

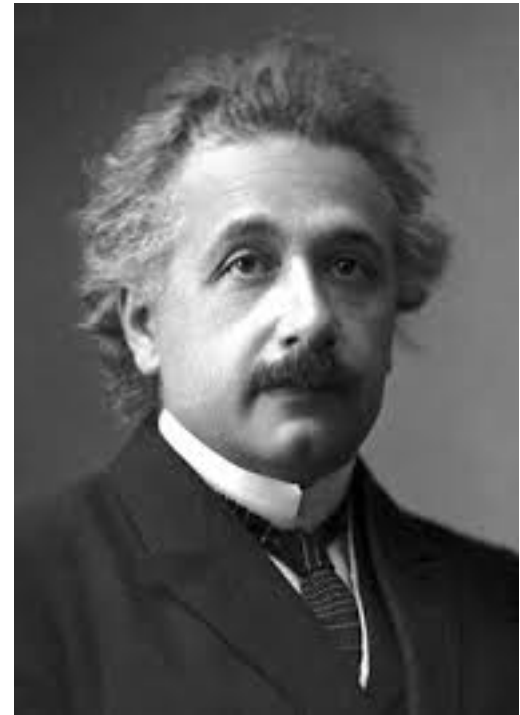
Supersymmetry, naturalness and the string landscape



Howard Baer
University of Oklahoma

NTU Energy Frontier meeting,
October 5-6, 2020

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

“...settling the ultimate fate of naturalness is perhaps
the most profound theoretical question
of our time”



Arkani-Hamed et al.,
arXiv:1511.06495

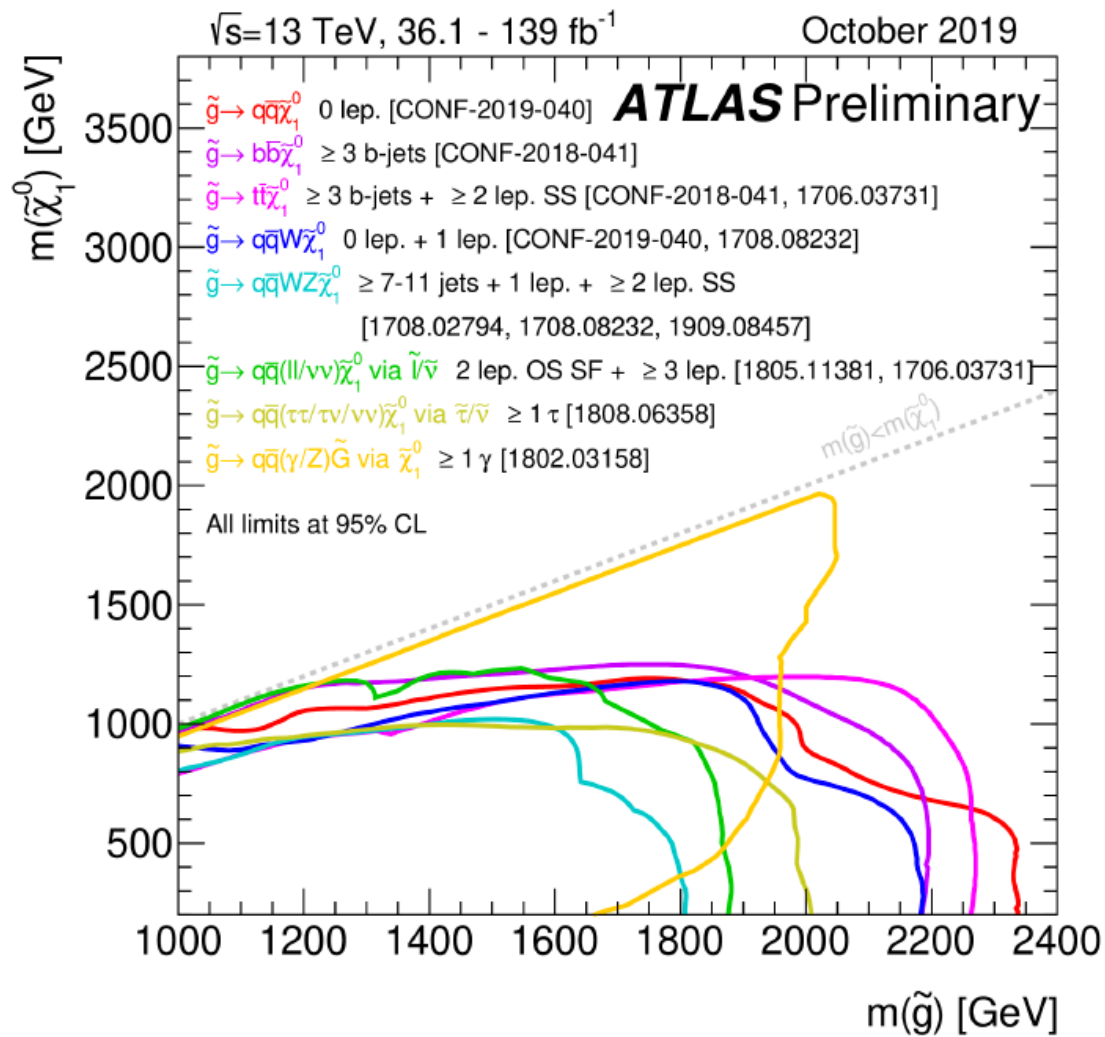
“Given the magnitude of the stakes
involved,
it is vital to get a clear verdict
on naturalness from experiment”

This should be matched by theoretical scrutiny
of what we mean by naturalness

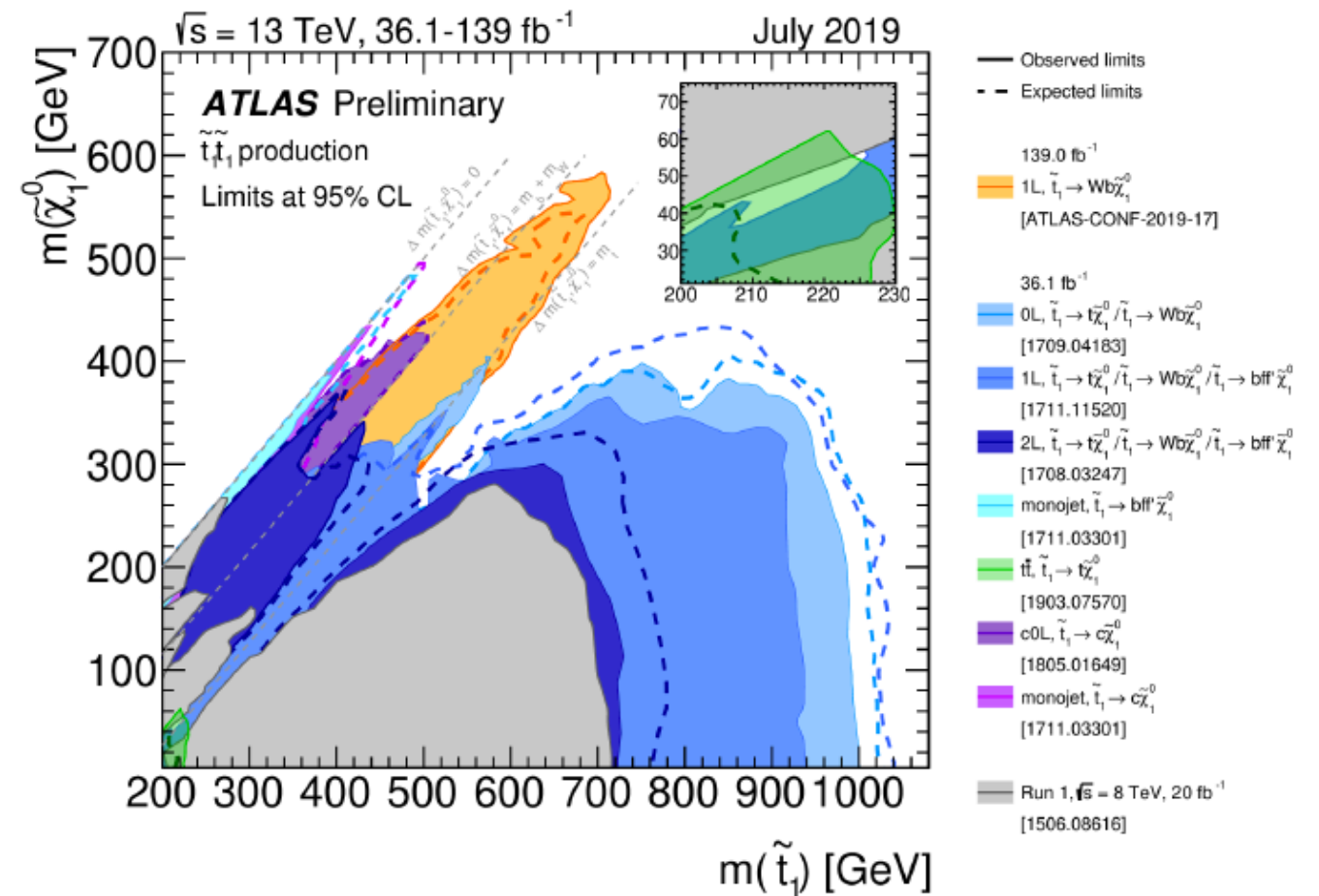
supersymmetry

- solves the big hierarchy problem: all quadratic divergences to mh cancel!
- supported by precision measurements/virtual effects:
gauge coupling unification;
 $m(\text{top}) \sim 173 \text{ GeV} \Rightarrow$ radiative EWSB;
 $m(h)$ exactly within narrow SUSY window;
 $m(W)$ vs. $m(t)$ precision EW
- So where are the sparticles?
- Where are the WIMPs?

Where are the sparticles?



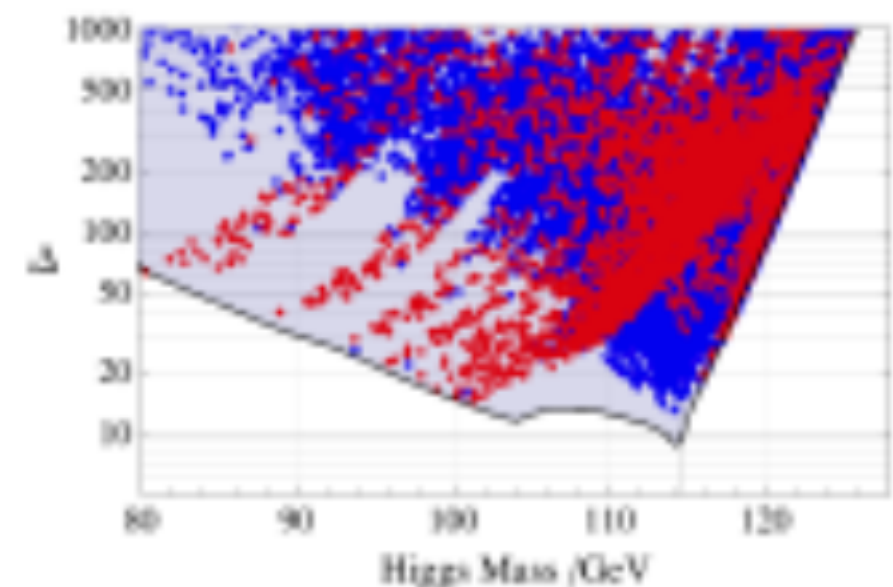
$$m_{\tilde{g}} > 2.25 \text{ TeV}$$



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

These bounds appear in sharp conflict with EW “naturalness”

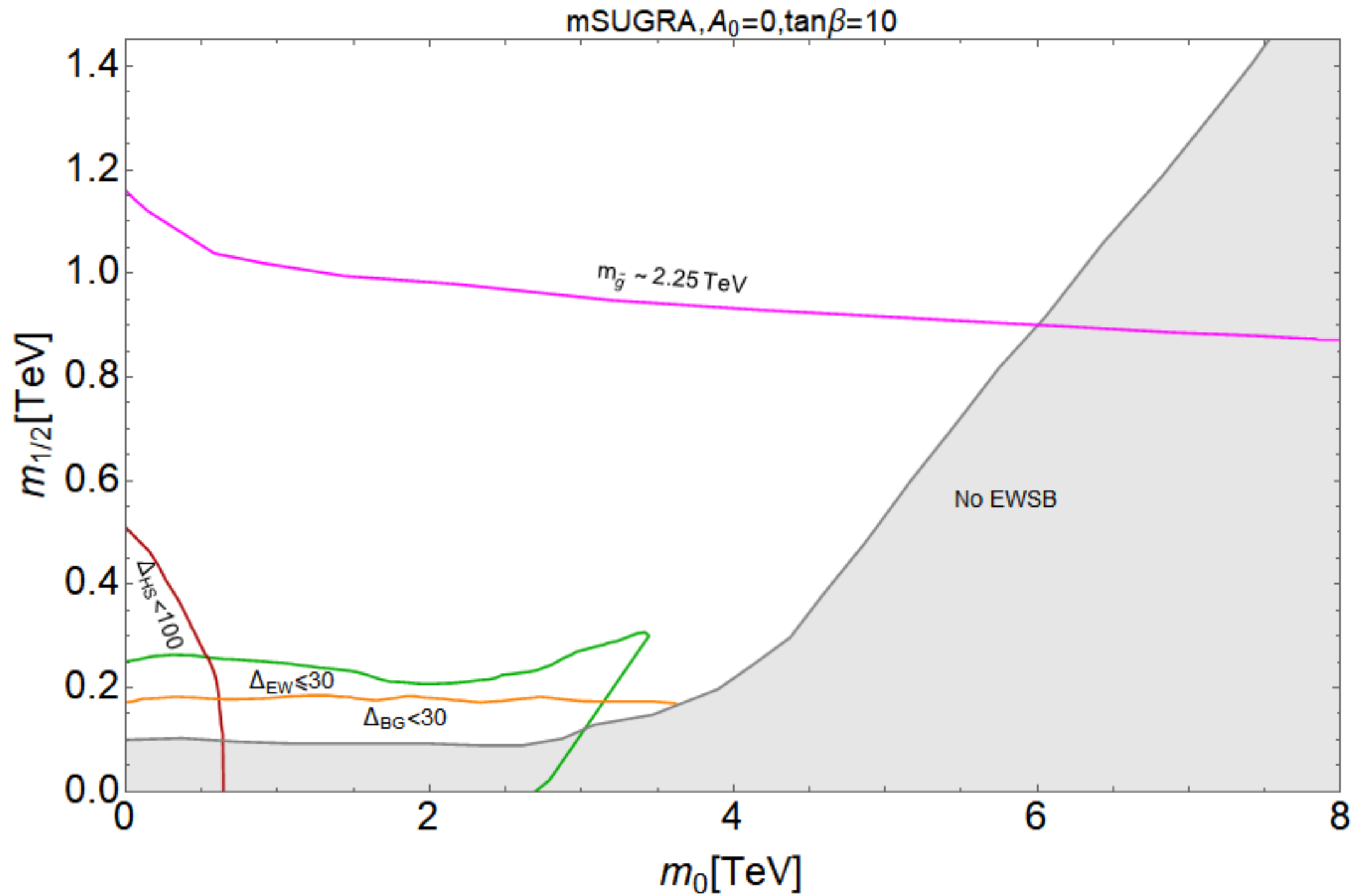
mass	
gluino	400 GeV
uR	400 GeV
eR	350 GeV
chargino	100 GeV
neutralino	50 GeV



Cassel, Ghilencea, Ross, 2009

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

Barbieri-Giudice 10% bounds, 1987



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

Putting Dirac and 't Hooft naturalness aside,
what we usually refer to as natural is **practical naturalness**

An observable $\mathcal{O} \equiv o_1 + \cdots + o_n$ is natural if
all *independent* contributions o_i to \mathcal{O} are comparable to or less than \mathcal{O}

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

The main requirements for low fine-tuning ($\Delta_{EW} \lesssim 30^1$)
are the following.

- $|\mu| \sim 100 - 350$ GeV[23–27] (where $\mu \gtrsim 100$ GeV is required to accommodate LEP2 limits from chargino pair production searches).
- $m_{H_u}^2$ is driven radiatively to small, and not large, negative values at the weak scale [21, 28].
- The top squark contributions to the radiative corrections $\Sigma_u^u(\tilde{t}_{1,2})$ are minimized for TeV-scale highly mixed top squarks[28]. This latter condition also lifts the Higgs mass to $m_h \sim 125$ GeV. For $\Delta_{EW} \lesssim 30$, the lighter top squarks are bounded by $m_{\tilde{t}_1} \lesssim 3$ TeV.
- The gluino mass, which feeds into the $\Sigma_u^u(\tilde{t}_{1,2})$ via renormalization group contributions to the stop masses[27], is required to be $m_{\tilde{g}} \lesssim 6$ TeV, possibly beyond the reach of the $\sqrt{s} = 13 - 14$ TeV LHC.²
- First and second generation squark and slepton masses may range as high as 5-30 TeV with little cost to naturalness[21, 22, 29, 30].

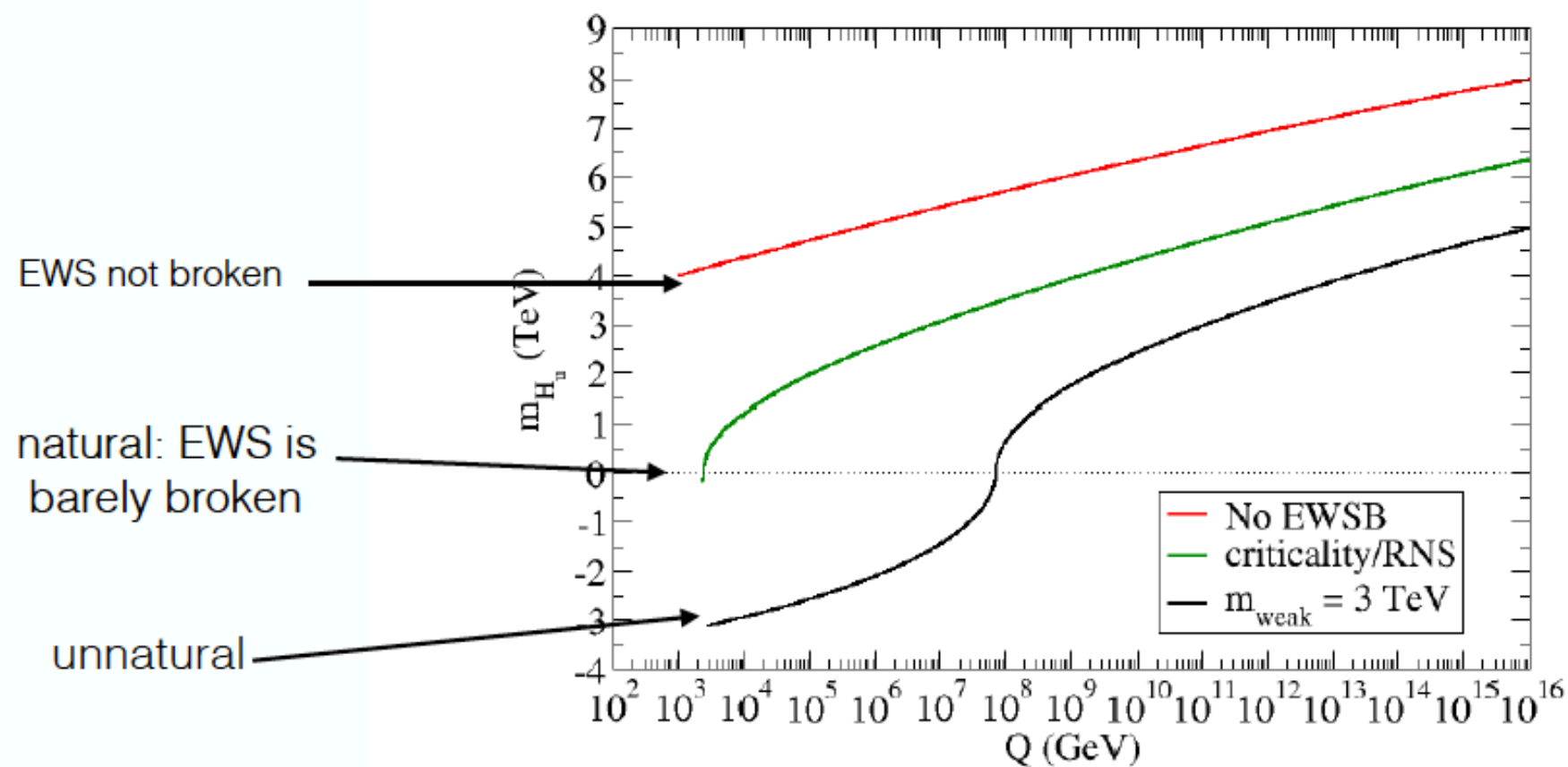
$$\Delta_{EW} \equiv \max_i |C_i| / (m_Z^2/2)$$

HB, Barger, Huang,
Mustafayev, Tata, arXiv:1207.3343

This measure is:
* model-independent,
* scale independent,
* most conservative
naturalness measure

The bigger the soft term, the more natural is its weak scale value,
until EW symmetry no longer broken: living dangerously!

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

Pie baking analogy:



1 kg pie= .2 kg(sugar)+.3 kg(flour)+
.1 kg(water)+.5 kg (apples)+
-.1 kg(evaporation)

Voila! It is very natural!

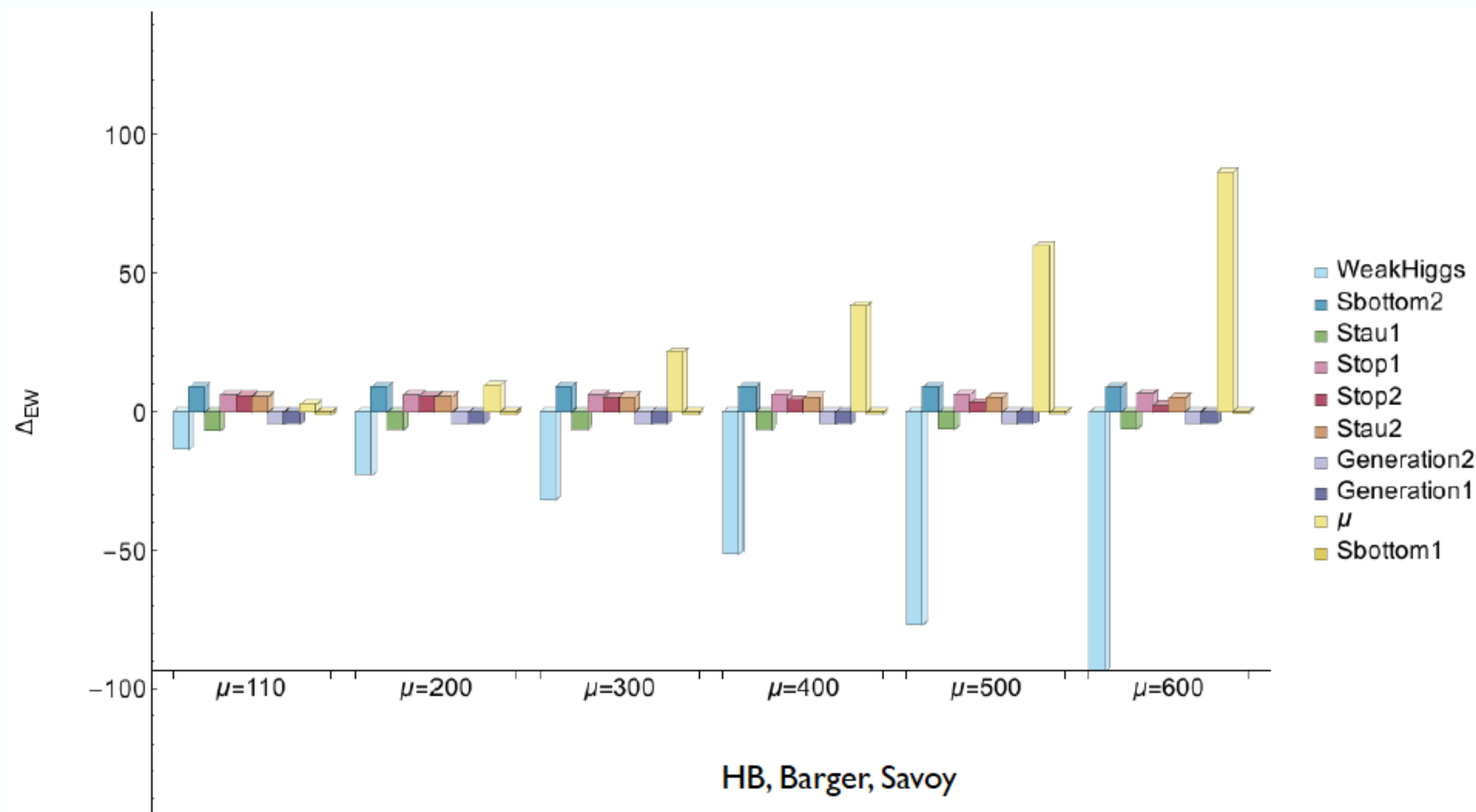
An unnatural recipe:



$$1\text{kg}(\text{pie}) = .2 \text{ kg}(\text{sugar}) + .3 \text{ kg}(\text{flour}) + .5 \text{ kg}(\text{apples}) + 10^4 \text{ kg}(\text{water}) - 10^4 \text{ kg}(\text{evaporation})$$

mathematically, it is possible-
but success seems highly implausible:
it is fine-tuned and hence
unnatural

How much is too much fine-tuning?



