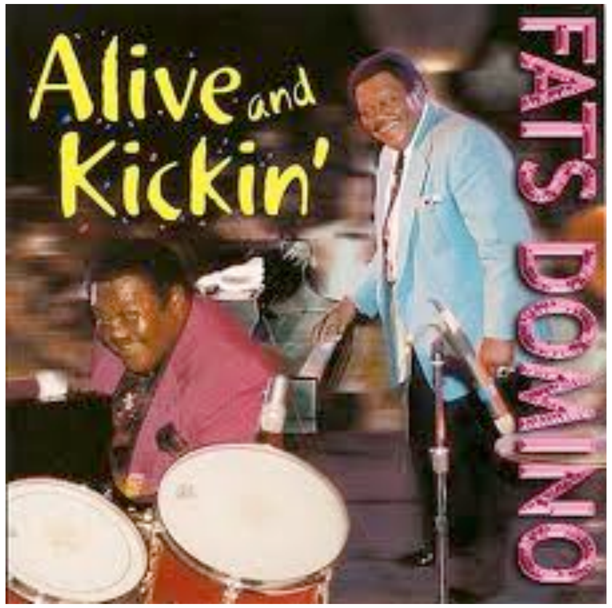
SUSY, alive and kickin’

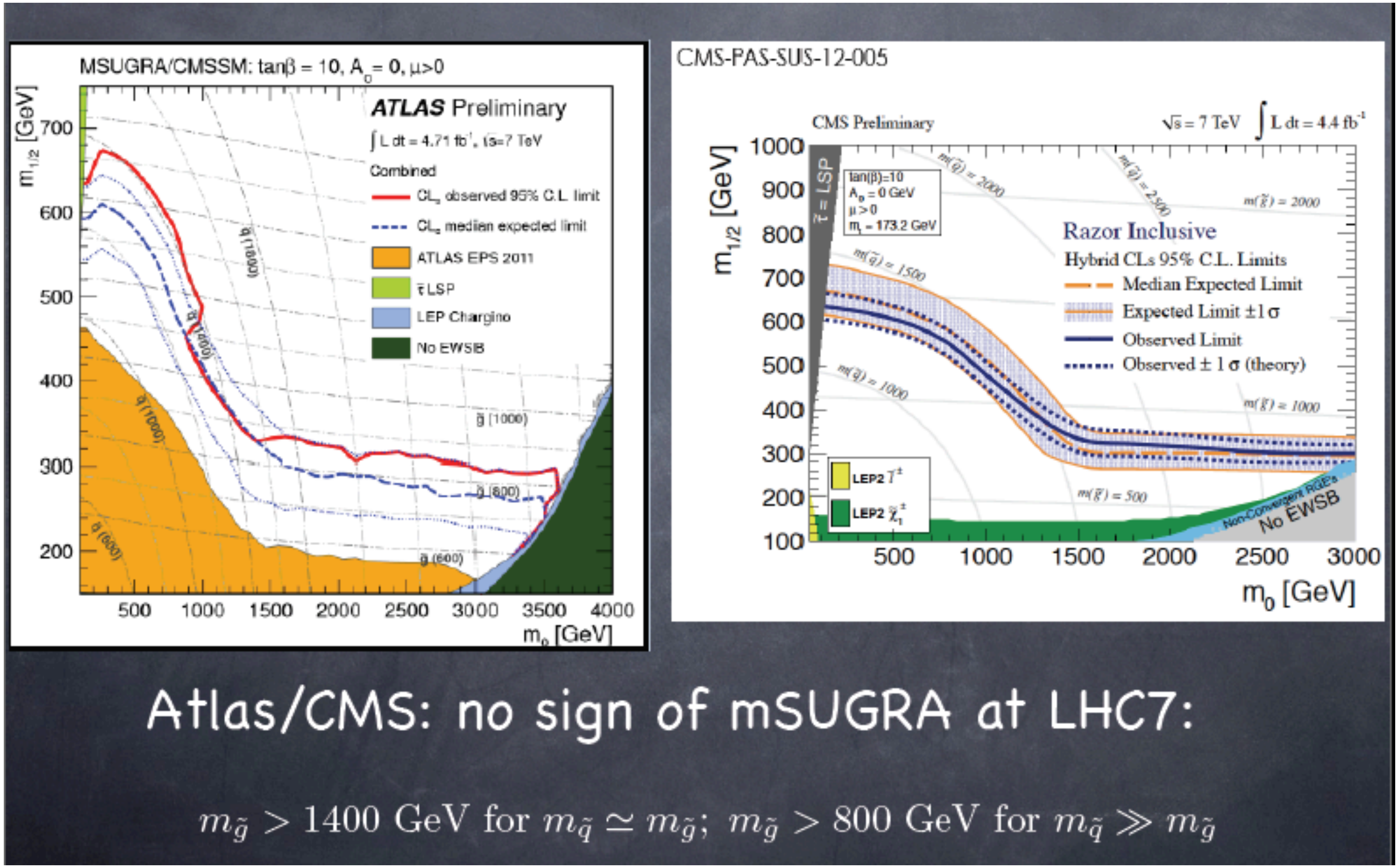
(and why construction of ILC should begin immediately)

Howard Baer
University of Oklahoma

(or how SUSY survived a storm of LHC data
to emerge more intriguing than ever)



What we learned from LHC7



Atlas/CMS: no sign of mSUGRA at LHC7:

$$m_{\tilde g} > 1400 \text{ GeV for } m_{\tilde q} \simeq m_{\tilde g};\ m_{\tilde g} > 800 \text{ GeV for } m_{\tilde q} \gg m_{\tilde g}$$

Oft-repeated story of SUSY electroweak naturalness:

sparticles should be <~ TeV:

Exacerbates ``Little Hierarchy Problem'':

disparity between weak scale and sparticle mass scale

Natural SUSY

Incarnation#1: Kitano-Nomura 2005

$$m_h^2 = |\mu|^2 + m_{H_u}^2|_{\mathrm{tree}} + m_{H_u}^2|_{\mathrm{rad}},$$

$$m_{H_u}^2|_{\mathrm{rad}} \simeq -\frac{3y_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2)\ln\left(\frac{M_{\mathrm{mess}}}{m_{\tilde{t}}}\right)$$

$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$$

$$m_{\tilde{t}}^2 \lesssim \frac{2\pi^2}{3y_t^2}\frac{M_{\mathrm{Higgs}}^2}{\left(1+\frac{x^2}{2}\right)\Delta^{-1}\ln\frac{M_{\mathrm{mess}}}{m_{\tilde{t}}}} \approx (700\ \mathrm{GeV})^2\frac{1}{1+\frac{x^2}{2}}\left(\frac{20\%}{\Delta^{-1}}\right)\left(\frac{3}{\ln\frac{M_{\mathrm{mess}}}{m_{\tilde{t}}}}\right)\left(\frac{M_{\mathrm{Higgs}}}{200\ \mathrm{GeV}}\right)^2$$

* low mu

* light 3rd generation

* light sub-TeV spectra in pre-LHC era model

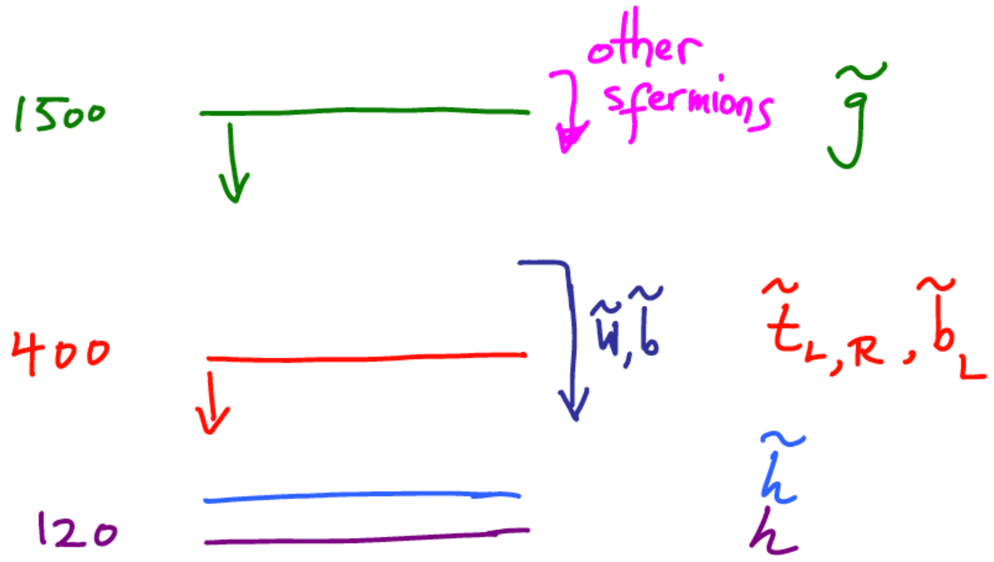
* M_mess not too far from TeV; minimize large logs

* sample spectra now highly excluded from LHC/m(h)

NS#2: post LHC7 but pre LHC8/Higgs

- Arkani-Hamed 2011
- Papucci et al.
- Brust et al.
- Essig et al.
- HB, Barger,Huang, Tata
- Wymant
- Arganda et al.

Most exciting, alive + natural SUSY spectrum

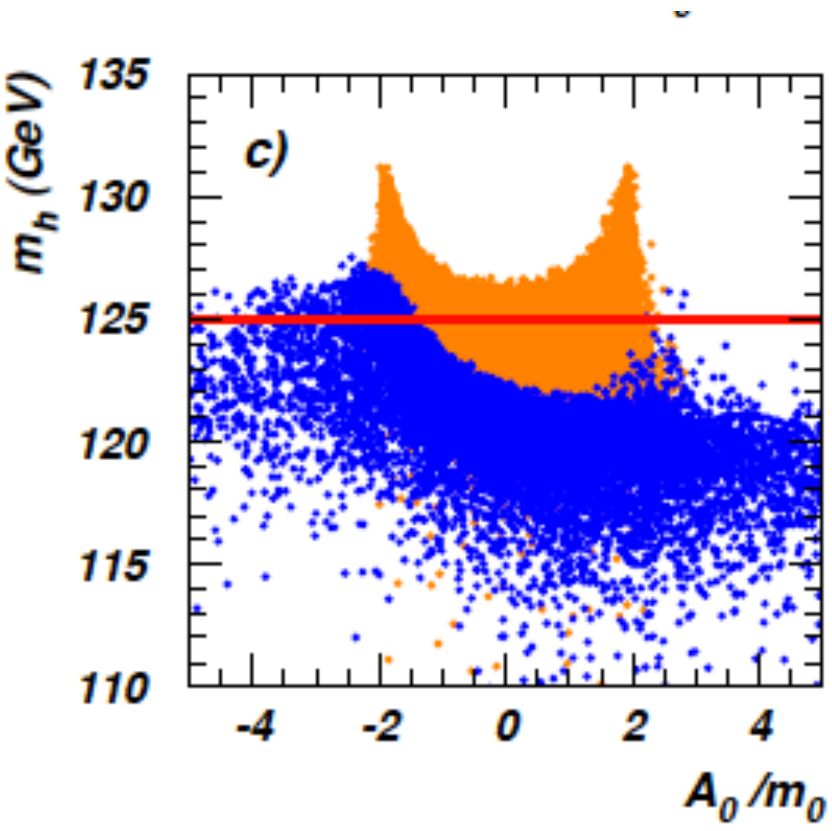


* mu~100-250 GeV
*m(t1,t2,b1)<~500 GeV
* m(gluino<1.5 TeV
m(sq,slep)~10-20 TeV

What we learned from LHC8

- Higgs-like resonance at ~125 GeV!
- m(h) falls squarely within MSSM window!
- requires: m(t1),m(t2)~ TeV regime
- large mixing
- or else, extra beyond MSSM mass contributions e.g. NMSSM, exotic matter,...

e.g. Hall, Pinner,Ruderman, JHEP1204(2012)131



blue:m0<5 TeV
orange: m0<20 TeV

HB, Barger, Mustafayev,
PRD85(2012)075010

What else?

- No sign of SUSY: in models such as mSUGRA
- $m_{\tilde{q}} \sim m_{\tilde{g}} > 1.4 \text{ TeV or } m_{\tilde{g}} >\sim 1 \text{ TeV if } m_{\tilde{g}} \ll m_{\tilde{q}}$
- Squark mass bound and even more m(h) (which needs m(t1,t2)> TeV) seemingly create even greater tension with naturalness bounds:
- Little Hierarchy Problem more severe?
- These results have prompted many groups to reconsider what weak scale SUSY would look like: is it now unlikely or even excluded?

see e.g. M. Shifman review, arXiv:1211.0004

Some reactions from community

- Ignore naturalness: e.g. K-L-O or Kane et al. G2MSSM stringy model with moduli stabilization: scalars ~100 TeV with AMSB-like gauginos and wino=LSP or live far out in mSUGRA plane (note: Kane et al. claim lower mu~.5-1 TeV so maybe not so bad, but still heavy stops)
- natural SUSY ala Kitano-Nomura successor models (Arkani-Hamed, Brust et al., Papucci et al.): these models, couched in MSSM, tend to have m(h)<125 GeV and large deviations to b-> s gamma
- compressed spectra: low energy release from cascade decays to maintain sub-TeV SUSY masses but hide SUSY from LHC
- RPV: similar approach: LSP decays hadronically
- retain naturalness (light stops) but give extra contributions to m(h): NMSSM , vector-like or other exotic matter: model builders delight
- accept some finetuning but try to minimize: HB/FP region of mSUGRA, effective SUSY
- re-examine naturalness

Traditional measure of EW finetuning:

Barbieri-Giudice (even earlier Ellis et al.) introduced the measure:

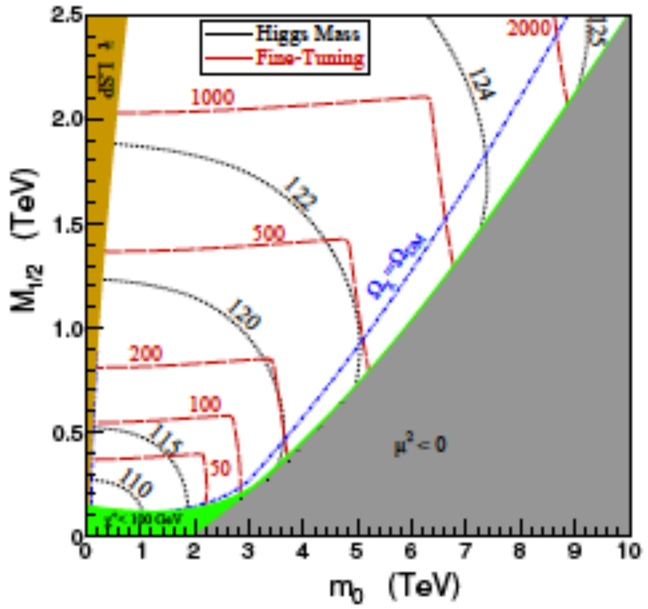
$$\Delta_{BG} \equiv max_i \left| \frac{\Delta m_Z^2 / m_Z^2}{\Delta a_i / a_i} \right| = max_i \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i} \right|$$

This measures fractional variation in m(Z)^2 due to fractional variation in parameters a_i

This measure was used by BG and DG to show that better than 10% EWFT requires m(chargino)<~100 GeV; SUSY already finetuned post-LEP2?

