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

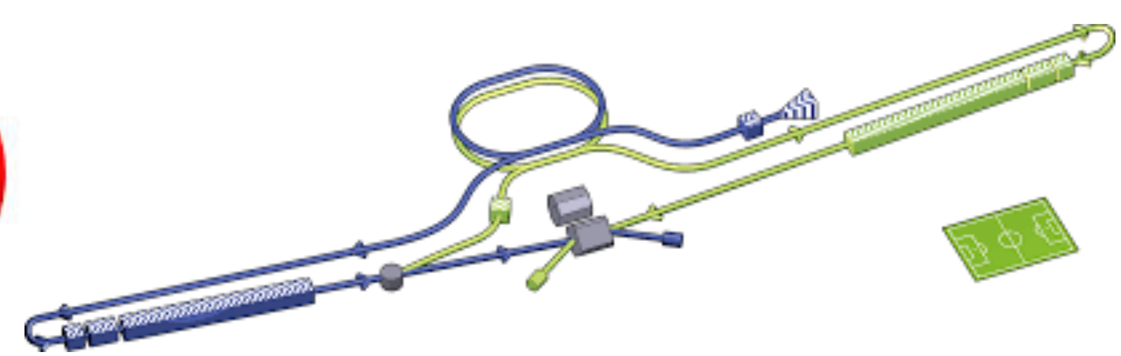
Howard Baer and collaborators
University of Oklahoma

LCWS2018, UT-Arlington, Oct. 23, 2018

or

Why

SUSY



The hypothesis of weak scale SUSY
(that nature is supersymmetric with SUSY breaking at or around the weak scale)
is remarkably simple and solves a host of problems

- SUSY- extension of Poincare group to its most general structure: super-Poincare

- scalar field quadratic divergences cancel thus stabilizing the weak scale: potentially solves SM naturalness problem

- local SUSY: supergravity

- the vague prediction: superpartners around the weak scale

In spirit of Karl Popper,
any scientific hypothesis must be falsifiable

SUSY has already met 3 tests:

- measured gauge coupling strengths consistent with SUSY unification
- $m(t) \sim 173$ GeV consistent with SUSY requirement for (radiative) breakdown of EW symmetry
- $m(h) \sim 125$ GeV in accord with narrow MSSM requirement that $m(h) < 135$ GeV
- BUT where are the sparticles? And where ought they to be?

The main raison d'etre for SUSY is to address the naturalness question: works admirably by eliminating quadratic divergences to m(h): BUT if sparticles too heavy, then re-introduce hierarchy problem in form of Little Hierarchy: why is m(h)~125 GeV and not m(sparticle)~1-10 TeV?

The notion of practical naturalness:

An observable $\mathcal{O}$ is natural if all *independent* contributions to $\mathcal{O} = a_1 + \cdots a_n$ are comparable to or less than $\mathcal{O}$

Or else, if one contribution, say $a_1 \gg \mathcal{O}$, then some other (independent) contribution would have to be *fine-tuned* to a large opposite-sign value to compensate and maintain $\mathcal{O}$ at its measured value

``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"

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

``...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

EW naturalness: why are m(W,Z,h)~100 GeV
while m(sparticles)~>1 TeV?

$$\text{Let } \mathcal{O} \equiv m_Z^2$$

EW minimization conditions relate m(Z) to SUSY Lagrangian parameters

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

For naturalness:

- $m_{H_u}^2$ driven to $\sim -(100-200)^2$ GeV^2 at weak scale
- superpotential Higgs/higgsino mass contribution $\mu \sim 100-200$ GeV
- TeV scale highly mixed top squarks minimize Σ_u^u (and raise $m_h \sim 125$ GeV)

Chan, Chattopadyaya, Nath

HB, Barger, Huang

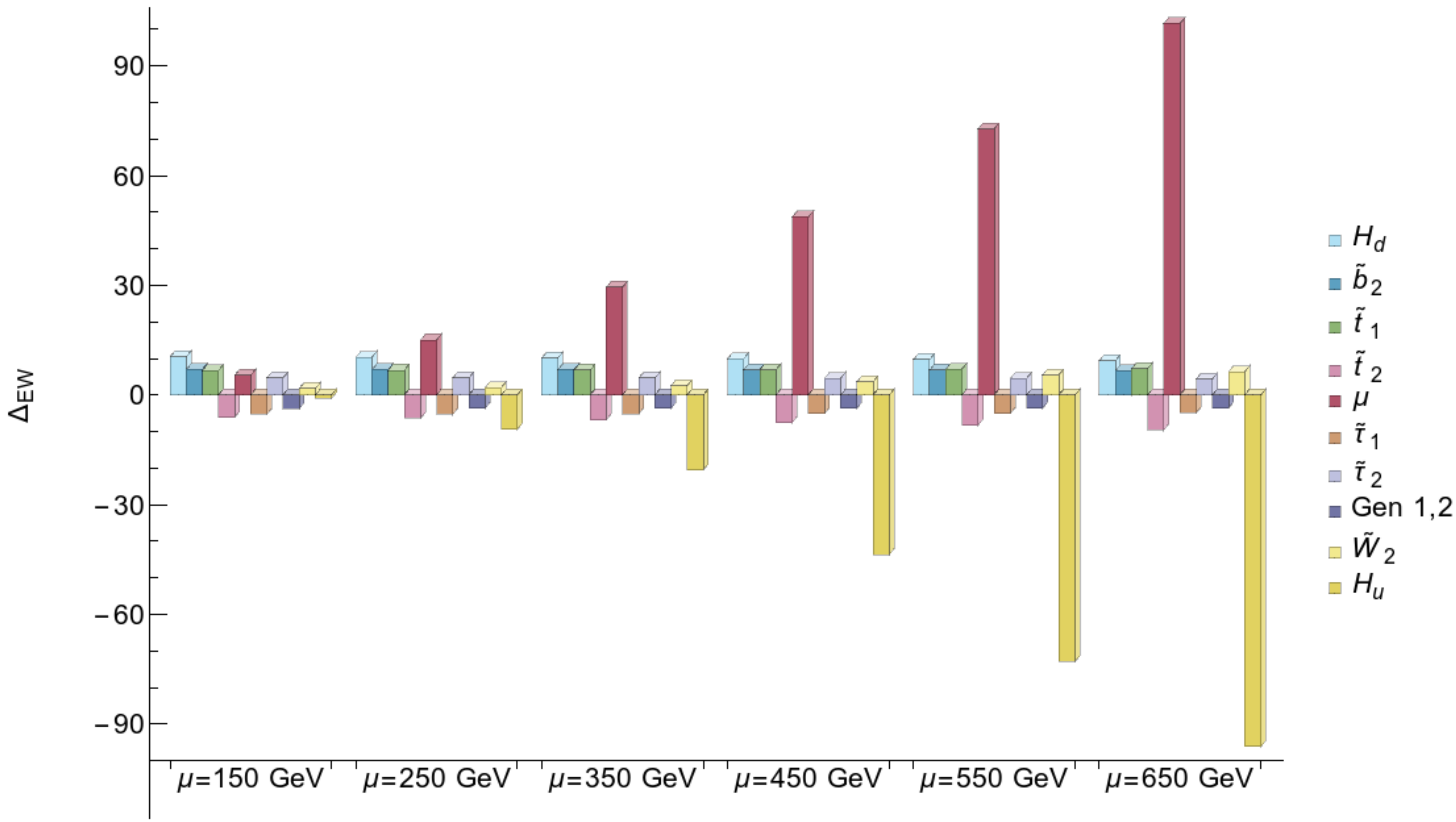
Perelstein, Shakya

HB, Barger, Huang, Mustafayev, Tata

Low value of $\Delta_{\rm EW} \equiv |max\ of\ each\ term\ on\ RHS|/(m_Z^2/2)$ is most conservative, unavoidable naturalness condition

Most important inference:
light higgsinos of mass mu~100-200 GeV hard to see at LHC
but easily discovered at ILC with $\sqrt{s} > 2m(higgsino) \sim 200-500$ GeV!

How much is too much fine-tuning?



HB, Barger, Savoy

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

Nature is natural $\Rightarrow \Delta_{EW} < 20 - 30$ (take 30 as conservative)

#3. What about EENZ/BG measure?

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

p_i are the theory parameters

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

apply to high (e.g. GUT) scale parameters

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

applied to most parameters,

Δ_{BG} large, looks fine-tuned for *e.g.* $m_{\tilde{t}_1} \sim 1$ TeV

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

#3. What about EENZ/BG measure?

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

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

Feng, Matchev, Moroi

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

But wait! in more complete models, soft terms not independent

violates prime directive!

e.g. in SUGRA, for well-specified hidden sector, each soft term calculated as multiple of m(3/2); soft terms must be combined!

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

in general:

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

since μ hardly runs, then

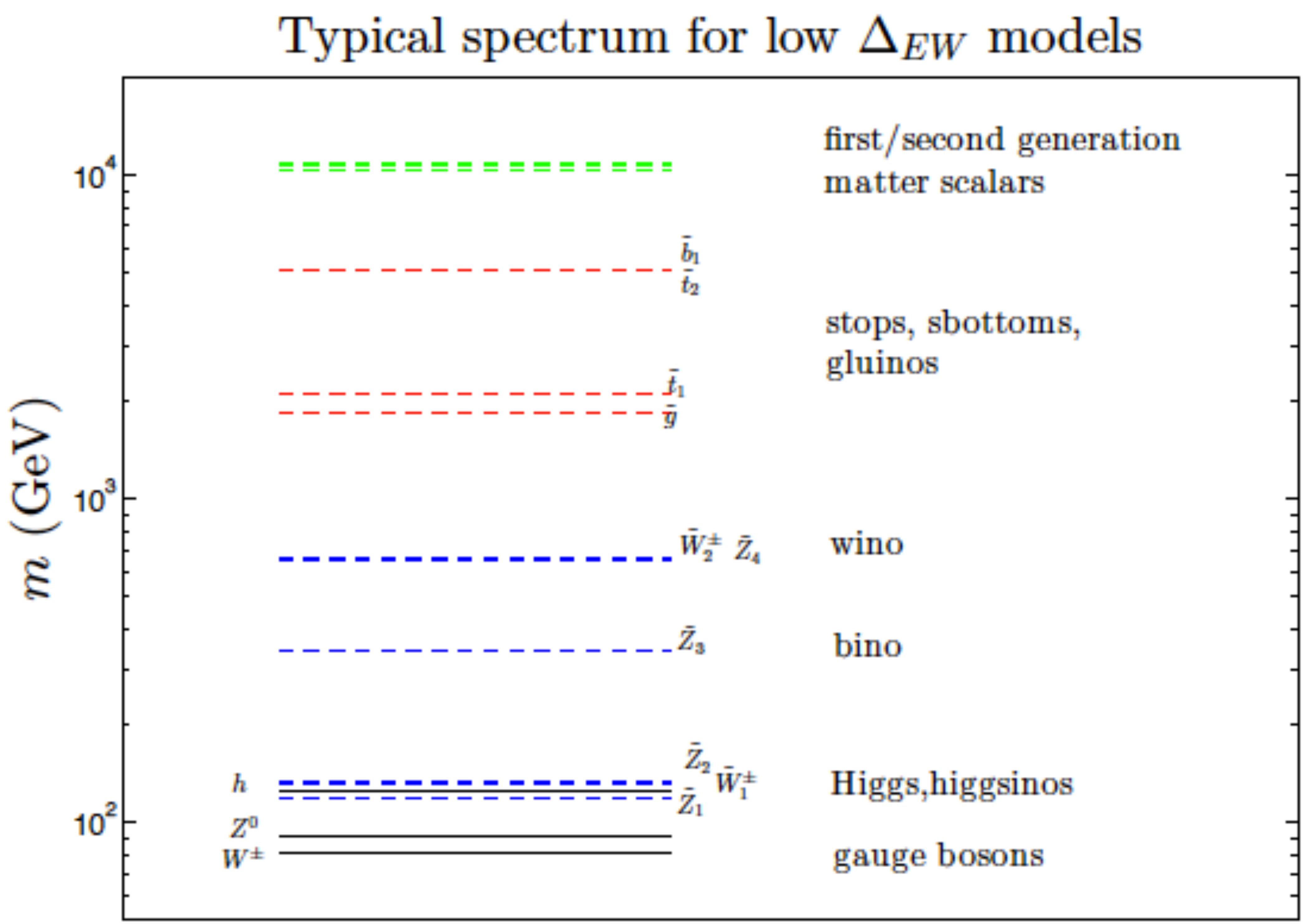
$$
\begin{aligned}
m_Z^2 &\simeq -2\mu^2 + a \cdot m_{3/2}^2 \\
&\simeq -2\mu^2 - 2m_{H_u}^2(weak)
\end{aligned}
$$

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

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

bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	0.35 TeV
gluino	400-600 GeV	~6 TeV
t1	450 GeV	3 TeV
sq/sl	550-700 GeV	10-30 TeV

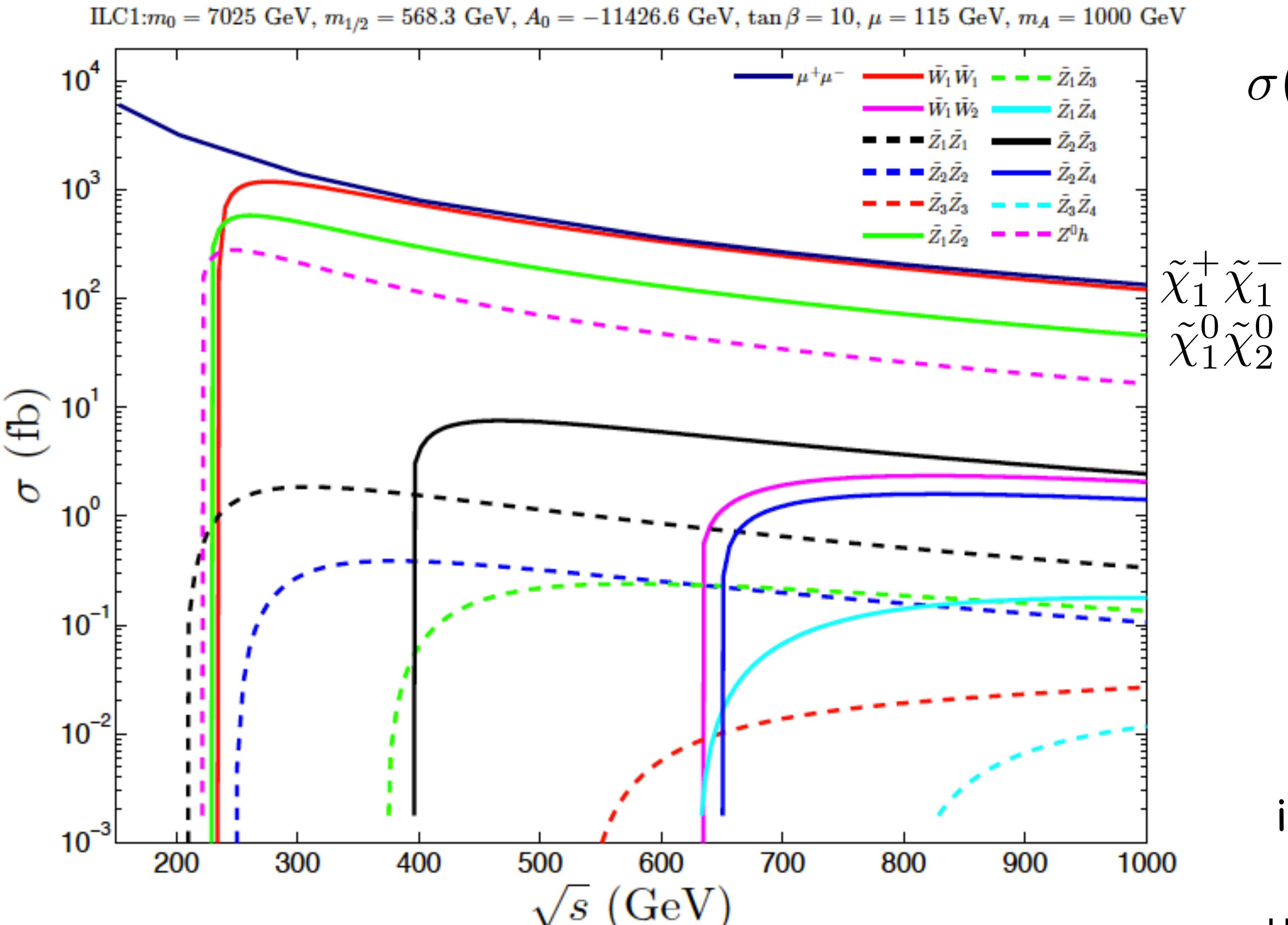
h(125) and LHC limits are perfectly compatible with 3-10% naturalness: no crisis for SUSY!



There is a Little Hierarchy, but it is no problem

$$\mu \ll m(soft) \text{ is OK}$$

Smoking gun signature: light higgsinos at ILC:
ILC is Higgs/higgsino factory!



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

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

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

Why might mu<<m(soft)?

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

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

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

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

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

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

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

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

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

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

HB, Barger, Sengupta, arXiv:1810.03713

1. Global symmetries fundamentally incompatible with gravity completion
2. Expect global symmetry to emerge as accidental (approximate) symmetry from some more fundamental gravity-safe (e.g. gauge or R-) symmetry
3. Krauss-Wilczek: gauge symmetry with charge Ne object condensing leaves charge e fields with Z_N discrete gauge symmetry
4. Babu et al.: Z22 symmetry works but charge 22 object in swampland?
5. Better choice: discrete R-symmetries which arise from compactification of extra dimensions in string theory

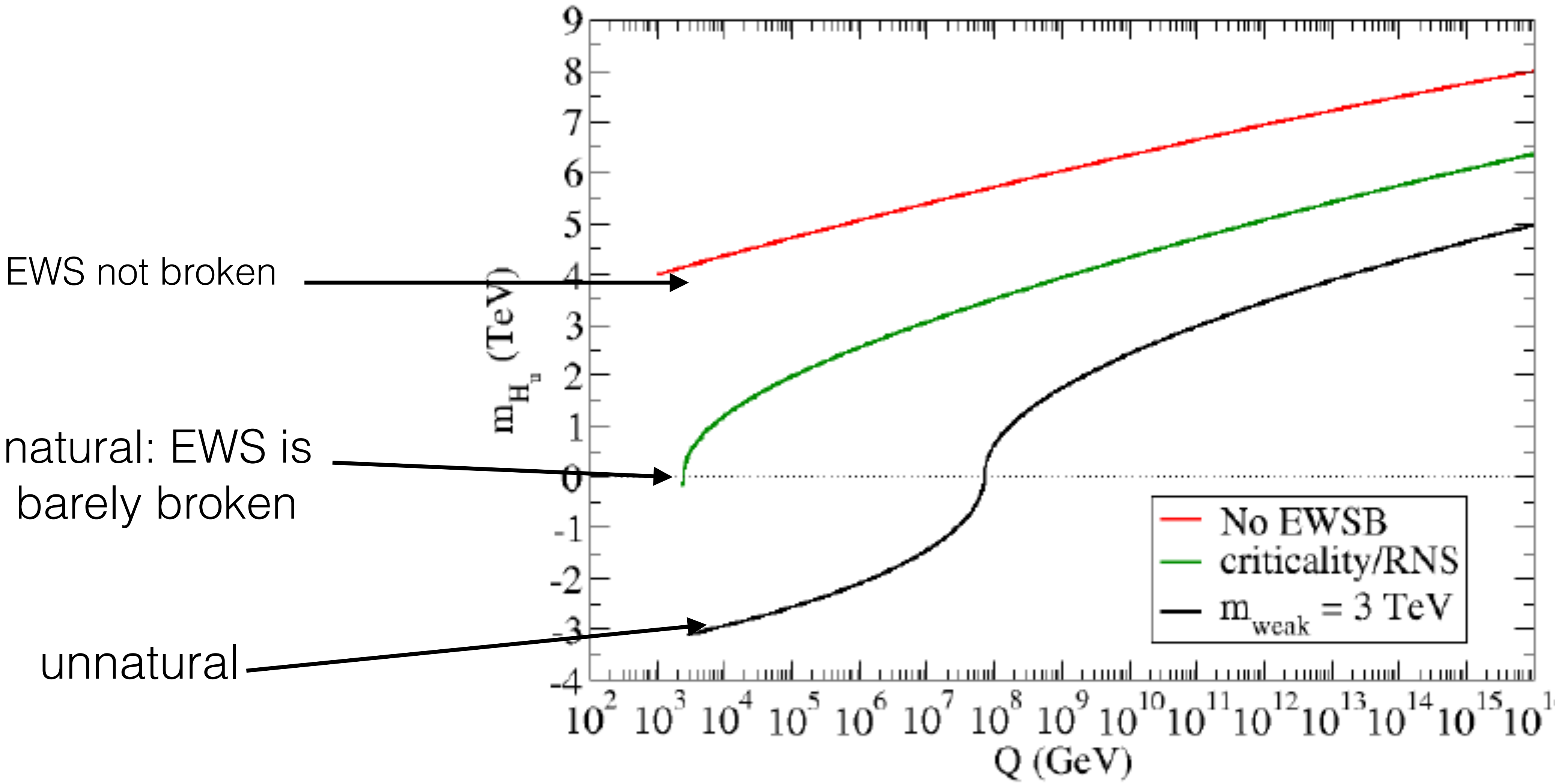
A model which works: Z(24) R symmetry (see also Lee et al.)

