Implications of naturalness and the string landscape for LHC SUSY searches

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Six questions

- What exactly do we mean by naturalness?
- Is naturalness important?
- Is there a naturalness crisis (is SUSY excluded)?
- Is the string landscape an alternative to naturalness?
- What does naturalness imply for SUSY searches at LHC Run 3 and beyond?
- What does naturalness imply for dark matter searches? mixed axion+higgsino-like WIMP (some other time)

What is naturalness?

- Dirac naturalness: no small or big numbers in a physical theory
- `tHooft naturalness: small numbers technically OK as long as -> 0 as theory becomes more symmetric: small m(e) is OK since -> 0 under restoration of chiral symmetry
- But what we mean in contemporary HEP discussions is what we call ``practical naturalness"

An observable $\mathcal{O}$ is natural if all *independent* contributions to $\mathcal{O}$ are comparable to or smaller than $\mathcal{O}$

e.g. if $\mathcal{O} = o_1 + \cdots + o_n$, and $o_1 \gg \mathcal{O}$, then some other contribution, say o_2, would have to be *finetuned* to a precise large opposite-sign value such that O is maintained at its measured value

Such finetunings, while logically possible, are thought to be highly implausible and hence ``unnatural"

Naturalness and predictivity

- Naturalness is closely related to predictivity in a physical theory
- e.g. in perturbation theory, we expect lowest order term comparable to $\mathcal{O}$ while higher order terms are increasingly tinier
- Dirac was bothered by this: divergent contributions
- But divergent contributions *dependent*: as one diverges, others diverge in oppposite sign such that precise cancellations occur
- QED OK: once diverges cancel, all contributions comparable or less than $\mathcal{O}$

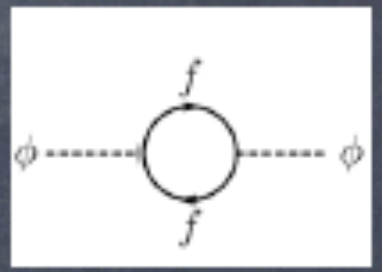
Is naturalness important?

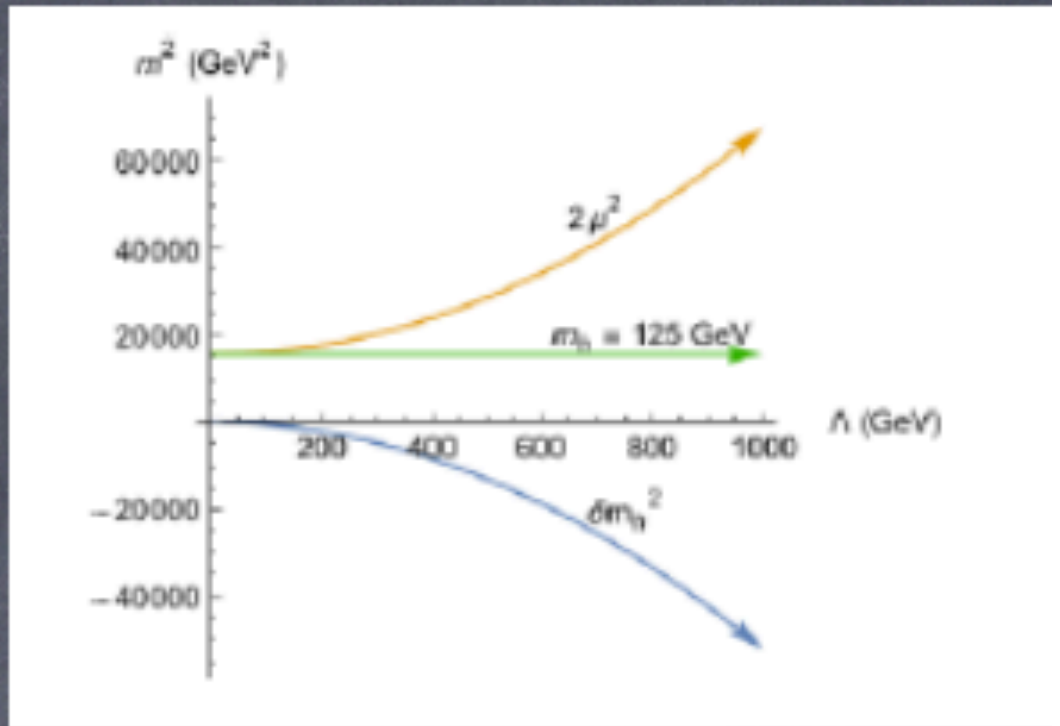
- The naturalness issue today relates to the magnitude of the weak scale

Biggest conundrum of SM: why is Higgs mass so small?

1. There is a lowest order mass term

2. Quantum corrections diverge quadratically with energy scale of new physics





$$m^2_{H_{SM}} = 2\mu^2 + \delta m^2_{H_{SM}}$$

$$\delta m^2_{H_{SM}} \simeq \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2$$

3. To avoid the pathology of fine-tuning, SM must be valid only to Lambda~1 TeV

4. Need theory which is free of quadratic divergences to extend e.g. to GUT scale

Another viewpoint:

Higgs mass (hierarchy) problem (SM):

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

$$m_h^2 \simeq 2\mu^2 + \delta m_h^2$$

$$\delta m_h^2 \simeq \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2$$

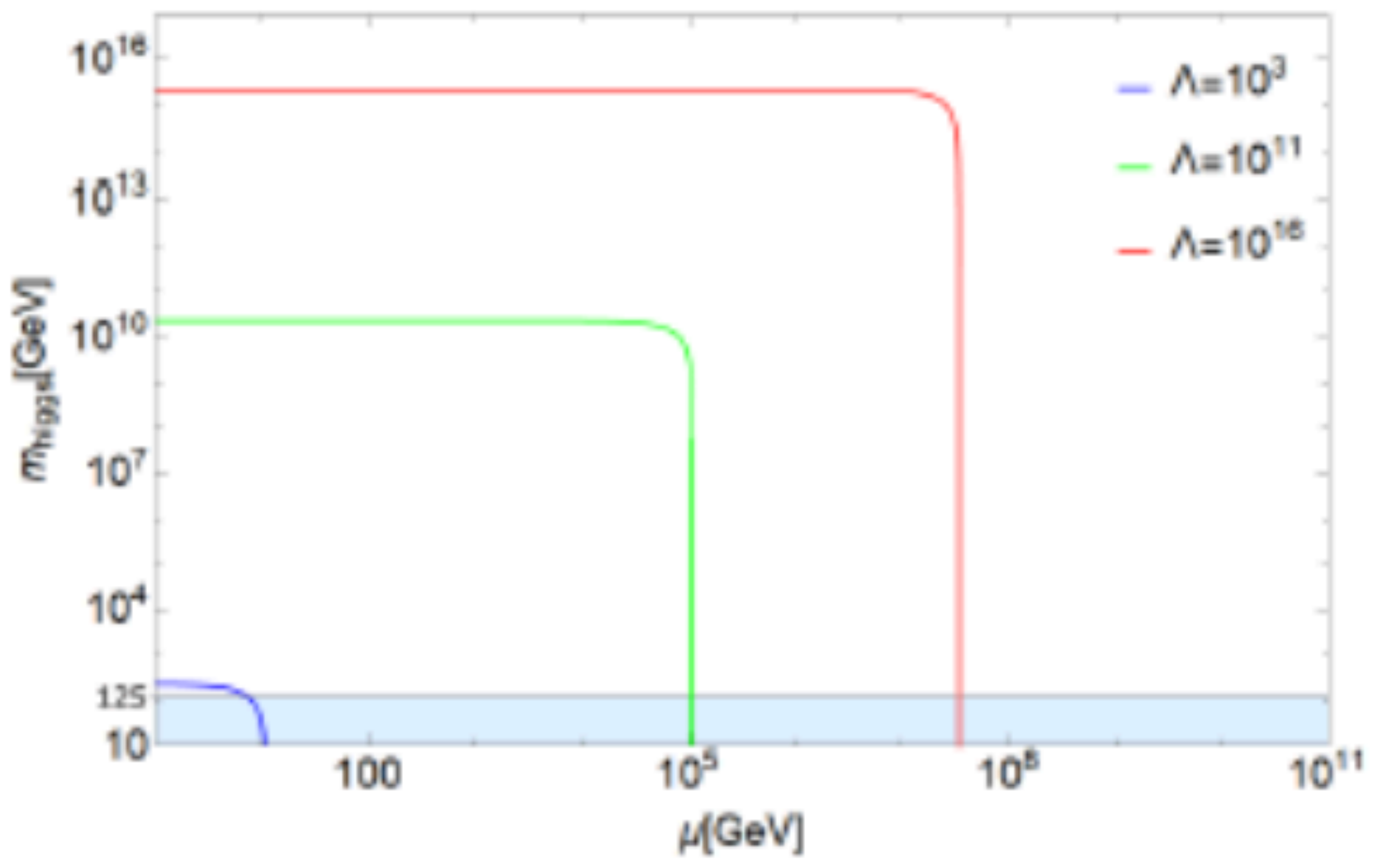


Figure 2: Value of $m_h(SM)$ versus SM μ parameter for theory cut-off values $\Lambda_{SM} = 10^3$, 10^{11} and 10^{16} GeV.

Hardly plausible that SM is valid much beyond the TeV scale

``...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

Is there a naturalness crisis (is SUSY excluded)?

- SM supersymmetrized (MSSM): all quadratic divergences cancel due to (super)symmetry

- log divergences remain [but log(big number) can be small number]

- naturalness can be used to place bounds on sparticle masses

e.g. EENZ/BG measure: apply to m(Z) $\Delta_{BG} \equiv max_i [c_i]$ where $c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$

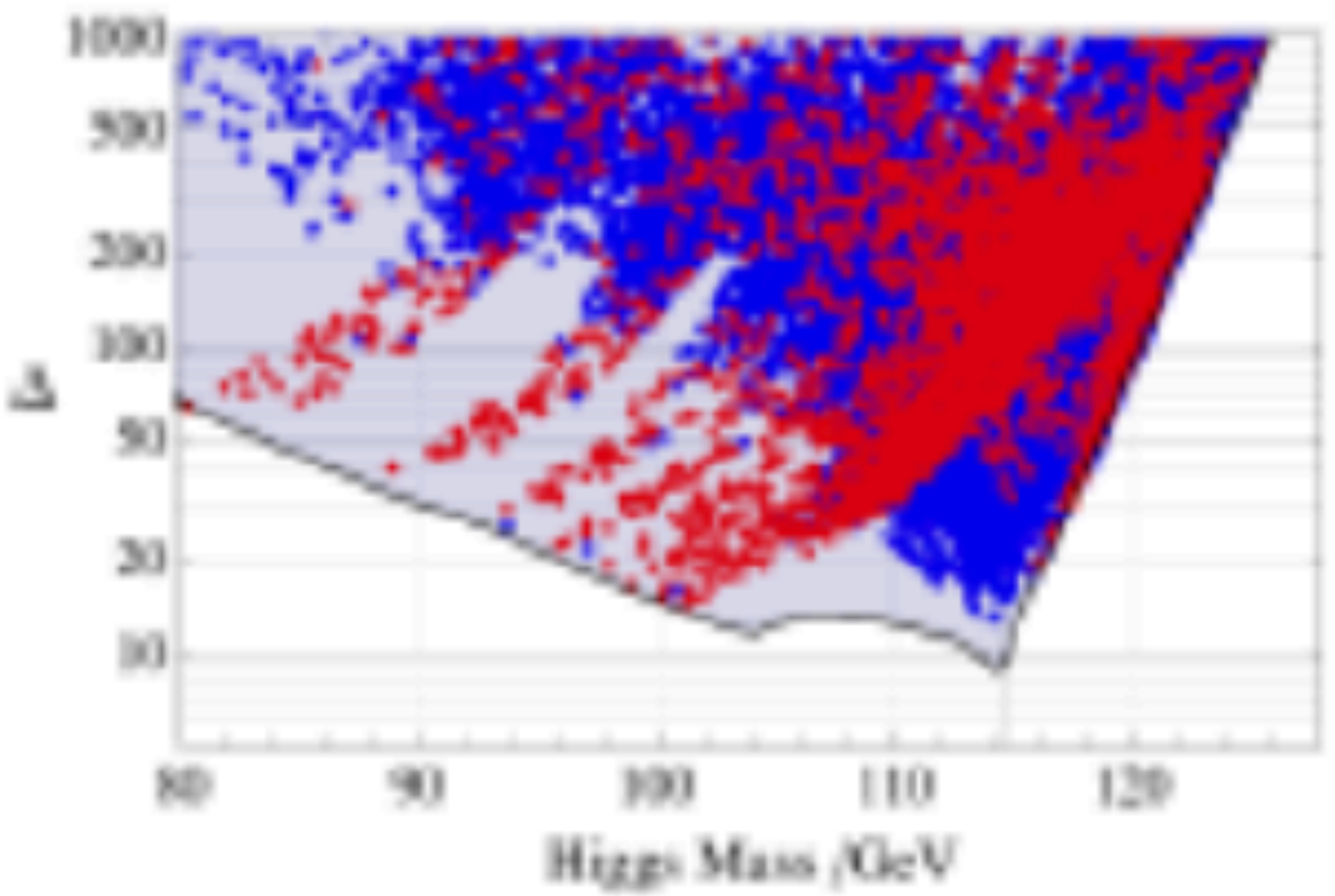
expand m(Z) in terms a high scale soft terms: DEL(BG) picks off RHS terms, compares to m(Z)^2

$$
\begin{aligned}
m_Z^2 = & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 \\
& + 0.047M_1M_3 - 0.42M_2^2 + 0.011M_2M_1 - 0.012M_1^2 \\
& - 0.65M_3A_t - 0.15M_2A_t - 0.025M_1A_t + 0.22A_t^2 \\
& + 0.004M_3A_b - 1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
& + .73m_{Q_3}^2 + .57m_{U_3}^2 + .049m_{D_3}^2 - .052m_{L_3}^2 + .053m_{E_3}^2 \\
& + .051m_{Q_2}^2 - .11m_{U_2}^2 + .051m_{D_2}^2 - .052m_{L_2}^2 + .053m_{E_2}^2 \\
& + .051m_{Q_1}^2 - .11m_{U_1}^2 + .051m_{D_1}^2 - .052m_{L_1}^2 + .053m_{E_1}^2 ,
\end{aligned}
$$

for tanb=10

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

Barbieri-Giudice 10% bounds, 1987



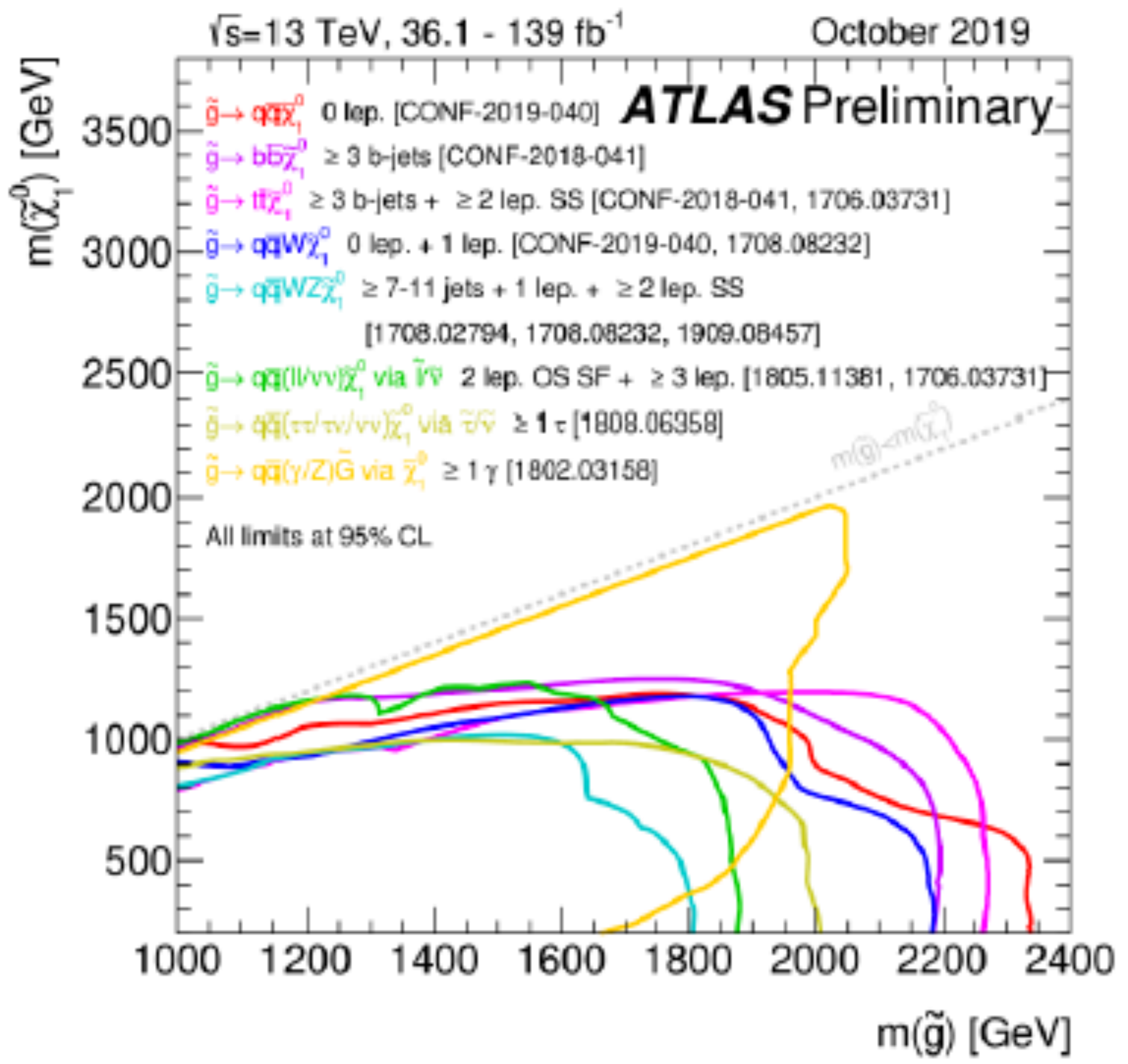
Cassel, Ghilencea, Ross,2009

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

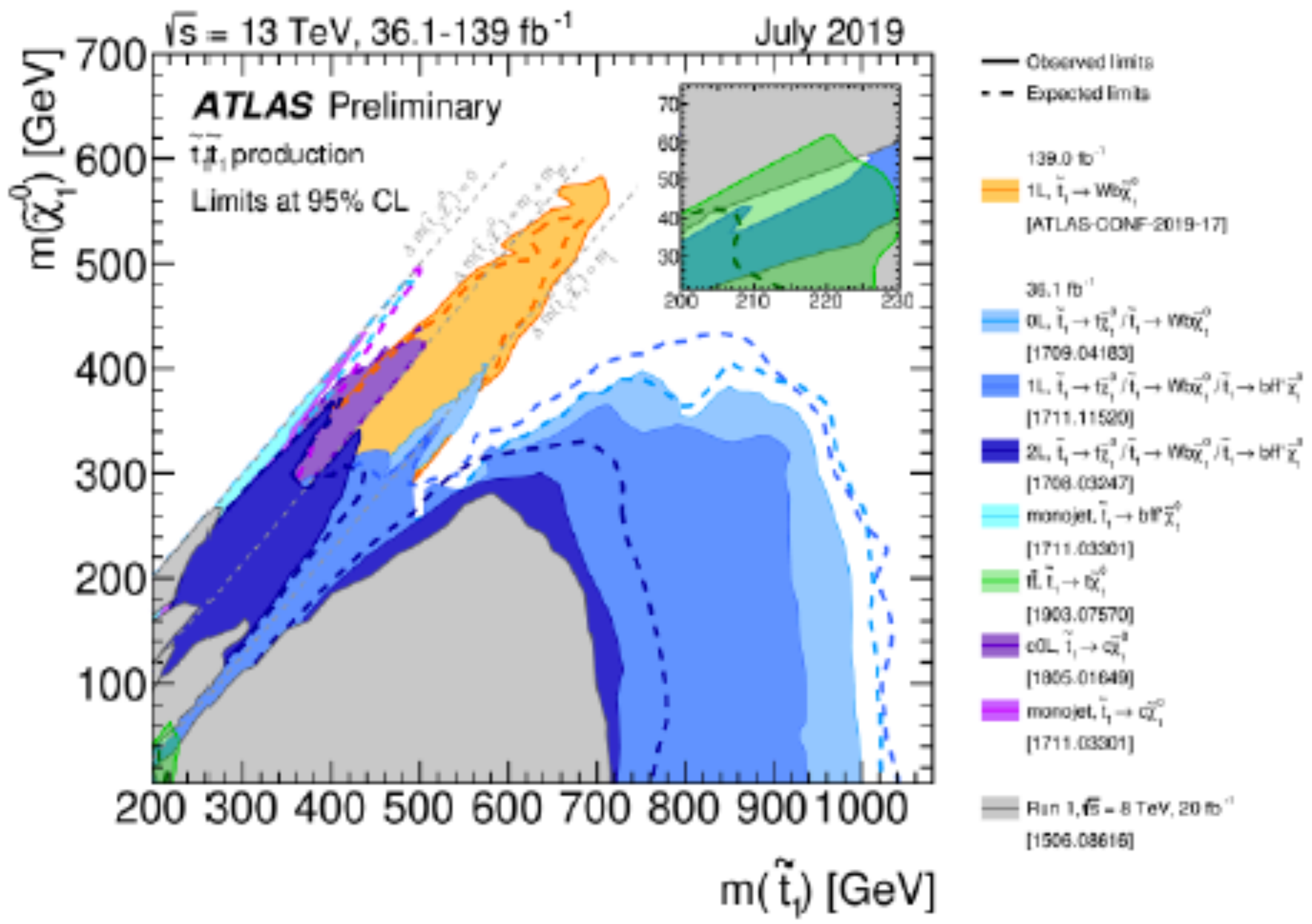
Compare to data

But where are the sparticles?

none seen so far at LHC



$m_{\tilde g} > 2.25$ TeV



$m_{\tilde t_1} > 1.1$ TeV

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

What could be wrong?