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

EENZ/BG naturalness

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

- depends on input parameters of model
- different answers for same inputs assuming different models

model	c_{m_0}	$c_{m_{1/2}}$	c_{A_0}	c_μ	c_{H_u}	c_{H_d}	Δ_{BG}
mSUGRA	156	762	1540	-25.1	---	---	1540
NUHM2	16041	762	1540	-25.1	-15208	-643.6	16041

parameters introduced to parametrize our ignorance of SUSY breaking;
not expected to be fundamental

e.g. SUSY with dilaton-dominated breaking: $m_0^2 = m_{3/2}^2$ with $m_{1/2} = -A_0 = \sqrt{3}m_{3/2}$

(**doesn't make sense** to use independent m_0 , $m_{1/2}$, A_0)

while Δ_{BG} tells us about fine-tuning in our computer codes,
what we really want to know is: **is nature fine-tuned or natural?**

For correlated soft terms, then $\Delta_{BG} \rightarrow \Delta_{EW}$

Alternatively, only place independent soft terms makes sense
is in **multiverse**: but then selection effects in action

Briefly revisit gauge hierarchy problem (SM):

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

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

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

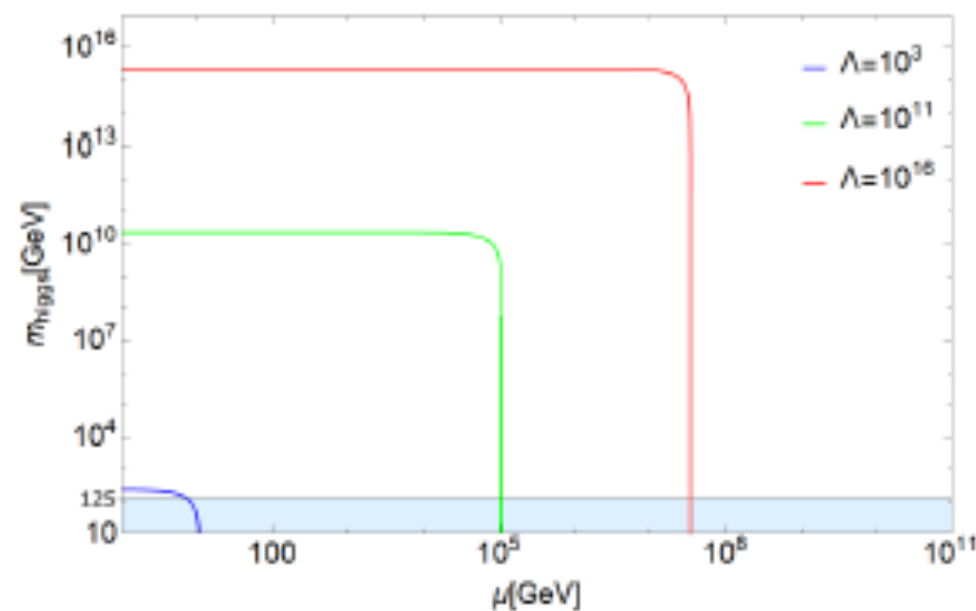


Figure 2: Value of $m_h(SM)$ versus SM μ parameter for theory cut-off values $\Lambda_{SM} = 10^3, 10^{11}$ and 10^{16} GeV.

Hardly plausible that SM is valid much beyond the TeV scale

High scale (HS, stop mass) measure

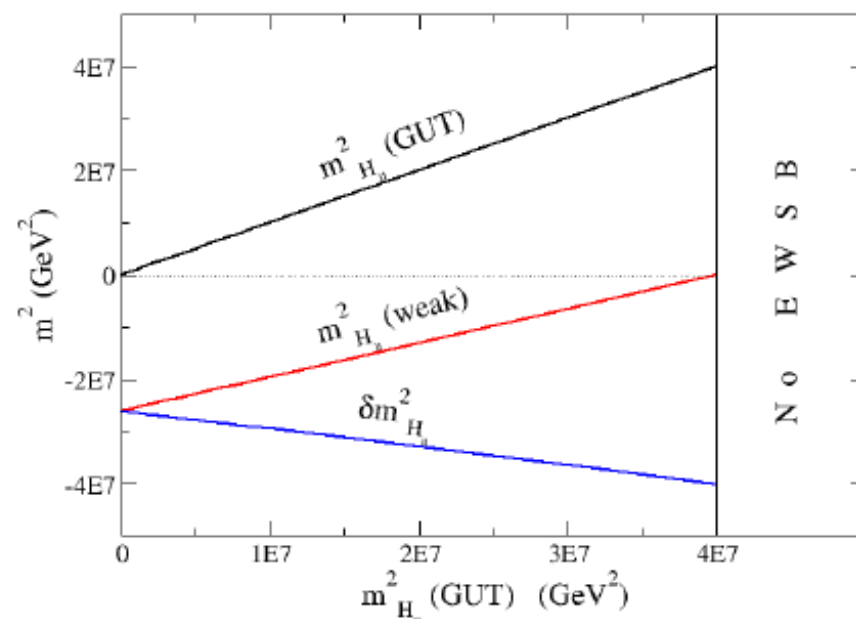
$$m_h^2 \simeq \mu^2 + m_{H_u}^2(\text{weak}) = \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$$

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

Implies 3 3rd generation squarks <500 GeV:
SUSY ruled out under $\Delta_{HS} \equiv \frac{\delta m_{H_u}^2}{m_h^2}$

BUT! too many terms ignored! **NOT VALID!**

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2} \left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t \right) \quad \text{where } t = \ln(Q^2/Q_0^2), \quad S = m_{H_u}^2 - m_{H_d}^2 + \text{Tr}[m_Q^2 - m_L^2 - 2m_U^2 + m_D^2 + m_E^2] \text{ and } X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2. \text{ By neglecting gauge terms and } S (S=0)$$



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

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

Recommendation: put this horse out to pasture

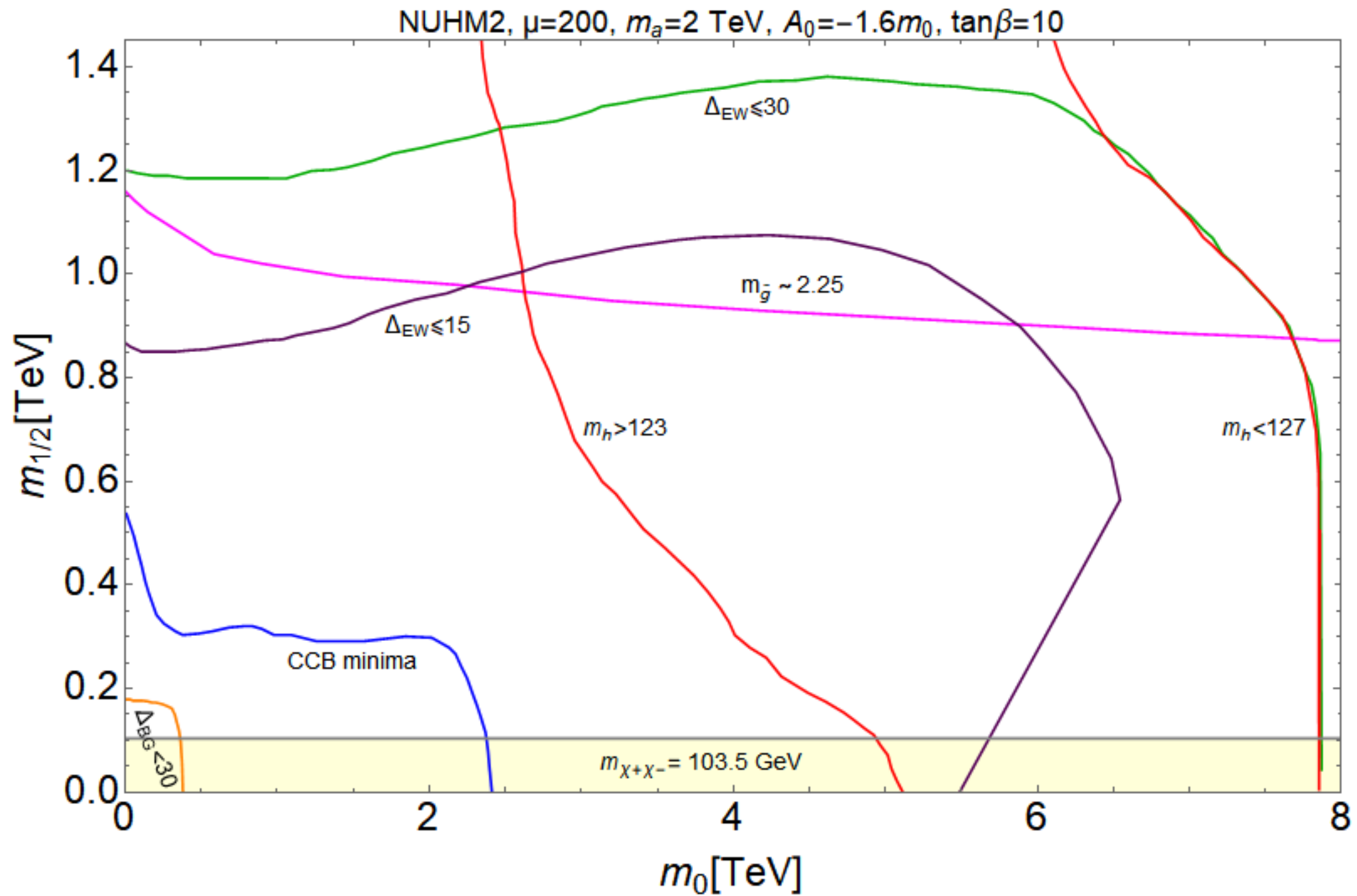
$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2} (m_{Q_3}^2 + m_{U_3}^2 + A_t^2) \ln(\Lambda/m_{SUSY})$$

R.I.P.

sub-TeV 3rd generation squarks **not** required for naturalness

NUHM2: non-universality of Higgs soft terms always allows low μ for $m_{H_u} \sim 1.3 m_0$

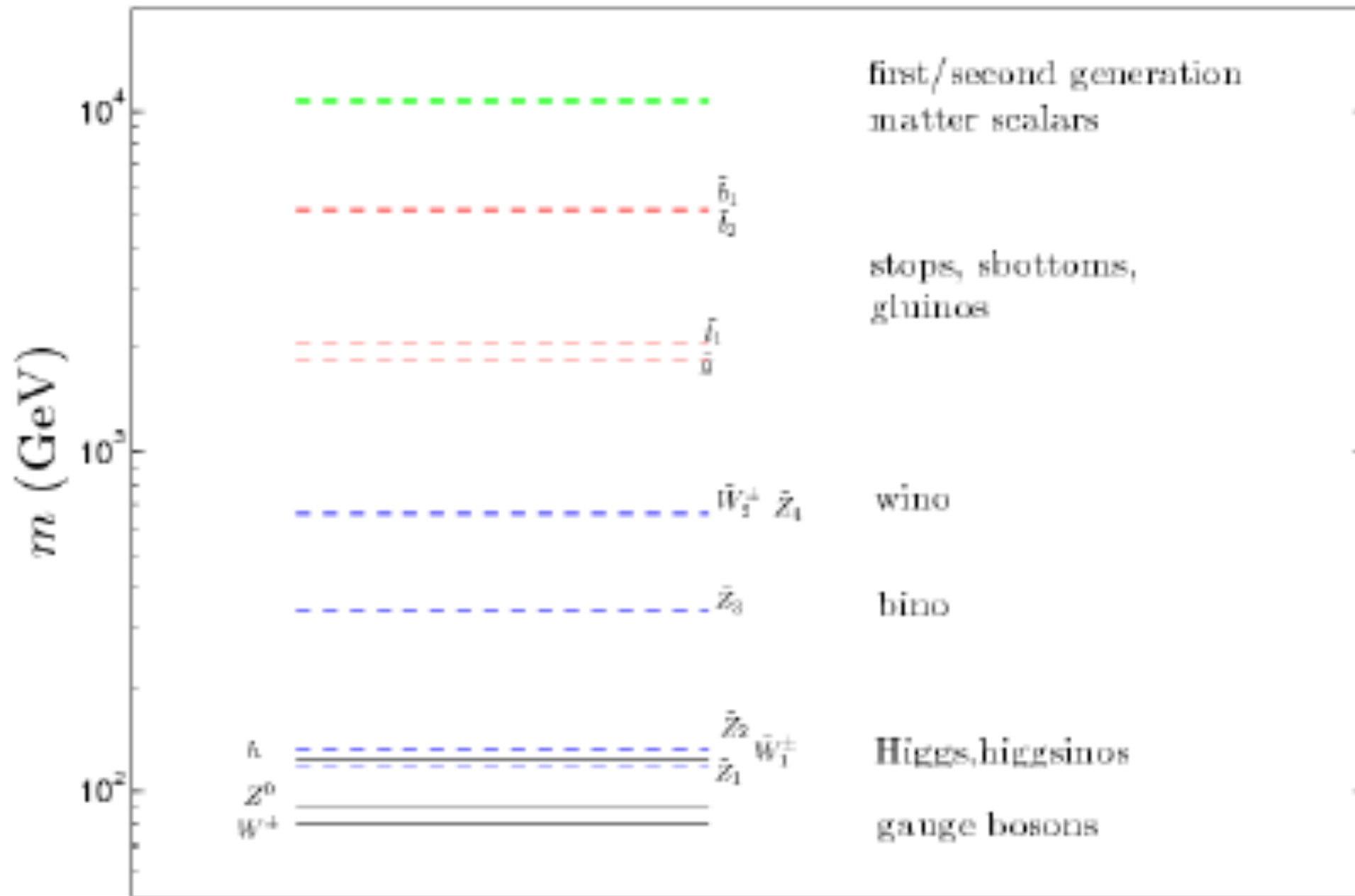
$$m_0, m_{1/2}, A_0, \tan\beta, \mu, m_A$$



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

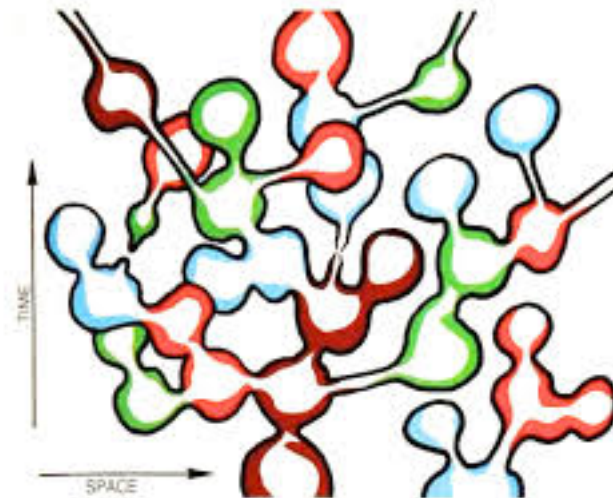
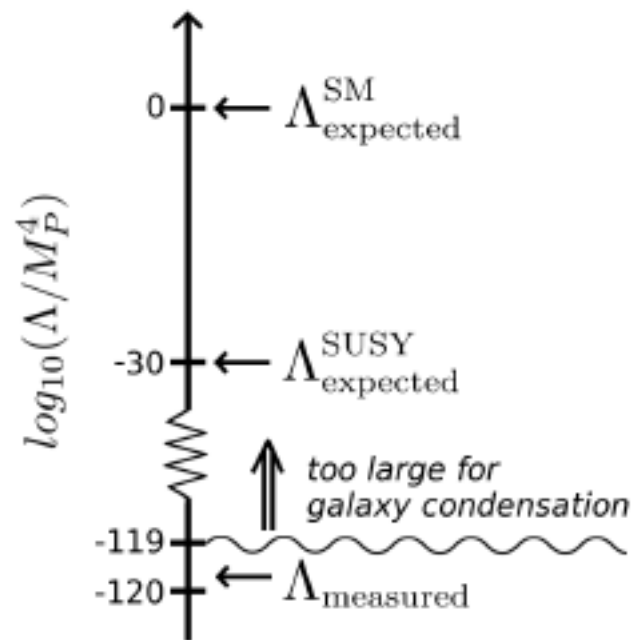
h(125) and LHC limits are perfectly compatible
with 3-10% naturalness: **no crisis!**

Typical spectrum for low Δ_{EW} models

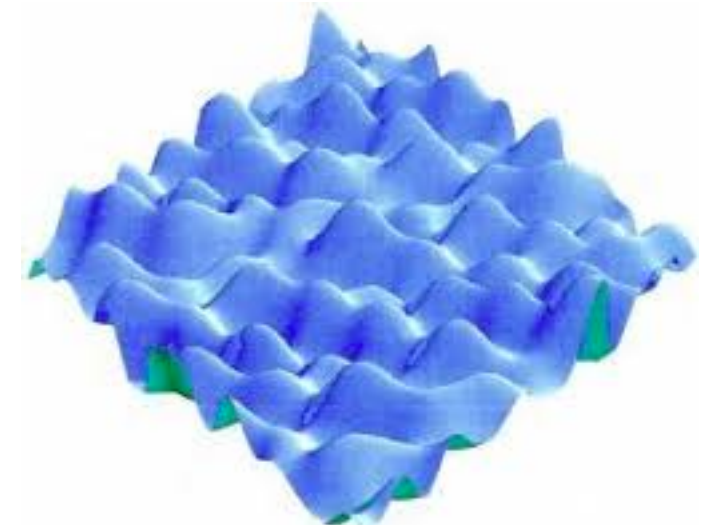


a **natural** sparticle spectrum for SUSY:
 only a re-shuffling is needed for natural spectra:
 only higgsinos need lie close to EW scale

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



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)



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

To handle string landscape and concomitant multiverse,
Douglas introduced concept of **stringy naturalness**

An effective field theory (or specific coupling or observable) T_1 is more natural in string theory than T_2 if the number of *phenomenologically acceptable* vacua leading to T_1 is larger than the number leading to T_2 .

(anthropics hides here)



This embodies Weinberg's prediction of CC

Can we apply similar reasoning to magnitude of weak scale?

$$m(\text{weak}) \sim m(W, Z, h) \sim 100 \text{ GeV}$$

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?

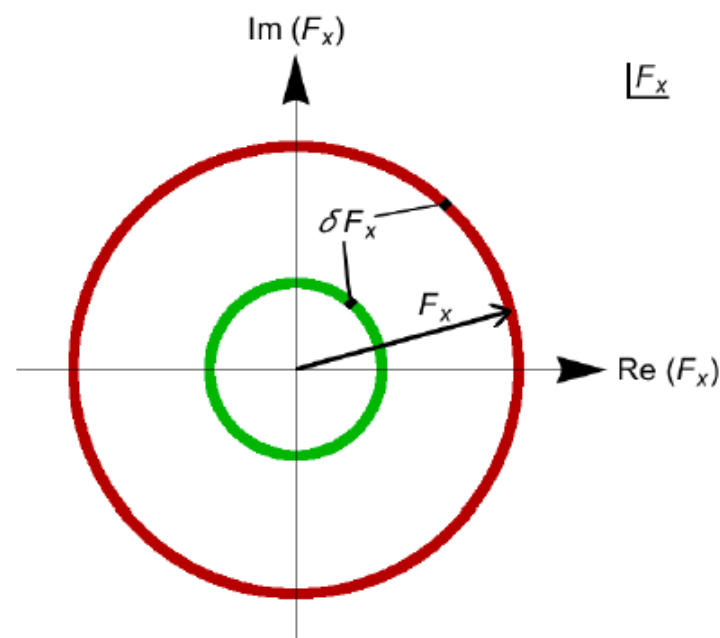
In string theory, usually multiple (~ 10) hidden sectors
containing a variety of F- and D- breaking fields

For comparable $\langle F_i \rangle$ and $\langle D_j \rangle$ values, then expect

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

Douglas ansatz

arXiv:0405279



Under single F-term
SUSY breaking,
expect **linear 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.

What about **f(selection)**?

