Progress in natural SUSY: radiatively-driven natural SUSY (RNS)

(and why we must get started on ILC immediately)

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References:

Radiative natural SUSY with a 125 GeV Higgs boson (with V. Barger, P. Huang, A. Mustafayev and X. Tata), Phys. Rev. Letters **109** 161802 (2012).

Radiative natural supersymmetry: reconciling electroweak finetuning with the Higgs mass (with Barger, Huang, Mickelson, Mustafayev and Tata), arXiv:1212.2655 (2012).

Same sign diboson signature from supersymmetry models with light higgsinos at the LHC (with V. Barger, P. Huang, D, Mickelson, A. Mustafayev, W. Sreethawong and X. Tata), Phys. Rev. Lett. **110** (2013) 151801.

- The story for more than 30 years: SUSY particles at or around the weak scale: if not, then SUSY is ``unnatural"
- No sign of SUSY particles so far at LHC8
- A seemingly troublesome Little Hierarchy is developing: m(sparticle) > 1 TeV >> m(W,Z,h)~100 GeV
- When do we give up on weak scale SUSY? (some already have, see e.g. Shifman, arXiv:1211.0004)

To proceed further, must get technical

m(Z,h) related to soft-SUSY breaking parameters via minimization condition:

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

Naturalness requires no uncorrelated large cancellations on RHS

$$\Delta_{\rm EW} = max\left(\left|\frac{-m_{H_u}^2\tan^2\beta}{\tan^2\beta-1}\right|, \left|\frac{-\Sigma_u^u(\tilde{t}_1)\tan^2\beta}{\tan^2\beta-1}\right|, \cdots, |-\mu^2|\right)/(M_Z^2/2)$$

$\Delta_{\rm EW} \sim 10-30$ then 3-10% EWFT

Delta_EW as constructed neglects large logs which are present in high scale theory: can insert these as follows:

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

Here, $$\delta m_{H_u}^2|_{rad} \simeq -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/M_{SUSY}^2\right)$$

Requiring no large contributions implies ``natural SUSY":

Taking $\Delta = 10$ (*i.e.* 10% EWFT) and Λ as low as 20 TeV

- $m_{\tilde{t}_i},\ m_{\tilde{b}_1} \lesssim 600$ GeV,
- $m_{\tilde{g}} \lesssim 1.5 - 2$ TeV.

This measure neglects correlations amongst soft parameters that can lead to large cancellations

As example: write $m^2_{H_u}$ in terms of GUT parameters

$$\begin{aligned}-2m^2_{H_u}(m_{weak}) &= 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\ &+0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\ &-0.025M_1A_t + 0.22A_t^2 + 0.004m_3A_b \\ &-1.27m^2_{H_u} - 0.053m^2_{H_d} \\ &+0.73m^2_{Q_3} + 0.57m^2_{U_3} + 0.049m^2_{D_3} - 0.052m^2_{L_3} + 0.053m^2_{E_3} \\ &+0.051m^2_{Q_2} - 0.11m^2_{U_2} + 0.051m^2_{D_2} - 0.052m^2_{L_2} + 0.053m^2_{E_2} \\ &+0.051m^2_{Q_1} - 0.11m^2_{U_1} + 0.051m^2_{D_1} - 0.052m^2_{L_1} + 0.053m^2_{E_1}\end{aligned}$$

If we write: $m_{H_u} = m_{U_3} = m_{Q_3} \equiv m_0$

as in mSUGRA/CMSSM, then large automatic cancellations in scalar mass direction: this is what is called ``focus point SUSY"

Feng, Matchev, Moroi

$$-2m^2_{H_u}(m_{\rm weak}) = 3.78m^2_{1/2} - 0.82A_0m_{1/2} + 0.22A_0^2 + 0.013m_0^2$$

