Why construction of ILC must begin immediately

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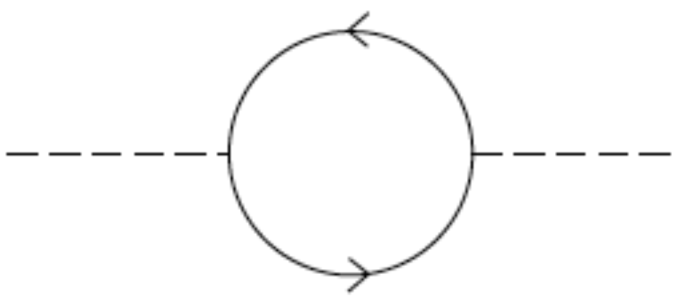
Perspective from the SUSY BSM group reporting to Snowmass 2013

- Discovery of Higgs h(125) by LHC completes the Standard Model!
- BUT....

- Problem #1: quantum corrections to m(h)^2 are quadratically divergent!



$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

Supersymmetry provides solution by canceling to all orders via superpartners

Story for past 32 years: need weak scale SUSY for realistic model

- Problem #2: strong CP
- why 3 not 4 light pions?
- t'Hooft solution: QCD theta vacuum:

$$\mathcal{L} \ni \bar{\theta} \frac{g_s^2}{32\pi^2} F_A^{\mu\nu} \tilde{F}_{A\mu\nu}$$

- But: nEDM => $\bar{\theta} < 10^{-10}$
- Solution: axion

MSSM: simplest SUSY realization

- gauge coupling unification
- m(t)~173 GeV: radiative EWSB
- EWPO (heavy SUSY)
- m(h)~115-135 GeV

Conundrum: no sign of SUSY at LHC in spite of theorists telling us for 30 years that m(sparticle)~m(weak)~m(Z)~m(h)!

What is basis for this statement?

Scalar potential minimization in MSSM:

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

EWFT condition:

no large uncorrelated contributions to m(Z)!

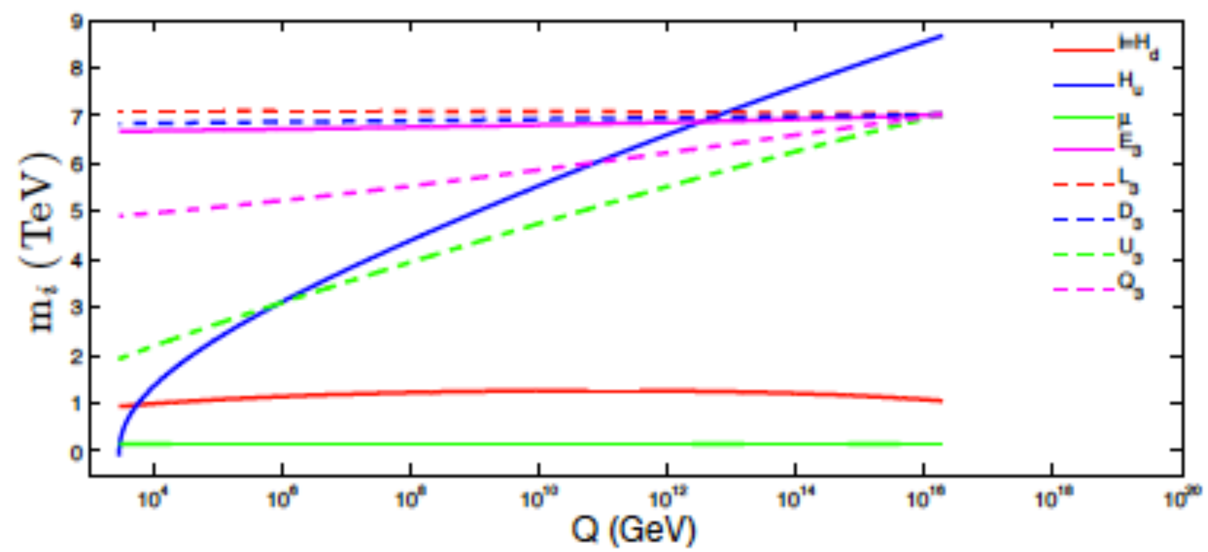
- $\mu^2 \sim m_Z^2/2$
- $-m_{H_u}^2 \sim m_Z^2/2$
- $\Sigma(\tilde{t}_{1,2}) \sim m_Z^2/2$

