Zeroing in on Natural Supersymmetry

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SUSY 2017, TIFR, Mumbai

SUSY has been an active area of phenomenological research since the early 1980s.

- Largest possible symmetry of the S-matrix
- Synthesis of bosons and fermions
- Possible connection to gravity (if SUSY is local) and to dark matter (if, motivated by other considerations, we impose R-parity conservation).

★ SUSY solves the big hierarchy problem. Low scale physics does not have quadratic sensitivity to high scales if the low scale theory is embedded into a bigger framework with a high mass scale, Λ. (Kaul-Majumdar, Witten)

Only reason for superpartners at the TeV scale.

Bonus: Measured gauge couplings at LEP unify in MSSM but not in SM

We have heard only about lower bounds close to 2 TeV on $m_{\tilde{g}}$ and 0.9 TeV on $m_{\tilde{t}_1}$ with weaker bounds on uncoloured superpartners. (Many talks at this meeting.)

Many bounds only in simplified models. (Snyder talk)

No sign of any signal. Take stock of what this says about our hopes and aspirations from the 1980s.

Supersymmetry and a Crisis on Physics, Lykken and Spiropulu

Fine-tuning price of the early LHC, Strumia

Naturalness Under Stress, Dine

N. Craig, GGI lectures.

Re-assess old arguments and try to understand whether the non-appearance of SUSY at the LHC should cause us concern and/or dismay.

- ⋆ WHERE DID OUR EXPECTATIONS COME FROM?

The physical mass of a spin-zero particle has the form (at one-loop),

$$m_\phi^2 \simeq m_{\phi 0}^2 + C_1 \frac{g^2}{16\pi^2}\Lambda^2 + C_2 \frac{g^2}{16\pi^2} m_{\rm low}^2 \log\left(\frac{\Lambda^2}{m_{\rm low}^2}\right) + C_3 \frac{g^2}{16\pi^2} m_{\rm low}^2 \; . \qquad (1)$$

- ★ Λ^2 term destabilizes the SM if the SM is generically coupled to new physics that has a high scale Λ; *e.g* GUTs.
- ★ Since Λ^2 terms are absent in softly broken SUSY, the Higgs sector and also vector boson masses are at most logarithmically sensitive to high scale physics. BIG HIERARCHY PROBLEM

In SUSY theories, $m_{\rm low} = m_{\rm SUSY}$ and the corrections are $\delta m_h^2 \sim C_2 \frac{g^2}{16\pi^2} m_{\rm SUSY}^2 \times logs \sim m_{\rm SUSY}^2$ (if the logarithm is 30-40). Since LHC says squarks and gluinos are much heavier than m_h^2 or M_Z^2 and so requires fine-tuning.

Setting $\delta m_h^2 < m_h^2 \Rightarrow m_{\rm SUSY}^2 < m_h^2$, and there was much optimism for superpartners at LEP/Tevatron.

$\Delta_{\log} = \frac{\delta m_h^2}{m_h^2}$ suggested as a measure of fine tuning.

WHAT WENT WRONG?

- ⋆ Perhaps $\delta m_h^2 < m_h^2$ is too stringent? Many examples of accidental cancellations in nature of one or two orders of magnitude.
- ⋆ Argument applies only to superpartners with large couplings to the EWSB sector (not, *e.g.* to first generation squarks probed at the LHC).
- ⋆ Most importantly, once we understand SUSY breaking, almost certainly we will find that contributions from the various superpartners are correlated, leading to the possibility of automatic cancellations.
  Ignoring this, will overestimate the UV sensitivity of any model.

Traditionally, the sensitivity is measured by checking the fractional change in M_Z^2 (rather than m_h^2) relative to the corresponding change in the independent parameters (p_i) of the theory. (Ellis, Enqvist, Nanopoulos, Zwirner, reinvented and explored by Barbieri and Giudice): $\Delta_{\rm BG} = Max_i \left\{ \frac{p_i}{M_Z^2}\frac{\partial M_Z^2}{\partial p_i} \right\}$,

$$\Delta_{\log} \geq \Delta_{\rm BG},$$

since $\Delta_{\log}$ ignores correlations we just mentioned.

Electroweak Fine-tuning (Baer, Barger,Huang,Mustafayev,XT)

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

(Σ_u^u, Σ_d^d are finite radiative corrections.)

Requiring no large cancellations on the RHS, motivates us to define,

$\Delta_{\rm EW} = max\left(\frac{m_{H_u}^2}{\frac{1}{2}M_Z^2}\frac{\tan^2\beta}{\tan^2\beta-1}, \frac{\Sigma_u^u}{\frac{1}{2}M_Z^2}\frac{tan^2\beta}{\tan^2\beta-1}, \cdots\right)$. Small $\Delta_{\rm EW} \Rightarrow m_{H_u}^2, \ \mu^2$ close to M_Z^2.