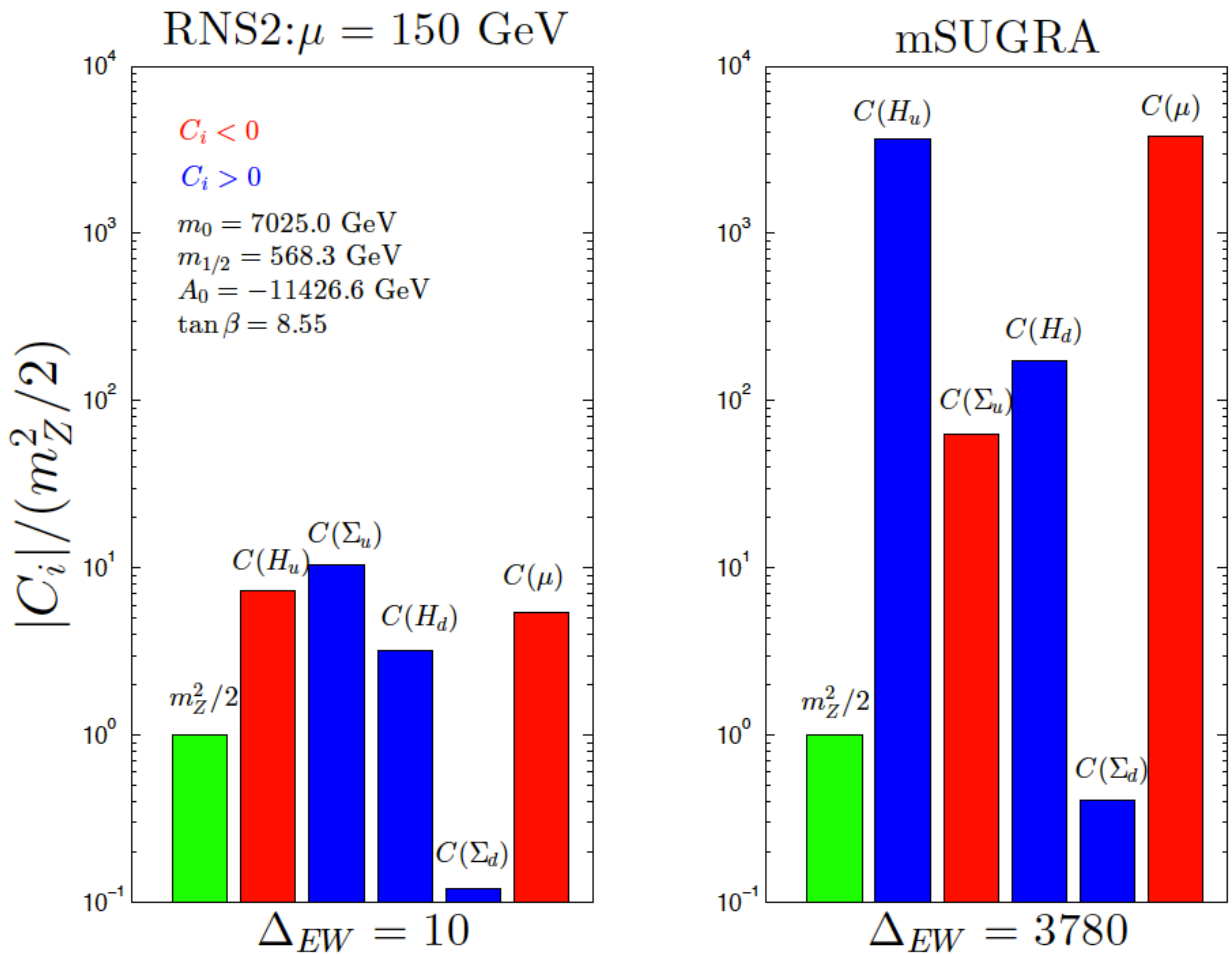
While I am not a proponent of mSUGRA/ CMSSM model, we can draw a lesson here:

Models such as mSUGRA, NUHM2 etc. are still ``effective field theories" whose parameters parametrize our ignorance of more fundamental TOE/string theory/meta-theory where high scale parameters are derived quantities which may allow for large cancellations

To allow for this possibility, Δ_{EW} provides the most conservative measure of finetuning: no large cancellations in m(Z) amongst weak scale parameters

What is then required for EW naturalness?