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

- mu~100-200 GeV (FP region or NUHM models)

$$\mu \sim \lambda m_{3/2}$$

NUHM model



- m_Hu^2 doesn't run too much negative

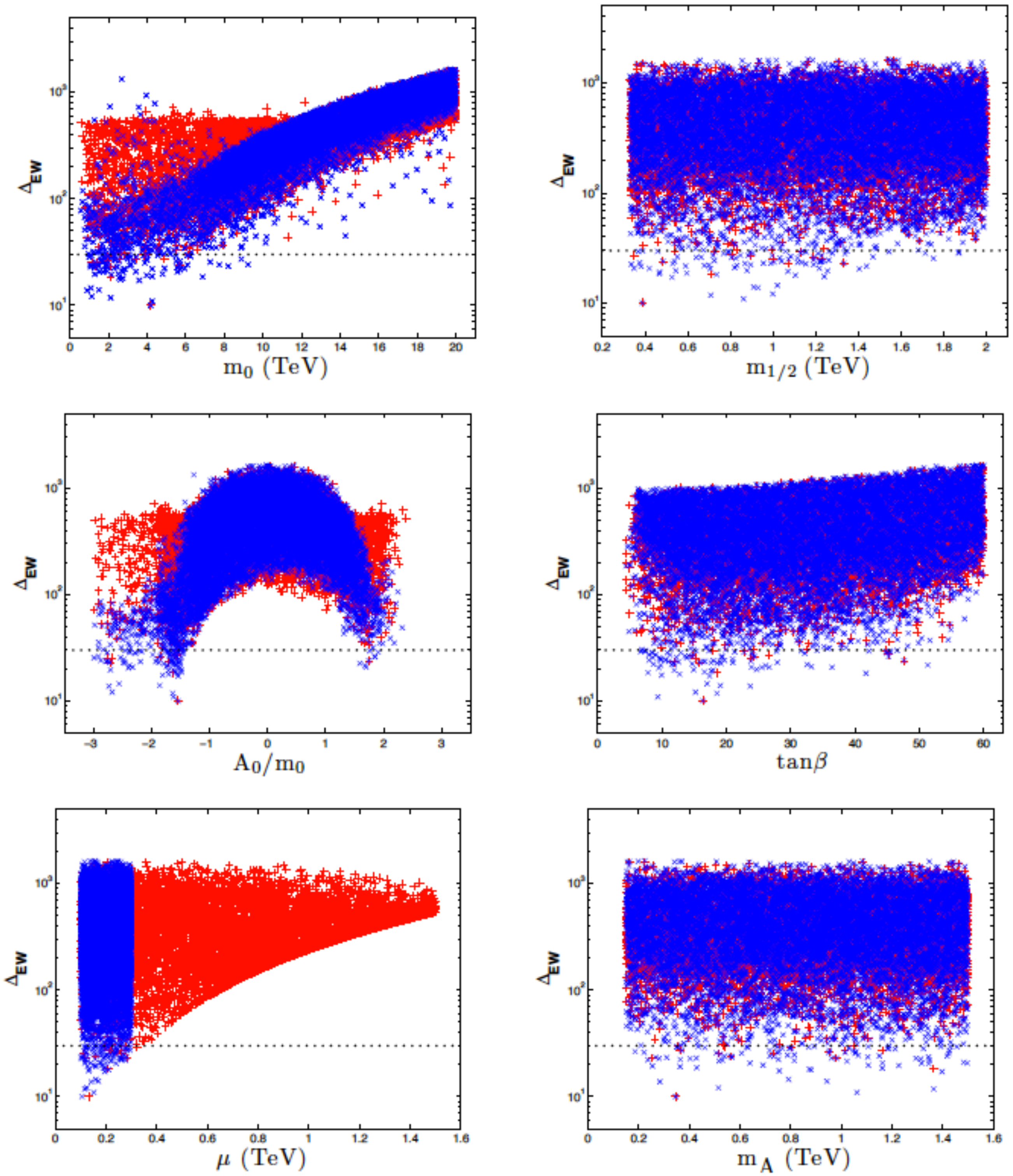
- radiative corrections not too big (no FP)

$$F(m^2) = m^2\left(\log(m^2/Q^2) - 1\right)$$

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

large A_t softens radiative corr'ns while lifting m(h)!

