Natural SUSY, string landscape and implications for LHC searches

Howard Baer
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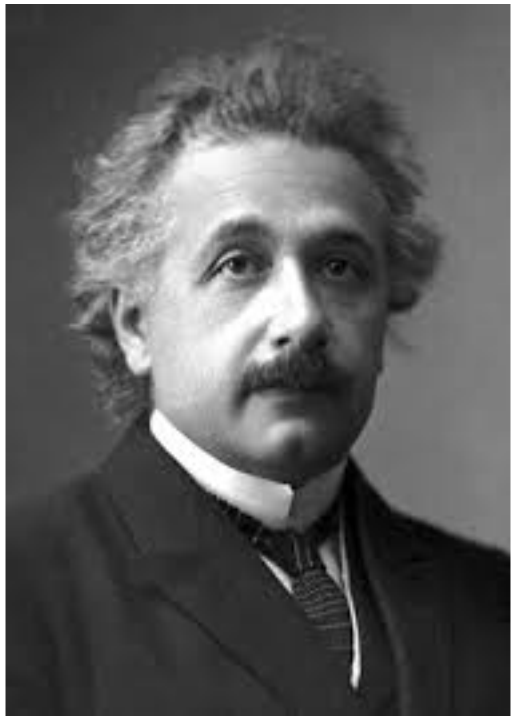
INFN Frascati talk
April 8, 2024

twin pillars of guidance:
naturalness & simplicity



``The appearance of fine-tuning in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained"

S. Weinberg

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

A. Einstein

We have seen from LHC: the Standard Model rules at E~100-200 GeV!

nonetheless, it is hardly the end of story since the SM is beset by several finetuning problems:

- Gauge hierarchy: how can weak scale be so much smaller than GUT/Planck scale?
- Strong CP problem (QCD): why is QCD theta parameter so small <~10^-10
- Cosmological constant: $\rho_{vac} \sim (0.003 \text{ eV})^4 \ll m_P^4$

The SM is beset by several finetuning problems:

most plausible solutions to date

- Gauge hierarchy: how can weak scale be so much smaller than GUT/Planck scale? SUSY
- Strong CP problem (QCD): why is QCD theta parameter so small <~10^-10 axion
- Cosmological constant: $\rho_{vac} \sim (0.003 \text{ eV})^4 \ll m_P^4$

anthropic vacua selection from multiverse/string vacua

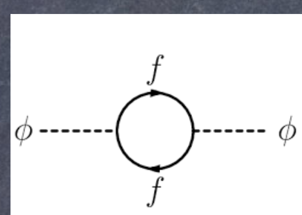
Each of these solutions affects phenomenology in a profound way

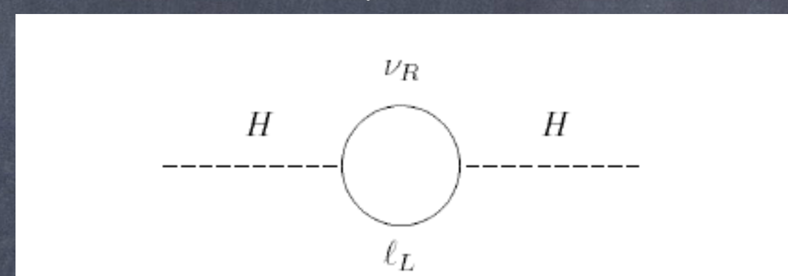
Hierarchy of scales problem in the SM

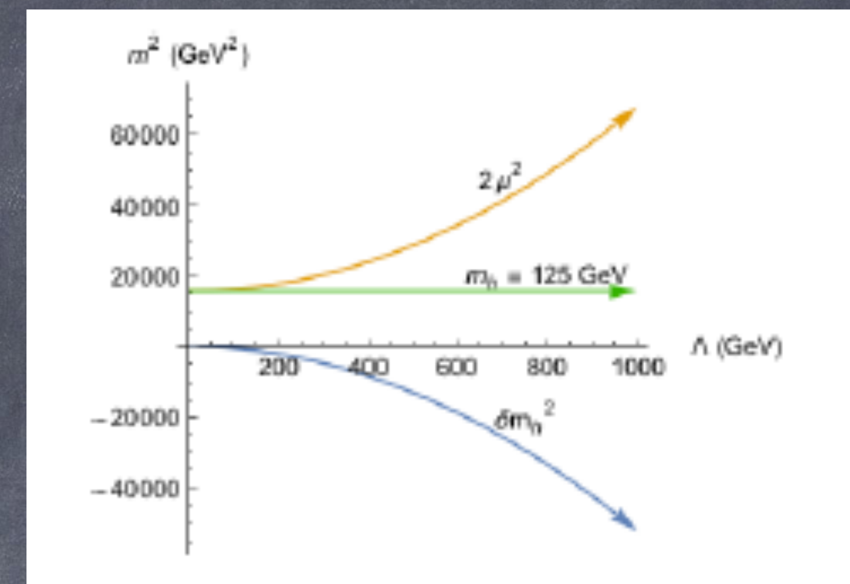
Biggest conundrum of SM: why is Higgs mass so small?

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/Planck scale

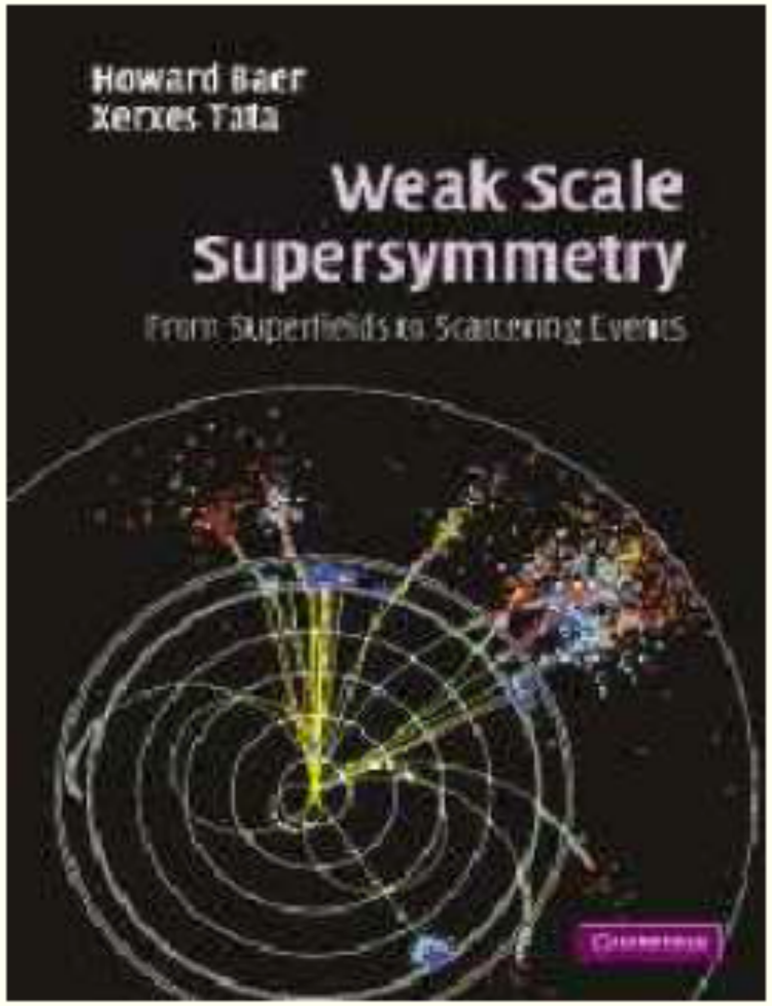
Supersymmetry: all quadratic divergences cancel!

Weak Scale Supersymmetry

HB and X. Tata

Spring, 2006; Cambridge University Press

- ⋆ Part 1: superfields/Lagrangians
  - 4-component spinor notation for exp'ts
  - master Lagrangian for SUSY gauge theories
- ⋆ Part 2: models/implications
  - MSSM, SUGRA, GMSB, AMSB, $\cdots$
- ⋆ Part 3: SUSY at colliders
  - production/decay/event generation
  - collider signatures
  - R-parity violation



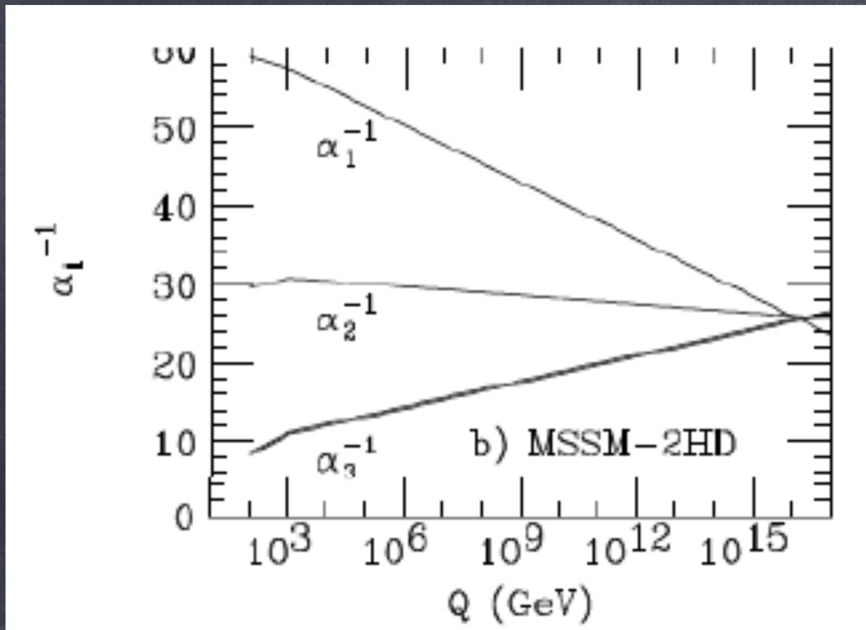
Minimal Supersymmetric Standard Model (MSSM)

- ⋆ Adopt gauge symmetry of Standard Model: $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - gauge boson plus spin $\frac{1}{2}$ gaugino $\in$ gauge superfield
- ⋆ SM fermions $\in$ chiral scalar superfields: $\Rightarrow$ scalar partner for each SM fermion helicity state
  - electron $\Leftrightarrow$ $\tilde{e}_L$ and $\tilde{e}_R$
- ⋆ *two* Higgs doublets to cancel triangle anomalies: H_u and H_d
- ⋆ add all admissible soft SUSY breaking terms
- ⋆ resultant Lagrangian has 124 parameters!
- ⋆ Lagrangian yields mass eigenstates, mixings, Feynman rules for scattering and decay processes
- ⋆ predictive model!

Physical states of MSSM:

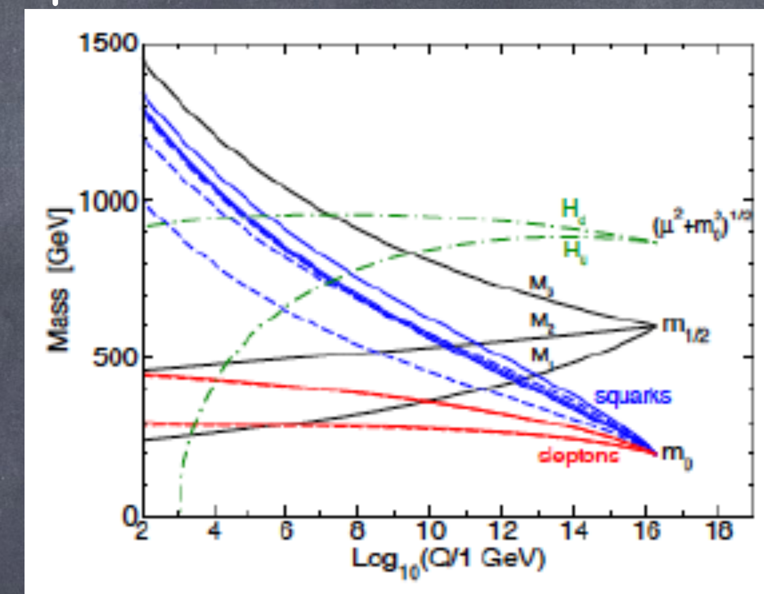
- ⋆ usual SM gauge bosons, quarks and leptons
- ⋆ gluino: $\tilde{g}$
- ⋆ bino, wino, neutral higgsinos$\Rightarrow$ neutralinos: $\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{Z}_3, \widetilde{Z}_4$
- ⋆ charged wino, higgsino $\Rightarrow$ charginos: $\widetilde{W}_1^{\pm}$, $\widetilde{W}_2^{\pm}$
- ⋆ squarks: $\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{d}_R, \cdots$, $\tilde{t}_1$, $\tilde{t}_2$
- ⋆ sleptons: $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_e, \cdots$, $\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_\tau$
- ⋆ Higgs sector enlarged: h, H, A, $H^{\pm}$
- ⋆ a plethora of new states to be found at LHC/ILC?!

The MSSM is supported by virtual quantum effects!

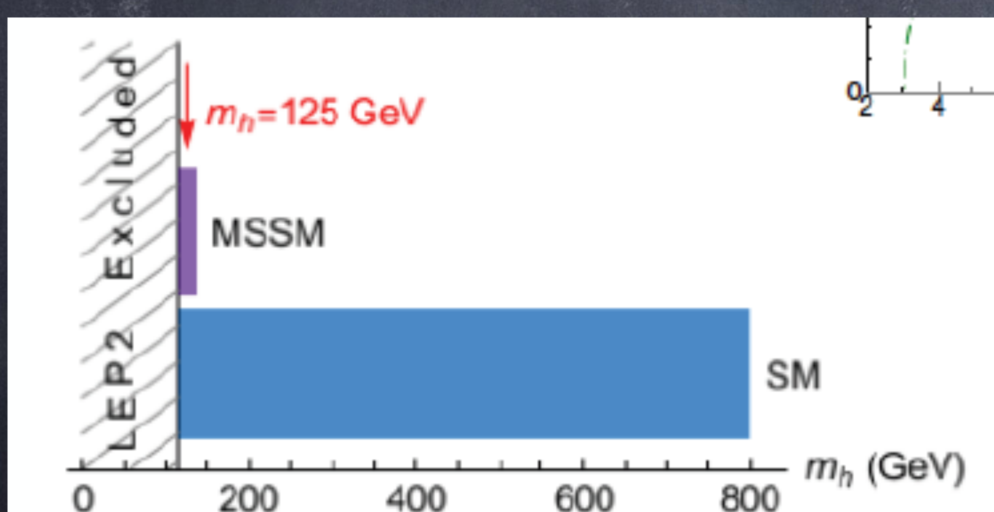


Unification of gauge couplings

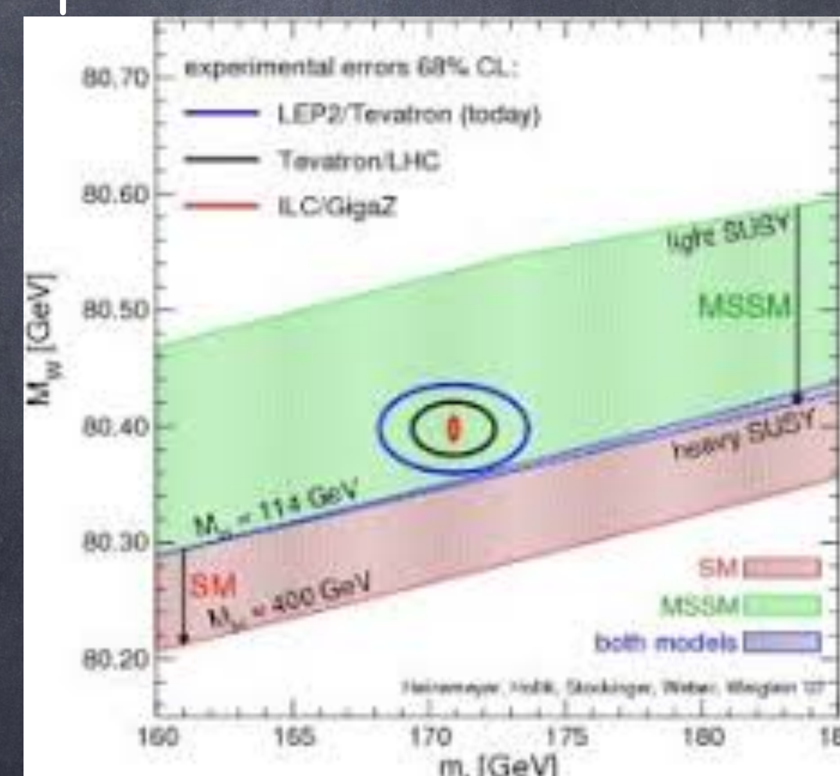
m(t)~150-200 GeV
required for radiative EWSB



m(h) just right



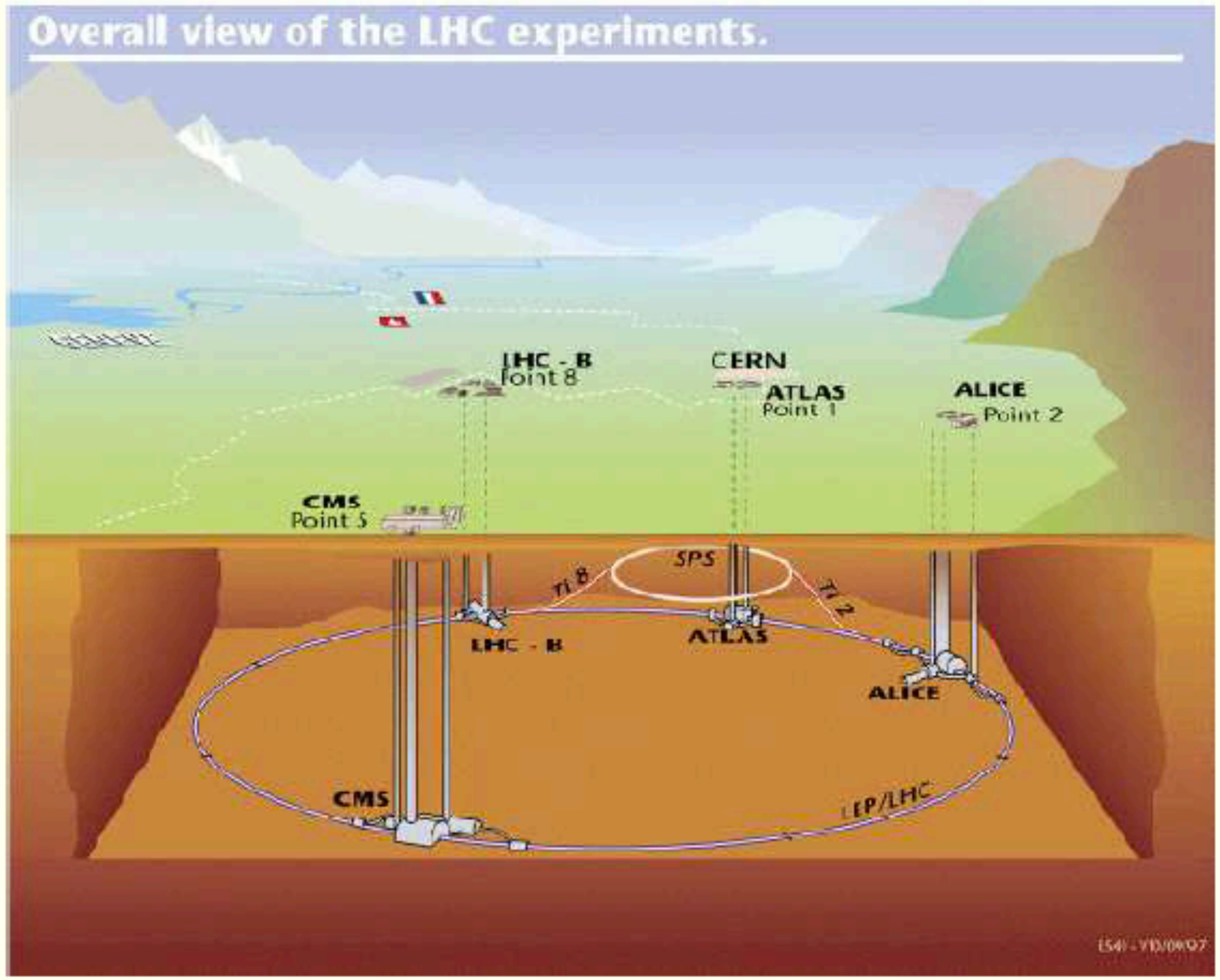
precision electroweak fits



Radiative corrections have proven to be a reliable guide to new physics

Direct search for superpartners at LHC

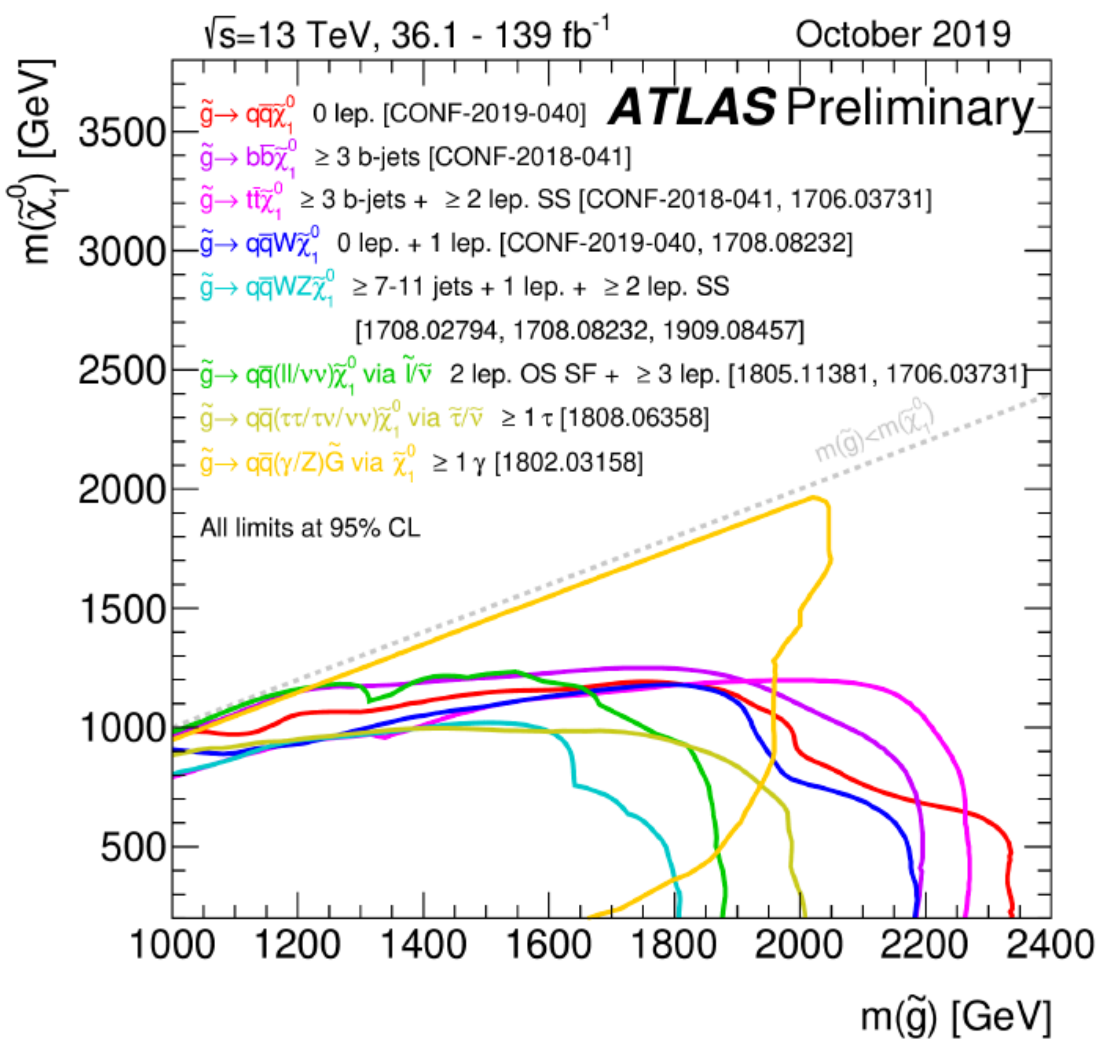
Layout of the LHC:two main detectors: Atlas and CMS