Some sample results using Δ_{BG}

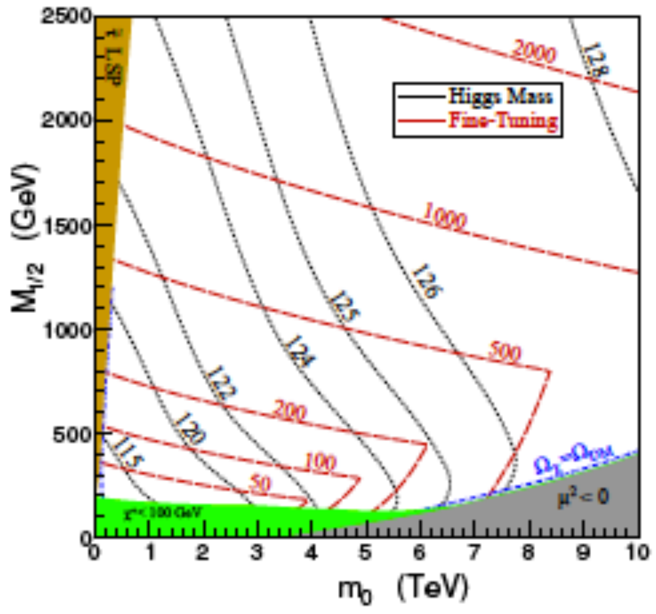
For recent review, see J. L. Feng, arXiv:1302.6587



Feng & Sanford, PRD86 (2012) 055015

A0=0 nearly excluded by m(h)~125 GeV results unless Delta>2000

$$a_i \ni \{m_0, m_{1/2}, A_0, B_0, \mu_0\}$$

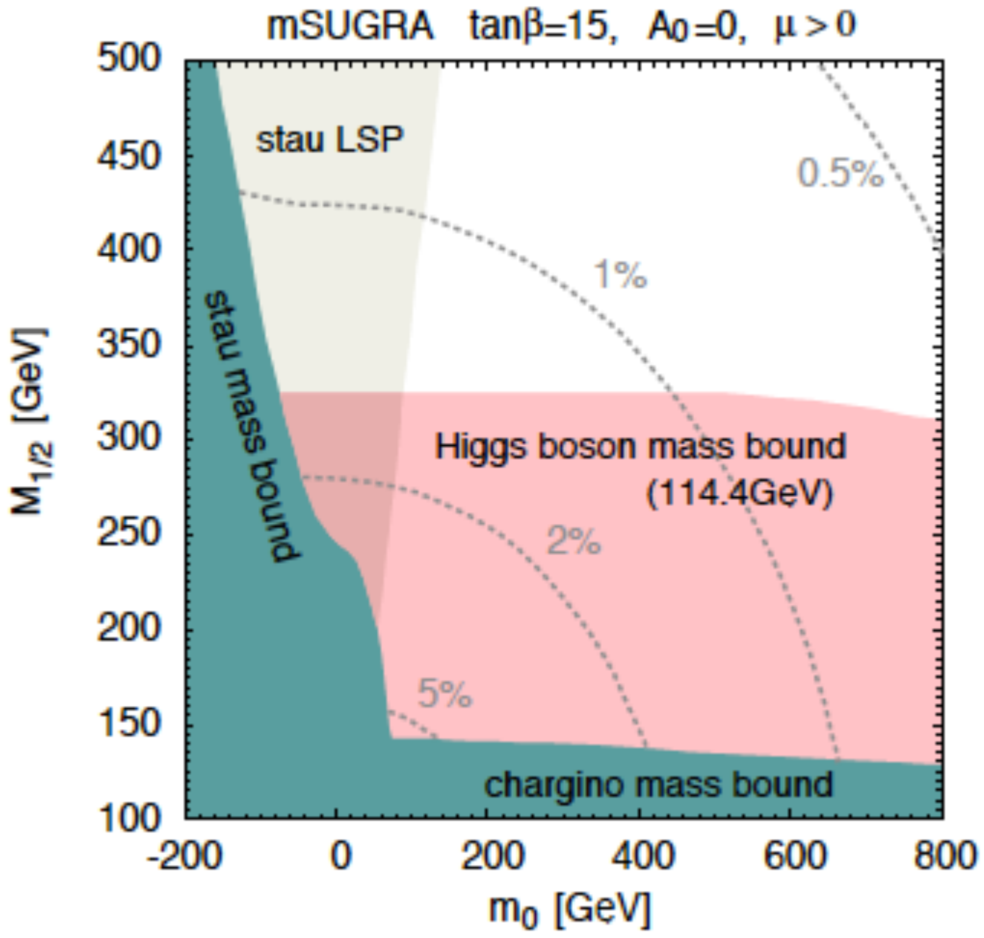


Allow non-universality, but with
mHu still fixed relative to m0;
can allow A0.ne.0 to raise m(h);
still, Delta>200-500

Hidden top Yukawa dependence since

$$\mathcal{L} \ni a_t = A_0 f_t$$

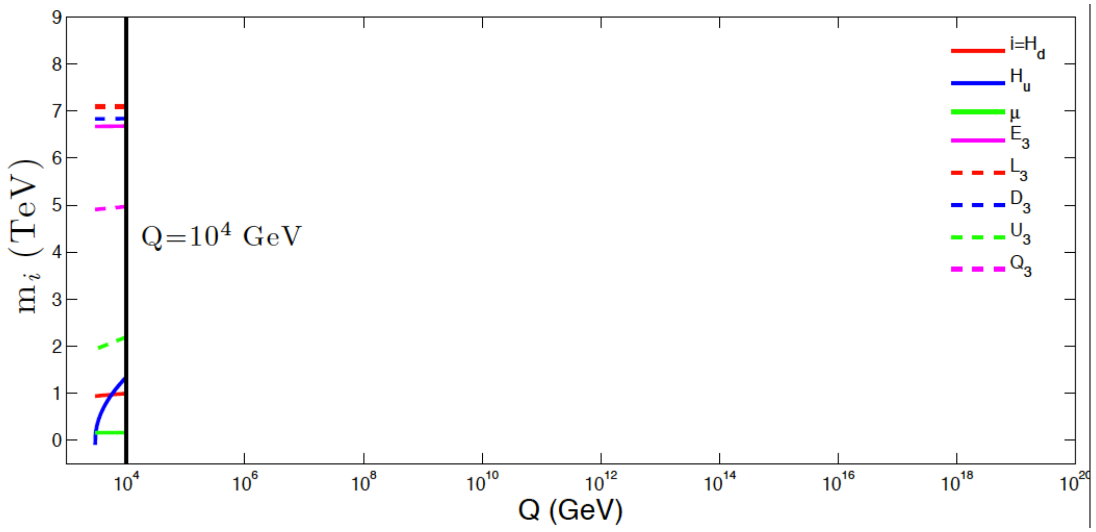
measure depends on highly on which high-scale parameter set one adopts

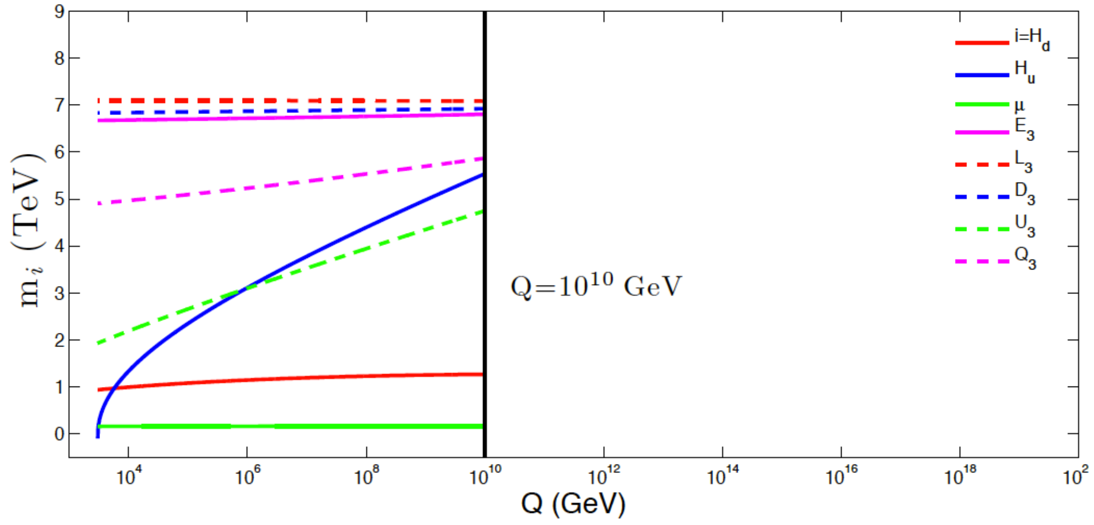


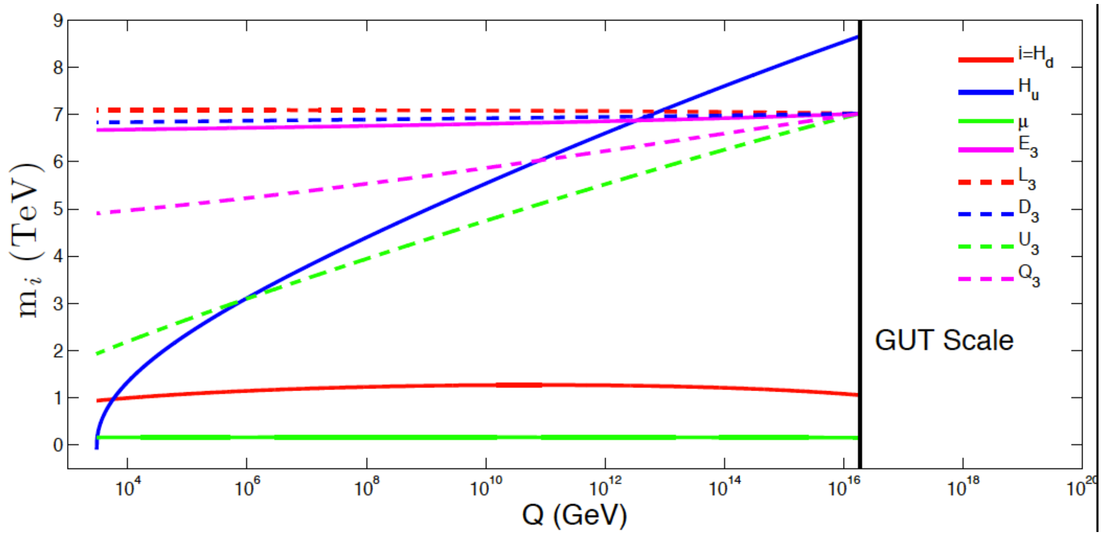
This plot from Kitano-Nomura PRD73 (2006) 095004
uses m(t) along with SUSY terms

The behavior is quite different:
low D_BG favors low m0, low mhf

Δ_{BG} also depends on where the high scale is







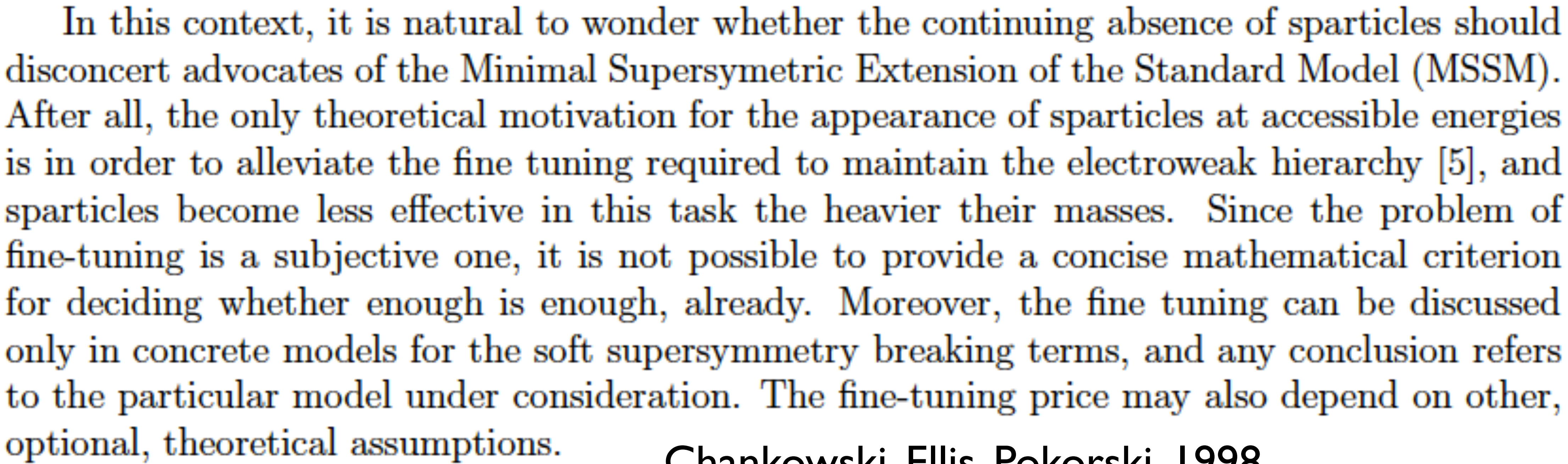
These three models have exactly the same weak scale spectra, but very different values of

$$\Delta_{BG}$$

Quotes from some practitioners of EWFT arguments

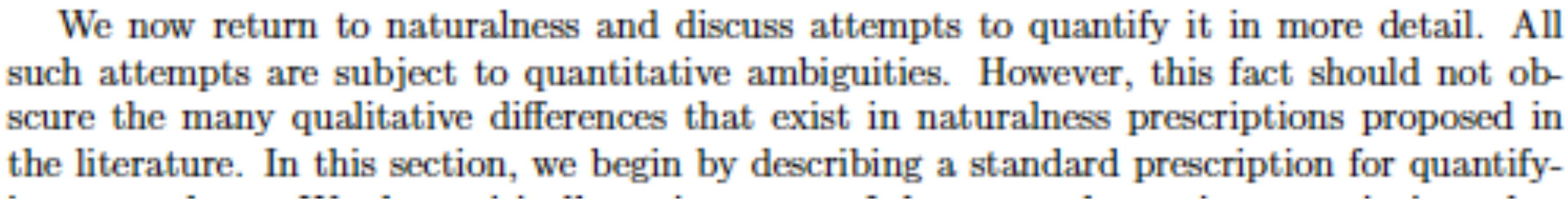
``...naturalness is a notoriously brittle and subjective subject...”

Feng & Sanford, 2012

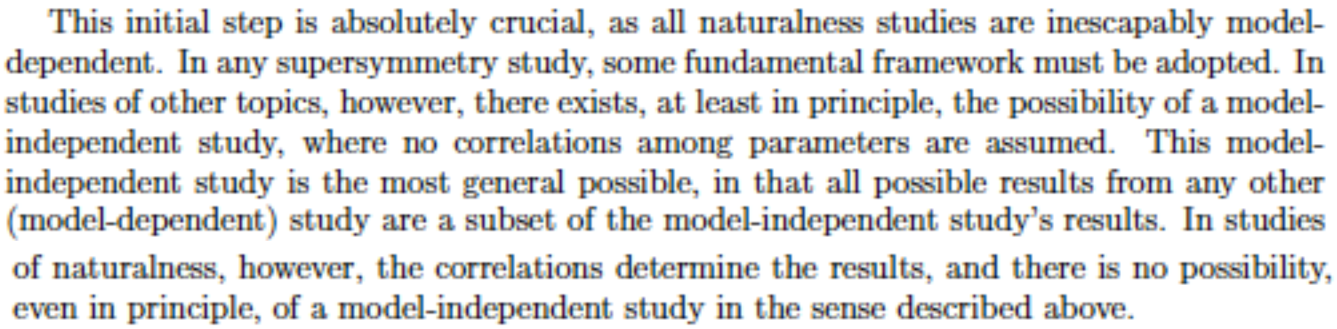


In this context, it is natural to wonder whether the continuing absence of sparticles should disconcert advocates of the Minimal Supersymetric Extension of the Standard Model (MSSM). After all, the only theoretical motivation for the appearance of sparticles at accessible energies is in order to alleviate the fine tuning required to maintain the electroweak hierarchy [5], and sparticles become less effective in this task the heavier their masses. Since the problem of fine-tuning is a subjective one, it is not possible to provide a concise mathematical criterion for deciding whether enough is enough, already. Moreover, the fine tuning can be discussed only in concrete models for the soft supersymmetry breaking terms, and any conclusion refers to the particular model under consideration. The fine-tuning price may also depend on other, optional, theoretical assumptions.

Chankowski, Ellis, Pokorski, 1998



We now return to naturalness and discuss attempts to quantify it in more detail. All such attempts are subject to quantitative ambiguities. However, this fact should not obscure the many qualitative differences that exist in naturalness prescriptions proposed in the literature. In this section, we begin by describing a standard prescription for quantify-



This initial step is absolutely crucial, as all naturalness studies are inescapably model-dependent. In any supersymmetry study, some fundamental framework must be adopted. In studies of other topics, however, there exists, at least in principle, the possibility of a model-independent study, where no correlations among parameters are assumed. This model-independent study is the most general possible, in that all possible results from any other (model-dependent) study are a subset of the model-independent study's results. In studies of naturalness, however, the correlations determine the results, and there is no possibility, even in principle, of a model-independent study in the sense described above.

Feng, 2013 review

We wish to refute these points of view

Re-phrase Little Hierarchy problem:

Question: how can it be that
m(Z)=91.2 GeV
while gluino and squark masses sit
at TeV or even
far beyond values?

Simple answer:
the parameters that enter the scalar potential and contribute to m(Z) are all not too far from m(Z)

By answering this question, we shall see that
naturally accommodating
both m(Z)=91.2 GeV and m(h)=125 GeV
is enormously constraining:
SUSY parameter space is not egalitarian
but instead these criteria are highly selective!

Furthermore, we will find the results are
model independent, and deeply rooted in
data (why is m(Z)=91.2 GeV?) instead
of theoretical wimsy,
and they are highly predictive!

