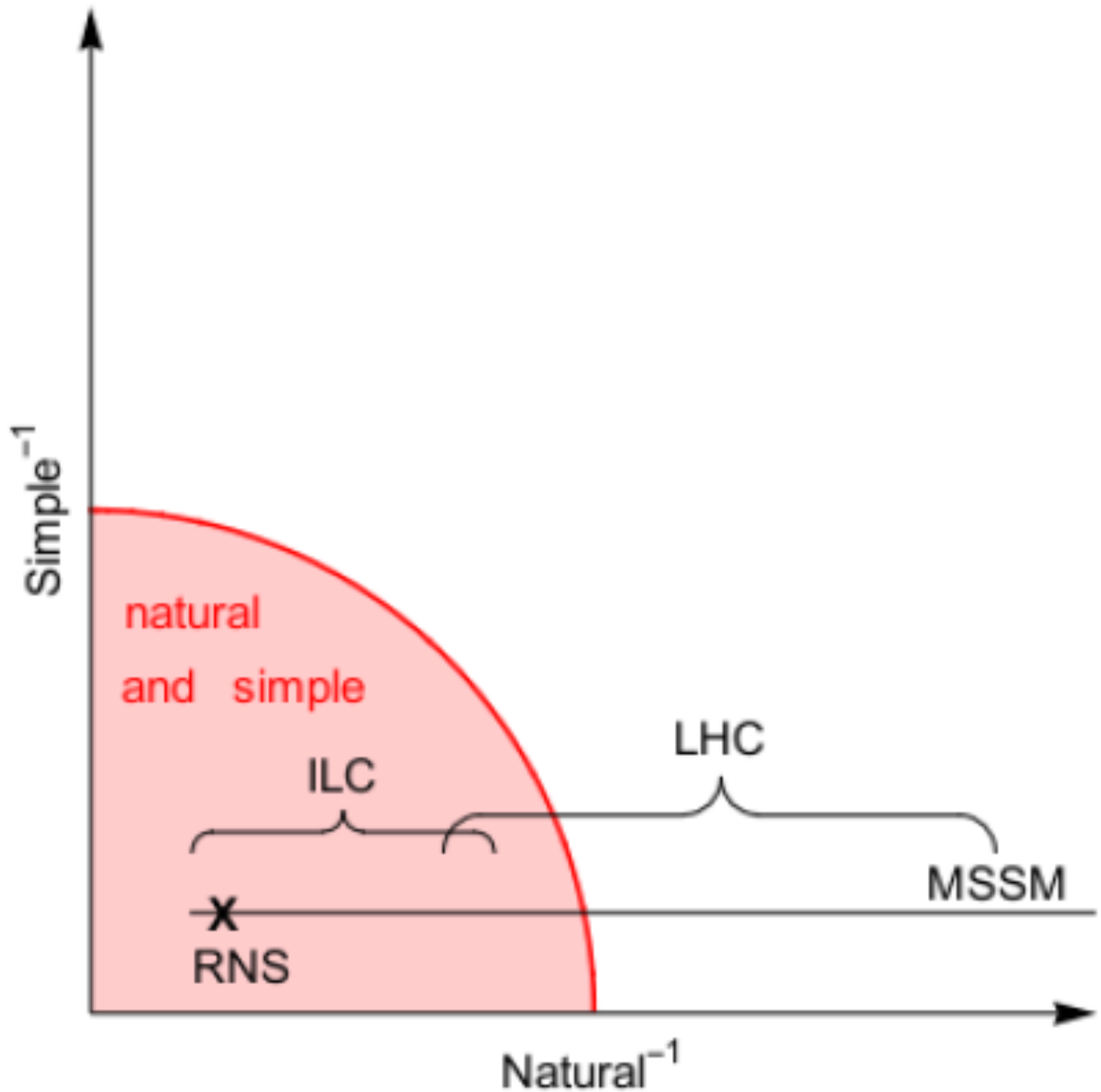
- thermal leptogenesis
- non-thermal (inflaton decay)
- oscillating sneutrino
- Affleck-Dine (AD)



