Naturalness
and weak scale SUSY

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DESY naturalness forum
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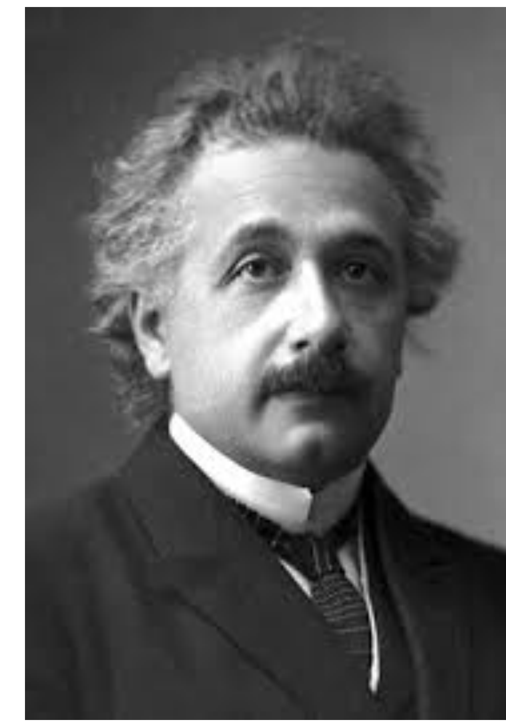
twin pillars of guidance:
naturalness & simplicity



``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

Lessons from yesterday

- Multi-parameter effective SUSY theories are useful because independent soft terms parametrize our ignorance of mechanics of SUSY breaking
- However, the fine-tuning calculation should be applied to the underlying more fundamental theory where soft terms are surely correlated
- With correlated soft terms, then both UV measures reduce to IR measure at tree level: $\Delta_{HS},\ \Delta_{BG} \rightarrow \Delta_{EW}$
- This is good news: there is only one answer for amount of fine-tuning and it is independent of scale choice at which spectra is generated: given some spectra, no matter where it comes from, all should agree on whether or not it is fine-tuned
- Re-evaluation of sparticle mass upper bounds shows low mu<200-300 GeV large A-term models with m(h)~125 GeV are still natural with mgl<6 TeV, mt1<3 TeV

Some topics lightly or not discussed

- Only required weak scale sparticles are higgsinos: hard to see at LHC but huge motivation for e+e- collider with roots>2m(higgsino)
- HL-LHC not enough to falsify natural SUSY: will need HE-LHC to probe m(gl)~6 TeV and m(t1)~3 TeV
- Requiring naturalness in both EW and QCD sector: DM= higgsino-like WIMP+axion admixture: usually mostly axions, but with suppressed axion/WIMP detection rates
- Non-holonomic soft terms may soften light higgsino argument, but these seem highly suppressed in more UV complete theories such as string-based models
- Some natural models all have light higgsinos but: NUHM2 (unified gauginos), natural generalized mirage mediation (compressed gauginos), natural anomaly mediation (mu<M2<M1<M3)
- Precision higgsino/collider measurements can reveal which of these cases or other would be realized in nature

Recall yesterday talk conclusion:

First order question:

why is the weak scale m(W,Z,h)~100 GeV?
Because mu(weak), mHu(weak)~100-200 GeV
and top squarks ~few TeV but highly mixed

Second order questions:

1. Why might mu<< m(soft)
2. Why might soft terms be at multi-TeV scale but with m(Hu) driven radiatively to mHu^2(weak)~-(100-200 GeV)^2?

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

- NMSSM: mu~m(3/2); but beware singlets!
- Giudice-Masiero: mu forbidden by some symmetry: generate via Higgs coupling to hidden sector
- Kim-Nilles: invoke SUSY version of DFSZ axion solution to strong CP: $W \ni \lambda_\mu S^2 H_u H_d / m_P$

KN: PQ symmetry forbids mu term, but then it is generated via PQ breaking $\mu \sim \lambda_\mu f_a^2 / m_P$

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

$m_{3/2} \sim m_{hid}^2 / M_P$

$f_a \ll m_{hid}$

Higgs mass tells us where to look for axion!

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

Little Hierarchy from radiative PQ breaking? exhibited within context of MSY/CCK model

Murayama, Suzuki, Yanagida (1992);
Gherghetta, Kane (1995)

Choi, Chun, Kim (1996)

Bae, HB, Serce, PRD91 (2015) 015003

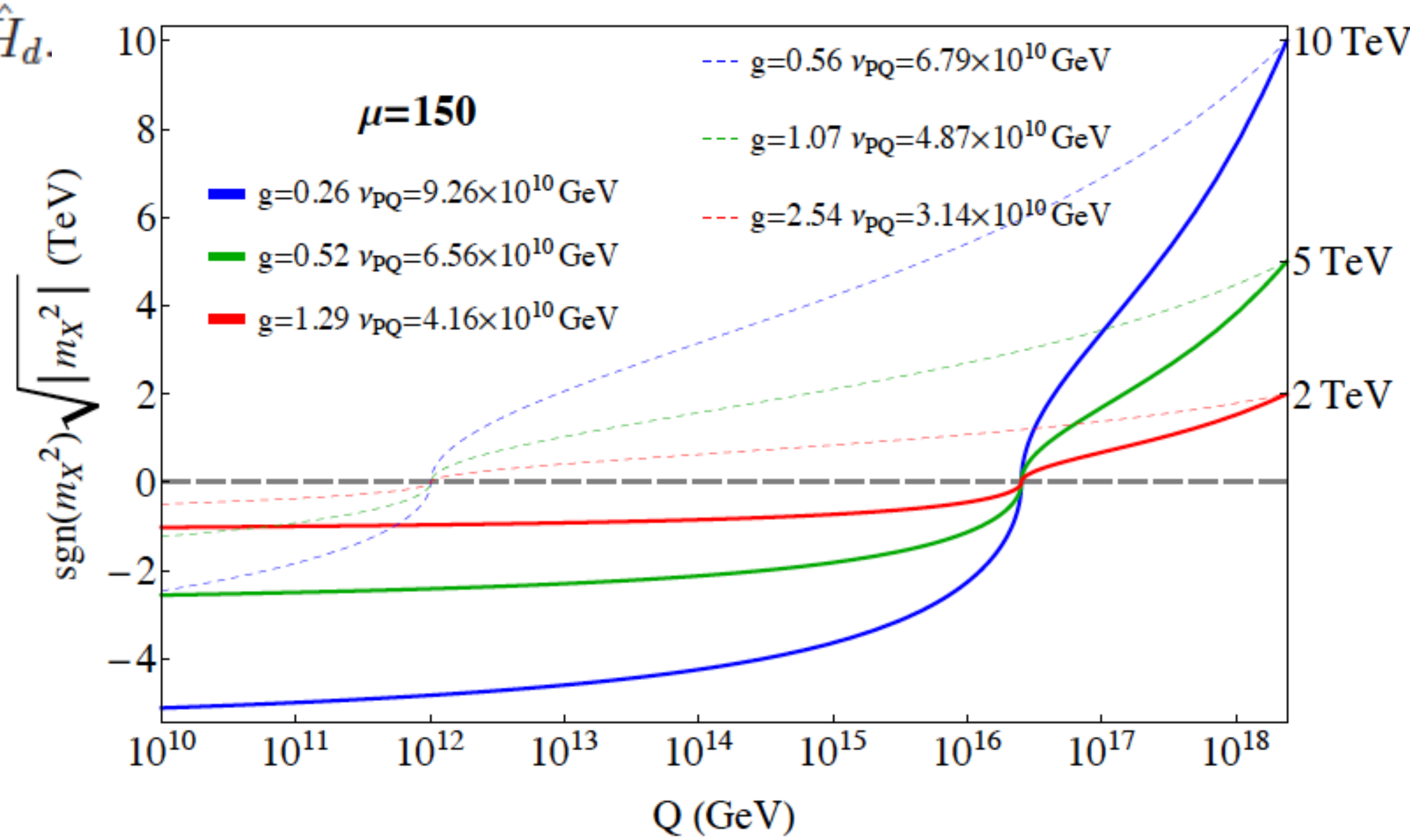
augment MSSM with PQ charges/fields:

$$\hat{f}' = \frac{1}{2} h_{ij} \hat{X} \hat{N}_i^c \hat{N}_j^c + \frac{f}{M_P} \hat{X}^3 \hat{Y} + \frac{g}{M_P} \hat{X} \hat{Y} \hat{H}_u \hat{H}_d .$$

SUSY breaking triggers PQ breaking: generate fa and MN

$$M_{N_i^c} = v_X \, h_i|_{Q=v_X}$$

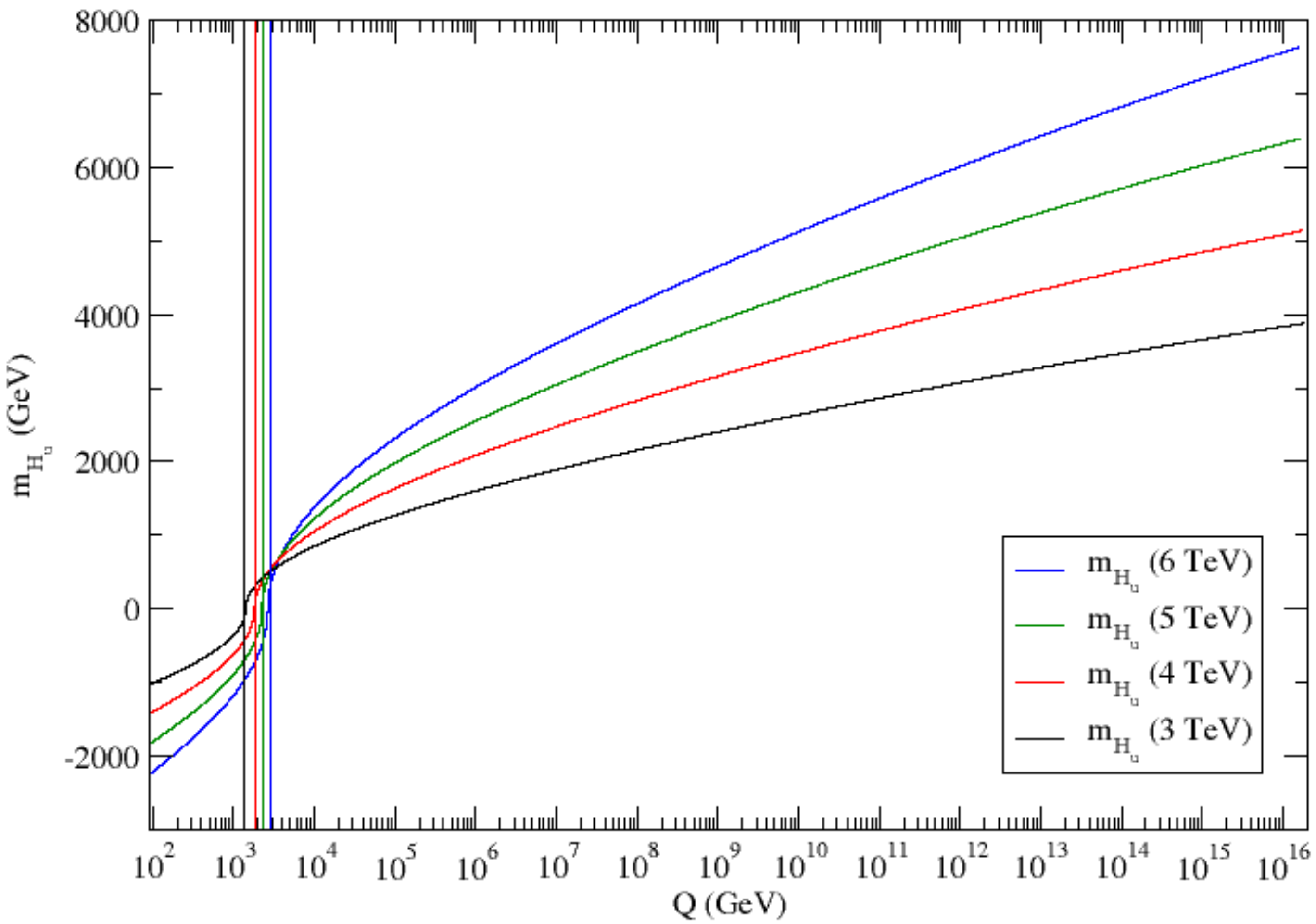
$$\mu = g \frac{v_X v_Y}{M_P} .$$



Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

Why might mHu have the value needed to give naturalness at weak scale?

1. For right correlations amongst soft terms, get "generalized focus point"



e.g.

For $\mu = 150$ GeV, $\tan\beta = 10$ and

$$
\begin{aligned}
m_0^2 &= m_{3/2}^2 \\
A_0 &= -1.6 m_{3/2} \\
m_{1/2} &= m_{3/2}/5 \\
m_{H_d}^2 &= m_{3/2}^2/2.
\end{aligned}
$$

$$m_{H_u}^2(GUT) = 1.8 m_{3/2}^2 - (212.52\ \text{GeV})^2.$$

$m_{H_u}^2(weak) \sim a \cdot m_{3/2}^2$ with correlated soft terms such that a is small: generalized focus point behavior

HB, Barger, Savoy, arXiv:1602.06973

Statistical analysis of SUSY breaking scale:
M. Douglas, hep-th/0405279

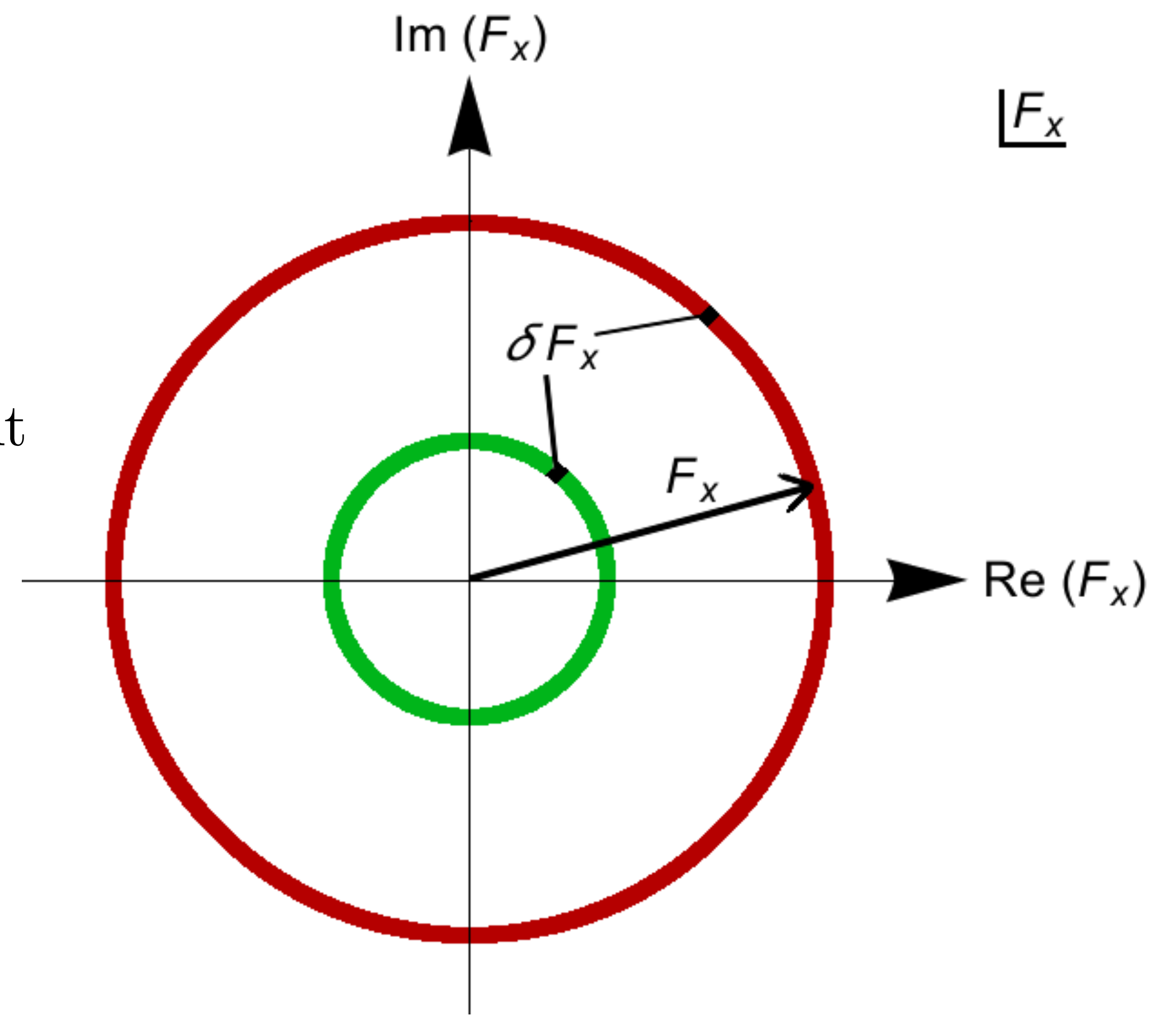
some reasonable assumptions

- string theory landscape contains vast ensemble of N=1, d=4 SUGRA EFTs at high scales
- the EFTs contain the SM as weak scale EFT
- the EFTs contain visible sector +potentially large hidden sector
- visible sector contains MSSM plus extra gauge singlets (e.g. a PQ sector, RN neutrinos,...)
- SUGRA is broken spontaneously via superHiggs mechanism via either F- or D- terms or in general a combination

Why do soft terms take on values needed for natural (barely-broken) EWSB?

2. string theory landscape?

- assume model like MSY/CCK where $\mu \sim 100$ GeV
- then $m(weak)^2 \sim |m^2_{H_u}|$
- If all values of SUSY breaking field $\langle F_X \rangle$ equally likely, then mild (linear) statistical draw towards large soft terms
- This is balanced by anthropic requirement of weak scale $m_{weak} \sim 100$ GEV



Anthropic selection of $m_{weak} \sim 100$ *GeV*:
If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them

$m(weak) <\sim 400$ GeV (Agrawal et al.)

Scalar potential is given by usual SUGRA form:

$$V = e^{K/m_P^2}\left(g^{i\bar{j}} D_i W D_{\bar{j}} W^* - \frac{3}{m_P^2}|W|^2\right) + \frac{1}{2}\sum_\alpha D_\alpha^2$$
$$= e^{K/m_P^2}\left(\sum_i |F_i|^2 - 3\frac{|W|^2}{m_P^2}\right) + \frac{1}{2}\sum_\alpha D_\alpha^2$$

- W = holomorphic superpotential
- K = real Kähler function
- $F_i = D_i W = DW/D\phi^i \equiv \partial W/\partial\phi^i + (1/m_P^2)(\partial K/\partial\phi^i)W$ are F-terms
- $D_\alpha \sim \sum \phi^\dagger g t_\alpha \phi$ are D-terms
- ϕ^i are chiral superfields

minimize V:

- $\partial V/\partial\phi^i = 0$
- $\partial^2 V/\partial\phi^i\partial\phi^j > 0$
- $\Lambda_{cc} = m_{hidden}^4 - 3e^{K/m_P^2}|W|^2/m_P^2$ with
- $m_{hidden}^4 = \sum_i |F_i|^2 + \frac{1}{2}\sum_\alpha D_\alpha^2$ is hidden sector mass scale

gravitino mass $m_{3/2} = e^{K/2m_P^2} m_P \sim m_{hidden}^2/m_P$ with $m_{hidden} \sim 10^{12}$ GeV

Denef&Douglas: statistics of SUSY breaking in landscape

DD observation: W_0 distributed uniformly as complex variable allows dynamical neutralization of Λ while not influencing SUSY breaking

Then, number of flux vacua containing spontaneously broken SUGRA with SUSY breaking scale m^2_{hidden} is:

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

- $f_{cc} \sim \Lambda/m^4$ where DD maintain $m \sim m_{string}$ and not m_{hidden}
- $f_{SUSY}(m^2_{hidden}) \sim (m^2_{hidden})^{2n_F+n_D-1}$ for uniformly distributed values of F and D breaking fields
- $f_{EWFT} \sim m^2_{weak}/m^2_{soft}$ (?) where $m_{soft} \sim m_{3/2} \sim m^2_{hidden}/m_P$

$$n = 2n_F + n_D - 1$$

$$f_{SUSY} \sim m^n_{soft}$$

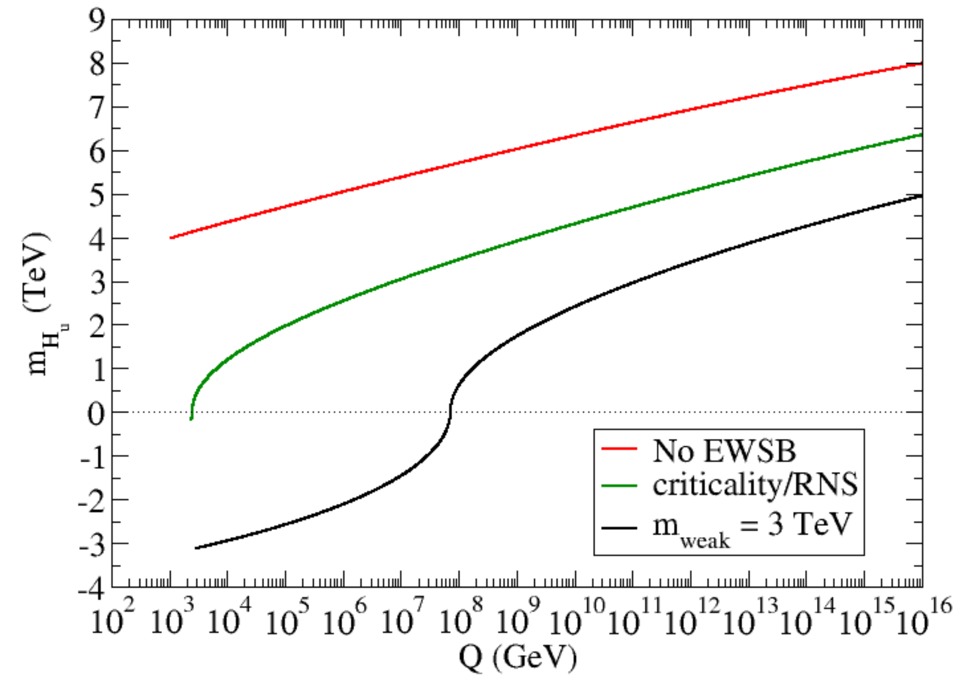
n_F	n_D	n
0	1	0
1	0	1
0	2	1
1	1	2
0	3	2
2	0	3
2	1	4

landscape favors high scale SUSY breaking
tempered by f(EWFT) anthropic penalty!

What about DD/AD anthropic penalty $f_{EWFT} \sim m^2_{weak}/m^2_{soft}$?

This fails in a variety of *practical* cases:

- A-terms get large: $\Rightarrow CCB$ minima
- $m^2_{H_u}$ too large: fail to break EW symmetry



Must require proper EWSB!