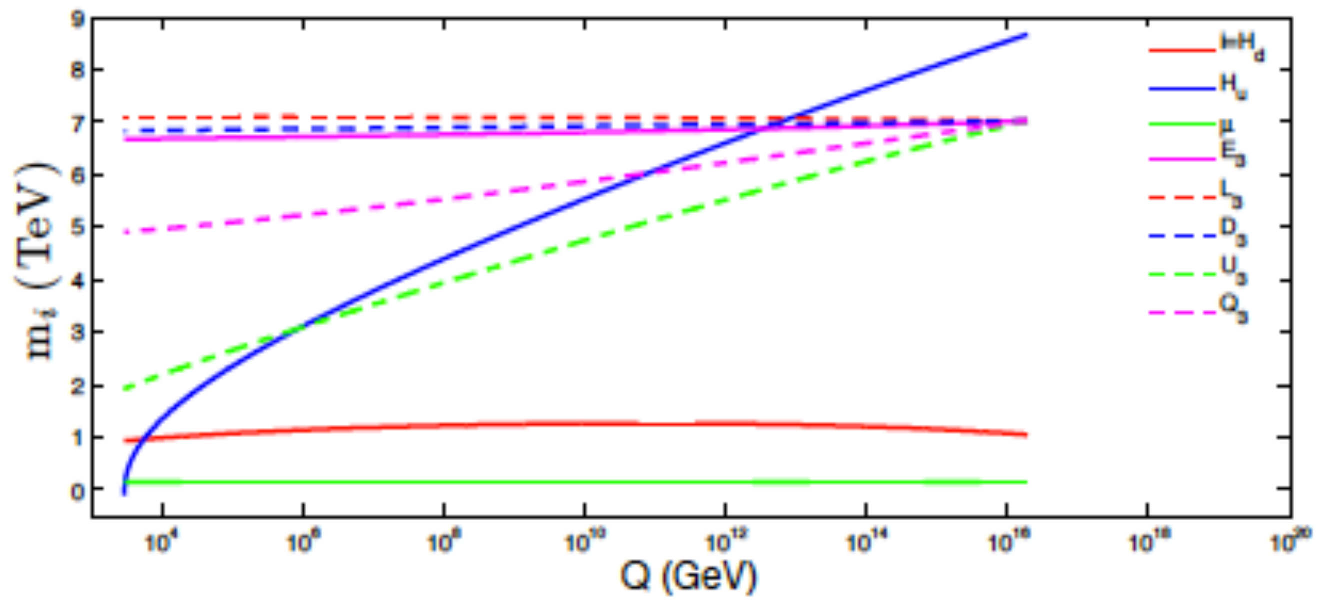
- superpotential mu term ~m(Z)~100-300 GeV
- m(H_u)^2 radiatively-driven to small values at EW scale: -(100-300)^2 GeV^2
- radiative corrections $\Sigma_u^u(\tilde{t}_{1,2})$ not too big: large mixing in stop sector softens radiative corrections whilst lifting m(h)~125 GeV
- mSUGRA, mGMSB, mAMSB finetuned under Delta_EW
- one realization of low Delta_EW models is Radiatively-driven natural SUSY, or RNS, which uses the NUHM2 parameter space

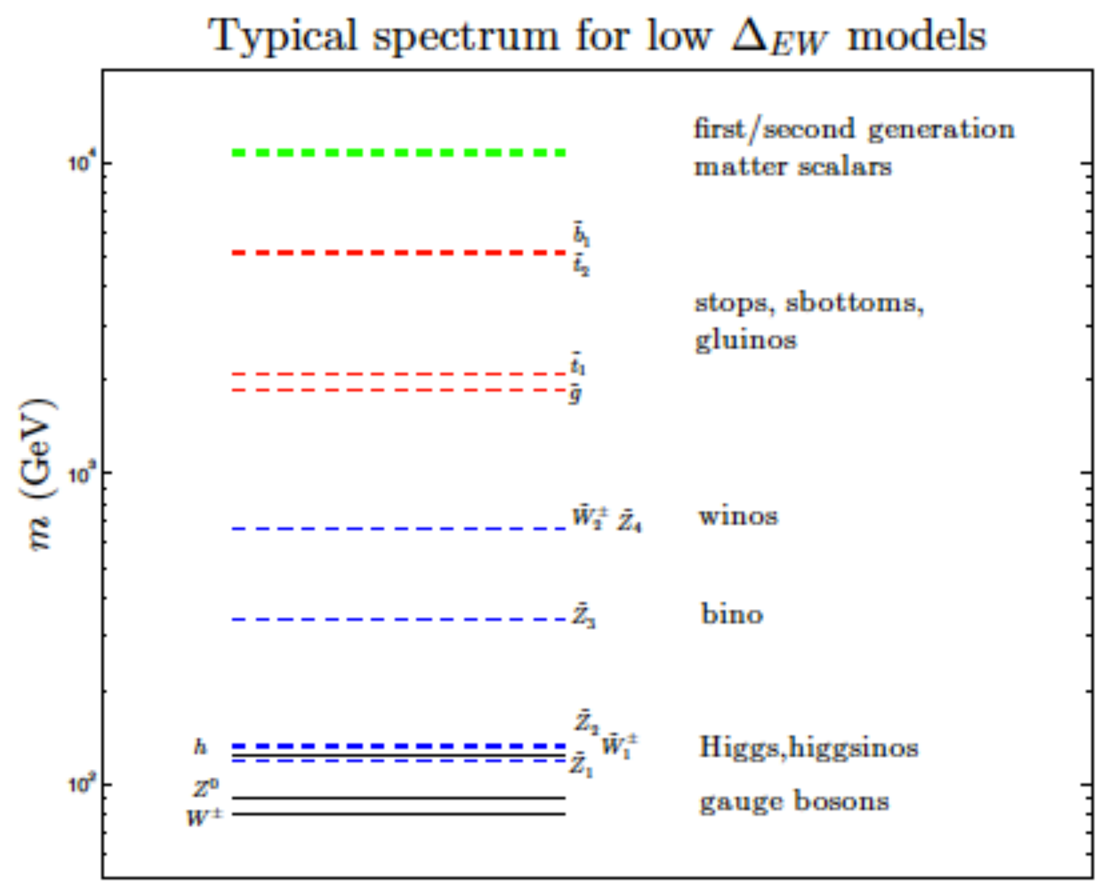


Plot shows why m(W,Z,h)~100 GeV is natural in RNS but not in mSUGRA/CMSSM

RNS spectra are characterized by the following features, with a typical spectrum shown in Fig. 1.