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

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

What about m(Hu)^2?

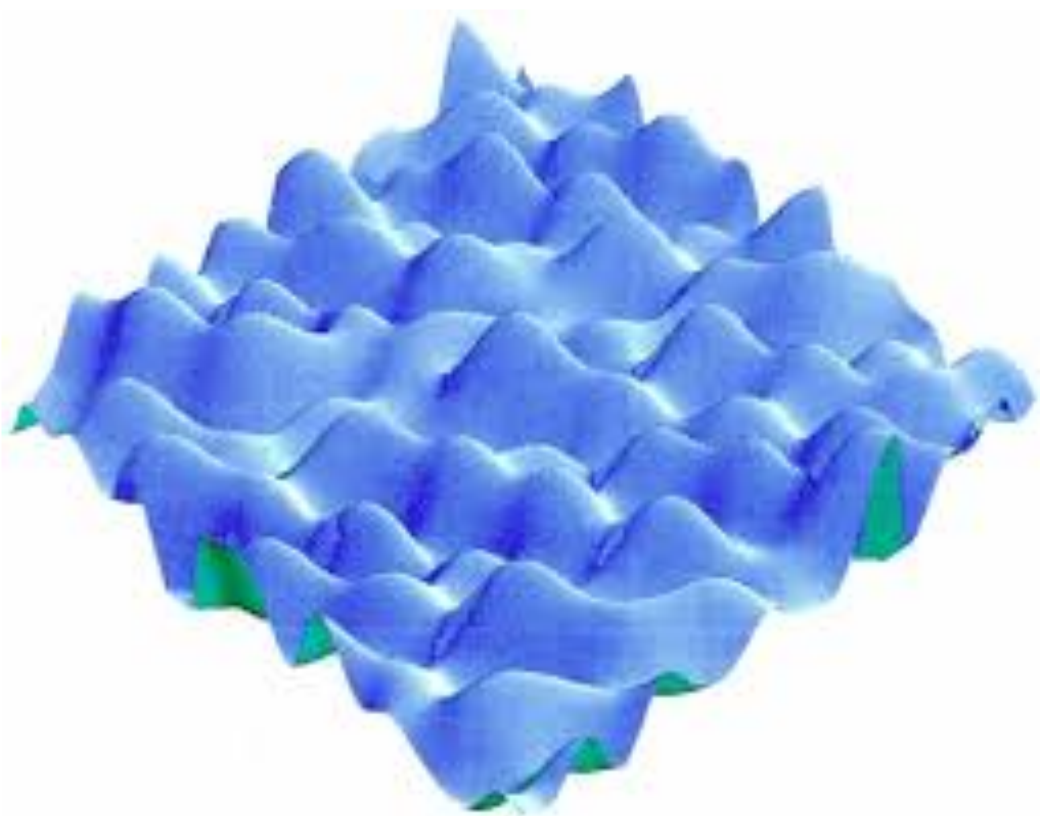
radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness

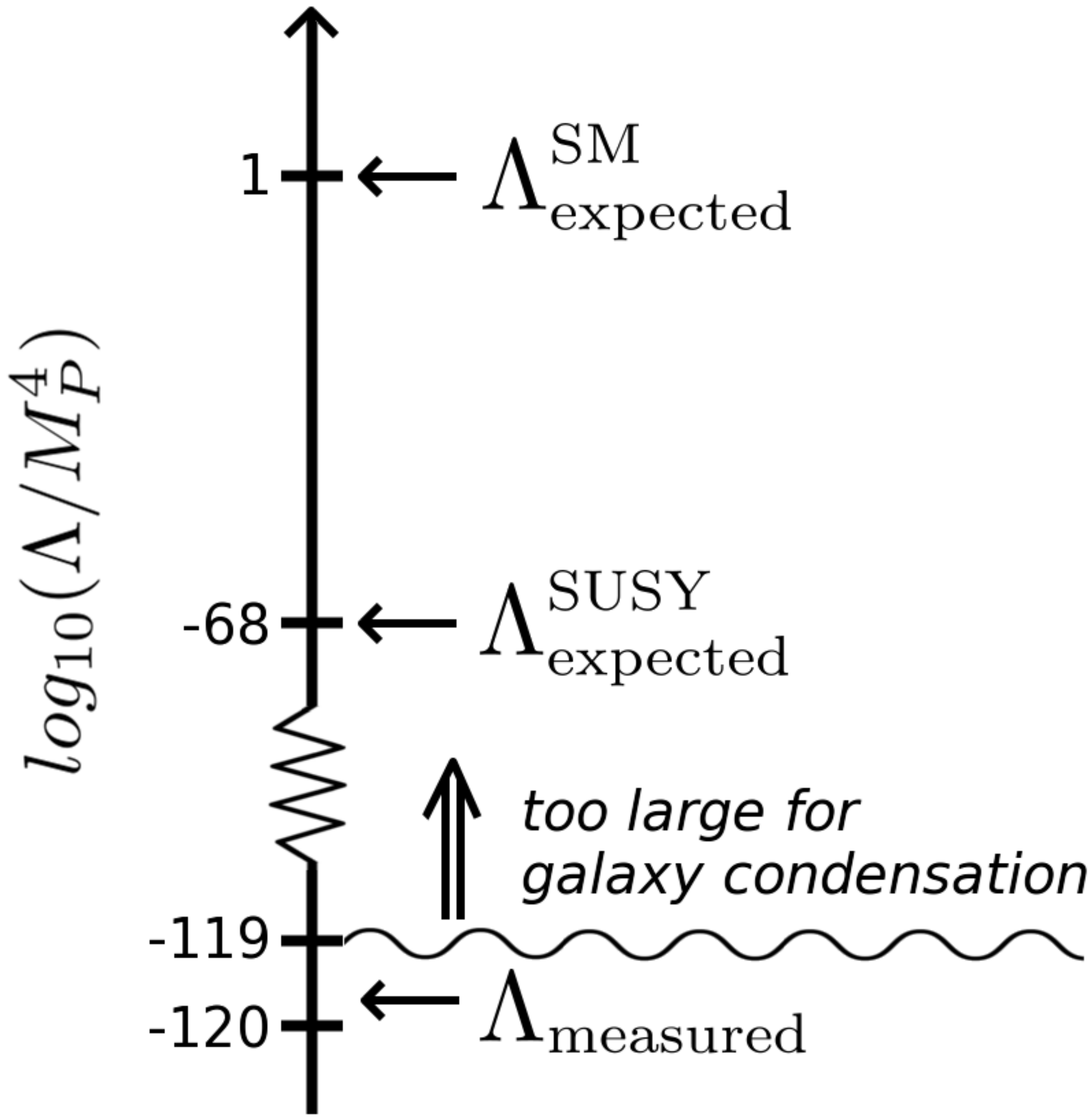


Evolution of the soft SUSY breaking mass squared term $sign(m_{H_u}^2)\sqrt{|m_{H_u}^2|}$ vs. Q

Landscape of string theory vacua provides solution to cosmological constant

$$n_{vac} \sim 10^{500}?$$





Weinberg; Bousso Polchinski; Denef Douglas;...

Can similar reasoning explain scale of soft SUSY breaking?

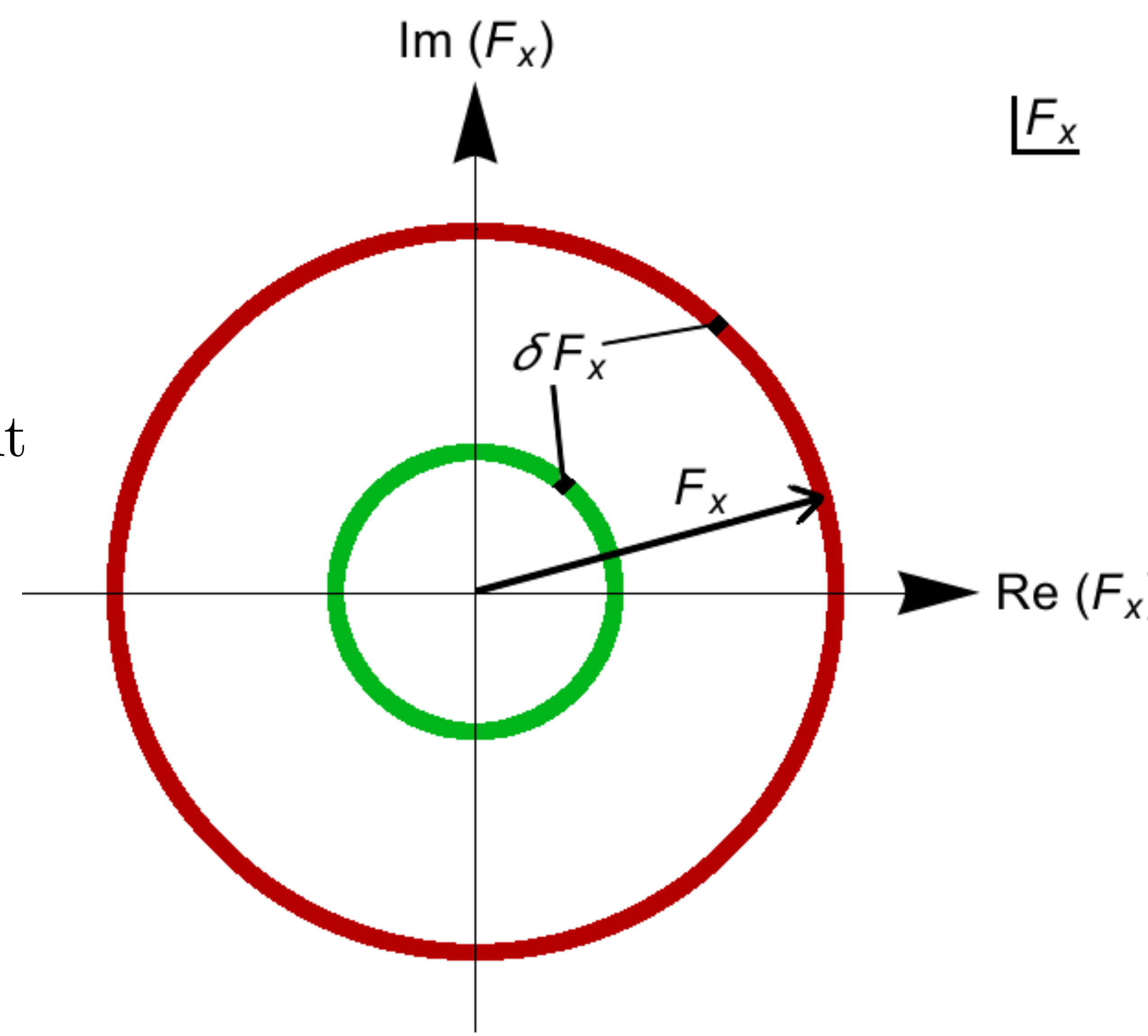
Statistical analysis of SUSY breaking scale in IIB theory:
M. Douglas, hep-th/0405279

start with 10^500 string vacua states

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

V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel, Phys. Rev. D **57** (1998) 5480;
V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel, Phys. Rev. Lett. **80** (1998) 1822.

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

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

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

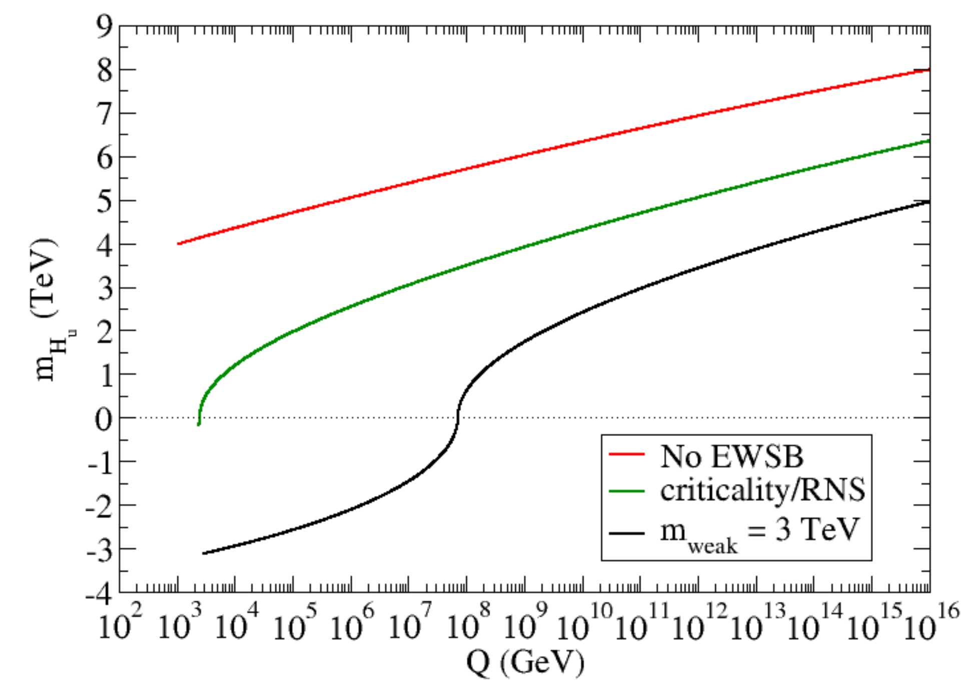
n_F	n_D	n
0	1	0
1	0	1
0	2	1
1	1	2
0	3	2
2	0	3
2	1	4

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

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

This fails in a variety of *practical* cases:

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



Must require proper EWSB!

Even if EWS properly broken, then

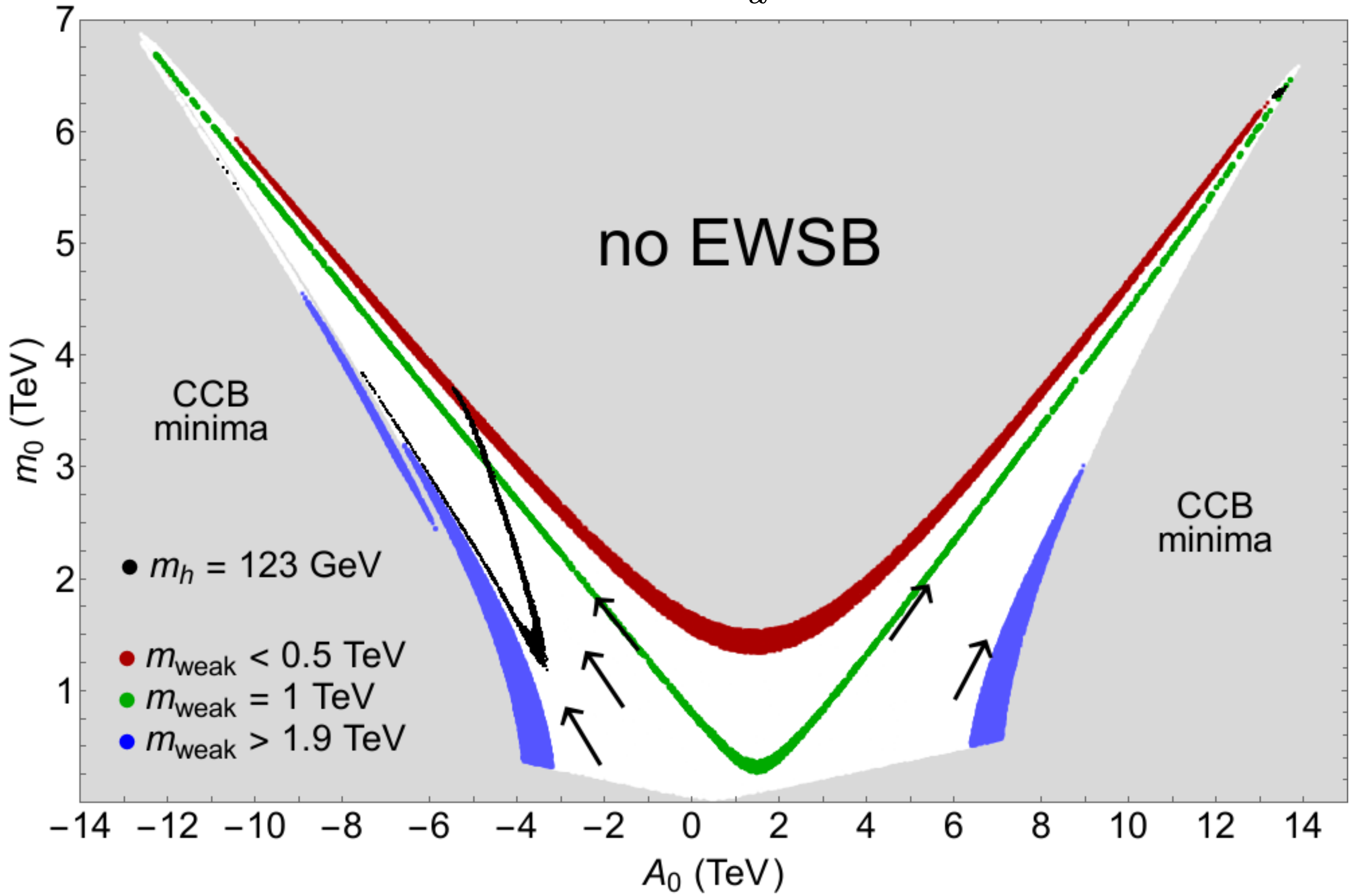
- large A_t *reduces* EWFT in the $\Sigma_u^u(\tilde{t}_{1,2})$
- large $m_{H_u}^2(m_{GUT})$ needed to radiatively drive $m_{H_u}^2$ to natural value at weak scale

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 $m_{H_{u,d}}^2$ and $\Sigma_{u,d}^{u,d}(i)$