In the MSSM, value of m(Z) is determined by combinations of parameters which enter into the scalar potential;

minimization leads to a relation between m(Z) and weak scale SUSY parameters:

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

The radiative corrections $\Sigma_u^u,\ \Sigma_d^d$ contain additional terms

$$\Delta_{\rm EW} \equiv max(C_i)/(M_Z^2/2)$$

$C_{H_u} \equiv |-m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)|,\ C_\mu \equiv |-\mu^2|$ and $\quad C_{H_d} \equiv |m_{H_d}^2/(\tan^2\beta - 1)|$

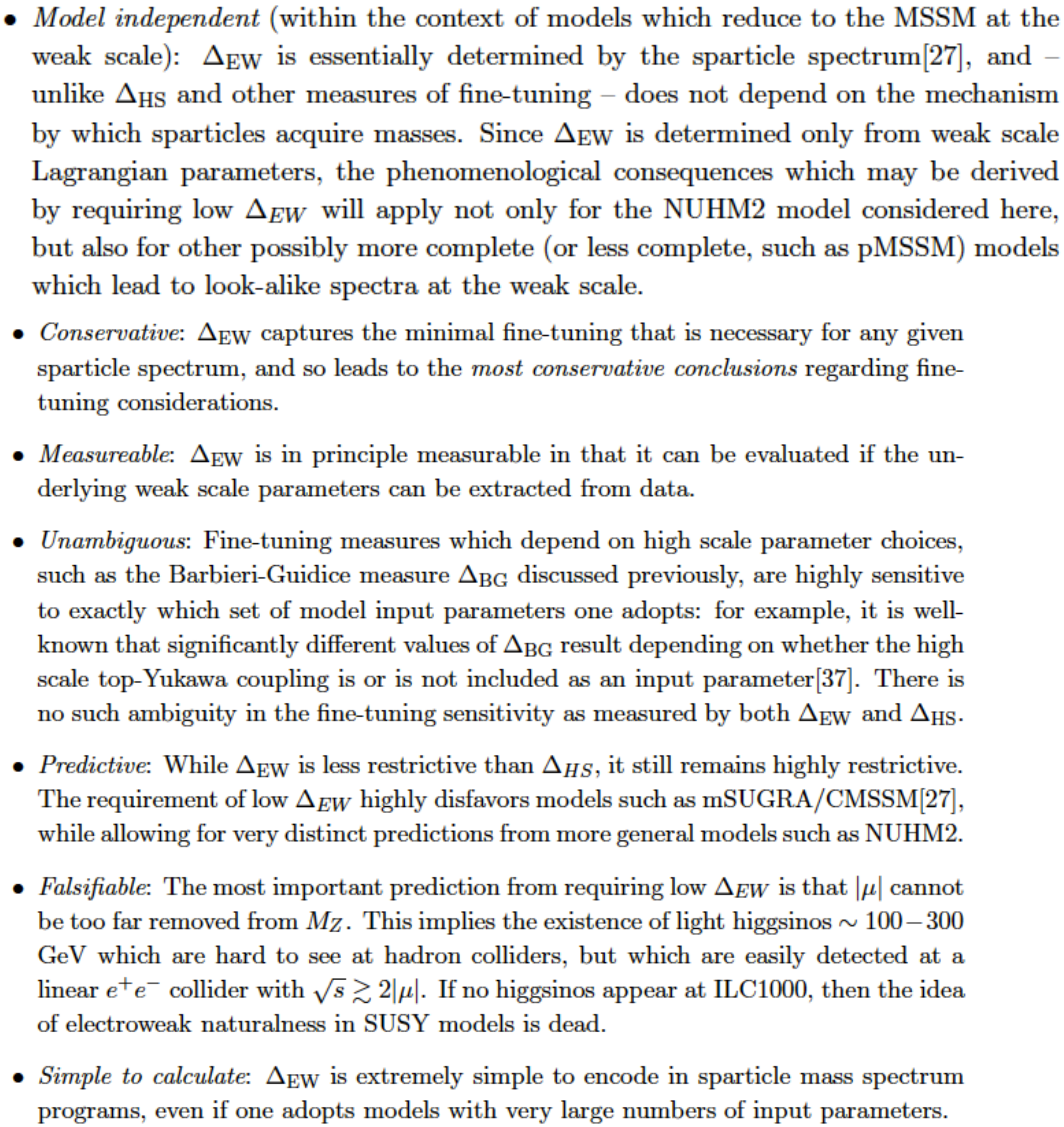
HB, Barger, Huang, Mustafayev, Tata, PRL109(2012)161802

- Delta_EW a purely weak scale relation

- Delta_EW measures how well the weak scale SUSY spectra conspire to give m(Z) =91.2 GeV instead of how well the high scale parameters conspire to do same

- We will impose low Delta_EW as a constraint on high scale SUSY models

Some virtues of Δ_{EW}



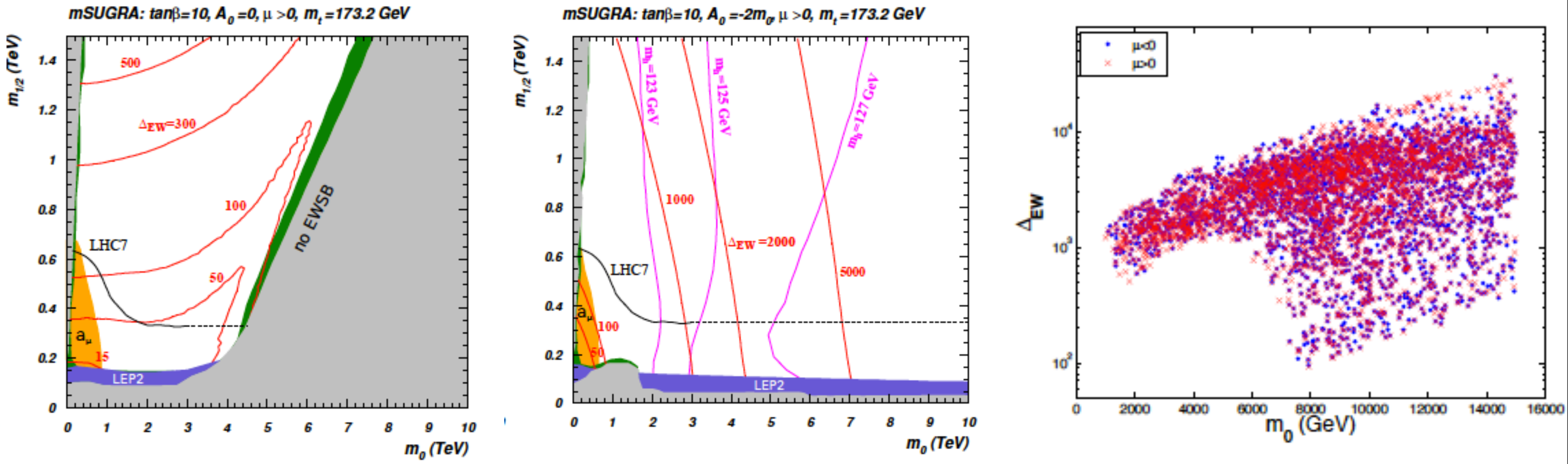
- *Model independent* (within the context of models which reduce to the MSSM at the weak scale): $\Delta_{\rm EW}$ is essentially determined by the sparticle spectrum[27], and – unlike $\Delta_{\rm HS}$ and other measures of fine-tuning – does not depend on the mechanism by which sparticles acquire masses. Since $\Delta_{\rm EW}$ is determined only from weak scale Lagrangian parameters, the phenomenological consequences which may be derived by requiring low Δ_{EW} will apply not only for the NUHM2 model considered here, but also for other possibly more complete (or less complete, such as pMSSM) models which lead to look-alike spectra at the weak scale.
- *Conservative*: $\Delta_{\rm EW}$ captures the minimal fine-tuning that is necessary for any given sparticle spectrum, and so leads to the *most conservative conclusions* regarding fine-tuning considerations.
- *Measureable*: $\Delta_{\rm EW}$ is in principle measurable in that it can be evaluated if the underlying weak scale parameters can be extracted from data.
- *Unambiguous*: Fine-tuning measures which depend on high scale parameter choices, such as the Barbieri-Guidice measure $\Delta_{\rm BG}$ discussed previously, are highly sensitive to exactly which set of model input parameters one adopts: for example, it is well-known that significantly different values of $\Delta_{\rm BG}$ result depending on whether the high scale top-Yukawa coupling is or is not included as an input parameter[37]. There is no such ambiguity in the fine-tuning sensitivity as measured by both $\Delta_{\rm EW}$ and $\Delta_{\rm HS}$.
- *Predictive*: While $\Delta_{\rm EW}$ is less restrictive than Δ_{HS}, it still remains highly restrictive. The requirement of low Δ_{EW} highly disfavors models such as mSUGRA/CMSSM[27], while allowing for very distinct predictions from more general models such as NUHM2.
- *Falsifiable*: The most important prediction from requiring low Δ_{EW} is that $|\mu|$ cannot be too far removed from M_Z. This implies the existence of light higgsinos $\sim 100-300$ GeV which are hard to see at hadron colliders, but which are easily detected at a linear e^+e^- collider with $\sqrt{s} \gtrsim 2|\mu|$. If no higgsinos appear at ILC1000, then the idea of electroweak naturalness in SUSY models is dead.
- *Simple to calculate*: $\Delta_{\rm EW}$ is extremely simple to encode in sparticle mass spectrum programs, even if one adopts models with very large numbers of input parameters.

HB, Barger, Huang, Mickelson, Mustafayev, Tata,
arXiv:1212.2655

What about high scale parameters?
Maybe only small portion of p-space leads
to low Delta_EW. What if I vary HS parameters and
Delta_EW moves up? Isn't this instability, and hence
aren't you really still finetuned?

No. Nature doesn't have any adjustable parameters.
We regard the MSSM as an effective theory where
the parameters ``parametrize" our ignorance
of a more fundamental theory where parameters are fixed.
The utility of parameters is that if you find a set which
allows for agreement with data, then use those to predict
further phenomena. Then devise an experiment to
check consistency. If predictions are verified, then model
may be a good description of nature.

While Delta_EW ignores large logs in mHu^2 running, even making use of these to generate low mHu^2 at weak scale, it is nonetheless highly constraining: e.g. mSUGRA at best 1% EWFT and usually much worse



Reason: as we increase m0 into low mu region to reduce EWFT, m(t1,t2) are dragged up and increase EWFT: culprit: mHu=m0

HB,Barger,Huang, Mickelson,Mustafayev,Tata, arXiv: 1210.3019

Each contribution ~m(Z)

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

Most important:

low $\Delta_{\rm EW}$ also requires $\mu^2 \sim M_Z^2/2$.

In models such as mSUGRA, mu is determined by m(Z) applied as constraint

here, mu is its own free parameter: NUHM models

Why should mu be so small when m(gl,sq) are so big?

Plausible: in gravity-mediation mu gets its mass differently, e.g. in Giudice-Masiero:

$\mu \sim \lambda m_{3/2}$ so that $|\mu| \ll m_{3/2}$

Next: how can $-m_{H_u}^2(m_{weak}) \sim m_Z^2/2$?

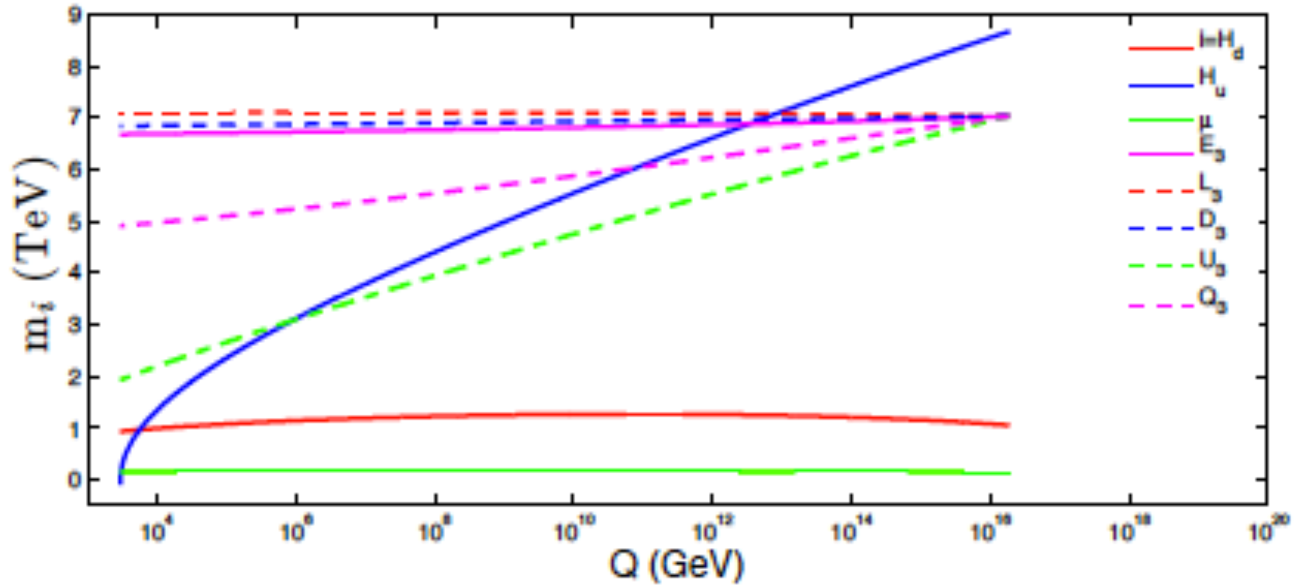
Large top Yukawa radiatively drives $m_{H_u}^2$ to small negative values

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$X_t = m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2$$

Large logs are a feature, not a hindrance; they are large because m(t)=173.2 GeV.

Why is m(t) so large?
I don't know, but I am glad it is.



In mSUGRA, this only happens in HB/FP region where stops also are heavy;
in NUHM models, this can occur even if lighter stops

$$m_{H_u}^2(m_{GUT}) \sim (1.3-2)m_0^2$$

Next: radiative corrections

Adopt Coleman-Weinberg eff. pot'l approach:

$$V_{Higgs} = V_{\rm tree} + \Delta V$$

$$\Delta V = \sum_i \frac{(-1)^{2s_i}}{64\pi^2}(2s_i+1)c_i m_i^4 \left[\log\left(\frac{m_i^2}{Q^2}\right) - \frac{3}{2}\right]$$

minimization gives:

$$\begin{aligned} B\mu v_d &= \left(m_{H_u}^2 + \mu^2 - g_Z^2(v_d^2 - v_u^2)\right) v_u + \Sigma_u \\ B\mu v_u &= \left(m_{H_d}^2 + \mu^2 + g_Z^2(v_d^2 - v_u^2)\right) v_d + \Sigma_d \,, \end{aligned}$$

$$\Sigma_{u,d} = \left.\frac{\partial \Delta V}{\partial h_{u,d}}\right|_{min}$$

$$\begin{aligned} \Sigma_u &= \Sigma_u^u v_u + \Sigma_u^d v_d \,, \\ \Sigma_d &= \Sigma_d^u v_u + \Sigma_d^d v_d \quad \text{and} \\ \Sigma_d^u &= \Sigma_u^d \end{aligned}$$

Σ_u^d terms cancel

$$\begin{aligned} \Sigma_u^u &= \left.\frac{\partial \Delta V}{\partial |h_u|^2}\right|_{min}, \\ \Sigma_d^d &= \left.\frac{\partial \Delta V}{\partial |h_d|^2}\right|_{min} \quad \text{and} \\ \Sigma_u^d &= \left.\frac{\partial \Delta V}{\partial (h_u h_d + \text{c.c.})}\right|_{min}. \end{aligned}$$

$$\begin{aligned} M_Z^2/2 &= \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2, \\ B\mu &= \left((m_{H_u}^2 + \mu^2 + \Sigma_u^u) + (m_{H_d}^2 + \mu^2 + \Sigma_d^d)\right)\sin\beta\cos\beta + \Sigma_u^d. \end{aligned}$$

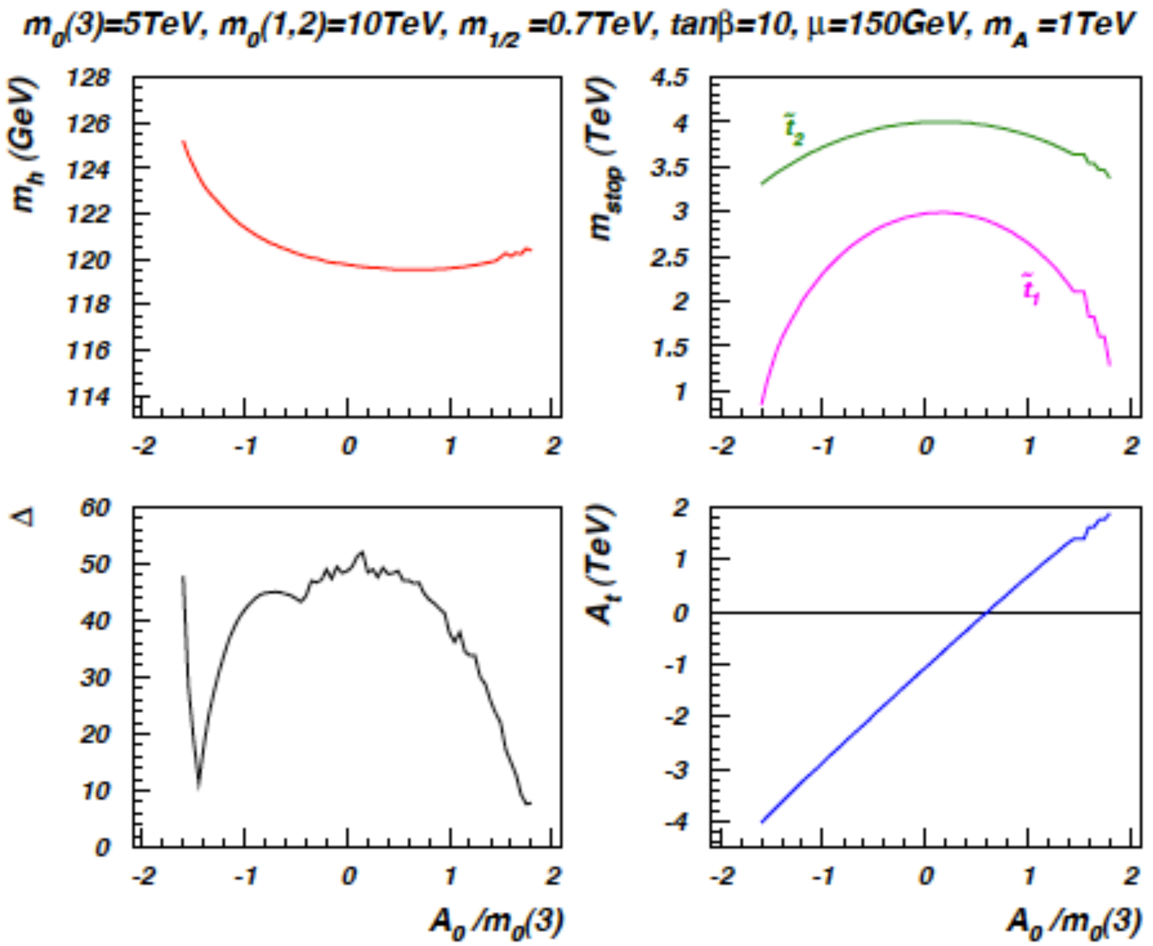
HB, Barger, Huang, Mickelson, Mustafayev, Tata, arXiv:1212.2655

largest contribution usually from stops:

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

$$F(m^2) = m^2\left(\log(m^2/Q^2) - 1\right), \text{ with } Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

large stop mixing softens both t1 and t2
radiative corrections
while increasing m(h) up to 125 GeV!