Even if EWS properly broken, then

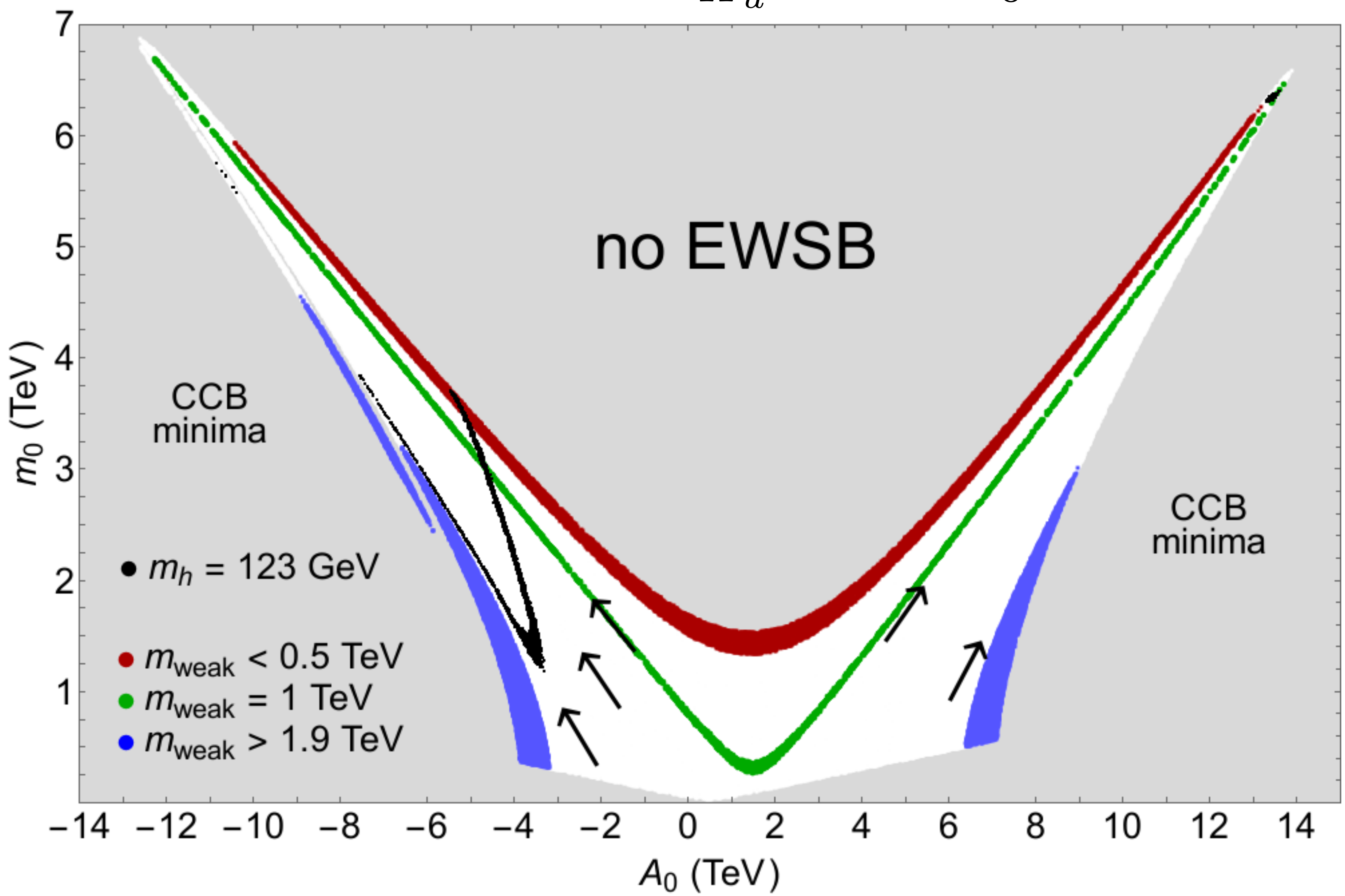
- large A_t *reduces* EWFT in the $\Sigma^u_u(\tilde{t}_{1,2})$
- large $m^2_{H_u}(m_{GUT})$ needed to radiatively drive $m^2_{H_u}$ to natural value at weak scale

Better proposal: $f_{EWFT} \Rightarrow \Theta(30 - \Delta_{EW})$
keeps calculated weak scale within factor ~ 4 of measured weak scale
$m_{weak} \equiv m_{W,Z,h} \sim 100$ GeV

Assume $\mu \sim 100-200$ GeV via *e.g.* rad PW breaking: then m_Z variable and may be large depending on soft terms $m^2_{H_{u,d}}$ and $\Sigma^{u,d}_{u,d}(i)$

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

$m_{H_u} = 1.3 m_0$



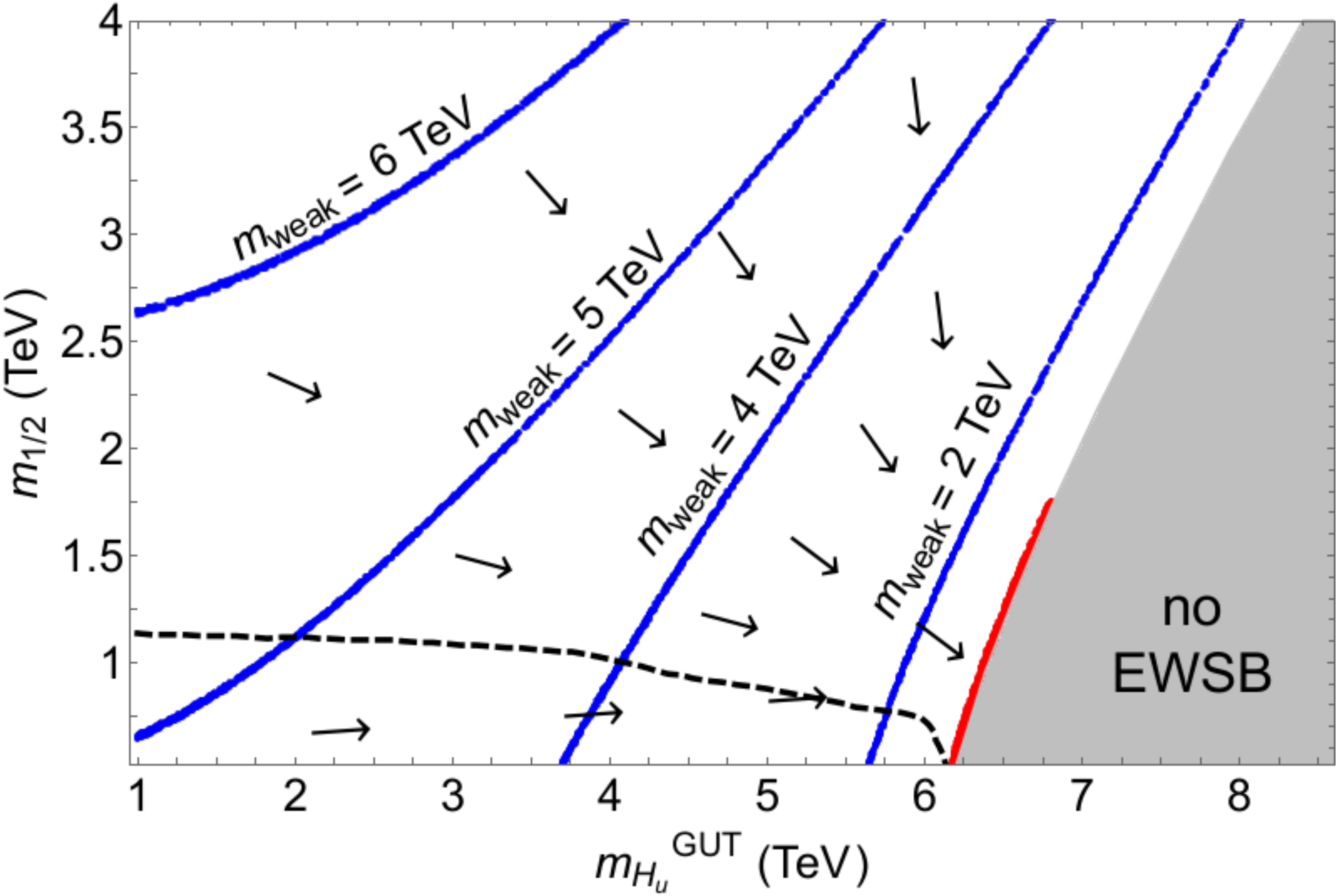
statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Denef, Douglas, JHEP0405 (2004) 072

Giudice, Rattazzi, NPB757 (2006) 19;

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

$m_0 = 5\ \mathrm{TeV}$



statistical/anthropic draw toward FP-like region

For practical calculations, adopt NUHM3 SUGRA model:

- $m_0(1,2)$ = gen(1,2) common soft mass
- $m_0(3)$ = gen(3) common soft mass
- $m_{H_u}^2$ up-Higgs soft mass
- $m_{H_d}^2$ down-Higgs soft mass
- $m_{1/2}$ = unified gaugino mass
- A_0 = unified trilinear soft term
- $\tan\beta$

Trade $m_{H_u}^2,\ m_{H_d}^2 \Leftrightarrow \mu,\ m_A$

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A \quad (NUHM3)$$

Recent work: place on more quantitative footing: scan soft SUSY breaking parameters 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,

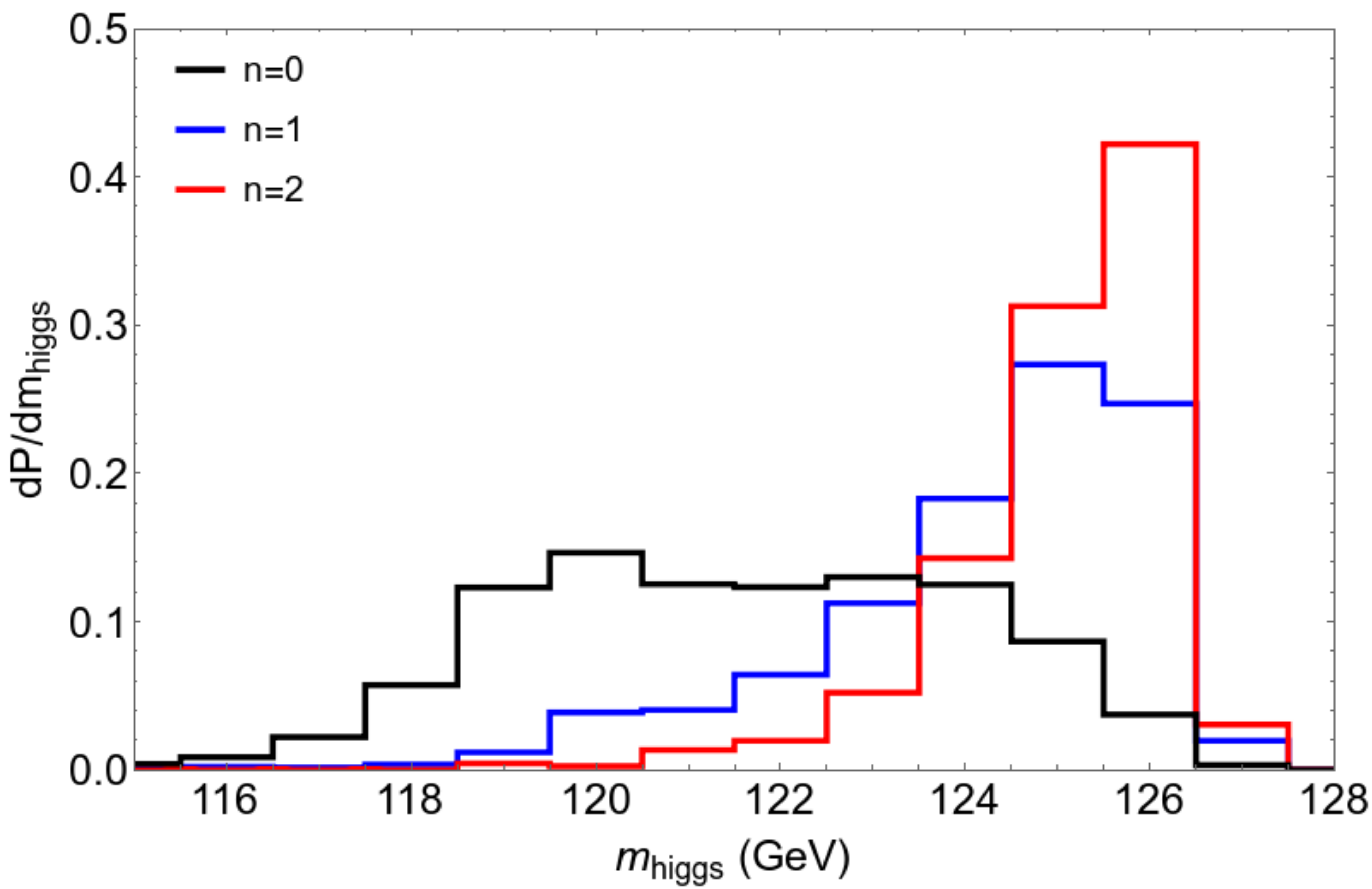
$\tan\beta$: $3 - 60$ (flat)

mu=150 GeV (fixed)

HB, Barger, Serce, Sinha (arXiv:1712.01399)

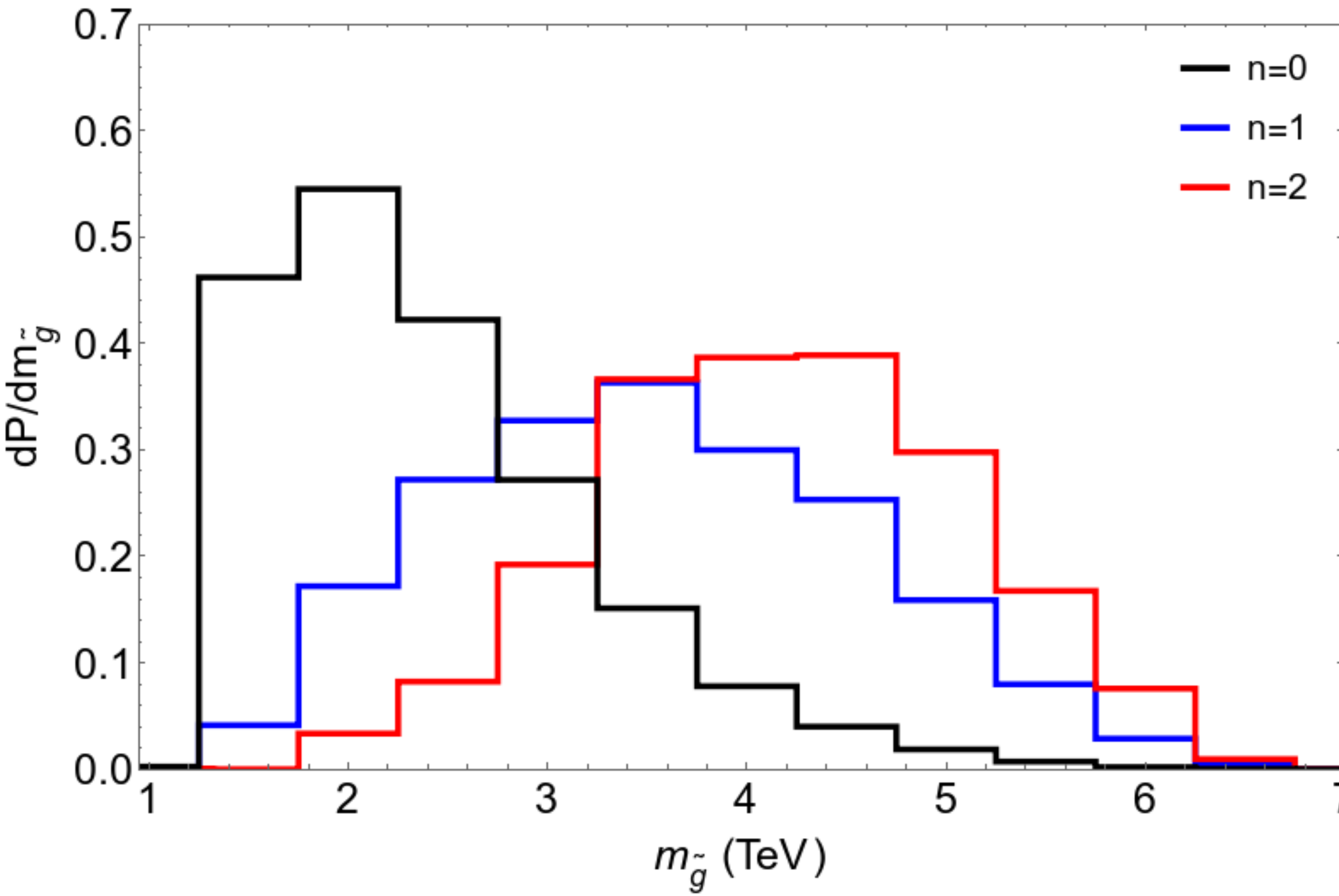
Making the picture more quantitative:

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



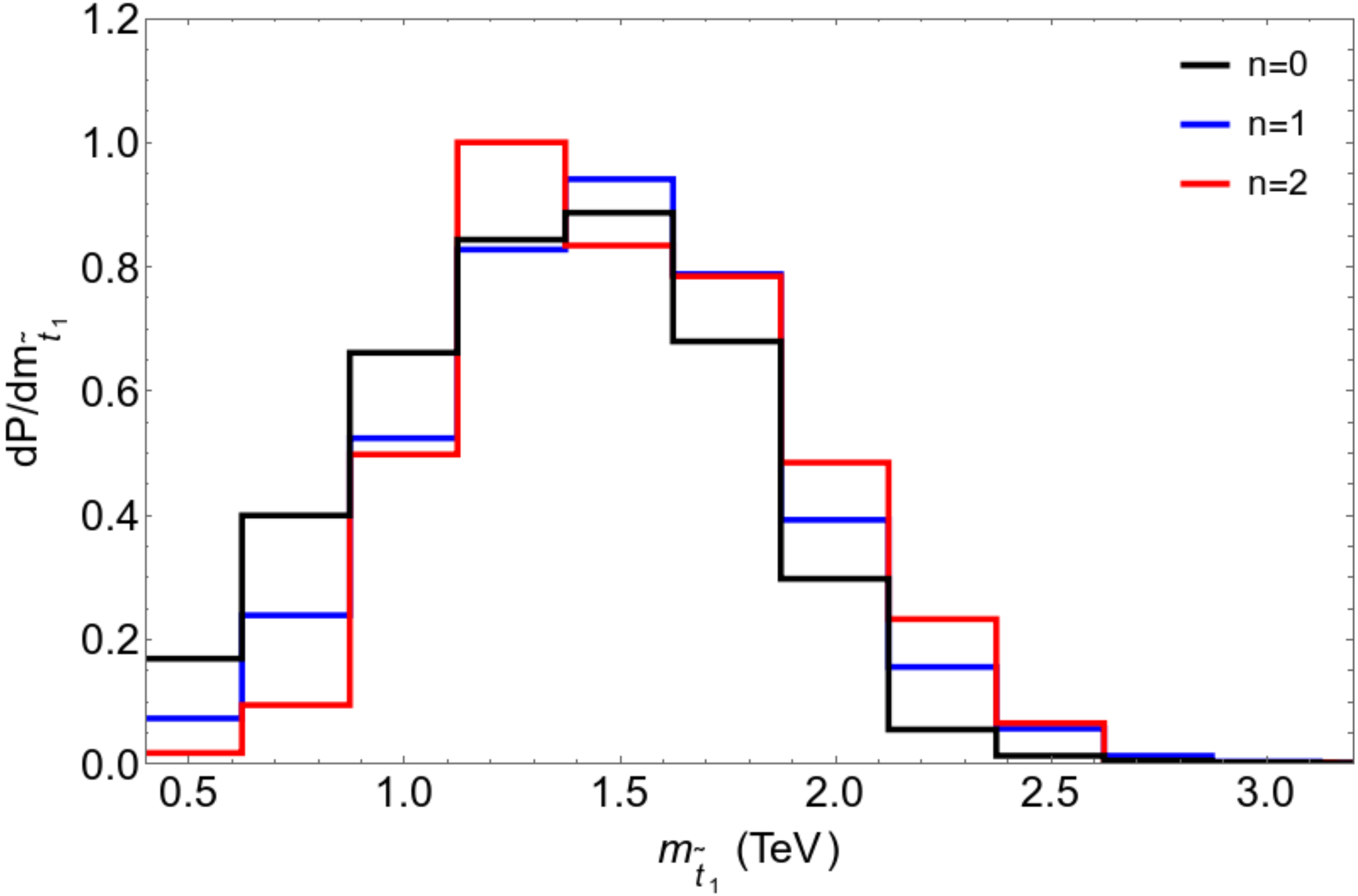
m(h)~125 most favored for n=1,2

What is corresponding distribution for gluino mass?



typically beyond LHC 14 reach (may need HE-LHC)

and m(t1)?



1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
n=0
n=1
n=2
$dP/dm_{\tilde{t}_1}$
$m_{\tilde{t}_1}$ (TeV)

Summary n=1,2:

- $m_h \sim 125 \pm 2$ GeV
- $m_{\tilde{g}} \sim 4 \pm 2$ 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
- $m_0(1,2) \sim 20 \pm 10$ TeV (for first/second generation matter scalars)

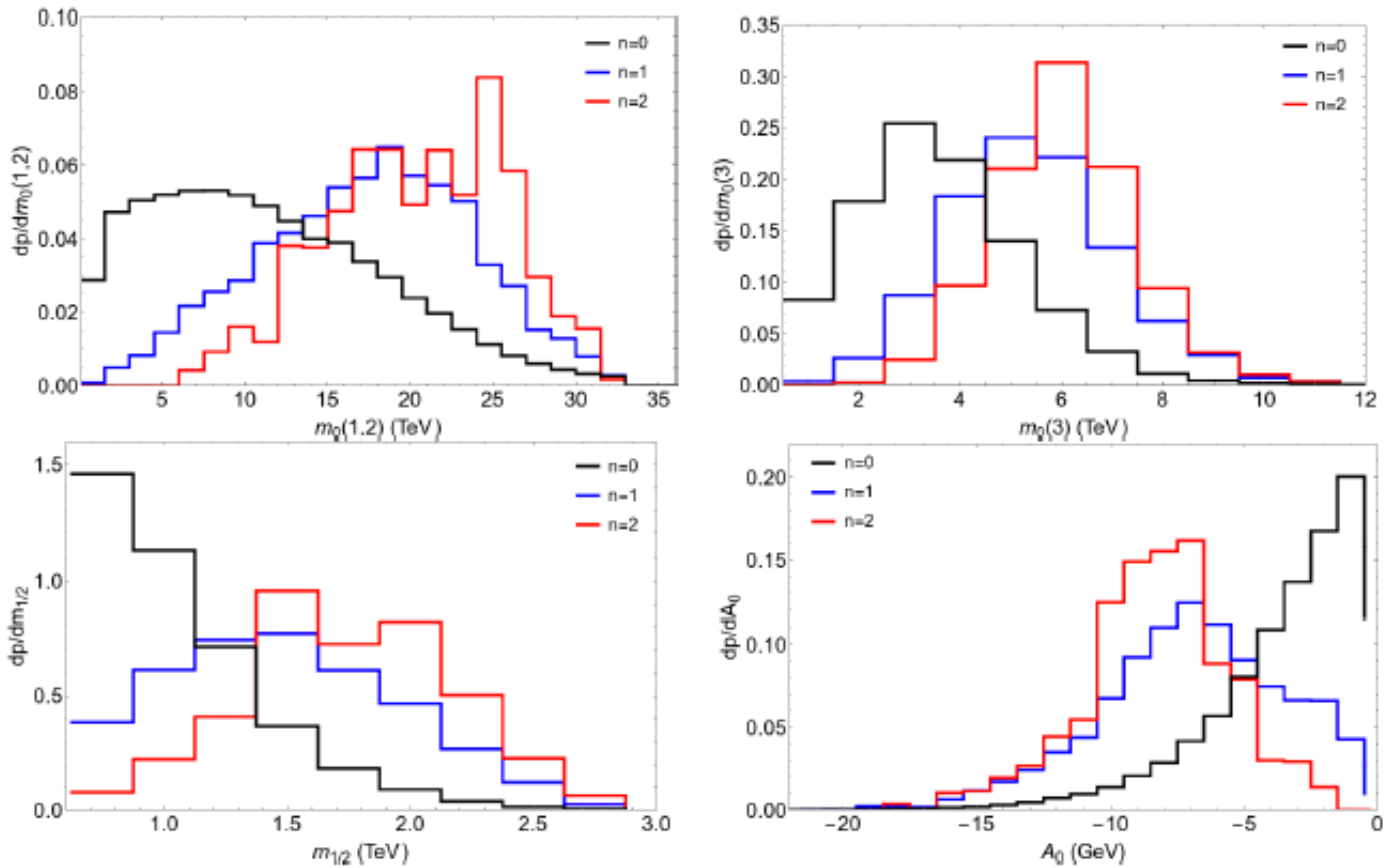
n>=3 case: soft terms pulled so hard usually gives CCB or no EWSB minima in scalar potential

some conclusions

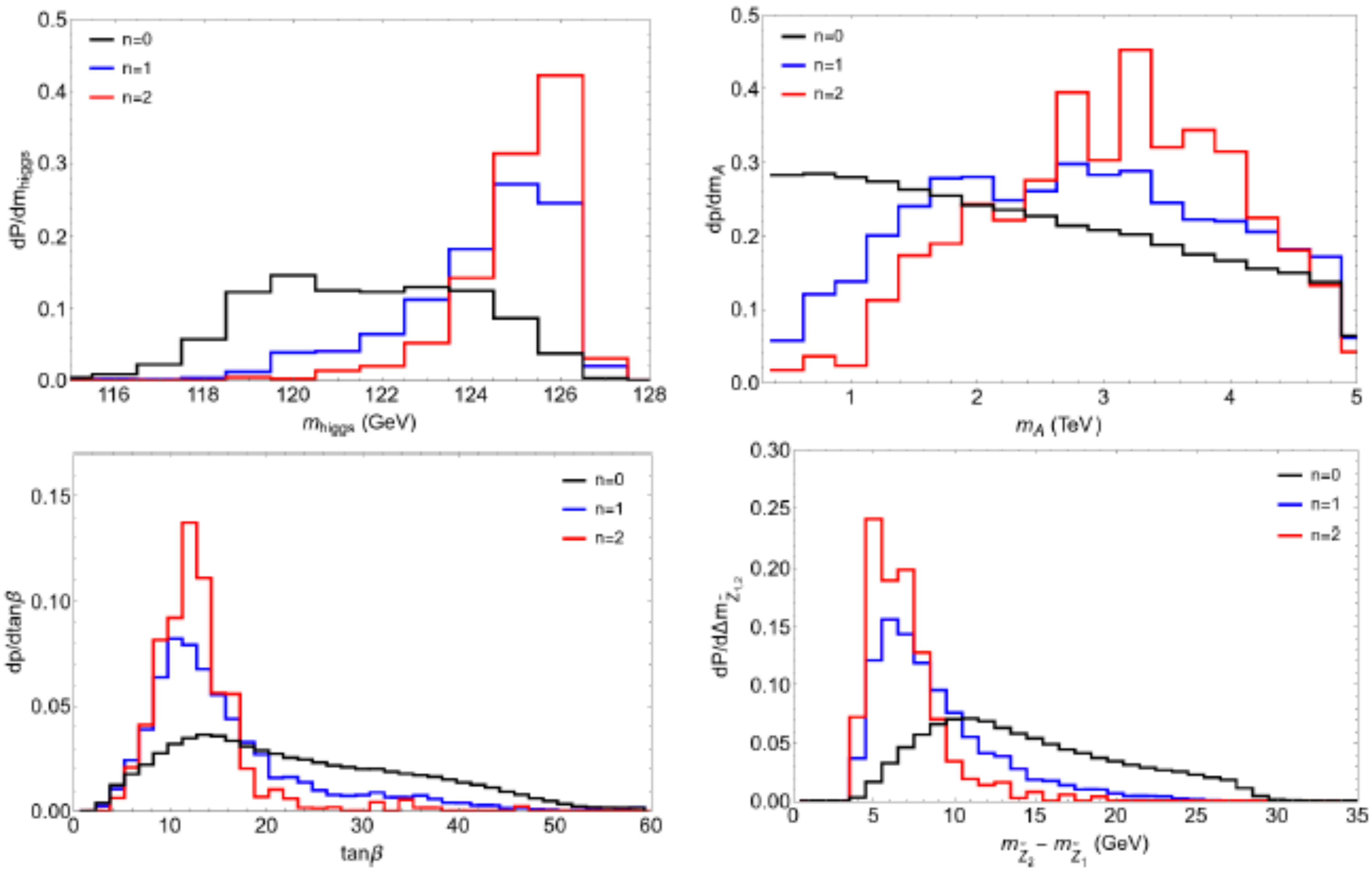
- mu problem modified: mu~m(weak)~100-200 GeV<< m(soft)~multi-TeV
- mu term linked to axion physics: Kim-Nilles/SUSY DFSZ
- PQ symmetry radiatively broken as consequence of SUSY breaking: unifies 3 intermediate mass scales: SUSY-breaking, PQ, Majorana nu
- A mild statistical draw on soft terms from the string landscape coupled with anthropic pull of weak scale to ~100 GeV -> m(h)~125 GeV
- The same draw provides a decoupling solution to SUSY flavor, CP, gravitino problem (and cosmological moduli problem) and expect m(3/2)~10-30 TeV
- Explains why LHC has so far seen no sign of SUSY
- most robust LHC search channel may be z1z2-> llj+MET
- HE-LHC (rs>27 TeV) may be needed for gluino/stop discovery
- dark matter a wimp/axion admixture?
- At ILC250, expect Higgs couplings very SM-like; need rs>2m(higgsino) to establish SUSY discovery/BSM physics

