A brief naturalness primer

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EF08 meeting
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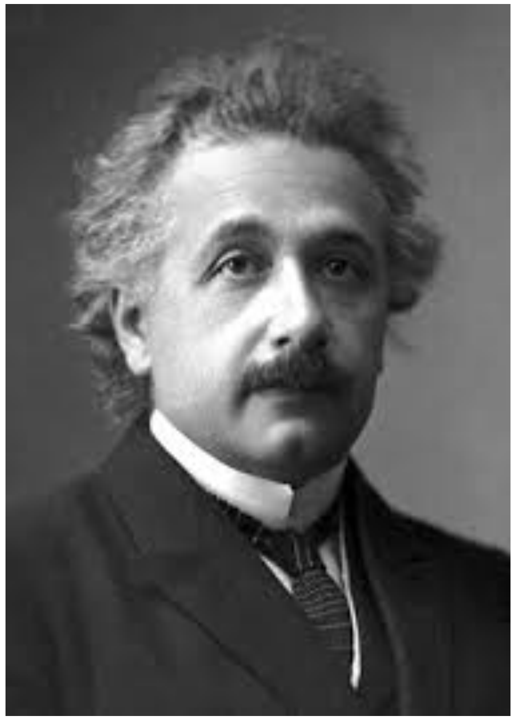
twin pillars of guidance:
naturalness & simplicity



``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

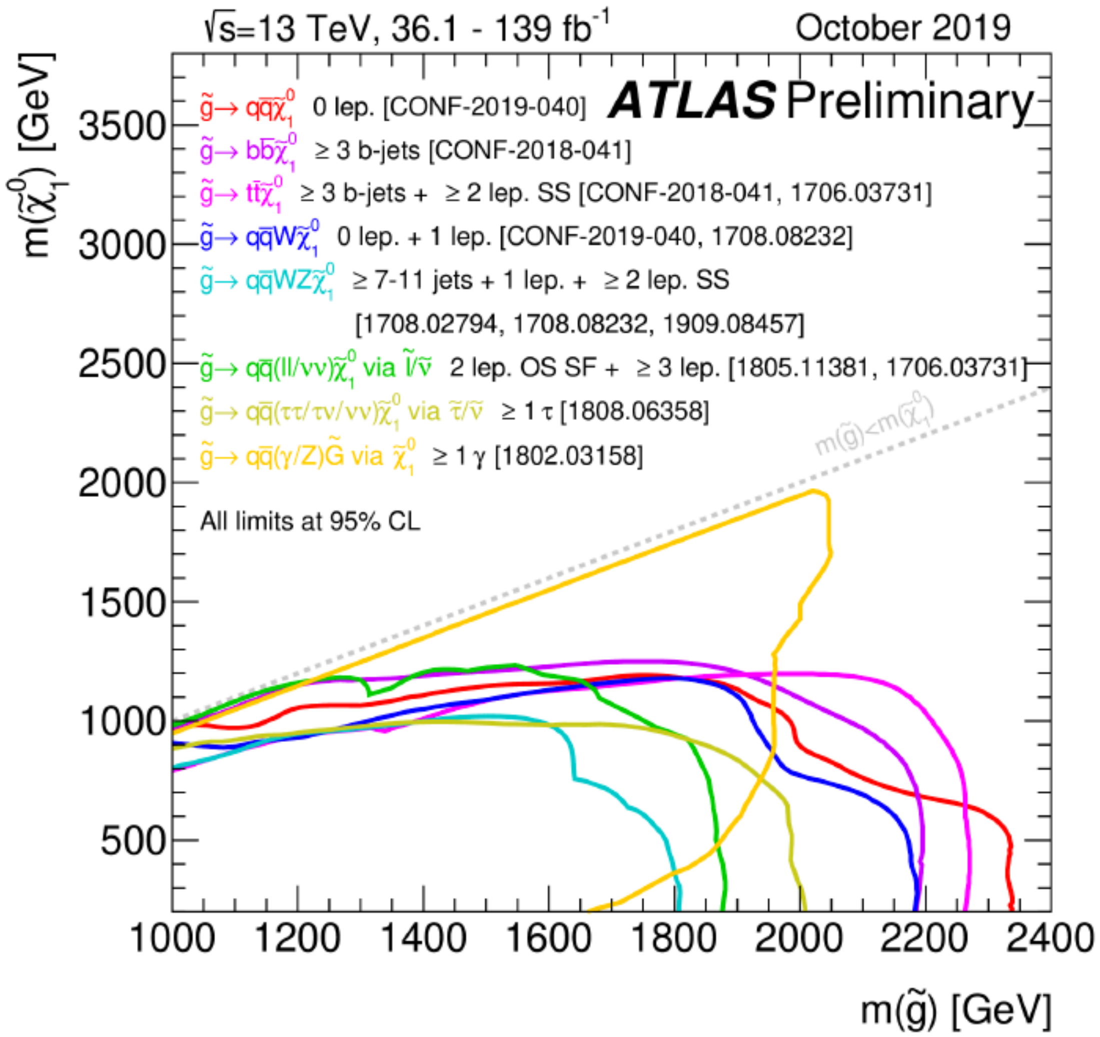
``…settling the ultimate fate of naturalness is perhaps
the most profound theoretical question
of our time''

Arkani-Hamed et al.,
arXiv:1511.06495

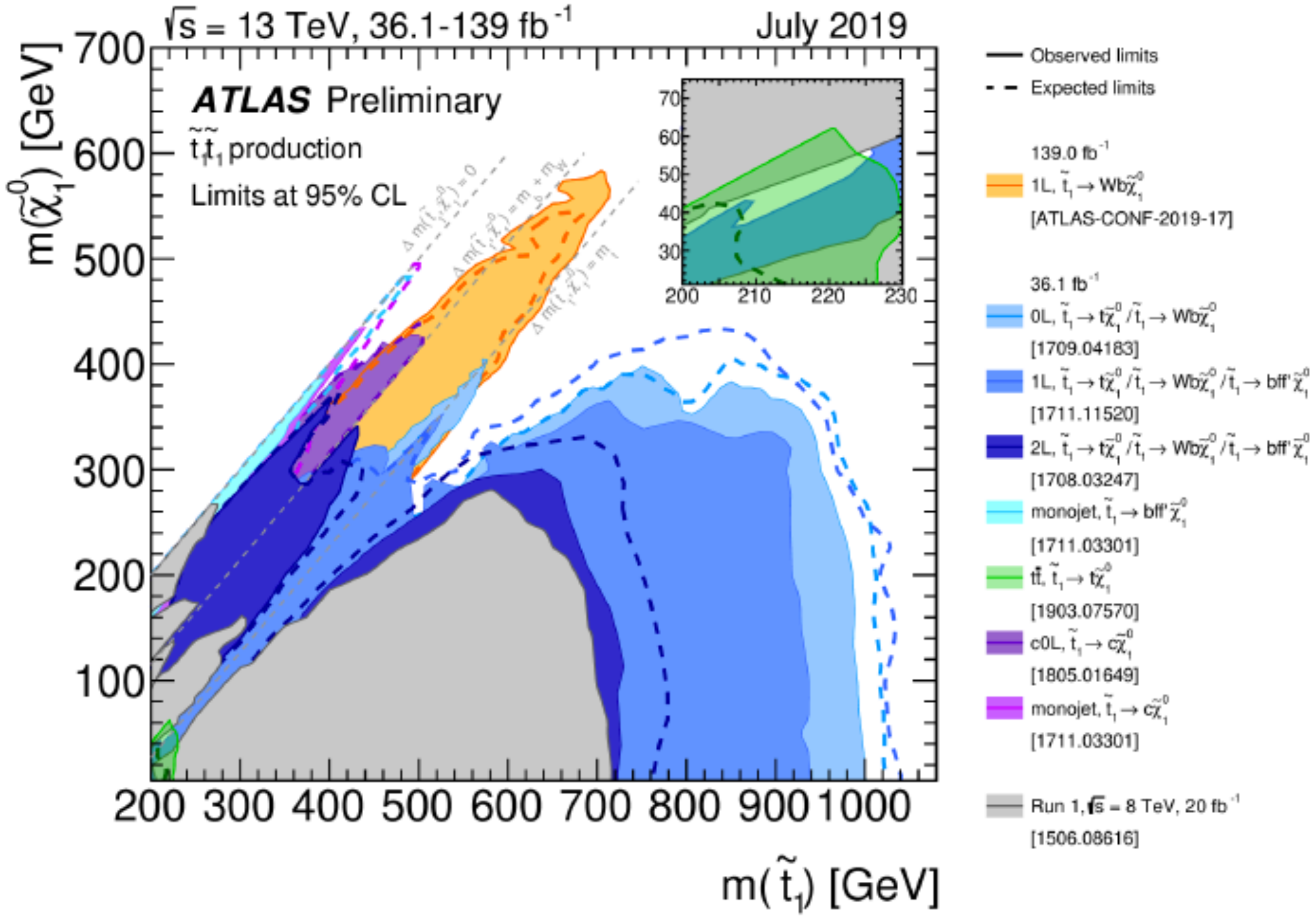
``Given the magnitude of the stakes
involved,
it is vital to get a clear verdict
on naturalness from experiment''

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

Where are the sparticles?
BG naturalness: m(gluino,stop)<~400 GeV



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

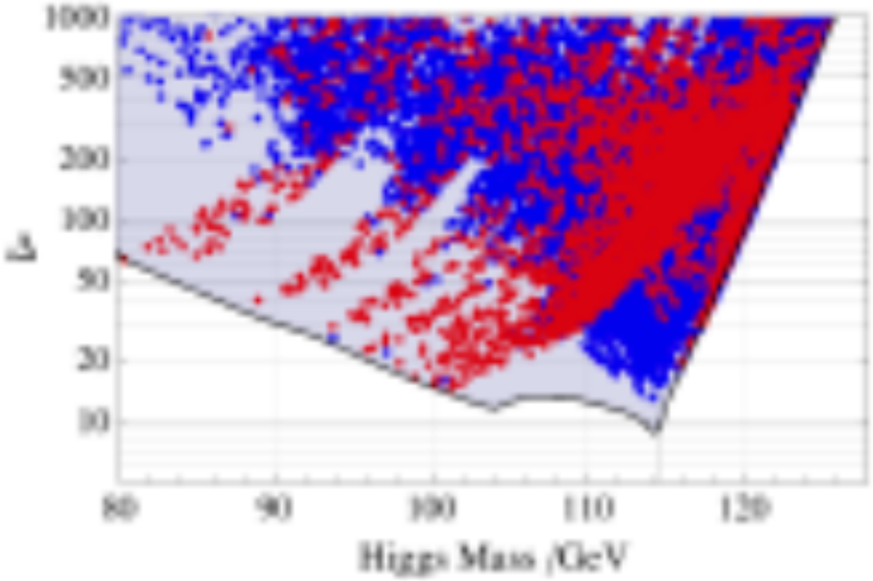


$m_{\tilde{t}_1} > 1.1$ TeV

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

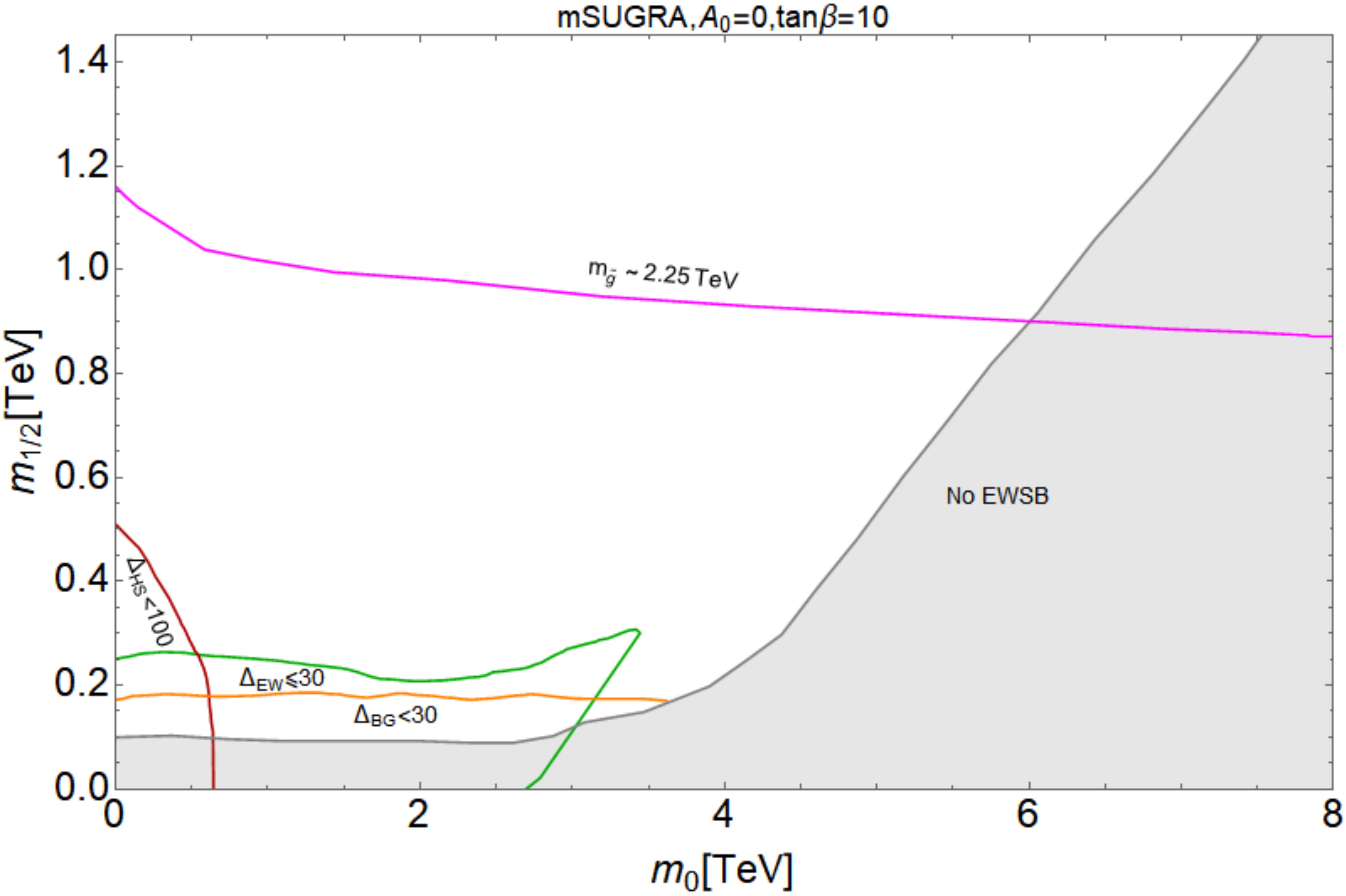
	mass
gluino	400 GeV
uR	400 GeV
eR	350 GeV
chargino	100 GeV
neutralino	50 GeV

Barbieri-Giudice 10% bounds, 1987



Cassel, Ghilencea, Ross,2009

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



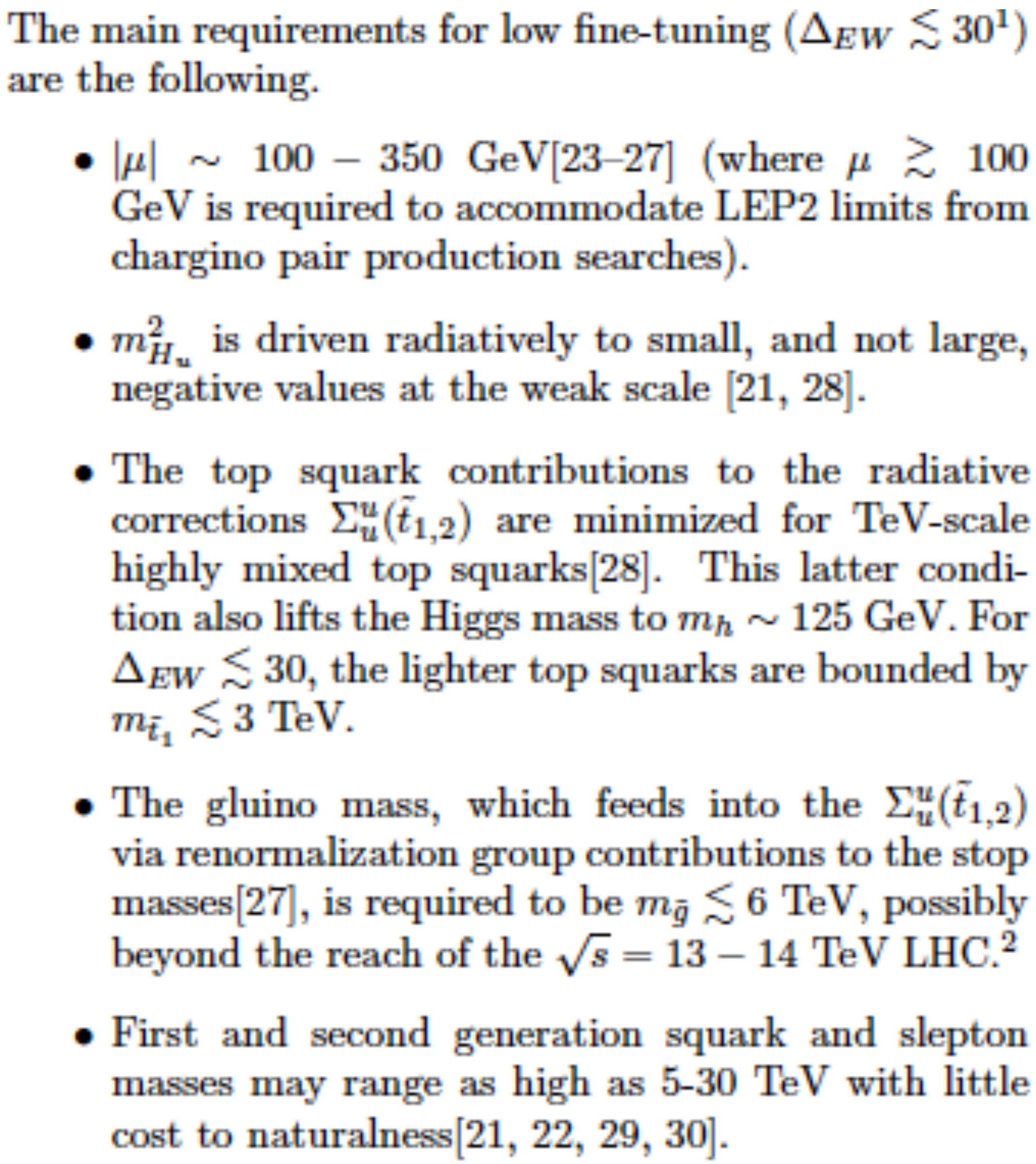
Is SUSY a failed enterprise (as is often claimed in popular press)?

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 then $\mathcal{O}$

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

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



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].

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

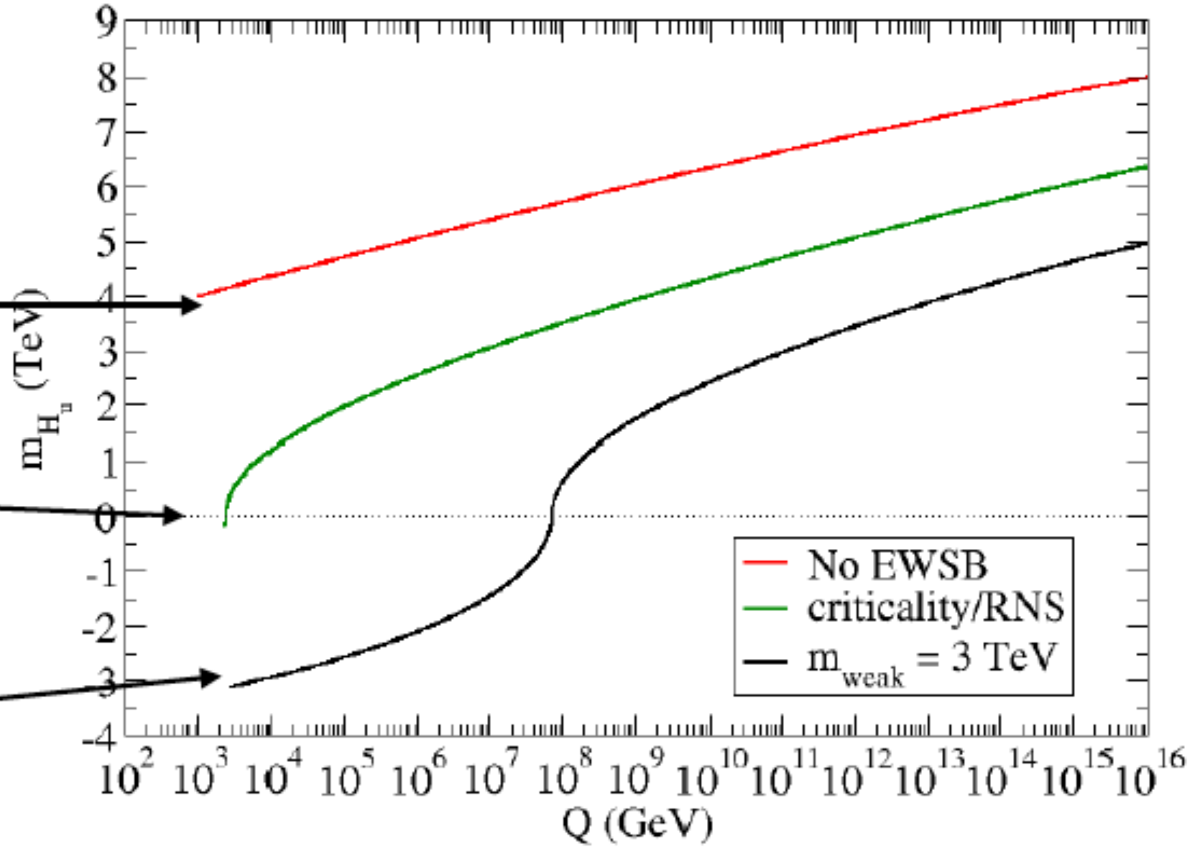
The bigger the soft term, the more natural is its weak scale value, until EW symmetry no longer broken: living dangerously!

