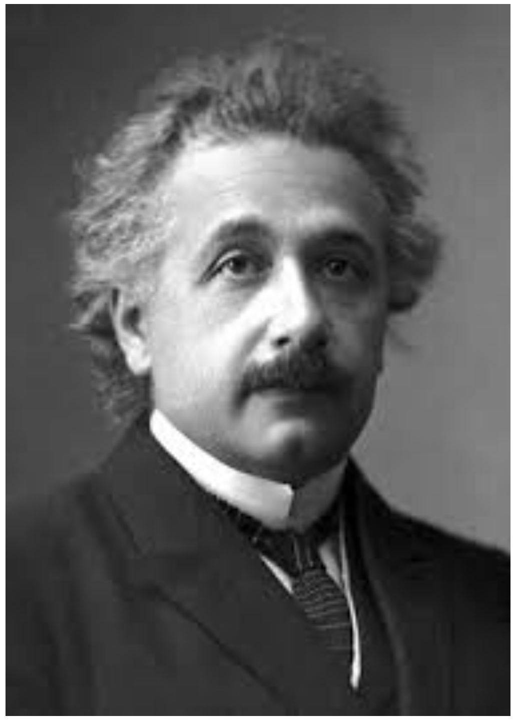
Higgs(ino) physics in the era of future accelerators

Howard Baer
University of Oklahoma

Corfu future accelerators,
April 2023

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

The Standard Model of Particle Physics

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g_{\mu A},\ W_{\mu i},\ B_\mu$
- ⋆ matter content: 3 generations quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \ u_R,\ d_R;\ \begin{pmatrix} \nu \\ e \end{pmatrix}_L,\ e_R \tag{1}$$

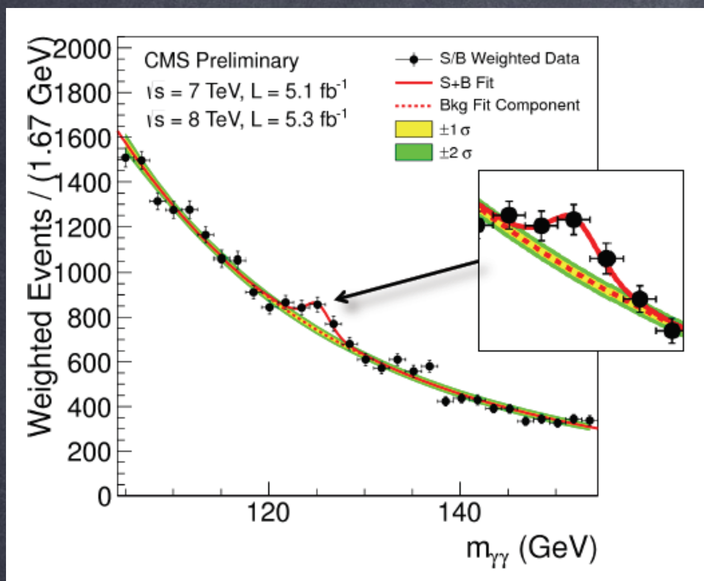
- ⋆ Higgs sector $\Rightarrow$ spontaneous electroweak symmetry breaking:

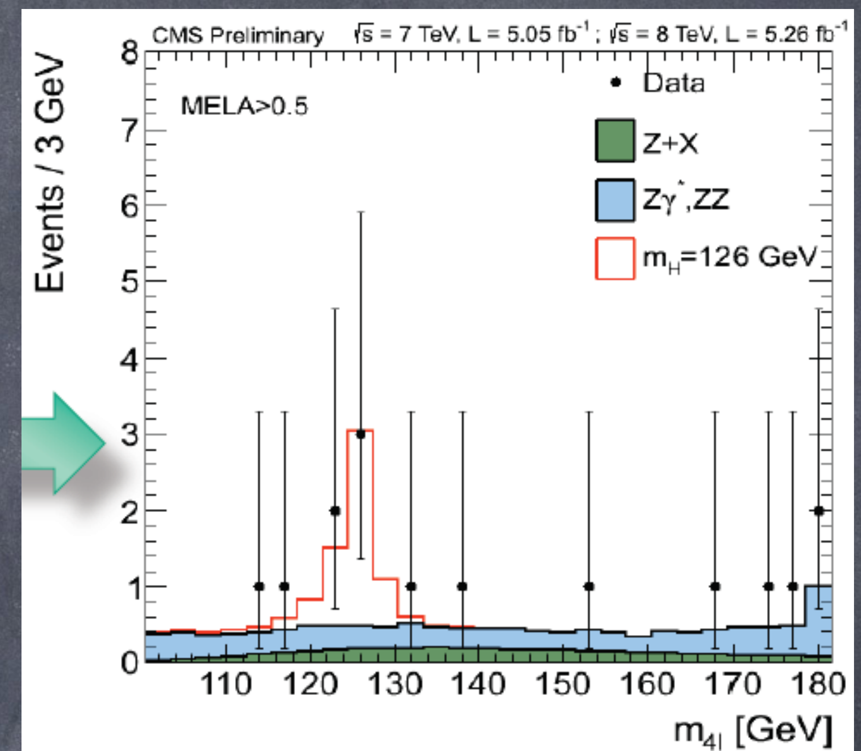
$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{2}$$

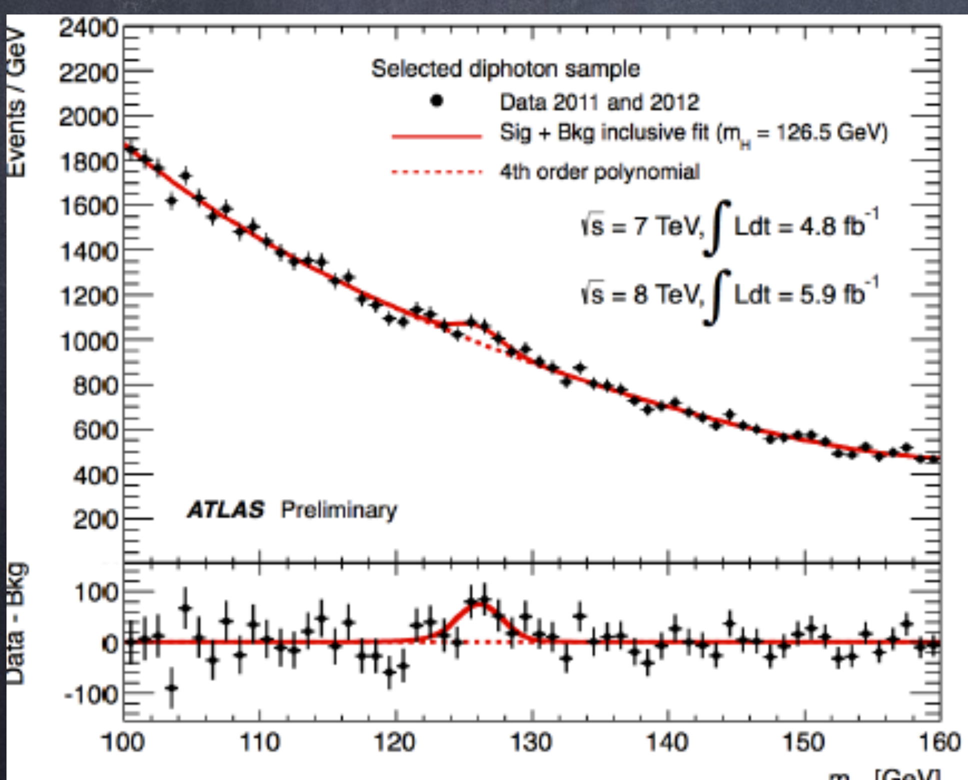
- ⋆ $\Rightarrow$ massive $W^\pm$, Z^0, massless γ, massive quarks and leptons; Higgs scalar H
- ⋆ $\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Yuk.} + \mathcal{L}_{Higgs}$: 19 parameters
- ⋆ good-to-excellent description of (almost) *all* accelerator data!

LHC Higgs discovery: July 4, 2012!

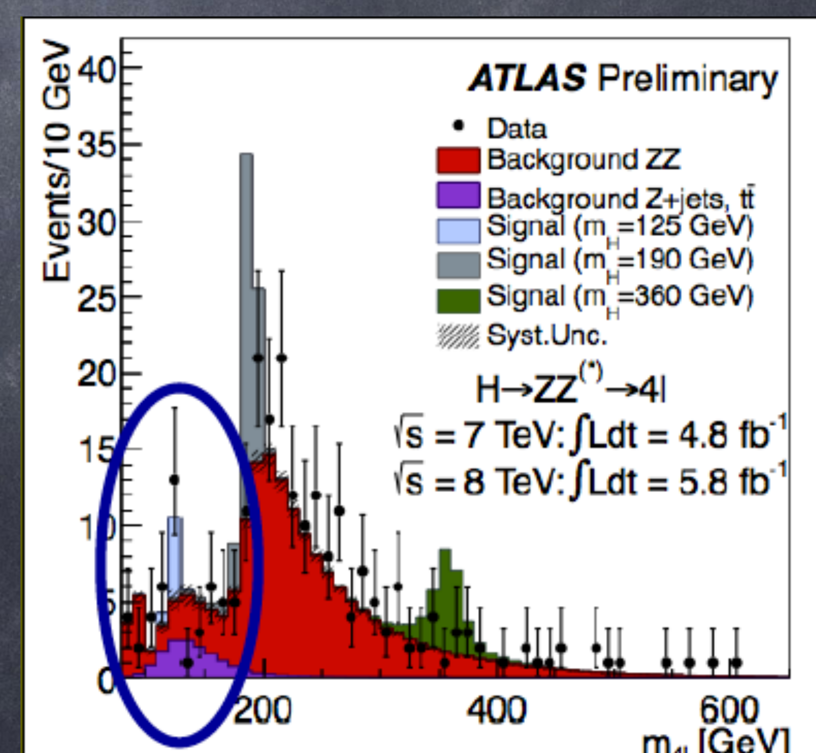
$$m_h \sim 125 \text{ GeV}$$





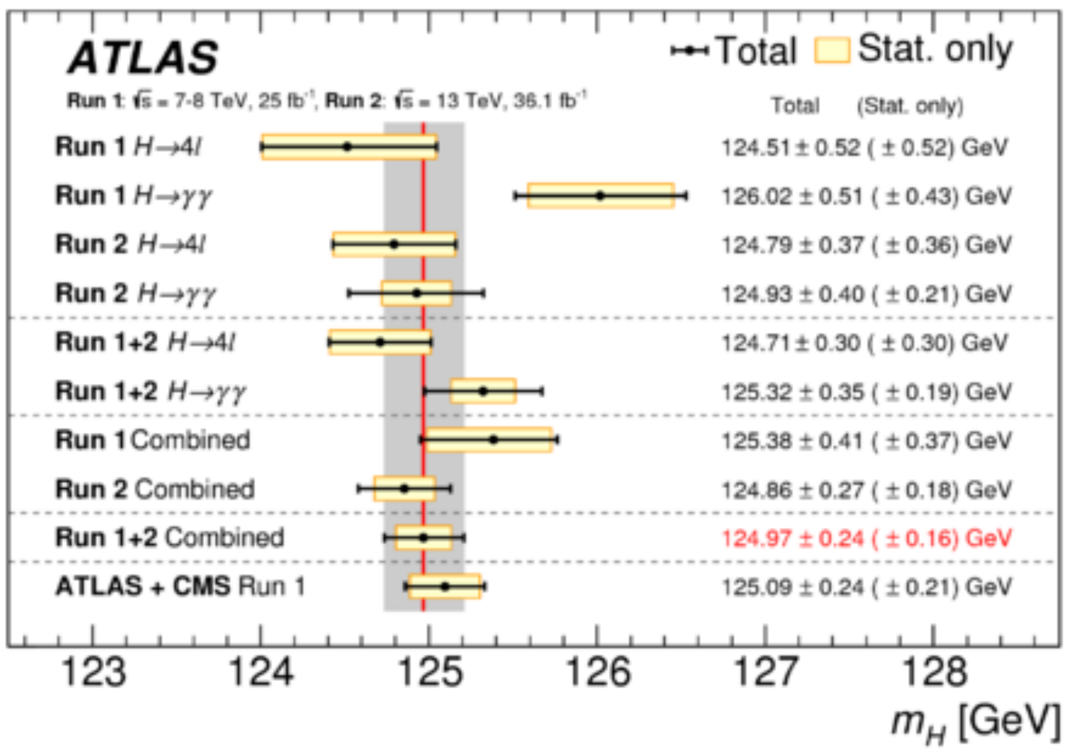


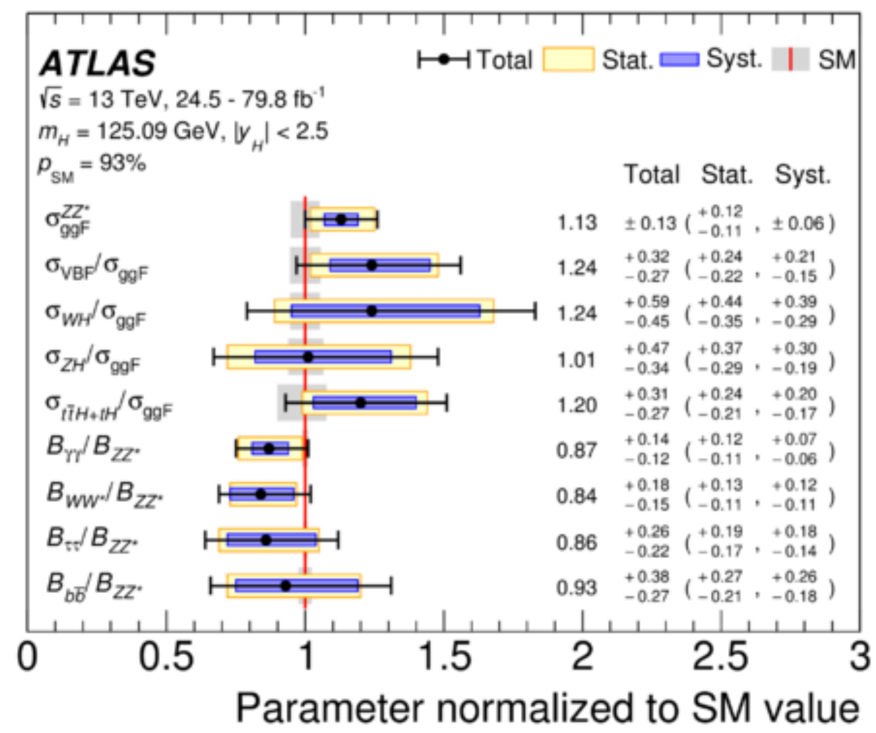
2013 Nobel

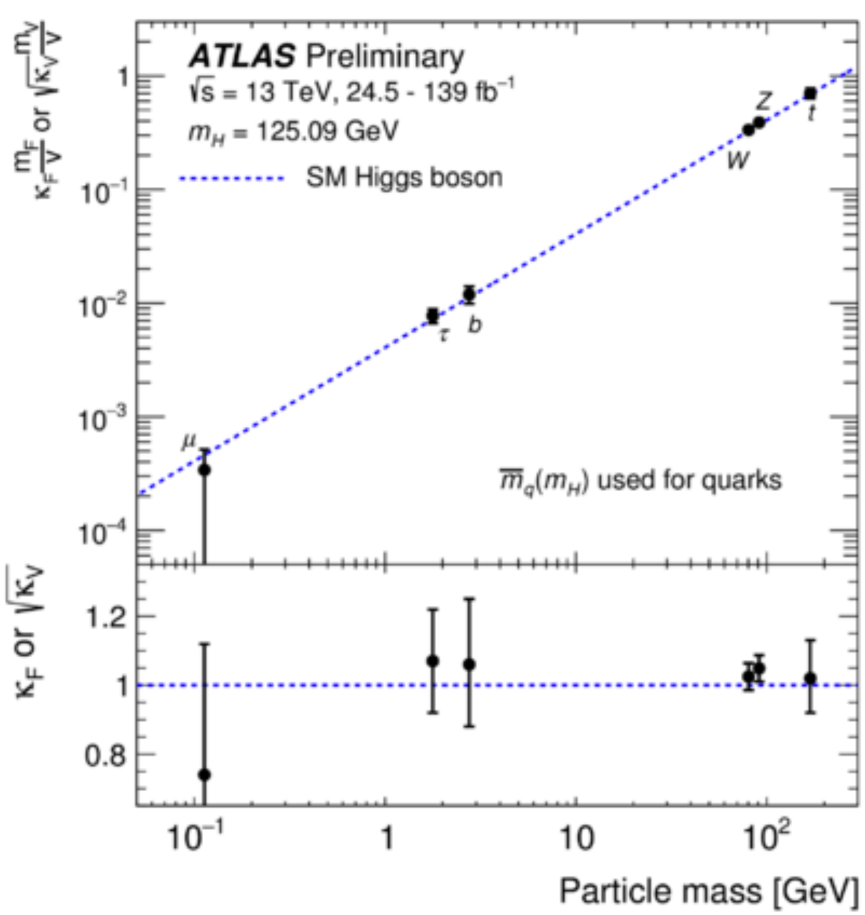


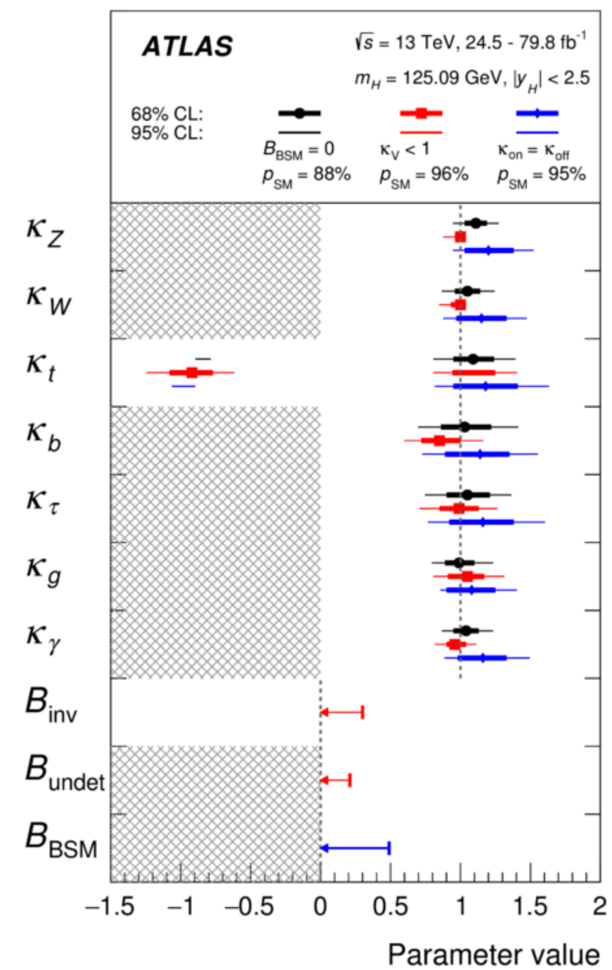
Excess of events also reported from CDF/D0

Higgs properties: m(h)=125.1 GeV and very SM-like!









- What to make of this?
- What happened to SUSY? (was expected)
- Is there a `naturalness' crisis?
- What does it imply for future collider facilities?

Standard Model is regarded as an
``effective field theory" valid at energy scales <~1 TeV

- Higgs mass instability
- strong CP problem
- cosmological constant
- inclusion of gravity
- origin of generations
- dark matter
- dark energy
- baryogenesis

expect new physics:
but what form?
and at what mass scale?

The top three SM finetuning problems:

and most plausible solutions to date

- Hierarchy problem: 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: $\rho_{vac} \sim (0.003\ \mathrm{eV})^4 \ll m_P^4$

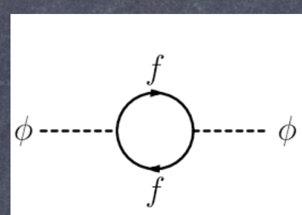
anthropic vacua selection from multiverse/string vacua

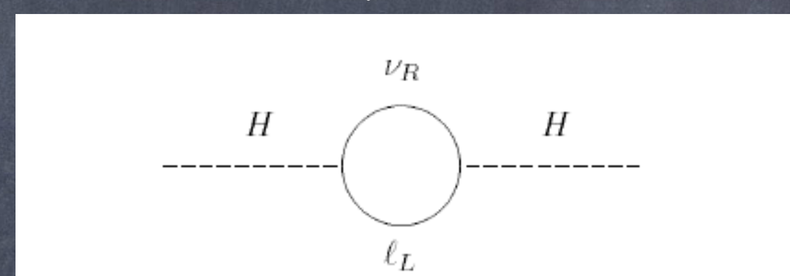
Hierarchy of scales problem in the SM

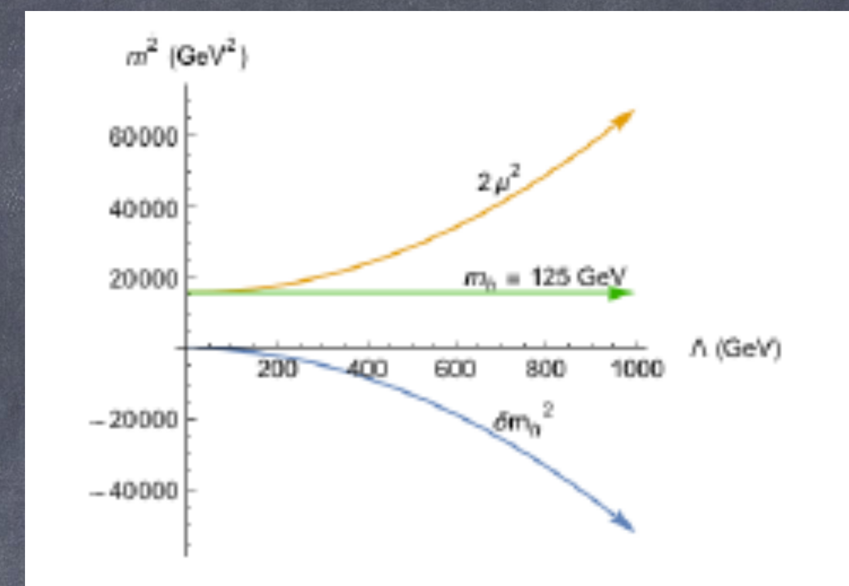
Biggest conundrum of SM: why is Higgs mass so small?

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

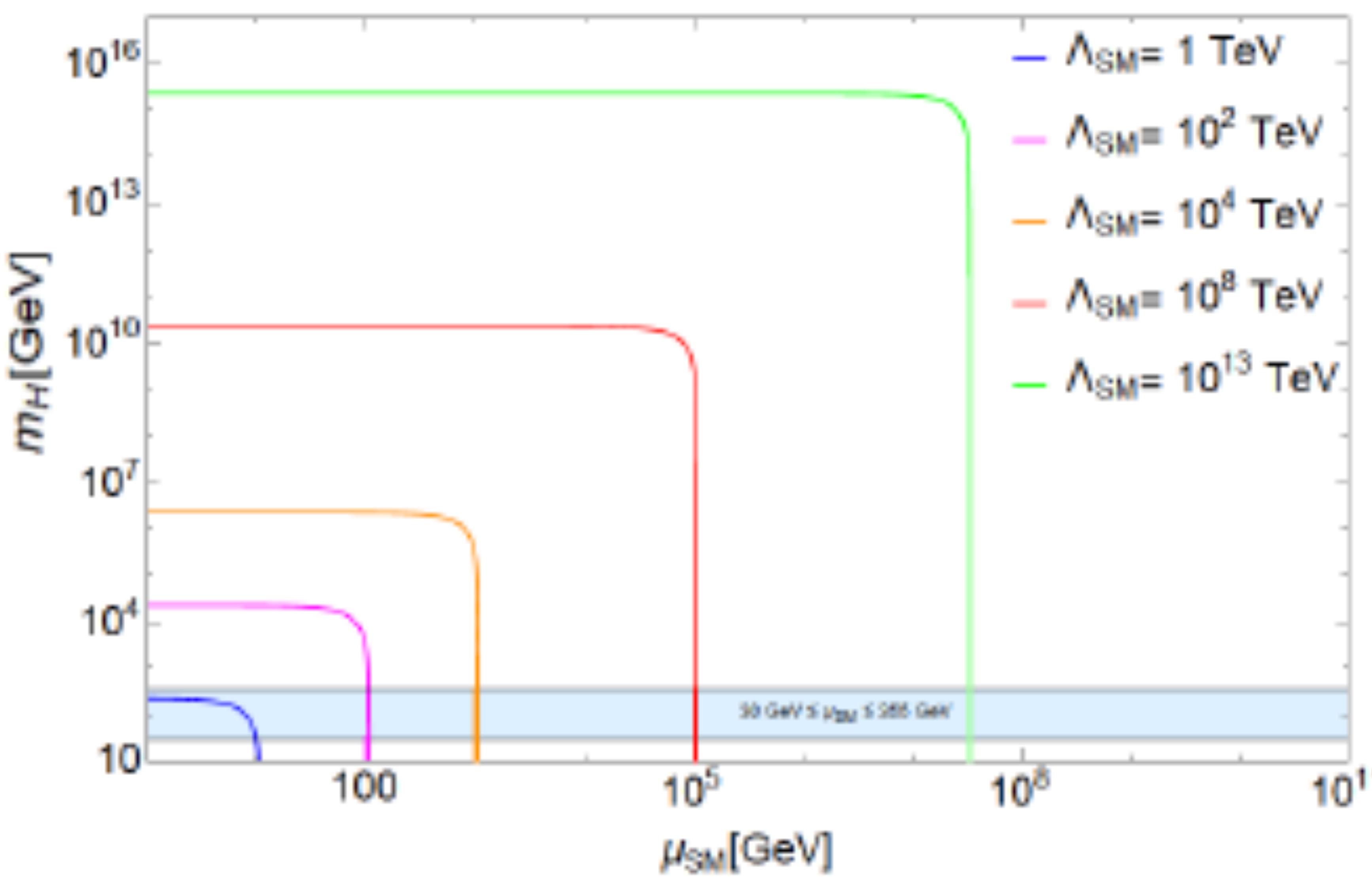
4. Need theory which is free of quadratic divergences to extend e.g. to GUT/Planck scale

another vantage point: SM is logically possible but highly implausible finetuning is needed!

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

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

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



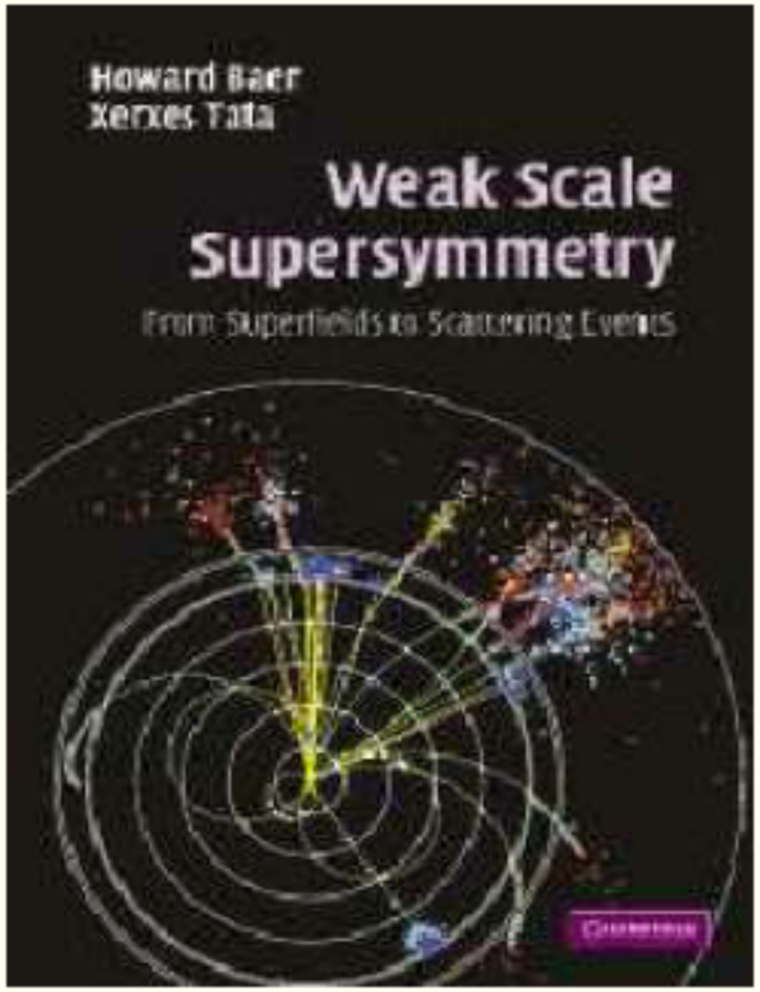
SUSY provides a clean/elegant solution to hierarchy problem

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



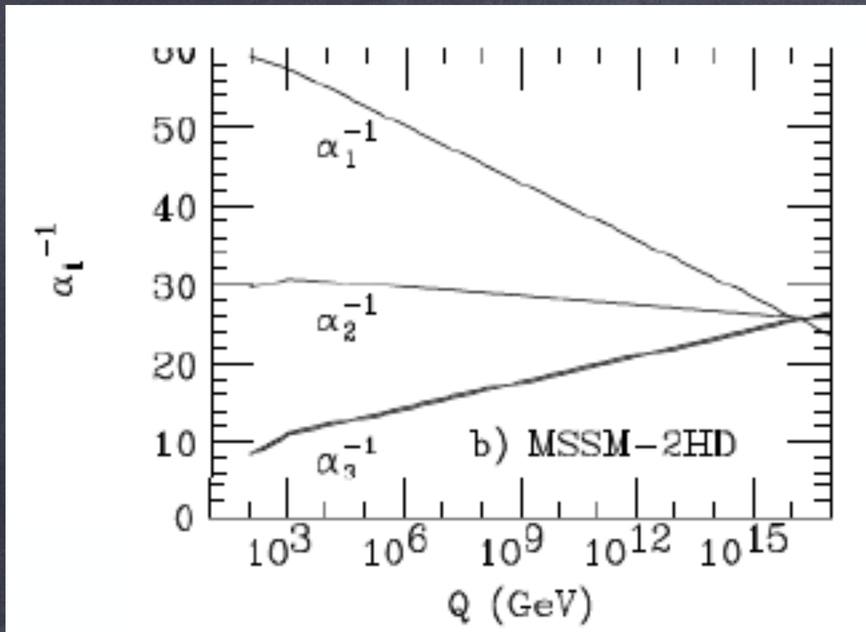
Minimal Supersymmetric Standard Model (MSSM)

- ⋆ 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?!

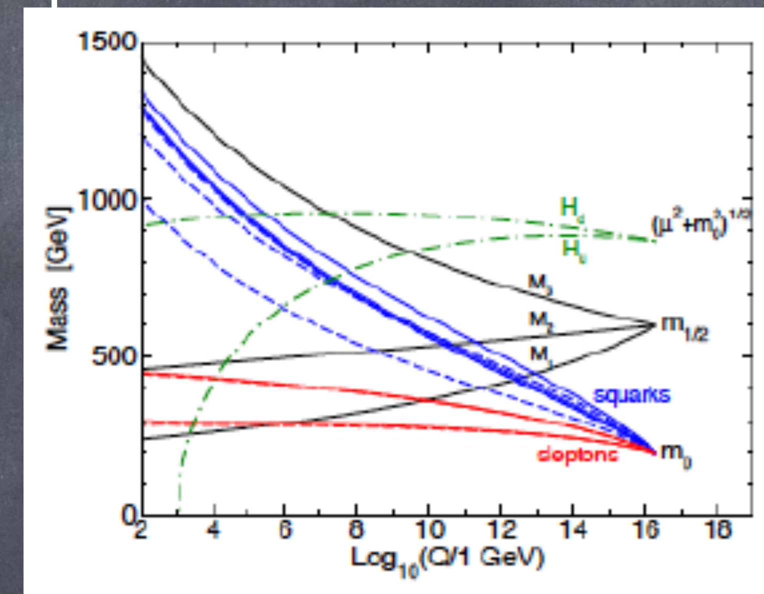
The MSSM is supported by virtual quantum effects!