Backup

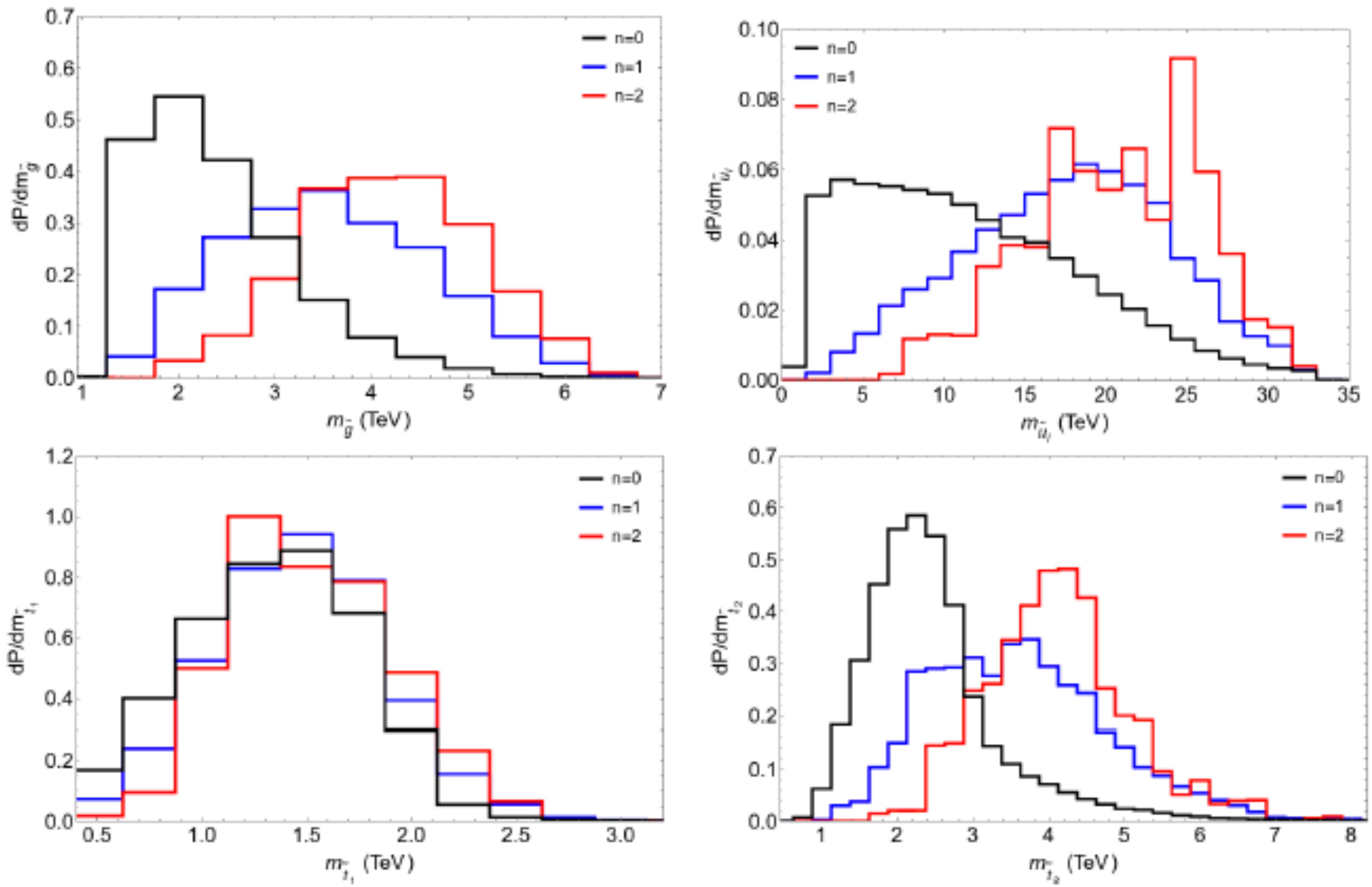
Probability distributions for input soft terms



Higgs and -ino sector



Some key strongly interacting sparticle probability distributions



Prospects for SUSY at LHC:

signature list for radiatively-driven natural SUSY:

- $\tilde{g}\tilde{g}$
- $\tilde{t}_1\tilde{t}_1^*$
- $\tilde{Z}_1\tilde{Z}_2$ (higgsino pair production)
- $\tilde{W}_2^{\pm}\tilde{Z}_4$ (wino pair production)

Summary of collider searches

- In light of recent LHC bounds (m(glno)>2 TeV, m(t1)>1 TeV) and m(h) requiring TeV-scale highly mixed top squarks, concern has arisen about an emerging Little Hierarchy problem characterized by m(weak)~100 GeV<< m(SUSY)~multi-TeV rendering perhaps SUSY as ``unnatural"
- We propose an improved naturalness measure based upon scalar potential minimization condition

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

This leads to upper bounds from naturalness:

DM=WIMP/axion mix?

- m(higgsinos)~100-300 GeV (the lighter the better)
- m(t1)<~3 TeV
- m(glno)<~6 TeV

process	current	HL-LHC	HE-LHC
glno-glno	m(glno)>2 TeV	~2.8 TeV	5.5 TeV
t1-t1	m(t1)>1 TeV	1.3 TeV	3.5 TeV
SSdB (winos)	x	m(W2)~1 TeV	?
z1z2j->l+lb+j+MET	barely	mu~250 GeV	?

Conclusions:
1. SUSY still natural;
2. hunt for nSUSY has only begun;
3. HL-LHC handle most SUSY with ino-mass unification;
4. other (e.g. mirage) may require HE-LHC to complete search

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

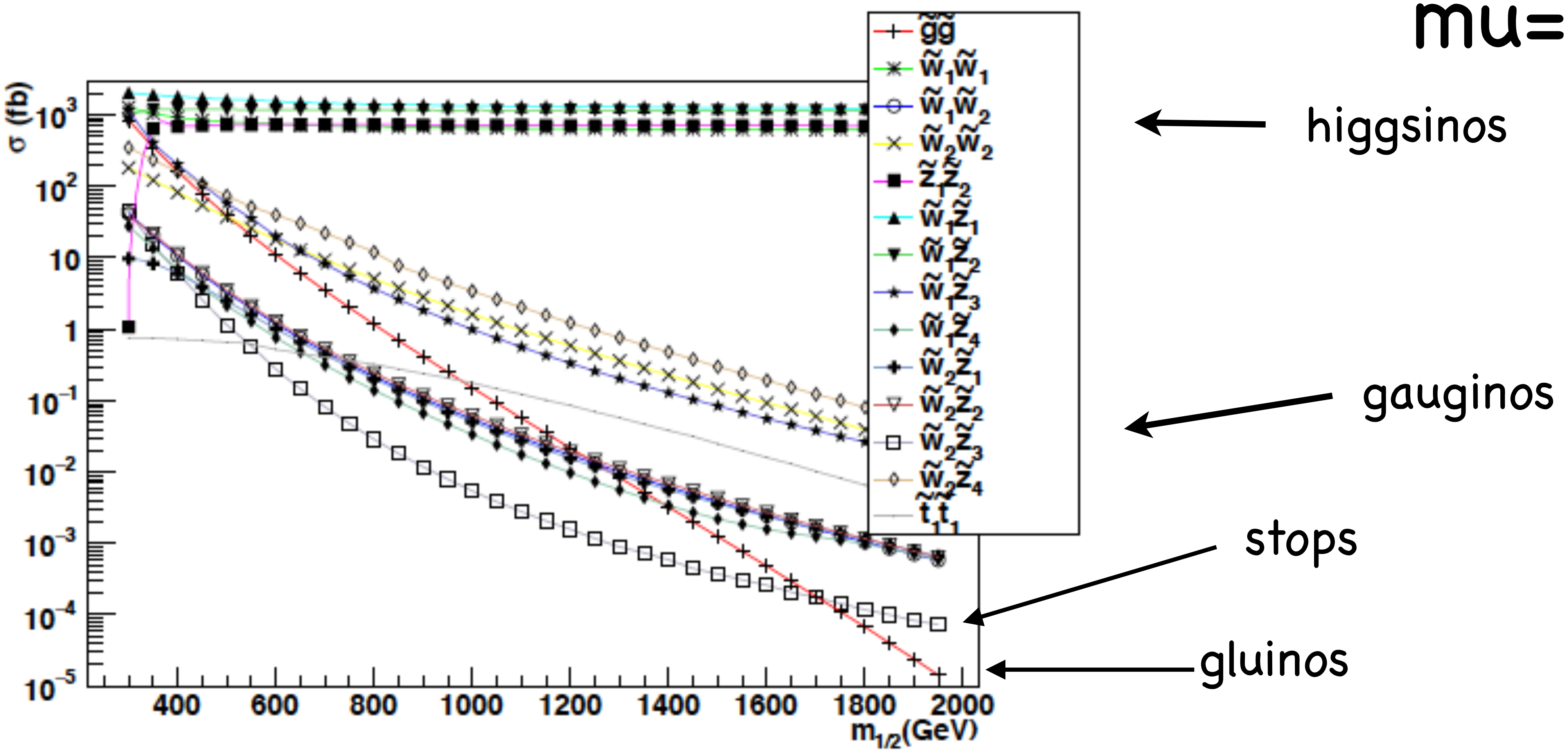
Conclusion: SUSY IS alive and well!

- many calculations of naturalness over-estimate fine-tuning
- naturalness: Little Hierarchy mu<< m(SUSY) allowed
- radiatively-driven naturalness: mu~100-200 GeV, m(t1)<3 TeV, m(gluino)<5-6 TeV
- SUSY DFSZ axion: solve strong CP, solve SUSY mu problem; generate mu<< m(SUSY)
- landscape pull on soft terms towards RNS, m(h)~125 GeV
- natural mirage-mediation/mini-landscape
- natural NUHM2: HL-LHC can cover via SSdB+Z1Z2j channels
- natural mirage/mini-landscape may escape detection at HL-LHC; need LHC33!
- expect ILC as higgsino factory
- DM= axion+higgsino-like WIMP admixture: detect both?

Backup

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

mu=150 GeV



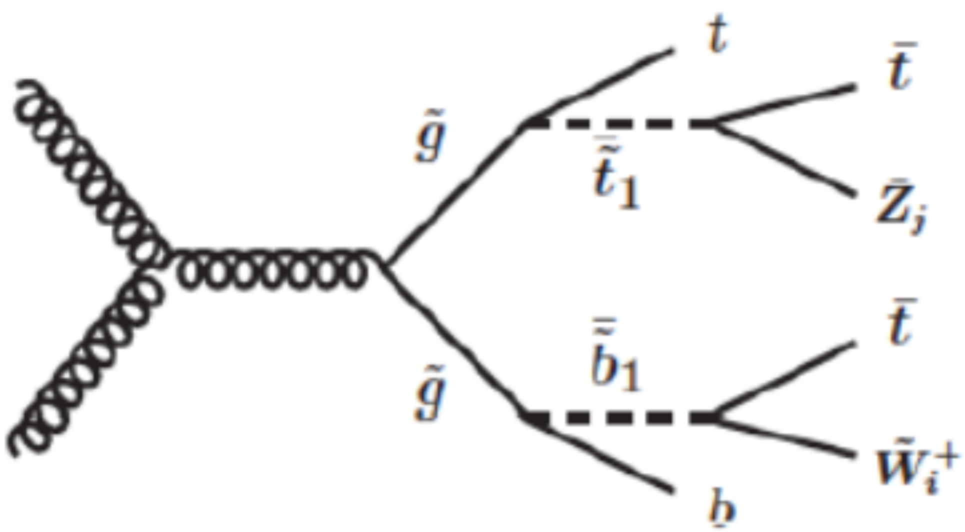
higgsino pair production dominant-but only soft visible energy release from higgsino decays

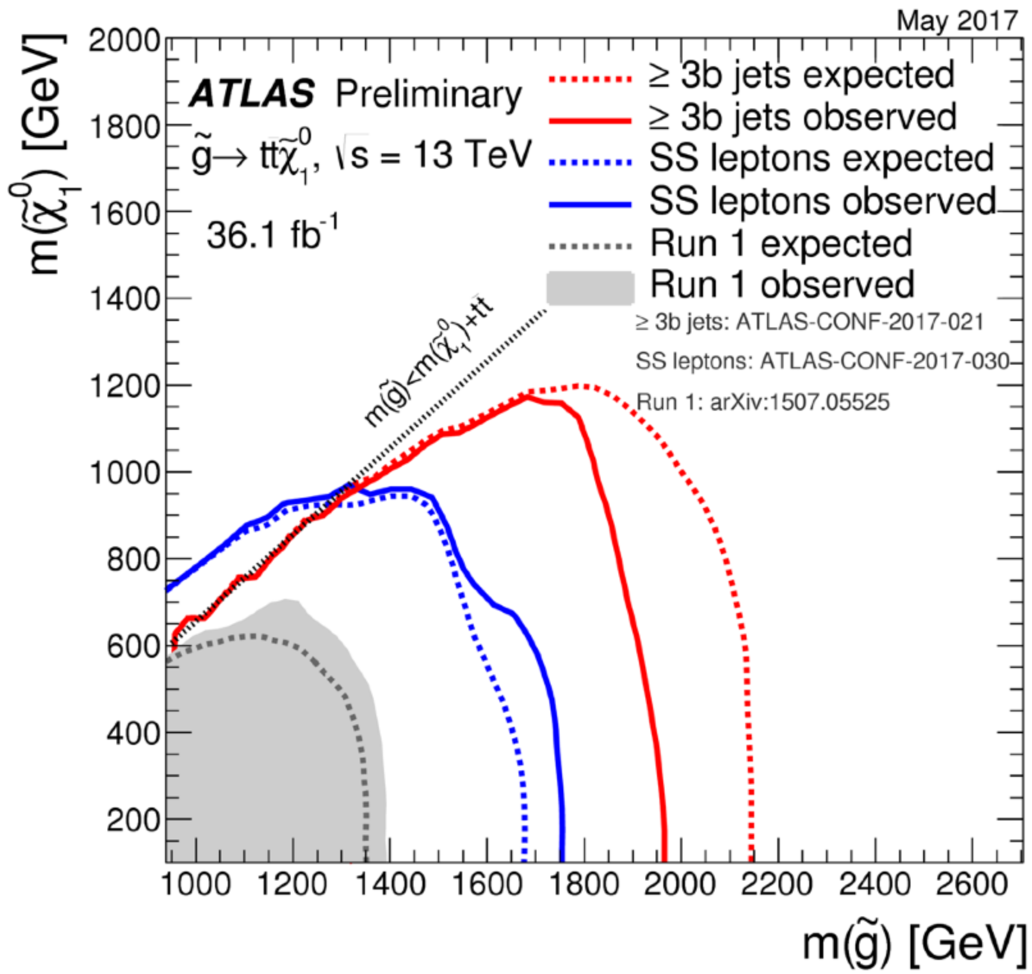
largest visible cross section: wino pairs

gluino pairs sharply dropping

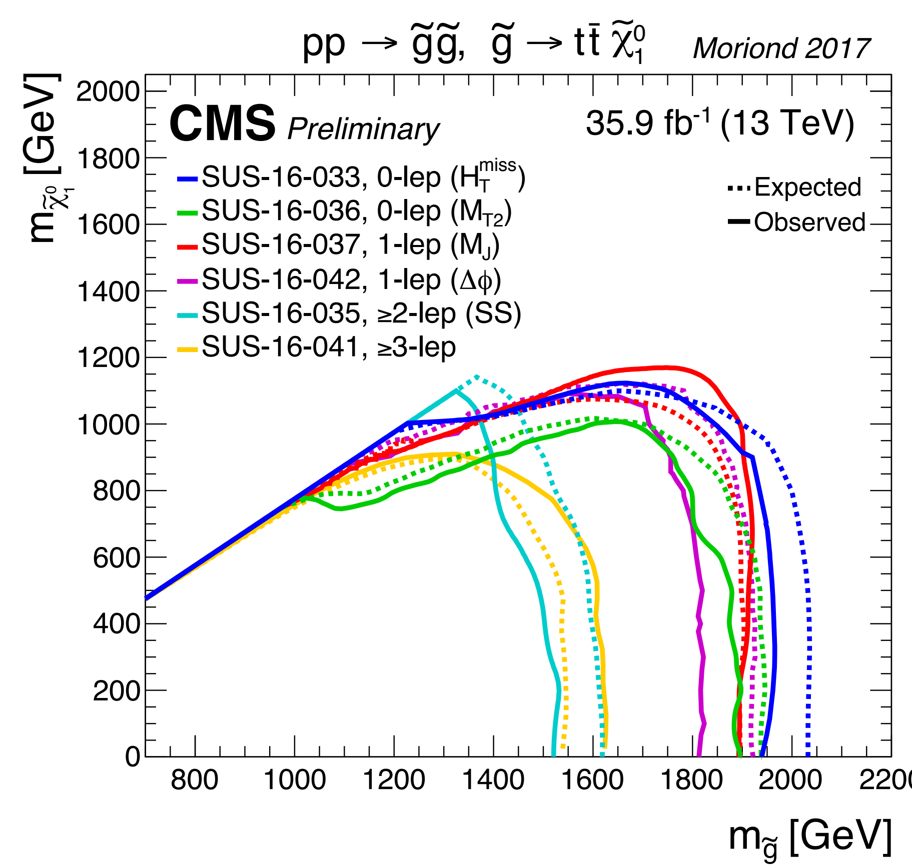
stops at bottom

gluino pair cascade decay signatures

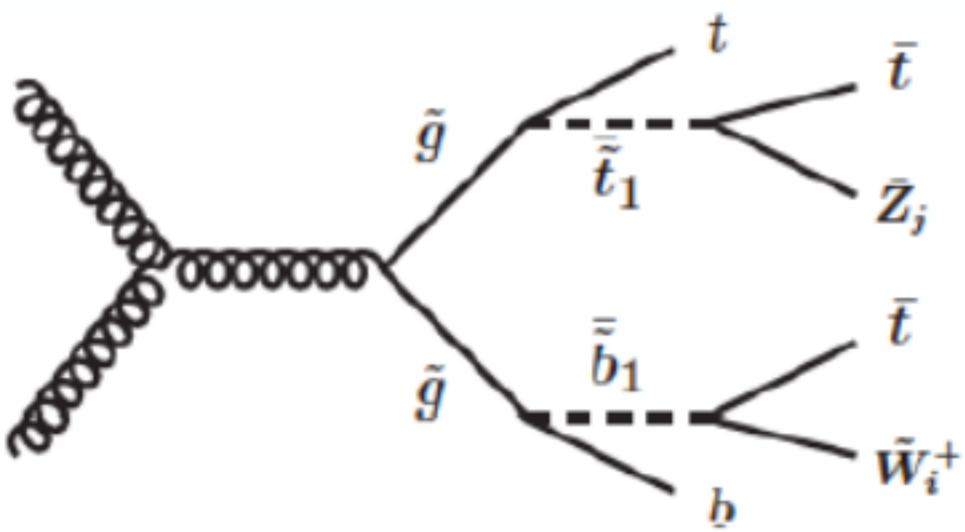




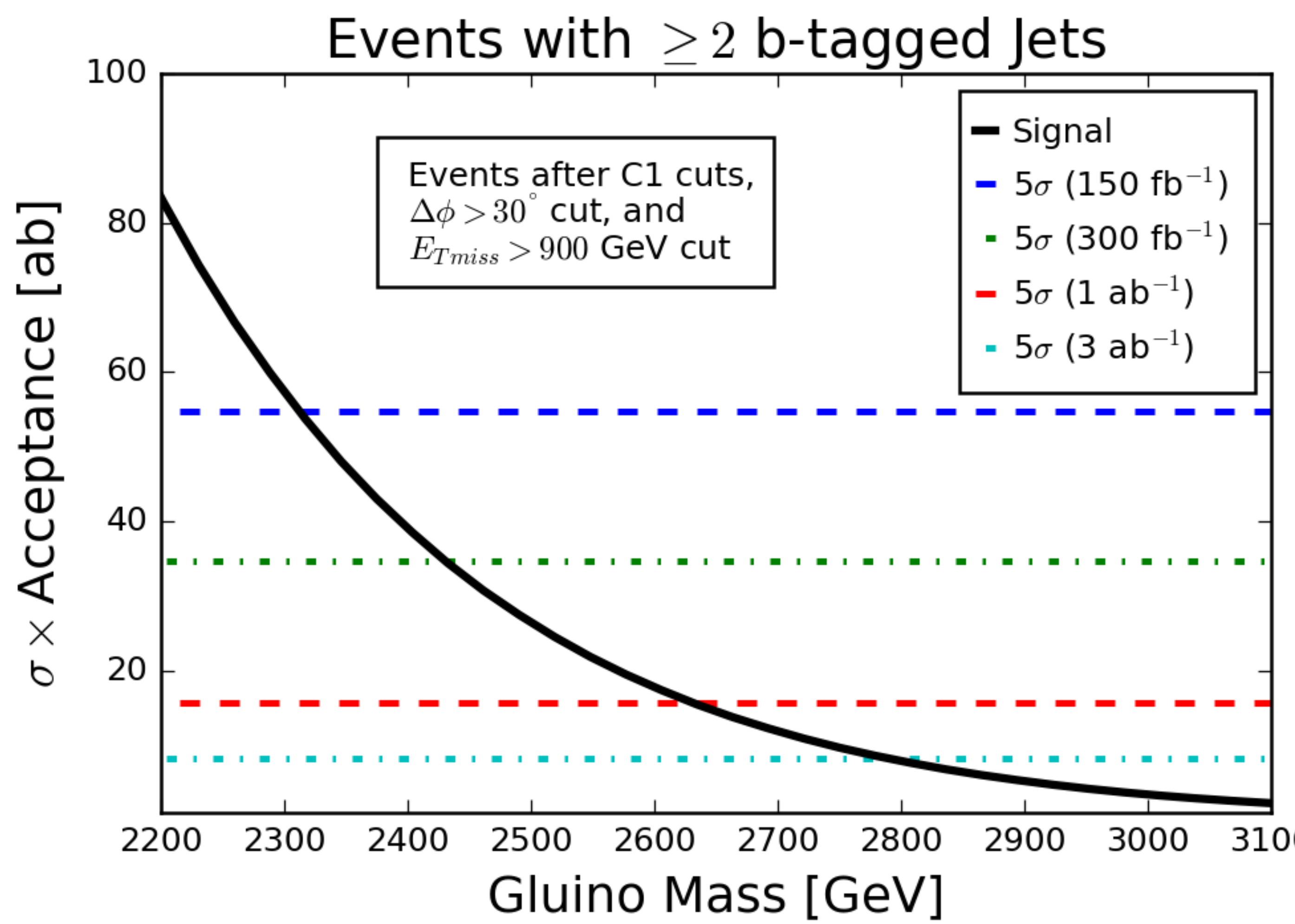
Current limits for m(Z1)~150 GeV:
m(glno)>~2 TeV