- Four light higgsinos $\widetilde{Z}_1$, $\widetilde{Z}_2$ and $\widetilde{W}_1^\pm$ with mass $\sim 100-300$ GeV. In fact, the lighter end of this range (closer to M_Z) is preferred by naturalness since $\Delta_{EW} \gtrsim |\mu^2|/(M_Z^2/2)$.
- Highly mixed top- and bottom-squarks and also gluinos in the $1-5$ TeV range (this is significantly heavier than the range predicted by earlier natural SUSY models[4, 5]).
- If gaugino mass unification is imposed, then $\widetilde{Z}_3$ will be bino-like at $\sim 0.2-0.8$ TeV and $\widetilde{Z}_4$ and $\widetilde{W}_2$ will be wino-like at $\sim 0.4-1.6$ TeV.
- First/second generation squarks and sleptons may be at the $5-30$ TeV range, thus providing at least a partial decoupling solution to the SUSY flavor/CP problems.



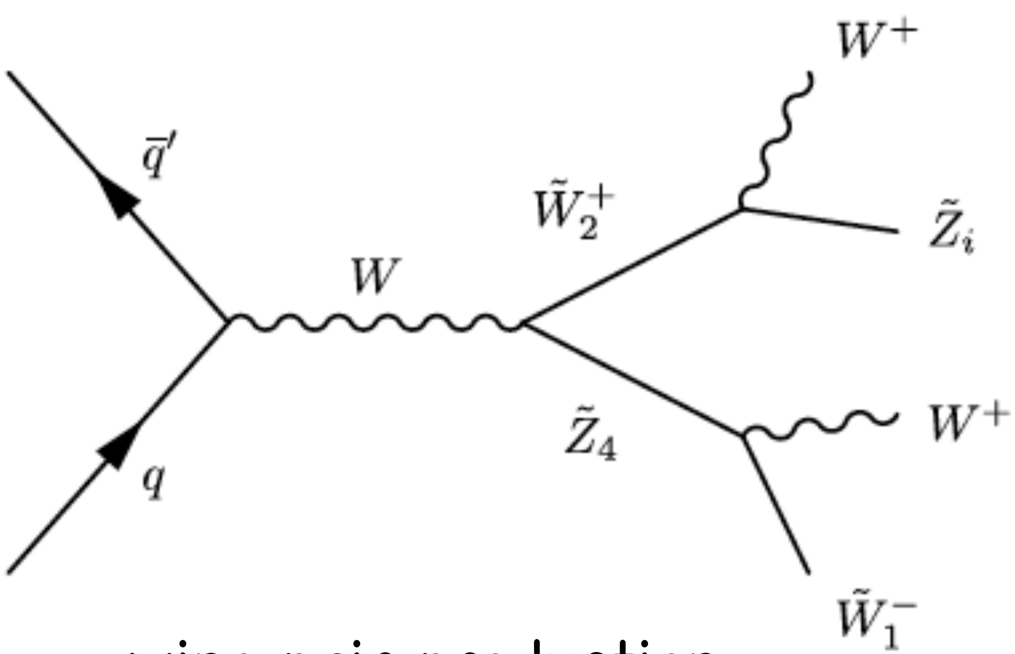


Under these conditions, there is a Little Hierarchy,
but it is no Problem!