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

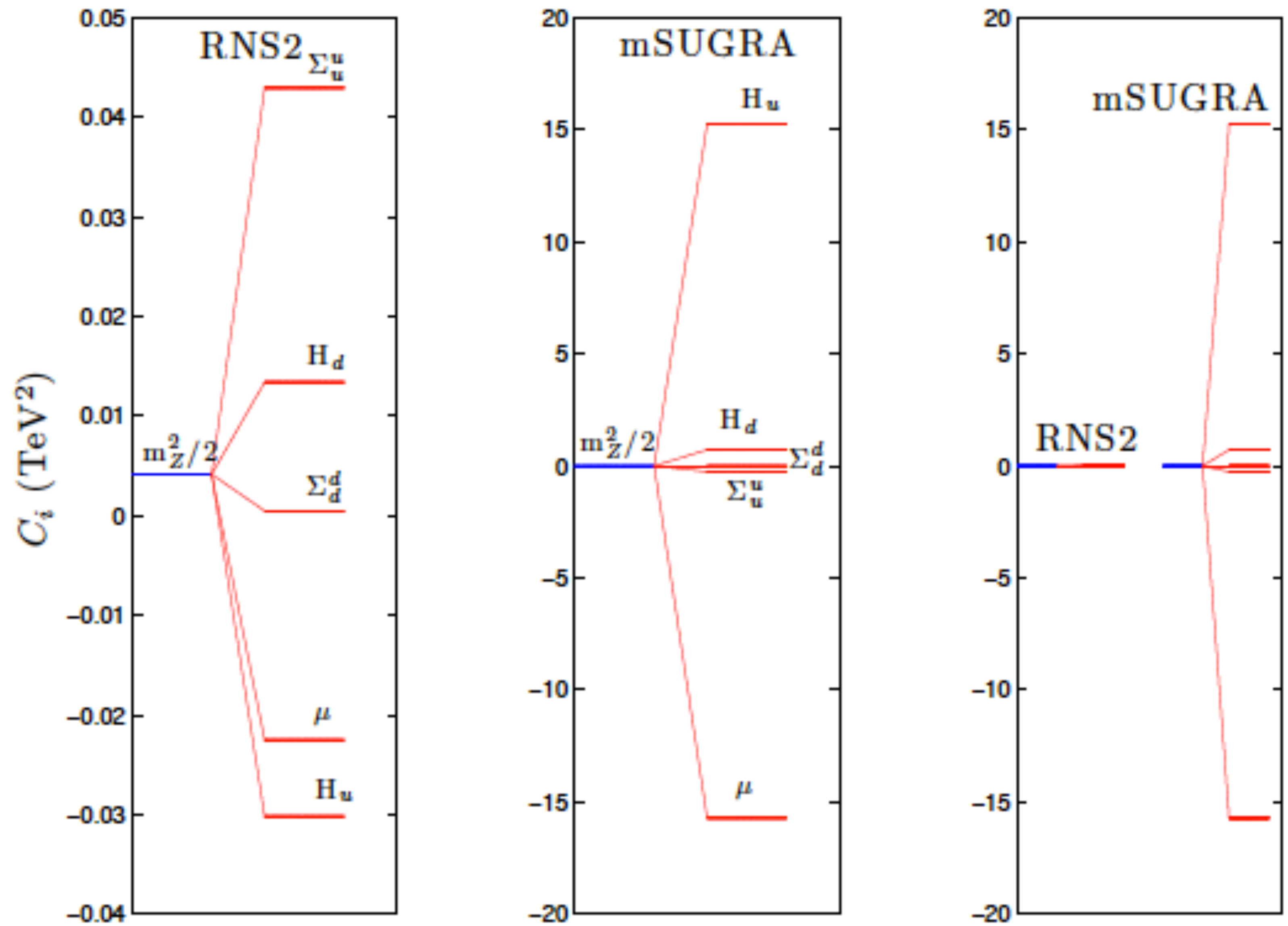
$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV. $A_0 = -11426.6$ GeV, $\tan\beta = 8.55$ with $\mu = 150$ GeV and $m_A = 1000$ GeV

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

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



SUSY spectra from radiatively-driven natural SUSY (RNS)

scan NUHM2 space:

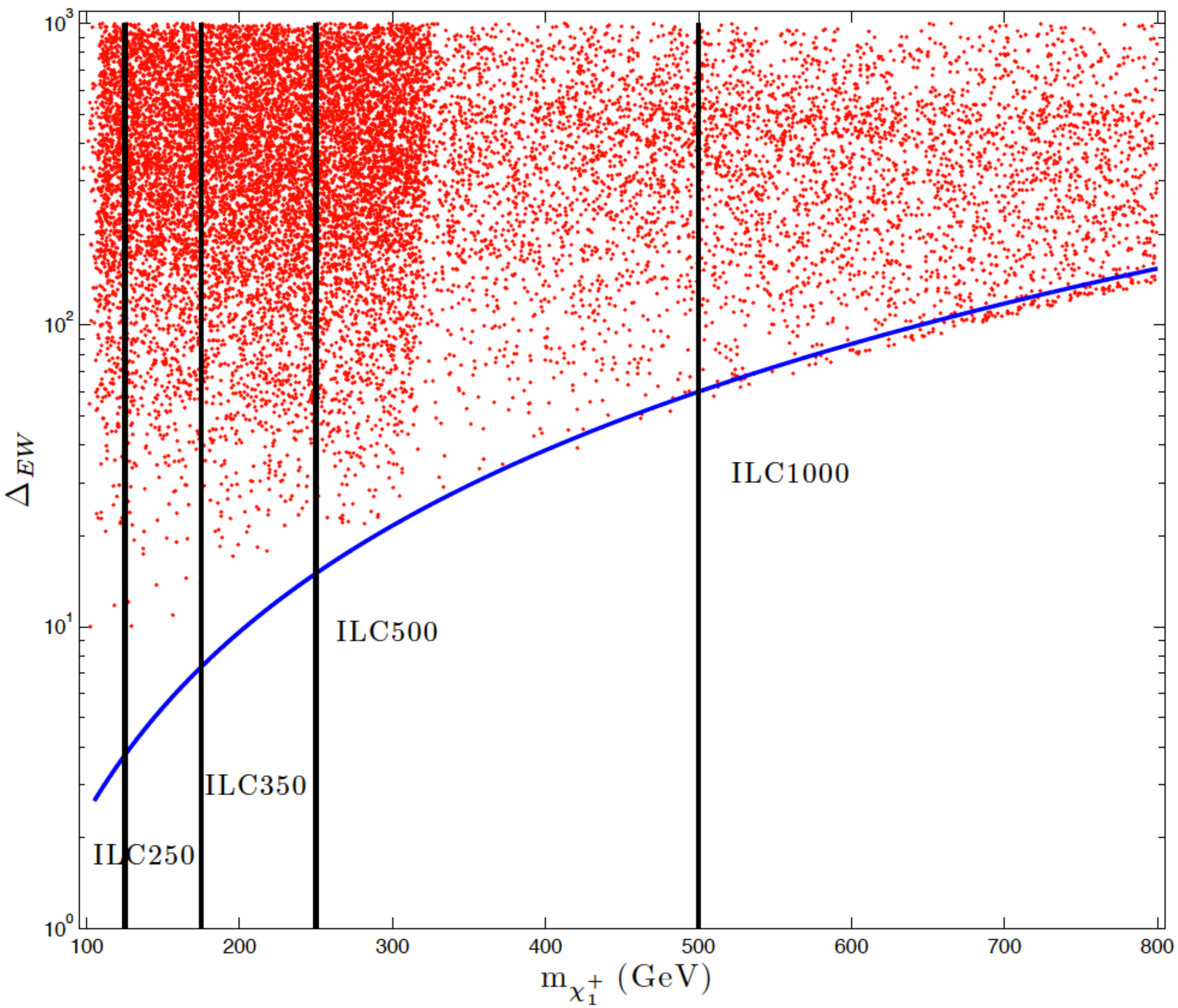
- light higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_{1,2}$ with mass $\sim 100-300$ GeV,
- gluinos with mass $m_{\tilde{g}} \sim 1-4$ TeV,
- heavier top squarks than generic NS models: $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-5$ TeV,
- first/second generation squarks and sleptons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

Very hard to see even at LHC14 when m(gl)>2 TeV

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

Smoking gun signature: 4 light higgsinos at ILC!