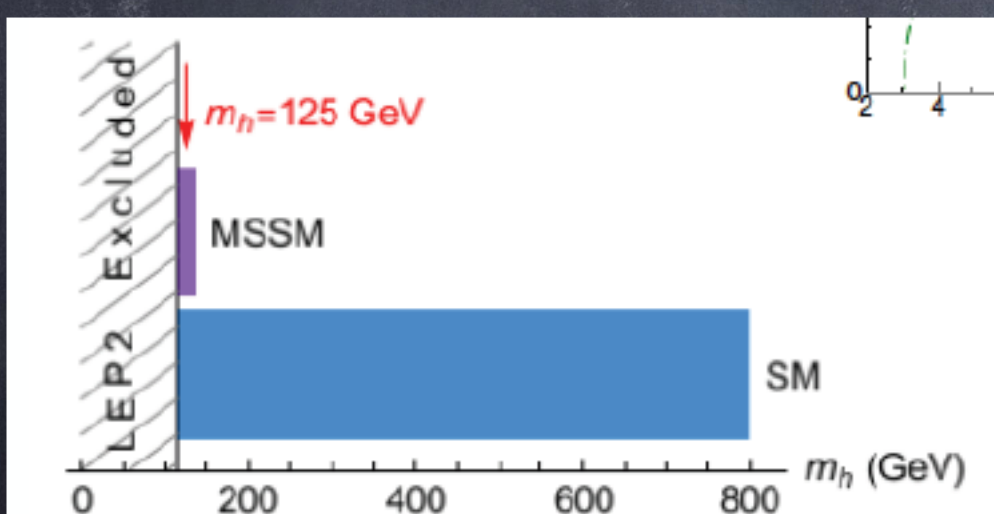
Unification of gauge couplings

m(t)~150-200 GeV

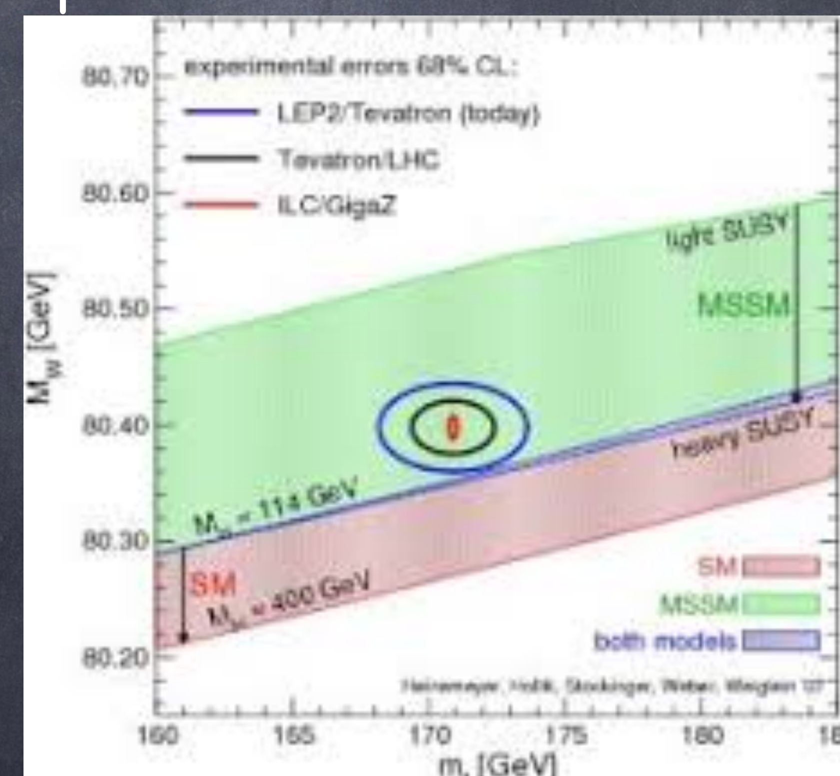
required for radiative EWSB



m(h) just right



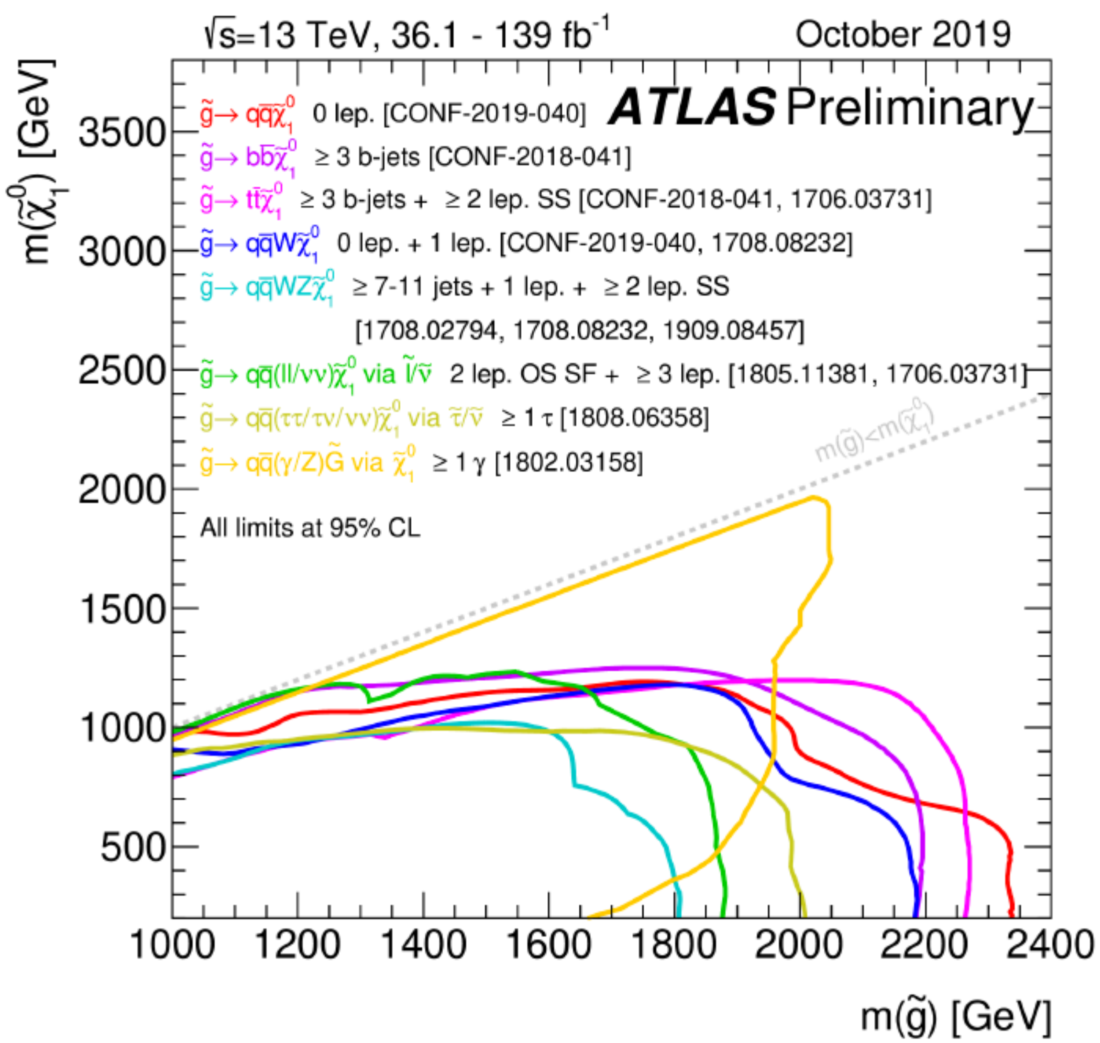
precision electroweak fits



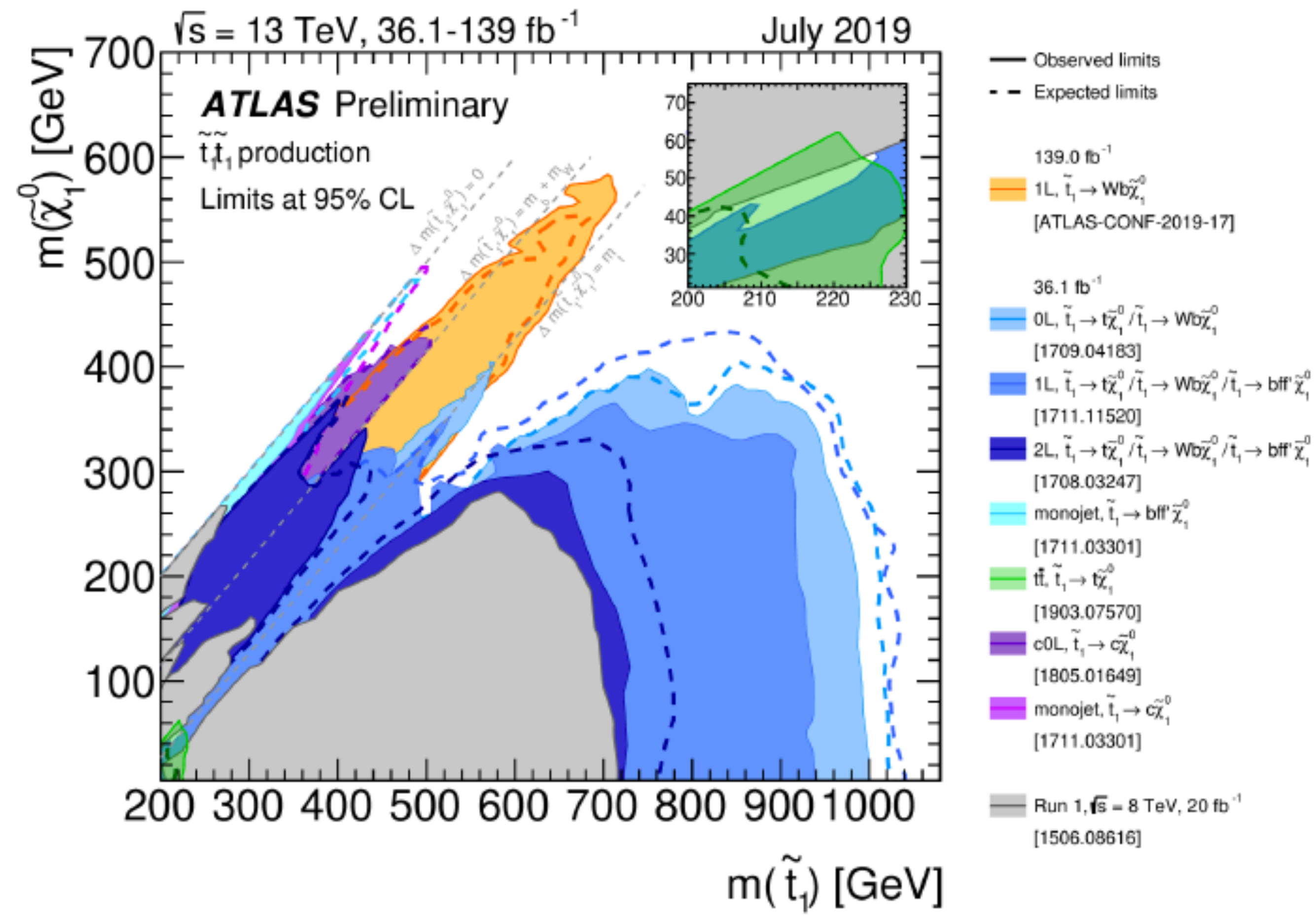
Radiative corrections have proven to be a reliable guide to new physics

But where are the sparticles?

none seen so far at LHC

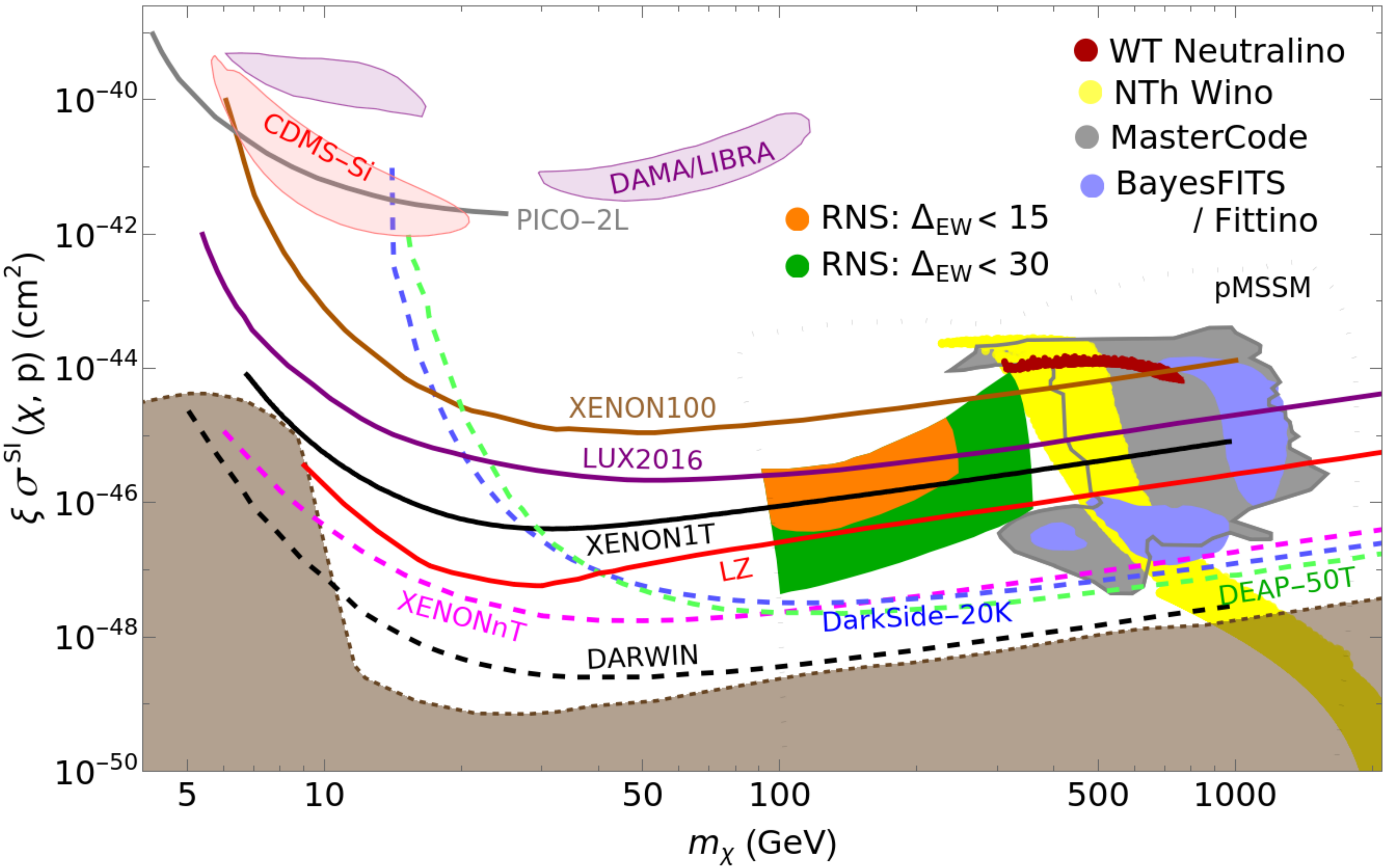


$m_{\tilde{g}} > 2.25$ TeV



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

Where are the WIMPs?

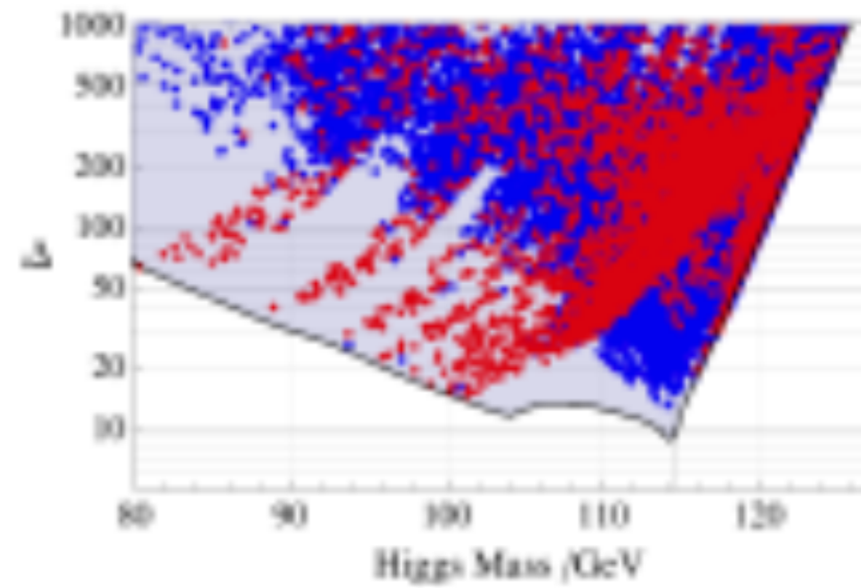


latest DD bounds from LZ2022: still no signal

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!?

``…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 provides a 't Hooft natural solution to the Big Hierarchy problem (BHP): as m(soft)->0, model becomes super- and EW- symmetric

But the present concern is: Little Hierarchy problem (LHP):

how is m(weak)~m(W,Z,h)<< m(soft)?

Introduce notion of practical naturalness:

HB, Barger, Savoy: arXiv:1509.02929

An observable $\mathcal{O}$ is *natural* if all contributions to $\mathcal{O}$ are $<\sim \mathcal{O}$

- *e.g* if $\mathcal{O} = a + b - c$, and if $a \gg \mathcal{O}$, then some *independent* contribution such as b would have to be fine-tuned to large opposite-sign value such as to maintain $\mathcal{O}$ at its measured value.
- Such a fine-tuning is regarded as unnatural and implausible, and indicative of some missing element in the theory (see Weinberg, Title page).
- A pit-fall occurs if $\mathcal{O} = a + b - b + c$ where $b \to$ *large*, *i.e.* contributions are *dependent*: **combine dependent terms before evaluating fine-tuning!**

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:

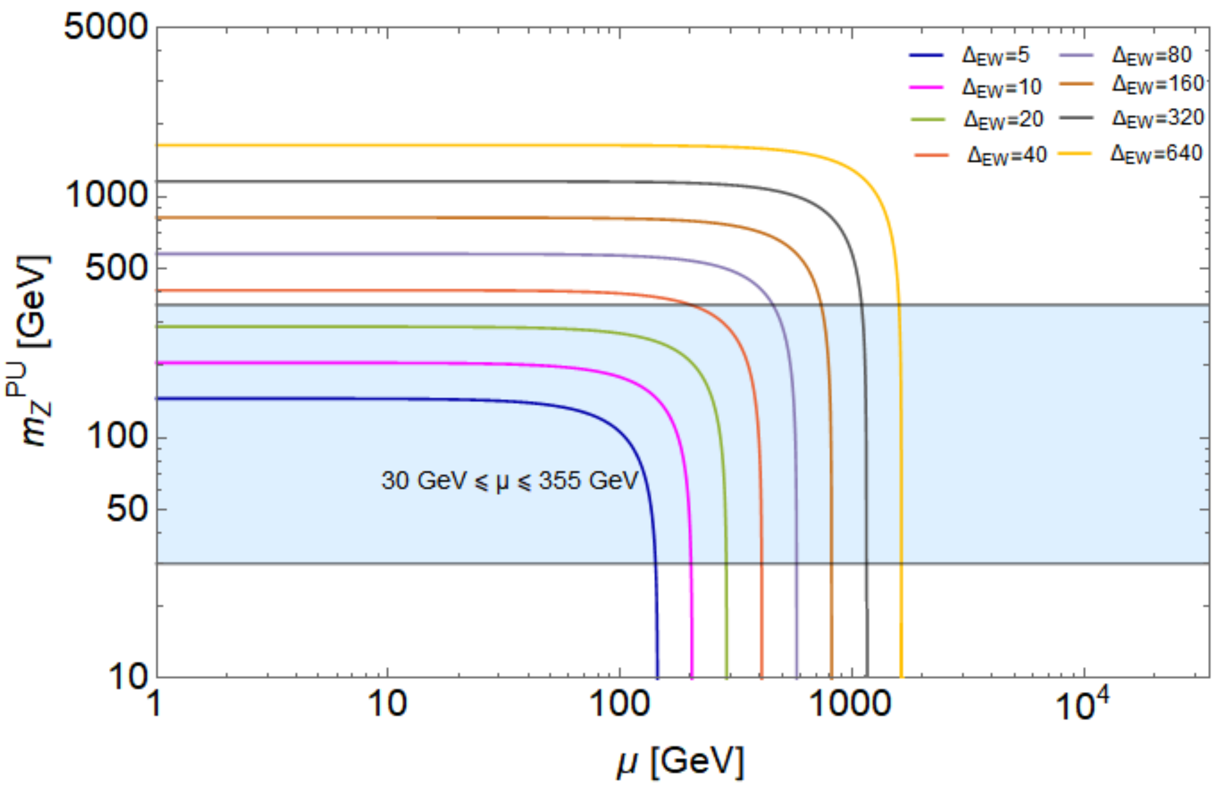
everybody does it but it is hidden inside spectra codes (Isajet, SuSpect, SoftSUSY, Spheno, SSARD)

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

SUSY breaking Higgs mass

>40 loop corrections

SUSY preserving mu parameter



finetuning required

natural solution

#1: Simplest SUSY measure: Δ_{EW}

No large uncorrelated cancellations in m(Z) or m(h); what you see is what you get!

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

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

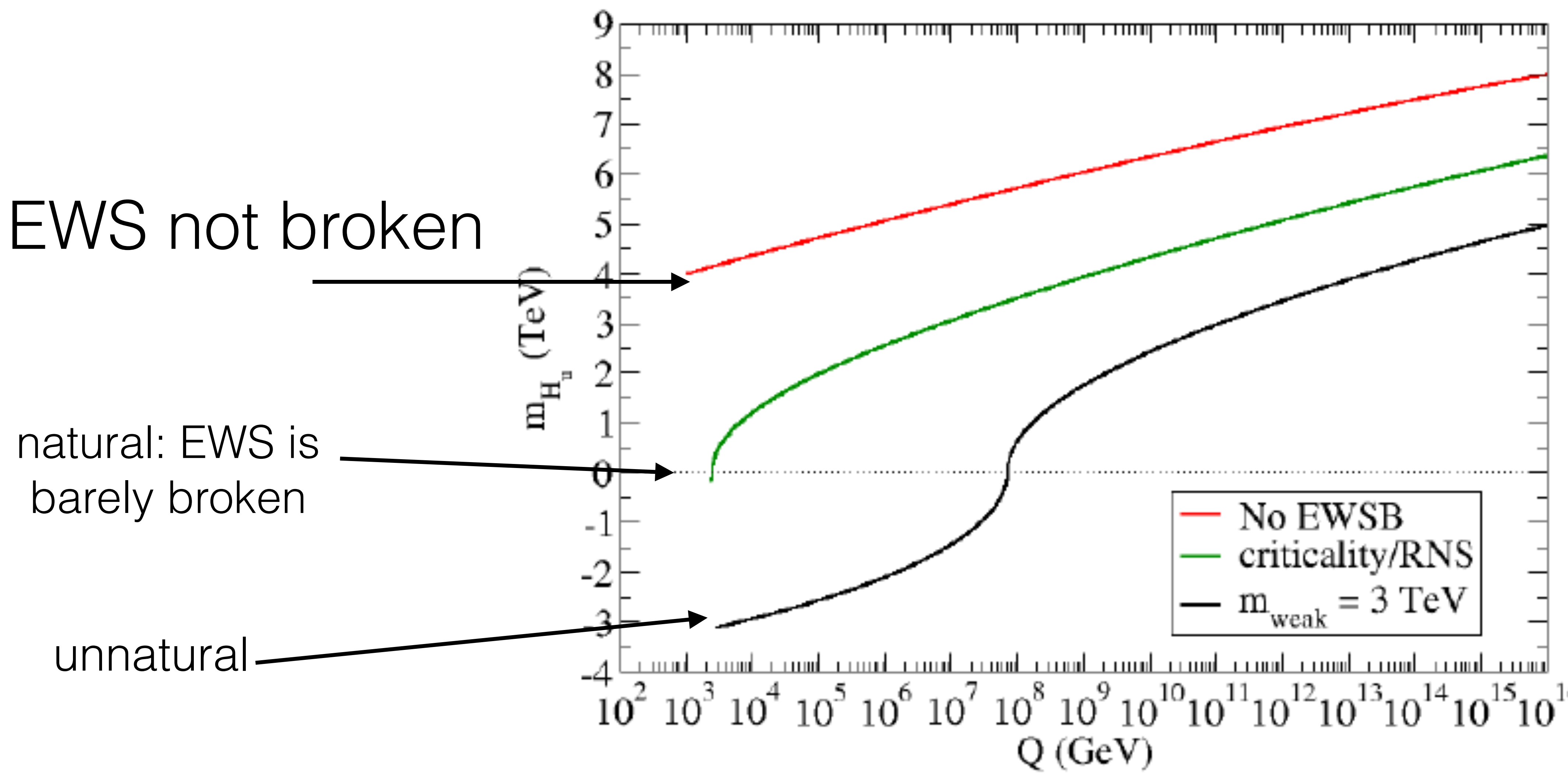
CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

Howard Baer,[1] Vernon Barger, Peisi Huang,[2] Azar Mustafayev,[3] and Xerxes Tata[4]
[1] Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019, USA
[2] Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA
[3] W. I. Fine Institute for Theoretical Physics, University of Minnesota, Minneapolis, MN 55455, USA

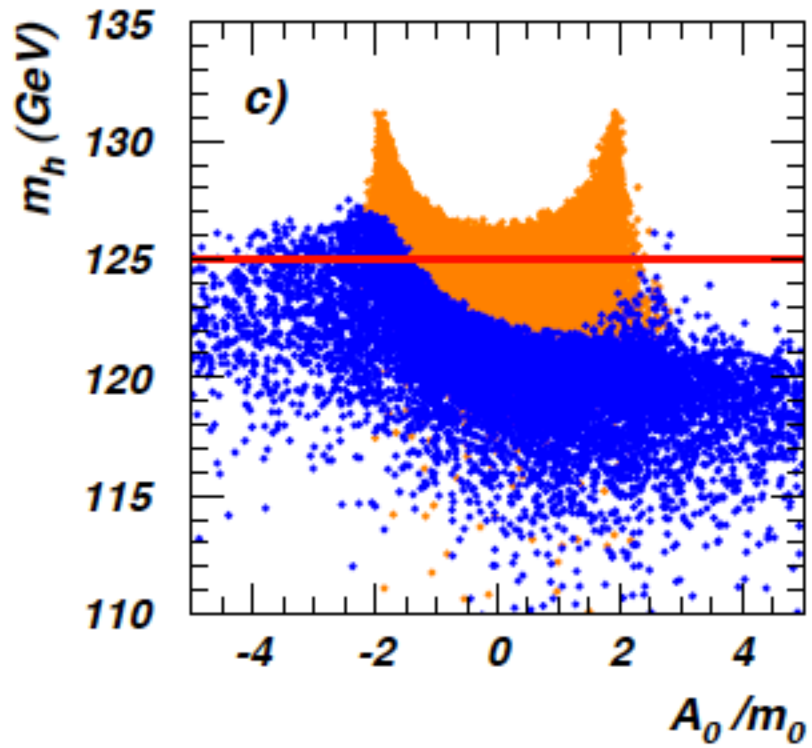
PRL109 (2012) 161802

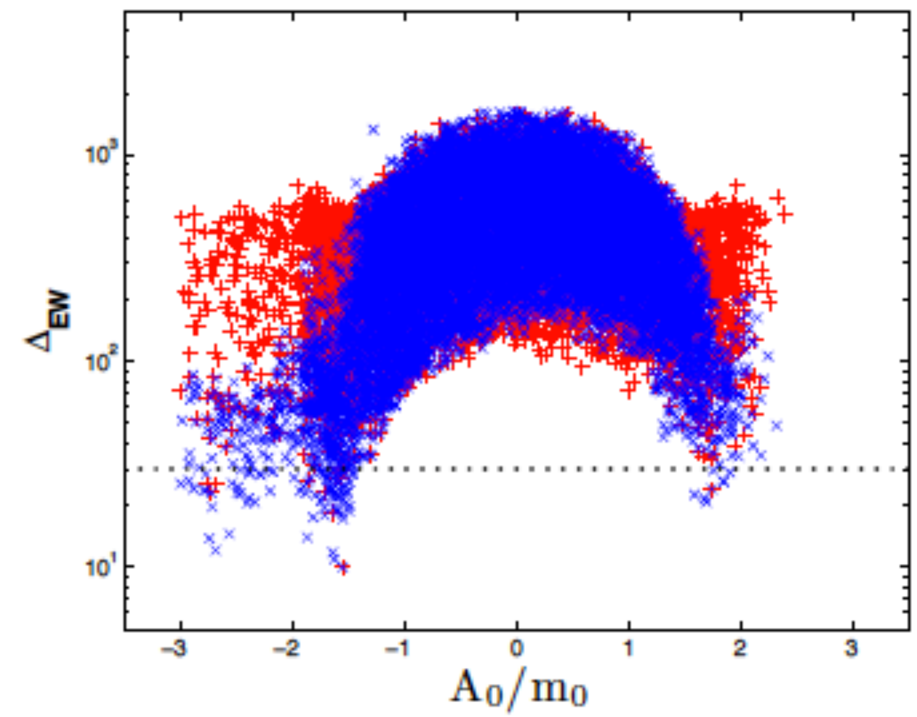
radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness



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

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



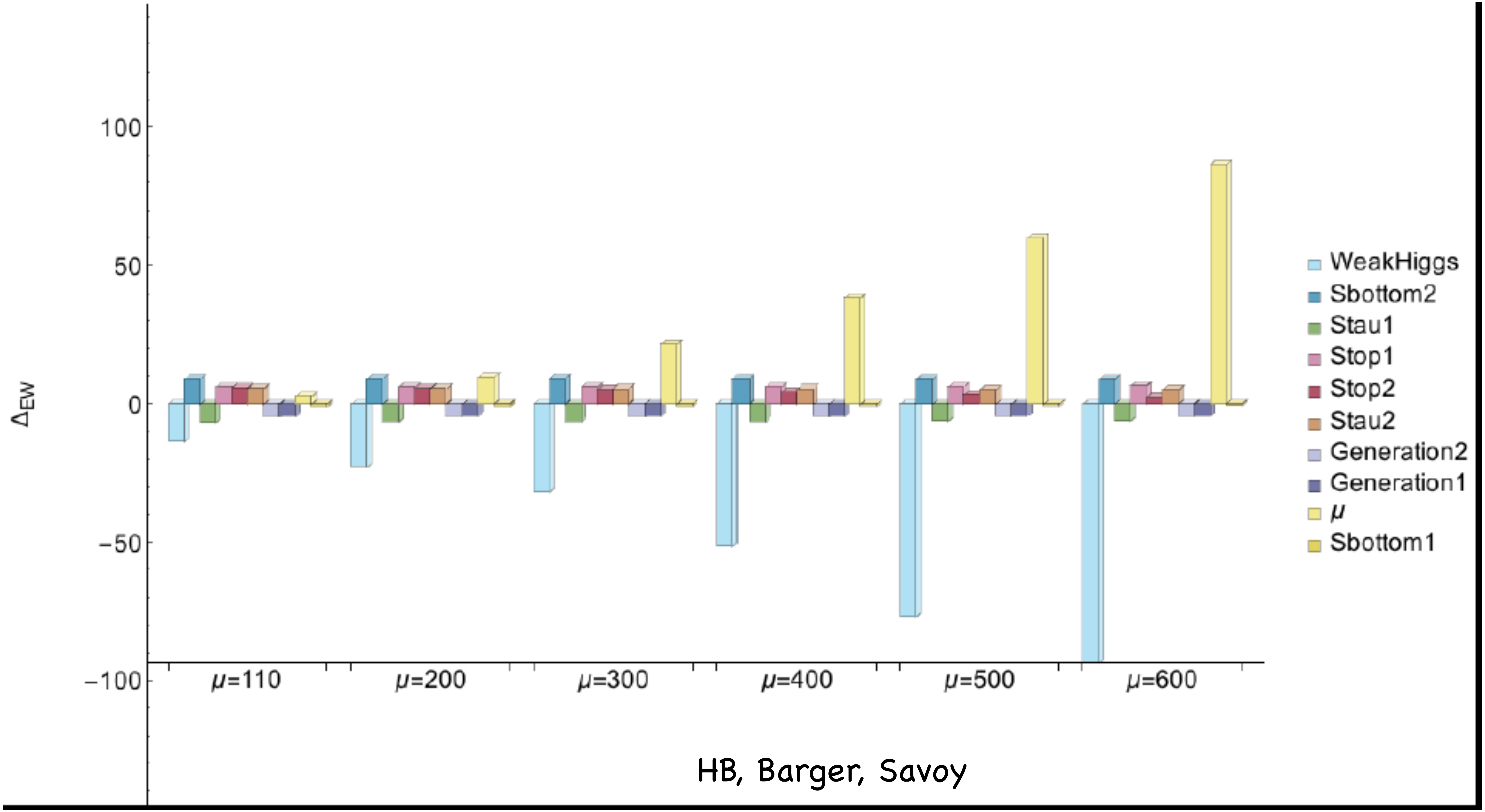


$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} x_W) \Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

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

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

How much is too much fine-tuning?



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!

other measures of finetuning

- log derivative measure: used arbitrary soft terms as free parameters in EFT which are necessarily correlated in more UV complete theory $\Delta = max_i|(p_i/m_Z^2)\partial m_Z^2/\partial p_i|$

- high scale measure: oversimplified higgs soft mass RGE thus deleting dependent terms that cancel against large logs $m_h^2 \sim \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$ with $\Delta \sim \delta m_{H_u}^2/m_h^2$

can overestimate finetuning by up to 3 orders of magnitude!