- parameters p_i introduced by hand to parametrize our ignorance of *correlations* which occur in more fundamental theory

- e.g Polonyi model of SUSY breaking: all soft terms calculable in terms of gravitino mass m32

$$\begin{aligned} m^2_{\phi_i} &= m^2_{3/2}, \\ A &= (3-\sqrt{3})m_{3/2}, \\ B &= A - m_{3/2} = (2-\sqrt{3})m_{3/2} \text{ while} \\ M &\sim m_{3/2} \end{aligned}$$

then major cancellations occur in m(Z)^2 expansion

what looked finetuned may in fact be natural

High scale (HS, stop mass) measure

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

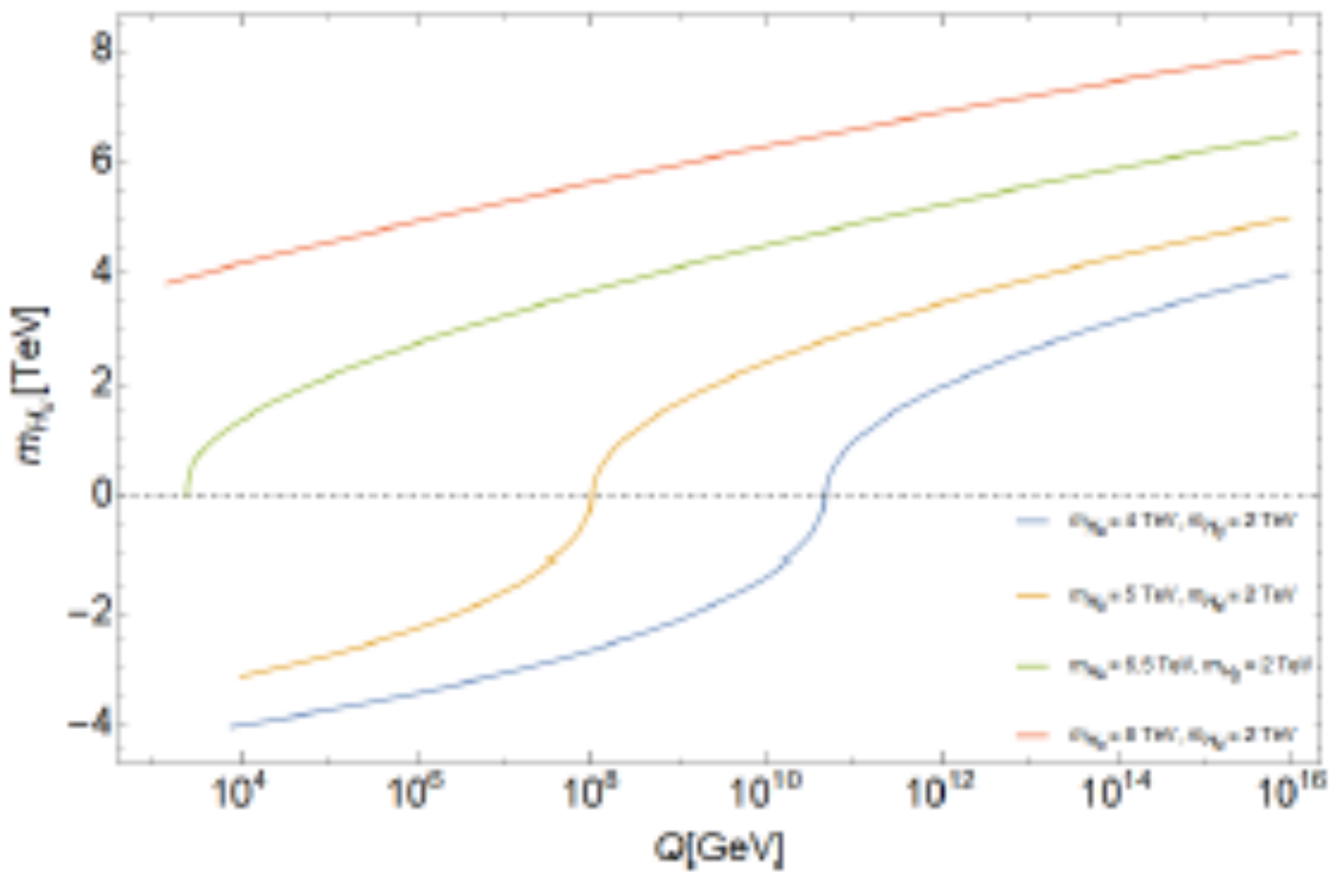
$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/m_{SUSY}^2\right)$$

Implies 3 3rd generation squarks <500 GeV:
SUSY ruled out under Δ_{HS}

BUT! too many terms ignored! NOT VALID!

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

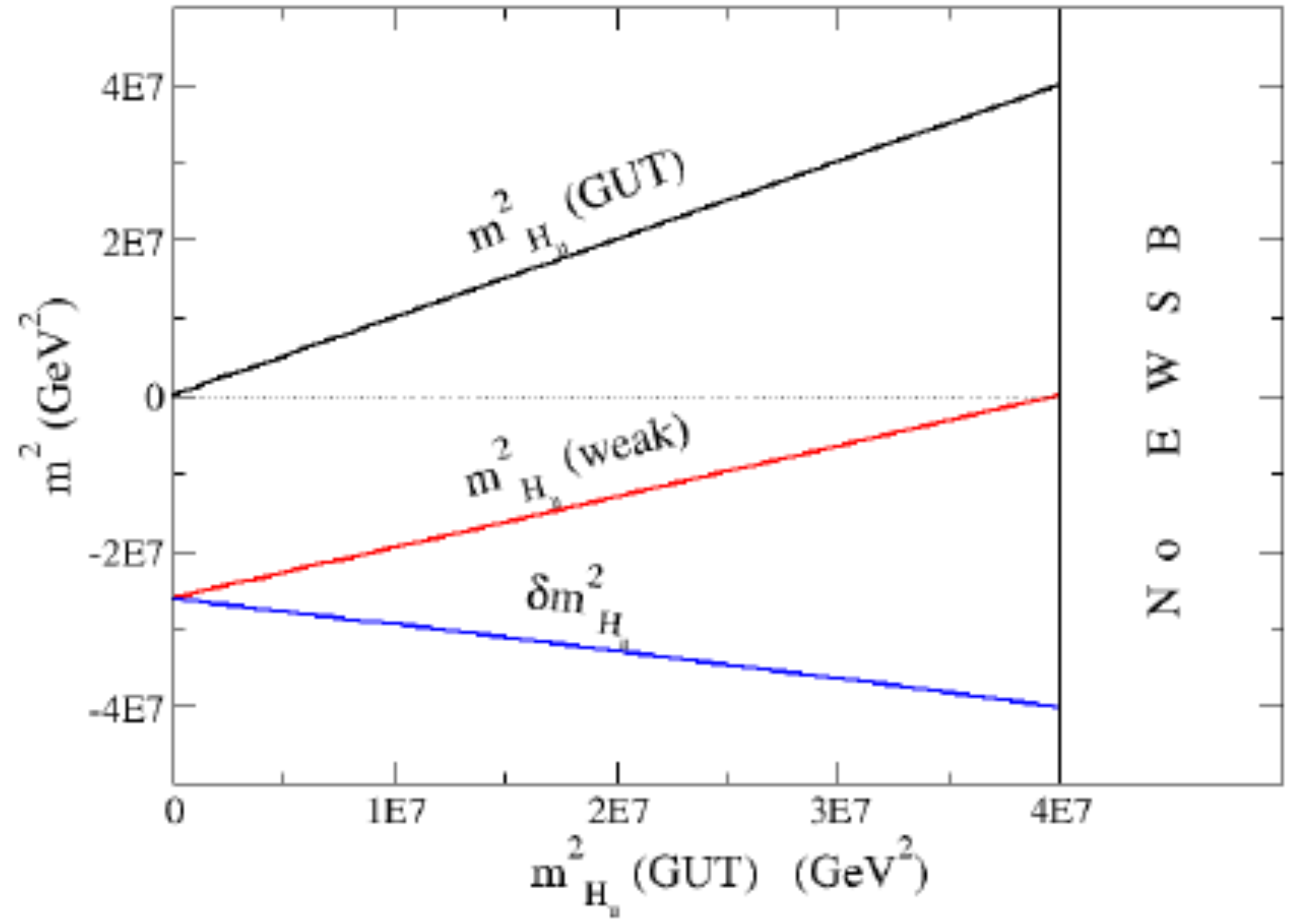
where $t = \ln(Q^2/Q_0^2)$, $S = m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$ and $X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$. By neglecting gauge terms and S ($S = 0$



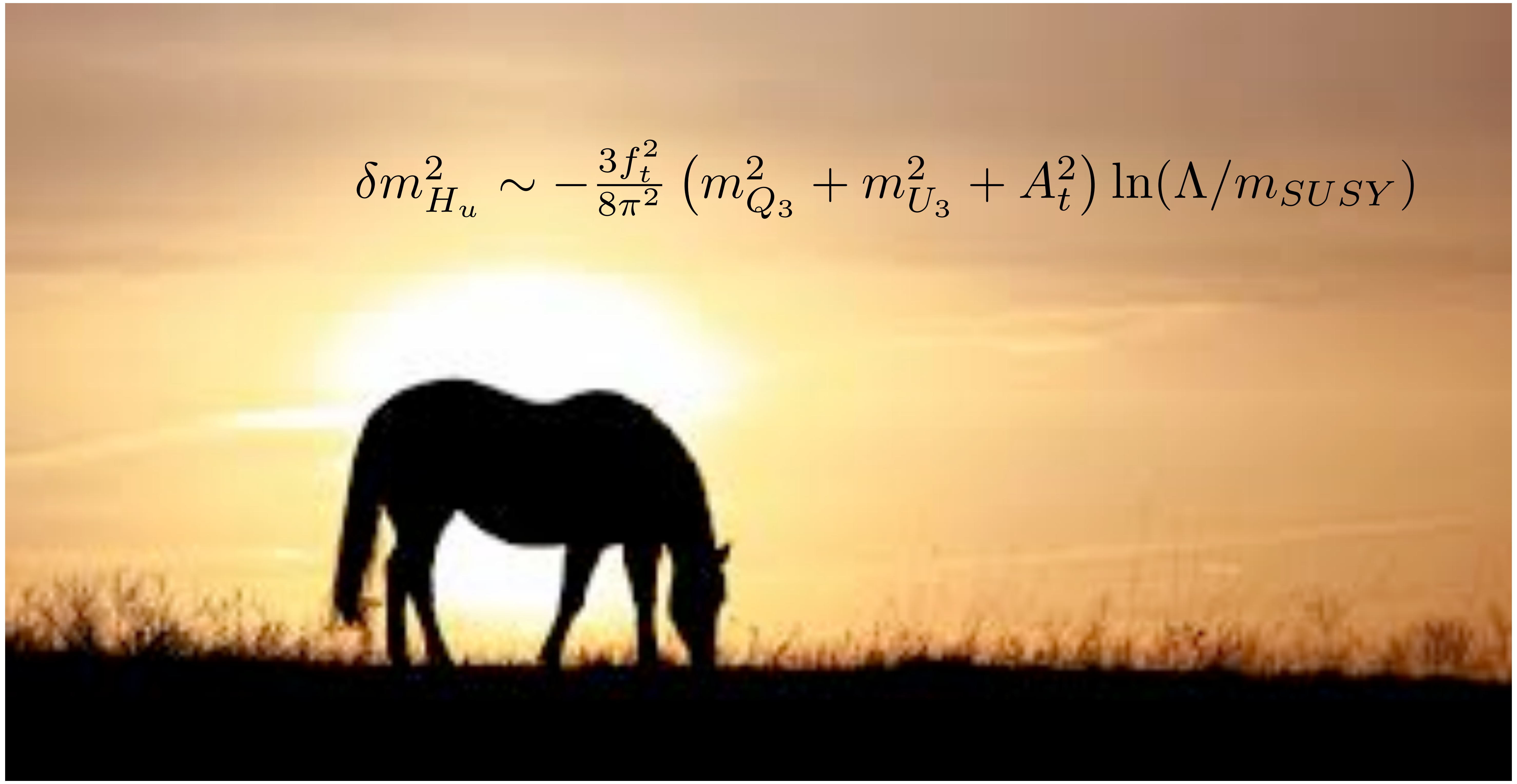
The bigger $m_{H_u}^2(\Lambda)$ is, the bigger is the cancelling correction- these terms are *not independent*.

For big enough $m_{H_u}^2(\Lambda)$, then $m_{H_u}^2$ driven to natural value at weak scale: *radiatively driven naturalness (RNS)*

HB, Barger, Mickelson, Padeffke, Savoy



Recommendation: put this horse out to pasture



R.I.P.

sub-TeV 3rd generation squarks not required for naturalness

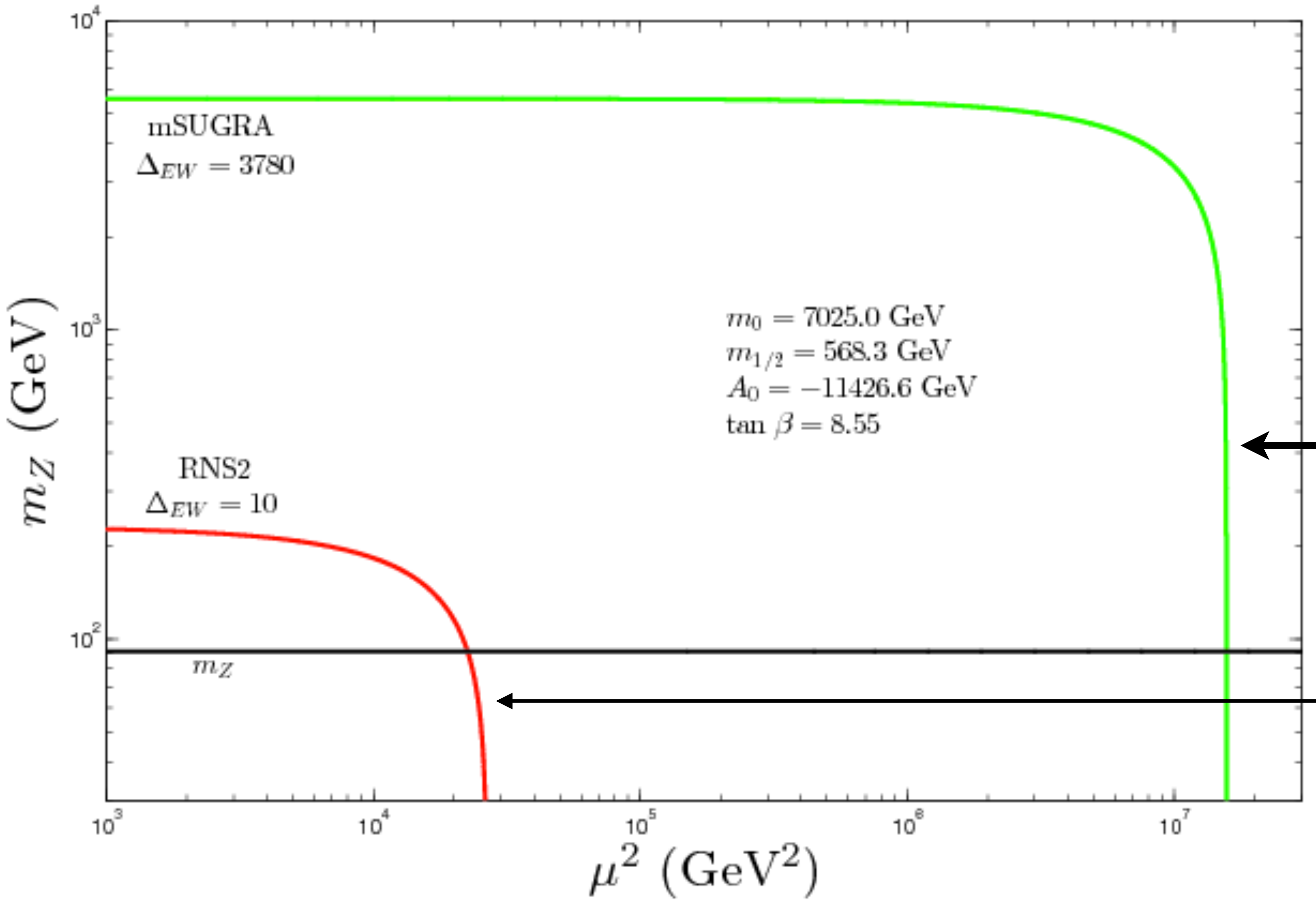
Next: simple electroweak fine-tuning in SUSY: minimize Higgs potential in MSSM to relate magnitude of weak scale m(Z) to SUSY Lagrangian; dial value of mu so that Z mass comes out right:
everybody does it but it is hidden inside spectra codes

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

SUSY breaking Higgs mass

>40 loop corrections

SUSY preserving mu parameter



finetuning required

natural solution

Simplest, most conservative SUSY measure: Δ_{EW}

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
- $m_{H_u}^2$ 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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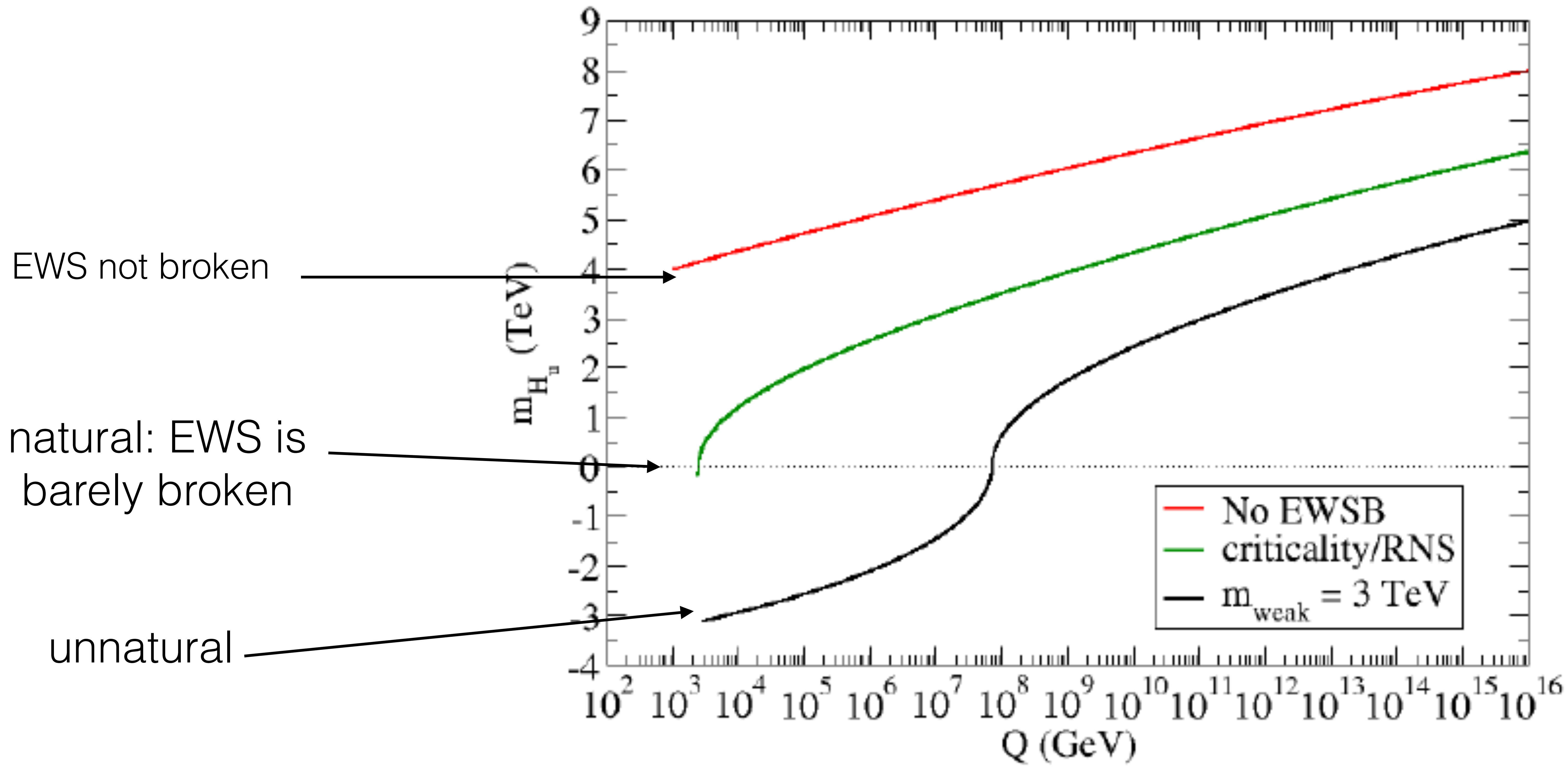
PRL109 (2012) 161802

