Introduction to:
SUSY tools meets models

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Part 1: SUSY tools

- SUSY event generation
- mass spectra codes/production rates/decays
- Les Houches accord/events
- dark matter density/detection/B-decays/g-2...
- automatic scattering calculations
- extrapolation and fitting

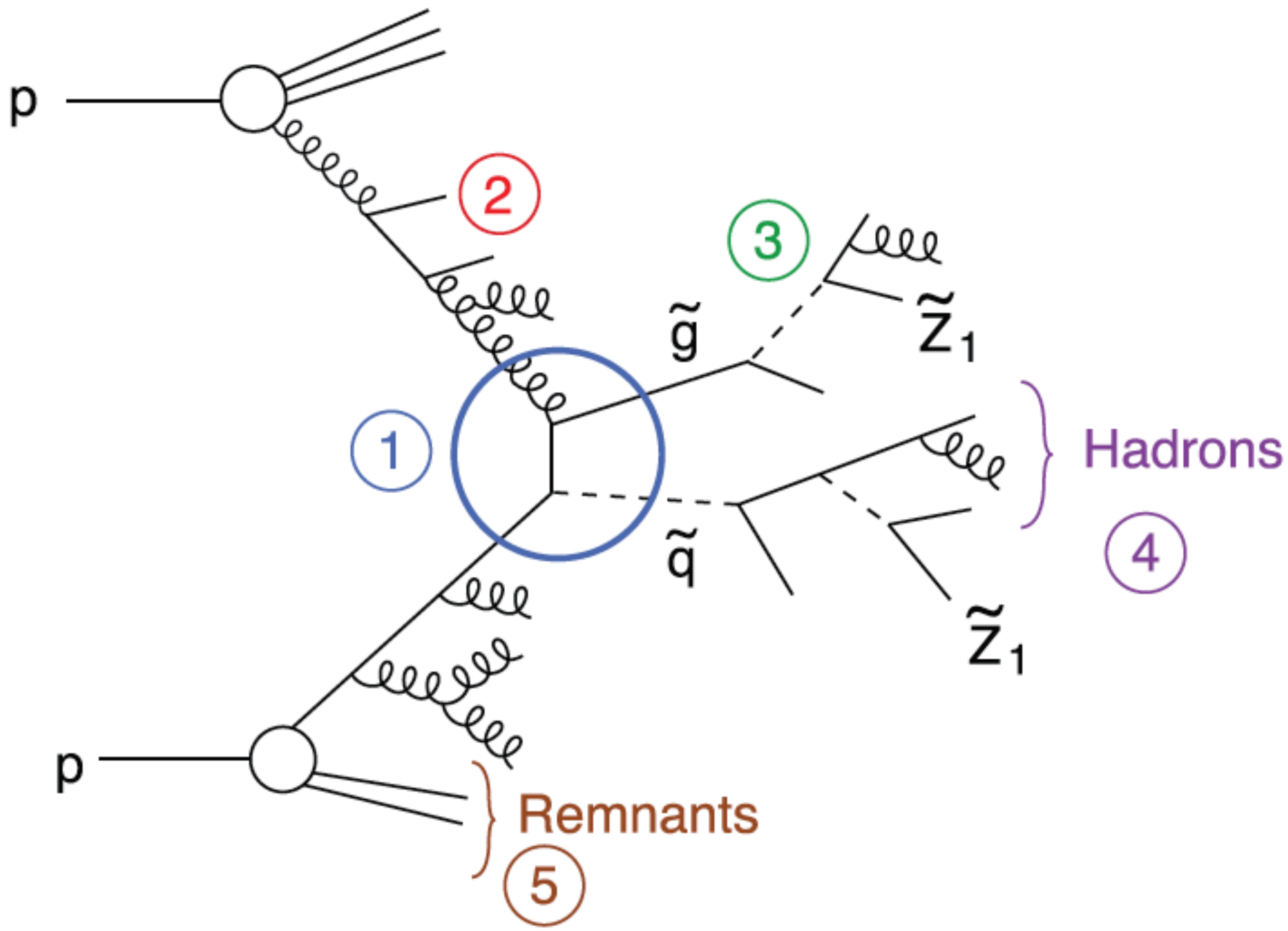
Part 2: meets models:
my perspective on SUSY post-LHC8
radiatively-driven natural SUSY

Disclaimer

I am probably the wrong person to give such a talk since I develop code only in accord with my own interests and hardly use other codes that I have not developed. As such, my views may well be out of date with respect to the status of codes other than my own. Furthermore, there exists a huge assortment of codes, some maintained and not maintained, some private and some public. It is likely not possible for me to cover all. So this talk will be very subjective...

Some history dating back to the dawn of time:

- 1967-1970: parton model and Drell-Yan theory of hadronic interactions
- 1973: QCD and SM
- 1977: Field-Feynman independent hadronization
- 1979: Fox-Wolfram parton shower algorithm
- 1979: Paige-Protopopescu, jet production at Isabelle pp collider (Isajet): hard scatter, parton convolution, jet broadening, hadronization, underlying event
- 1979: Sjostrand FF hadronization code
- 1982: Lund (string) hadronization, JETSET (e+e-)
- 1985: Sjostrand initial state shower algorithm, multiple scatter algorithm
- 1986: Lund hadron-hadron code: Pythia
- 1987: Marchessini-Webber: Hadron emission reactions with interfering gluons (Herwig); angle ordered QCD emissions; cluster hadronization



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

Some SUSY history

- 1974: Wess-Zumino 4-d SUSY field theory
- 1975: Salam-Strathdee: superfields, SUSY gauge theory,
- 1975-1983: Cremmer et al., supergravity development, SUGRA gauge theories, SUGRA breaking
- 1977: Fayet, MSSM, phenomenology, R-parity
- 1981: Witten, Kaul; SUSY solution to gauge hierarchy problem
- 1981: Dimopoulos, Georgi, SUSY GUTs
- 1982-1984: Arnowitt, Chamseddine, Nath; Barbieri, Ferrara, Savoy; Nilles; Hall, Lykken, Weinberg; Hidden sector SUGRA breaking, realistic models
- 1984: UA1. UA2 monojet excitement
- 1987-1990: a lull in activity during first string revolution
- 1990: LEP results, gauge coupling unification
- 1998-2000s: new mediation mechanisms, model building, GMSB, AMSB, gaugino, mirage,...

SUSY phenomenology

- late 1970s: Fayet: first efforts
- 1982: Kane-Leveille, Harrison-Llewellyn-Smith: hadroproduction of SUSY particles
- 1978-1983: early beam dump results
- 1982: e+e- monophoton/slepton searches
- 1983: Ellis, Hagelin, Nanopoulos, Srednicki: Zen events: one-hand clapping: from ppbar-> W->W1+Z1 (monojets+MET)
- 1983: Dawson, Eichten, Quigg: SUSY at hadron colliders
- 1984: F. Paige, SUSY production, simple decays into Isajet
- UA1, UA2 monojet results at CERN SppbarS@546 GeV: interpret within SUSY context: Ellis, Kowalski; Barger et al; Barnett, Haber,Kane
- 1987: UA1, UA2 excluded regions in m(squark) vs. m(gluino) plane; simplified models; m(gl), m(sq) >~50-60 GeV for decay to massless photino

First tools for SUSY prize

Frank Paige, 1984, Isajet

LBL-18479 (1984)

Cascade decays

In 1984, was clear the simple decays were inadequate $\tilde{g} \to q\bar{q}\tilde{\gamma}, q\tilde{q}; \quad \tilde{q} \to q\tilde{\gamma}, q\tilde{g}$

1985: added in decays to winos and zinos as well; constructed parton level generator: leptons +jets+MET signatures

HB,Ellis,Gelmini,Nanopoulos,Tata, PLB161(1985)175

For event generation, needed separate $\tilde{q}_L, \ \tilde{q}_R$ production

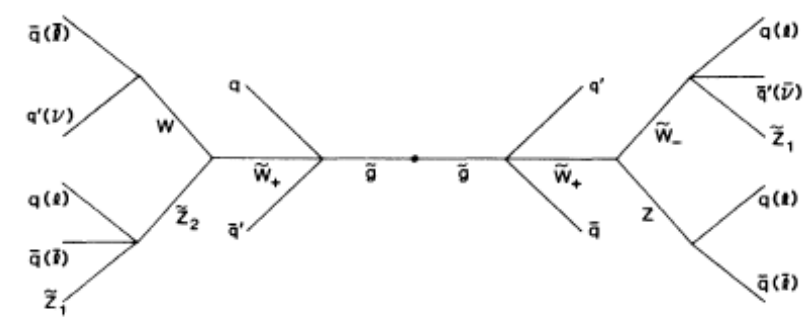
HB, X. Tata, PLB160(1985)159

Similar branching fractions by Gamberini

G. Gamberini,ZPC30 (1986) 605

Gluino/squark multistep (cascade) decays to charginos/neutralinos

HB, V. Barger, D. Karatas, X. Tata, PRD36(1987)96



Further decays:

Gluino Decays to W and Z Bosons at the SSC (with R.M. Barnett, M. Drees, J. Gunion, H. Haber, D. Karatas and X. Tata), Proceedings of Univ. Wisconsin-Madison Workshop on the SSC, May 1987.

Calculation and Phenomenology of Two Body Decays of Neutralinos and Charginos to W, Z and Higgs Bosons (with J. Gunion, H. Haber, R. Barnett, M. Drees, D. Karatas and X. Tata), Proceedings of Univ. Wisconsin-Madison Workshop on the SSC, May 1987.

Event generation with cascade decays

1987: Fermilab Tevatron started up at 1.8 TeV; CDF limits

Constructed parton-level event generator: SUSYSM

Effect of Cascade Decays on the Tevatron Gluino and Squark Mass Bounds (with X.Tata and J.Woodside), Phys.Rev.Letters **63**, 352 (1989).

Gluino Cascade Decay Signatures at the Tevatron Collider (with X.Tata and J.Woodside) Phys.Rev. **D41**, 906 (1990).

Gluino, squark decays to 3rd generation:

Phenomenology of Gluino Decays via Loops and Top Quark Yukawa Coupling (with X. Tata and J. Woodside), Phys. Rev. **D42**, 1568 (1990).

Then merge SUSYSM with Pythia

Multilepton Signals from Supersymmetry at Supercolliders (with X. Tata and J. Woodside), Phys. Rev. **D45**, 142 (1992).

Cascade decays to Higgs bosons

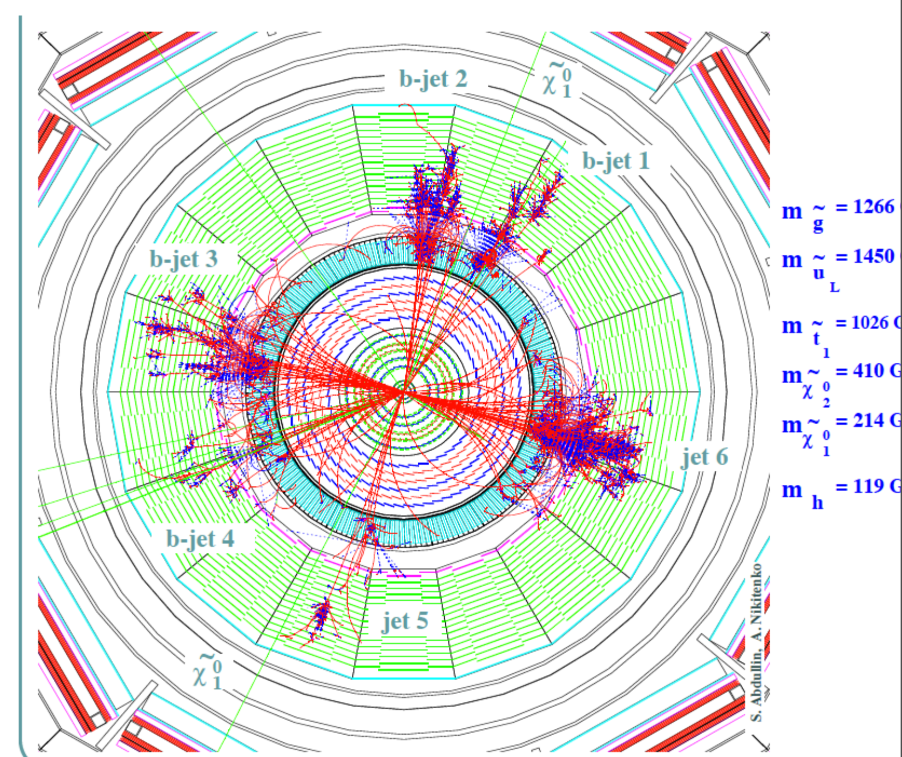
Supercollider Signals from Gluino and Squark Decays to Higgs Bosons (with M. Bisset, X. Tata and J. Woodside), Phys. Rev. **D46**, 303 (1992).

At this point (1992), the new particles group at CDF consisted of one person:
Jim Freeman, who had worked with Frank et al. on SUSY at SSC in 1984;
he constructed a crude interface between cascade decay subroutines & Isajet

Tata and I then joined with Frank to hardwire all sparticle production and cascade decays into Isajet 7.0

Simulating Supersymmetry with ISAJET 7.0/ISASUSY 1.0, (with F. Paige, S. Protopopescu and X. Tata), FSU-HEP-930329, proceedings of Workshop on Physics at Current Accelerators and the Supercollider, Argonne, IL June, 1993.

At this point, we had event generation as predicted by SUSY using MSSM inputs.



Further refinements: for large tan(B), include b, tau-Yukawa couplings

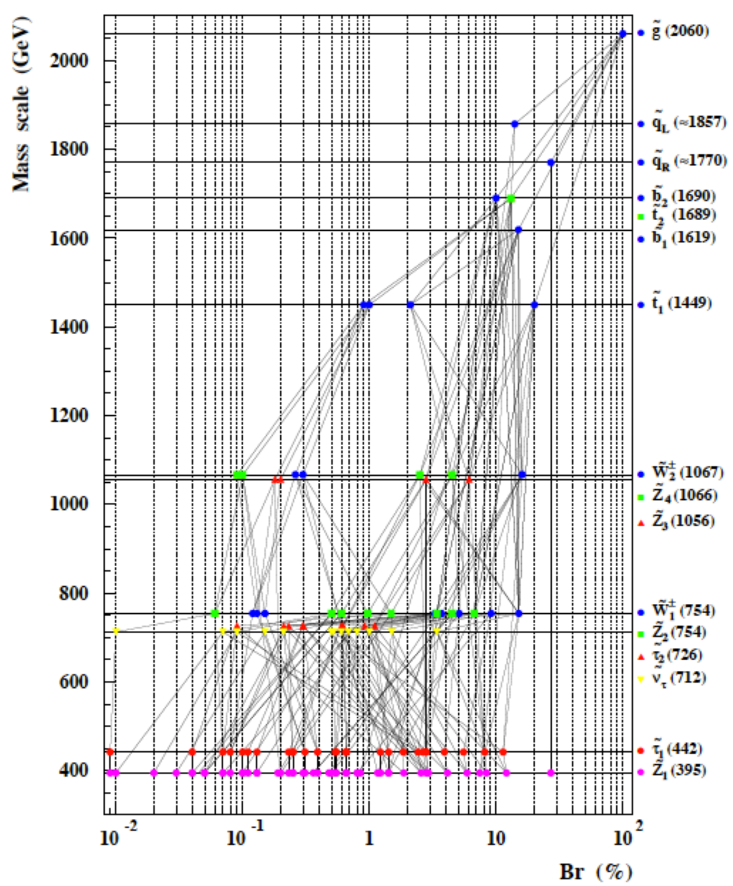
Collider Phenomenology for Supersymmetry with Large $\tan\beta$ (with C. H. Chen, M. Drees, F. Paige and X. Tata), Phys. Rev. Letters **79**, 986 (1997).