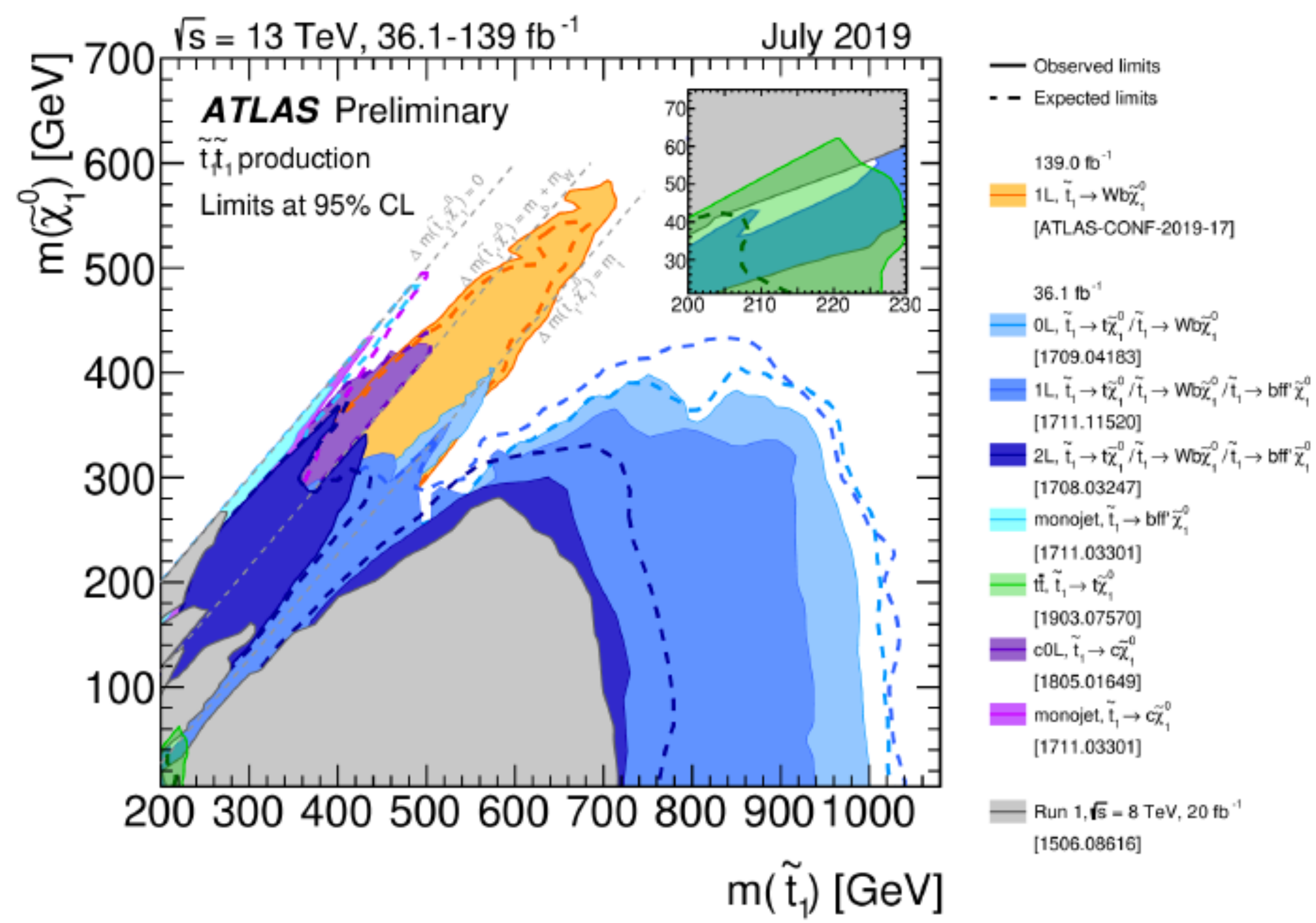
Nowadays: almost always within simplified models

But where are the sparticles?

none seen so far at LHC

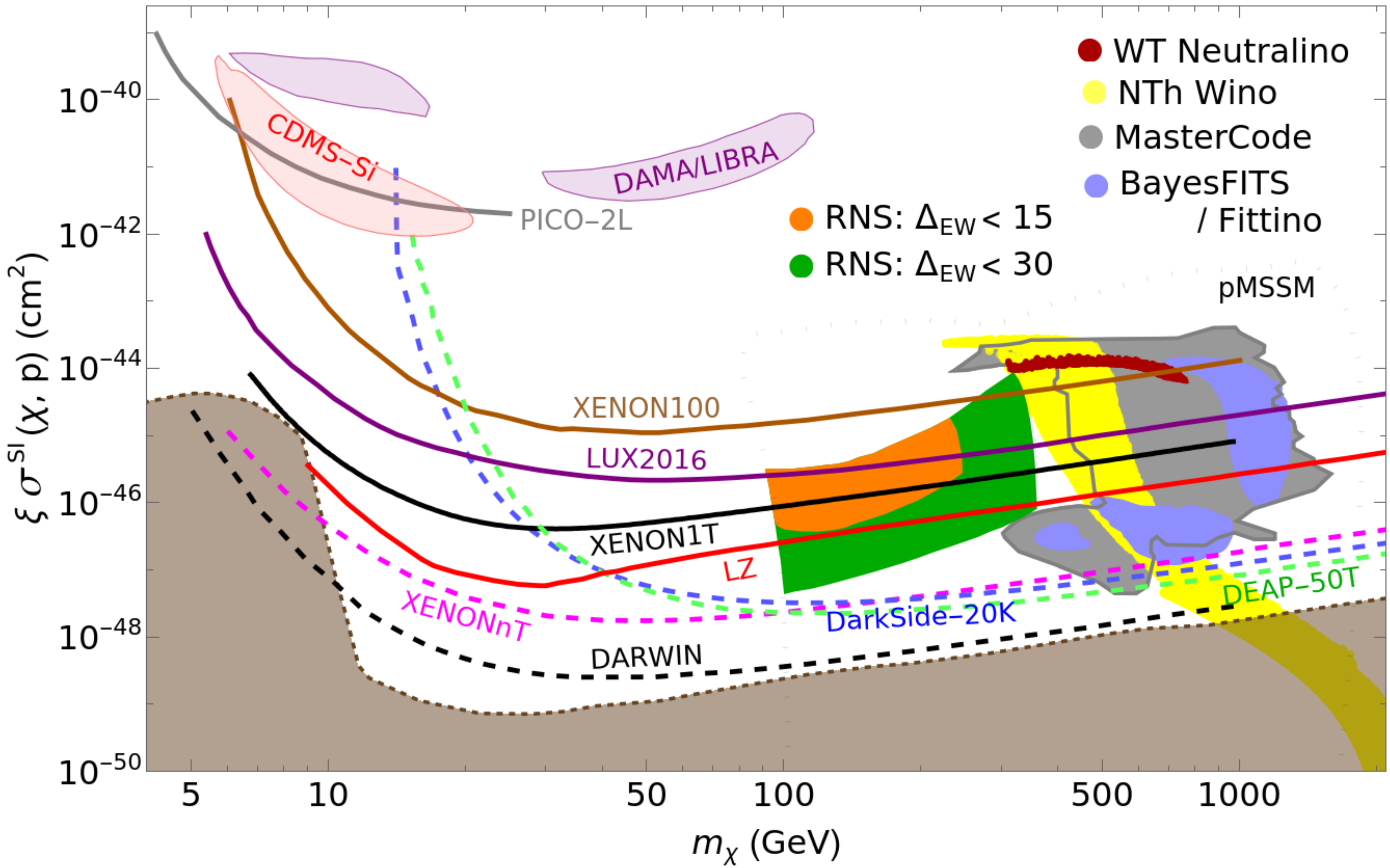


$$m_{\tilde{g}} > 2.25 \text{ TeV}$$



$$m_{\tilde{t}_1} > 1.1 \text{ TeV}$$

Where are the WIMPs?

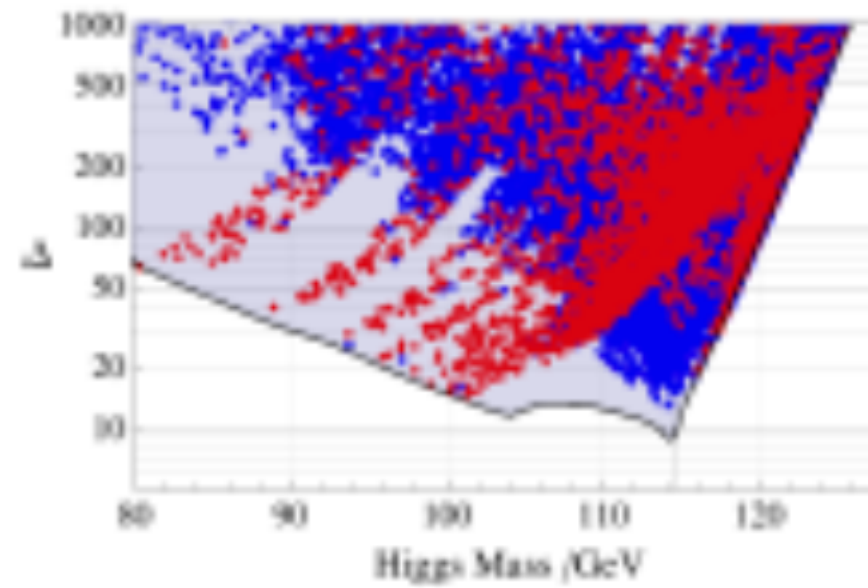


latest DD bounds from LZ2022: still no signal

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!?

Pardon this slide but I grew up in Wisconsin in the 1960s; Vince Lombardi, legendary football coach

``…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

SUSY solves Big Hierarchy ('t Hooft natural): but LHC => Little Hierarchy m(weak)~100 GeV<< m(soft)~ TeV?

- It is (mistakenly) believed that weak scale SUSY is no longer natural due to strong LHC constraints on sparticle masses (m(glno)>2.2 TeV) and the rather large value of m(h)~125 GeV

- 1. BG naturalness measure overestimates finetuning by factors of 10-1000 due to adopting various soft terms as independent when in realistic SUGRA models these are in fact *dependent*: soft terms computed as multiples of gravitino mass m_3/2

- 2. Higgs mass finetuning measure breaks soft terms into *dependent* contributions which each vary as they are tuned: violates finetuning rule, leading again to overestimates by orders of magnitude 10-1000

- 3. EW finetuning measure: mandatory and model independent: if you run spectra codes, this is where finetuning actually occurs!

PHYSICAL REVIEW D 88, 095013 (2013)

How conventional measures overestimate electroweak fine-tuning in supersymmetric theory

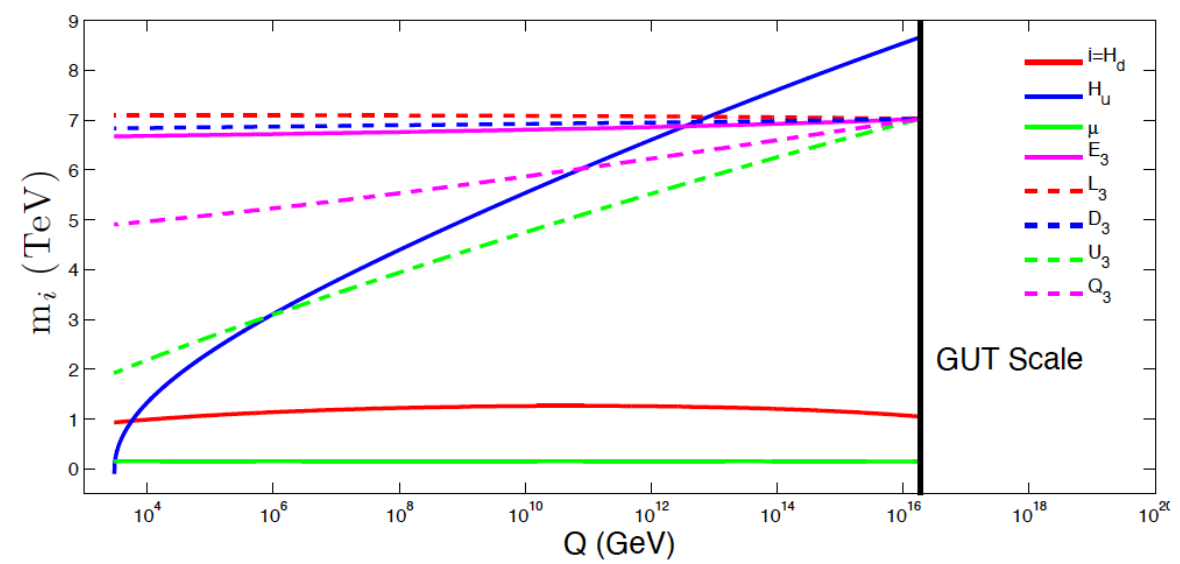
Howard Baer,[1,*] Vernon Barger,[2,†] and Dan Mickelson[1,‡]

practical naturalness: all *independent* contributions to an observable should be comparable to or less than the observable

[This is the way naturalness has been successfully applied by e.g. Gaillard and Lee to predict the value of m(charm) shortly before it was discovered]

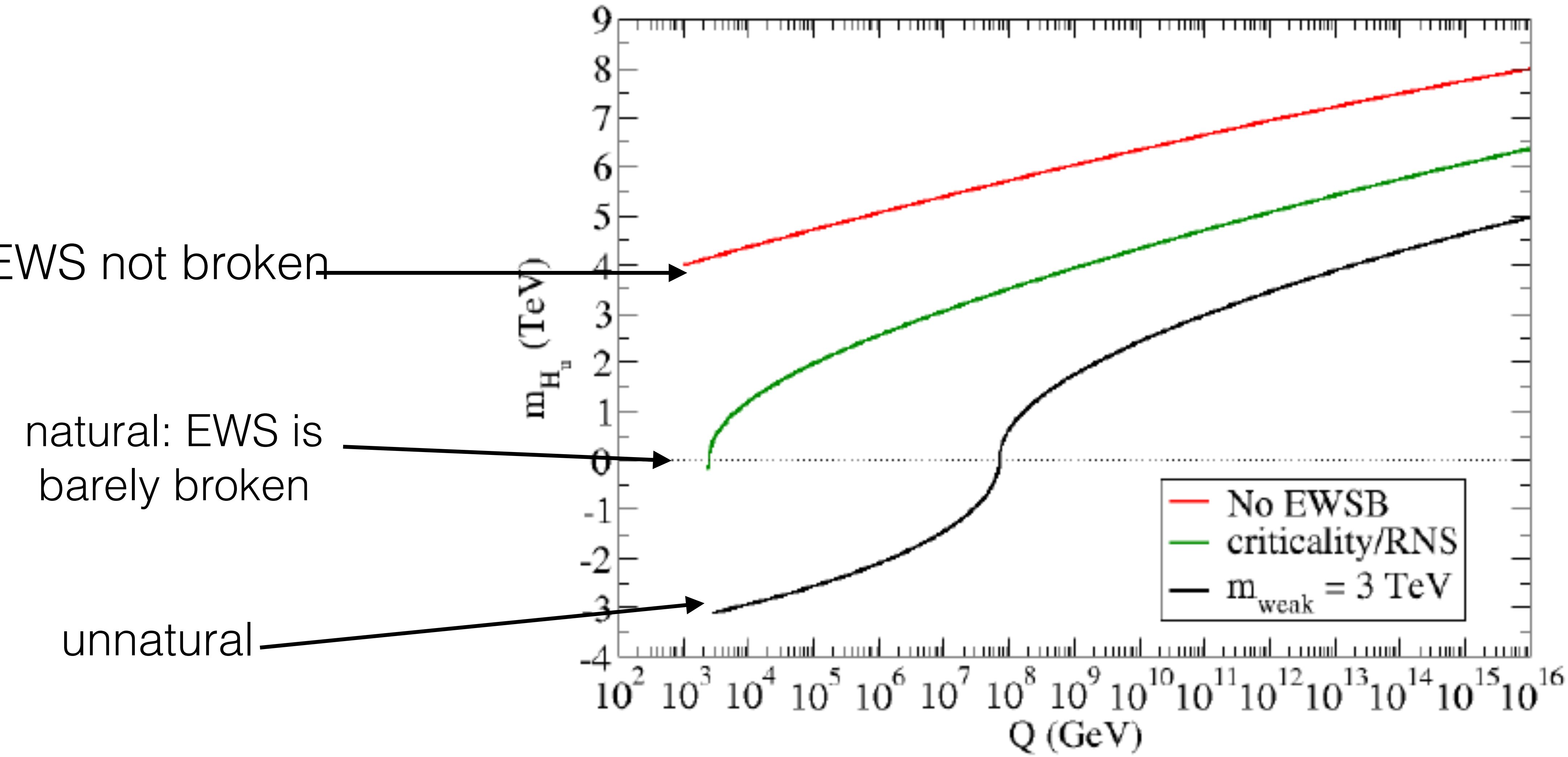
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$
$$\simeq -m_{H_u}^2 - \Sigma_u^u(\tilde{t}_{1,2}) - \mu^2.$$

$$\Delta_{EW} = max|\text{term on RHS}|/(m_Z^2/2)$$



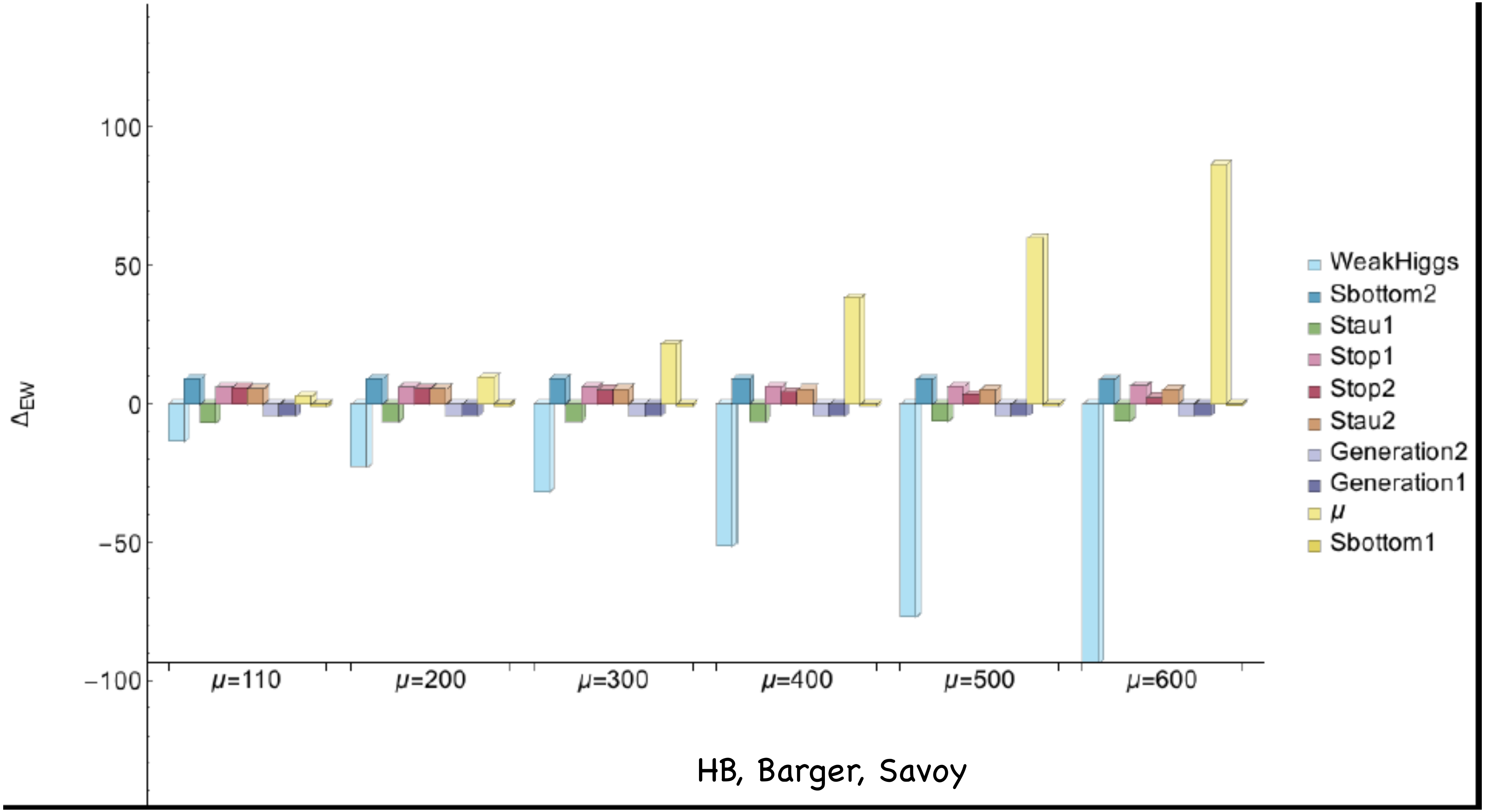
1. mu~m(Z)~100-300 GeV: LSP is higgsino-like!
2. m(Hu)~m(Z)~100-300 GeV can be radiatively driven to small (natural) values
3. top squarks loop suppressed: range up to 3 TeV
4. gluinos enter at 2-loops: can range up to 6 TeV

SUSY with radiatively-driven naturalness is natural! review: arXiv:2002.03013 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

How much is too much fine-tuning?

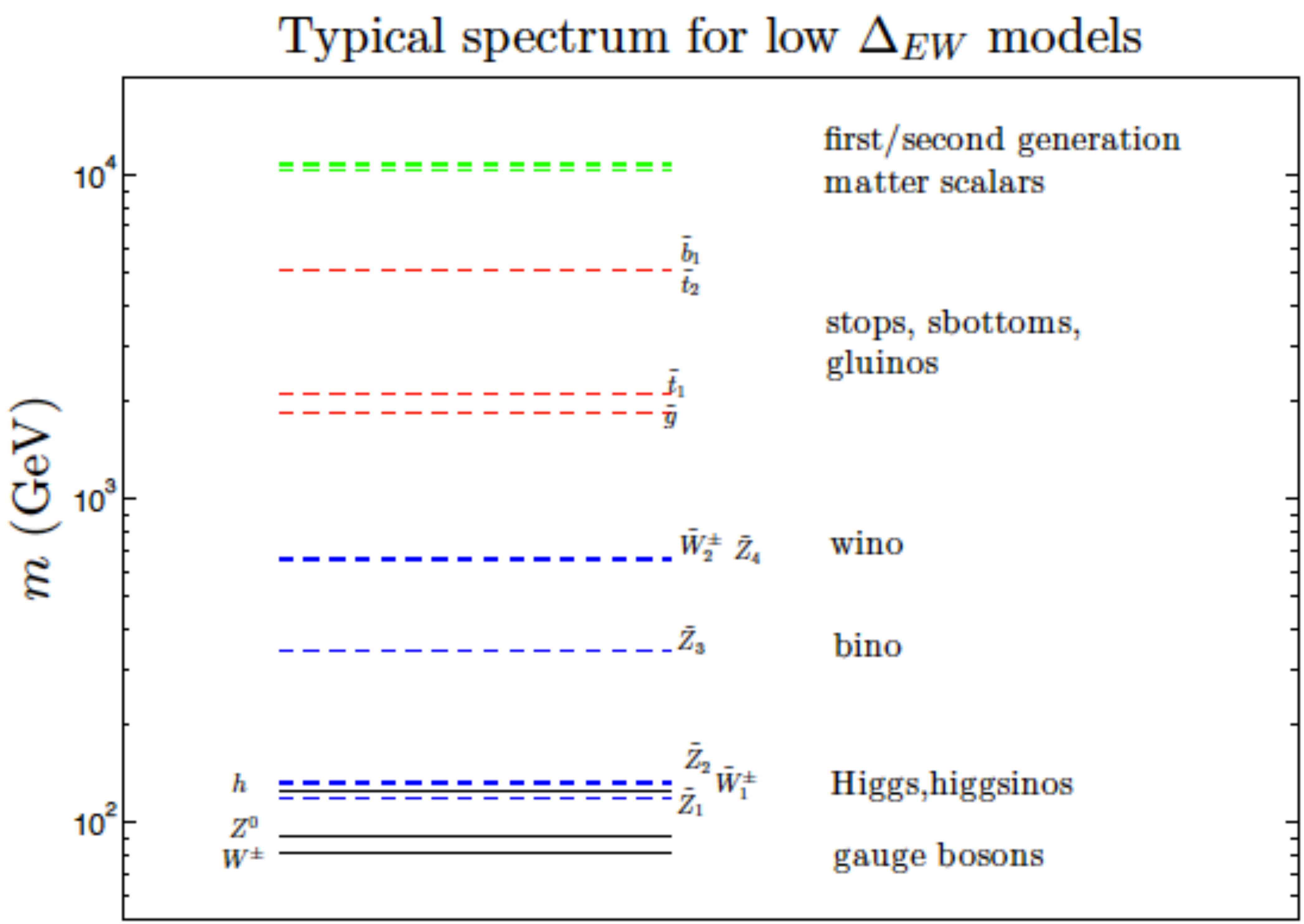


HB, Barger, Savoy

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!



There is a Little Hierarchy, but it is no problem

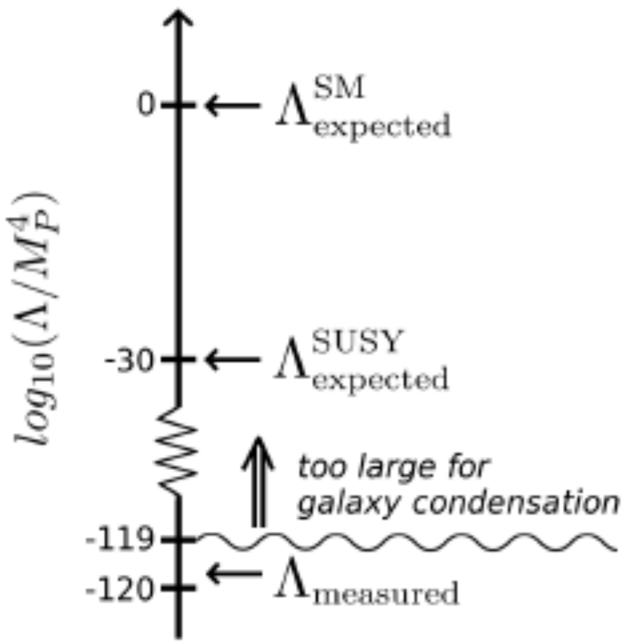
$\mu \ll m_{3/2}$ higgsinos likely the lightest superparticles!

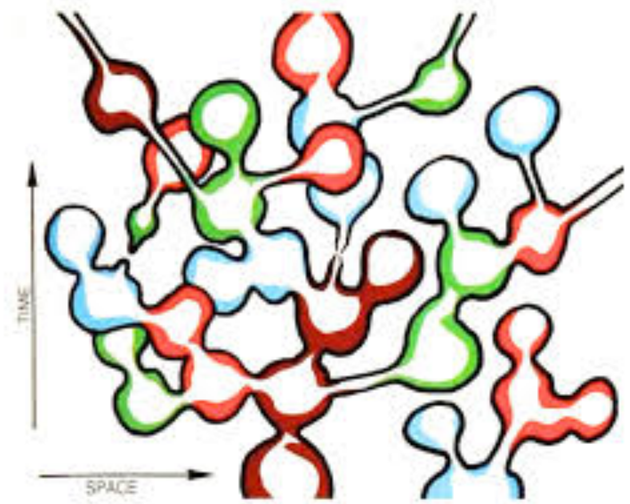
Takeaway lesson:
policy decisions for future accelerators
should not be based on
faulty naturalness estimates!