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

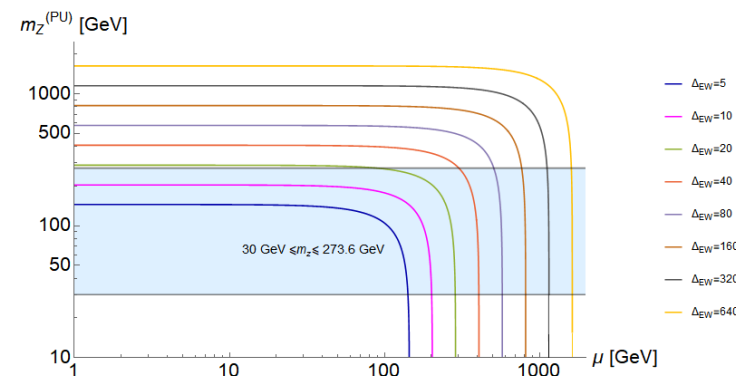
to penalize soft terms straying too far from weak scale

This doesn't work for variety of cases

- Too big soft terms can lead to CCB minima: must veto such vacua
- Bigger $m(H_u)^2$ leads to more natural value at weak scale
- Bigger $A(t)$ trilinear suppresses t_1, t_2 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 μ value so no longer available for tuning; then $m_Z(PU) \approx 91.2$ GeV



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

Must veto too large $m(weak)$ values: nuclear physics screwed up
(Agrawal, Barr, Donoghue, Seckel, 1998)

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

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

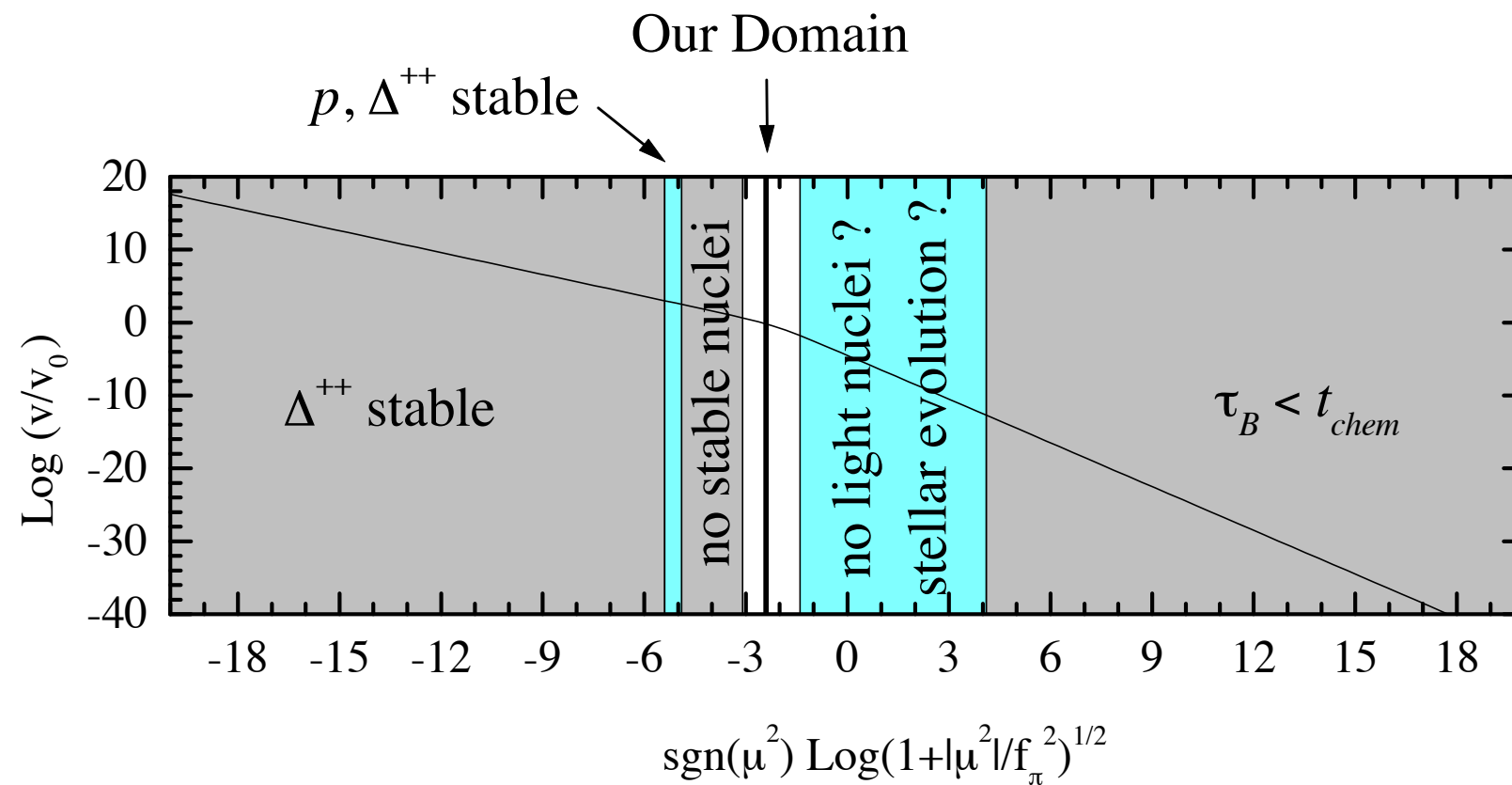
pocket-universe value of weak scale

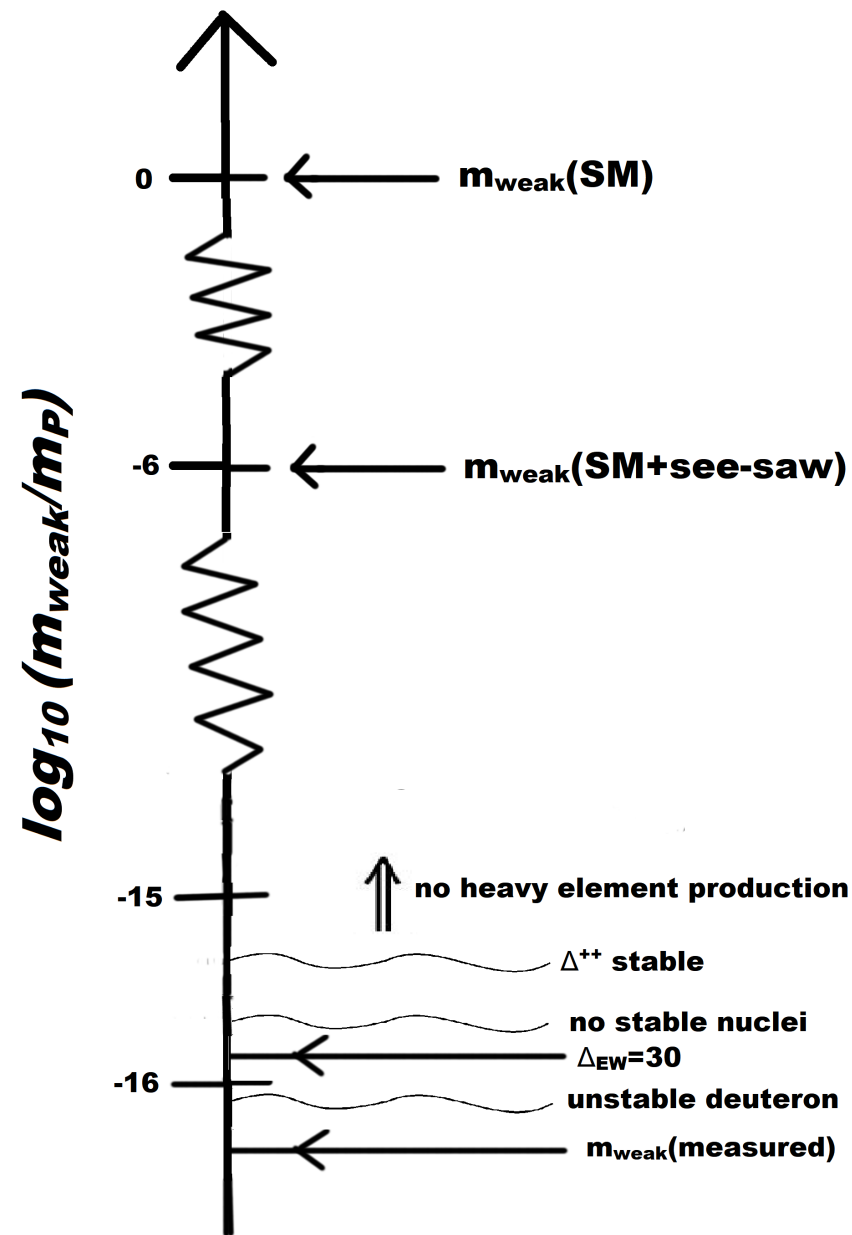
cannot deviate by more than

factor 2-5 from its measured value

lest disasters occur in nuclear physics: no nuclei, no atoms

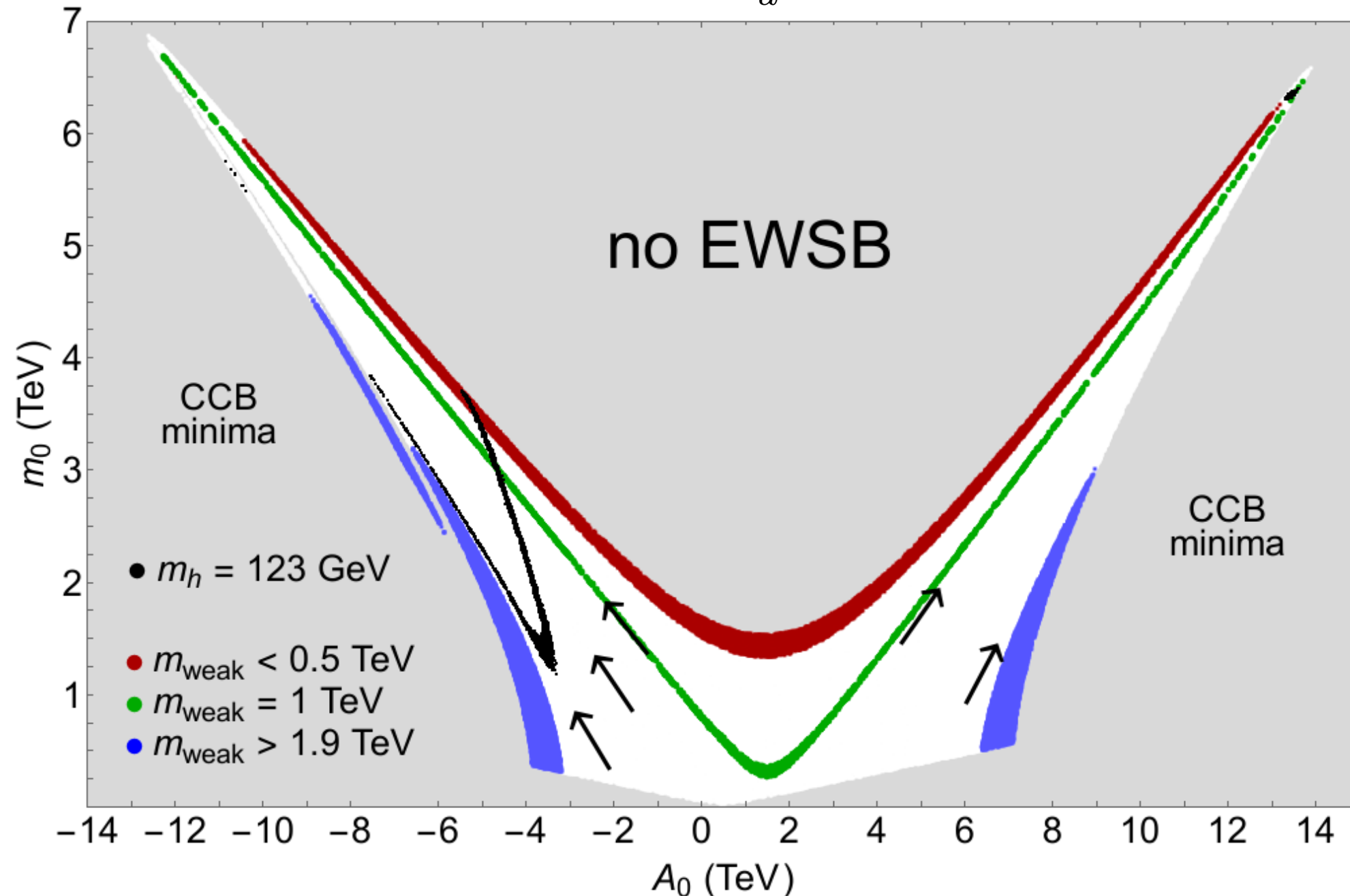
(violates atomic principle)





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

$$m_{H_u} = 1.3m_0$$



statistical draw to large soft terms balanced by
anthropic draw toward red ($m(\text{weak}) \sim 100$ GeV):
then $m(\text{Higgs}) \sim 125$ GeV and natural SUSY spectrum!

Denef, Douglas, JHEP0405 (2004) 072

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

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

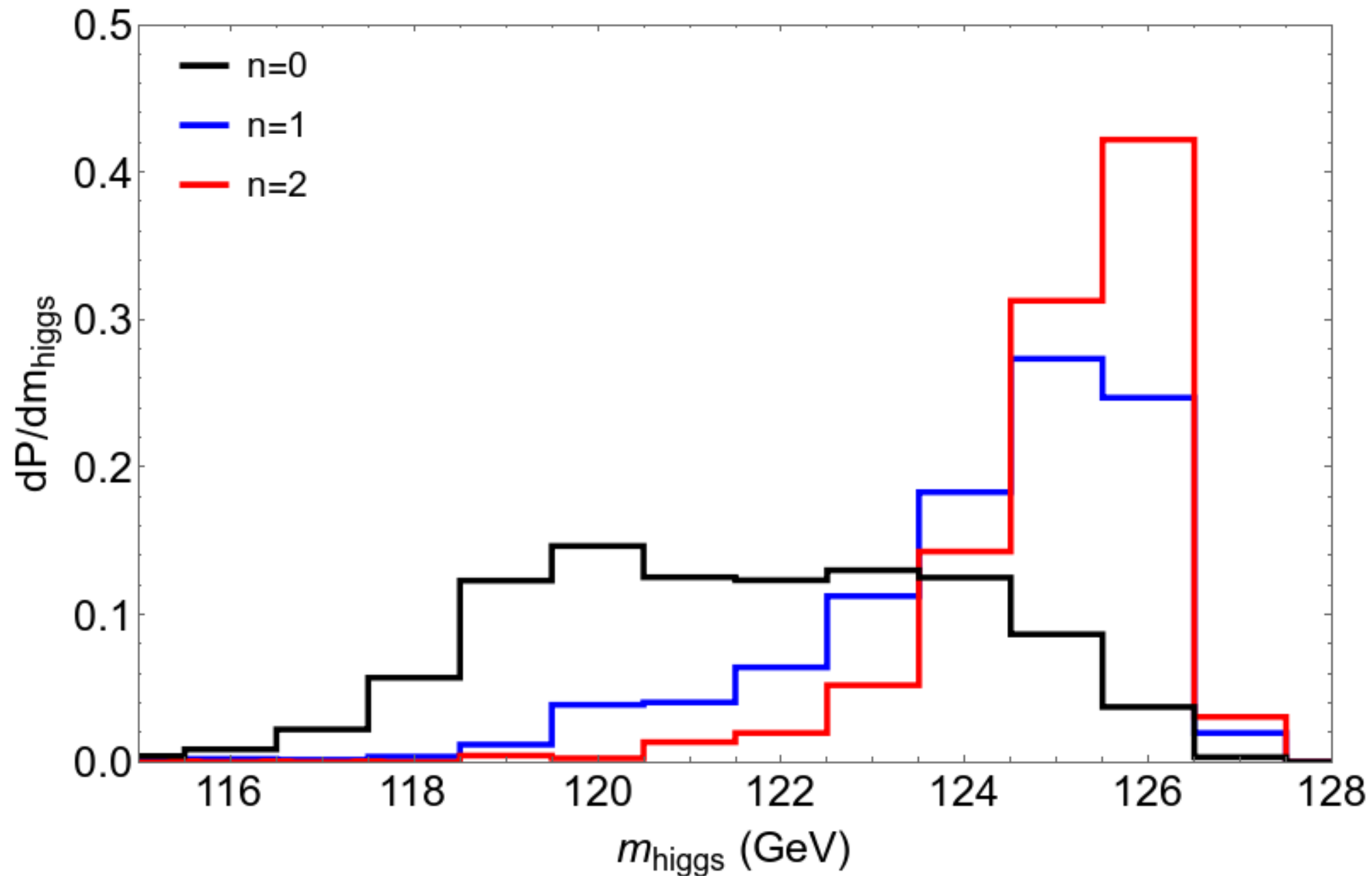
We scan according to m_{soft}^n over:

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

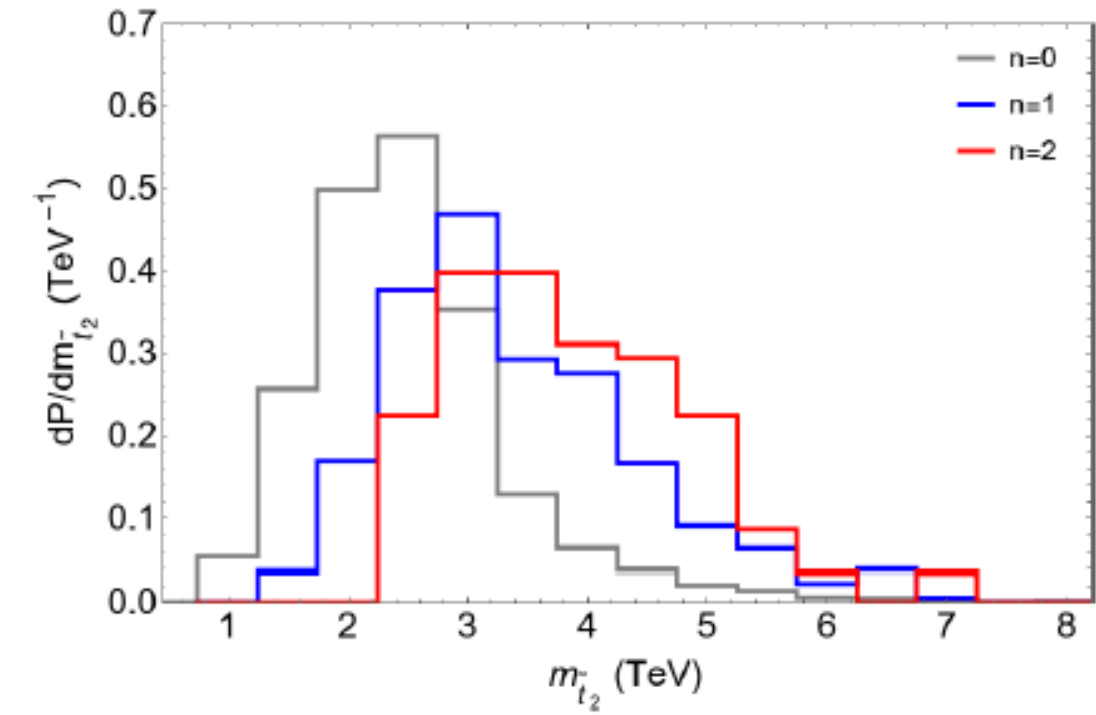
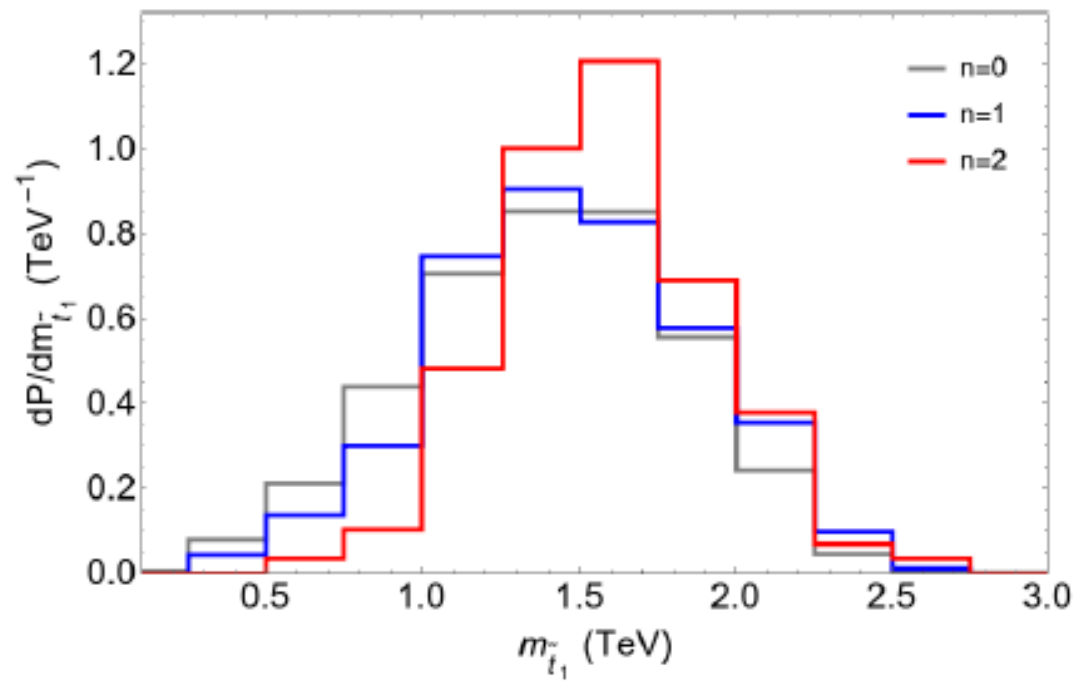
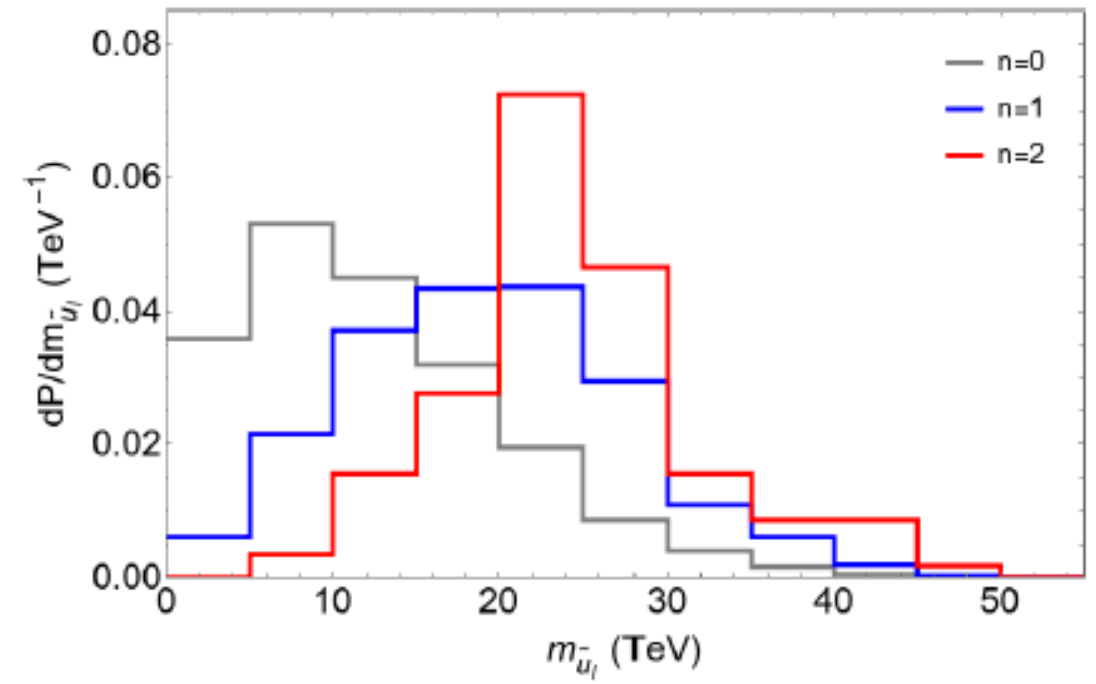
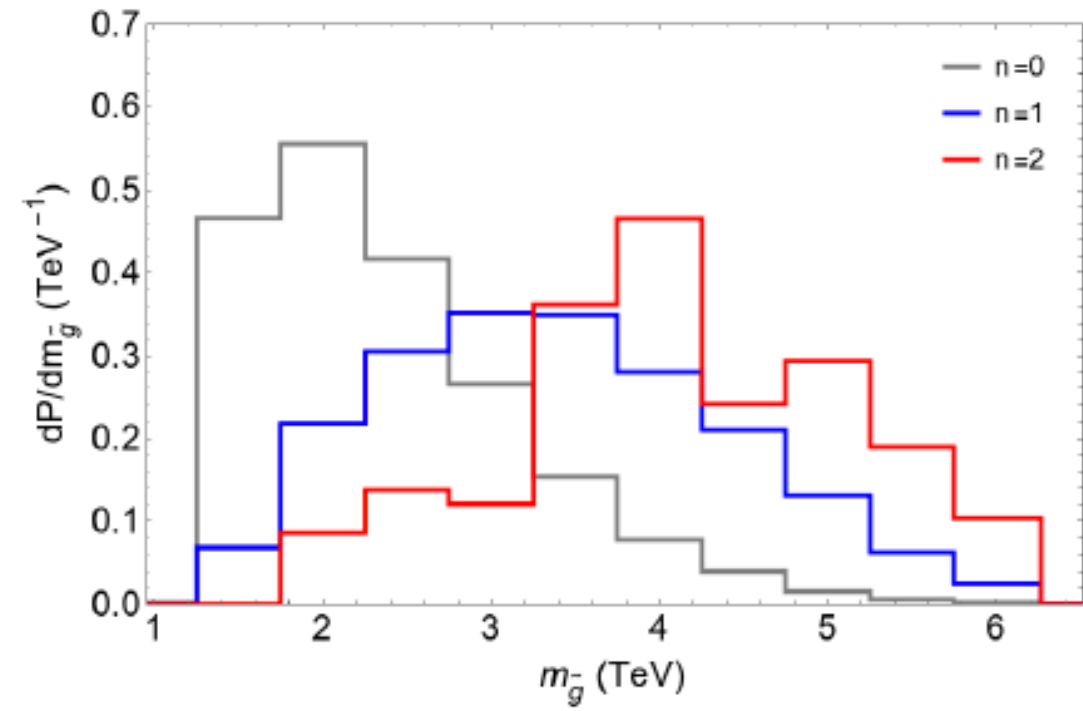
$\mu=150 \text{ GeV (fixed)}$