gravitino problem plus axino/saxion problem: still plenty room

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

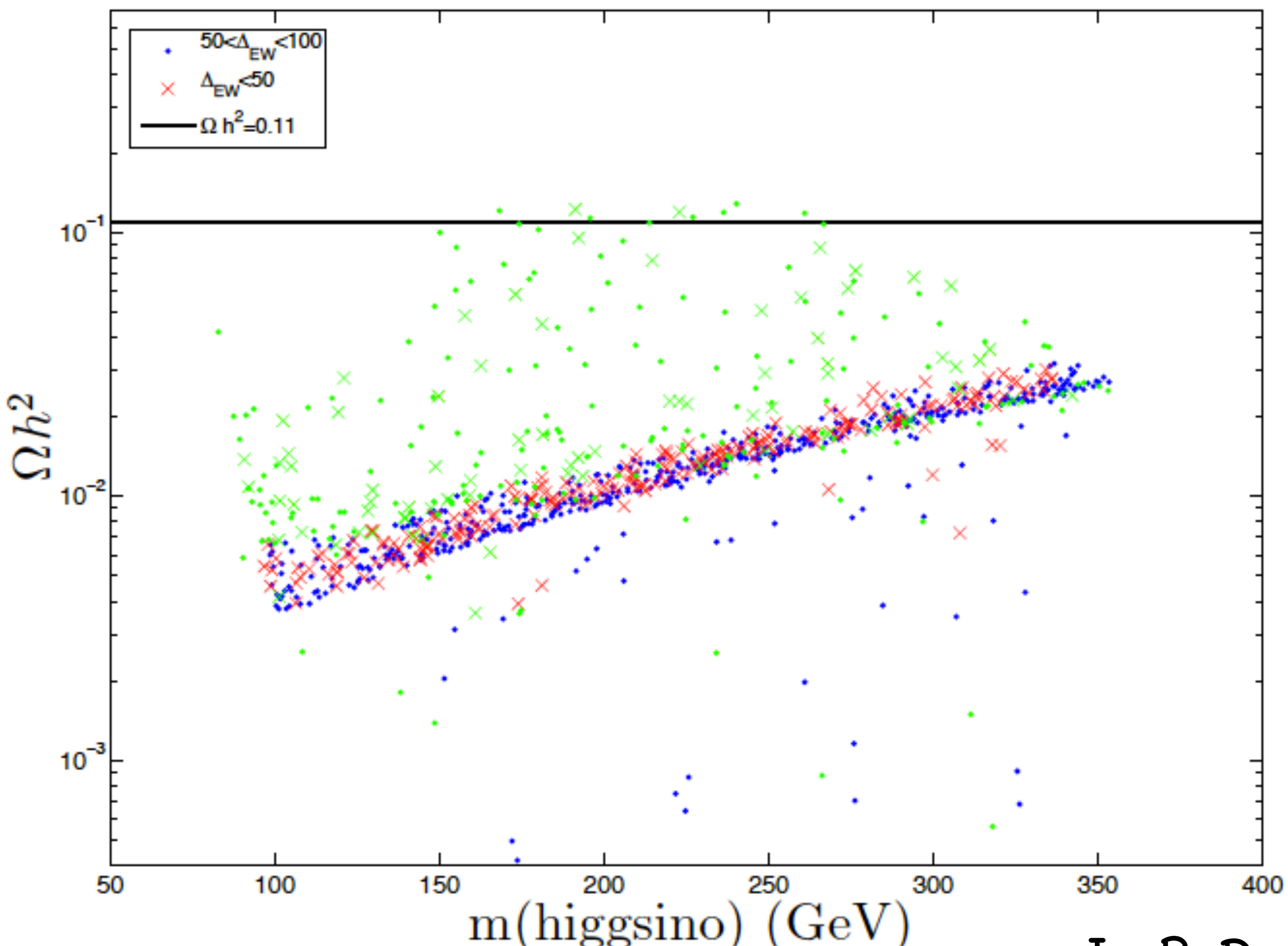
Bae,HB, Serce, Zhang, arXiv:1510.00724



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)