Take note: European strategy report
and US Snowmass/P5 reports!

How does this all relate to string landscape?

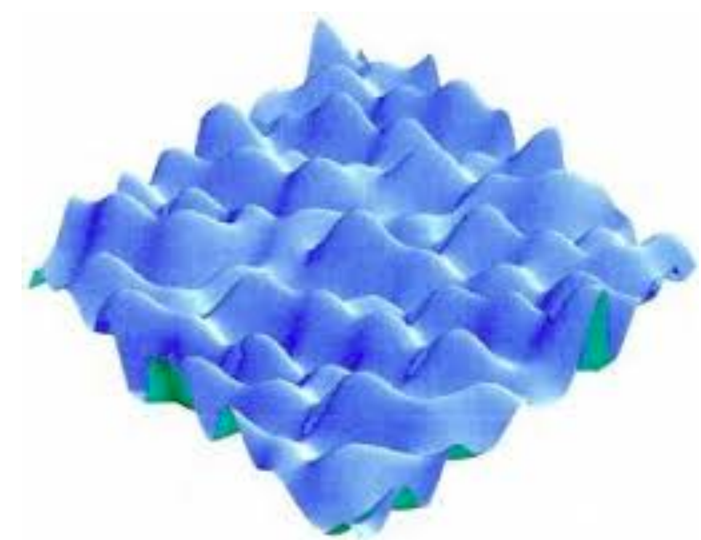
It is sometimes invoked that maybe we should abandon naturalness: after all, isn't the cosmological constant (CC) fine-tuned?





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

Apply similar reasoning to origin of weak scale (which arises from SUSY breaking in SUSY models):

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 in hidden sector via superHiggs mechanism via either F- or D- terms or in general a combination

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

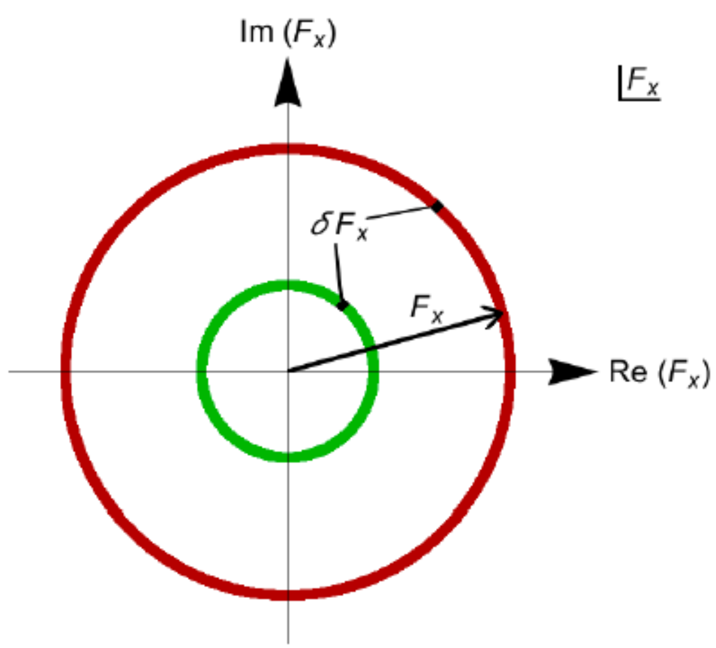


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

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

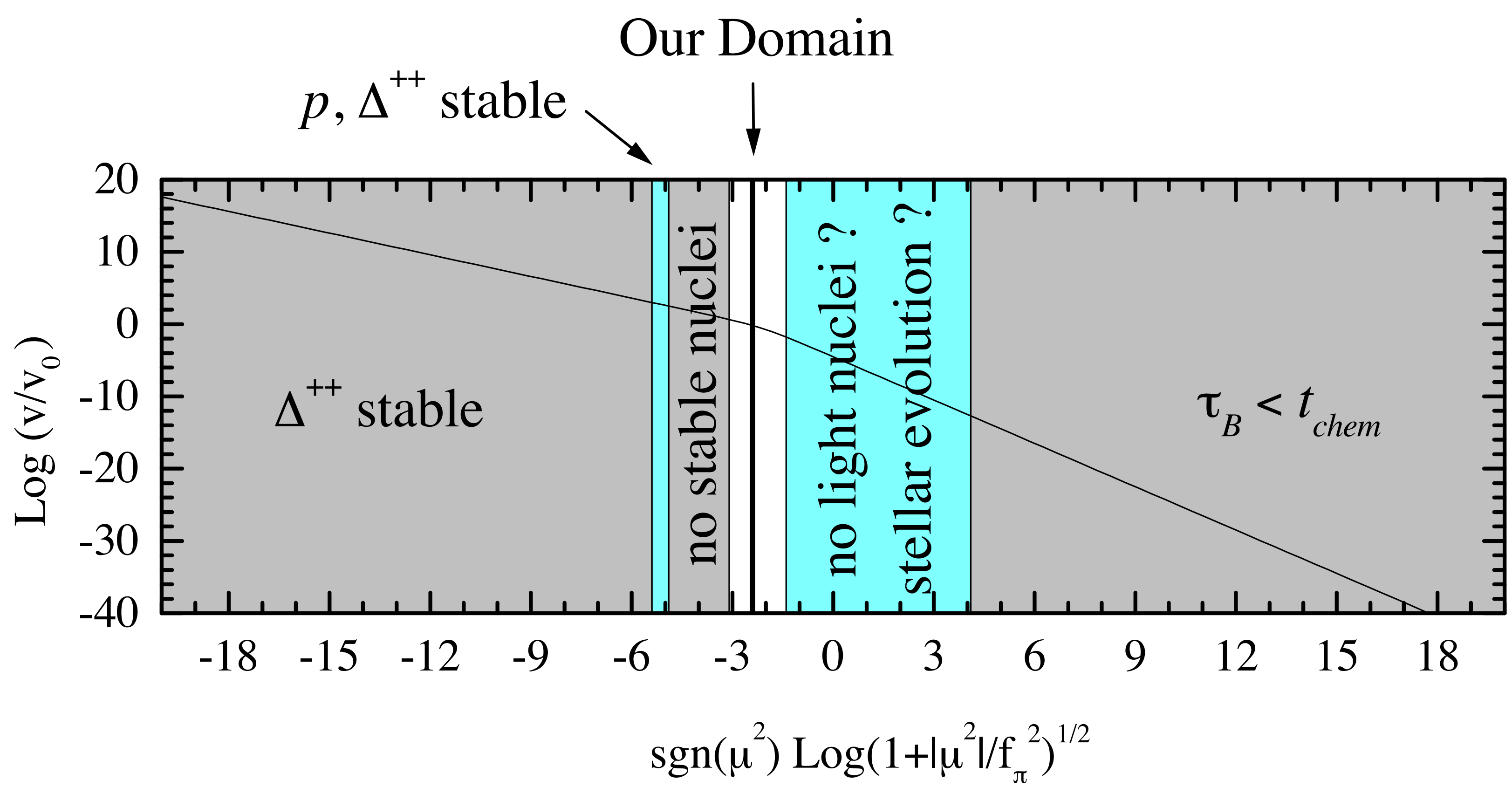
For uniform values of SUSY breaking fields, expect landscape to prefer high scale of SUSY breaking!

$$m_{hidden}^4 = \sum_i F_i F_i^\dagger + D_\alpha D_\alpha$$

What about f_selection ?

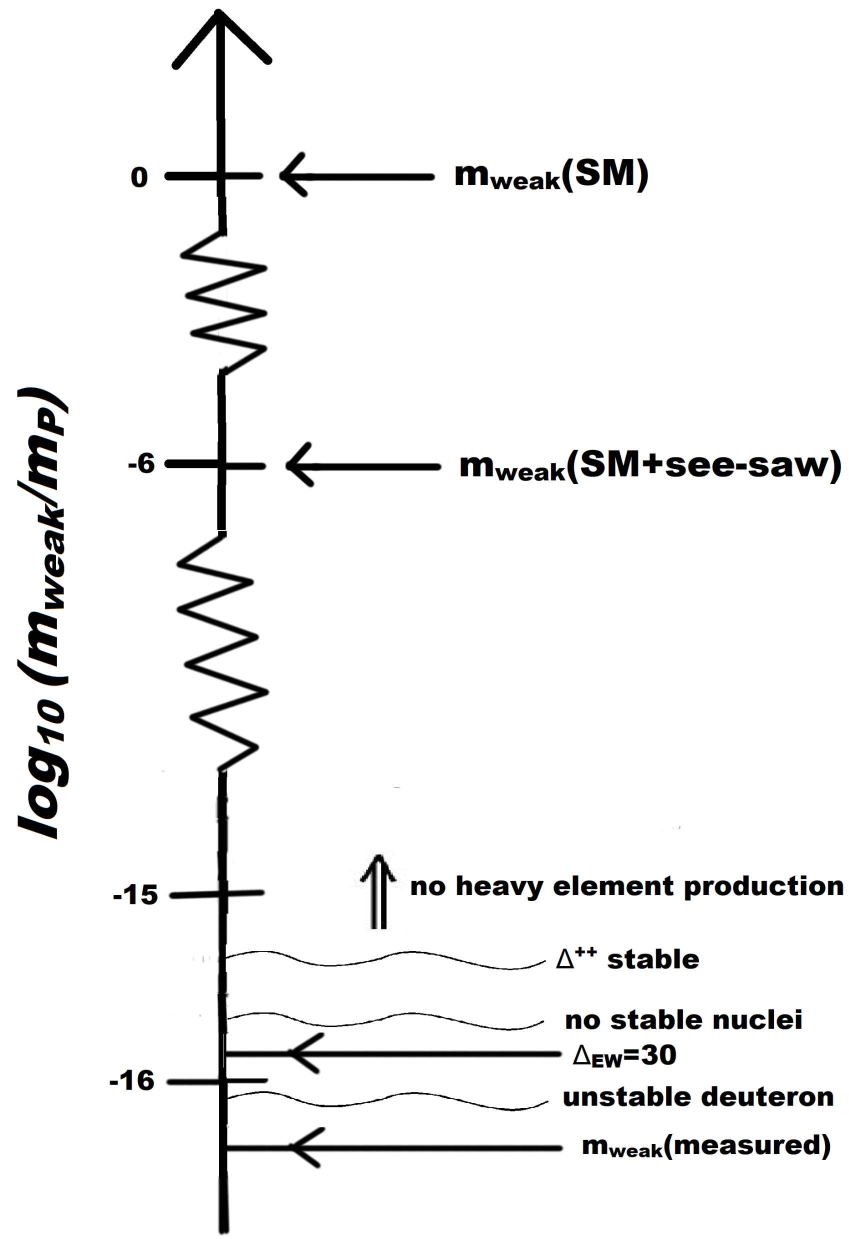
Agrawal, Barr, Donoghue, Seckel result (1998):

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)

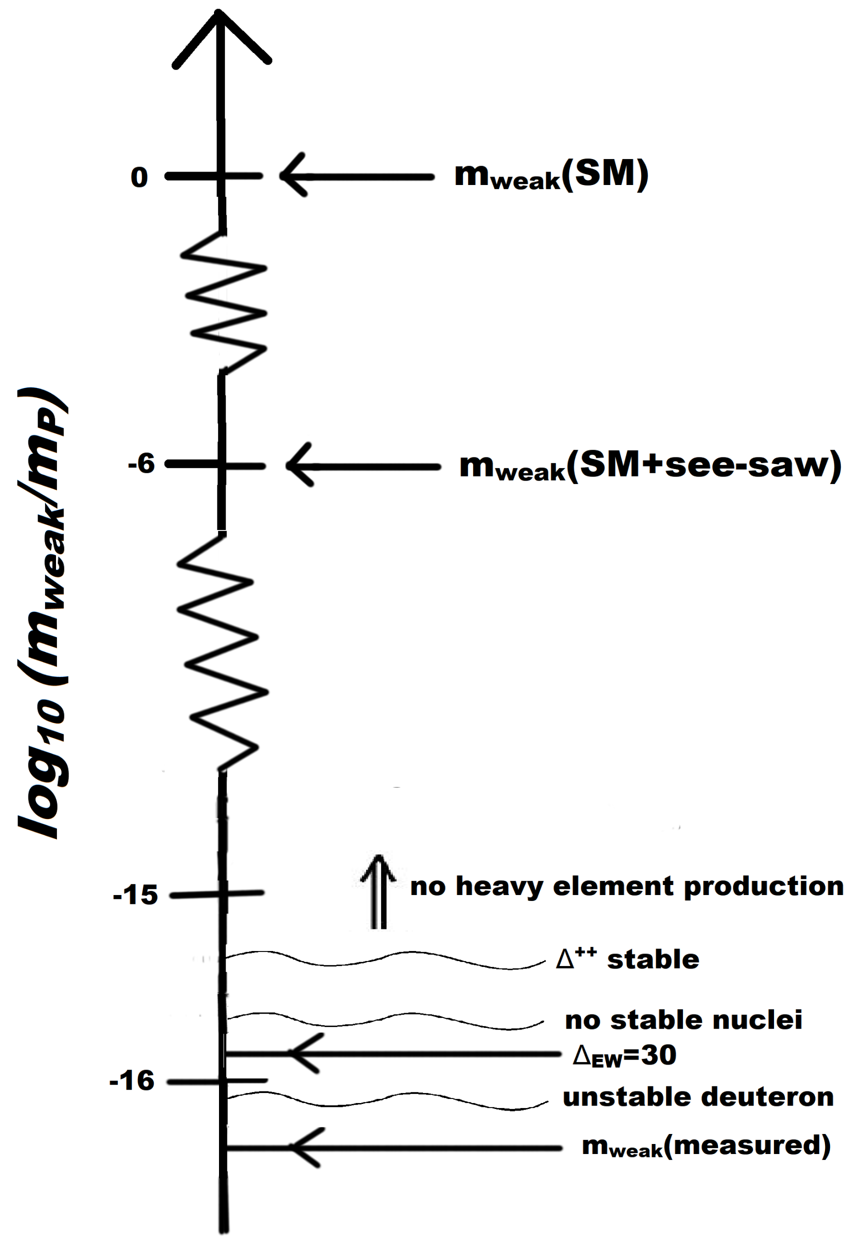


m(weak) must lie within ABDS window to have atoms/chemistry:
~50 GeV < m(weak) < ~350 GeV

ABDS window <=> DEW<~30

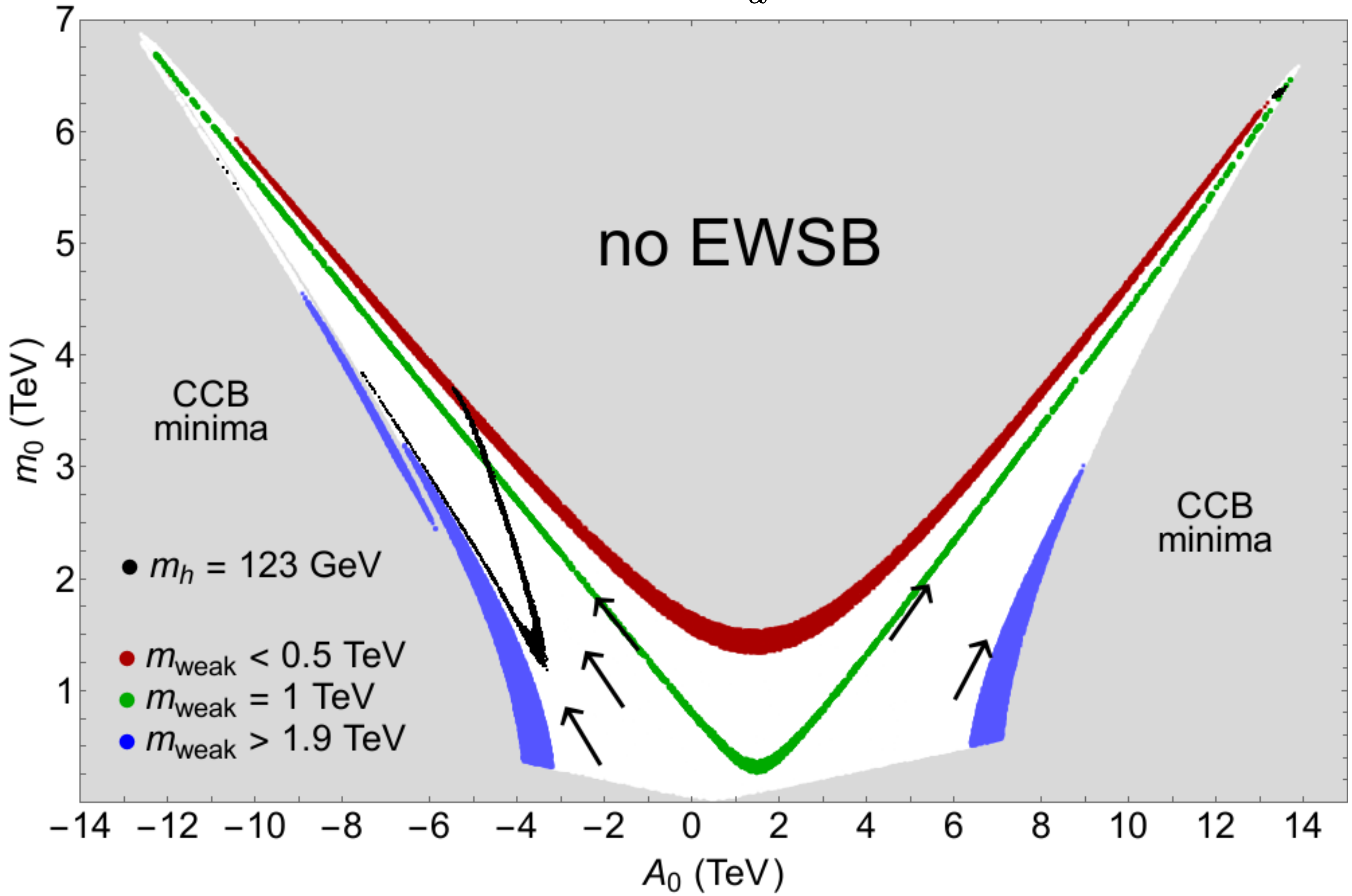


Veto pocket universes with CCB minima or minima leading to weak scale a (conservative) factor four greater than our value m(W,Z,h)~100 GeV



Veto pocket universes with CCB minima or noEWSB
or minima leading to weak scale a
(conservative) factor four greater
than our value m(W,Z,h)~100 GeV

$m_{H_u} = 1.3 m_0$



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^n_{soft} 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)

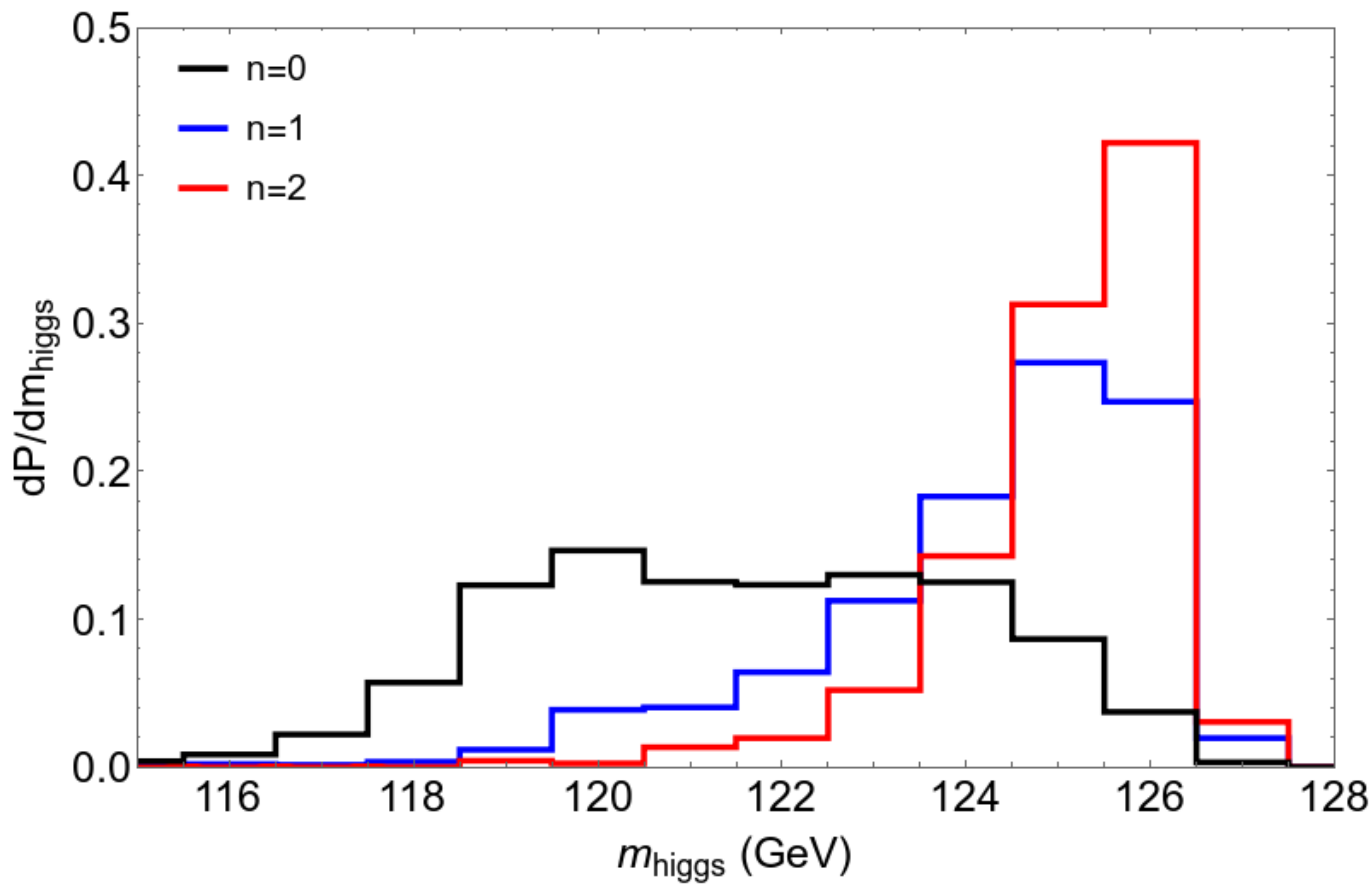
mu=150 GeV (fixed)

(then rescale to mZ=91.2 GeV to compare apples with apples)

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

Making the picture more quantitative:

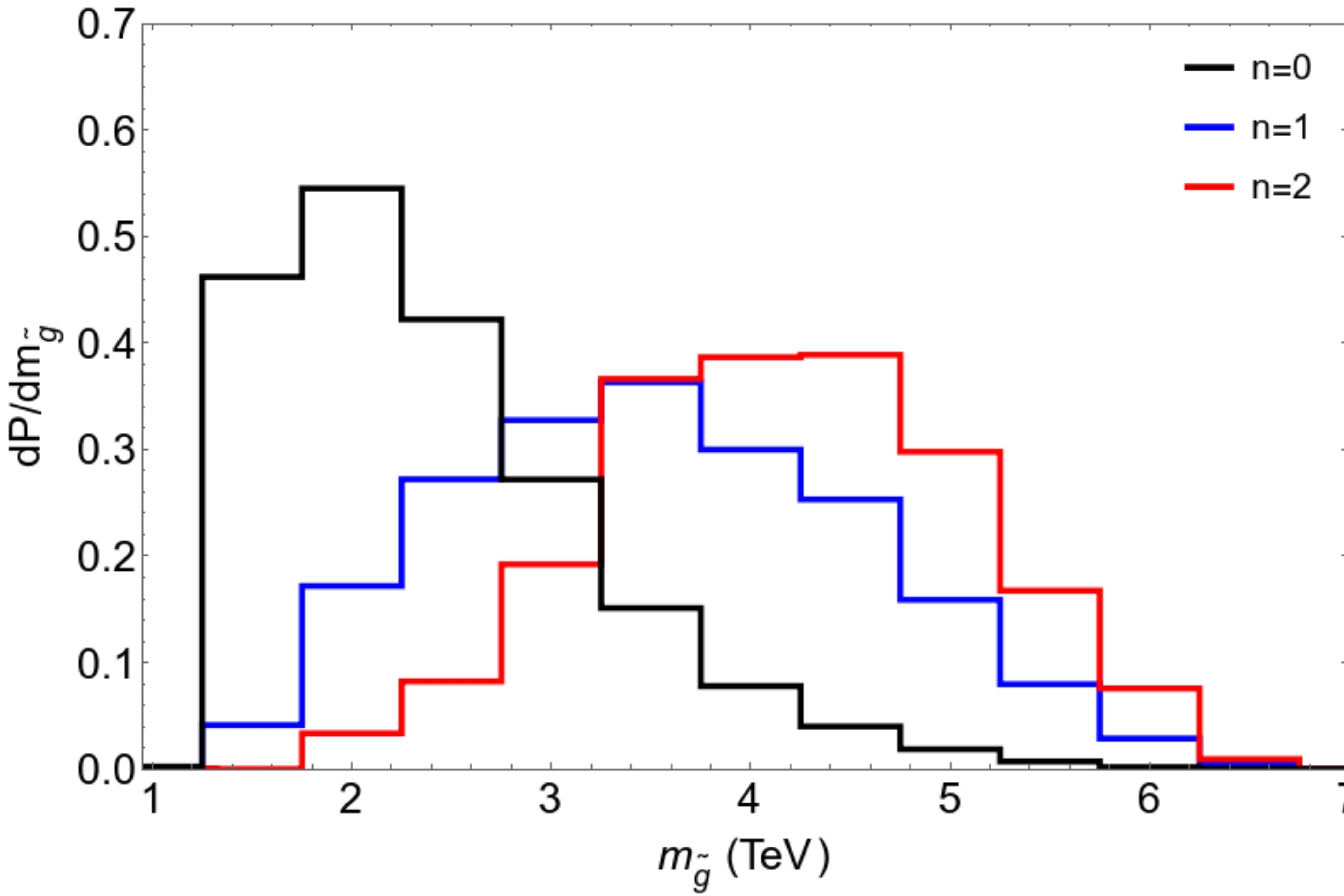
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