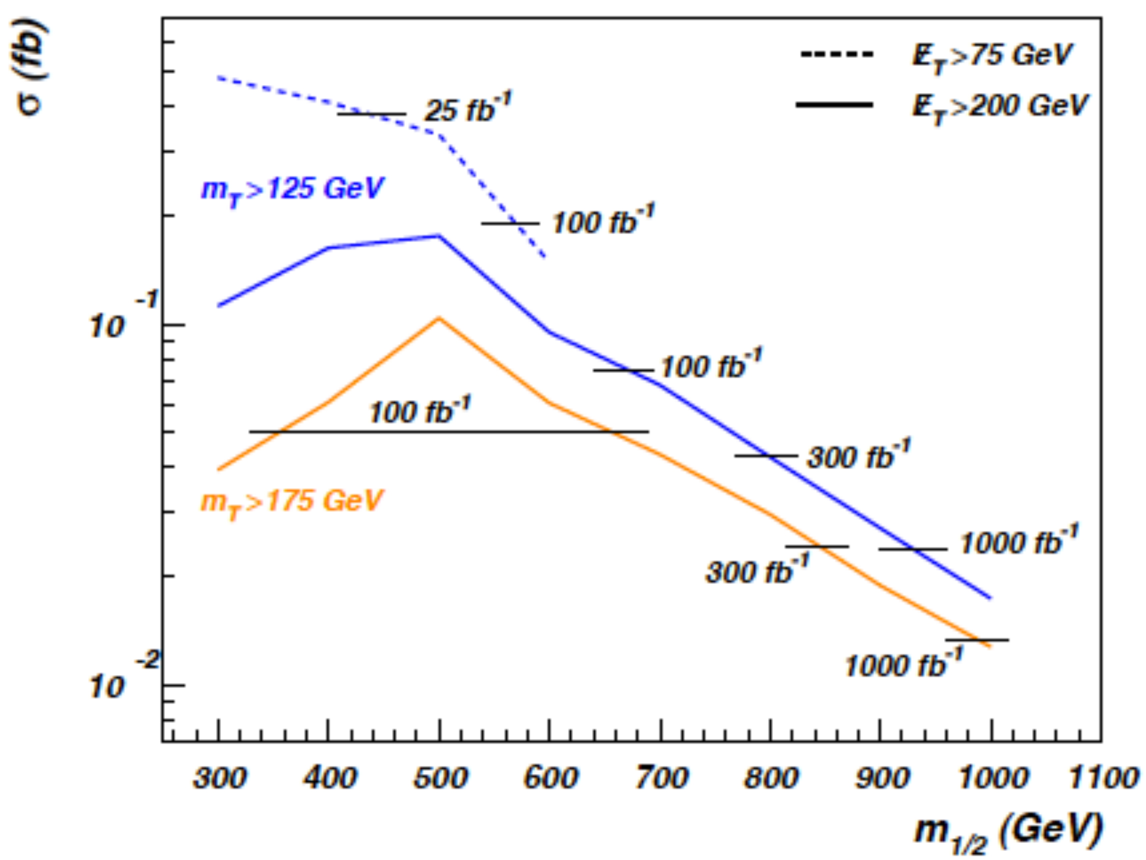
Radiatively-driven natural SUSY at LHC

- Usual gluino pair cascade signatures: LHC14 reach to m(gl)~1.8 TeV for 300 fb^-1
- Light higgsinos produced in abundance but low visible energy release from compressed spectra makes them very difficult to extract from background
- Qualitatively new hadronically-quiet same-sign diboson signature: allows extra reach LHC14 to ~2.1 TeV in m(gl)

LHC SSdB signature from SUSY models with light higgsinos:

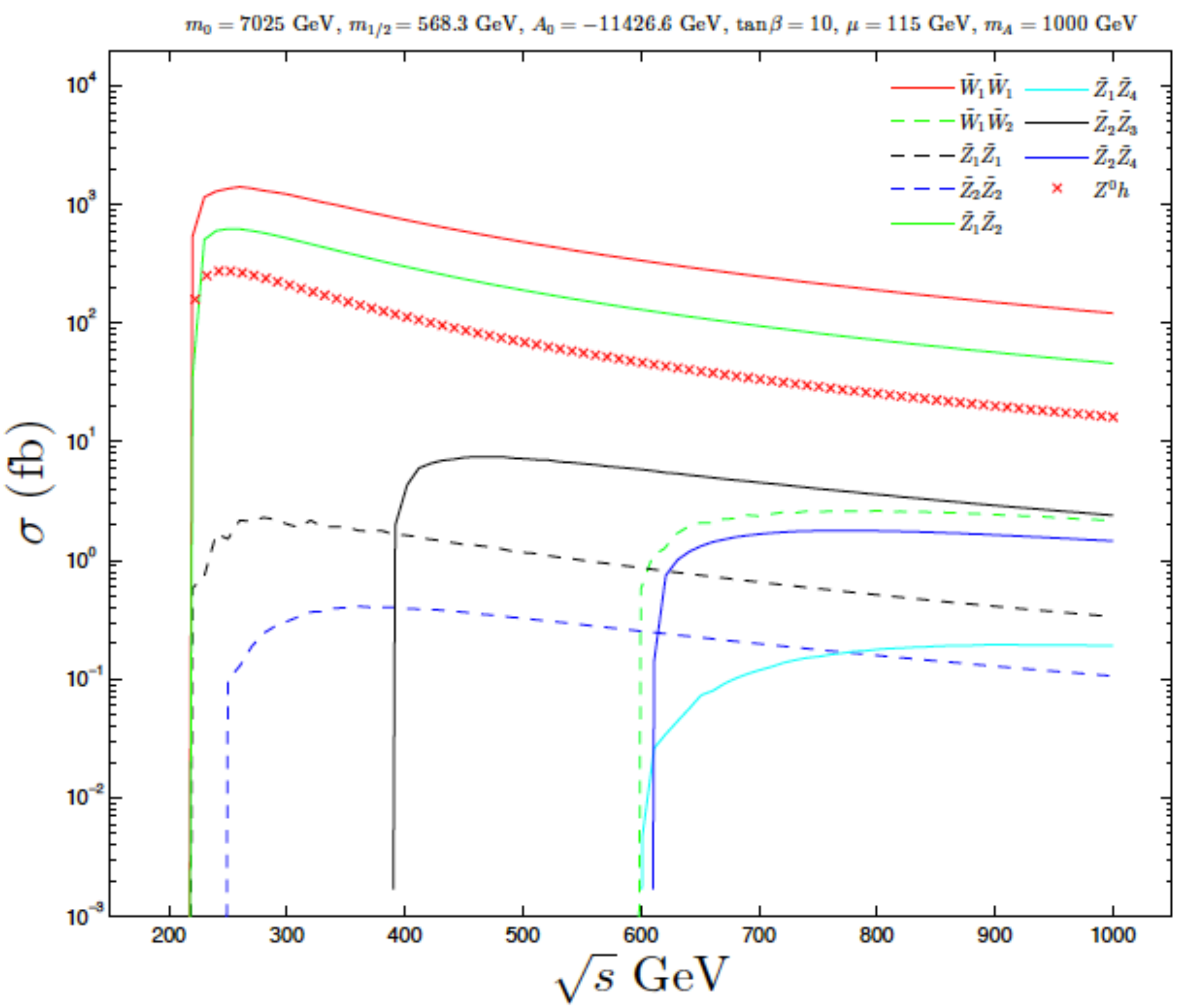


wino pair production



While the SSdB signature is characteristic, it only probes m(gl)<~2 TeV while in RNS m(gl) can range up to ~5 TeV with low Δ_{EW}