Important point: >1000 2->2 SUSY production processes at LHC

~10 decay modes per particle

~10^5 2->n processes which can operate

SUSY may not look like a simplified models!



Decay paths of a single gluino

Monte Carlo is the way forward for simulations consistent with most models

Other codes:

1996: S. Mrenna implements SUSY reactions, decays in Pythia (Spythia) [low tan(B)]

~2000: Herwig group develops IsaWIG interface: read in Isajet cascade decay table

2001: P. Richardson implements complete spin correlations in Herwig cascade decays using density matrices (tour de force)

2004: P. Skands et al. develop Les Houches Accord: read mass spectra/decay tables into Pythia, Herwig; no longer need for Isajet-like integrated structure; different codes feed into one another

2007: P. Skands et al. develop Les Houches Event format: generate events at parton level, read into Pythia, Herwig for showering, hadronization, underlying event

2009: Sherpa: Gleisberg, Hoche, Krauss, Schonherr, Schumann, Siegert, Winter; O'Mega interface

e+e- codes:

1987: Cascade decays for e+e- colliders

Searching for Supersymmetry at e^+e^- Supercolliders (with A. Bartl, D. Karatas, W. Majerotto and X. Tata) Int. Journal of Mod. Phys. **A4** 4111(1989).

Further decays: Bartl, Majerotto, Porod

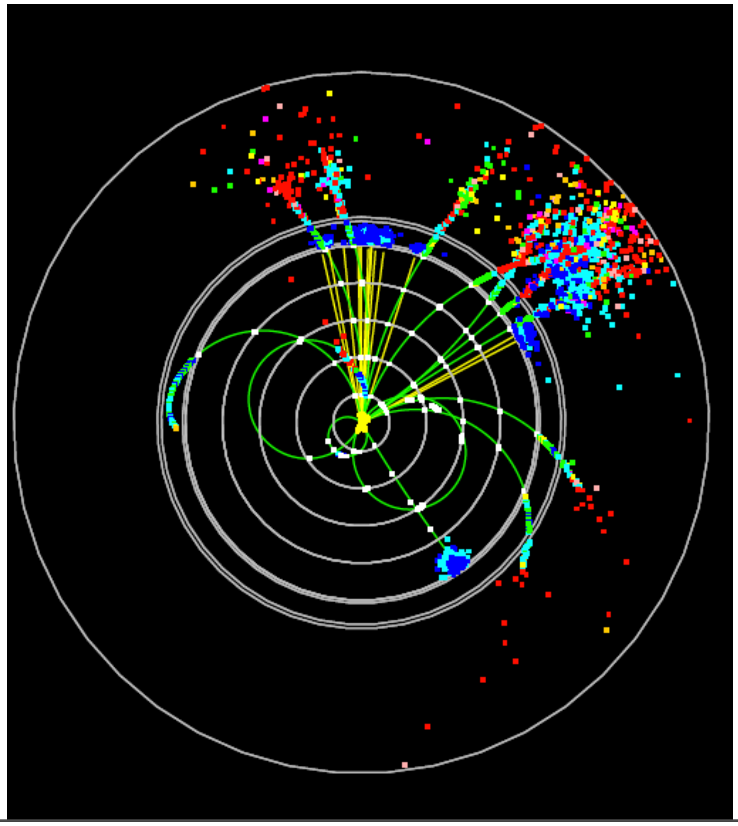
1994: e+e- -> SUSY in Isajet

SUSYGEN: Katsanevas and Morawitz, 1998? (LEP)

Polarized beams:

Supersymmetry Studies at Future Linear e^+e^- Colliders, (with R. Munroe and X. Tata), Phys. Rev. D54, 6735 (1996).

Brem/beamstrahlung: adaptation of M. Drees code into Isajet



Sparticle mass codes:

Gauge coupling RGEs: Dimopoulos, Raby Wilczek, PRD24 (1981) 1681

1-loop soft terms:1984

[12]L. E. Ibañez and G. G. Ross, Phys. Lett. **B110**, 215 (1982); K. Inoue *et al.* Prog. Theor. Phys. **68**, 927 (1982) and **71**, 413 (1984); L. Ibañez, Phys. Lett. **B118**, 73 (1982); J. Ellis, J. Hagelin, D. Nanopoulos and M. Tamvakis, Phys. Lett. **B125**, 275 (1983); L. Alvarez-Gaumé. J. Polchinski and M. Wise, Nucl. Phys. **B221**, 495 (1983).

N. K. Falck, Z. Phys. **C30**, 247 (1986)

LEP gauge coupling unification spurred numerous private codes:
e.g. Drees, Nojiri; Arnowitt, Nath; Ramond et al;
Barger, Berger, Ohmann; Kane, Kolda, Roszkoski,Wells; Ellis, Falk, Olive,...

1994: public code: Isasugra; SUSY searches in m0 vs. mhf plane

Multi-channel Search for Minimal Supergravity at $p\bar{p}$ and e^+e^- Colliders, (with C.H. Chen, R. Munroe, F. Paige and X. Tata), Phys. Rev. **D51**, 1046 (1995).

1998: SuSpect: Djouadi, Kneur, Moultaka

two-loop RGEs:

[9]S. Martin and M. Vaughn, Phys. Rev. **D50**, 2282 (1994); Y. Yamada, Phys. Rev. **D50**, 3537 (1994); I. Jack and D. R. T. Jones, Phys. Lett. **B333**, 372 (1994).

complete 1-loop sparticle masses: D. Pierce, Bagger,
Matchev, Zhang Nucl. Phys. **B491**, 3 (1997)

Sparticle Spectra:

1994: Isasugra: HB, F. Paige, X. Tata

1998: SuSpect: , Djouadi, Kneur, Moultaka;
merged with Sdecay, Hdecay for decay tables:
Muhlleitner, Spira; SUSYHiT

2000: FeynHiggs: Higgs mass and decays, Heinemeyer, Hollik, Weiglein

2002: SoftSUSY: Allanach

2003: Spheno: Porod, includes decay table

2003: Comparison: Allanach, Kraml, Porod

2004: Les Houches accord, Skands et al.

2005: NMSSMtools, Ellwanger, Gunion, Hugonie

2007: CPsuperH: Lee, Pilaftsis, Carena, Choi, Drees, Ellis, Wagner

Sparticle production:

Leading order: event generators, etc.

1996: NLO: Prospino, Beenaker, Hopker, Spira w/ Zerwas, Plehn,...

2013: Resummino: Fuks, Klasen, Lamprea, Rothering

Matrix element computers: exact tree-level 2->n processes: expanding for loop processes

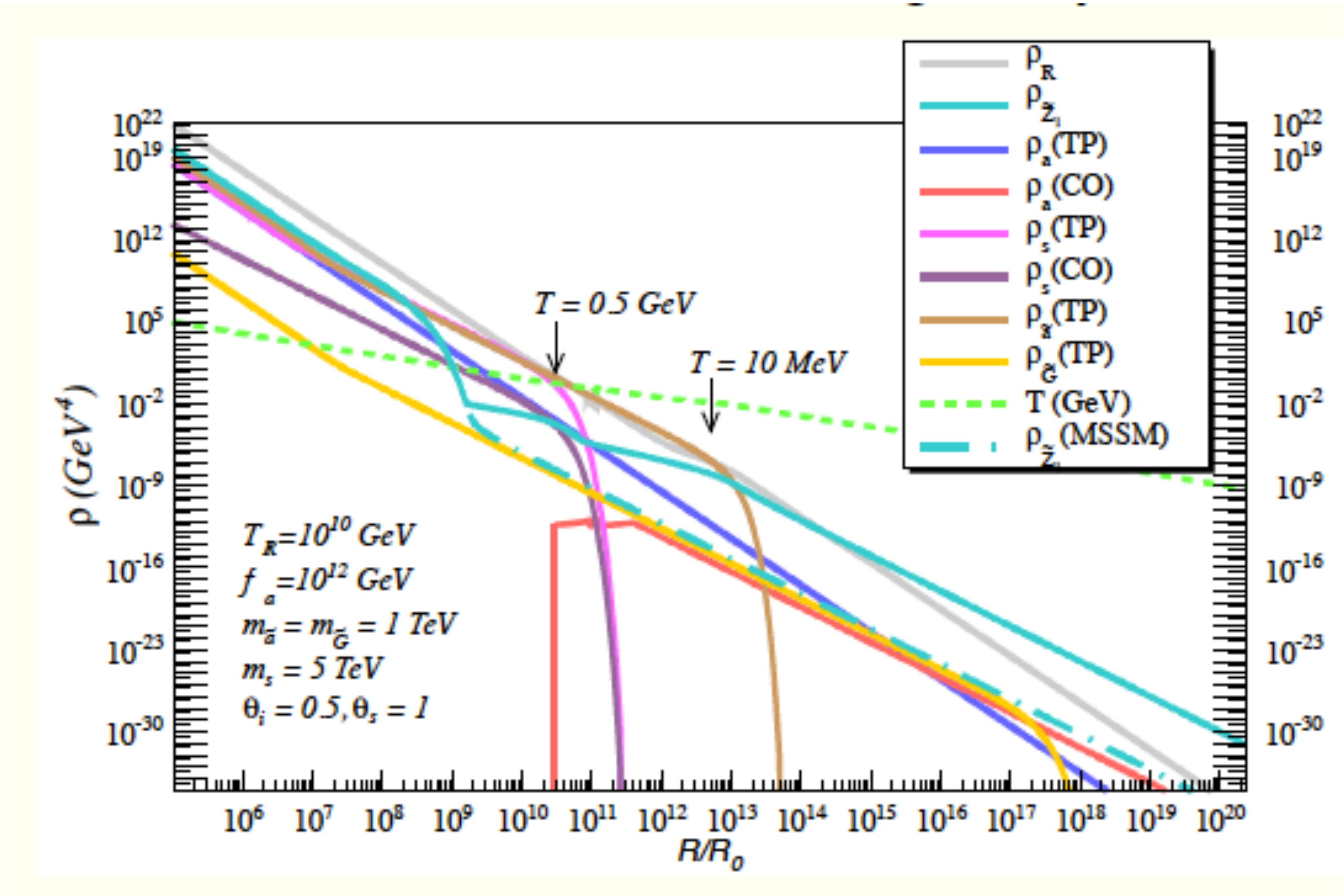
- 1997: CompHEP/CalcHEP, LanHEP (Boos, Pukhov, Belyaev, Semenov,...)
- 1994, MadGraph, Stelzer, Long, Maltoni,...
- 1995: SUSY-Grace: Jimbo et al.
- 2001?: O'Mega, Whizard: Ohl, Reuter, Schwinn

Dark matter: neutralino relic density; direct/indirect detection rates; many include also B-decays, (g-2)_mu, etc.

- Private codes: numerous: Drees, Nojiri; Kane, Kolda et al.; Ellis, Olive, Falk; HB, Brhlik; Roszkowski
- 1996: Neutdriver (Jungman, unmaintained)
- 2000: DarkSUSY: Gondolo, Edsjo,....
- 2002: Micromegas: Belanger, Pukhov
- 2002: IsaReD, IsaTools: HB, Balazs, A. Belyaev
- 2009: SuperIso: Mahmoudi (B-decays etc.)
- 2010: SUSY_flavor: Rosiek, Chankowski, Dedes, Jager, Tanedo

some present work: 8 coupled Boltzmann evaluation of mixed axion, neutralino CDM: not yet public...

KJ Bae, HB, A. Lessa



Fitting, extrapolation: extracting SUSY parameters from collider measurements

- Sfitter: Lefaye, Plehn, D. Zerwas (2004)
- Fittino: Bechtle, Desch, Wienemann (2005)

2006: SPA convention: P. Zerwas et al.:
a convention for scale choice/renormalization scheme so various codes can communicate...