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



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

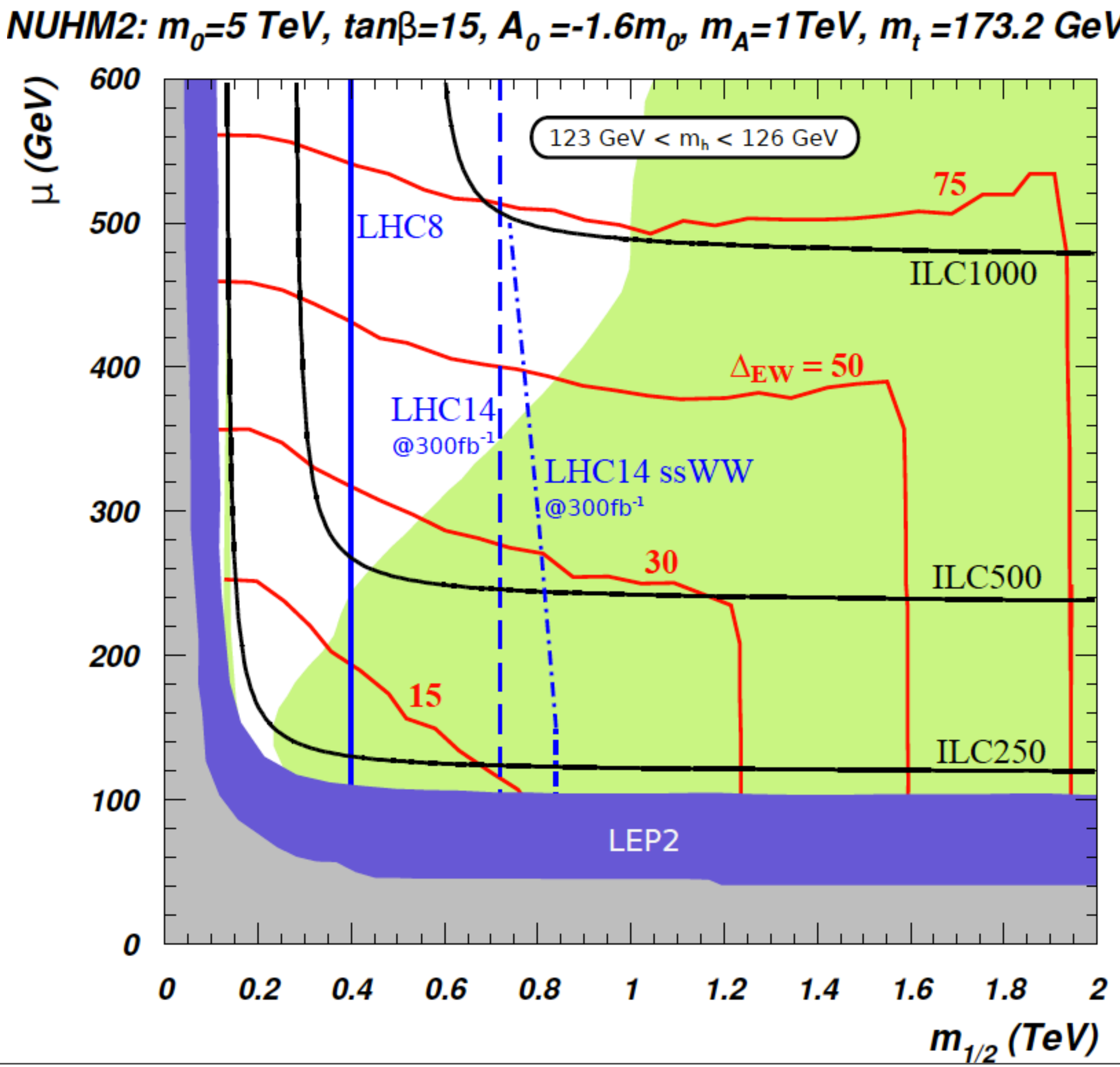
$$\sqrt{s} \sim \sqrt{2\Delta_{EW}}m_Z$$

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

- Thus, we see that the only SUSY particles guaranteed ~m(weak) are higgsinos:

- m(Z)~m(higgs)~m(higgsino)

- ILC will be higgsino factory in addition to Higgs factory

- m(chi+) / m(chi0) to ~2 GeV;
  deltaM(chi+,chi0) to ~5 MeV;
  pol. x-sections to 1-2% ; detailed talks: see afternoon BSM session: Sert, Rolbiecki

- Either ILC w/ root(s)~500-600 GeV discovers light higgsinos or the idea of SUSY weak scale naturalness is dead!

For the lower range of m(gluino)~<2 TeV, LHC may discover! But as colored sparticle masses increase, then cross sections lower: precision studies limited by statistics

At the ILC, SUSY is really simplified: can cover all NSLP-LSP combinations for arbitrary mass differences (meta-stable, kinks, prompt,...) like at LEP

Other featured studies:

* general ewkino scan joint with LHC:
Higgsino, Wino or Bino LSP, scan the other two parameters ->
plot 5sigma discovery range / 2sigma
exclusion range for LHC (Delphes) / ILC (SGV)