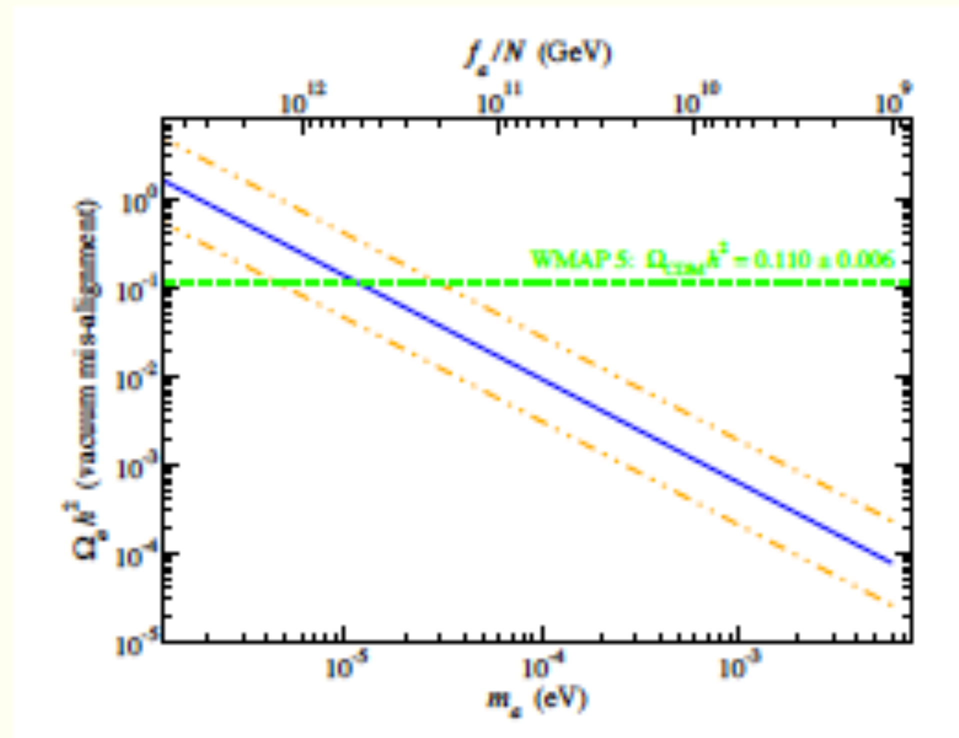
Best solution after 35 years:
PQWW/KSVZ/DFSZ invisible axion

In SUSY, axion accompanied by axino and saxion

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

Axion cosmology

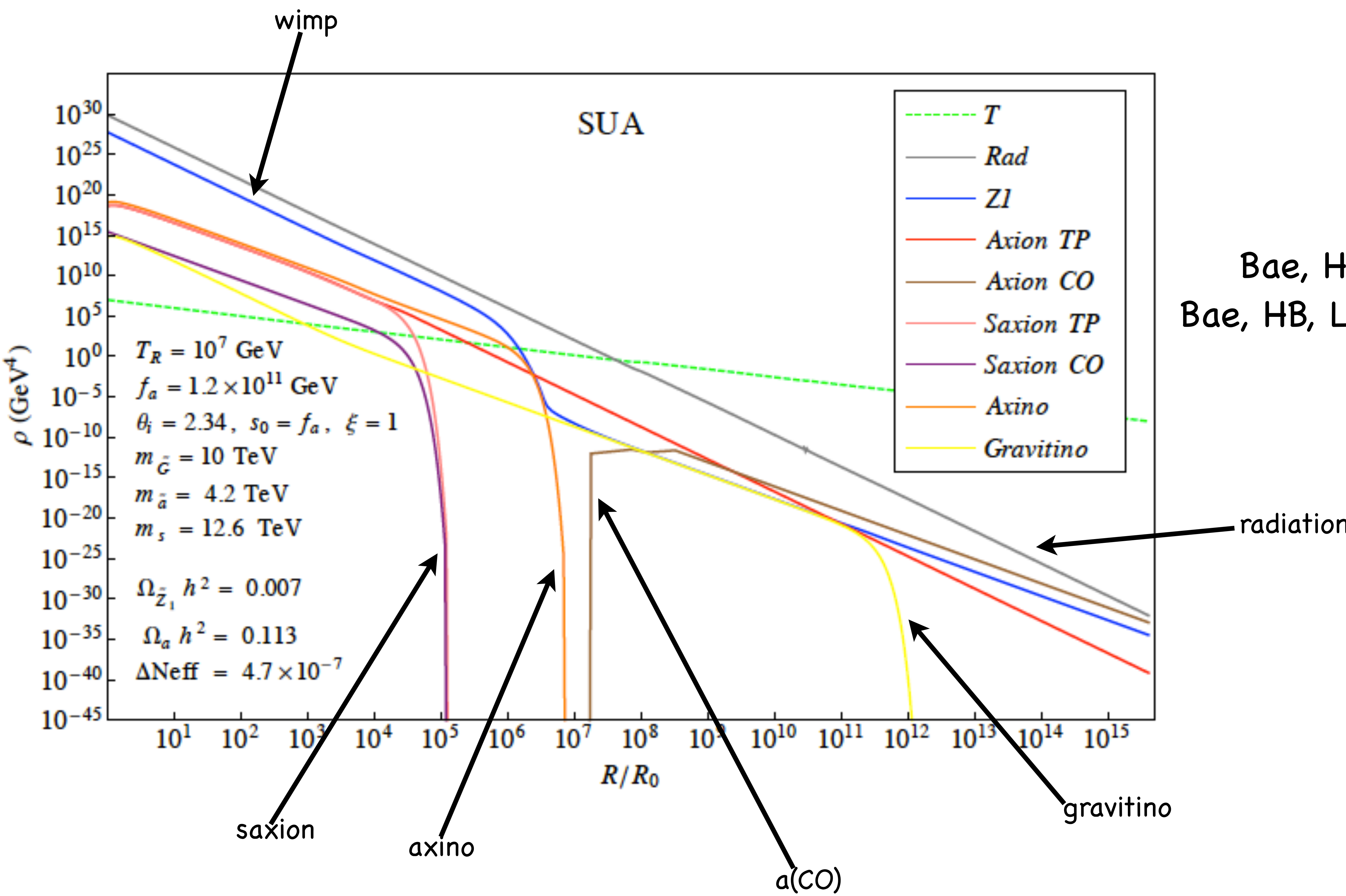
- ⋆ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$:
    $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
-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