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

EWS not broken

natural: EWS is barely broken

unnatural



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)

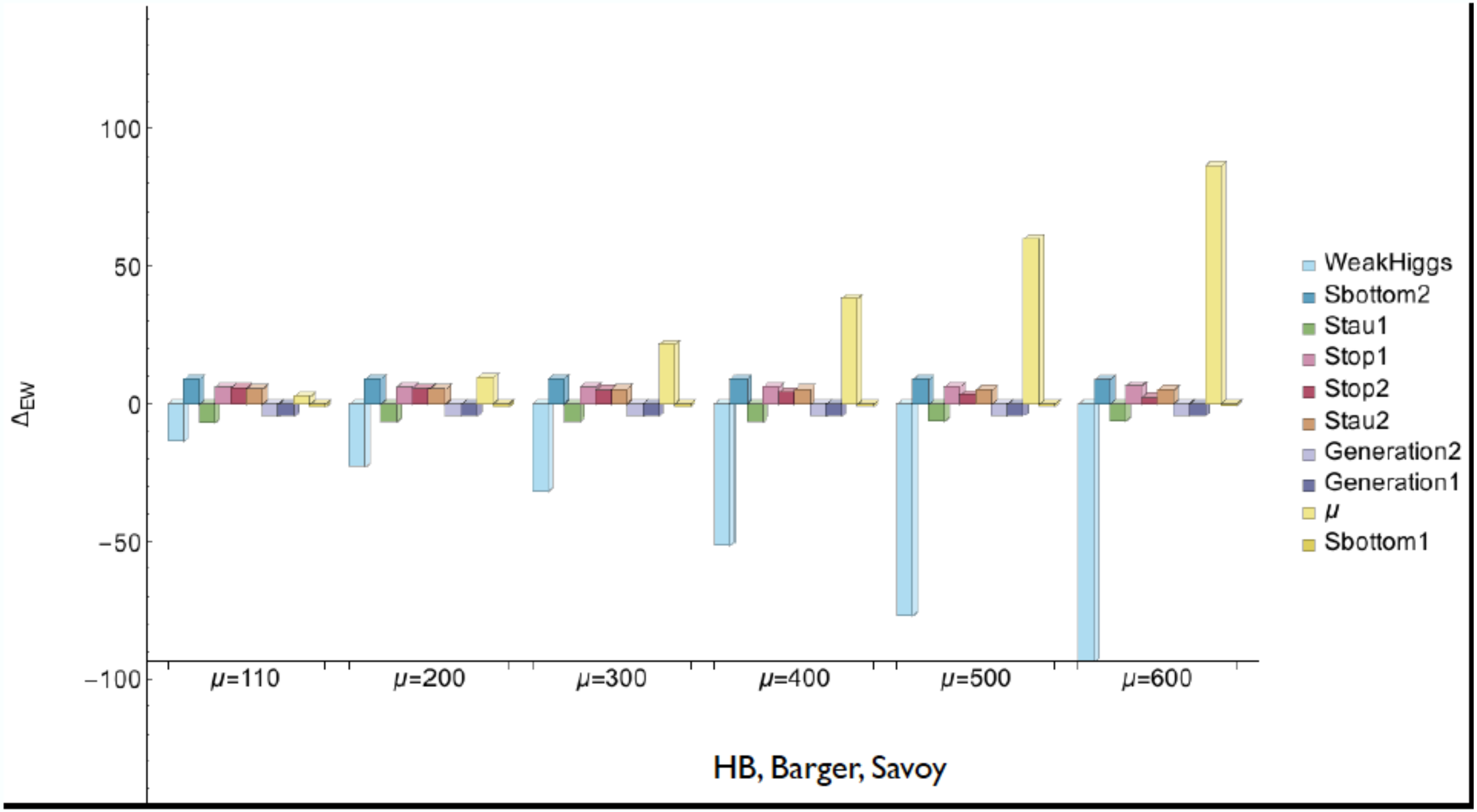
Voila! It is very natural!

An unnatural recipe:

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

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

How much is too much fine-tuning?



HB, Barger, Savoy

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

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 m0, mhf, A0)

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 $\Delta_{BG} \to \Delta_{EW}$

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

High scale (HS, stop mass) measure

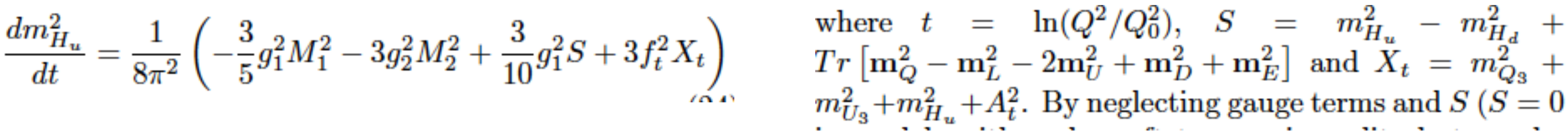
$$m_h^2 \simeq \mu^2 + m_{H_u}^2(weak) = \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$$

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

Implies 3 3rd generation squarks <500 GeV:

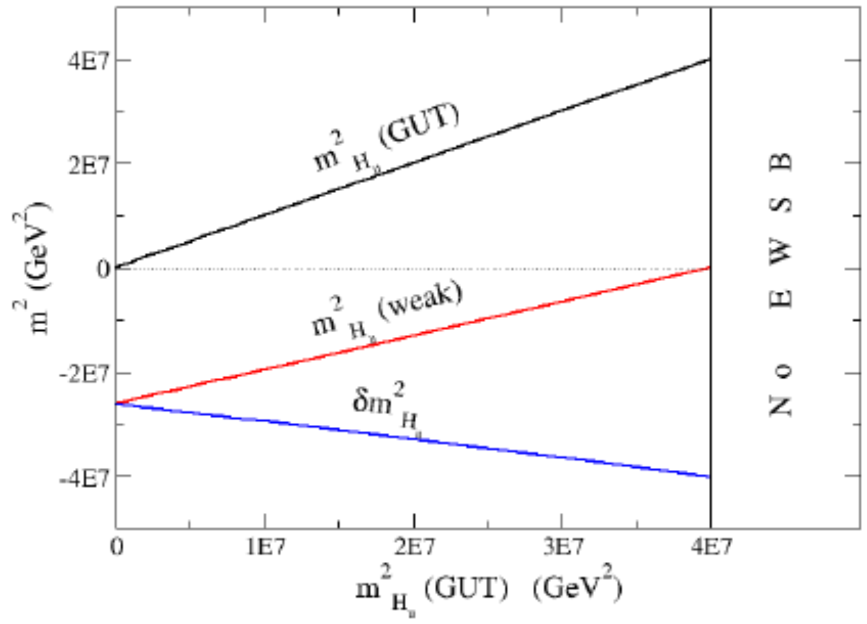
SUSY ruled out under $\Delta_{HS} \equiv \frac{\delta m_{H_u}^2}{m_h^2}$

BUT! too many terms ignored! NOT VALID!



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

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



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

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

HB, Barger, Mickelson, Padeffke, Savoy
arXiv:1309.2984 and 1404.2277

Gauge hierarchy problem (SM):

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

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

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

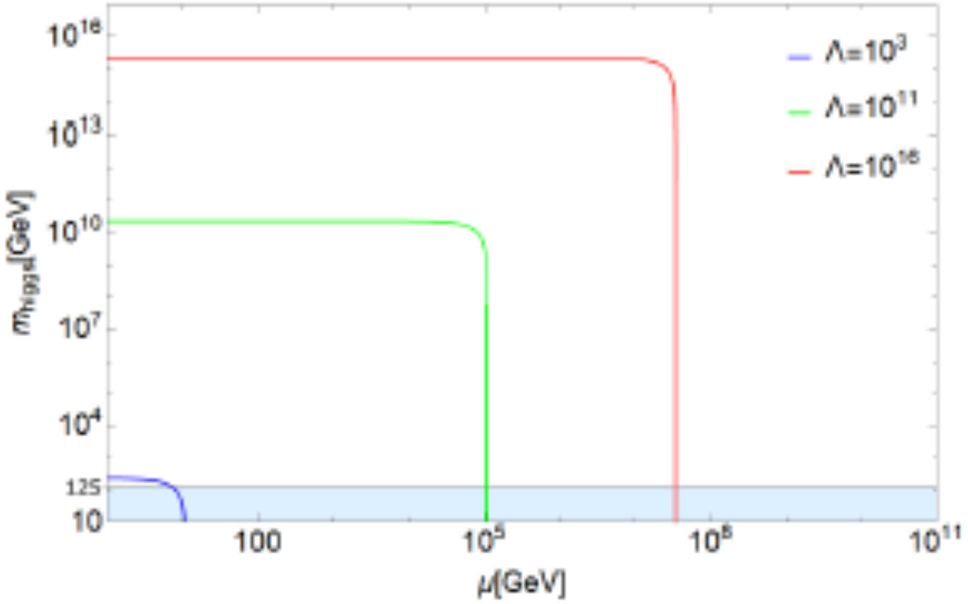
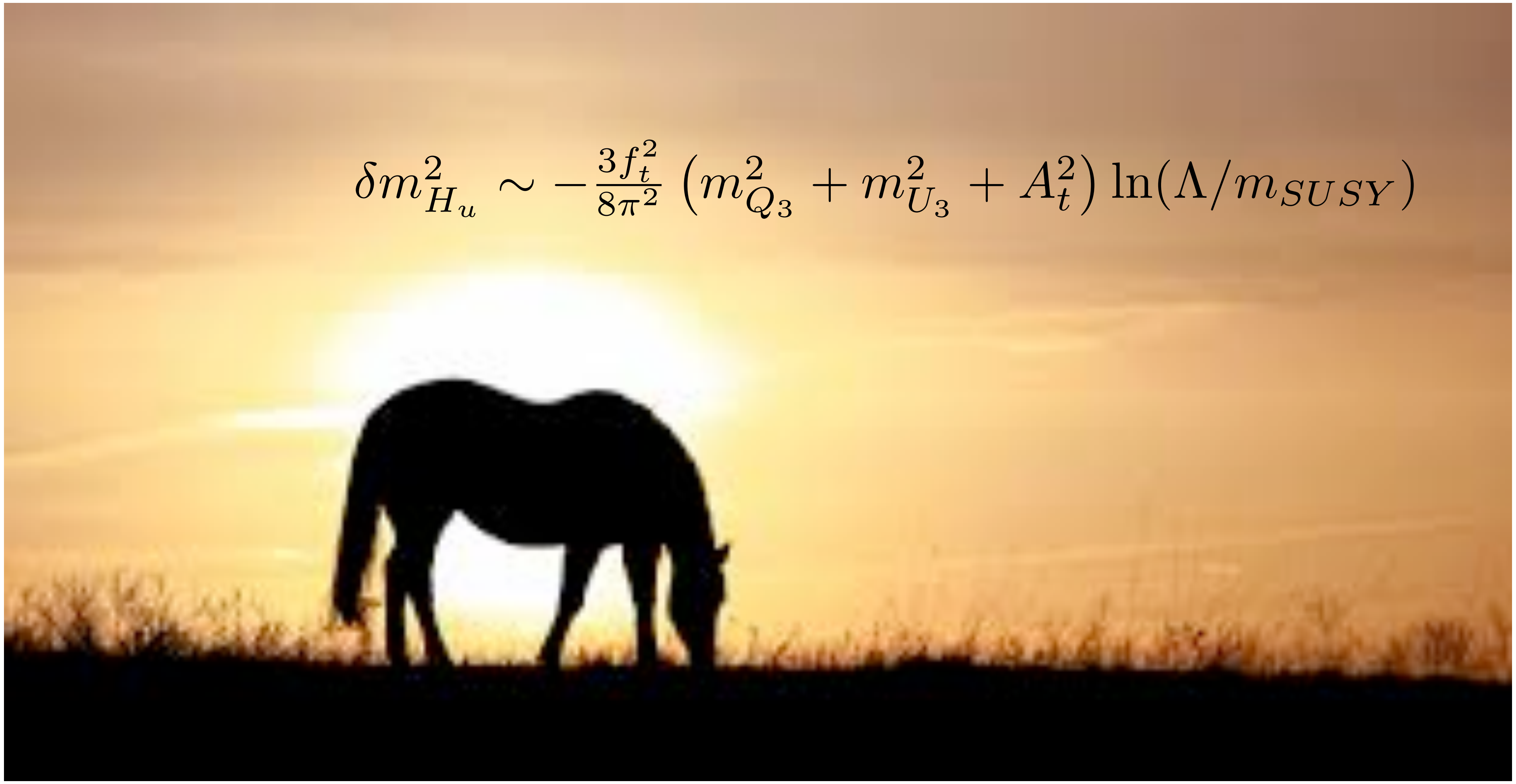


Figure 2: Value of $m_h(SM)$ versus SM μ parameter for theory cut-off values $\Lambda_{SM} = 10^3$, 10^{11} and 10^{16} GeV.

Hardly plausible that SM is valid much beyond the TeV scale

Recommendation: put this horse out to pasture



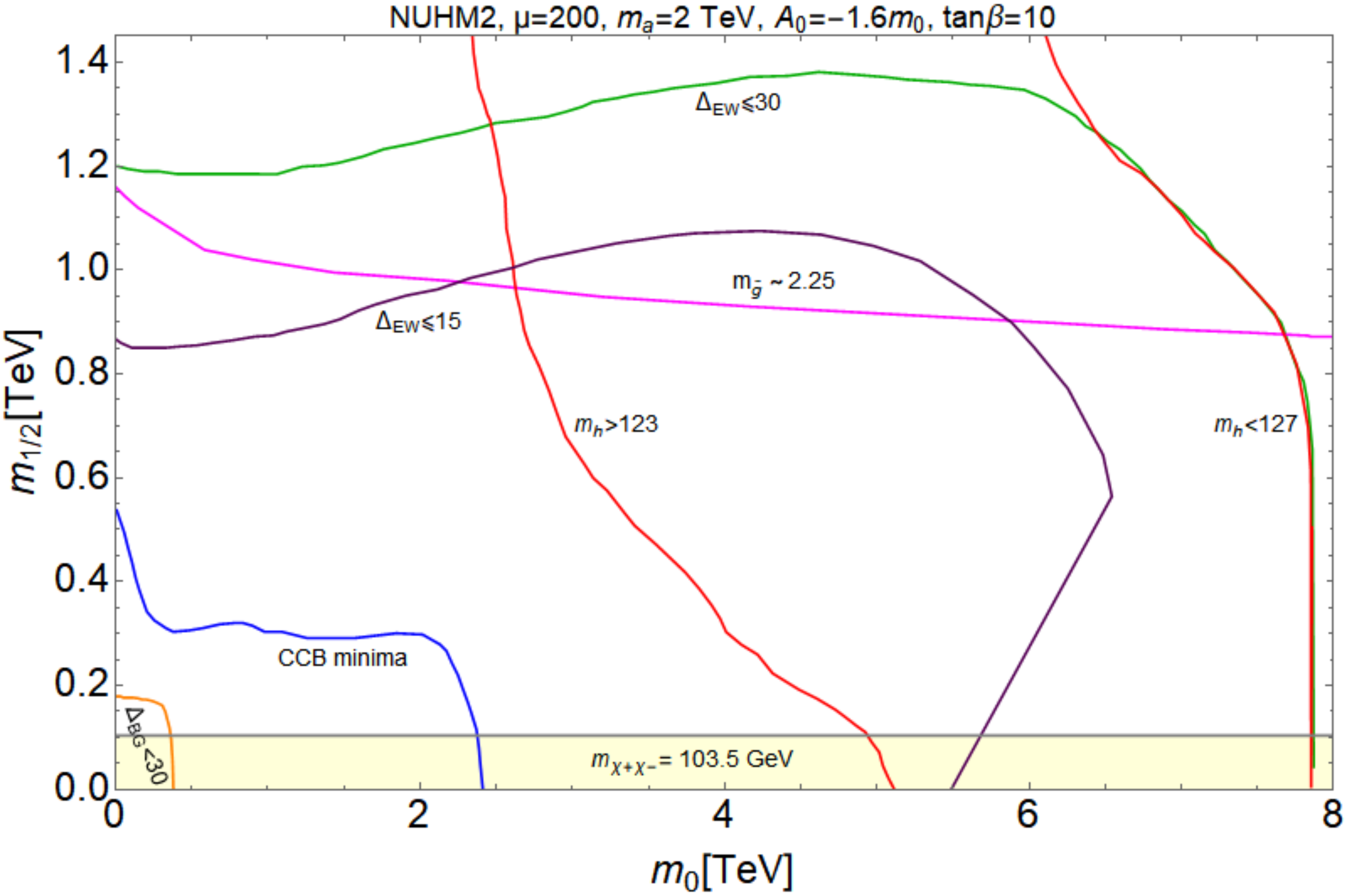
$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + A_t^2\right)\ln(\Lambda/m_{SUSY})$$

R.I.P.

sub-TeV 3rd generation squarks not required for naturalness

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

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



HB, Barger, Salam, arXiv:1906.07741

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

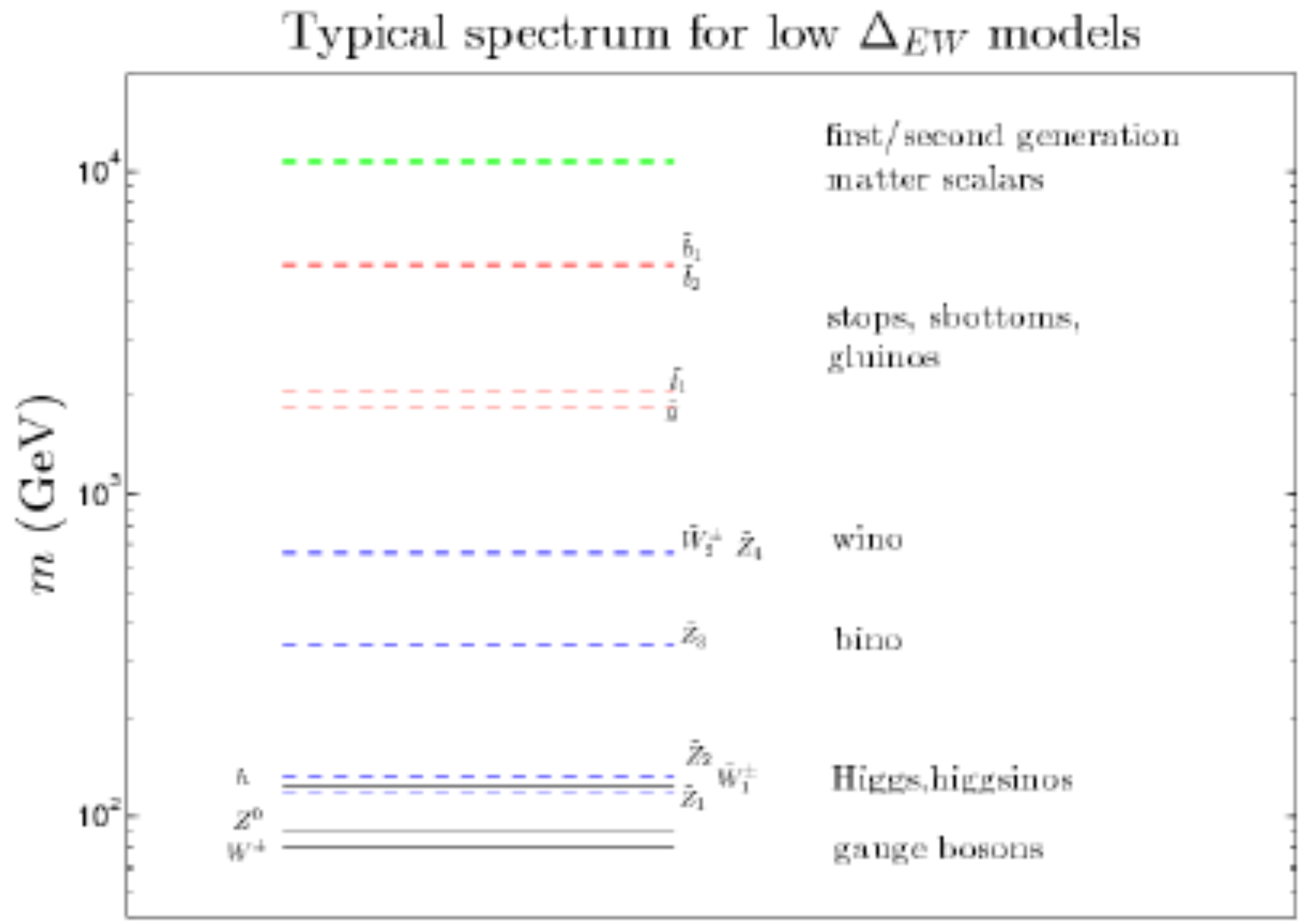
h(125) and LHC limits are perfectly compatible with 3-10% naturalness: no crisis!

Model independence of Delta(EW)

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

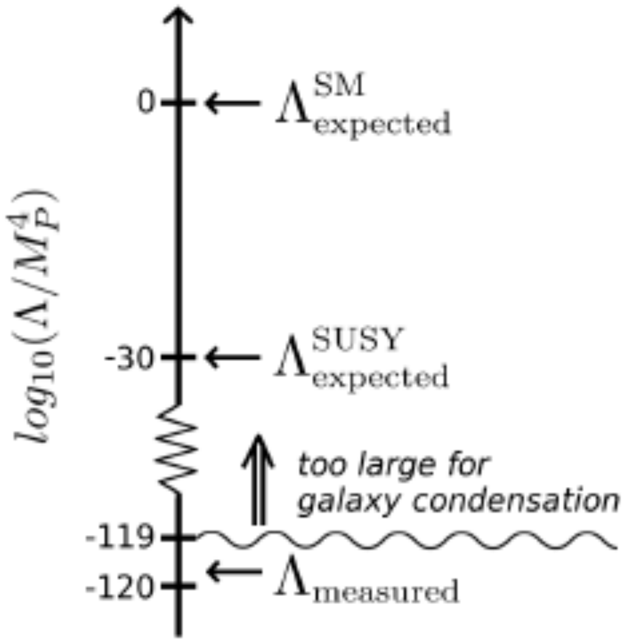
- This is not true for Δ_{BG} which wildly fluctuates depending on scale and in fact $\Delta_{BG} \to \Delta_{EW}$ for the pMSSM

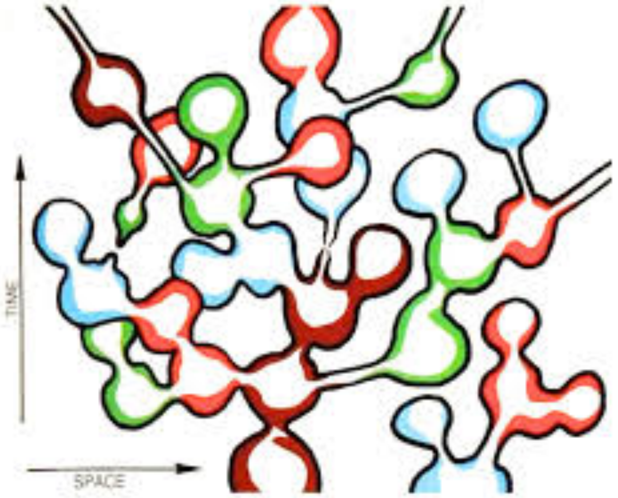
- For Δ_{HS}, log term $\to\sim 30$ at $\Lambda = m_{GUT}$ but log $\to 0$ for $\Lambda \sim m_{weak}$



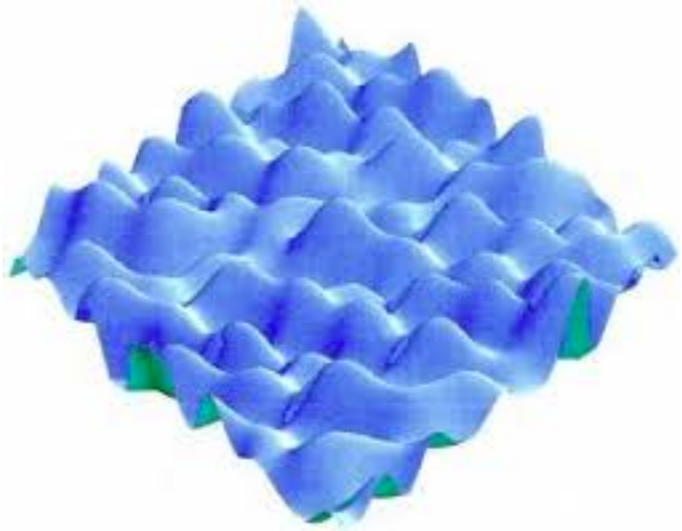
a natural sparticle spectrum for SUSY:
only higgsinos need lie close to EW scale

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





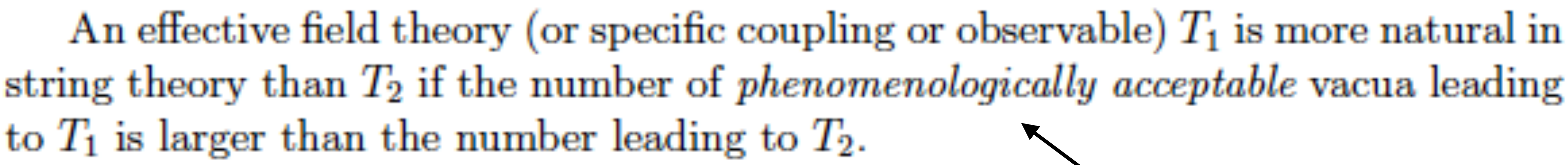
In the landscape with 10^500 vacua with different CCs,
then the tiny value of the CC may not be surprising since
larger values would lead to runaway pocket universes
where galaxies wouldn't condense-
anthropics: no observers in such universes (Weinberg)



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(weak)~=m(W,Z,h)~100 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 <Fi> and <Dj> values, then expect

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

Douglas ansatz

arXiv:0405279

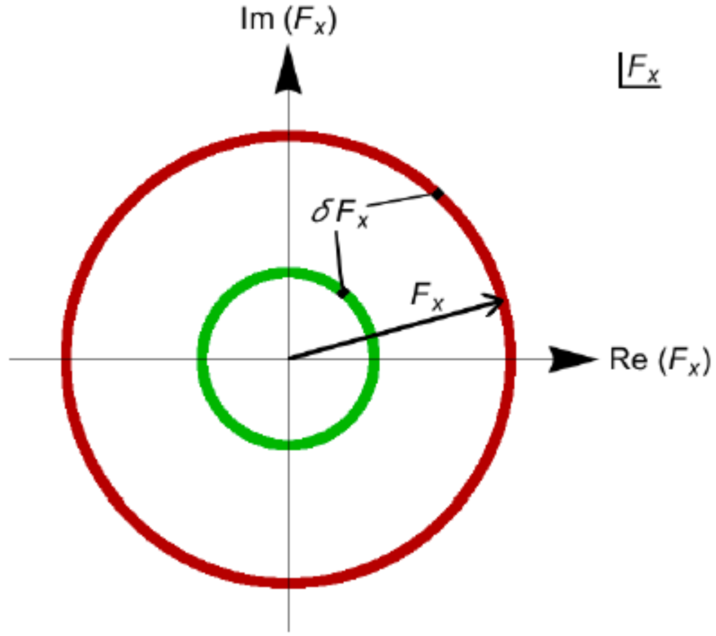


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

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

What about f(selection)?