gluino pair cascade decay signatures



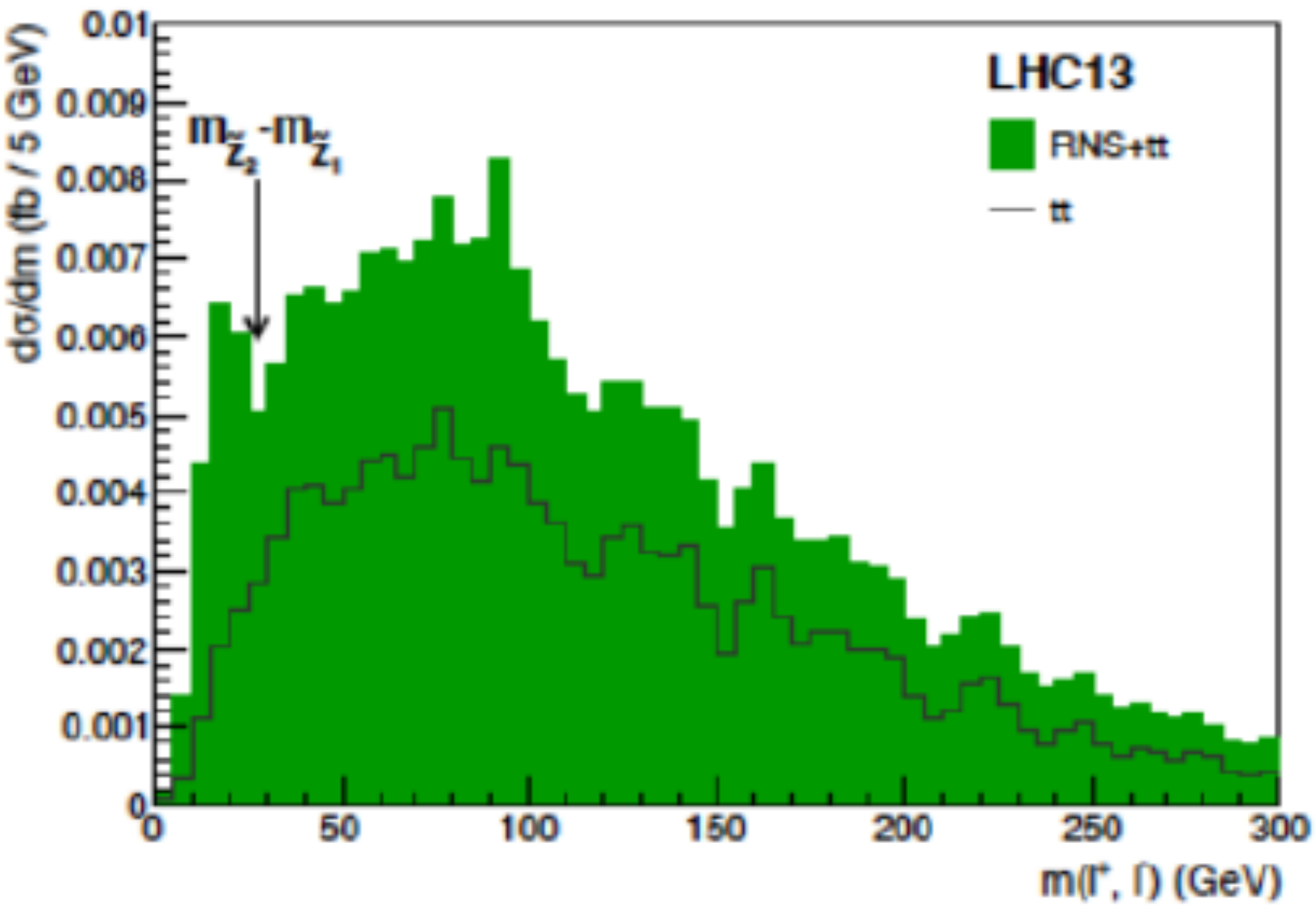
Estimated HL-LHC reach for gluinos



HL-LHC reach to
m(glno)~2.8 TeV;
RNS: m(glno)<~5 TeV

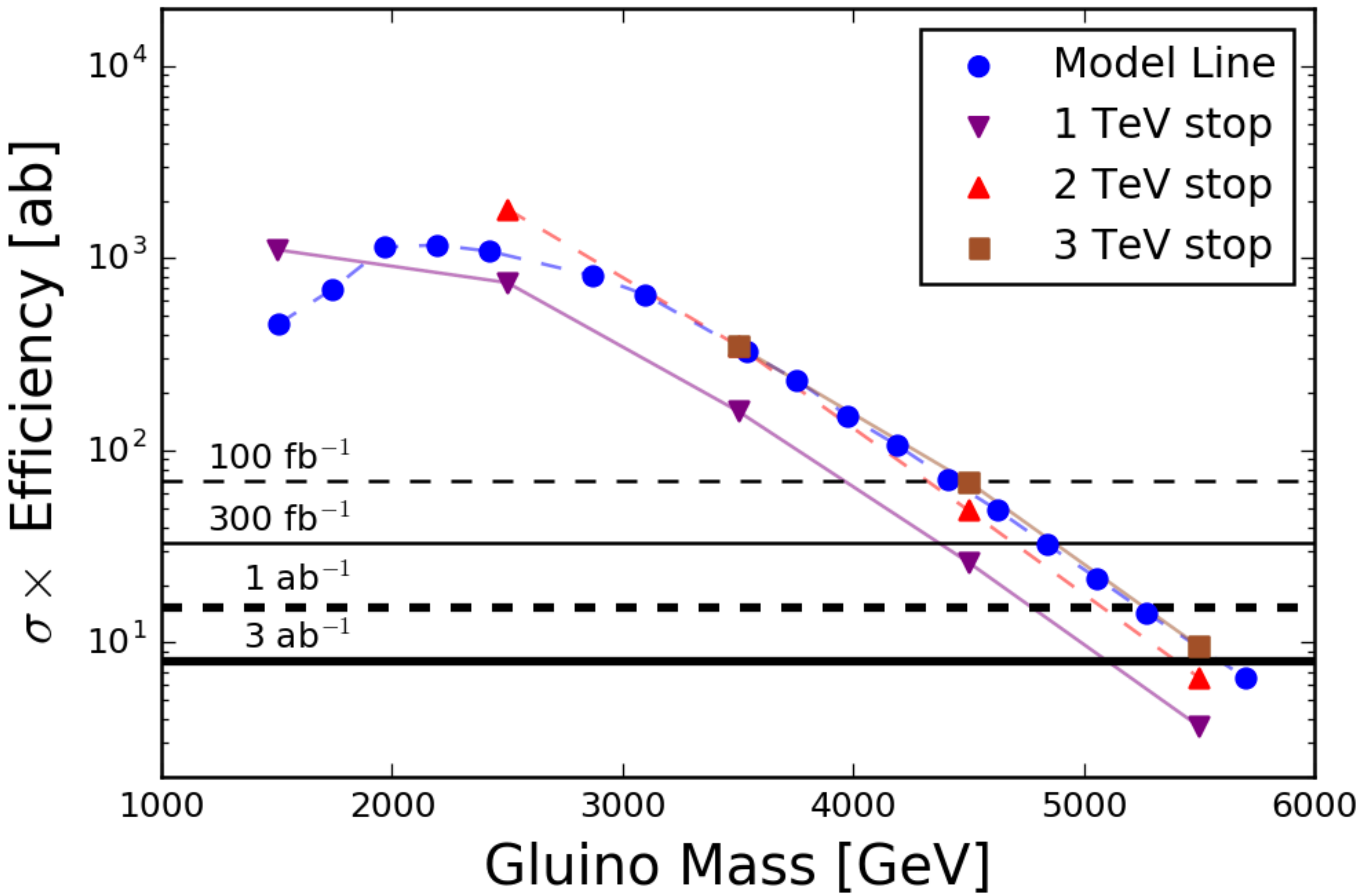
HB, Barger, Huang, Gainer, Savoy, Sengupta, Tata

LHC14 has some reach for gluino pair production in RNS; if a signal is seen, should be distinctive



OS/SF dilepton mass edge apparent from cascade decays with z2->z1+l+lbar

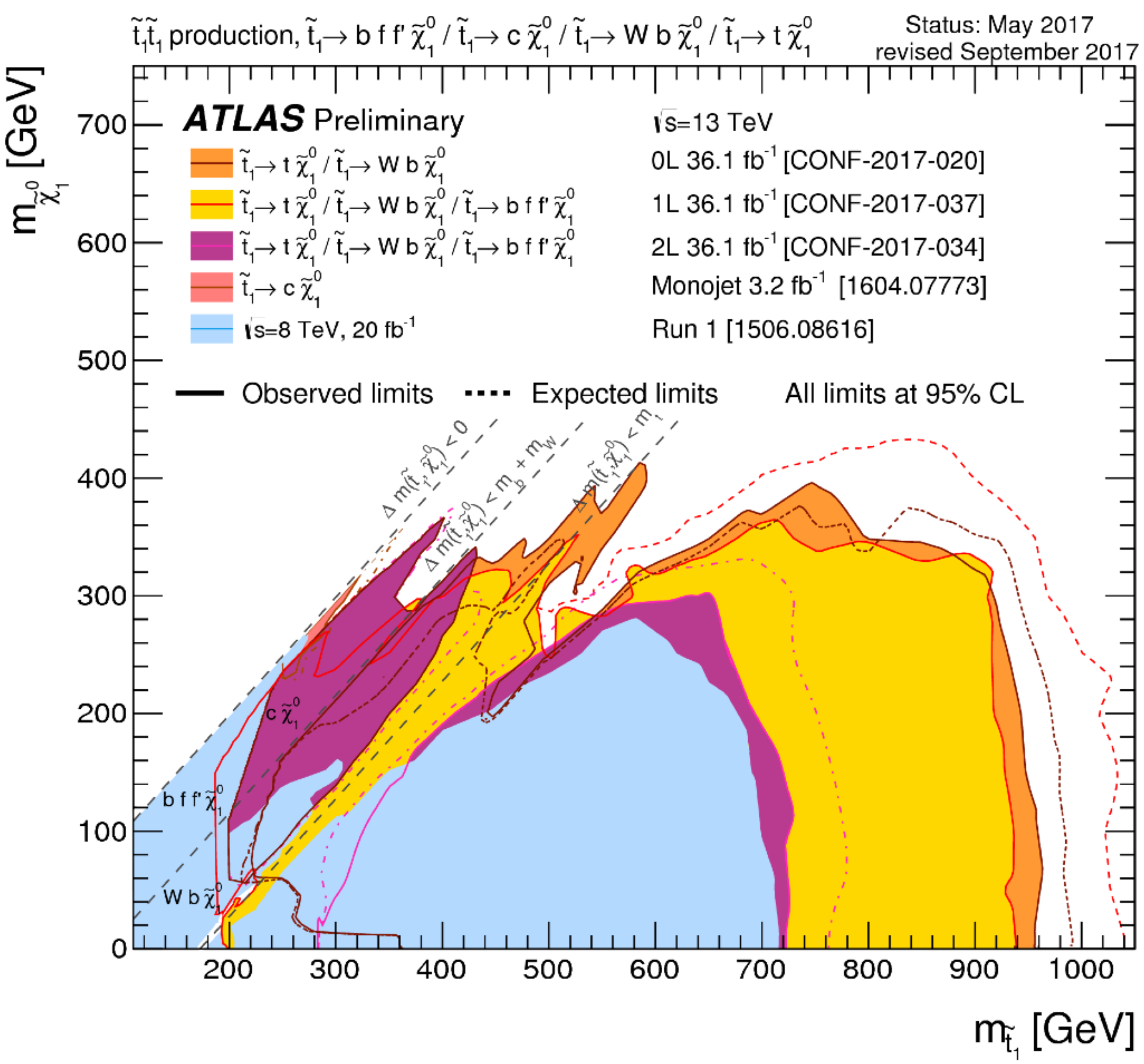
Gluino 5-sigma reach at LHC33: to about m(glno)~5-5.5 TeV

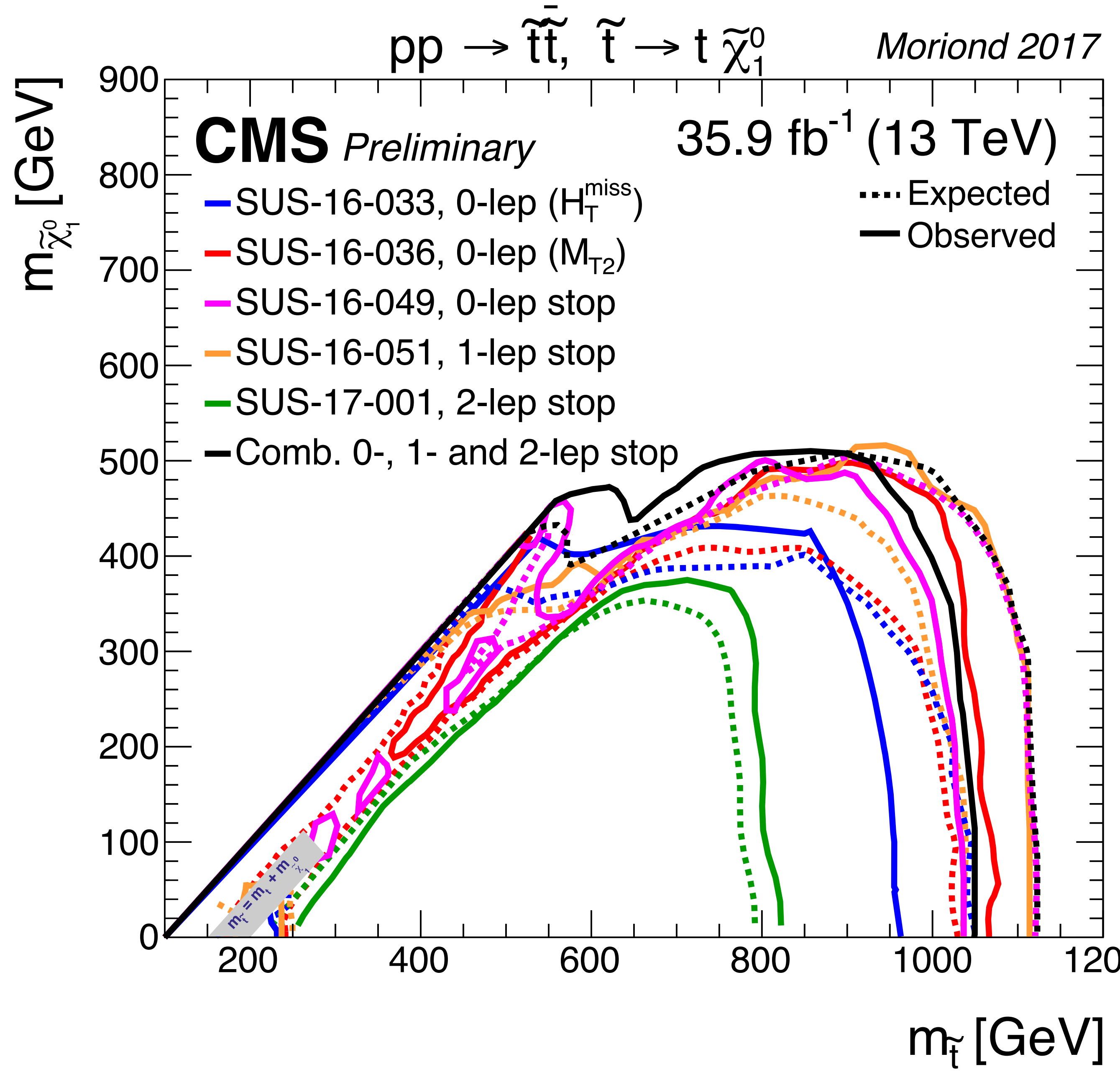


>=4 jets; >=2-b-jets;MET>1500 GeV

HB,Barger, Gainer,Huang, Savoy, Serce, Tata

Present limits on top squarks from LHC

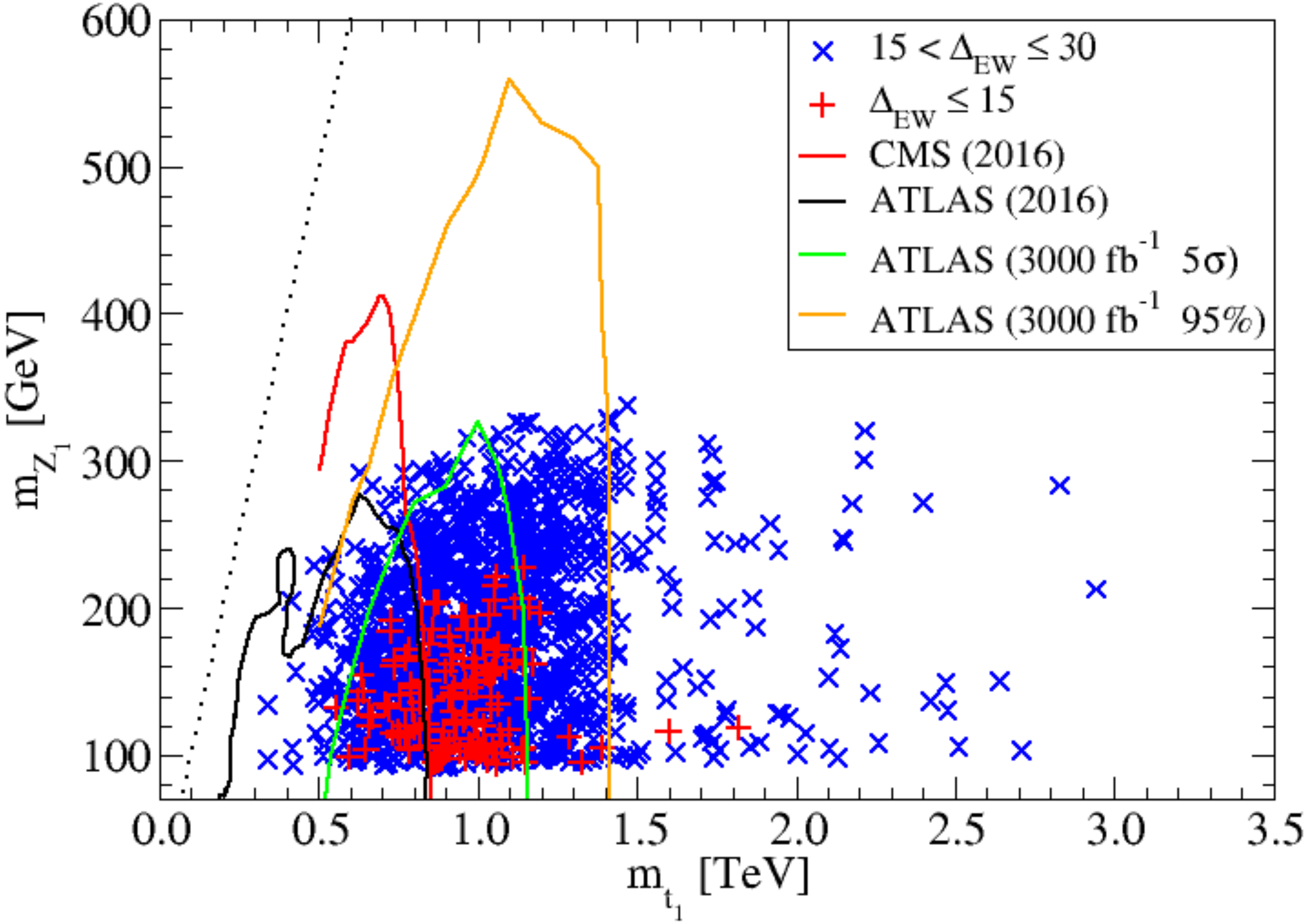




Evidently m(t1)>~1 TeV for m(LSP)~150 GeV

* TeV-scale top squark needed for m(h)~125 GeV
* Also needed for b-> s gamma

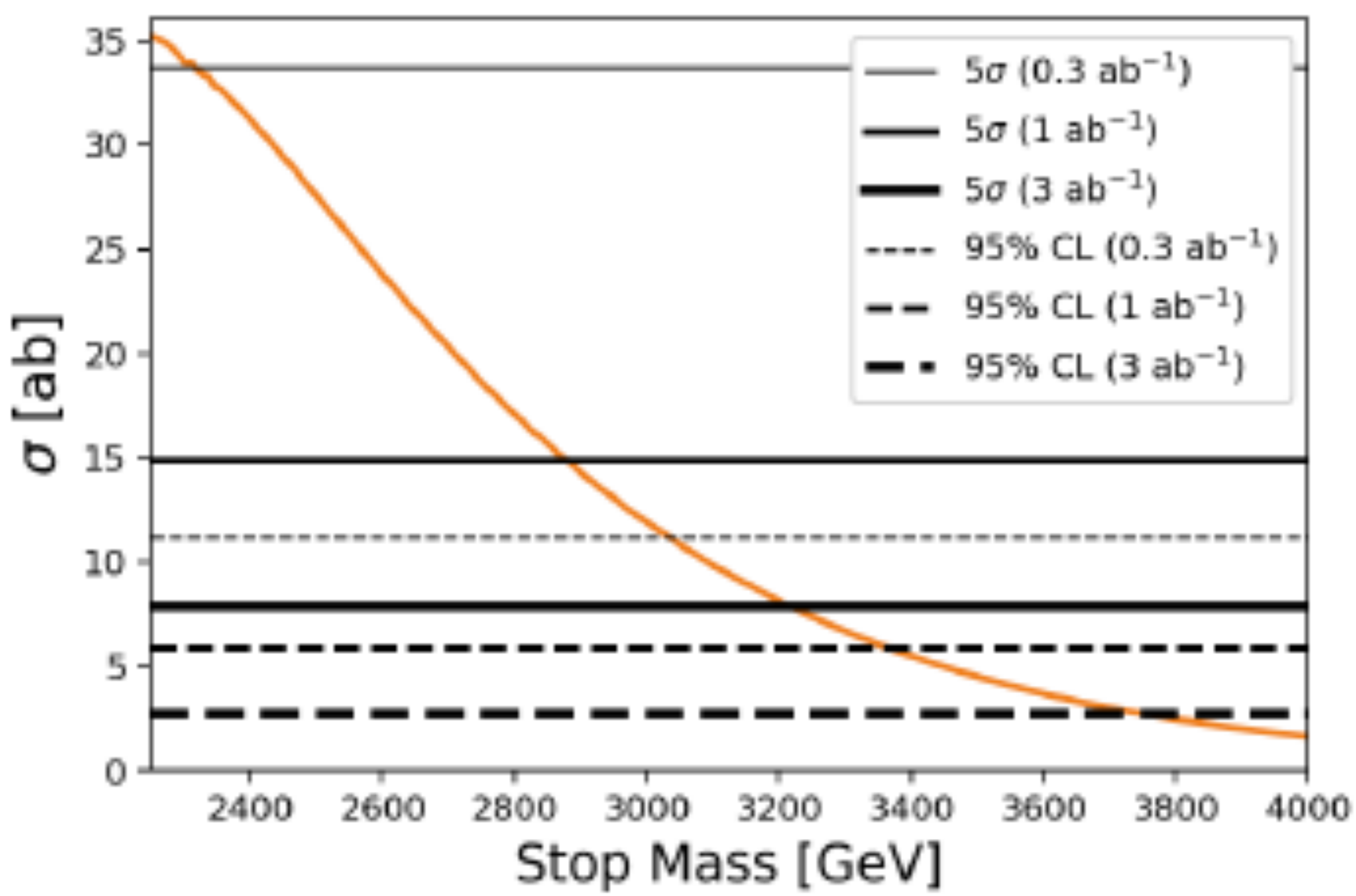
Prospects for top squarks in natural SUSY



m(t1) can range up to 3 TeV with little cost to naturalness;
the hunt for stops has only begun!