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

$$m_{H_u} = 1.3 m_0$$



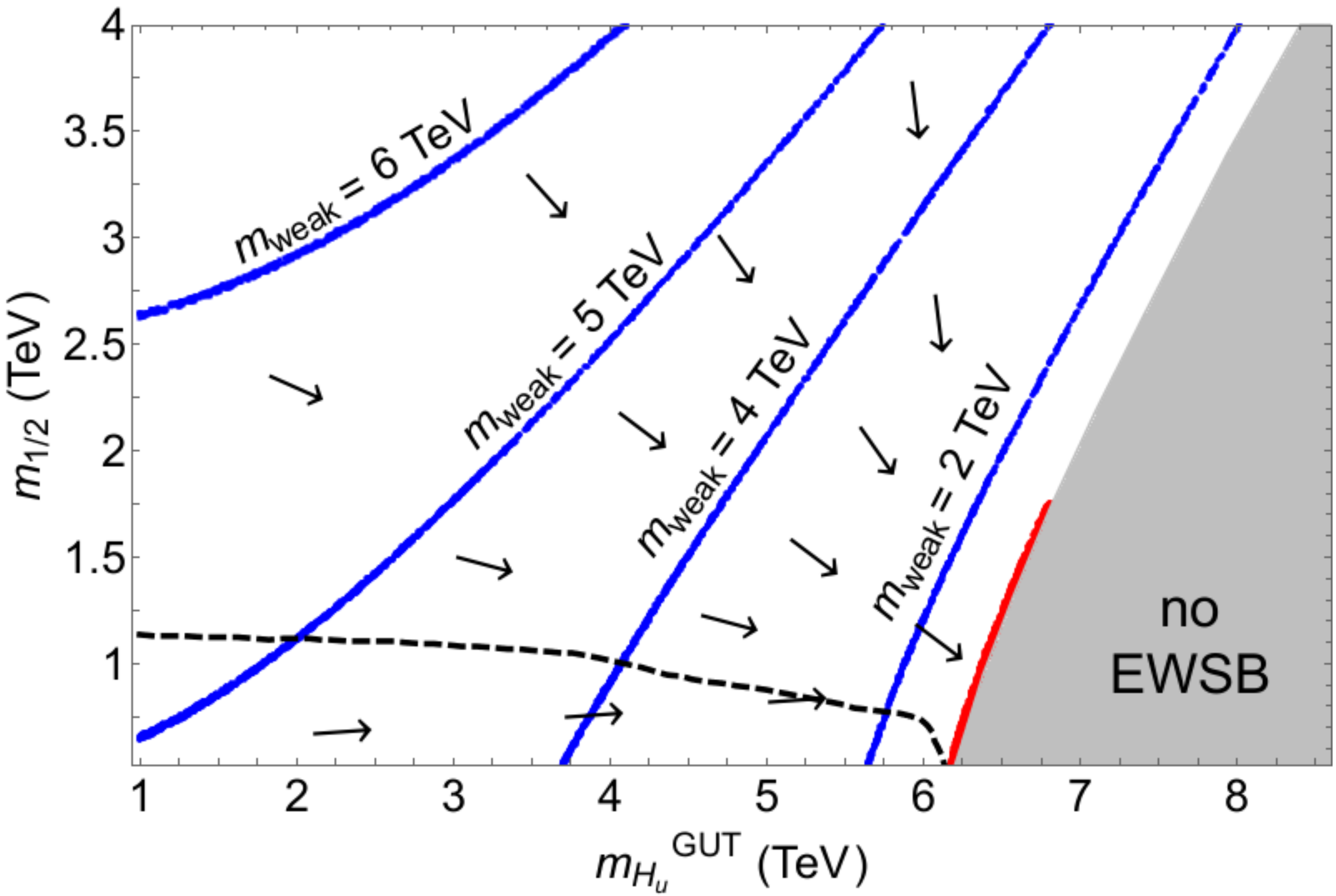
statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Denef, Douglas, JHEP0405 (2004) 072

Giudice, Rattazzi, NPB757 (2006) 19;

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

$m_0 = 5$ TeV



statistical/anthropic draw toward FP-like region

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,

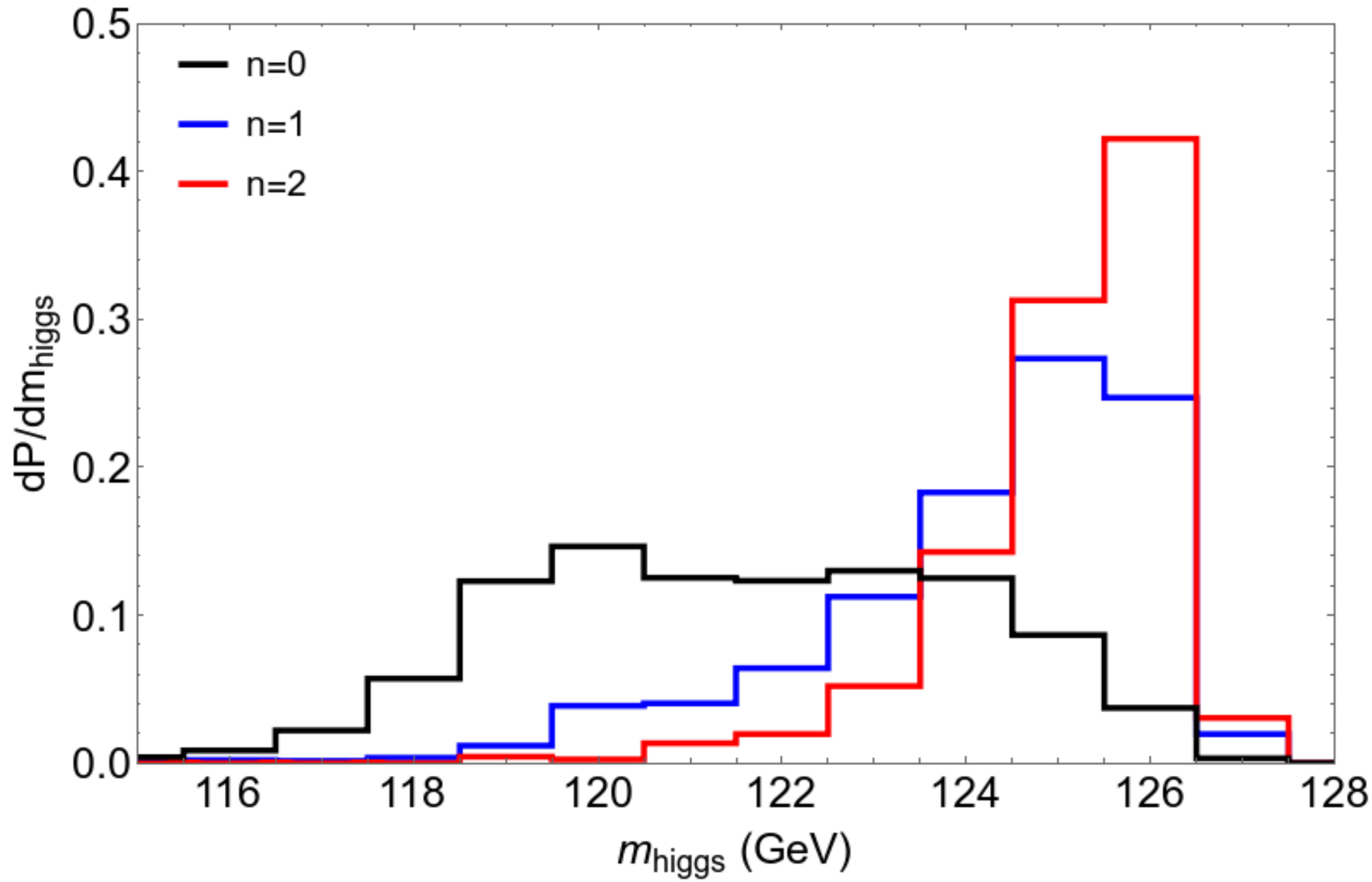
$\tan\beta$: $3 - 60$ (flat)

mu=150 GeV (fixed)

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

Making the picture more quantitative:

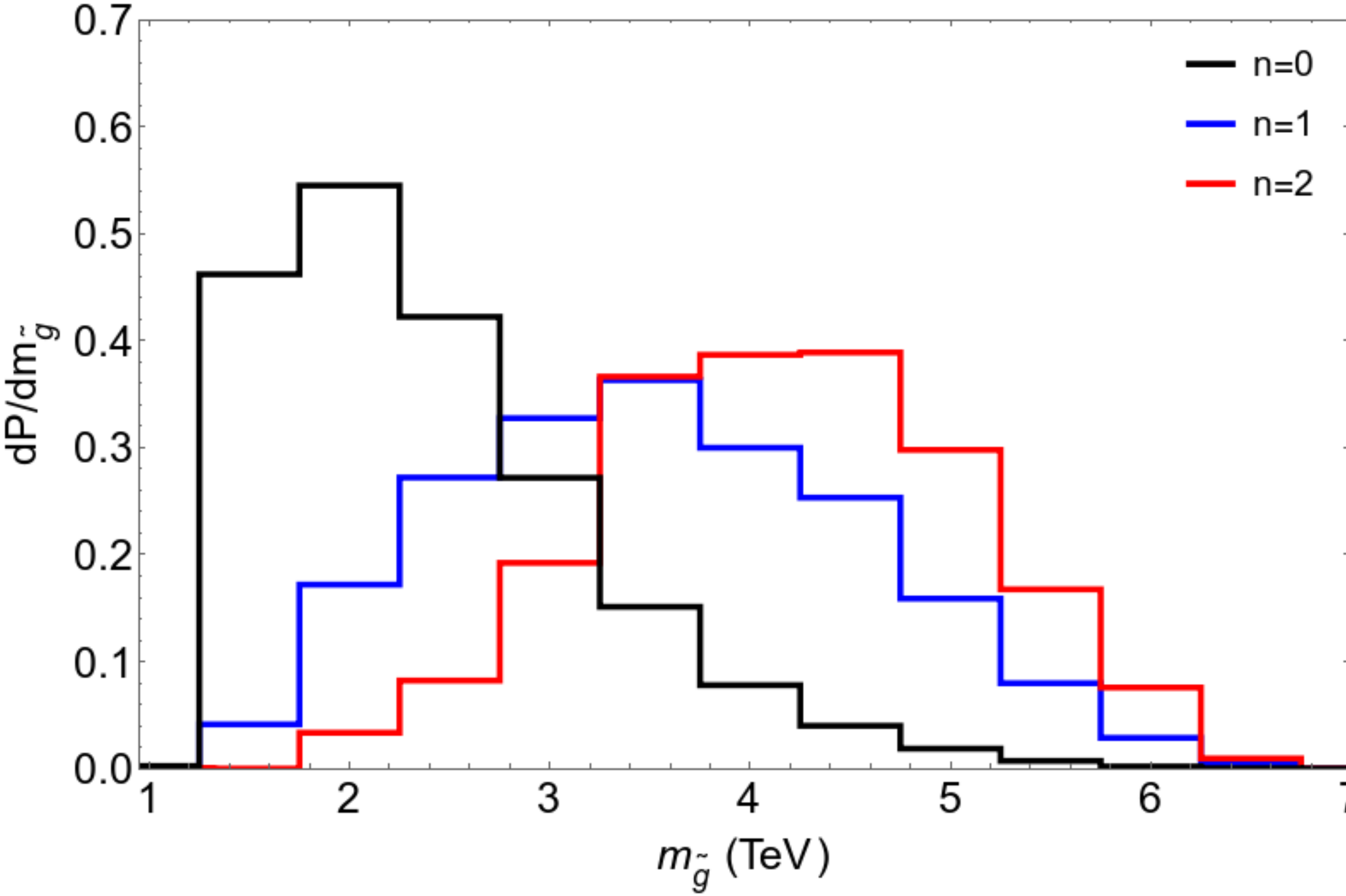
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



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

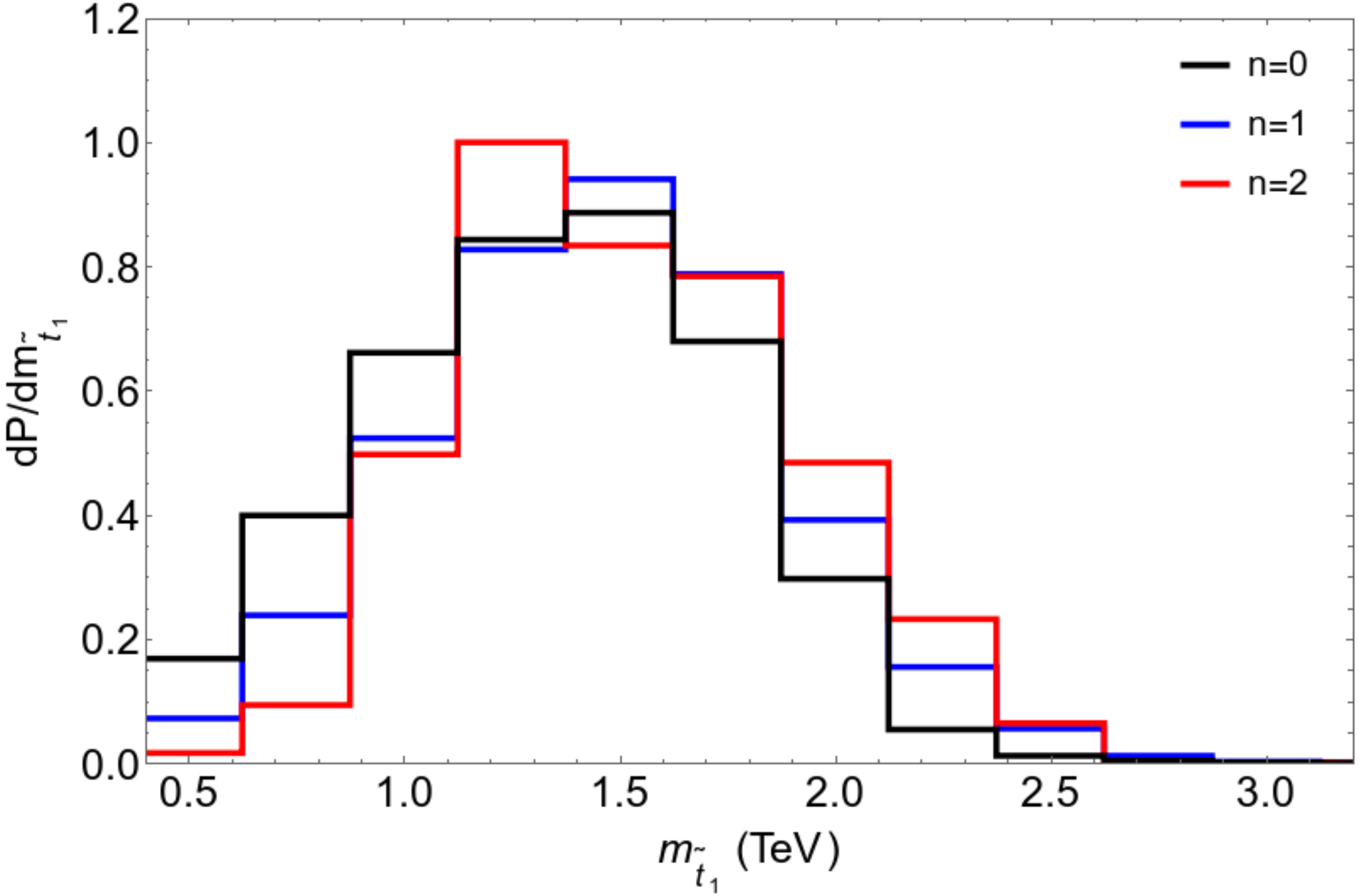
HB,Barger, Serce, Sinha

What is corresponding distribution for gluino mass?



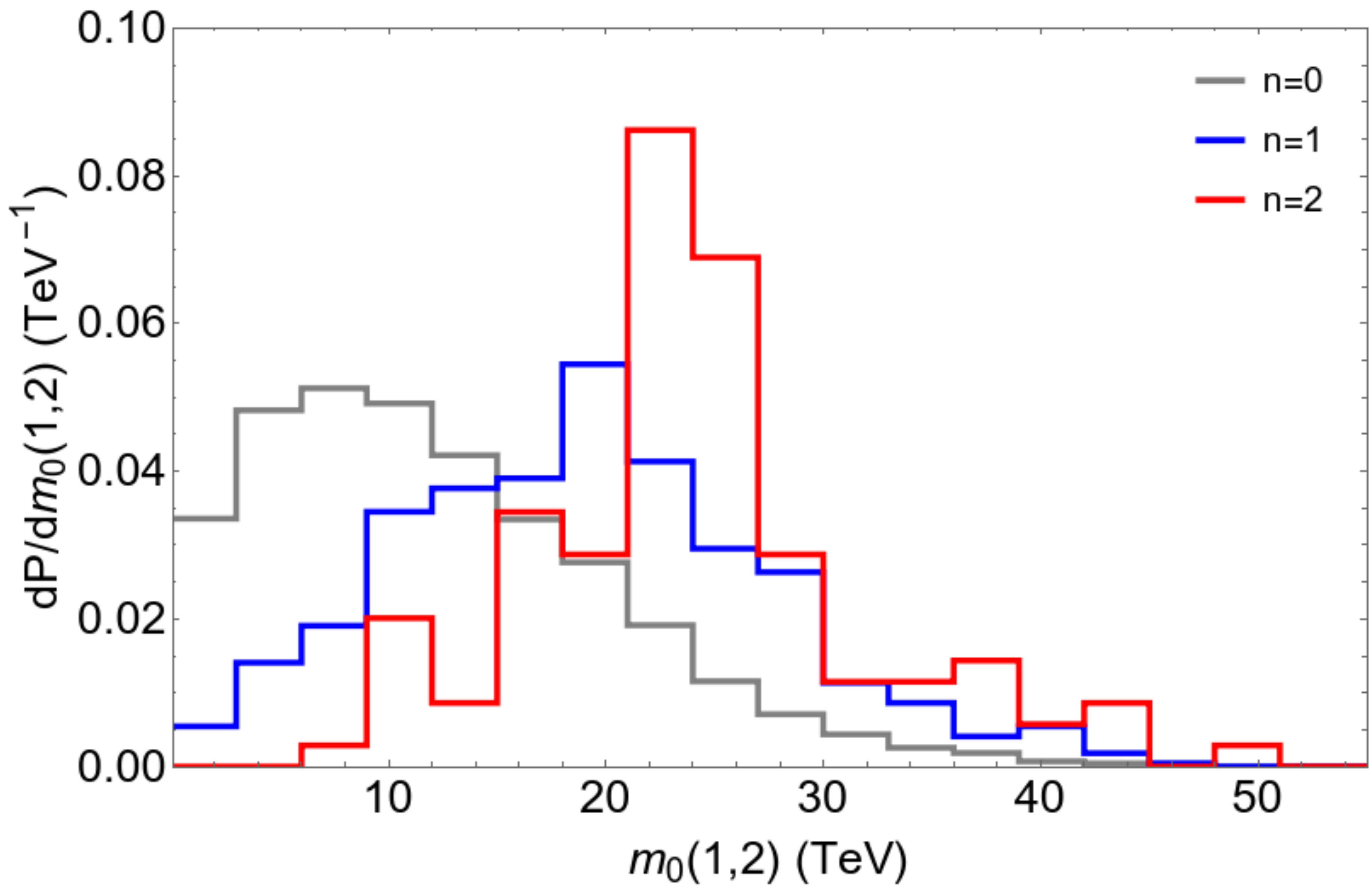
typically beyond LHC 14 reach (may need HE-LHC)

and m(t1)?



n=0
n=1
n=2
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
$dP/dm_{\tilde{t}_1}$
$m_{\tilde{t}_1}$ (TeV)

first/second generation sfermions pulled
to 10-30 TeV thus softening any SUSY flavor/CP problems



What role would ILC play with predicted light higgsinos?