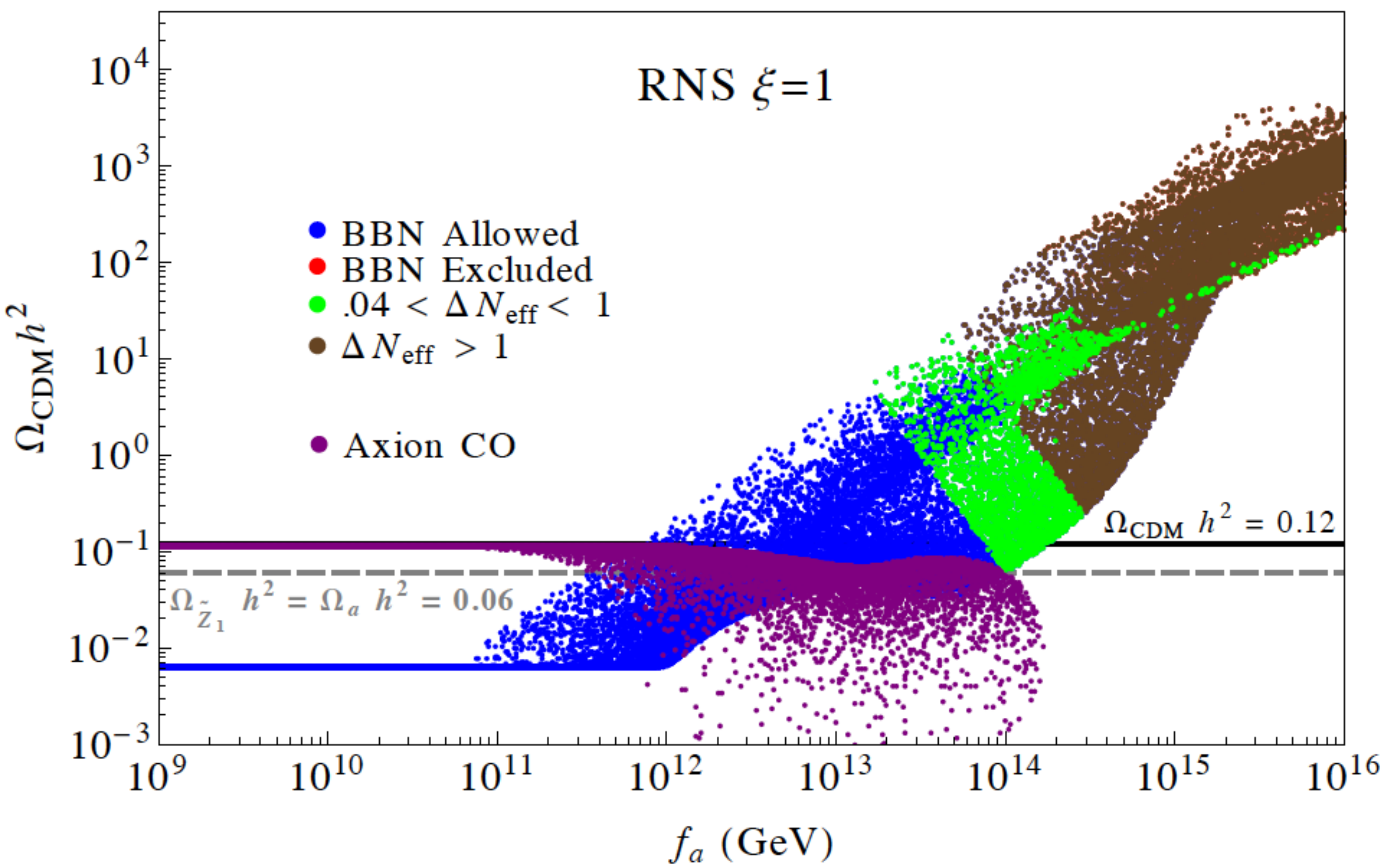
mixed axion-neutralino production in early universe