HL-LHC reach extends to m(t1)~1.2-1.4 TeV

Reach of LHC33 for top squarks



- $\tilde{t}_1 \to b\tilde{W}_1; \sim 50\%$
- $\tilde{t}_1 \to t\tilde{Z}_1; \sim 25\%$
- $\tilde{t}_1 \to t\tilde{Z}_2; \sim 25\%$

- A. $\tilde{t}_1\tilde{t}_1^* \to b\bar{b} + E_T^{\rm miss} \quad \sim 25\%$,
- B. $\tilde{t}_1\tilde{t}_1^* \to b\bar{t},\ \bar{b}t + E_T^{\rm miss} \quad \sim 50\%$,
- C. $\tilde{t}_1\tilde{t}_1^* \to t\bar{t} + E_T^{\rm miss} \quad \sim 25\%$.

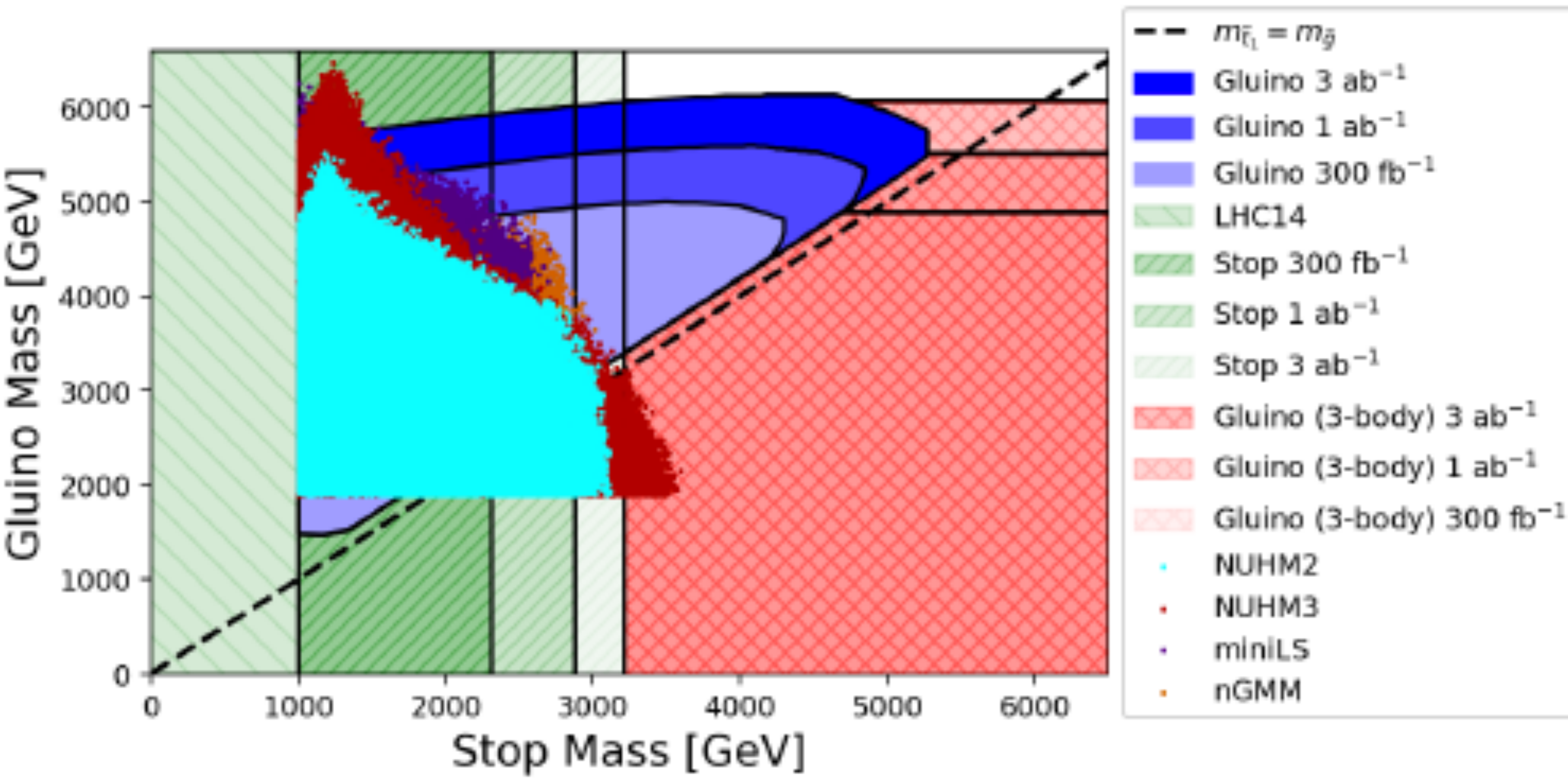
LHC33 reach extends to m(t1)~3-3.8 TeV

n(b-jets)>=2; MET>750 GeV

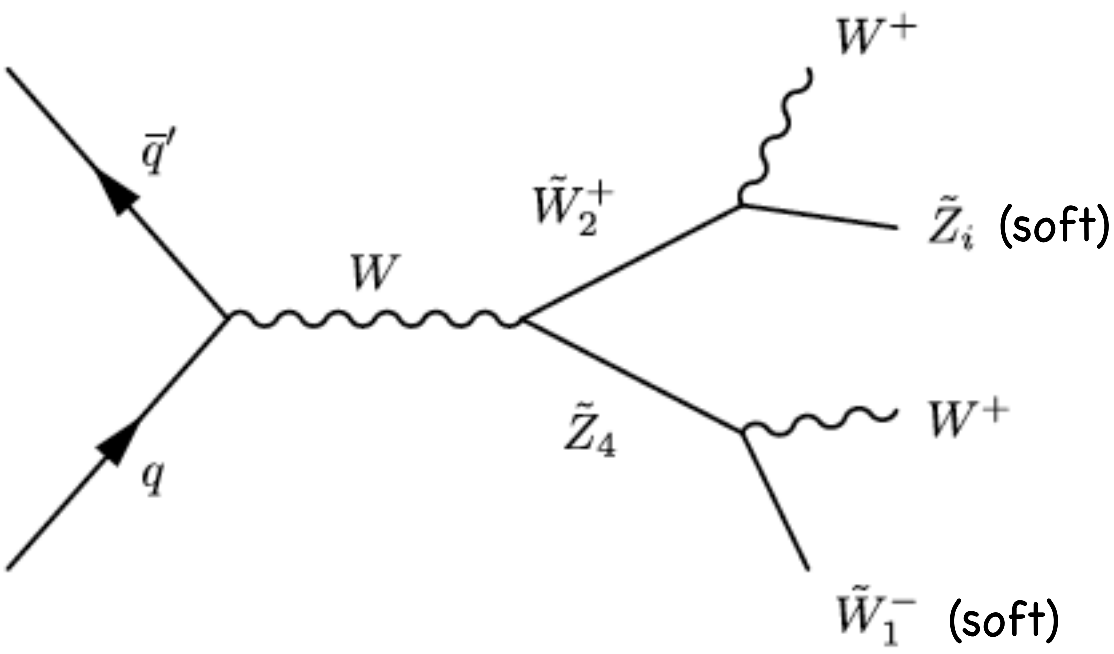
HB, Barger, Gainer, Serce, Tata

Combined LHC33 reach for t1 and glno covers all natural SUSY p-space!

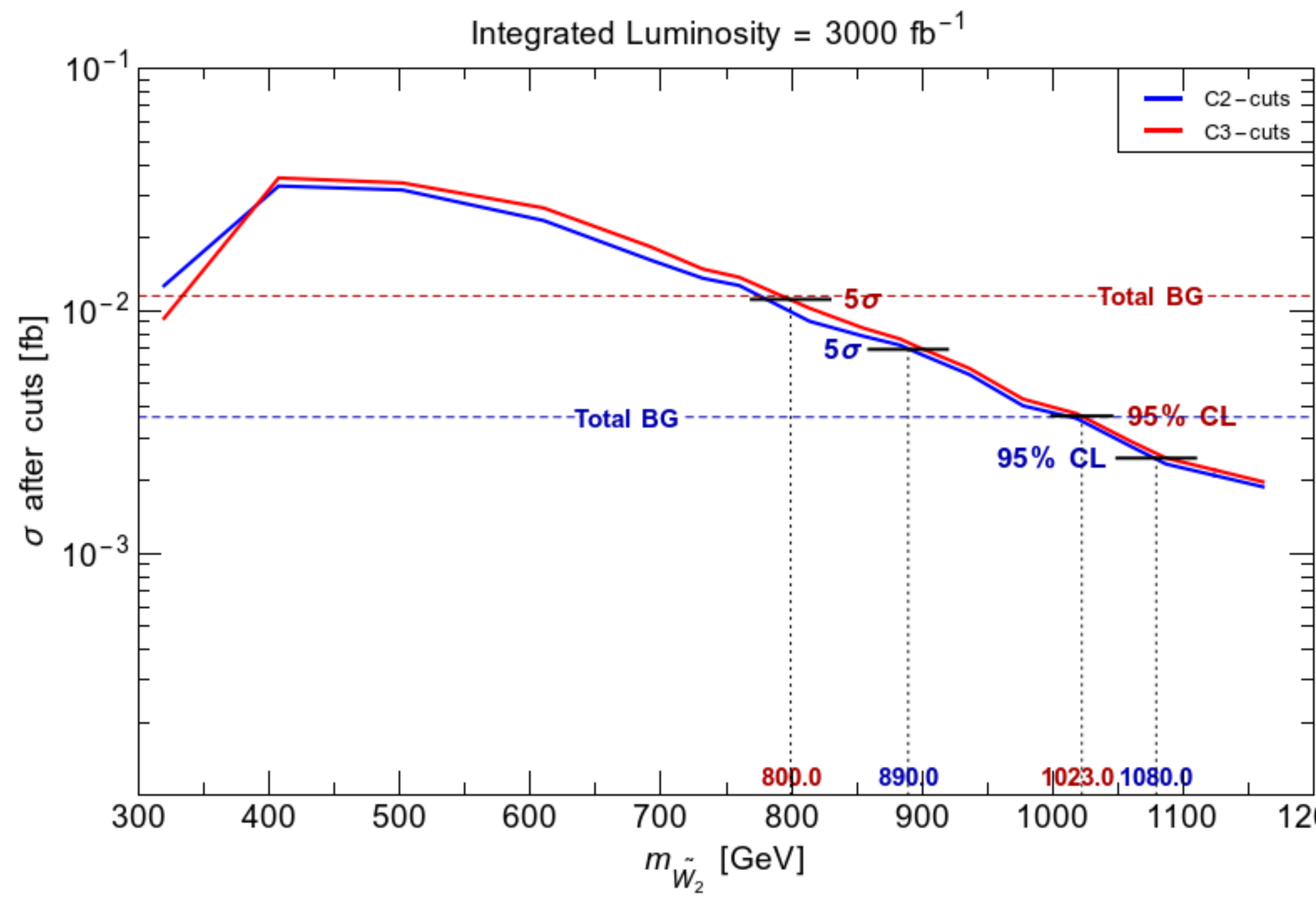
(need to re-do for LHC27)



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



wino pair production

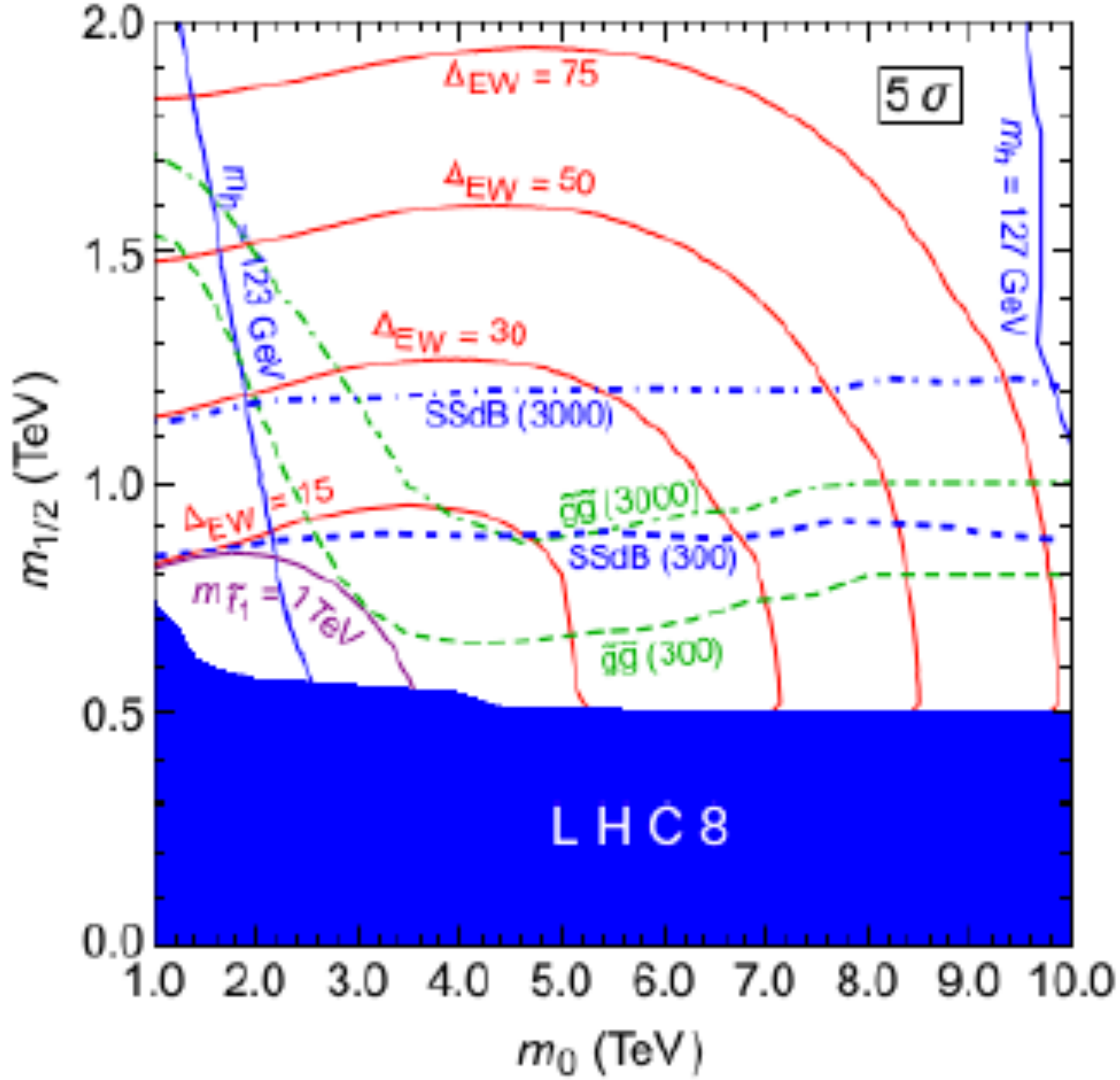


This channel offers good reach of LHC14 for RNS; it is also indicative of wino-pair prod'n followed by decay to higgsinos

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

HB, Barger, Gainer, Sengupta, Tata

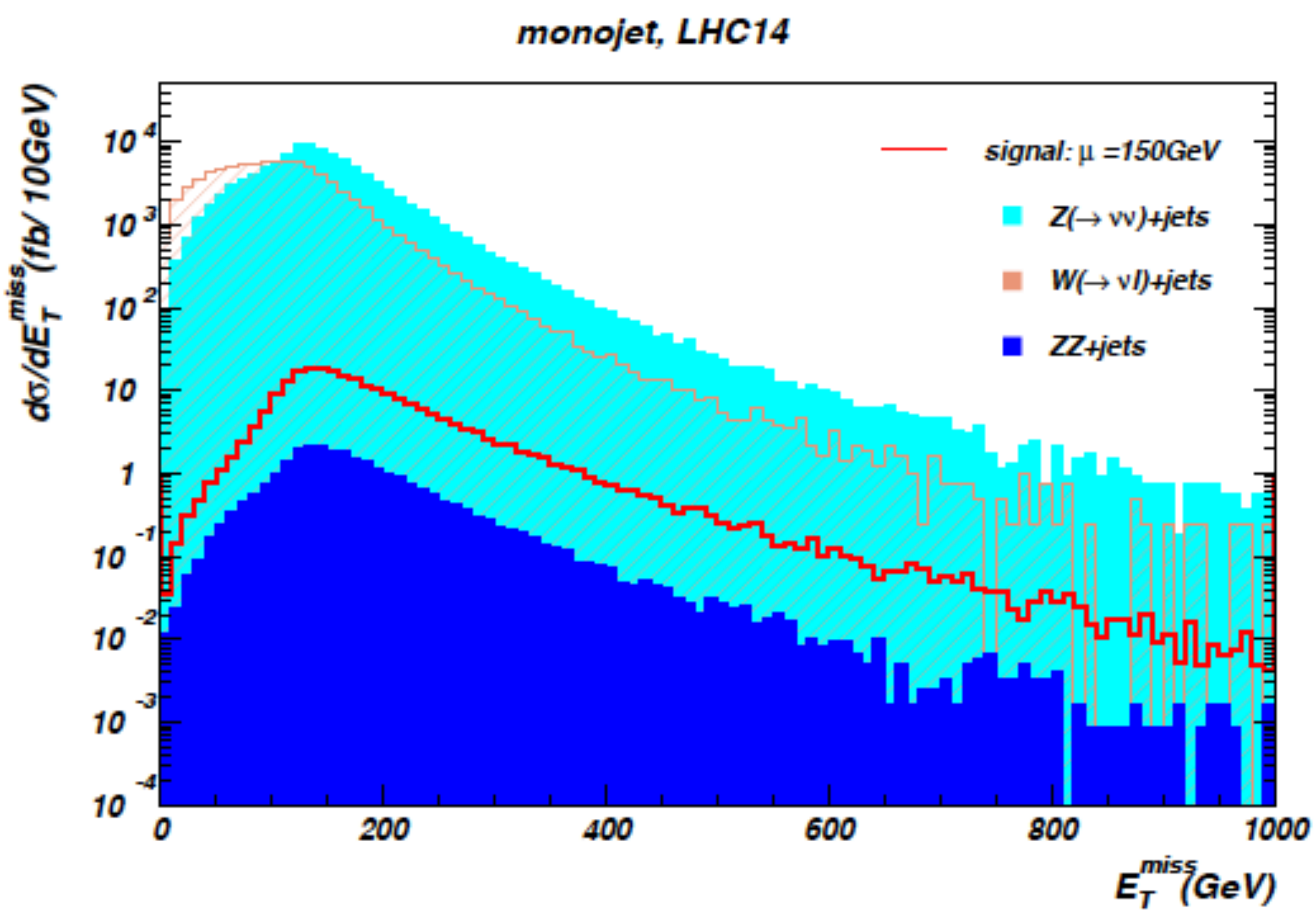
Good old m0 vs. mhf plane still viable, but needs mu~100-200 GeV as possible in NUHM2 instead of CMSSM/mSUGRA



For models with ino mass unif'n, reach via SSdB may exceed glno pairs for high luminosity

HB,Barger,Savoy, Tata; arXiv:1604.07438

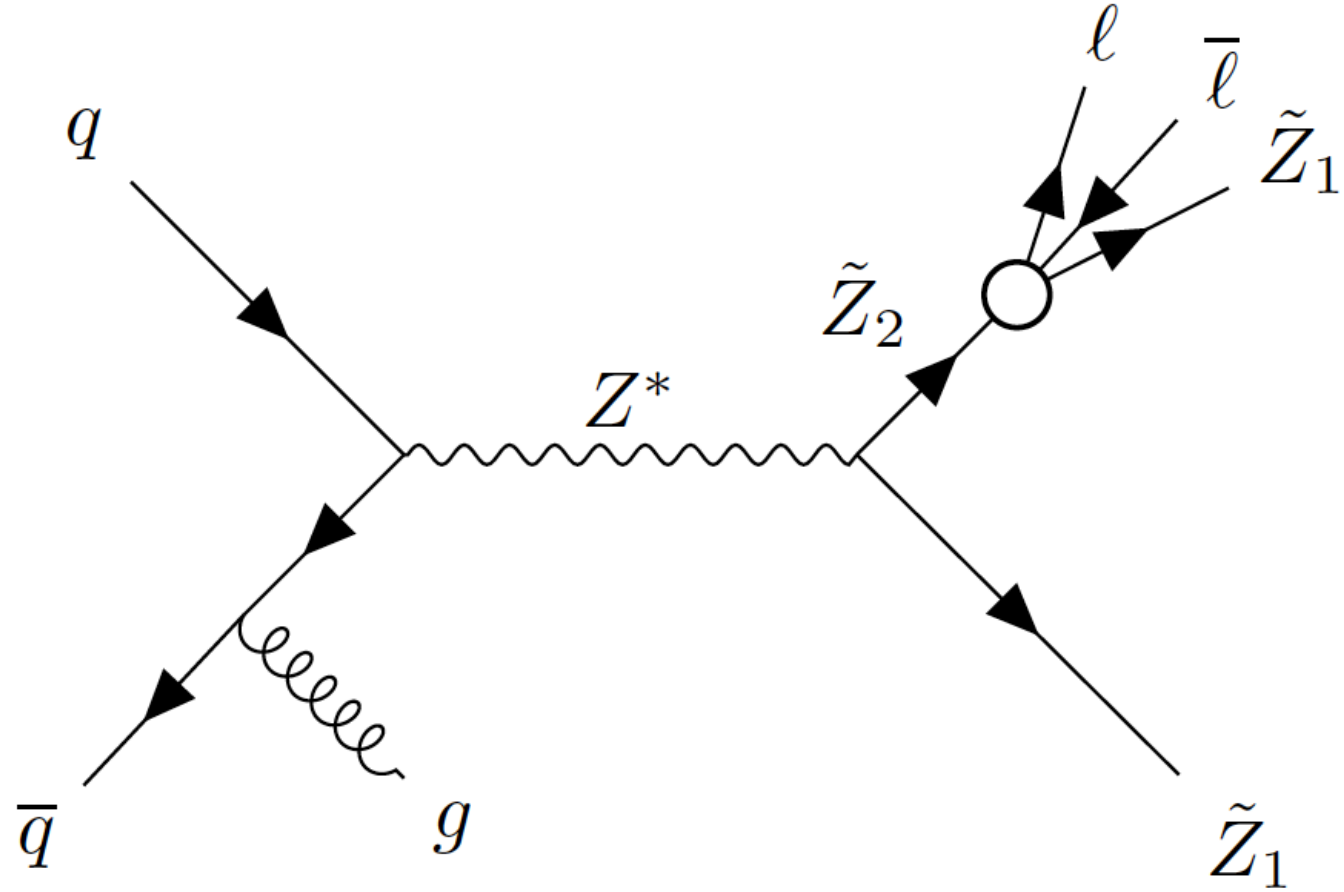
See direct higgsino pair production recoiling from ISR (monojet signal)?