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

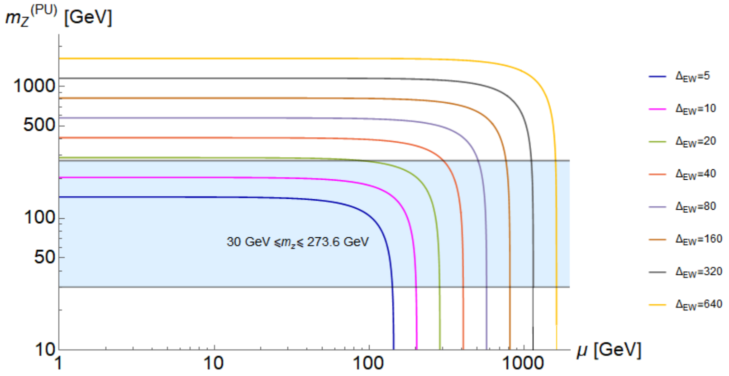
to penalize soft terms straying too far from weak scale

This doesn't work for variety of cases

- Too big soft terms can lead to CCB minima: must veto such vacua
- Bigger m(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



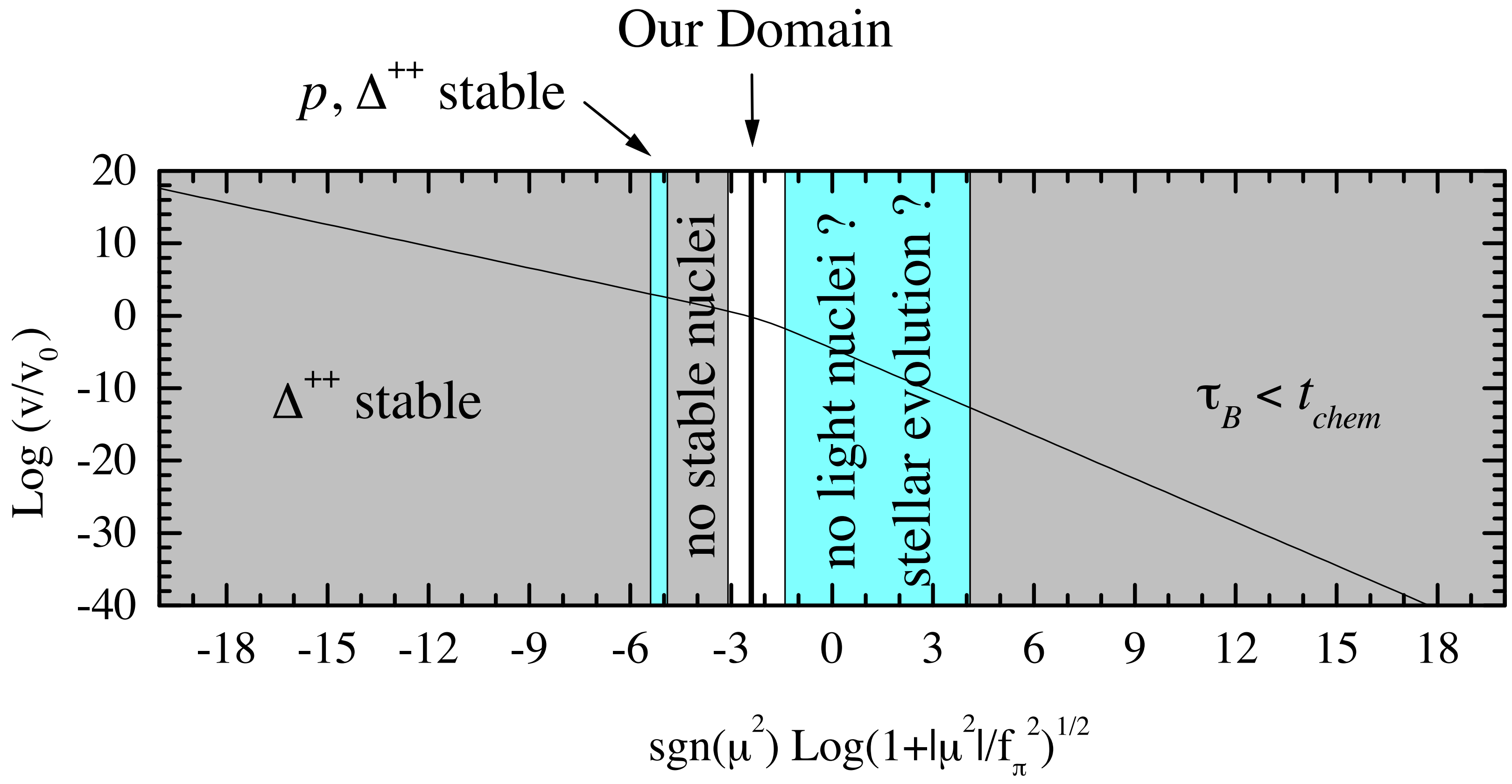
Then for statistically selected soft terms, m(weak) is output, not input

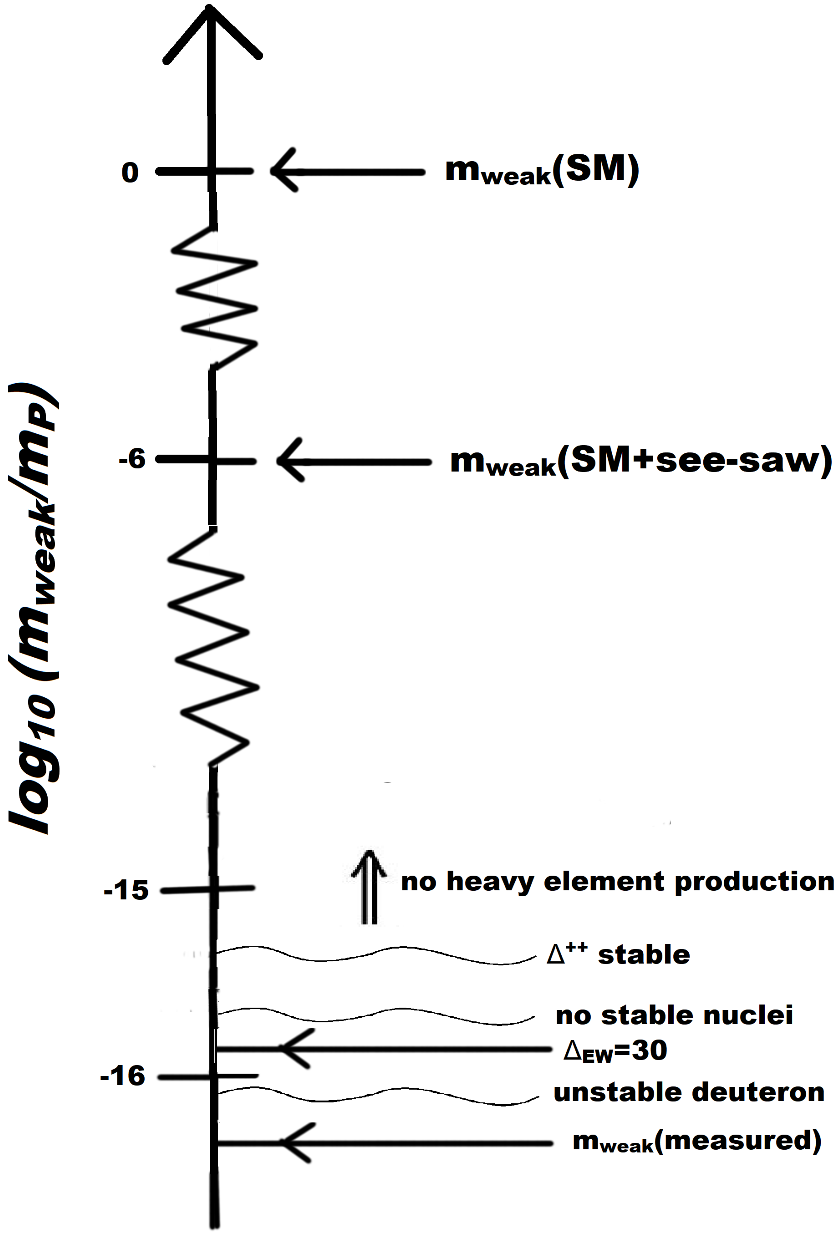
Must veto too large m(weak) values: nuclear physics screwed up
(Agrawal, Barr, Donoghue, Seckel, 1998)

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

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

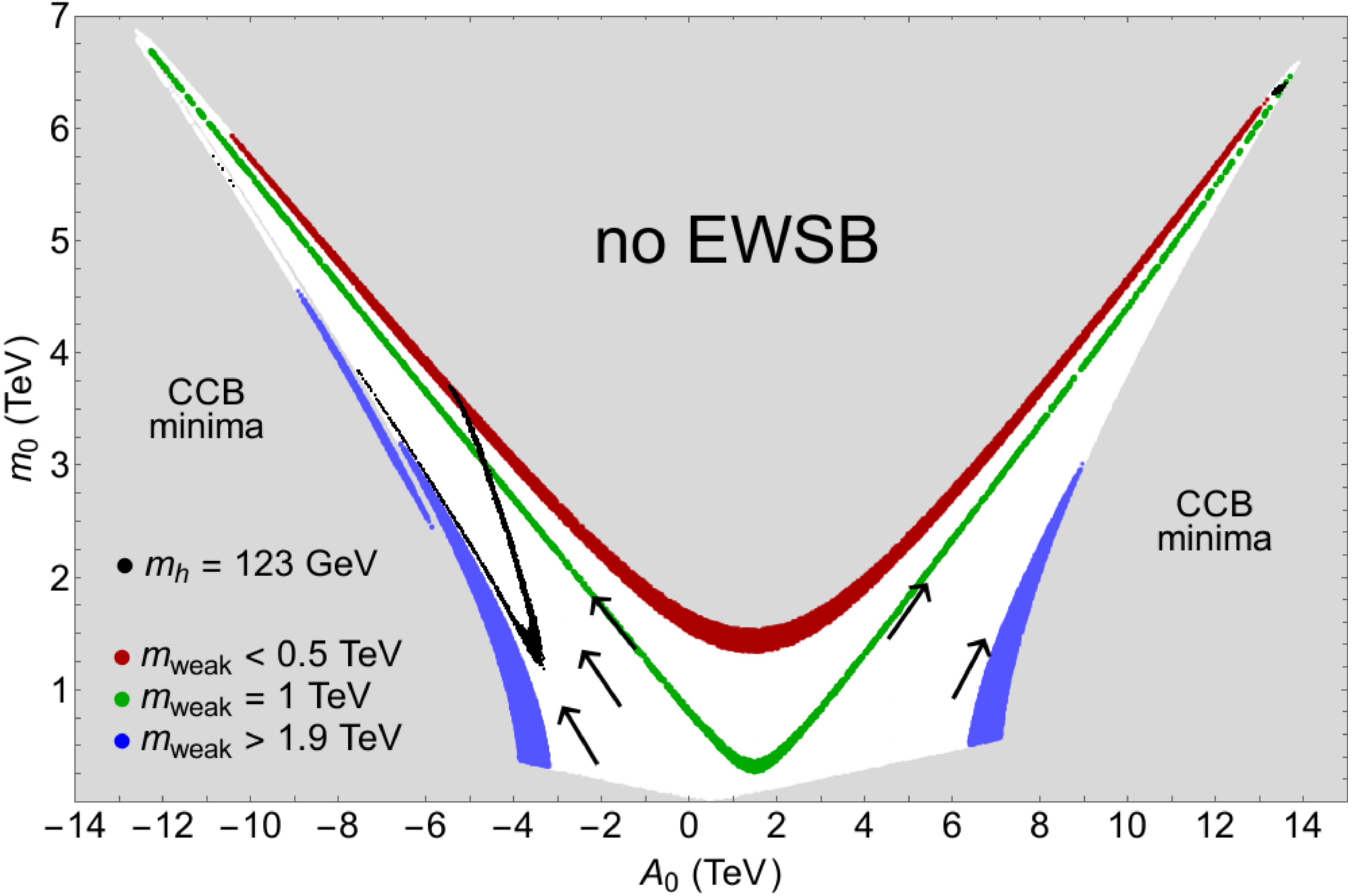
pocket-universe value of weak scale
cannot deviate by more than
factor 2-5 from its measured value
lest disasters occur in nuclear physics: no nuclei, no atoms
(violates atomic principle)





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

$$m_{H_u} = 1.3 m_0$$

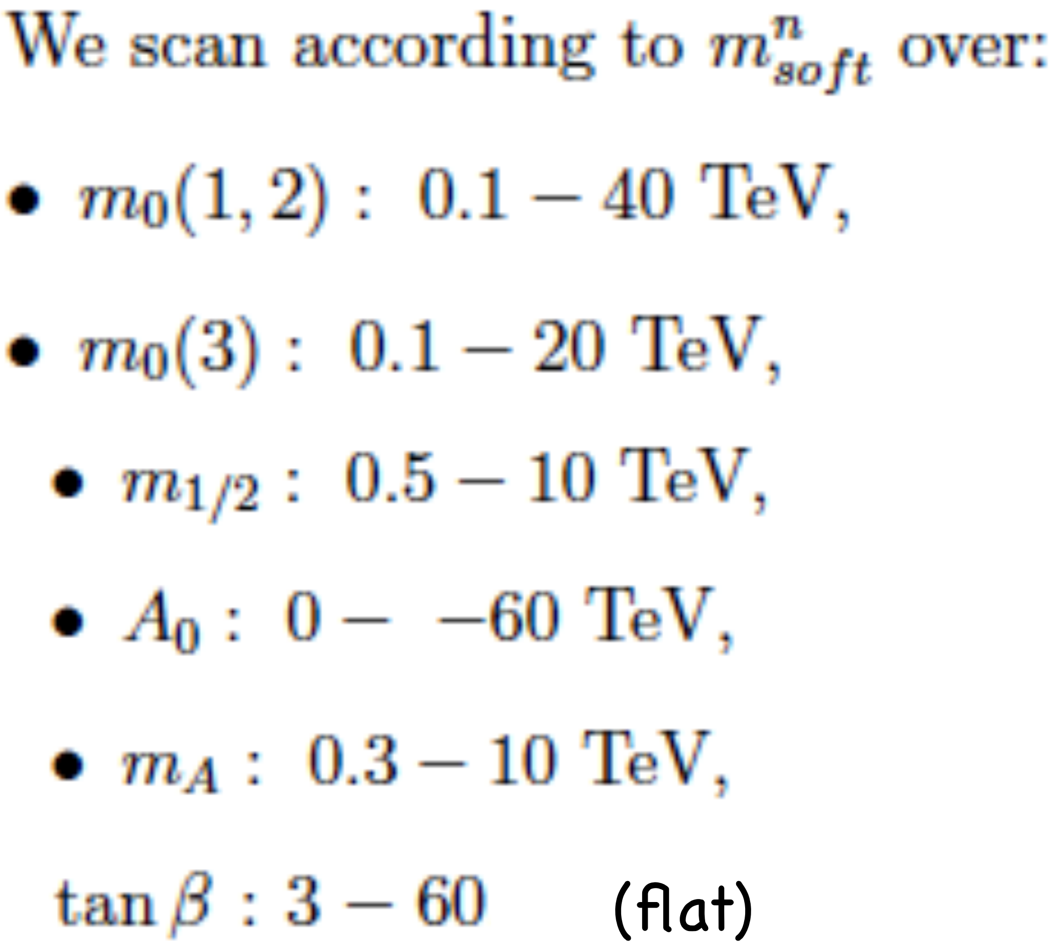


statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

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(soft)^n along with f(EWFT) penalty



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

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

$\tan\beta:3-60$

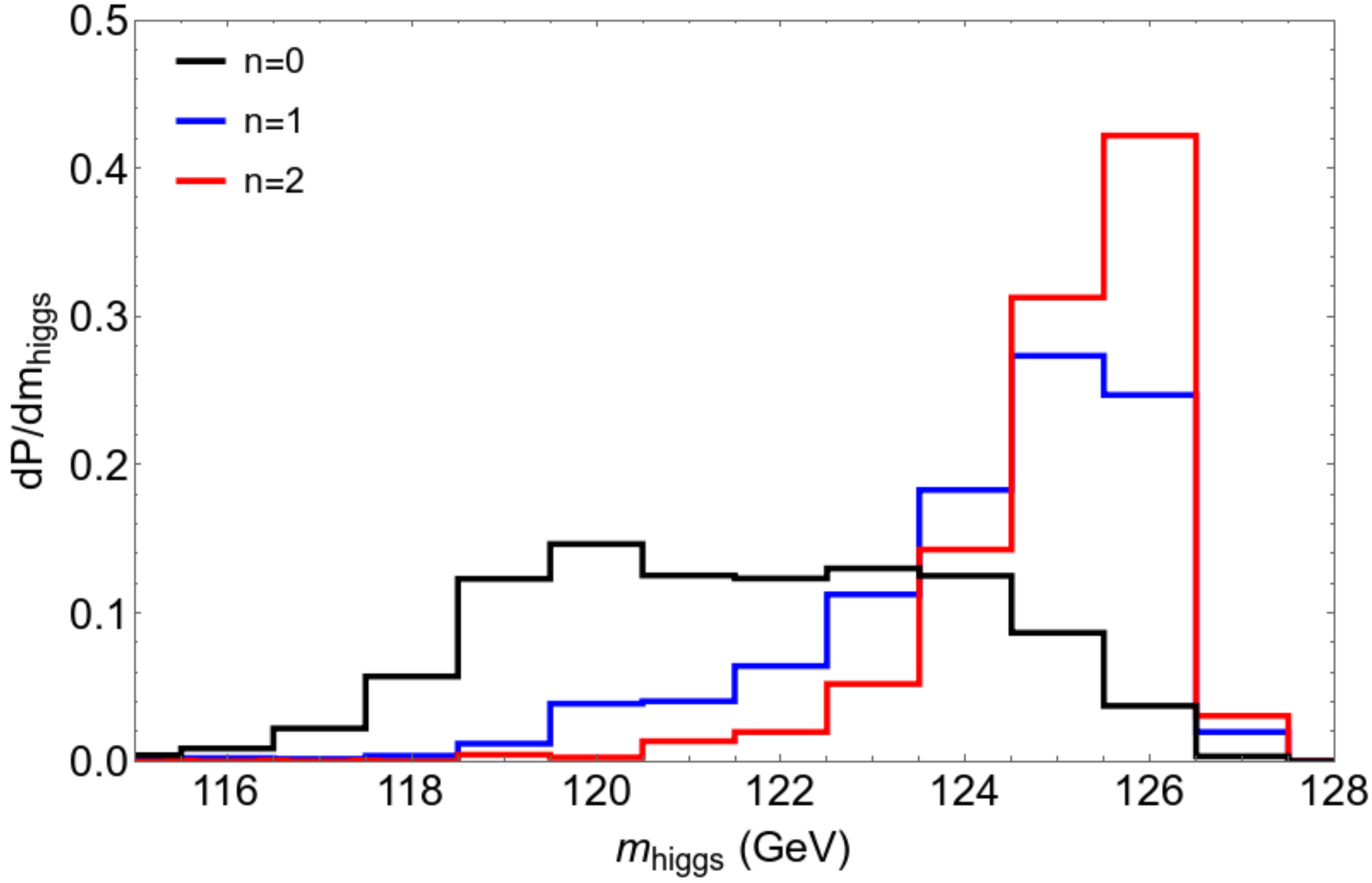
(flat)

mu=150 GeV (fixed)

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

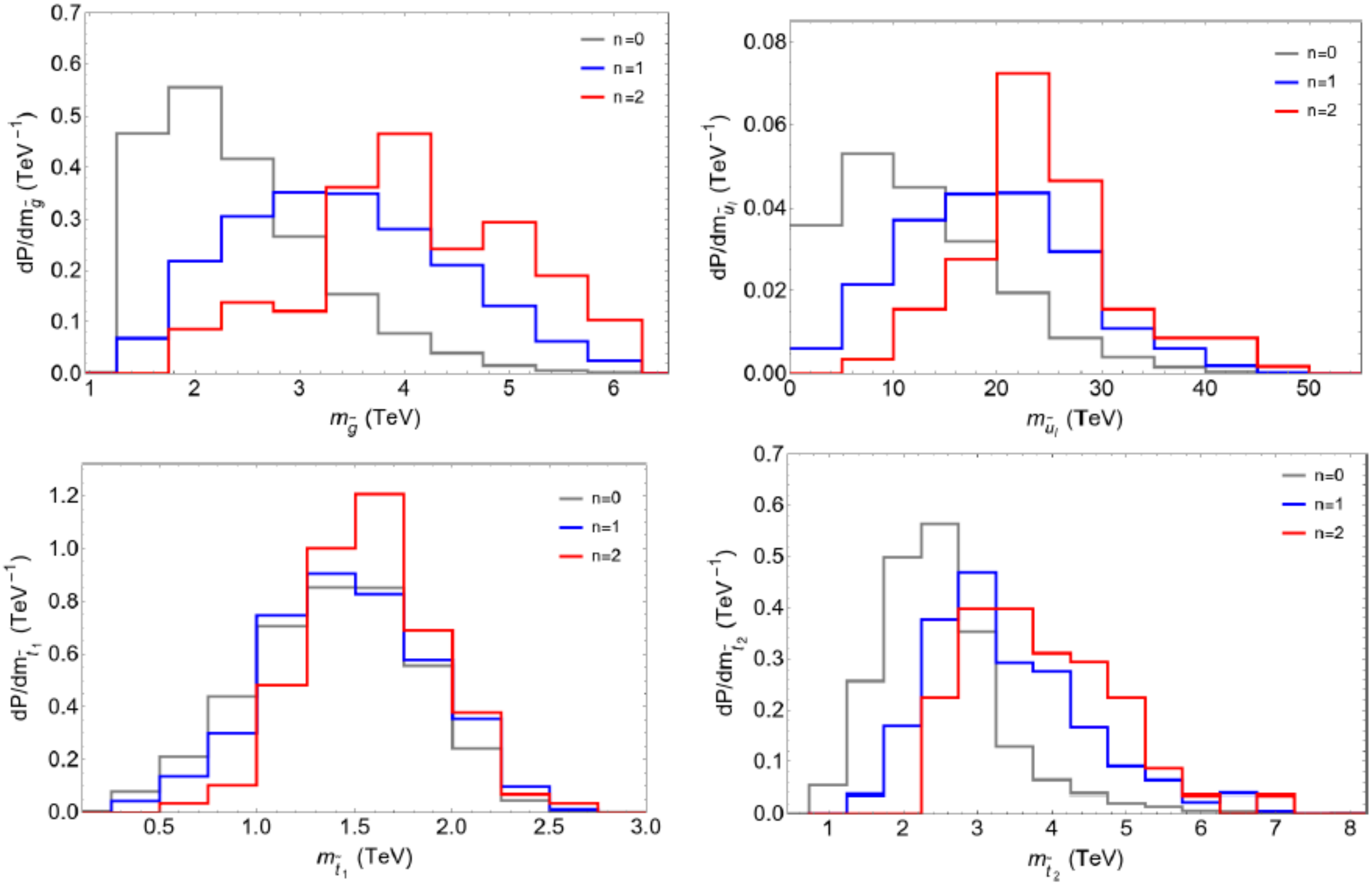
Making the picture more quantitative:

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



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

HB,Barger, Serce, Sinha



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,
- $\tan\beta \sim 13 \pm 7$,
- $m_{\widetilde{W}_1, \tilde{Z}_{1,2}} \sim 200 \pm 100$ 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).