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

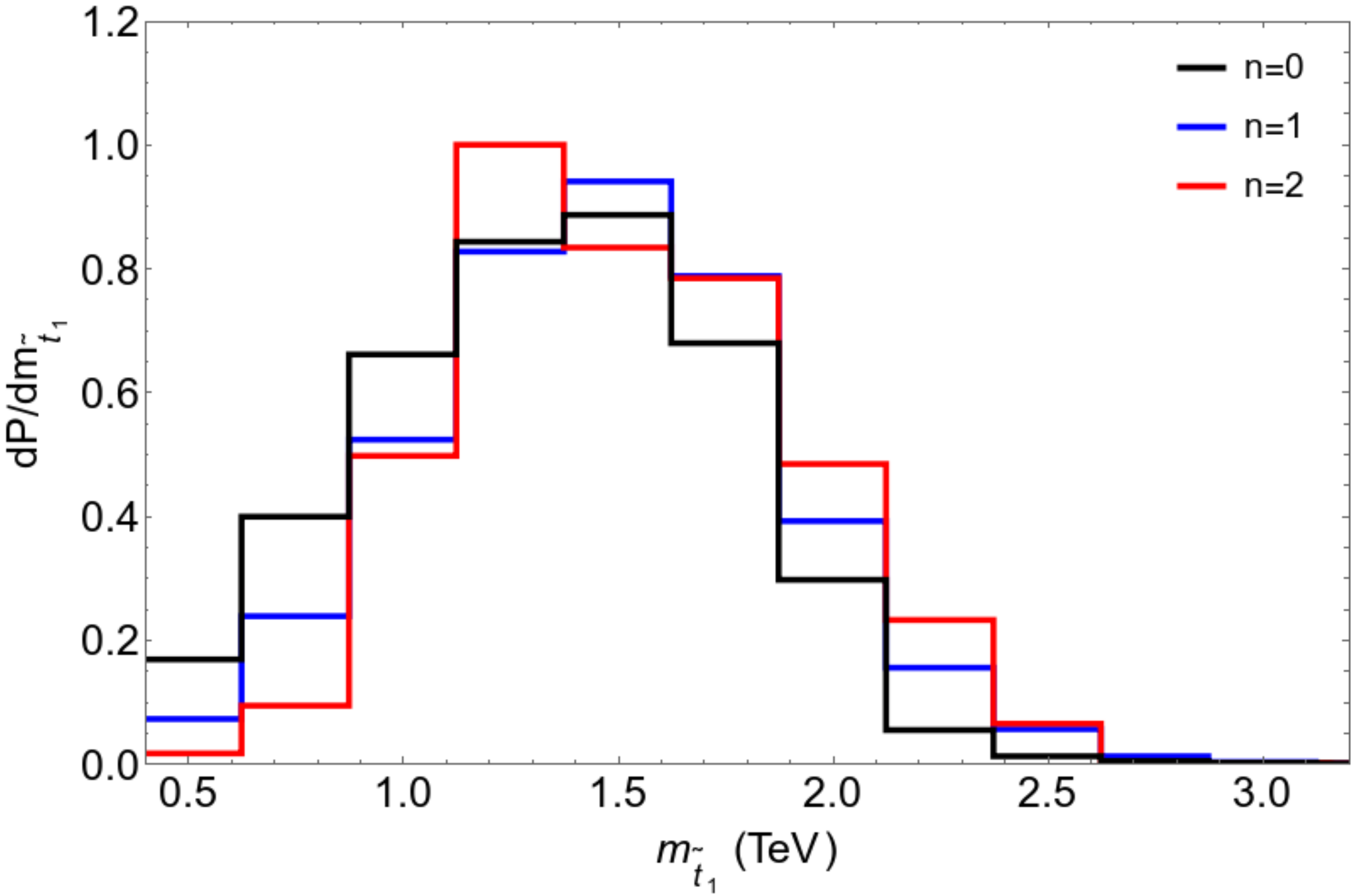
HB,Barger, Serce, Sinha

What is corresponding distribution for gluino mass?



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

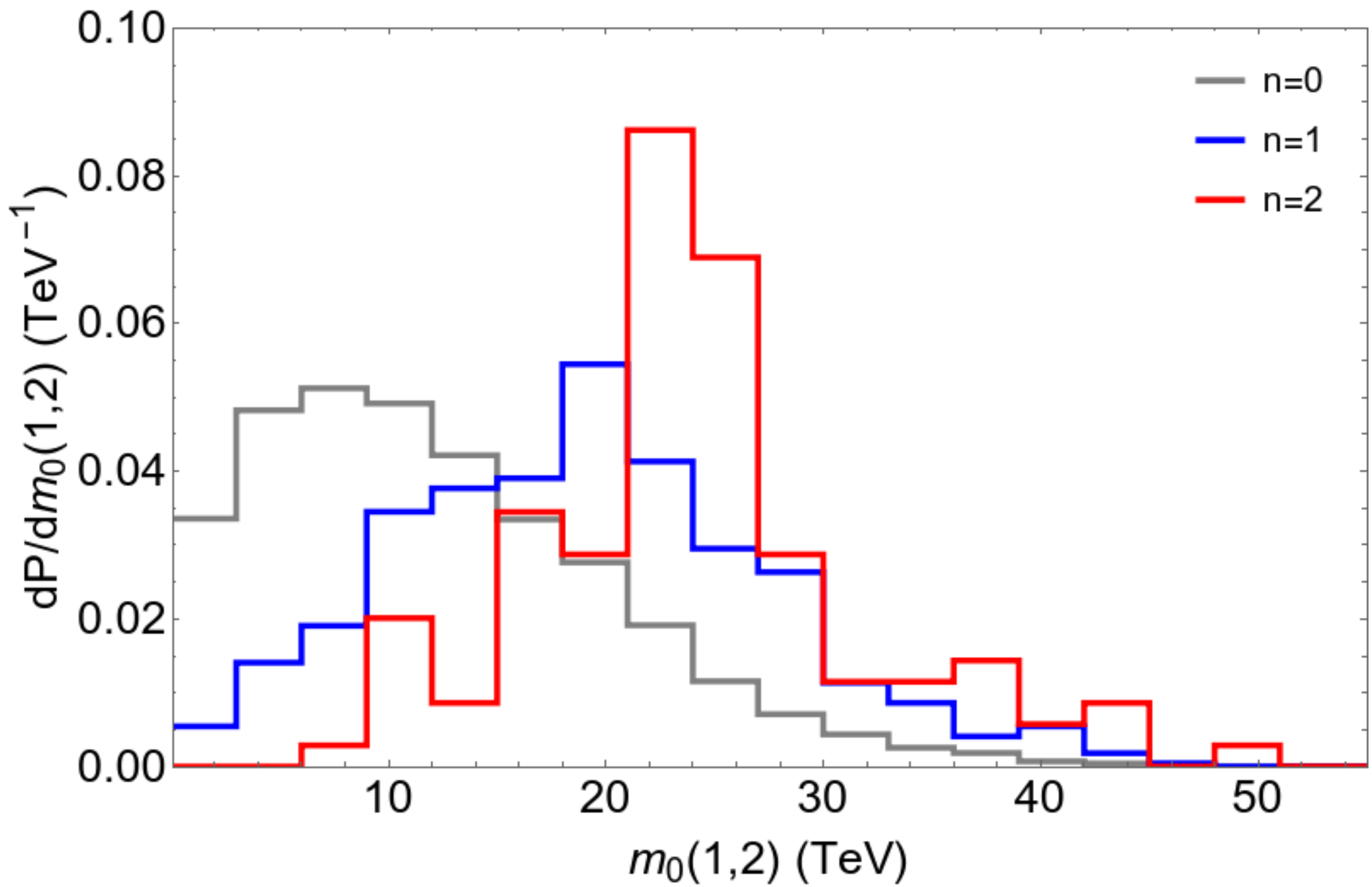
and top-squark mass m(t1)?



m(t1) typically beyond present LHC reach first/second generation sfermions pulled to 10-40 TeV:

landscape mixed decoupling/quasi-degeneracy sol'n
to SUSY flavor/CP problems

HB, Barger, Sengupta, arXiv:1910.00090



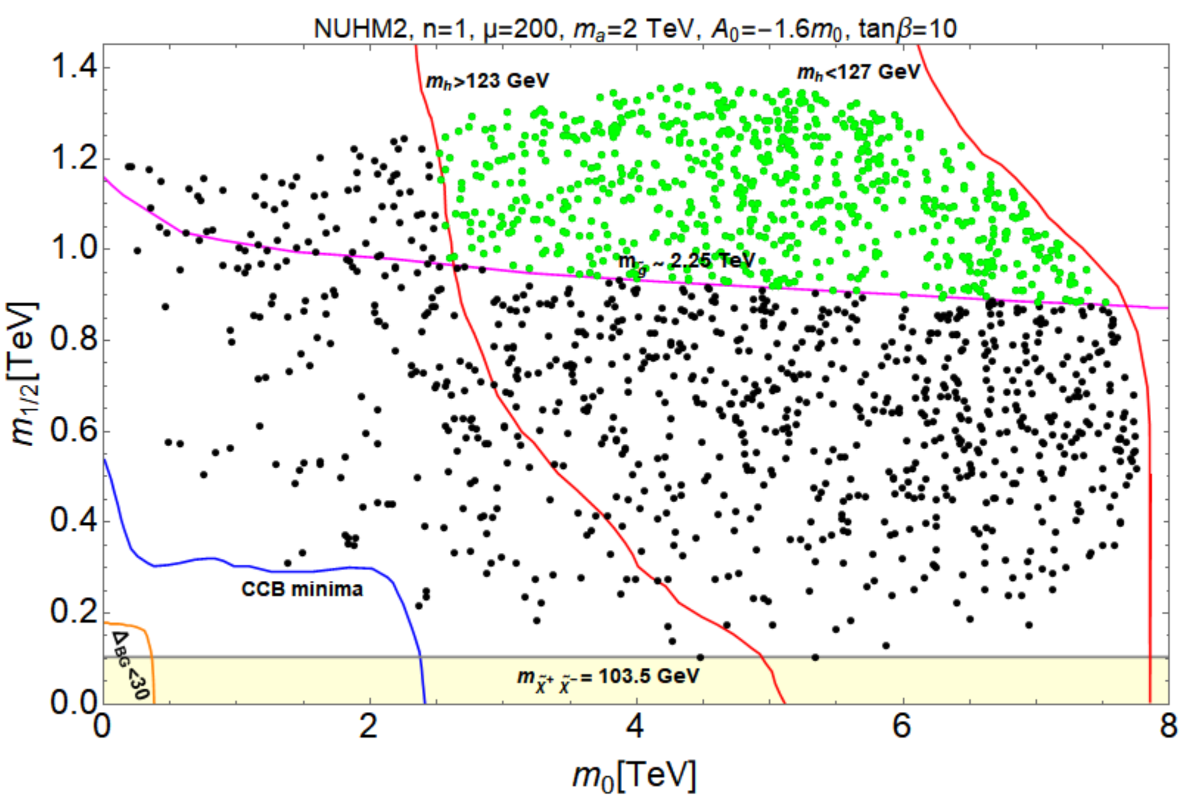
Stringy naturalness: higher density of points are more stringy natural!

conventional natural: favor low m0, mhf

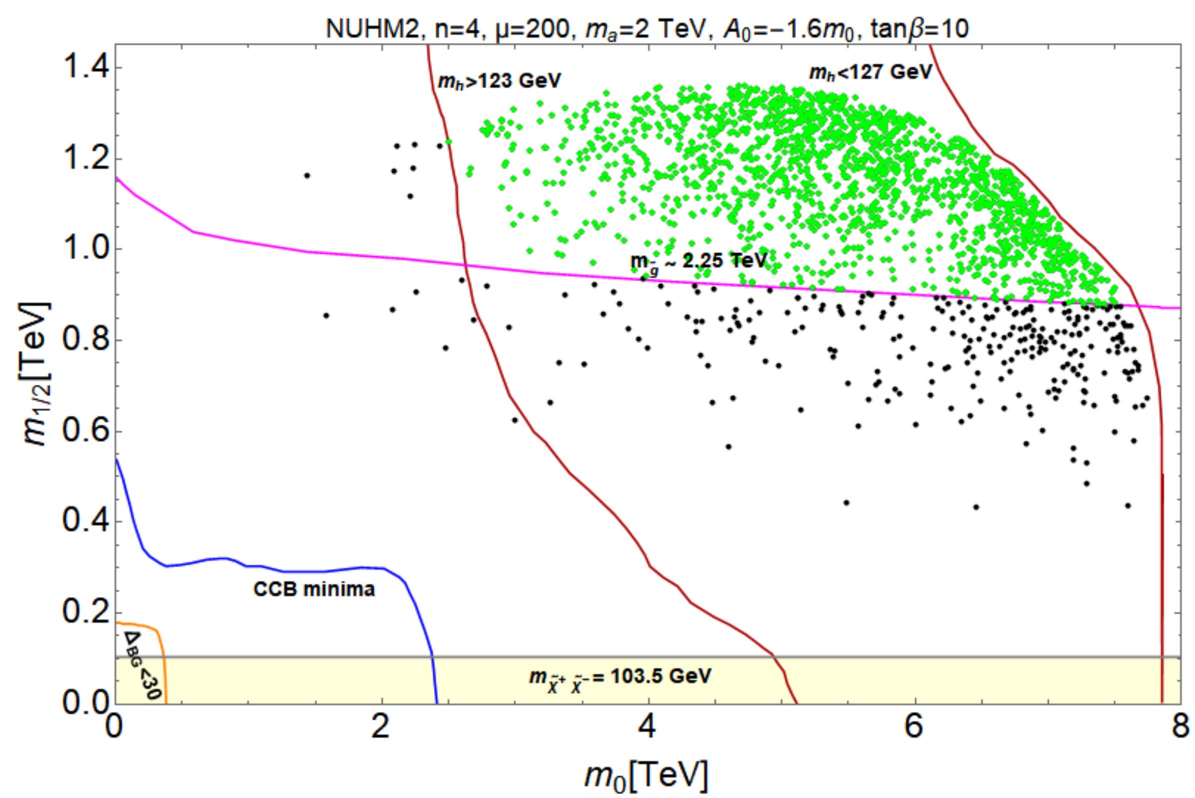
stringy naturalness: favor high m0, mhf so long as m(weak)~100 GeV

HB, Barger, Salam, arXiv:1906.07741

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



$$m(soft)^1$$

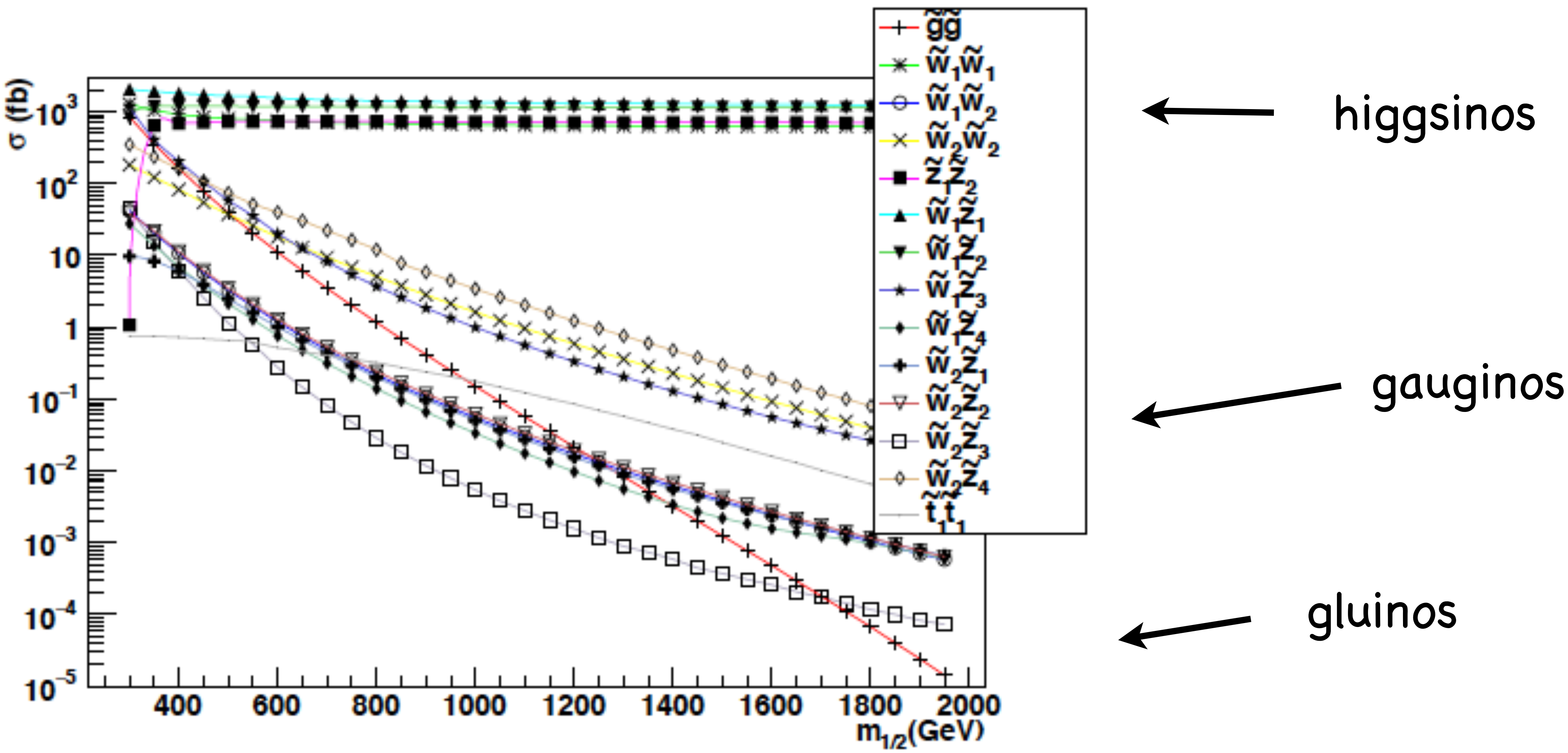


$$m(soft)^4$$

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

Prospects for discovering landscape/natural SUSY at LHC and ILC

Sparticle prod'n along Radiative Natural SUSY model-line at LHC14:



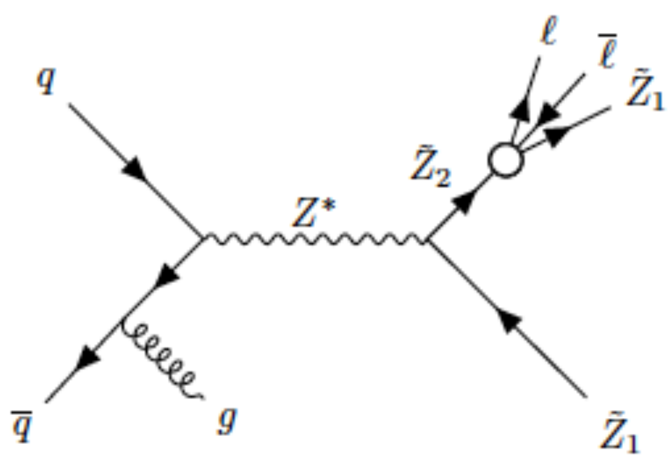
higgsino pair production dominant–but only soft visible energy release from higgsino decays

largest visible cross section: wino pairs

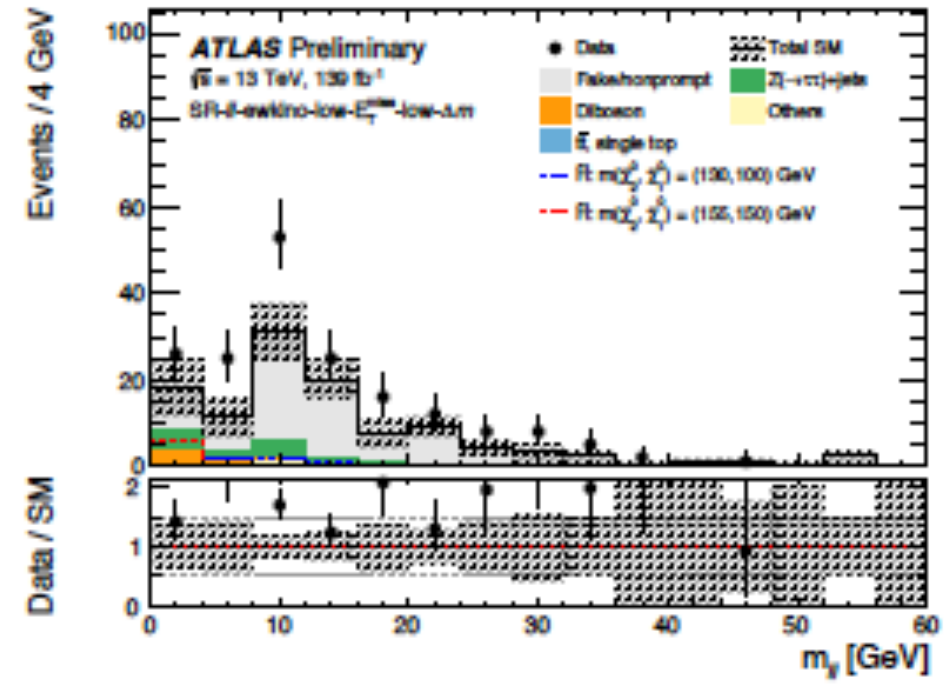
gluino pairs sharply dropping

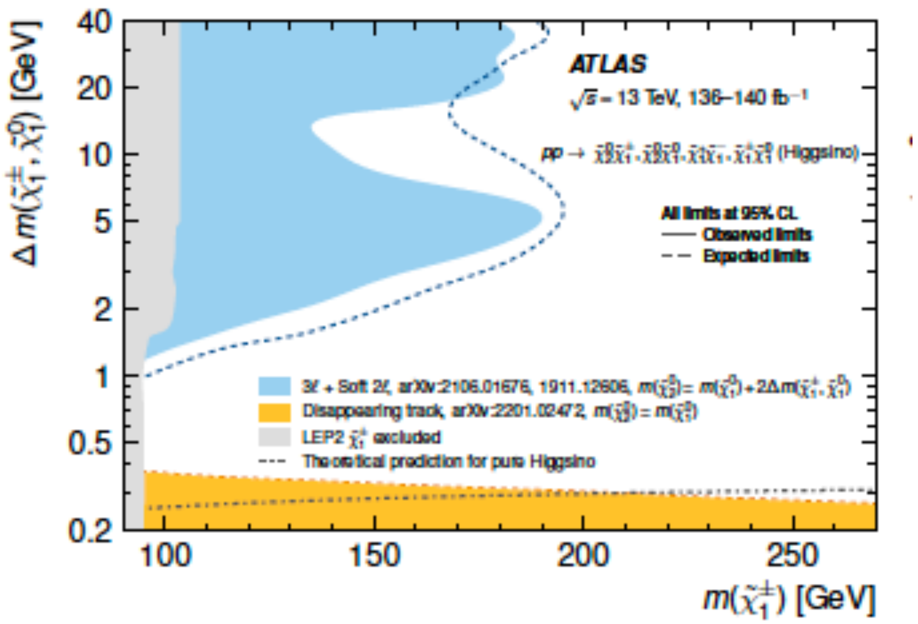
Natural SUSY: only higgsinos need lie close to weak scale

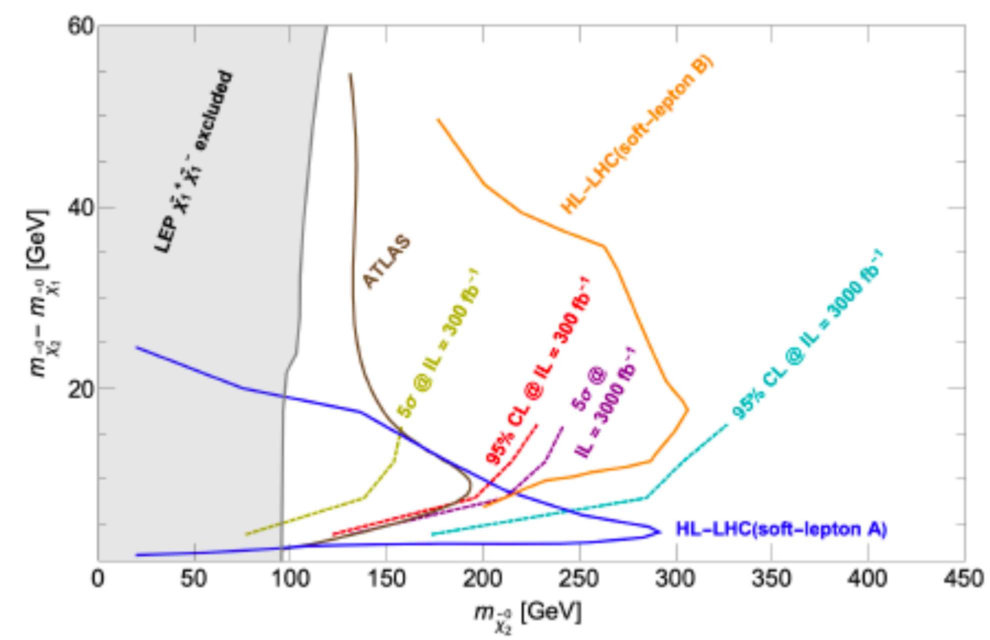
Soft dilepton+jet+MET signature from higgsino pair production