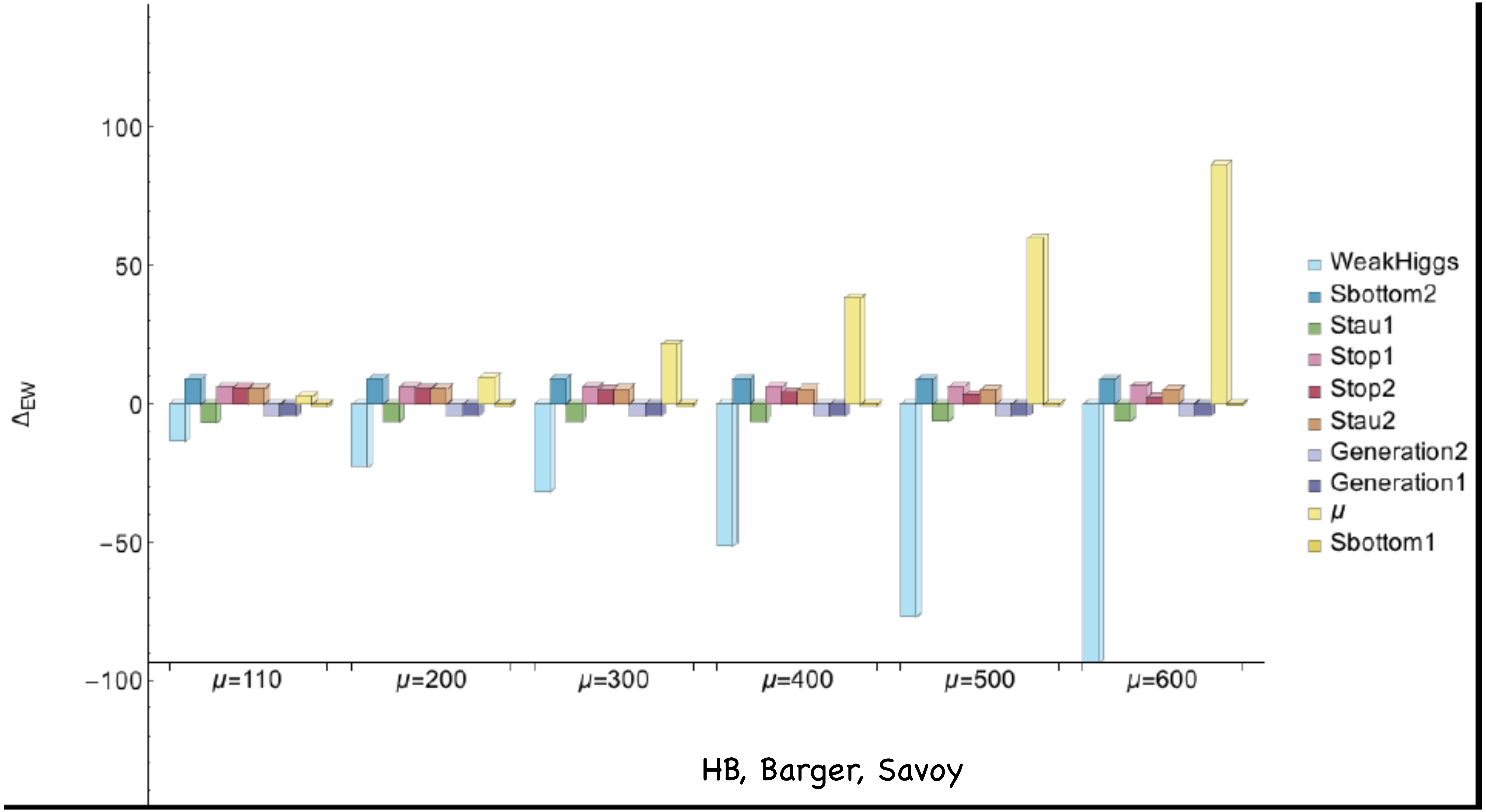
radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness



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

(We will see soon how the green curve is statistically favored by string landscape)

How much is too much fine-tuning?



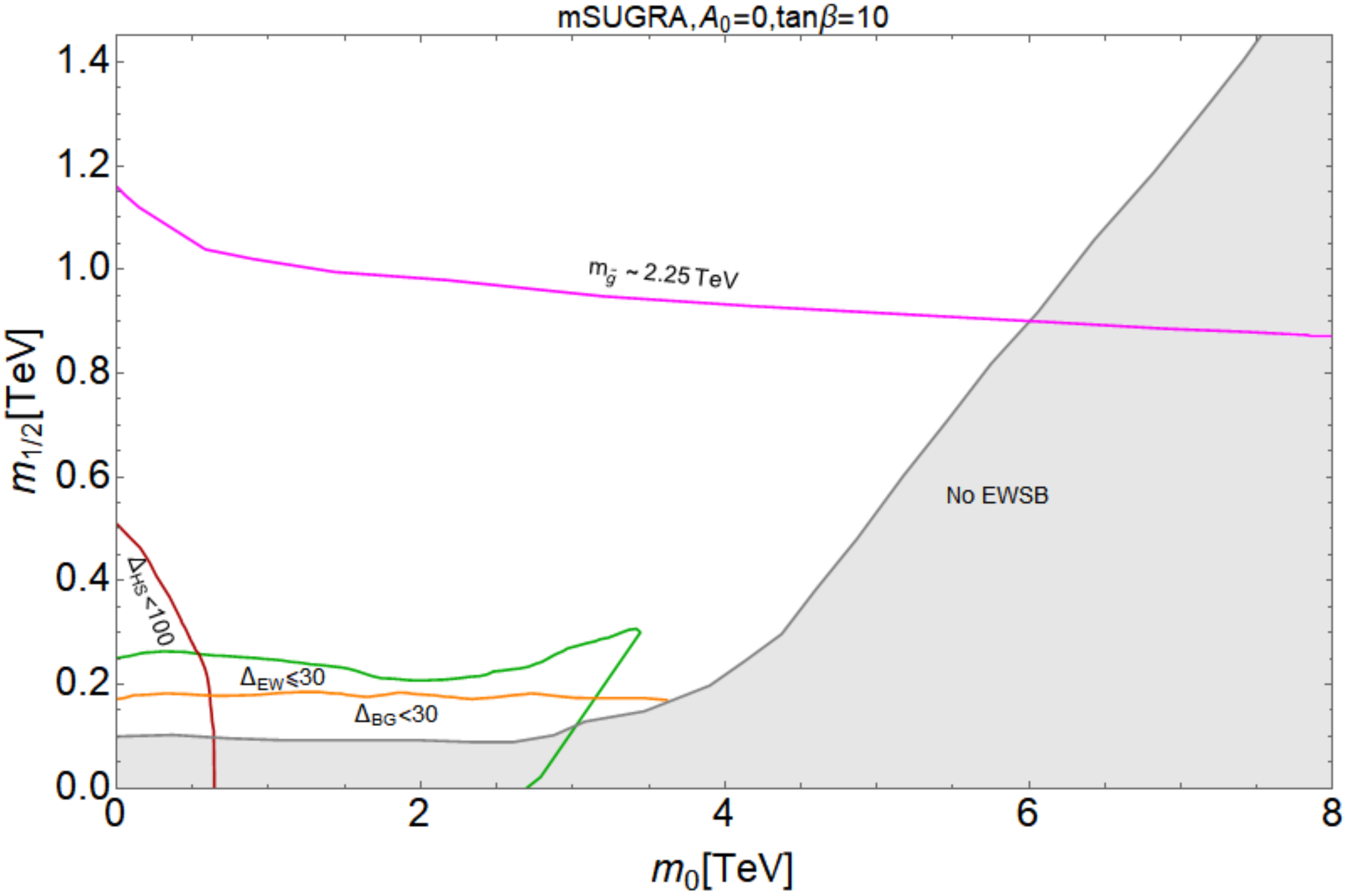
HB, Barger, Savoy

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

bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	350 GeV
gluino	400-600 GeV	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!

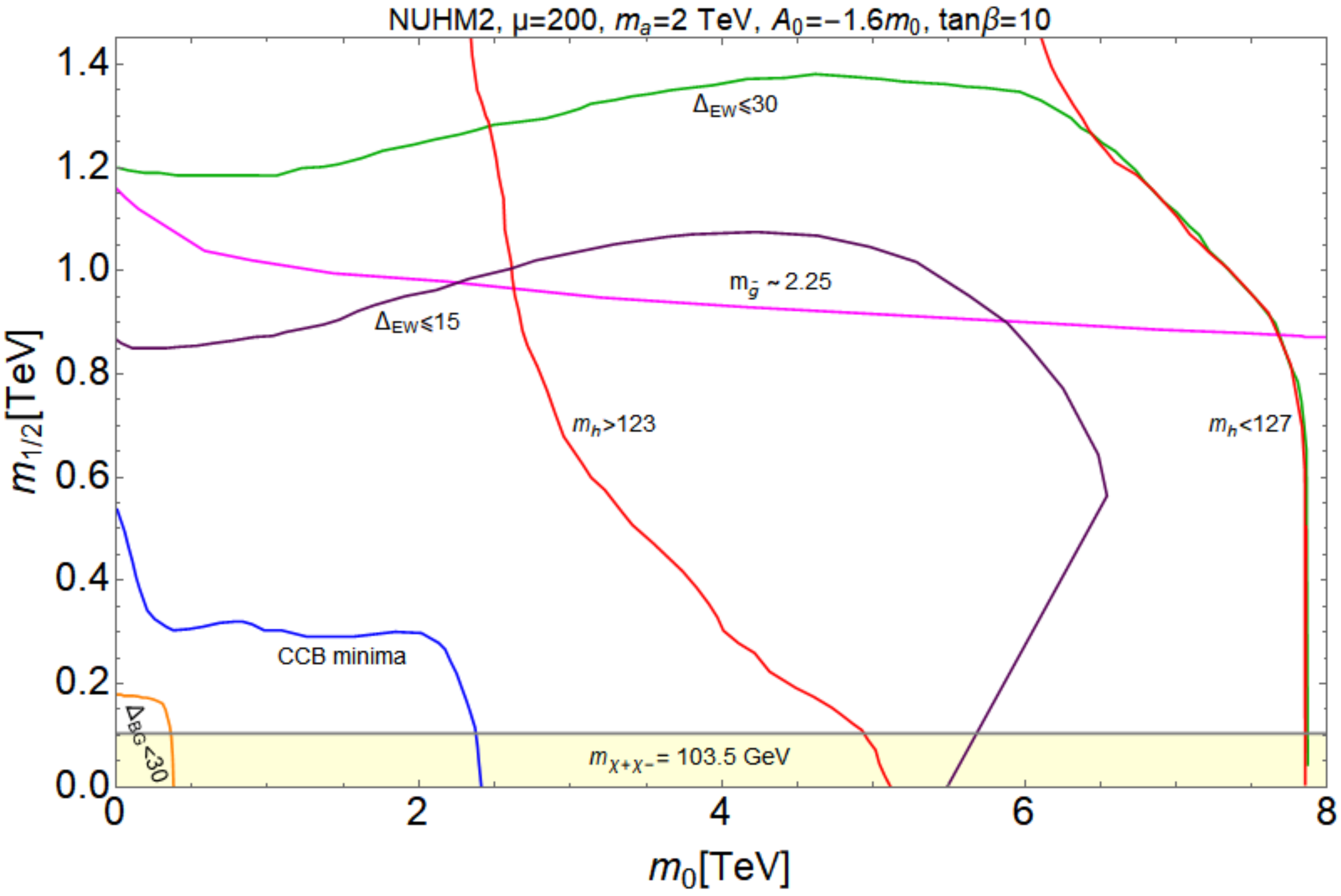
allowed p-space by all three measures in CMSSM:



Is SUSY a failed enterprise (as is often claimed in popular press)?

NUHM2: non-universality of Higgs soft terms
always allows low mu for mHu~1.3 m0

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A$



HB, Barger, Salam

Model independence of Delta(EW)

- A final advantage of Δ_{EW} is that for a given SUSY mass spectrum, the value of Δ_{EW} is independent of how the spectra is generated: whether it is generated from GUT scale parameters or in the pMSSM or any intermediate scale.

- This is not true for Δ_{BG} which wildly fluctuates depending on scale and in fact $\Delta_{BG} \to \Delta_{EW}$ for the pMSSM

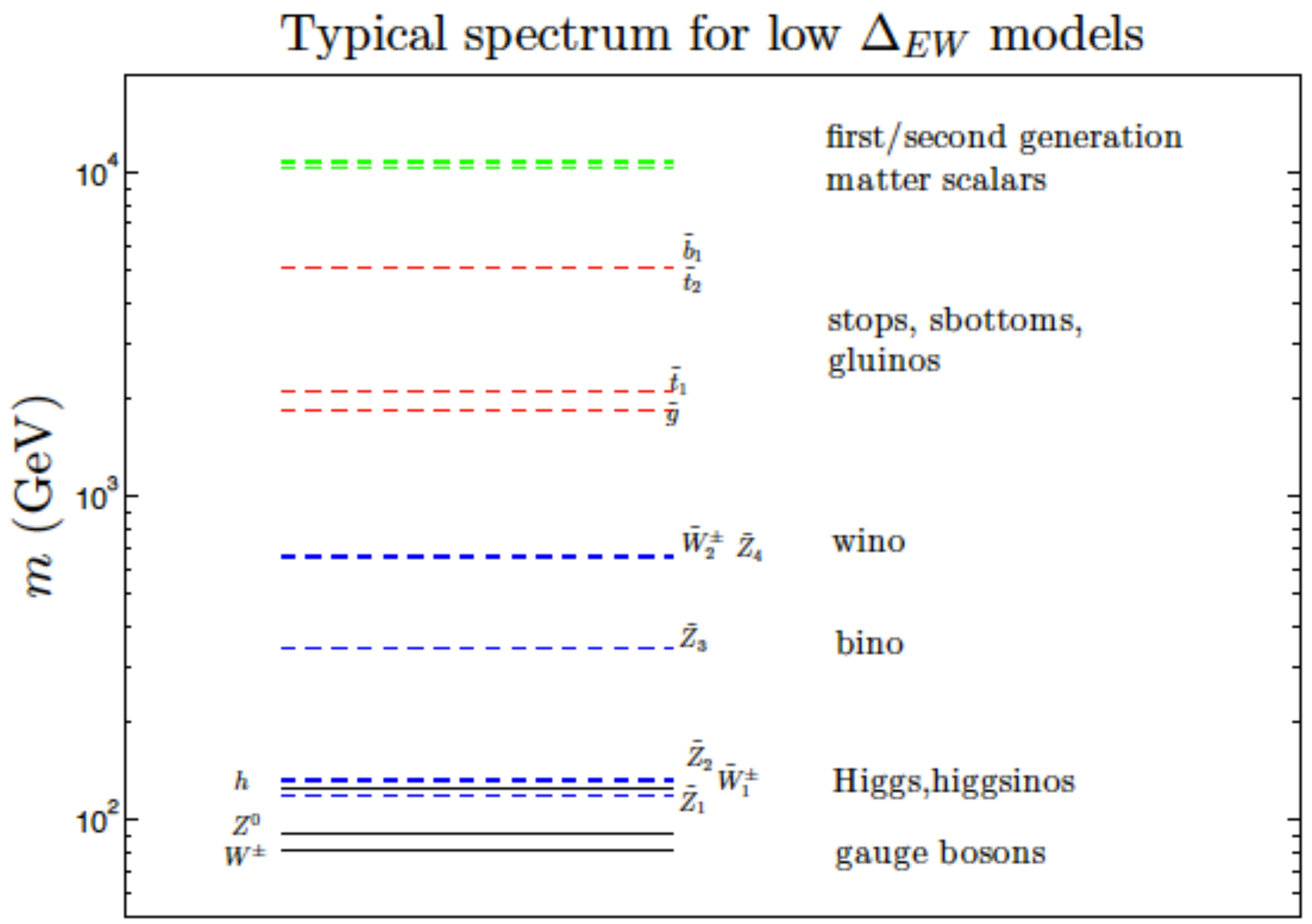
- For Δ_{HS}, log term $\to\sim 30$ at $\Lambda = m_{GUT}$ but log $\to 0$ for $\Lambda \sim m_{weak}$

  so DHS->0 for pMSSM

For Snowmass 2021: have developed publicly available code DEW4SLHA which calculates DEW from any SUSY Les Houches Accord file-
can use your favorite spectra generator code or even pMSSM

HB, Barger, Dakotah Martinez, arXiv:2111.03096

to download, see dew4slha.com

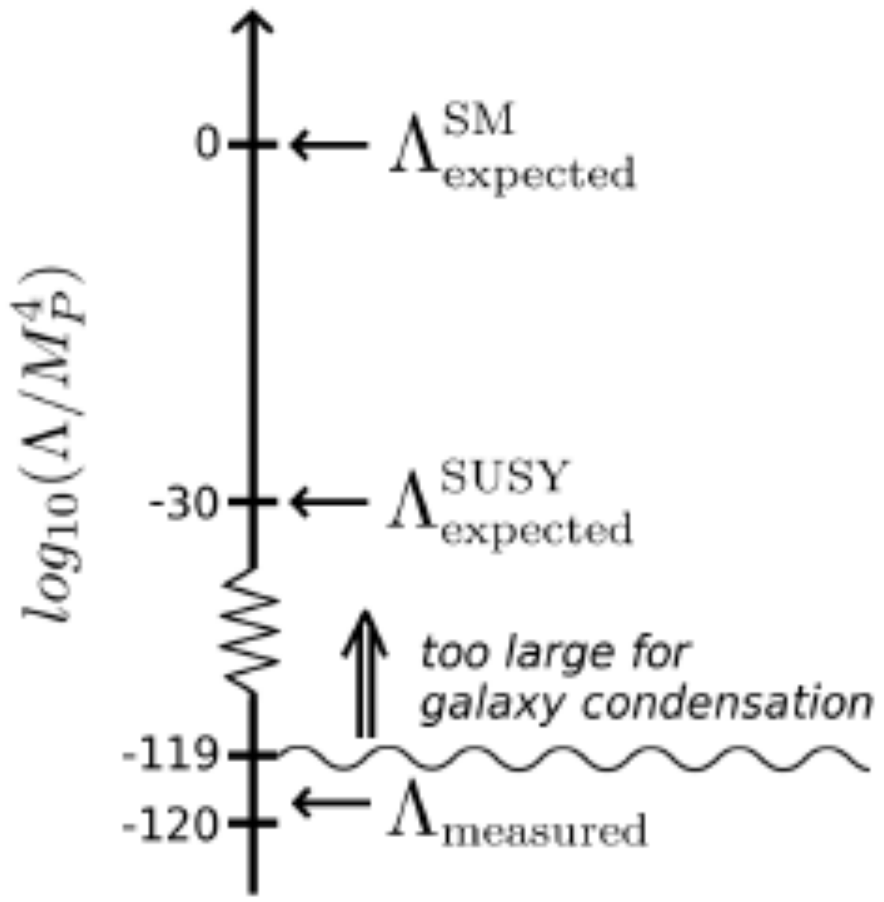


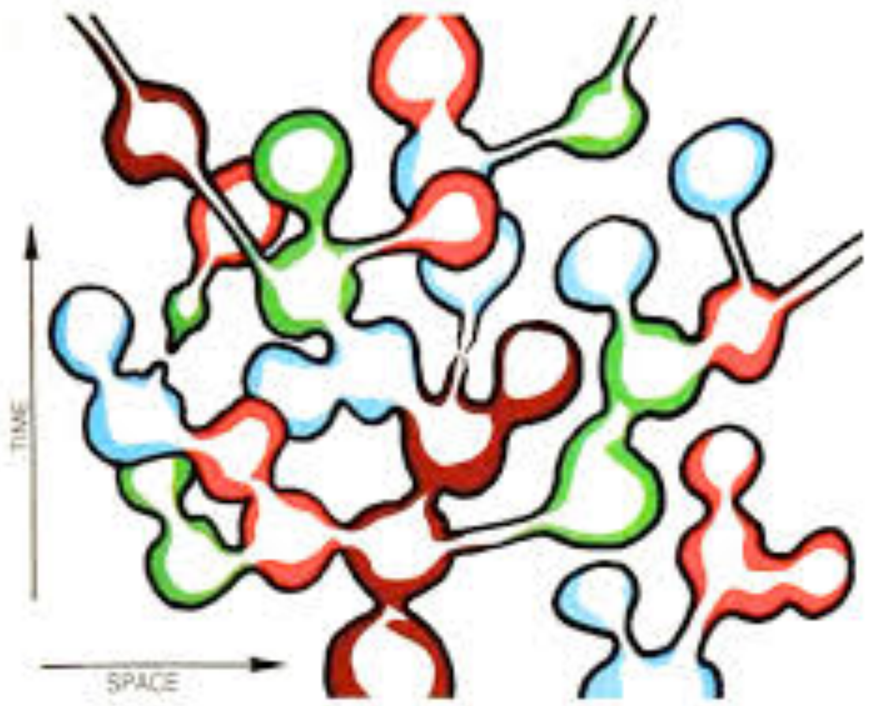
There is a Little Hierarchy, but it is no problem

$\mu \ll m_{3/2}$ higgsinos likely the lightest superparticles!