Supersymmetry parameter analysis: SPA convention and project
Juan Antonio Aguilar-Saavedra (Lisbon, IST), A. Ali (DESY), Benjamin C. Allanach (Cambridge U., DAMTP), Richard L. Arnowitt (Texas A-M), Howard A. Baer (Florida State U.), Jonathan A. Bagger (Johns Hopkins U.), Csaba Balazs (Argonne, HEP), Vernon D. Barger (Wisconsin U., Madison), M. Barnett (LBL, Berkeley), A. Bartl (Vienna U.) *et al.*. Nov 2005. 19 pp.
Published in **Eur.Phys.J. C46 (2006) 43-60**

Special for this workshop: Sarah by F. Staub:

Sarah

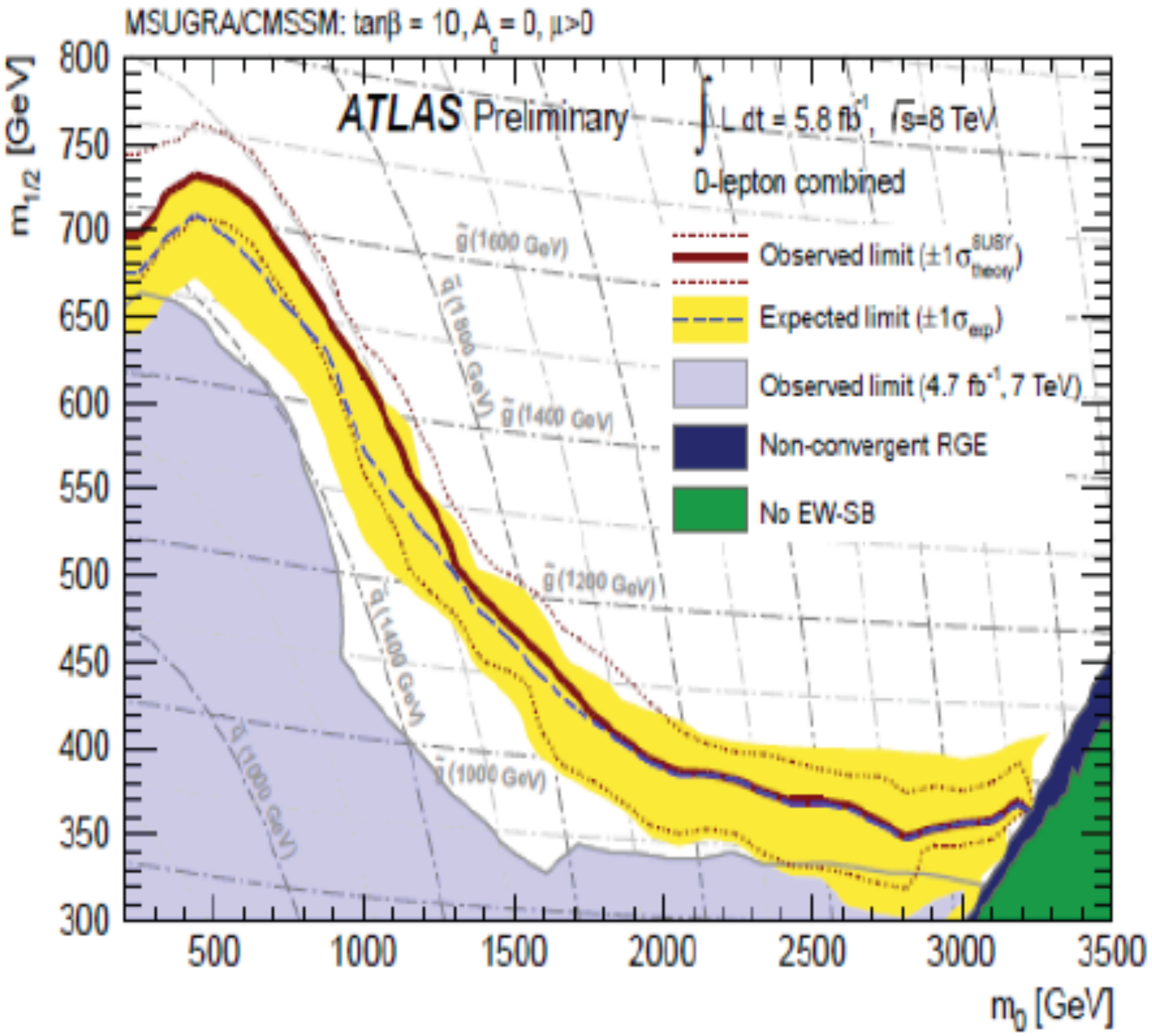
F. Staub
(Submitted on 3 Jun 2008 (v1), last revised 6 Nov 2012 (this version, v6))
SARAH is a Mathematica package for building and analyzing supersymmetric models. SARAH just needs the gauge structure, particle content and superpotential to produce all information about the gauge eigenstates of a model. Breaking of gauge symmetries and mixings of particles can easily be in a second step and entire Lagrangian is derived automatically. Also the gauge fixing terms are derived by SARAH in R_Xi gauge, and the corresponding ghost interactions are calculated. Using this information, SARAH can calculate the all mass matrices, tadpole equations and vertices at tree-level for the given model. In addition, the expressions for the 1- and 2-loop renormalization group equations of all parameters can be calculated and an automatic calculation for the 1-loop corrections to self energies and the tadpoles are possible.
SARAH can write all information about the model to LaTeX files, or create a model files for FeynArts/FormCalc, WHIZARD/OMEGA and CalcHep/CompHep, which can also be used for dark matter studies using MicrOmegas, and in the UFO format which is supported by MadGraph 5. Beginning with version 3, SARAH is also the first available spectrum-generator-generator: based on the derived, analytical expression it creates source code for SPheno to calculate the mass spectrum as well the SUSY decays with high precision. In that way, it is possible to implement new models in SPheno without the need to write any Fortran code by hand. Already many models beyond the MSSM are included in the public version of SARAH and the implementation of new models is easy and straightforward.

Meta-tools, by O'Leary

Presentation/tutorial on Wednesday

- Are all these efforts in vain?
- Does SUSY exist?
- What have we learned from LHC?
- When do we give up on weak scale SUSY?
- Increasing emphasis on naturalness:
- Tools meet models:

What have we learned from LHC8?



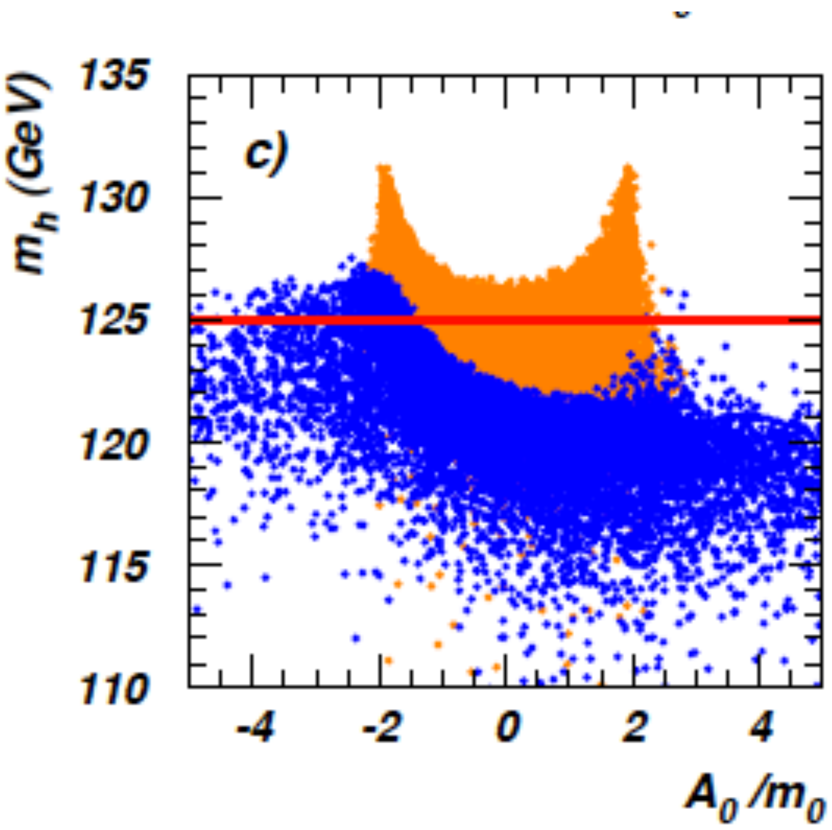
$$m_{\tilde{g}} > 1.5 \text{ TeV for } m_{\tilde{q}} \simeq m_{\tilde{g}}$$

$$m_{\tilde{g}} > 1 \text{ TeV for } m_{\tilde{q}} \gg m_{\tilde{g}}$$

Squarks and gluinos likely beyond TeV range!

What else have 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,...



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

HB, Barger, Mustafayev, PRD85(2012)075010

Little Hierarchy Problem:

Question: how can it be that m(Z)=91.2 GeV, m(h)~125 GeV while gluino and squark masses sit at TeV or even far beyond values?

i.e. why aren't m(Z), m(h) also > 1 TeV?

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

No large uncorrelated contributions to m(Z)!

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

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

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

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

New measure of naturalness:

how can m(Z)=91.2 GeV when sparticles >> TeV?

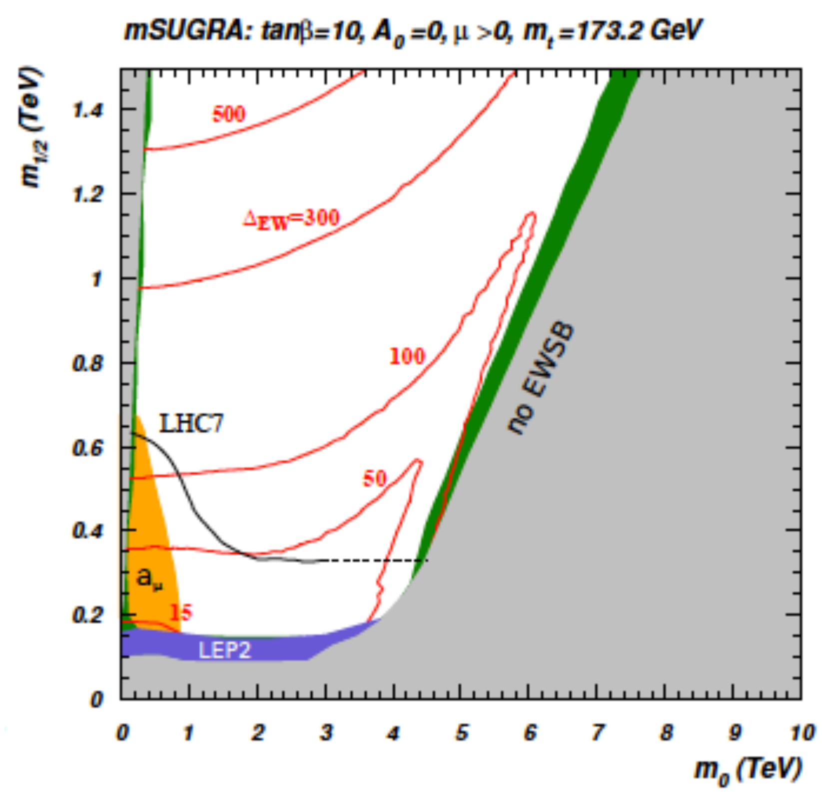
$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \quad \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

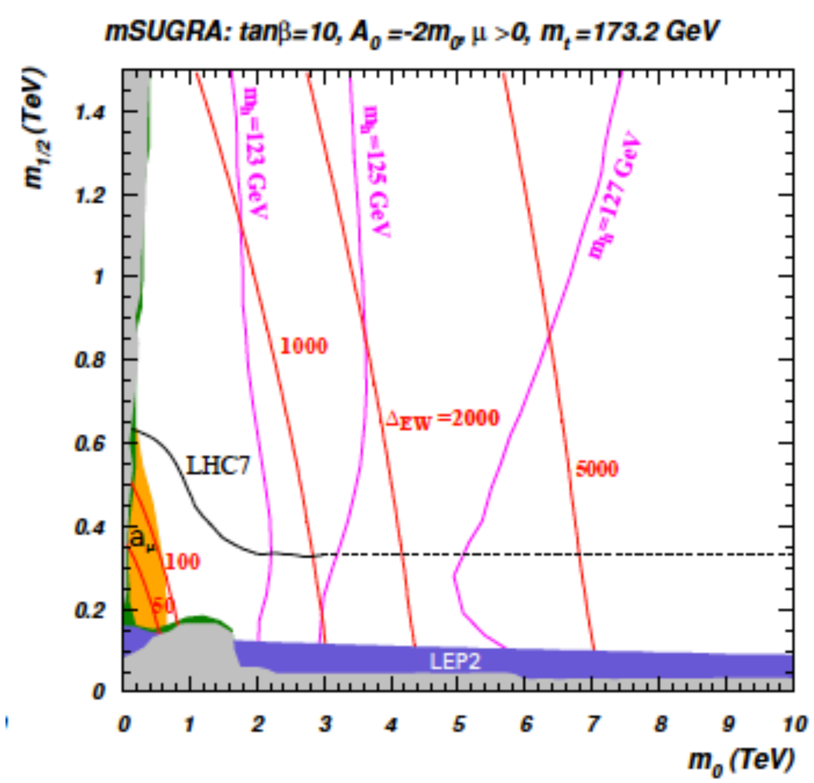
Each contribution to m(Z) relation ought be of order m(Z)!
i.e. no large cancellations amongst independent contributions to m(Z)

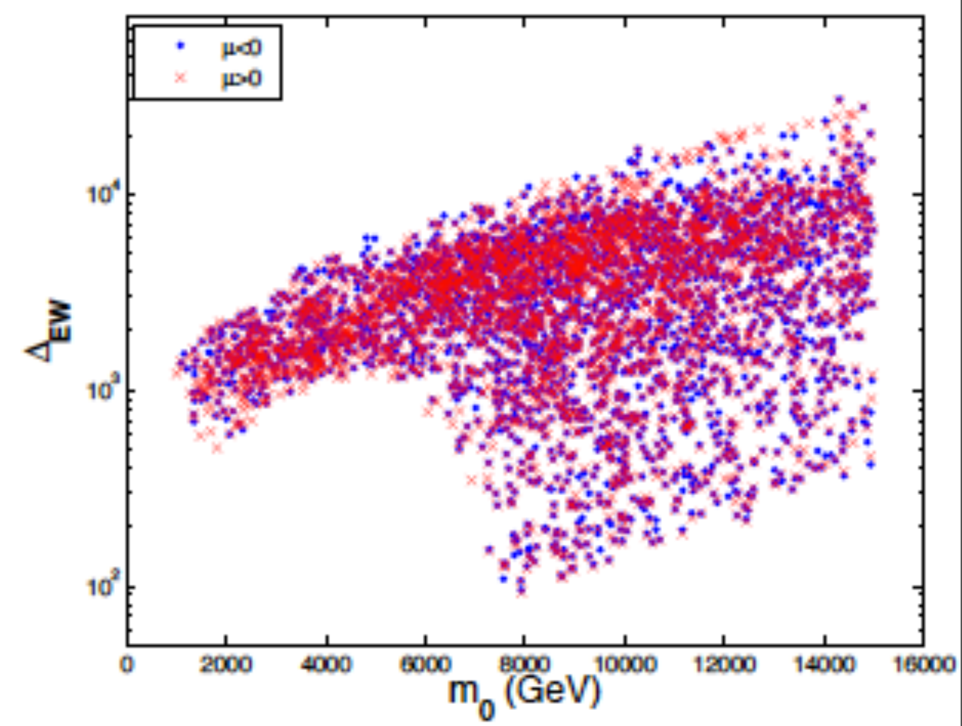
$$\Delta_{\rm EW} \equiv max(C_i)/(M_Z^2/2)$$

- Model independent (impose at weak scale!)
- Conservative (necessary but perhaps not sufficient)
- measureable (reconstruct from weak scale Lagrangian)
- unambiguous (depends on spectra not parameters)
- predictive [m(higgsino)~m(higgs)]
- falsifiable (no light higgsinos at 1 TeV ILC then SUSY EW naturalness dead)
- simple to compute (Isajet 7.83)

Which sorts of models can naturally accommodate the M_weak<<M_SUSY little hierarchy? Not 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 or Kim-Nilles:

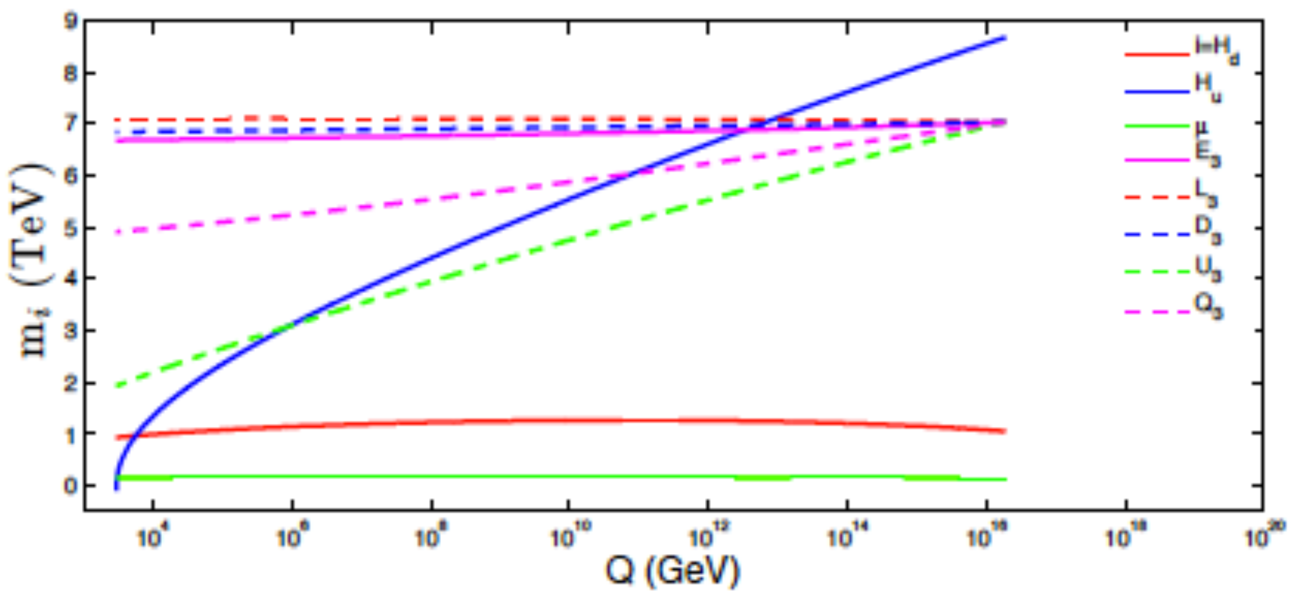
$\mu \sim \lambda m_{3/2}$ so that $|\mu| \ll m_{3/2}$

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

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

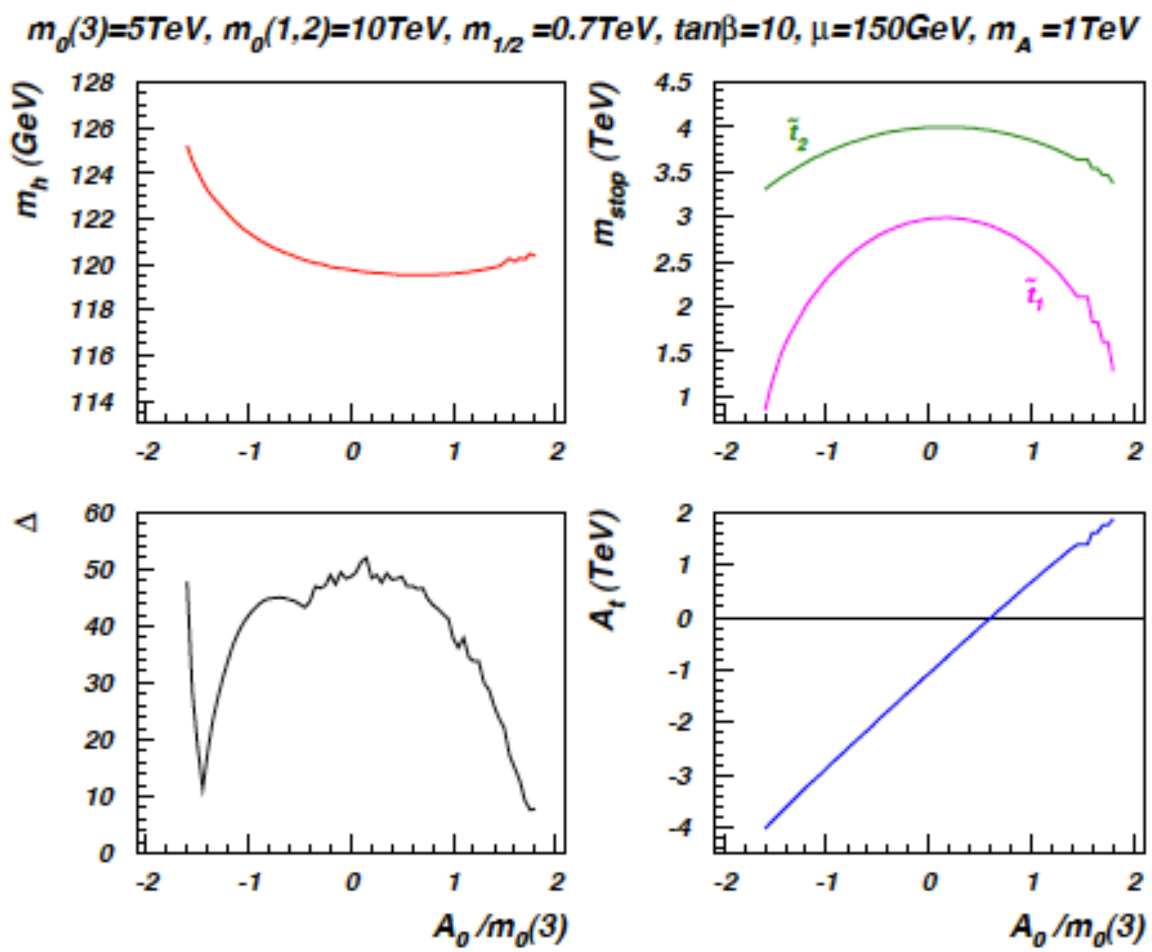
$$\begin{aligned} M_Z^2/2 &= \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2, \\ B\mu &= \left((m_{H_u}^2 + \mu^2 + \Sigma_u^u) + (m_{H_d}^2 + \mu^2 + \Sigma_d^d)\right)\sin\beta\cos\beta + \Sigma_u^d. \end{aligned}$$

HB, Barger, Huang, Mickelson, Mustafayev, Tata, arXiv:1212.2655 largest contribution usually from stops:

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

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

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

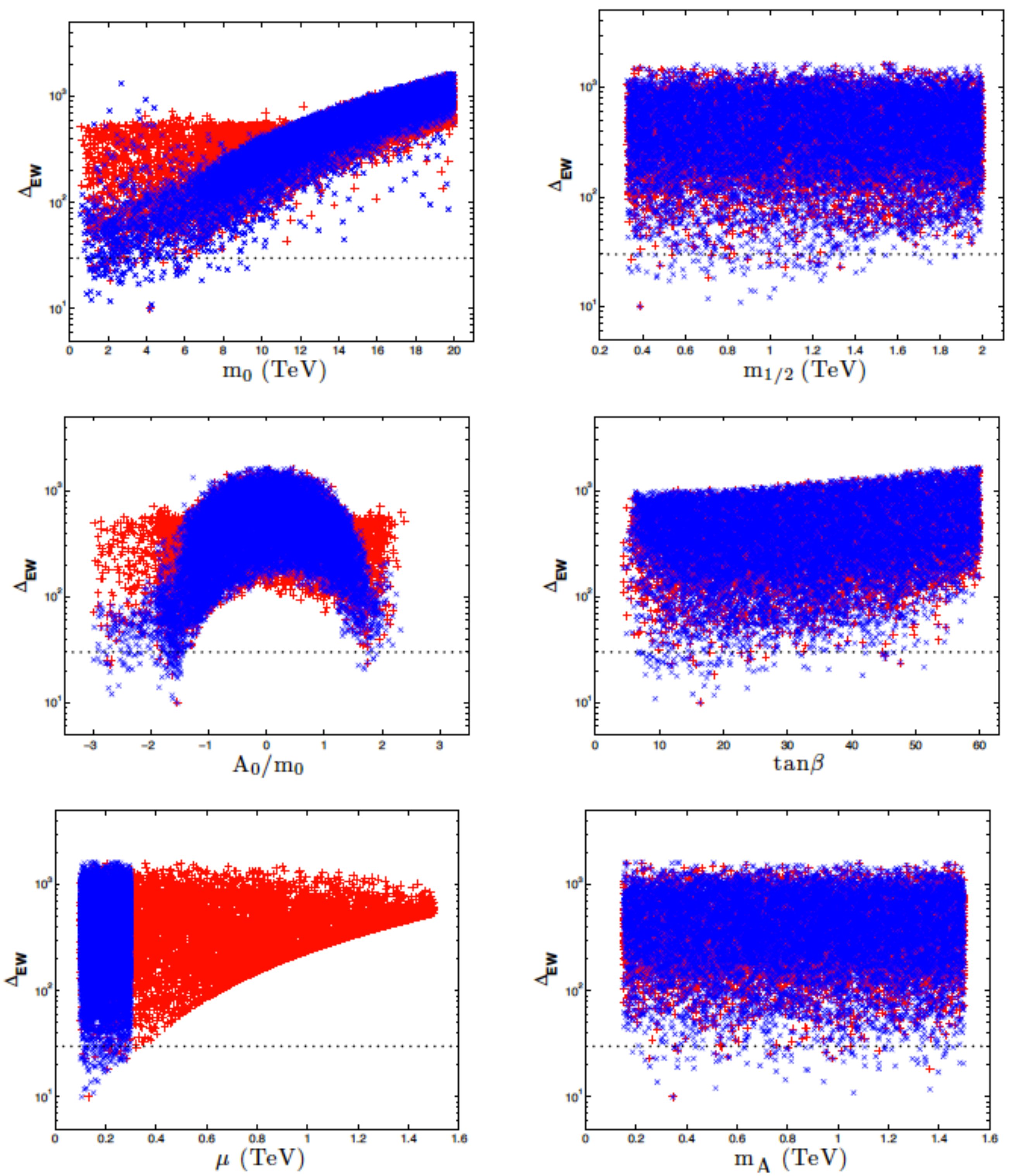
One need not depart too far from mSUGRA/ CMSSM to find a model which allows low Delta_EW while maintaining desirable features of SUSY GUTs:

2-extra parameter non-universal Higgs model

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

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

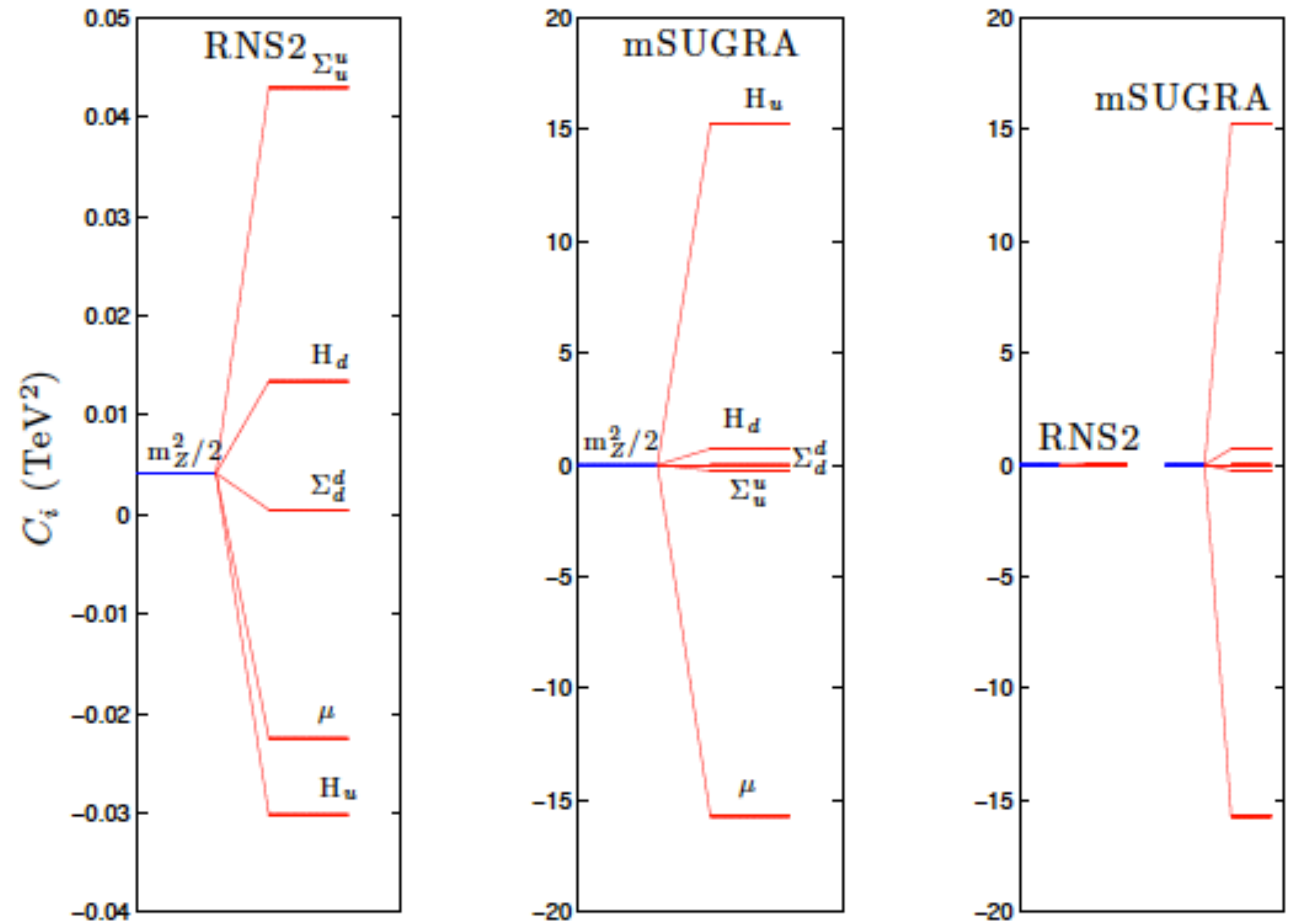
$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV. $A_0 = -11426.6$ GeV, $\tan\beta = 8.55$ with $\mu = 150$ GeV and $m_A = 1000$ GeV