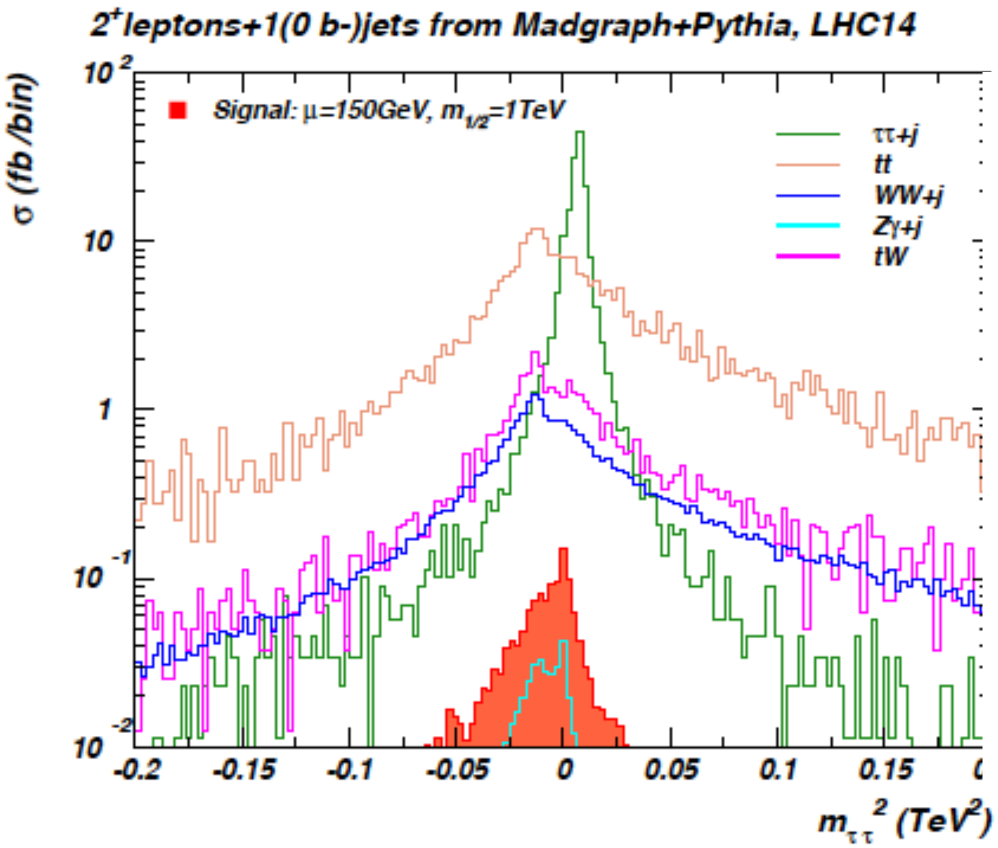
typically 1% S/BG after cuts: very tough to do!

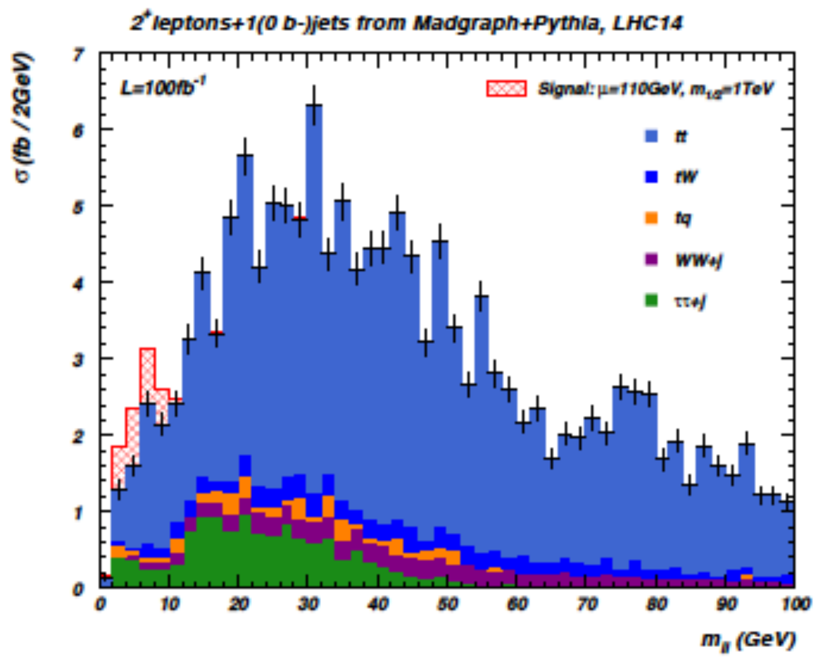
What about $pp \to \tilde{Z}_1 \tilde{Z}_2 j$ with $\tilde{Z}_2 \to \tilde{Z}_1 \ell^+ \ell^-$?

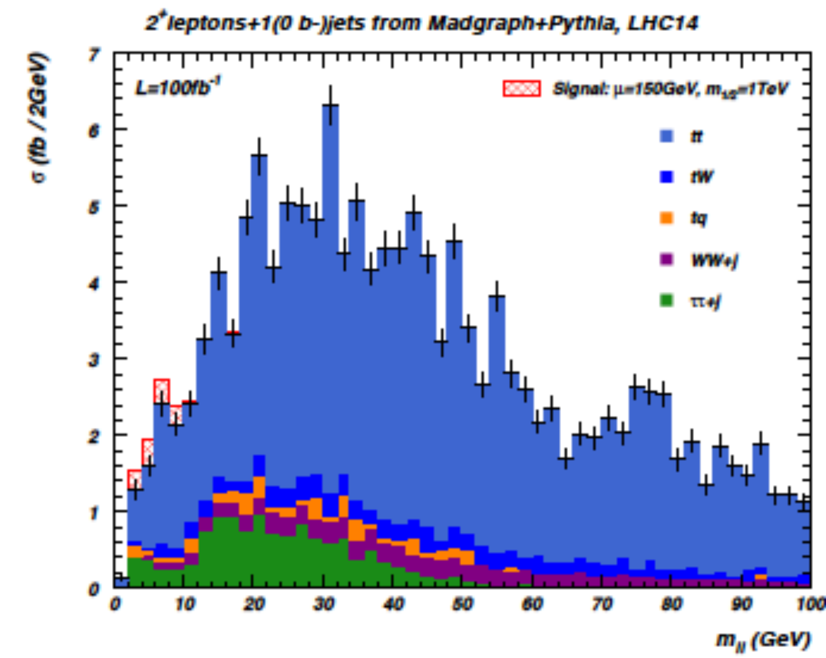
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;



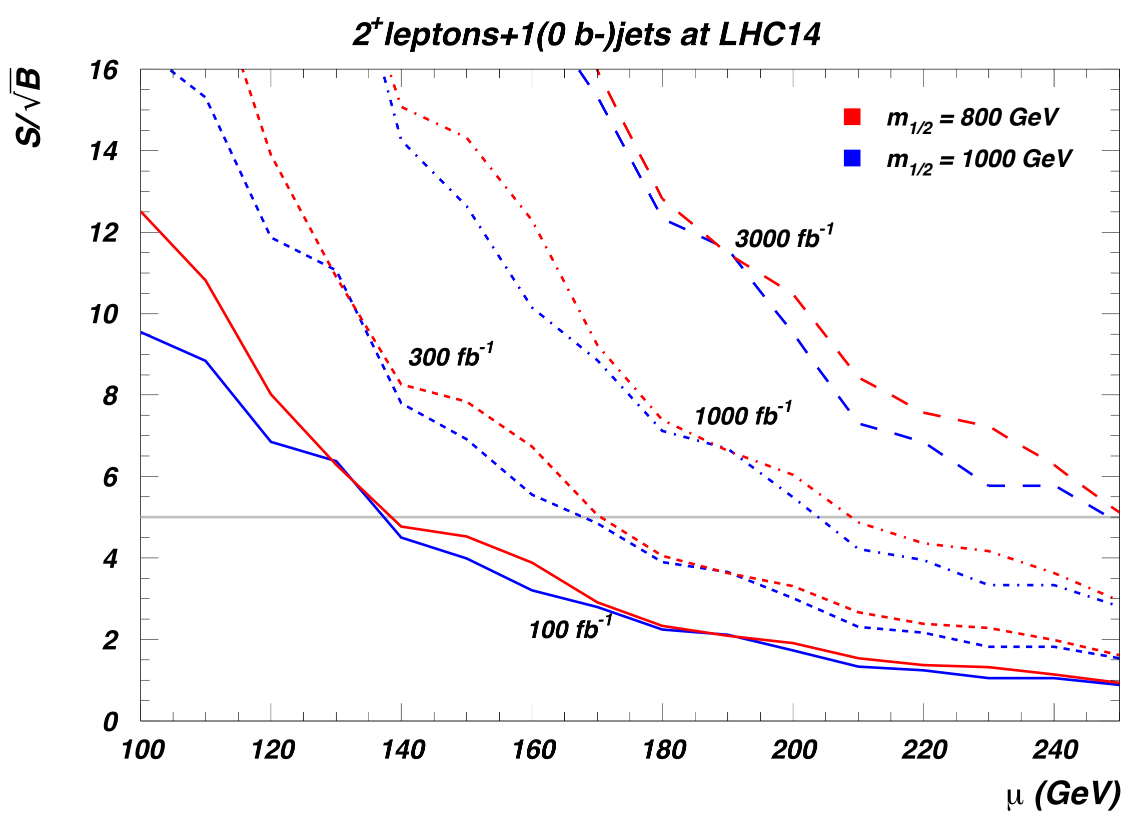
use MET to construct m^2(tau-tau)







cut m(ditau)^2<0



HL-LHC 5-sigma reach
to mu~250 GeV!

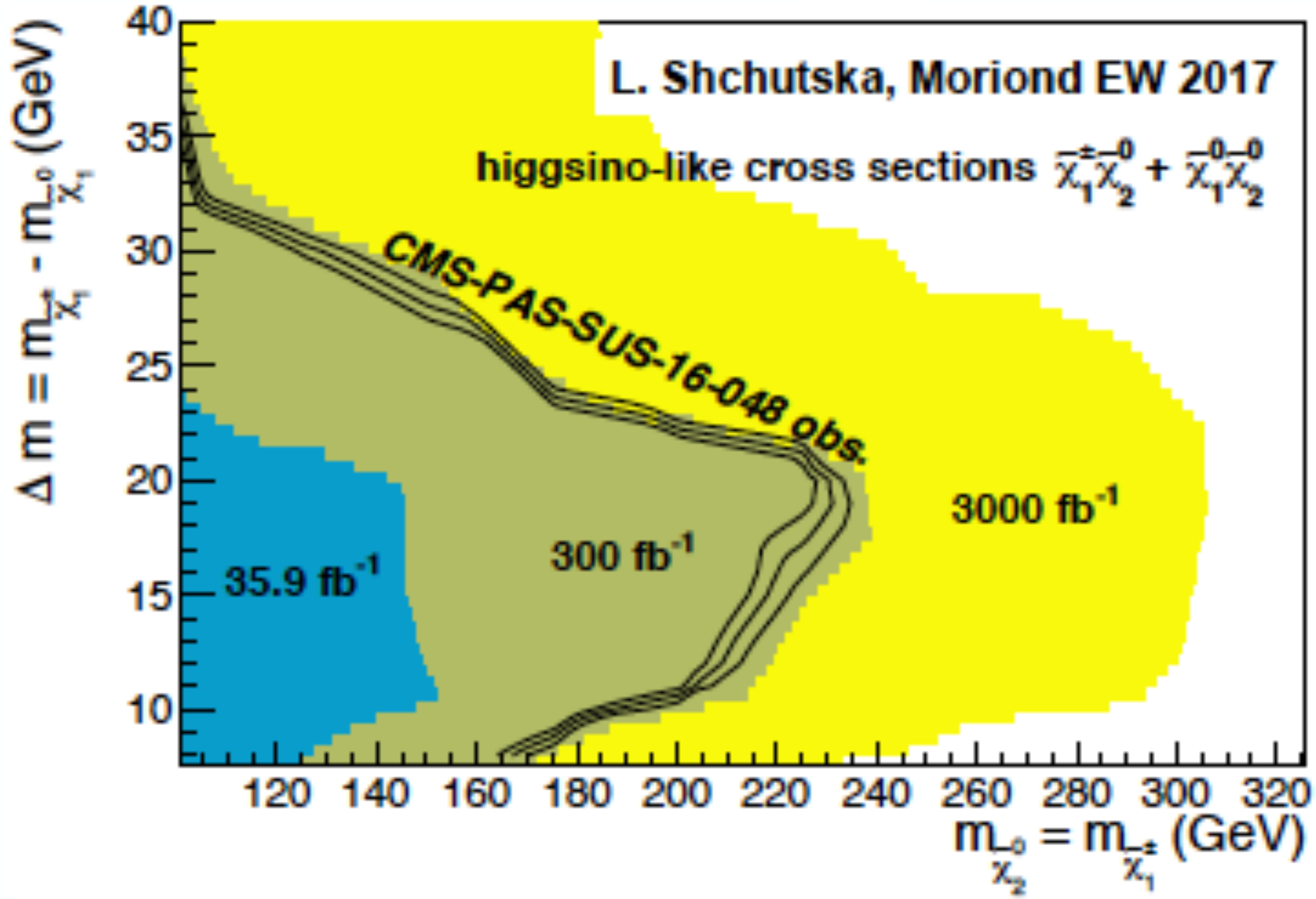
HB, Mustafayev, Tata

CMS analysis: this may be the most important SUSY discovery channel at LHC since it directly probes higgsinos which can't be too far from m(W,Z,h)

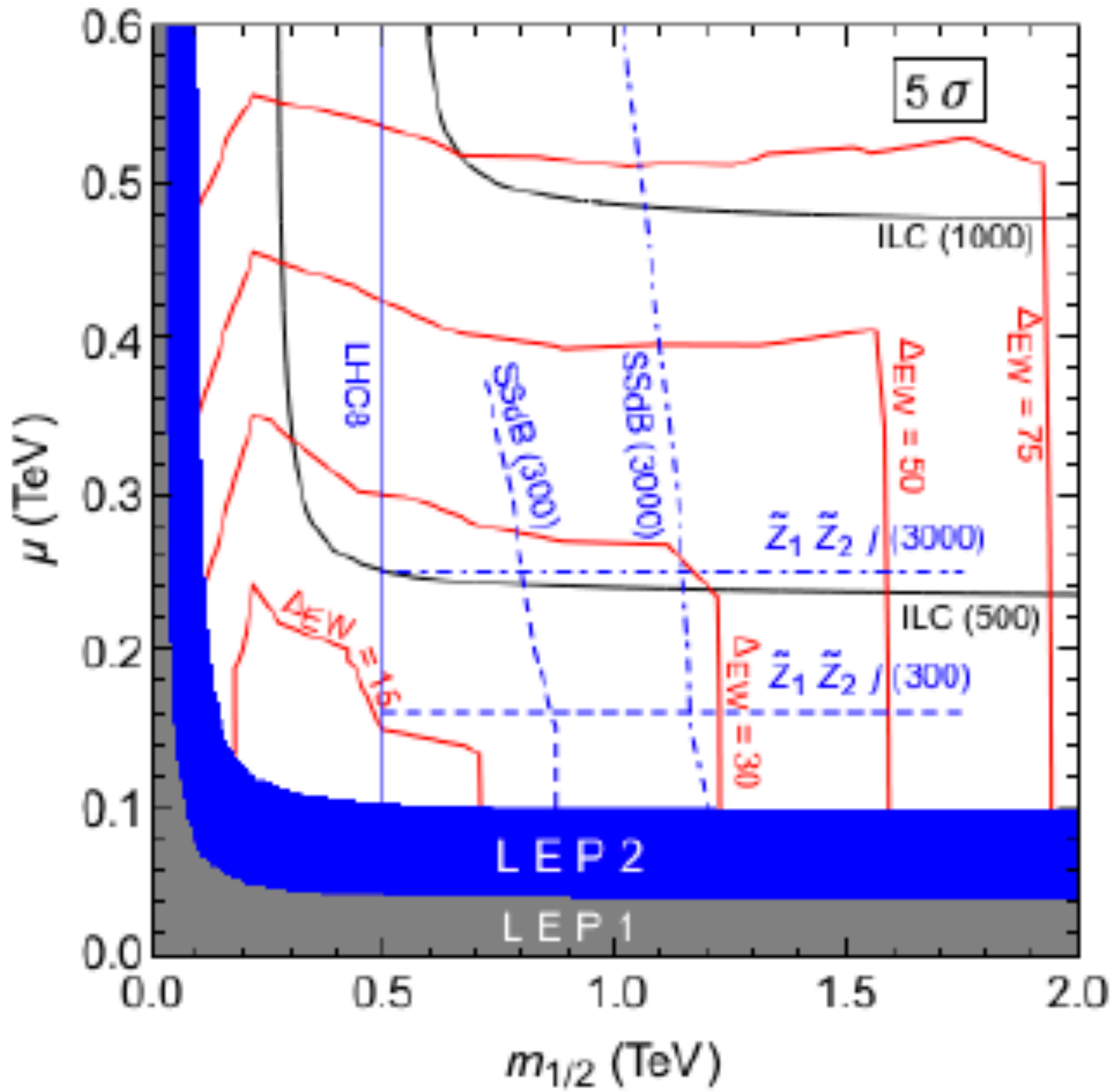
Atlas study underway- results soon?

NatSUSY z2-z1 mass gap may range down to 3 GeV so need to ID very soft, low m(ll) leptons

Higgsino cross section (projection only)



panoramic view of reach of HL-LHC for natural SUSY

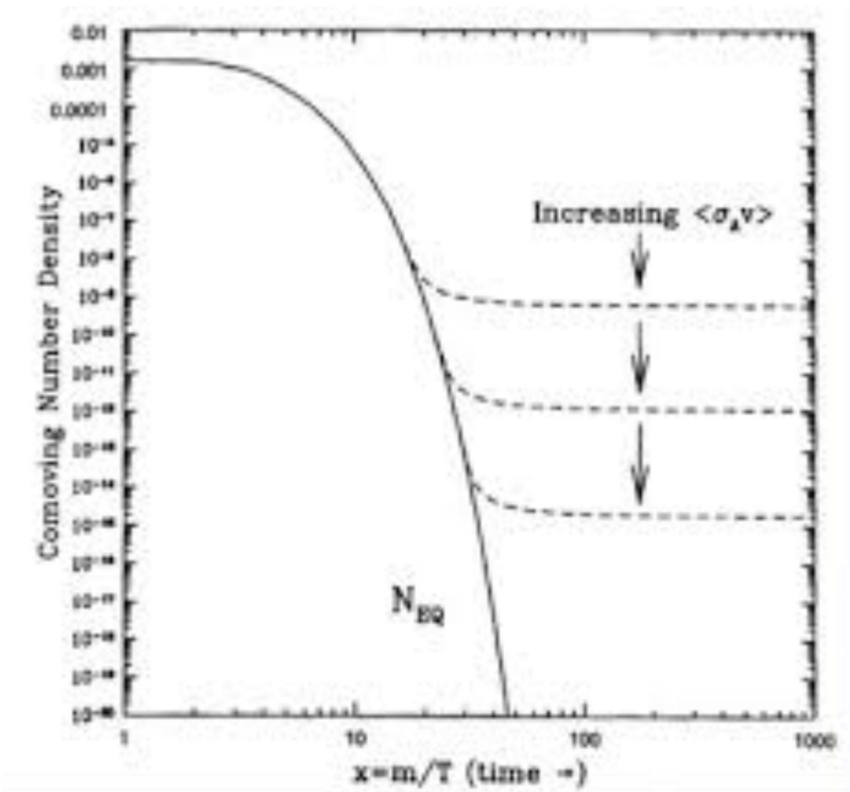


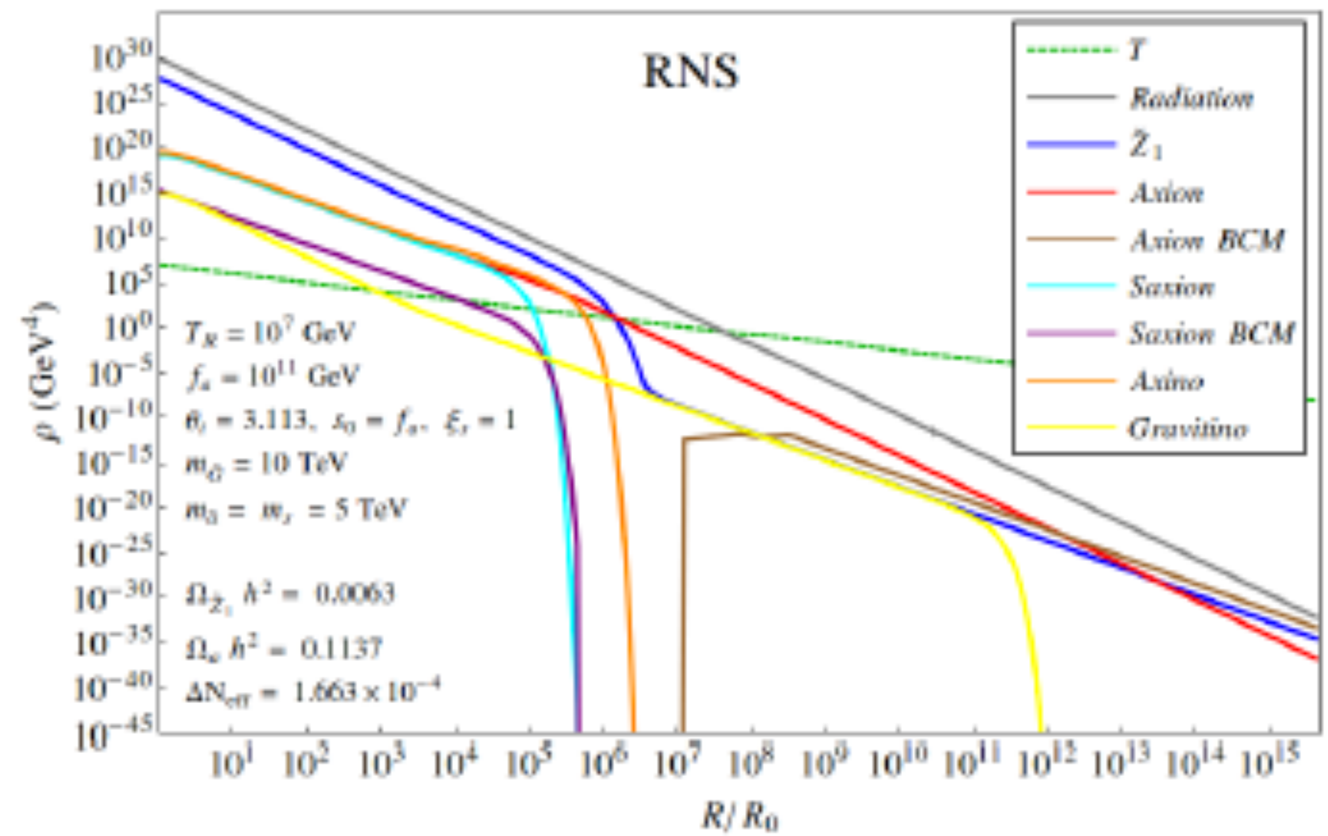
Combined SSdB/lljMET searches may cover all Nat SUSY p-space at HL-LHC for models with ino mass unification; in mirage scenario, z2-z1 mass gap can be reduced and M2 can be much higher than in NUHM2

What happens to SUSY WIMP dark matter?