How does this all relate to string landscape?

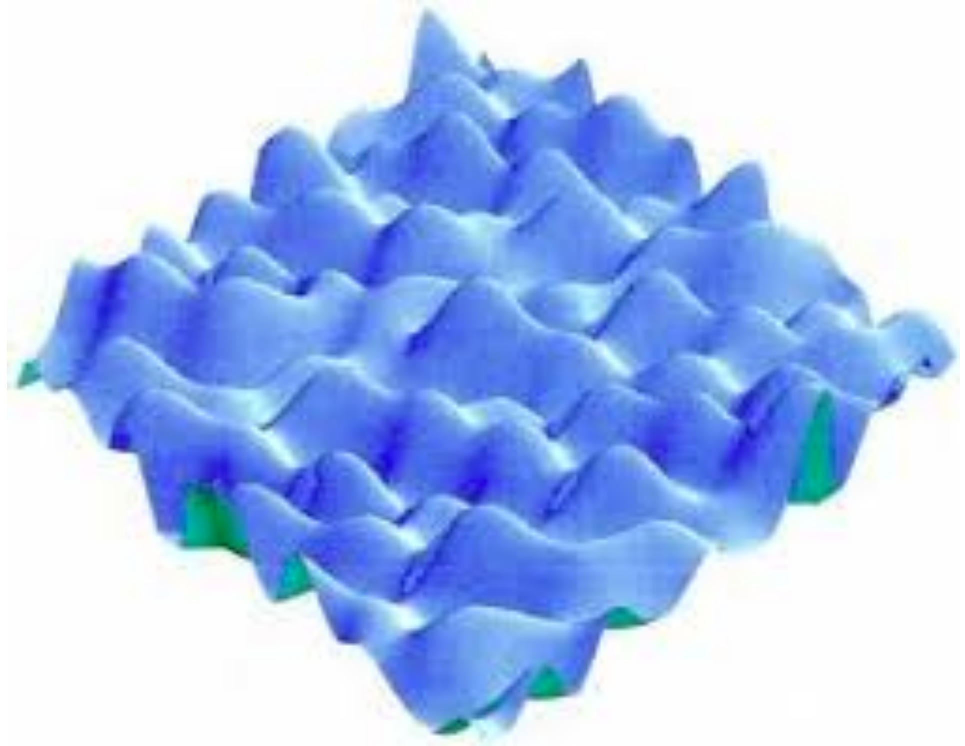
It is sometimes invoked that maybe we should abandon naturalness:
after all, isn't the cosmological constant (CC) fine-tuned?





eternally inflating
multiverse

In the landscape with 10^500 vacua with different CCs,
then the tiny value of the CC may not be surprising since
larger values would lead to runaway pocket universes
where galaxies wouldn't condense-
anthropics: no observers in such universes (Weinberg)



Bousso &
Polchinski

The CC is as natural as possible subject to the condition
that it leads to galaxy condensation

For some recent review material, see M. Douglas,
The String Theory Landscape, 2018, Universe 5 (2019) 7, 176

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
- no preferred value for Fx (distributed as complex number) or Da (distributed as real number)

In fertile patch of vacua with MSSM as weak scale effective theory but with no preferred SUSY breaking scale...

$$dP/d\mathcal{O} \sim f_{prior} \cdot f_{selection}$$

What is f(prior) for SUSY breaking scale?

In string theory, usually multiple (~10) hidden sectors containing a variety of F- and D- breaking fields

For comparable <Fi> and <Dj> values, then expect

$$f_{prior} \sim m_{soft}^{2n_F+n_D-1}$$

Douglas ansatz

arXiv:0405279

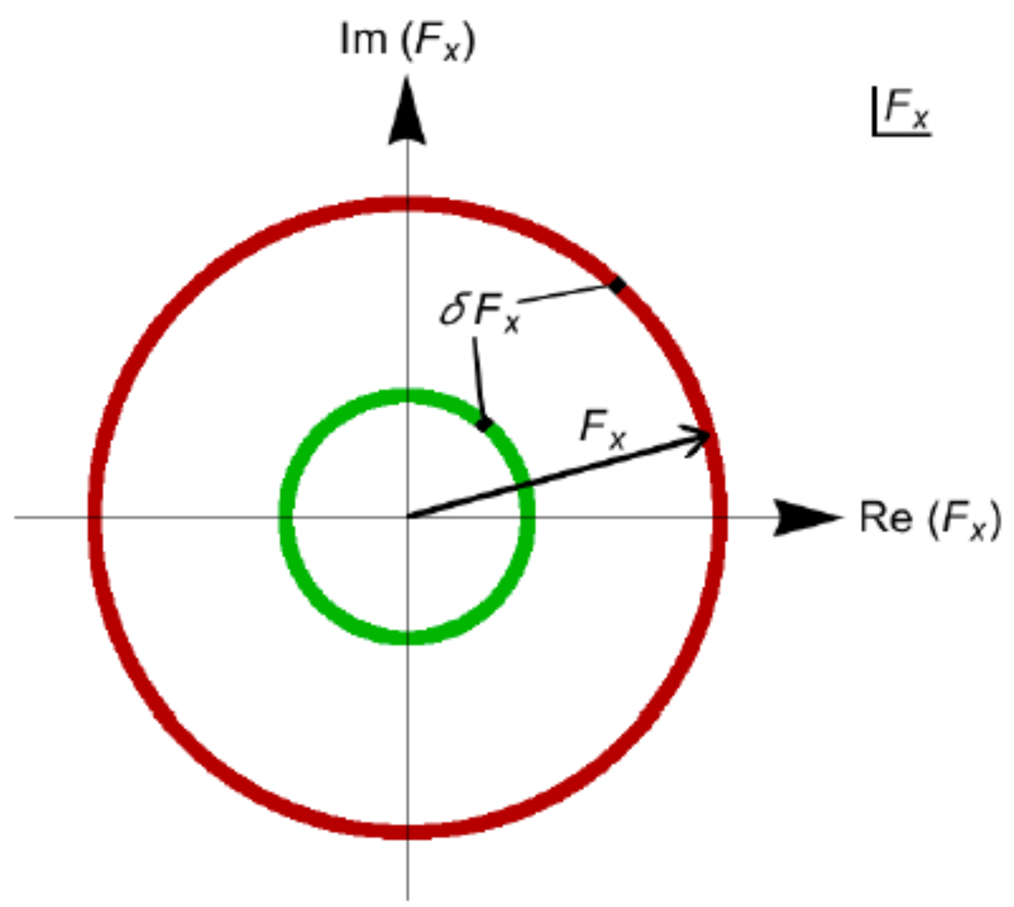


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

Under single F-term SUSY breaking, expect linearly increasing statistical selection of soft terms

For uniform values of SUSY breaking moduli, expect landscape to prefer high scale of SUSY breaking!

What about f(selection)?

Originally, people adopted $f_{EWFT} \sim m_{weak}^2/m_{soft}^2$

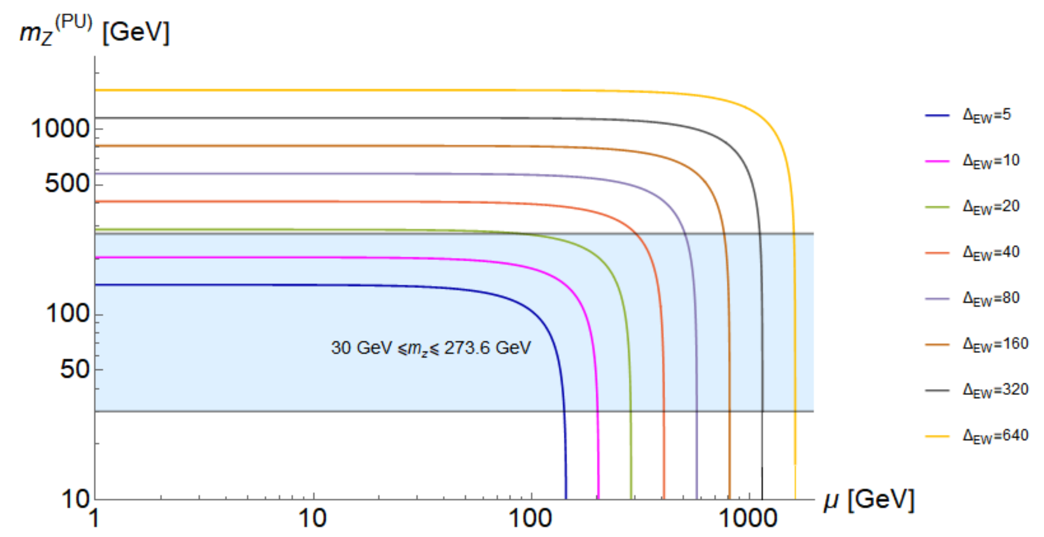
to penalize soft terms straying too far from weak scale

This doesn't work for variety of cases

- Too big soft terms can lead to CCB minima: must veto such vacua
- Bigger m(Hu)^2 leads to more natural value at weak scale
- Bigger A(t) trilinear suppresses t1, t2 contribution to weak scale

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

Adopt mu value so no longer available for tuning; then mZ(PU).ne.91.2 GeV



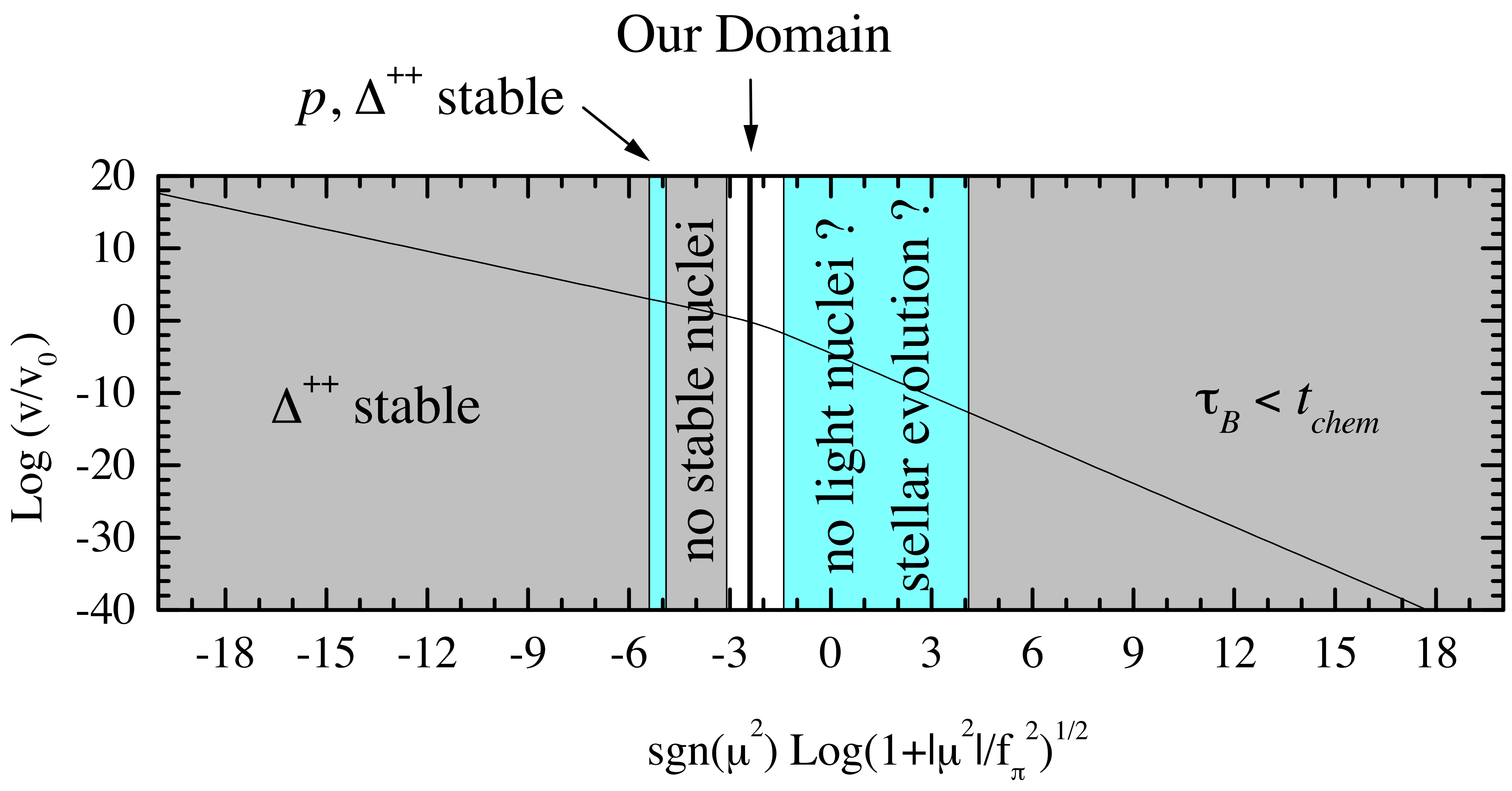
Then for statistically selected soft terms, m(weak) is output, not input

Must veto too large m(weak) values: nuclear physics screw up: no complex atoms
(Agrawal, Barr, Donoghue, Seckel, 1998)

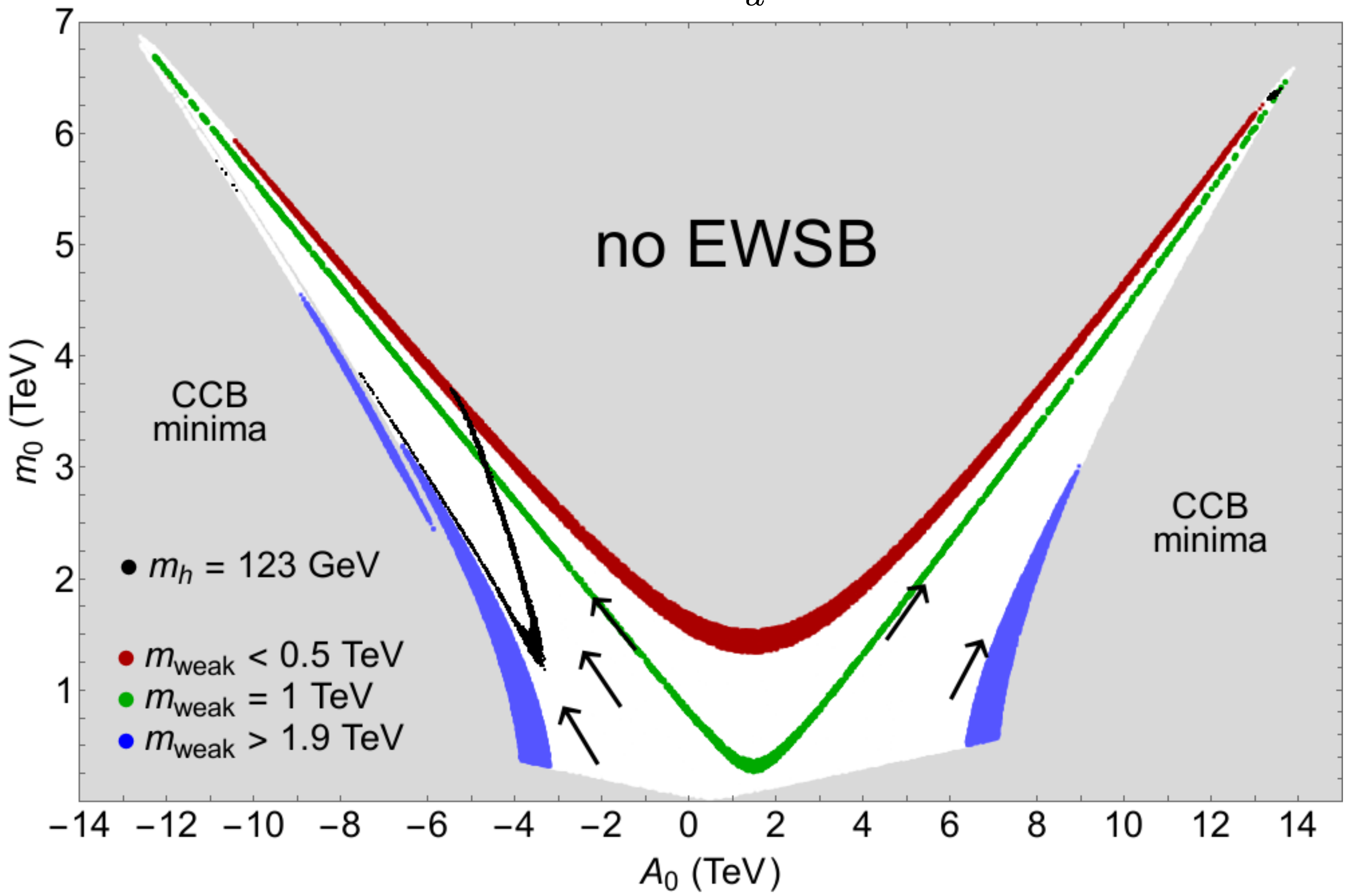
Factor four deviation of weak scale from measured value => $\Delta_{EW} < 30$

Agrawal, Barr, Donoghue, Seckel result (1998):

pocket-universe value of weak scale
cannot deviate by more than
factor 2-5 from its measured value
lest disasters occur in nuclear physics: no nuclei, no atoms
(violates atomic principle)



$$m_{H_u} = 1.3 m_0$$



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!