RNS

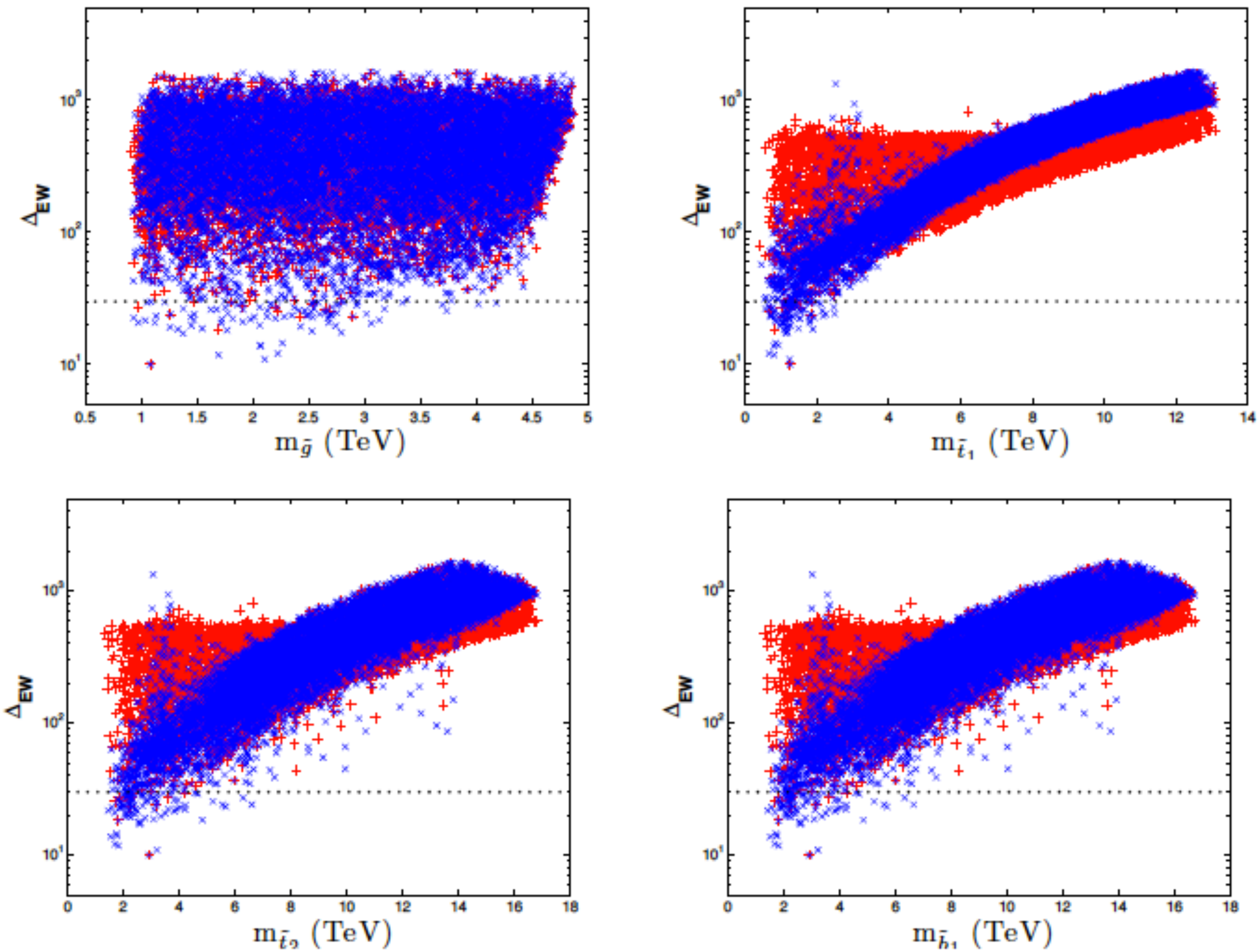
- $C_{\Sigma_u^u} \sim (205 \text{ GeV})^2$
- $C_{H_d} \sim (114 \text{ GeV})^2$
- $C_{\Sigma_d^d} \sim (22 \text{ GeV})^2$
- $C_\mu \sim -(148 \text{ GeV})^2$
- $C_{H_u} \sim -(173 \text{ GeV})^2$
- $m_Z^2/2 \simeq (65 \text{ GeV})^2$

mSUGRA

- $C_{H_u} \simeq (3.87 \text{ TeV})^2$
- $C_\mu \simeq -(3.93 \text{ TeV})^2$



Sparticle masses:



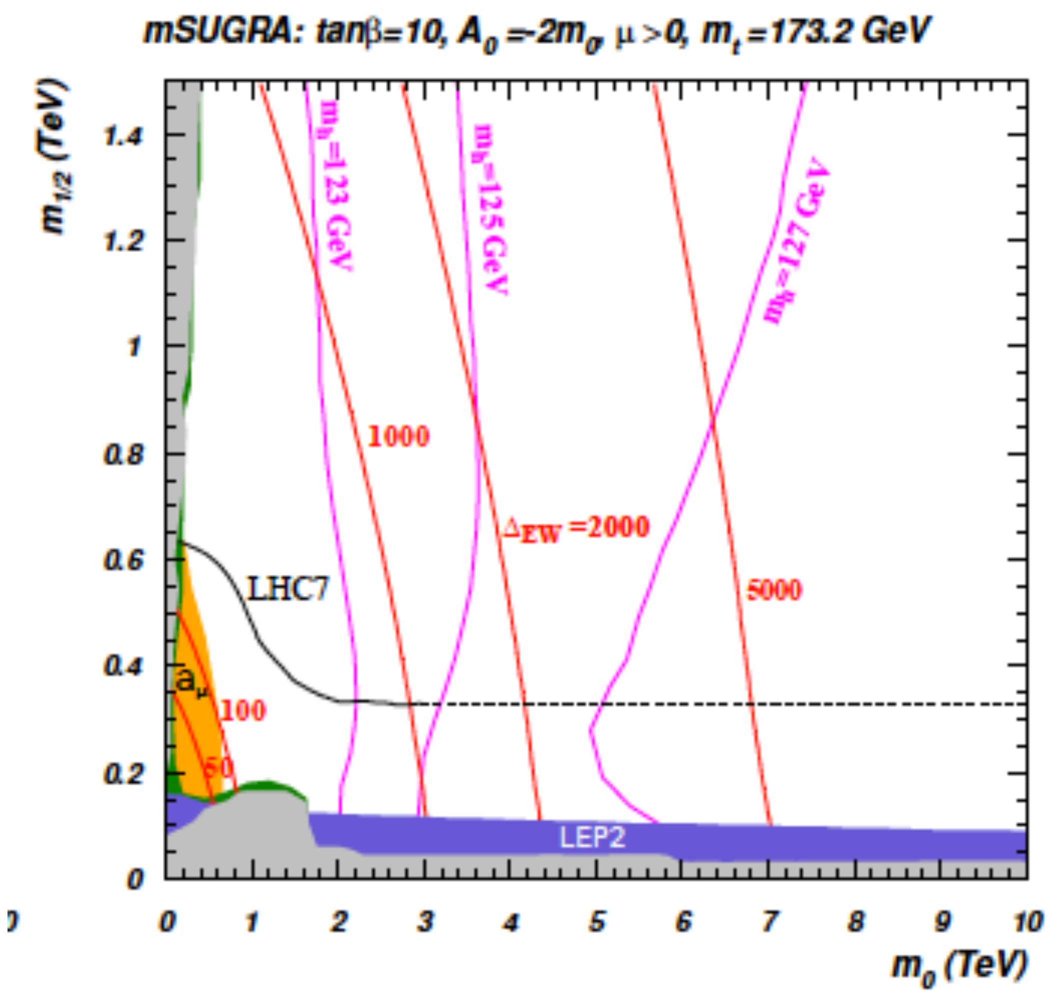
SUSY spectra from radiatively-driven natural SUSY (RNS)

scan NUHM2 space:

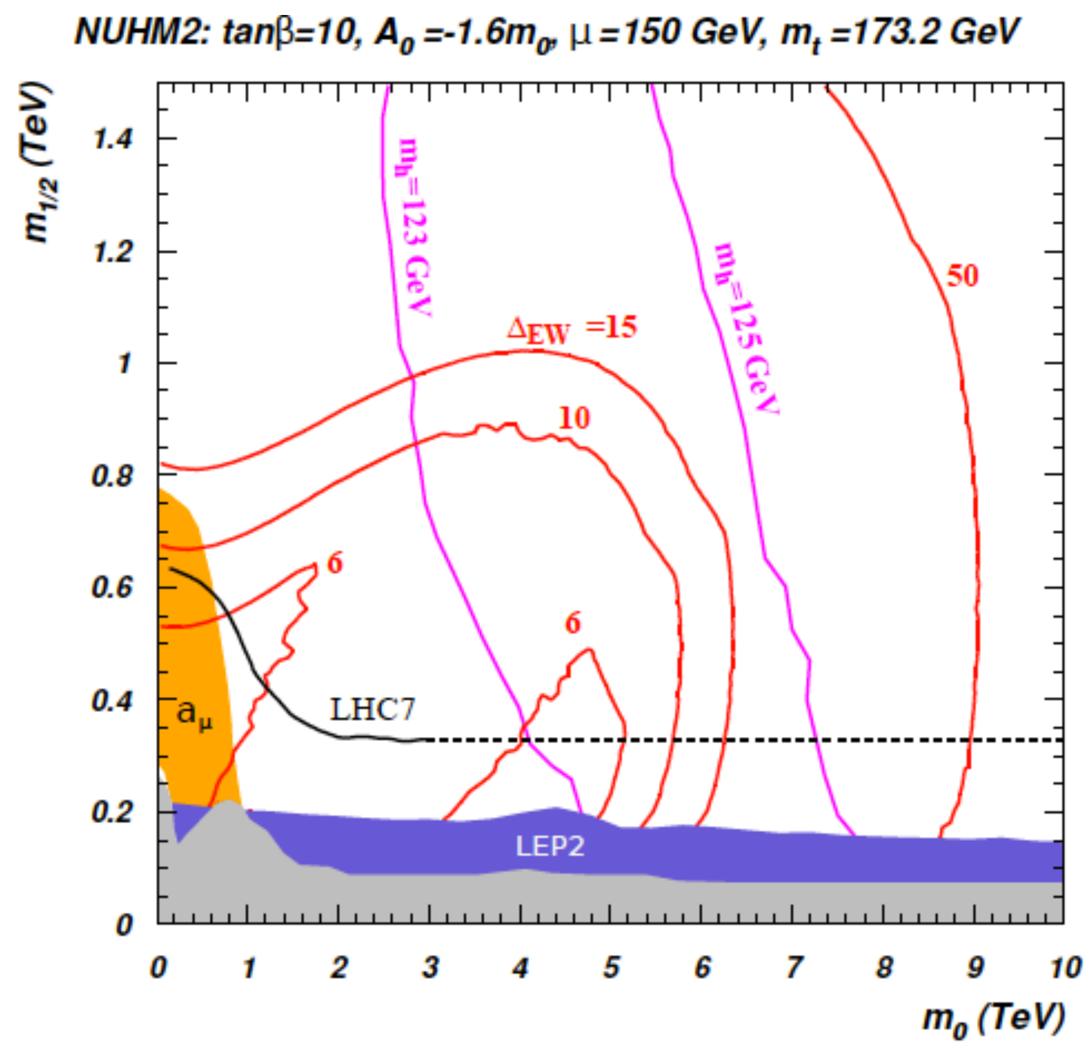
- light higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_{1,2}$ with mass $\sim 100-300$ GeV,
- gluinos with mass $m_{\tilde{g}} \sim 1-4$ TeV,
- heavier top squarks than generic NS models: $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-5$ TeV,
- first/second generation squarks and sleptons 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?

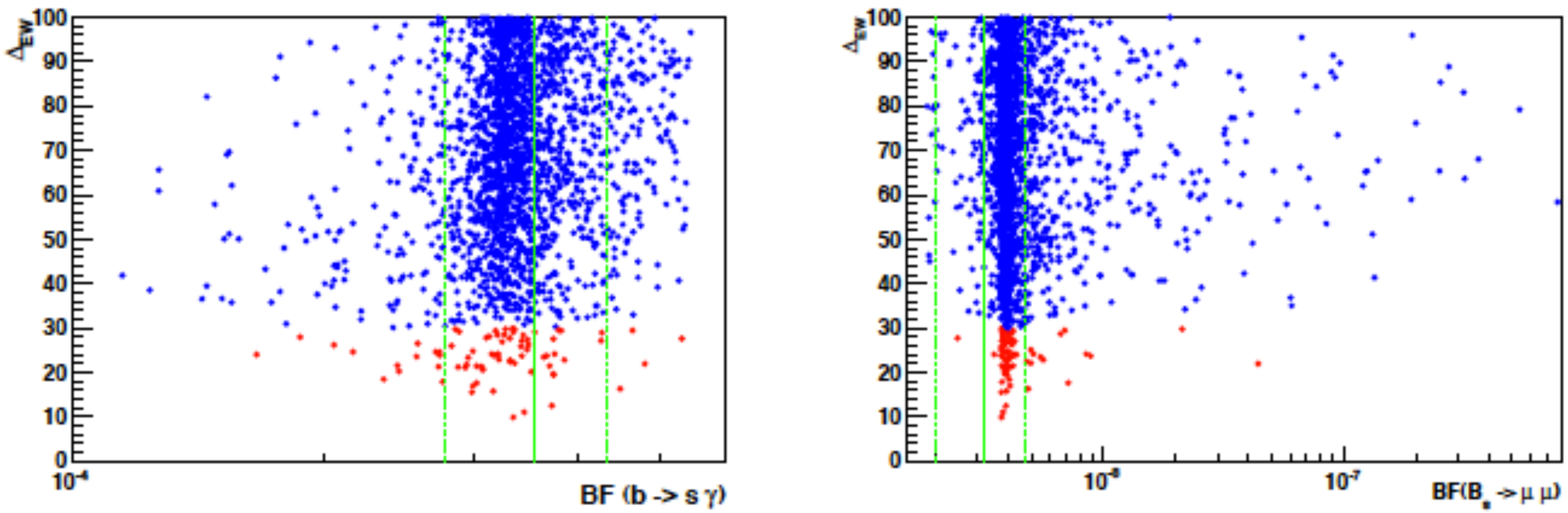


=>



Little Hierarchy Problem melts away!