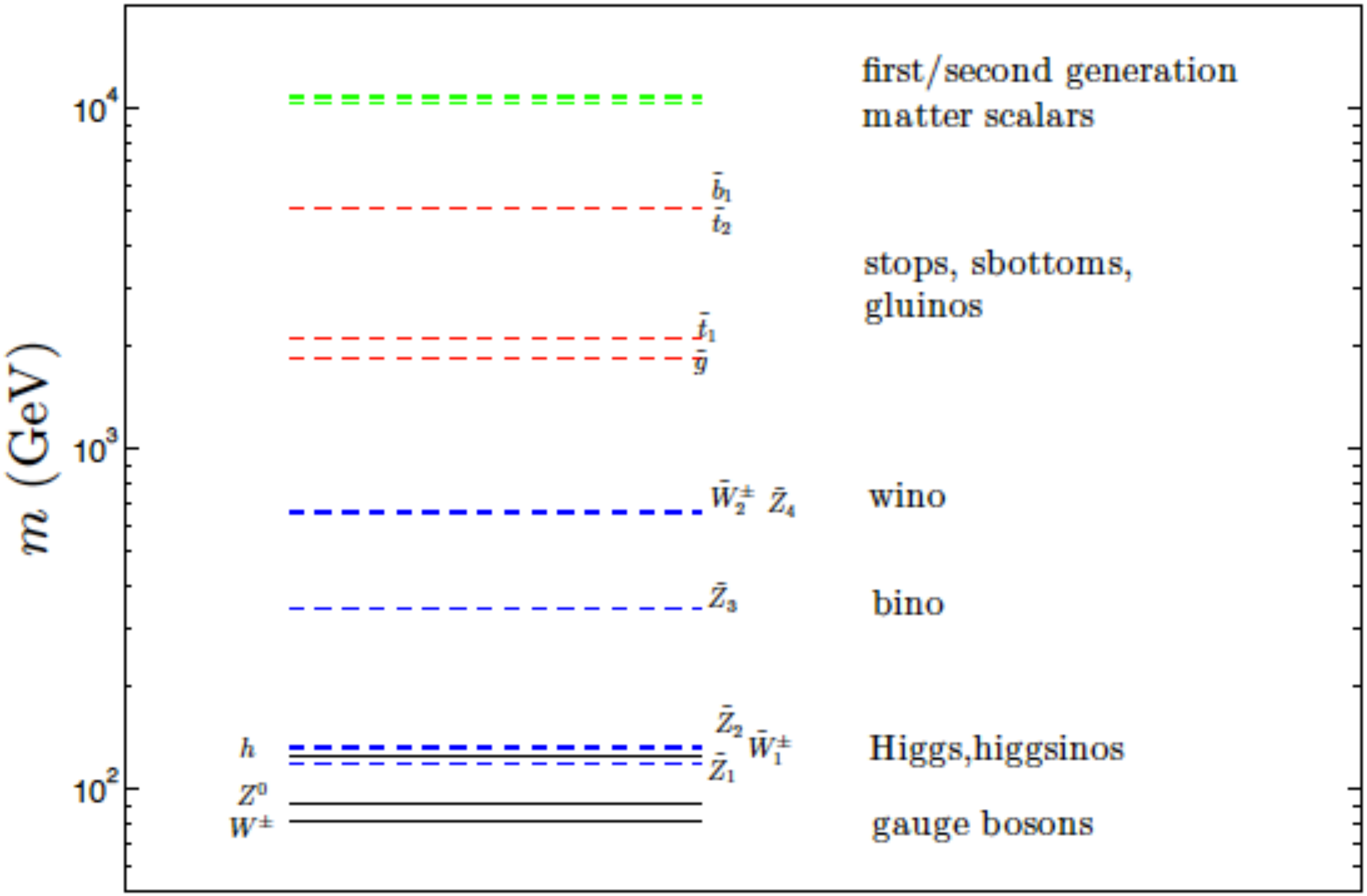
(For details, see paper below or backup slides)

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,‡]
[1]Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019, USA
[2]Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA
(Received 17 September 2013; published 18 November 2013)

Typical spectrum for low Δ_{EW} models



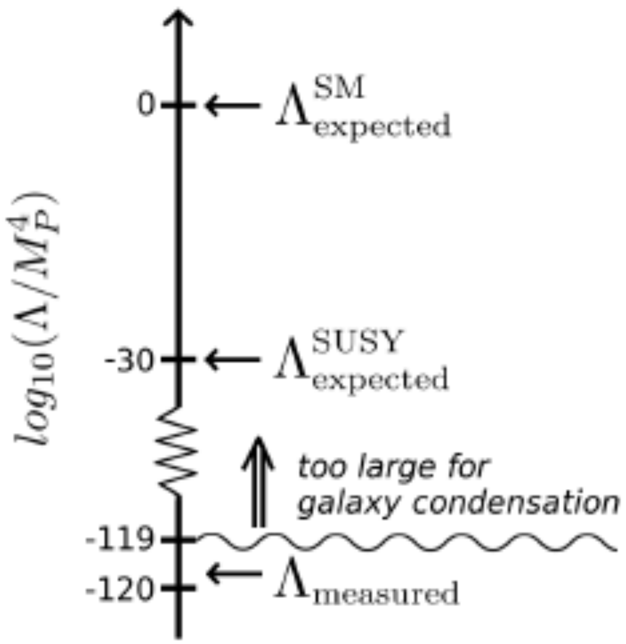
There is a Little Hierarchy, but it is no problem

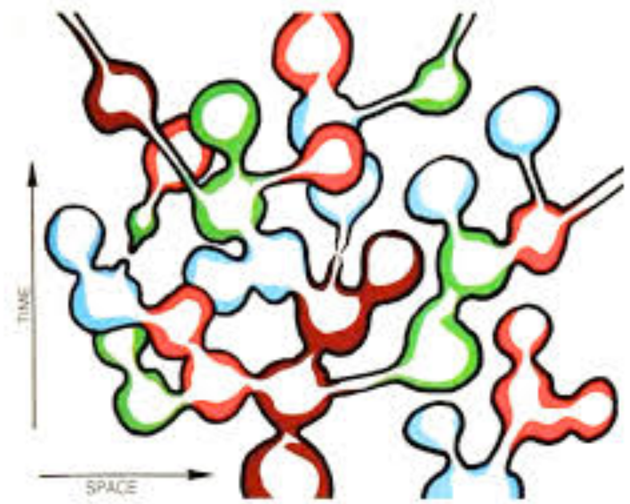
$\mu \ll m_{3/2}$ higgsinos likely the lightest superparticles!

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

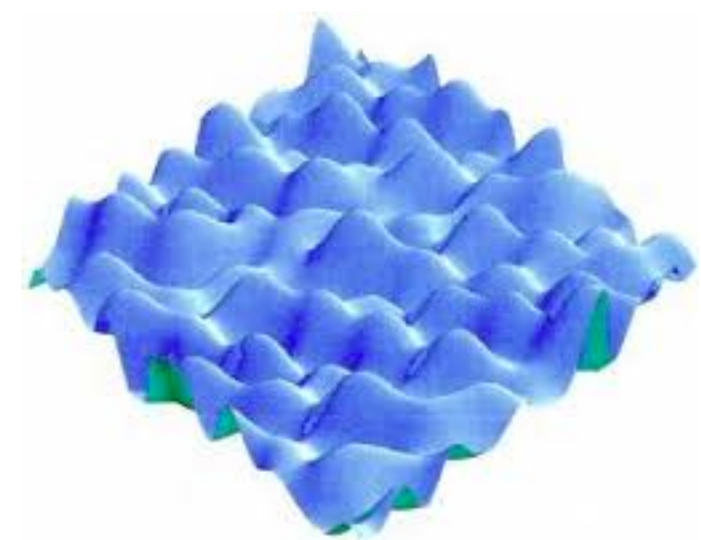
String theory after 2001: the string landscape

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; Susskind; Douglas

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

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

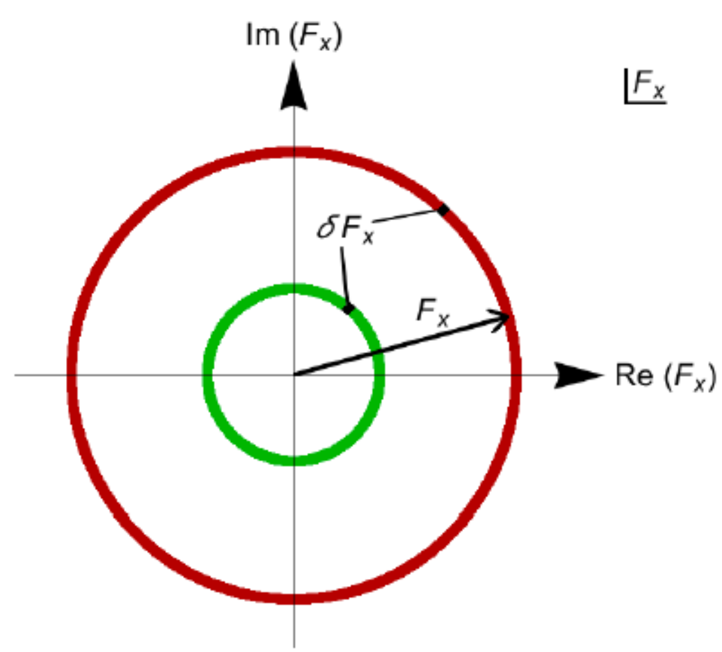


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

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

What about f(selection)?

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

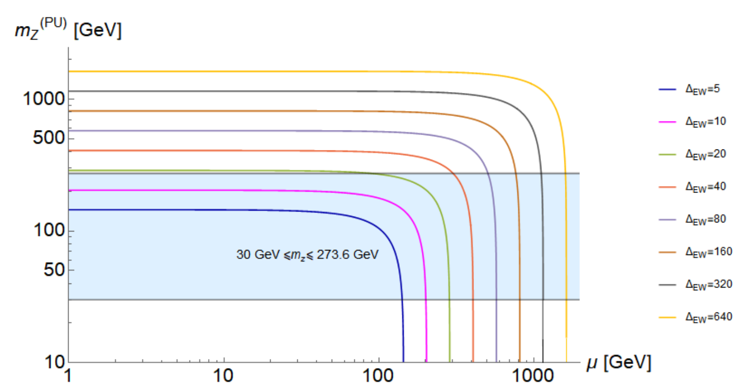
to penalize soft terms straying too far from weak scale

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



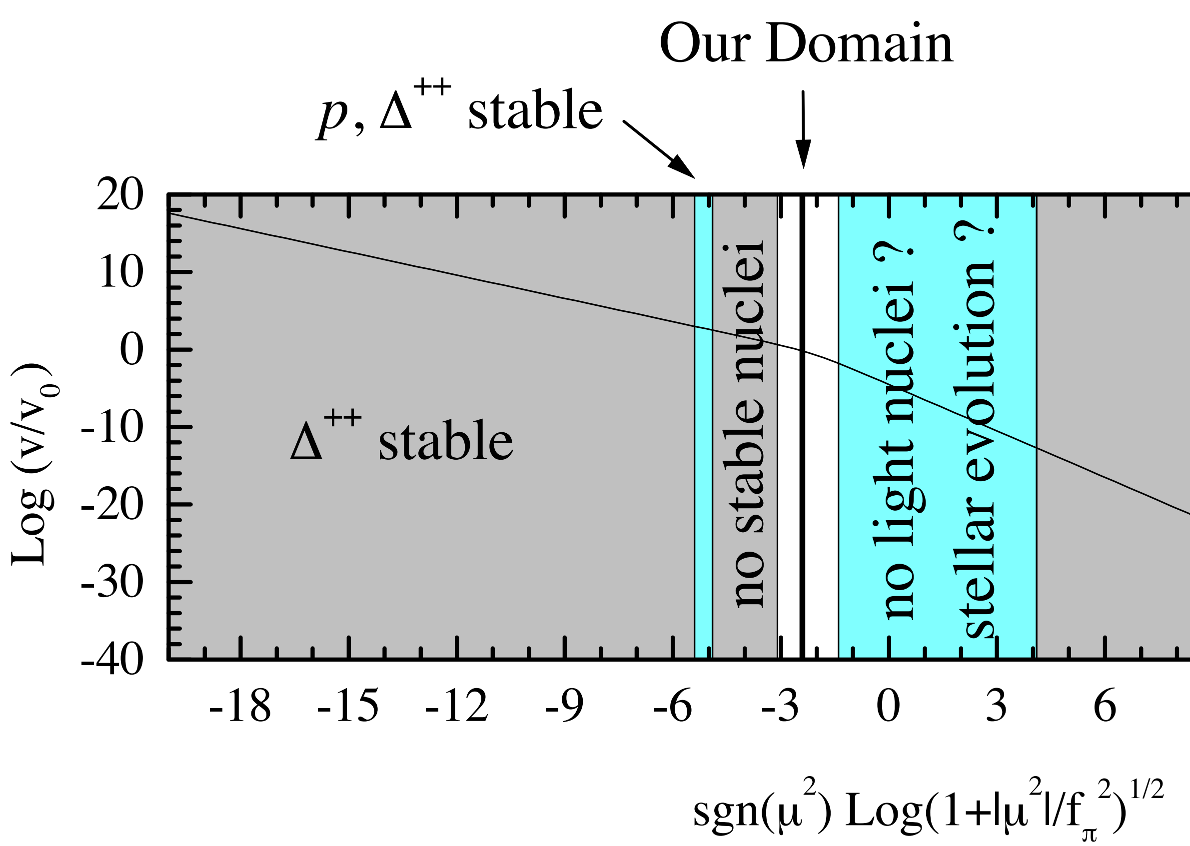
Then for statistically selected soft terms, m(weak) is output, not input

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

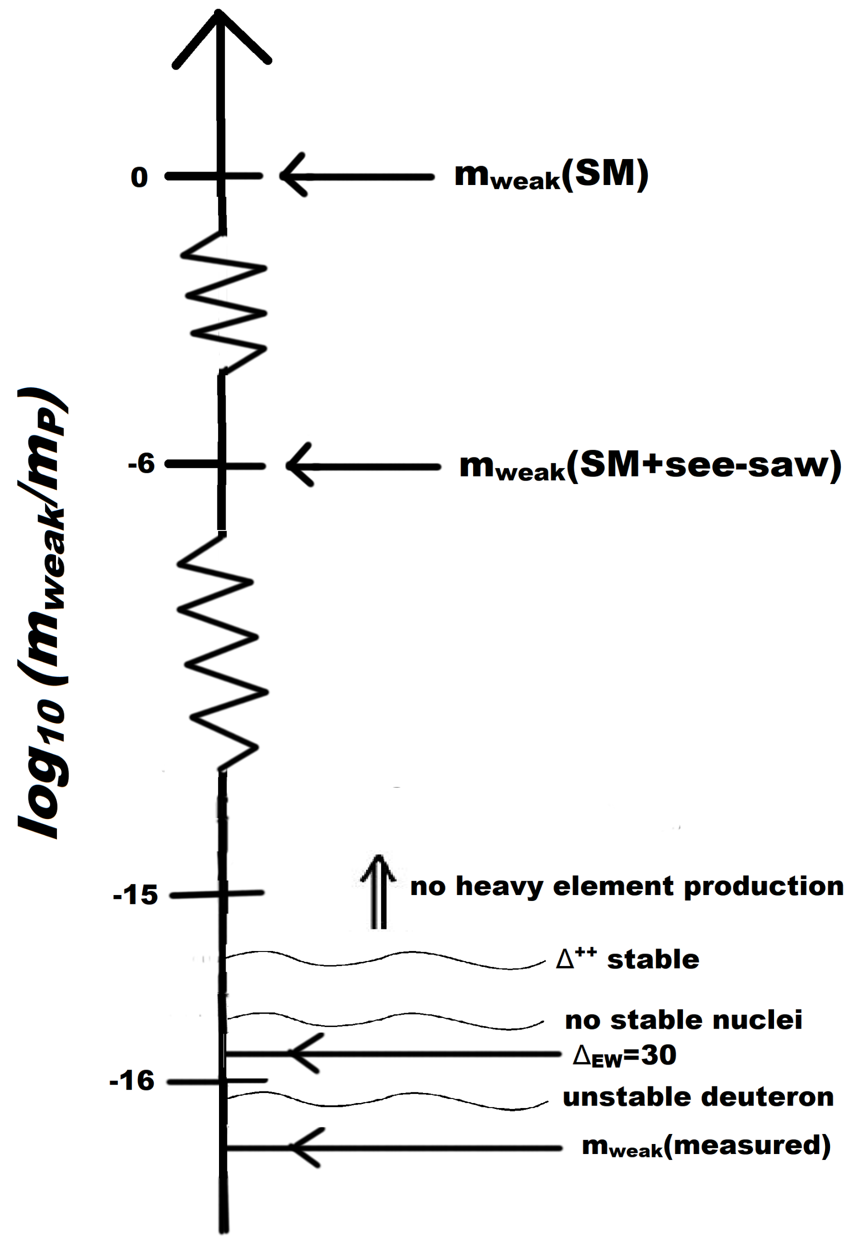
Factor four deviation of weak scale from measured value => $\Delta_{EW} < 30$

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)

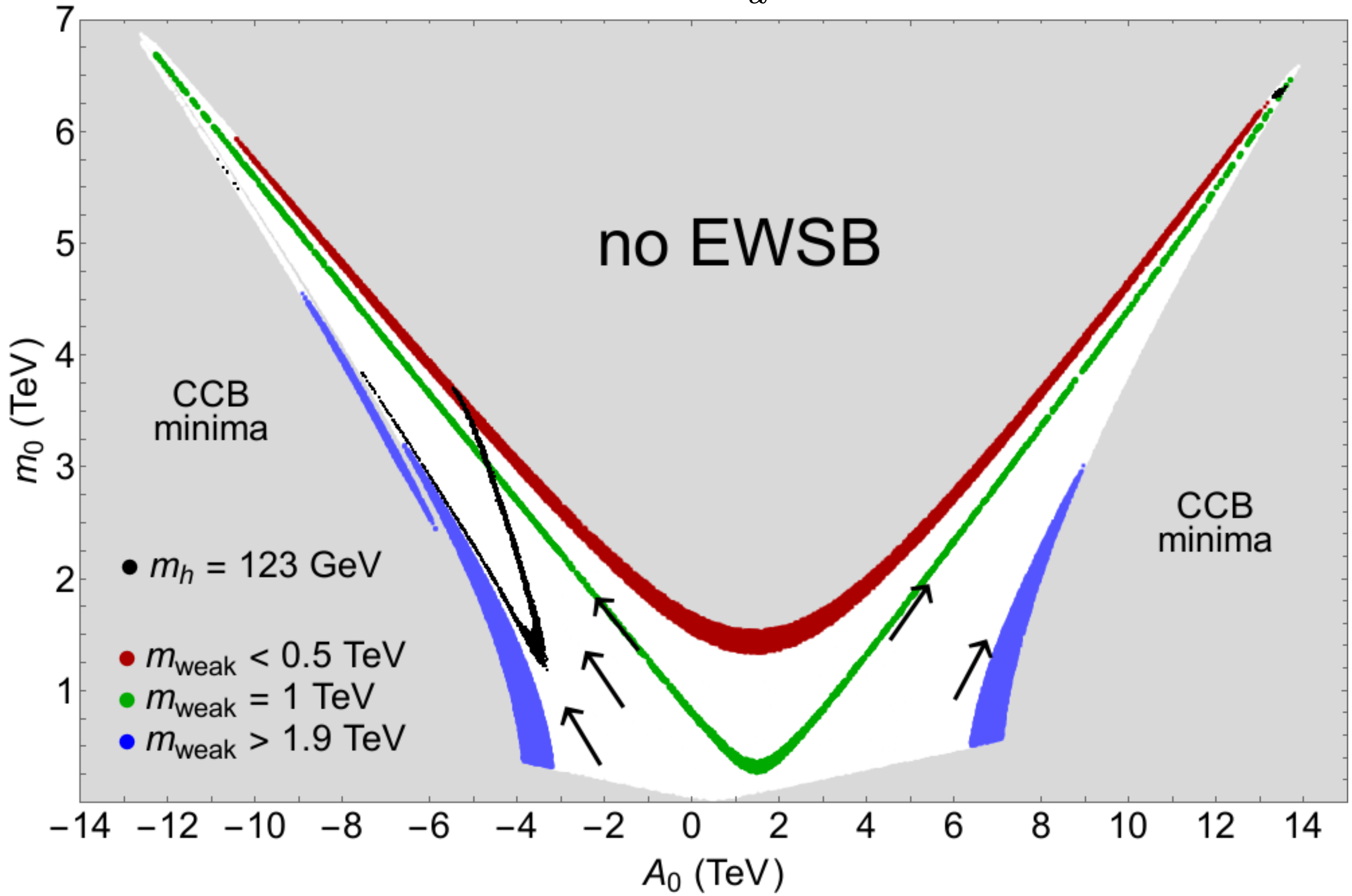


m(weak) must lie within ABDS window to have atoms/chemistry



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

$m_{H_u} = 1.3 m_0$



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,

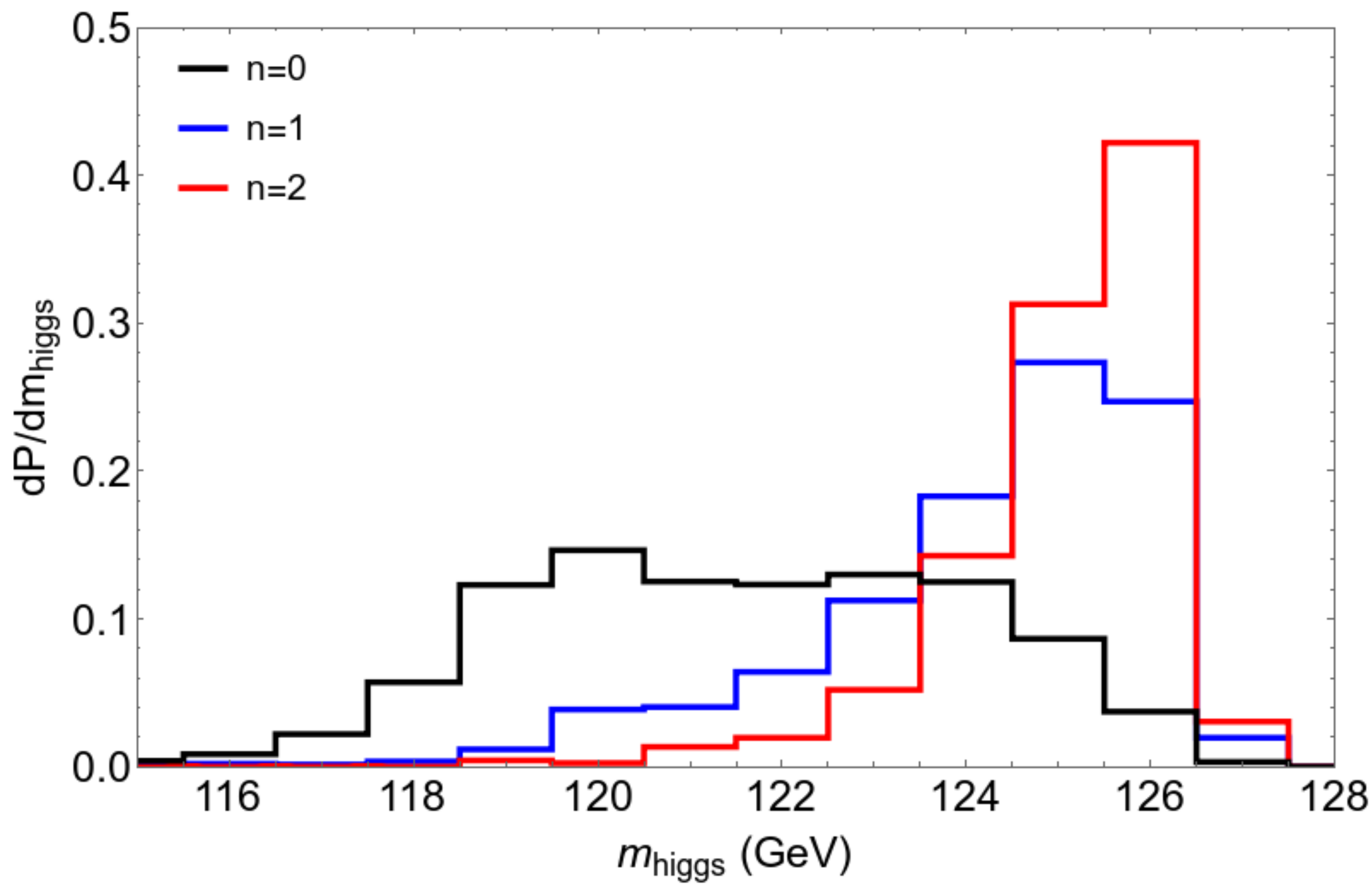
$\tan\beta$: $3 - 60$ (flat)

mu=150 GeV (fixed)

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

Making the picture more quantitative:

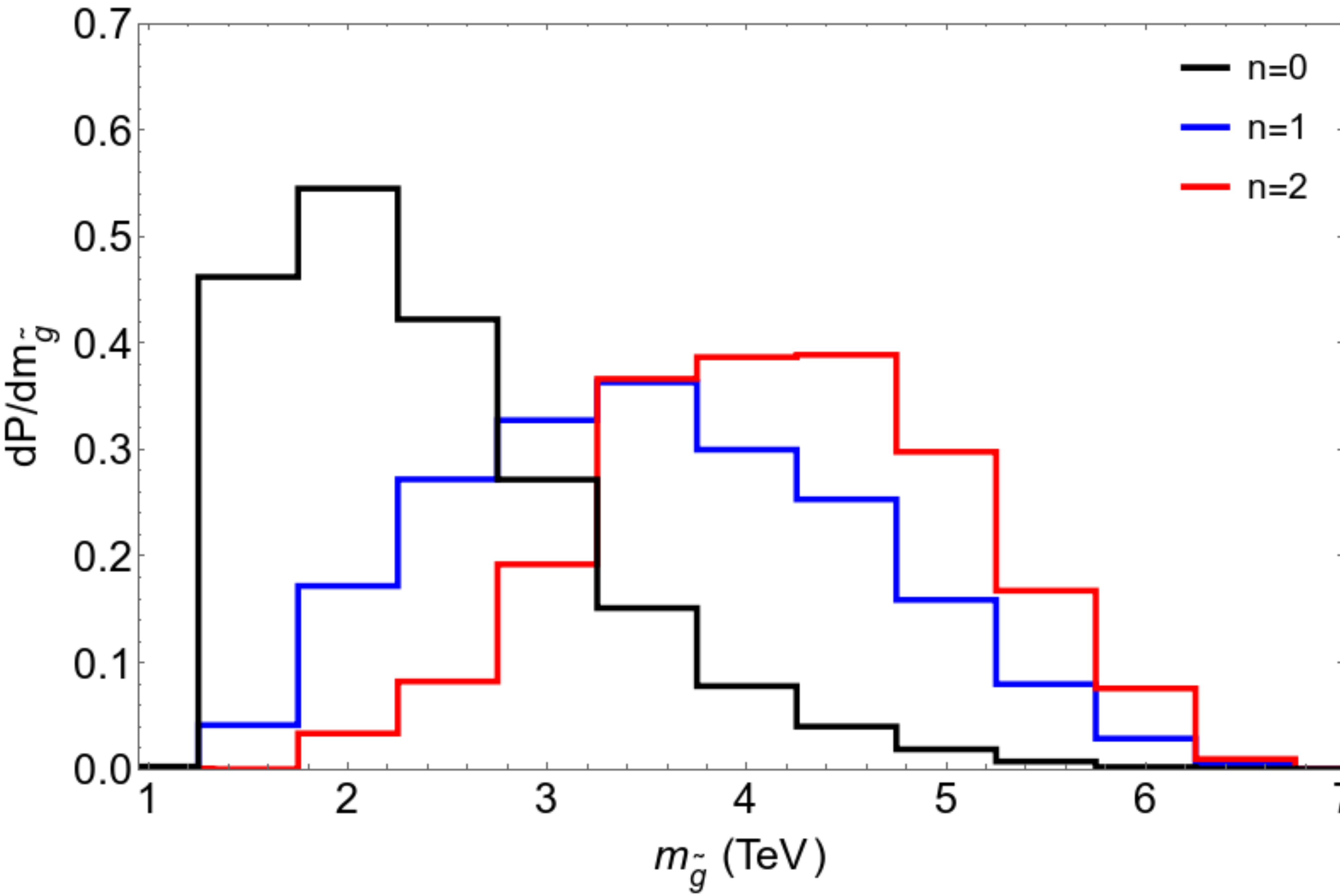
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



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

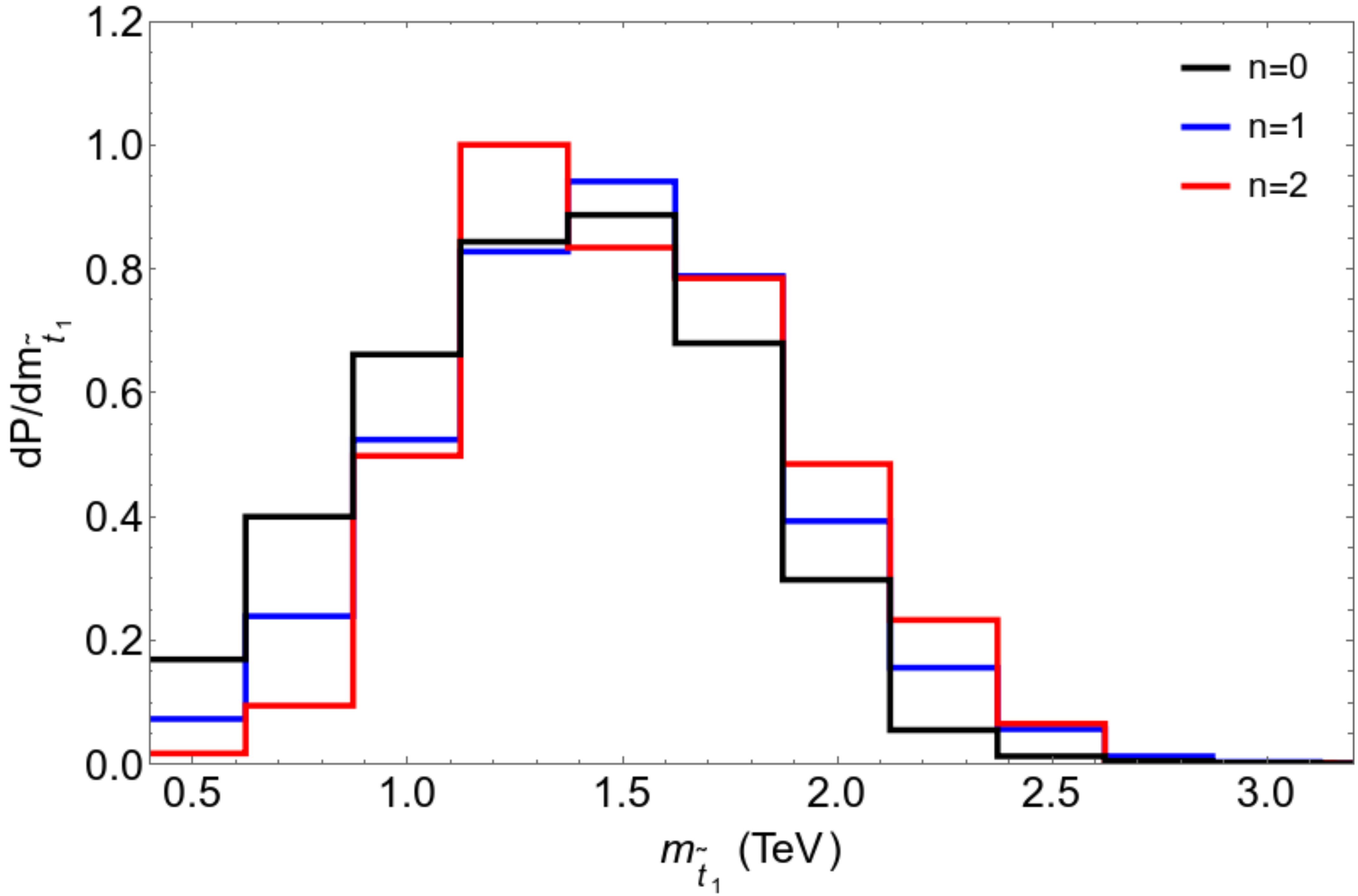
HB, Barger, Serce, Sinha, arXiv:1712.01399

What is corresponding distribution for gluino mass?



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

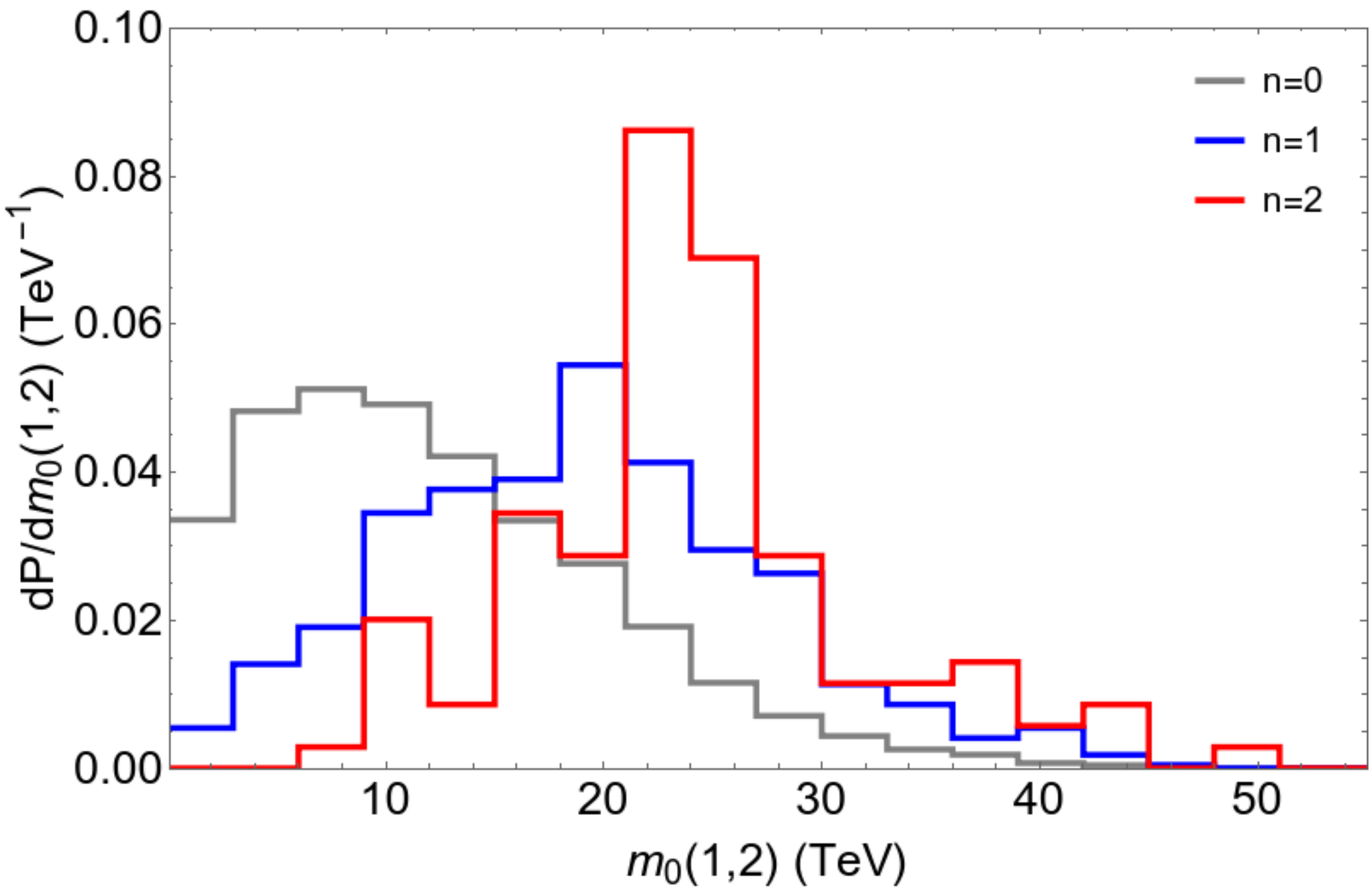
and top-squark mass m(t1)?