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

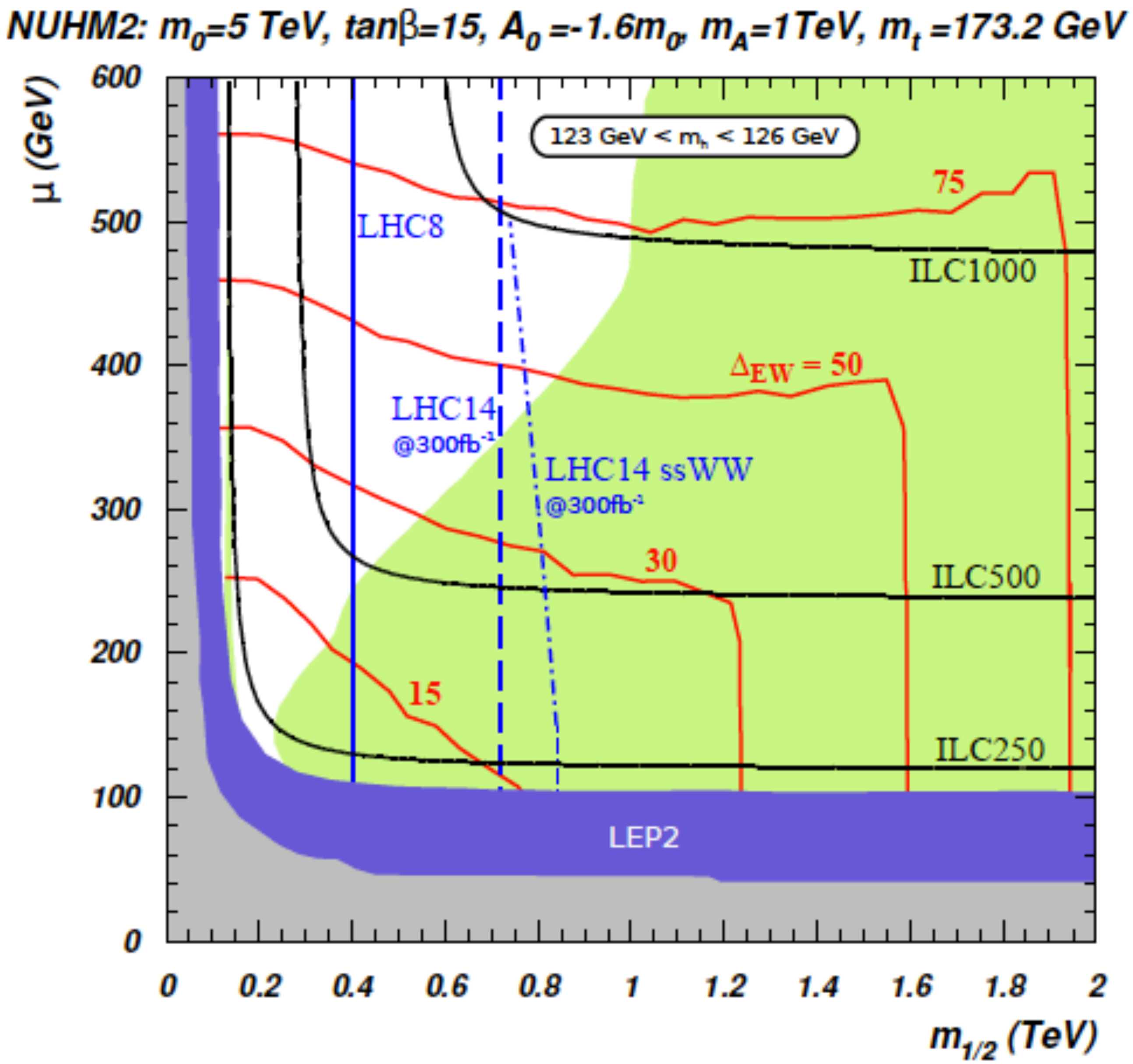


$$\sigma(higgsino) \gg \sigma(Zh)$$

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

ILC either sees light higgsinos or natural SUSY dead

LHC/ILC complementarity



When to give up on naturalness in SUSY?

If ILC(600-800) sees no light higgsinos

Dark matter: thermally-produced higgsino-like LSP at 100-300 GeV underabundant by factor 10-15

An attractive resolution is to invoke PQ solution to strong CP problem

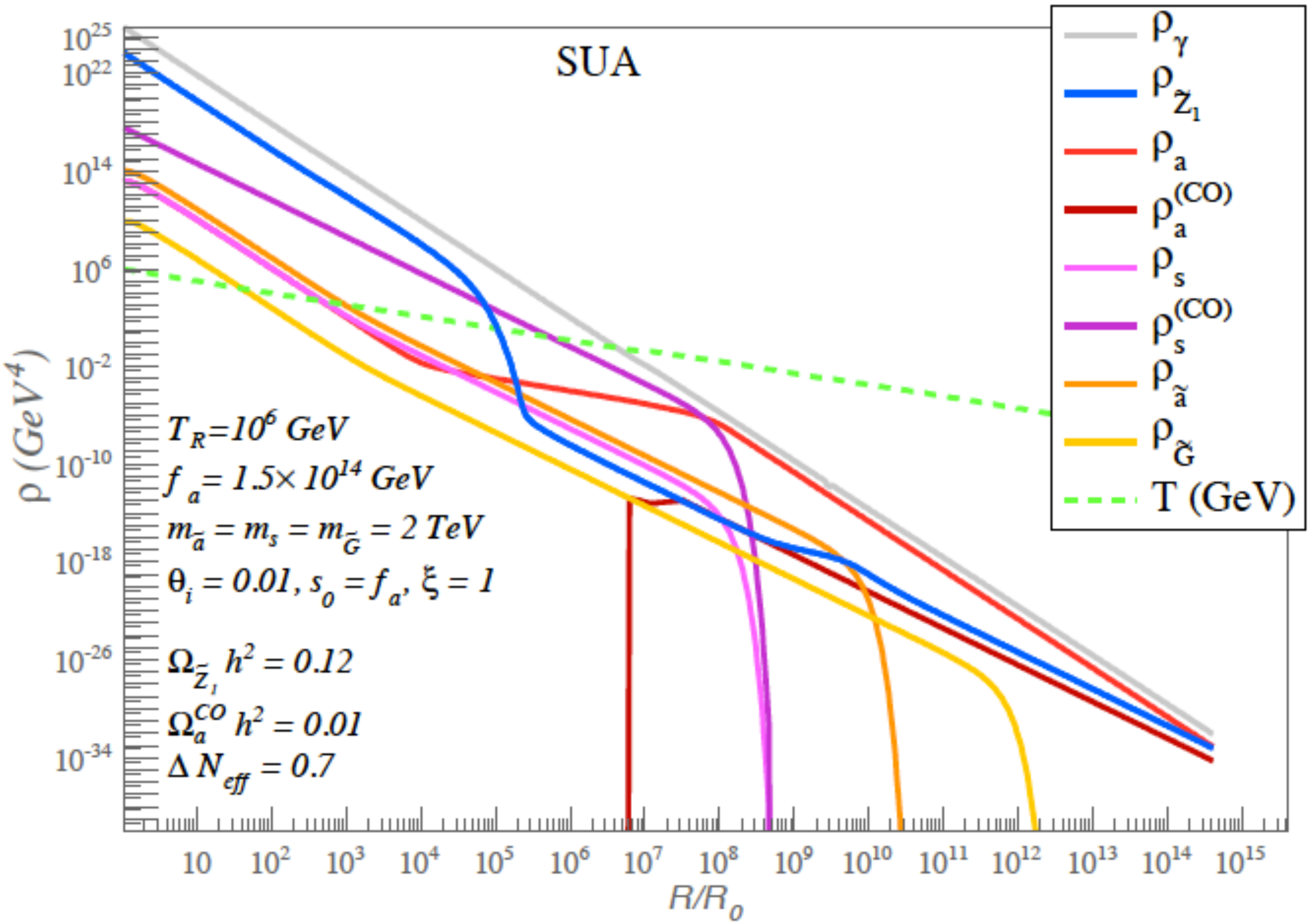
Dark matter is then a higgsino/axion mixture: 2 dark matter particles