What happens to B constraints?
These are trouble for older Natural SUSY models

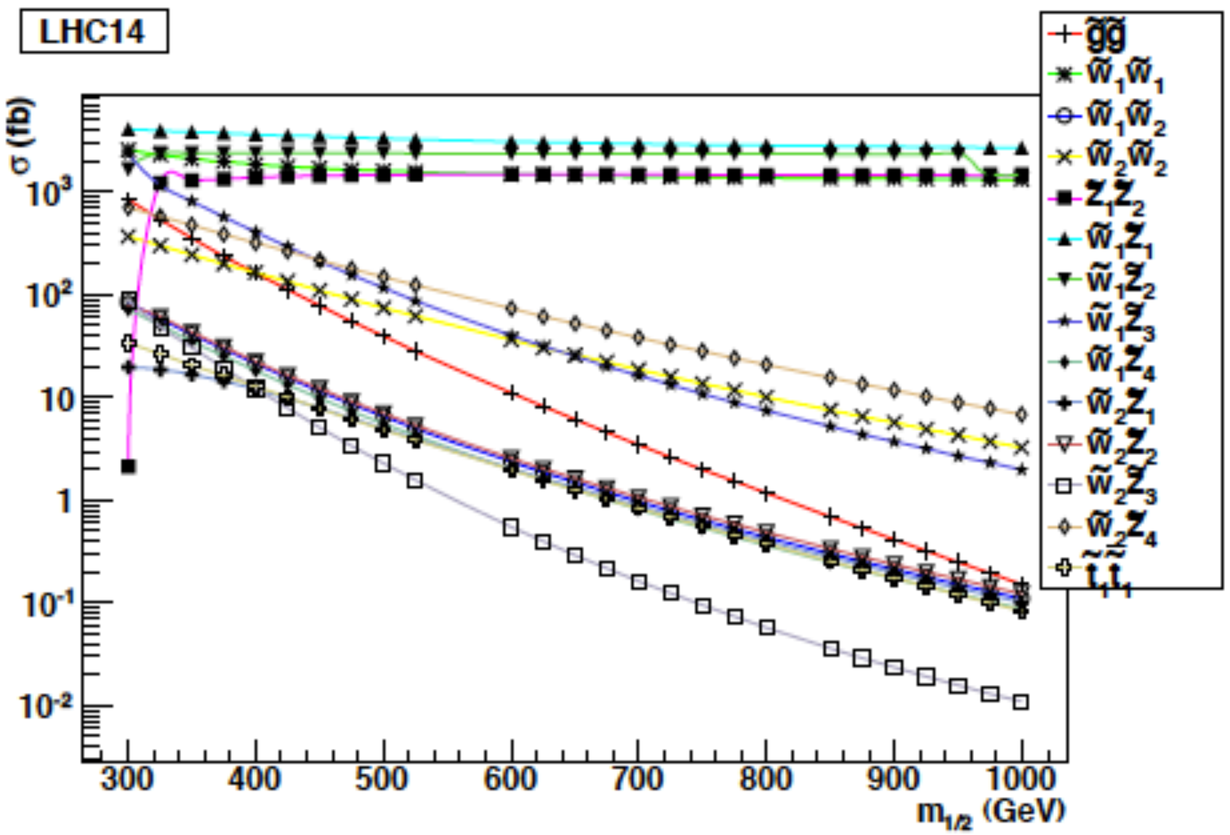


Heavier top squarks ameliorate these

Prospects for radiatively-driven NS at LHC

Model line with

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



$$pp \to \tilde{g}\tilde{g}X$$

$$\tilde{g} \to tb\tilde{W}_i,\ t\bar{t}\tilde{Z}_i$$

$$\tilde{Z}_2 \to \ell^+\ell^-\tilde{Z}_1$$

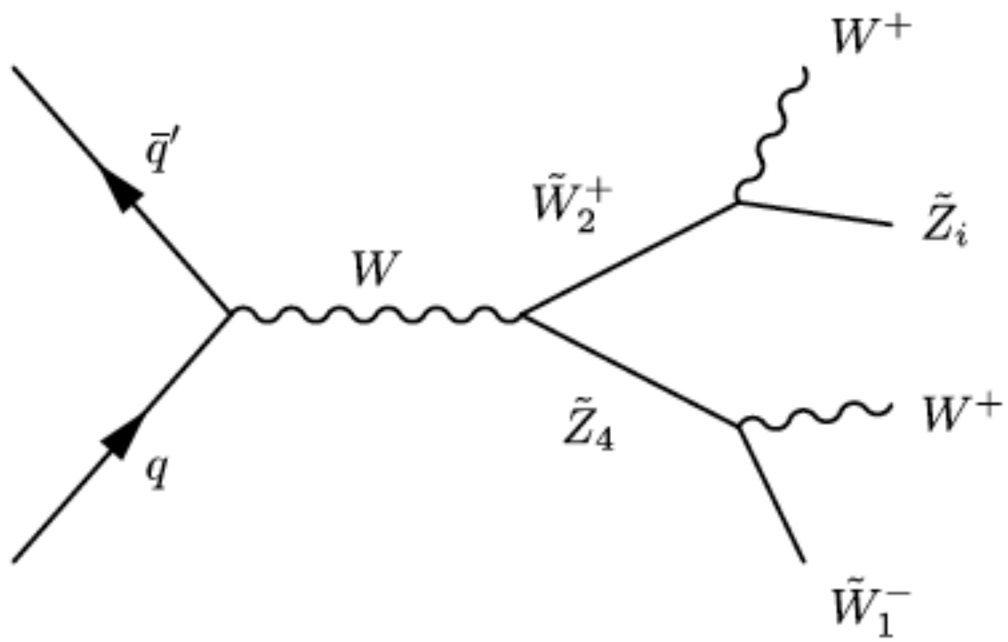
$$m_{\tilde{Z}_2} - m_{\tilde{Z}_1} <\sim 10 - 20\ \text{GeV}$$

LHC14 reach for gluino pairs:

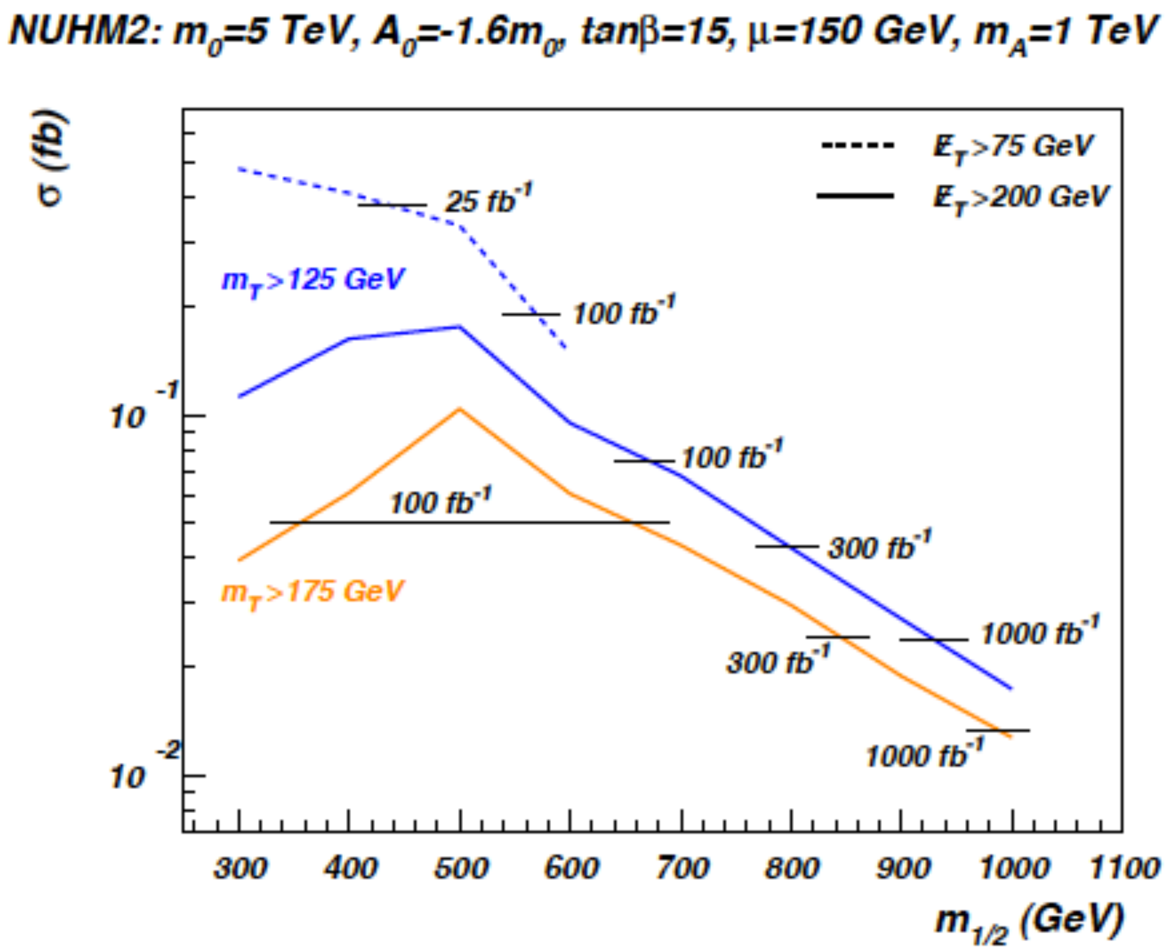
Int. lum. (fb^{-1})	$m_{1/2}$ (GeV)	$m_{\tilde{g}}$ (TeV) [$\tilde{g}\tilde{g}$]
10	400	1.4
100	840	1.6
300	920	1.8
1000	1000	2.0

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).
- $m_T^{min} \equiv \min\left[m_T(\ell_1, \not{E}_T), m_T(\ell_2, \not{E}_T)\right] > 125$ GeV

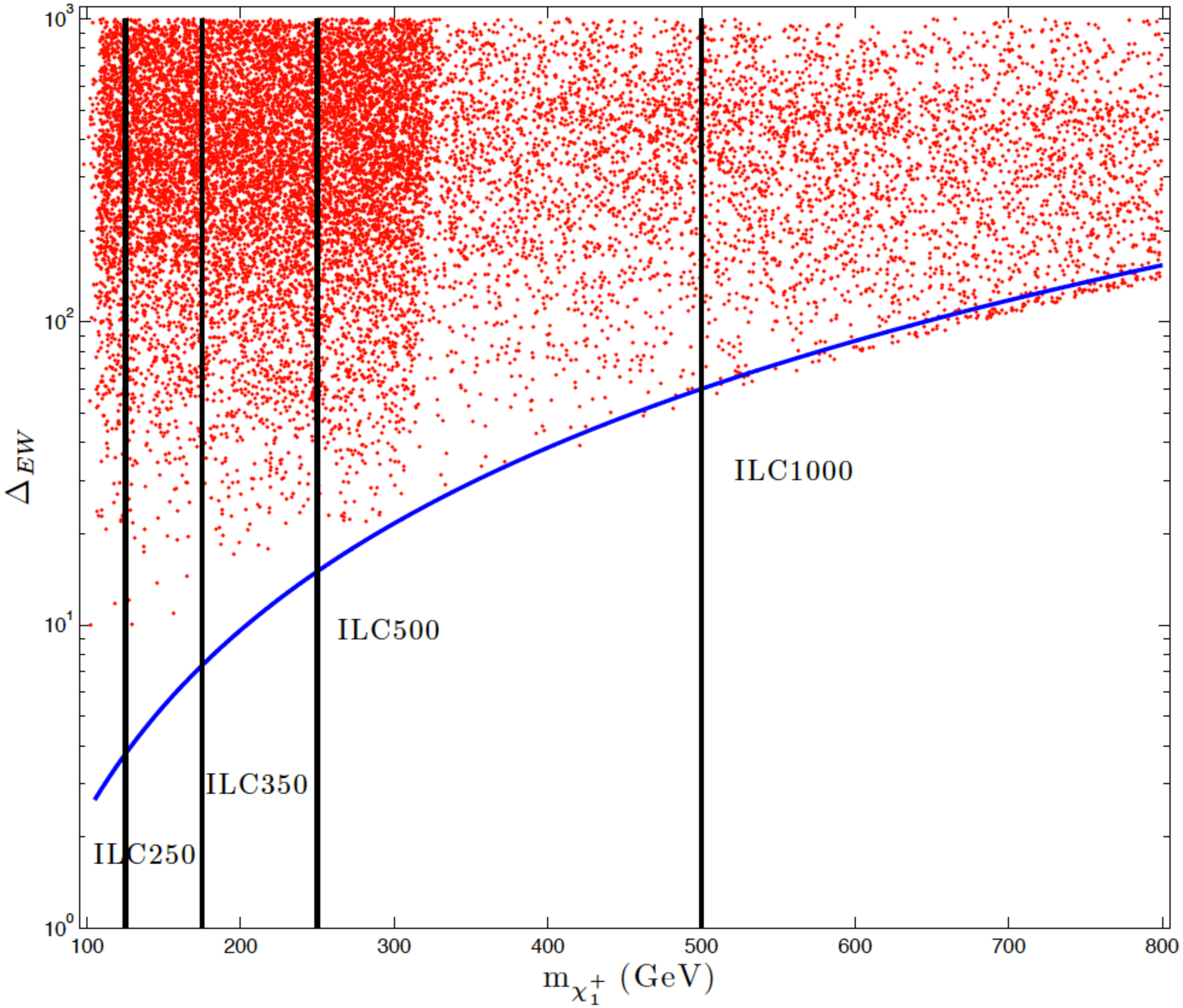
$\not{E}_T > 200$ GeV

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!

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



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

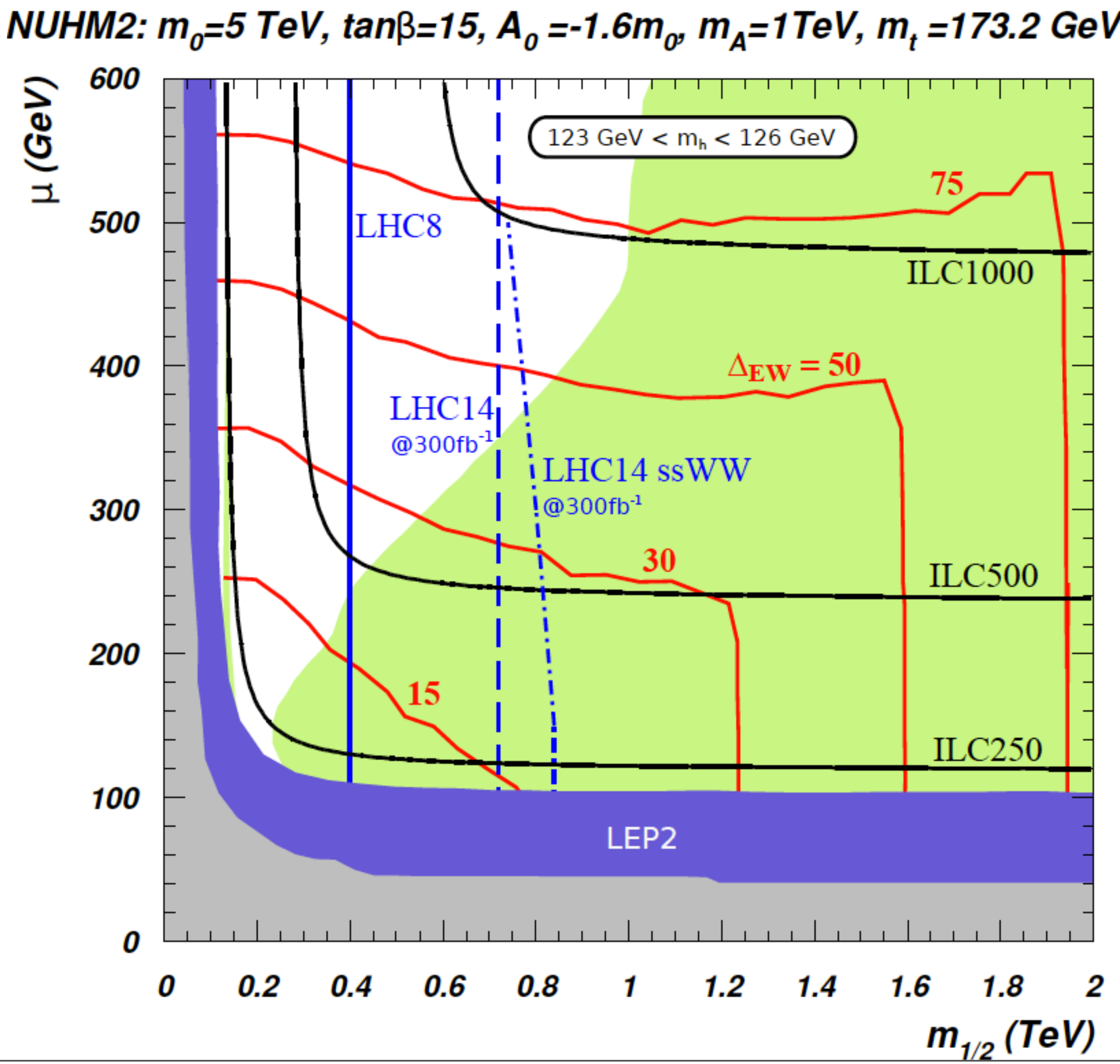
$$\sqrt{s} \sim \sqrt{2\Delta_{EW}} m_Z$$

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

$$\Delta_{EW}$$

measure and check if nature is EWFT'd?