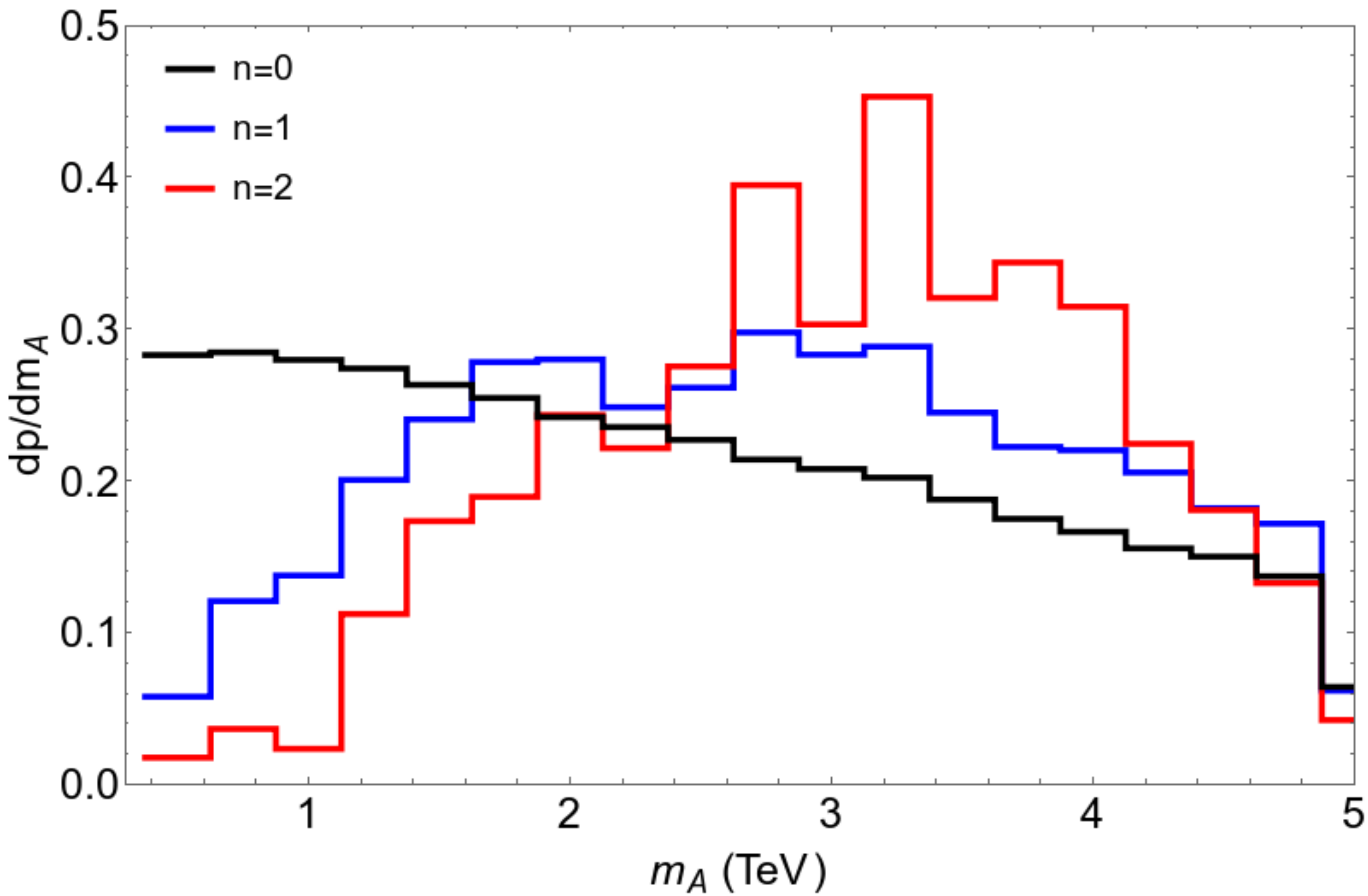
m(t1) typically beyond present LHC reach

first/second generation sfermions pulledto 10-40 TeV:

decoupling sol'n to SUSY flavor/CP problems



Landscape=> h boson has m~125 GeV and very SM-like; heavy Higgs bosons A, H, H^+-: multi-TeV scale



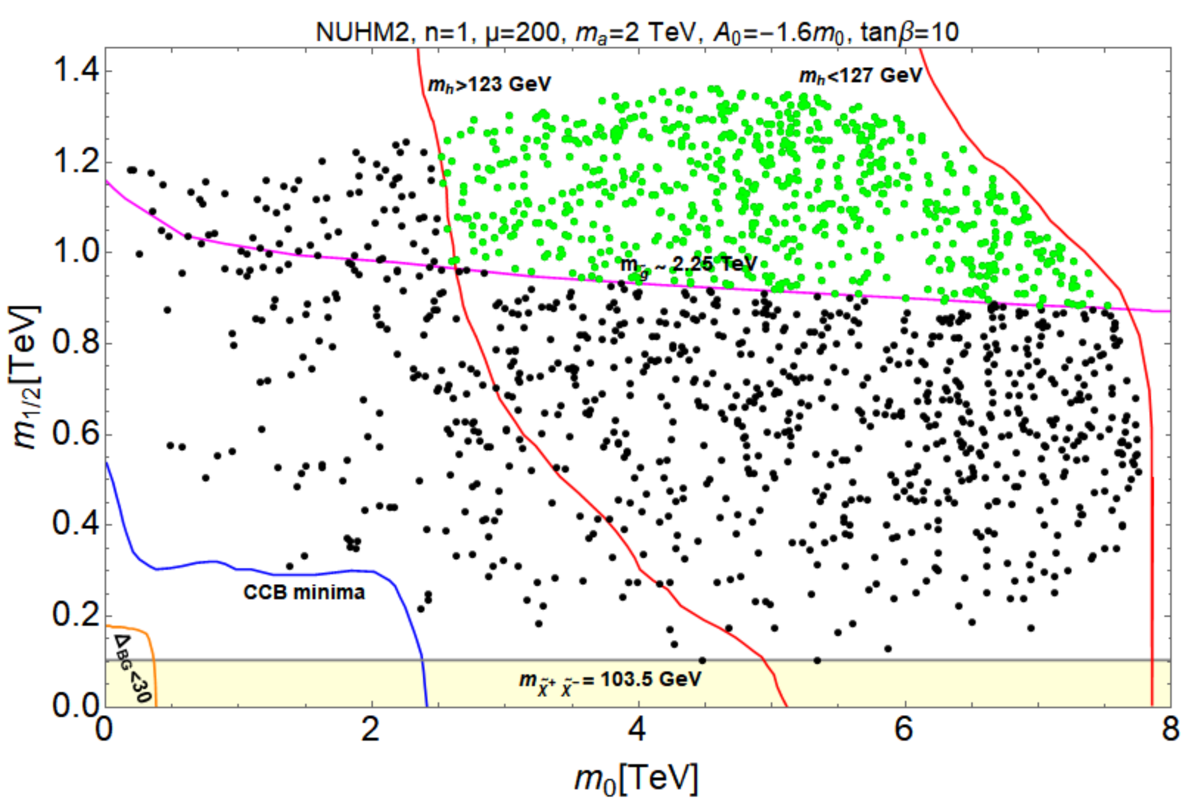
Stringy naturalness: higher density of points are more stringy natural!

conventional natural: favor low m0, mhf

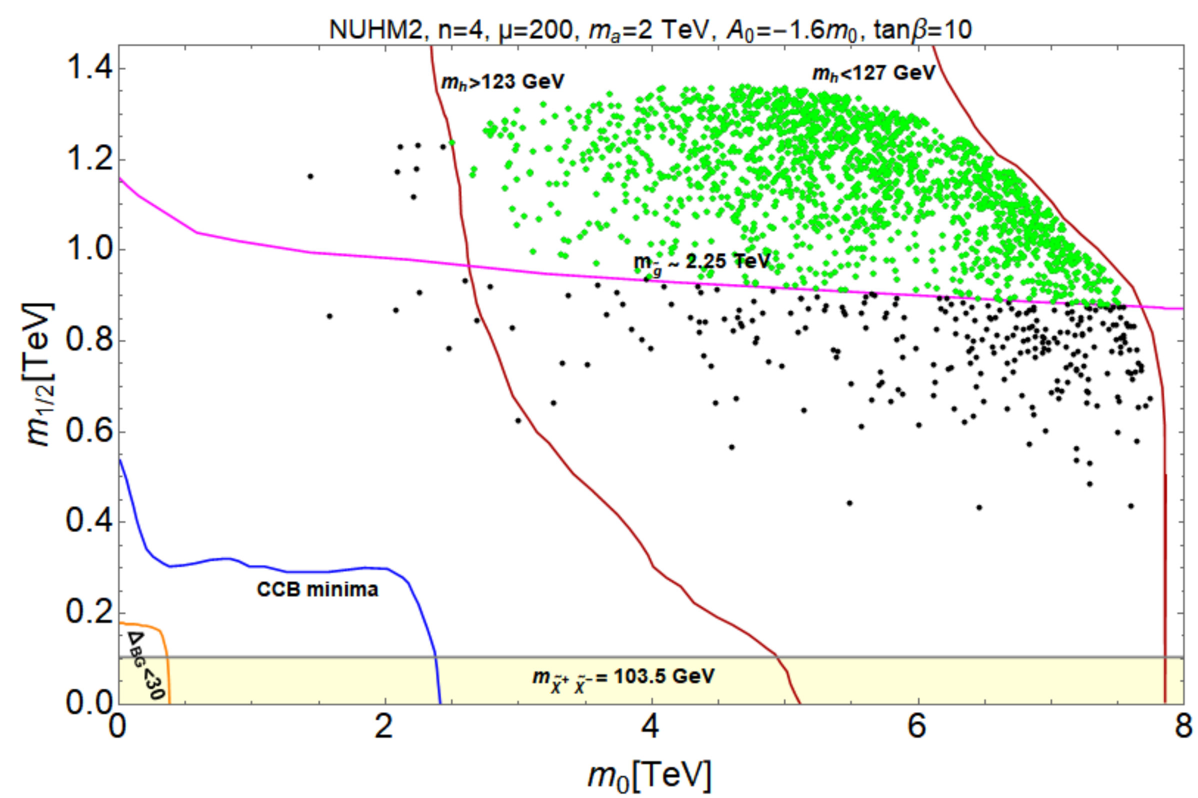
stringy naturalness: favor high m0, mhf so long as m(weak)~100 GeV

HB, Barger, Salam, arXiv:1906.07741

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



$m(soft)^1$

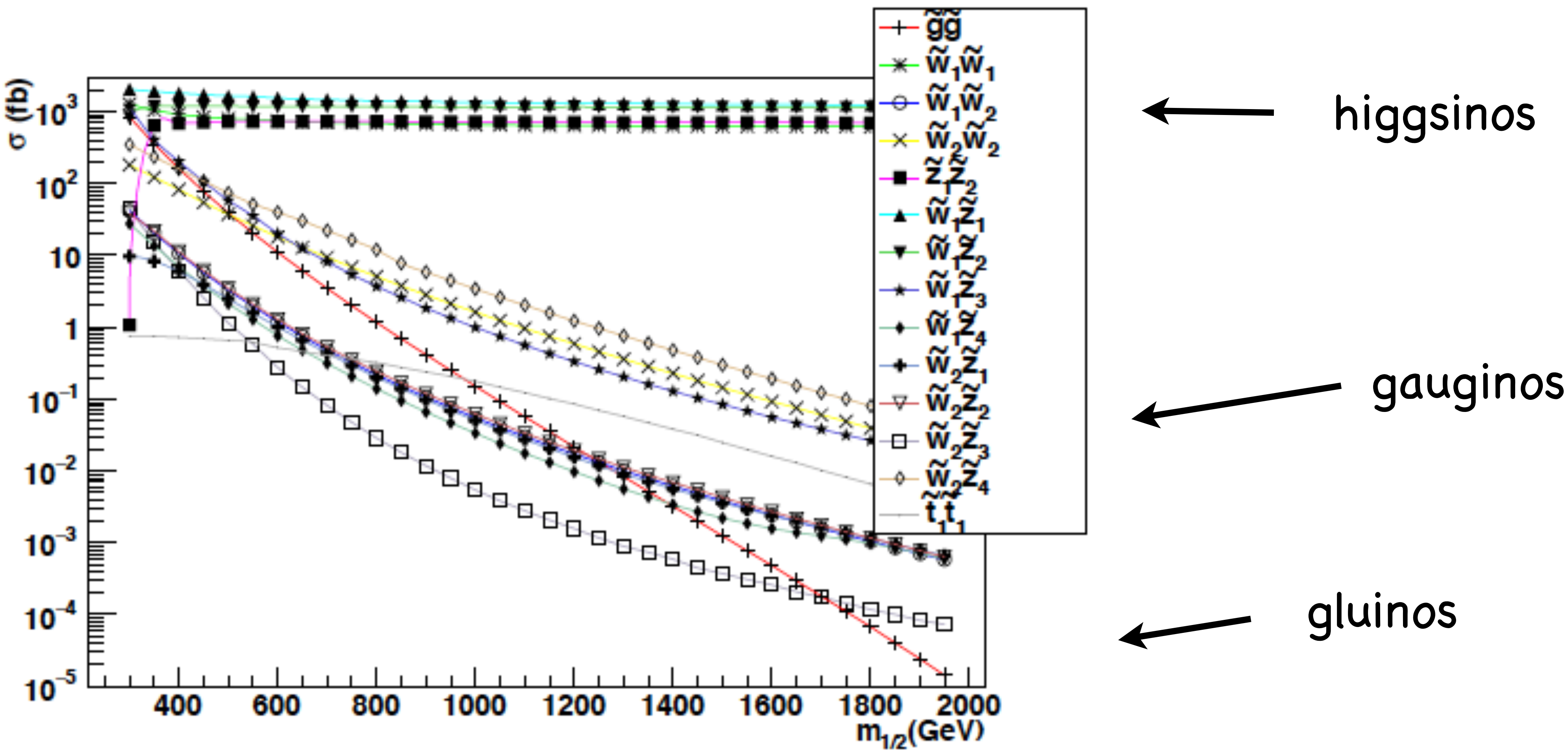


$m(soft)^4$

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

Prospects for discovering Higgs and higgsinos at LHC and ILC

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



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

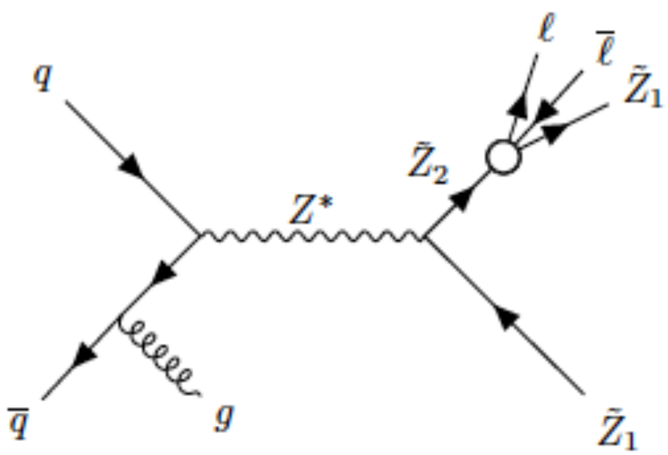
largest visible cross section: wino pairs

gluino pairs sharply dropping

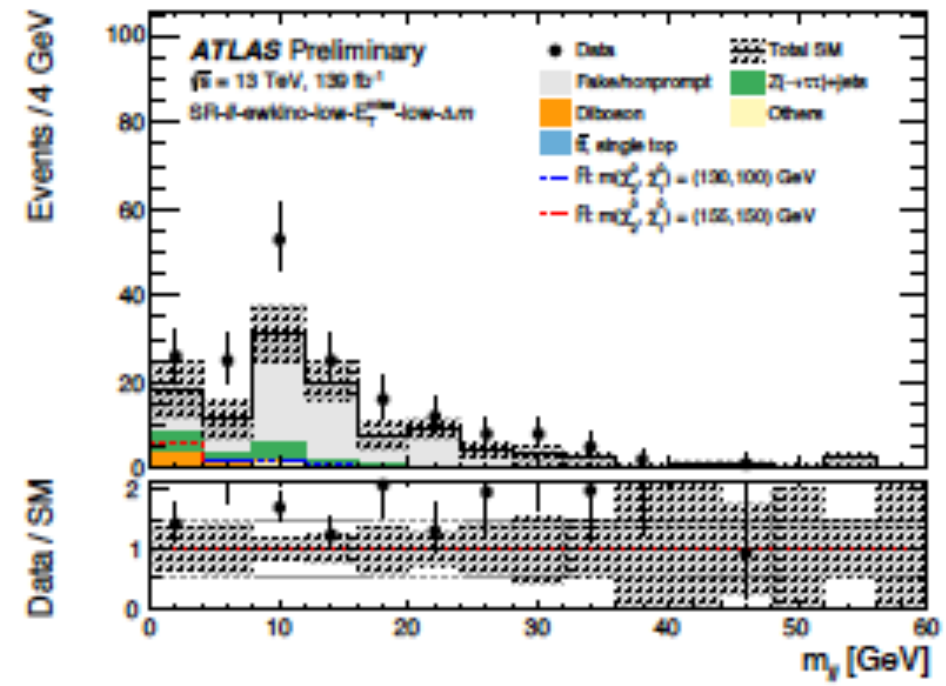
HL-LHC best bet: higgsino pair production

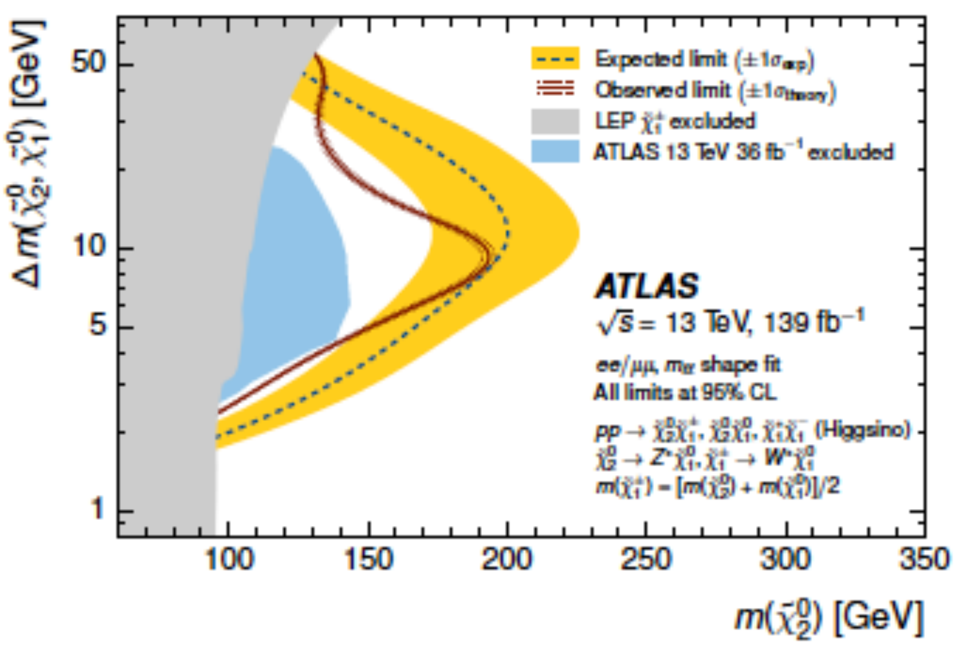
Natural SUSY: only higgsinos need lie close to weak scale

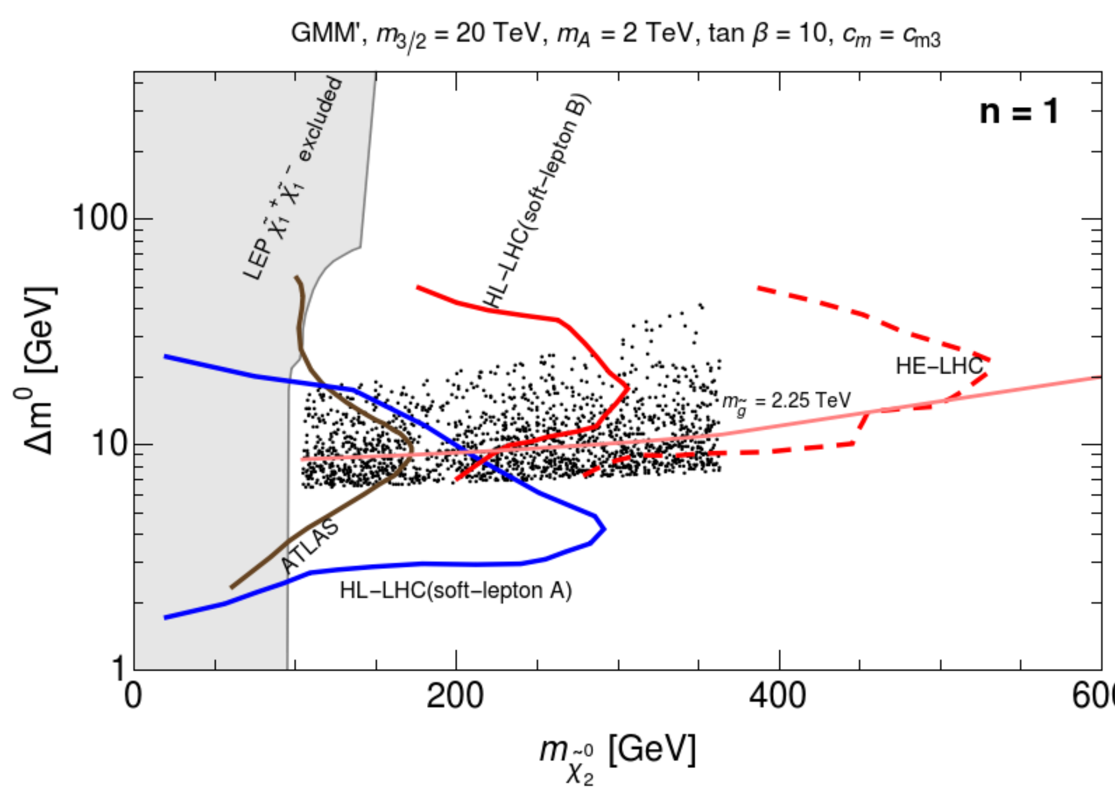
Soft dilepton+jet+MET signature from higgsino pair production



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

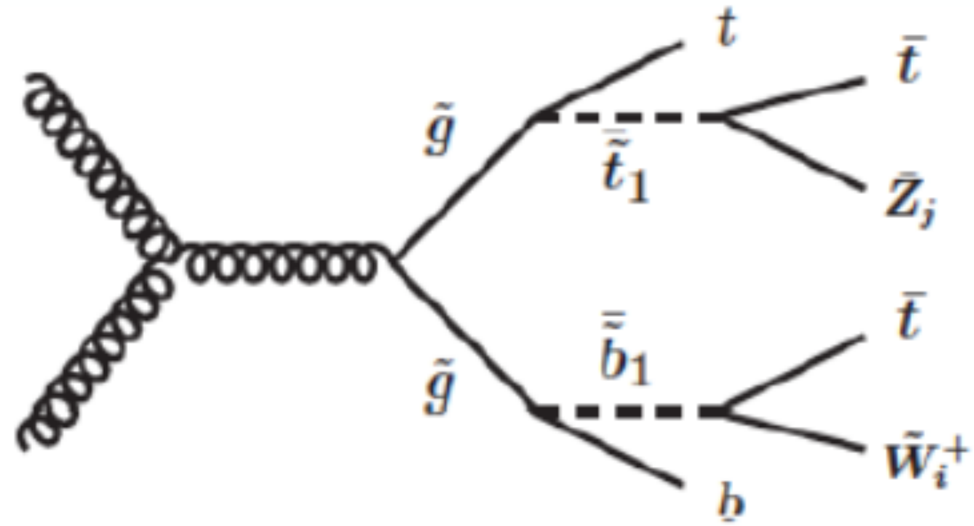




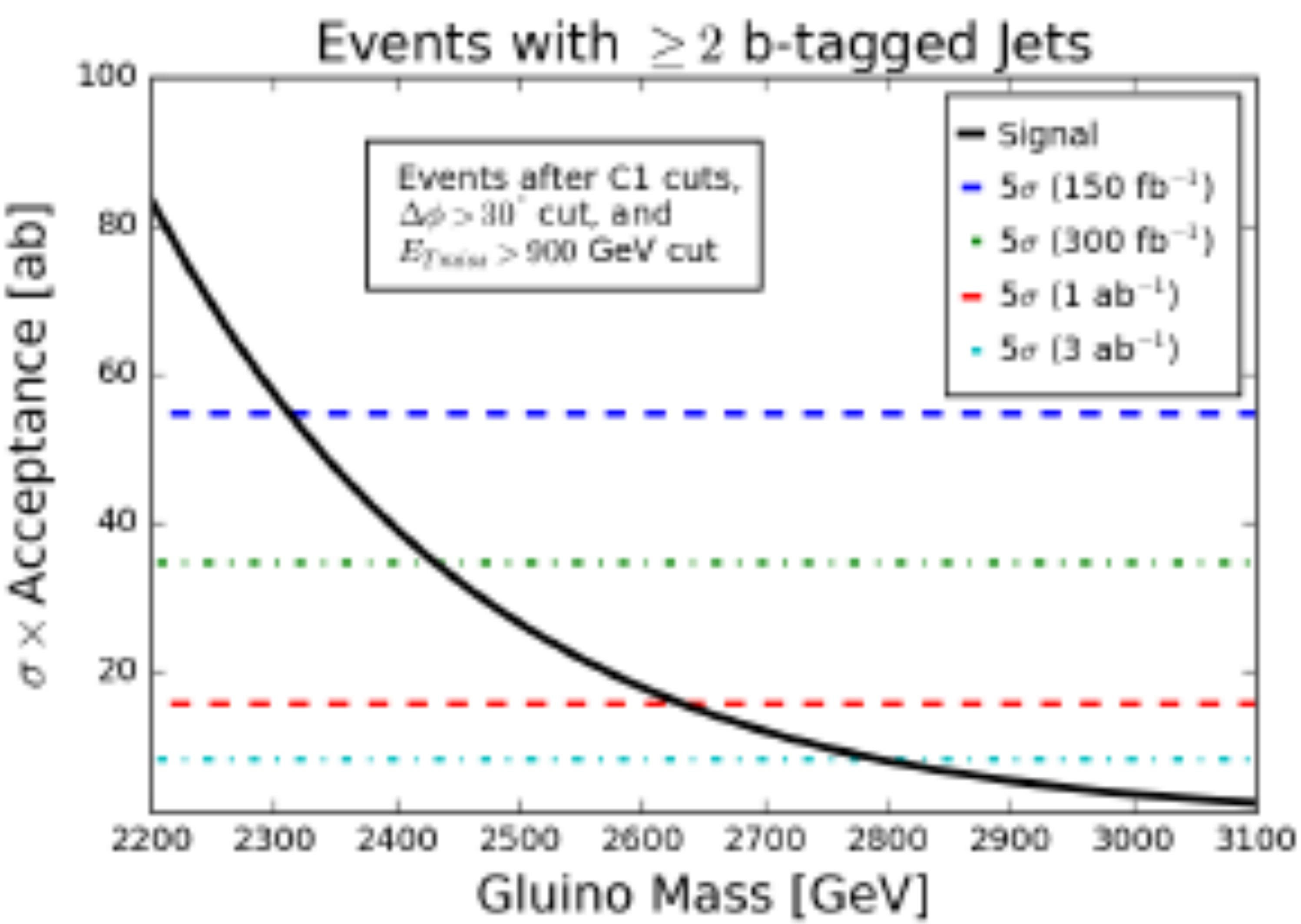


It appears that HL-LHC can see much of natural SUSY p-space;
signal in this channel should emerge slowly as more integrated luminosity accrues

gluino pair cascade decay signatures



LHC14

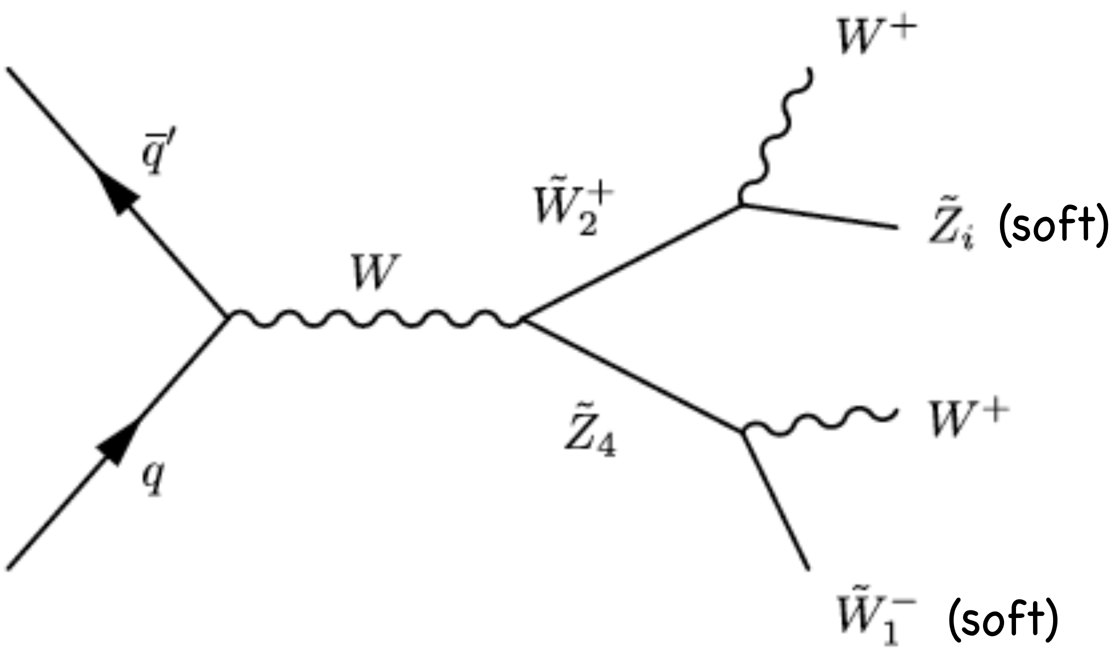


HB, Barger, Gainer, Huang, Savoy, Sengupta,Tata

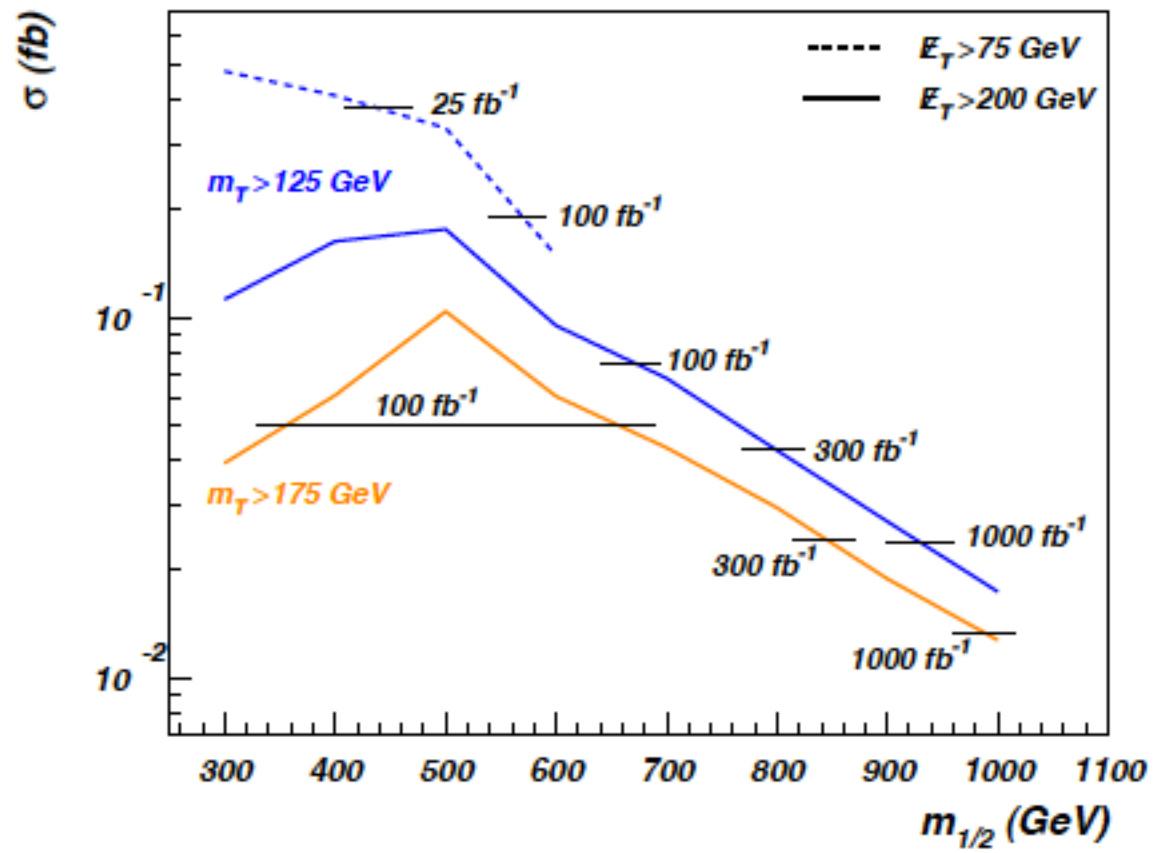
HL-LHC to probe m(gl)~2.8 TeV

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

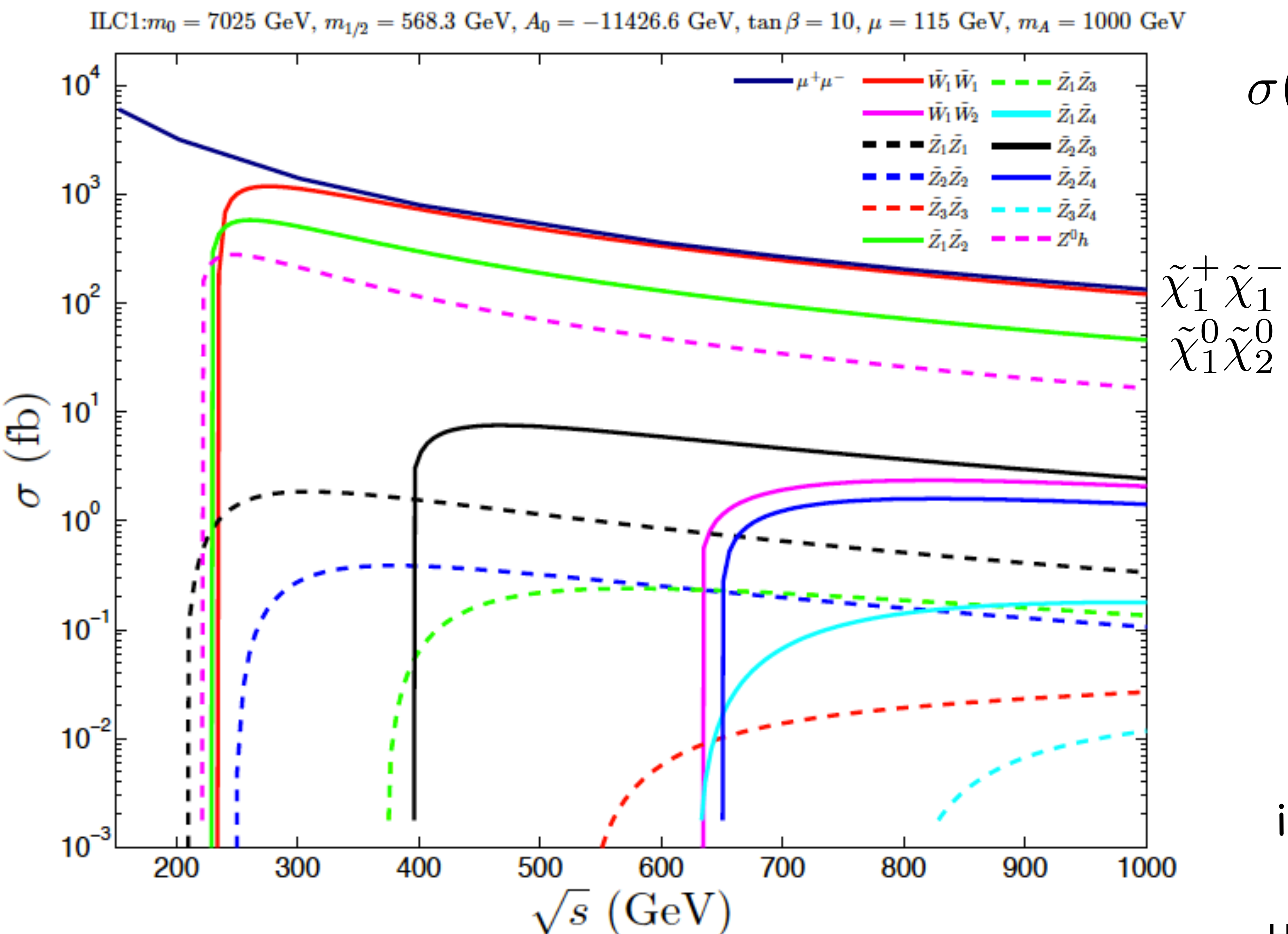


This channel offers added reach of LHC14 for natSUSY; it is also indicative of wino-pair prod'n followed by decay to higgsinos