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;
HB, Barger, Salam, Sengupta, Tata,2007.09252;
HB, Barger, Sengupta, Tata, 2109.14030



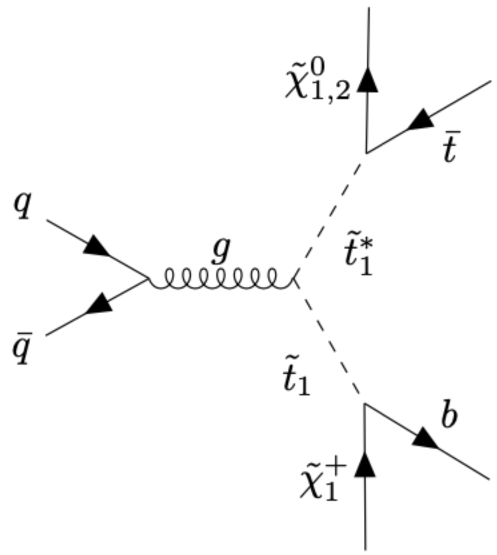


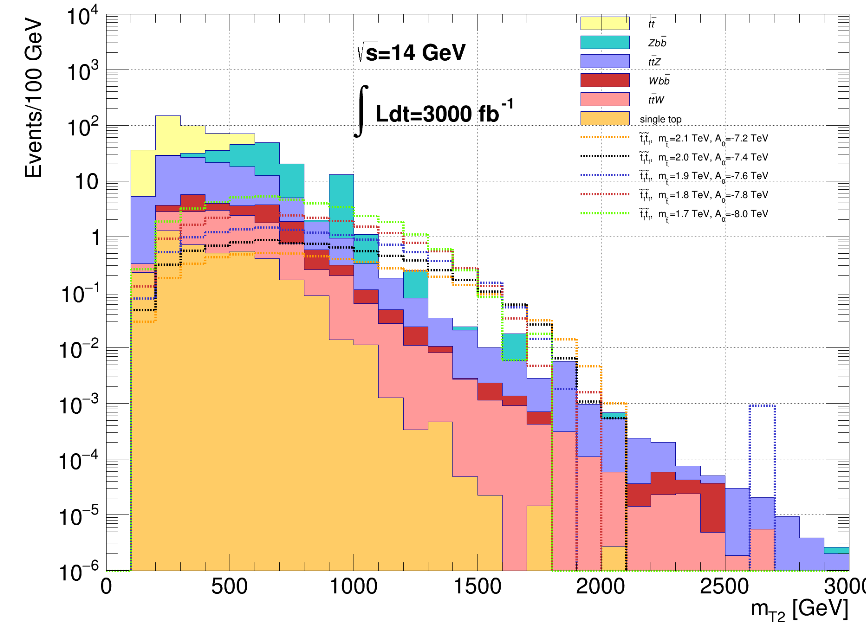


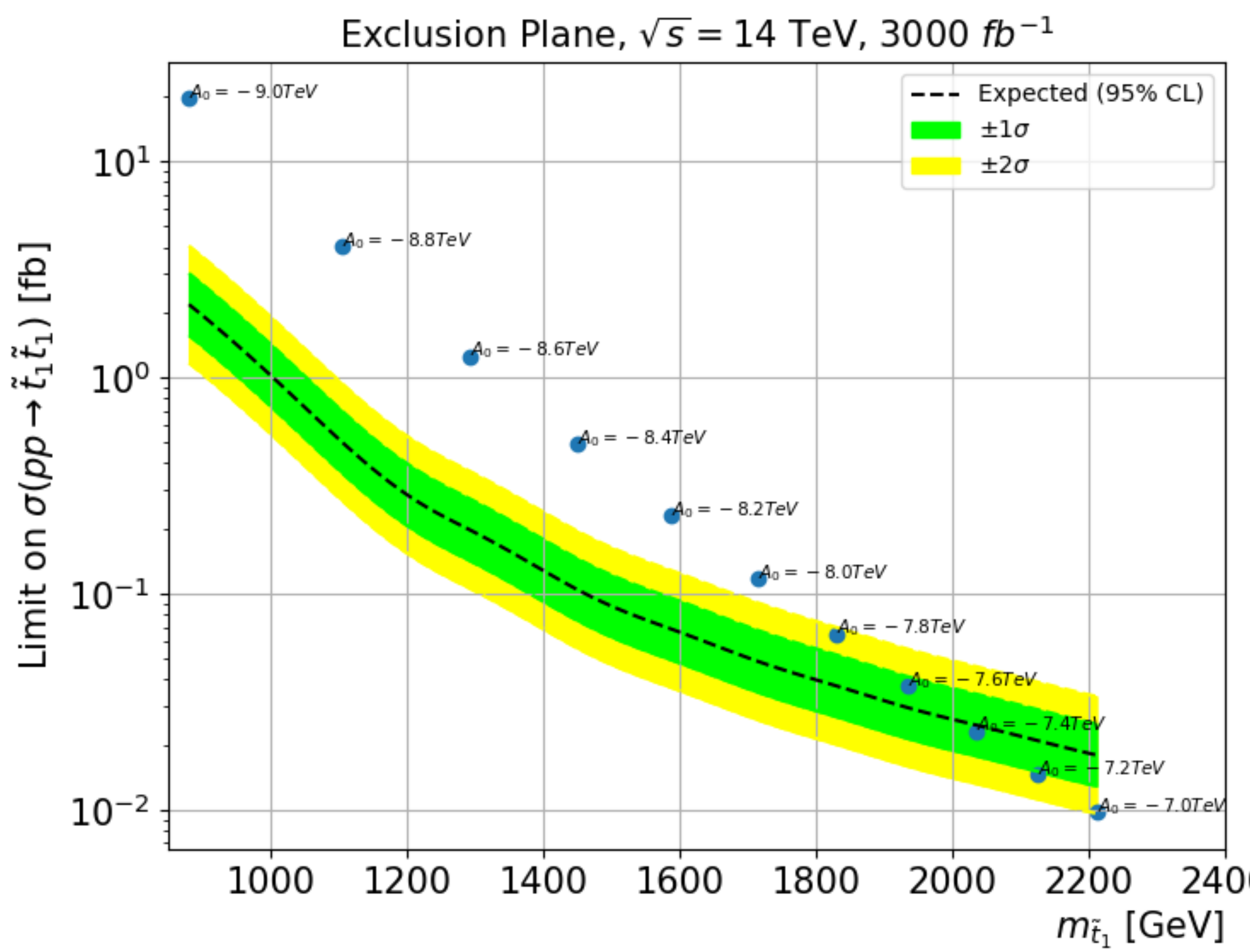
It appears that HL-LHC can see much (but not all) of natural SUSY p-space; signal in this channel should emerge slowly as more integrated luminosity accrues

ATLAS/CMS: 2-sigma excess from Run 2!

top-squark pair production:



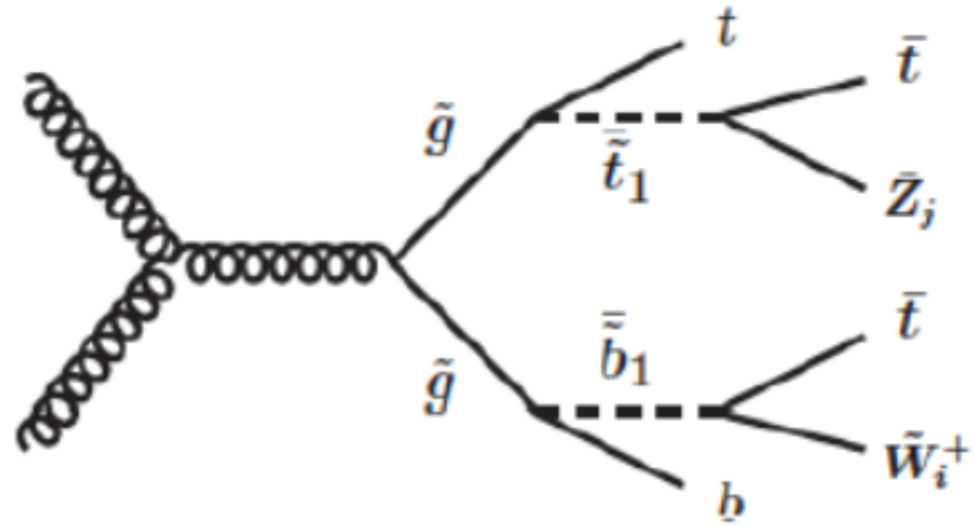




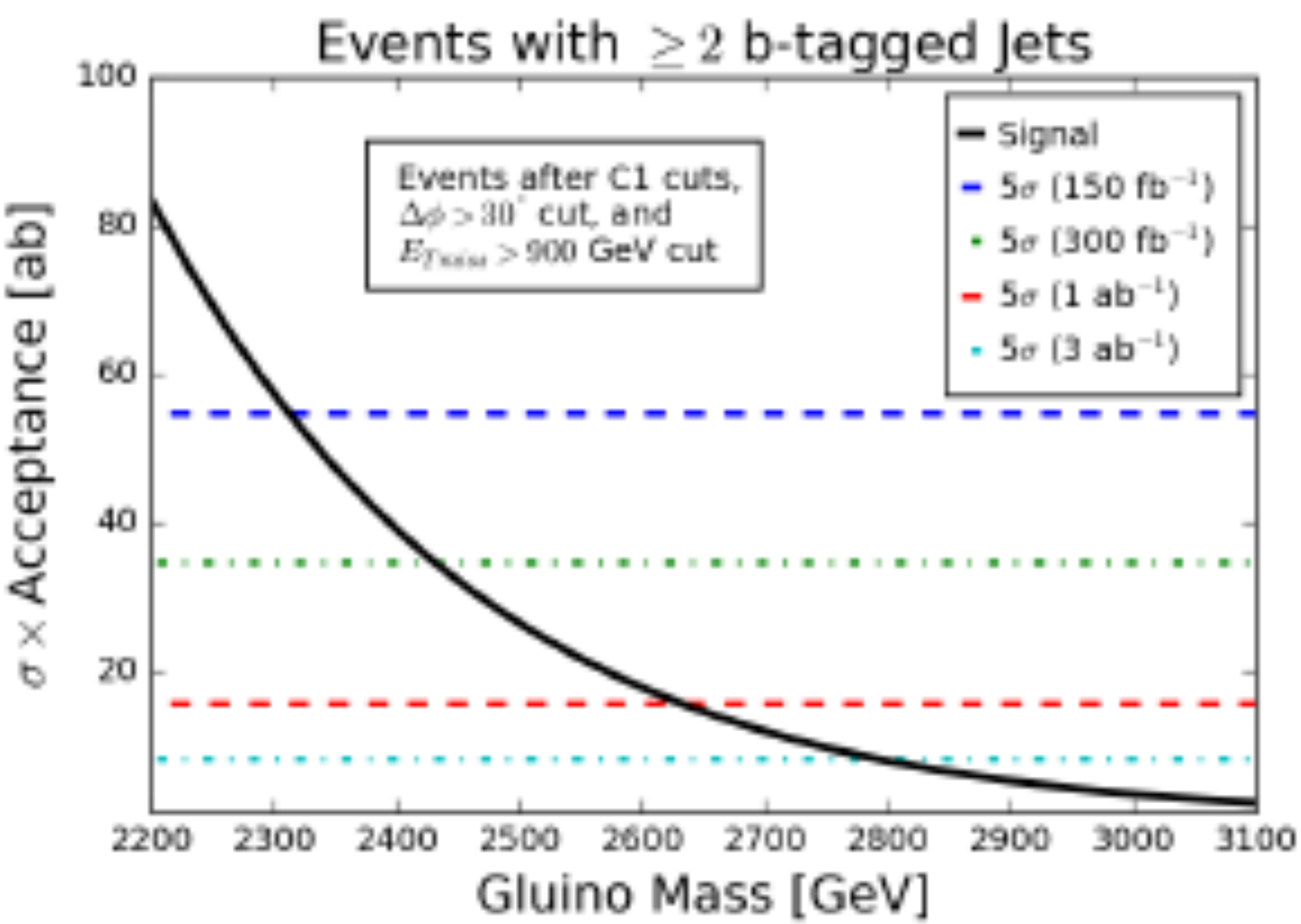
HL-LHC can see
m(t1)~1.7-2 TeV
@5sigma/ 95% CL

HB, Barger,
Dutta, Sengupta, Zhang

gluino pair cascade decay signatures



LHC14

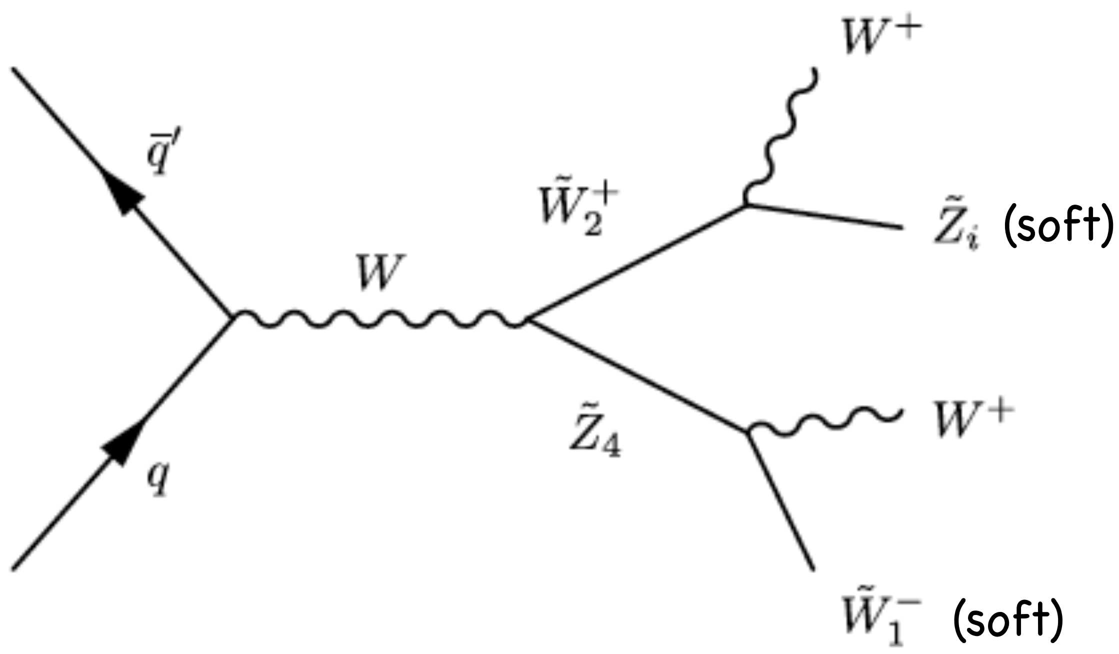


HB, Barger, Gainer, Huang, Savoy, Sengupta,Tata

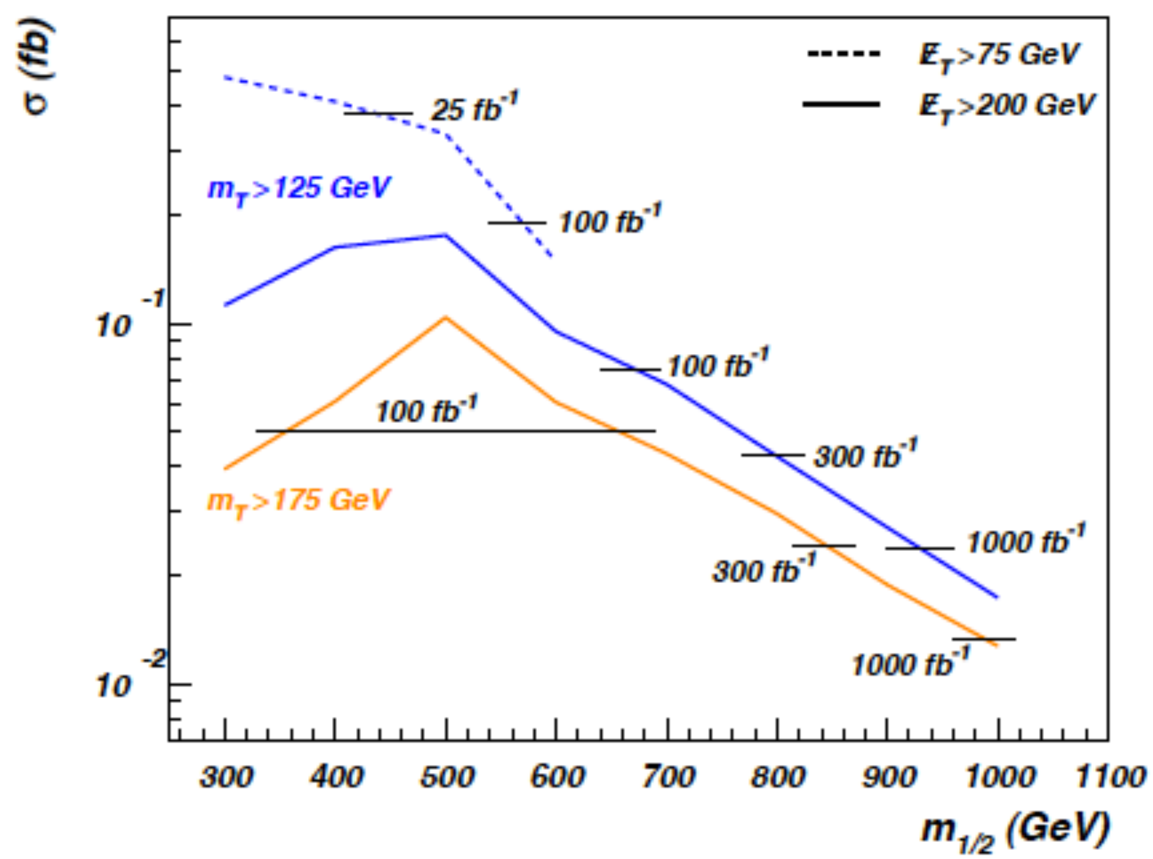
HL-LHC to probe m(gl)~2.8 TeV

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

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



wino pair production



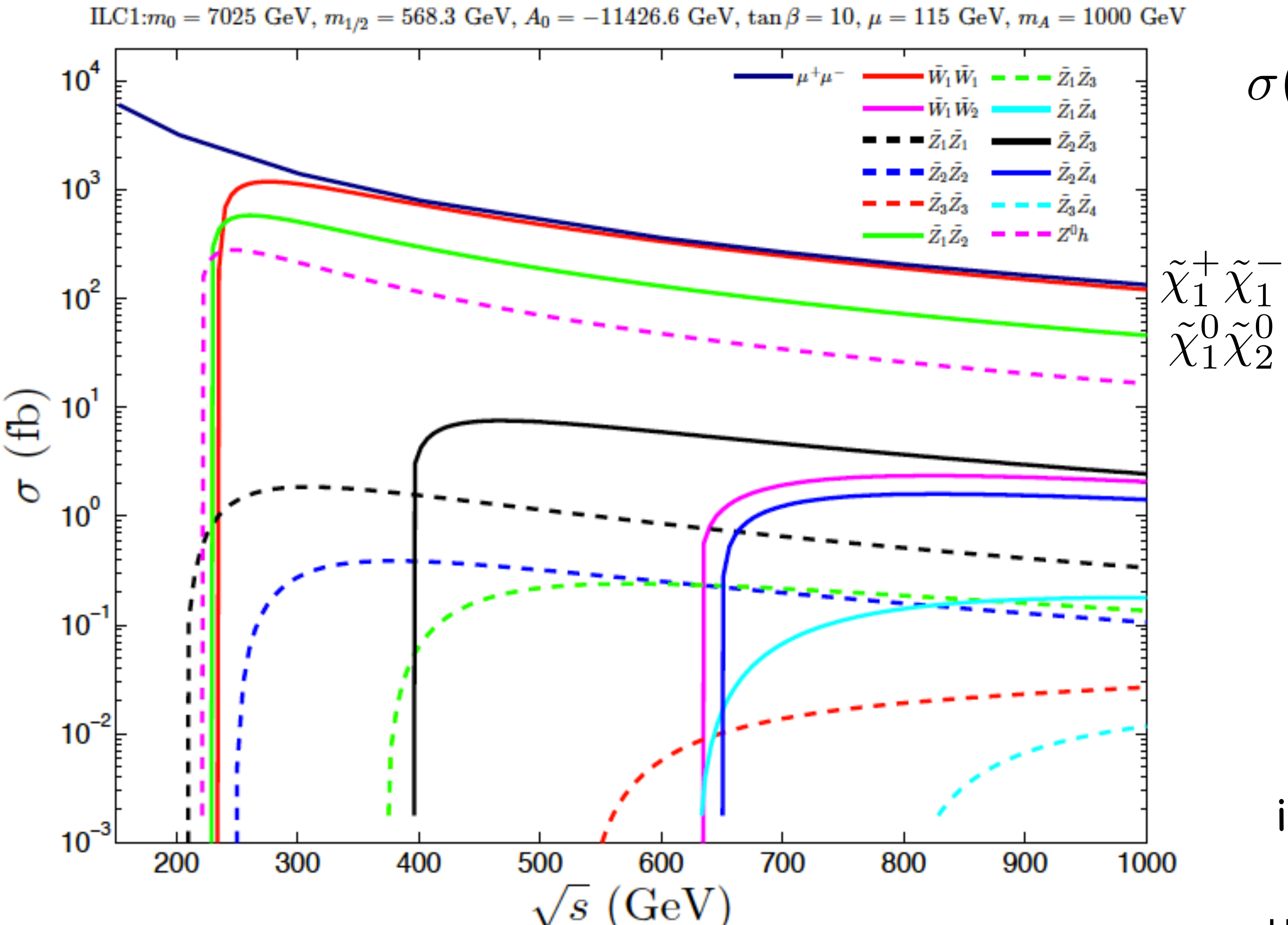
This channel offers added reach of LHC14 for natSUSY; it is also indicative of wino-pair prod'n followed by decay to higgsinos

So far: no distinct ATLAS/CMS analysis

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

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



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

3-15 GeV higgsino mass gaps no problem in clean ILC environment

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

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to (\ell\nu_\ell\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$$

measure $m(jj) < m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and $E(jj)$

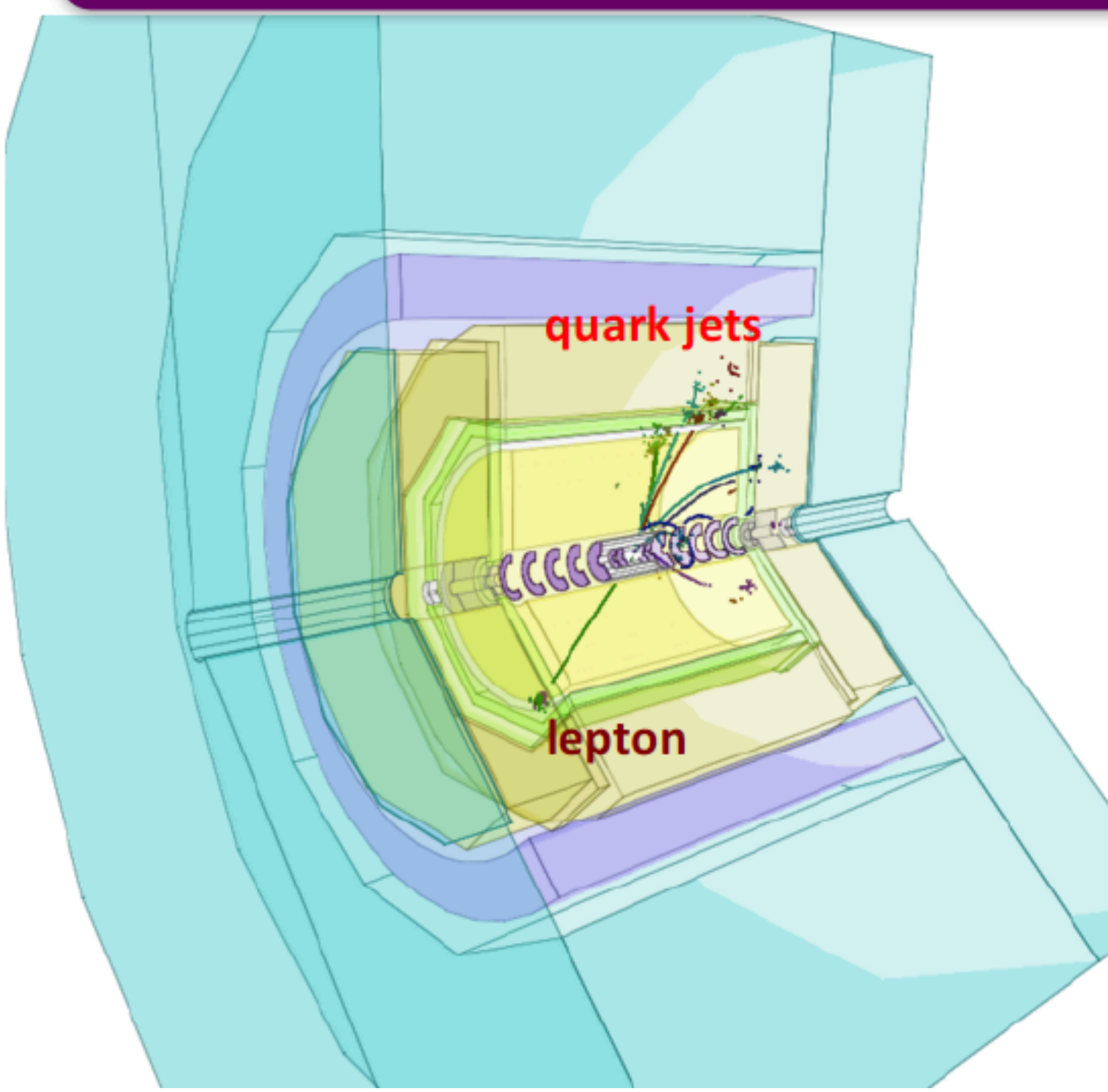
soft visible particles since small higgsino mass gaps