Production and decay of saxions/axinos in early universe can augment or diminish LSP abundance

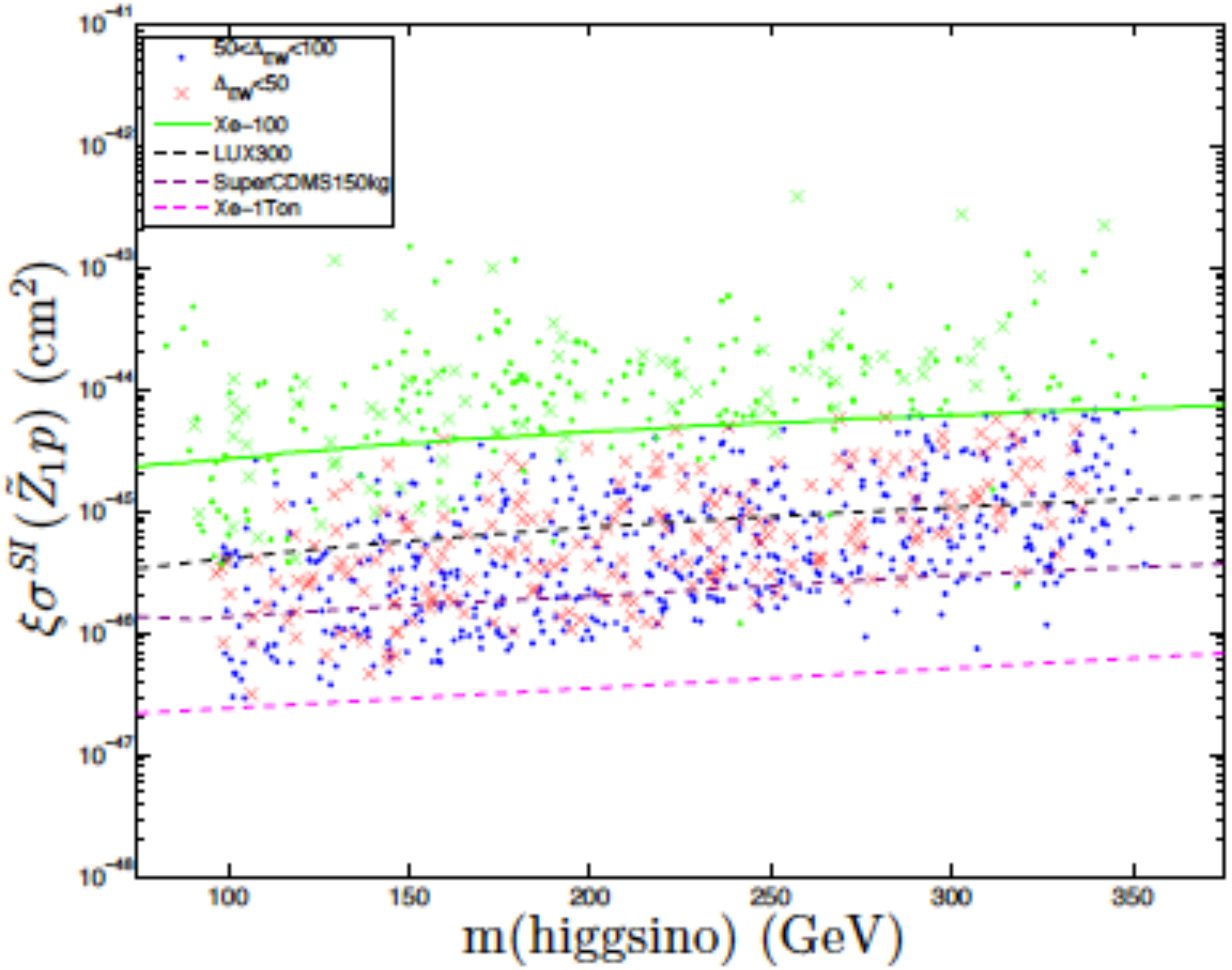
Depending on PQ parameters, axion or higgsinos may dominate

Even with diminished higgsino abundance, still detectable at Xe-1-ton

mixed axion/higgsino DM production



Bae, HB, Lessa



Higgsino DD rate never small because naturalness/ino mass unif'n enforces mainly higgsino but non-negligible gaugino component for LSP