HB, Barger, Huang, Mustafayev, Tata,
PRL109(2012)161802

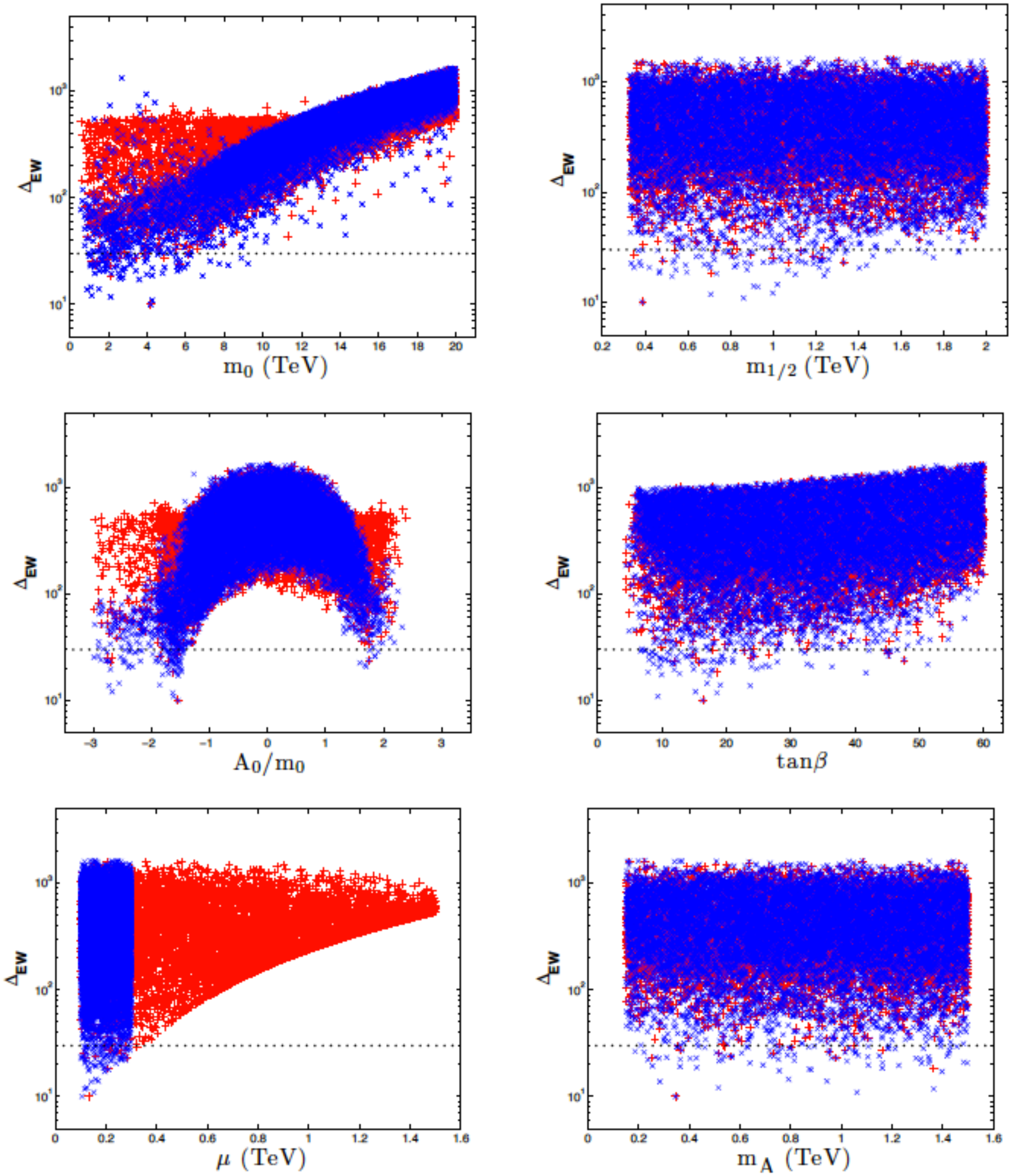
One need not depart too far from mSUGRA/CMSSM to find a model which allows low Delta_EW while maintaining desirable features of SUSY GUTs:

2-extra parameter non-universal Higgs model

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \quad \text{and} \quad m_A.$$

Here, we trade $m_{H_u}^2,\ m_{H_d}^2 \Rightarrow\ \mu,\ m_A$

Which parameter choices lead to low EWFT and how low can Δ_{EW} be?



$\Delta_{EW} \sim 10$ or 10% $EWFT$

High-scale models with low Δ_{EW} :

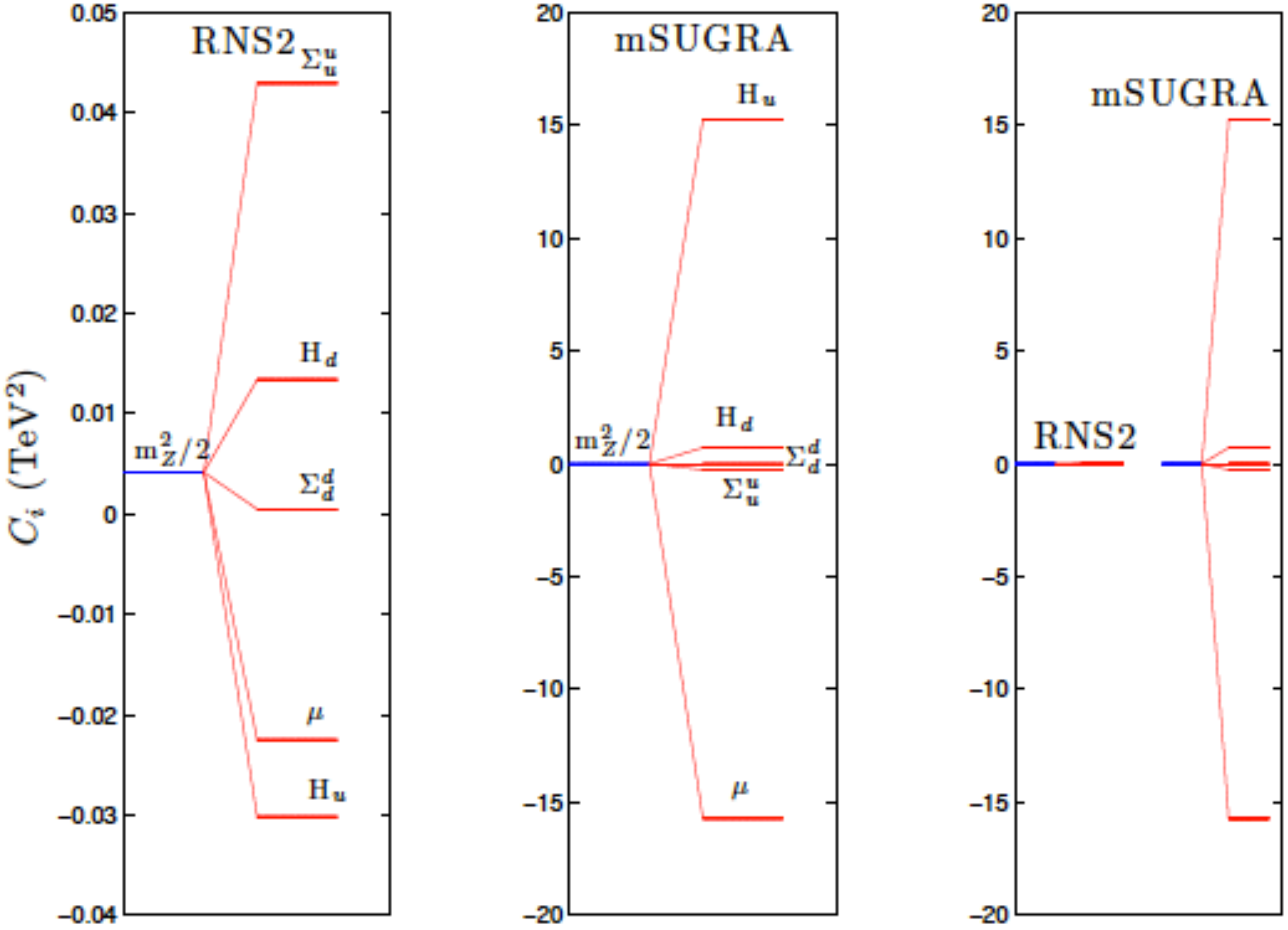
Radiatively-driven natural SUSY, or RNS

HB, Barger, Huang, Mickelson, Mustafayev, Tata, arXiv:1212.2655

Compare RNS to mSUGRA for similar parameters

$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV, $A_0 = -11426.6$ GeV, $\tan\beta = 8.55$ with $\mu = 150$ GeV and $m_A = 1000$ GeV

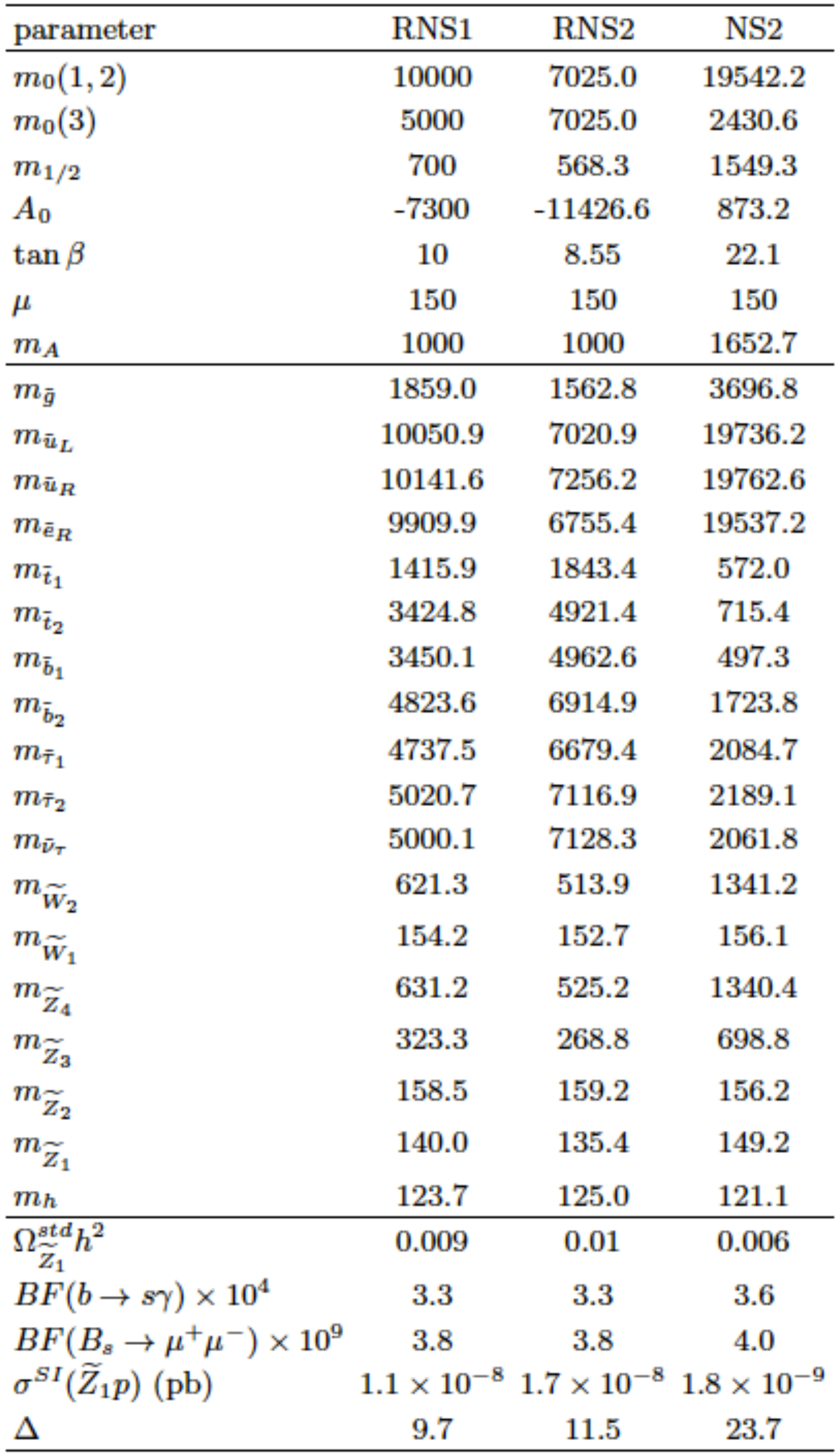
- $C_{\Sigma_u^u} \sim (205 \text{ GeV})^2$
- $C_{H_d} \sim (114 \text{ GeV})^2$
- $C_{\Sigma_d^d} \sim (22 \text{ GeV})^2$
- $C_\mu \sim -(148 \text{ GeV})^2$
- $C_{H_u} \sim -(173 \text{ GeV})^2$
- $m_Z^2/2 \simeq (65 \text{ GeV})^2$



SUSY spectra from radiatively-driven natural SUSY (RNS)

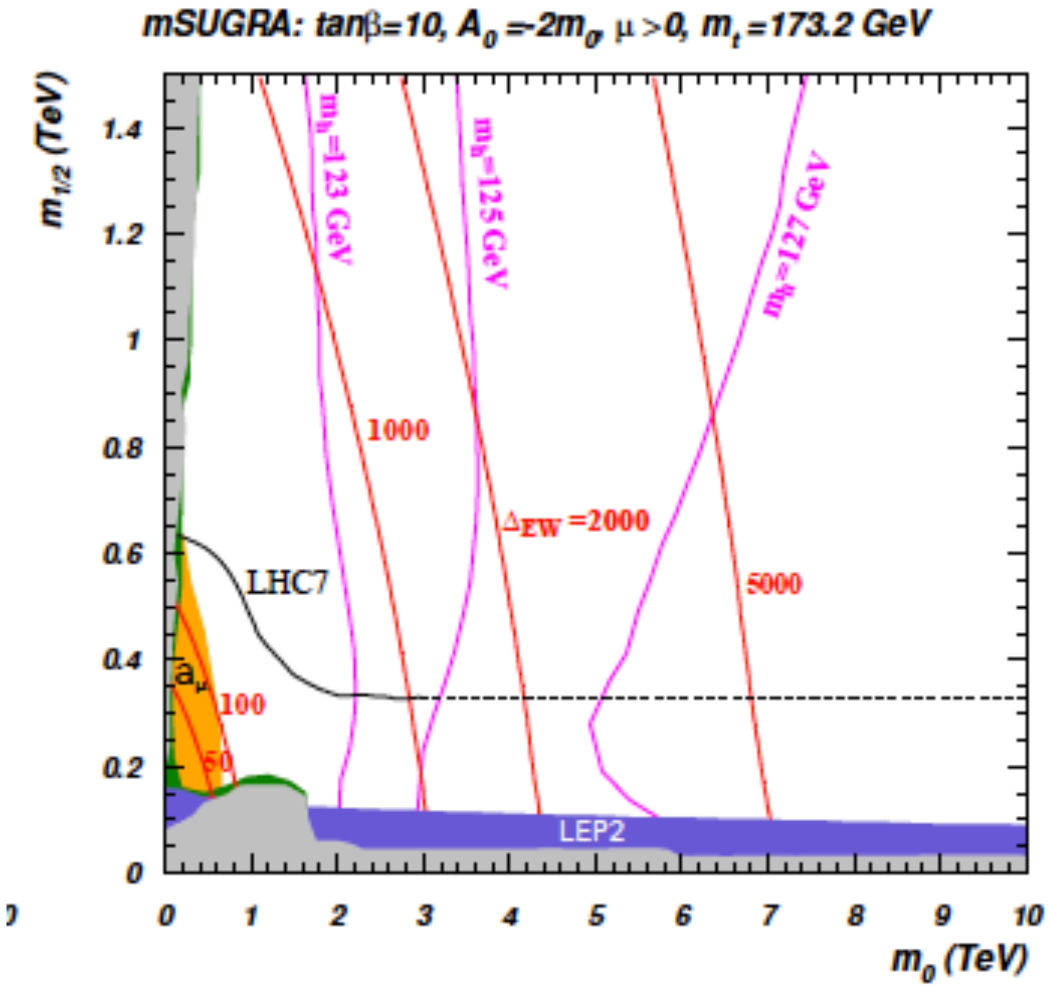
scan NUHM2 space:

- light higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_{1,2}$ with mass $\sim 100-300$ GeV,
- gluinos with mass $m_{\tilde{g}} \sim 1-4$ TeV,
- heavier top squarks than generic NS models: $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-5$ TeV,
- first/second generation squarks and sleptons with mass $m_{\tilde{q},\tilde{\ell}} \sim 1-8$ TeV. The $m_{\tilde{\ell}}$ range can be pushed up to 20-30 TeV if non-universality of generations with $m_0(1,2) > m_0(3)$ is allowed.