Making the picture more quantitative:

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



$m(h) \sim 125$ most favored for $n=1,2$



HB, Barger, Serce, Sinha

From our $n = 1, 2$ results which favor a value $m_h \sim 125$ GeV, then we also expect

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

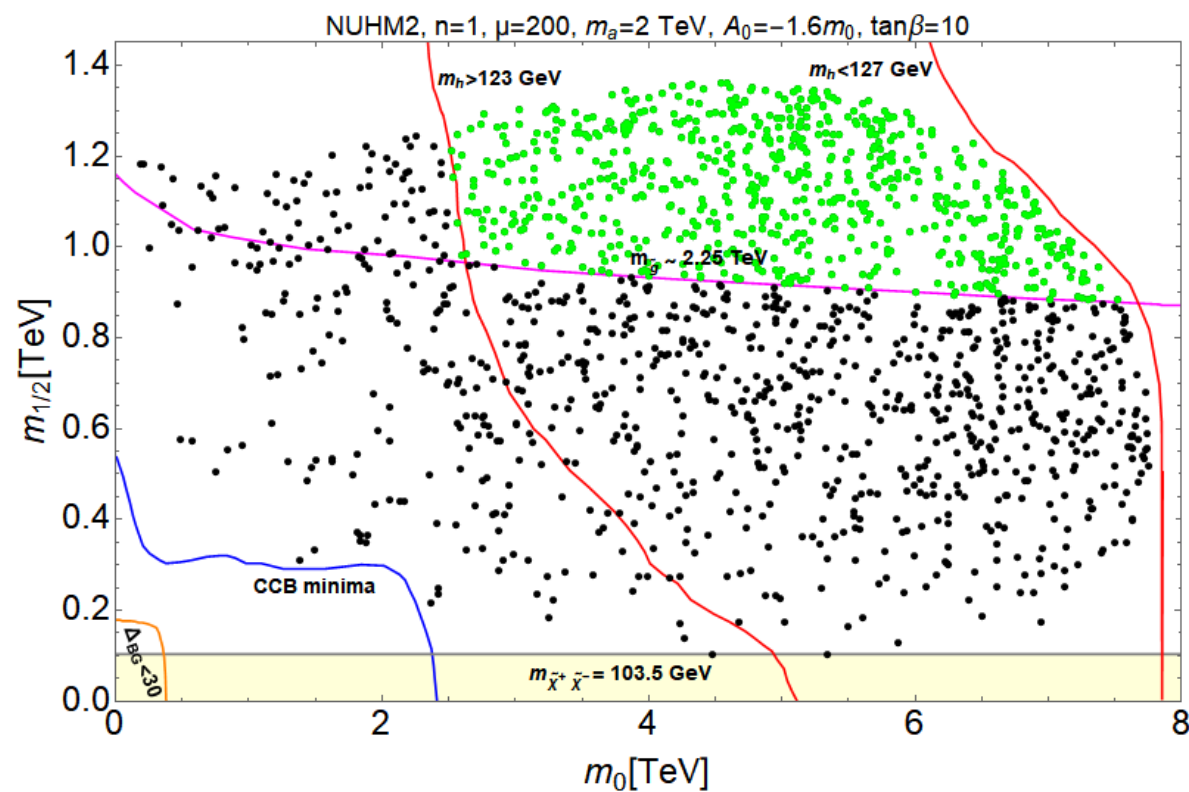
From stringy naturalness, expect LHC to see Higgs with $m(h) \sim 125$ GeV but as yet no sign of sparticles!

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

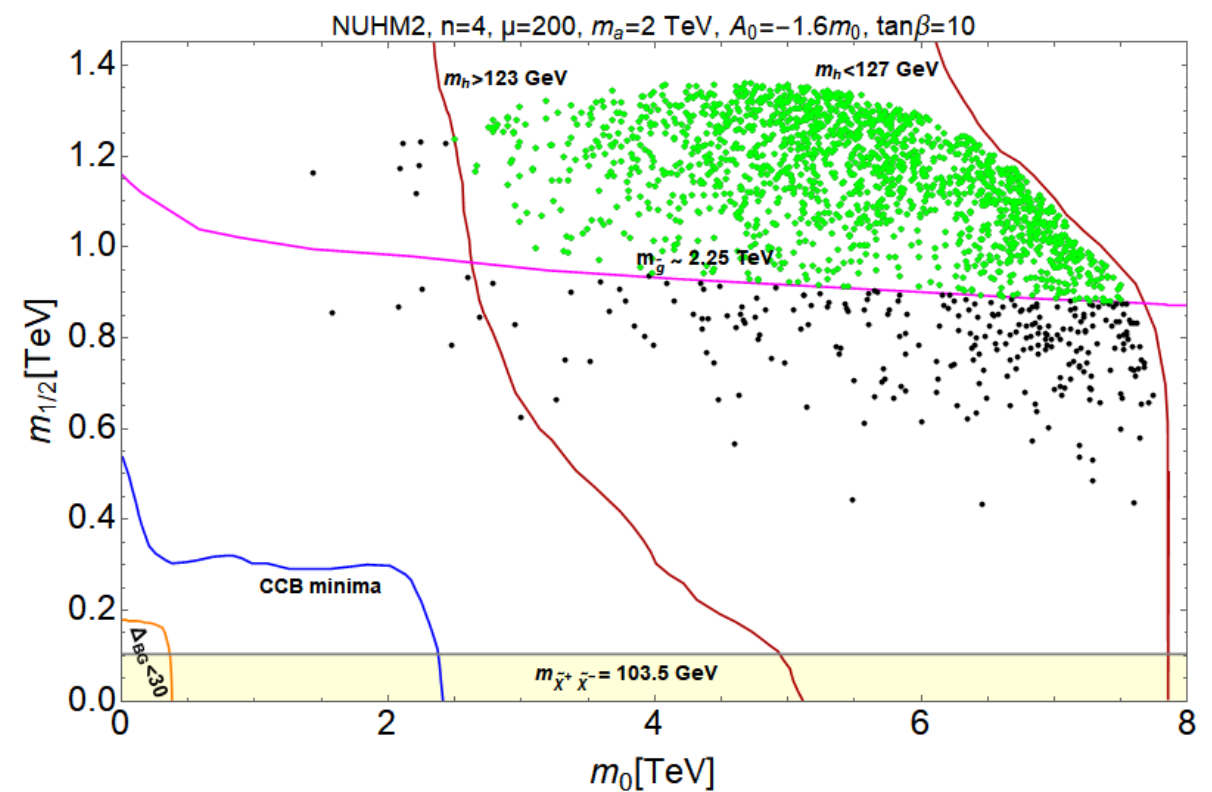
conventional natural: favor low m_0 , m_h

stringy naturalness: favor high m_0 , m_h so long as $m(\text{weak}) \sim 100$ GeV

HB, Barger, Salam, arXiv:1906.07741



$m(\text{soft})^1$



$m(\text{soft})^4$

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

Final note on scalar non-degeneracy and SUSY flavor/CP problem

Analysis of soft terms in flux compactifications =>
various soft terms—ino masses, A-terms, scalar masses
should scan independently on landscape due to
different functional dependence of soft terms on
compactified manifold

HB, Barger, Salam, Sengupta
arXiv:2005.13577

This is **good** in that for radiatively driven naturalness,
A-terms, ino masses, various scalars are as large as
possible subject to appropriate EWSB and not-too-large
derived value of $m(\text{weak}) \sim m(W, Z, h) \sim 100\text{--}350$ GeV

On other hand, much work has been done to avoid
SUSY FCNC and CP violating processes that arise
from non-degenerate scalars and soft term phases

In spite of expected non-degeneracy and phases,
landscape offers its own solution to SUSY flavor/CP problems in that
first/second gen scalars lifted to 20–40 TeV regime with quasi-degeneracy;
upper bound arises from generation independent 2-loop RGEs
that pull first/second generation scalars to common upper bound and
third generation (save highly mixed t_1) to ~ 5 TeV level

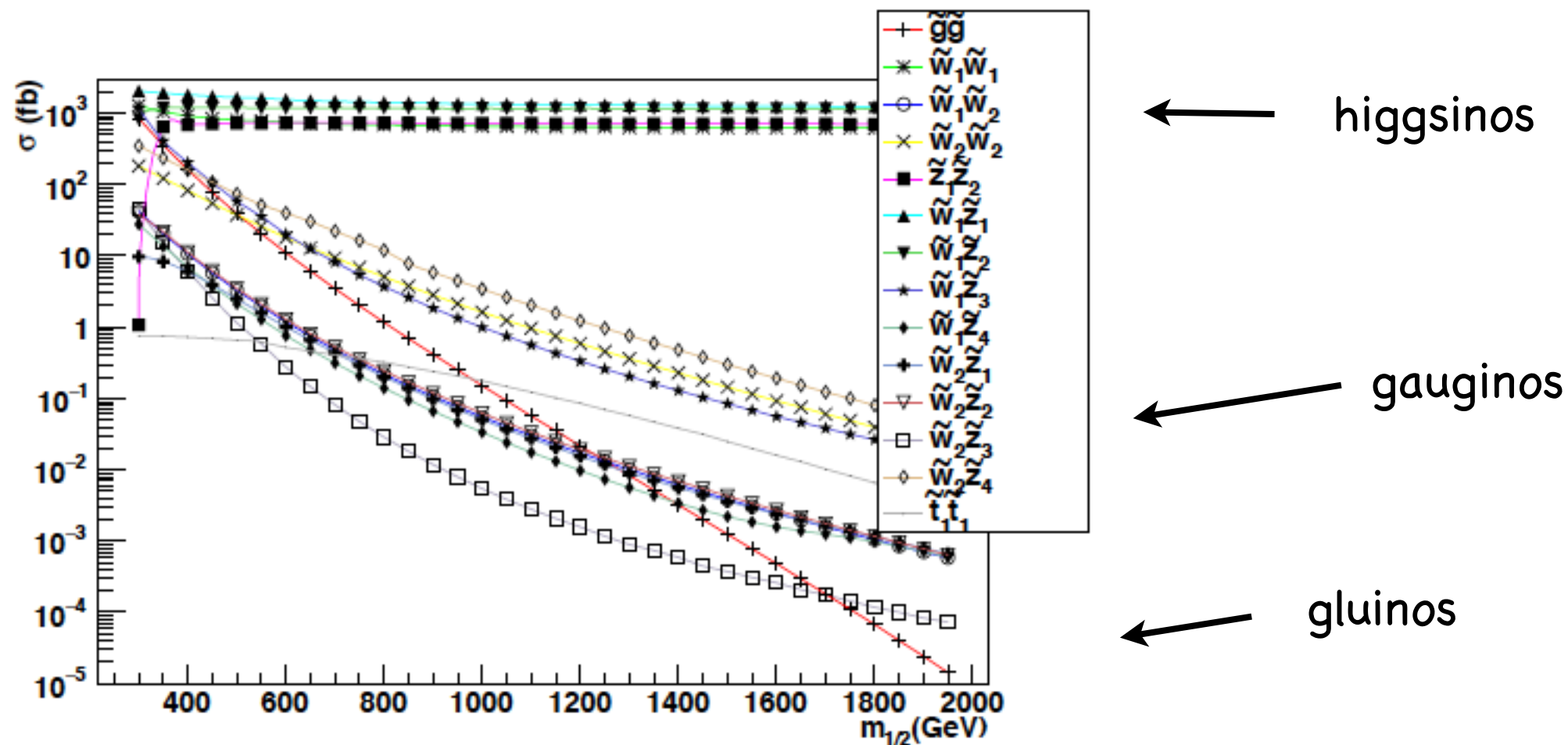
Conclusions:

- Time to set aside old notions of naturalness: BG and HS
- Plenty of natural parameter space under model independent DEW
- $\mu \sim 100\text{--}350$ GeV: light higgsinos
- other sparticle contributions to $m(\text{weak})$ are loop suppressed– masses can be TeV \rightarrow multi-TeV
- stringy naturalness: what the string landscape prefers
- draw to large soft terms provided $m(\text{weak}) \sim (2\text{--}5) \times 100$ GeV
- predicts LHC sees $m_h \sim 125$ GeV but as yet no sign of sparticles
- under stringy naturalness, a 3 TeV gluino more natural than 300 GeV gluino
- landscape \rightarrow non-universal scalars but also quasi-degeneracy/decoupling sol'n to SUSY flavor and CP problems

Prospects for discovering SUSY

with radiatively-driven naturalness
at LHC and ILC

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

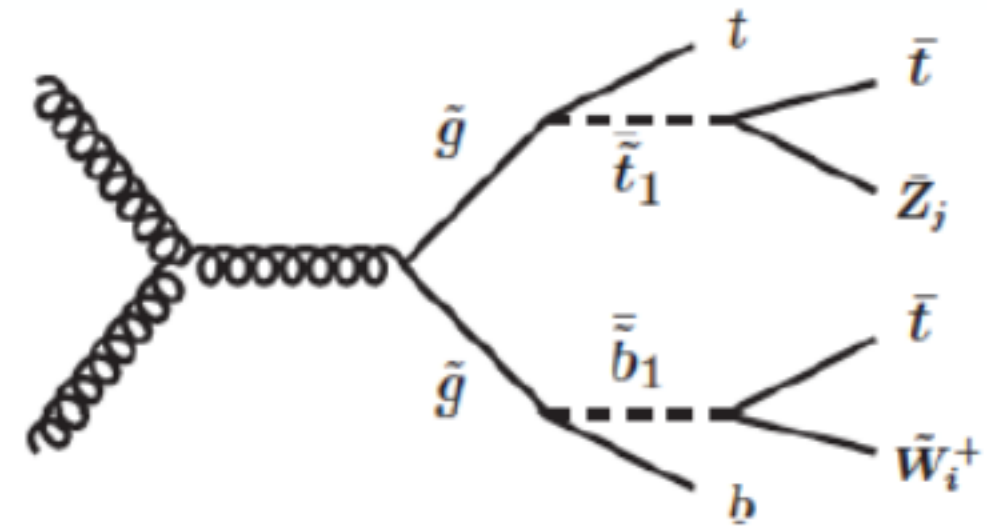


higgsino pair production dominant—but only soft visible energy release from higgsino decays

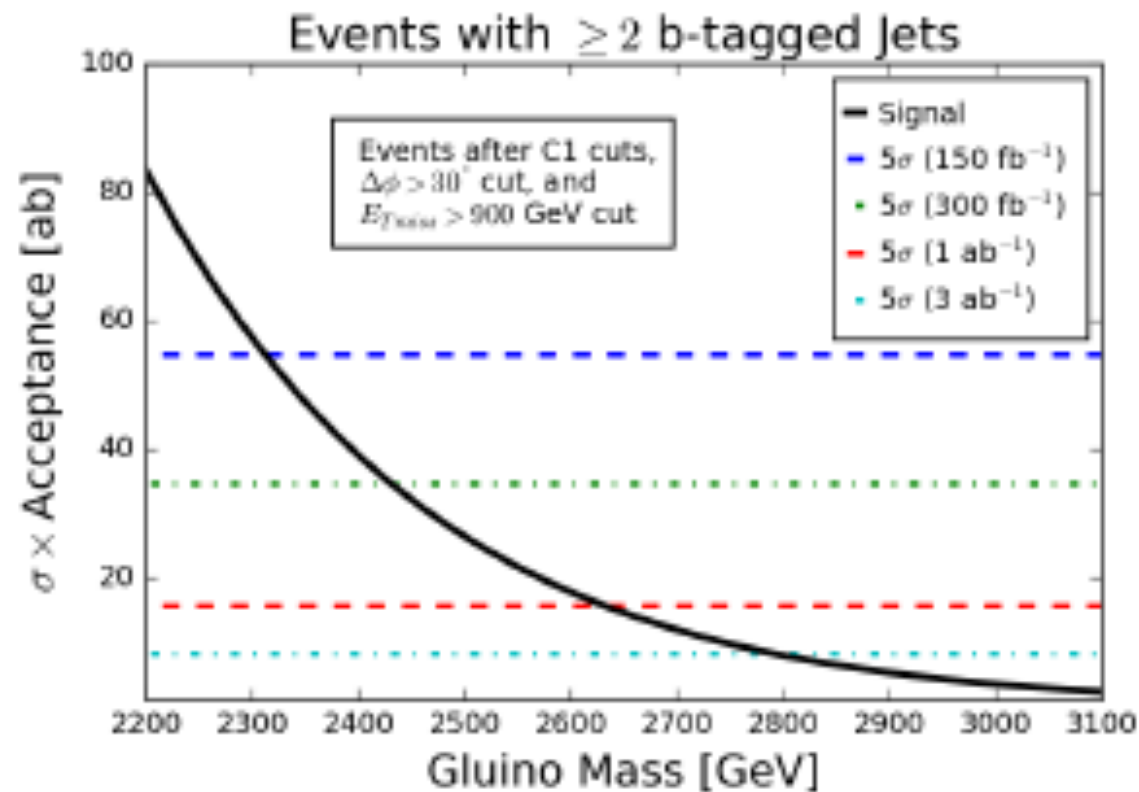
largest visible cross section: **wino pairs**

gluino pairs sharply dropping

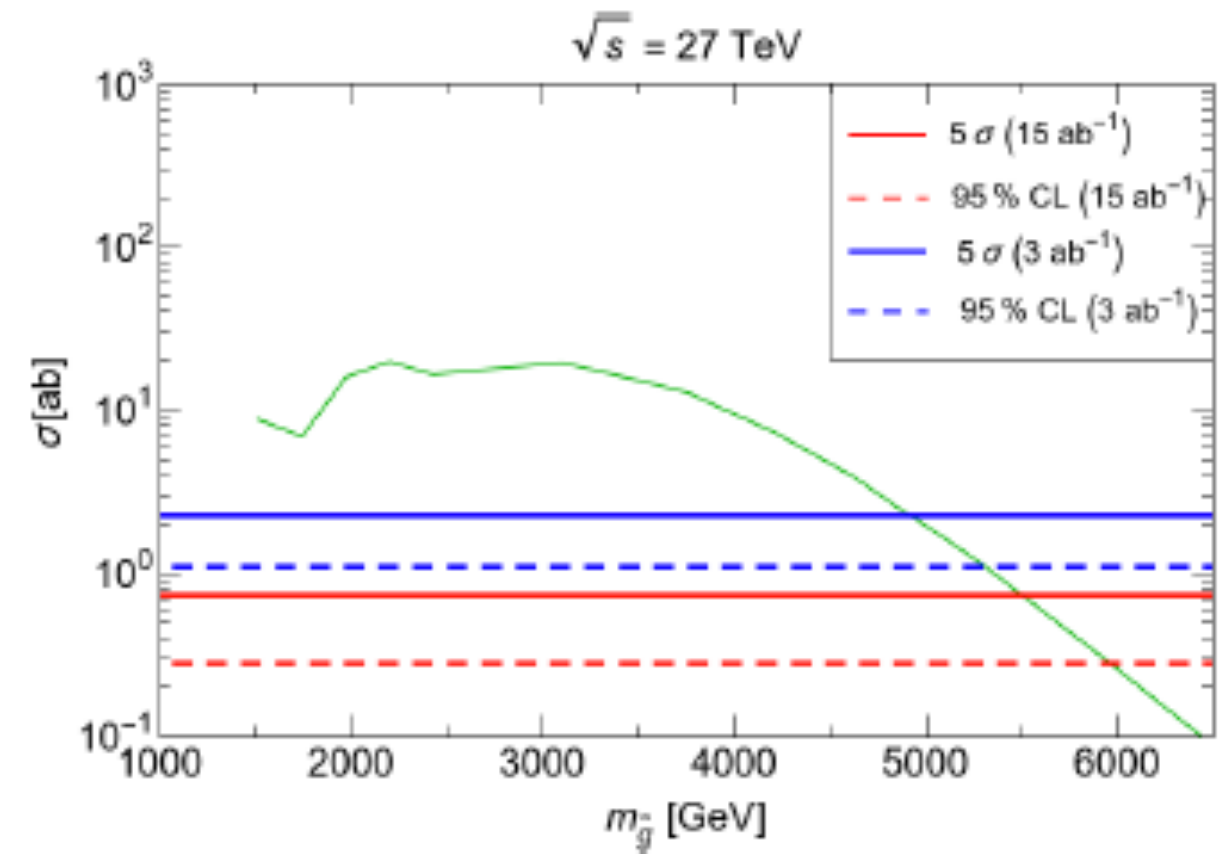
gluino pair cascade decay signatures



LHC14



LHC27

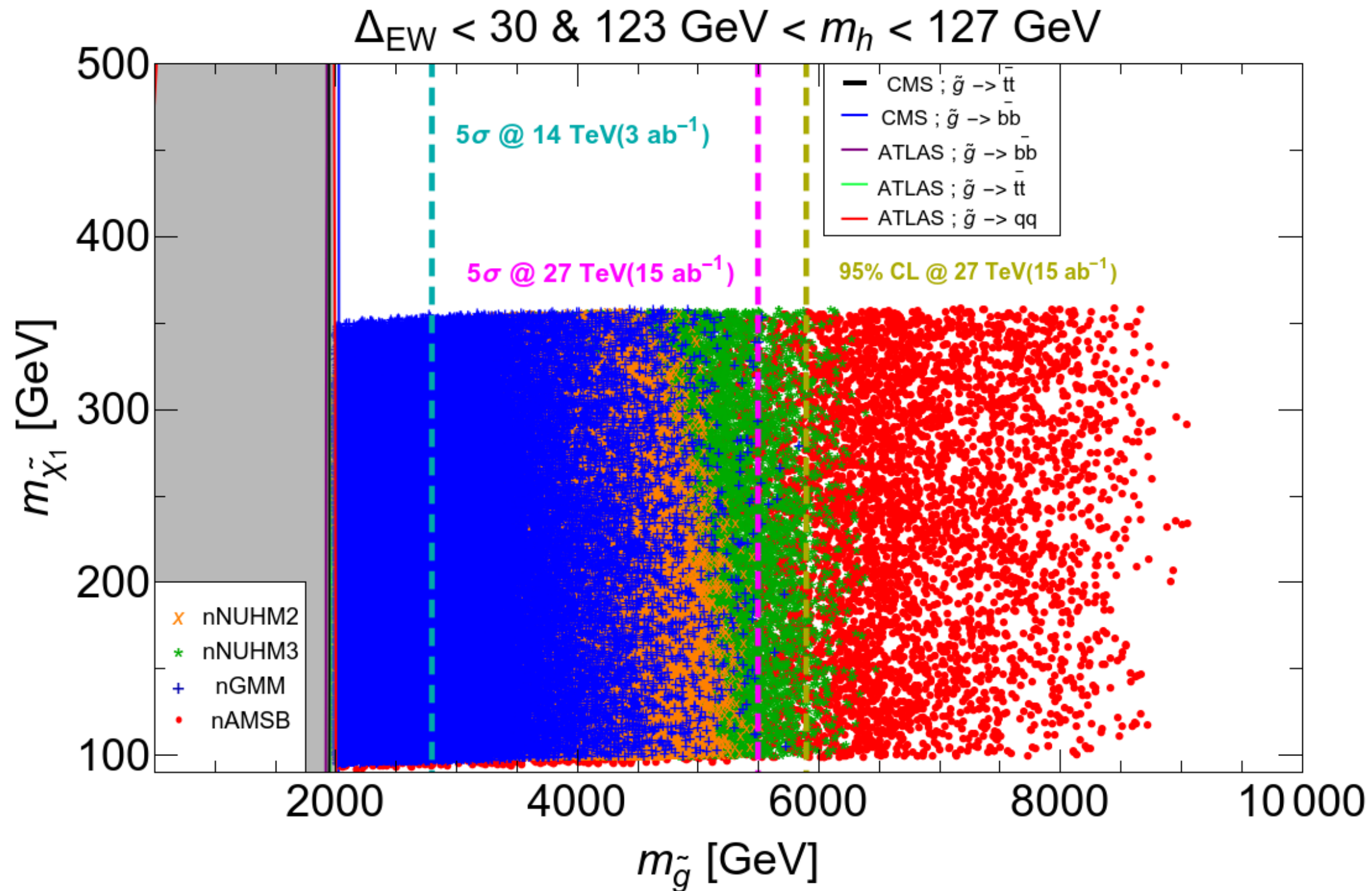


HB, Barger, Gainer, Huang, Savoy, Sengupta, Tata

HL-LHC to probe $m(\text{gl}) \sim 2.8 \text{ TeV}$
 HE-LHC to probe $m(\text{gl}) \sim 5.5\text{--}6 \text{ TeV}$