LHC/ILC complementarity



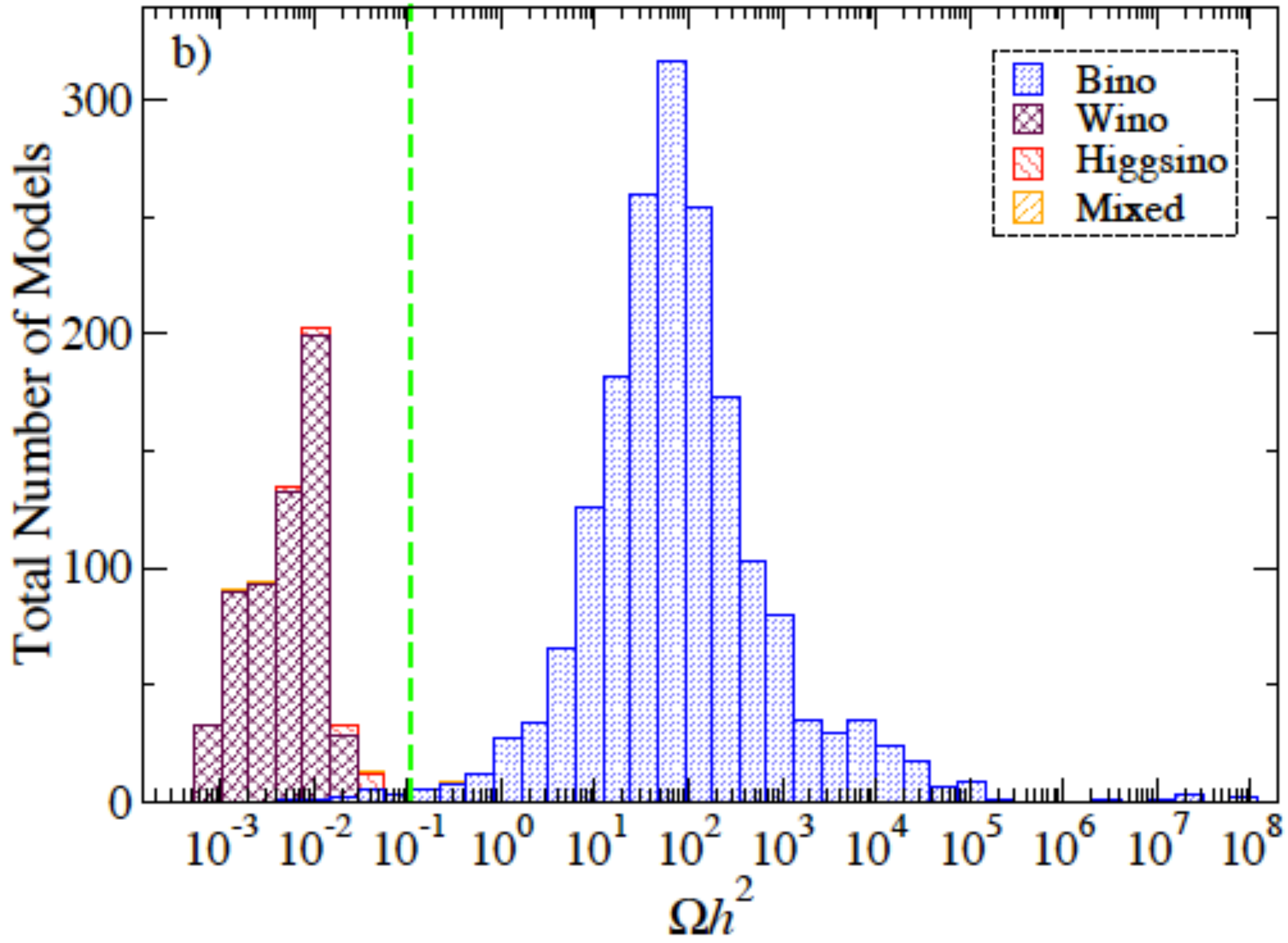
While LHC has some capacity, it will require ILC to draw the story of SUSY electroweak naturalness to a conclusion!

A. Mustafayev plot

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

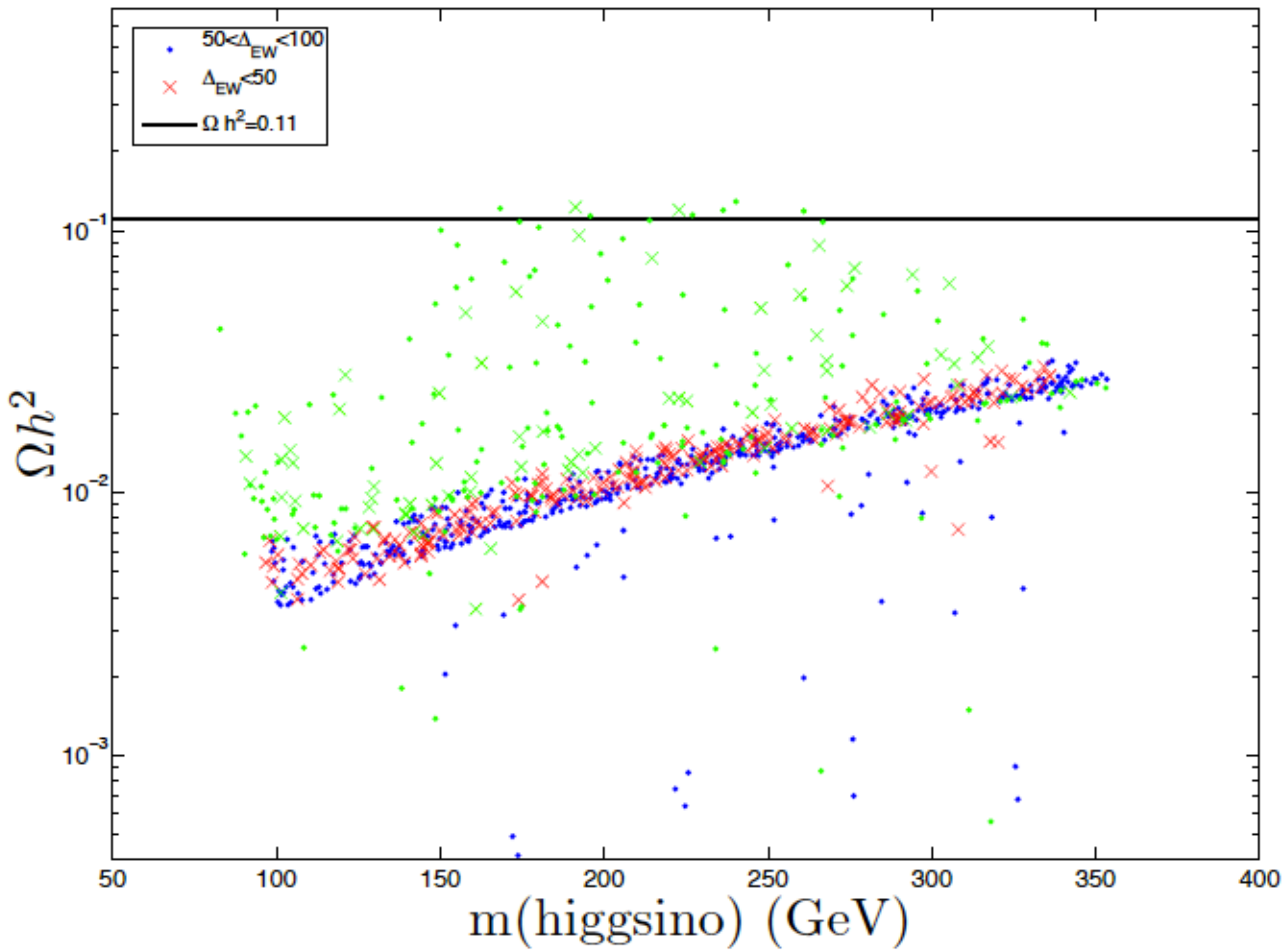
Lightest neutralino all by itself in general not good DM candidate: too much or too little CDM

Scan over 19 parameters:



HB, Box, Summy
JHEP1010(2010)023

Standard thermal abundance for RNS model



green: already excluded by WIMP searches

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

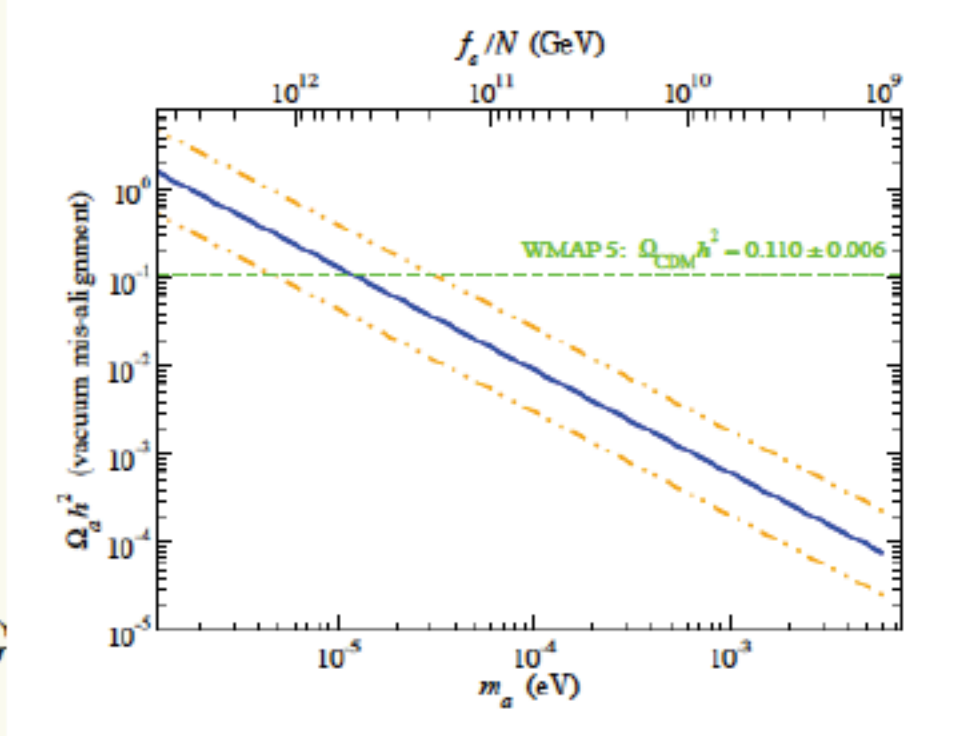
Invoke Peccei-Quinn sol'n to strong CP problem with SUSY

PQMSSM: Axions + SUSY $\Rightarrow$ 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$\rightarrow$ 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

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
- ⋆ $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} \theta_i^2 h^2$
- ⋆ astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 G$



What if $m_{\tilde{a}} > m_{\widetilde{Z}_1}$ so $\widetilde{Z}_1 = LSP$?

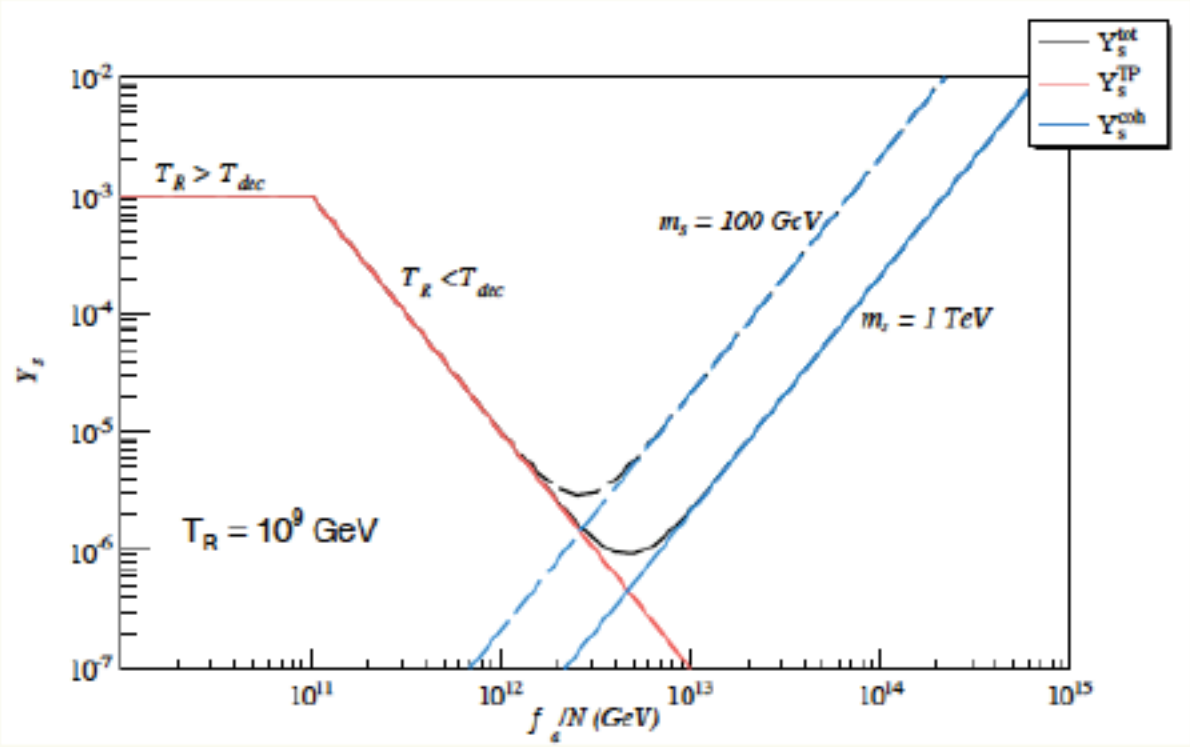
- (see also Choi, Kim Lee, Seto)
- Expect mixed axion/neutralino CDM: which will dominate?
- Neutralinos produced thermally as usual (RD, MD or DD universe)
- Axino production and decay (e.g. $\tilde{a} \to \widetilde{Z}_1\gamma$) will augment neutralino production.
- Decay produced $\widetilde{Z}_1$s at temp $T_D = \sqrt{\Gamma_{\tilde{a}} M_P}/(\pi^2 g_*(T_D)/90)^{1/4}$ can re-annihilate if $\langle\sigma v\rangle n_{\widetilde{Z}_1}(T_D) > H(T_D)$
- Axions produced as usual via vacuum misalignment (but evaluate in RD, MD or DD universe); can be diluted by entropy from axino decay
- Neglecting saxions, expect to work best for models with too low of usual thermal abundance (wino-like or higgsino-like neutralinos)
- HB, Lessa, Rajagopalan, Sreethawong, JCAP**1106** (2011) 031

What about cosmology of saxion field $s(x)$?