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

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,

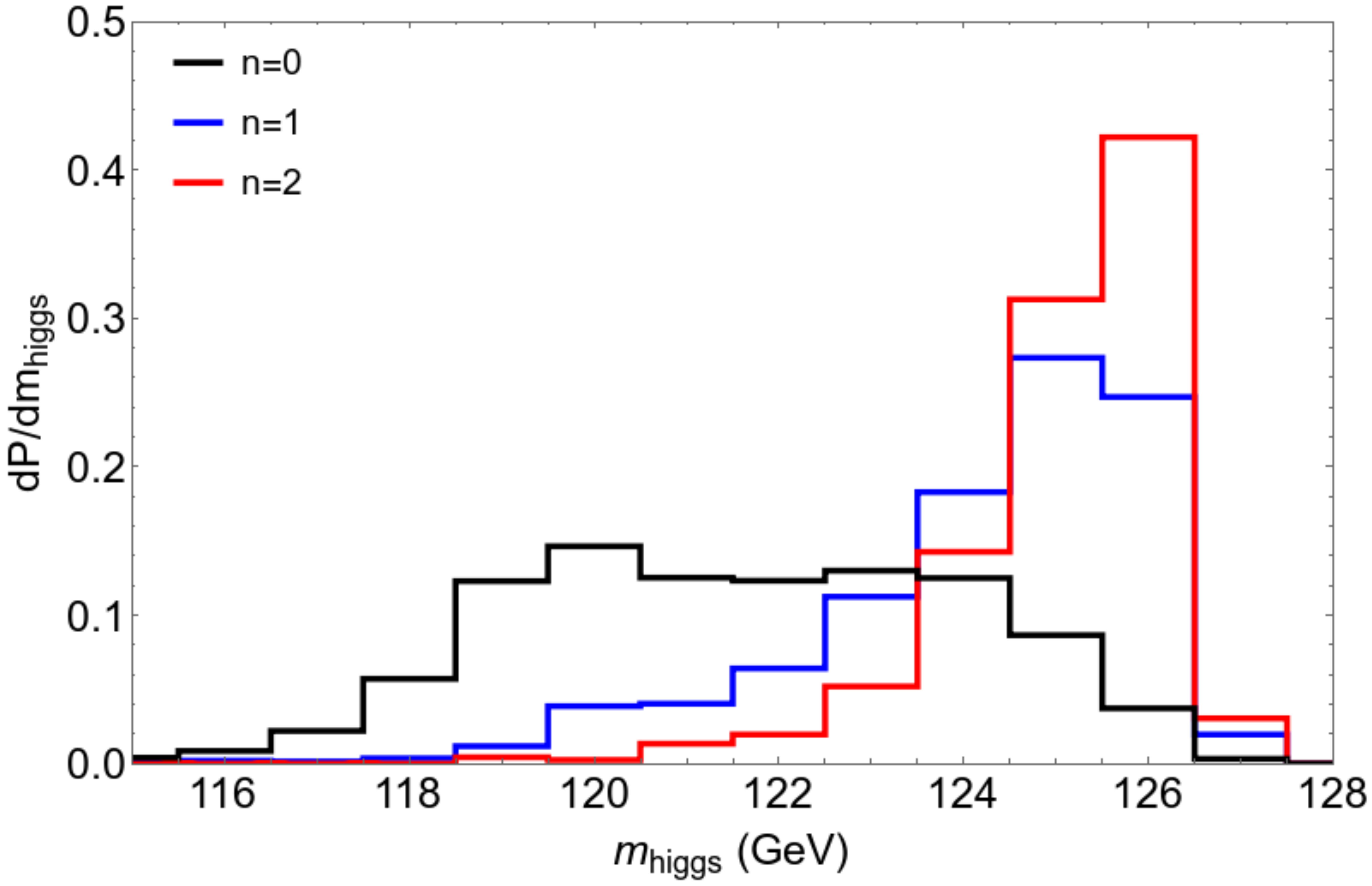
$\tan\beta$: 3 – 60 (flat)

mu=150 GeV (fixed)

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

Making the picture more quantitative:

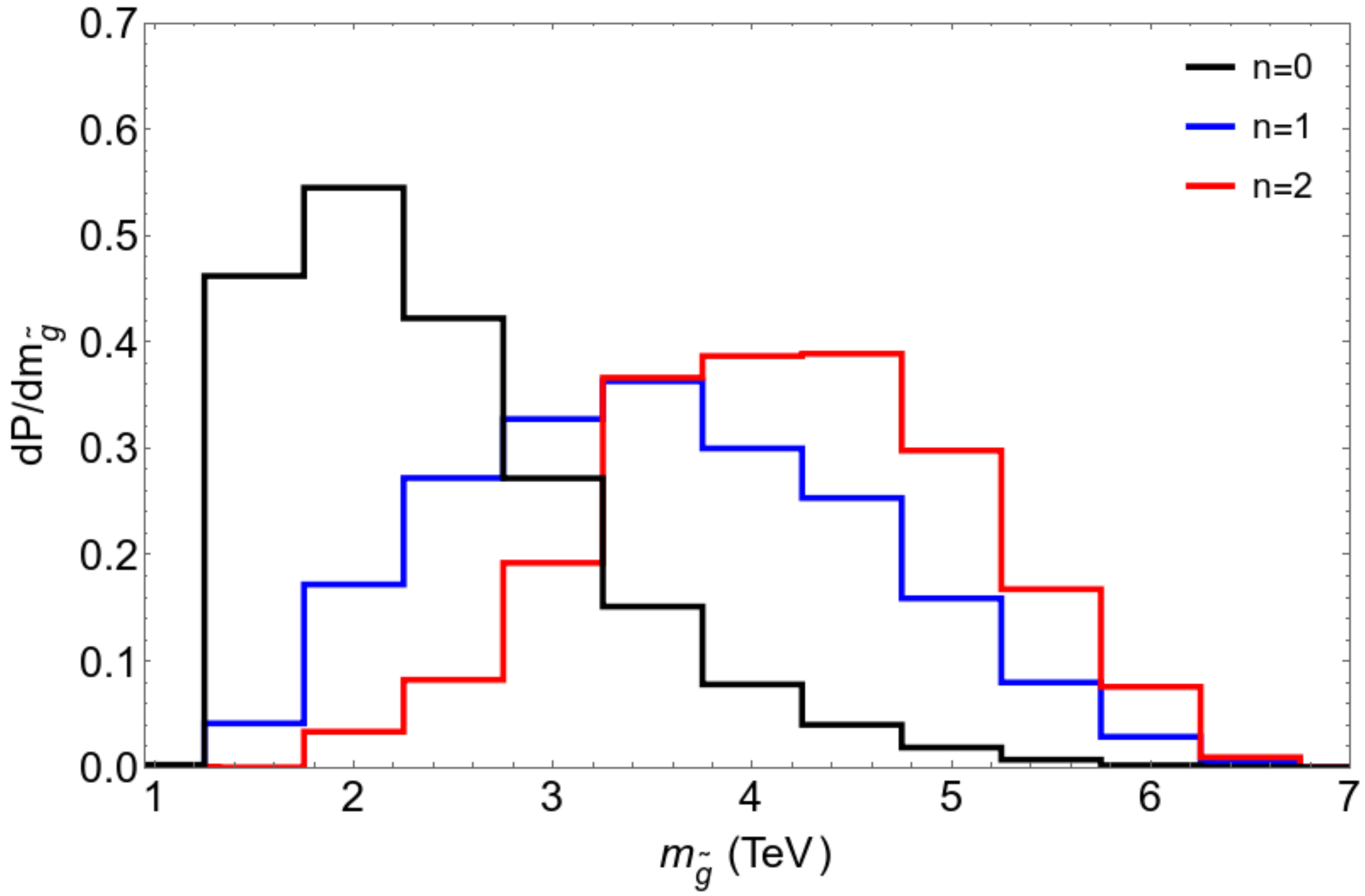
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



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

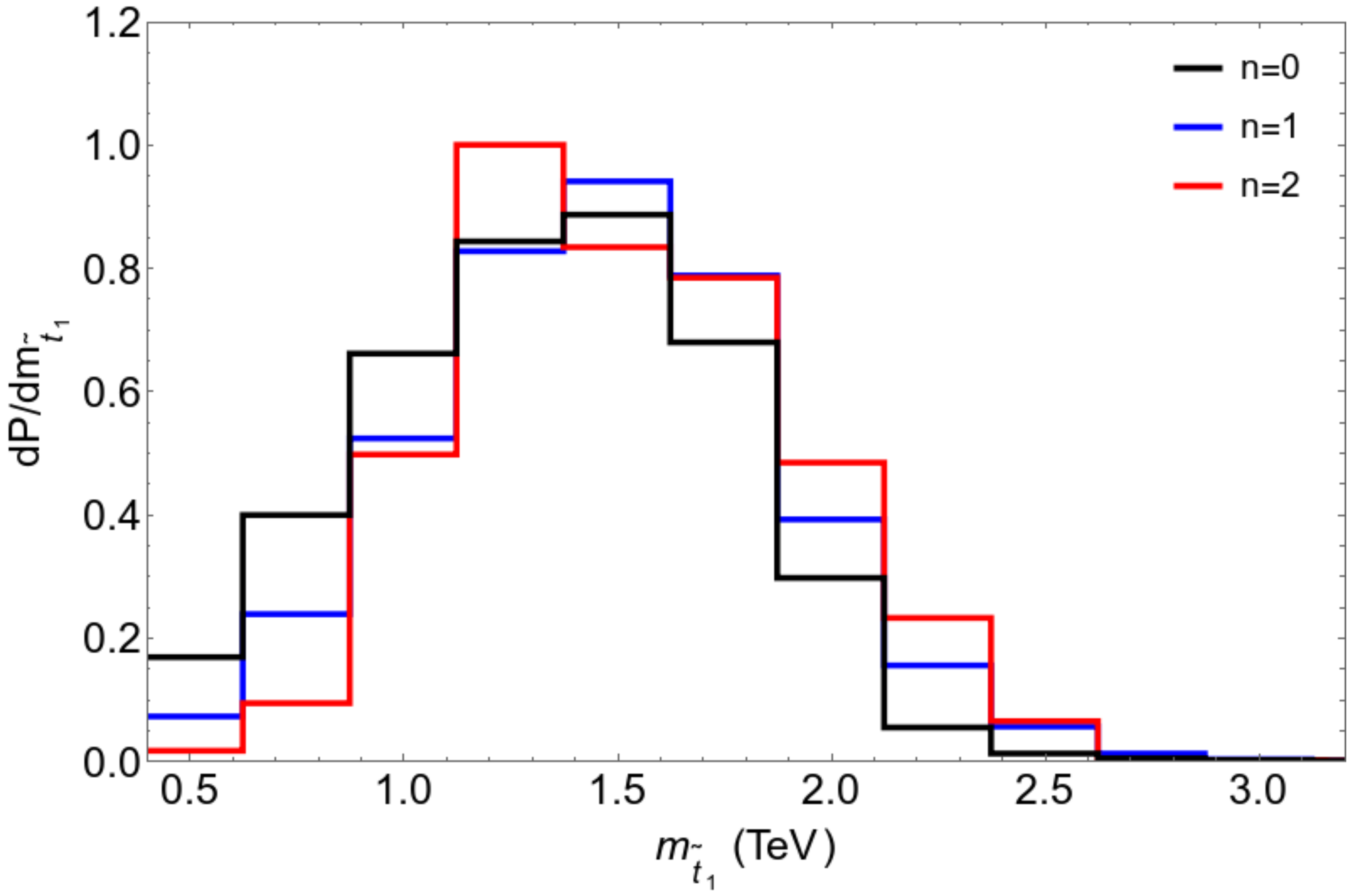
HB,Barger, Serce, Sinha

What is corresponding distribution for gluino mass?



gluino typically beyond LHC 14 reach
(need higher energy hadron collider)

and top-squark mass m(t1)?



m(t1) typically beyond present LHC reach

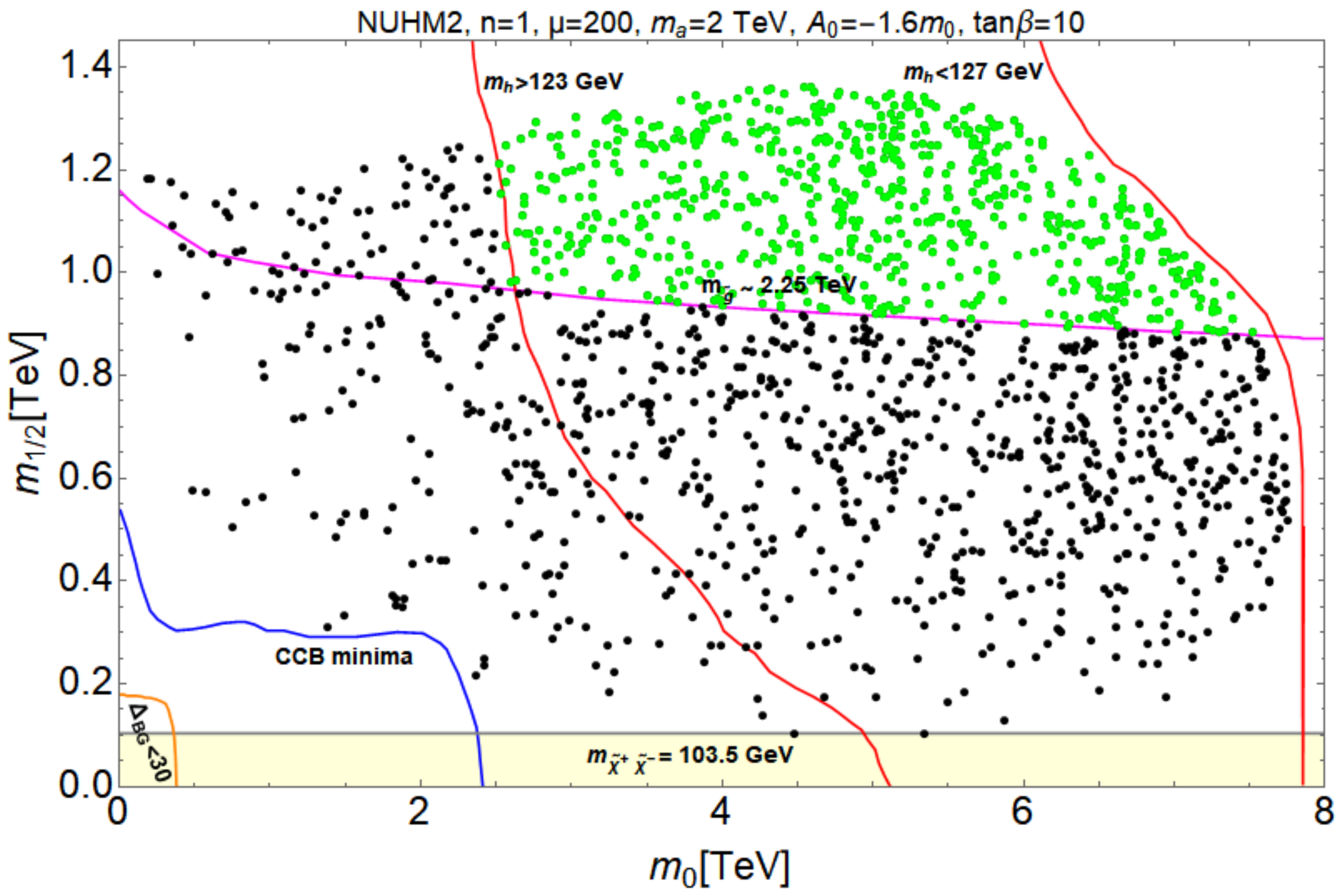
Stringy naturalness: higher density of points are more stringy natural!

conventional natural: favor low m0, mhf

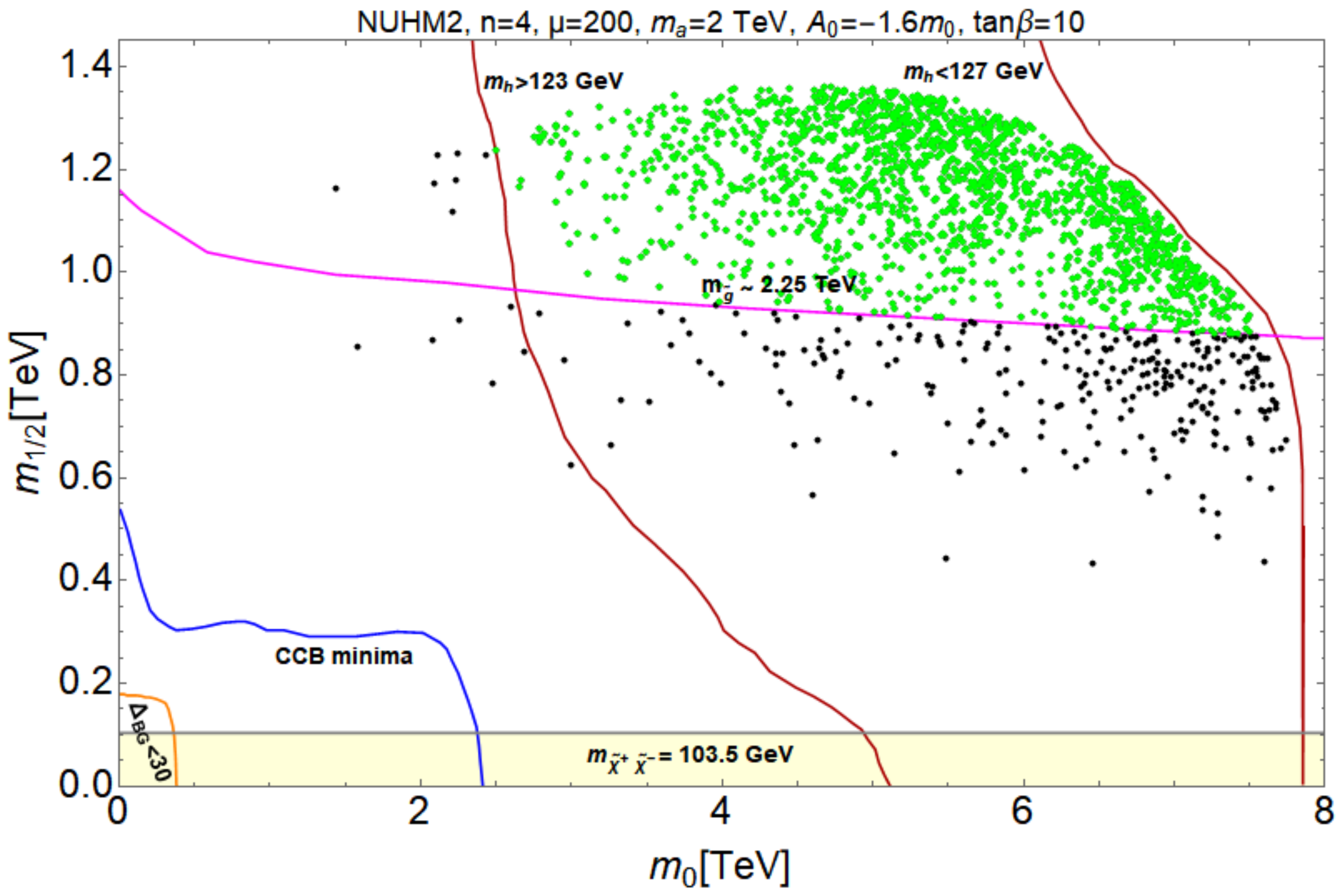
stringy naturalness: favor high m0, mhf so long as m(weak)~100 GeV

HB, Barger, Salam, arXiv:1906.07741

Living dangerously: Arkani-Hamed, Dimopoulos, Kachru, hep-ph/0501082



$$m(soft)^1$$

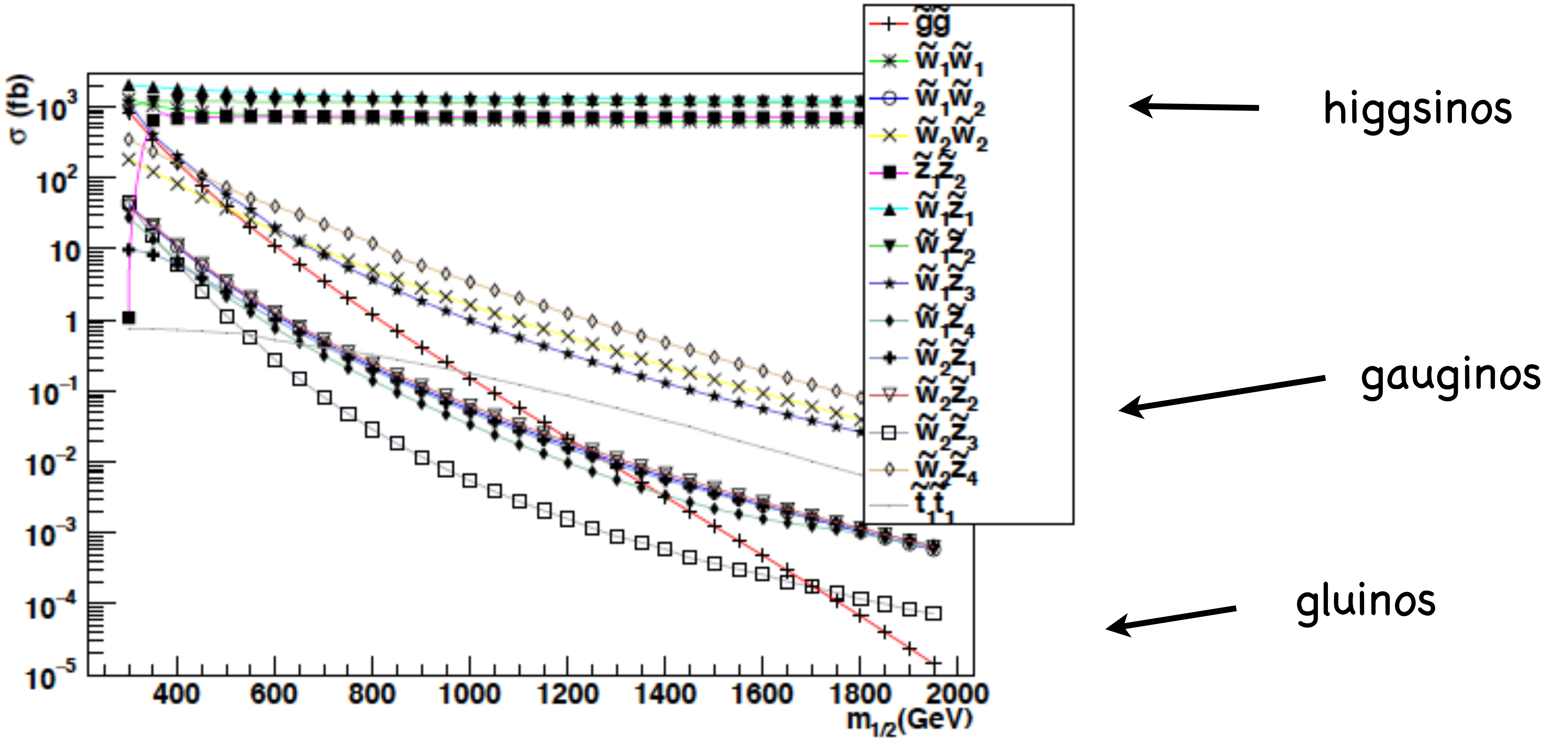


$$m(soft)^4$$

Under stringy naturalness, a 3 TeV gluino is more natural than a 300 GeV gluino!