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]

[1]University of Oklahoma, Norman, OK 73019, USA
[2]DESY, Notkestrasse 85, 22607 Hamburg, Germany
[3]KEK, Tsukuba, Ibaraki, Japan
[4]ICEPP, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

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

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

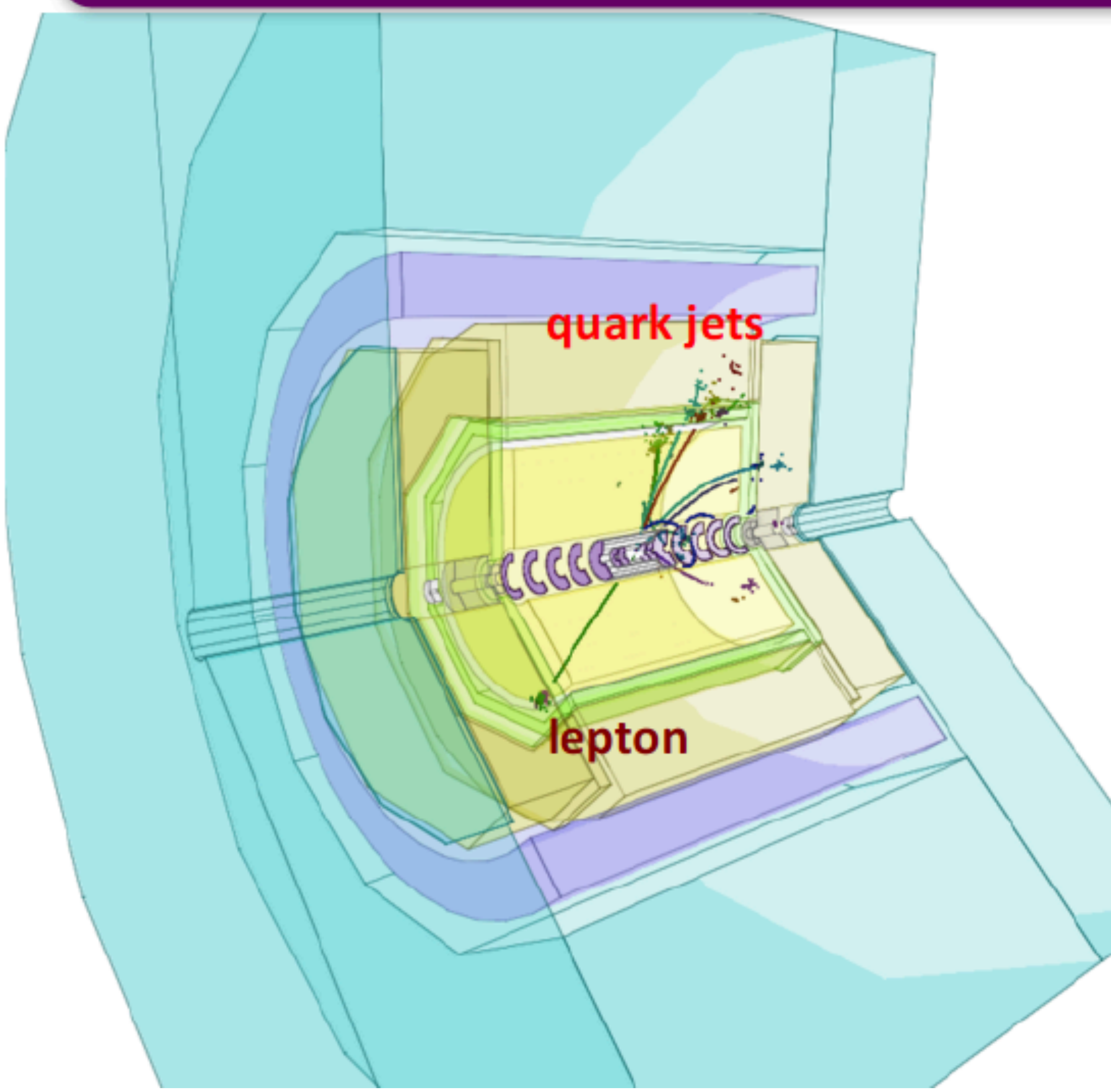
soft visible particles since small higgsino mass gaps

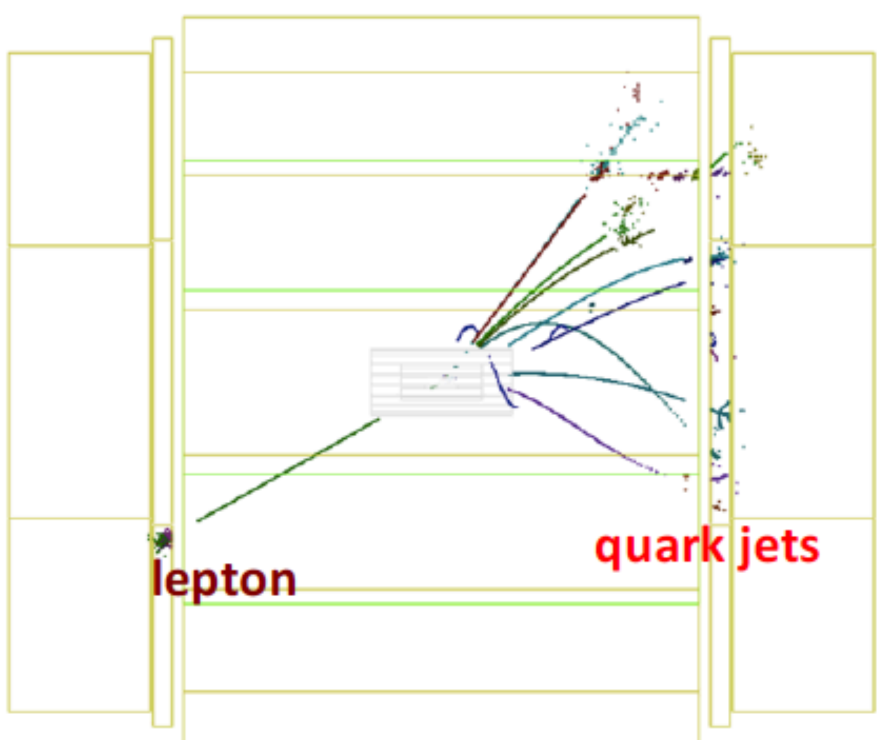
How do these signals look in the detector? (2)

√s =500 GeV

Chargino pair production with semileptonic decay

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



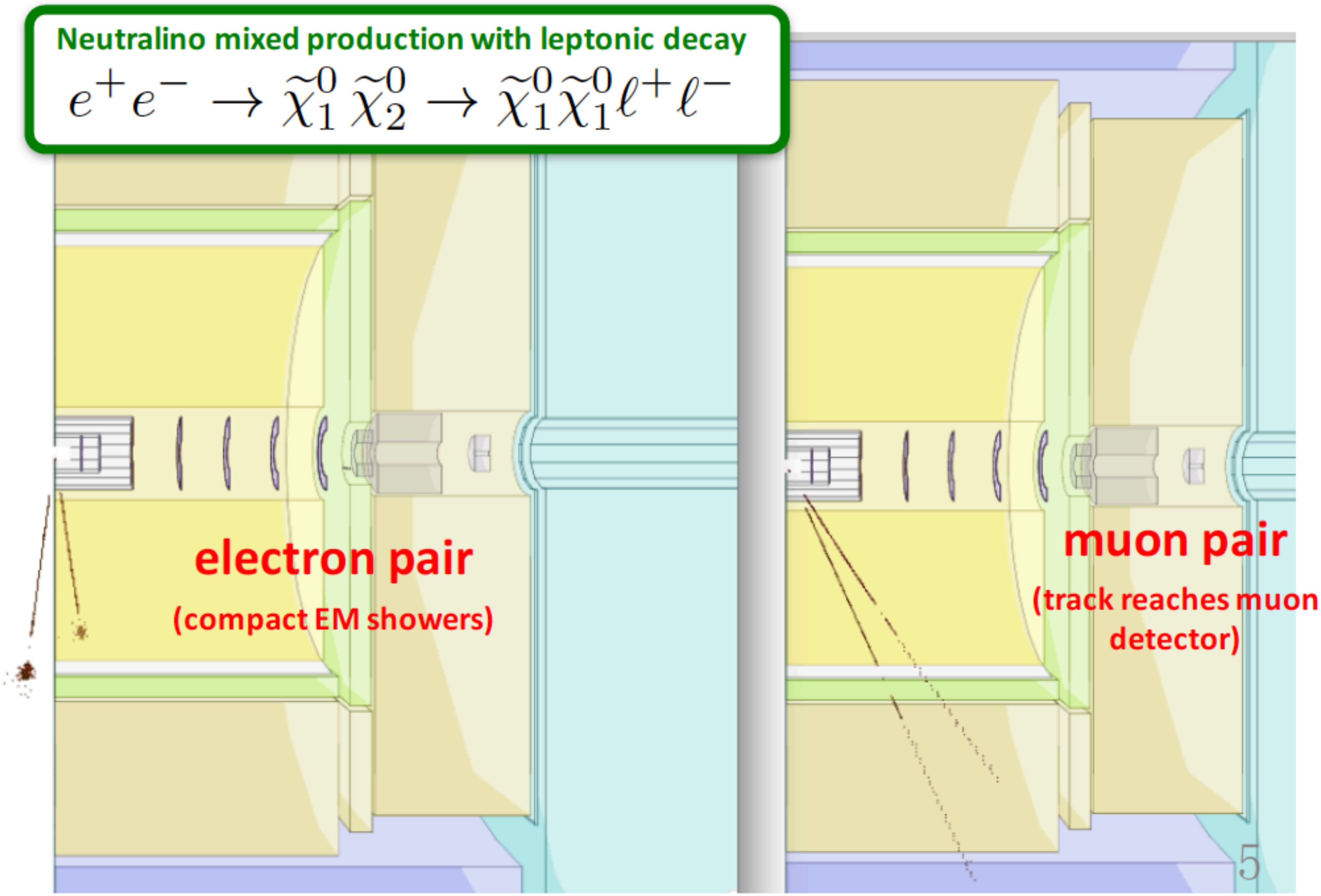


$$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 + (\ell^+\ell^-\tilde{\chi}^0_1)$$

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

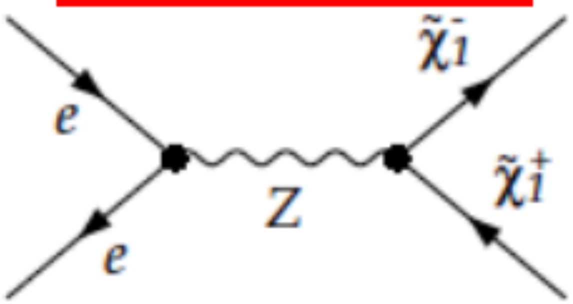
How do these signals look in the detector? (1)

√s =500 GeV

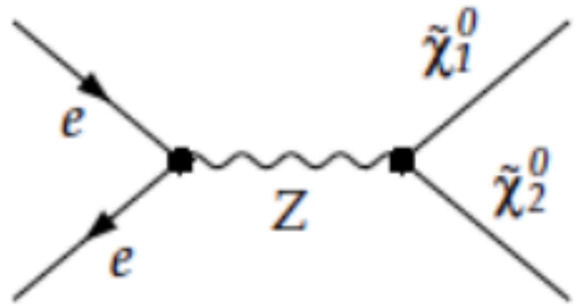


Benchmarks in this Study

Charginos ($\chi_1^+ \chi_1^-$)



Neutralinos ($\chi_1^0 \chi_2^0$)



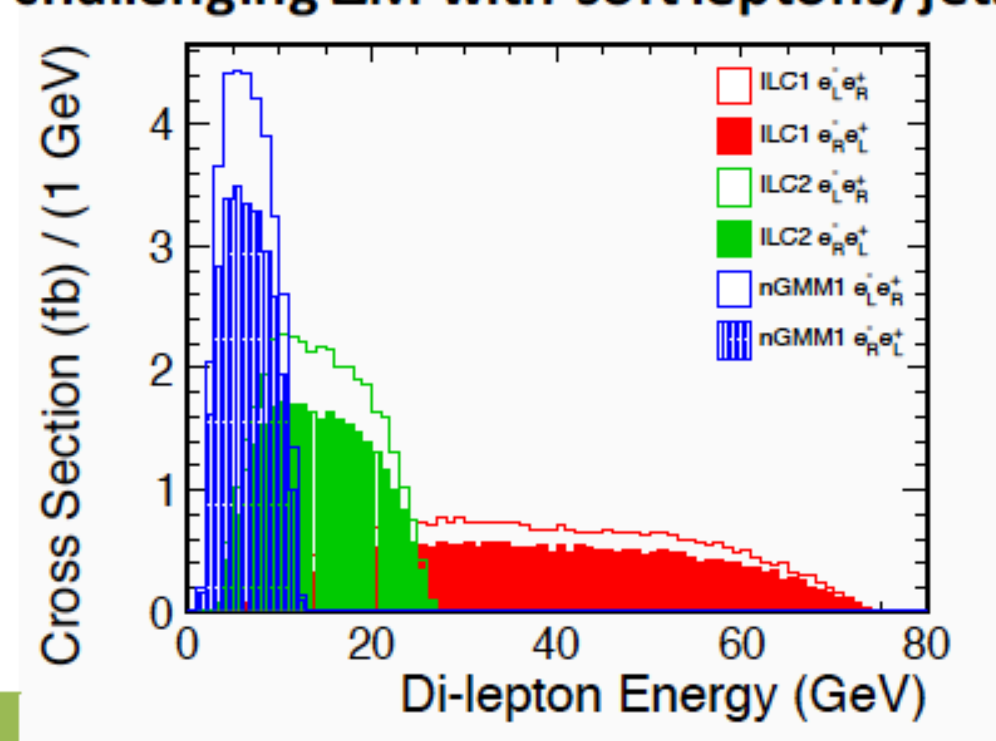
4 light Higgsinos

- $\sqrt{s}$ = 500 GeV
- full ILD detector simulation

ΔM complies with naturalness (no use of ISR tag)

Unit: GeV	ILC1	ILC2	nGMM1
M(N1)	102.7	148.1	151.4
M(N2)	124.0	157.8	155.8
ΔM(N2,N1)	**21.3**	**9.7**	**4.4**
M(C1)	117.3	158.3	158.7
ΔM(C1,N1)	**14.6**	**10.2**	**7.3**

Good precision achievable even for challenging ΔM with soft leptons/jets



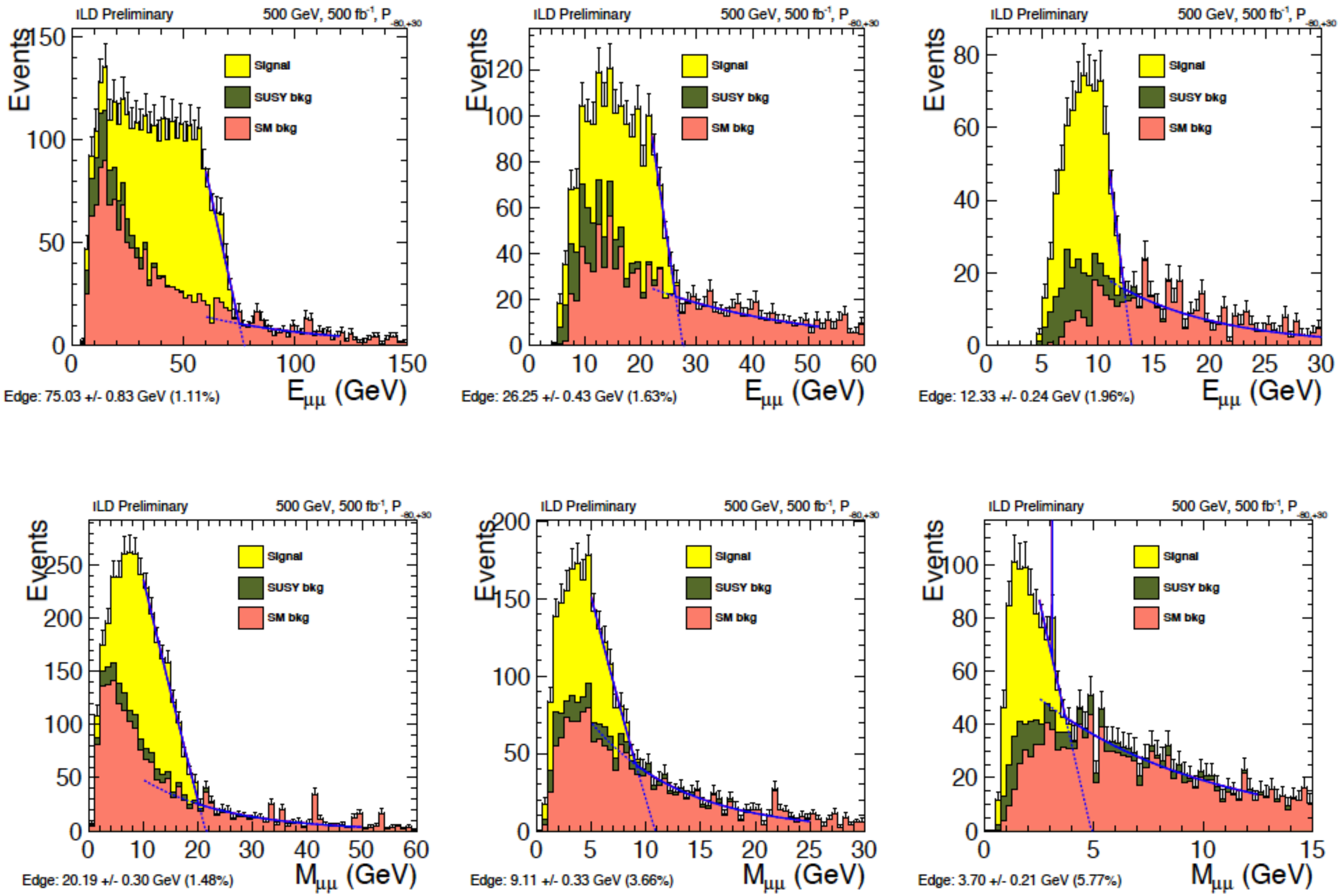
Process (Pe-,Pe+)	ILC1	ILC2	nGMM1
C1C1 (-1,+1)	1799.9	1530.5	1520.6
C1C1 (+1,-1)	334.5	307.2	309.5
N1N2 (-1,+1)	490.9	458.9	463.5
N1N2 (+1,-1)	378.5	353.8	357.3

Event Generator: WHIZARD v1.95, DBD setup, TDR beam parameters

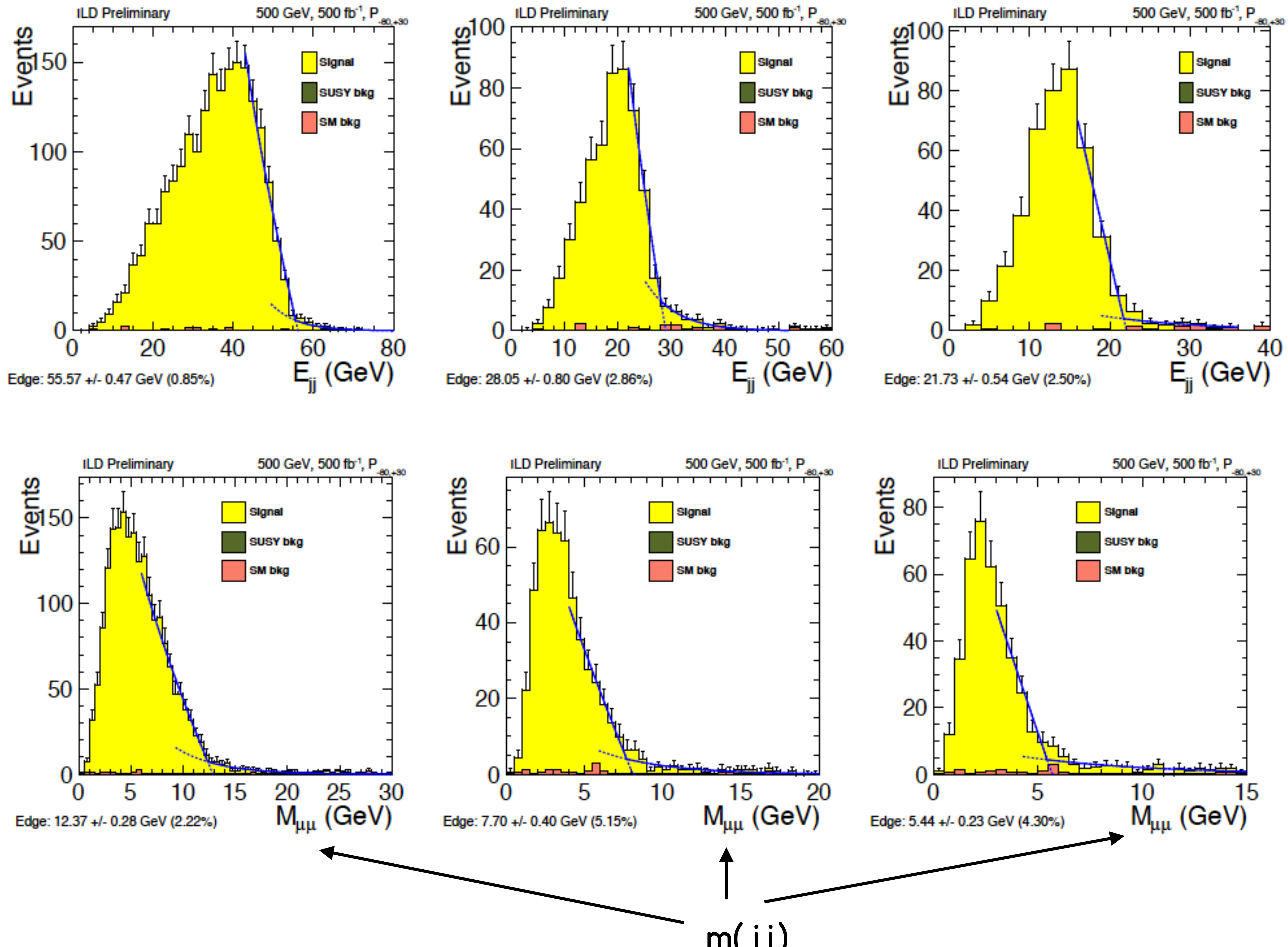
Cross sections for $\sqrt{s}$ = 500 GeV

Similar for all benchmarks

$E(\ell^+\ell^-)$ and $m(\ell^+\ell^-)$ measurements $\Rightarrow m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ to $\sim 1\%$ typically



$E(jj)$ and $m(jj)$ measurements $\Rightarrow m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ to $\sim 1\%$ typically