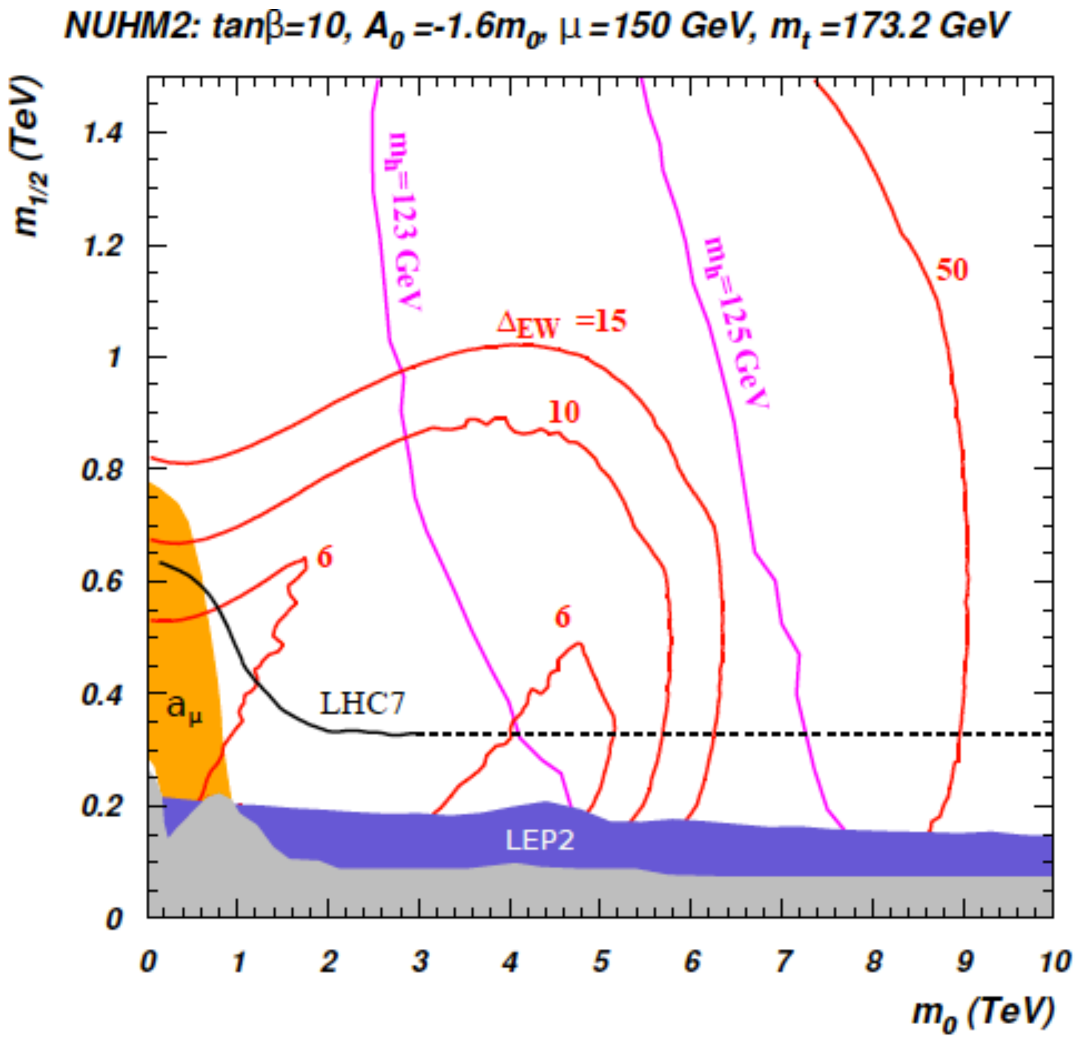


parameter	RNS1	RNS2	NS2
$m_0(1,2)$	10000	7025.0	19542.2
$m_0(3)$	5000	7025.0	2430.6
$m_{1/2}$	700	568.3	1549.3
A_0	-7300	-11426.6	873.2
$\tan\beta$	10	8.55	22.1
μ	150	150	150
m_A	1000	1000	1652.7
$m_{\tilde{g}}$	1859.0	1562.8	3696.8
$m_{\tilde{u}_L}$	10050.9	7020.9	19736.2
$m_{\tilde{u}_R}$	10141.6	7256.2	19762.6
$m_{\tilde{e}_R}$	9909.9	6755.4	19537.2
$m_{\tilde{t}_1}$	1415.9	1843.4	572.0
$m_{\tilde{t}_2}$	3424.8	4921.4	715.4
$m_{\tilde{b}_1}$	3450.1	4962.6	497.3
$m_{\tilde{b}_2}$	4823.6	6914.9	1723.8
$m_{\tilde{\tau}_1}$	4737.5	6679.4	2084.7
$m_{\tilde{\tau}_2}$	5020.7	7116.9	2189.1
$m_{\tilde{\nu}_\tau}$	5000.1	7128.3	2061.8
$m_{\widetilde{W}_2}$	621.3	513.9	1341.2
$m_{\widetilde{W}_1}$	154.2	152.7	156.1
$m_{\widetilde{Z}_4}$	631.2	525.2	1340.4
$m_{\widetilde{Z}_3}$	323.3	268.8	698.8
$m_{\widetilde{Z}_2}$	158.5	159.2	156.2
$m_{\widetilde{Z}_1}$	140.0	135.4	149.2
m_h	123.7	125.0	121.1
$\Omega^{std}_{\widetilde{Z}_1}h^2$	0.009	0.01	0.006
$BF(b \to s\gamma) \times 10^4$	3.3	3.3	3.6
$BF(B_s \to \mu^+\mu^-) \times 10^9$	3.8	3.8	4.0
$\sigma^{SI}(\widetilde{Z}_1 p)$ (pb)	1.1×10^{-8}	1.7×10^{-8}	1.8×10^{-9}
Δ	9.7	11.5	23.7

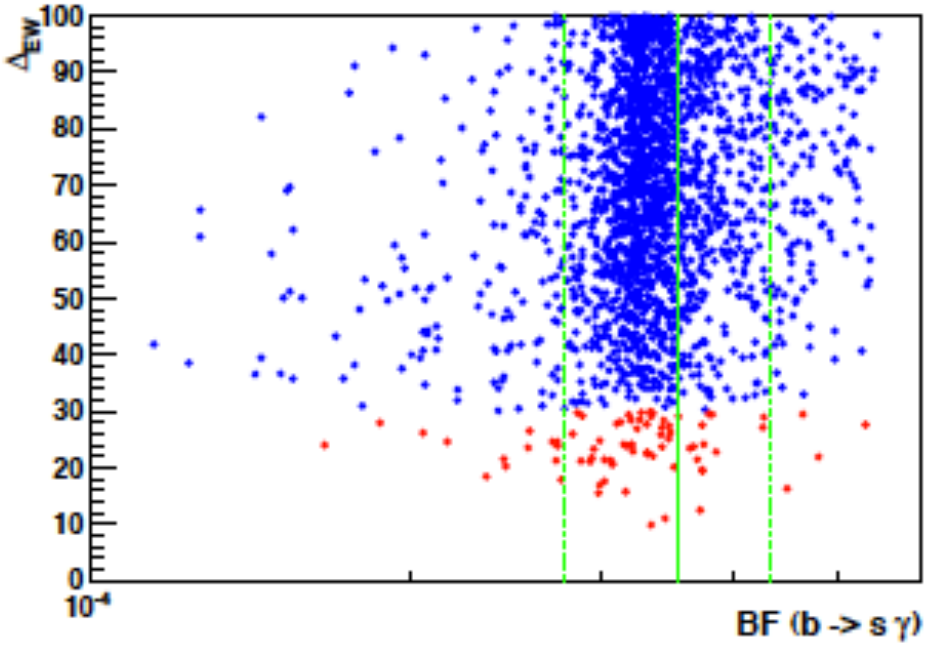
What happens to mSUGRA plane?

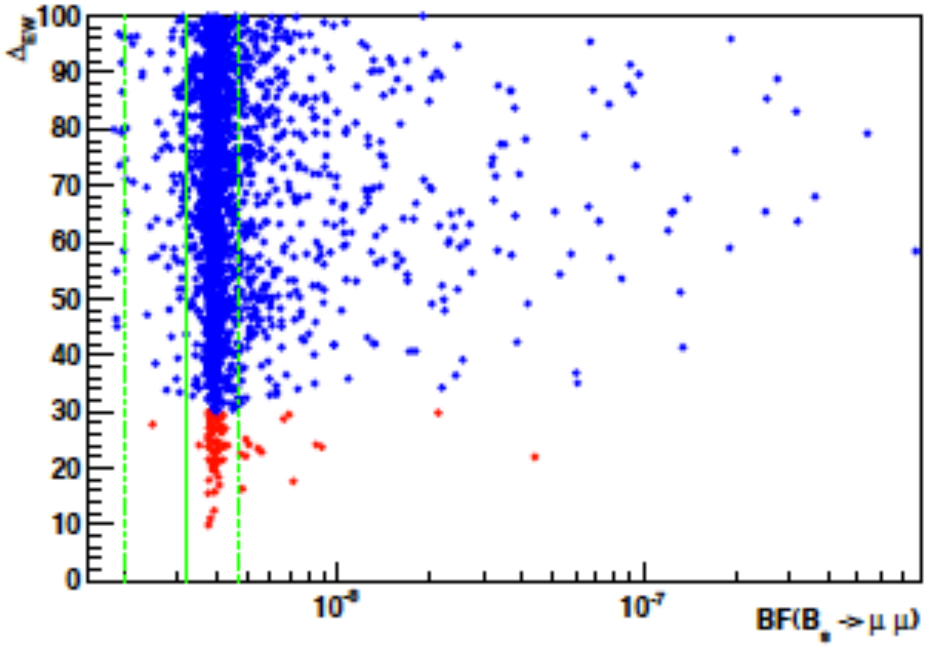


=>



What happens to B constraints?
These are trouble for version#1,2 NS models



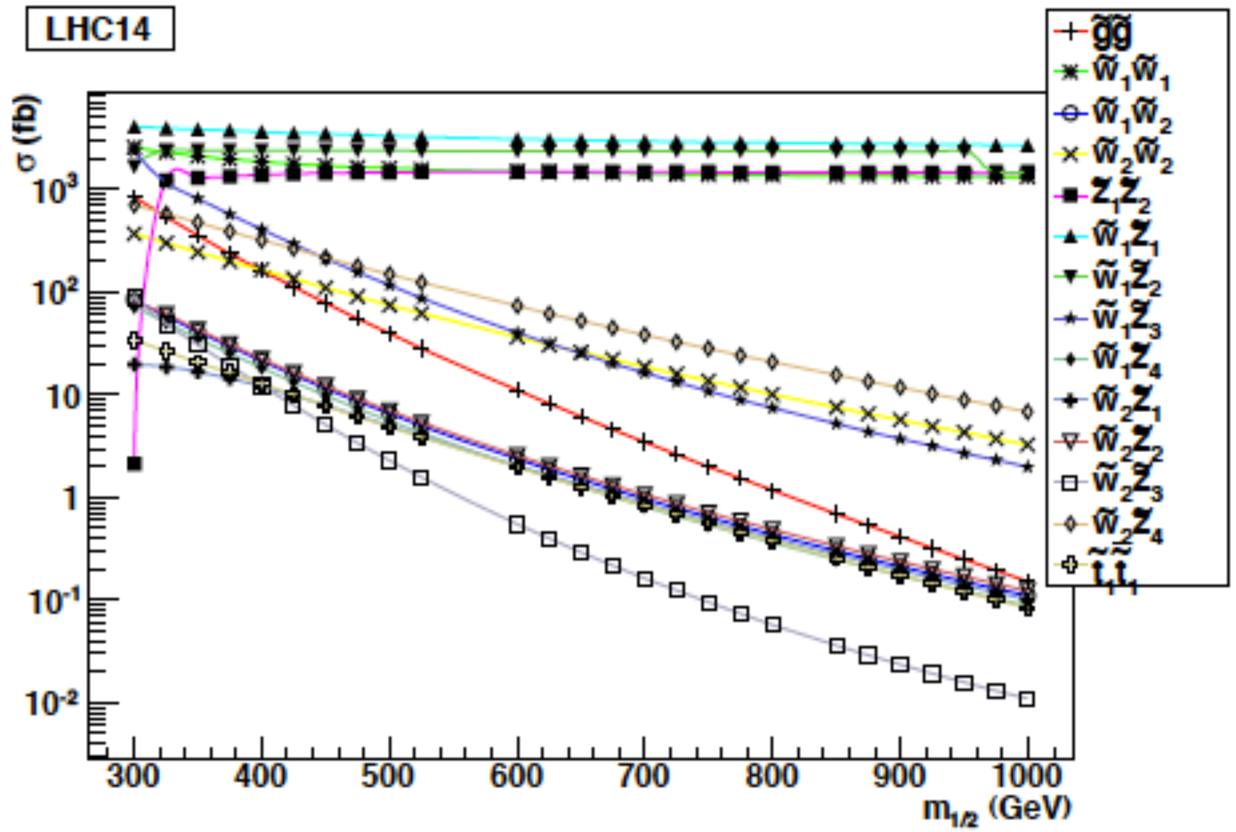


Heavier top squarks ameliorate these

Prospects for radiatively-driven NS at LHC

Model line with

$$m_0 = 5\ \mathrm{TeV},\ m_{1/2},\ A_0 = -1.6m_0,\ \tan\beta = 15,\ \mu = 150\ \mathrm{GeV},\ m_A = 1\ \mathrm{TeV}$$



$$pp \to \tilde g\tilde g X$$

$$\tilde g \to tb\tilde W_i,\ t\bar t\tilde Z_i$$

$$\tilde Z_2 \to \ell^+\ell^-\tilde Z_1$$

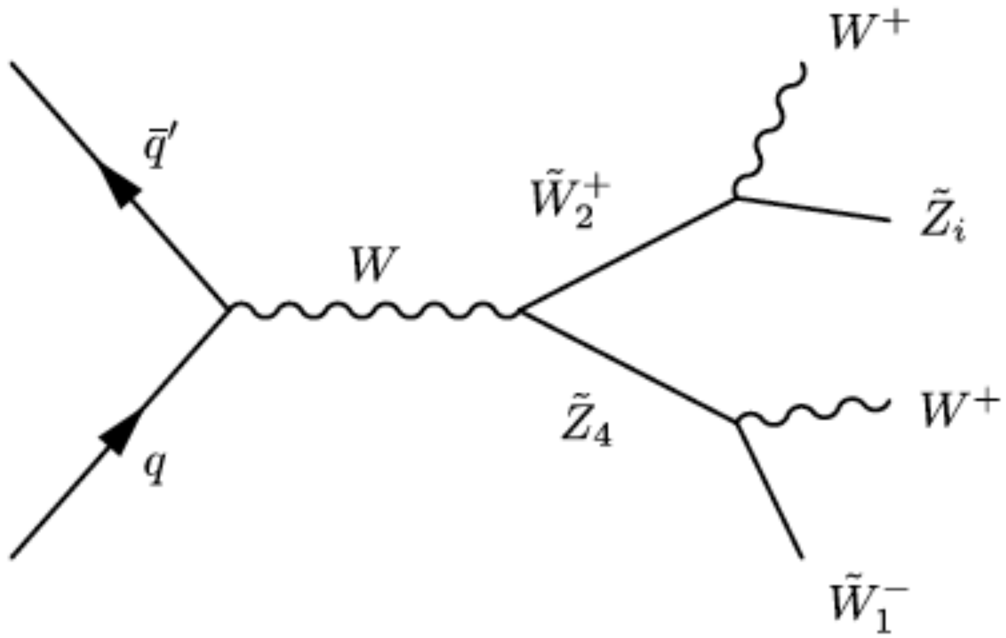
$$m_{\tilde Z_2} - m_{\tilde Z_1} <\sim 10 - 20\ \mathrm{GeV}$$