RNS in simplified model parameter space

Compare upper bounds on $m(\tilde{g})$ from naturalness ($\Delta_{EW} < 30$)
to HL/HE-LHC reach

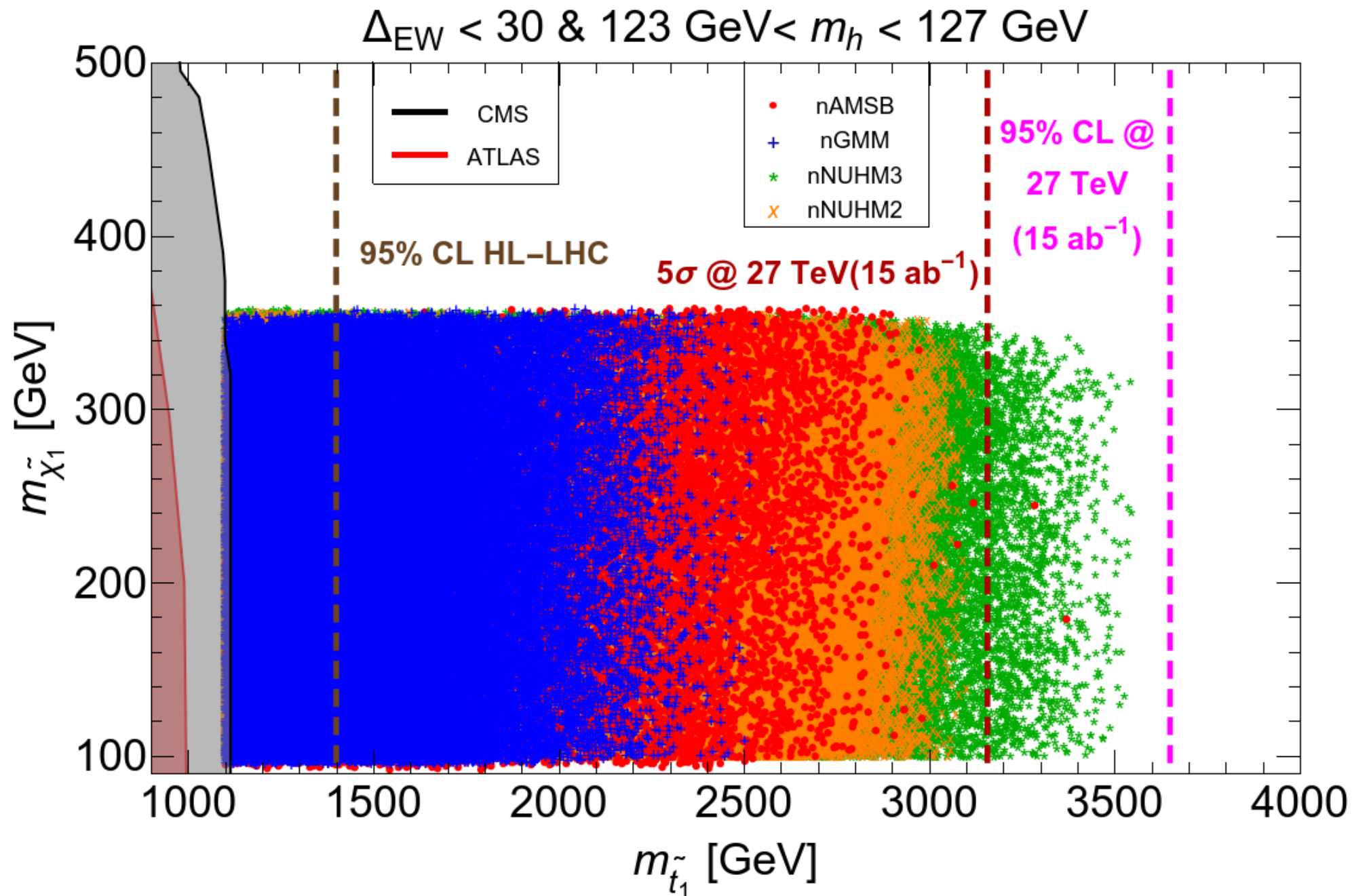


HB, Barger, Gainer, Sengupta, Serce, Tata

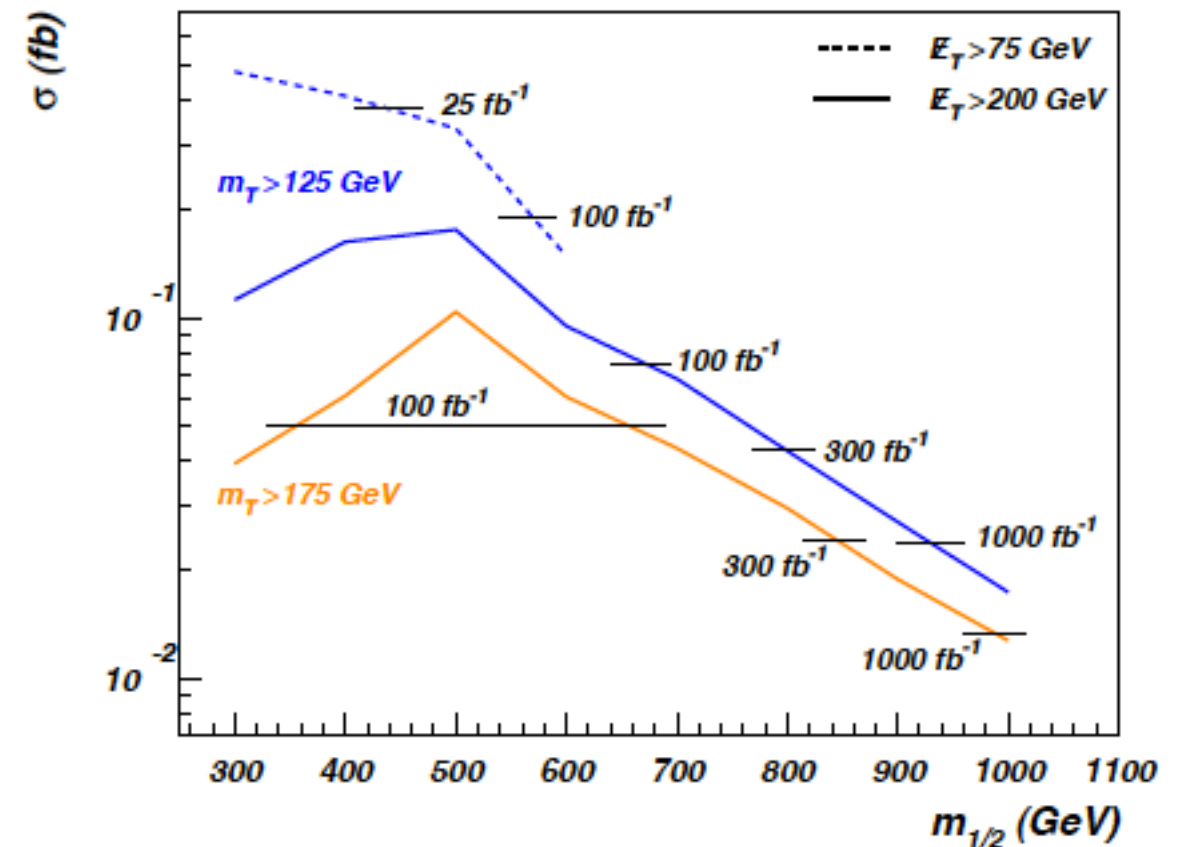
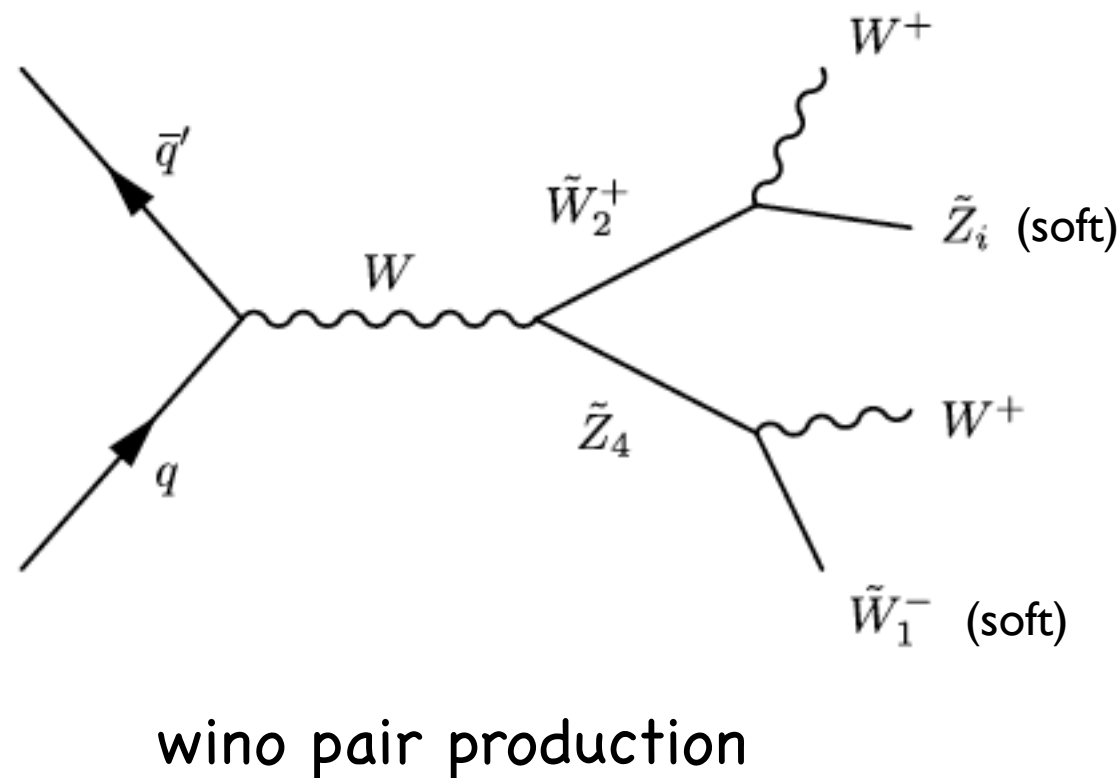
Will need LHC energy upgrade to 27 TeV to cover all natural SUSY p-space (except nAMSB)

Top squark searches:

HE-LHC can see entire natural p-space:
discover or falsify natural SUSY!

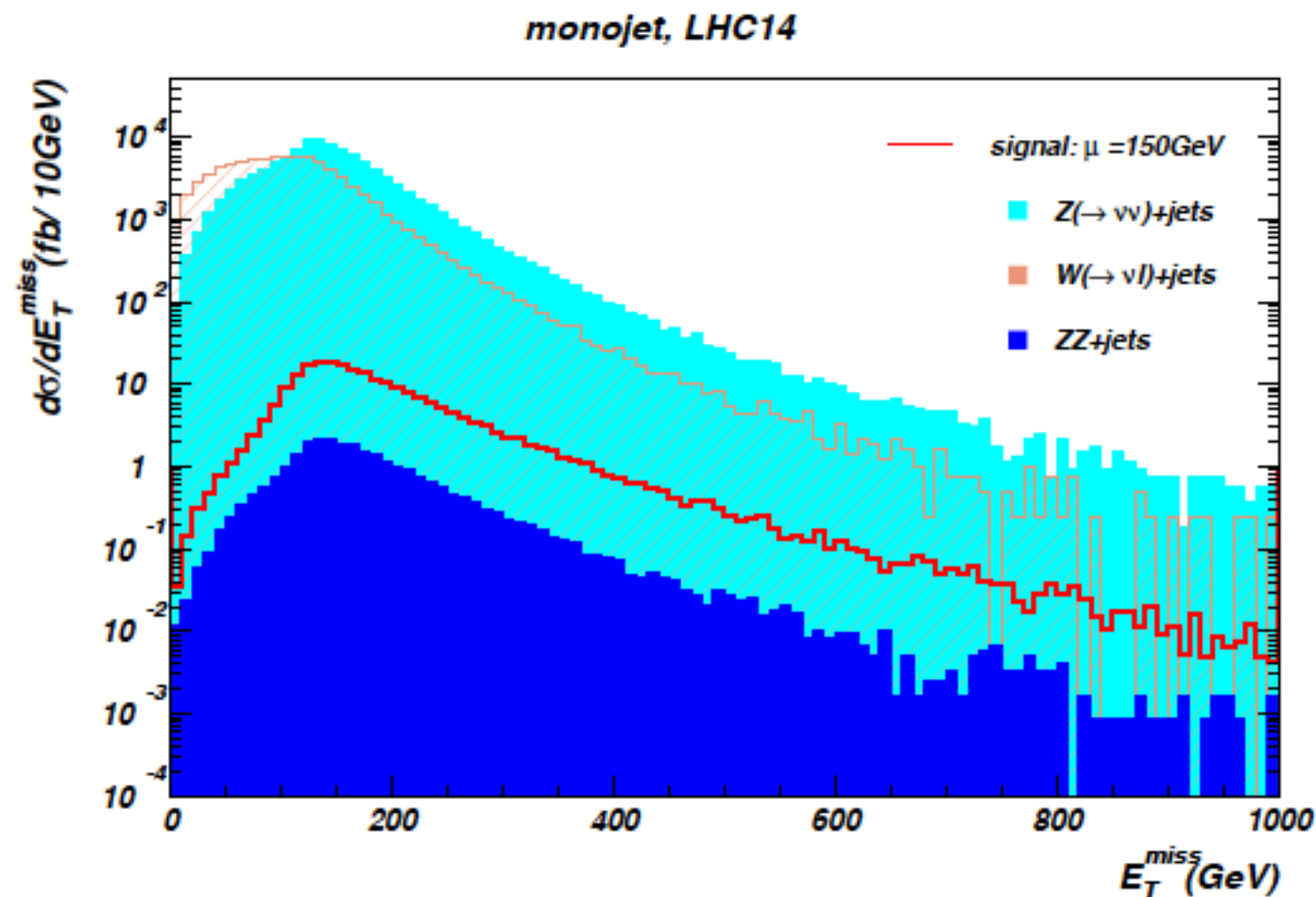


Distinctive new same-sign diboson (SSdB) signature from SUSY models with light higgsinos!



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

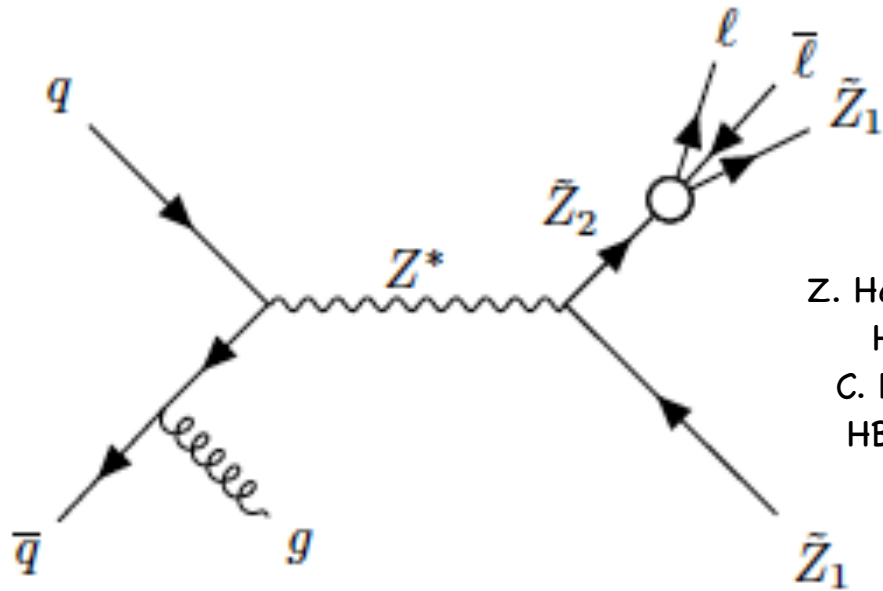
See direct higgsino pair production recoiling from ISR (monojet signal)?



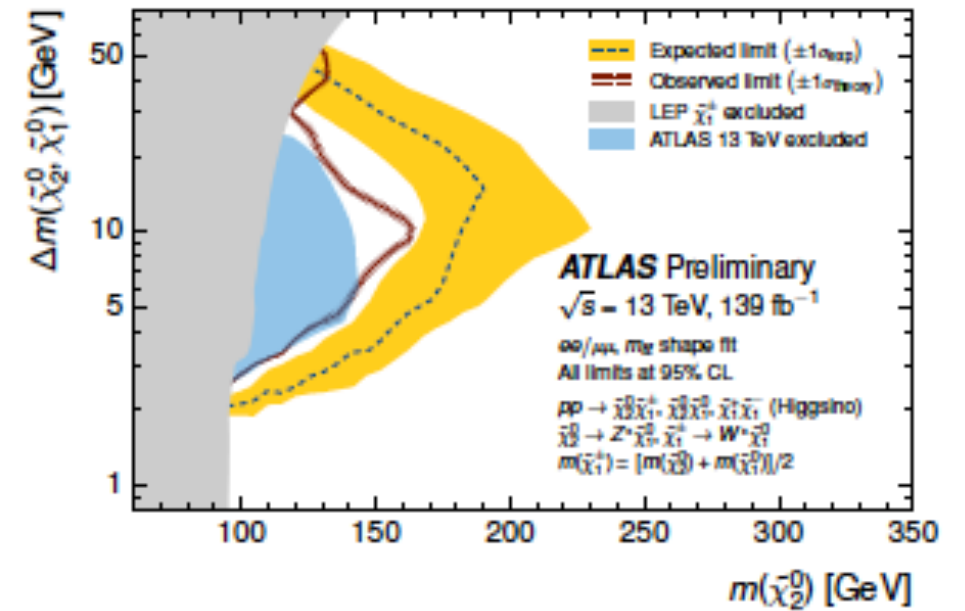
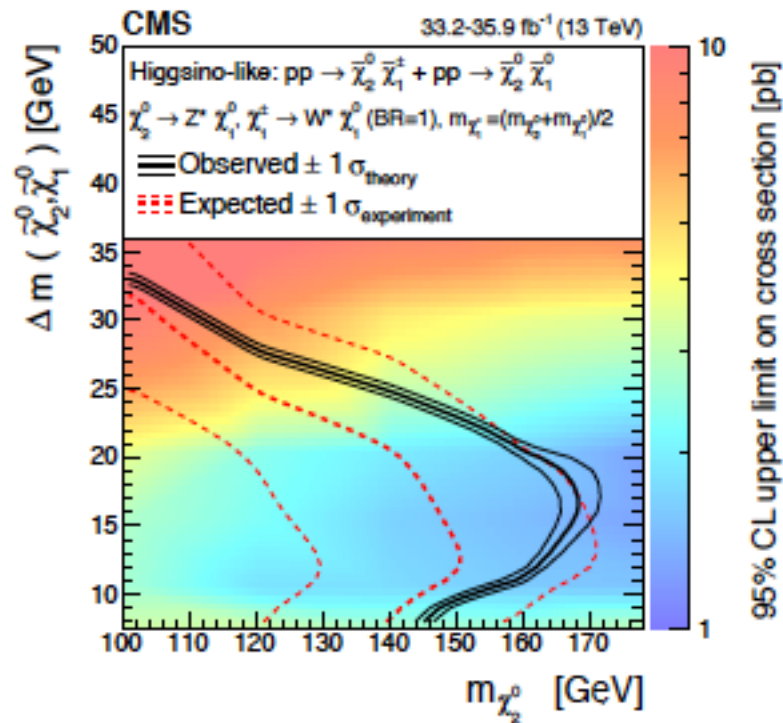
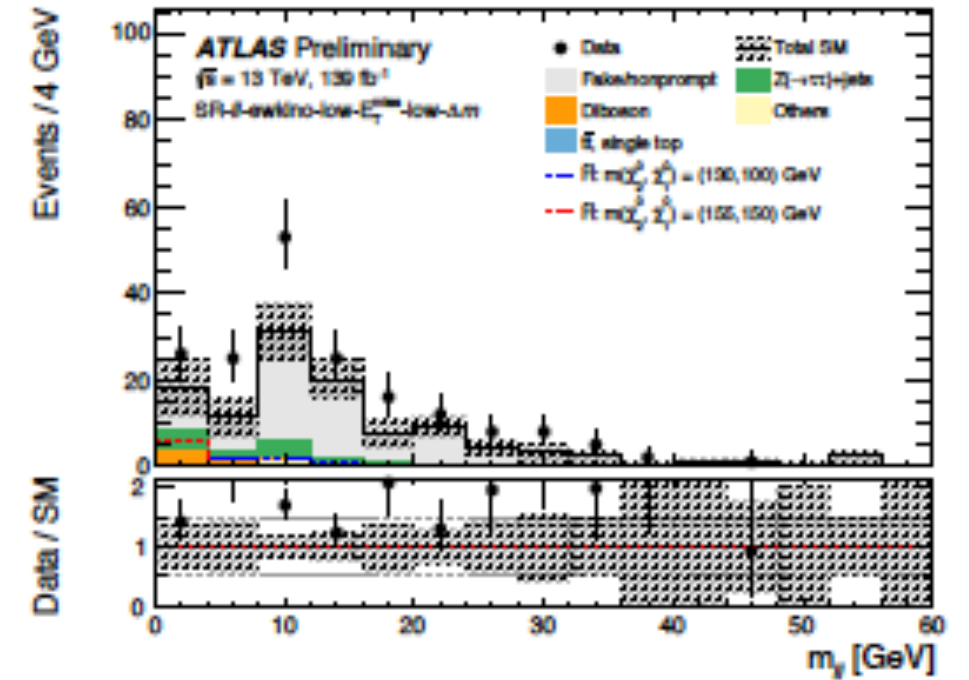
typically 1% S/BG after cuts:
very tough to do!