- higgsino-like WIMPs thermally underproduced
- 3 not four light pions => QCD theta vacuum
- F.F~ term should be present but neutron(EDM)=> it is tiny
- strong CP problem => axions: no fine-tuning in QCD sector
- SUSY context: axion superfield, axinos and saxions
- DM= axion+higgsino-like WIMP admixture
- DFSZ SUSY axion: solves mu problem with mu<< m_3/2!
- ultimately detect both WIMP and axion?

usual picture => mixed axion/WIMP

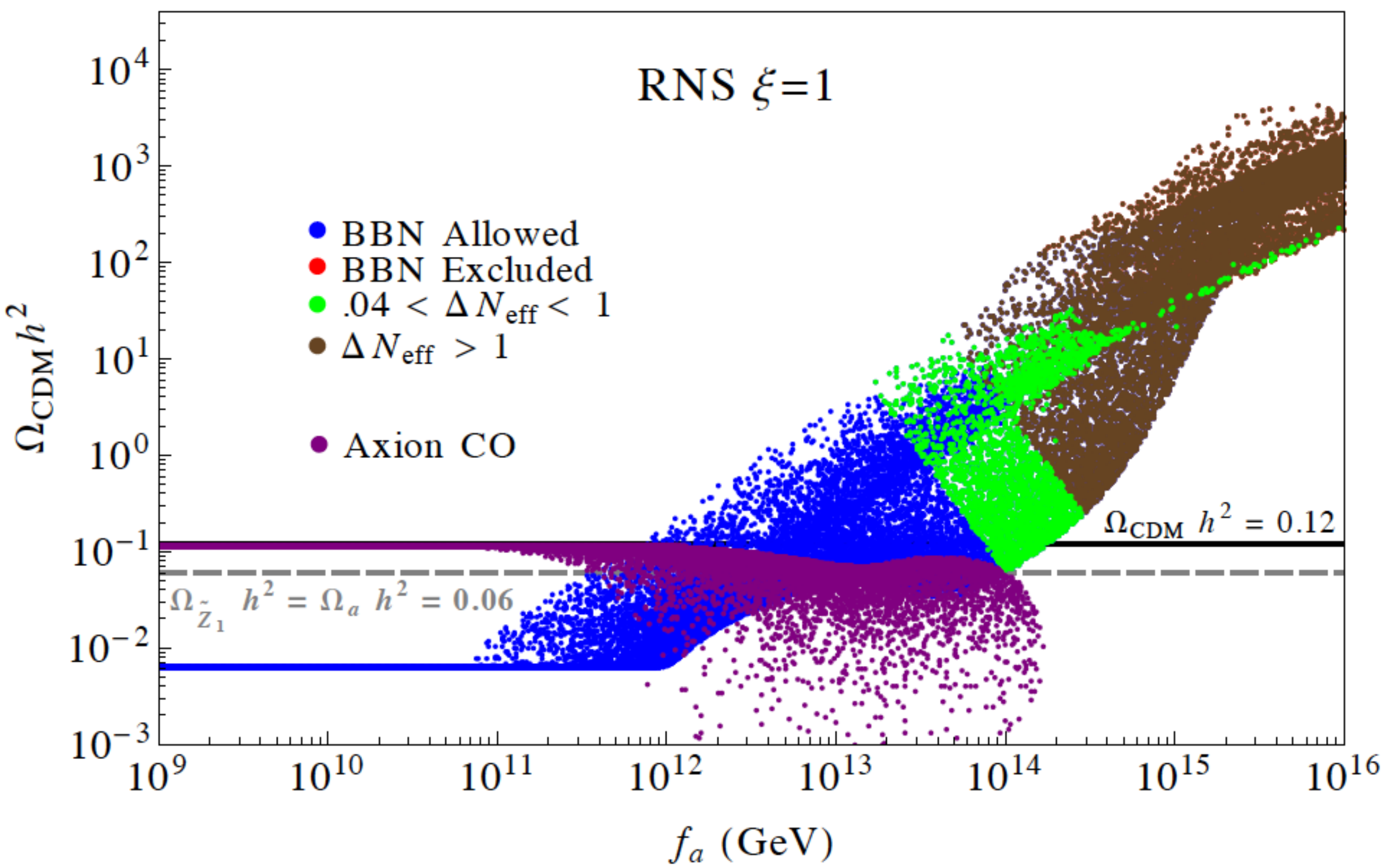




KJ Bae, HB, Lessa, Serce

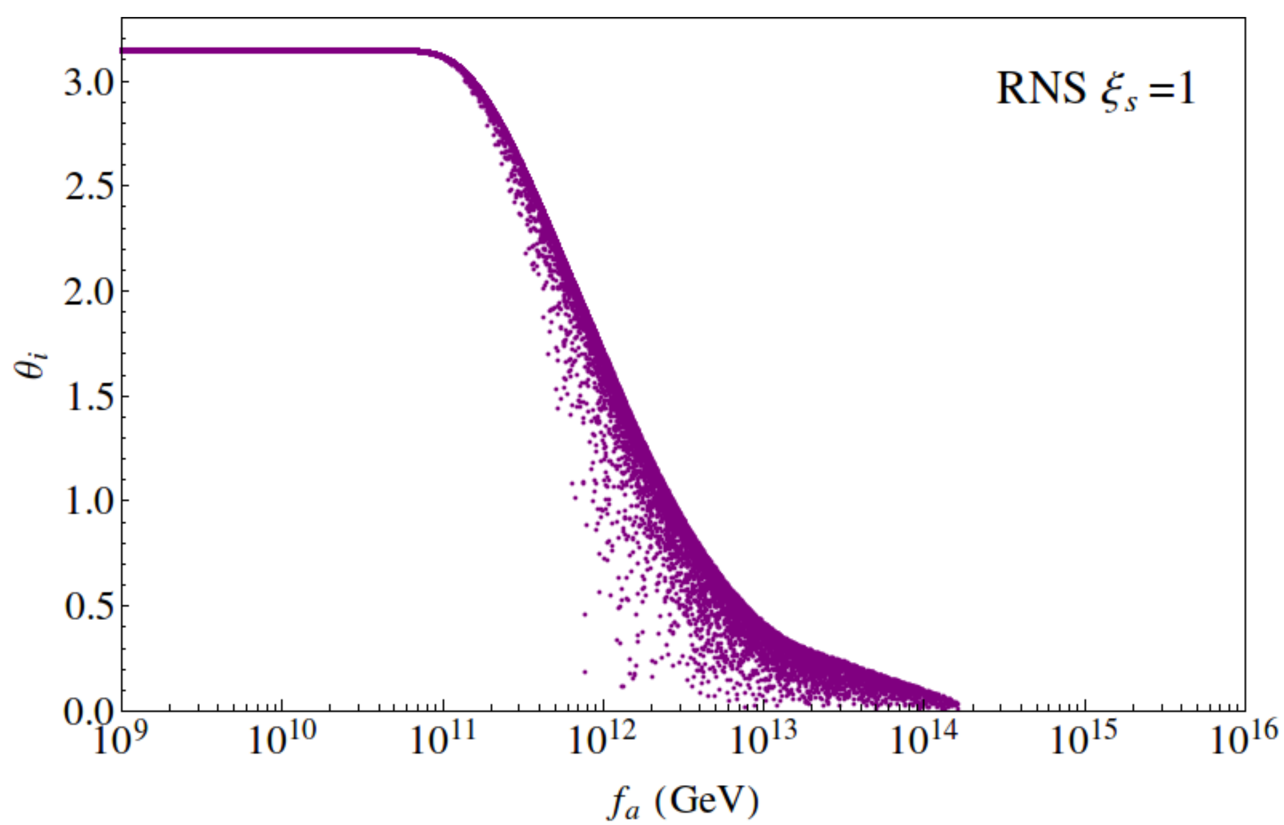
much of parameter space is axion-dominated with 10-15% WIMPs

=>



higgsino abundance

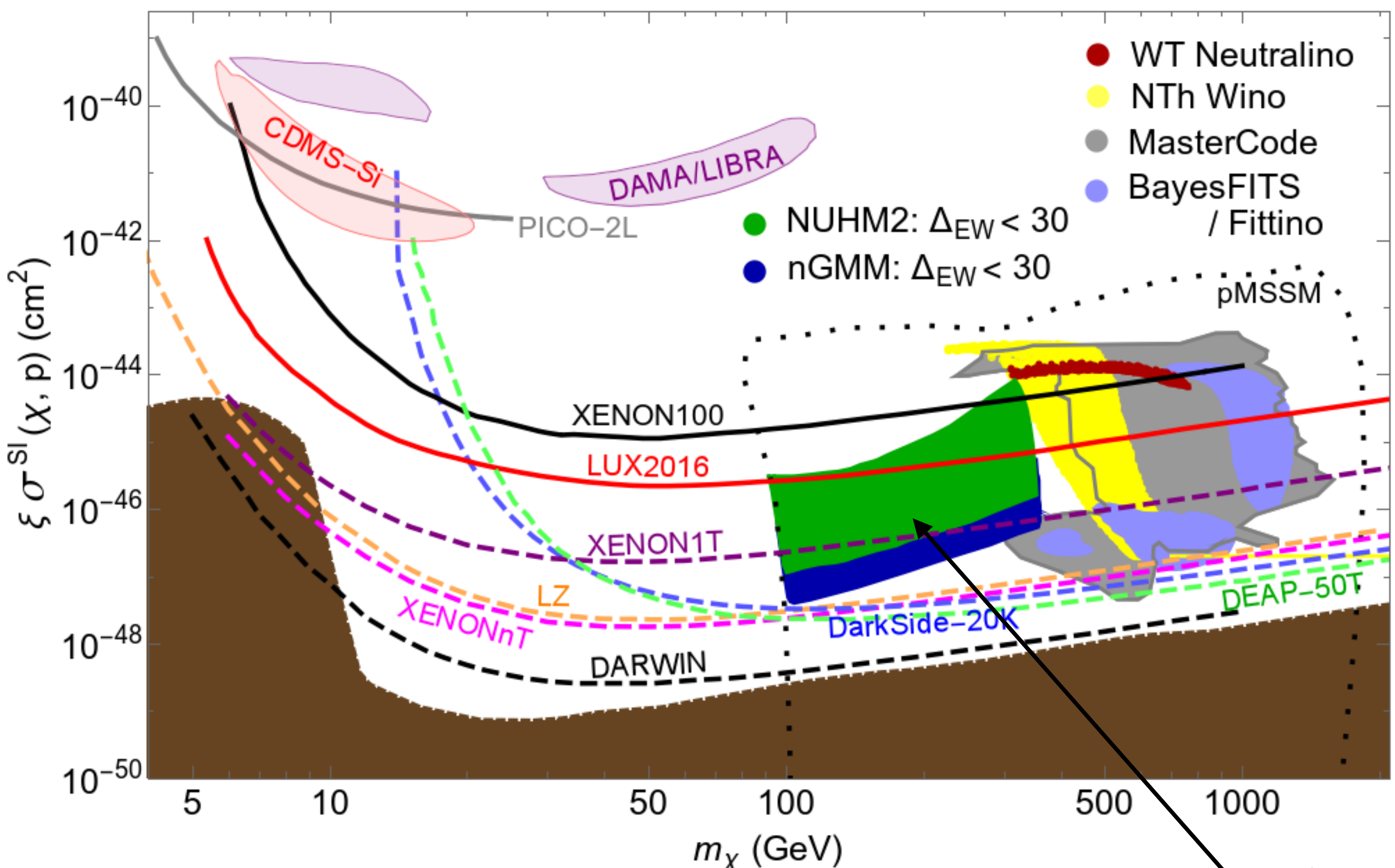
axion abundance



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

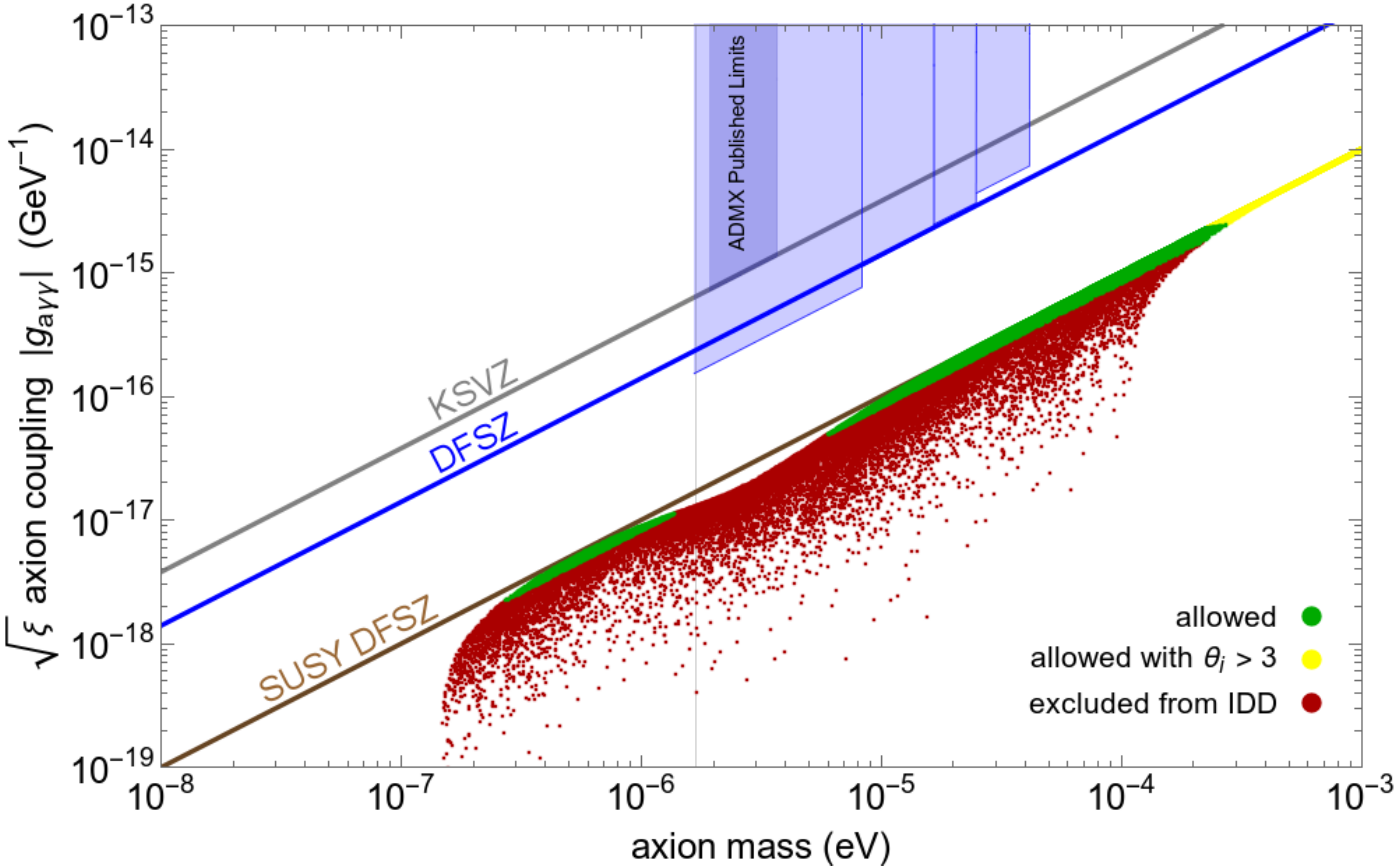
$$\mathcal{L} \ni -X_{11}^h \overline{\widetilde{Z}}_1 \widetilde{Z}_1 h$$

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

Xe-1-ton now operating!

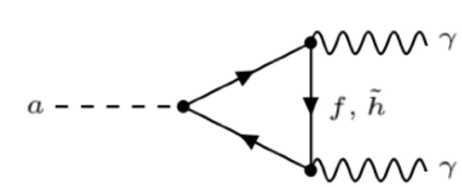
natural SUSY

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



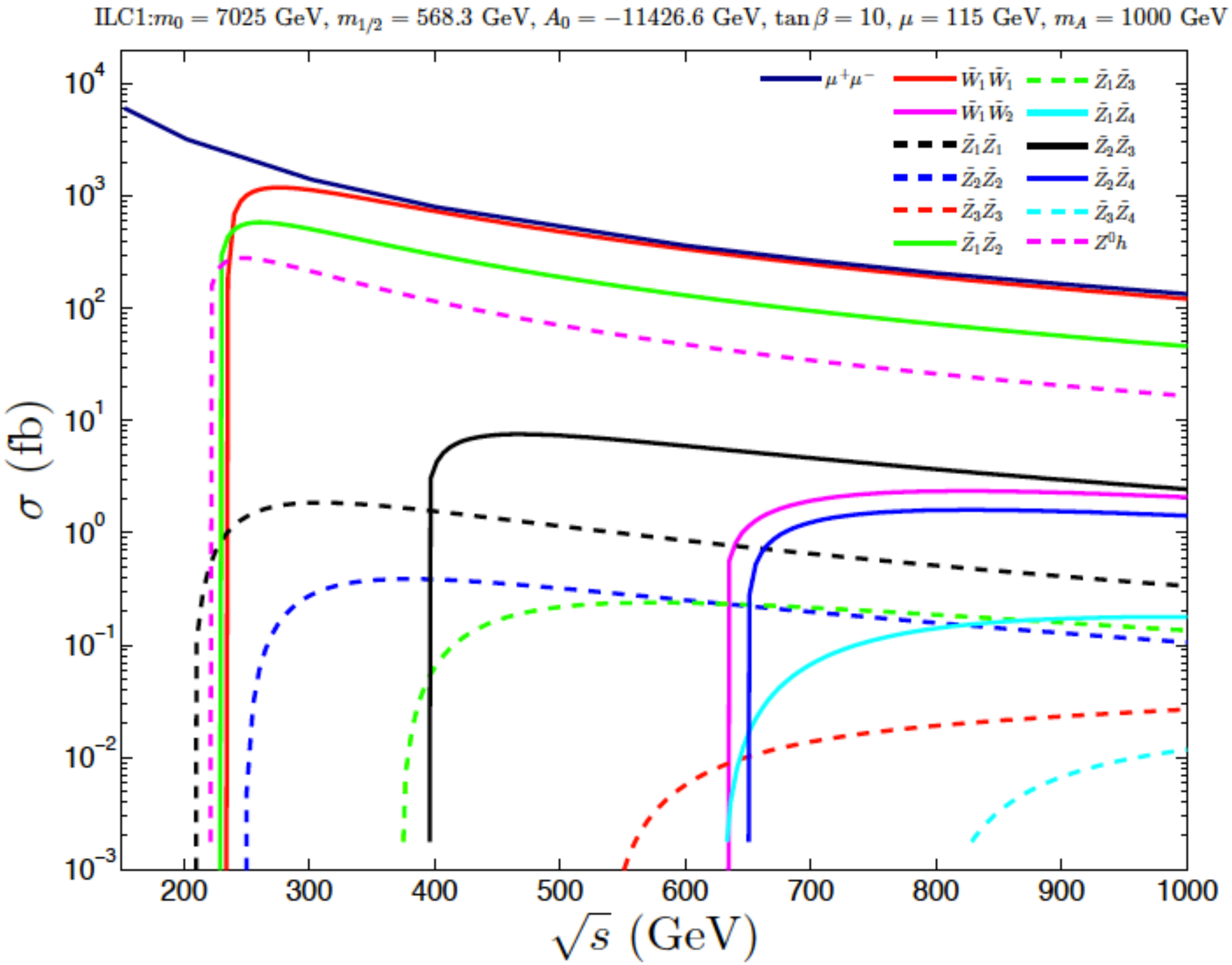
SUSY DFSZ axion: large range in m(a) but coupling reduced

may need to probe broader and deeper!



Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



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

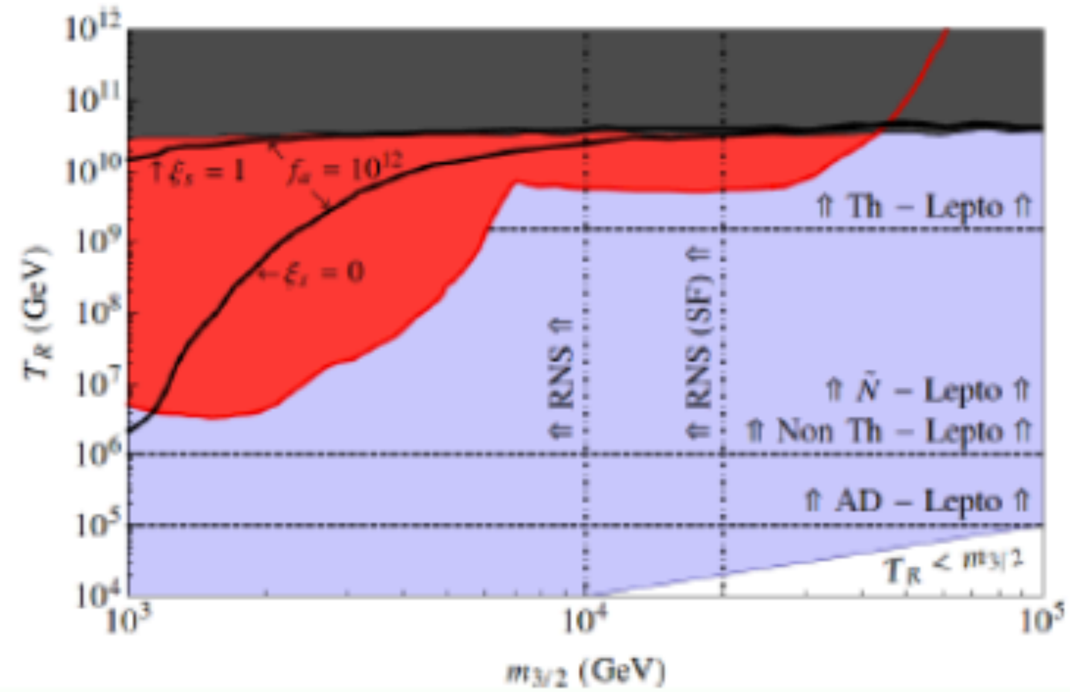
10-15 GeV higgsino mass
gaps no problem
in clean ILC environment

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

ILC either sees light higgsinos or MSSM dead

Baryogenesis scenarios for radiative natural SUSY

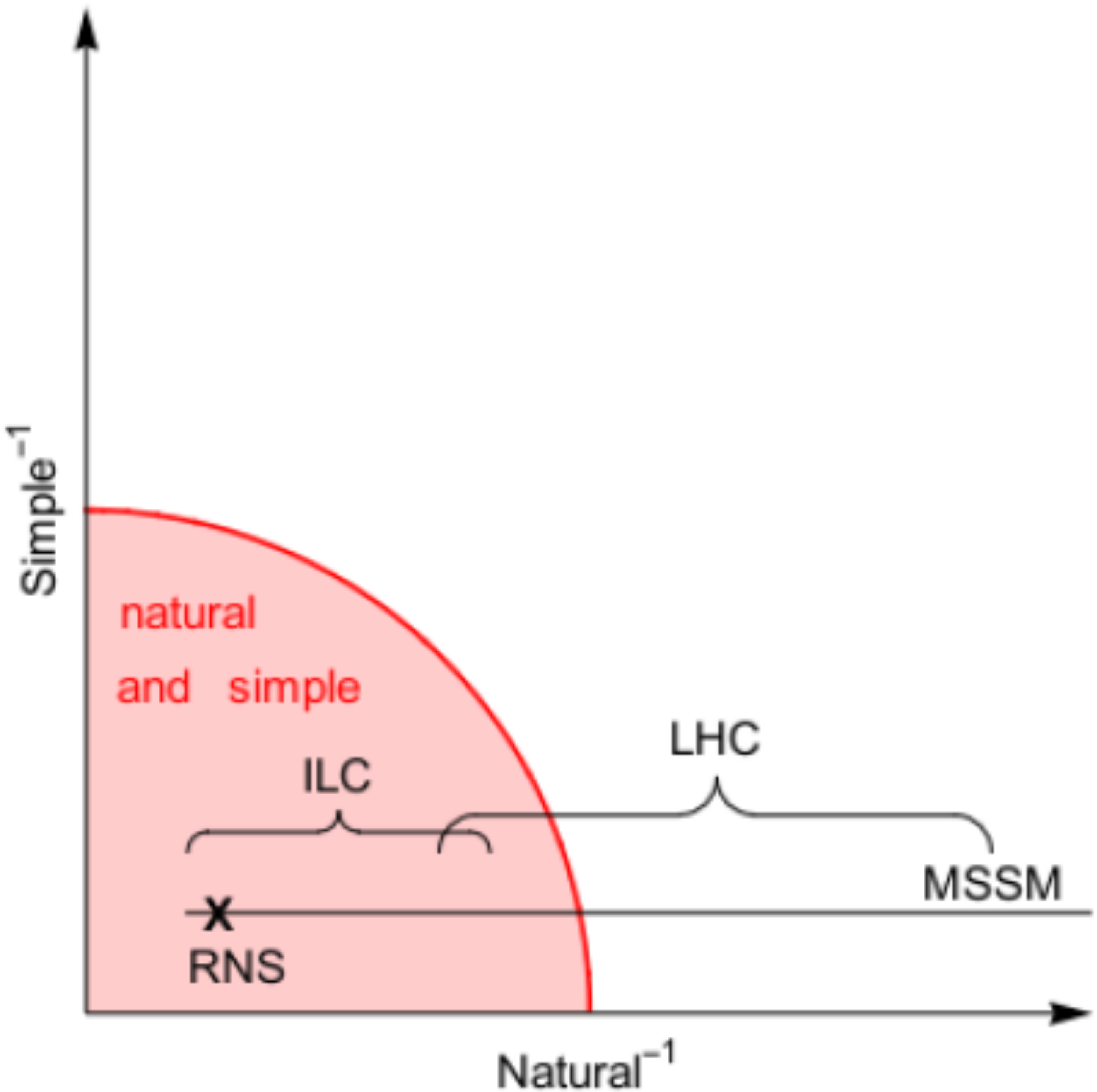
- thermal leptogenesis
- non-thermal (inflaton decay)
- oscillating sneutrino
- Affleck-Dine (AD)



gravitino problem plus axino/saxion problem: still plenty room

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

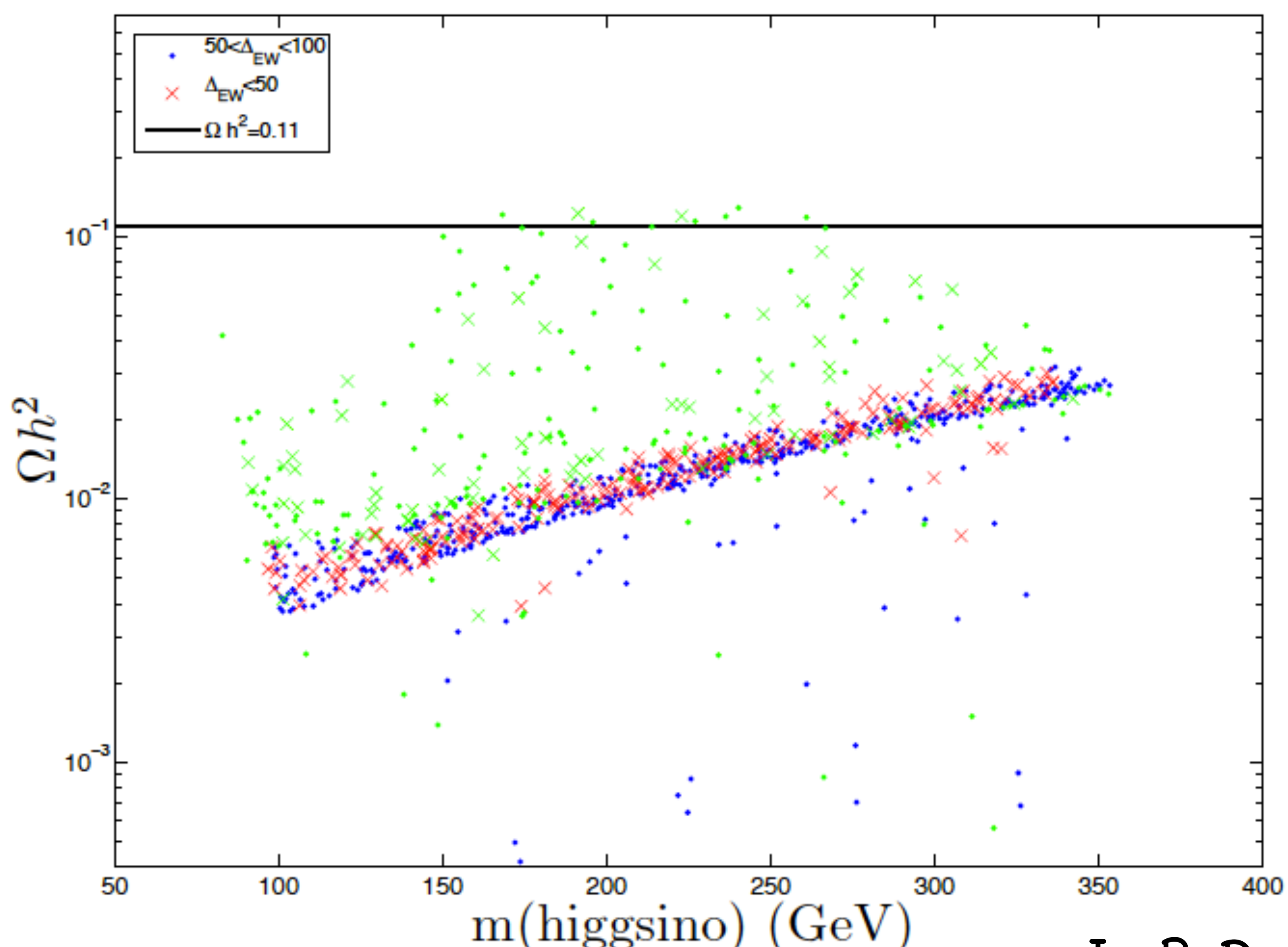
Bae,HB, Serce, Zhang, arXiv:1510.00724



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

Dark matter in RNS

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)