- 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

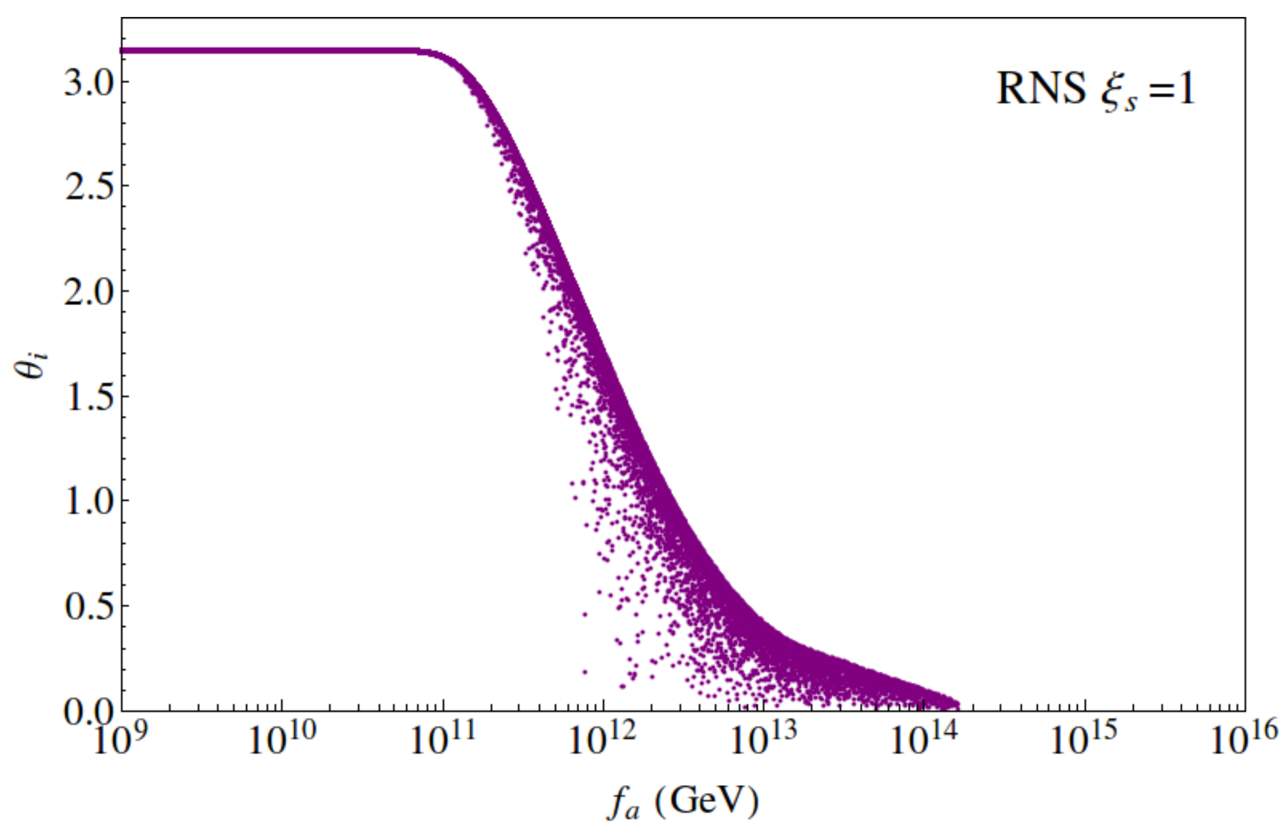


Bae, HB, Chun;
Bae, HB, Lessa, Serce