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 $E(jj)$

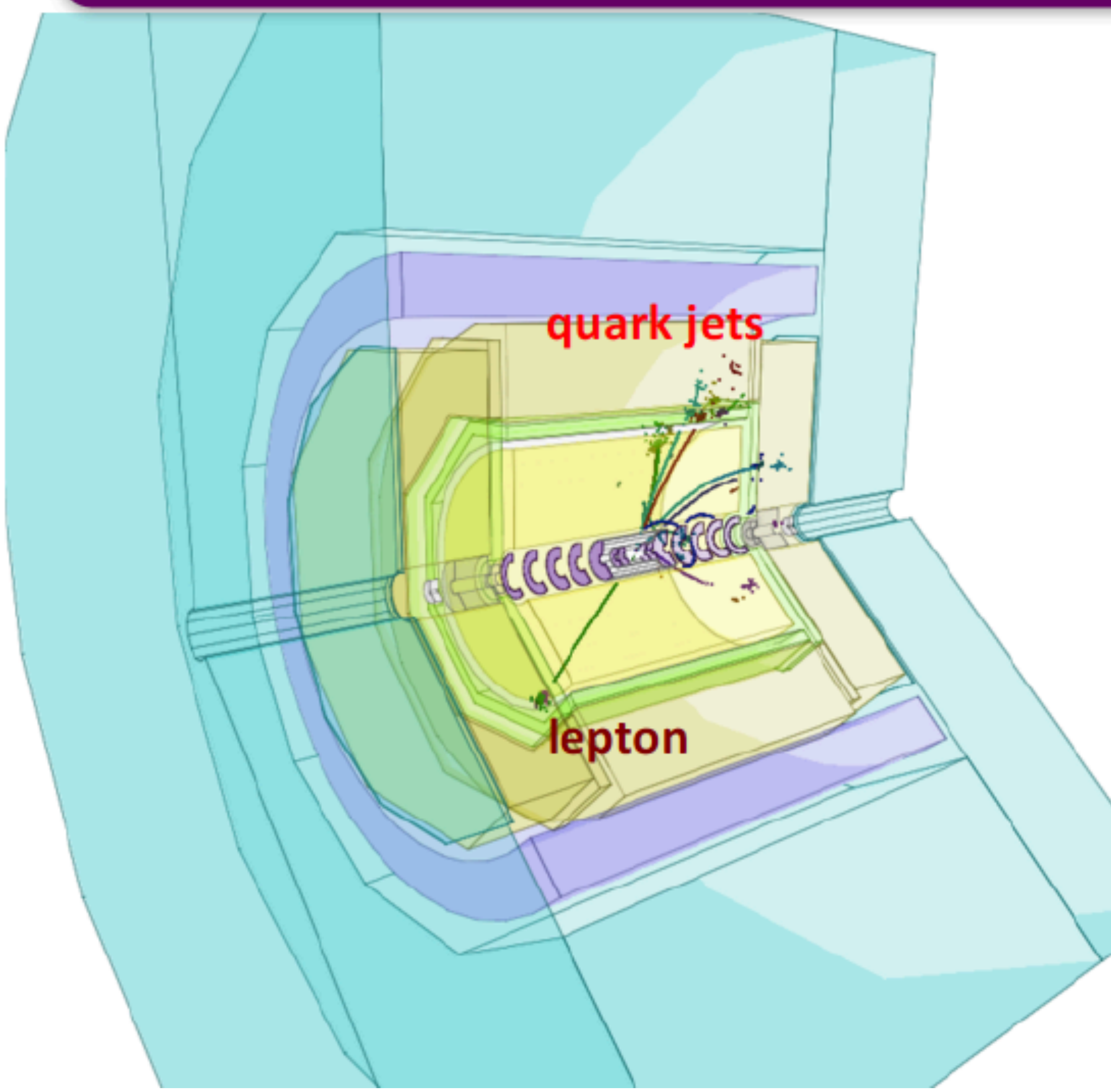
soft visible particles since small higgsino mass gaps

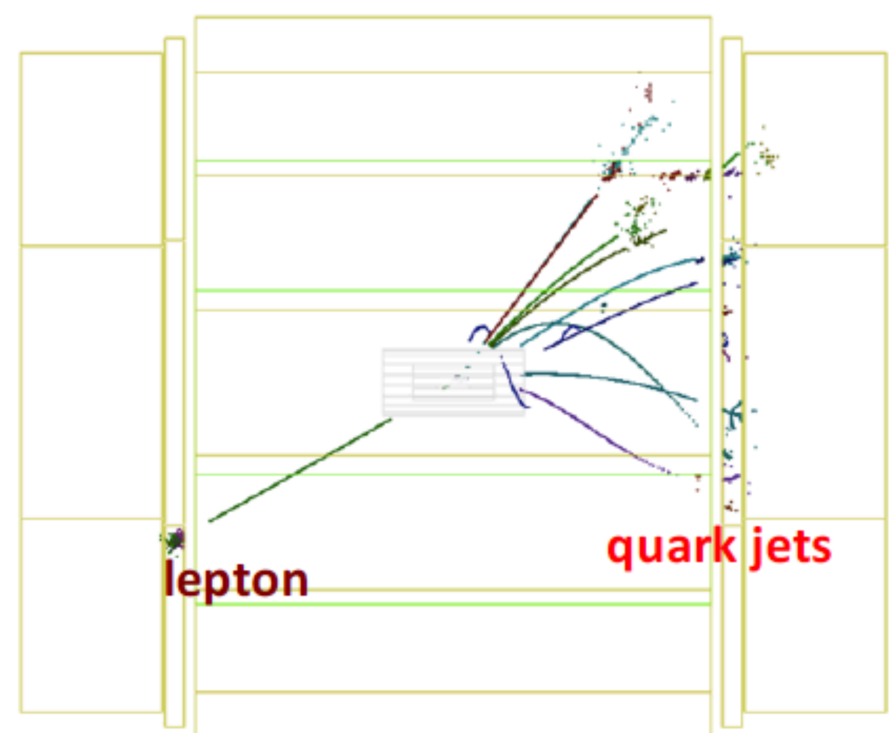
How do these signals look in the detector? (2)

√s =500 GeV

Chargino pair production with semileptonic decay

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





HB, Berggren, Fujii, List, Lehtinen, Tanabe, Yan, PRD101 (2020) 095026

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

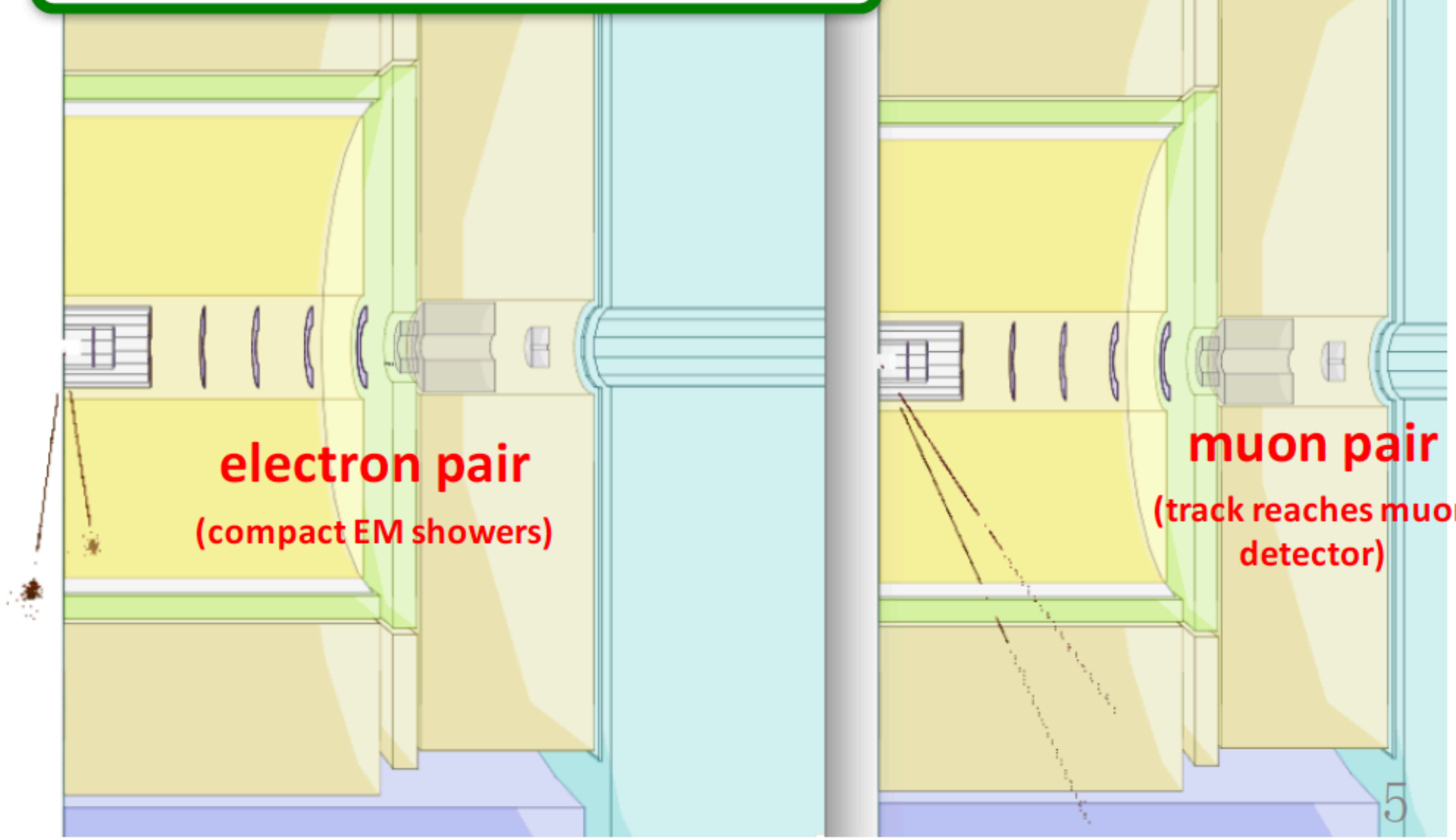
measure $m(\ell^+\ell^-) < m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ and $E(\ell^+\ell^-)$

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

√s =500 GeV

Neutralino mixed production with leptonic decay

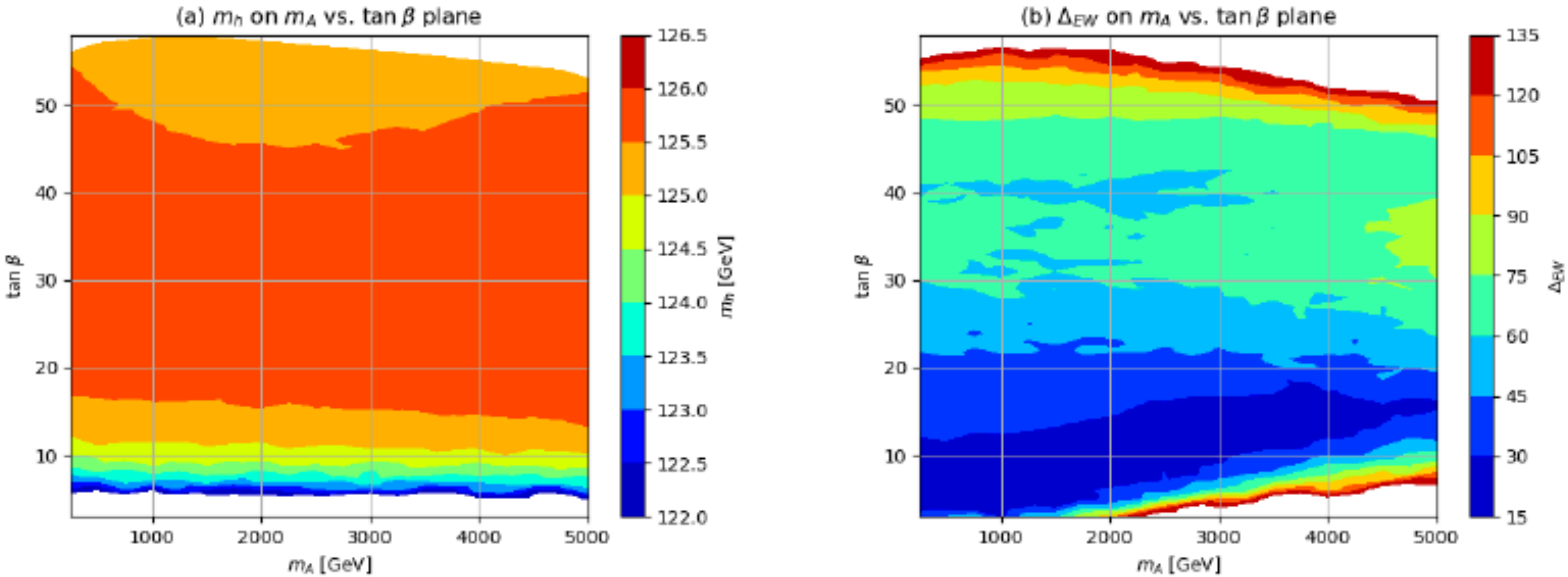
$$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell^+\ell^-$$



HB, Berggren, Fujii, List, Lehtinen, Tanabe, Yan, PRD101 (2020) 095026

Prospects for heavy SUSY Higgs bosons at HL-LHC

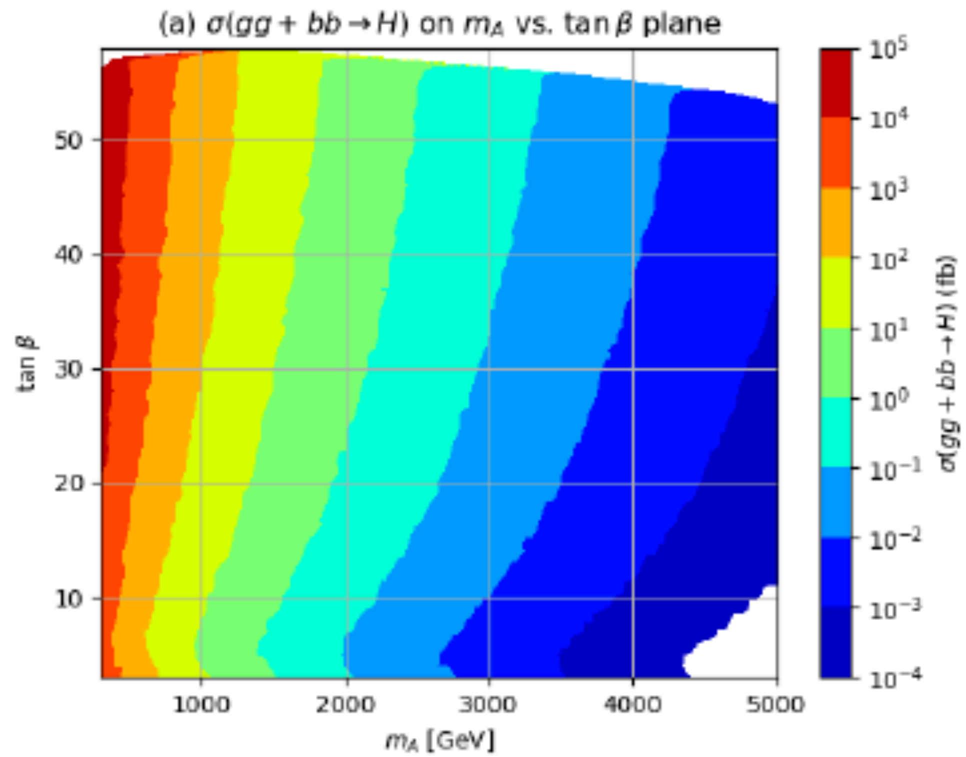
traditional results in mA vs. tanb plane

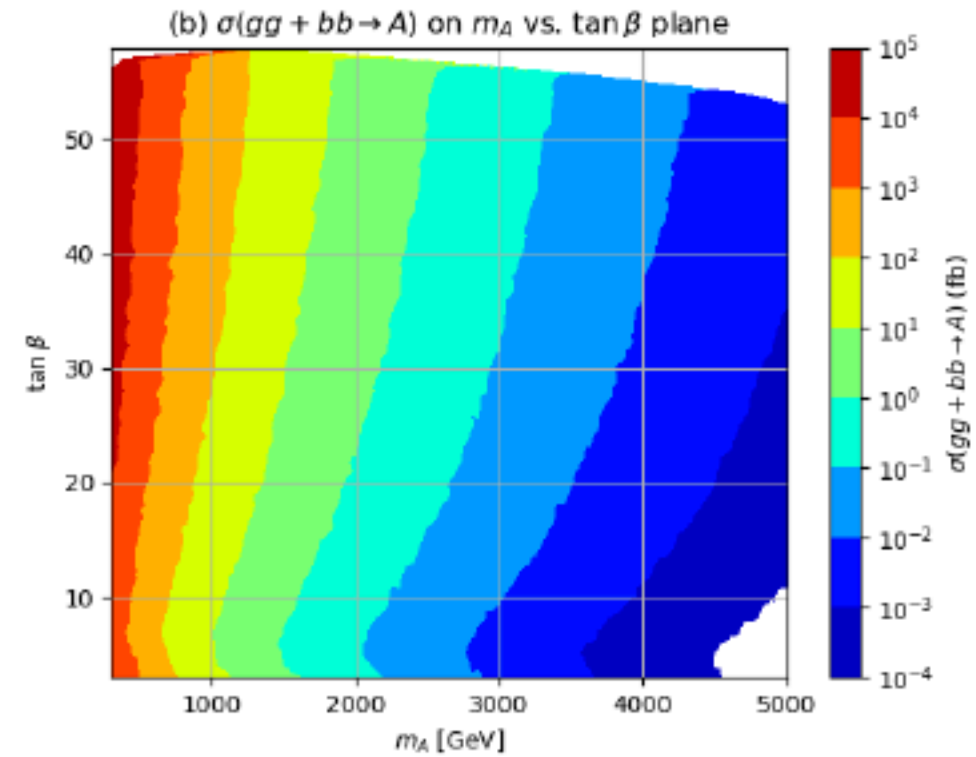


In EW natural SUSY, it is
easy to get mh~125 GeV (large -A0)
and low DEW<~30

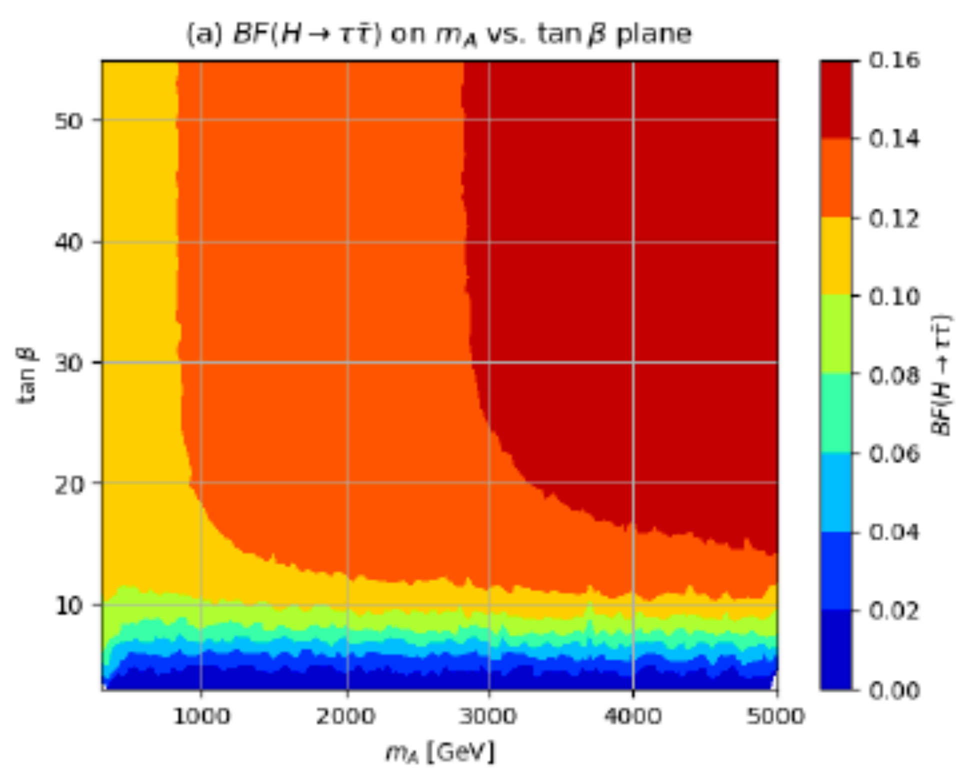
HB, Barger, Tata, Zhang, arXiv:2209.00063

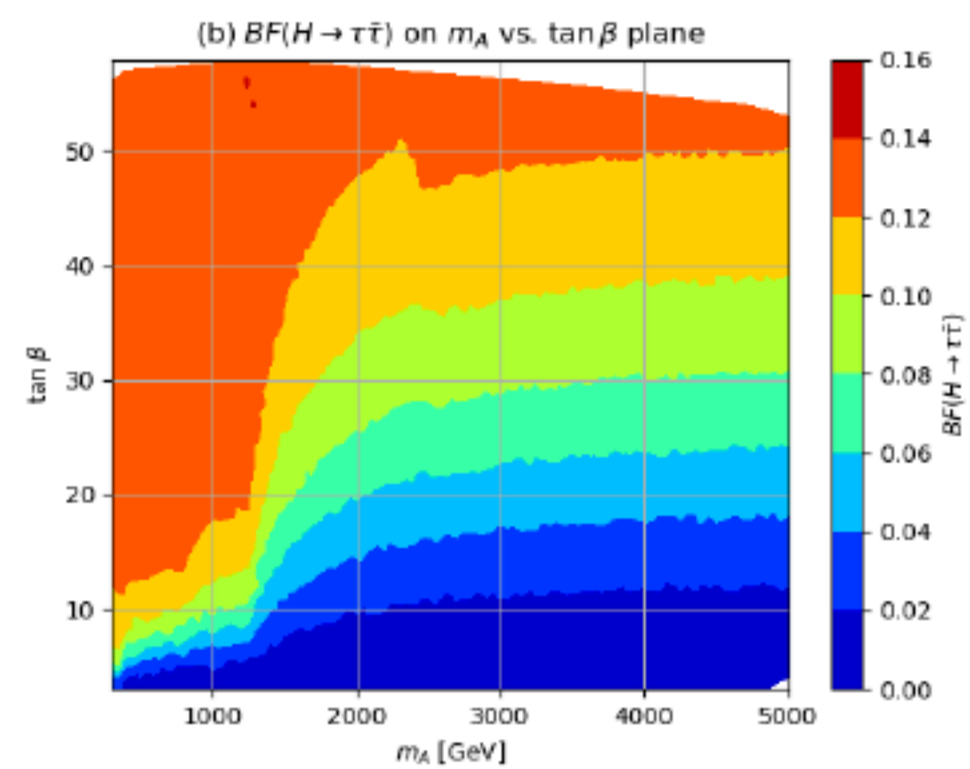
Direct s-channel production of A, H:





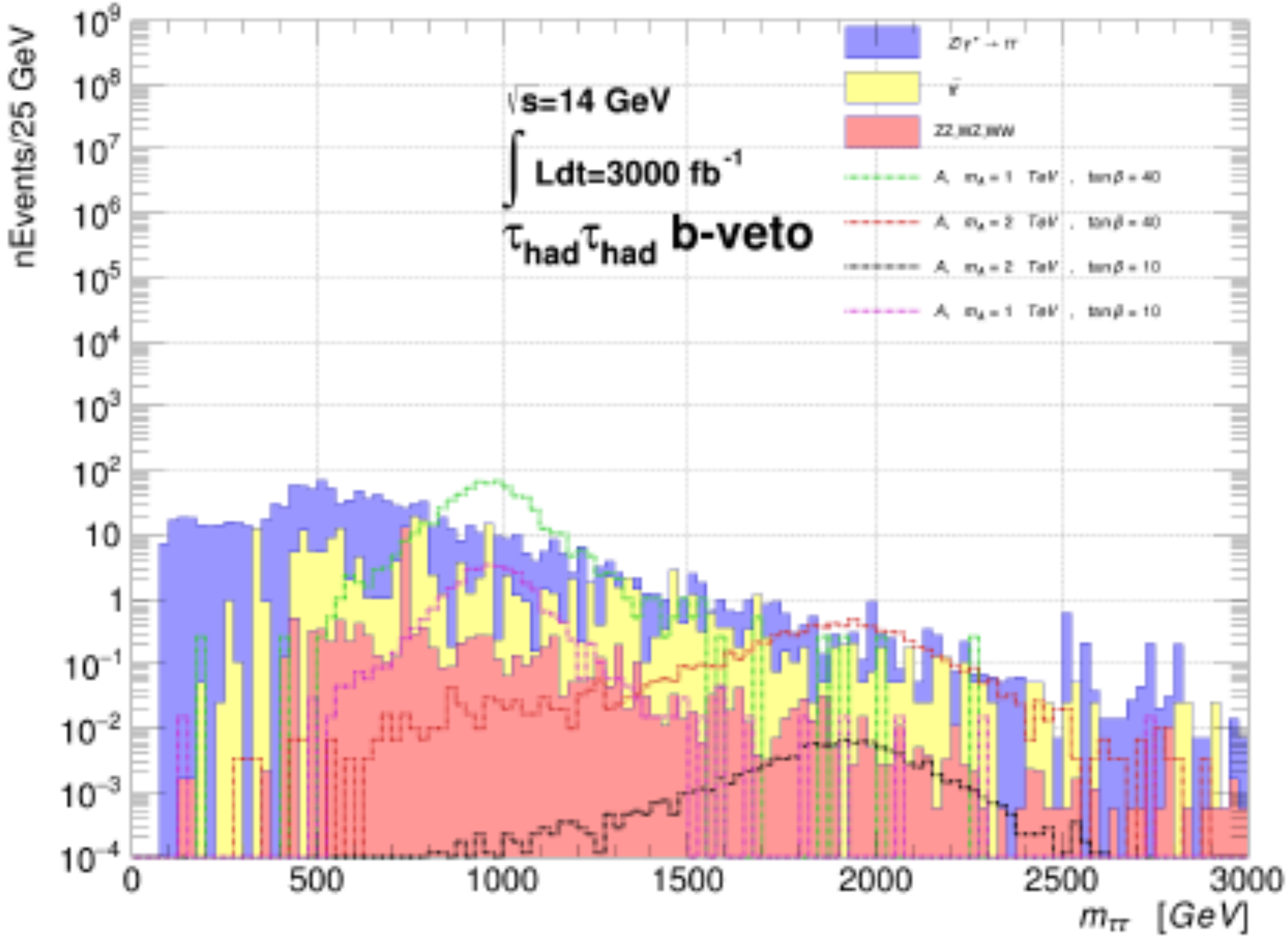
best decay channel: ditau





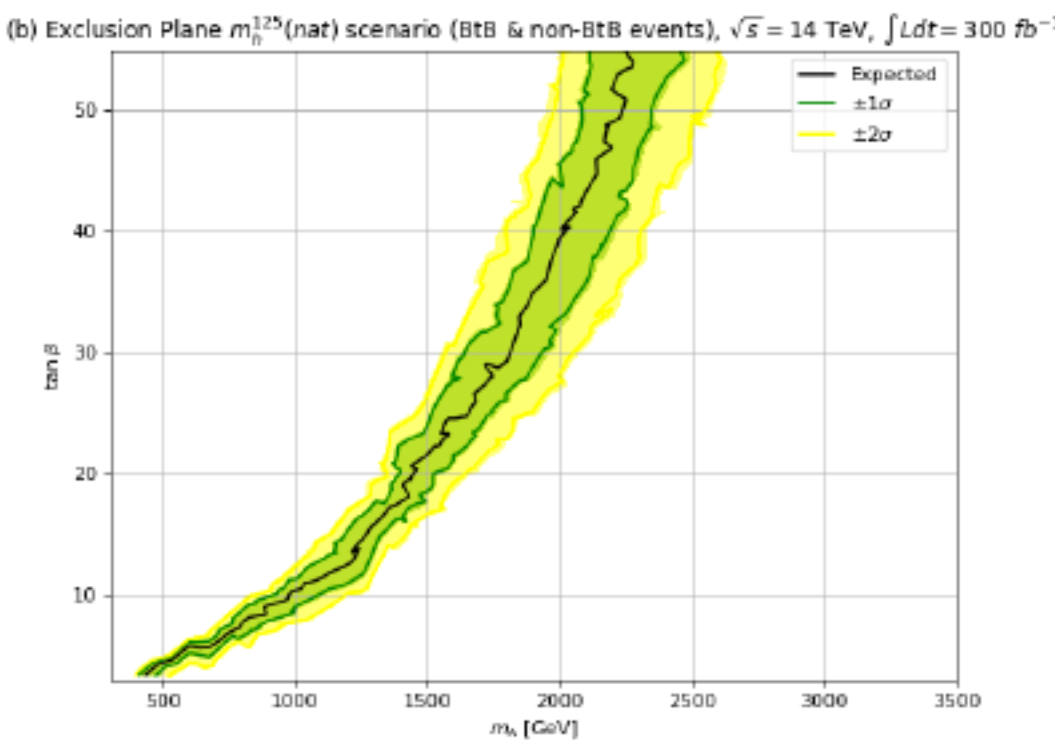
unnatural SUSY natural SUSY

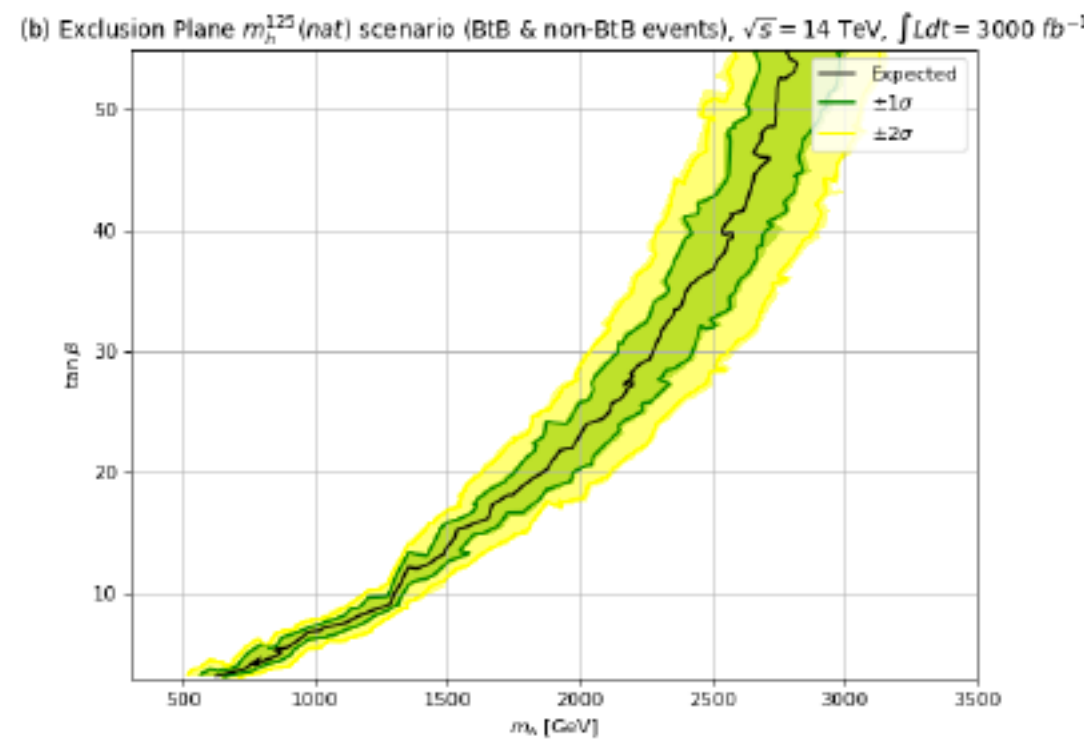
Best signature: H,A->tautaubar
with nu's aligned with tau's:
can reconstruct ditau mass!