LHC14 reach for gluino pairs:

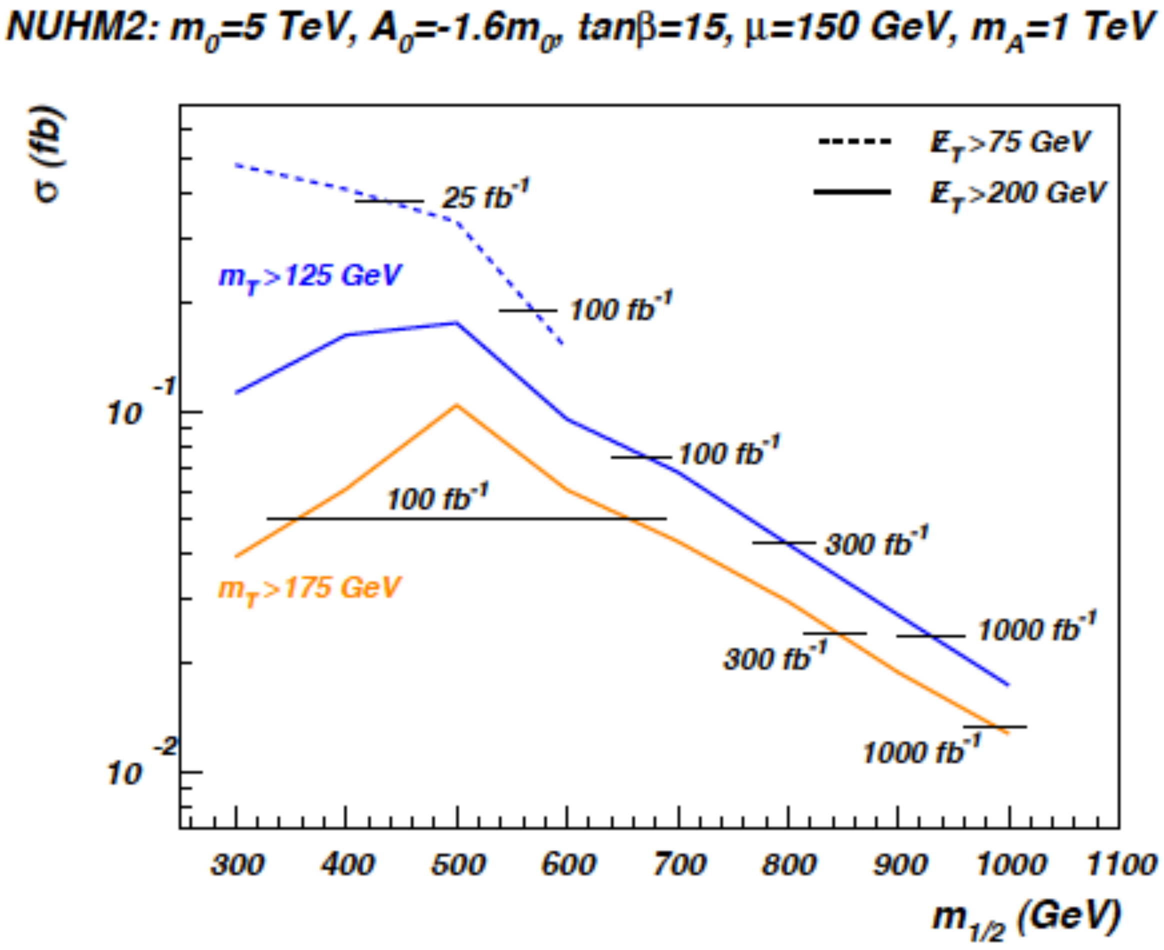
Int. lum. (fb^{-1})	$m_{1/2}$ (GeV)	$m_{\tilde g}$ (TeV) $[\tilde g\tilde g]$
10	400	1.4
100	840	1.6
300	920	1.8
1000	1000	2.0

HB, Barger,Lessa,Tata, PRD86(2012)117701

Distinctive new signature for LHC: same-sign dibosons from models with light higgsinos



HB, Barger, Huang, Mickelson, Mustafayev, Sreethawong, Tata, arXiv:1302.5816, (PRL in press)



- *exactly* 2 isolated same-sign leptons with $p_T(\ell_1) > 20$ GeV and $p_T(\ell_2) > 10$ GeV,
- $n(b-jets) = 0$ (to aid in vetoing $t\bar{t}$ background).
- $m_T^{\rm min} \equiv \min\left[m_T(\ell_1,\not{E}_T), m_T(\ell_2,\not{E}_T)\right] > 125$ GeV

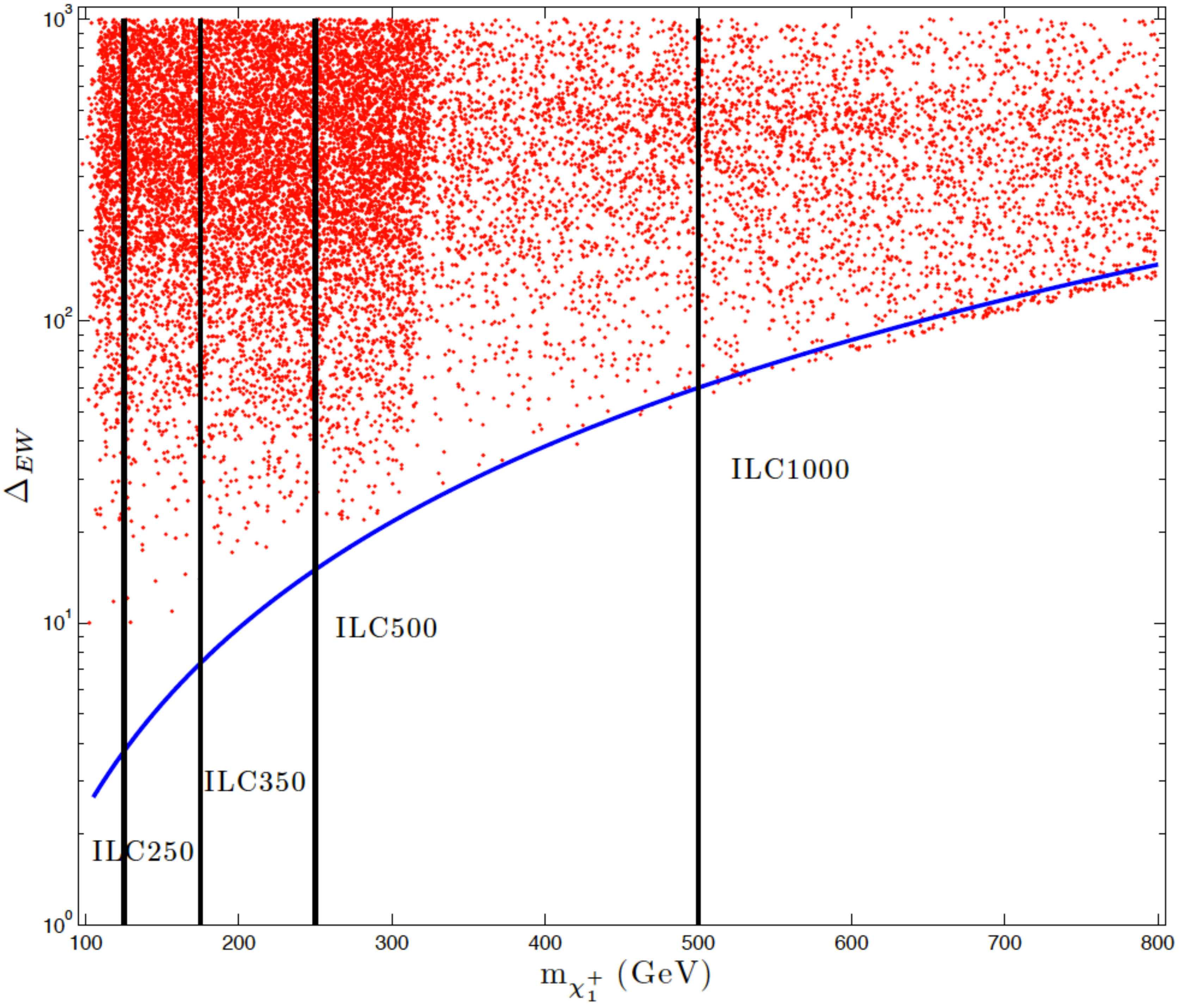
$\not{E}_T' > 200$ GeV

Int. lum. (fb^{-1})	$m_{1/2}$ (GeV)	$m_{\tilde{g}}$ (TeV)	$m_{\tilde{g}}$ (TeV) $[\tilde{g}\tilde{g}]$
10	400	0.96	1.4
100	840	2.0	1.6
300	920	2.2	1.8
1000	1000	2.4	2.0

Reach at LHC14 exceeds usual gluino pair search!

Smoking gun signature: 4 light higgsinos at ILC!

$$e^+e^- \to \tilde{W}_1^+\tilde{W}_1^-,\ \tilde{Z}_1\tilde{Z}_2$$



$$m_{\tilde{W}_1^\pm},\ m_{\tilde{Z}_{1,2}}$$

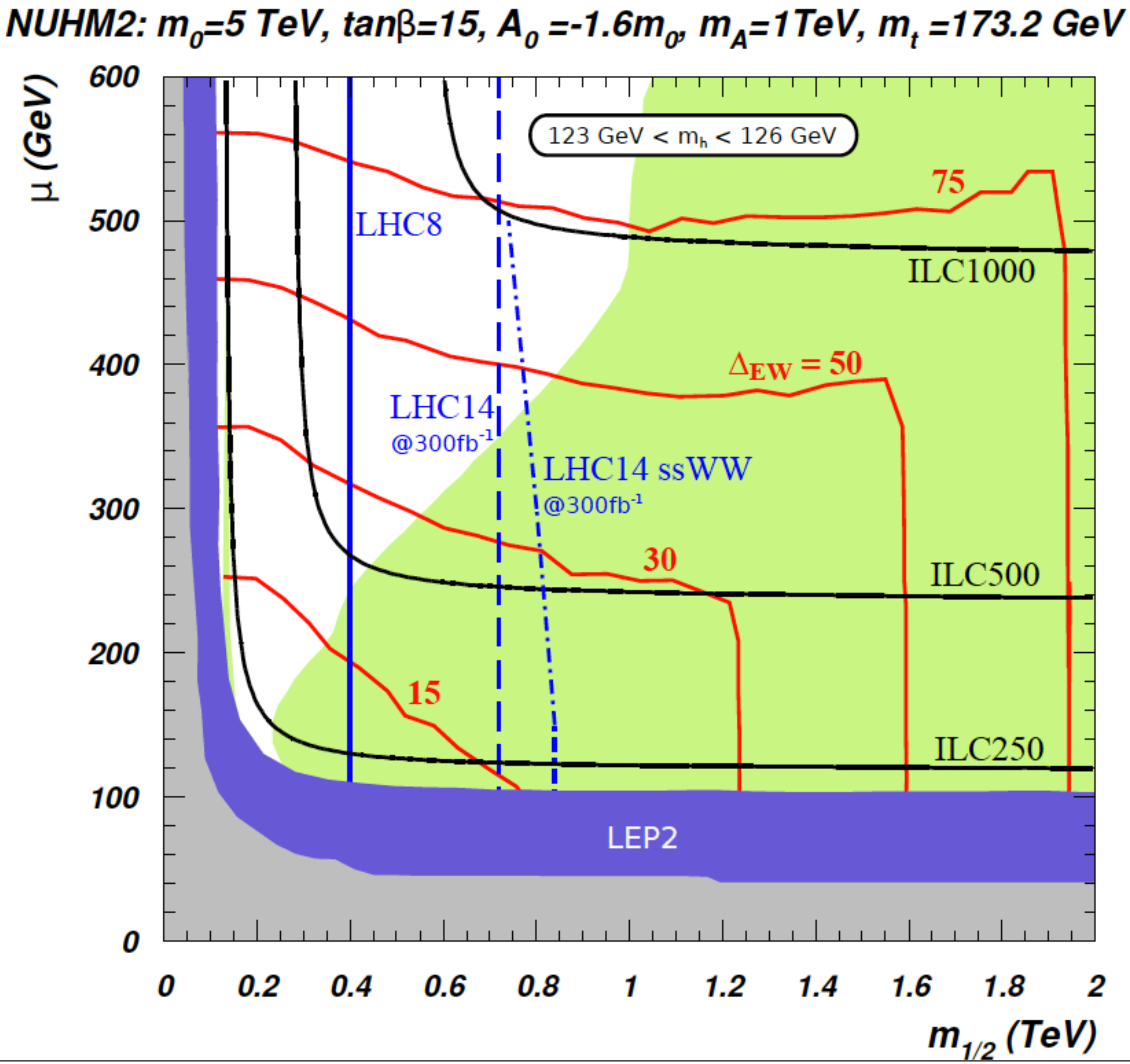
$$\sqrt{s} \sim \sqrt{2\Delta_{EW}}m_Z$$

ILC/CLIC have capability to measure SUSY parameters and actually reconstruct

$$\Delta_{EW}$$

measure and check if nature is EWFT'd!

LHC/ILC complementarity



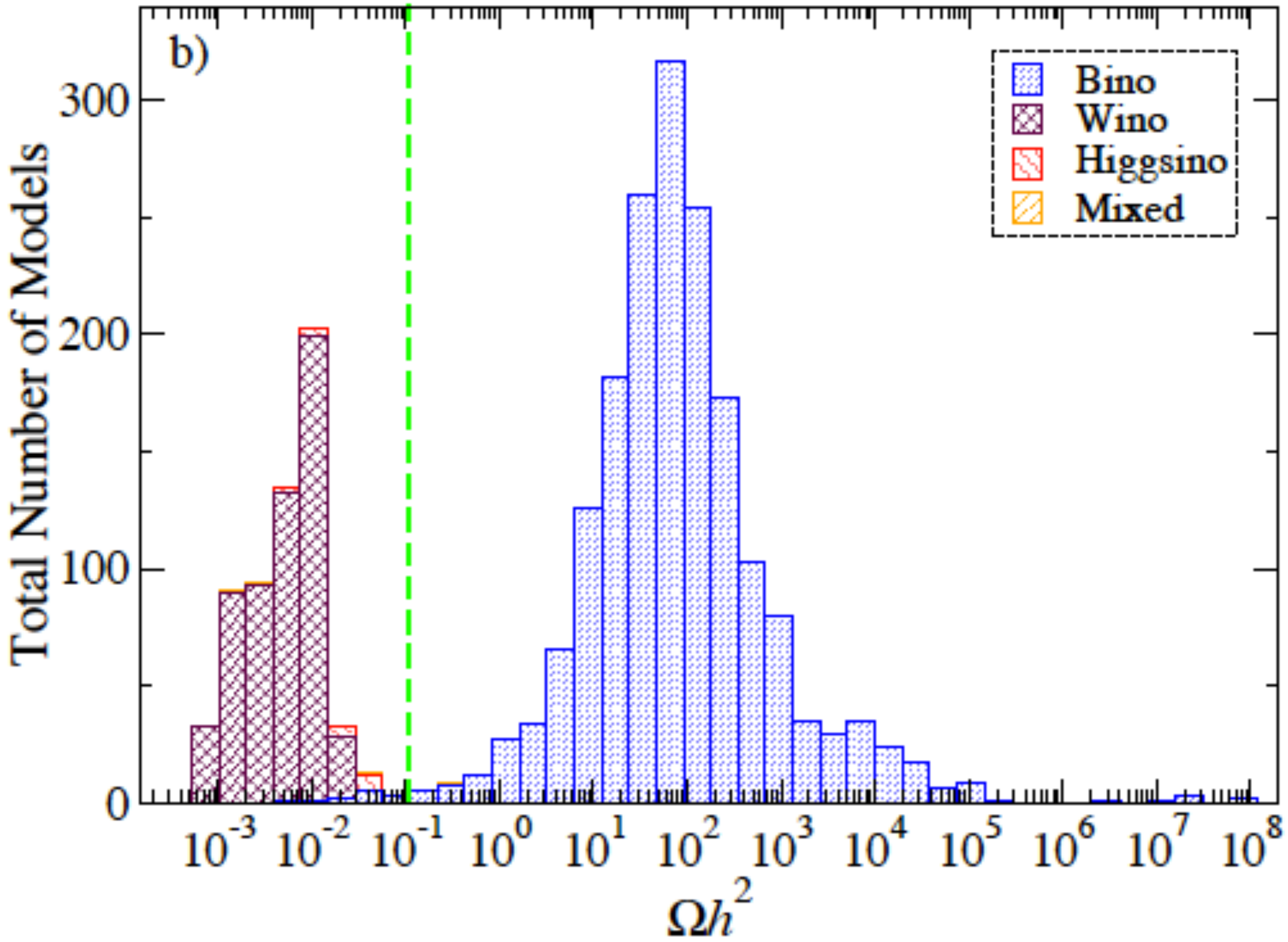
While LHC has
some capacity, it will
require ILC to draw the story
of SUSY electroweak
naturalness to a conclusion!