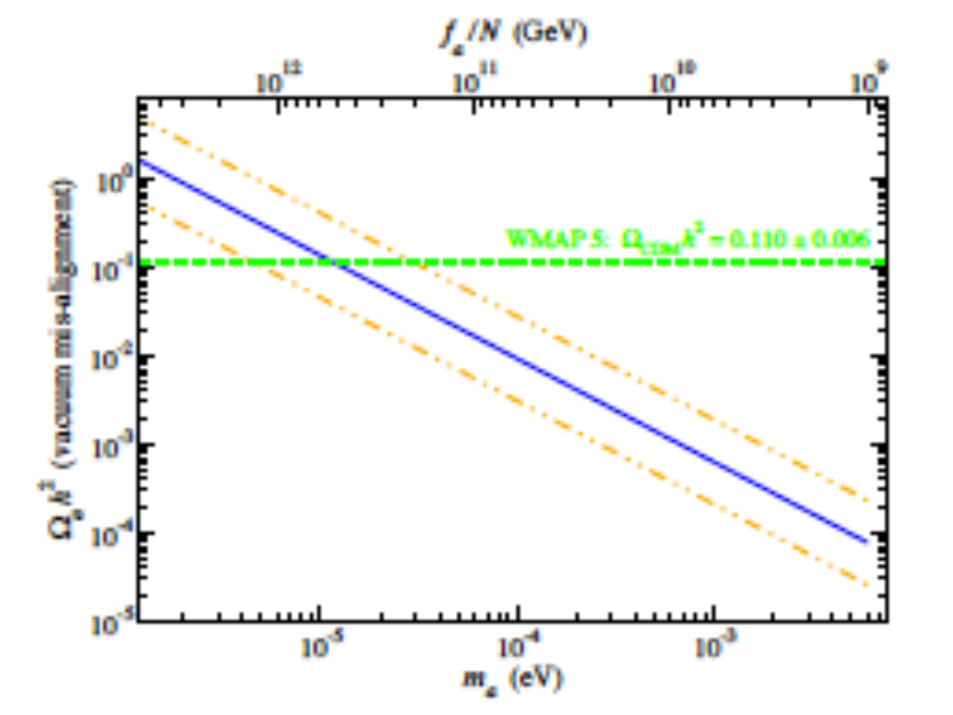
Best solution after 35 years:
PQWW/KSVZ/DFSZ invisible axion

In SUSY, axion accompanied by axino and saxion

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

Axion cosmology

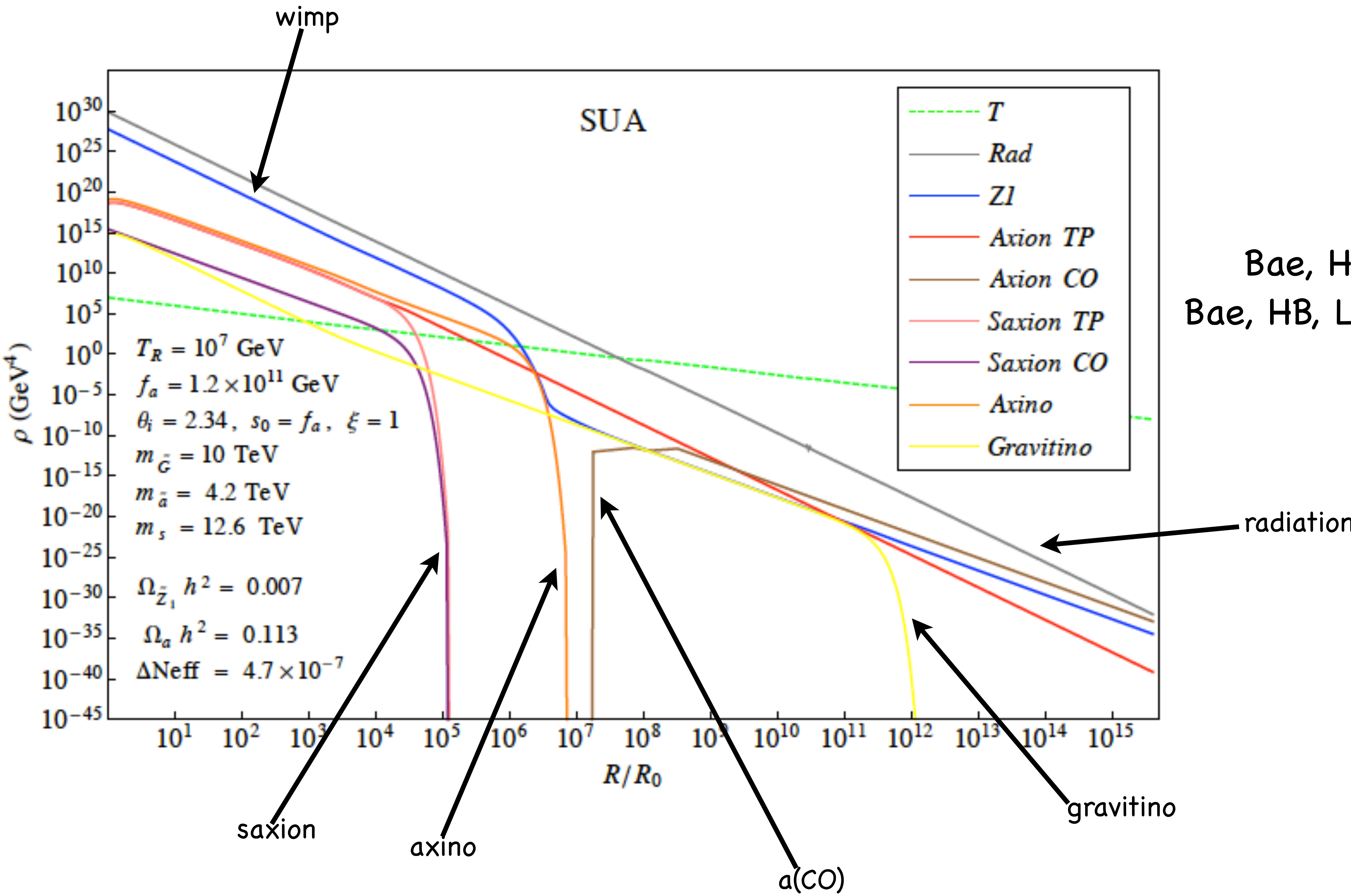
- ★ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$: $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ★ a(x) 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 $\Rightarrow f_a \gtrsim 10^9 GeV$



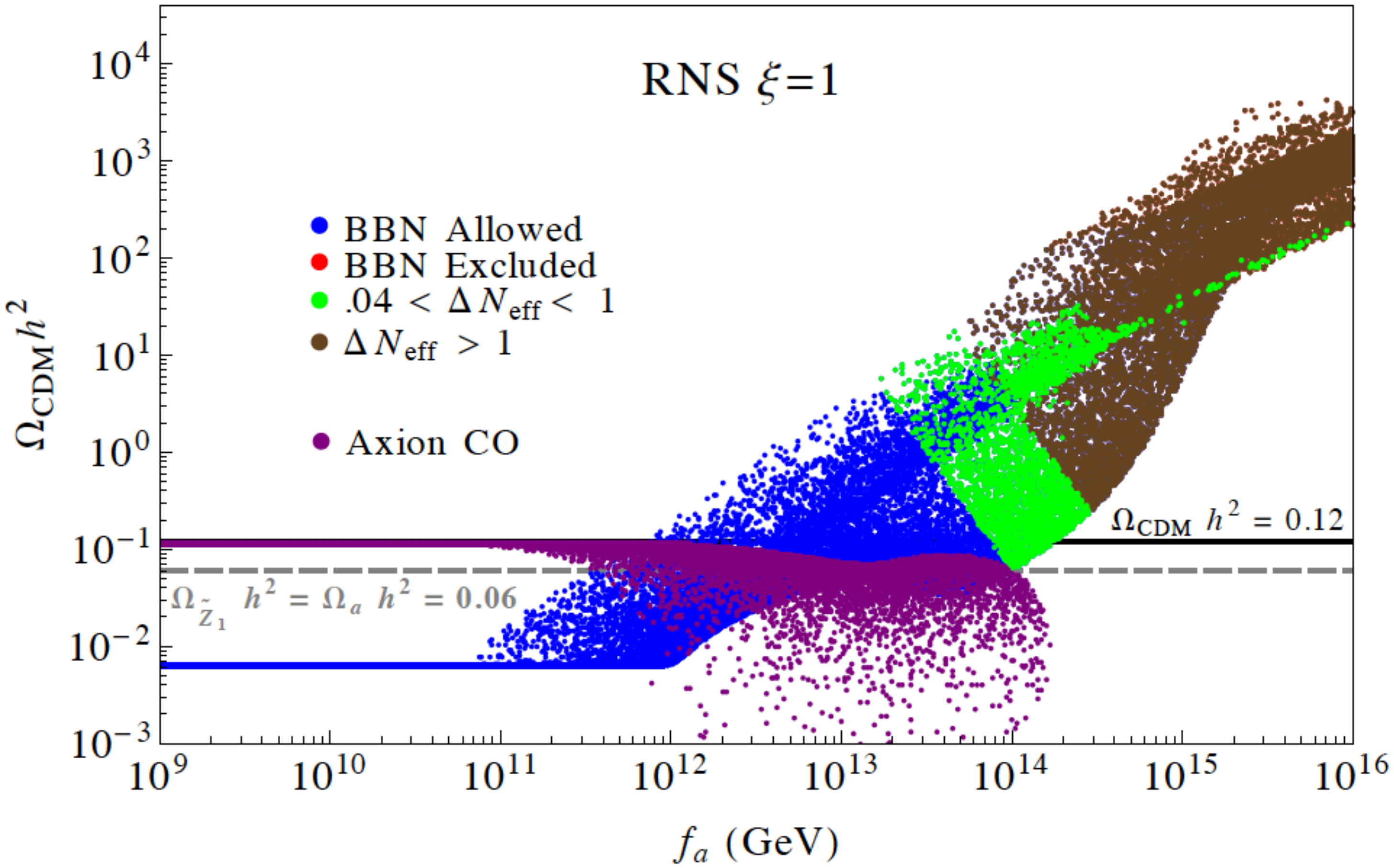
mixed axion-neutralino production in early universe

- 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

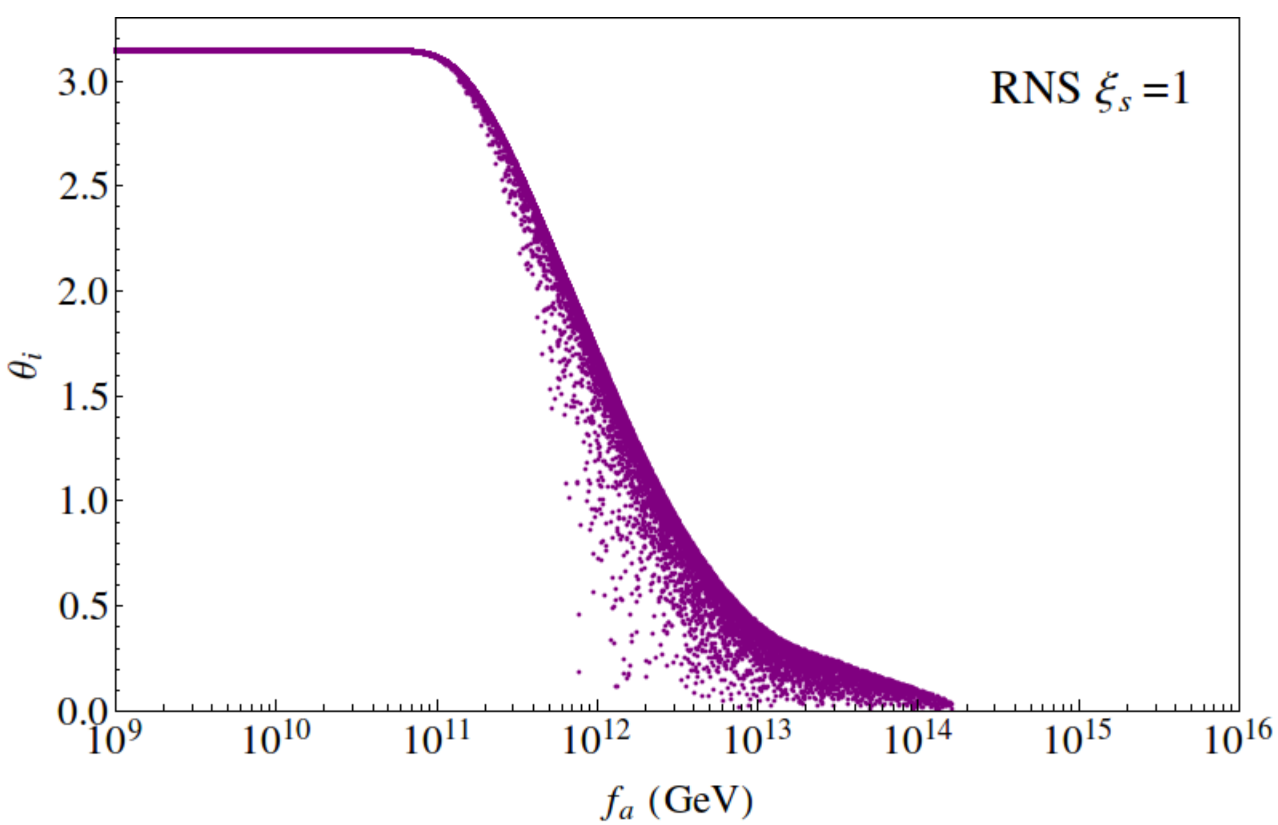


Bae, HB, Chun;
Bae, HB, Lessa, Serce



higgsino abundance

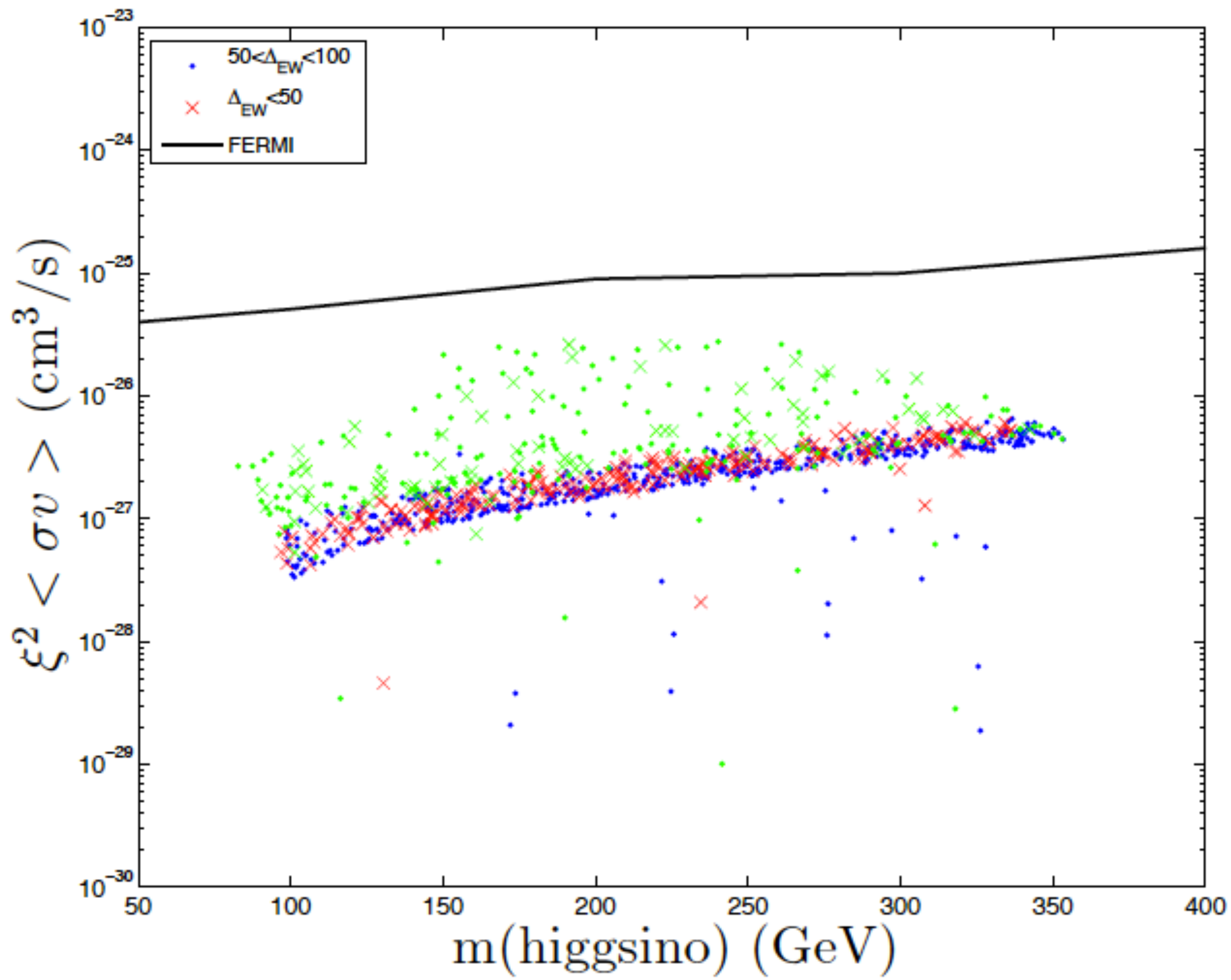
axion abundance



mainly axion CDM for fa<~10^12 GeV; for higher fa, then get increasing wimp abundance

Bae, HB,Lessa,Serce

Higgsino detection via halo annihilations:

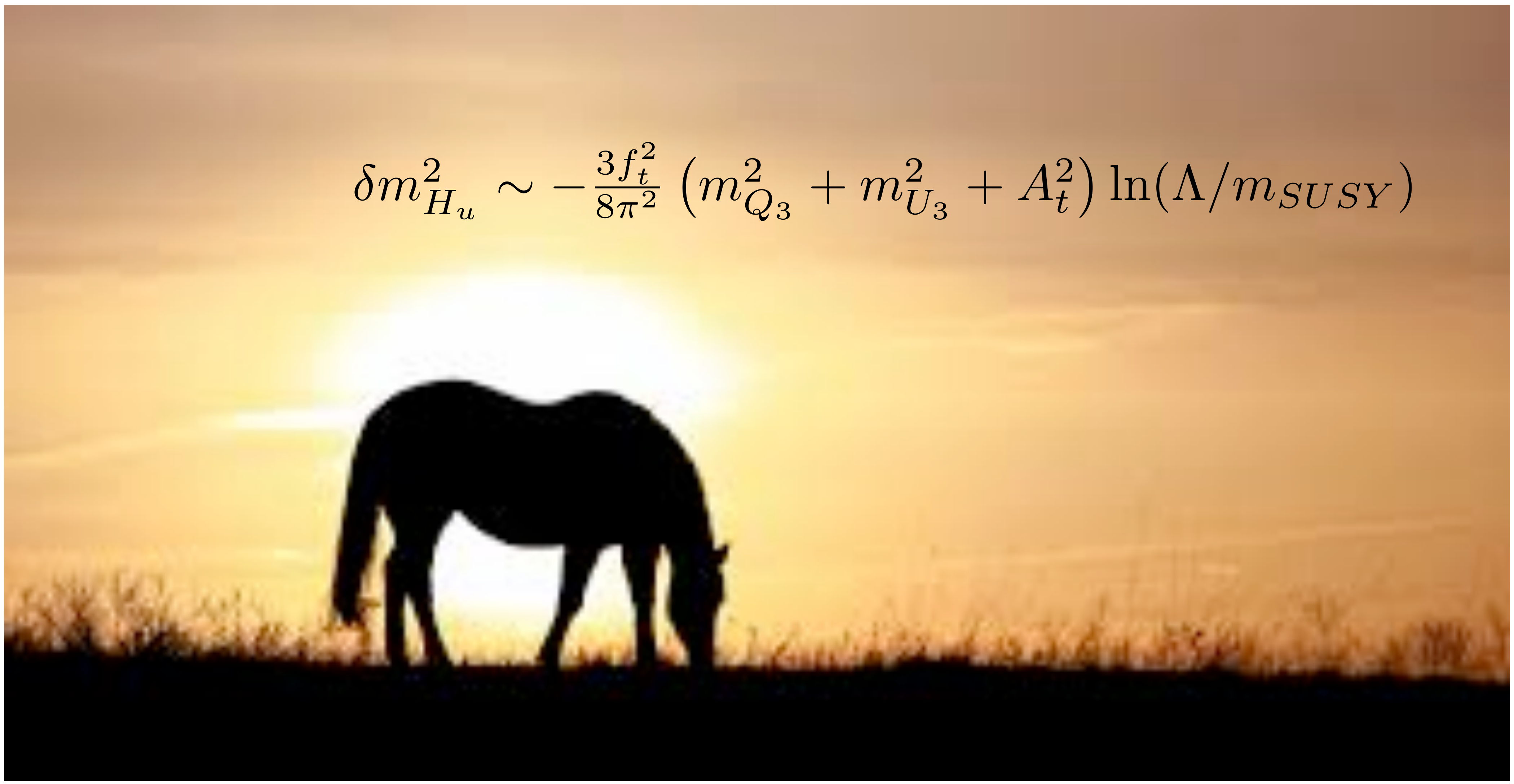


green: excluded by Xe-100

annihilation rate is high but rescaling is squared

Gamma-ray sky signal is factor 10-20 below current limits

Recommendation: put this horse out to pasture



R.I.P.

sub-TeV 3rd generation squarks not required for naturalness