HB, Barger, Tata, Zhang, arXiv:2209.00063

2-sigma exclusion contours for H, A-> ditau in natural SUSY at LHC14 with 300 (3000) fb-1





HB, Barger, Tata, Zhang, arXiv:2209.00063

HL-LHC exclusion reaches to mA~1.3 TeV for tanb=10

mA~2.5 TeV for tanb=40

H,A-> SUSY offers new discovery channels!

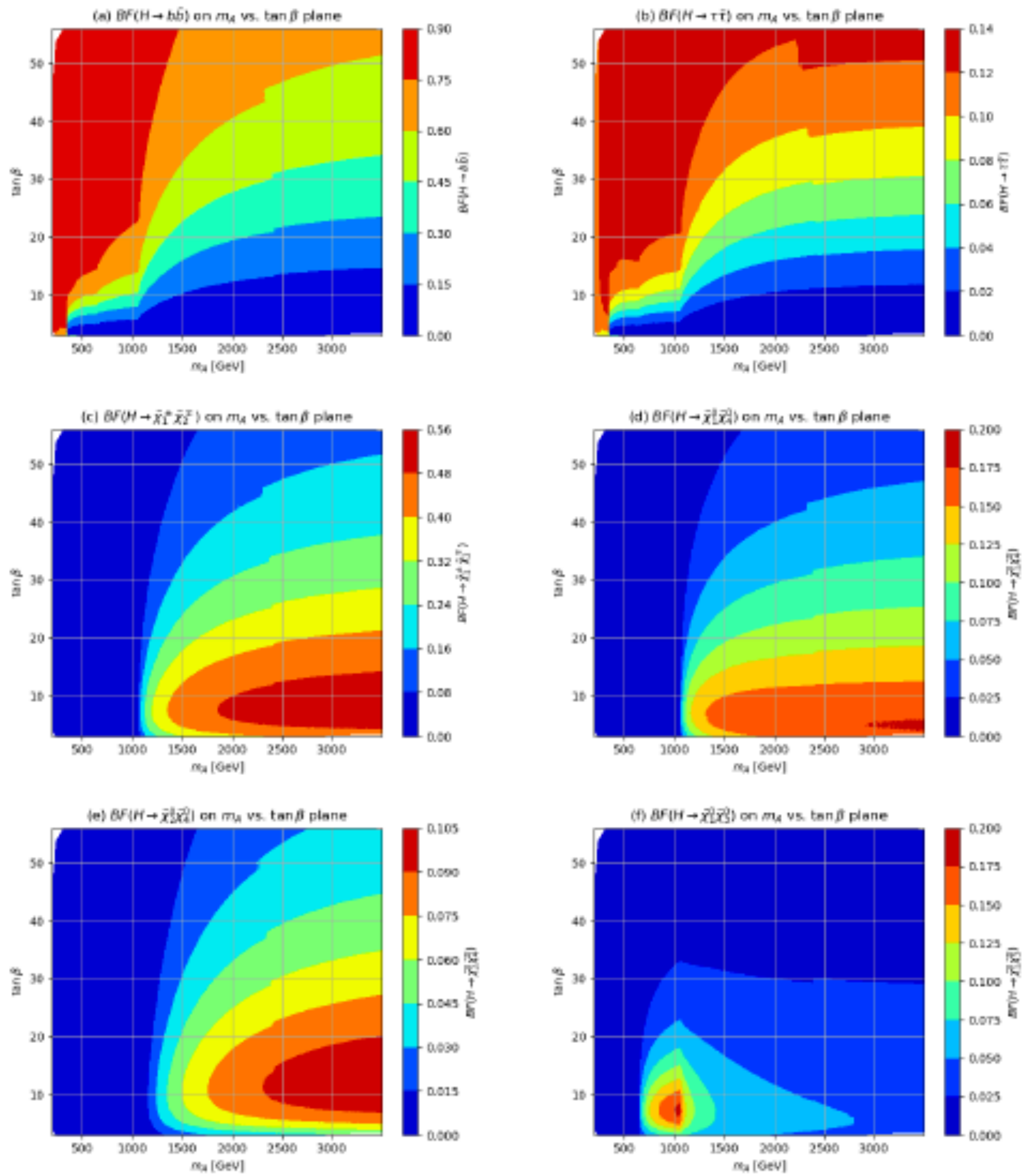


Figure 2: Branching fractions for H to a) $b\bar{b}$, b) $\tau\bar{\tau}$, c) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$, d) $\tilde{\chi}_1^0\tilde{\chi}_4^0$, e) $\tilde{\chi}_2^0\tilde{\chi}_4^0$ and f) $\tilde{\chi}_1^0\tilde{\chi}_3^0$ from Isajet 7.88 [36].

HB, Barger, Tata, Zhang, arXiv: 2212.09198

H,A-> SUSY-> (W,Z,h)+MET

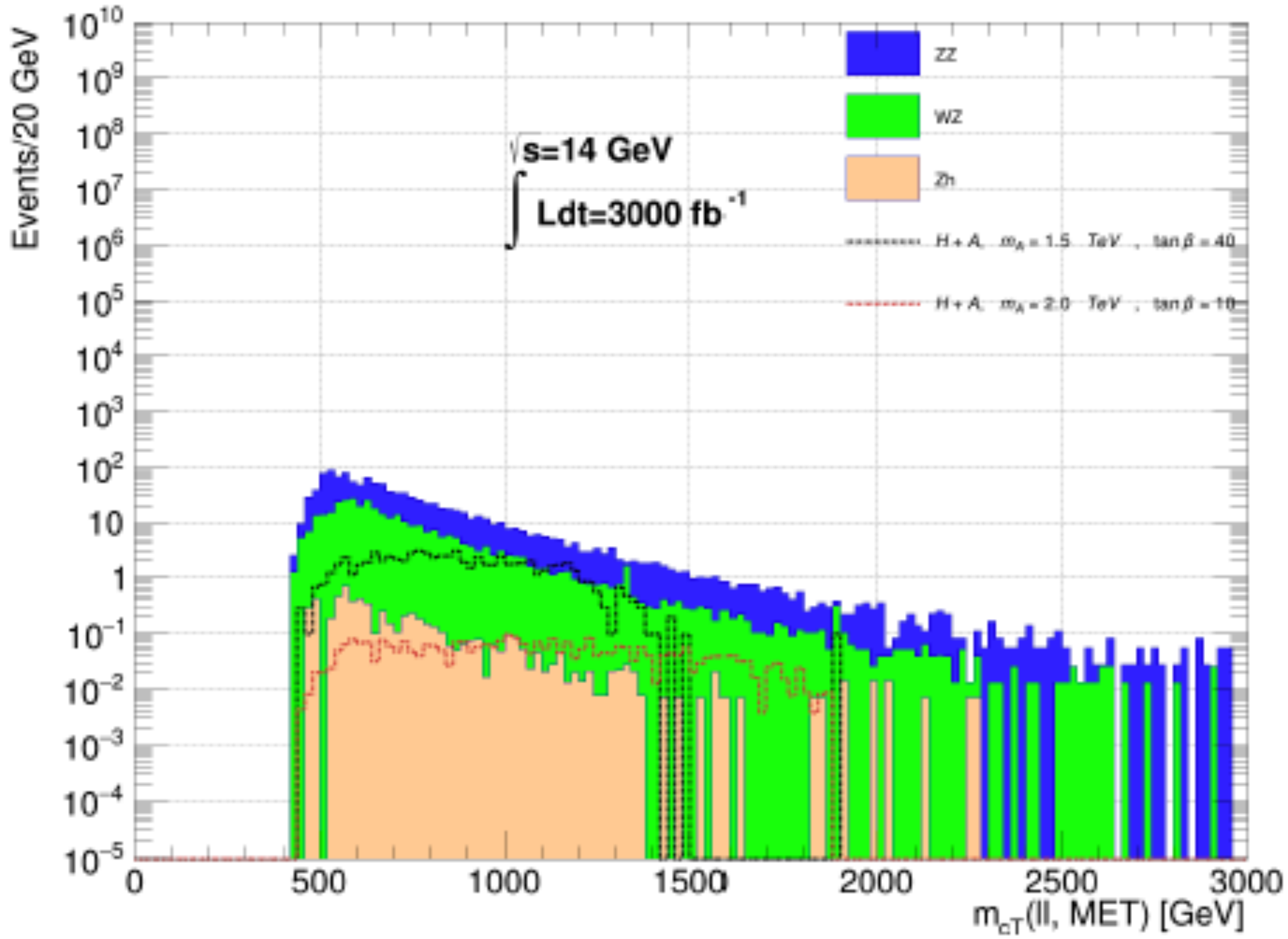
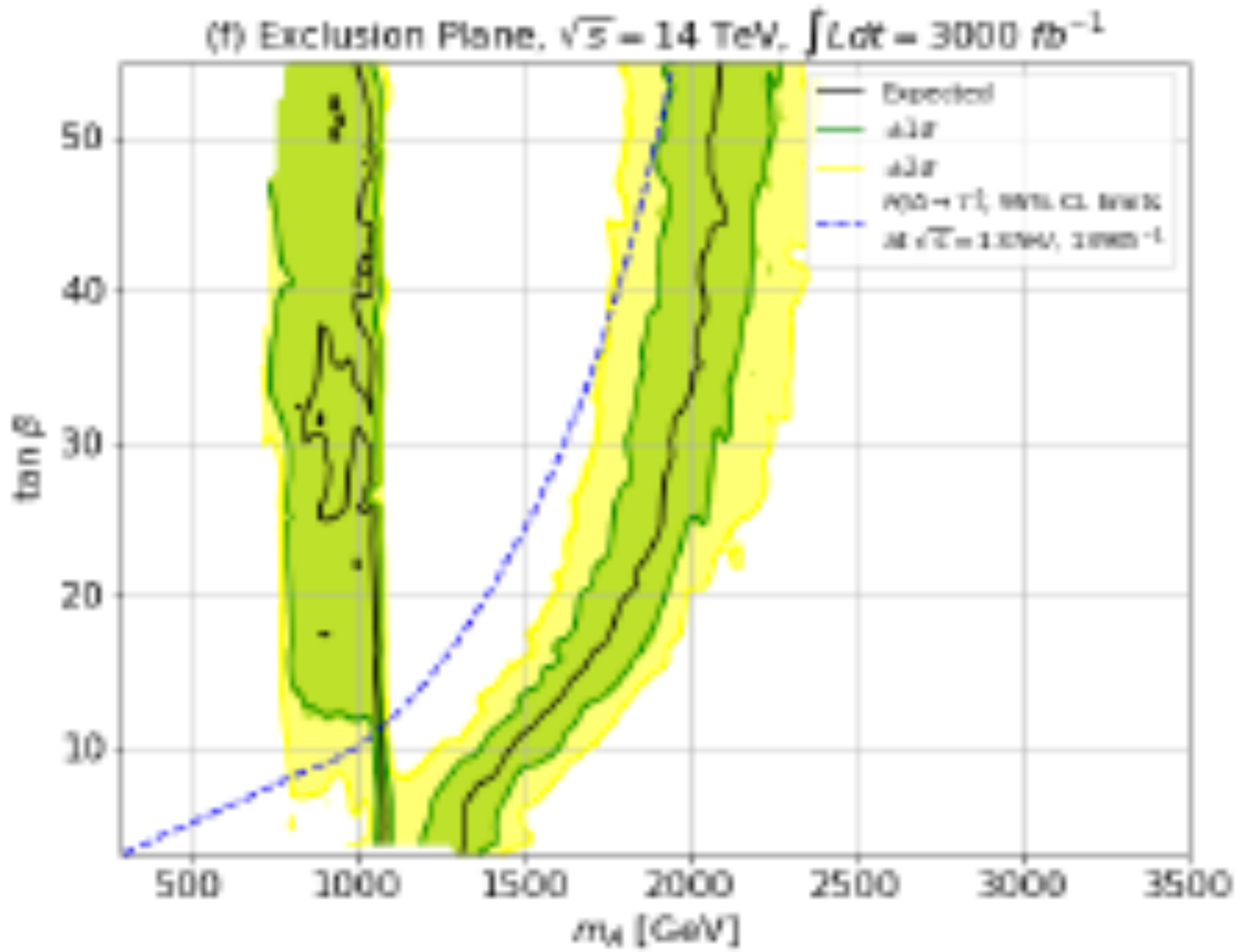


Figure 5: Distribution in $m_{cT}(\ell\bar{\ell}, \not{E}_T)$ for $pp \to H, A \to Z + \not{E}_T$ with $Z \to \ell^+\ell^-$ decay events at $\sqrt{s} = 14$ TeV. We show two signal distributions (dashed) along with dominant SM backgrounds (not stacked).

look for buildup of excess mT at very high energies!

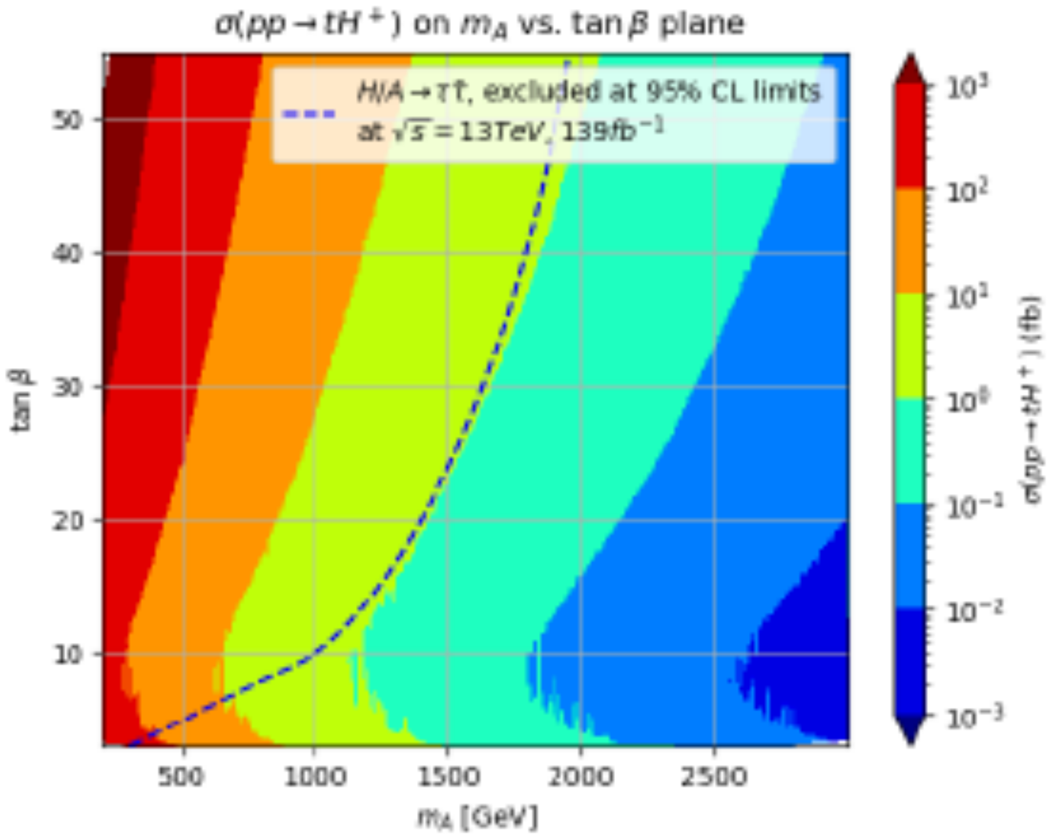
HL-LHC exclusion plane for combined 6 H,A->nat SUSY channels

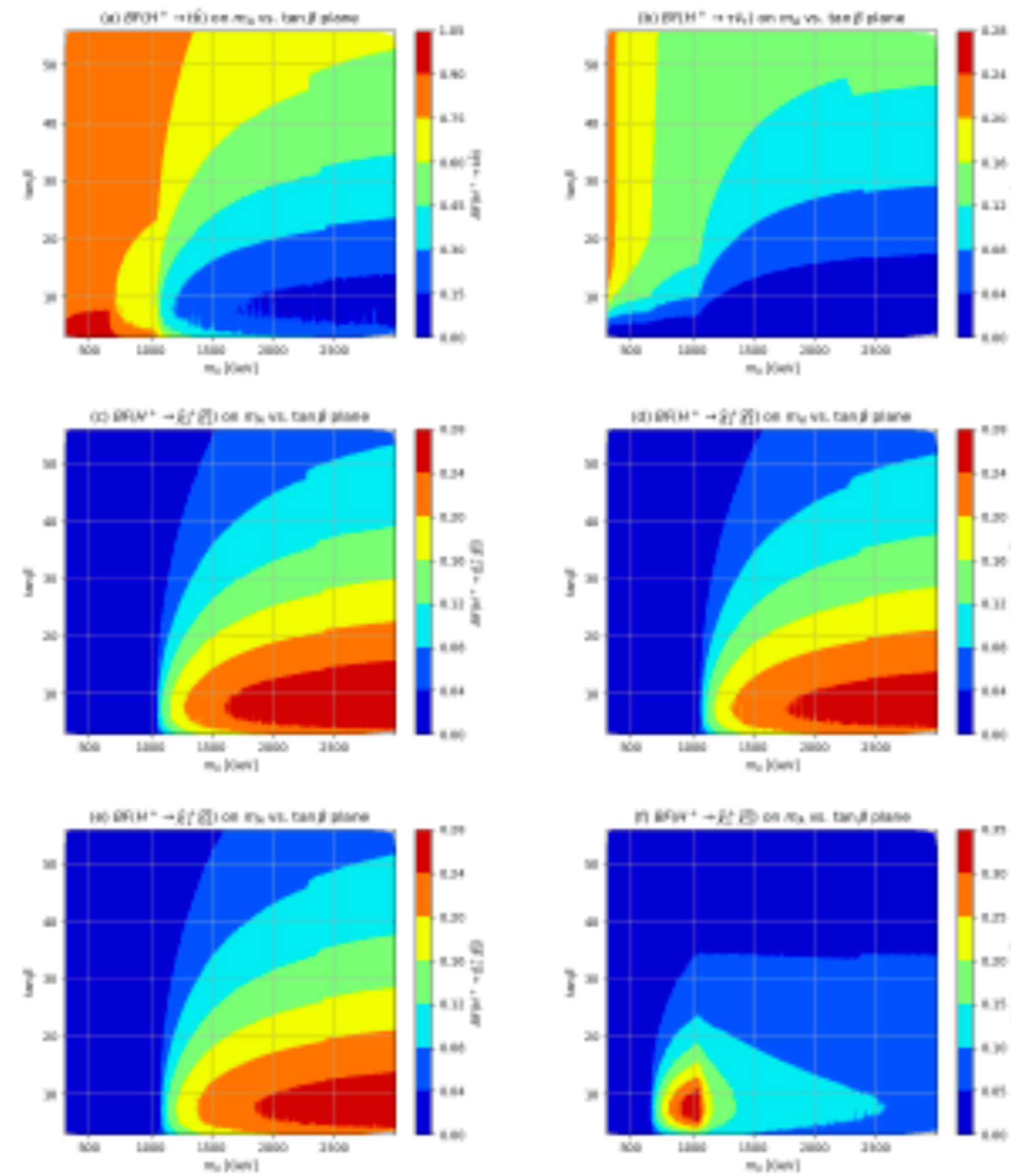


some new p-space opens up

HB, Barger, Tata, Zhang, arXiv:2209.00063

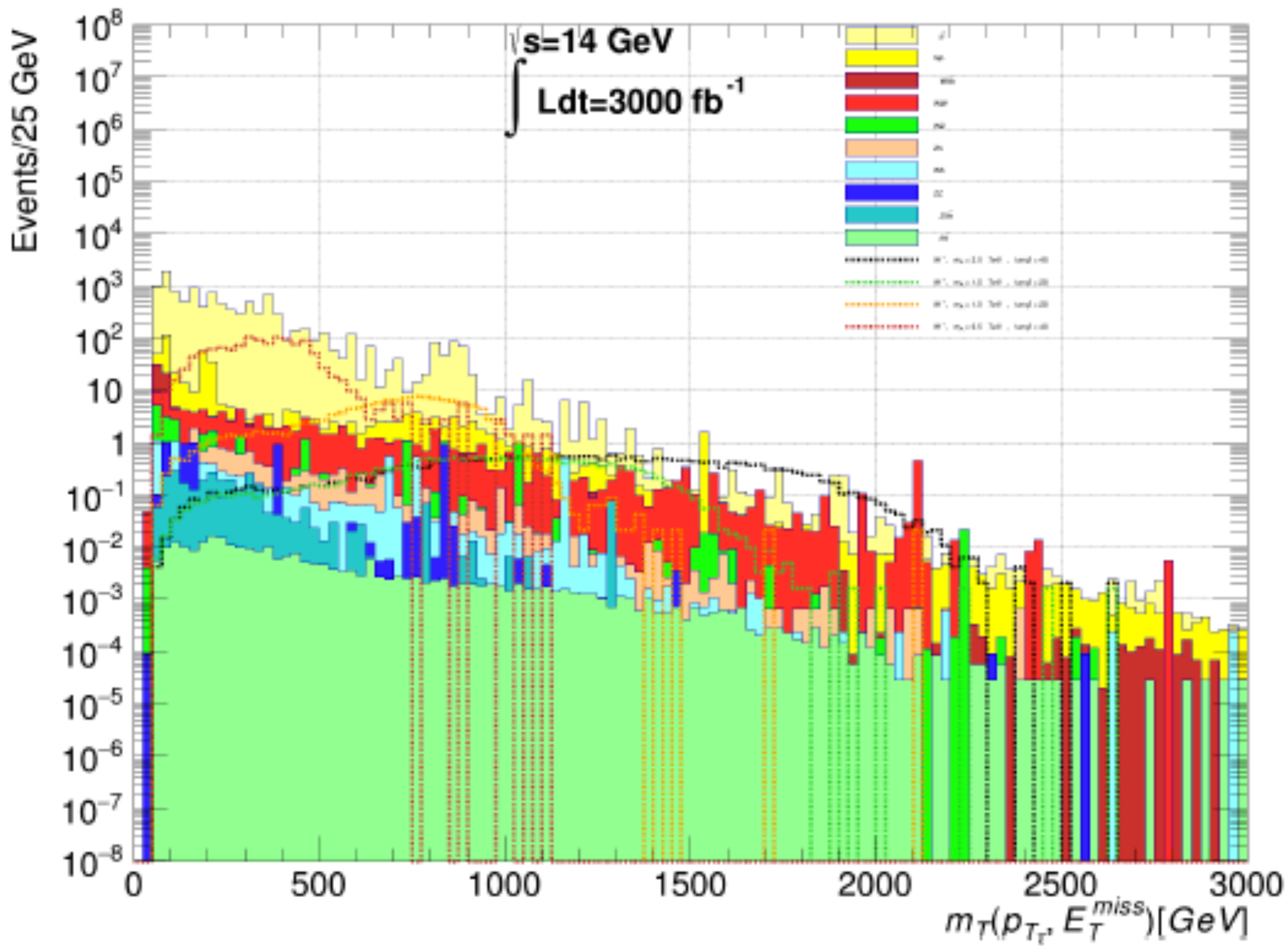
See pp-> tH^+ at HL-LHC?





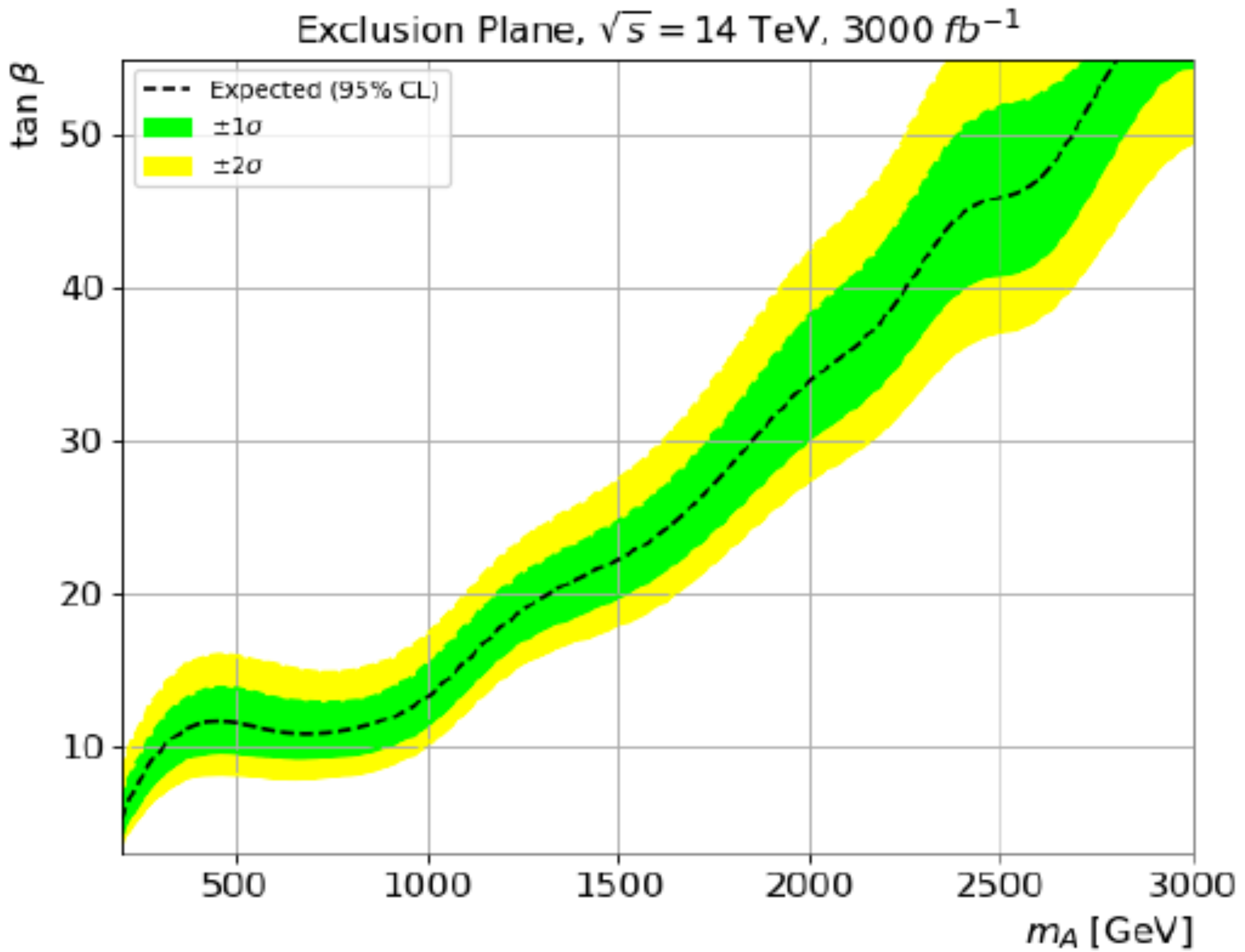
HB, Barger, Tata, Zhang, in progress

H^+ -> tau+nu_tau channel seems best



HB, Barger, Tata, Zhang, in progress

HL-LHC exclusion plot for pp-> tH^+-> t+(tau+nu)



HB, Barger, Tata, Zhang, in progress

more exotic heavy Higgs signatures await FCChh!