A. Mustafayev plot

What about DM in RNS? I heard higgsino-like wimp isn't a good DM candidate?

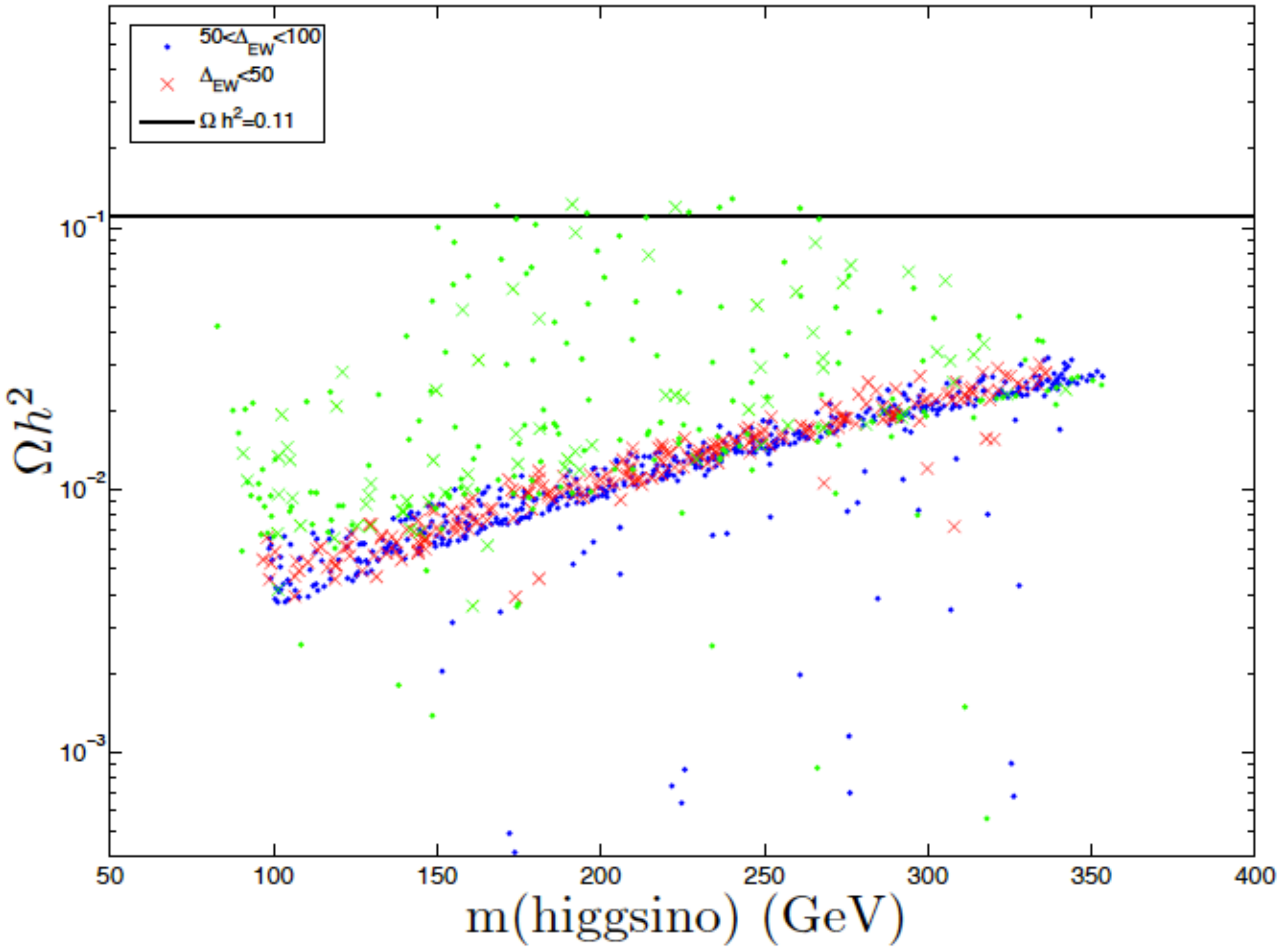
Lightest neutralino all by itself in general not good DM candidate: too much or too little CDM

Scan over 19 parameters:



HB, Box, Summy
JHEP1010(2010)023

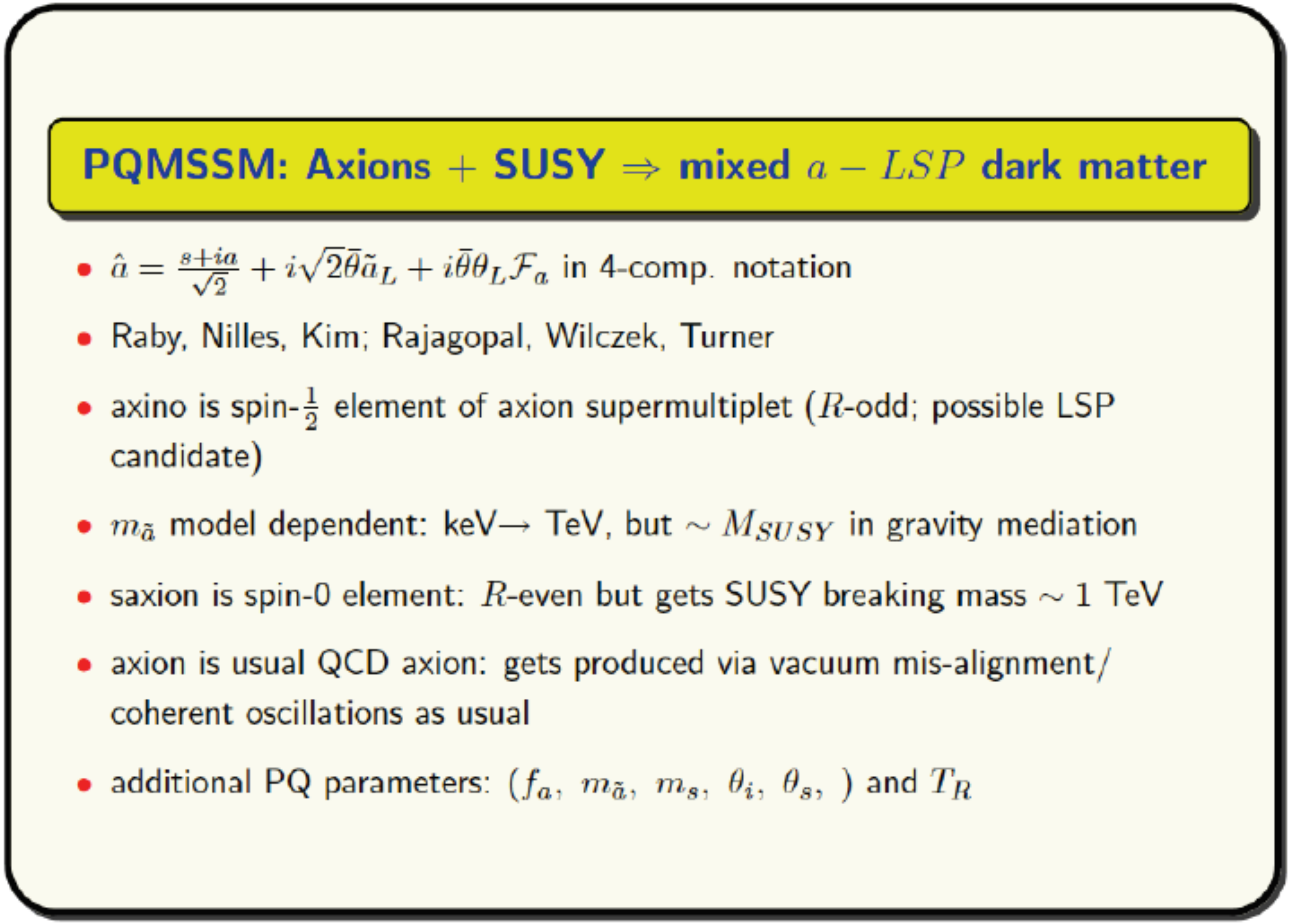
Standard thermal abundance for RNS model



green: already excluded by WIMP searches

$$\Omega^{std}_{\tilde{Z}_1} h^2 \sim 10 - 15 \text{ low}$$

Invoke Peccei-Quinn sol’n to strong CP problem with SUSY

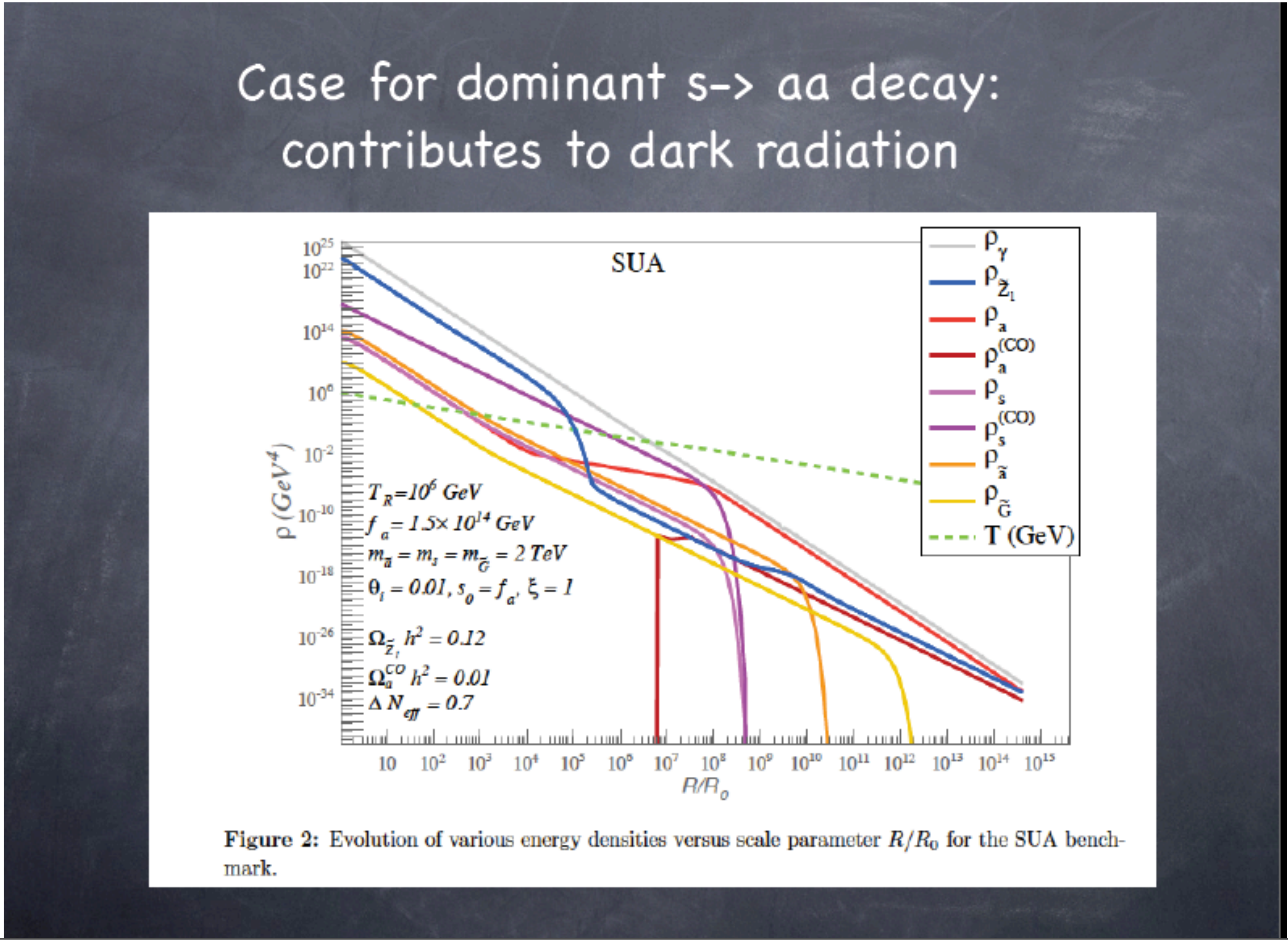


PQMSSM: Axions + SUSY ⇒ mixed $a-LSP$ dark matter

- $\hat{a}=\frac{s+ia}{\sqrt{2}}+i\sqrt{2}\bar{\theta}\tilde{a}_L+i\bar{\theta}\theta_L\mathcal{F}_a$ in 4-comp. notation
- Raby, Nilles, Kim; Rajagopal, Wilczek, Turner
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; possible LSP candidate)
- $m_{\tilde{a}}$ model dependent: keV→ TeV, but $\sim M_{SUSY}$ in gravity mediation
- saxion is spin-0 element: R-even but gets SUSY breaking mass ~ 1 TeV
- axion is usual QCD axion: gets produced via vacuum mis-alignment/ coherent oscillations as usual
- additional PQ parameters: $(f_a,\ m_{\tilde{a}},\ m_s,\ \theta_i,\ \theta_s,\ )$ and T_R

Coupled Boltzmann calculation of mixed axion-neutralino abundance

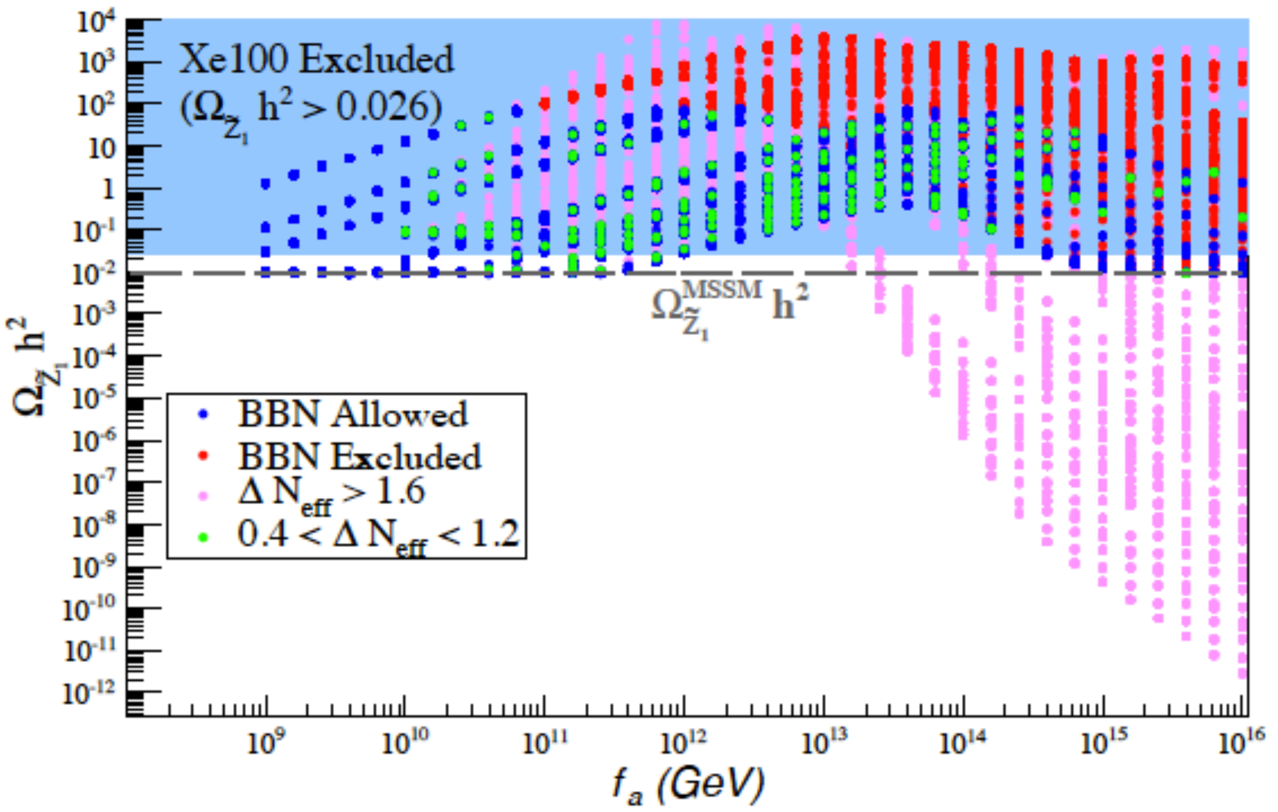
Bae, HB, Lessa, arXiv:1301.7428



Case for dominant s-> aa decay: contributes to dark radiation

Figure 2: Evolution of various energy densities versus scale parameter R/R_0 for the SUA benchmark.