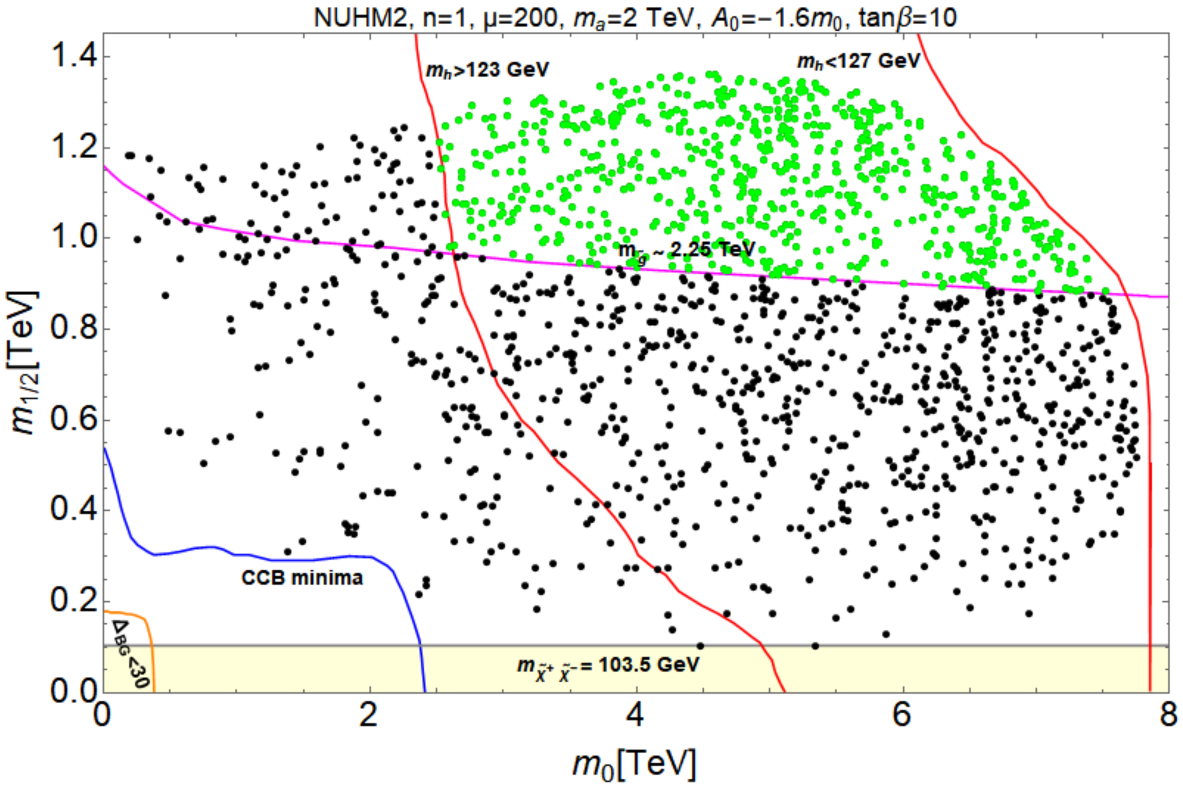
From stringy naturalness, expect LHC to see Higgs with m(h)~125 GeV but as yet no sign of sparticles!

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

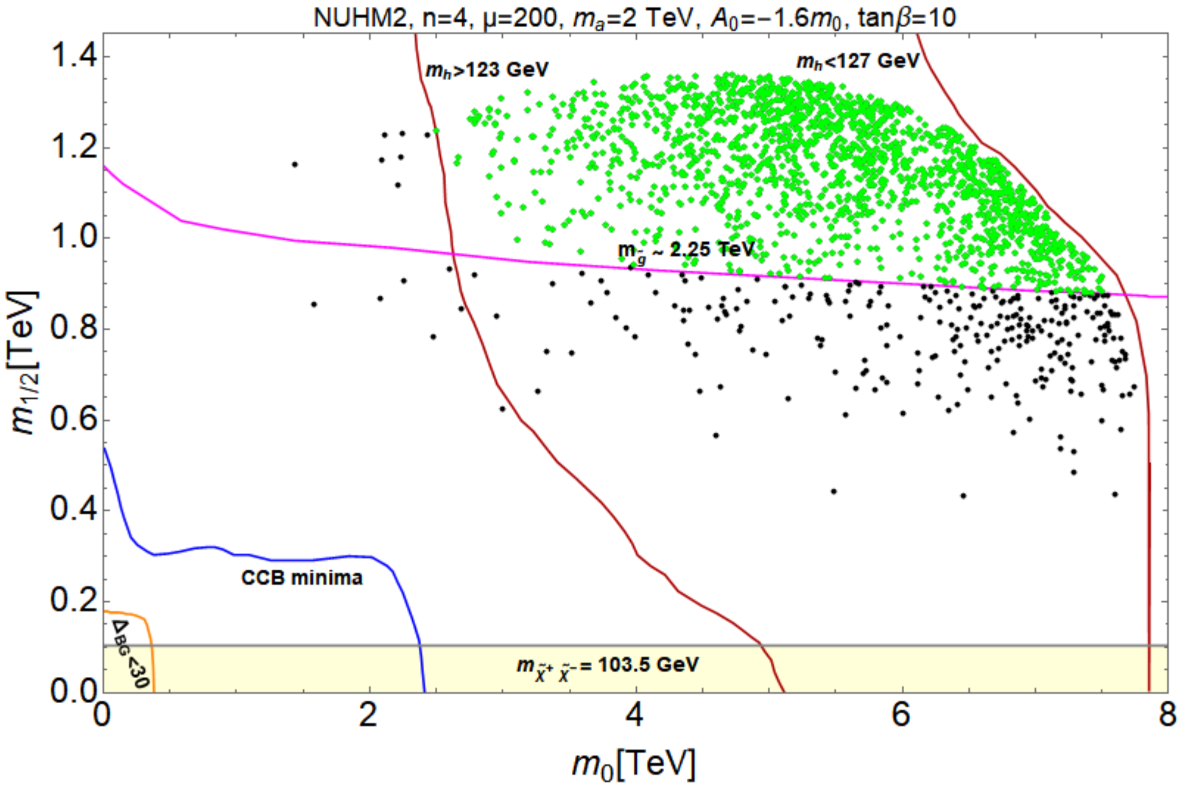
conventional natural: favor low m0, mhf

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

HB, Barger, Salam, arXiv:1906.07741



$$m(soft)^1$$



$$m(soft)^4$$

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(weak)~m(W,Z,h)~100-350 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 t1) to ~5 TeV level

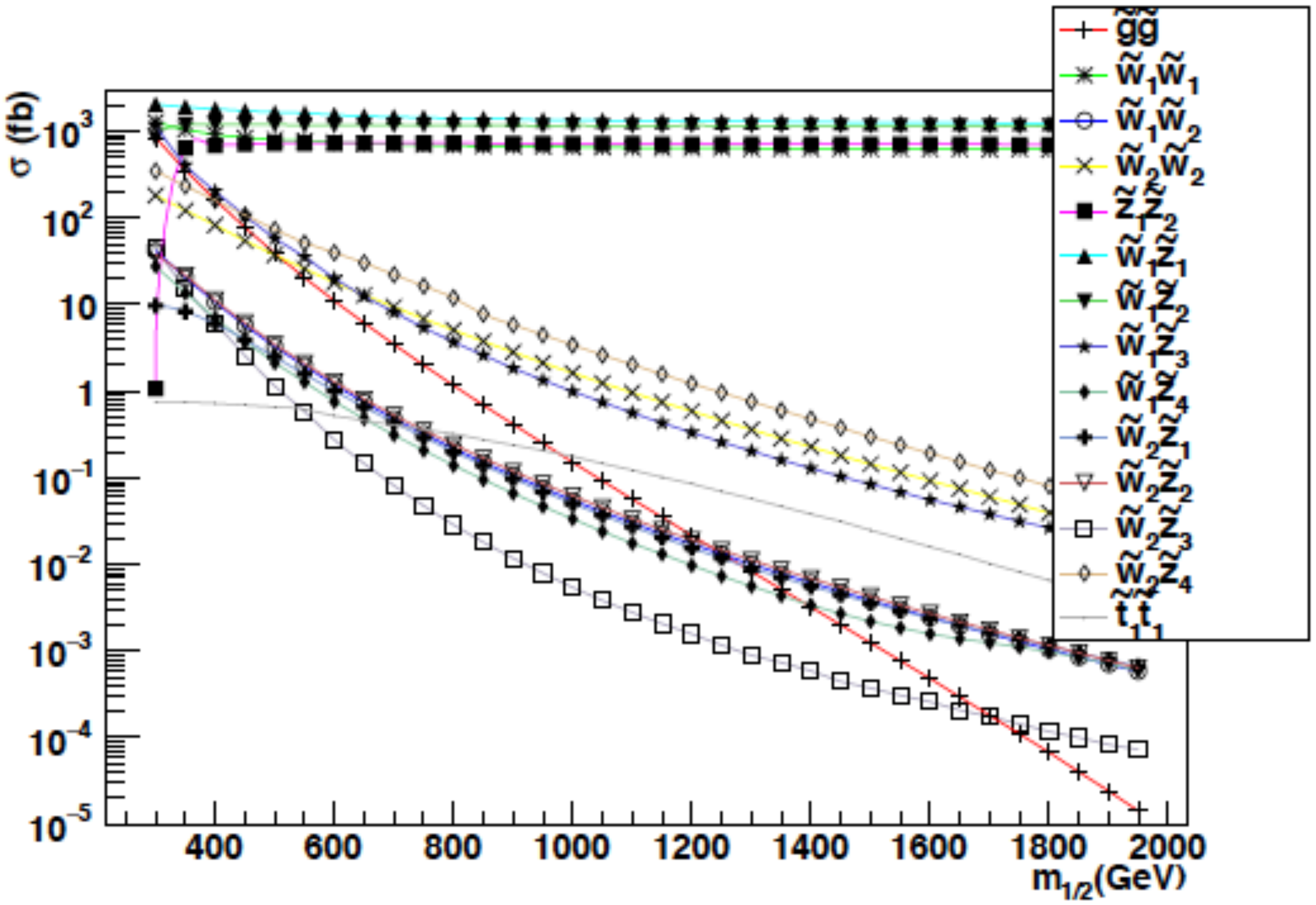
HB, Barger, Sengupta, arXiv:1910.00090

Conclusions:

- Time to set aside old notions of naturalness: BG and HS
- Plenty of natural parameter space under model independent 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 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:



higgsinos

gauginos

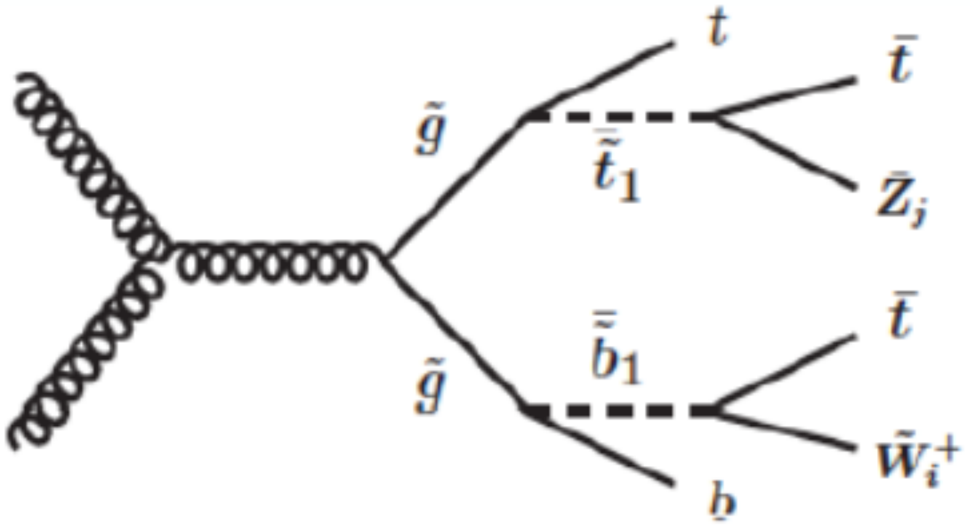
gluinos

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

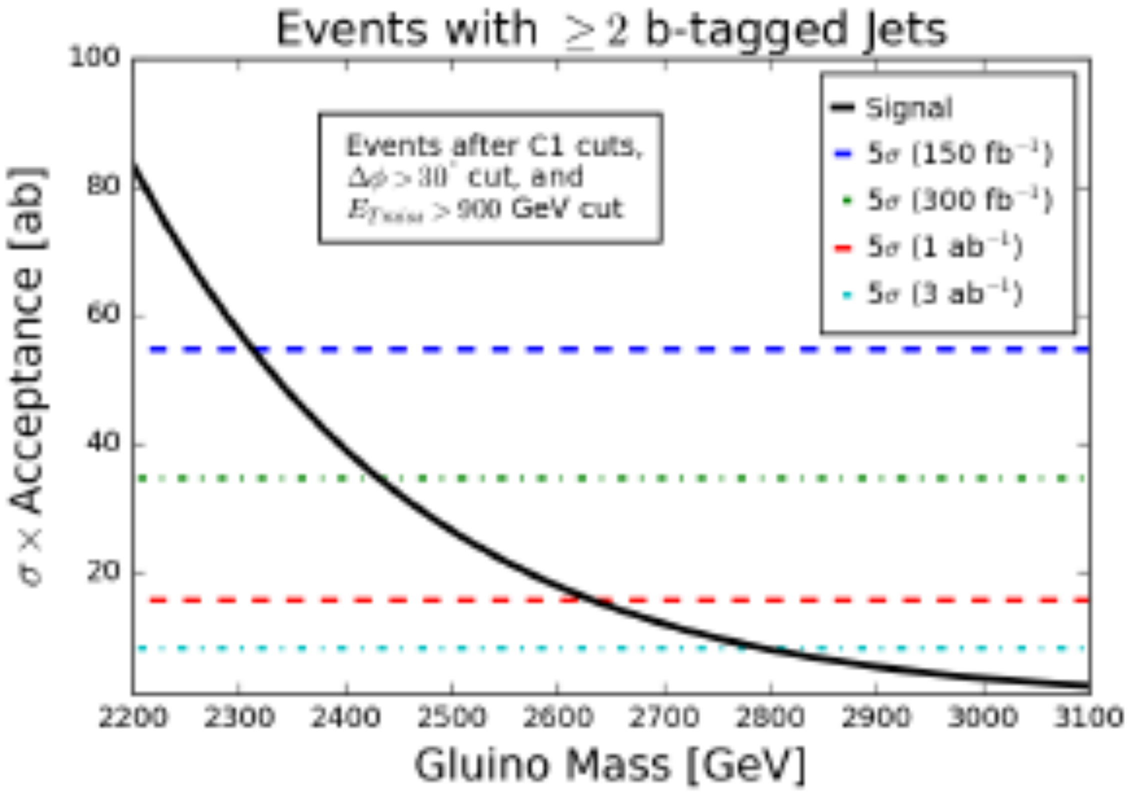
largest visible cross section: wino pairs