What does naturalness imply for LHC SUSY searches at Run 3 and beyond?

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



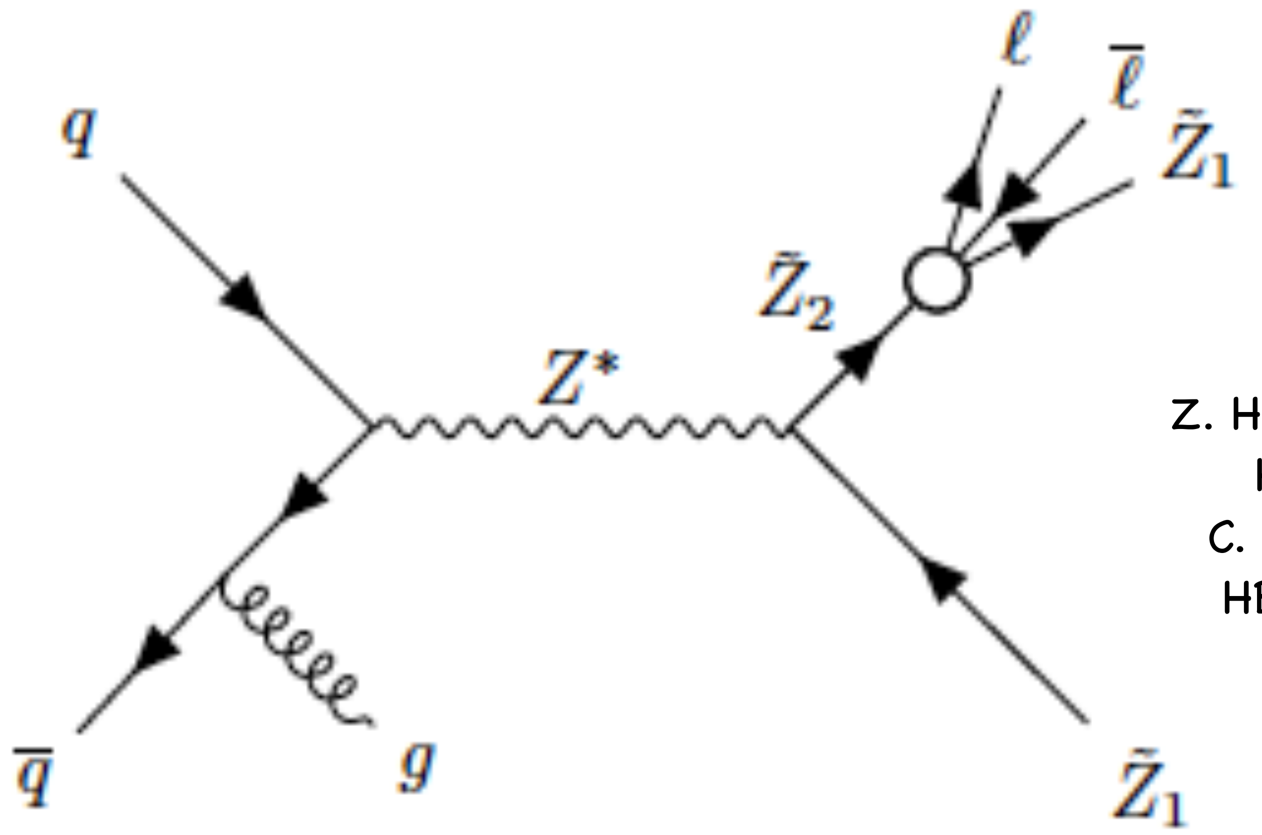
higgsino pair production dominant-but only soft visible energy release from higgsino decays

largest visible cross section: wino pairs

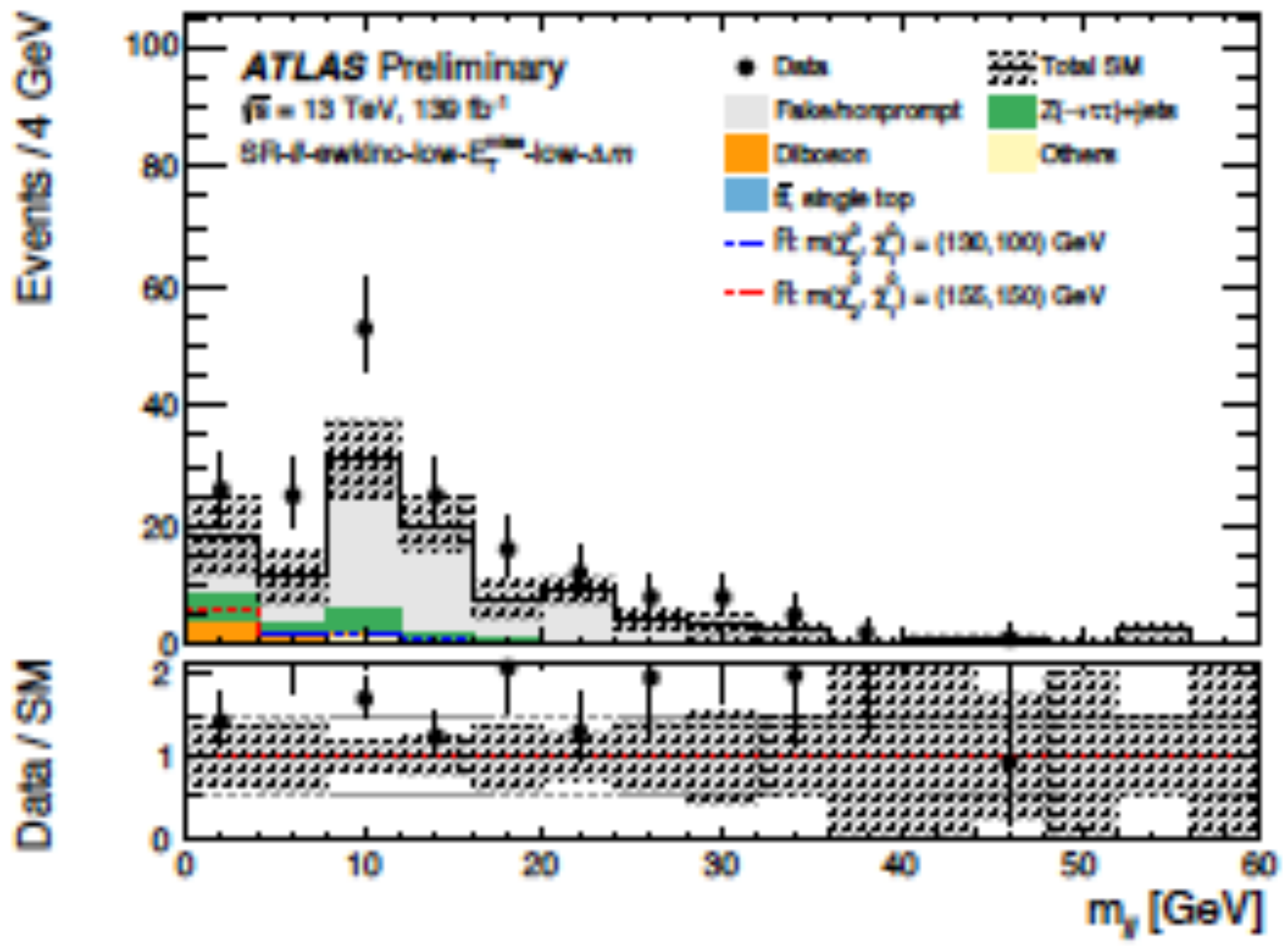
gluino pairs sharply dropping

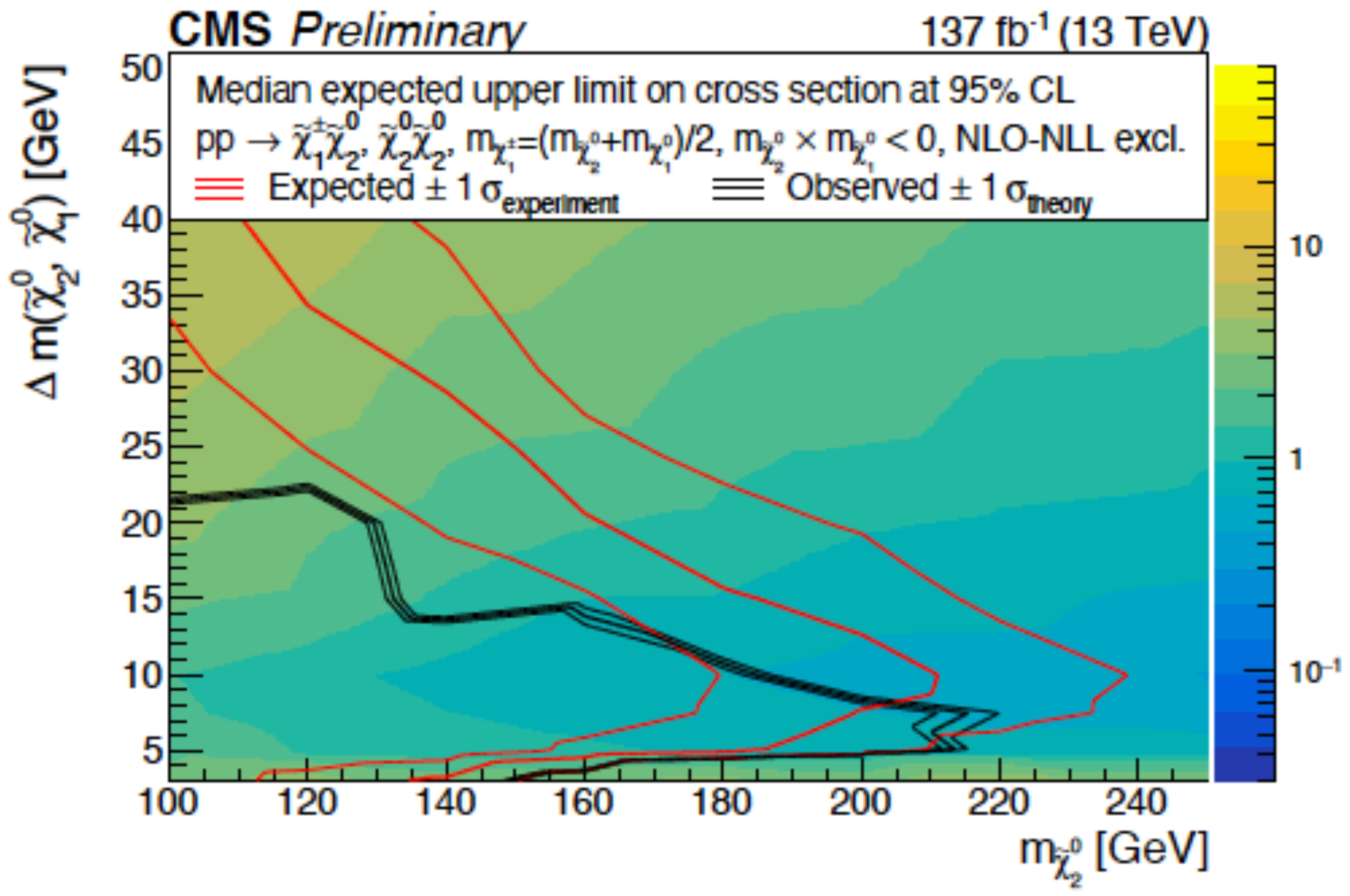
Natural SUSY: only higgsinos need lie close to weak scale

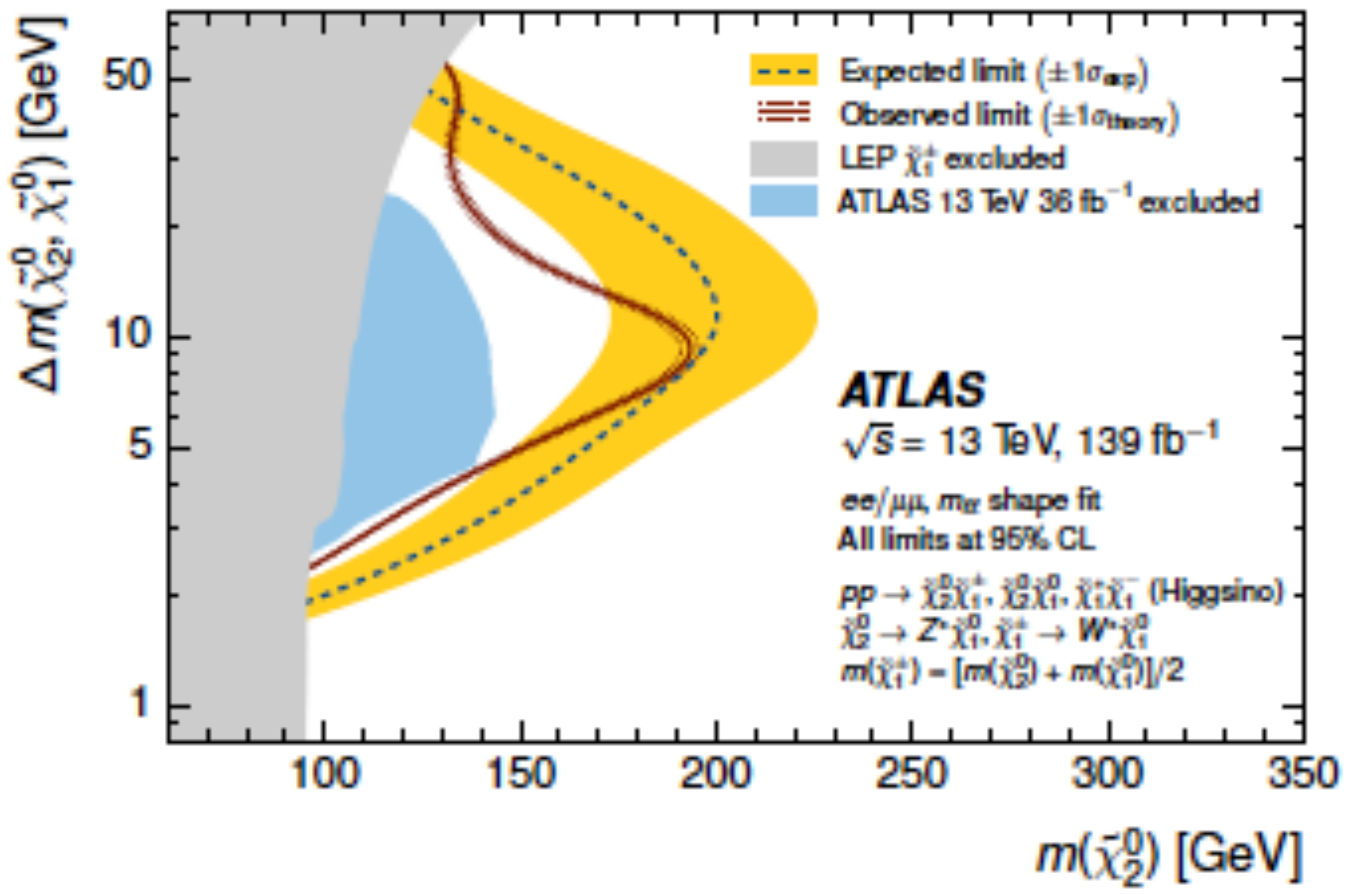
Soft dilepton+jet+MET signature from higgsino pair production



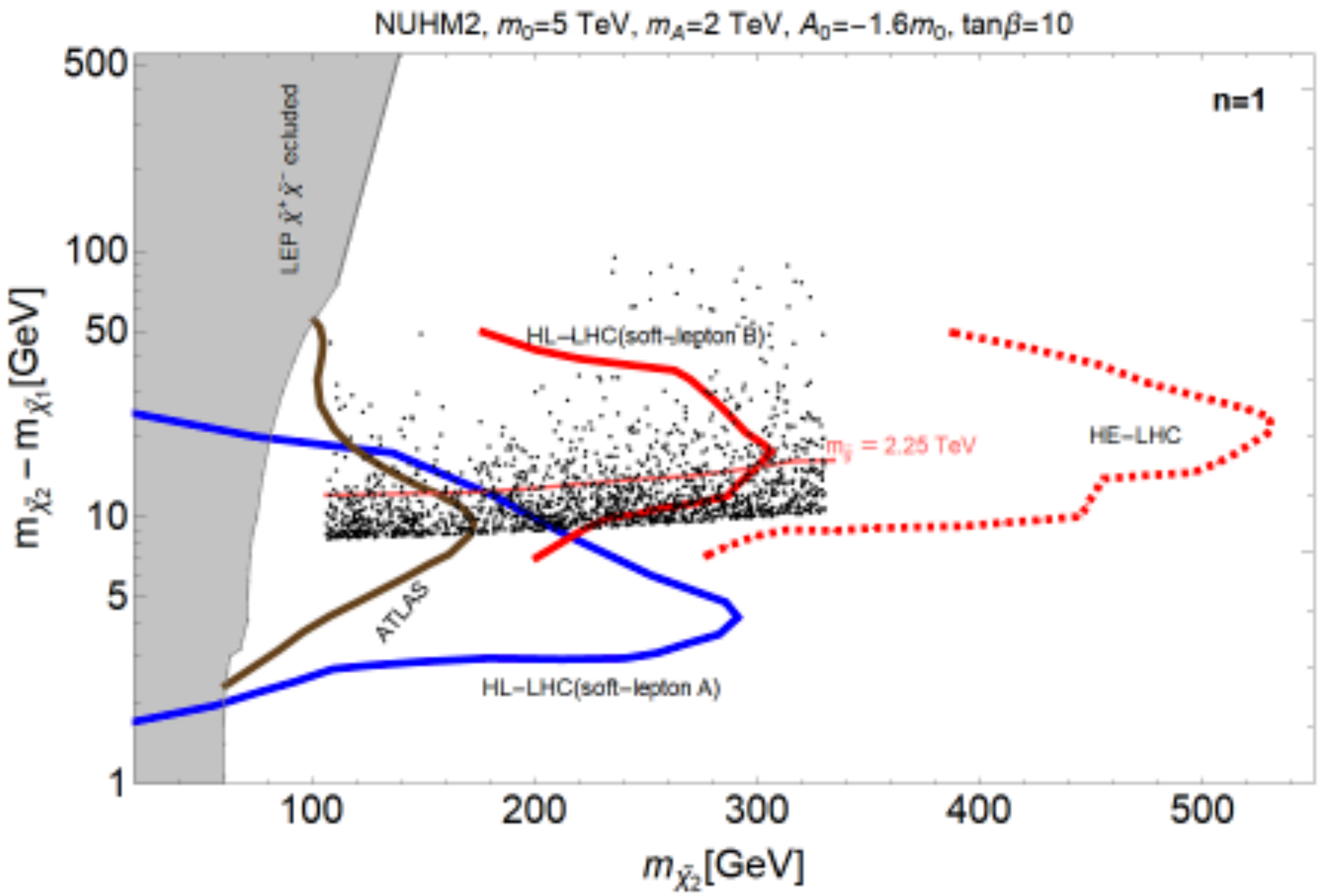
HB, Barger, Huang, 1107.5581;
Z. Han, Kribs, Martin, Menon, 1401.1235;
HB, Mustafayev, Tata; 1409.7058;
C. Han, Kim, Munir, Park, 1502.03734;
HB, Barger, Savoy, Tata, 1604.07438