Natural SUSY: only higgsinos need lie close to weak scale

Soft dilepton+jet+MET signature from higgsino pair production



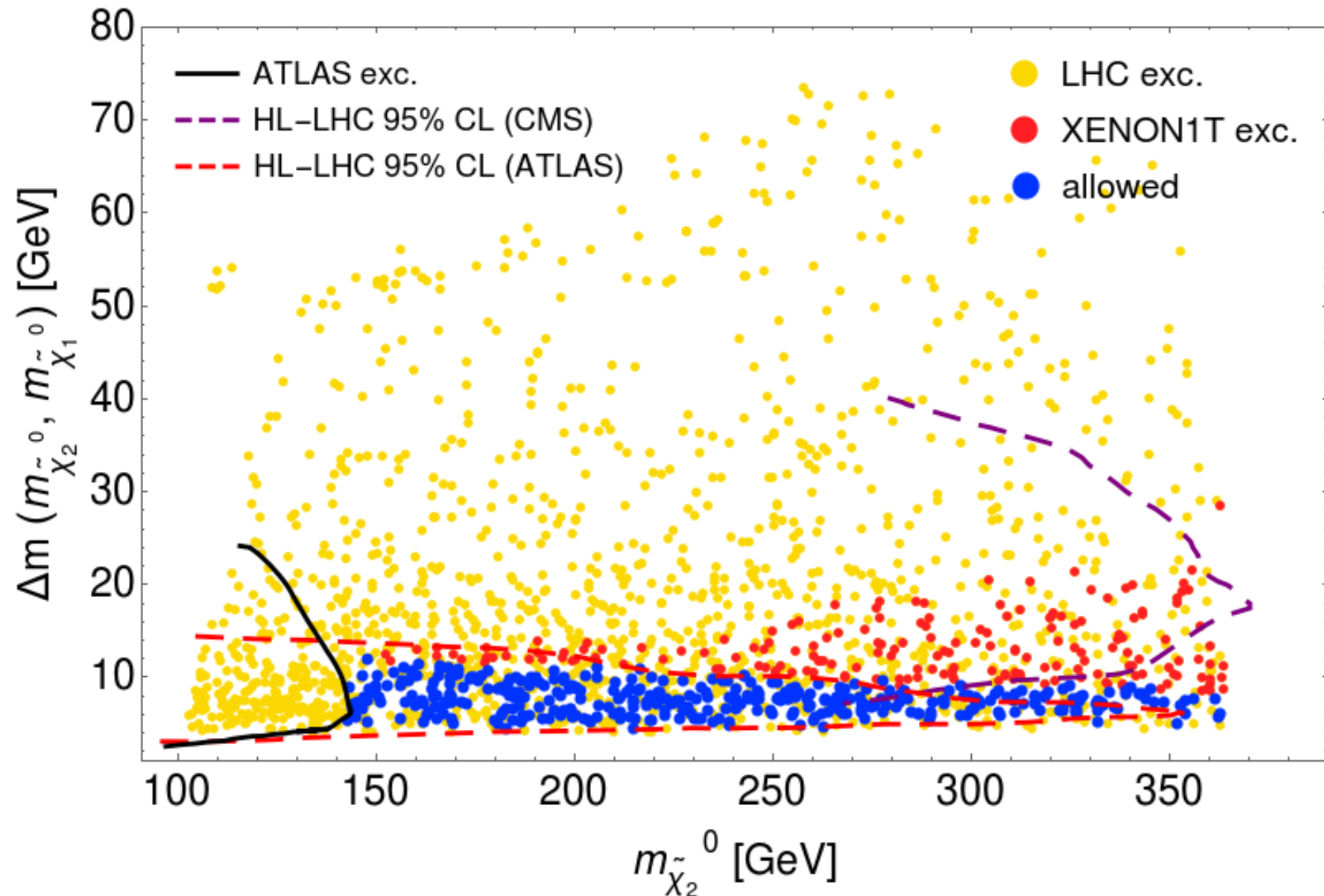
HB, Barger, Huang, 1107.5581;
Z. Han, Kribs, Martin, Menon, 1401.1235;
HB, Mustafayev, Tata; 1409.7058;
C. Han, Kim, Munir, Park, 1502.03734;
HB, Barger, Savoy, Tata, 1604.07438



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

Only higgsinos required to lie near weak scale

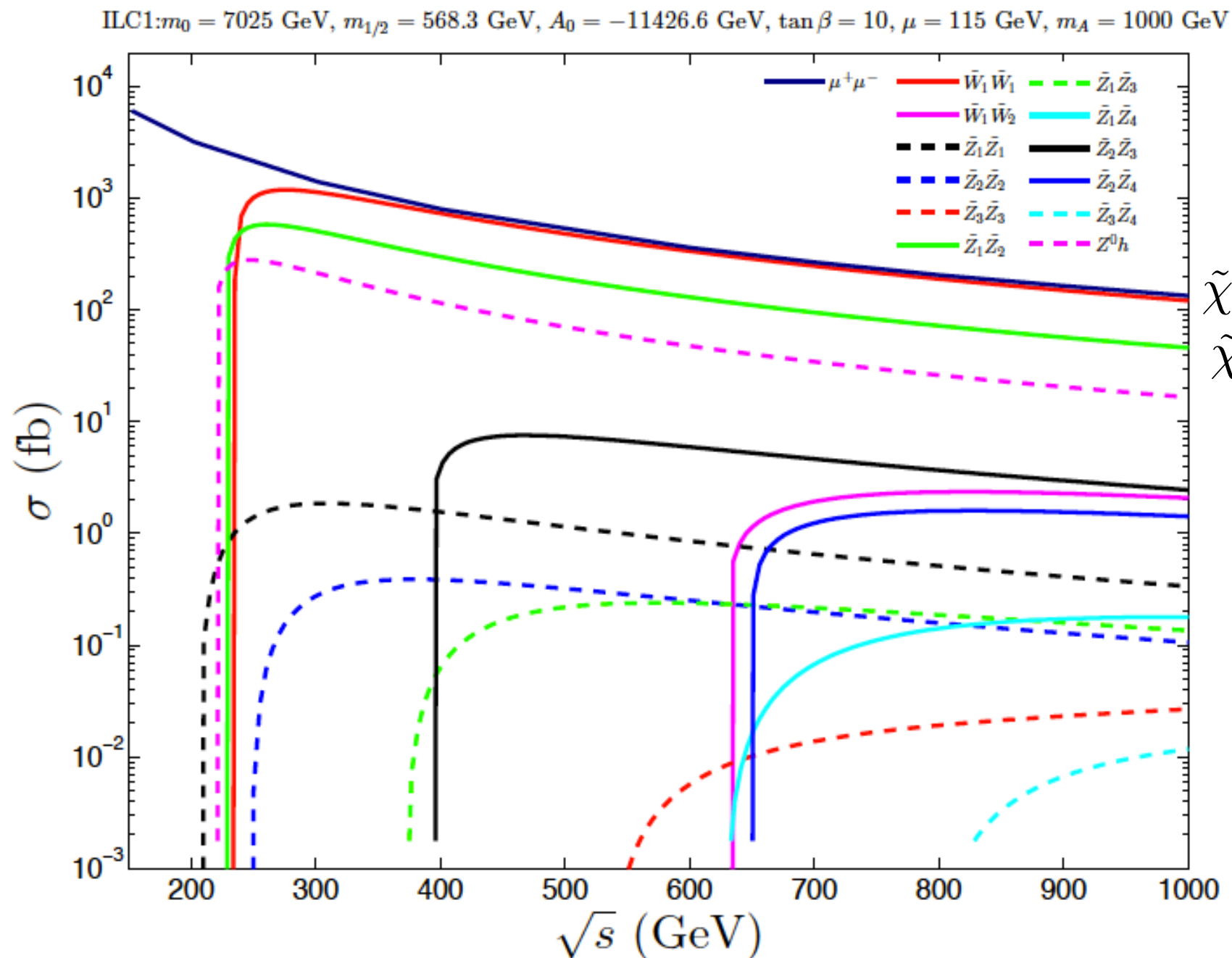
blue points are stringy natural



Signal in soft-dilepton+jet+MET channel should gradually emerge at LHC14 as more and more integrated luminosity accrues!

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



$$\sigma(\text{higgsino}) \gg \sigma(Zh)$$

$$\begin{array}{l} \tilde{\chi}_1^+ \tilde{\chi}_1^- \\ \tilde{\chi}_1^0 \tilde{\chi}_2^0 \end{array}$$

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

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404.7510

This slide is dedicated to Prof. Uriel Nauenberg, my host during my honeymoon, 1994

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

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

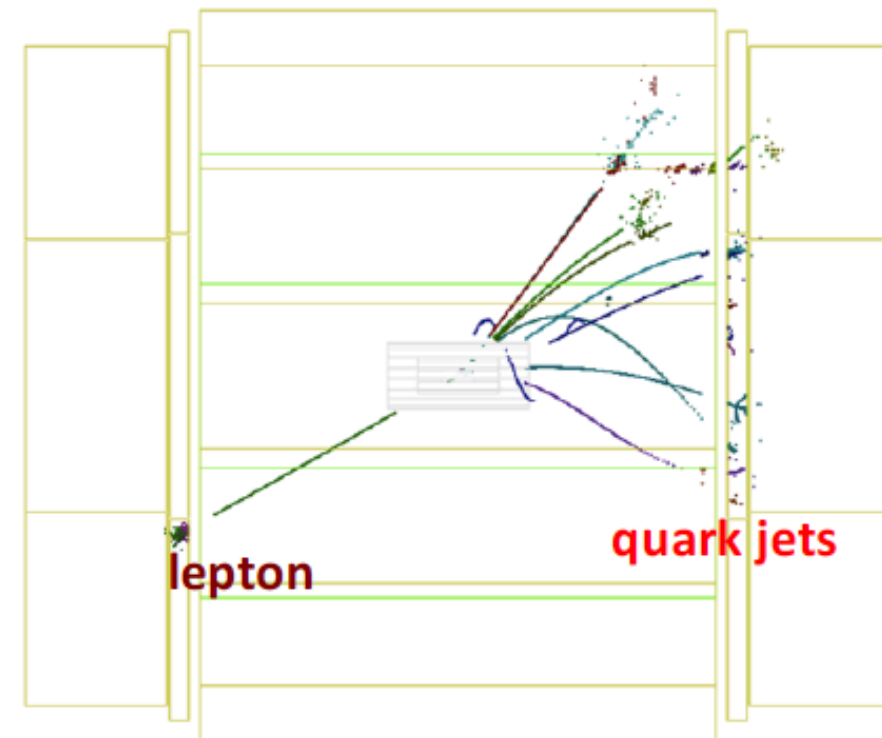
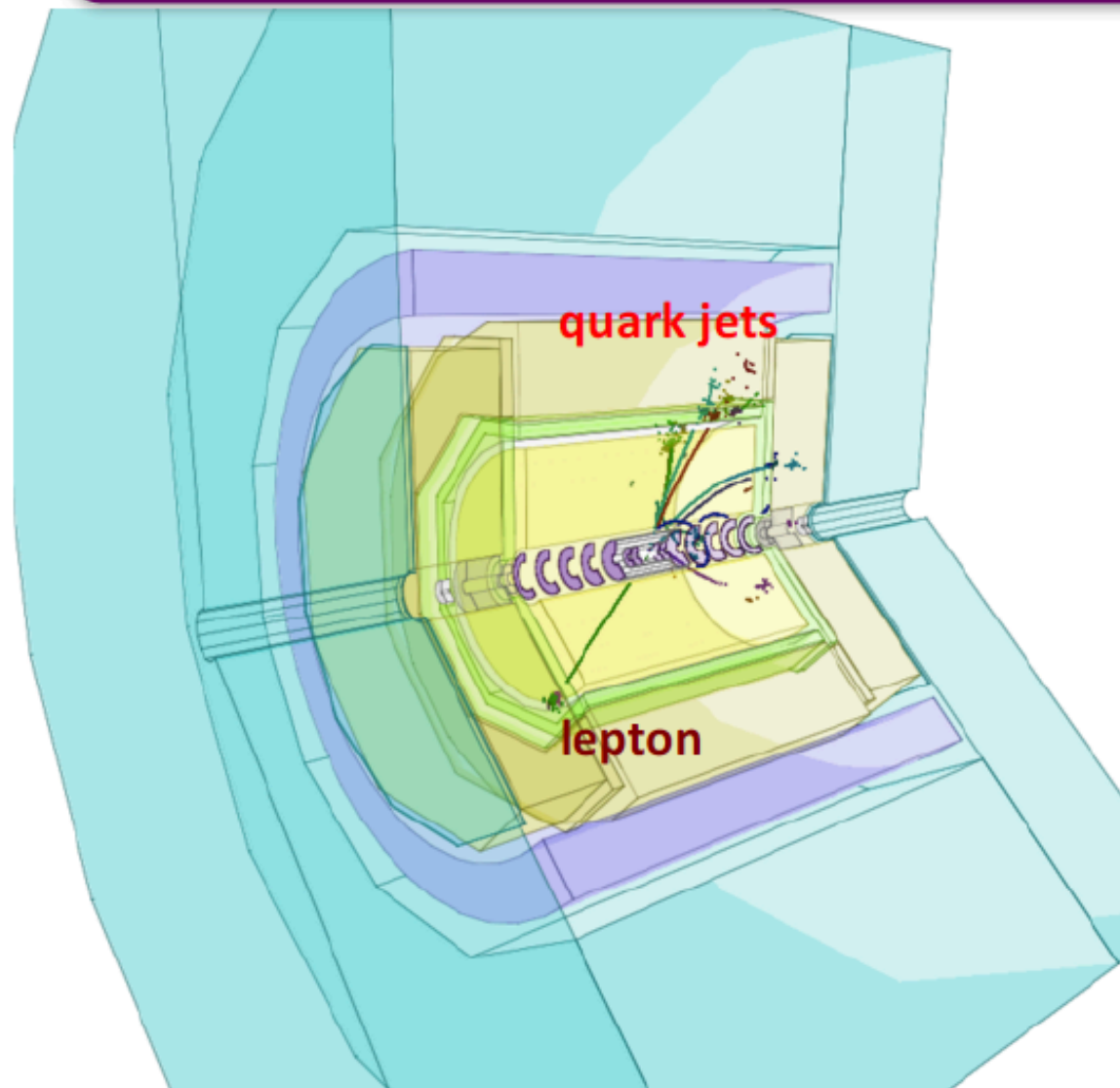
soft visible particles since small higgsino mass gaps

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

$\sqrt{s} = 500 \text{ GeV}$

Chargino pair production with semileptonic decay

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



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

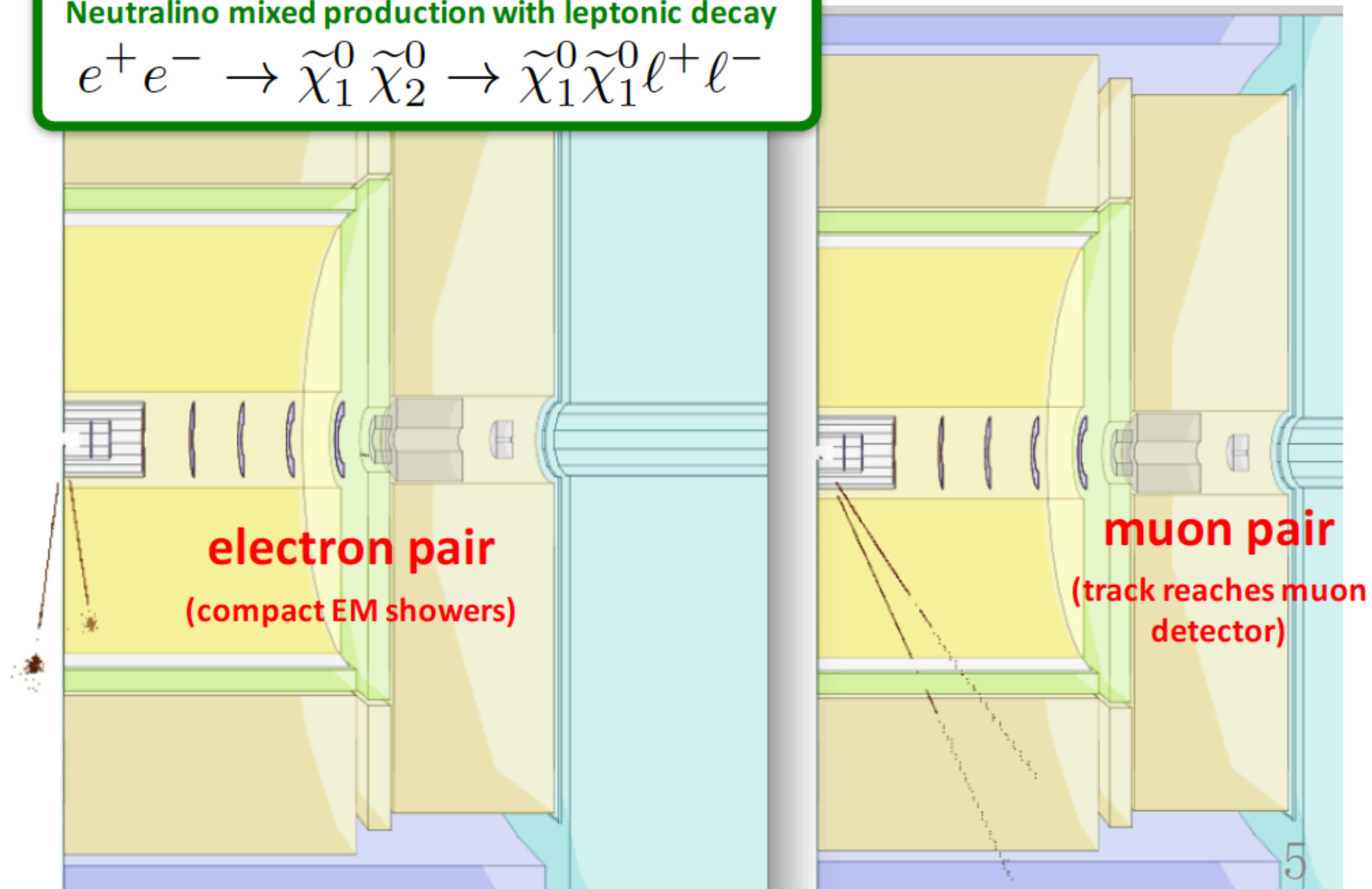
measure $m(\ell^+ \ell^-) < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ and $E(\ell^+ \ell^-)$

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

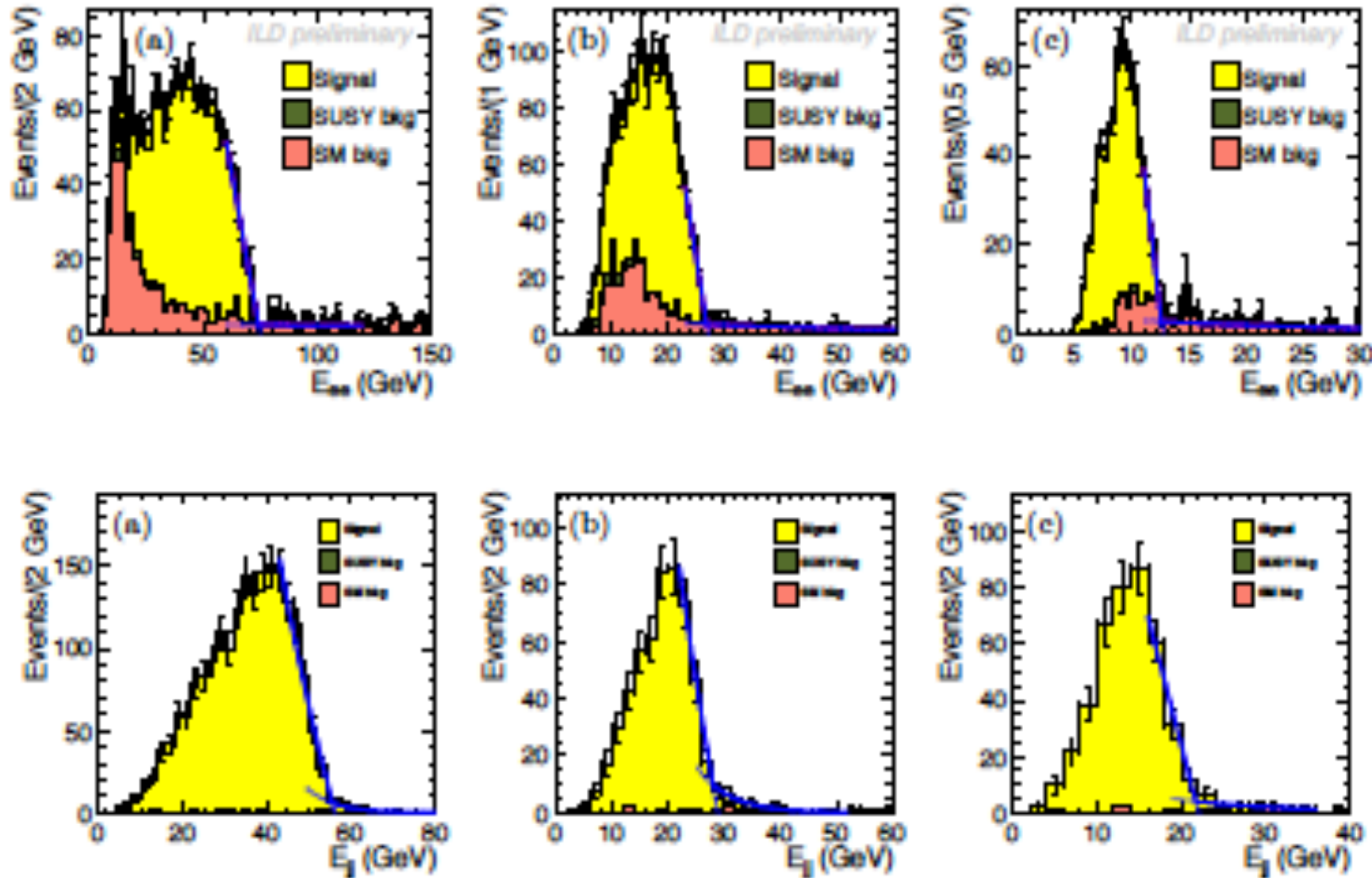
$\sqrt{s} = 500$ GeV

Neutralino mixed production with leptonic decay

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



Precise measurements of lepton/jet energy and mass edges
allow for $\sim 1\%$ level extraction of higgsino masses!