gluino pairs sharply dropping

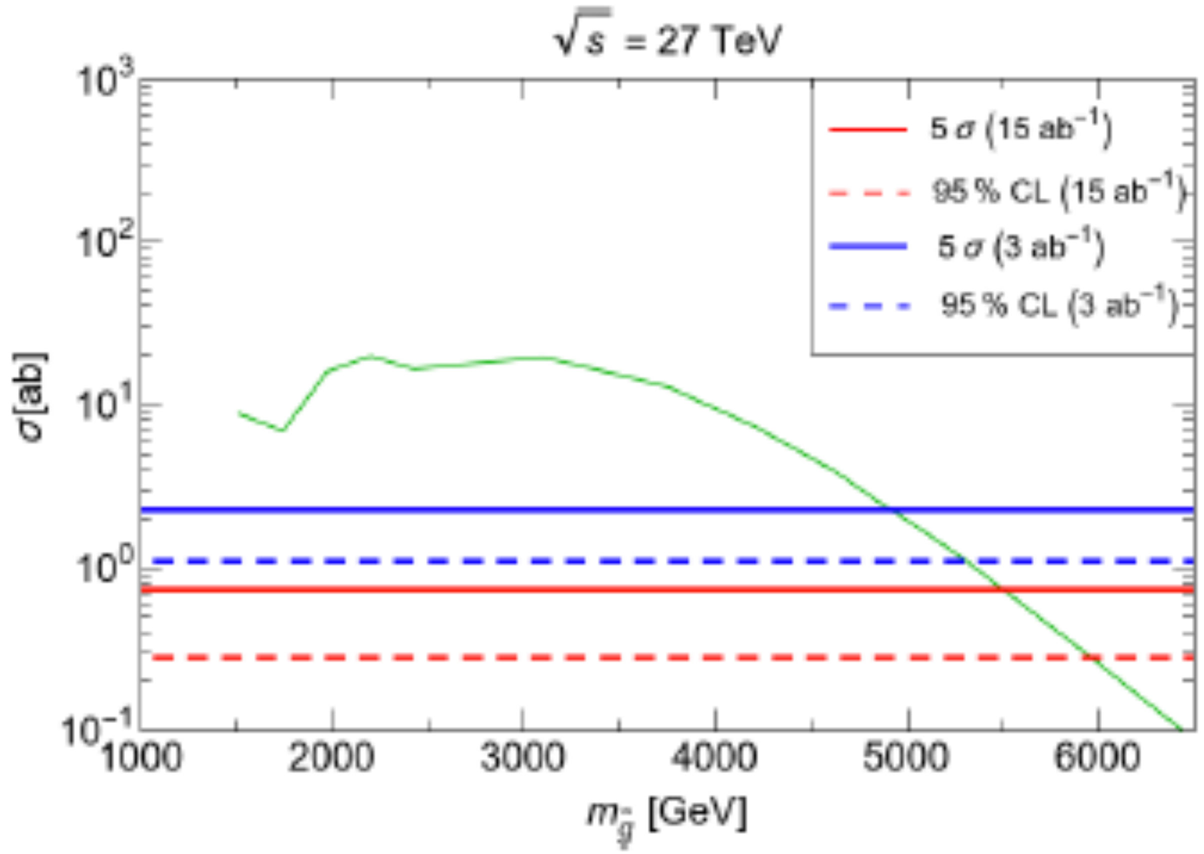
gluino pair cascade decay signatures



LHC14



LHC27

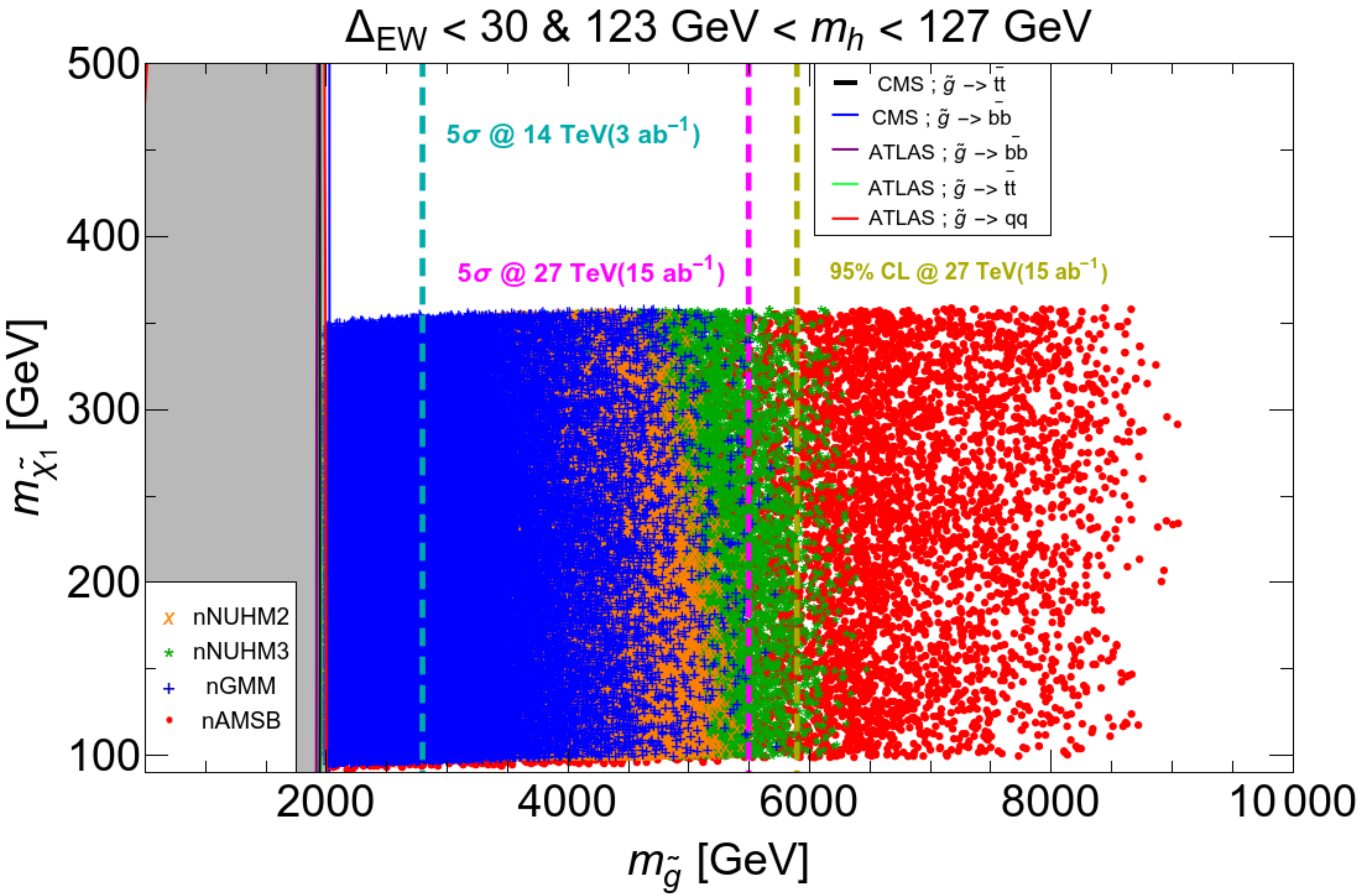


HB, Barger, Gainer, Huang, Savoy, Sengupta,Tata

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

RNS in simplified model parameter space

Compare upper bounds on m(gl) from naturalness (DEW<30)
to HL/HE-LHC reach

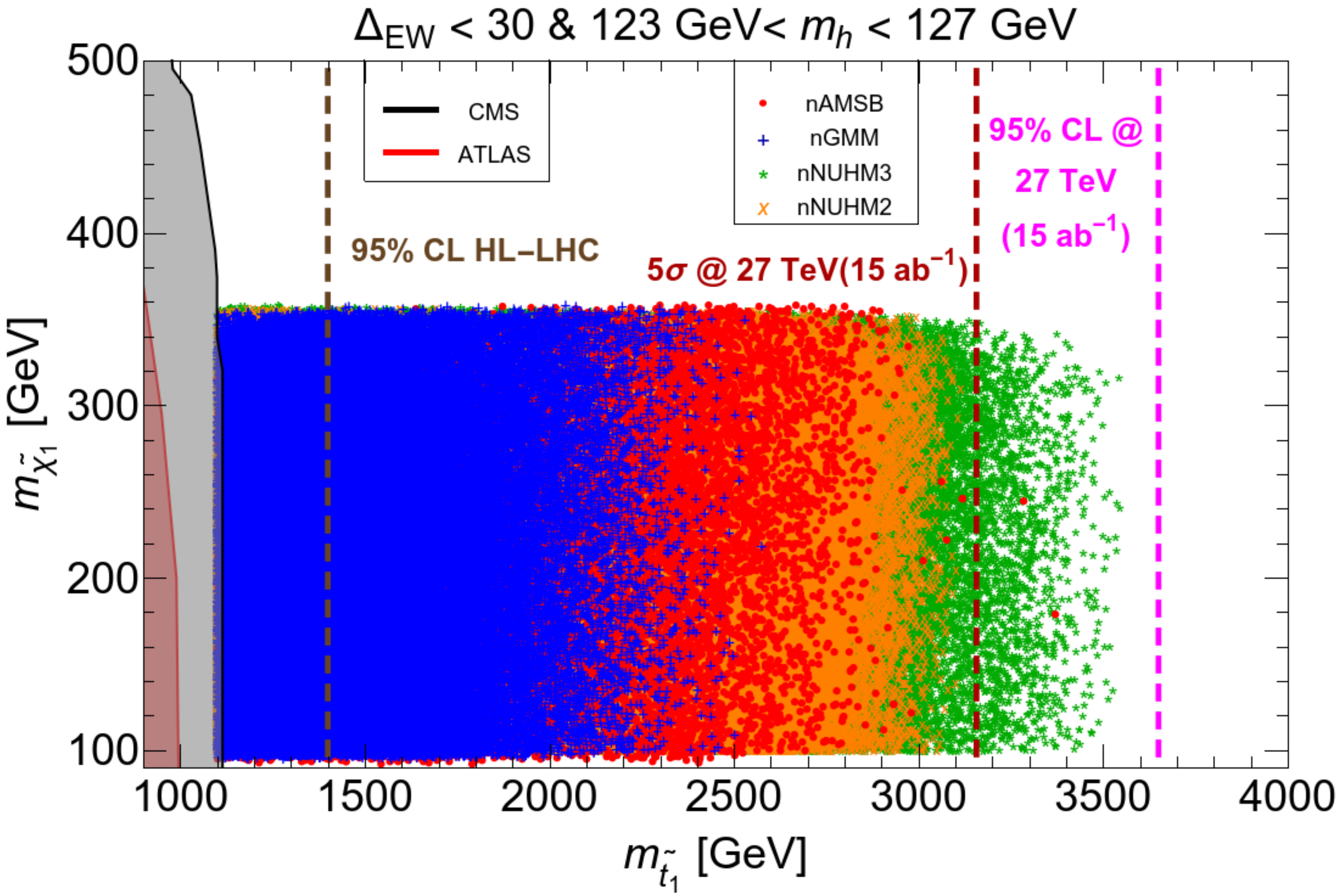


$\Delta_{EW} < 30$ & 123 GeV $< m_h < 127$ GeV

HB, Barger, Gainer, Sengupta, Serce, Tata

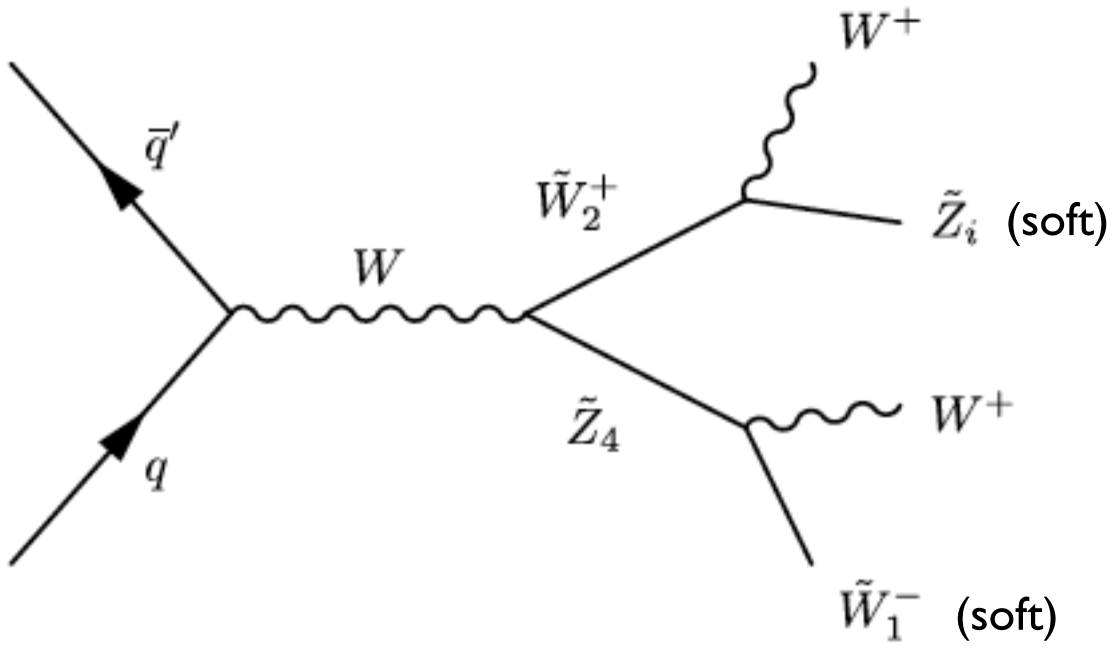
Will need LHC energy upgrade to 27 TeV to cover all natural SUSY p-space (except nAMSB)

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

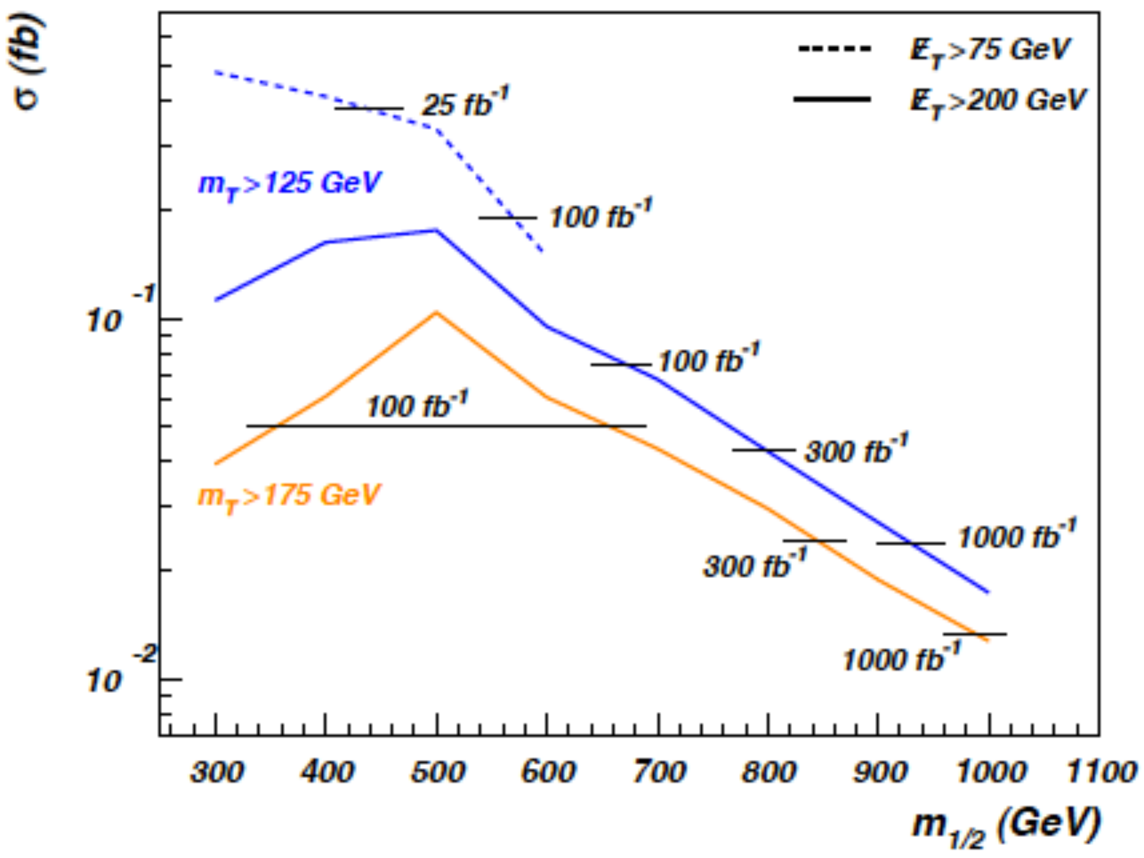


HB, Barger, Gainer, Sengupta, Serce, Tata

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



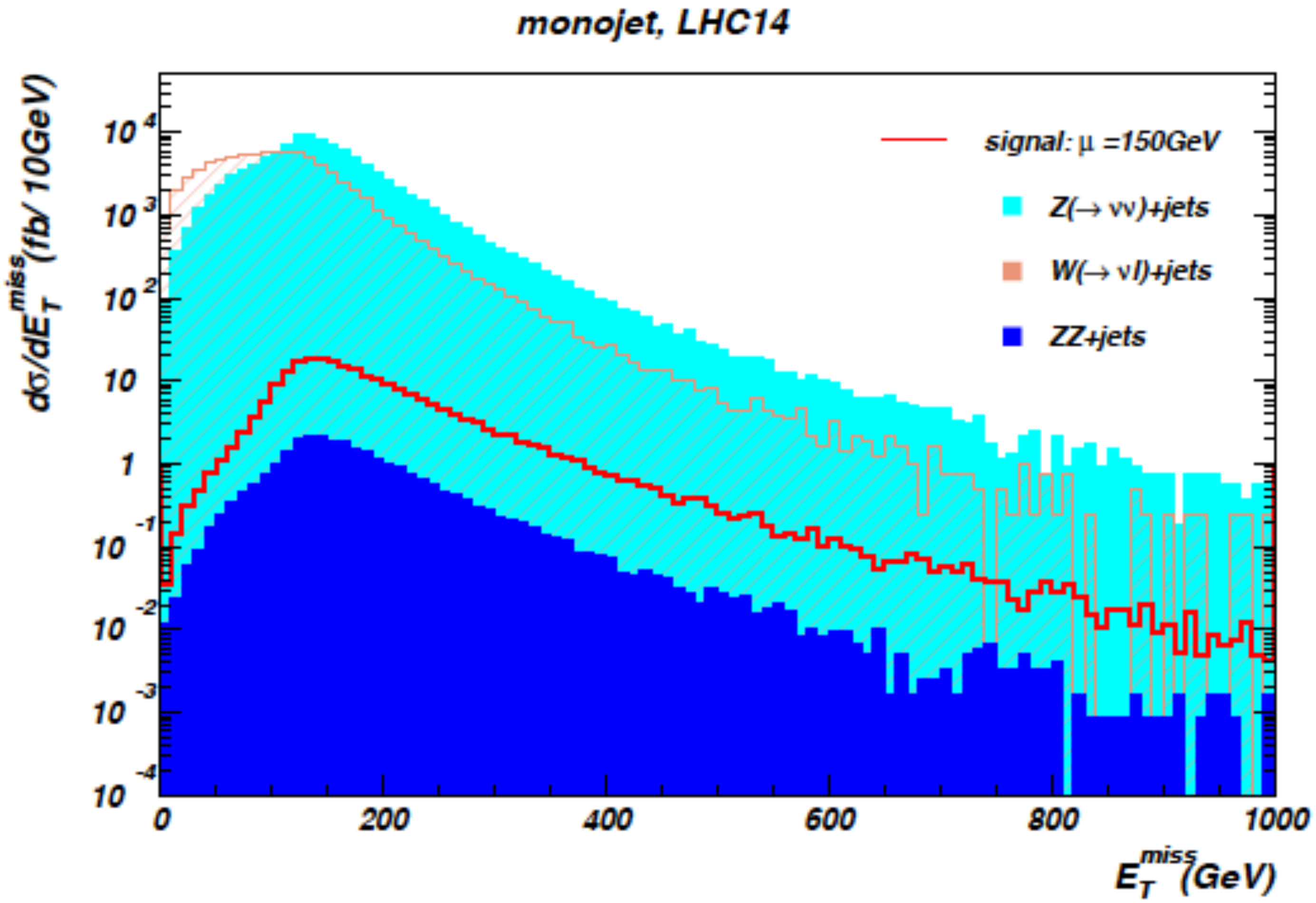
wino pair production



This channel offers added reach of LHC14 for nSUSY; 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.

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

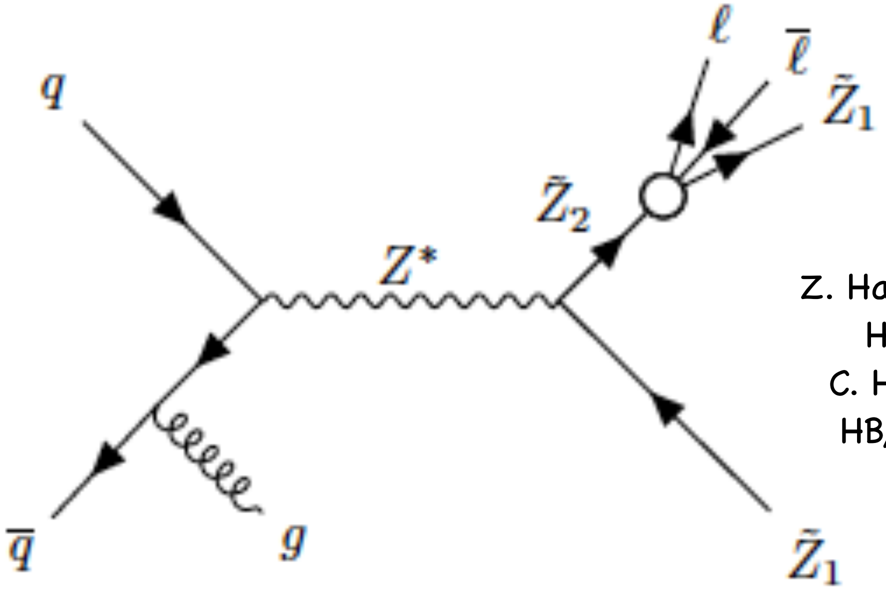


typically 1% S/BG after cuts:
very tough to do!

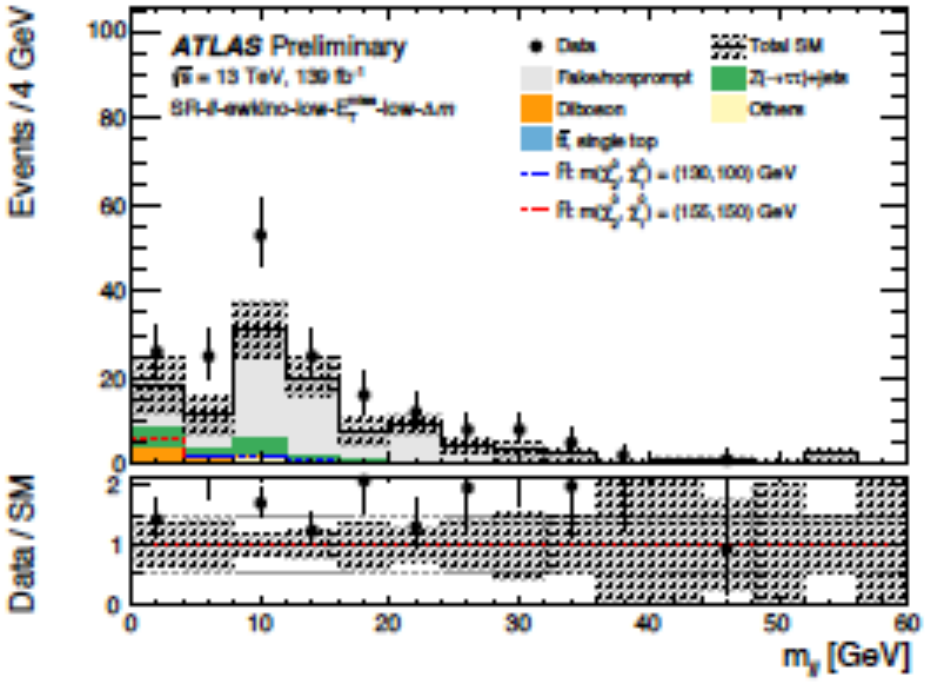
HB, Mustafayev, Tata

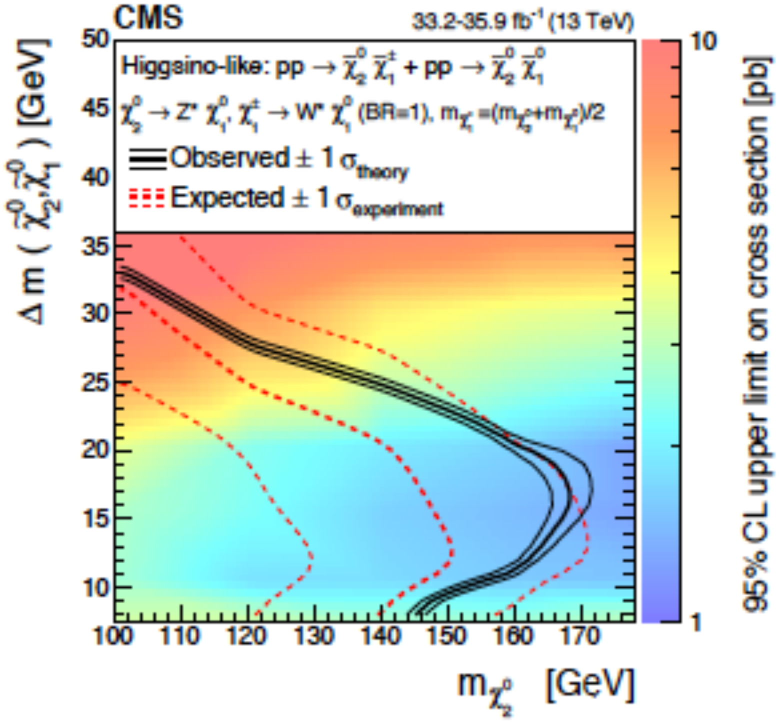
Natural SUSY: only higgsinos need lie close to weak scale

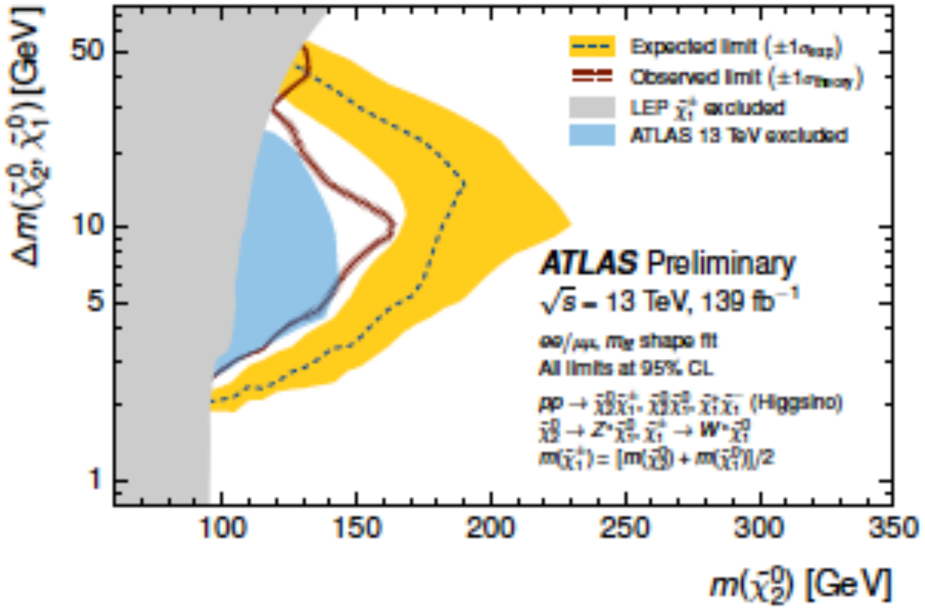
Soft dilepton+jet+MET signature from higgsino pair production