Mixed higgsino-axion CDM in radiative natural SUSY



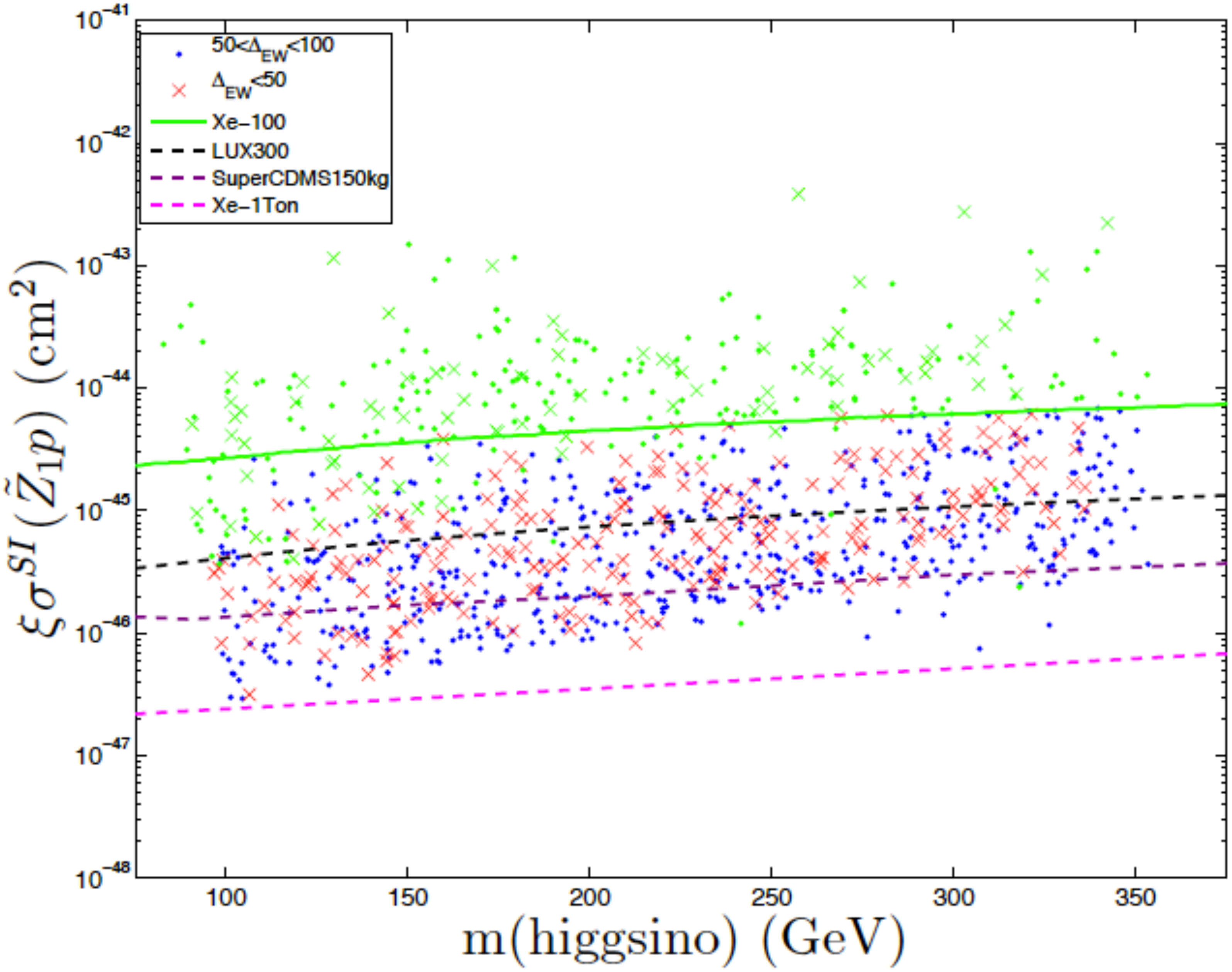
$f_a \sim 10^{14}$ GeV *allowed*!

(string theorists
take note)

Abundance of higgsinos is boosted due to
thermal production and decay of axinos
in early universe: the axion saves the day for
WIMP direct detection!

Detection of relic axions
also possible

Direct higgsino detection rescaled for minimal local abundance

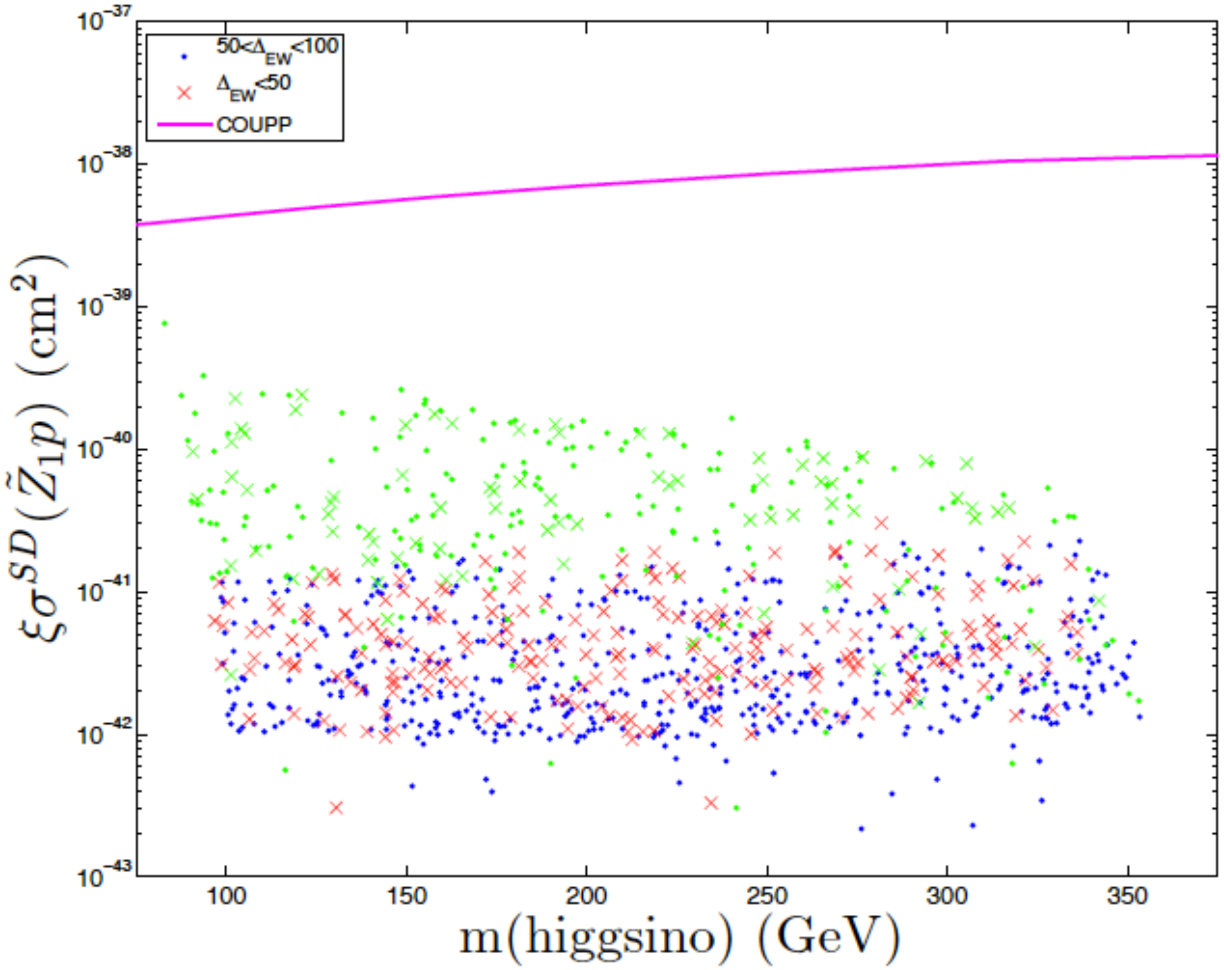


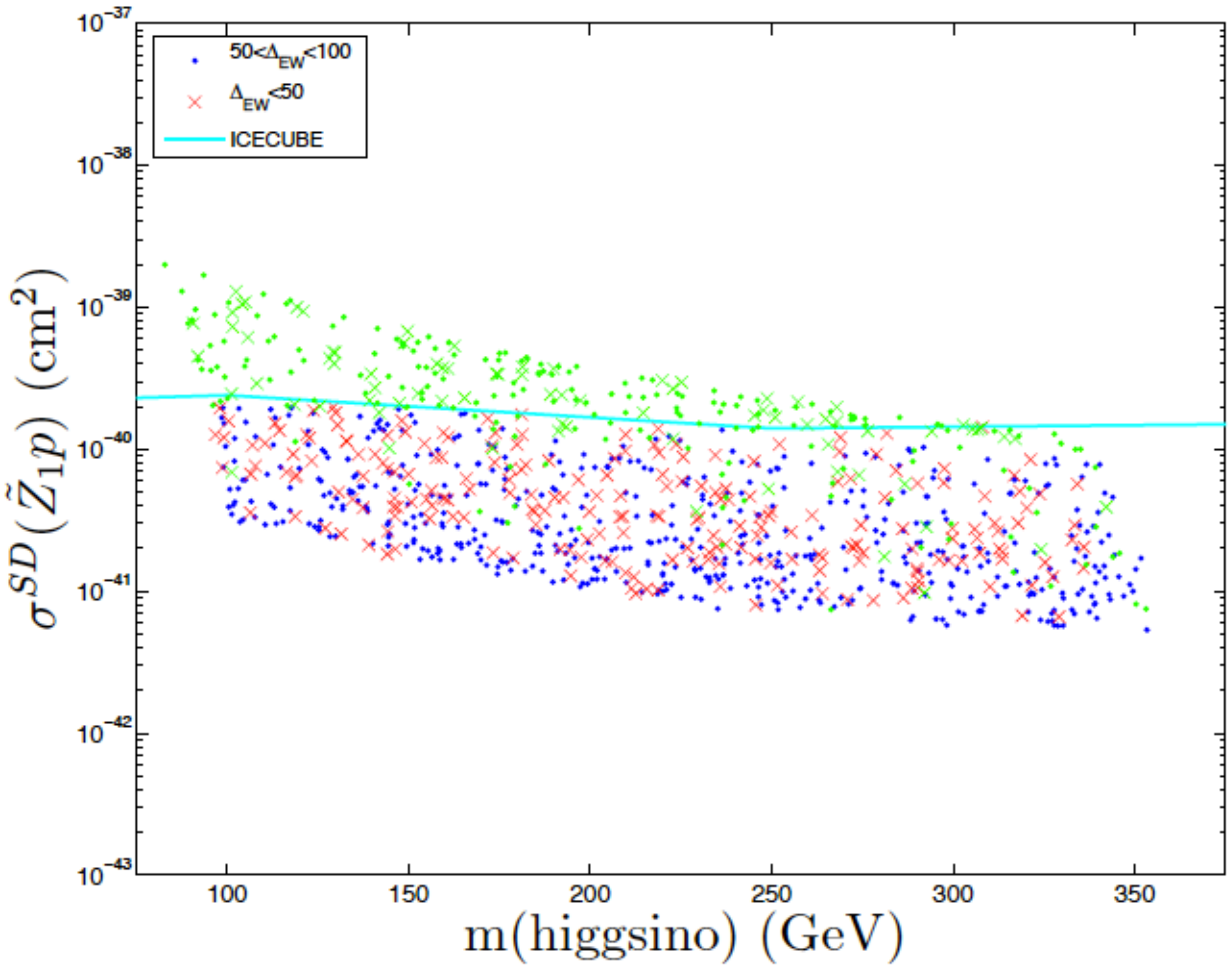
HB, Barger, Mickelson
arXiv:1303.3816

Deployment of Xe-1ton
coming soon!

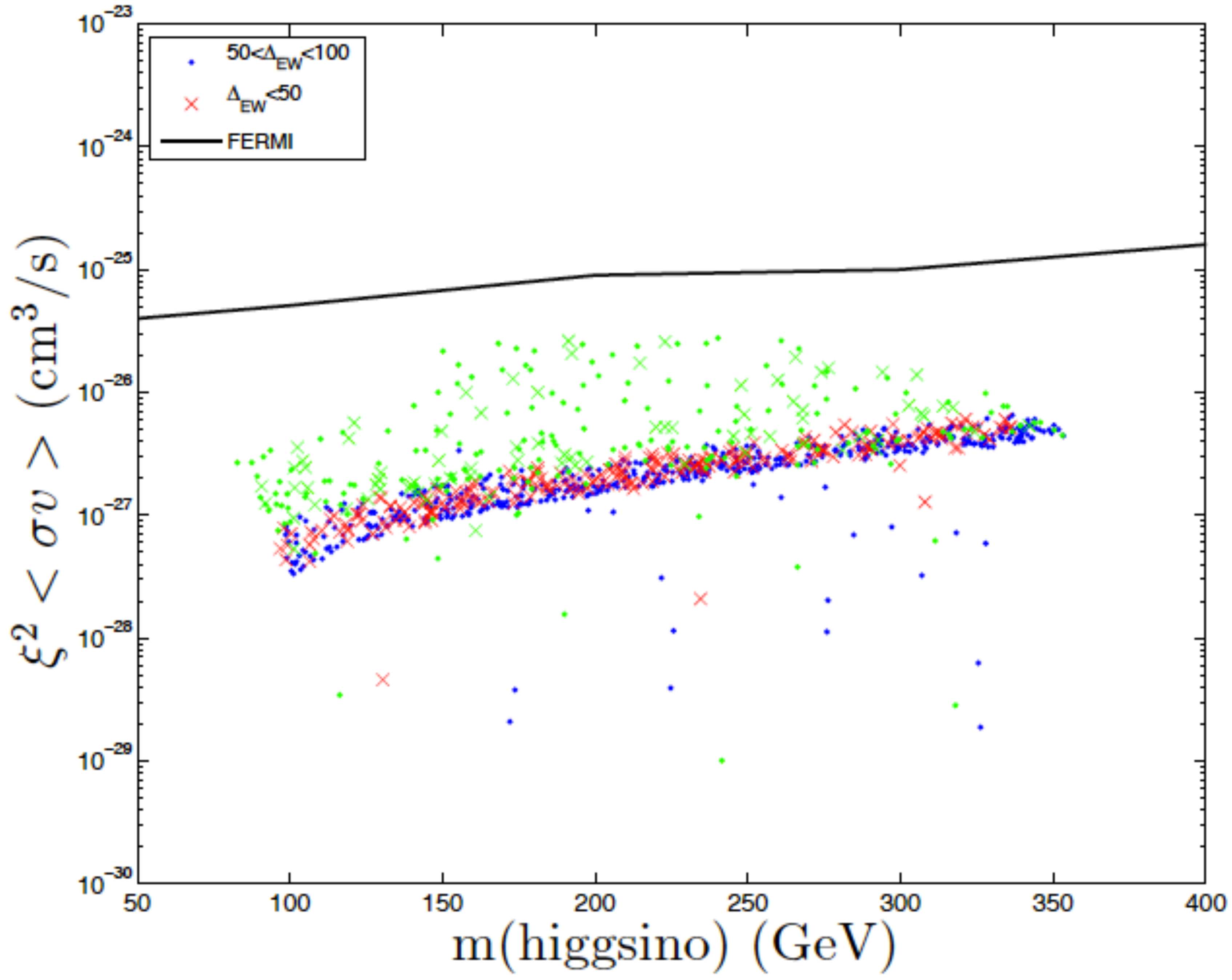
Can test completely with ton scale detector or equivalent (subject to minor caveats)

Spin-dependent higgsino detection:





Higgsino detection via halo annihilations:



Conclusions:

- SUSY is ``alive and kickin':" better than before
- m(h)=125 and low EWFT-> increase predictivity
- new signals for LHC: SS dibosons
- huge motivation to build ILC/higgsino factory: direct test of SUSY naturalness!
- underabundance of higgsino-like WIMPs just what is needed: room for axions
- test via direct WIMP search: higgsino-like WIMPs not far off, but local abundance < usual
- possibly see axions as well if f_a<10^12 GeV