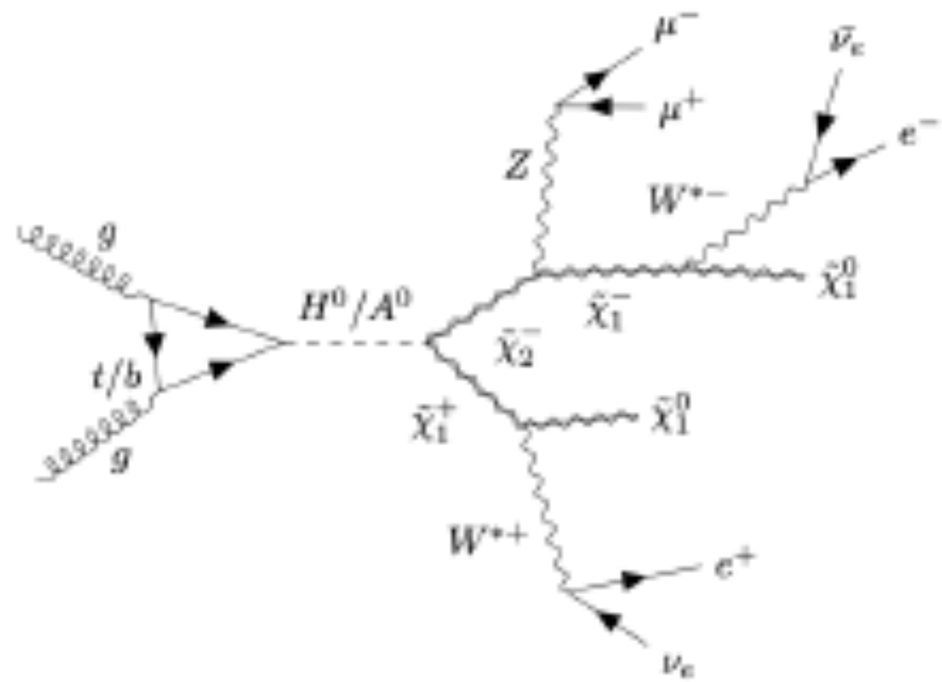


FIG. 1: Feynman diagram for $gg \to H,\ A(\to \tilde{\chi}_2^{\pm}\tilde{\chi}_1^{\mp} \to 4\ell + \not{E}_T) + X$ production; there is a similar diagram for $H,\ A$ production via $b\bar{b}$ fusion.

pp-> A,H-> SUSY-> 4l+MET;

HB, Barger, Jain, Kao, Sengupta, Tata, arXiv:2112.02232

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

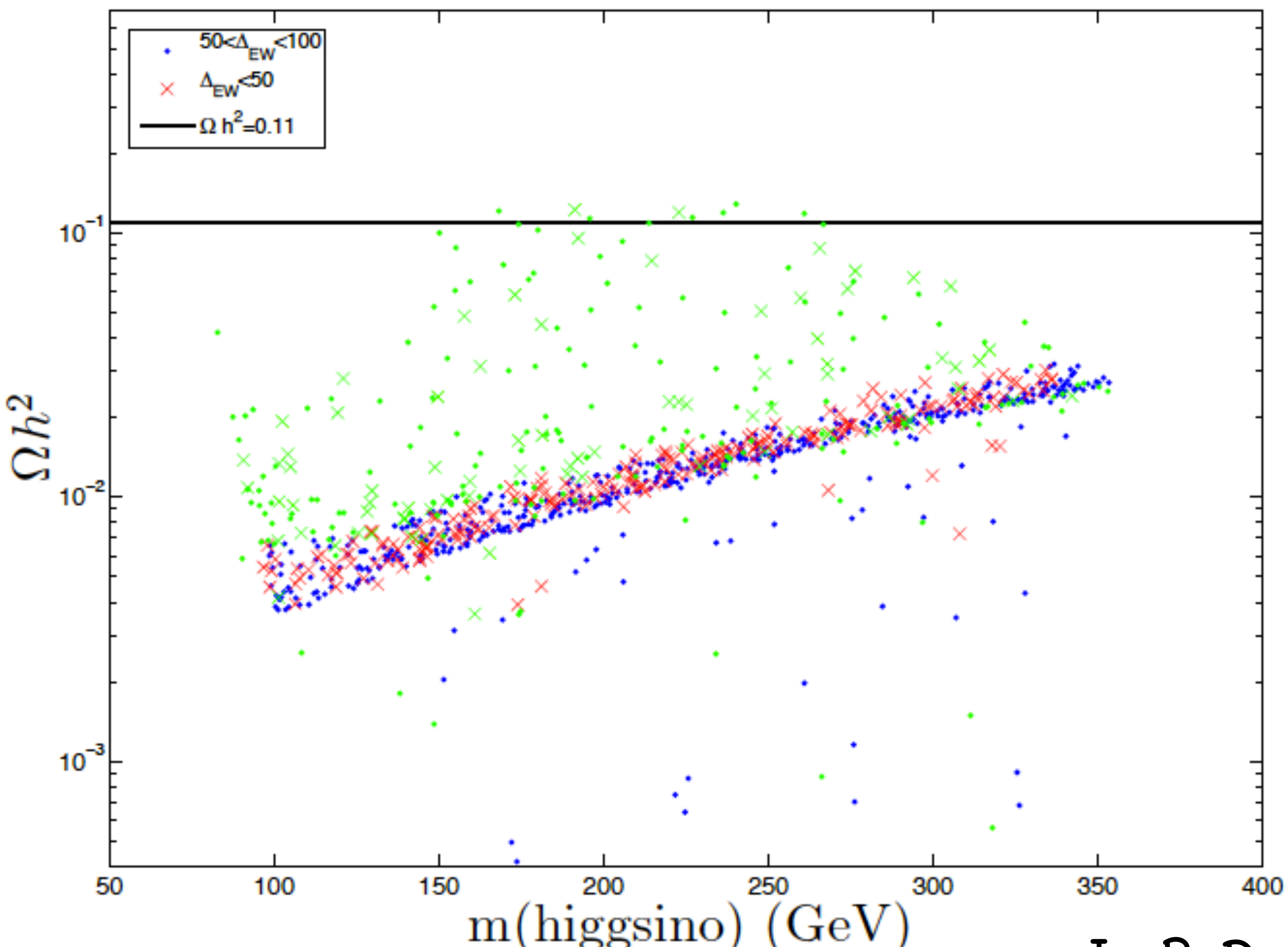
Conclusions:

- Time to set aside old/flawed measures 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
- 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 CMP
- most promising: LHC-> light higgsinos via soft dilepton+jet+MET channel
- see heavy Higgs H, A , H^+ up to ~1-3 TeV at HL-LHC (depending on tanb)
- ILC: for sqrt{s}>2m(higgsino), expect light higgsinos
- dark matter: a mix of axions+higgsino-like WIMPs (typically mainly axions)

More slides:
DM, baryogenesis, aspects of naturalness

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

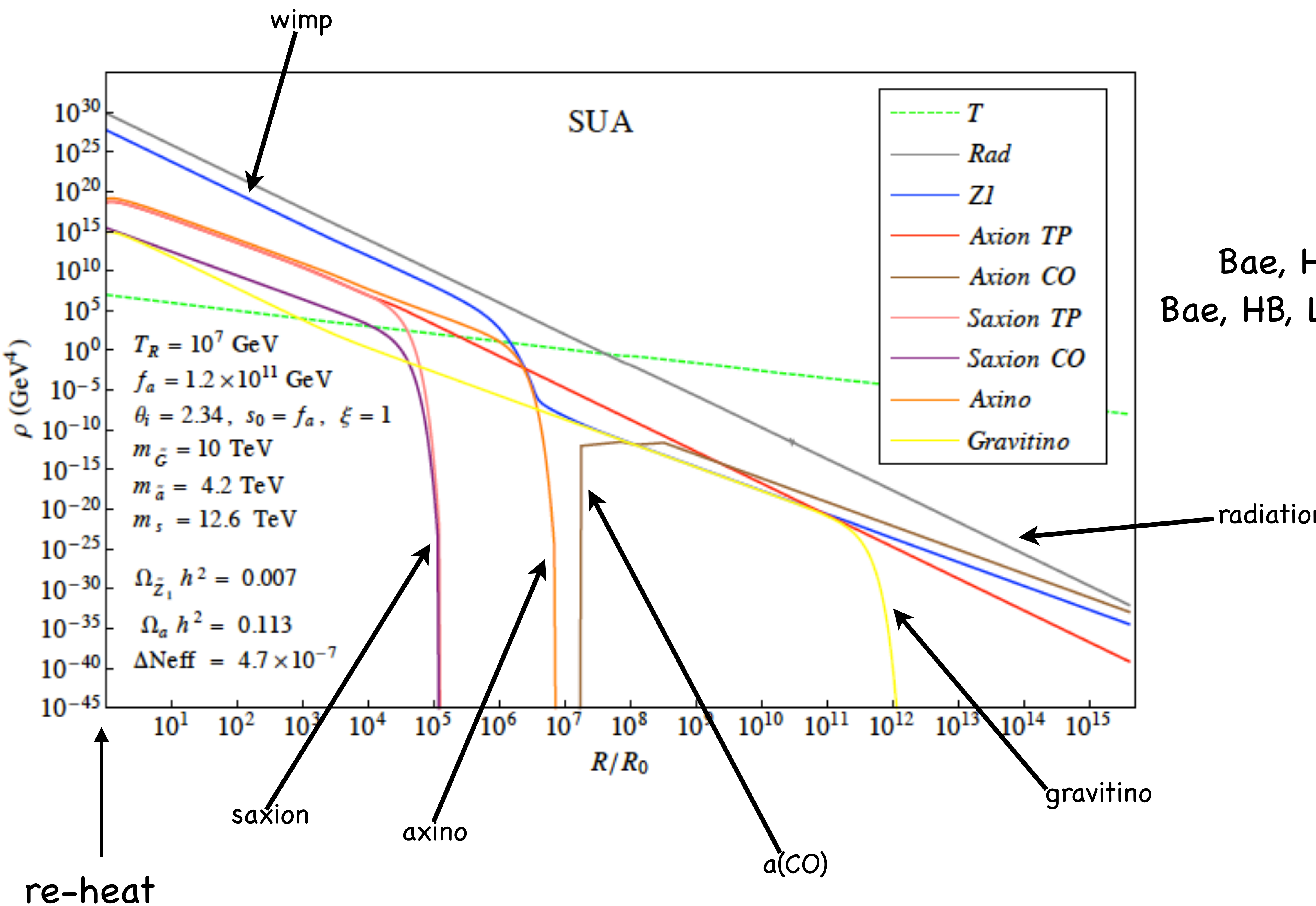
In SUSY, axion accompanied by axino and saxion

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

mixed axion-neutralino production in early universe

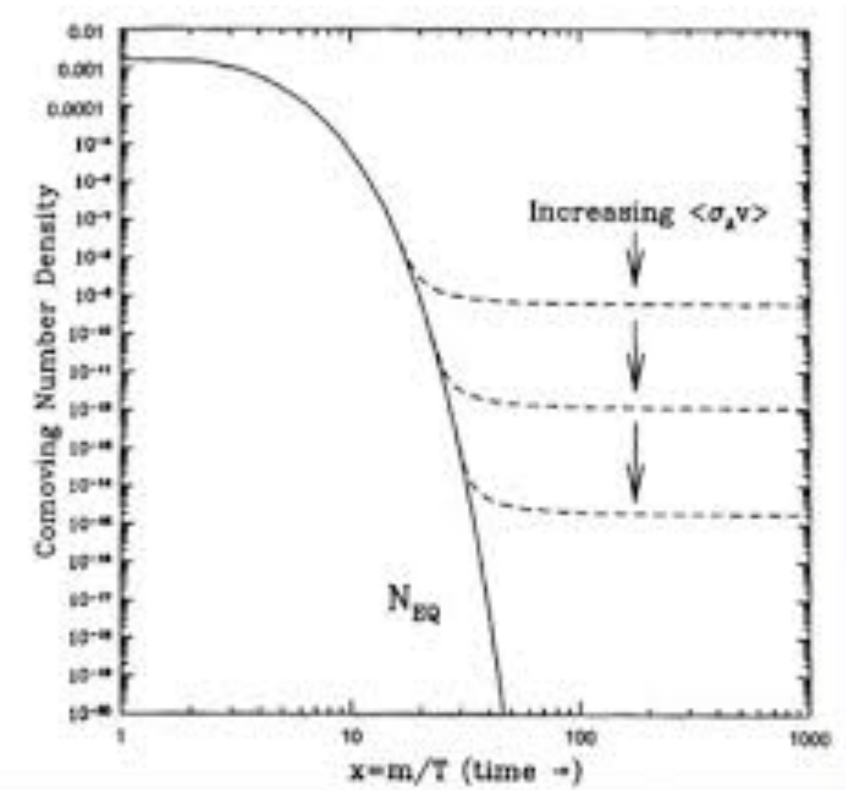
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: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

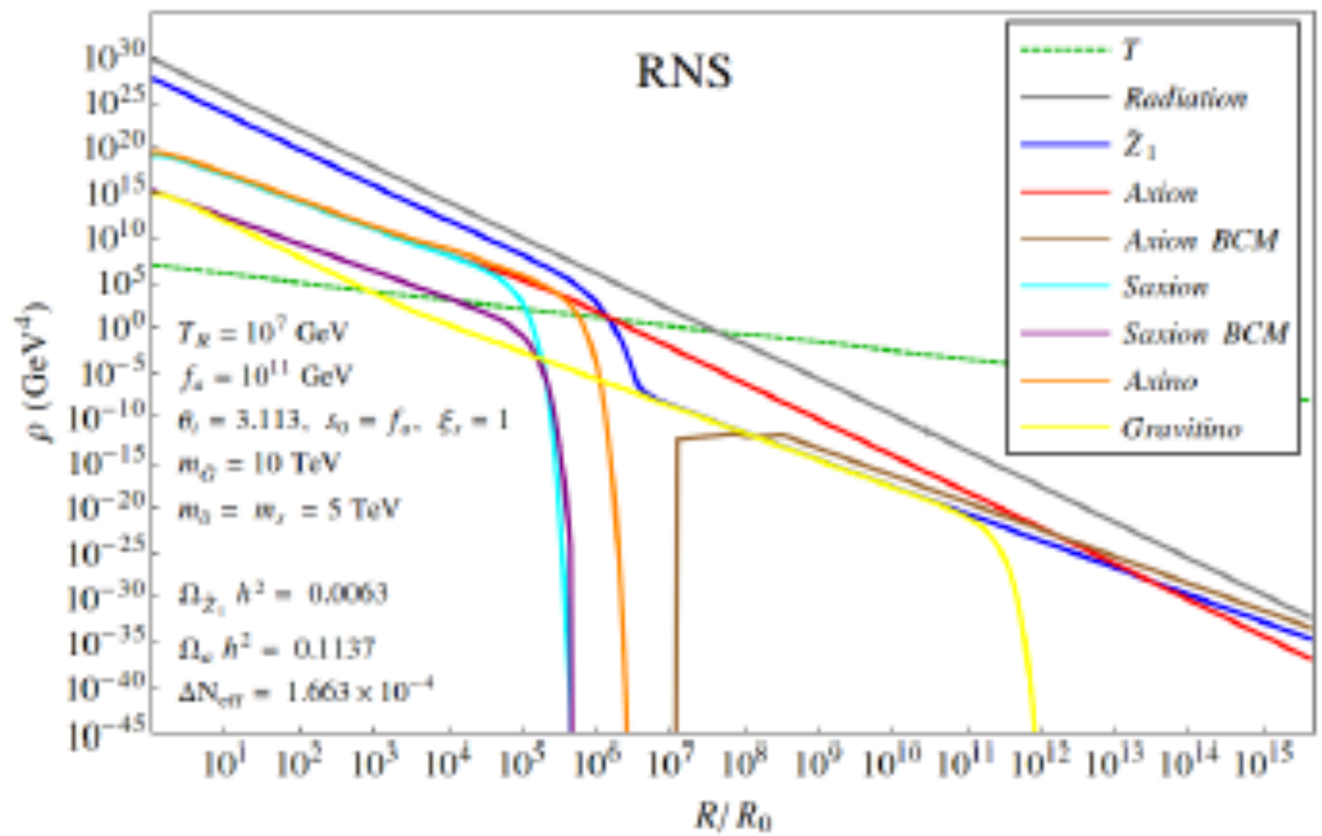
DM production in SUSY DFSZ: solve eight coupled Boltzmann equations



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

usual picture => mixed axion/WIMP

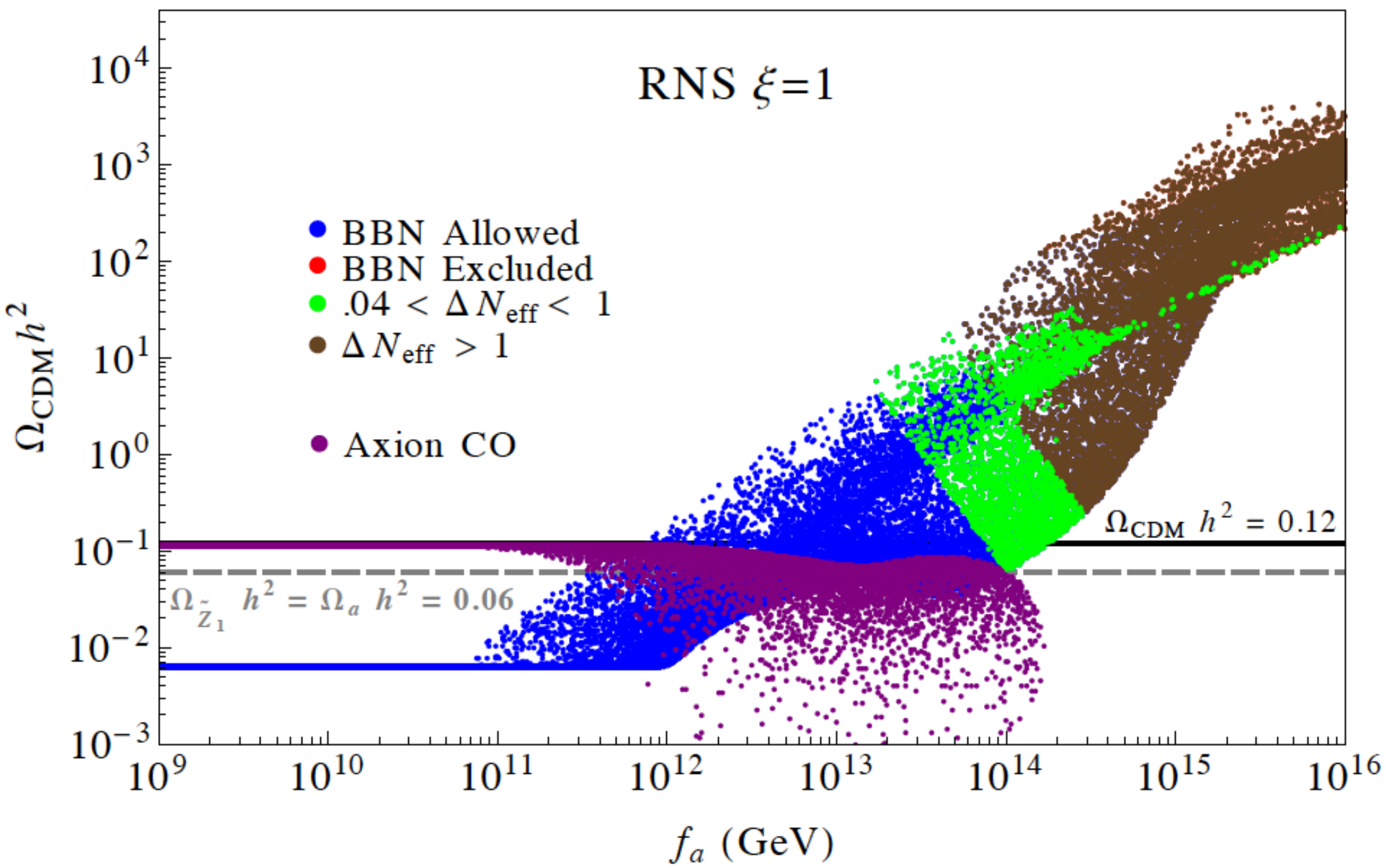




KJ Bae, HB, Lessa, Serce

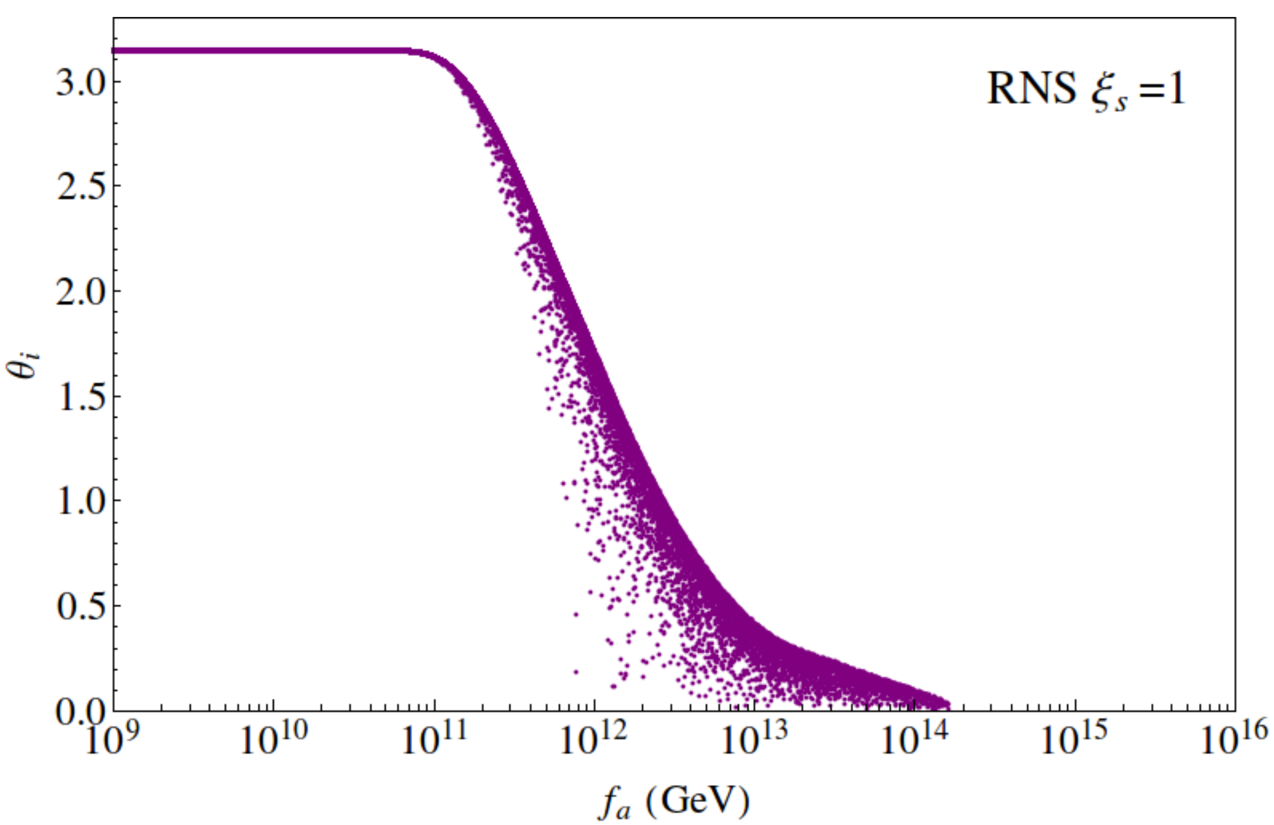
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

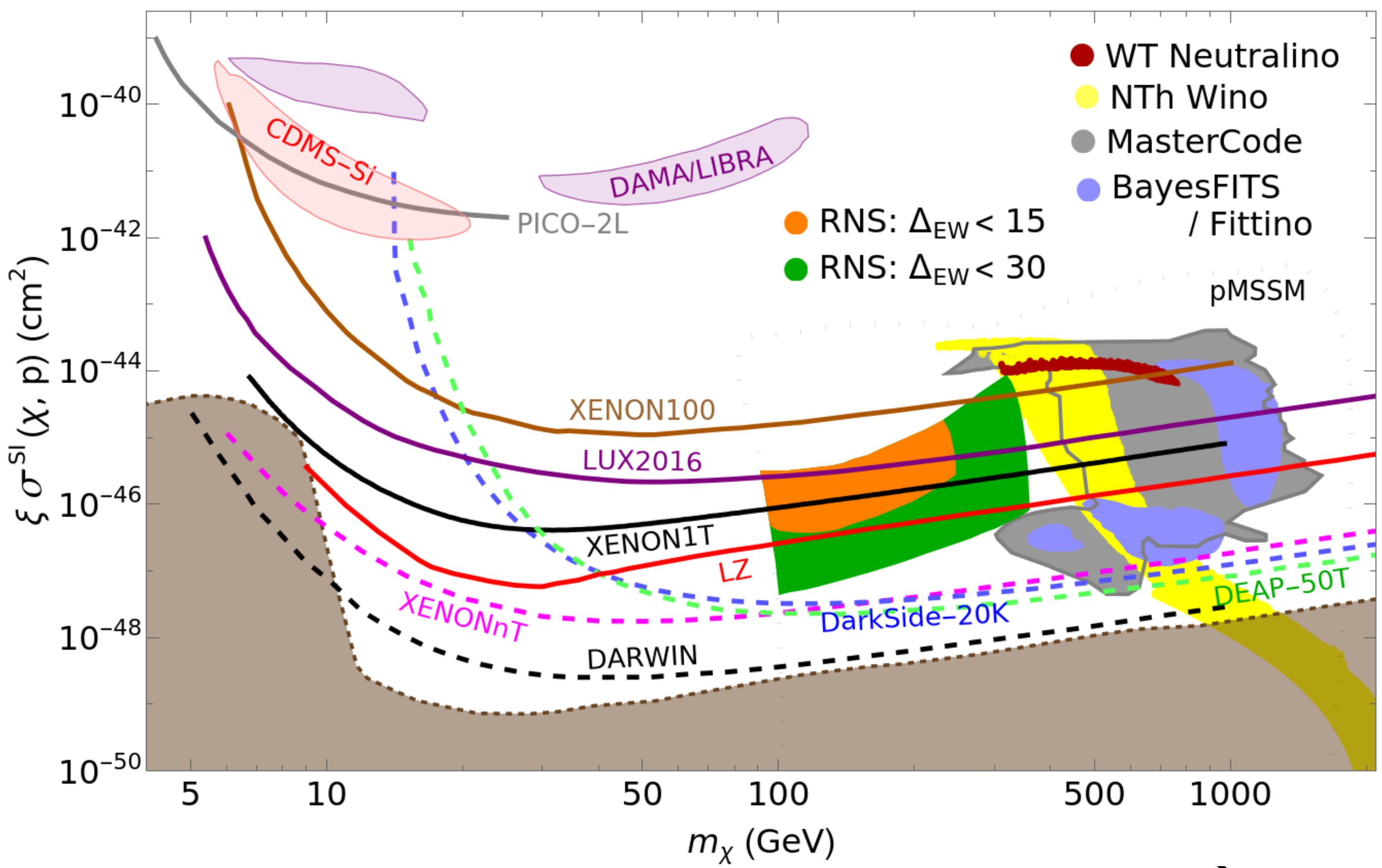
axion abundance



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

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

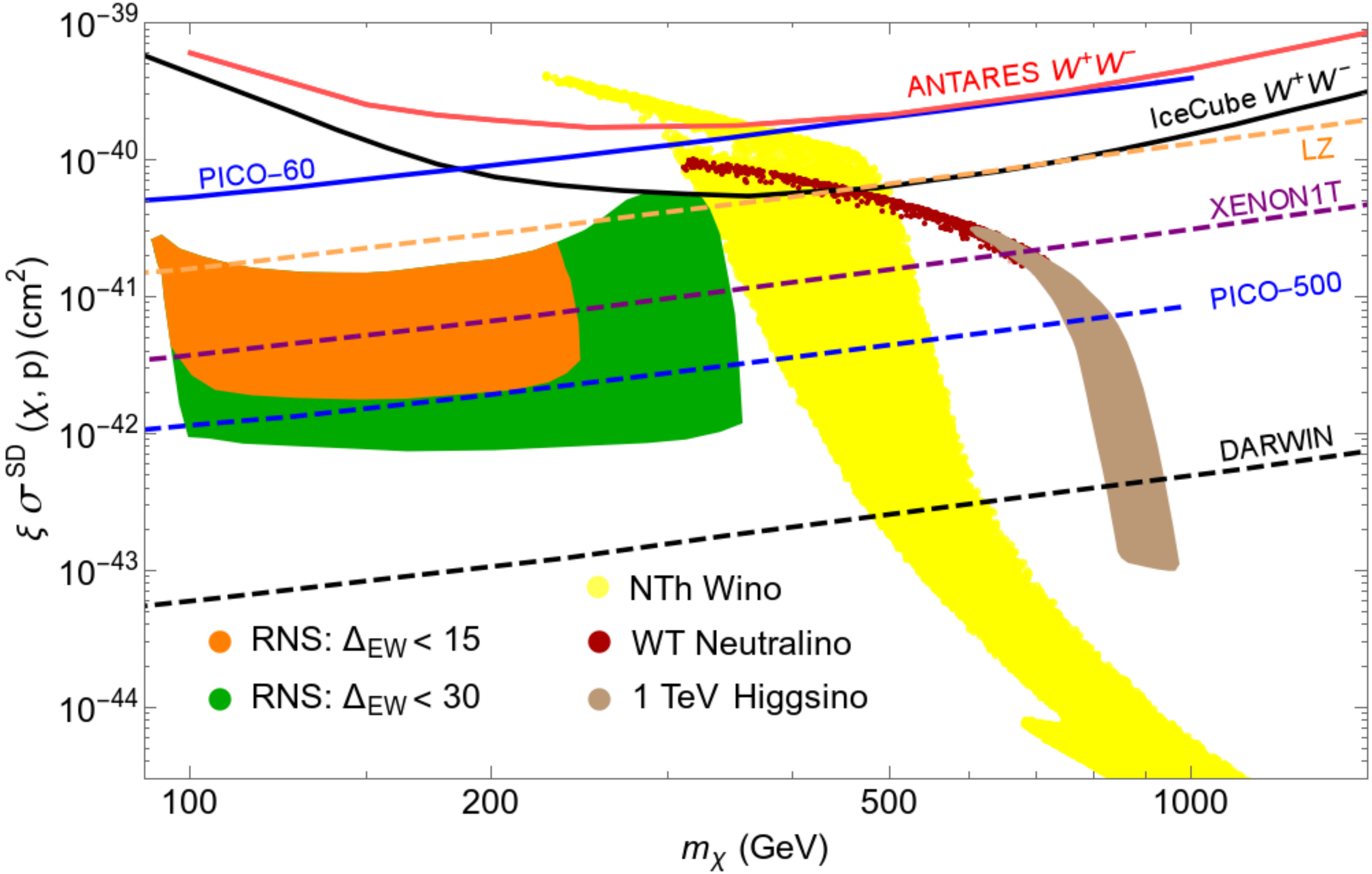
$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

includes latest LZ2022 results!

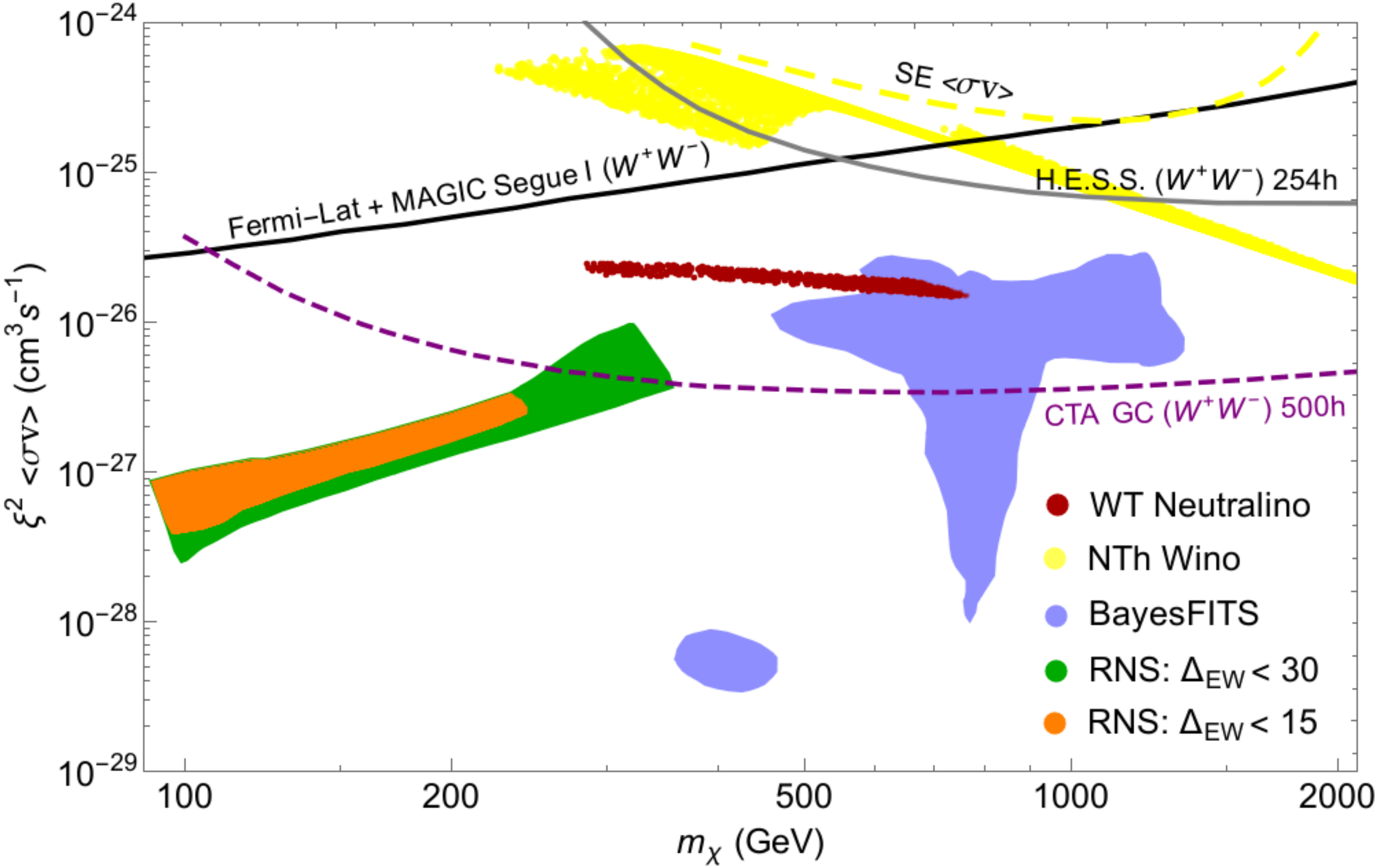
natural SUSY

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

Prospects for SD WIMP searches:

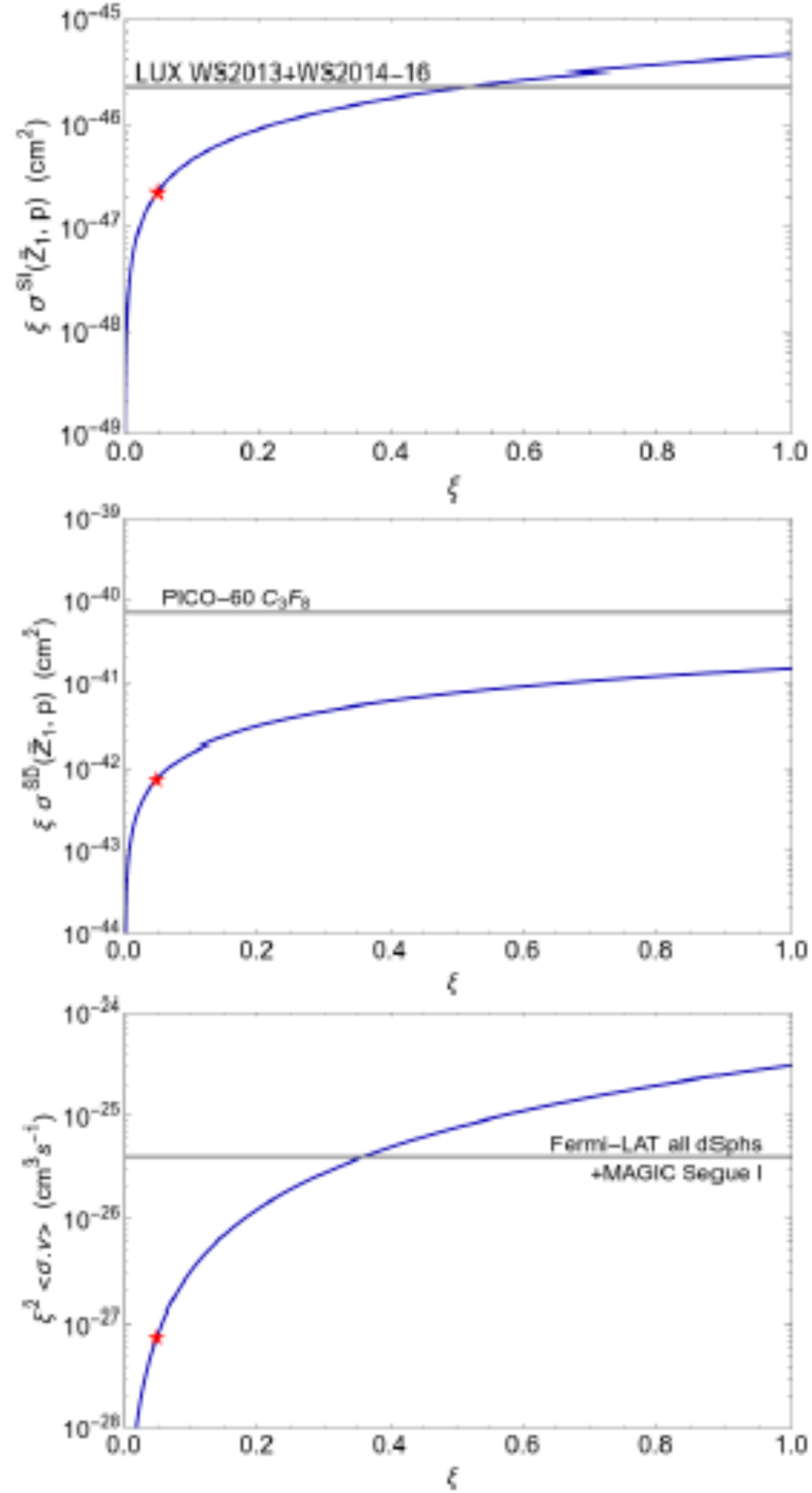


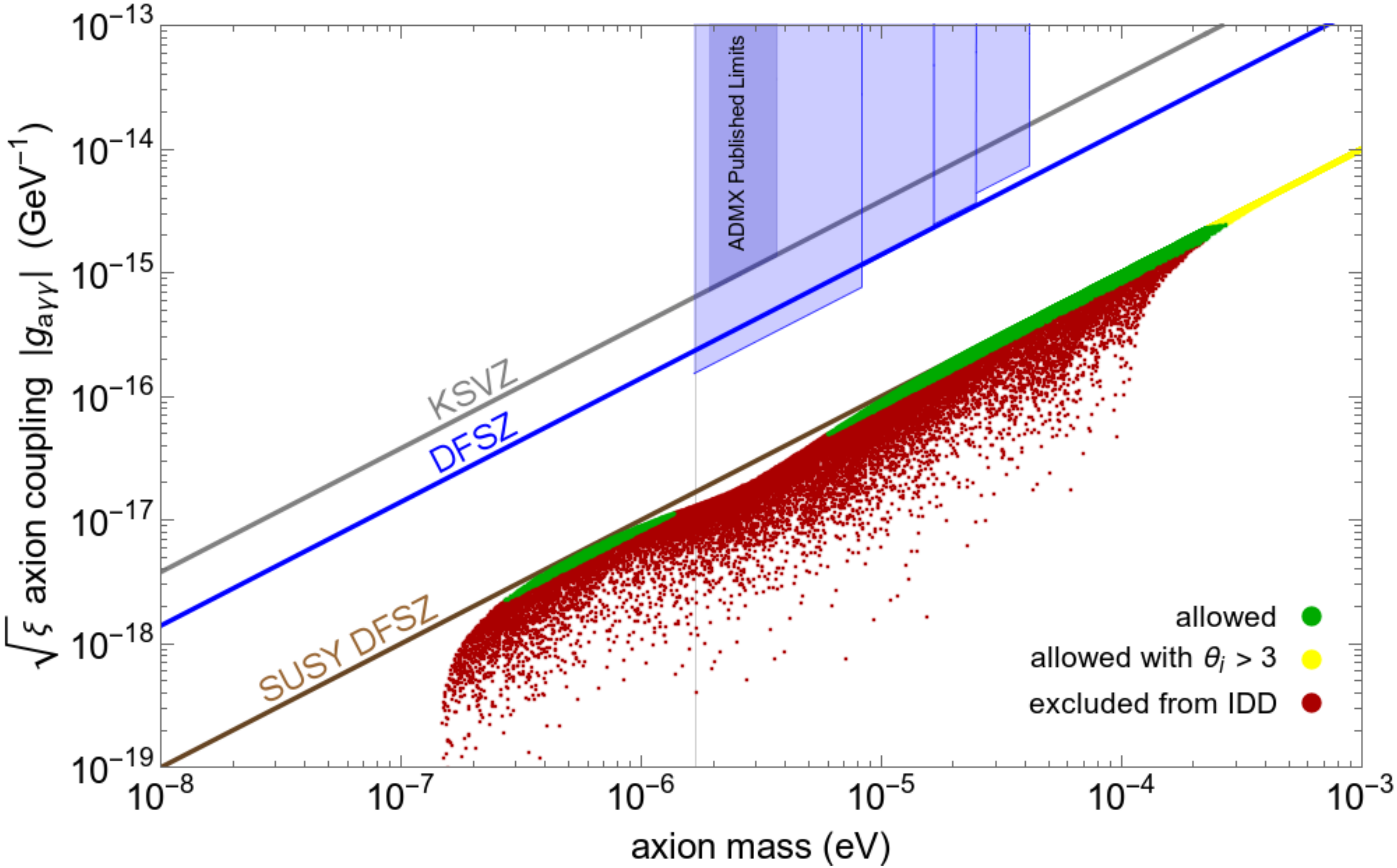
Prospects for IDD WIMP searches:



suppressed by square of diminished WIMP abundance

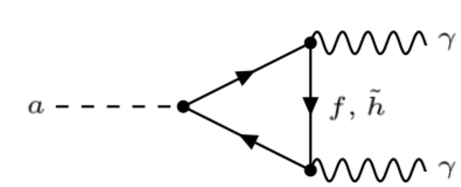
As ξ increases due to non-thermal WIMP production from saxion/axino decay, then axion parameter space becomes constrained by WIMP searches

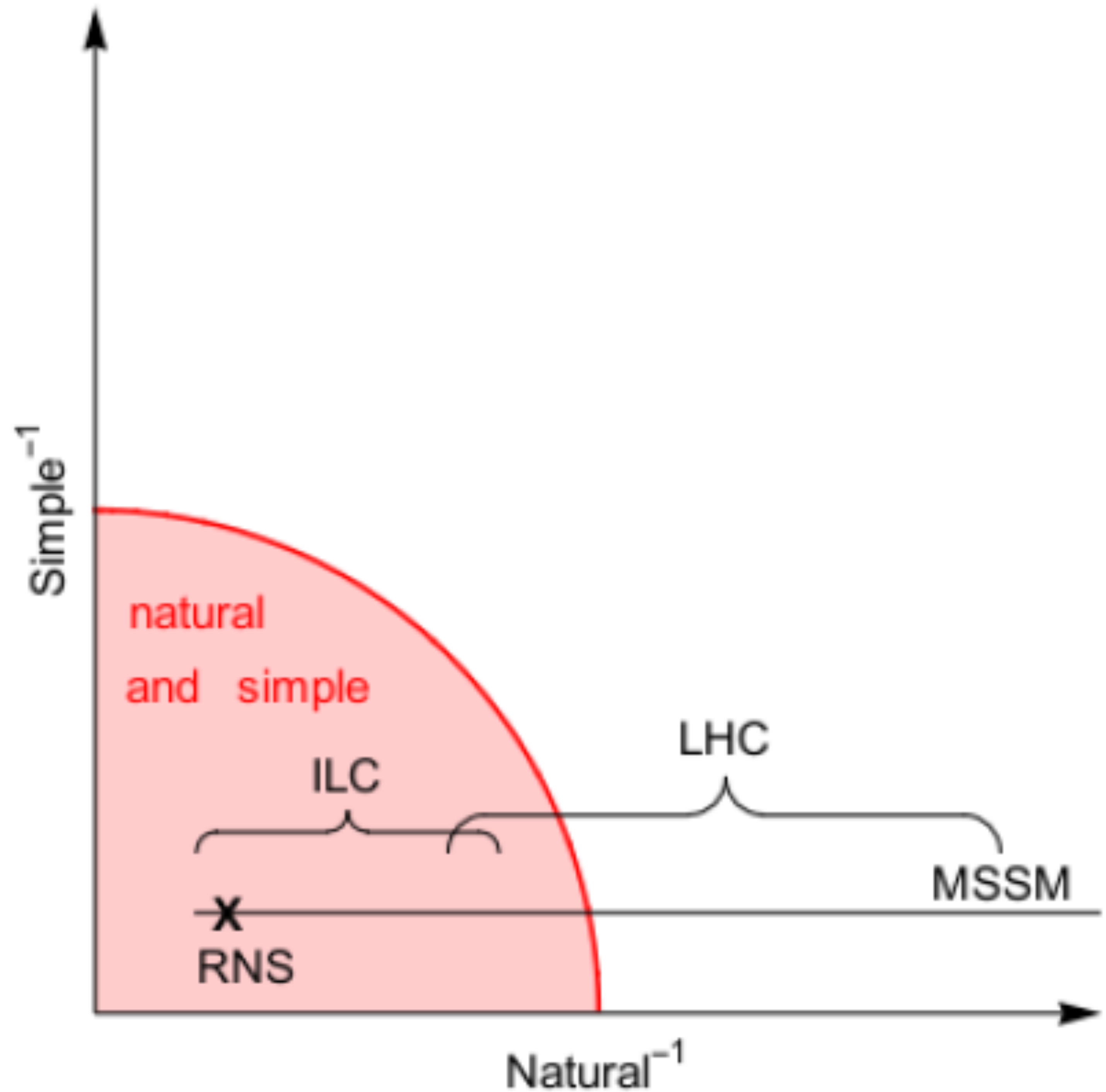




SUSY DFSZ axion: large range in m(a) but coupling reduced

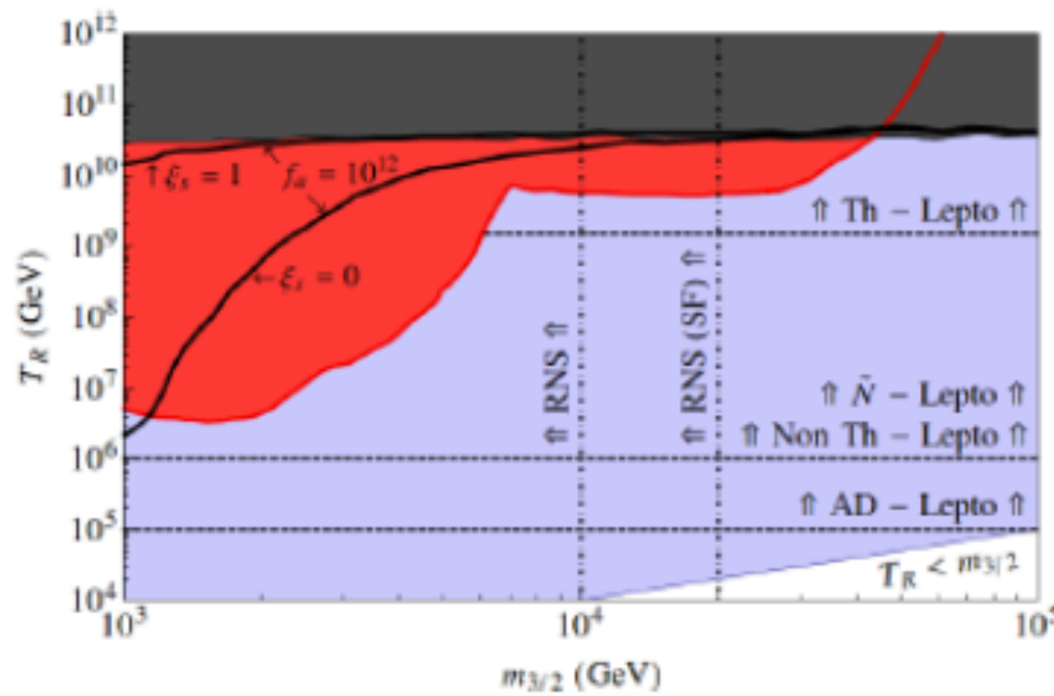
may need to probe broader and deeper!




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

Baryogenesis scenarios for radiative natural SUSY

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



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

gravitino problem plus axino/saxion problem: still plenty room

Bae,HB, Serce, Zhang, arXiv:1510.00724

#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

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

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

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

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

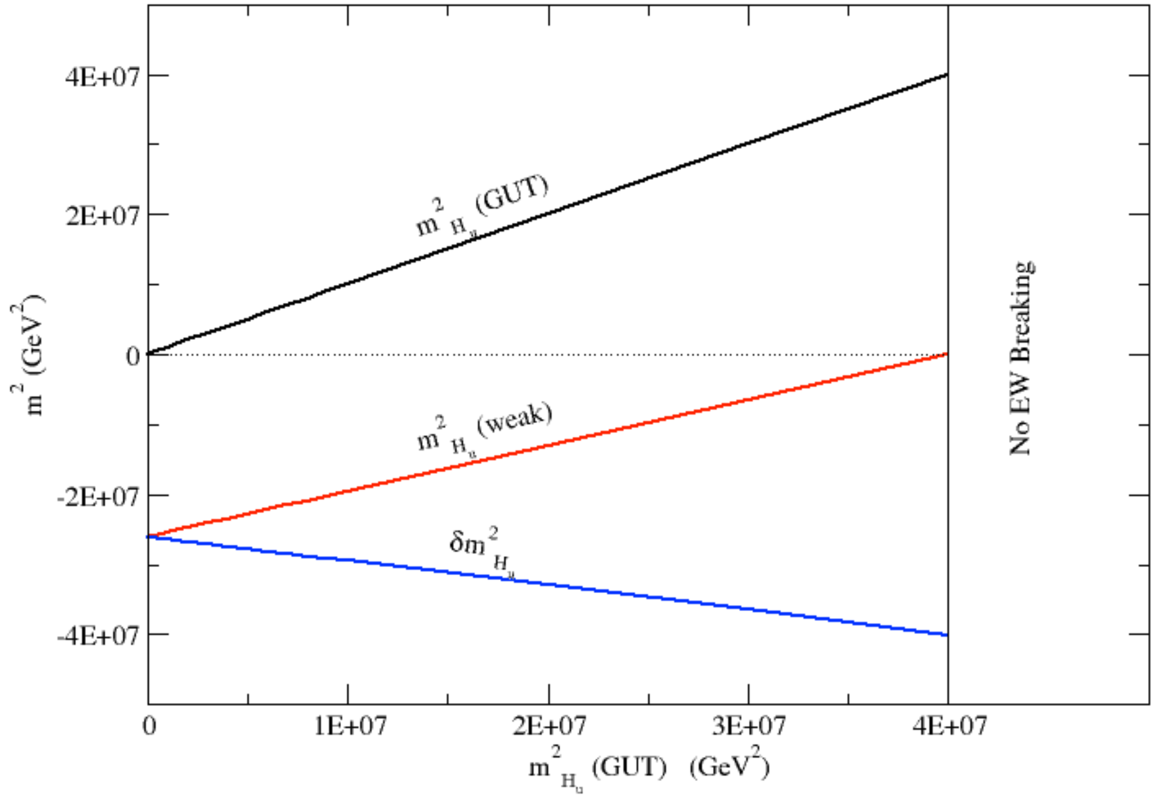
old natural SUSY then A_t can't be too big

What's wrong with this argument?

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

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

violates prime directive!



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

HB, Barger, Savoy

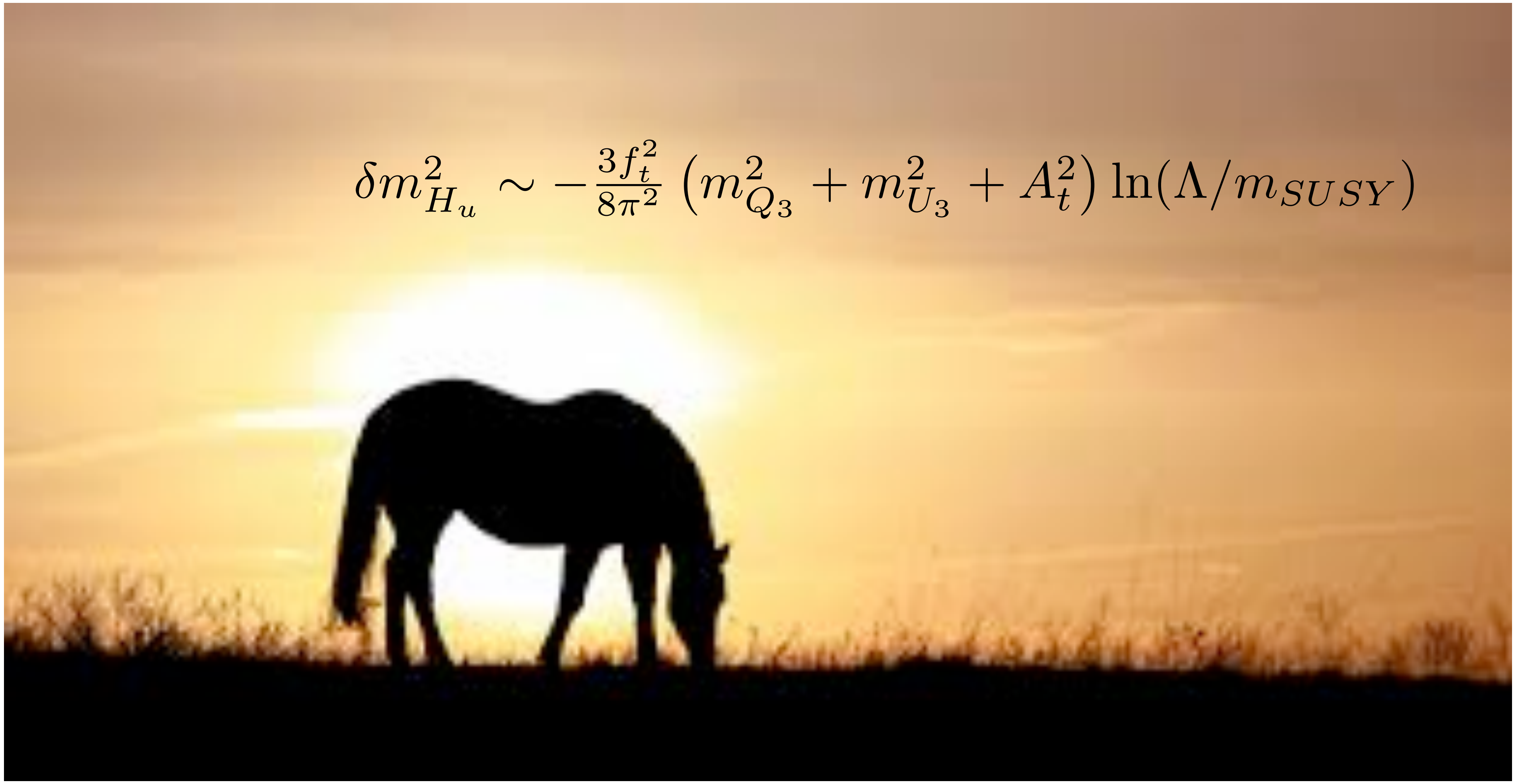
To fix: combine dependent terms:

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



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

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

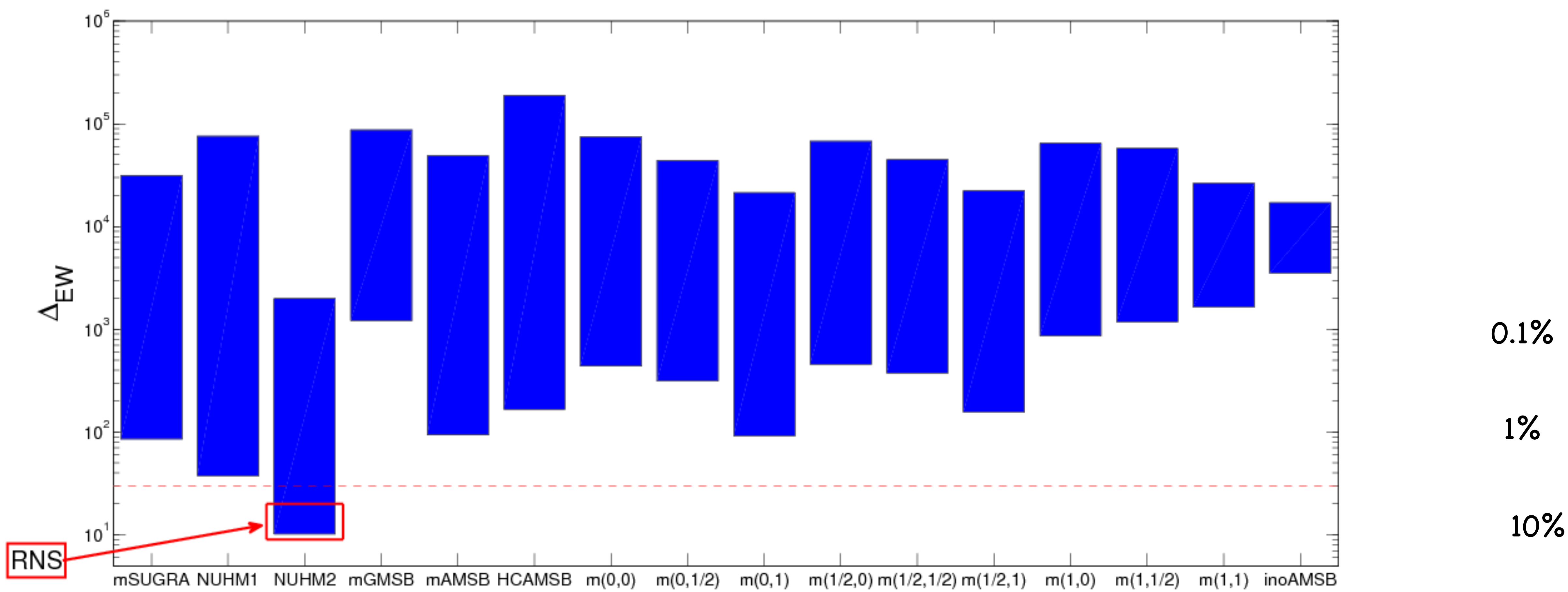
$$m_{H_u}^2(weak) \sim -(100-200)^2 \text{ GeV}^2 \sim -a \cdot m_{3/2}^2/2$$

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.

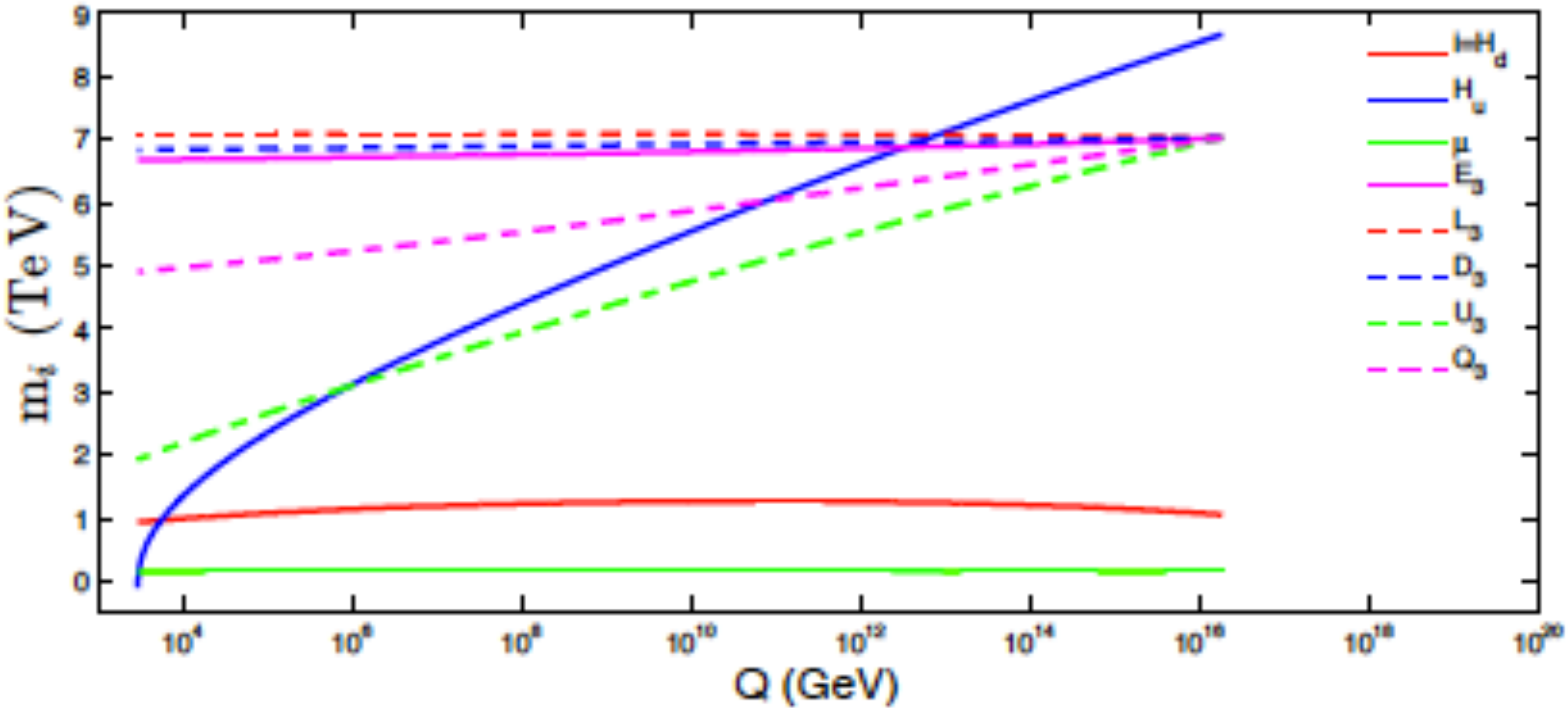
scan over p-space with m(h)=125.5+-2.5 GeV:



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:

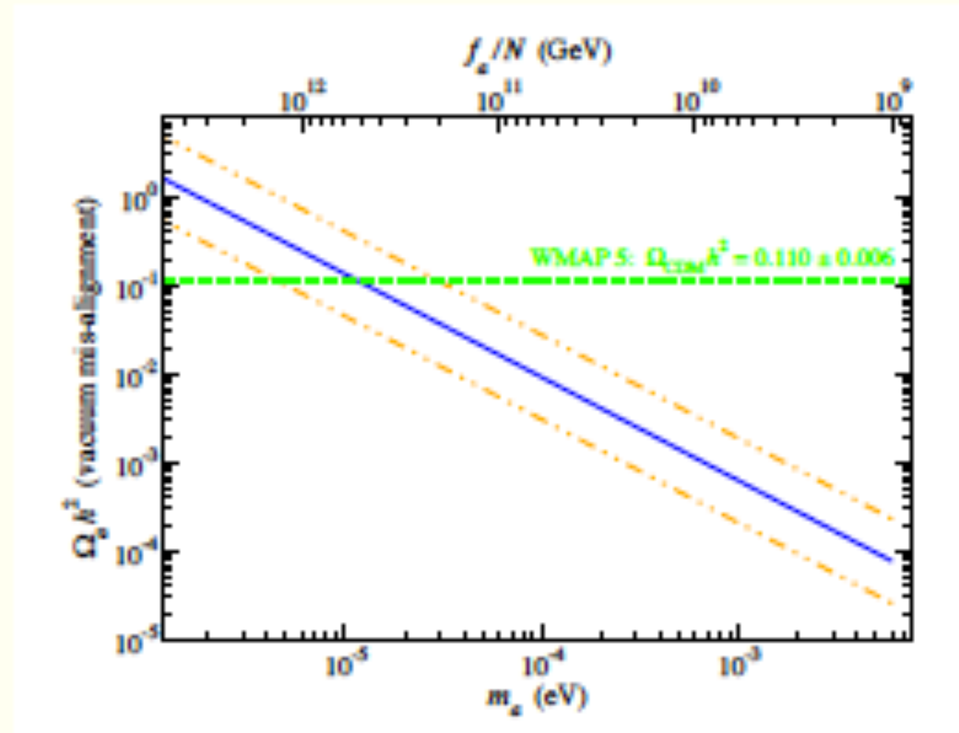
(typically need mHu~25-50% higher than m0)

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!

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

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

HB, Barger, Sengupta, arXiv:1810.03713

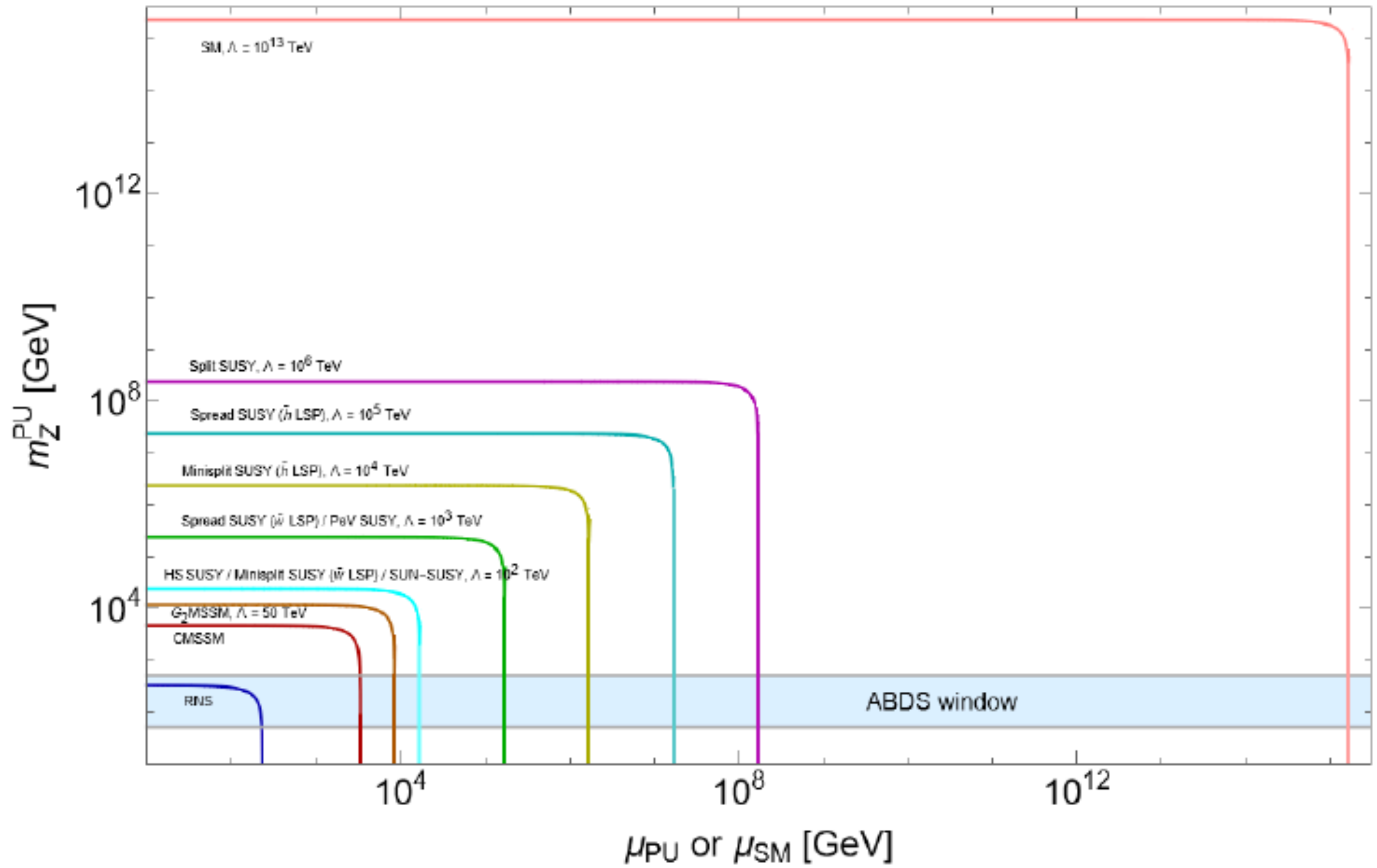
1. Global symmetries fundamentally incompatible with gravity completion
2. Expect global symmetry to emerge as accidental (approximate) symmetry from some more fundamental gravity-safe (e.g. gauge or R-) symmetry
3. Krauss-Wilczek: gauge symmetry with charge Ne object condensing leaves charge e fields with Z_N discrete gauge symmetry
4. Babu et al.: Z22 symmetry works but charge 22 object in swampland?
5. Better choice: discrete R-symmetries which 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
- $\mu \sim \lambda_\mu f_a^2/m_P$

Are finetuned or natural models preferred by landscape?



It is sometimes claimed
that the landscape provides
an alternative to naturalness;
we find, all things being equal,
this is not so:
finetuned models have a
tiny p-space for sampling on
the landscape compared
to natural models

model	$\tilde{m}(1,2)$	$\tilde{m}(3)$	gauginos	higgsinos	m_h	P_μ
SM	-	-	-	-	-	$7 \cdot 10^{-27}$
CMSSM ($\Delta_{EW} = 2641$)	~ 1	~ 1	~ 1	~ 1	$0.1 - 0.13$	$5 \cdot 10^{-3}$
PeV SUSY	$\sim 10^3$	$\sim 10^3$	~ 1	$1 - 10^3$	$0.125 - 0.155$	$5 \cdot 10^{-6}$
Split SUSY	$\sim 10^6$	$\sim 10^6$	~ 1	~ 1	$0.13 - 0.155$	$7 \cdot 10^{-12}$
HS-SUSY	$\gtrsim 10^2$	$\gtrsim 10^2$	$\gtrsim 10^2$	$\gtrsim 10^2$	$0.125 - 0.16$	$6 \cdot 10^{-4}$
Spread ($\tilde{h}$LSP)	10^5	10^5	10^2	~ 1	$0.125 - 0.15$	$9 \cdot 10^{-10}$
Spread ($\tilde{w}$LSP)	10^3	10^3	~ 1	$\sim 10^2$	$0.125 - 0.14$	$5 \cdot 10^{-6}$
Mini-Split ($\tilde{h}$LSP)	$\sim 10^4$	$\sim 10^4$	$\sim 10^2$	~ 1	$0.125 - 0.14$	$8 \cdot 10^{-8}$
Mini-Split ($\tilde{w}$LSP)	$\sim 10^2$	$\sim 10^2$	~ 1	$\sim 10^2$	$0.11 - 0.13$	$4 \cdot 10^{-4}$
SUN-SUSY	$\sim 10^2$	$\sim 10^2$	~ 1	$\sim 10^2$	0.125	$4 \cdot 10^{-4}$
G_2MSSM	$30 - 100$	$30 - 100$	~ 1	~ 1	$0.11 - 0.13$	$2 \cdot 10^{-3}$
RNS/landscape	$5 - 40$	$0.5 - 3$	~ 1	$0.1 - 0.35$	$0.123 - 0.126$	1.4

Table 1: A survey of some unnatural and natural SUSY models along with general expectations for sparticle and Higgs mass spectra in TeV units. We also show relative probability measure P_μ for the model to emerge from the landscape. For RNS, we take $\mu_{min} = 10$ GeV.

HB,Barger,
Martinez,Salam