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



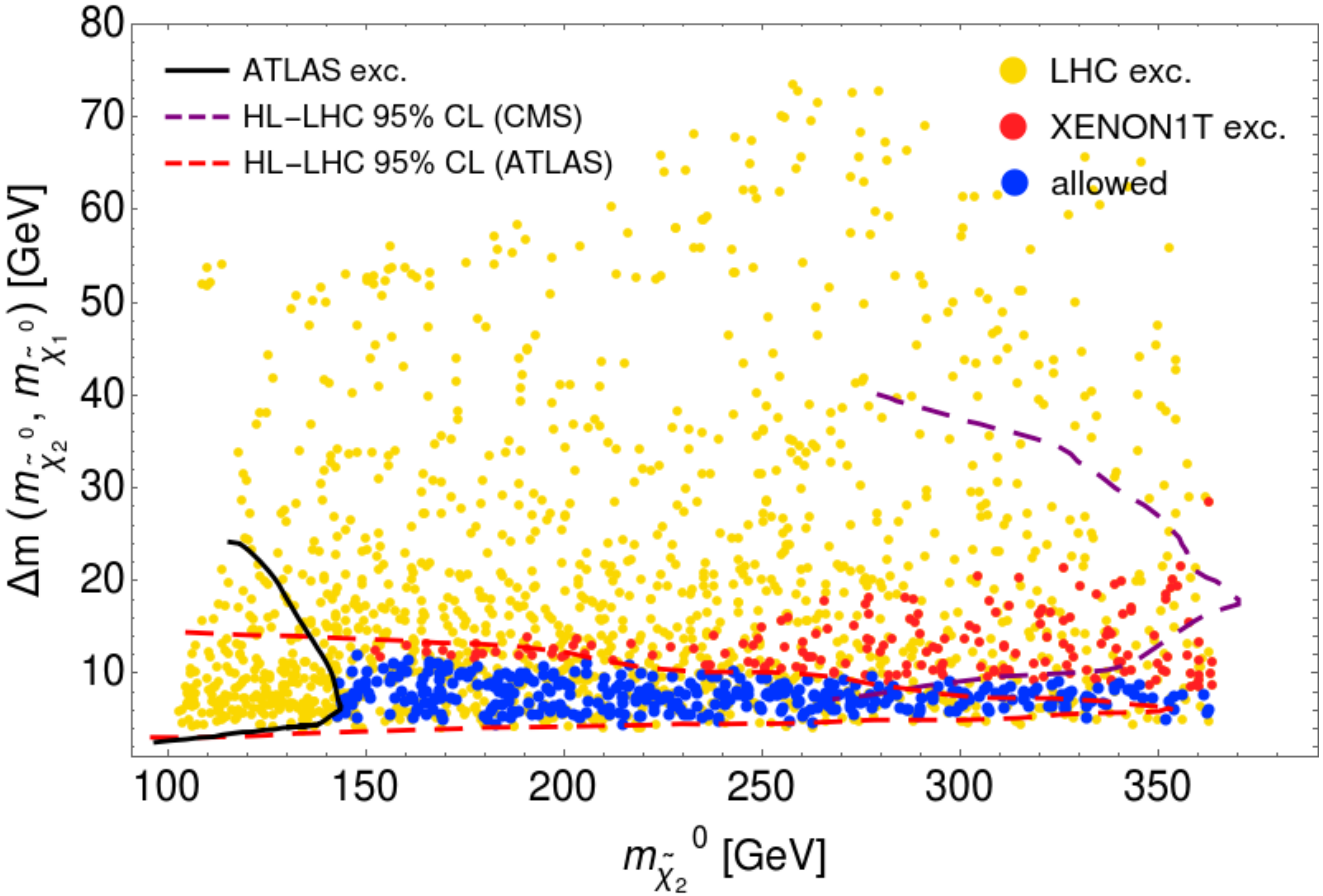




It appears that HL-LHC can see entire natural SUSY p-space;
signal in this channel should emerge slowly as more integrated luminosity accrues

Only higgsinos required to lie near weak scale

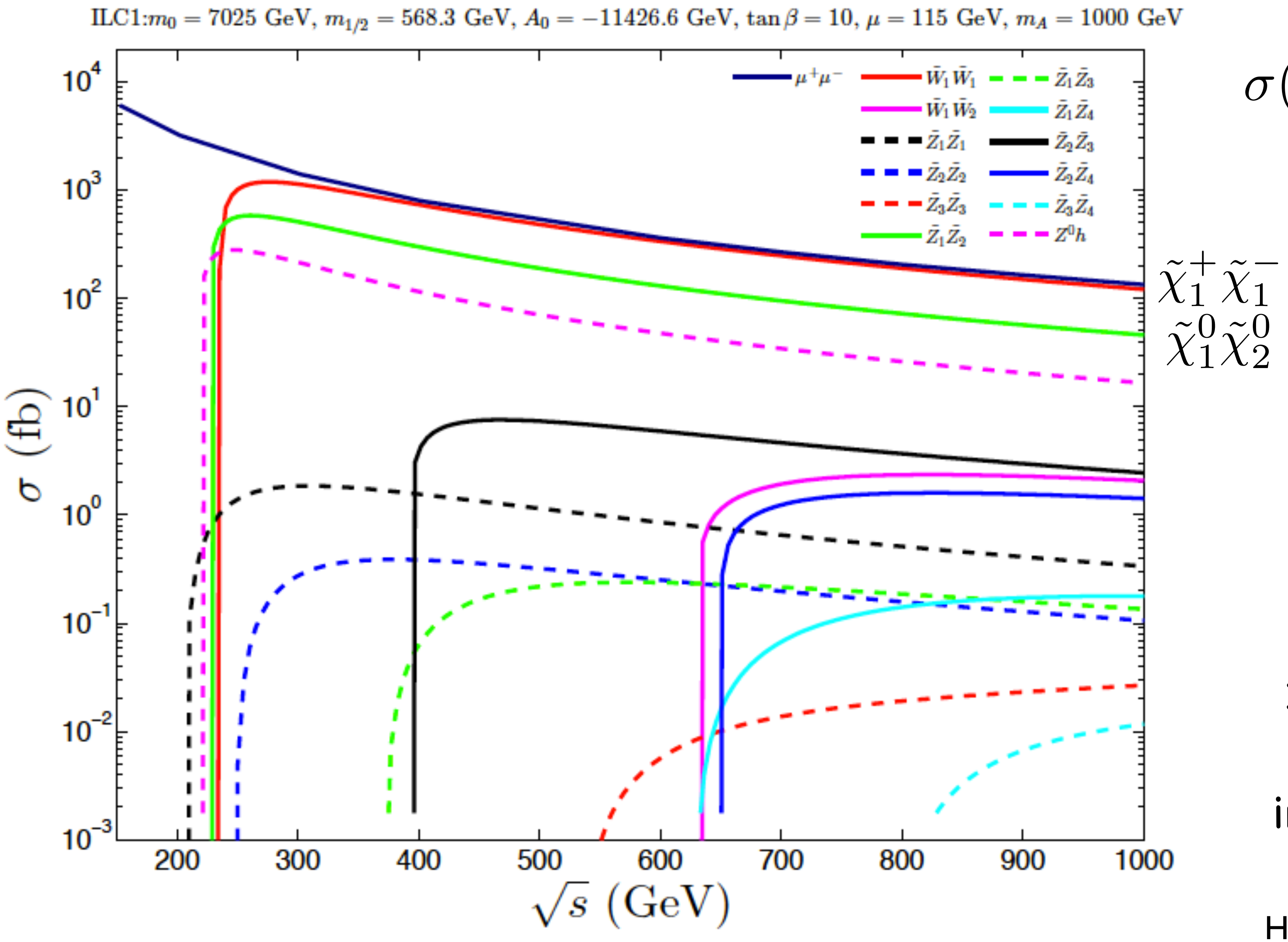
blue points are stringy natural



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!



ILC1:$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV, $A_0 = -11426.6$ GeV, $\tan\beta = 10$, $\mu = 115$ GeV, $m_A = 1000$ GeV

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

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

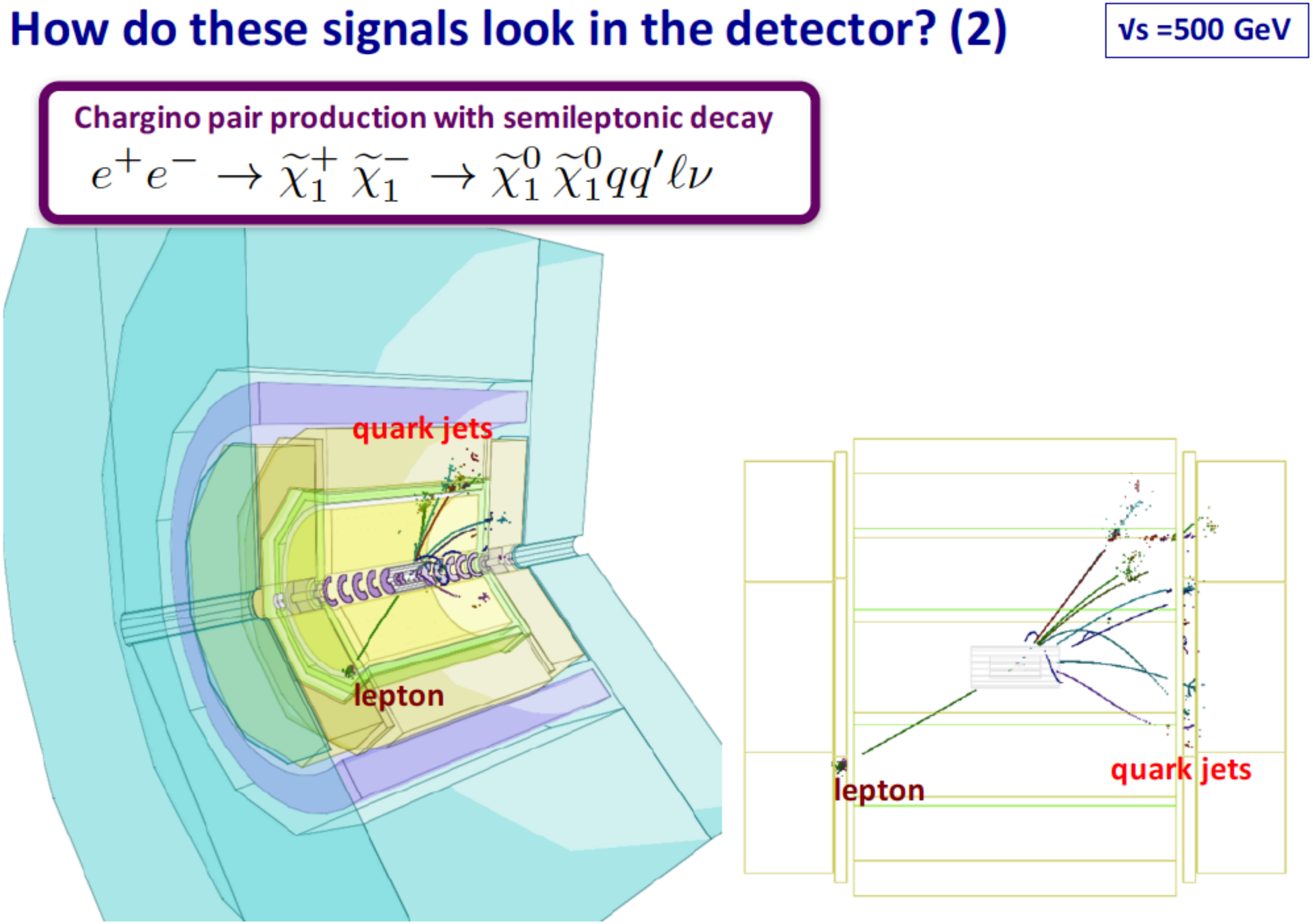
HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

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

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

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)

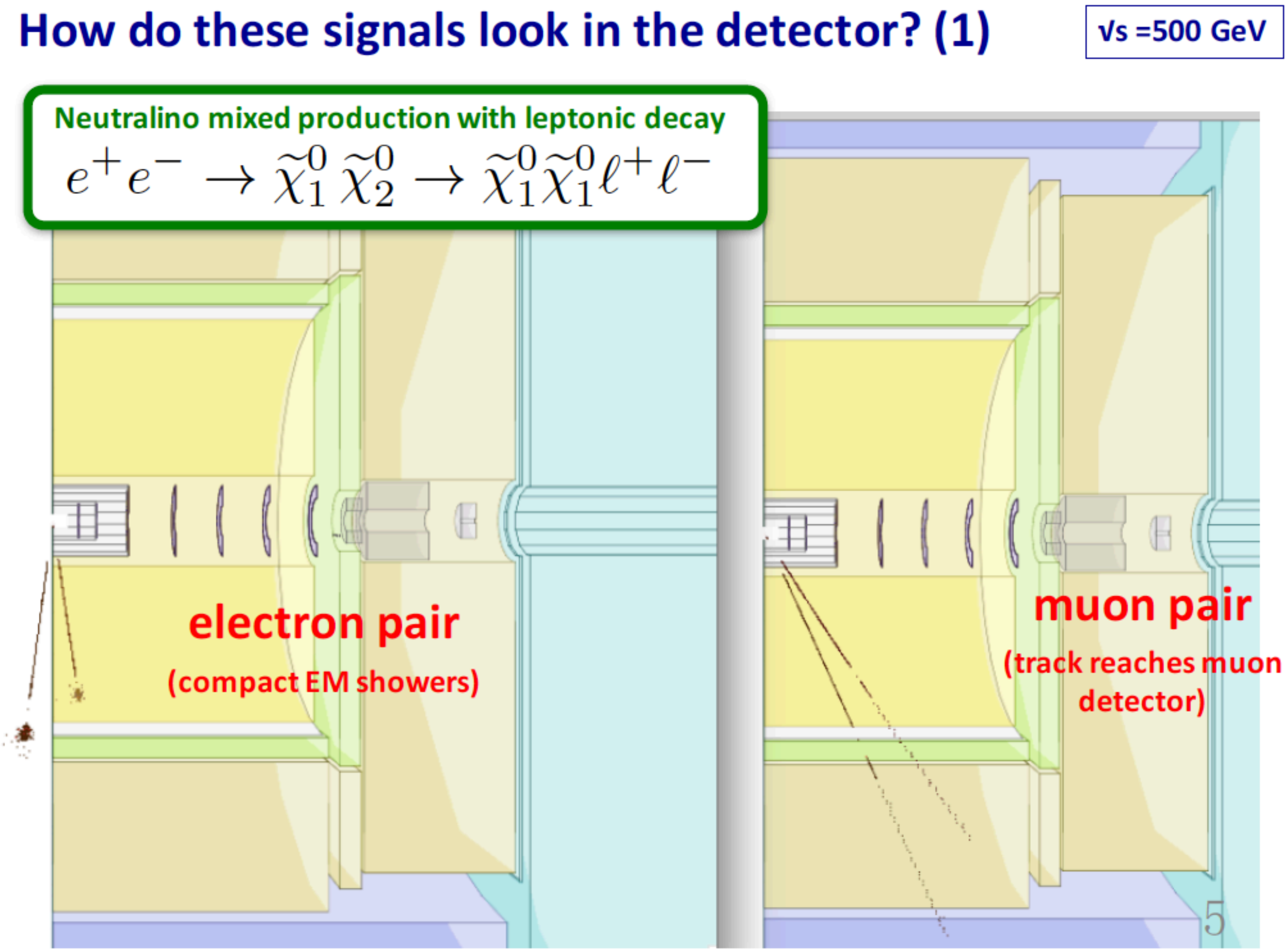
√s =500 GeV

Chargino pair production with semileptonic decay

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

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

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

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

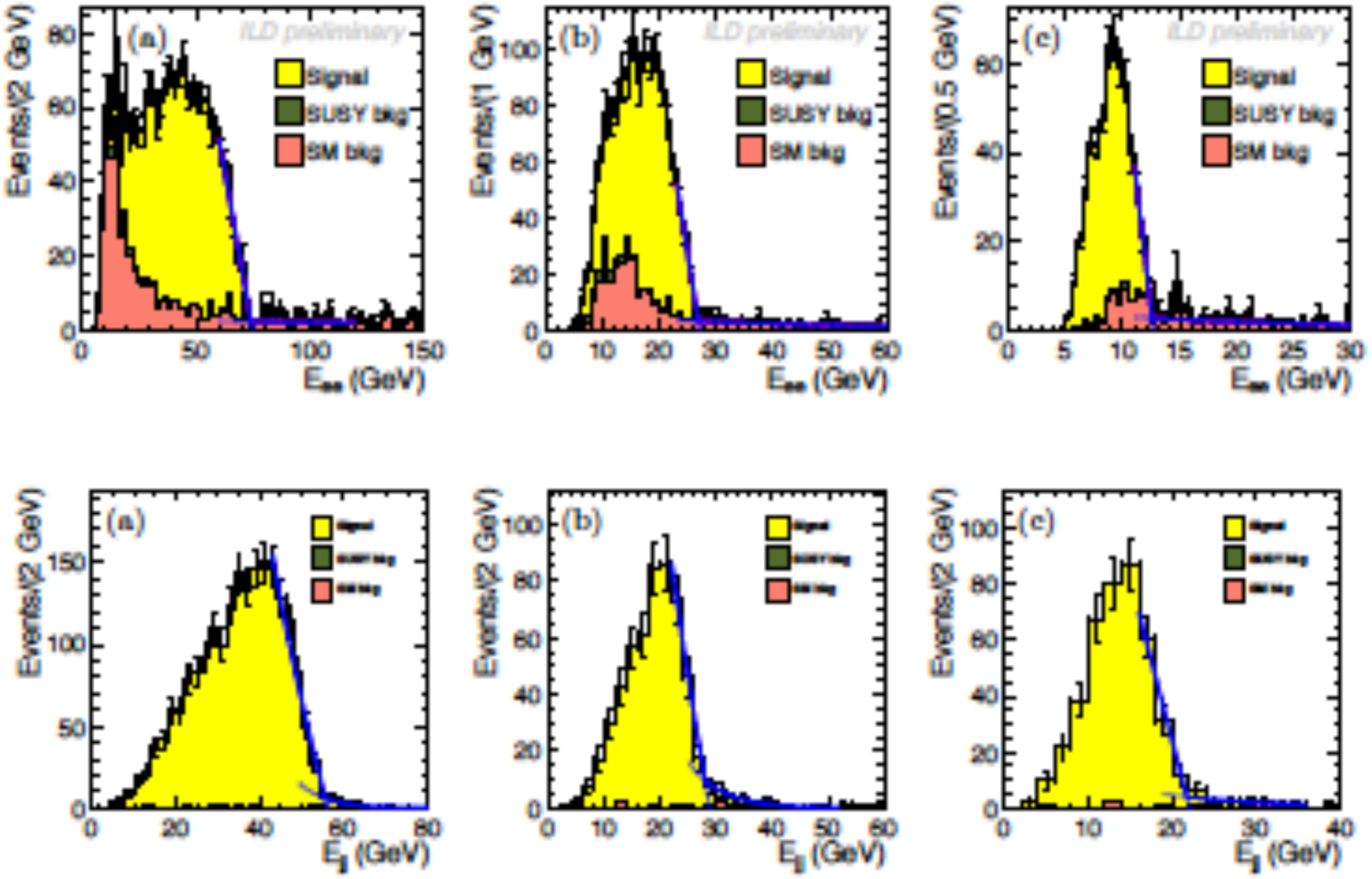
electron pair

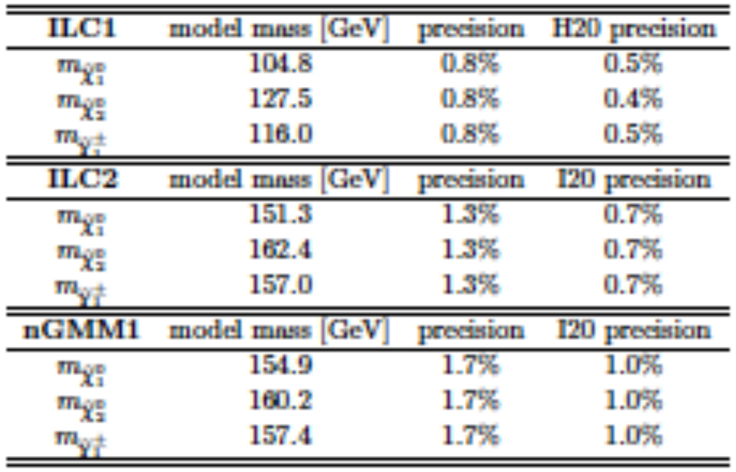
(compact EM showers)

muon pair

(track reaches muon detector)

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

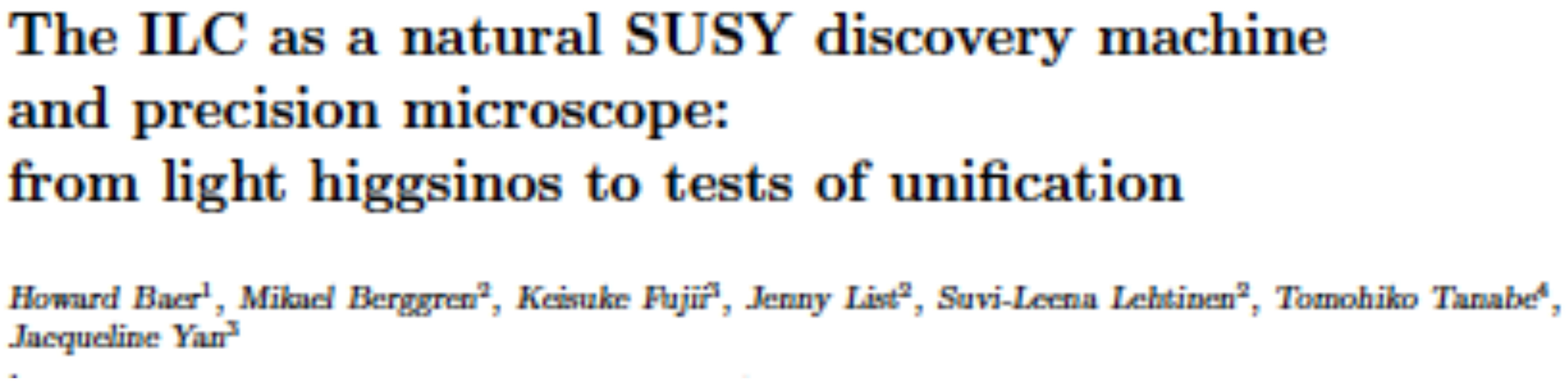




ILC1	model mass [GeV]	precision	H20 precision
$m_{\tilde{\chi}_1^0}$	104.8	0.8%	0.5%
$m_{\tilde{\chi}_2^0}$	127.5	0.8%	0.4%
$m_{\tilde{\chi}_1^\pm}$	116.0	0.8%	0.5%