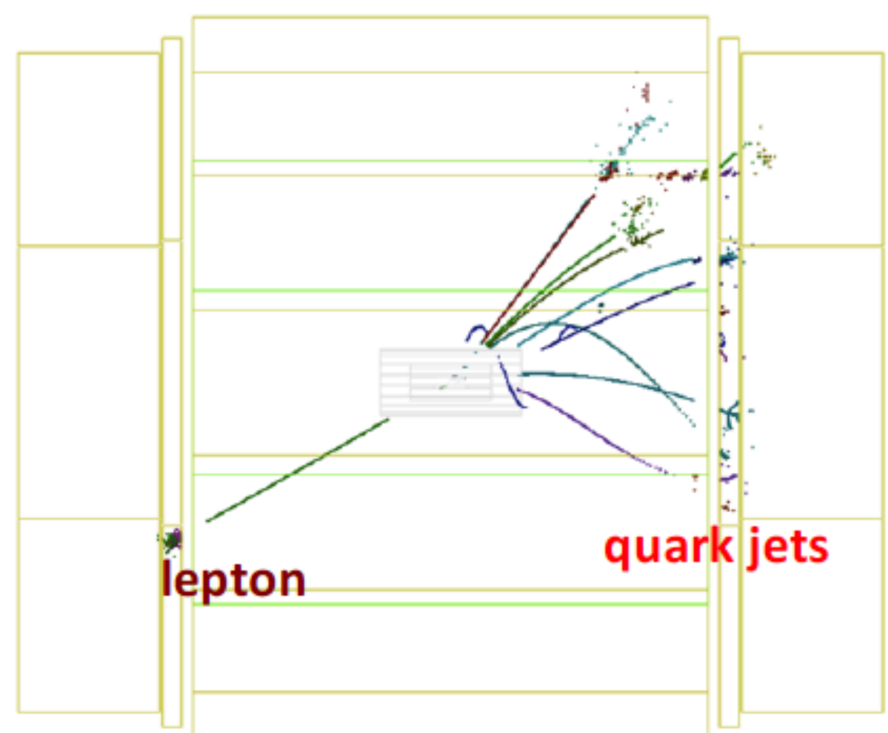
How do these signals look in the detector? (2)

$\sqrt{s}$ =500 GeV

Chargino pair production with semileptonic decay

$$e^+e^- \to \tilde{\chi}_1^+\,\tilde{\chi}_1^- \to \tilde{\chi}_1^0\,\tilde{\chi}_1^0 q q'\ell\nu$$





HB, Berggren, Fujii, List, Lehtinen, Tanabe, Yan, arXiv: 1912.06643

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + (\ell^+\ell^-\tilde{\chi}_1^0)$$

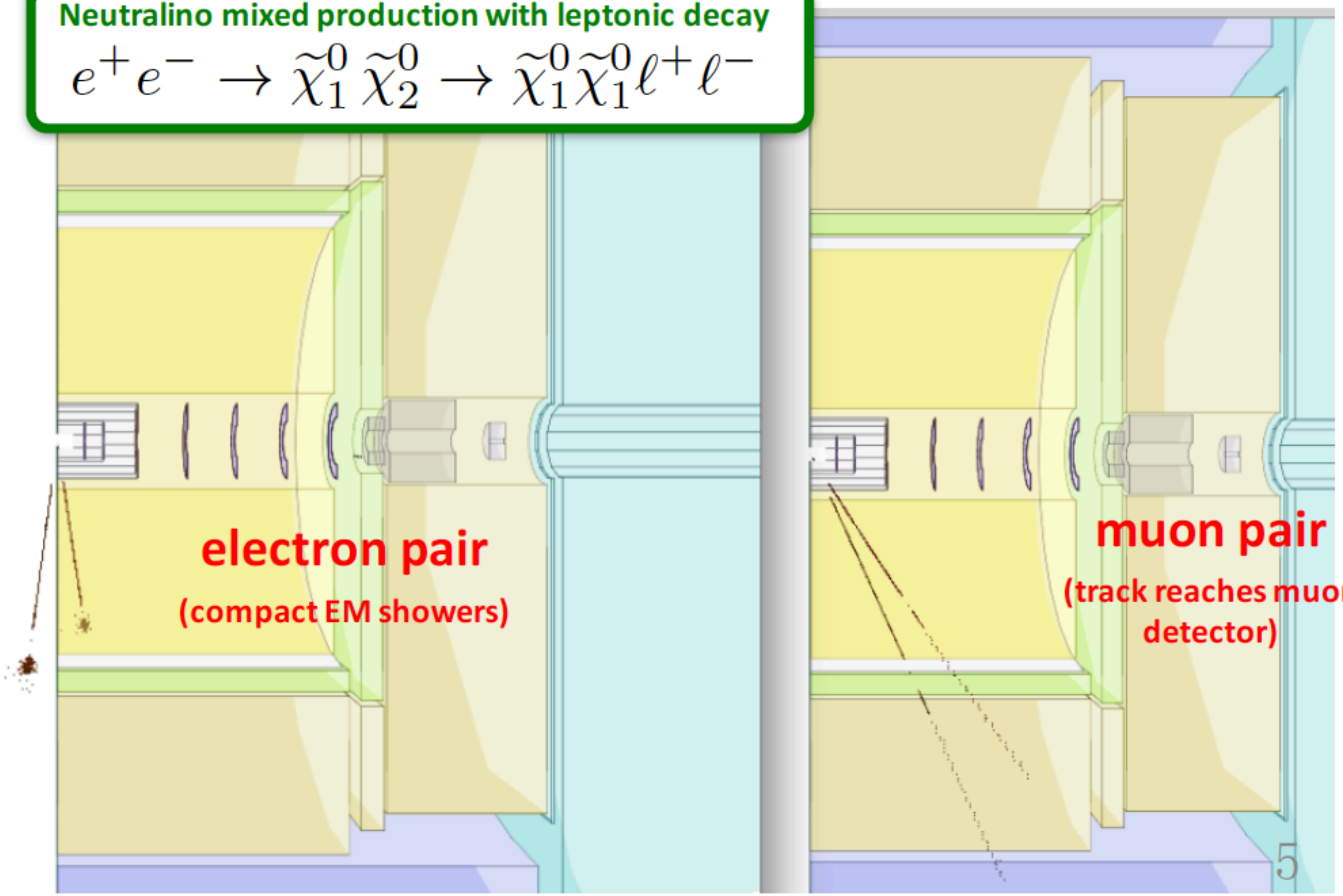
measure $m(\ell^+\ell^-) < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ and $E(\ell^+\ell^-)$

How do these signals look in the detector? (1)

√s =500 GeV

Neutralino mixed production with leptonic decay

$$e^+e^- \to \widetilde{\chi}_1^0\,\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0\ell^+\ell^-$$



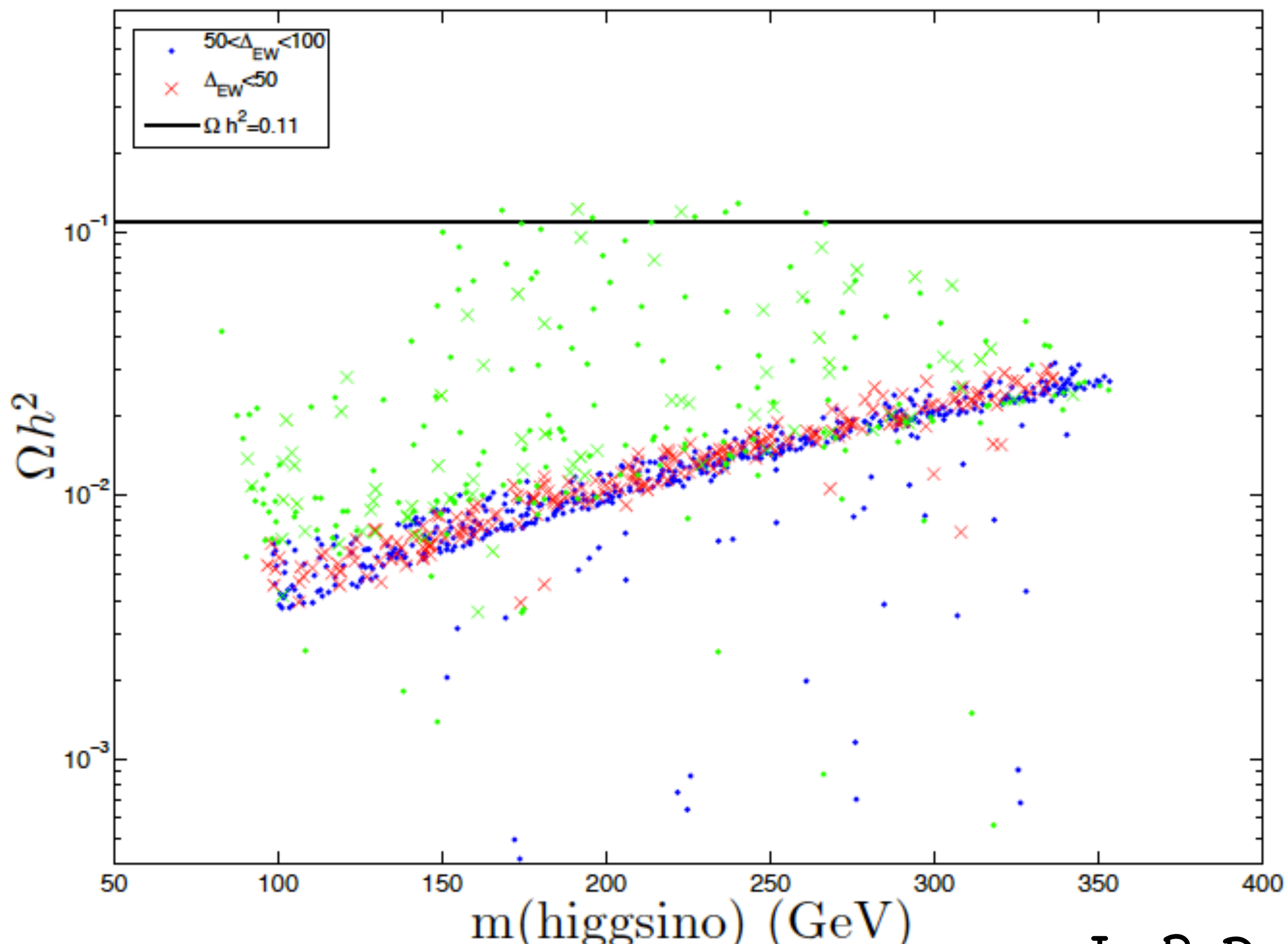
HB, Berggren, Fujii, List, Lehtinen, Tanabe, Yan, arXiv: 1912.06643

For further reading:

- The string theory landscape, Bousso & Polchinski, Sci. Am. 291 (2004) 60-69
- Midi-review: Status of weak scale supersymmetry after LHC Run 2 and ton-scale noble liquid WIMP searches, HB, Barger, Salam, Sengupta, Sinha, arXiv: 2002.03013

Dark matter from SUSY with radiatively-driven naturalness

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

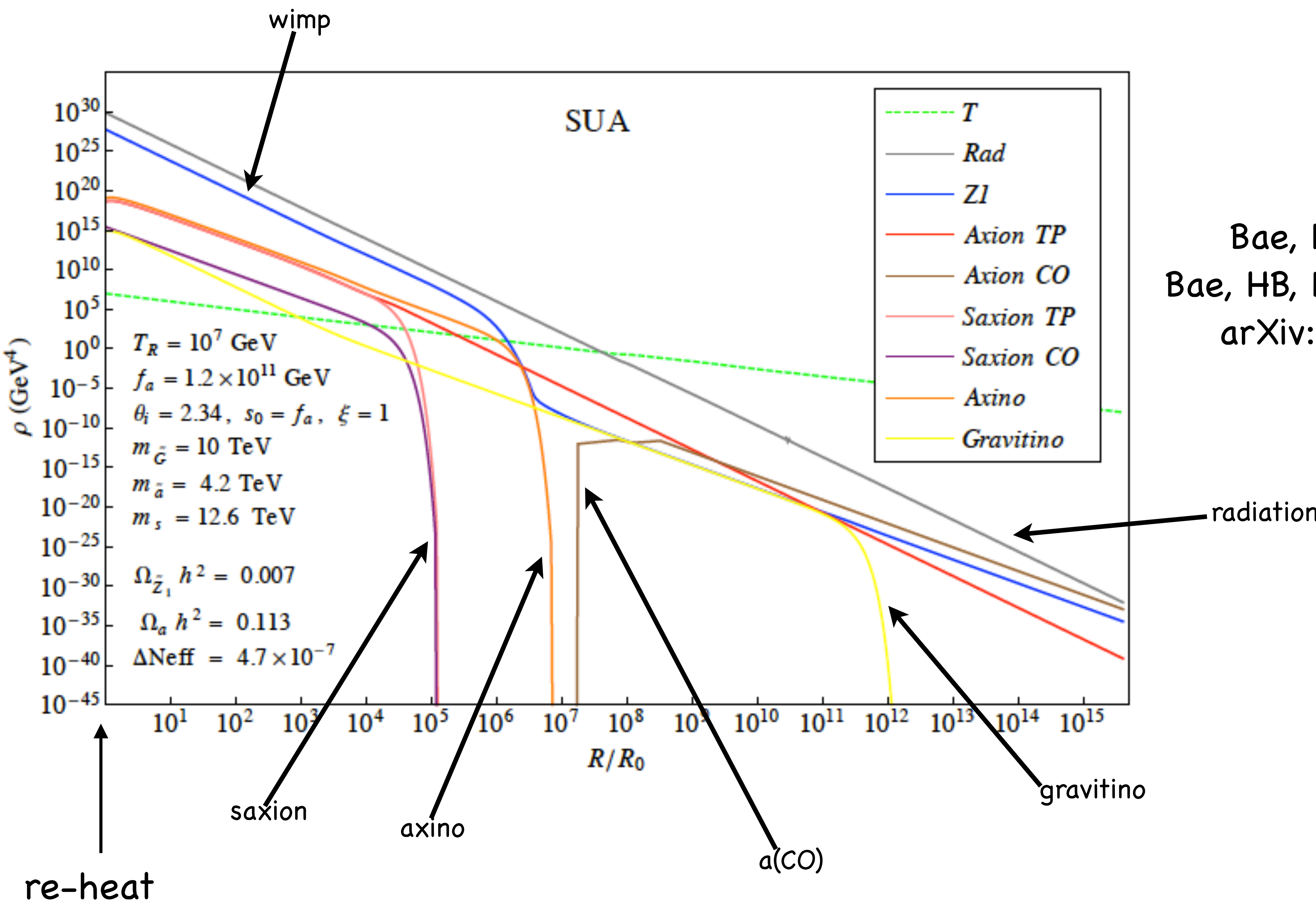
In SUSY, axion accompanied by axino and saxion

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

mixed axion-neutralino production in early universe: 2 CDM particles

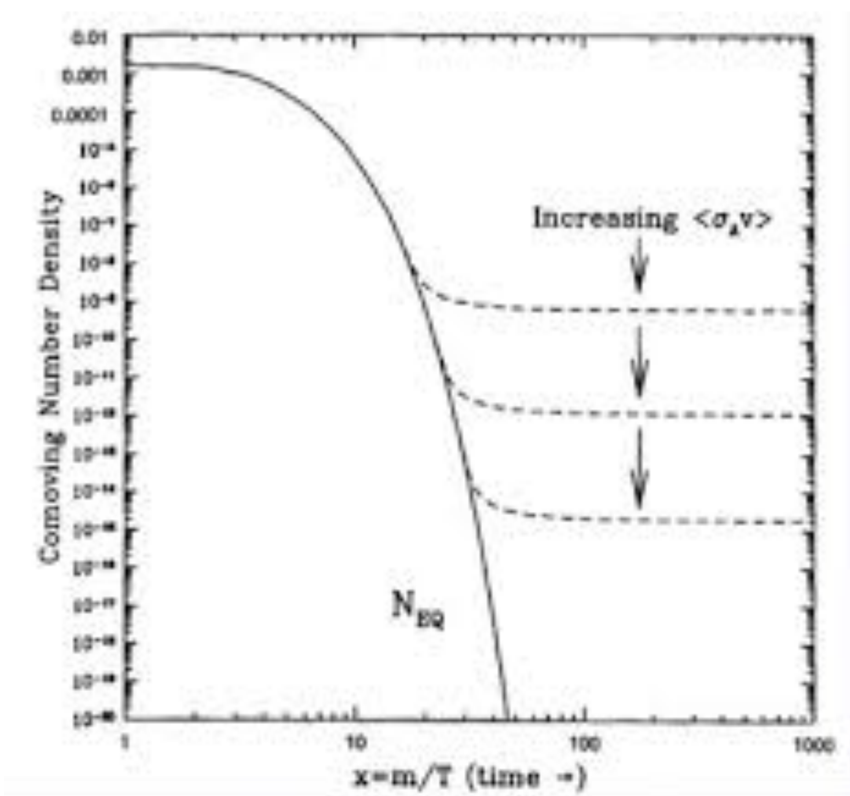
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: dark radiation ($\Delta N_{eff} < 1.6$)
- axinos: TP
  - $\tilde{a} \to SUSY$ augments neutralinos
- gravitinos: TP, decay to SUSY

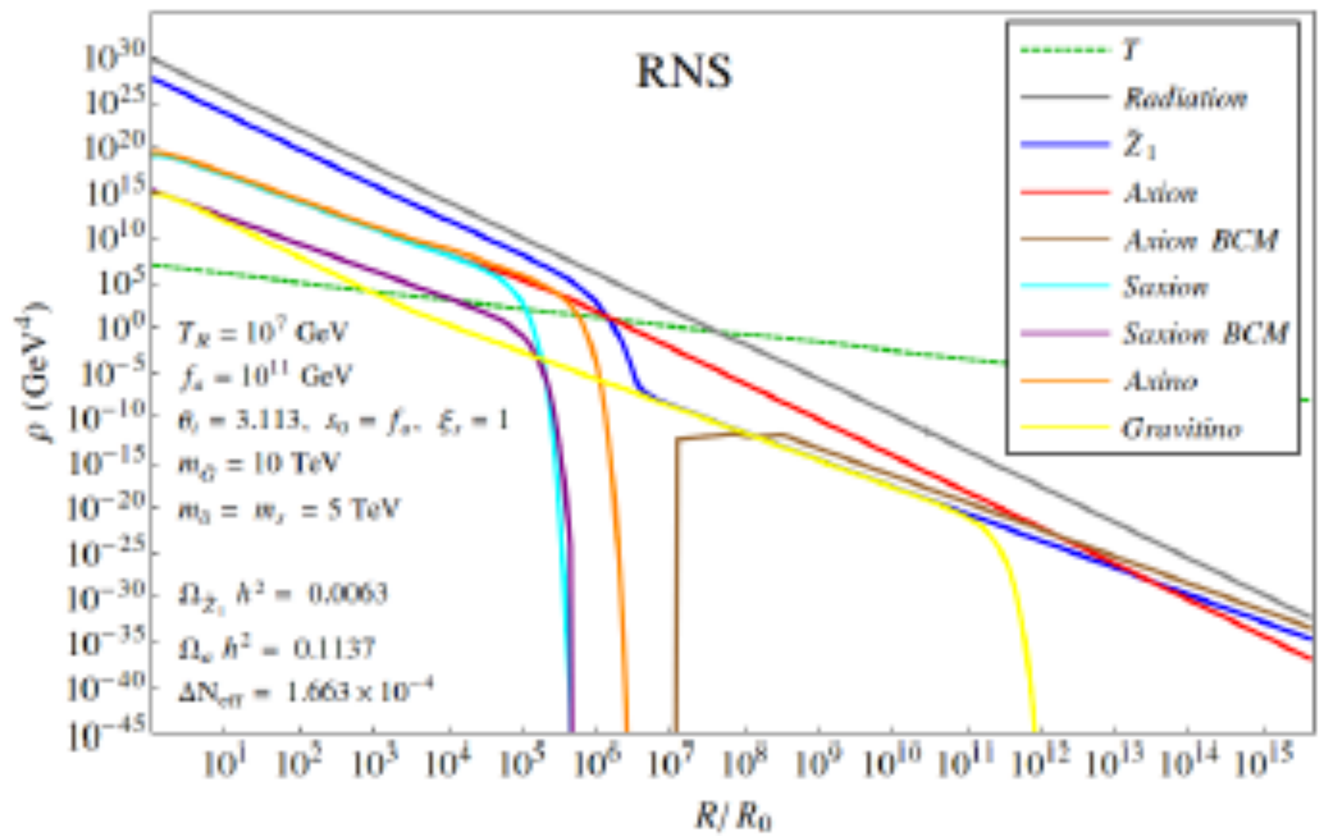
DM production in SUSY DFSZ: solve eight coupled Boltzmann equations



Bae, HB, Chun;
Bae, HB, Lessa, Serce;
arXiv:1406.4138

usual picture => mixed axion/WIMP

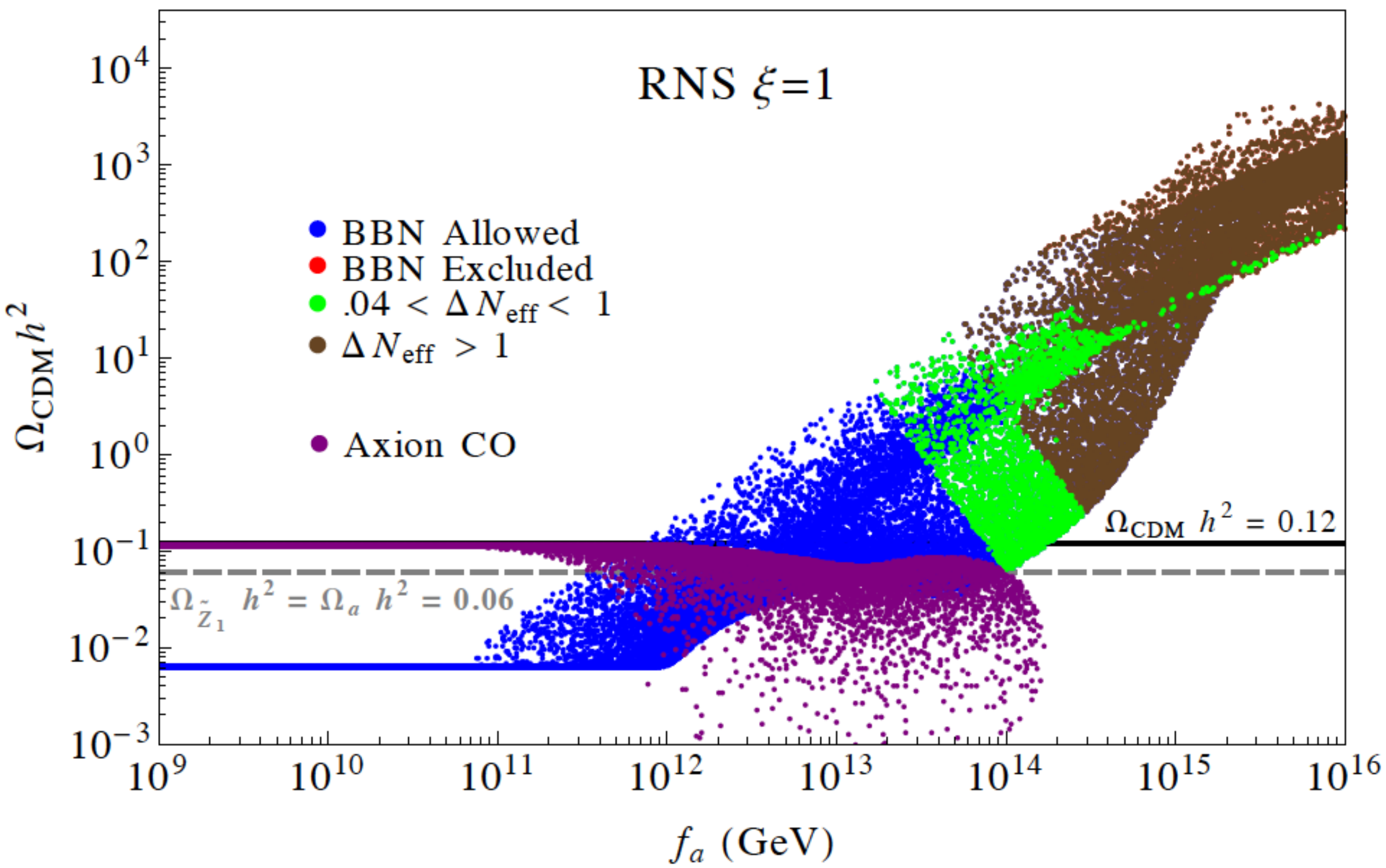




KJ Bae, HB, Lessa, Serce

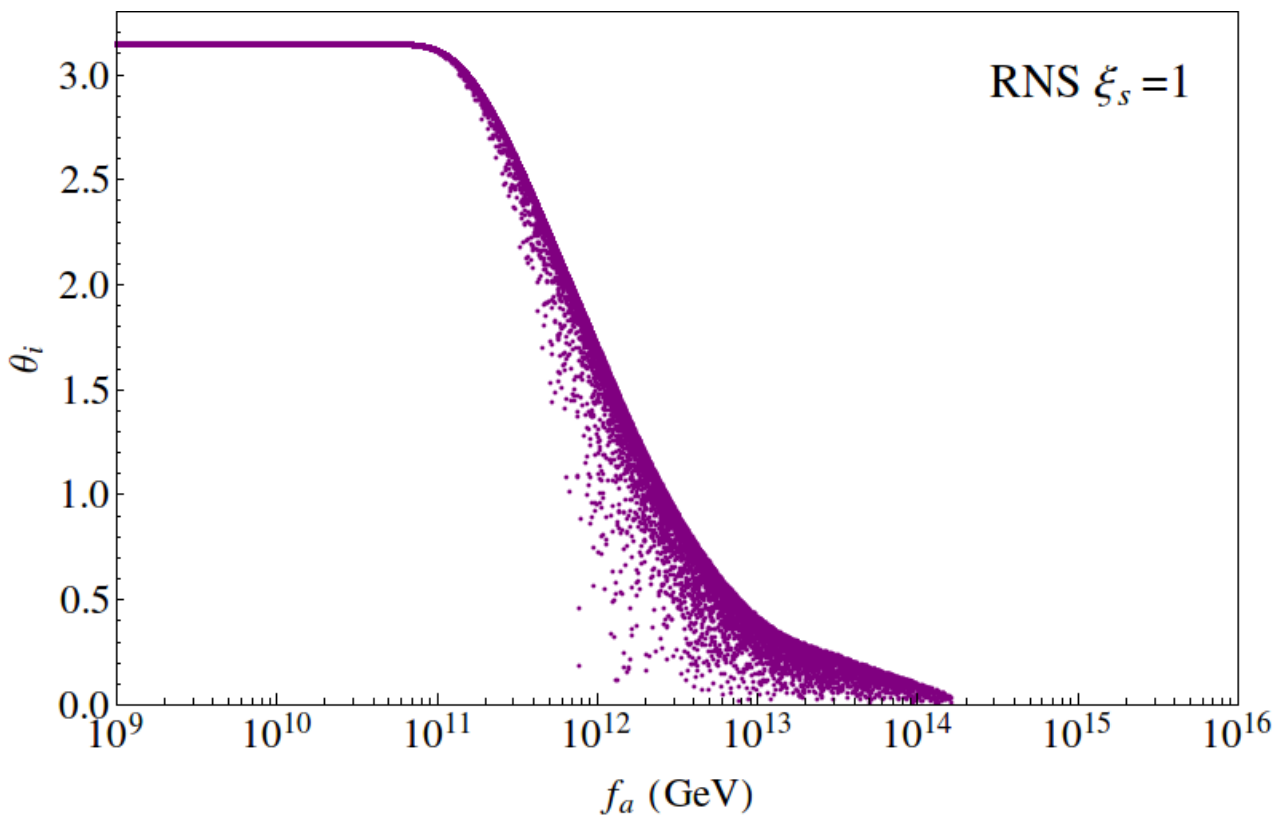
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