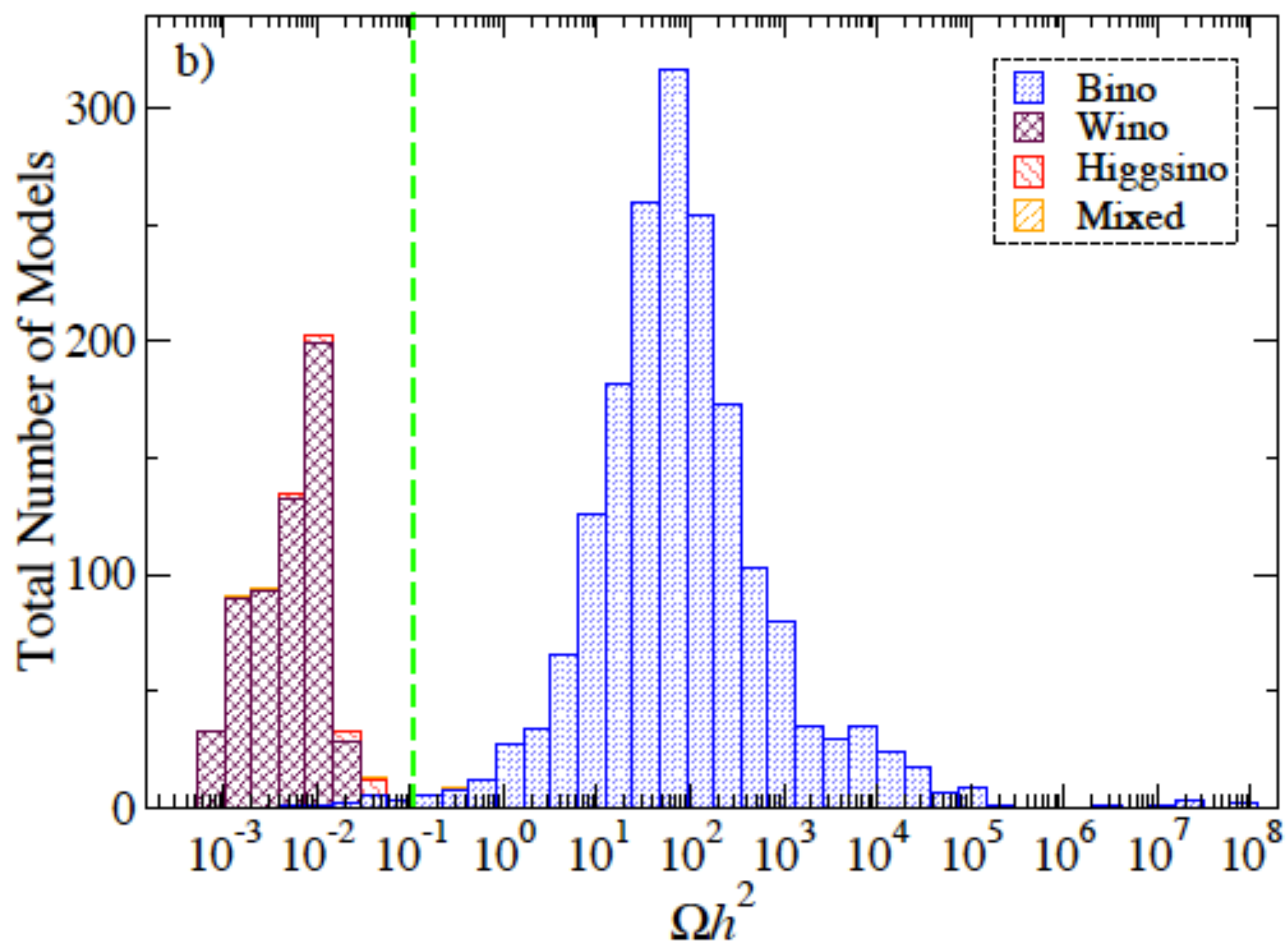
* a complexified SUSY model:
simplified models can give very misleading messages at LHC ->
study a very rich spectrum with many concurring decay chains:
STC benchmark (aka TDR4) both from LHC
(Delphes) and ILC (full sim / SGV)

* connection to intensity frontier:
bRPV: can do neutrino physics at colliders:
cf talks by LHC and ILC (Vormwald) later