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%

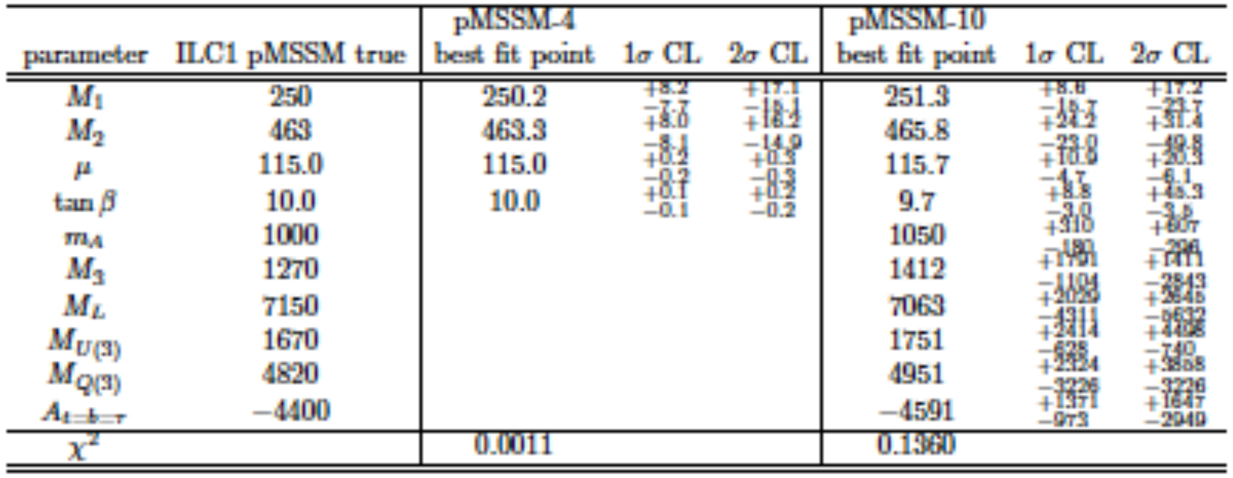
nGMM1	model mass [GeV]	precision	I20 precision
$m_{\tilde{\chi}_1^0}$	154.9	1.7%	1.0%
$m_{\tilde{\chi}_2^0}$	160.2	1.7%	1.0%
$m_{\tilde{\chi}_1^\pm}$	157.4	1.7%	1.0%



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

Howard Baer[1], Mikael Berggren[2], Keisuke Fujii[3], Jenny List[2], Suvi-Leena Lehtinen[2], Tomohiko Tanabe[4], Jacqueline Yan[3]

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



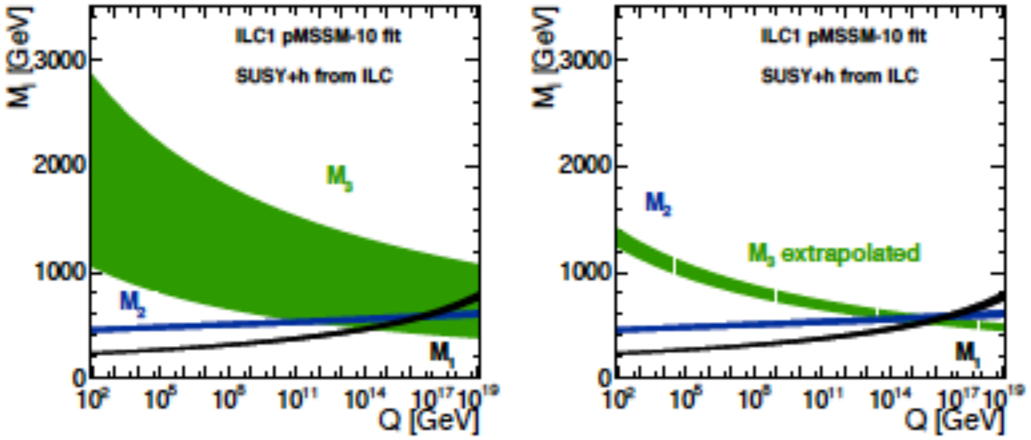
parameter	ILC1 pMSSM true	pMSSM-4 best fit point	1σ CL	2σ CL	pMSSM-10 best fit point	1σ CL	2σ CL
M_1	250	250.2	$^{+8.2}_{-7.7}$	$^{+17.1}_{-15.1}$	251.3	$^{+8.6}_{-15.7}$	$^{+17.2}_{-23.7}$
M_2	463	463.3	$^{+8.0}_{-8.1}$	$^{+18.2}_{-14.9}$	465.8	$^{+24.2}_{-23.0}$	$^{+31.4}_{-49.8}$
μ	115.0	115.0	$^{+0.2}_{-0.2}$	$^{+0.3}_{-0.3}$	115.7	$^{+10.9}_{-4.7}$	$^{+20.3}_{-6.1}$
$\tan\beta$	10.0	10.0	$^{+0.1}_{-0.1}$	$^{+0.2}_{-0.2}$	9.7	$^{+8.8}_{-3.0}$	$^{+45.3}_{-3.6}$
m_A	1000				1050	$^{+310}_{-180}$	$^{+607}_{-206}$
M_3	1270				1412	$^{+1791}_{-1104}$	$^{+1411}_{-2843}$
M_L	7150				7063	$^{+2029}_{-4311}$	$^{+2845}_{-6632}$
$M_{U(3)}$	1670				1751	$^{+2414}_{-628}$	$^{+4498}_{-740}$
$M_{Q(3)}$	4820				4951	$^{+2324}_{-3226}$	$^{+3858}_{-3226}$
$A_{t=b=\tau}$	−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 M1 and M2 via
global fit to higgsino/higgs
observables

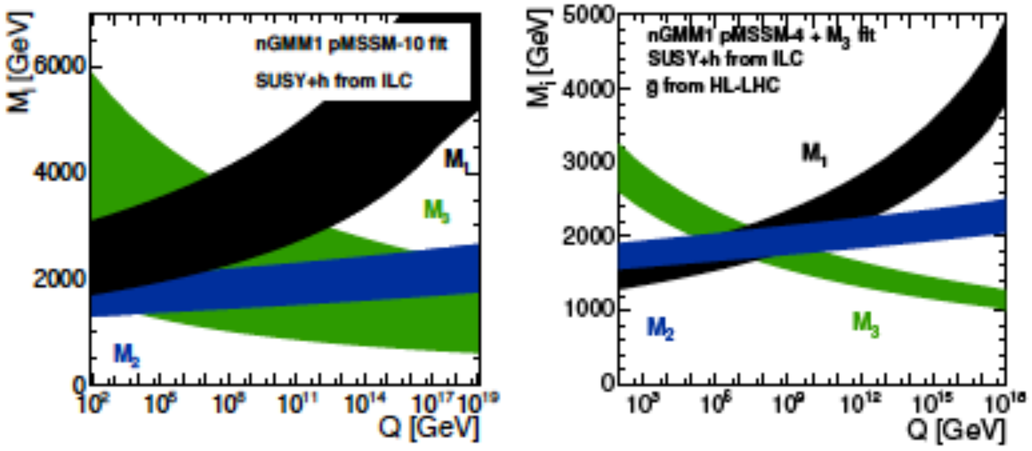
HB, Berggren, Fujii, List,
Lehtinen, Tanabe and Yan
(to appear shortly)

Test gaugino mass unification!



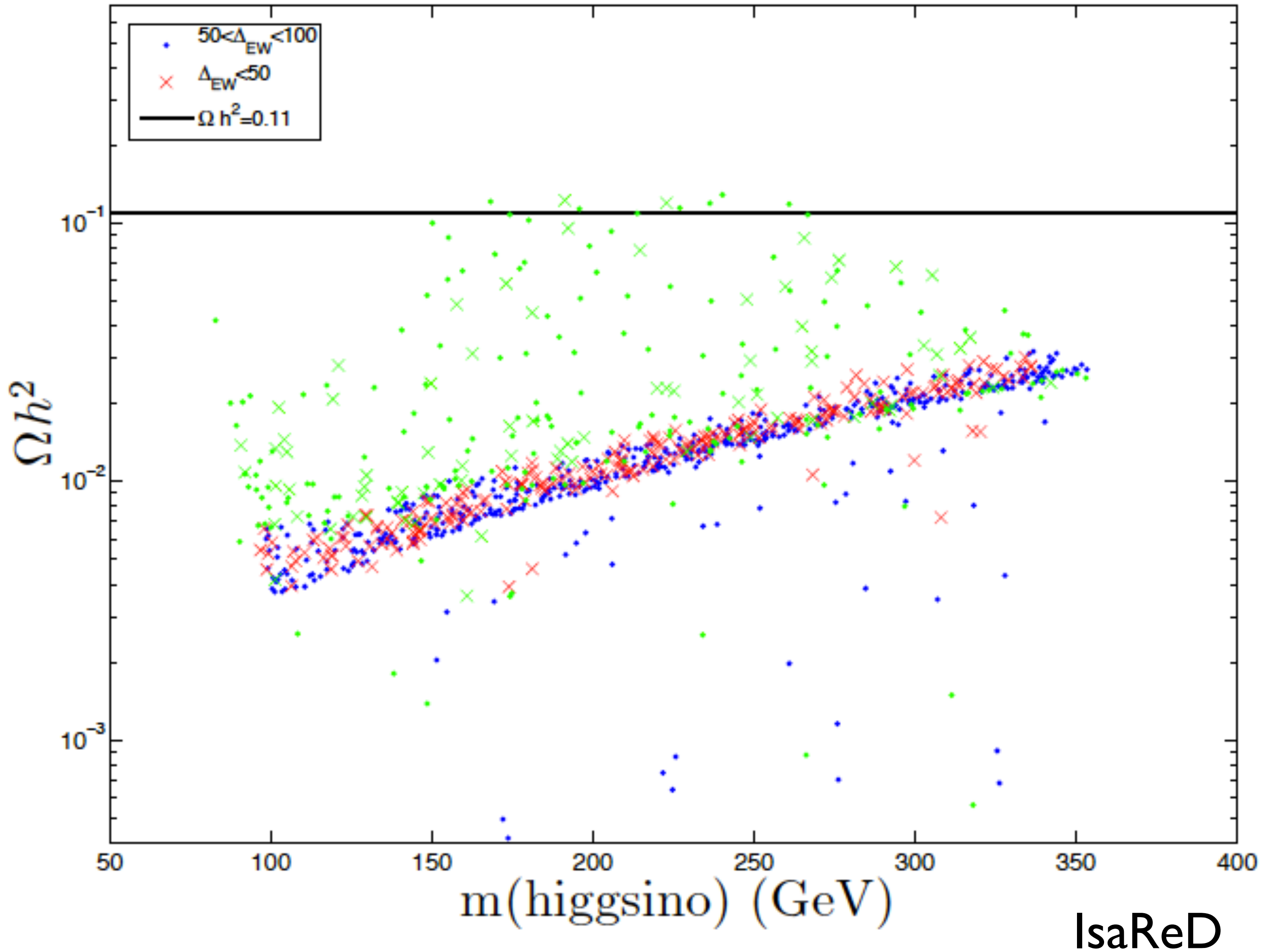
gaugino masses unify at mGUT
in NUHM2,3 models

natural mirage mediation benchmark point;
unify at intermediate mirage scale



Dark matter from SUSY with radiatively-driven naturalness

Mainly higgsino-like WIMPs with m(WIMP)~100-300 GeV thermally underproduce DM



IsaReD

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

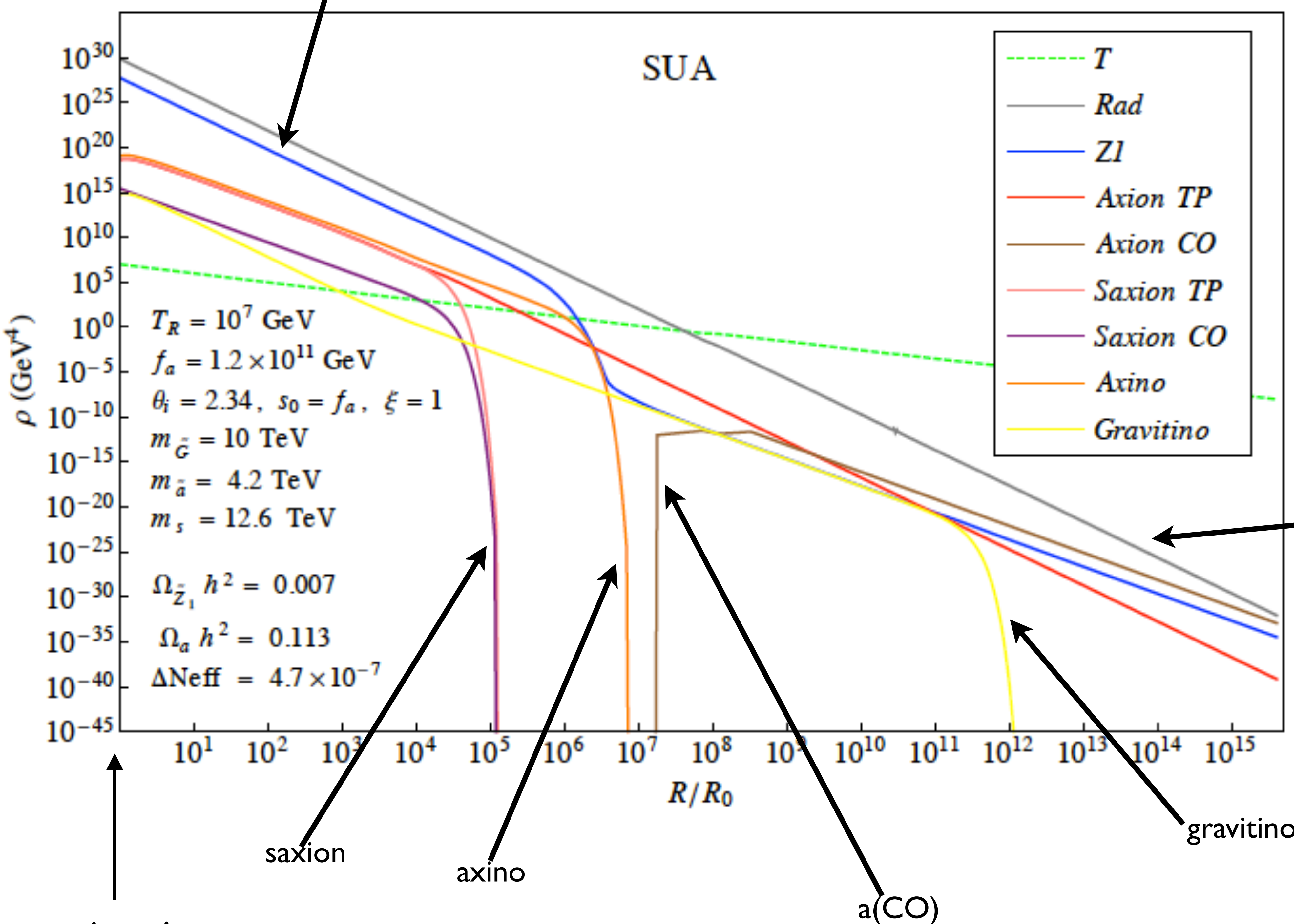
In SUSY, axion accompanied by axino and saxion

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 $s \to aa$, 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



wimp

radiation

saxion

axino

a(CO)

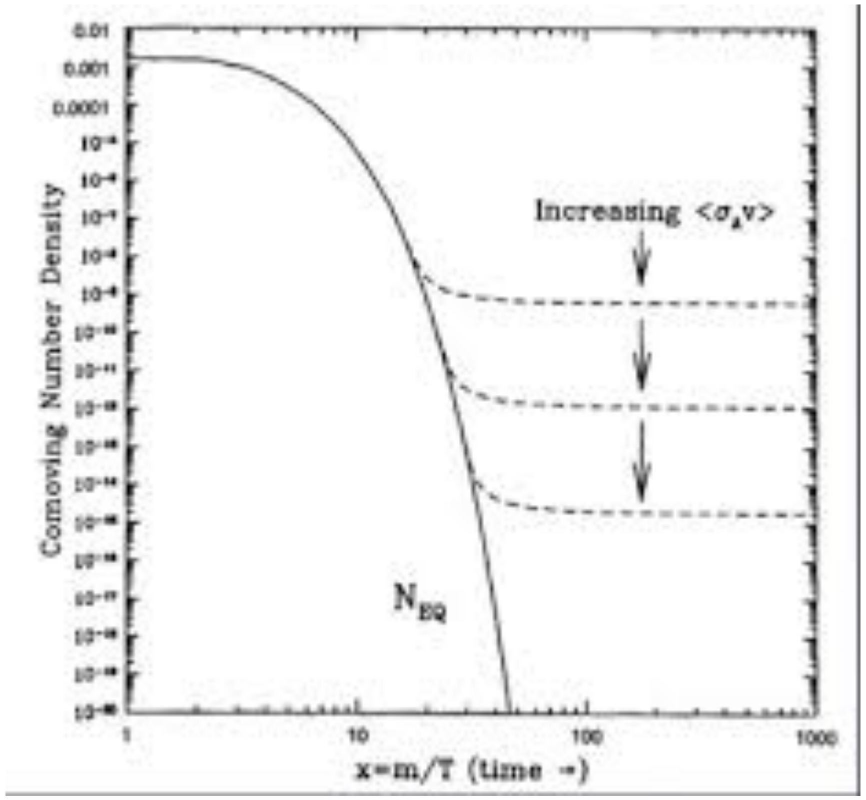
gravitino

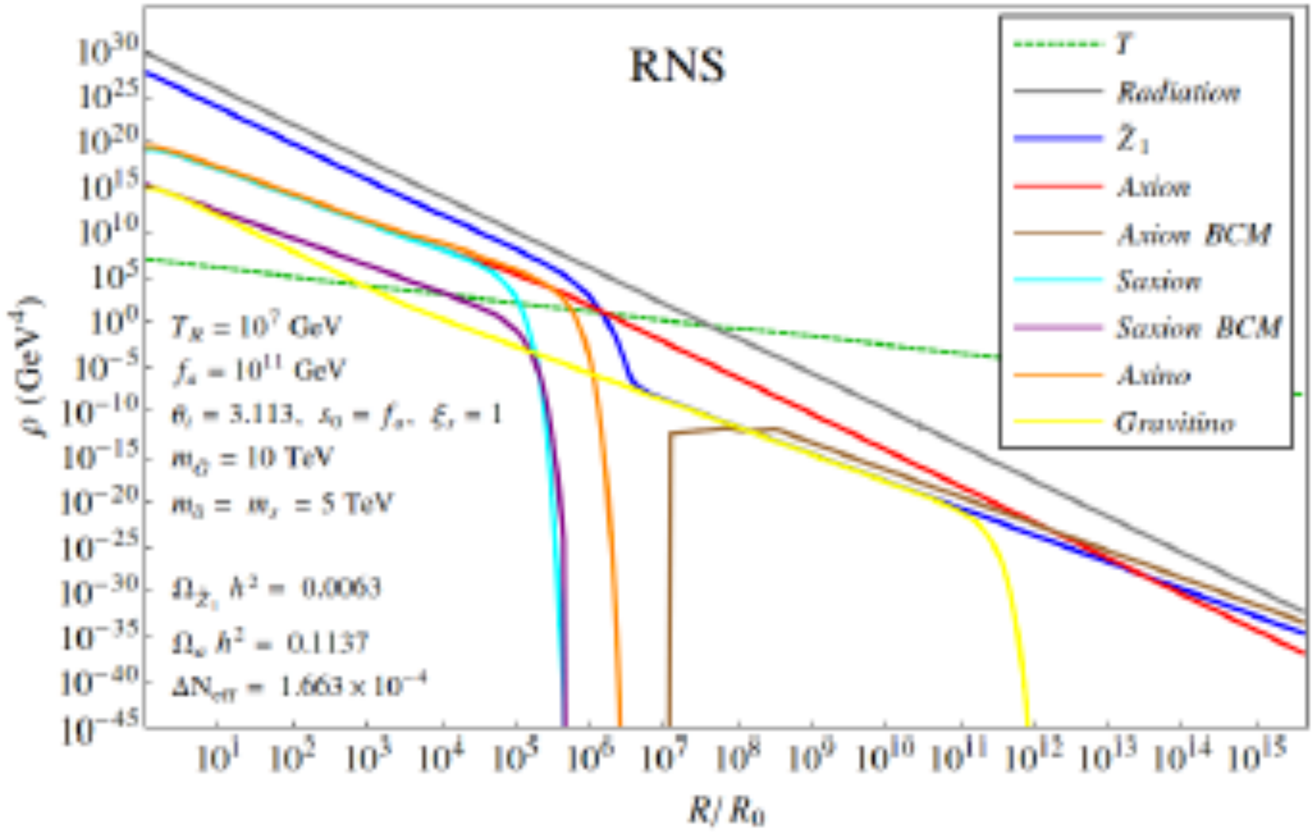
re-heat

Bae, HB, Chun;