★ HB, Kraml, Lessa, Sekmen [JCAP1104 (2011)039]

★ saxion production in early universe

- Thermal production dominates at low f_a
- production via coherent oscillations dominates at large f_a



Dark matter production rates depend on saxion decays

- s-> gg, (entropy dilution)
- s-> glno+glno (LSP production)
- s-> aa (dark radiation; Neff constraints)
- s-> hh (entropy dilution)
- s-> hgno+hgno (LSP production)

Coupled Boltzmann calculation of mixed axion-neutralino abundance

Bae, HB, Lessa, arXiv:1301.7428

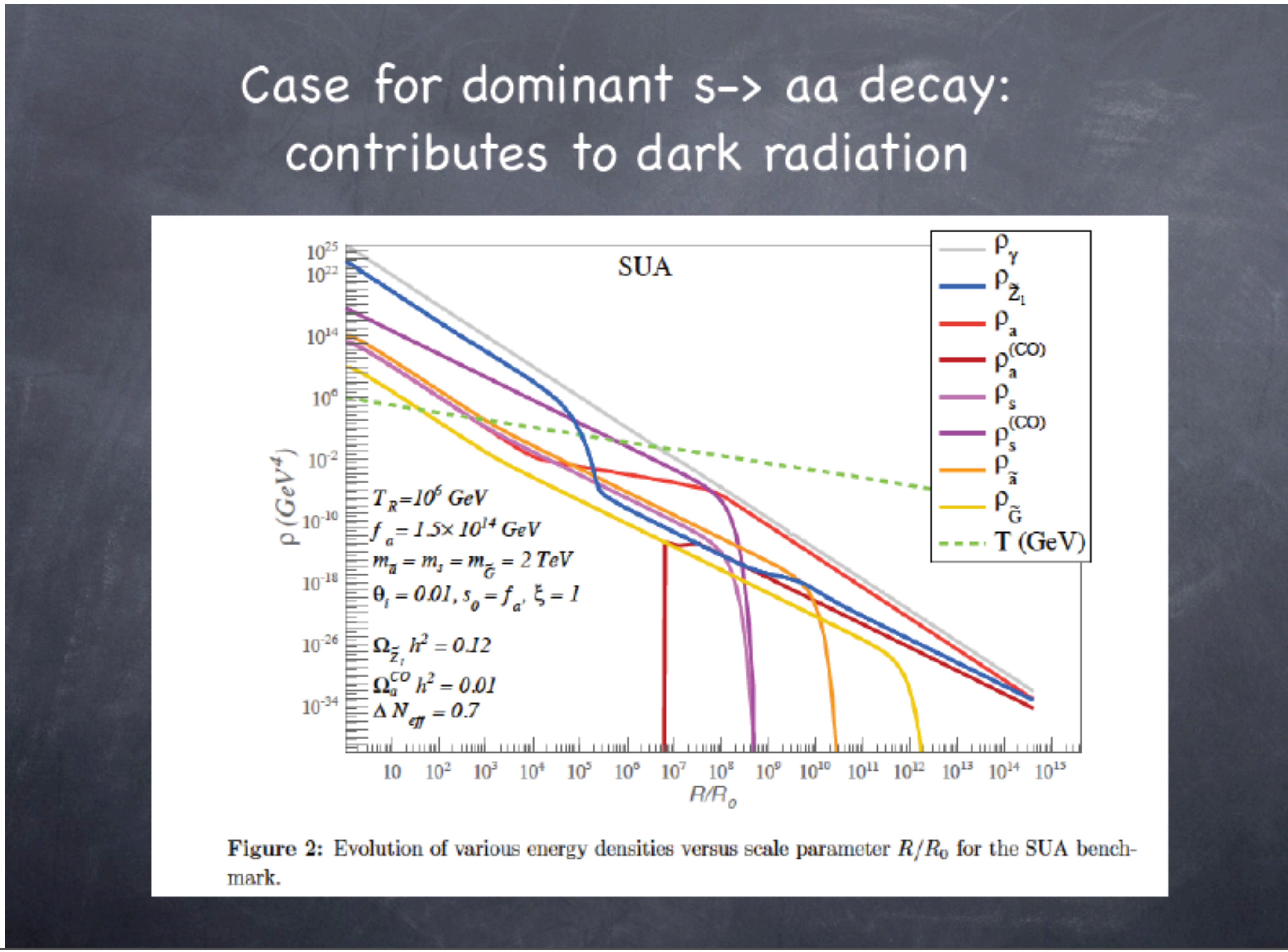
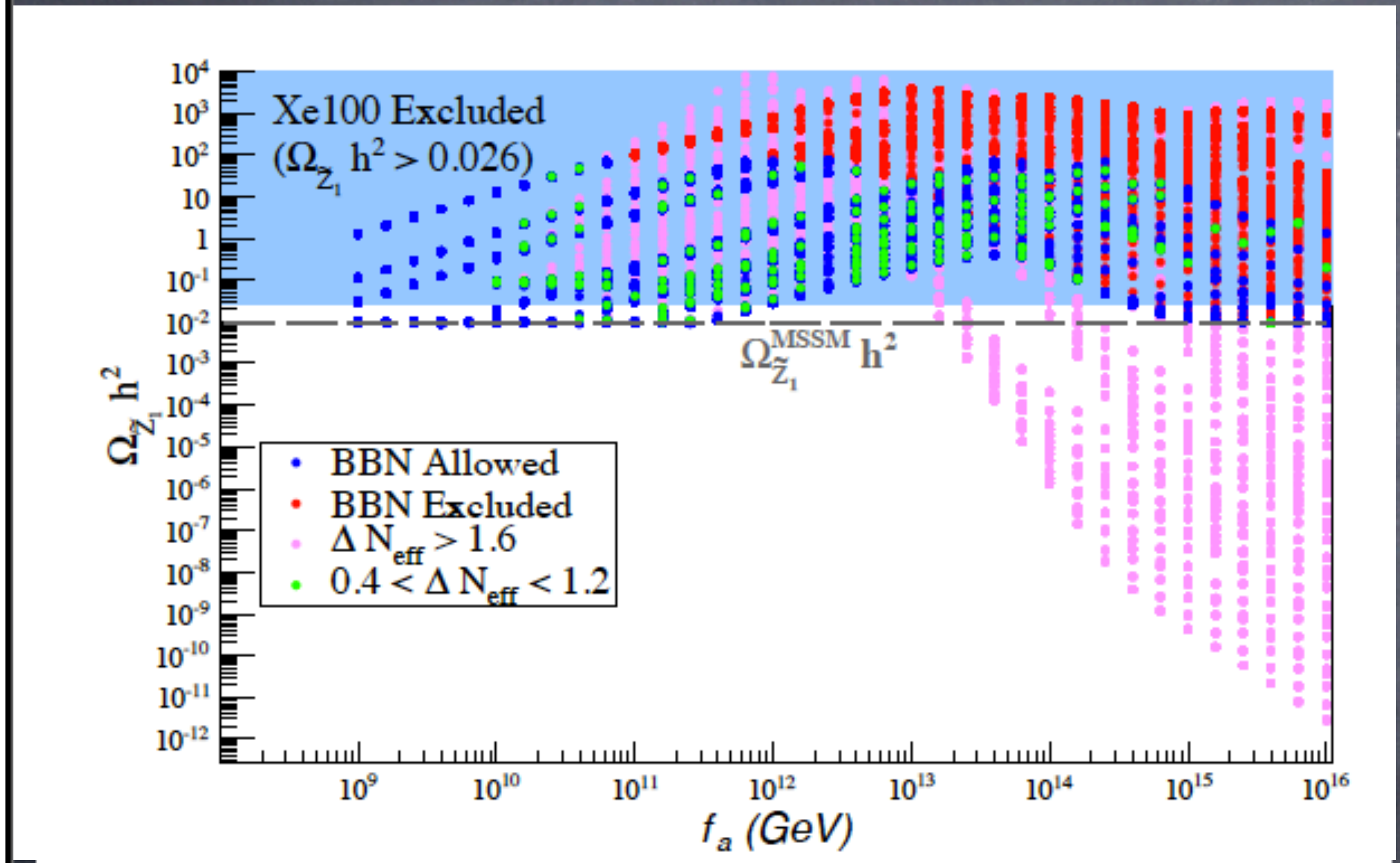


Figure 2: Evolution of various energy densities versus scale parameter R/R_0 for the SUA benchmark.

Mixed higgsino-axion CDM in radiative natural SUSY



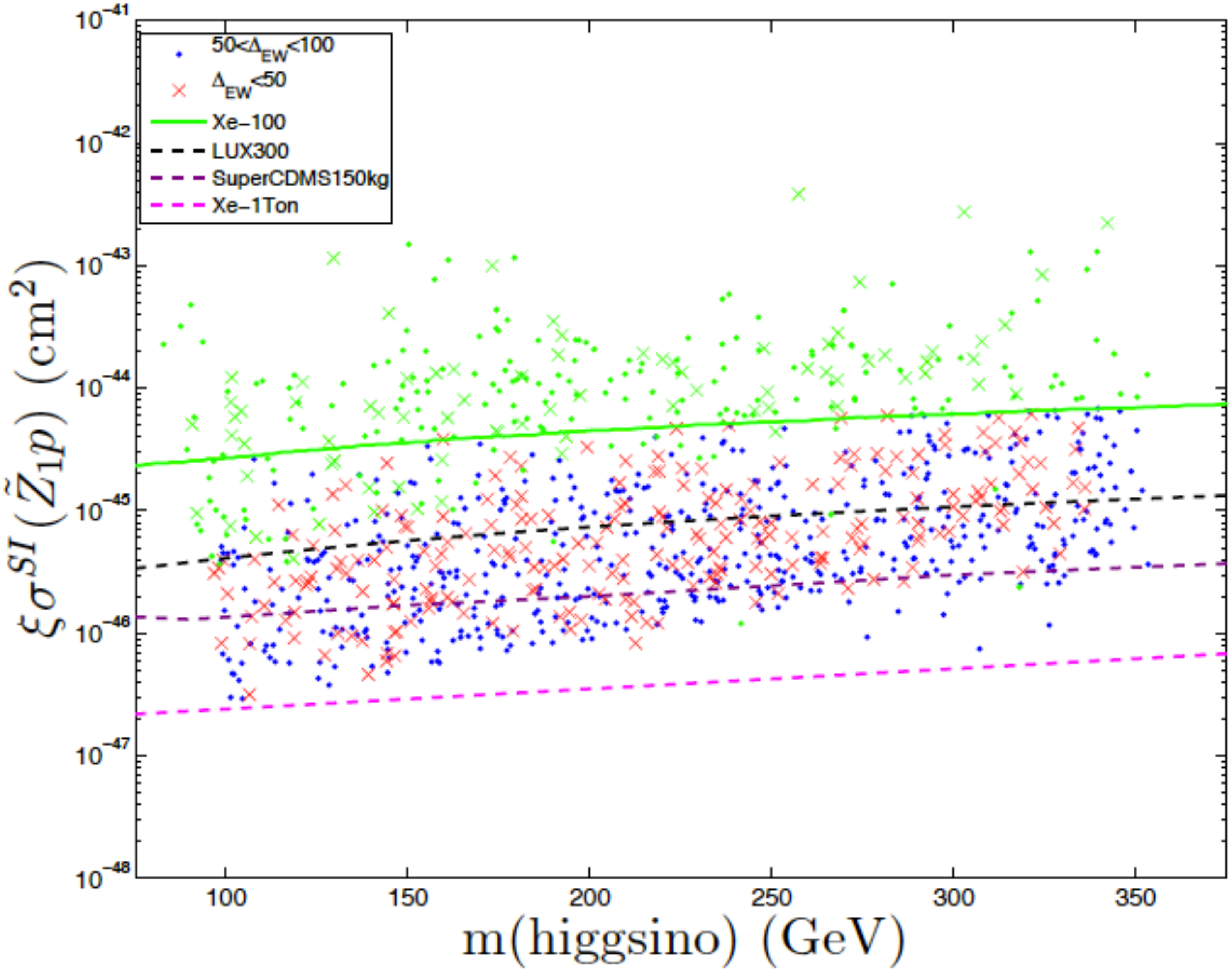
$f_a \sim 10^{14}$ GeV *allowed*!

(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)

Conclusions

- Delta_EW is more robust measure of Little Hierarchy problem
- Why are m(Z),m(h)~100 GeV while sparticle masses are >> 1 TeV?
- mu~ m(Z): light higgsinos (ILC!)
- m(Hu) driven somewhat, not grossly, negative
- large mixing in stop sector

Under these conditions, the Little Hierarchy remains
but the ``Problem” seems
to melt away and the old paradigm of
SUSY GUTs remains strong:
but with huge implications for collider/dark matter searches!

- The low lying sparticles (higgsinos) have severely compressed spectra: hard to see at LHC (but new signatures e.g. SS dibosons)

- No large cancellations in m(Z), m(h)=> ILC is the right machine to build!

- Dark matter production more intricate than usual story: here, we suggest mixed axion-higgsino (co-dark-matter) particles: possibly detect both WIMPS and axions?