ILC1	model mass [GeV]	precision	H20	precision
$m_{\tilde{\chi}_1^0}$	104.8	0.8%	0.5%	
$m_{\tilde{\chi}_2^0}$	127.5	0.8%	0.4%	
$m_{\tilde{\chi}_1^\pm}$	116.0	0.8%	0.5%	
ILC2	model mass [GeV]	precision	I20	precision
$m_{\tilde{\chi}_1^0}$	151.3	1.3%	0.7%	
$m_{\tilde{\chi}_2^0}$	162.4	1.3%	0.7%	
$m_{\tilde{\chi}_1^\pm}$	157.0	1.3%	0.7%	
nGMM1	model mass [GeV]	precision	I20	precision
$m_{\tilde{\chi}_1^0}$	154.9	1.7%	1.0%	
$m_{\tilde{\chi}_2^0}$	160.2	1.7%	1.0%	
$m_{\tilde{\chi}_1^\pm}$	157.4	1.7%	1.0%	

The ILC as a natural SUSY discovery machine
and precision microscope:
from light higgsinos to tests of unification

Howard Baer¹, Mikael Berggren², Keisuke Fujii³, Jenny List², Suvi-Leena Lehtinen², Tomohiko Tanabe⁴,
Jacqueline Yan³

Higgsino mass splittings are sensitive to (inaccessible?)
bino and wino masses:

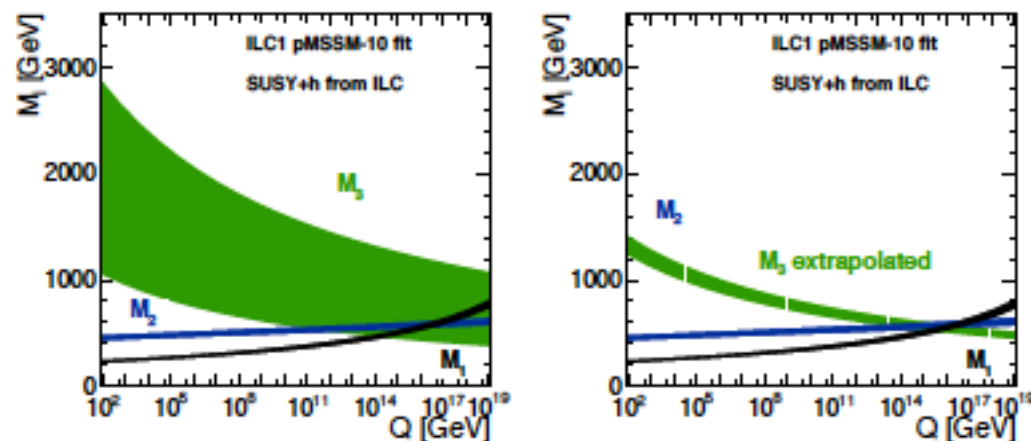
parameter	ILC1 pMSSM true	pMSSM-4 best fit point	1 σ CL	2 σ CL	pMSSM-10 best fit point	1 σ CL	2 σ CL
M_1	250	250.2	+8.2 -7.7	+17.1 -16.1	251.3	+8.8 -8.3	+17.2 -16.7
M_2	463	463.3	+8.0 -8.1	+16.2 -14.9	465.8	+8.2 -7.9	+16.4 -15.8
μ	115.0	115.0	+0.2 -0.2	+0.3 -0.3	115.7	+0.9 -0.7	+1.0 -0.9
$\tan\beta$	10.0	10.0	+0.1 -0.1	+0.2 -0.2	9.7	+0.1 -0.1	+0.2 -0.2
m_A	1000				1050	+310 -180	+807 -296
M_3	1270				1412	+1104 -1104	+2843 -2843
M_L	7150				7063	+2030 -4311	+4426 -5532
$M_{U(3)}$	1670				1751	+2314 -628	+4426 -740
$M_{Q(3)}$	4820				4951	+2324 -3226	+3888 -3226
$A_{t-b-\tau}$	-4400				-4591	+1371 -973	+1647 -2949
χ^2		0.0011			0.1360		

Table 23: Fitted parameters in ILC1 pMSSM-4 and pMSSM-10, after 10^6 Markov chain points. All units in GeV except for $\tan\beta$ and χ^2 .

extract M_1 and M_2 via
global fit to higgsino/higgs
observables

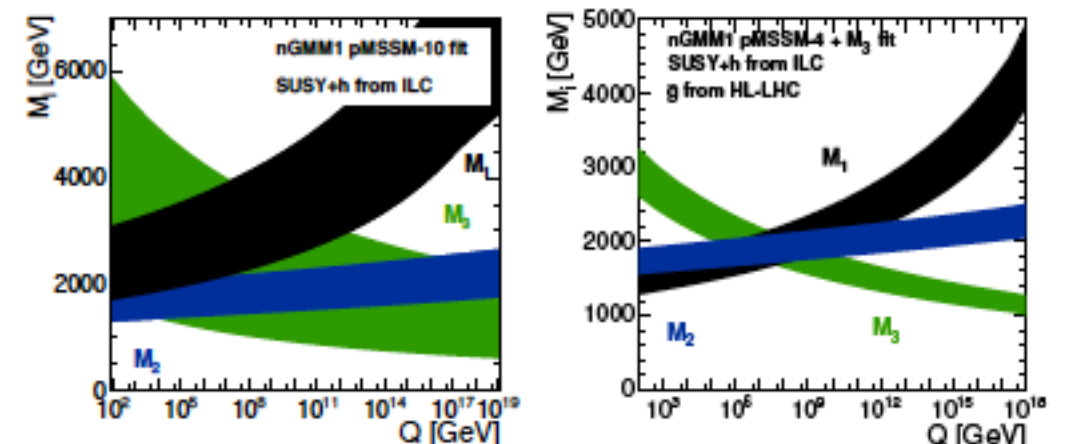
HB, Berggren, Fujii, List,
Lehtinen, Tanabe and Yan
(to appear shortly)

Test gaugino mass unification!



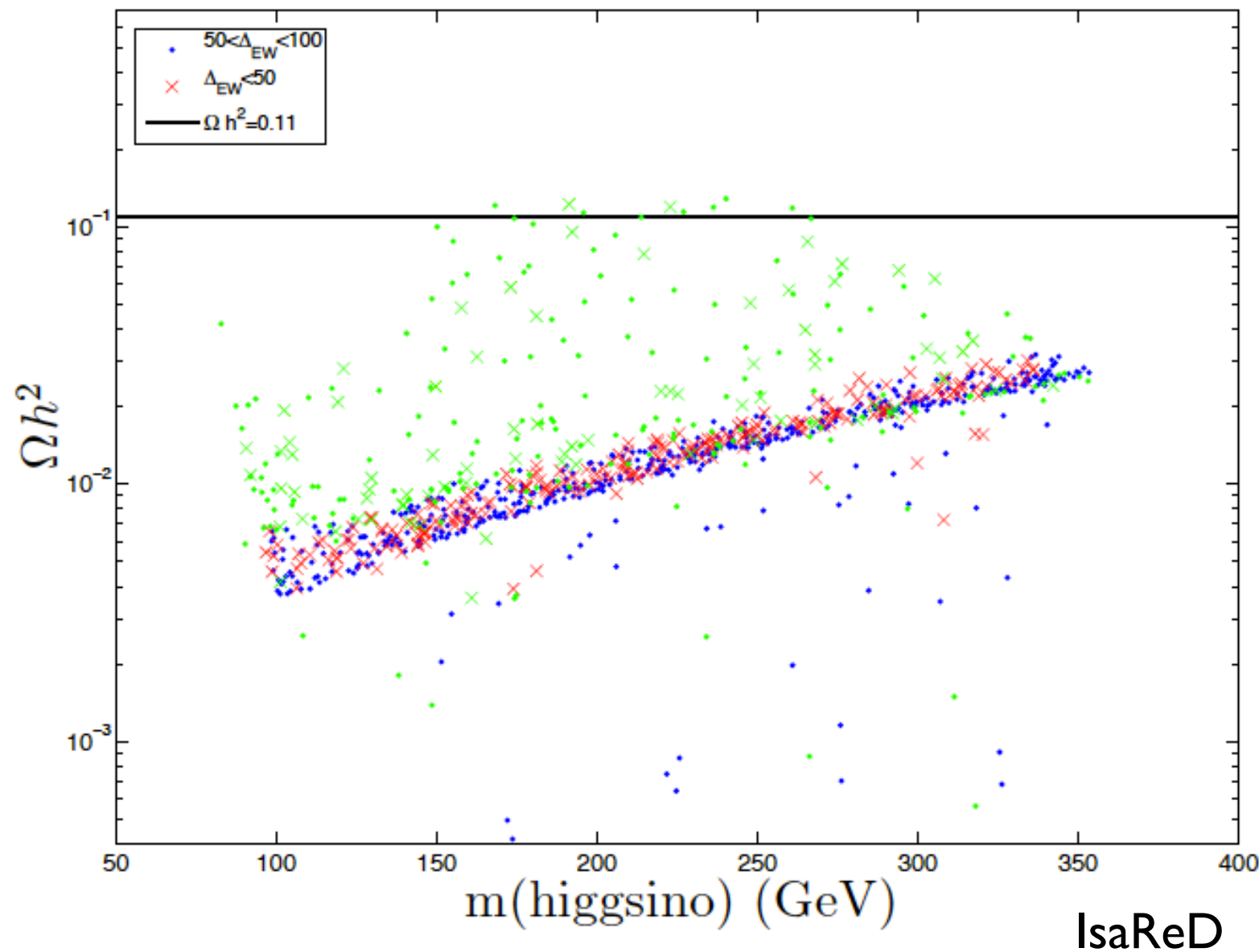
gaugino masses unify at mGUT
in NUHM2,3 models

natural mirage mediation benchmark point;
unify at intermediate mirage scale



Dark matter from SUSY
with radiatively-driven naturalness

Mainly higgsino-like WIMPs with $m(\text{WIMP}) \sim 100\text{--}300\text{ GeV}$
thermally underproduce DM



green: excluded;
red/blue: allowed

HB, Barger, Mickelson (2013)

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

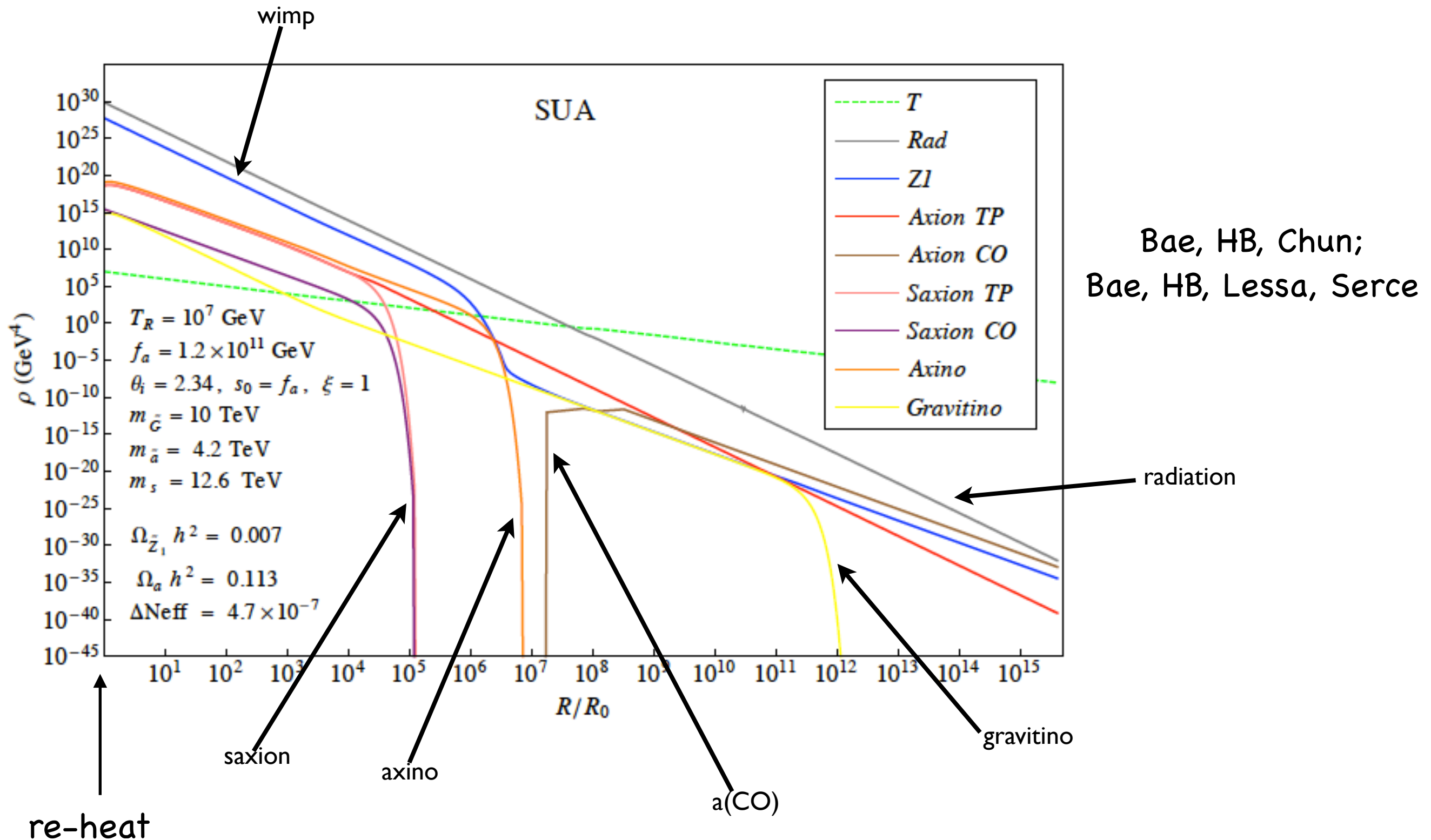
Changes DM calculus:

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 $s \rightarrow aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
 - $s \rightarrow gg$: entropy dilution
 - $s \rightarrow SUSY$: augment neutralinos
 - $s \rightarrow aa$: dark radiation ($\Delta N_{eff} < 1.6$)
- axinos: TP
 - $\tilde{a} \rightarrow SUSY$ augments neutralinos
- gravitinos: TP, decay to SUSY

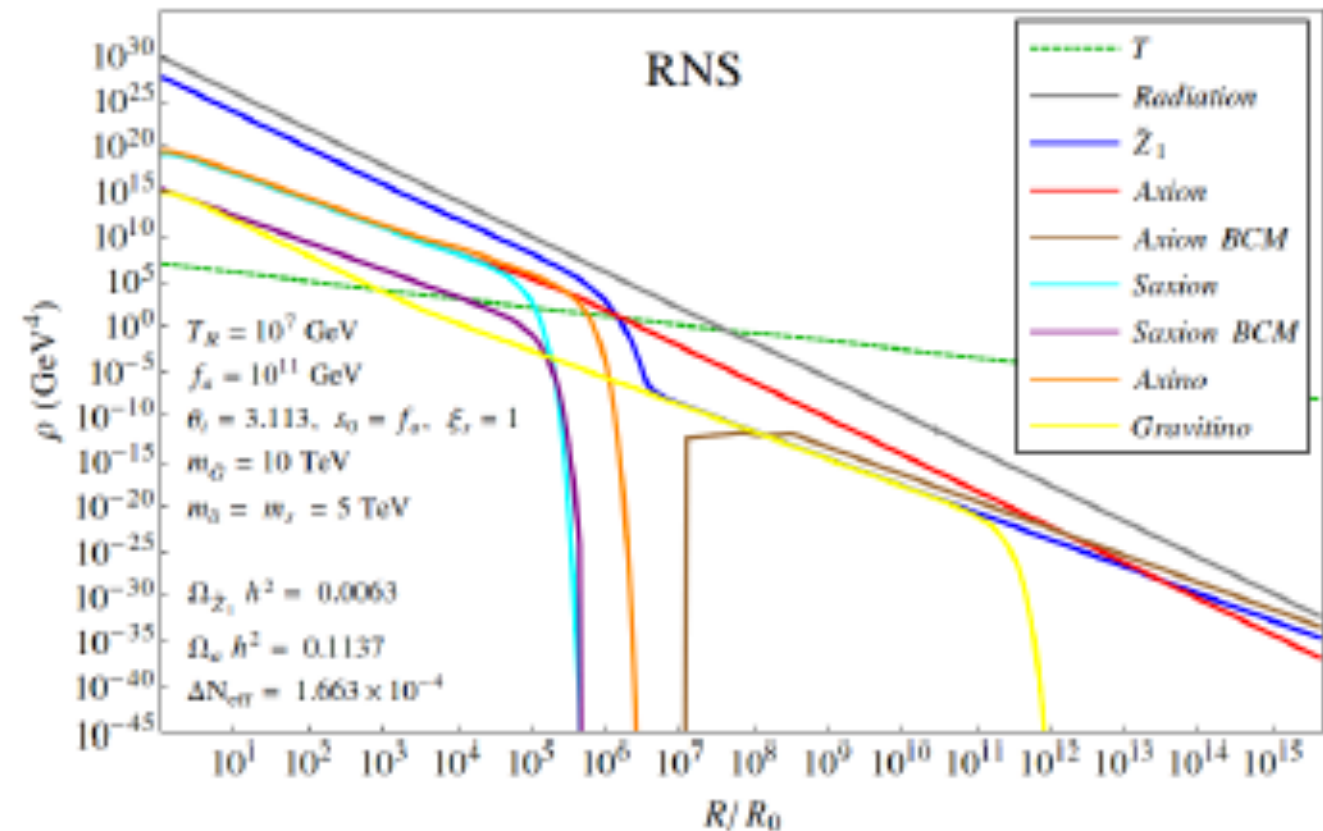
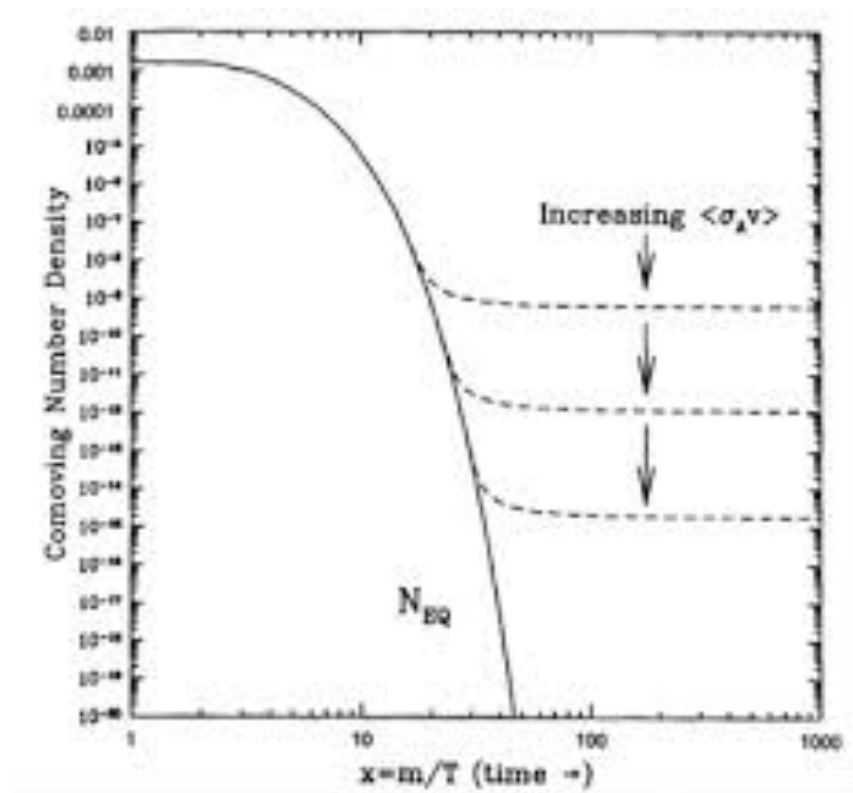
DM production in SUSY DFSZ: solve eight coupled Boltzmann equations