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

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

Coupled Boltzmann calculation of mixed axion-neutralino abundance

Bae, HB, Lessa, arXiv:1301.7428

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

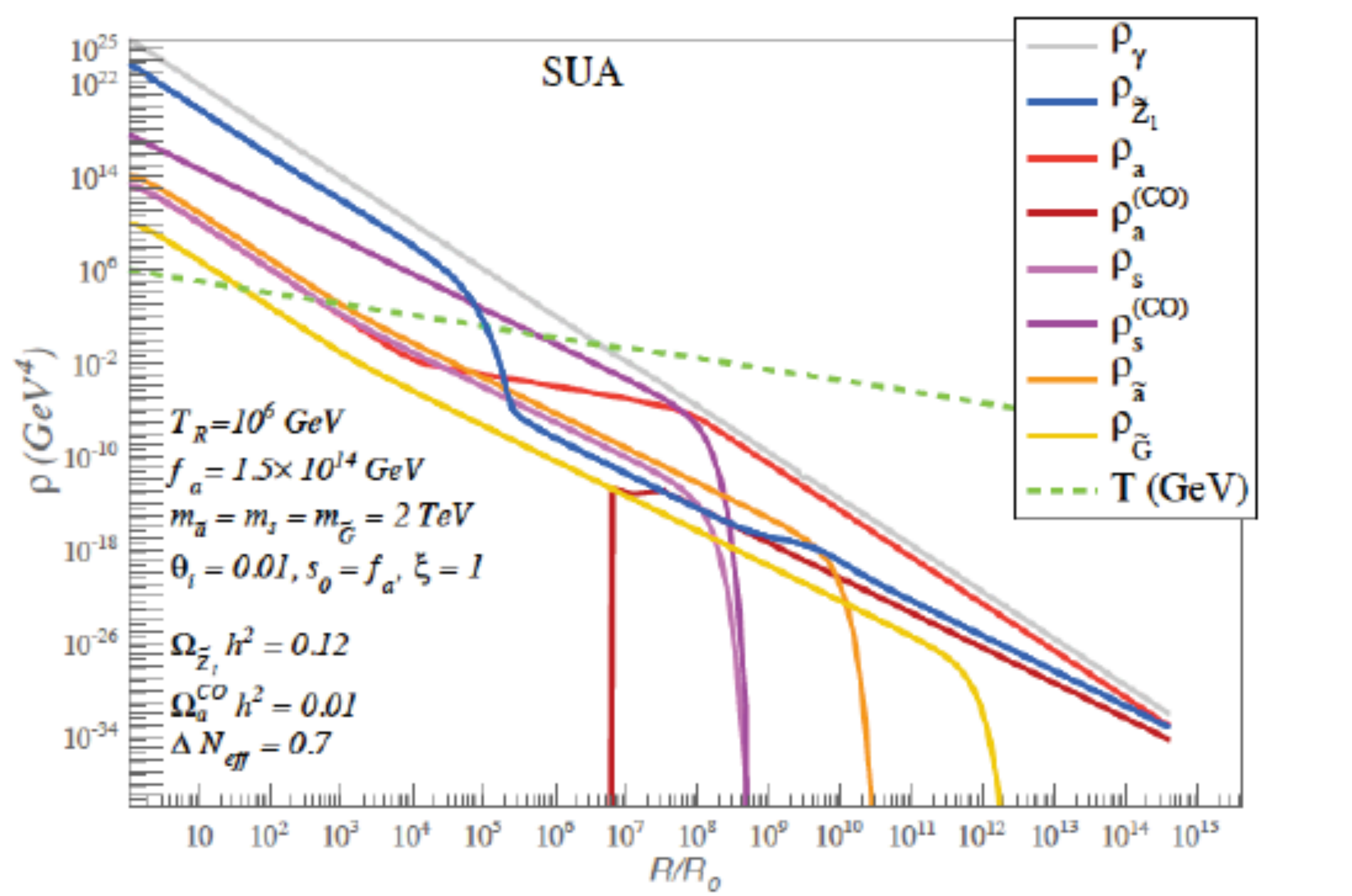


Figure 2: Evolution of various energy densities versus scale parameter R/R_0 for the SUA benchmark.

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?