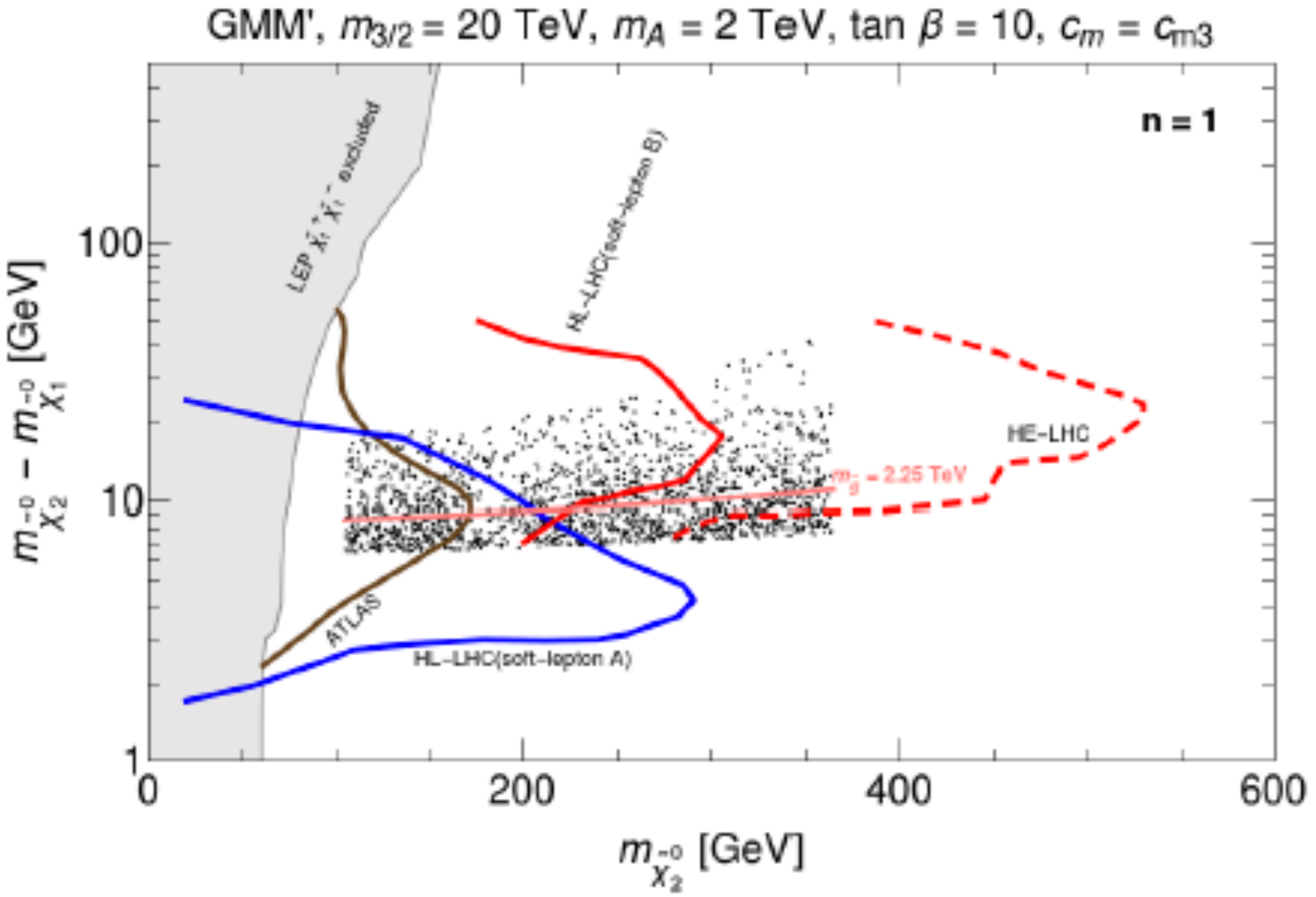




It appears that HL-LHC can see much of natural SUSY p-space;
signal in this channel should emerge slowly as more integrated luminosity accrues



NUHM2 with n=1 landscape draw (dots)



natural generalized mirage mediation
with n=1 landscape draw (dots)

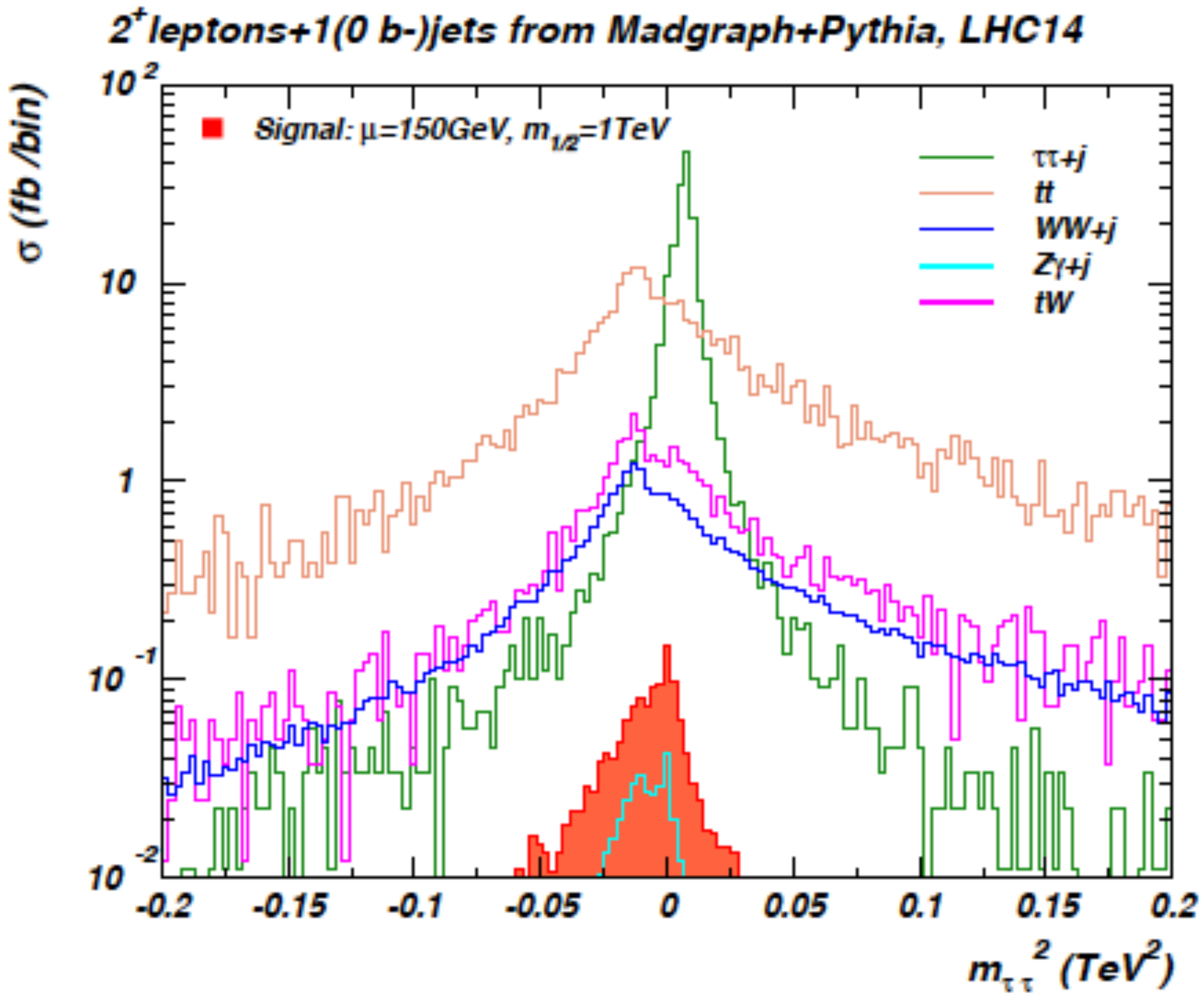
HB, Barger, Salam, Sengupta, Tata
arXiv: 2007.09252

Monojet plus soft dilepton signal from light higgsino pair production at LHC14

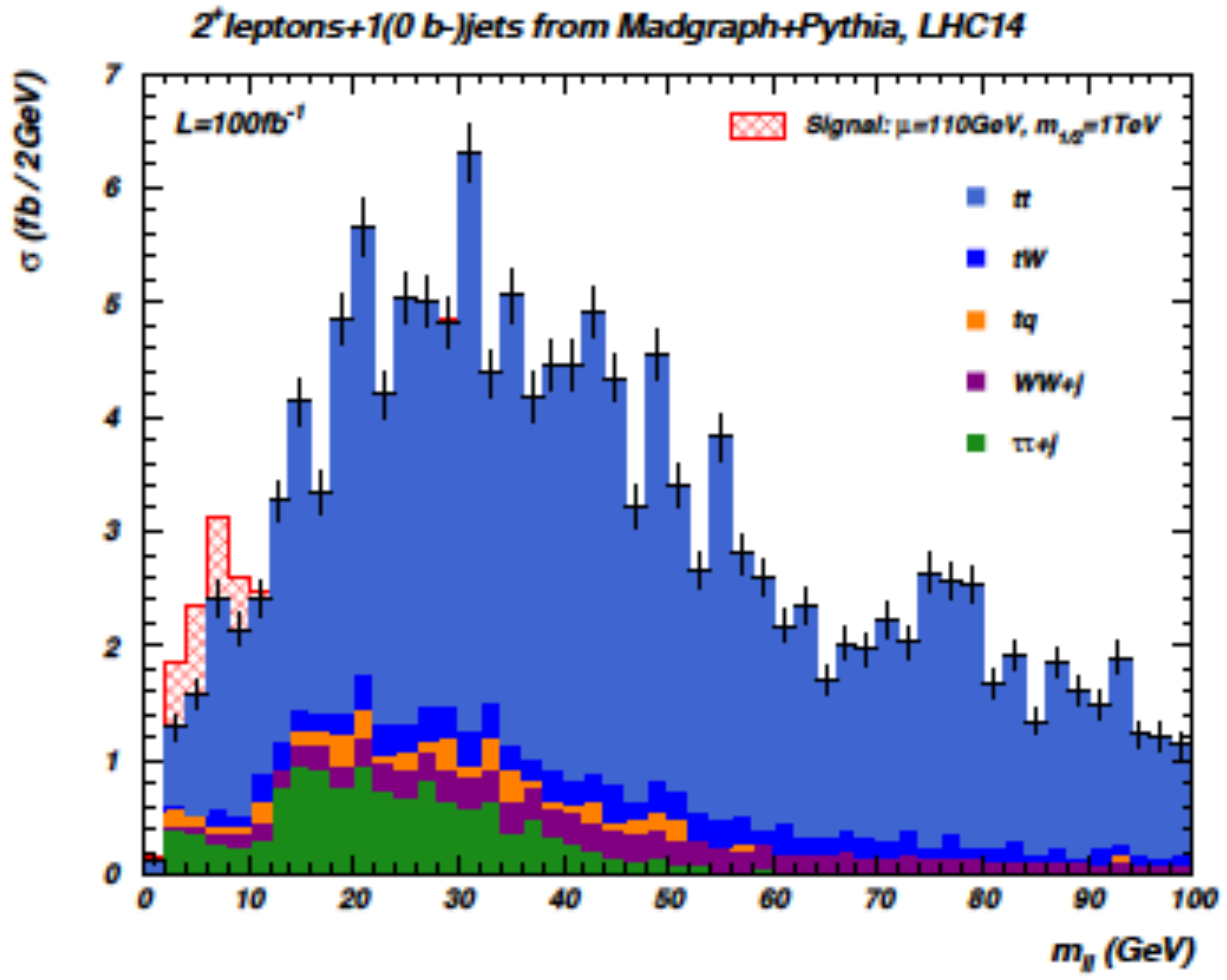
Howard Baer[1,2*], Azar Mustafayev[3†] and Xerxes Tata[3§]

- Published in: *Phys.Rev.D* 90 (2014) 11, 115007 • e-Print: 1409.7058 [hep-ph]

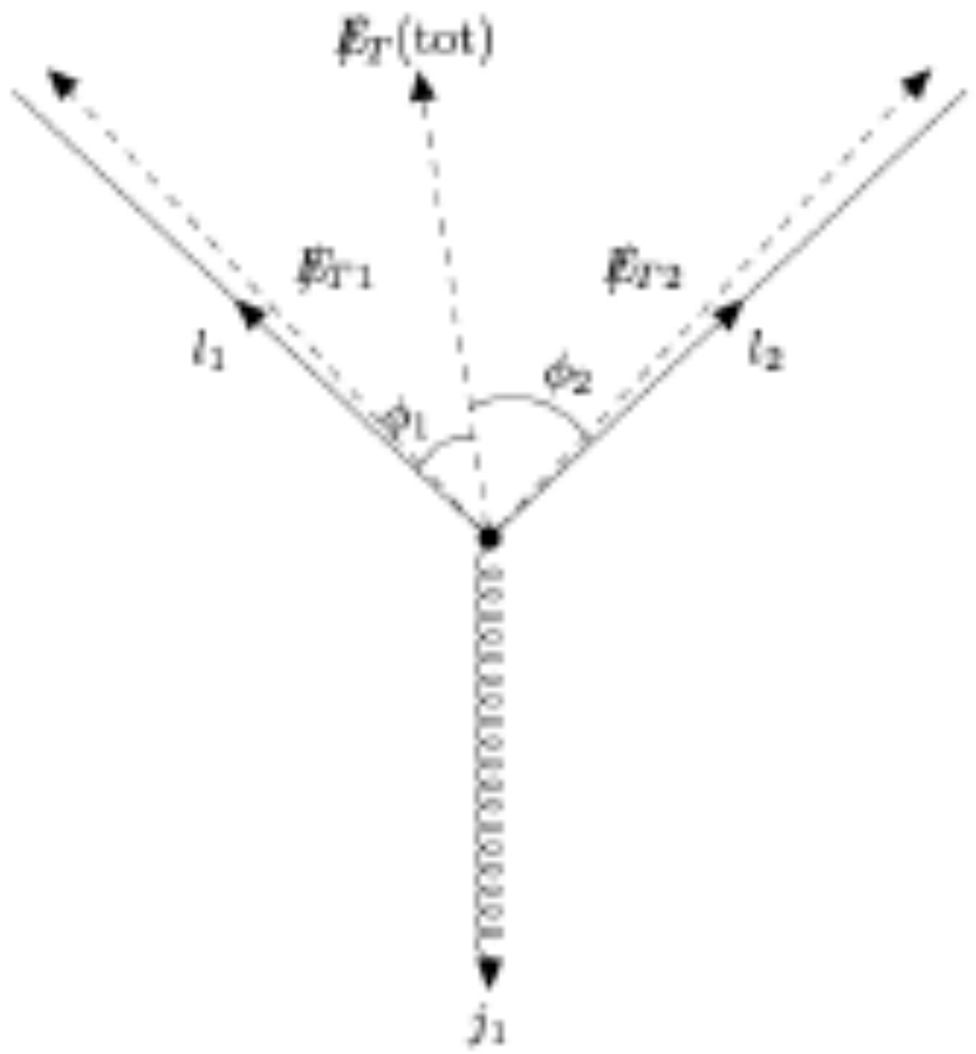
(CMS take note- left out of latest paper)



m(tautau)^2<0 cuts out bulk of tau pair BG but leaves some from virtual tau pair production and jet mismeasurement



New angular (and other) cuts to improve higgsino pair signal at HL-LHC;
HB, Barger, Sengupta, Tata, arXiv:2109.14030



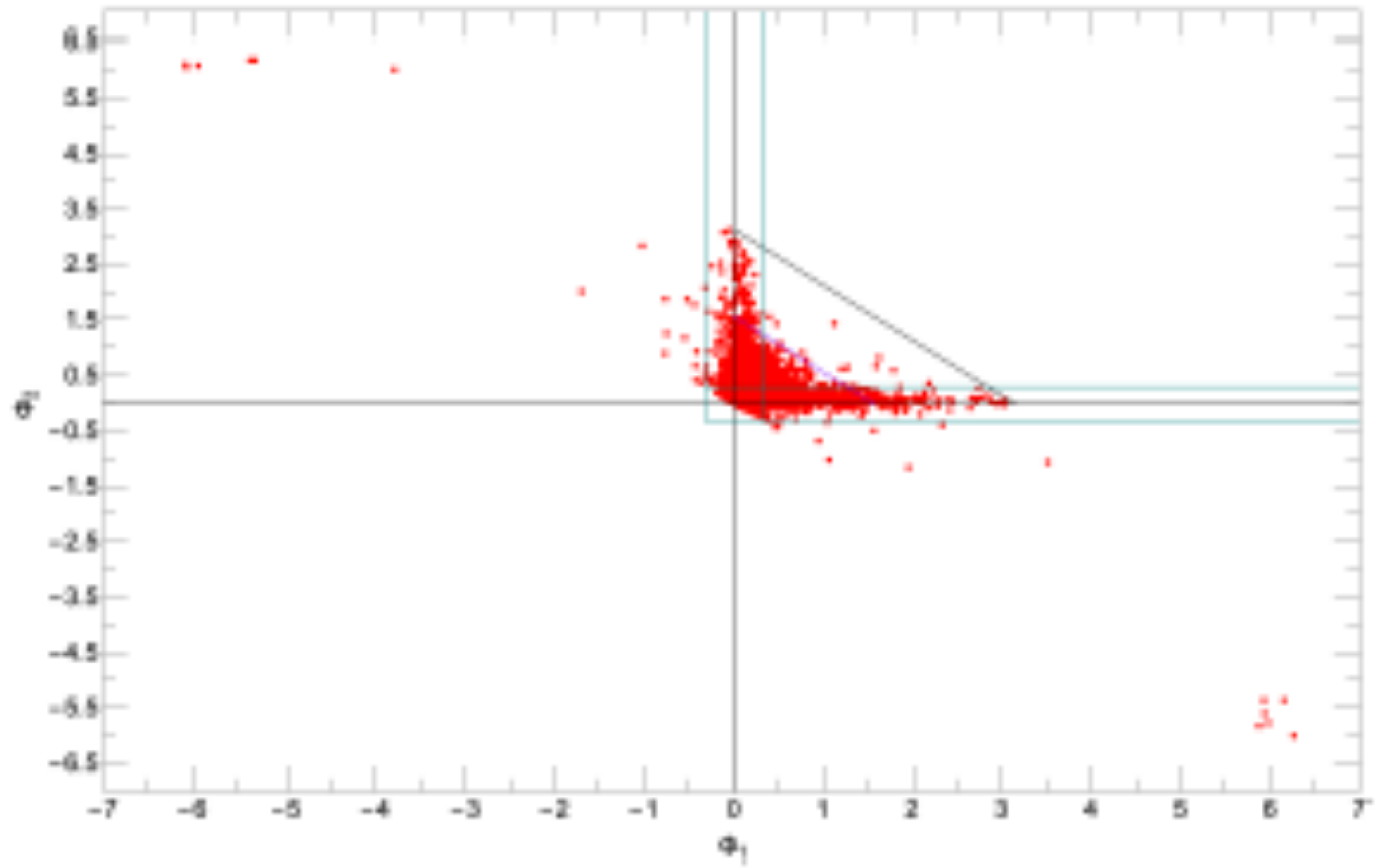


Figure 3: Distribution in ϕ_1 vs. ϕ_2 plane for $\tau\bar{\tau}j$ background after $C1$ cuts, requiring also that $n_j = 1$.