usual picture

=>

mixed axion/WIMP



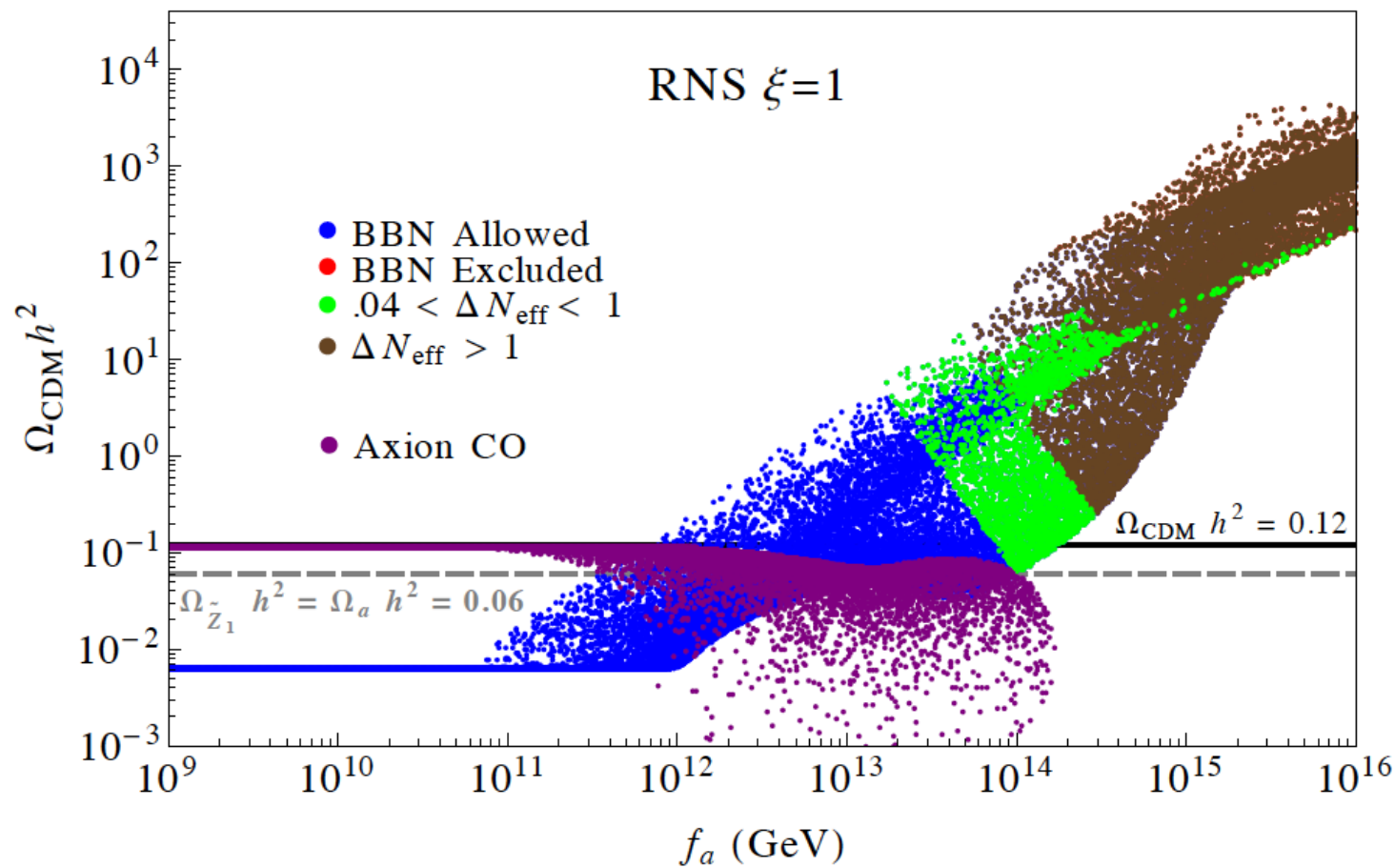
KJ Bae, HB, Lessa, Serce

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



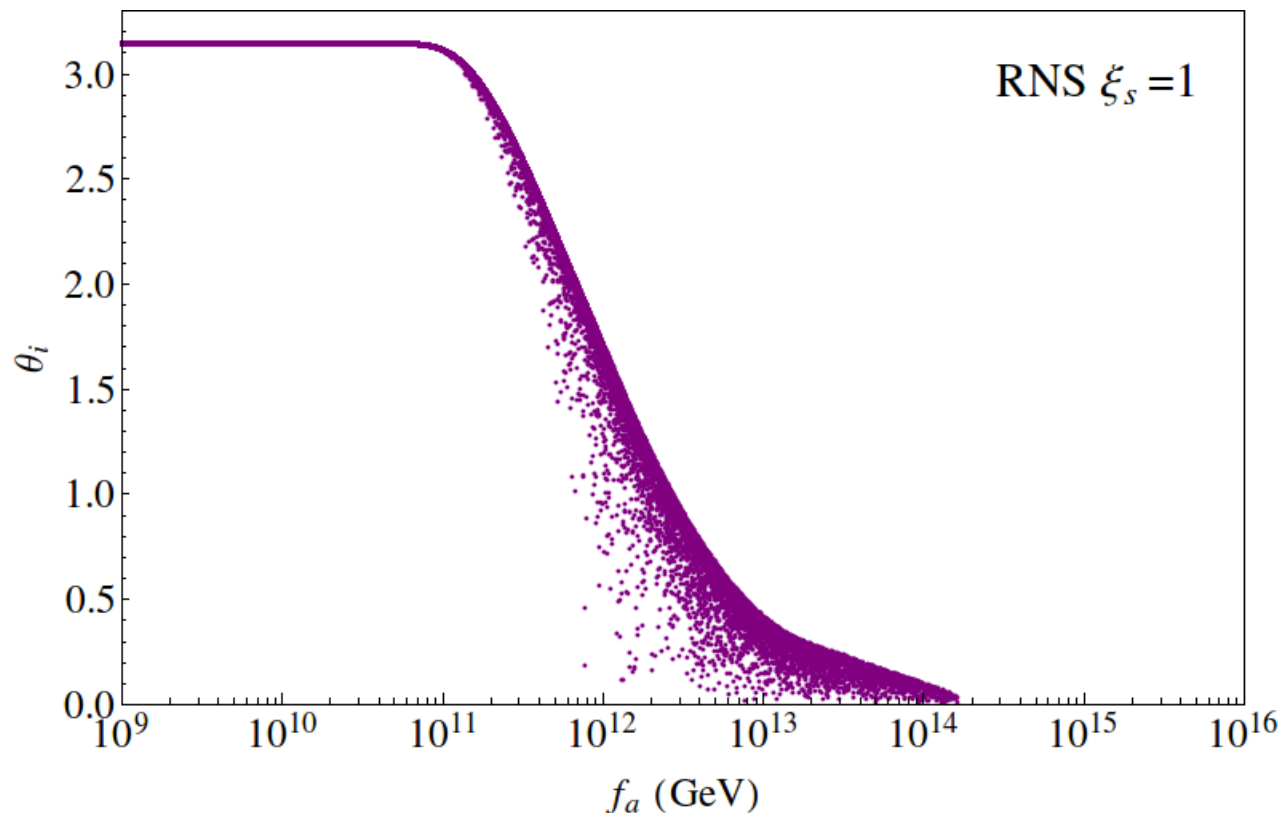
\Rightarrow





higgsino abundance

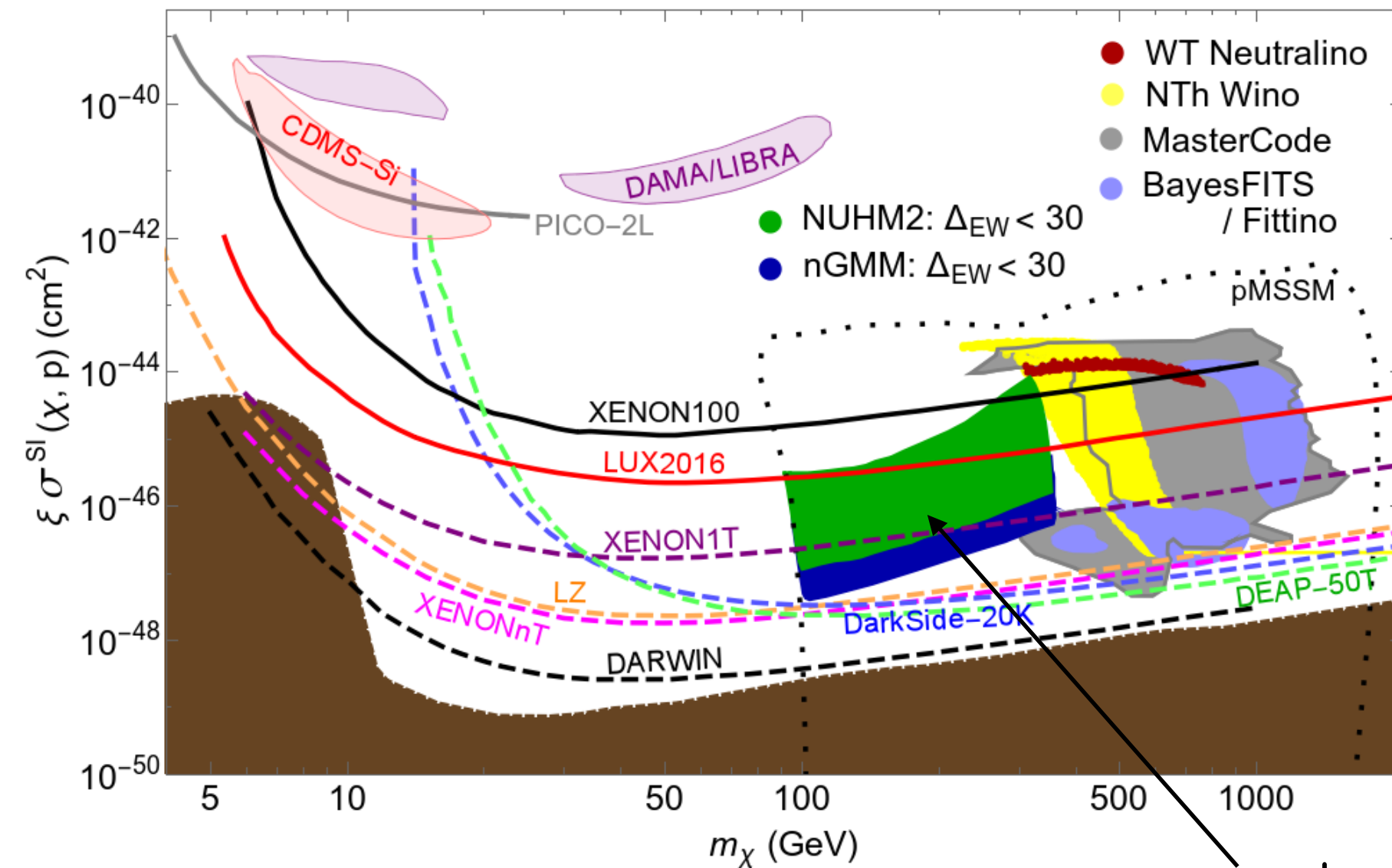
axion abundance



mainly axion CDM
for $f_a < \sim 10^{12}$ GeV;
for higher f_a , then
get increasing wimp
abundance

Direct higgsino detection rescaled

for minimal local abundance $\xi \equiv \Omega_{\chi}^{TP} h^2 / 0.12$



Bae, HB, Barger, Savoy, Serce

$$\mathcal{L} \ni -X_{11}^h \bar{\tilde{Z}}_1 \tilde{Z}_1 h$$

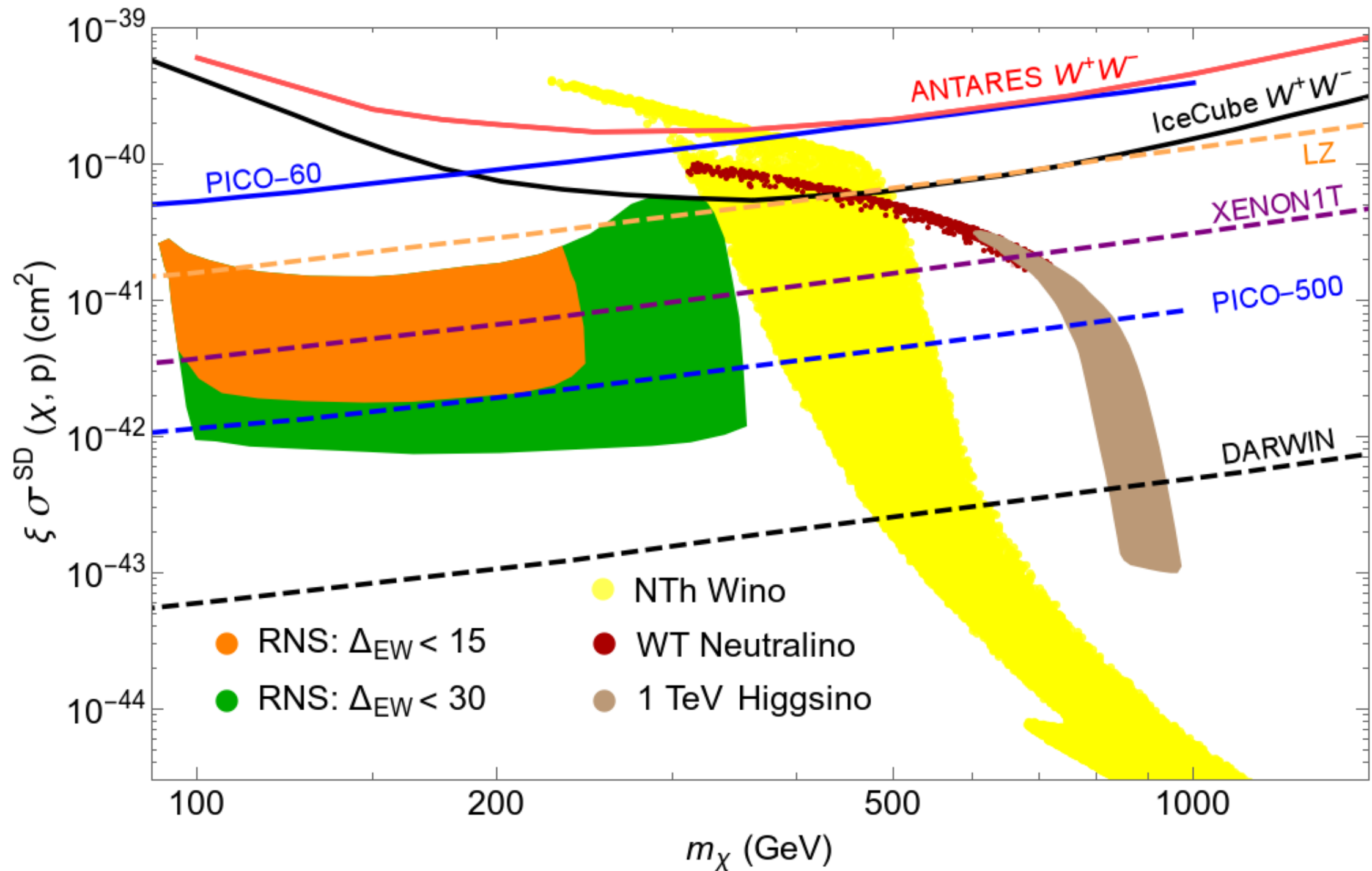
$$X_{11}^h = -\frac{1}{2} \left(v_2^{(1)} \sin \alpha - v_1^{(1)} \cos \alpha \right) \left(g v_3^{(1)} - g' v_4^{(1)} \right)$$

Xe-1-ton
now operating!

natural SUSY

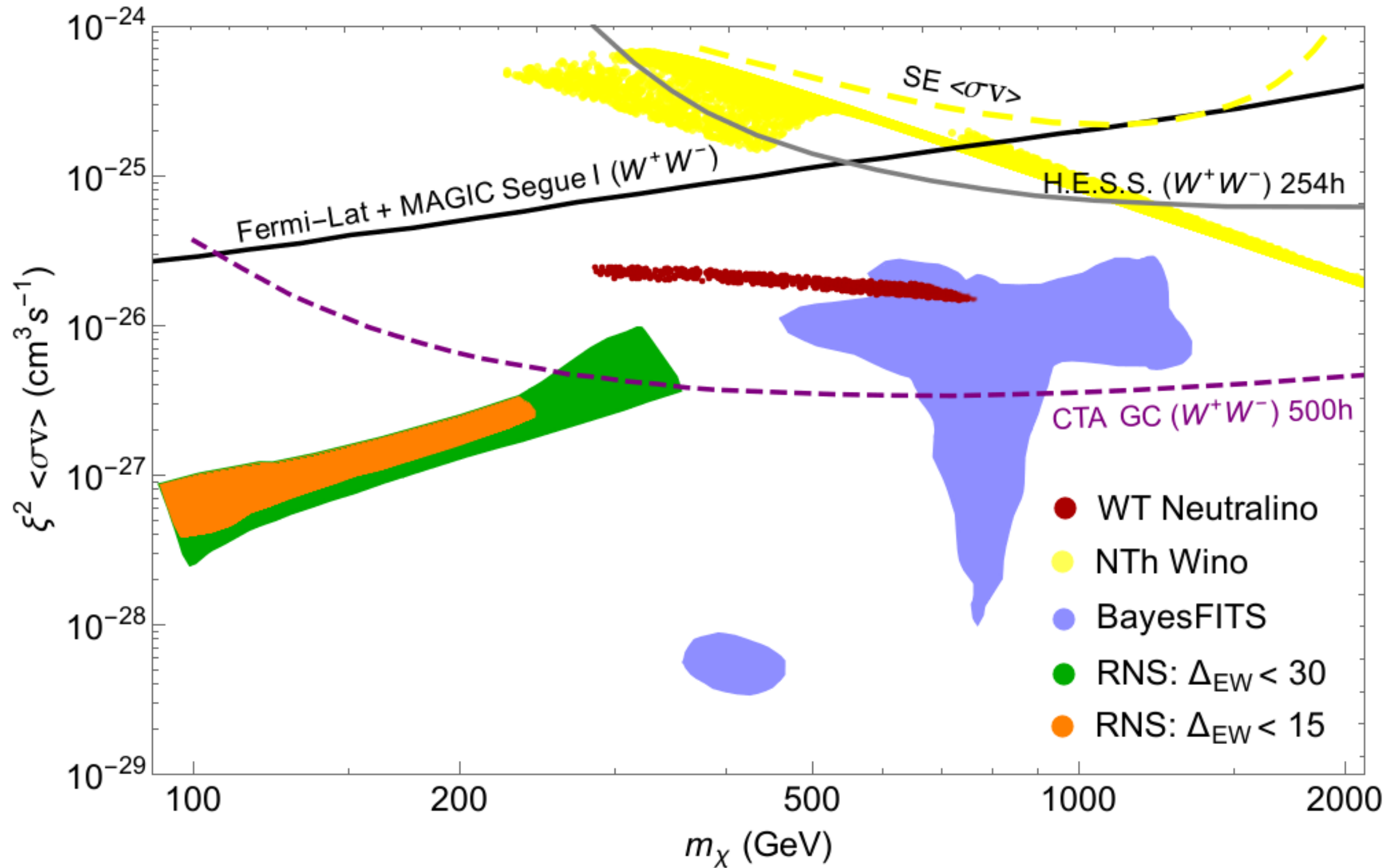
Can test RNS completely with ton scale detector
or equivalent (subject to minor caveats)

Prospects for SD WIMP searches:

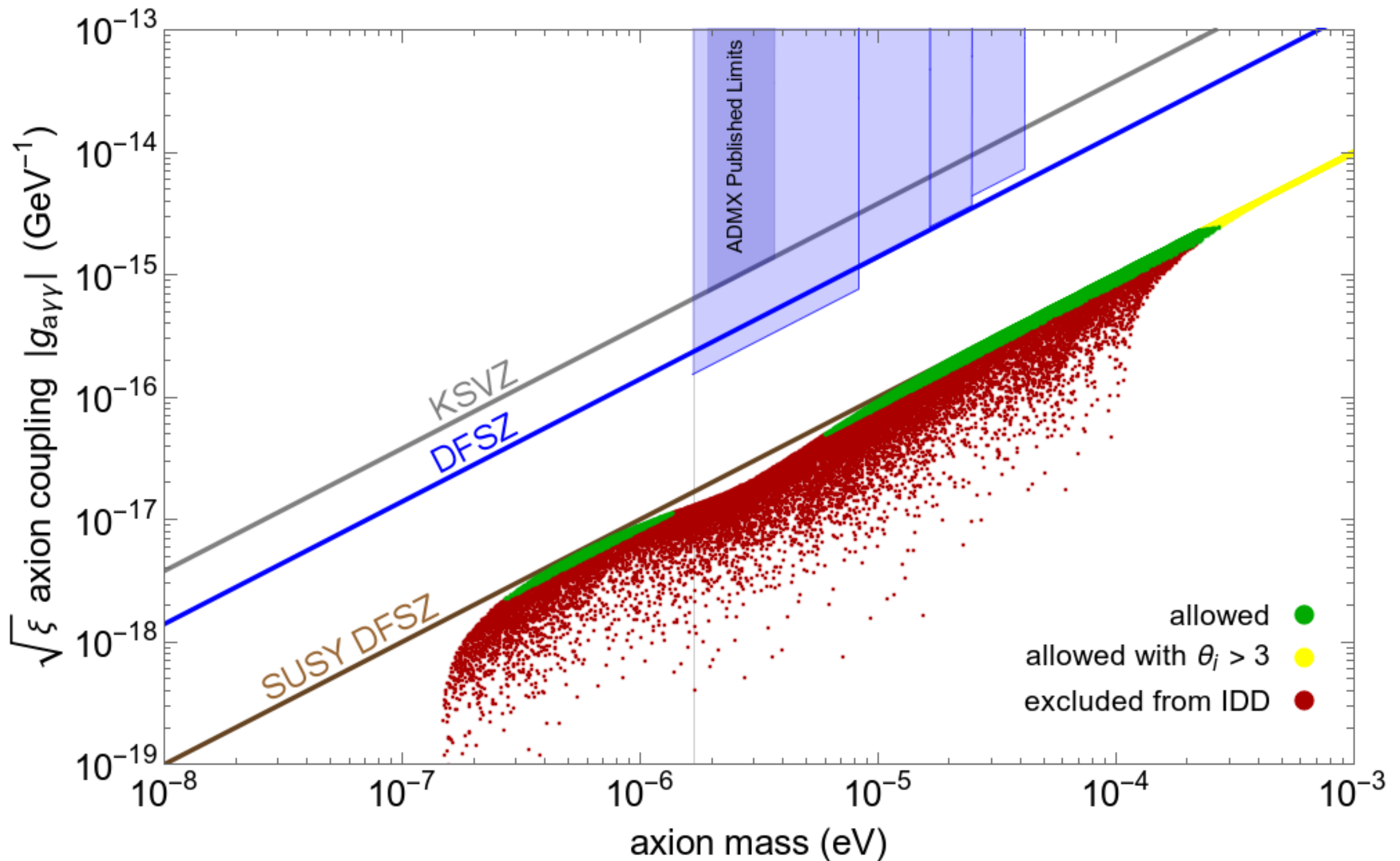


(Will need major upgrades)

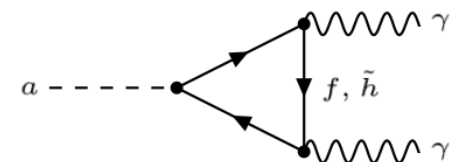
Prospects for IDD WIMP searches:



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!



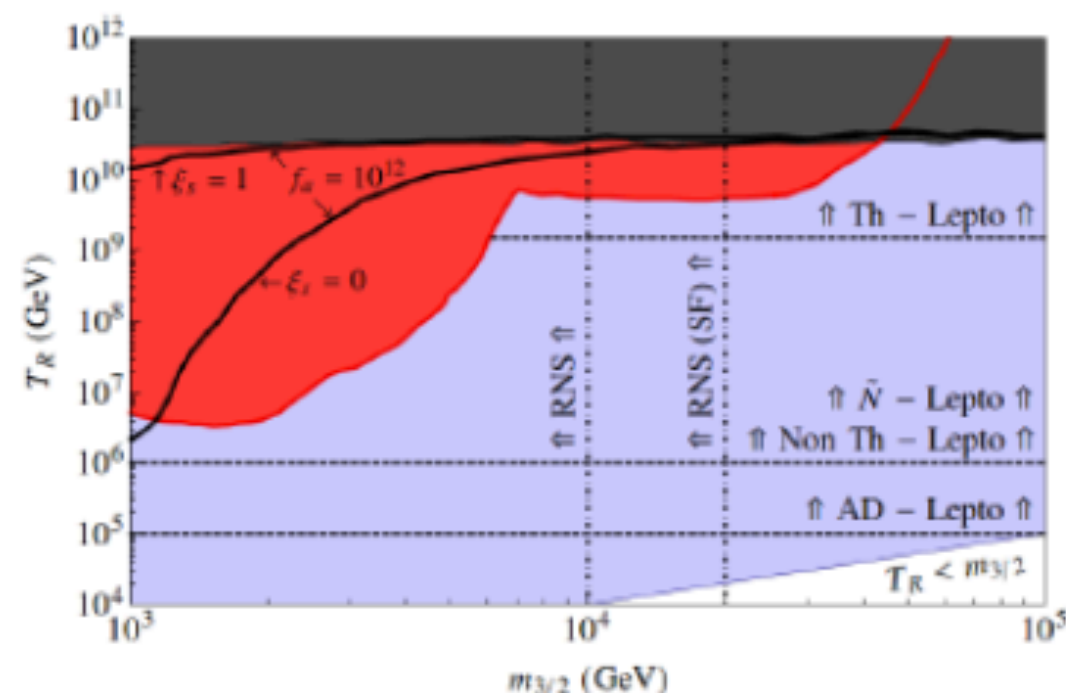
Conclusions

- SUSY still highly motivated
- Natural regions of p-space with light higgsinos exists
- Higgsinos pairs => Soft Dilepton+Jet+MET signature at HL-LHC
- Gluinos, stops might have to wait for HE-LHC
- Stringy naturalness: LHC should see $m_h \sim 125$ GeV plus no sparticles so far
- Discrete R-symmetries solve SUSY μ , RPV, p-decay
- $Z(24)^R$ yields gravity safe axion model with $f_a \sim 10^{11}$ GeV
- Amusingly, both R-parity and $U(1)_{PQ}$ arise as accidental, approximate symmetries from underlying $Z(24)^R$
- WIMPs not seen because subdominant component of DM compared to axions
- But should see WIMPs at multi-ton noble liquid detectors
- Axion coupling suppressed by presence of higgsinos- likely invisible with present tech.

Baryogenesis scenarios for radiative natural SUSY

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

gravitino problem plus
axino/saxion problem:
still plenty room



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

Bae, HB, Serce, Zhang, arXiv:1510.00724