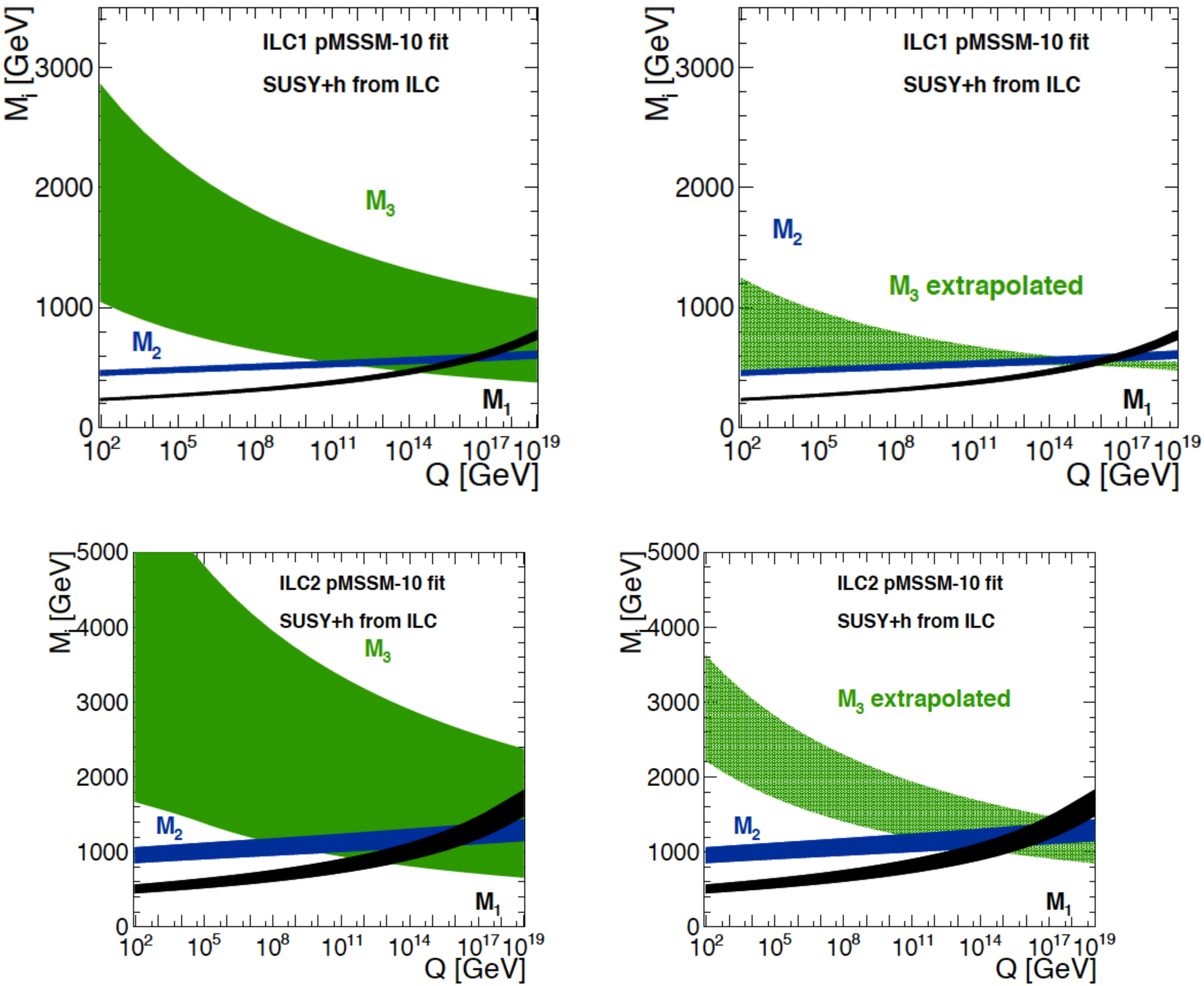


- weak scale fits ⇒ absolute higgsino masses and mass gaps
- masses and gaps allow sensitivity to gaugino masses $M_1(bino)$ and $M_2(wino)$
- combine with polarized beam σs
- combine with fits to h properties
- extract gaugino masses and other SUSY parameters

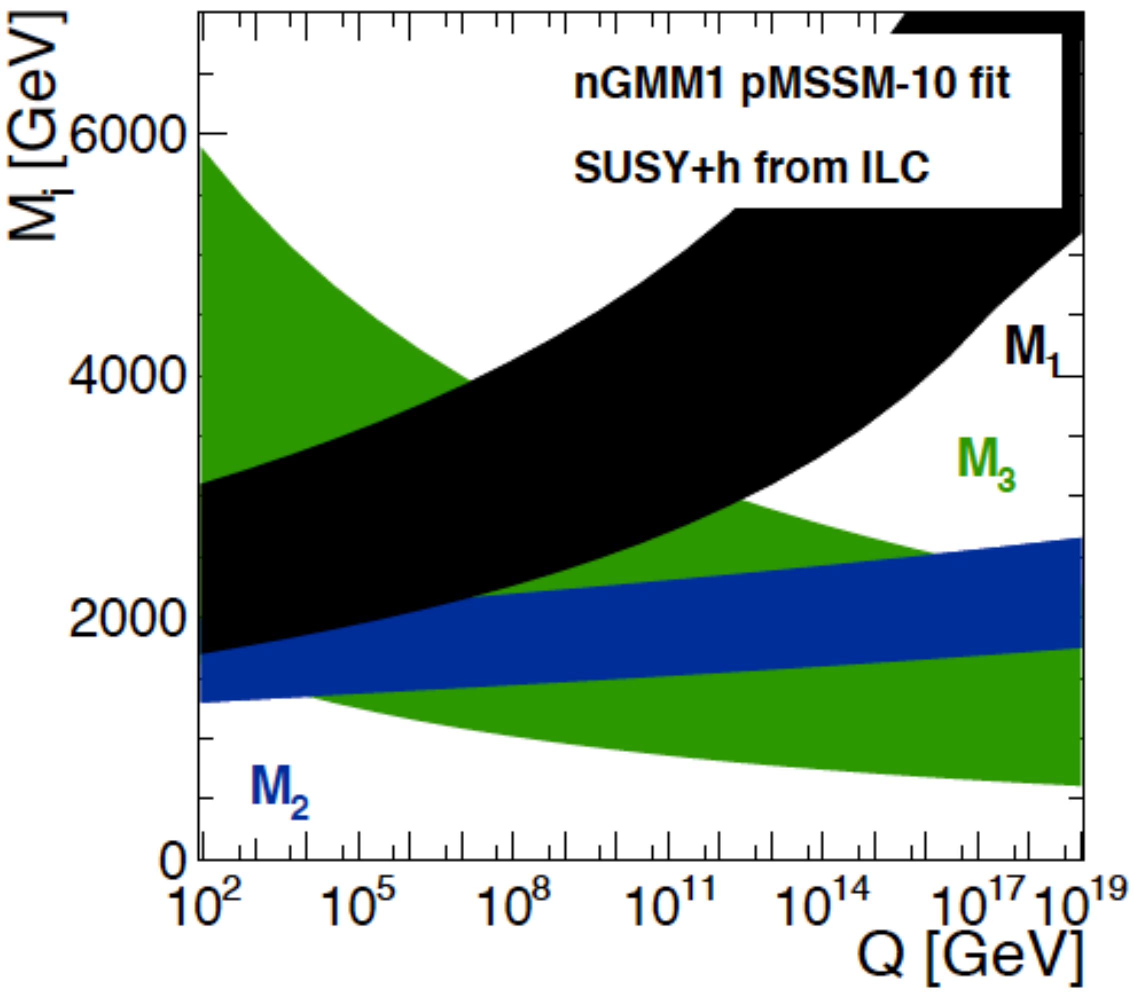
parameter	ILC1 NUHM2 true	best fit point	1σ CL	2σ CL
$M_{1/2}$	568.3	556.7	$^{+24.3}_{-20.3}$	$^{+37.7}_{-43.1}$
μ	115.0	105.3	$^{+12.8}_{-8.2}$	$^{+14.0}_{-14.5}$
$\tan\beta$	10.0	11.4	$^{+5.6}_{-1.6}$	$^{+11.4}_{-1.6}$
m_A	1000	968	$^{+167}_{-65}$	$^{+288}_{-130}$
M_0	7025	7685	$^{+1243}_{-1917}$	$^{+2311}_{-2095}$
A_0	−10427	−11064	$^{+2695}_{-1422}$	$^{+2927}_{-2698}$
χ^2	0.0013	0.0011		

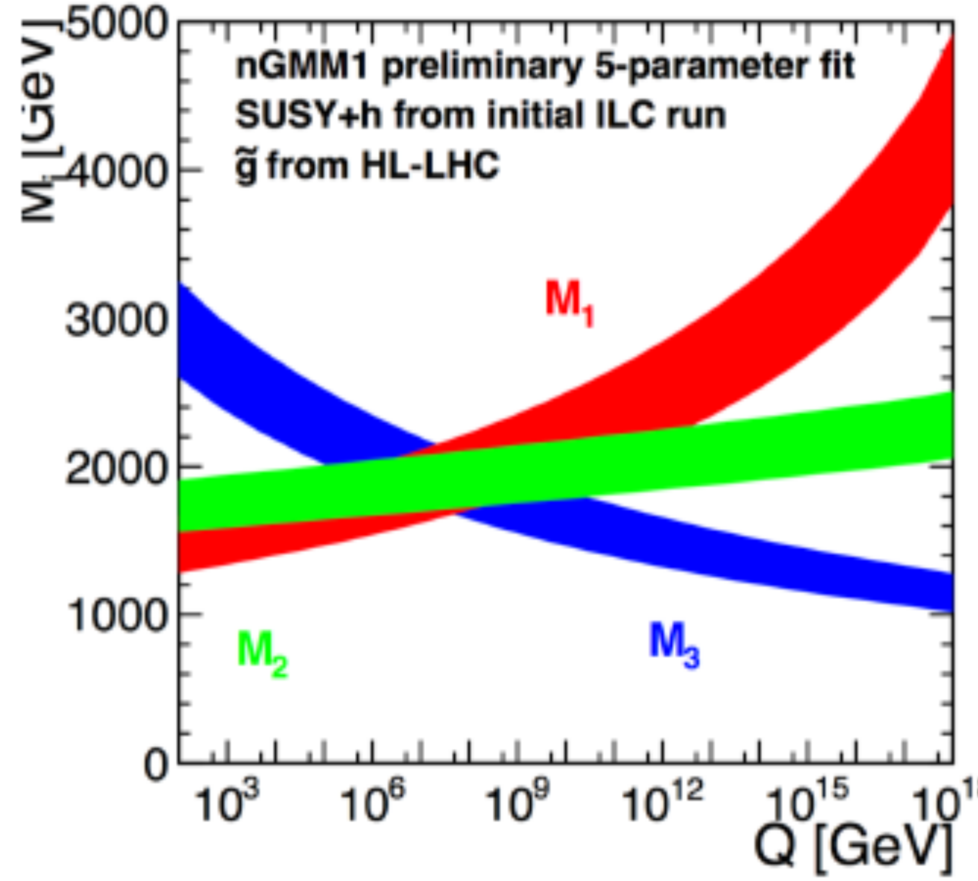
parameter	ILC1 pMSSM true	pMSSM-4 best fit point	pMSSM-4 1σ CL	pMSSM-4 2σ CL	pMSSM-10 best fit point	pMSSM-10 1σ CL	pMSSM-10 2σ CL
M_1	250	250.2	$^{+8.2}_{-7.7}$	$^{+17.1}_{-15.1}$	251.3	$^{+8.6}_{-15.7}$	$^{+17.2}_{-23.7}$
M_2	463	463.3	$^{+8.0}_{-8.1}$	$^{+16.2}_{-14.9}$	465.8	$^{+24.2}_{-23.0}$	$^{+31.4}_{-49.8}$
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	$^{+8.8}_{-3.0}$	$^{+45.3}_{-3.5}$
m_A	1000				1050	$^{+310}_{-180}$	$^{+607}_{-296}$
M_3	1270				1412	$^{+1791}_{-1104}$	$^{+1411}_{-2843}$
$M_{L(3)}$	7150				7063	$^{+2029}_{-4311}$	$^{+2645}_{-5632}$
$M_{U(3)}$	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		

Check scale for M1=M2 ino mass unification?
Combine with LHC gluino mass measurement?



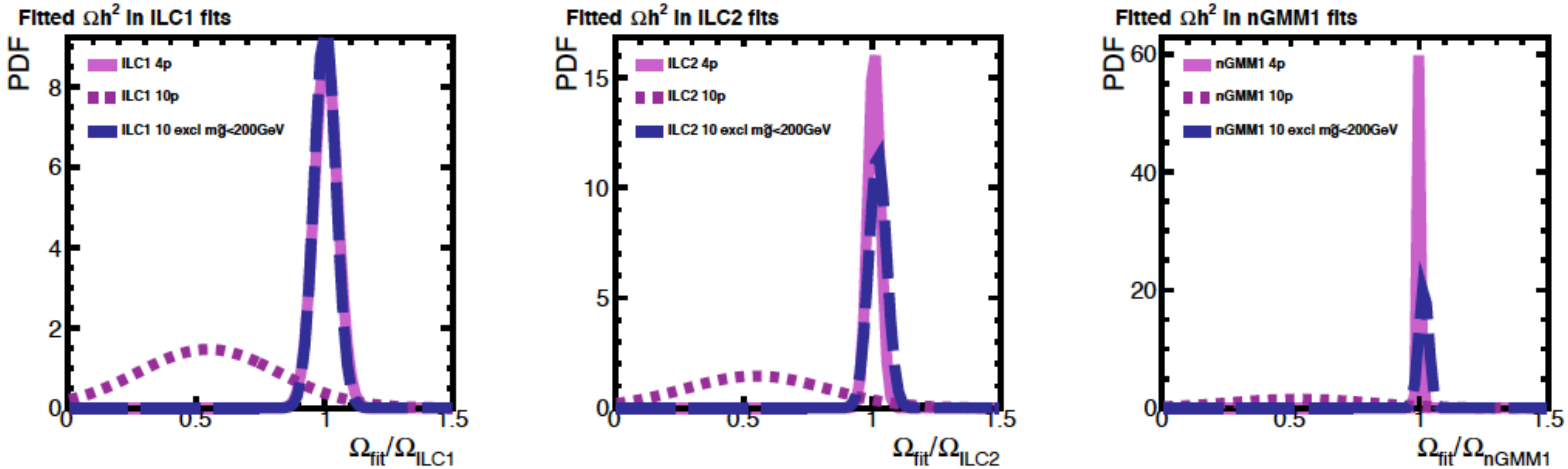
Compare with mirage unification scenario where gaugino masses unify at intermediate scale:





nGMM1 (ILC initial stage)

Can also test WIMP dark matter properties:



Higgsino-like DM underproduced-
cross check with direct detection rates:
confirm need 2nd DM particle: axion?

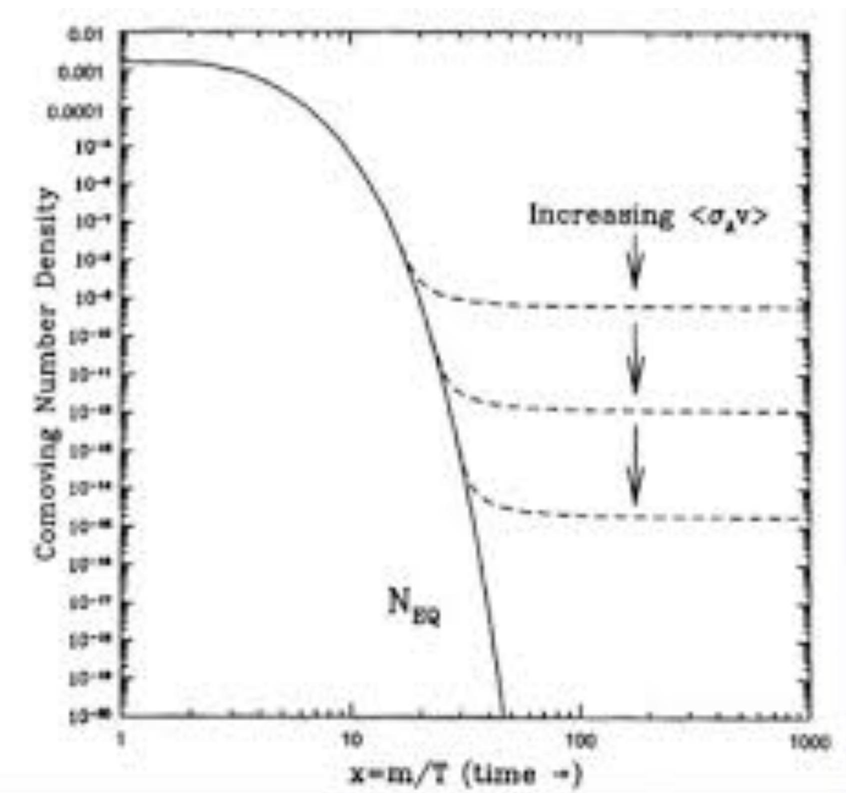
Conclusions:

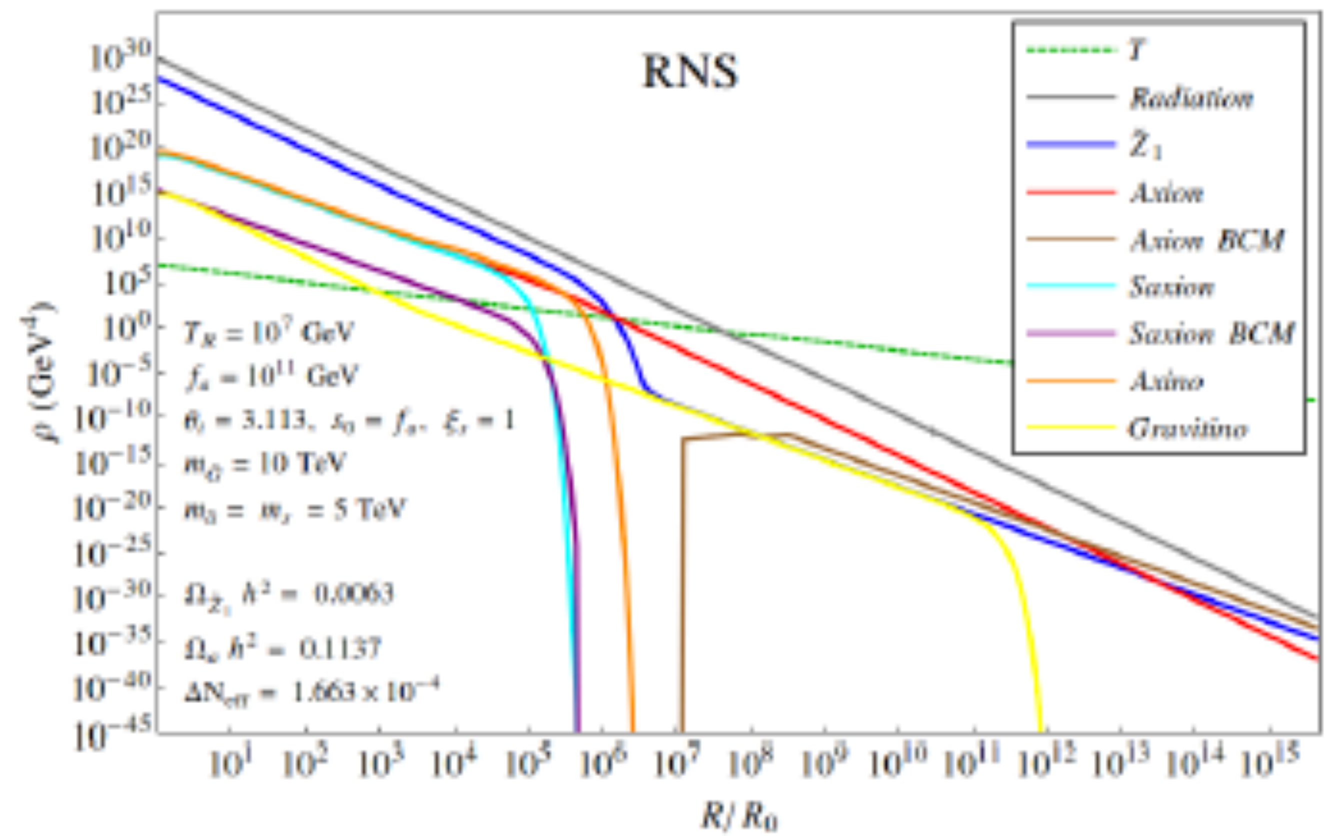
- Naturalness: light higgsinos ~100-300 GeV
- Stops, gluinos OK in multi-TeV range
- mu emerges from gravity-safe SUSY axion model: Z(24)^R
- DM= axion+higgsino admixture
- natural soft terms, m(h)=125 GeV from statistics of string landscape
- ILC500: SUSY discovery machine and higgsino factory
- precision higgsino measurements allow tests of gaugino unification

What happens to SUSY WIMP dark matter?