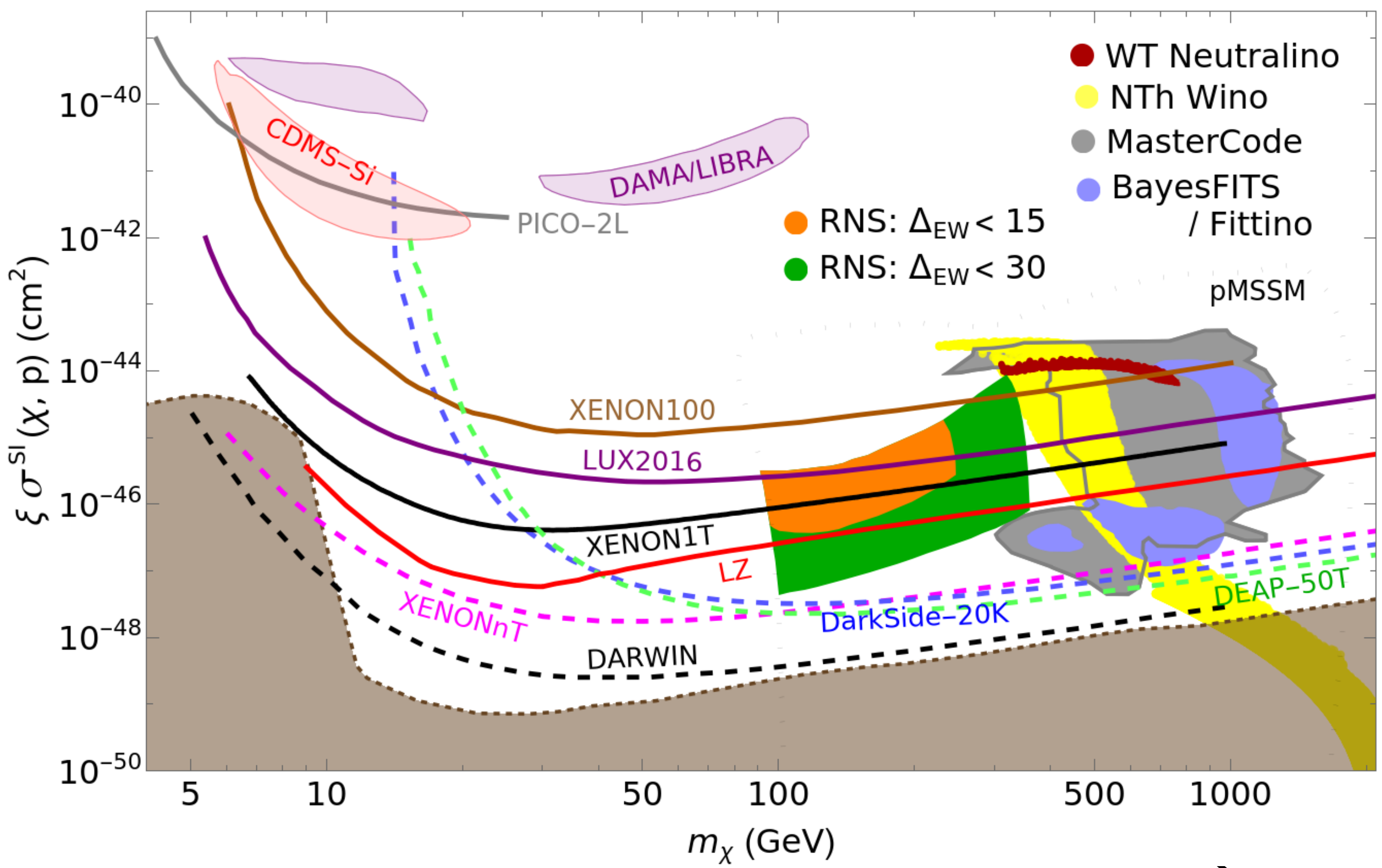
axion abundance



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 $\xi \equiv \Omega_{\chi}^{TP} h^2/0.12$



Bae, HB, Barger,Savoy,Serce

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

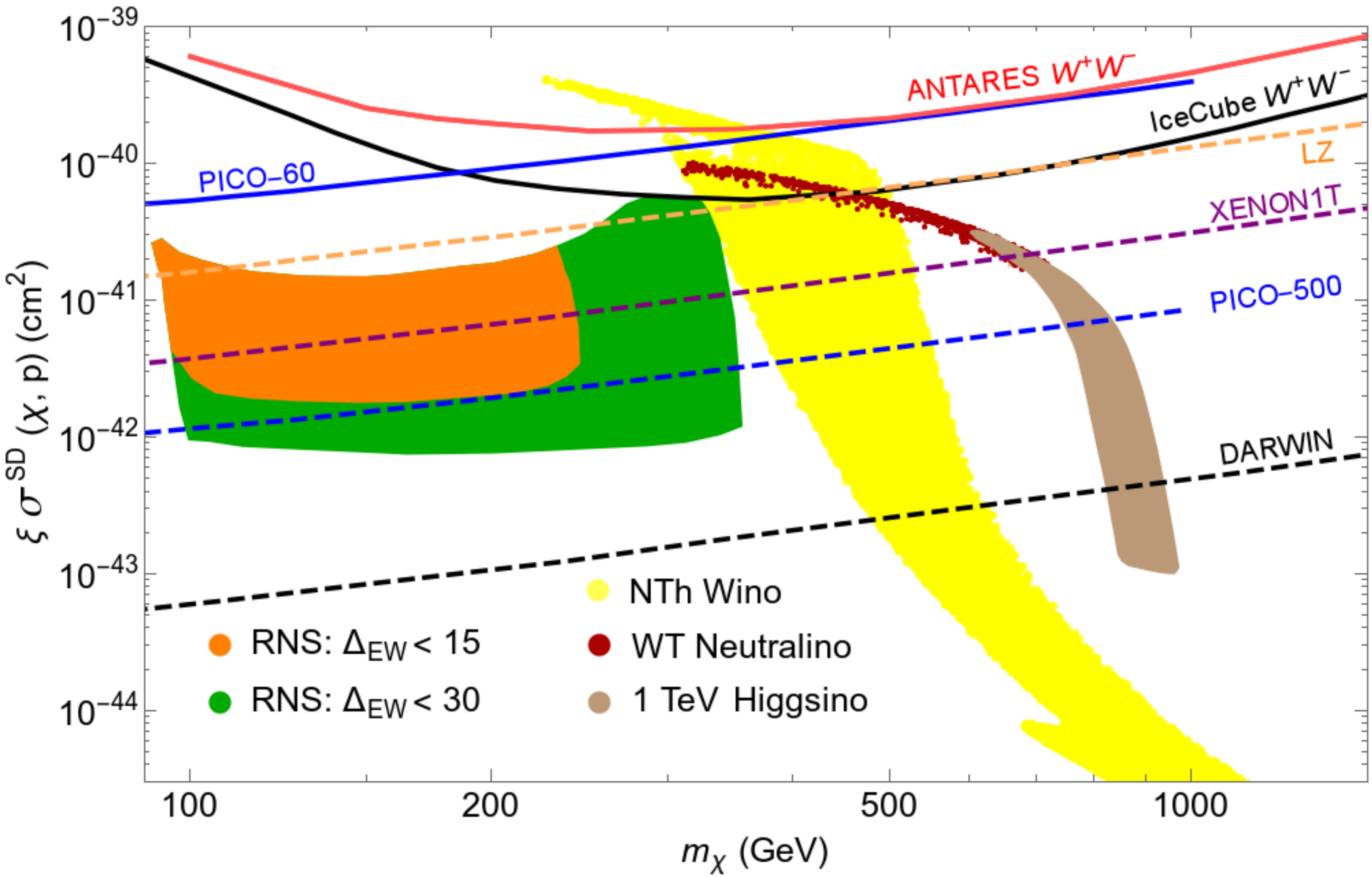
$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

includes latest LZ2022 results!

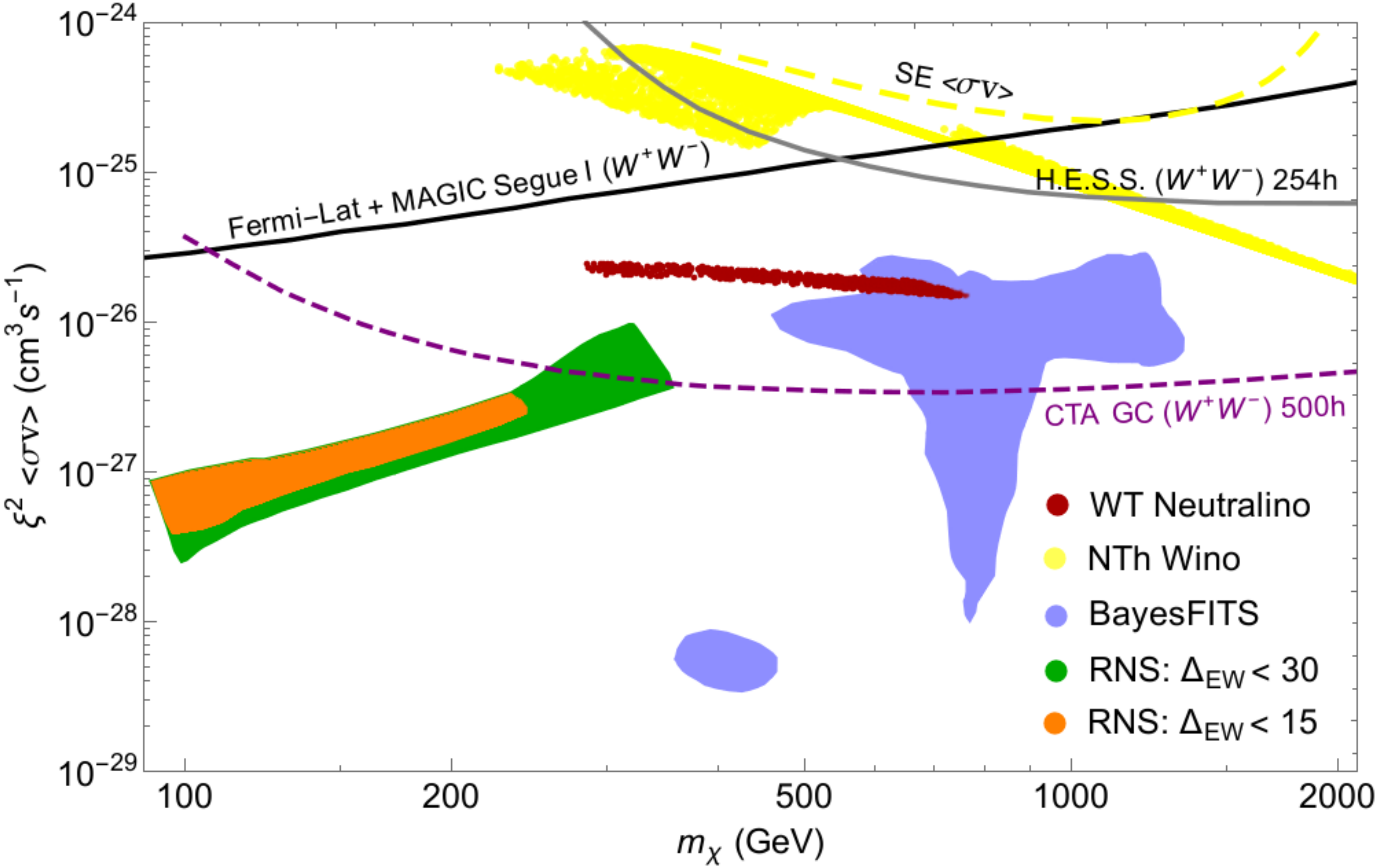
natural SUSY

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

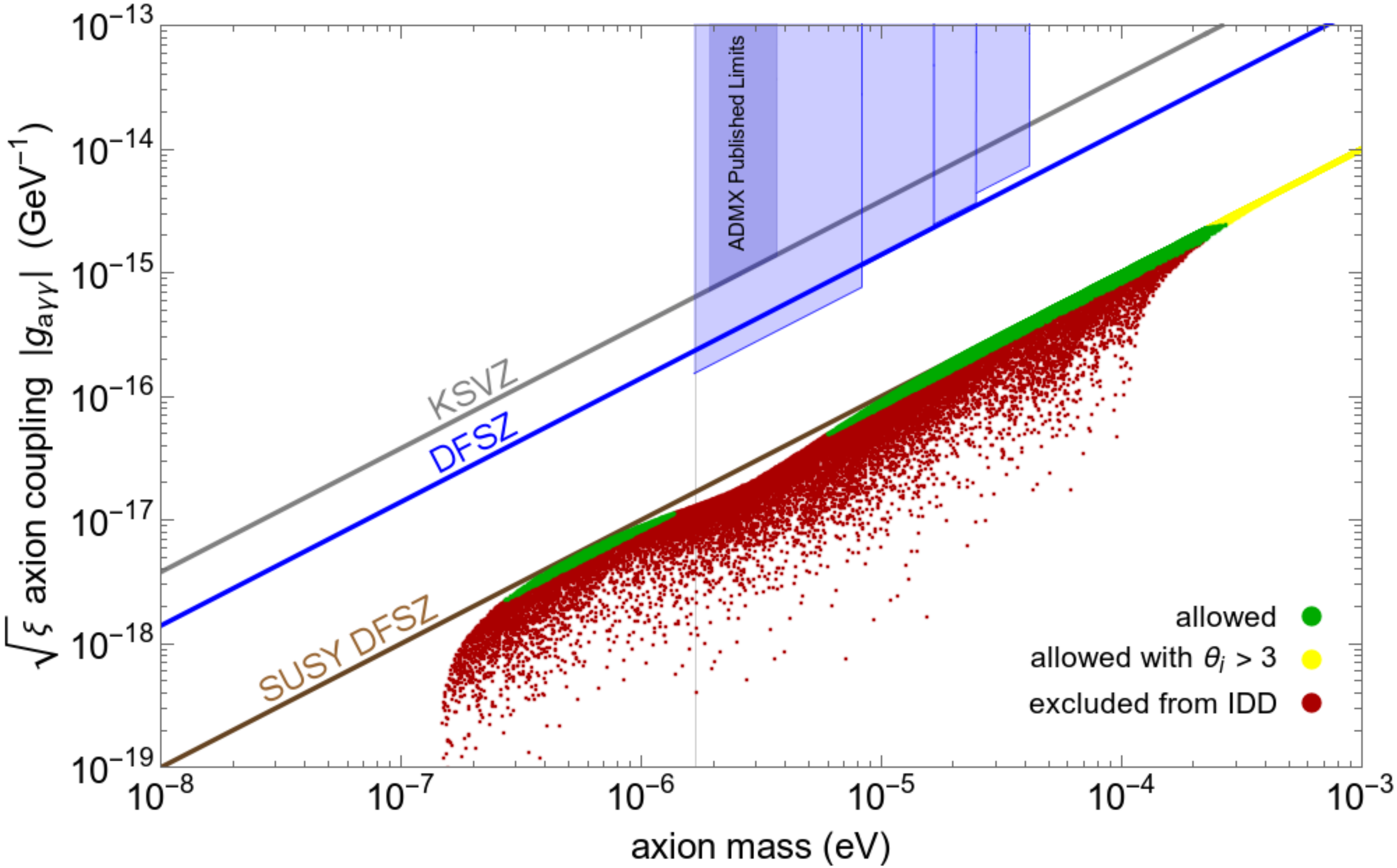
Prospects for SD WIMP searches:



Prospects for IDD WIMP searches:

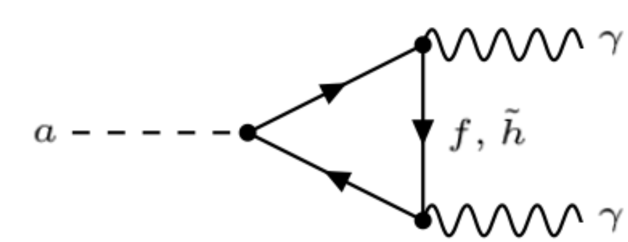


suppressed by square of diminished WIMP abundance



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

may need to probe broader and deeper!



Bae, HB, Serce:arXiv:1705.01134

SUSY solution to axion quality problem!

Gravity safe, electroweak natural axionic solution to strong CP and SUSY μ problems

HB, Barger, Sengupta, arXiv:1810.03713

1. Global symmetries fundamentally incompatible with gravity completion
2. Expect global symmetry to emerge as accidental (approximate) symmetry from some more fundamental gravity-safe (e.g. gauge or R-) symmetry
3. Discrete R-symmetries (intrinsically supersymmetric) and arise from compactification of extra dimensions in string theory

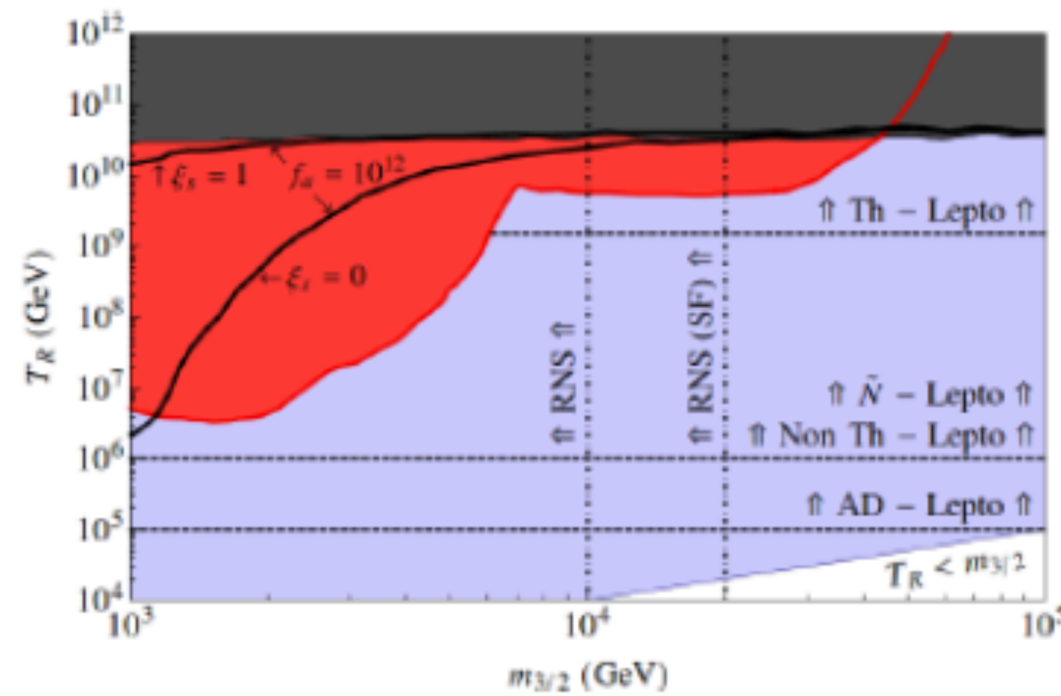
A model which works: Z(24) R symmetry (see also Lee et al.)

$$W \ni f_u Q H_u U^c + f_d Q H_d D^c + f_\ell L H_d E^c + f_\nu L H_u N^c + M_N N^c N^c/2 + \lambda_\mu X^2 H_u H_d/m_P + f X^3 Y/m_P + \lambda_3 X^p Y^q/m_P^{p+q-3}$$

- Lowest dimension PQ breaking operator contributing to scalar PQ potential $\sim 1/m_P^8$: enough suppression so that PQ is gravity-safe
- Also forbids/suppresses RPV/p-decay operators
- $\mu \sim \lambda_\mu f_a^2/m_P$

Baryogenesis scenarios for radiative natural SUSY

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



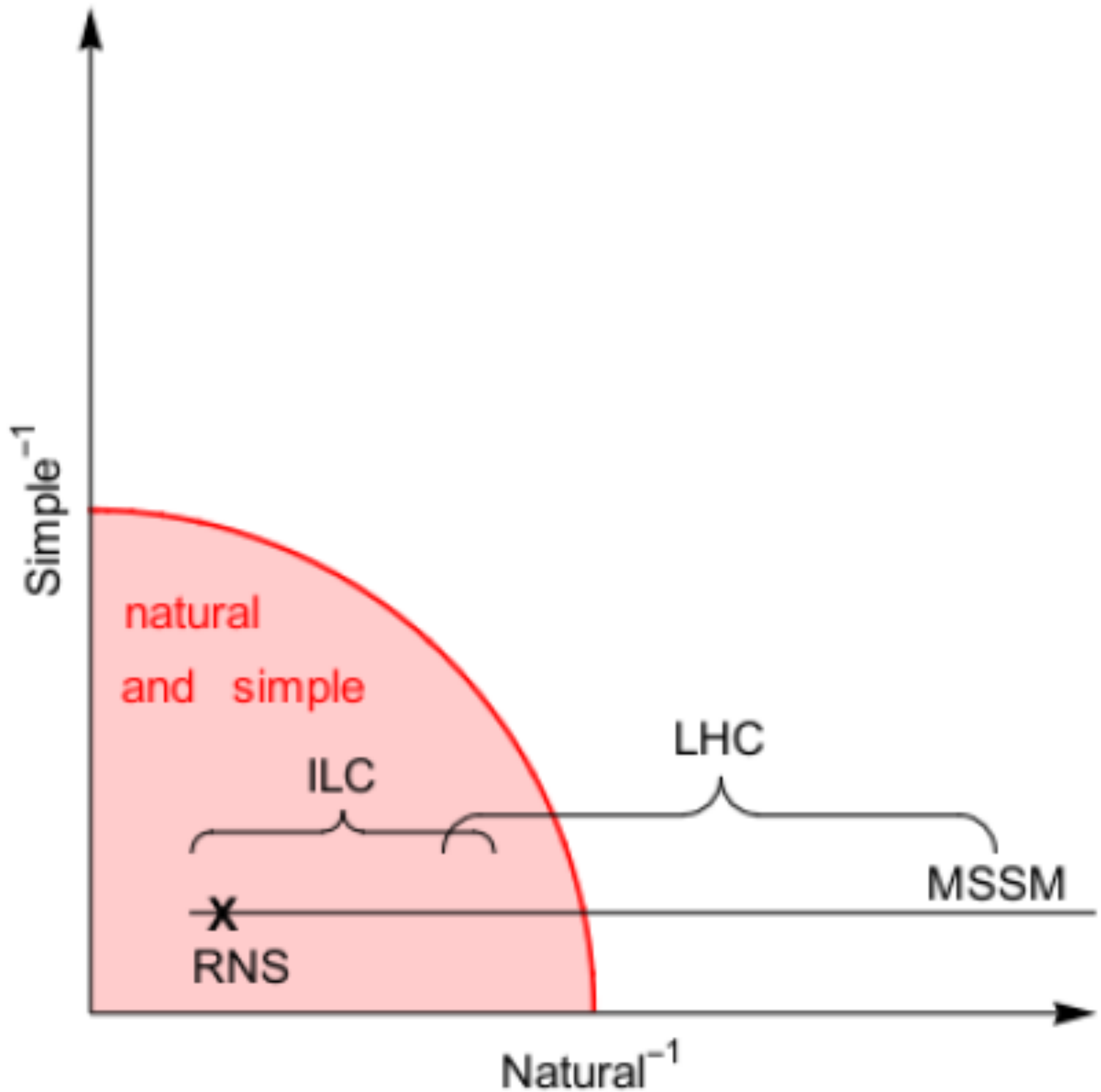
$$f_a = 10^{11},\ 10^{12}\ \mathrm{GeV}$$

gravitino problem plus axino/saxion problem: still plenty room

Bae,HB, Serce, Zhang, arXiv:1510.00724

Conclusions:

- Time to set aside old notions of naturalness:
- Plenty of natural parameter space under model independent measure DEW
- mu~100-350 GeV: light higgsinos!
- other sparticle contributions to m(weak) are loop suppressed- masses can be TeV->multi-TeV
- stringy naturalness: what the string landscape prefers
- draw to large soft terms provided m(weak)~(2-5)*100 GeV
- predicts LHC sees mh~125 GeV but as yet no sign of sparticles
- LHC best bet: higgsino pair production/soft dileptons: small excess ATLAS/CMS
- under stringy naturalness, a 3 TeV gluino more natural than 300 GeV gluino
- landscape-> non-universal 1st/2nd gen. scalars at 20-40 TeV: natural but gives quasi-degeneracy/decoupling sol'n to SUSY flavor, CP and cosmological moduli problems
- dark matter: a mix of axions+higgsino-like WIMPs (typically mainly axions)
- SUSY solves axion quality problem via Z(24)^R symmetry


Simple^{-1}
natural
and simple
ILC
LHC
MSSM
RNS
Natural^{-1}

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

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

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

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

neglect gauge pieces, S, mHu and running;
then we can integrate from m(SUSY) to Lambda

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

$$\Delta_{HS} \sim \delta m_h^2/(m_h^2/2) < 10$$

$$m_{\tilde{t}_{1,2},\tilde{b}_1} < 500\ \mathrm{GeV}$$

$$m_{\tilde{g}} < 1.5\ \mathrm{TeV}$$

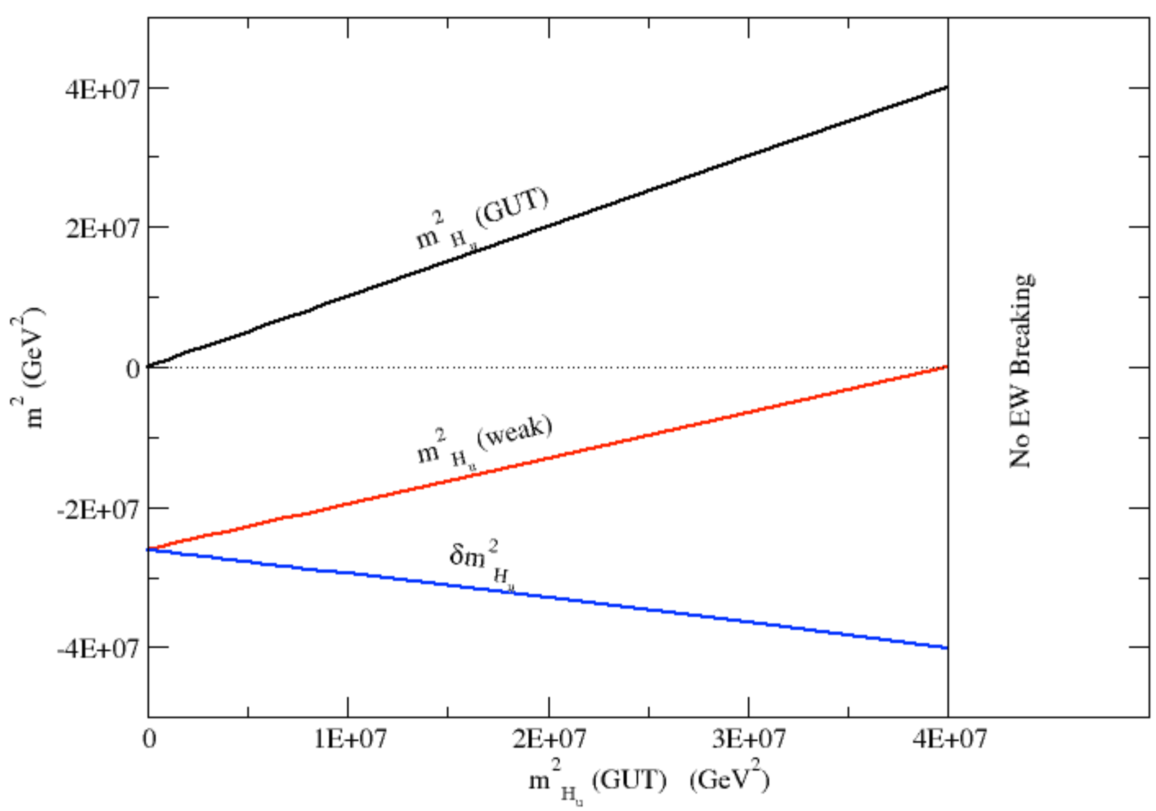
old natural SUSY then A_t can't be too big

What's wrong with this argument?

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

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

violates prime directive!



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

HB, Barger, Savoy

To fix: combine dependent terms:

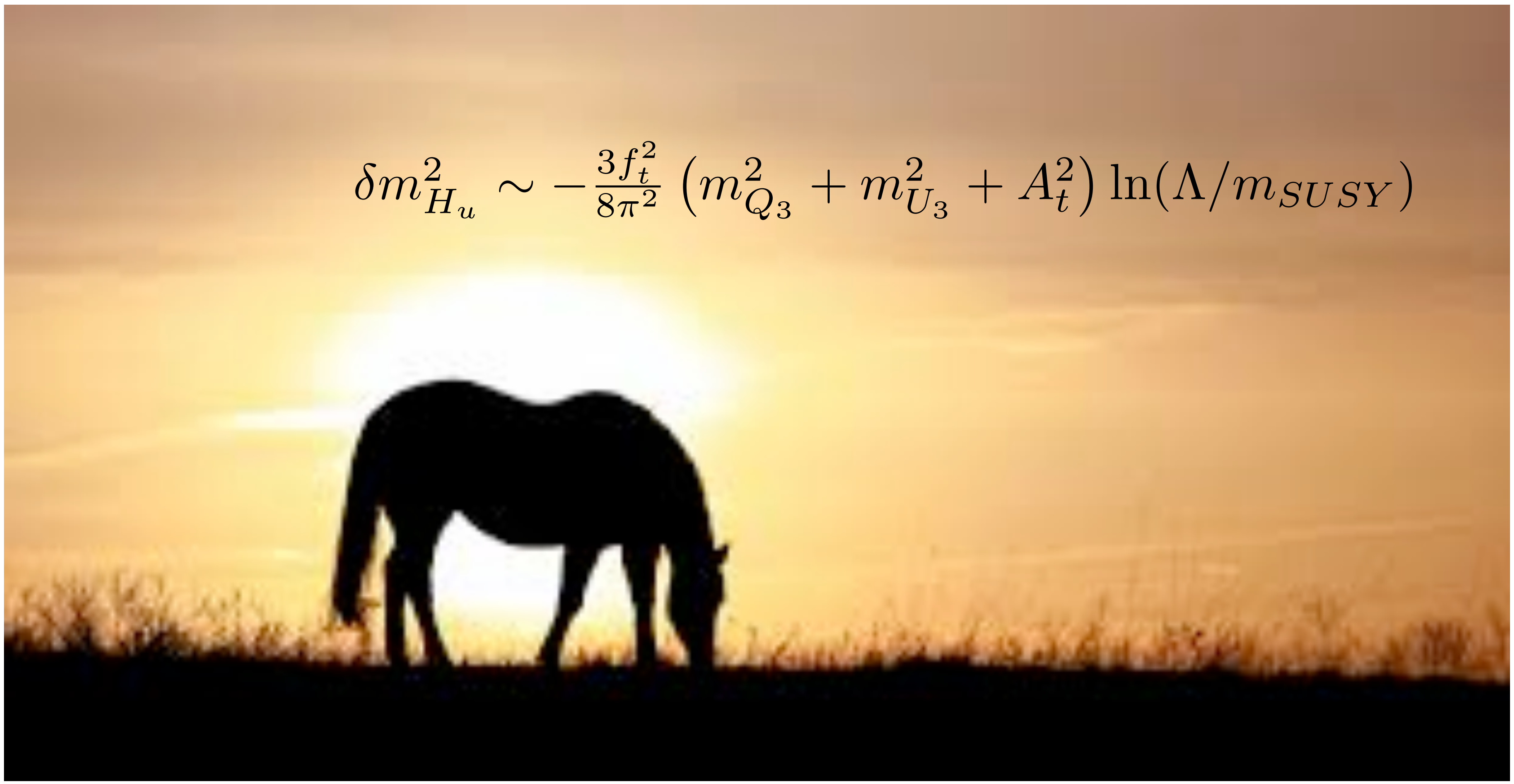
$m_h^2 \simeq \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ where now both μ^2 and $\left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ are $\sim m_Z^2$

After re-grouping: $\Delta_{HS} \simeq \Delta_{EW}$

Instead of: the radiative correction $\delta m_{H_u}^2 \sim m_Z^2$
we now have: the radiatively-corrected $m_{H_u}^2 \sim m_Z^2$

Recommendation: put this horse out to pasture

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



R.I.P.

sub-TeV 3rd generation squarks not required for naturalness

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

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.* $m_{\tilde{t}_1} \sim 1$ TeV

$\Delta_{BG}(Q_3) \simeq 0.73\frac{1000^2}{91.2^2} \sim 100$

#3. What about EENZ/BG measure?

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

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

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

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

For correlated scalar masses $\equiv m_0$,
scalar contribution collapses:
what looks fine-tuned isn't: *focus point SUSY*
multi-TeV scalars are *natural*

Feng, Matchev, Moroi

Even with FP, still
fine-tuned on m(gluino) :(

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 $m_{1/2} = -A_0 = \sqrt{3} m_{3/2}$

in general:

$$\begin{aligned} m_{H_u}^2 &= a_{H_u} \cdot m_{3/2}^2, \\ m_{Q_3}^2 &= a_{Q_3} \cdot m_{3/2}^2, \\ A_t &= a_{A_t} \cdot m_{3/2}, \\ M_i &= a_i \cdot m_{3/2}, \\ & \cdots . \end{aligned}$$

since μ hardly runs, then

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

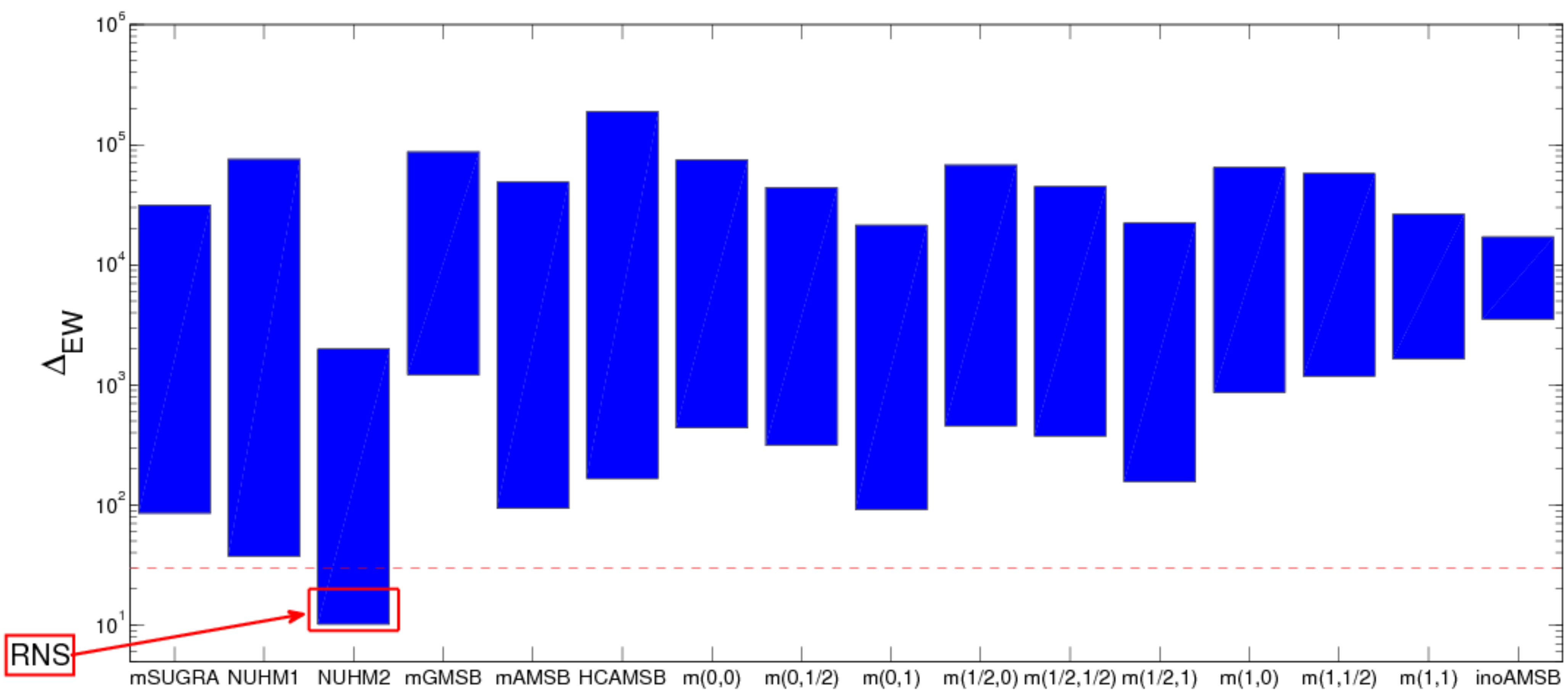
$$m_{H_u}^2(weak) \sim -(100-200)^2 \text{ GeV}^2 \sim -a \cdot m_{3/2}^2/2$$

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

Δ_{EW} is highly selective: most constrained models are ruled out except NUHM2 and its generalizations:

J. Ellis, K. Olive and Y. Santoso, *Phys. Lett.* **B 539** (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, *Nucl. Phys.* B **652** (2003) 259; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *J. High Energy Phys.* **0507** (2005) 065.

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



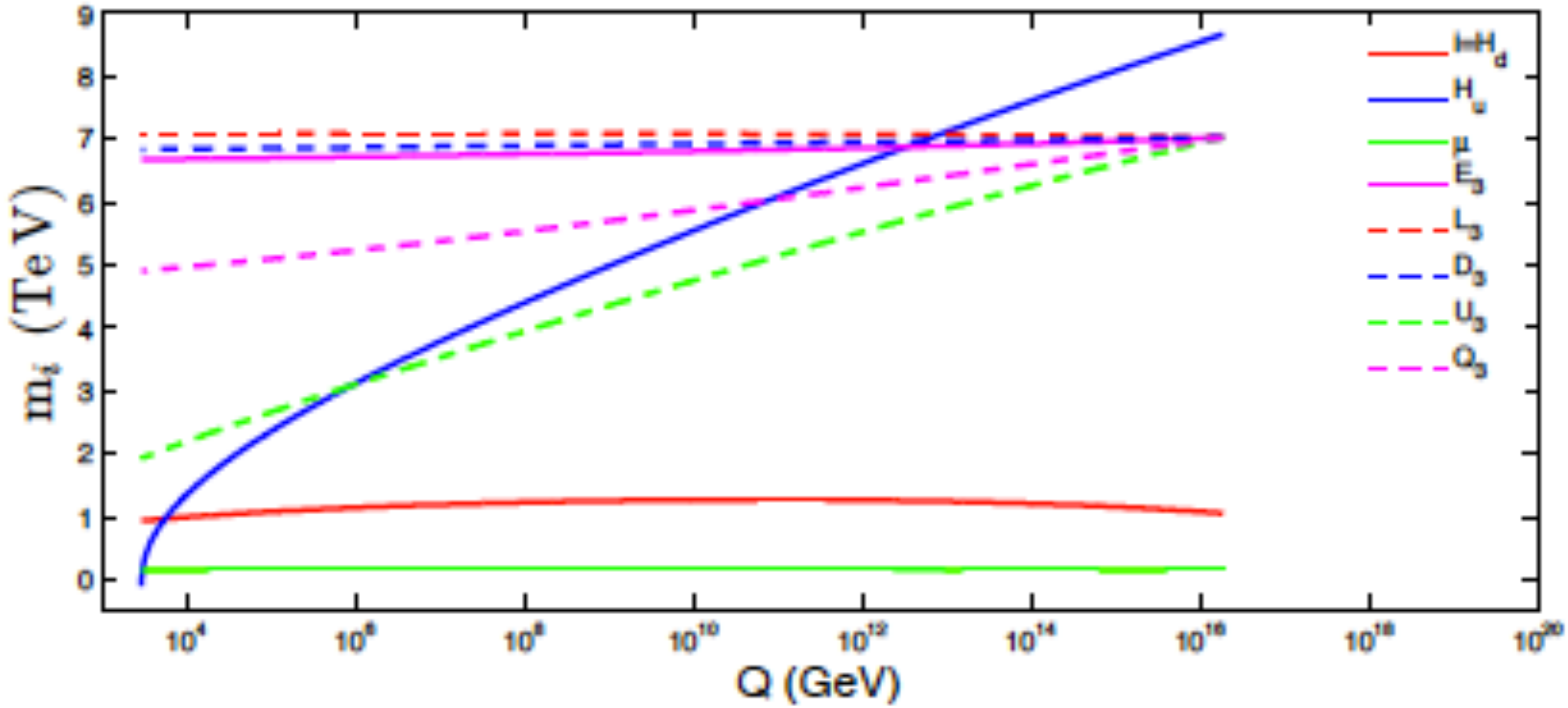
0.1%

1%

10%

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:

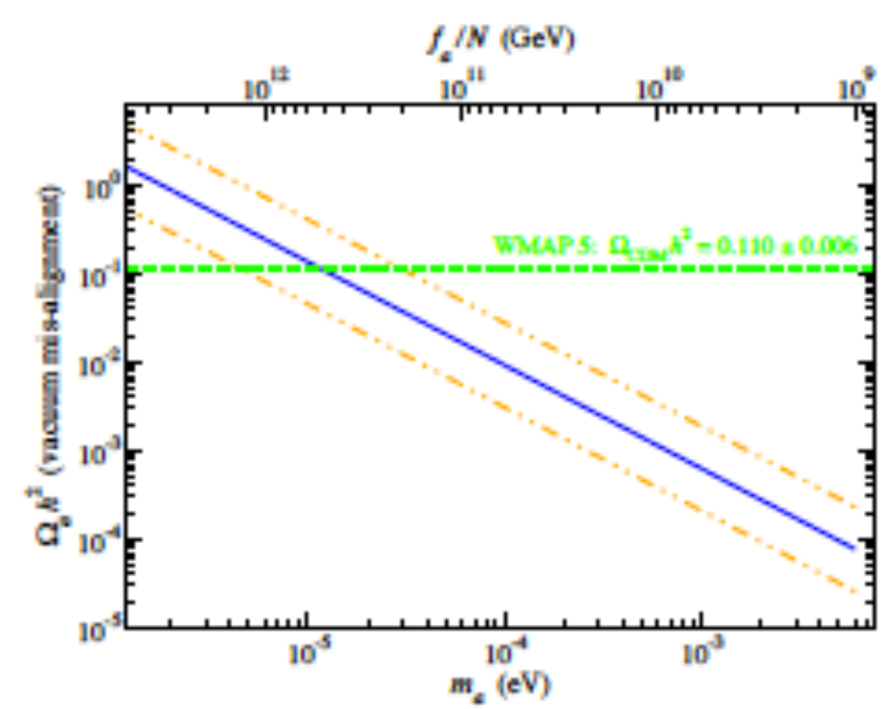
(typically need mHu~25-50% higher than m0)

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]].

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
- ⋆ $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times10^{-6}eV}{m_a}\right]^{7/6}\theta_i^2 h^2$
- ⋆ astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 GeV$



Why might mu<<m(soft)?

SUSY mu problem: mu term is SUSY, not SUSY breaking: expect mu~M(Pl) but phenomenology requires mu~m(Z)

- NMSSM: mu~m(soft); but beware singlets!
- Giudice-Masiero: mu forbidden by some symmetry: generate via Higgs coupling to hidden sector: mu~m(soft)
- Kim-Nilles: invoke SUSY version of DFSZ axion solution to strong CP:

KN: PQ symmetry forbids mu term, but then it is generated via PQ breaking

$$\mu \sim \lambda_\mu f_a^2/m_P$$

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

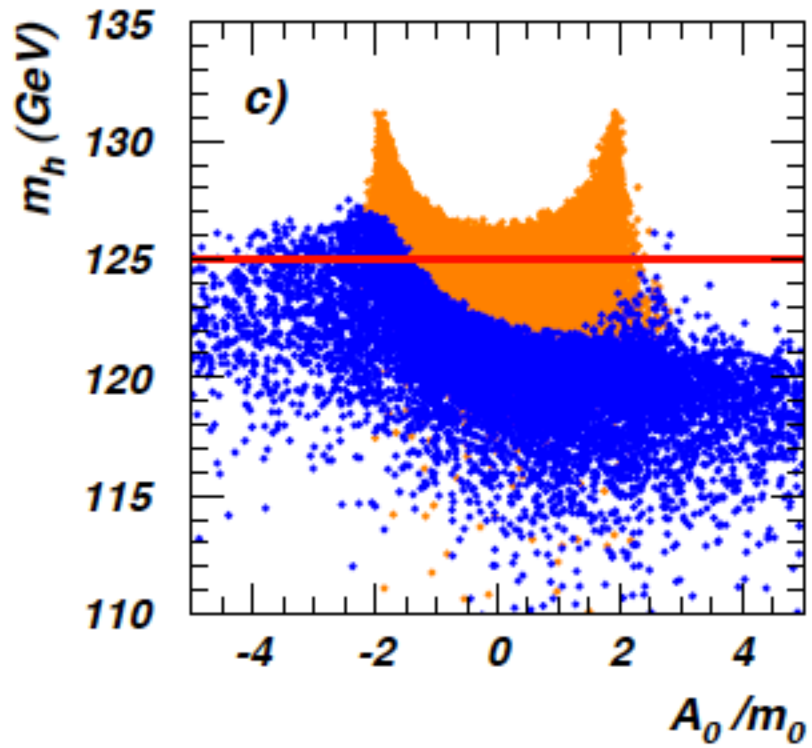
Little Hierarchy due to mismatch between PQ breaking and SUSY breaking scales?

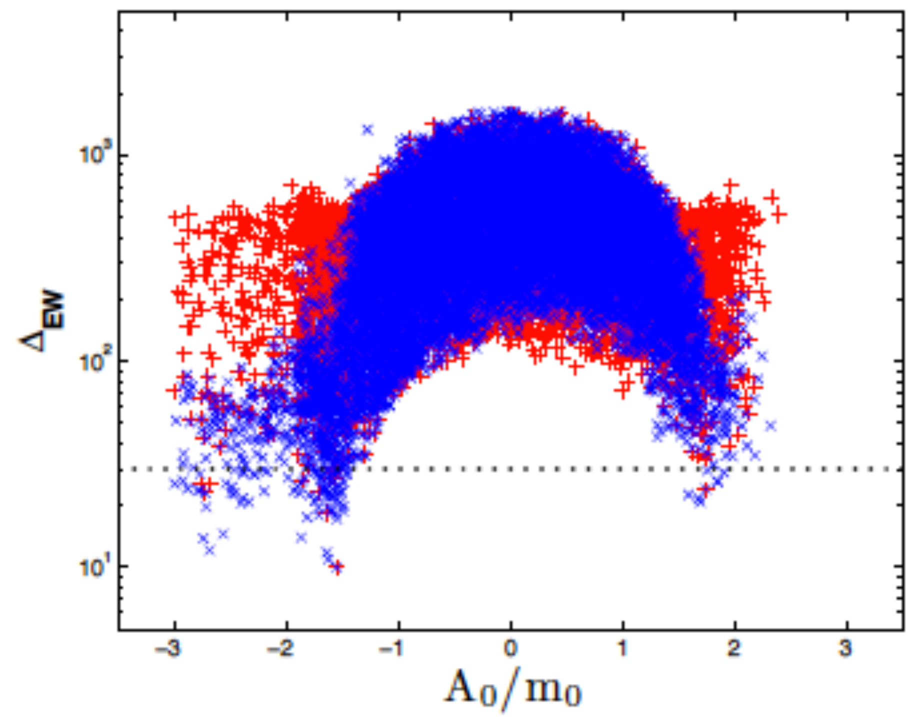
$$f_a < m_{hidden} \Rightarrow$$
$$\mu \ll m(soft)$$

Higgs mass m(h)~mu tells us where to look for axion!

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

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





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

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

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