higgsino abundance

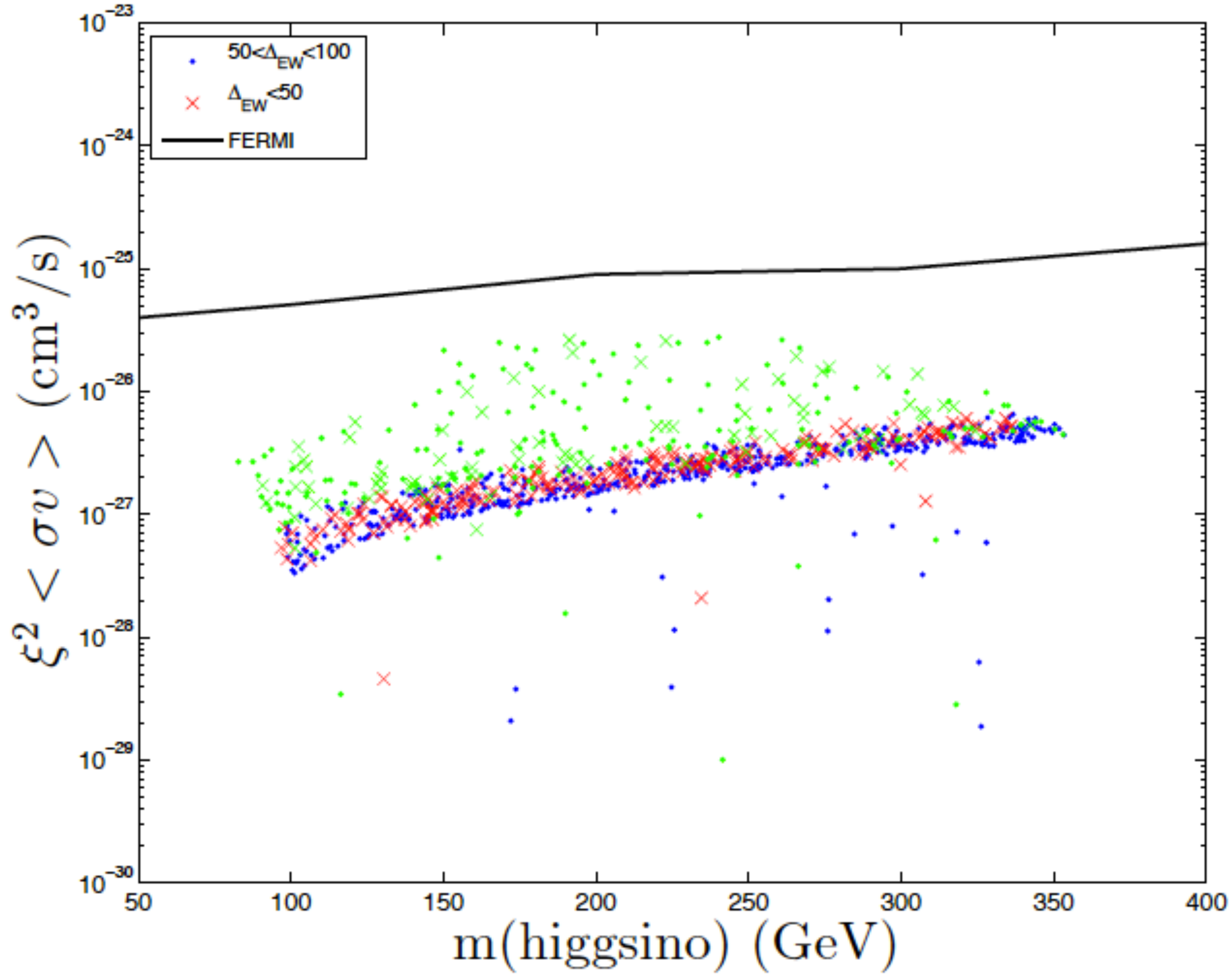
axion abundance



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:

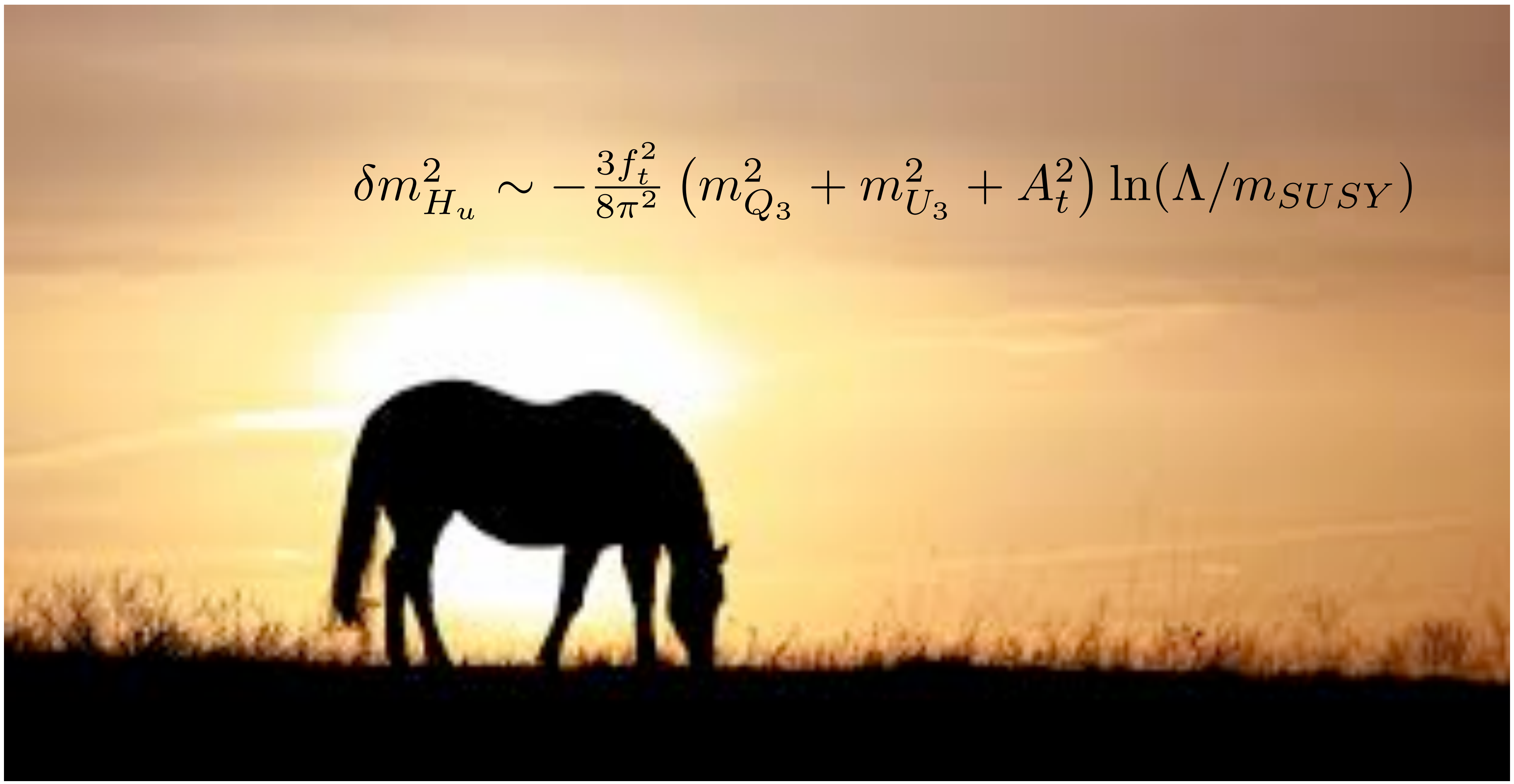


green: excluded by Xe-100

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