- higgsino-like WIMPs thermally underproduced
- 3 not four light pions => QCD theta vacuum
- EDM(neutron) => 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

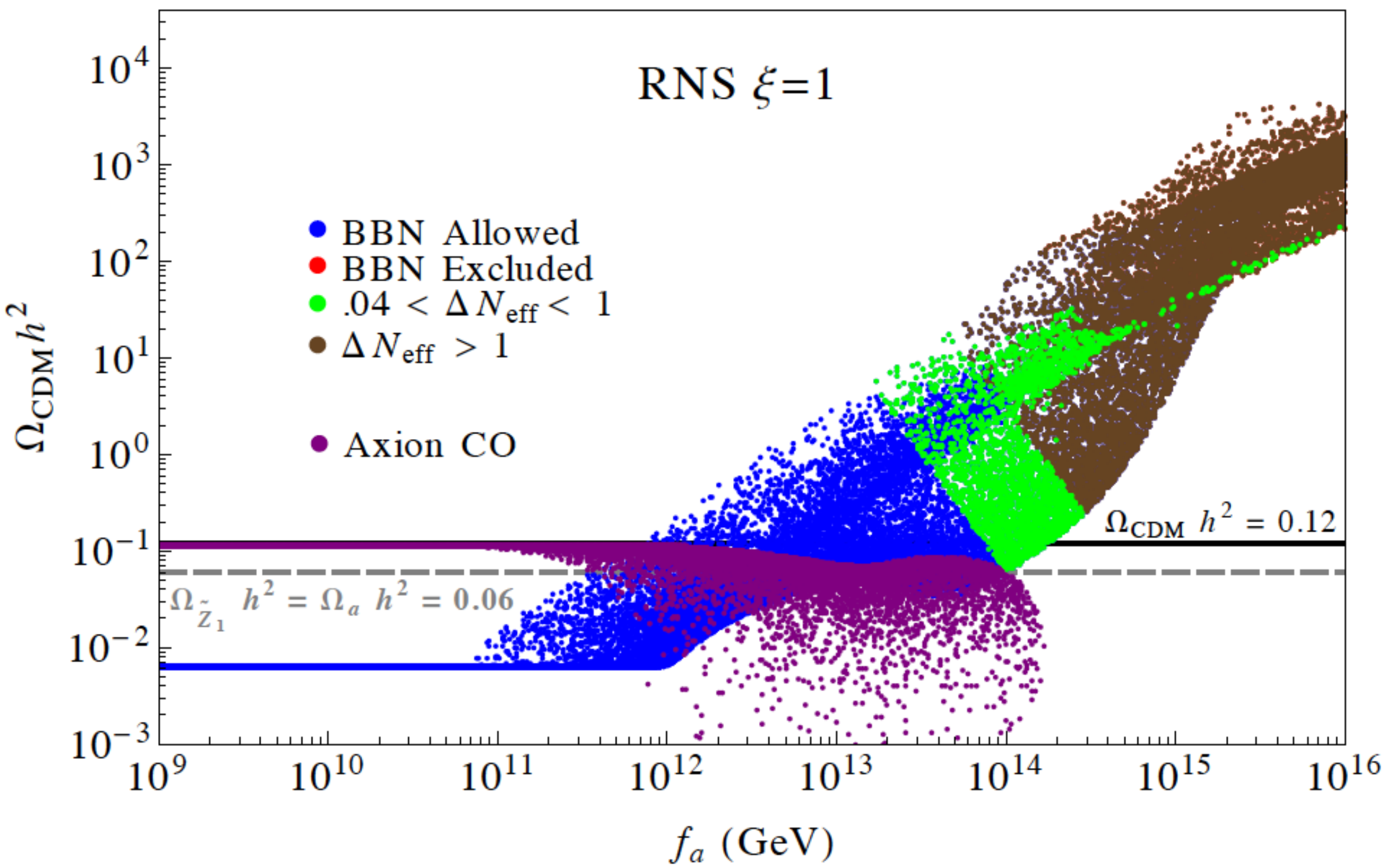




KJ Bae, HB, Lessa, Serce

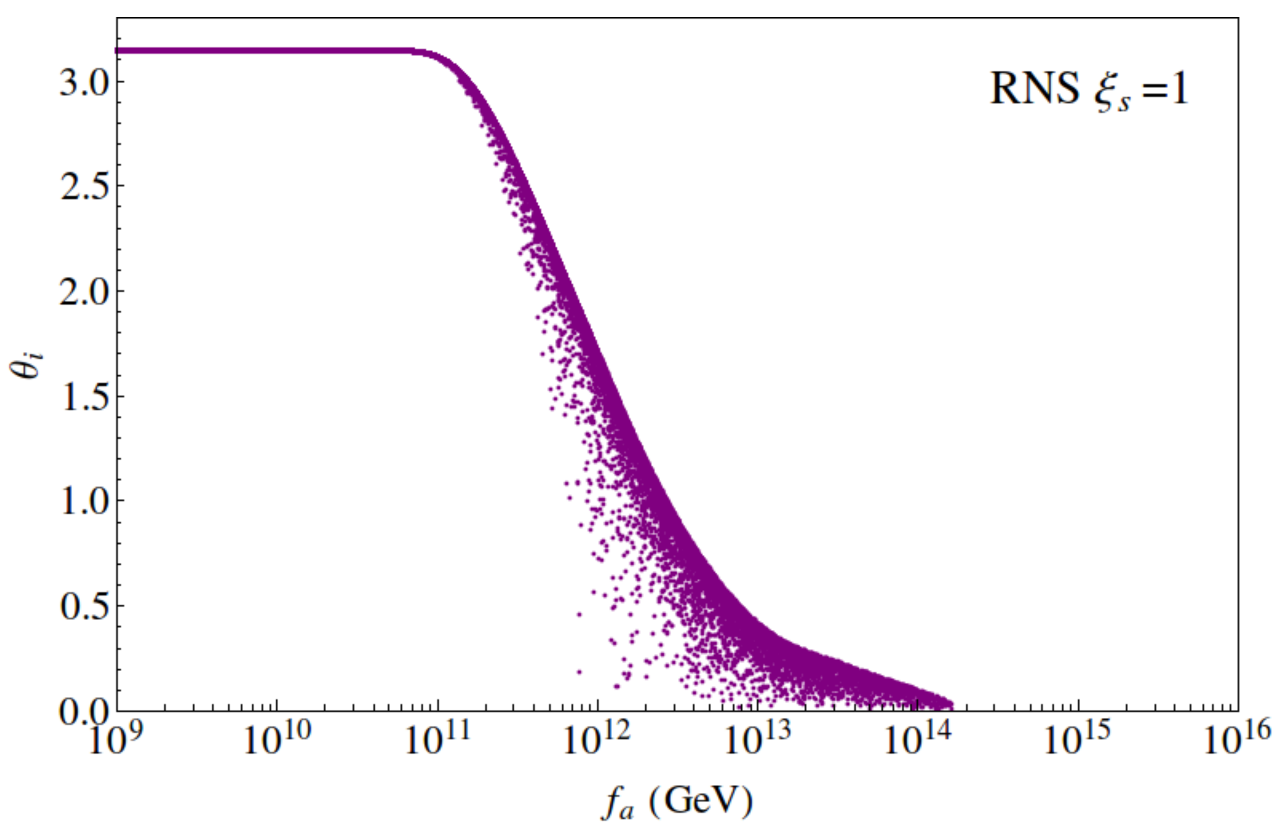
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

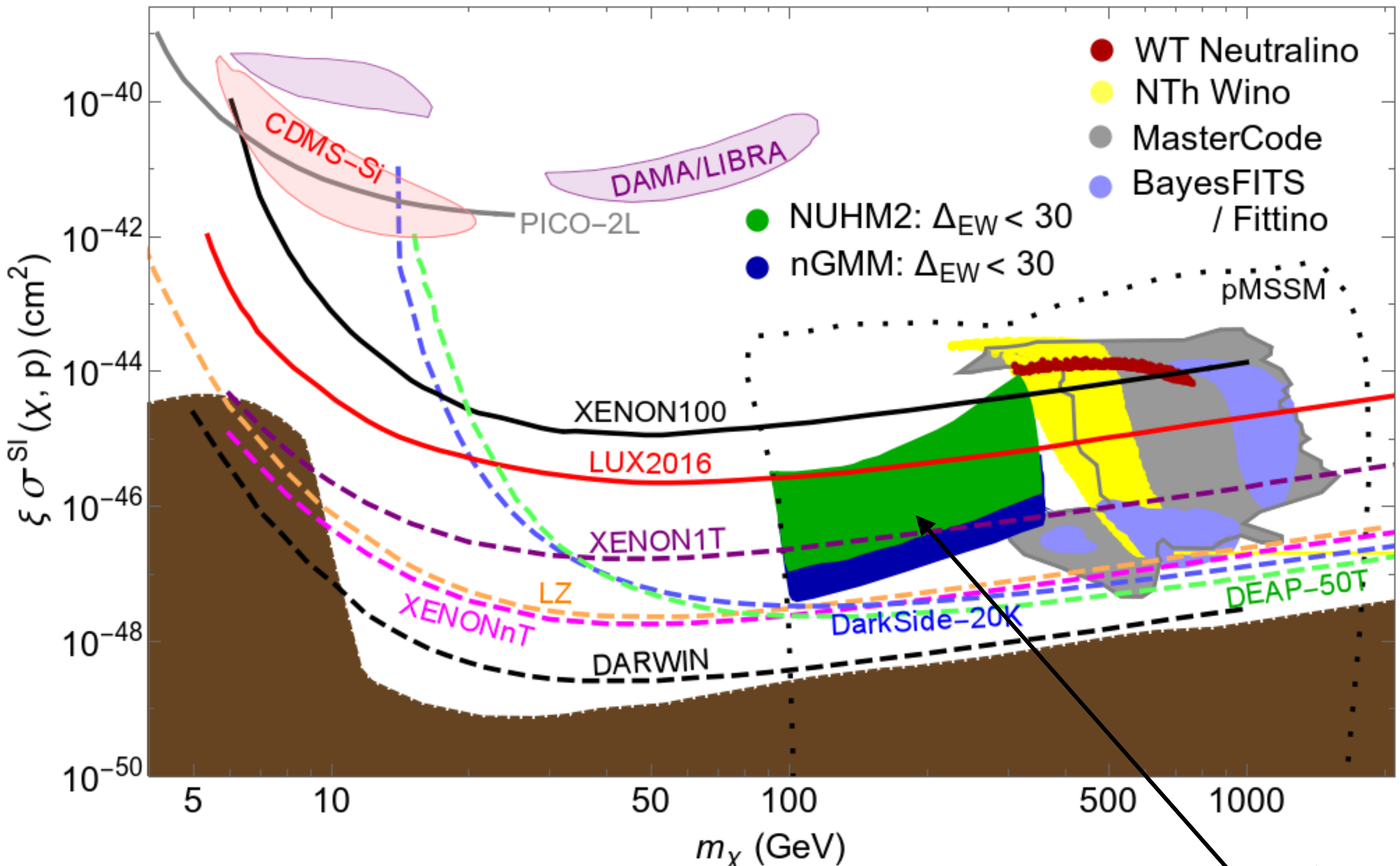
axion abundance



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



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

Conclusion: SUSY is alive and well!

- old 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?
- higgsino-like WIMP detection likely; axion more difficult

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

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

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

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

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

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

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

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

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

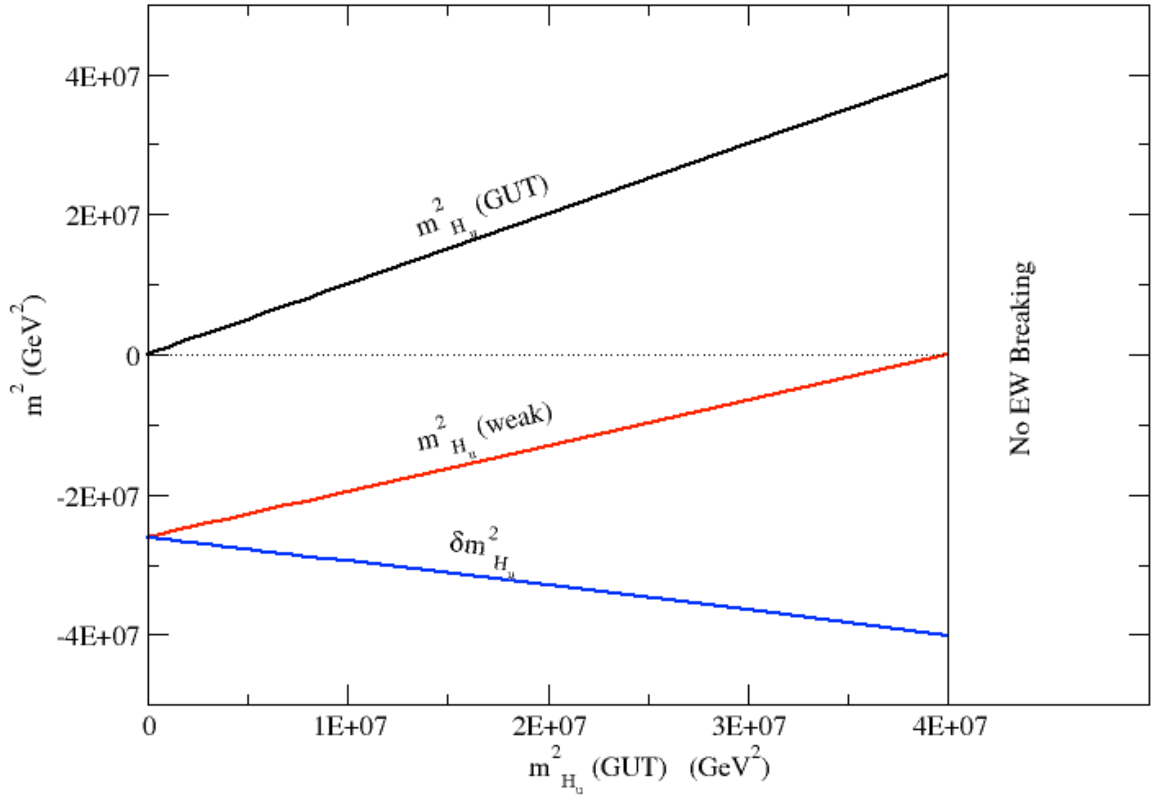
old natural SUSY then A_t can't be too big

What's wrong with this argument?

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

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

violates prime directive!



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

HB, Barger, Savoy

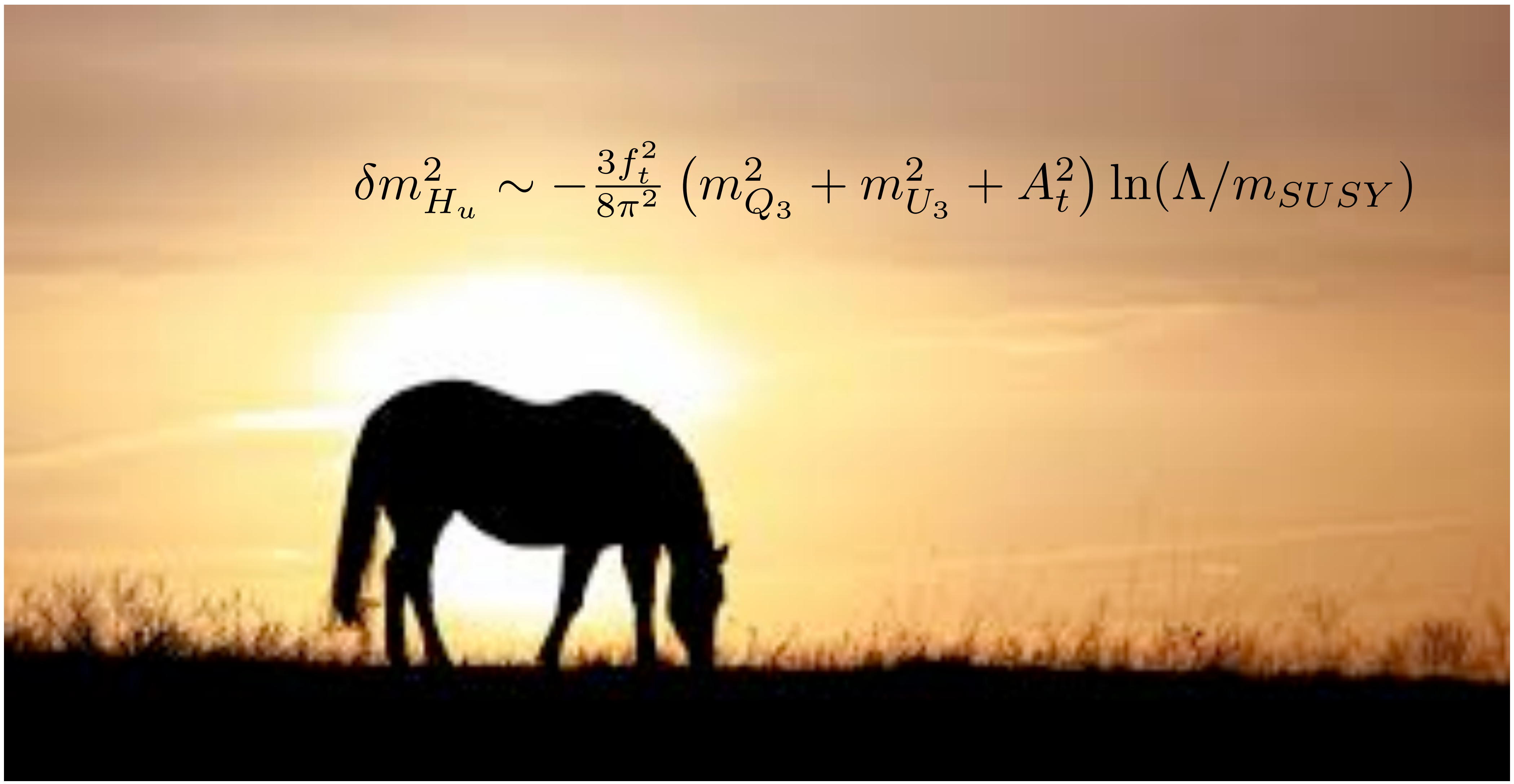
To fix: combine dependent terms:

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

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

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

Recommendation: put this horse out to pasture



R.I.P.