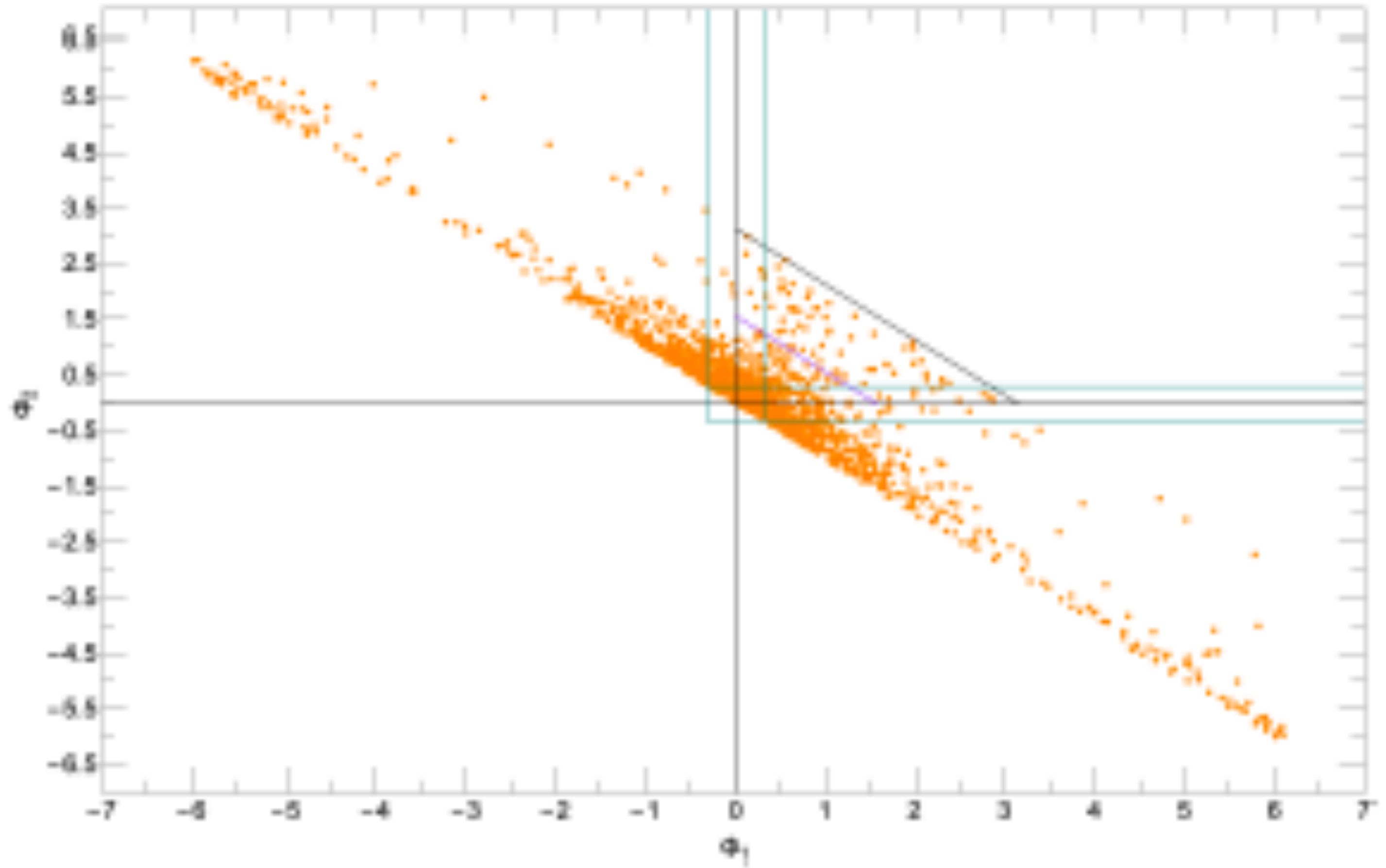


Figure 5: Distribution in ϕ_1 vs. ϕ_2 plane for signal point BM1 after $C1$ cuts, requiring also that $n_j = 1$.

signal BM point

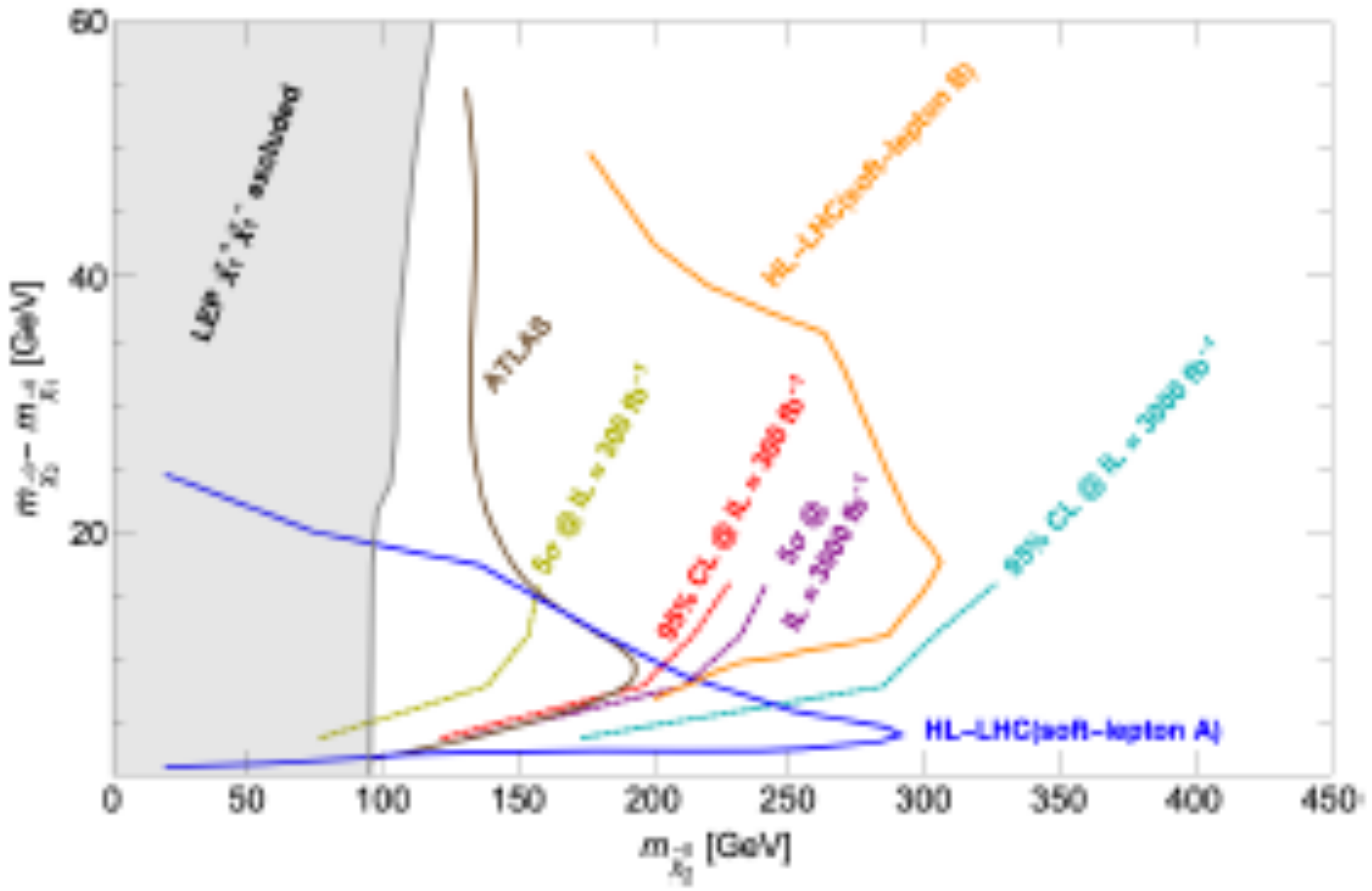
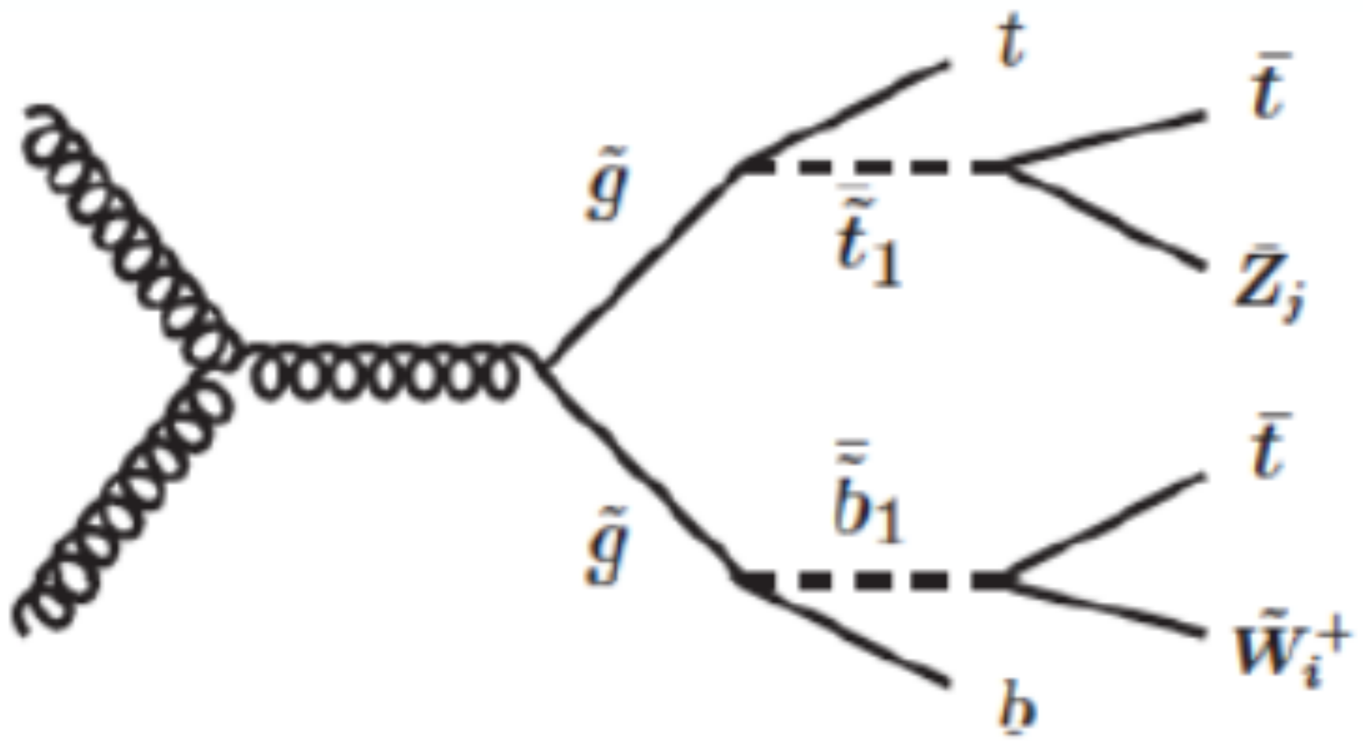


Figure 21: The projected 5σ reach and 95% CL exclusion contours for LHC14 with 300 and 3000 fb^{-1} in the $m_{\tilde{\chi}_2^0}$ vs. Δm plane after $C4$ cuts. Also shown is the current 95% CL exclusion (ATLAS) and the projected 95% CL exclusions from two different analyses for the HL-LHC [42].

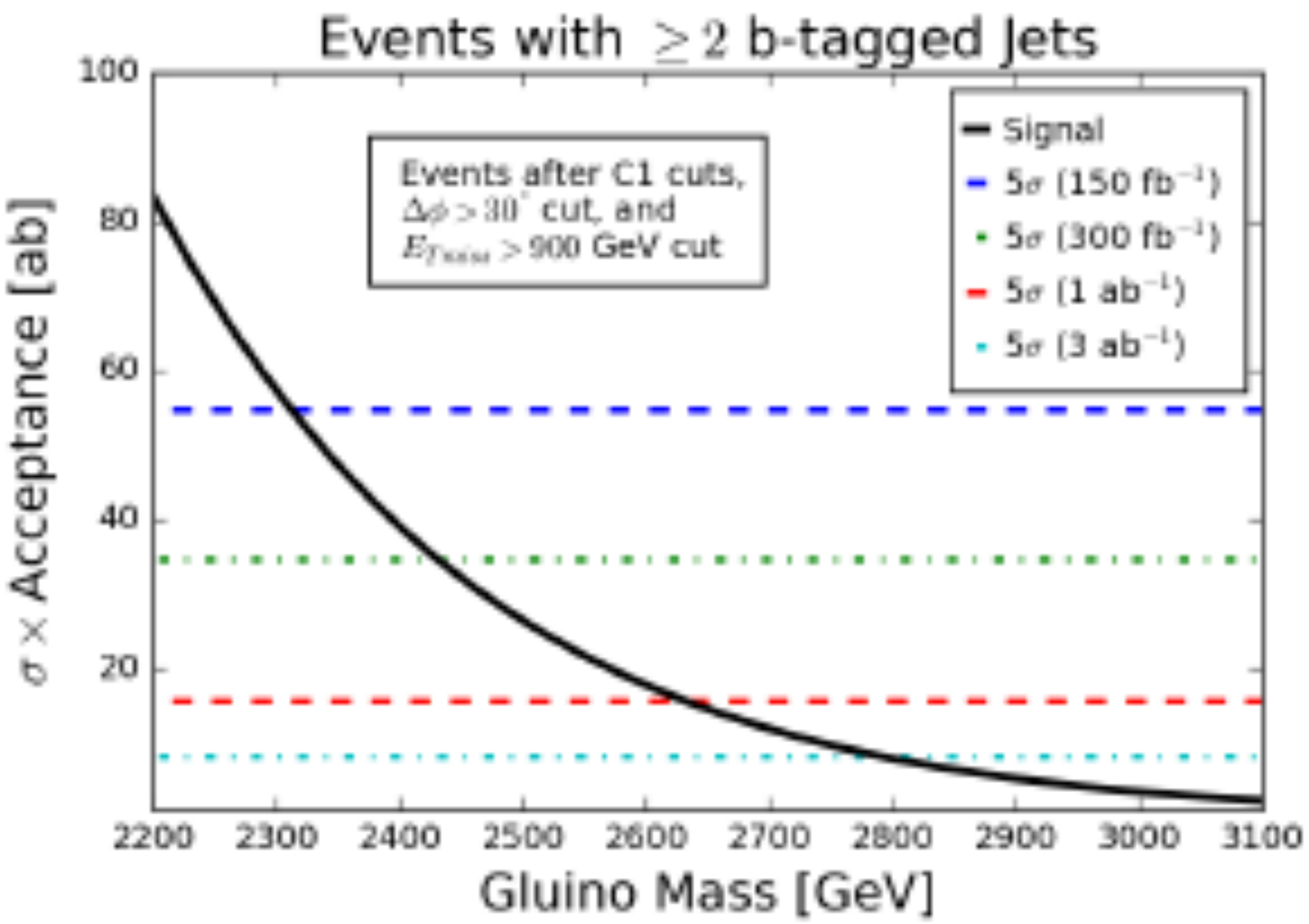
Snowmass 2021;
EF08 contribution

greatly extended reach at HL-LHC!

gluino pair cascade decay signatures



LHC14

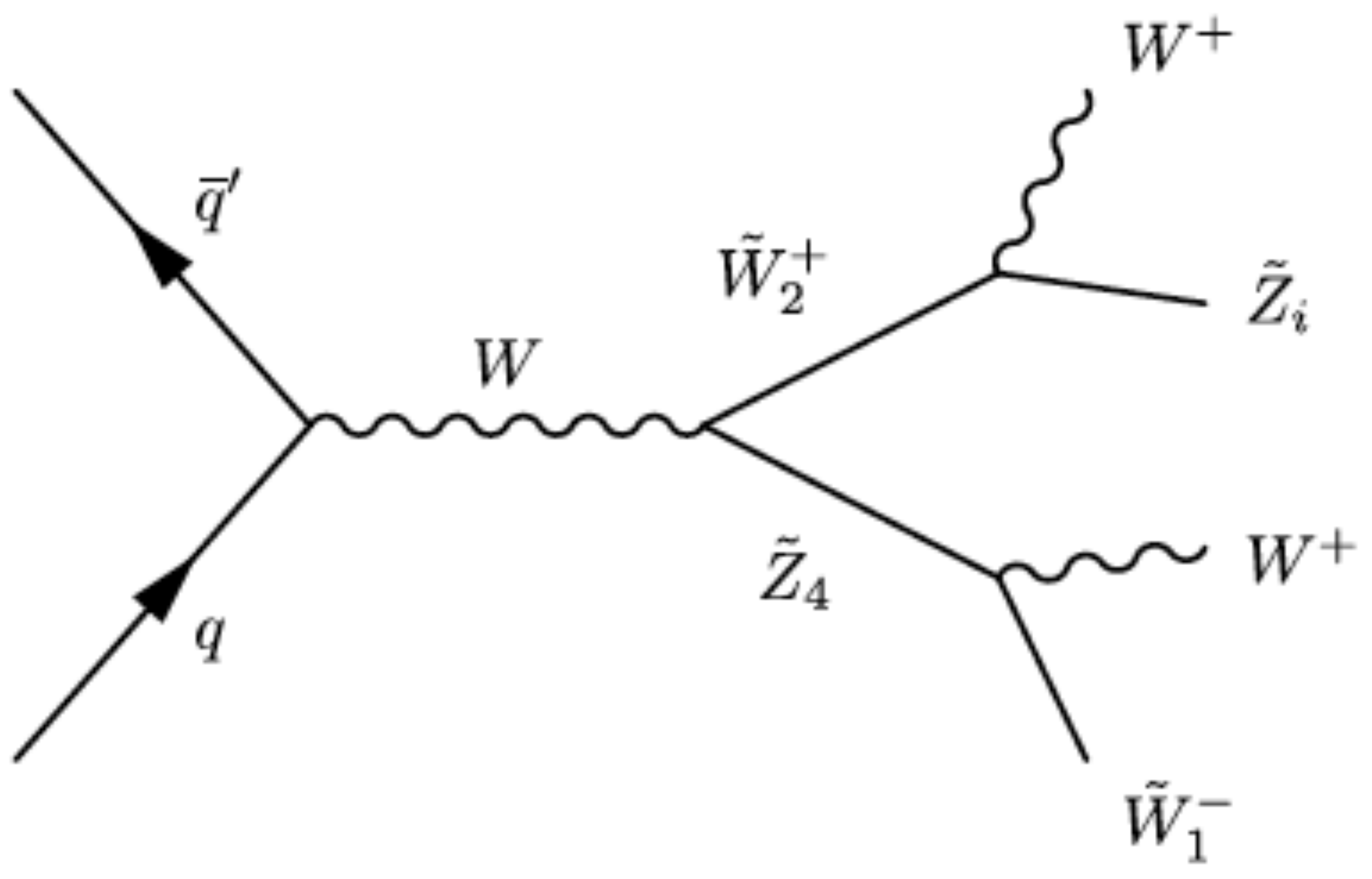


HB, Barger, Gainer, Huang, Savoy, Sengupta,Tata

HL-LHC to probe m(gl)~2.8 TeV
HE-LHC to probe m(gl)~5.5-6 TeV

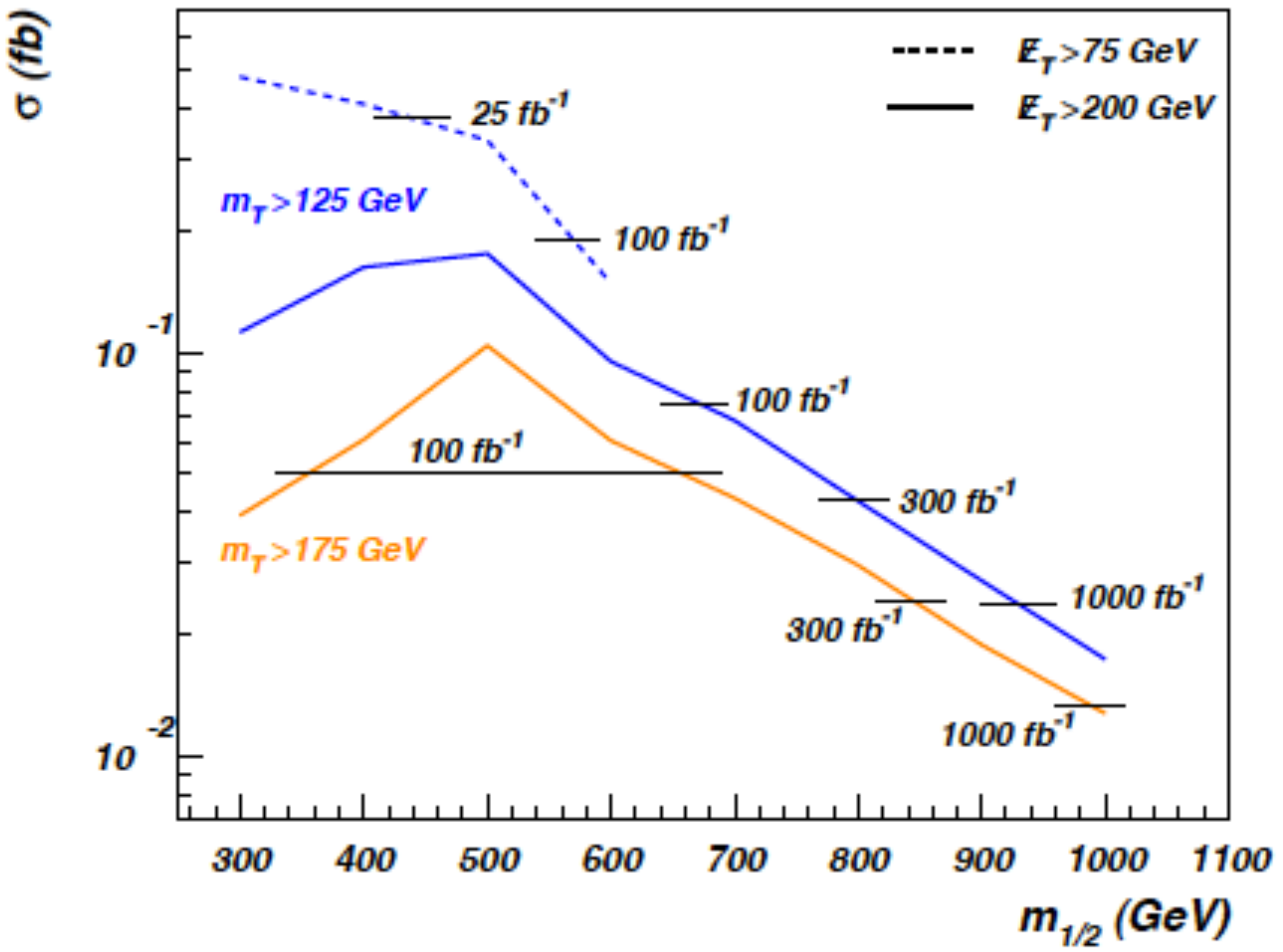
FCC-hh(100) to probe m(gl)~10 TeV

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



(soft)

(soft)



wino pair production

This channel offers added reach of LHC14 for natSUSY; 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, Sengupta, Tata, arXiv: 1710.09103

So far, no ATLAS or CMS search in this well-motivated channel!

Conclusions

- Old naturalness measures overestimate finetuning
- Plenty of SUSY p-space left under conservative D(EW)
- Four light higgsinos~100-350 GeV
- String landscape: statistical draw to large soft terms balanced by anthropic requirement that pocket-universe m(weak)^PU<4m(weak)^OU: natSUSY emergent from string landscape!
- predicts mh~125 GeV; sparticles beyond present LHC reach
- search for soft di-, tri- leptons plus jet(s)+MET from light higgsinos
- same-sign diboson-> SS dilepton+MET from wino pair production
- usual gluino pair/top-squark pair production
- DM: mainly SUSY DFSZ axions plus light higgsino-like WIMPs