Bae, HB, Lessa, Serce

usual picture => mixed axion/WIMP

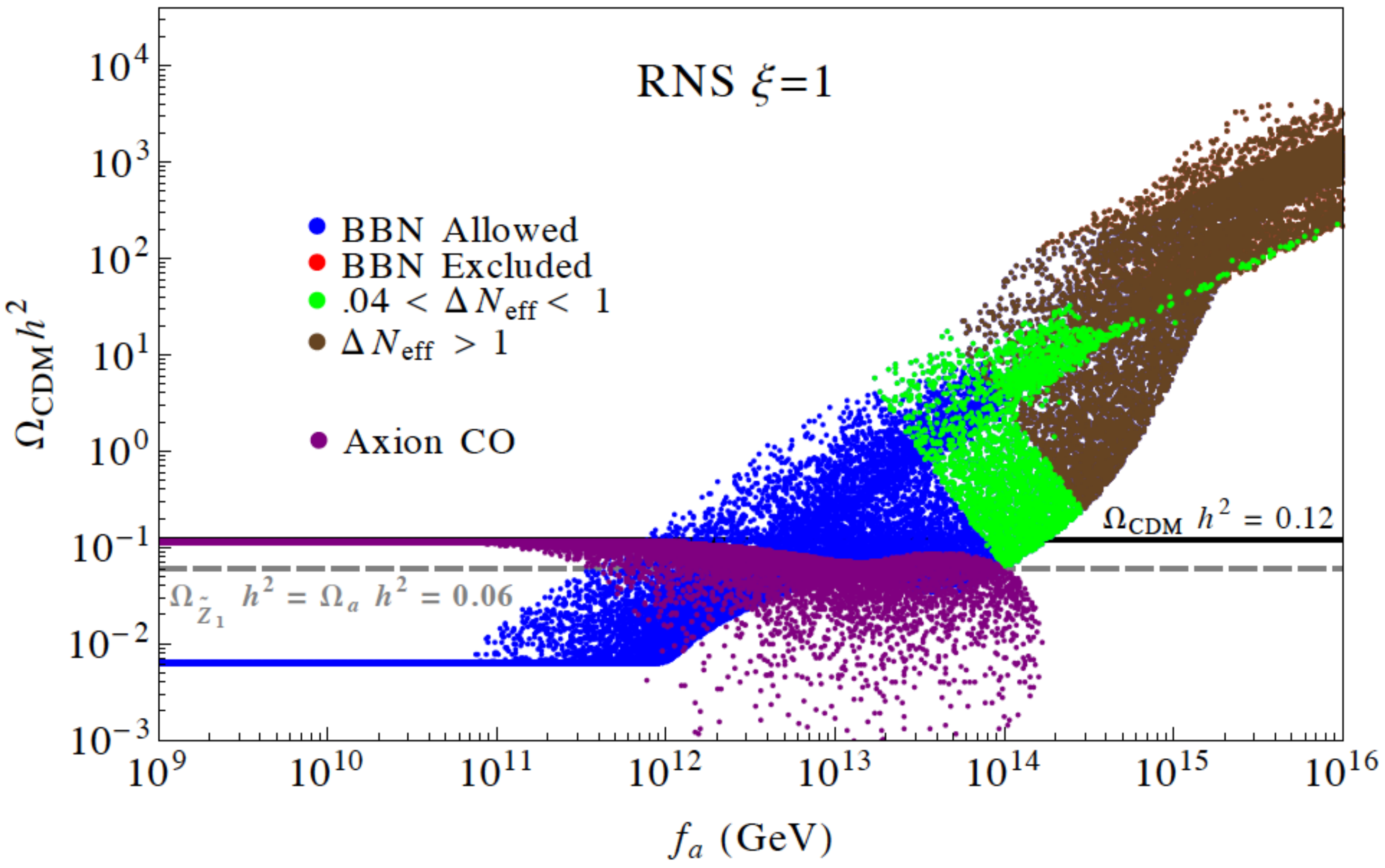




KJ Bae, HB, Lessa, Serce

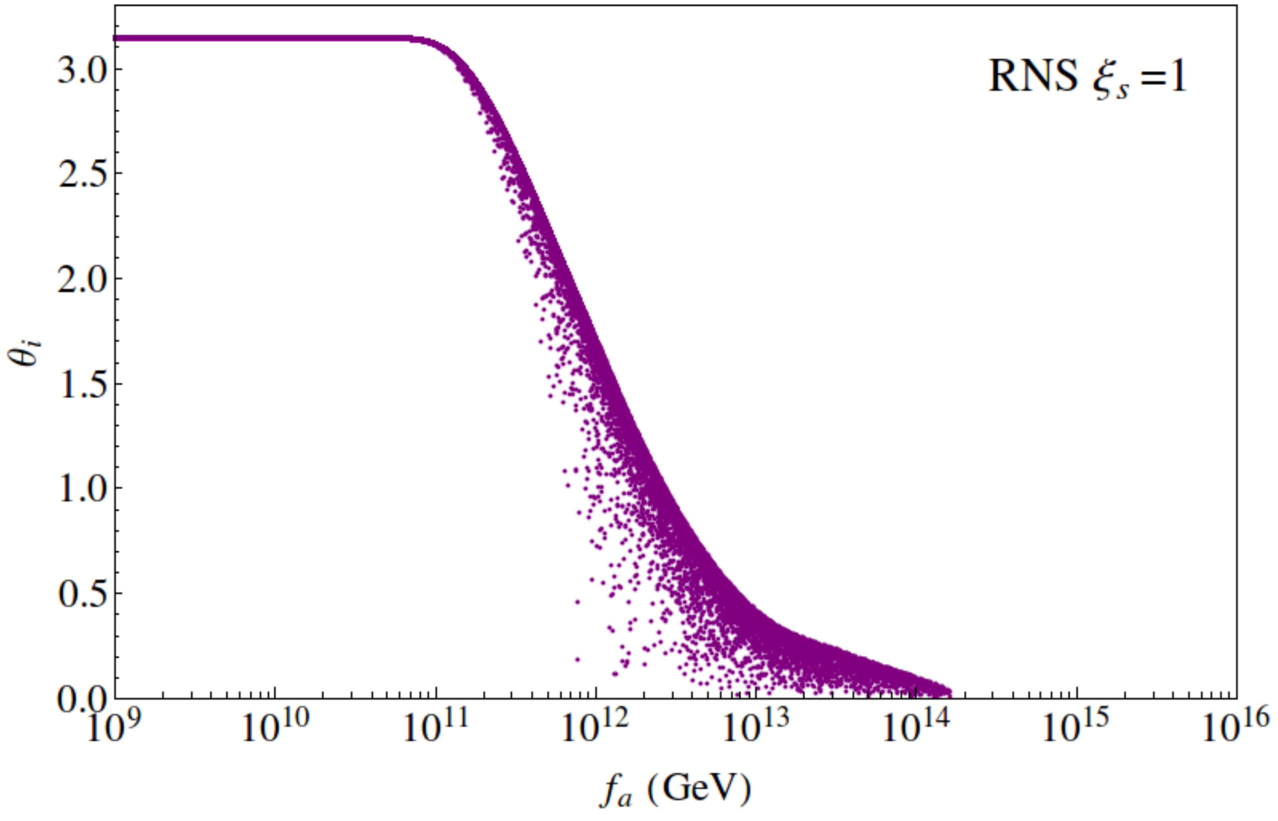
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

axion abundance



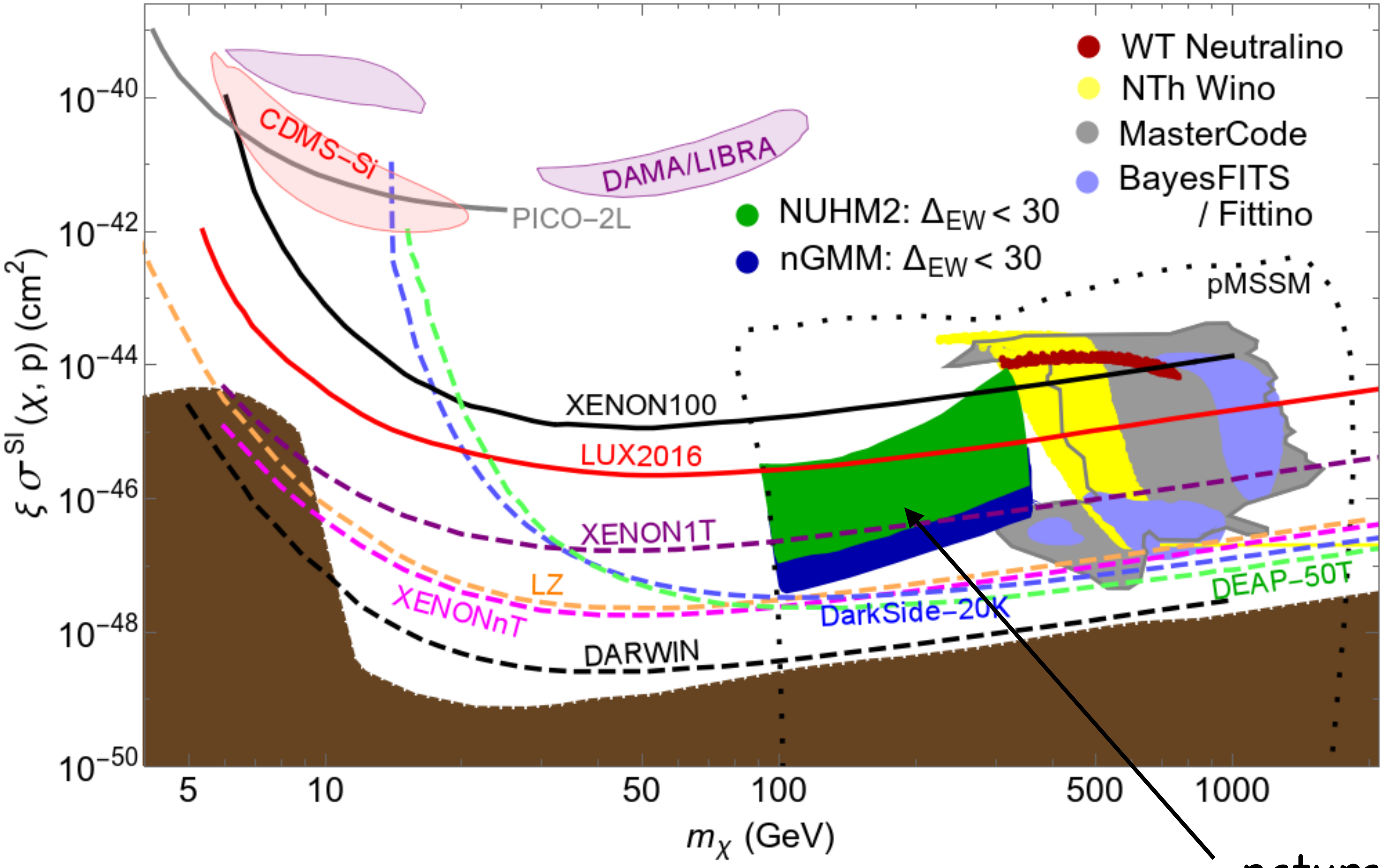
mainly axion CDM

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



natural SUSY

Bae, HB, Barger,Savoy,Serce

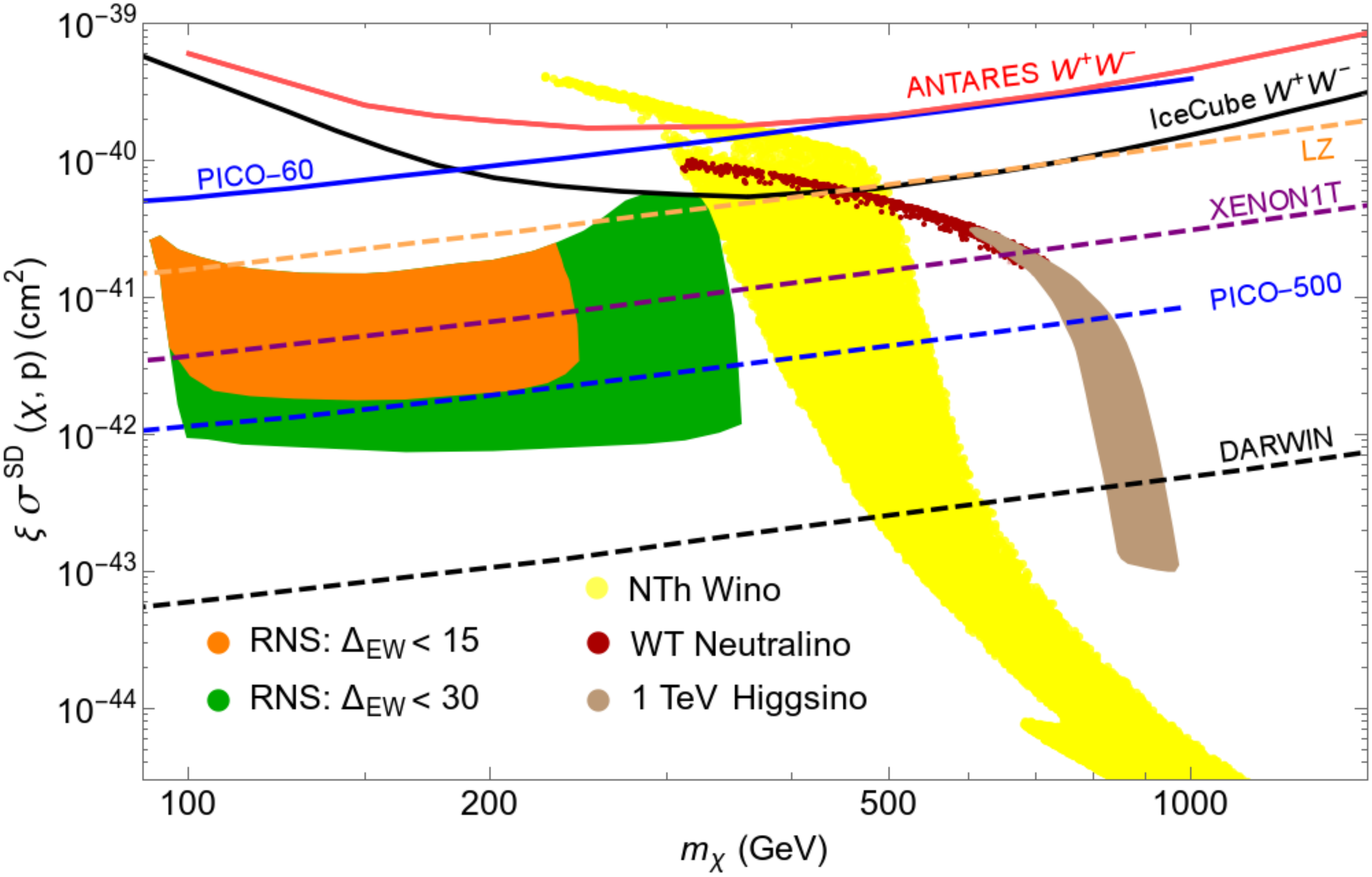
$$\mathcal{L} \ni -X_{11}^h \overline{\widetilde{Z}}_1 \widetilde{Z}_1 h$$

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

Xe-1-ton
now operating!

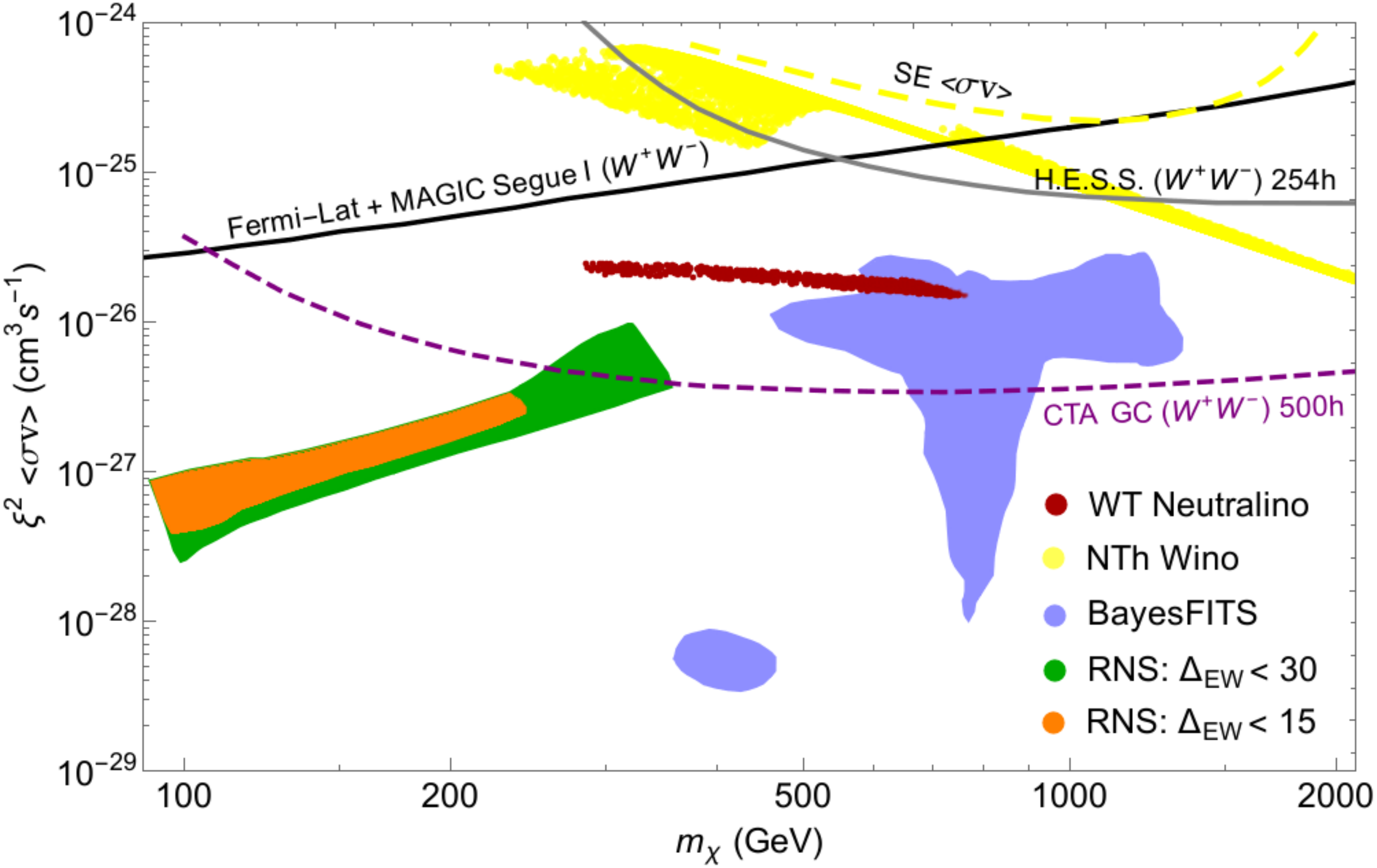
Can test RNS completely with ton scale detector or equivalent (subject to minor caveats)

Prospects for SD WIMP searches:

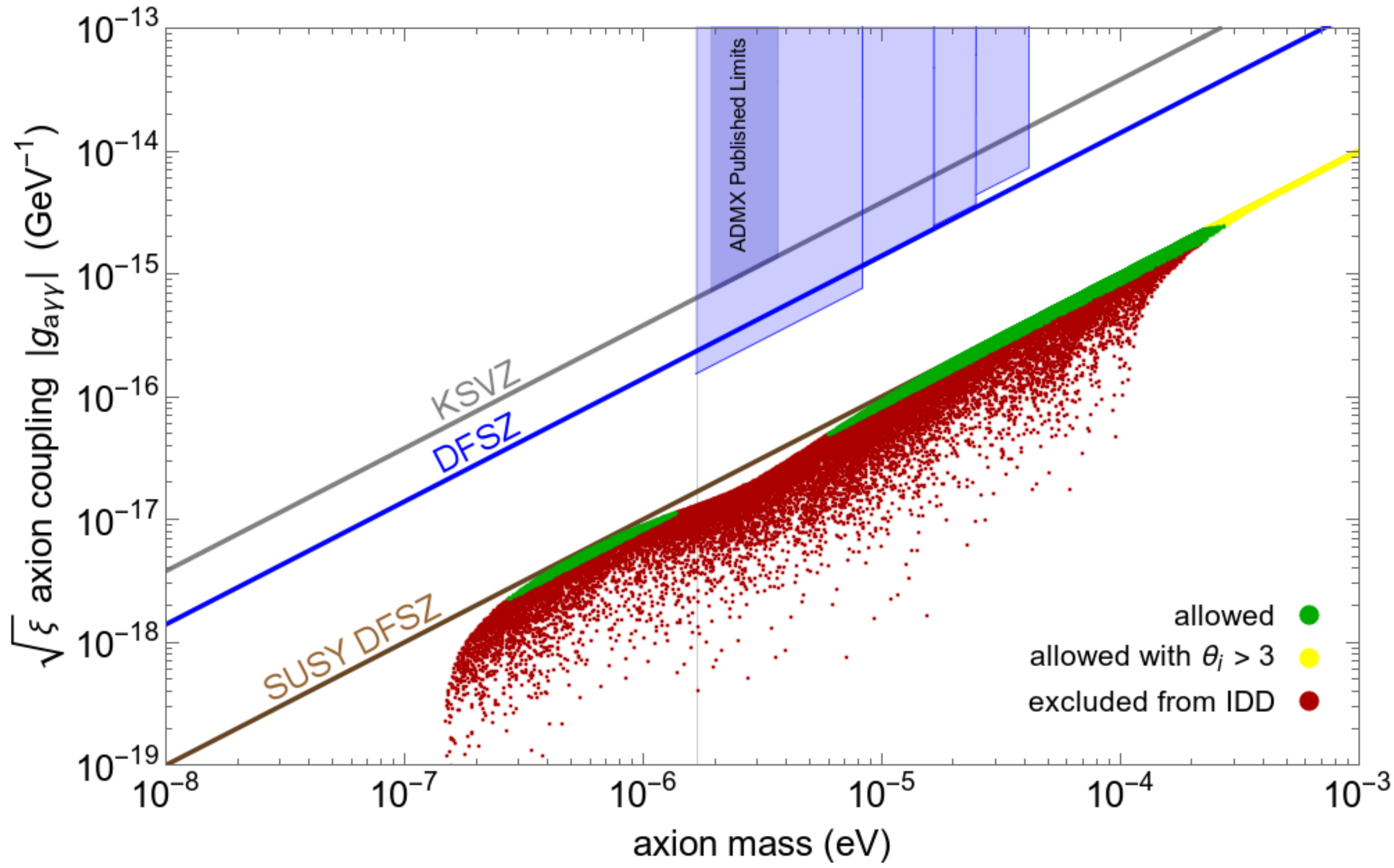


(Will need major upgrades)

Prospects for IDD WIMP searches:

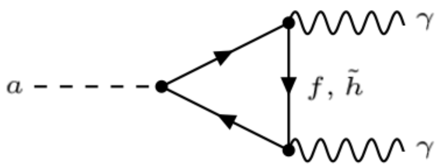


suppressed by square of diminished WIMP abundance



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

may need to probe broader and deeper!

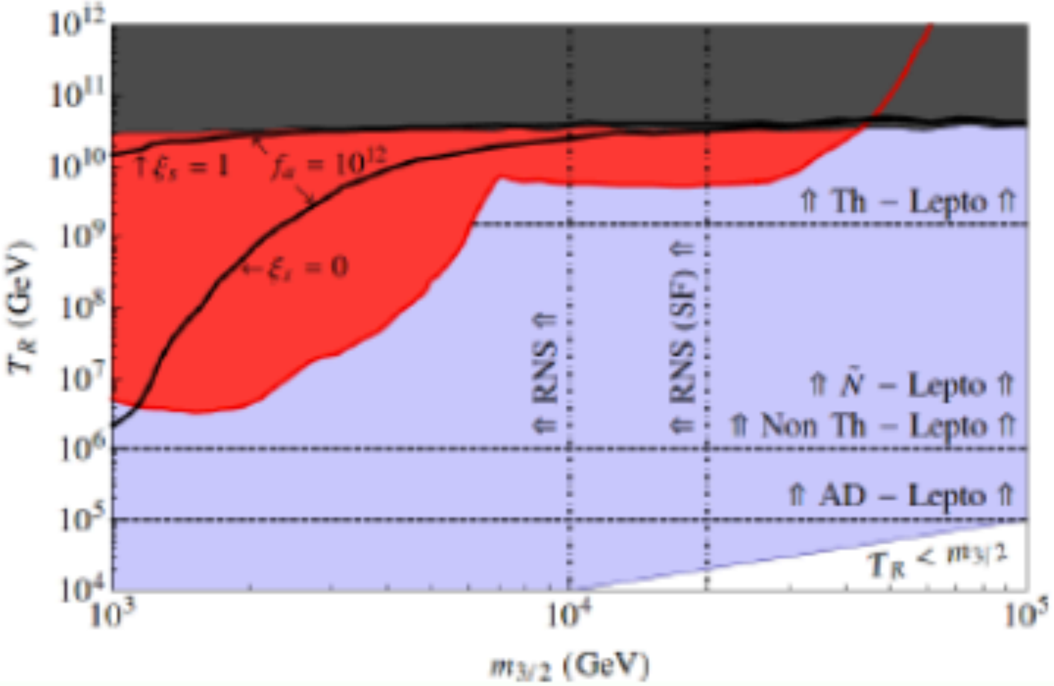


Conclusions

- 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 mh~125 GeV plus no sparticles so far
- Discrete R-symmetries solve SUSY mu, RPV,p-decay
- Z(24)^R yields gravity safe axion model with fa~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

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

Bae,HB, Serce, Zhang, arXiv:1510.00724