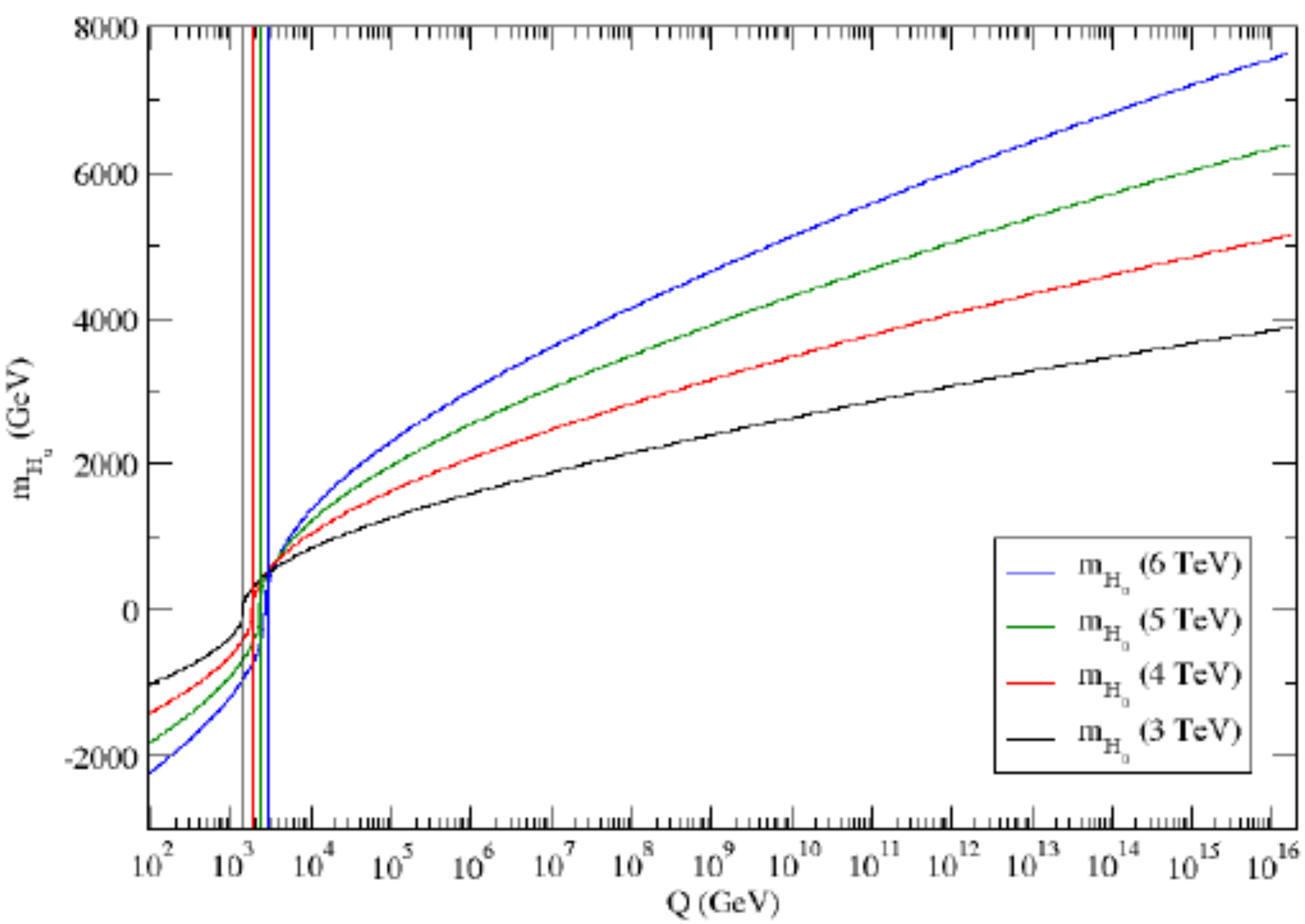
sub-TeV 3rd generation squarks not required for naturalness

If one has the right parameter correlations, can always get generalized focus point behavior for mHu:

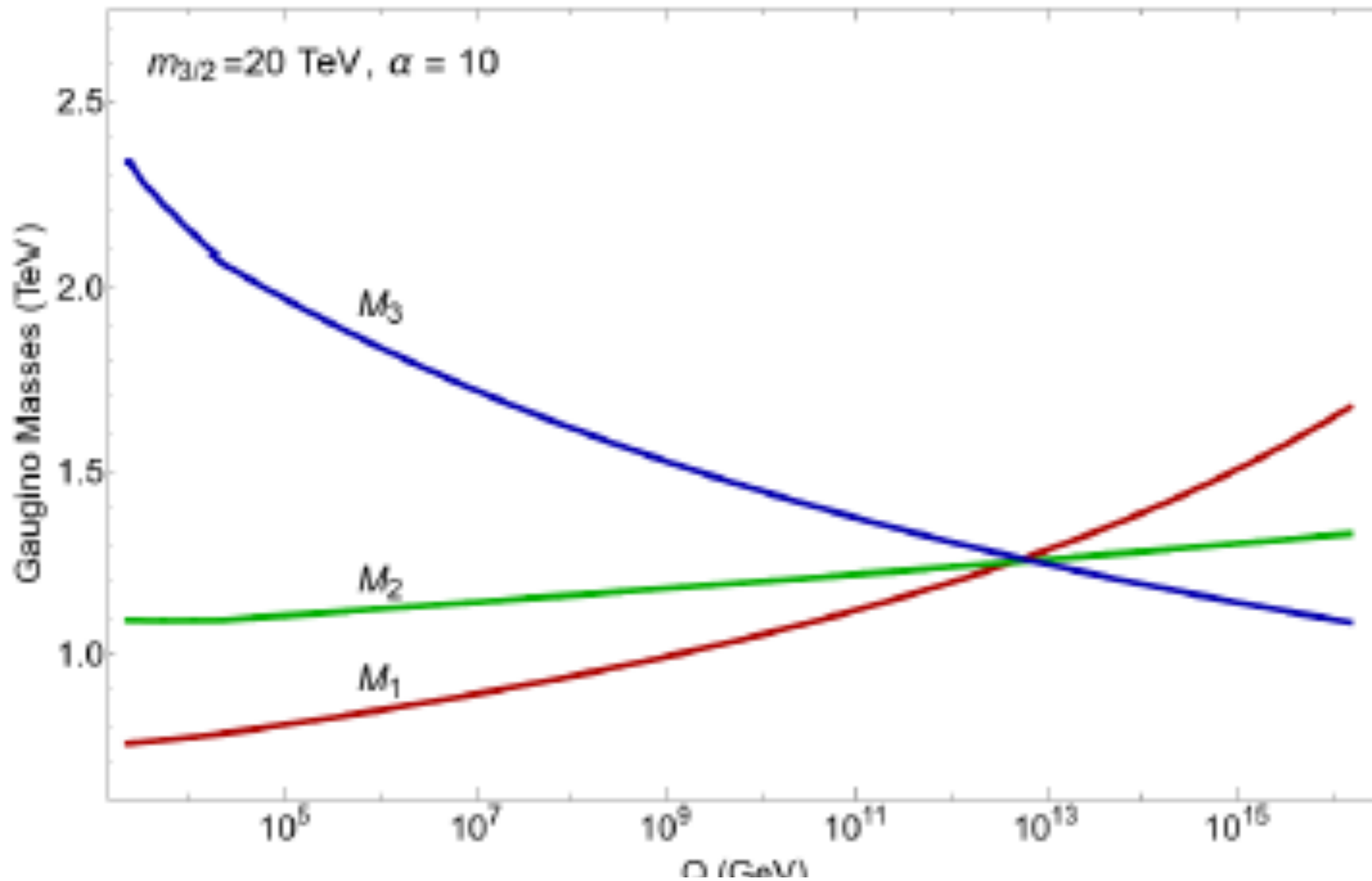
$$\begin{aligned} m_0^2 &= m_{3/2}^2 \\ A_0 &= -1.6 m_{3/2} \\ m_{1/2} &= m_{3/2}/5 \\ m_{H_d}^2 &= m_{3/2}^2/2. \end{aligned}$$

$$\mu \simeq 150 \text{ GeV}$$

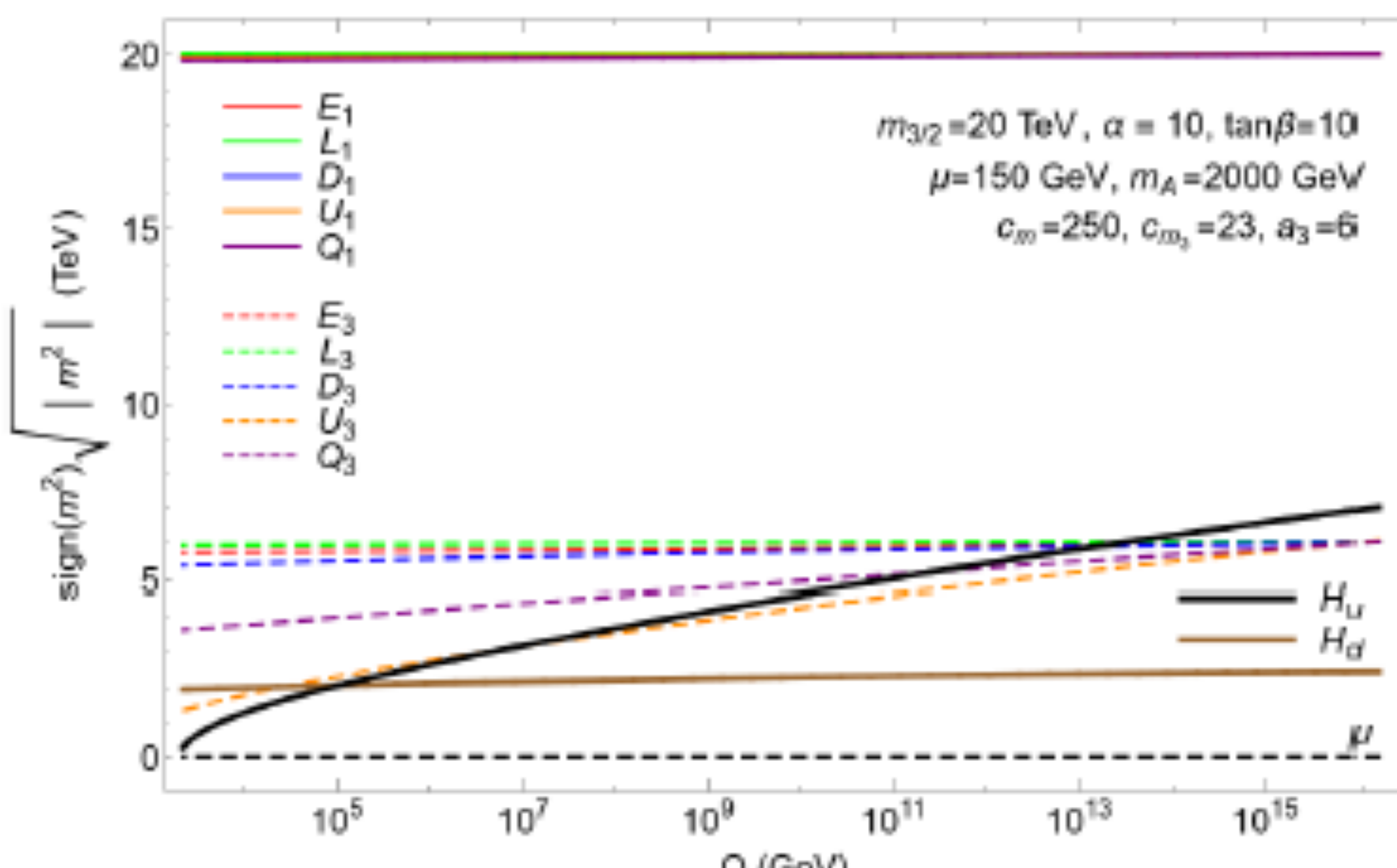
$$m_{H_u}^2(GUT) = 1.8 m_{3/2}^2 - (212.52 \text{ GeV})^2.$$



HB, Barger, Savoy



m3/2 =20 TeV, α = 10
Gaugino Masses (TeV)
M3
M2
M1
Q (GeV)

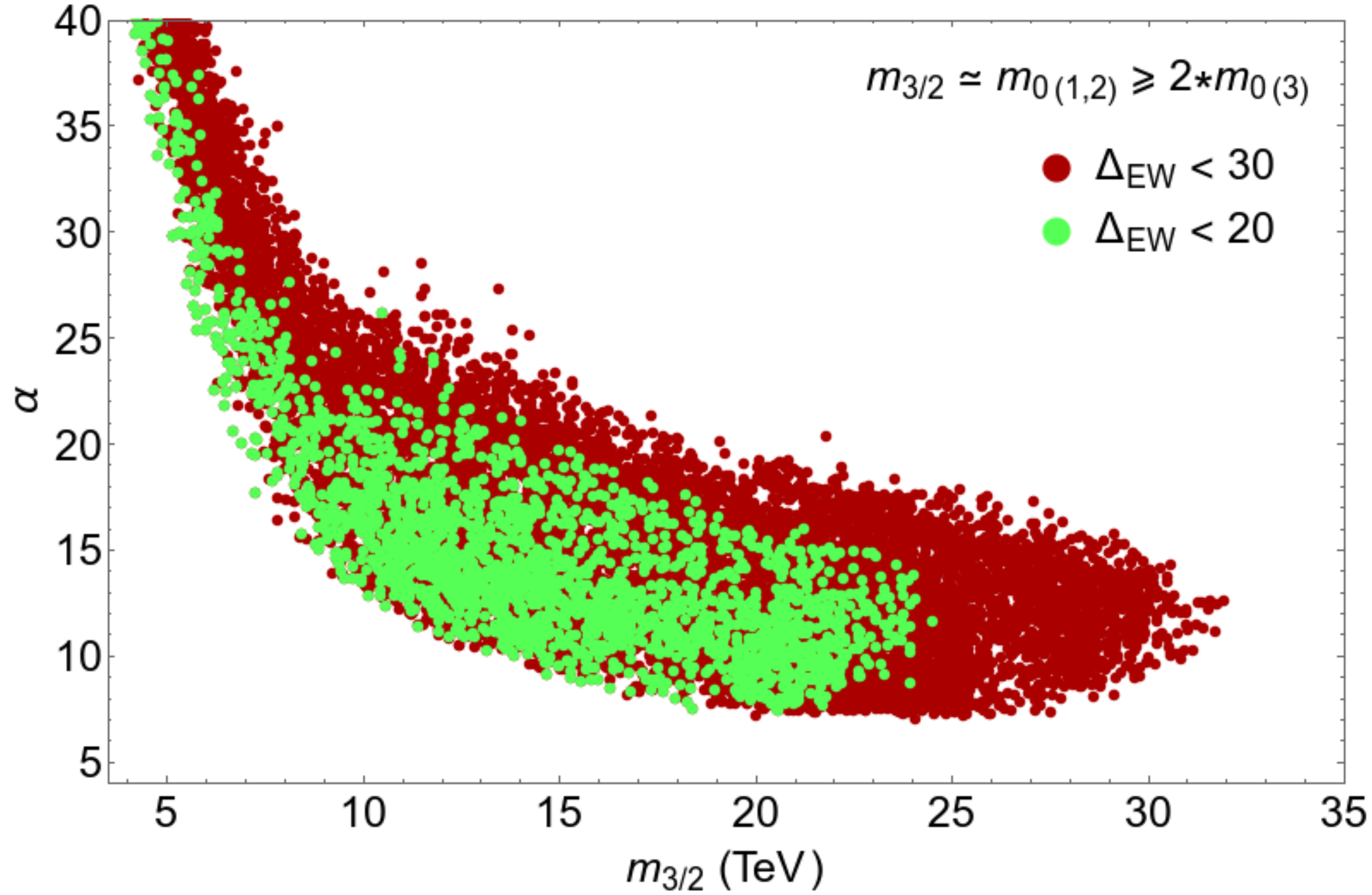


E1
L1
D1
U1
Q1
E3
L3
D3
U3
Q3
m3/2 =20 TeV, α = 10, tanβ=10
μ=150 GeV, mA=2000 GeV
cm=250, cm3=23, a3=6
Hu
Hd
μ
sign(m²)√|m²| (TeV)
Q (GeV)

$$\Delta_{EW} = 17.6$$

To generate minilandscape, take:

$c_m = 16\pi^2/\alpha)^2$ so that $m_0(1,2) \simeq m_{3/2}$



Then get upper bound $m_{3/2} < 25 - 30$ TeV and $\alpha > 7$
else too large $m_0(1,2)$ drives 3rd generation tachyonic

Martin, Vaughn, 2-loop RGEs

Increased upper bound on m(gluino)<6 TeV

Alpha bound => mirage unif scale >10^11 GeV
(not too much compression of inos)