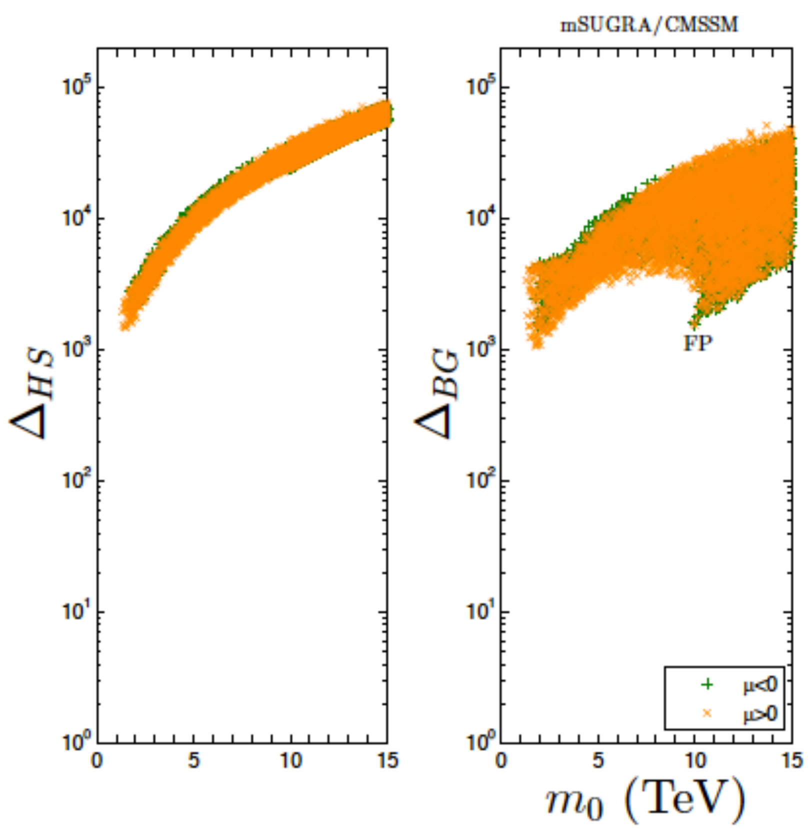
Backup:

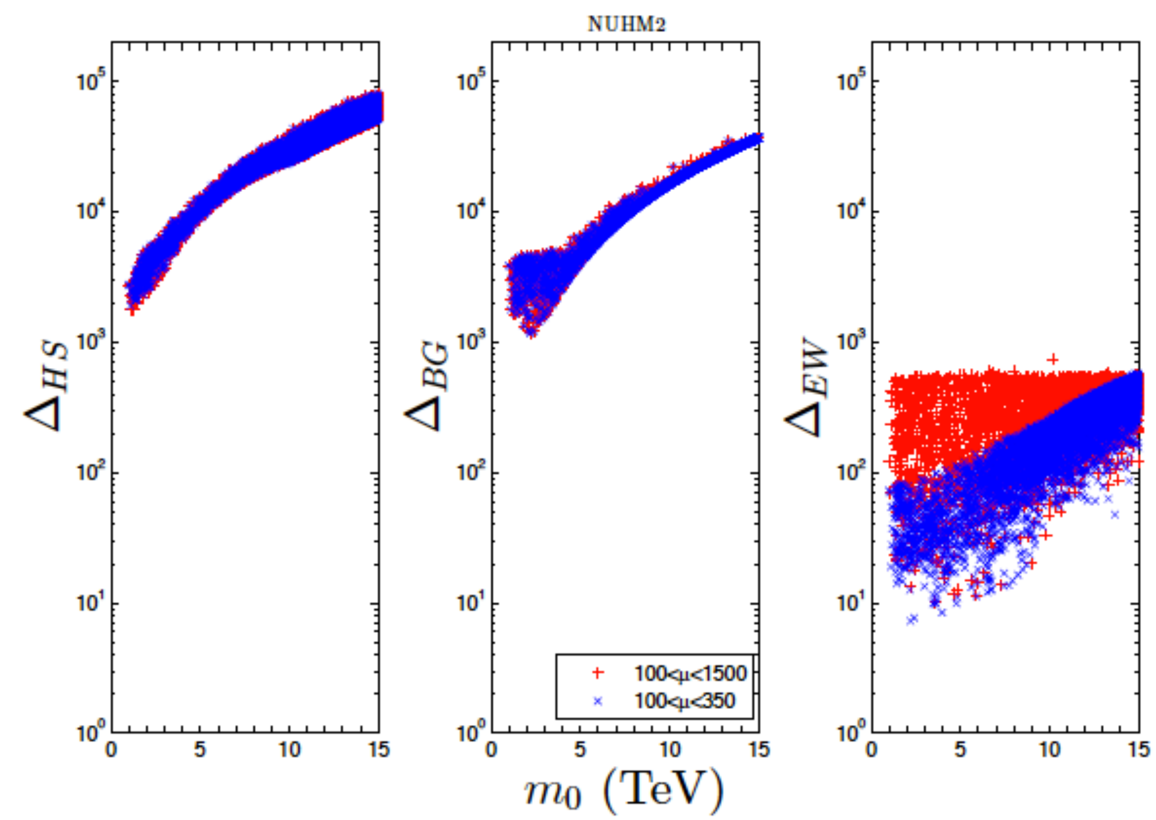
$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2(\Lambda) + \delta m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - (\mu^2(\Lambda) + \delta\mu^2)$$

$$\Delta_{\rm HS} \equiv max_i|B_i|/(m_Z^2/2)$$

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

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





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