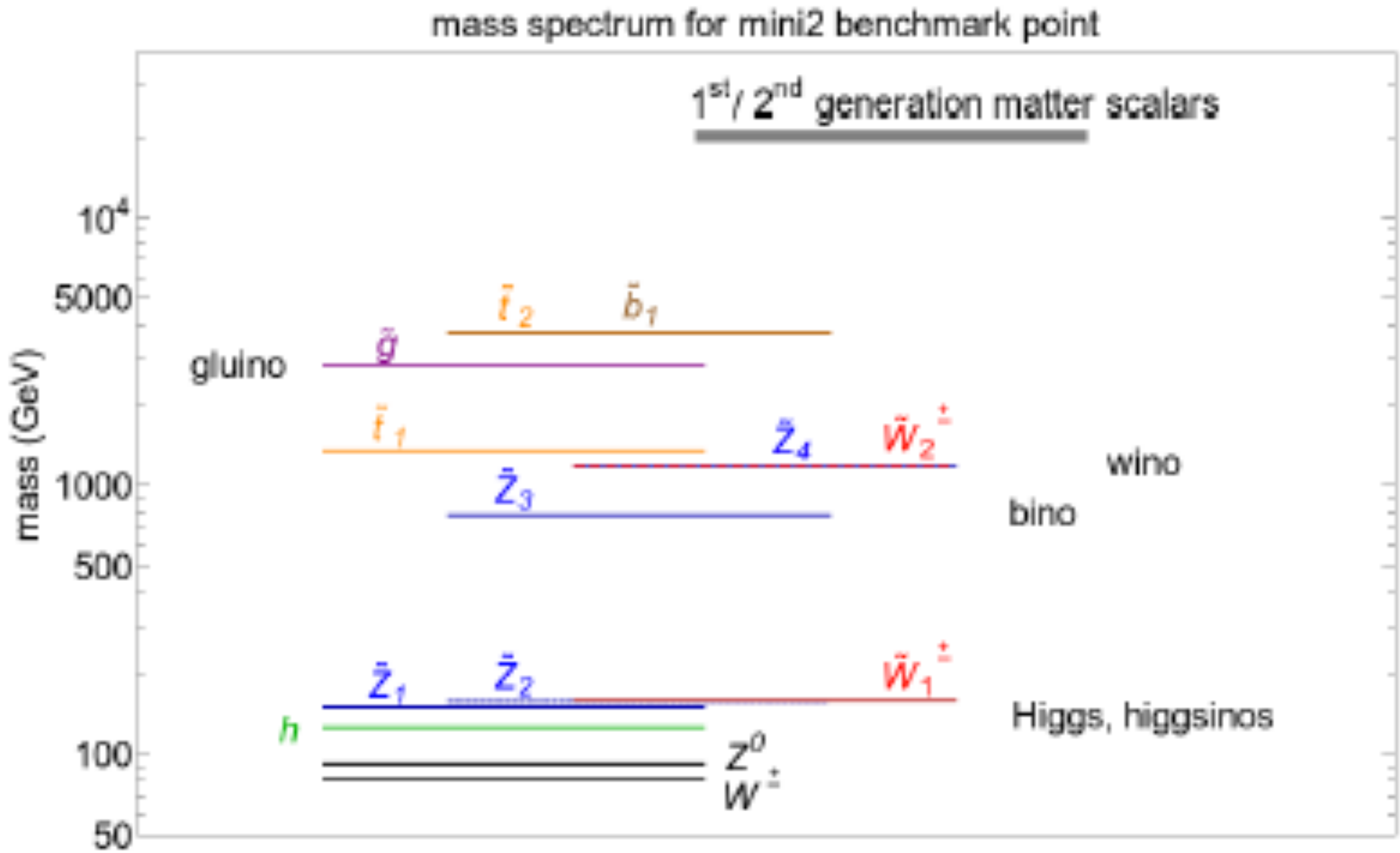
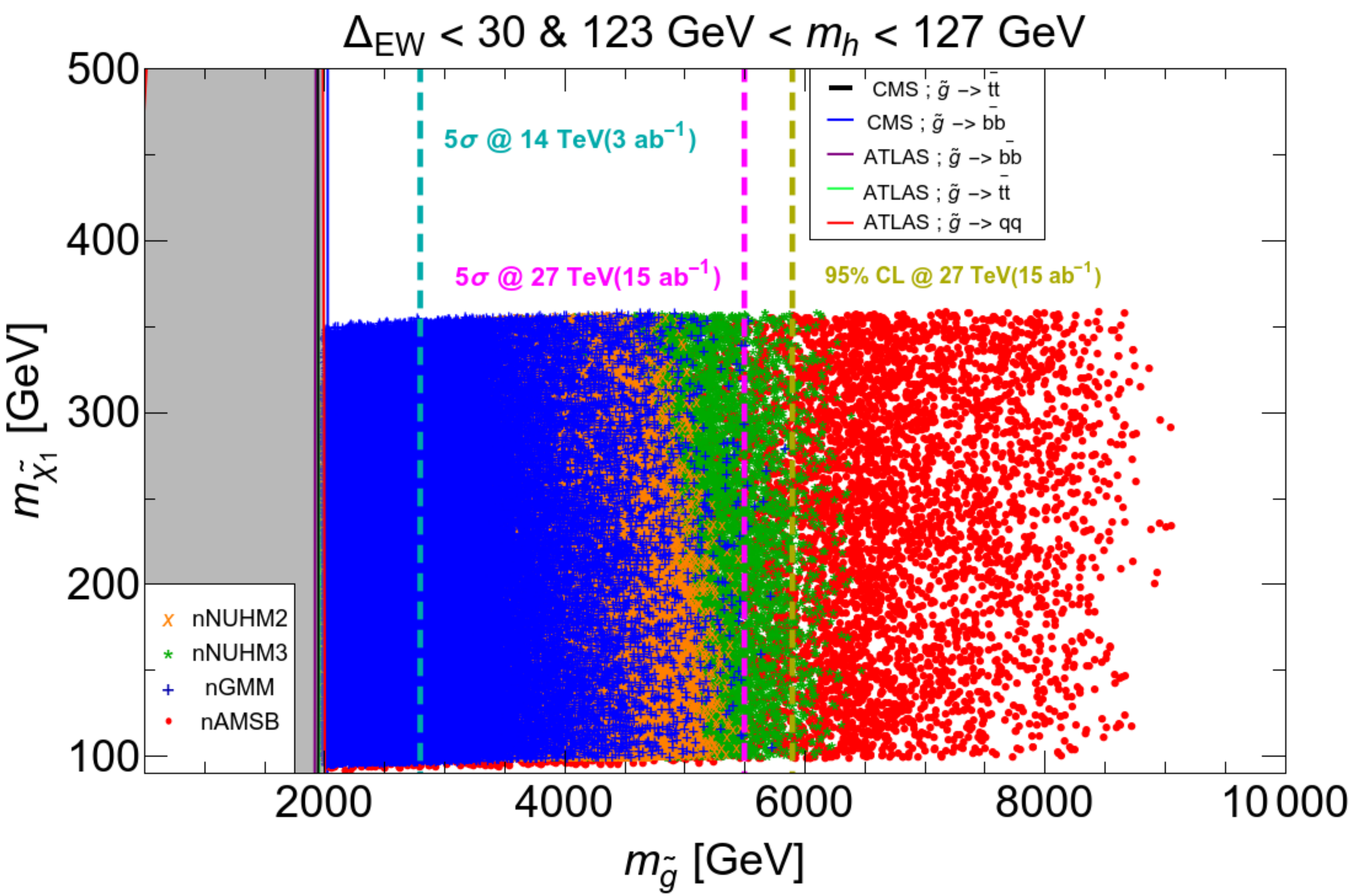
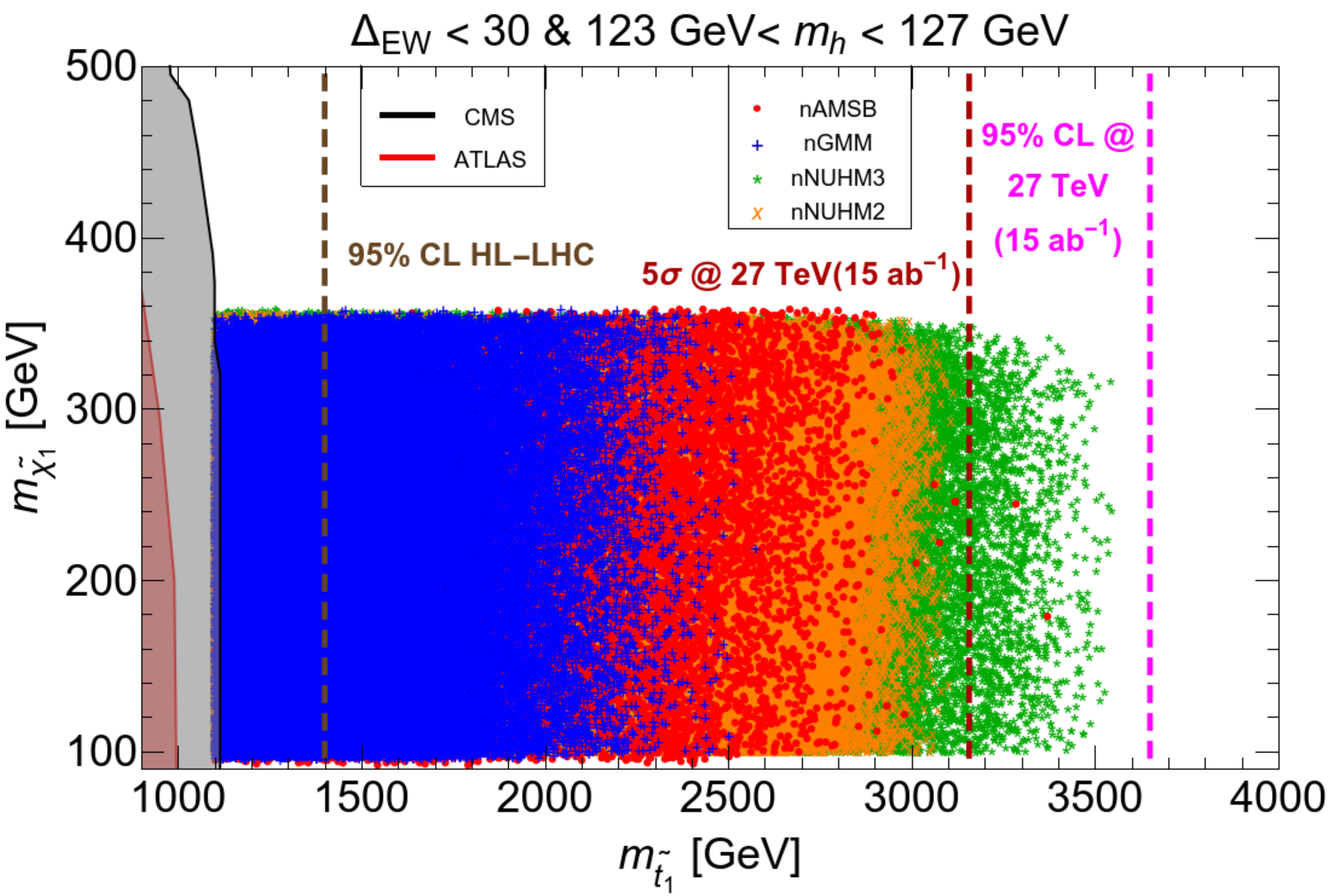


Figure 7: The superparticle mass spectra from the natural mini-landscape point mini2 of Table 1.

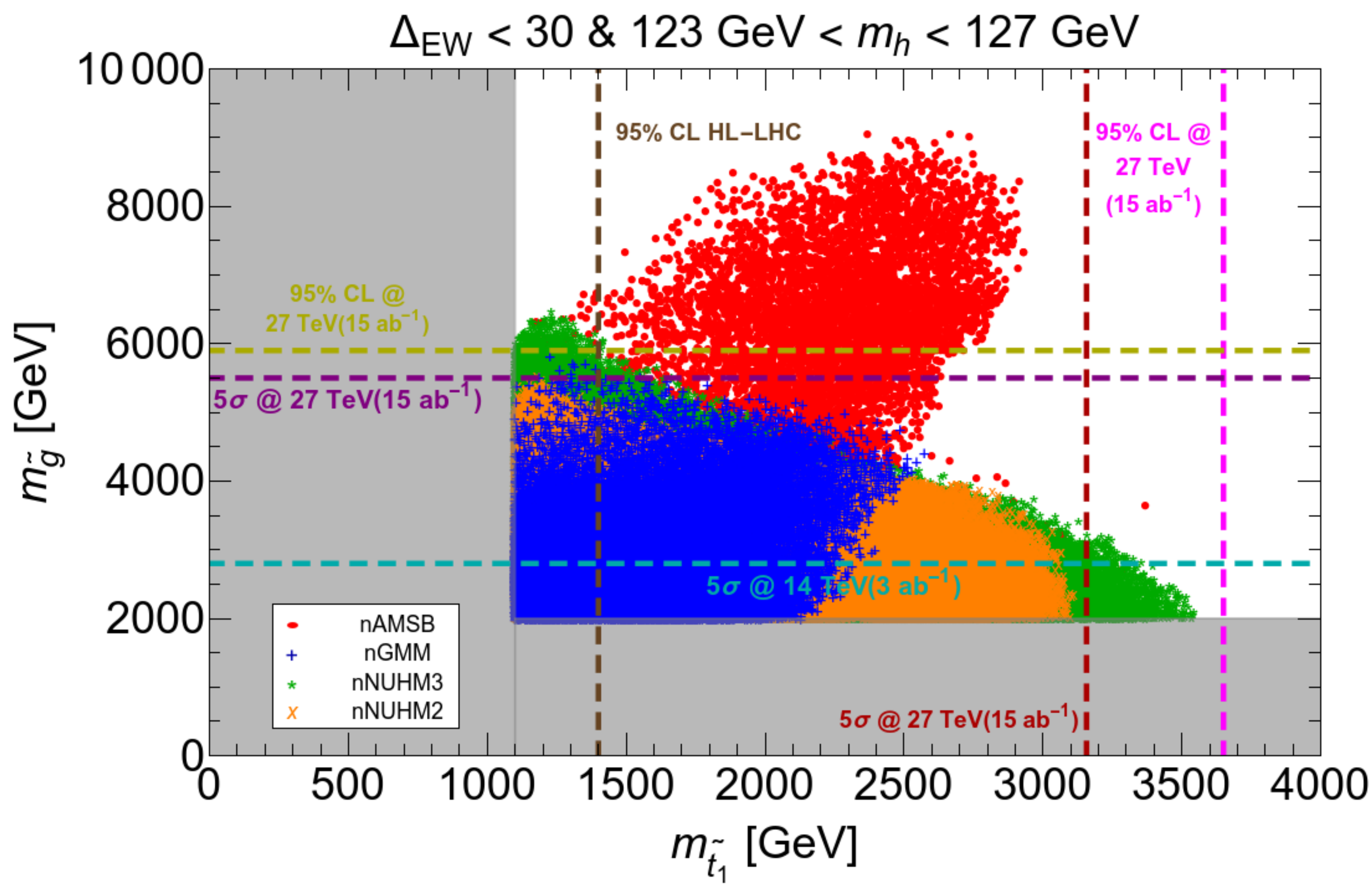
Due to compressed gaugino spectra, minilandscape
can probably hide from HL-LHC while maintaining naturalness



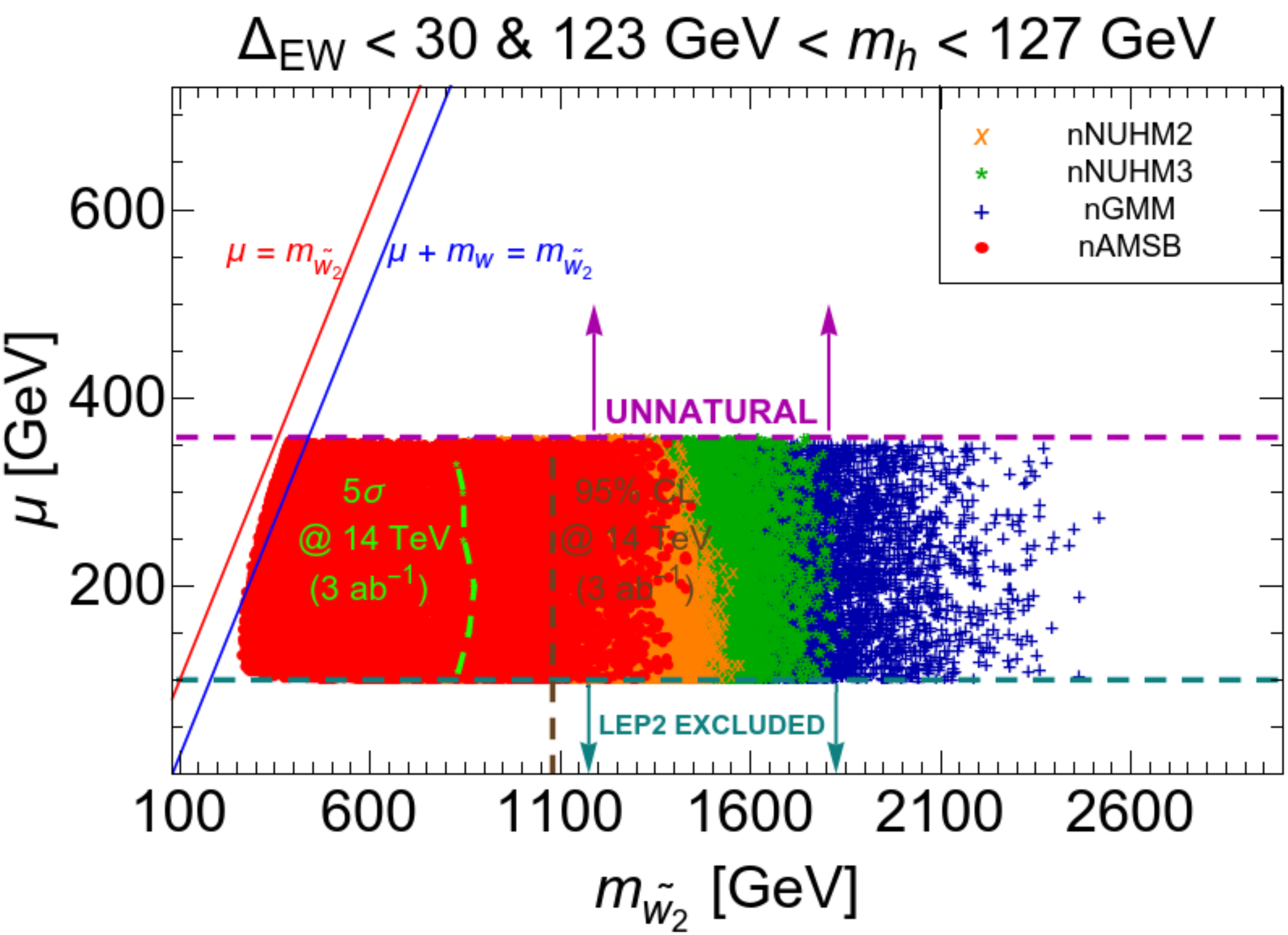
Δ_{EW} < 30 & 123 GeV < m_h < 127 GeV
CMS ; $\tilde{g} \to t\bar{t}$
CMS ; $\tilde{g} \to b\bar{b}$
ATLAS ; $\tilde{g} \to b\bar{b}$
ATLAS ; $\tilde{g} \to t\bar{t}$
ATLAS ; $\tilde{g} \to qq$
5σ @ 14 TeV(3 ab^{-1})
5σ @ 27 TeV(15 ab^{-1})
95% CL @ 27 TeV(15 ab^{-1})
nNUHM2
nNUHM3
nGMM
nAMSB
$m_{\tilde{\chi}_1}$ [GeV]
$m_{\tilde{g}}$ [GeV]



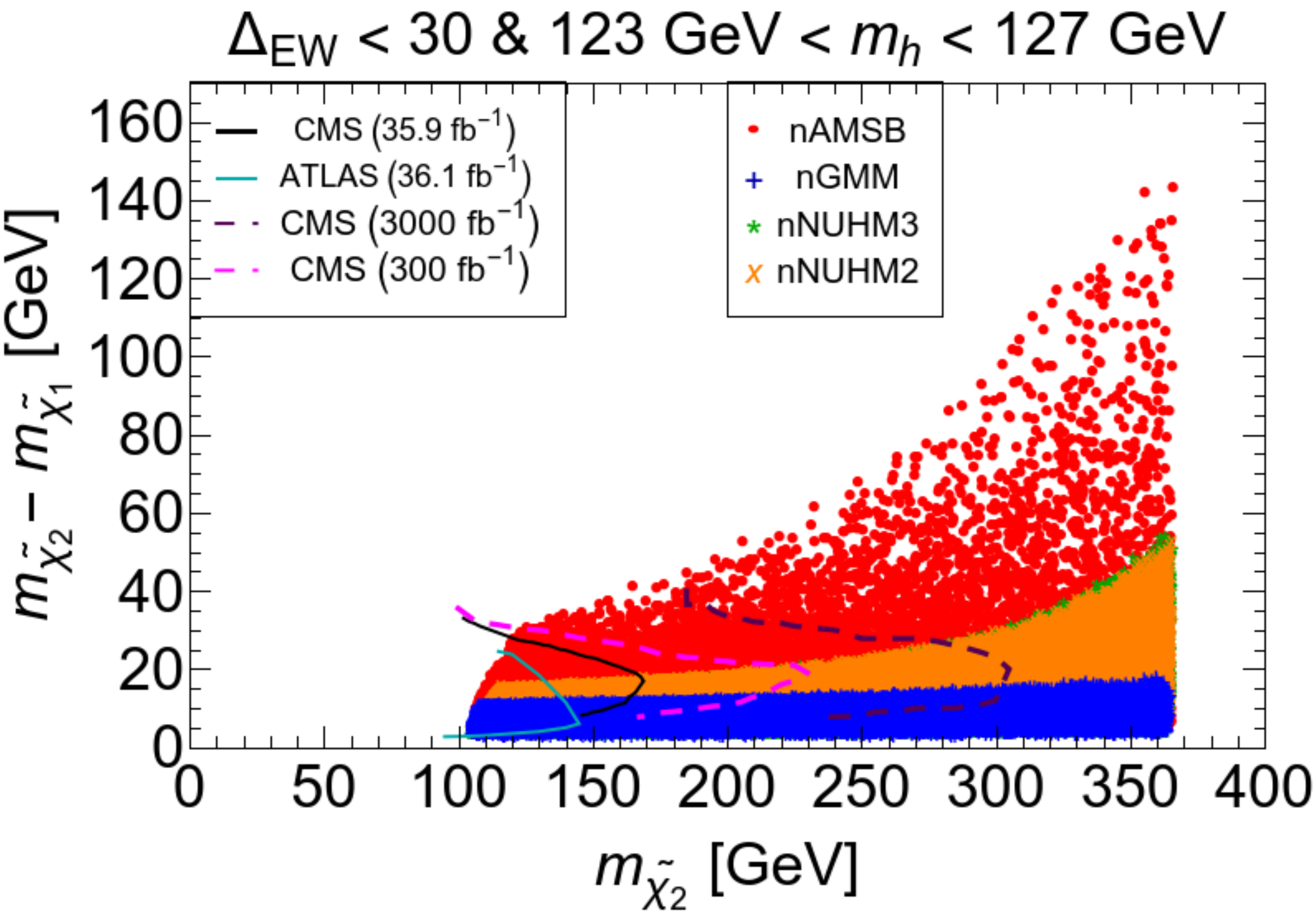
$\Delta_{EW} < 30$ & 123 GeV< m_h < 127 GeV
CMS
ATLAS
nAMSB
nGMM
nNUHM3
nNUHM2
95% CL HL–LHC
5σ @ 27 TeV(15 ab^{-1})
95% CL @ 27 TeV (15 ab^{-1})
$m_{\tilde{\chi}_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]



Δ_{EW} < 30 & 123 GeV < m_h < 127 GeV
95% CL HL−LHC
95% CL @ 27 TeV (15 ab^{-1})
95% CL @ 27 TeV(15 ab^{-1})
5σ @ 27 TeV(15 ab^{-1})
5σ @ 14 TeV(3 ab^{-1})
5σ @ 27 TeV(15 ab^{-1})
nAMSB
nGMM
nNUHM3
nNUHM2
$m_{\tilde{g}}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]



Δ_{EW} < 30 & 123 GeV < m_h < 127 GeV
nNUHM2
nNUHM3
nGMM
nAMSB
$\mu = m_{\tilde{w}_2}$
$\mu + m_W = m_{\tilde{w}_2}$
UNNATURAL
5σ
@ 14 TeV
(3 ab^{-1})
95% CL
@ 14 TeV
(3 ab^{-1})
LEP2 EXCLUDED
600
400
200
μ [GeV]
100
600
1100
1600
2100
2600
$m_{\tilde{w}_2}$ [GeV]



Δ_{EW} < 30 & 123 GeV < m_h < 127 GeV
CMS (35.9 fb^{-1})
ATLAS (36.1 fb^{-1})
CMS (3000 fb^{-1})
CMS (300 fb^{-1})
nAMSB
nGMM
nNUHM3
nNUHM2
$m_{\tilde{\chi}_2} - m_{\tilde{\chi}_1}$ [GeV]
$m_{\tilde{\chi}_2}$ [GeV]
0
20
40
60
80
100
120
140
160
0
50
100
150
200
250
300
350
400