Since $\Delta_{\rm EW}$ has no large logs in it, $\Delta_{\rm EW} \leq \Delta_{\rm BG}$. For this same reason, it cannot be interpreted as a measure of fine-tuning in a high scale theory.

However, if UV scale parameters of the are suitably correlated so the log $\frac{\Lambda^2}{m_{\rm SUSY}^2}$ terms essentially cancel, $\Delta_{\rm BG} \to \Delta_{\rm EW}$ (modulo technical caveats).

(The large logs are hidden because in I wrote $m_{H_u}^2 = m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$.)

The utility of $\Delta_{\rm EW}$

- ⋆ $\Delta_{\rm EW}$ is essentially determined by the SUSY spectrum.
- ⋆ If $\Delta_{\rm EW}$ is large, the underlying theory that leads to the spectrum will be fine-tuned. A small $\Delta_{\rm EW}$ does not imply the theory is not fine-tuned, but leaves open the possibility of finding a UV theory with appropriately correlated SUSY breaking parameters.
- ⋆ In the absence of a theory of SUSY breaking, advocate using $\Delta_{\rm EW}$ in phenomenological discussions of fine-tuning prevents us from prematurely discarding phenomenologically viable models based on fine-tuning considerations.
- ⋆ Many aspects of the phenomenology depend just on the spectrum, so this can be investigated even without knowledge of the underlying high scale theory.
- ⋆ Low $\Delta_{\rm EW} \Longrightarrow$ low $|\mu|$, but squarks (including stops) may be much heavier.

Light higgsinos are a robust feature of the simplest models with low fine-tuning.

Loopholes to light higgsino argument

- ⋆ Assumes that μ is independent of soft SUSY breaking parameters.
- ⋆ Assumes the higgsino mass arises mostly from $|\mu|$; SUSY breaking higgsino mass would be hard SUSY breaking in the presence of singlets that couple to the Higgs sector). Grisaru, Girardello recently re-empasized by Ross, Schmidt-Hoberg, Staub. Chattopadhyay talk.
- ⋆ The Higgs could be a (pseudo) Goldstone boson in a theory with global symmetry even if $|\mu|$ is large. Cancellations that give low Higgs mass (and concomitantly low M_Z^2) are then a result of a symmetry. Cohen, Kearney, Luty.
- ⋆ Extended models with Dirac gauginos and supersoft SUSY breaking. Nelson & Roy; Martin

These "heavy higgsino" models all have many extra TeV scale fields.

We regard light higgsinos as a necessary condition for naturalness (at least in the simplest models), and explore its observational implications.

Realizing Small $\Delta_{\rm EW}$

In the weak scale EWSB condition, in order not to have large cancellations, we clearly need to have $m^2_{H_u}$(weak) (and also μ^2) close to M_Z^2. This is not guaranteed in mSUGRA, but always possible in the NUHM2 model, since $m^2_{H_u}$ is an adjustable parameter. Tune $m^2_{H_u}(\Lambda)$ to get small $m^2_{H_u}$(weak).

$$\text{NUHM2 parameters}: m_0, m_{1/2}, A_0, \tan\beta \ + m^2_{H_u}, m^2_{H_d}$$

Finally, to get small $\Delta_{\rm EW}$, we also have to ensure that the finite radiative corrections from SUSY particle loops, Σ^u_u, are small. This requires large, negative A_0.

This large magnitude of A_0 simultaneously raises m_h to its observed value!

Since $m^2_{H_u}$ is radiatively driven to small values, refer to this as radiatively-generated Natural SUSY (RNS) as realized in the NUHM2 model.

Remember, $\Delta_{\rm EW}$ is a bound on the fine-tuning, so we are not saying that the NUHM2 model point has low fine-tuning. Indeed, the fact that A_0 and $m^2_{H_u}$ have to be adjusted to get low $\Delta_{\rm EW}$ says otherwise.

However, if we had a theory of soft-parameters that predicted $A_0 = -1.6 m_0$ and $m^2_{H_u} = 1.64 m_0^2$ and $m_{1/2} \simeq 0.4 m_0$, this underlying theory would not be fine-tuned. We do not have such a theory today!!!![a]

Correlation	$\Delta_{\rm BG}$
None	3168
$A_0 = -1.6 m_0$, $m^2_{H_u} = 1.64 m_0^2$	257
$m_{1/2} = 0.4 m_0$	15.4
$\Delta_{\rm EW}$	11.3

Parameter correlations reduce $\Delta_{\rm BG}$ and bring it close to $\Delta_{\rm EW}$. (Mustafayev and XT)

[a]Our interpretation of $\Delta_{\rm EW}$ differs from that of Baer and collaborators in e.g. arXiv:1404.2277, but as a practical matter there is no difference

Why talk about low $\Delta_{\rm EW}$ when we don't have a top down theory with low $\Delta_{\rm BG}$?

We have no real idea of how the soft parameters arise, and so throwing up our hands and saying that $\Delta_{\rm BG}$ is large in this or that model seems premature, when we know that correlations between model parameters can reduce the fine-tuning.

Since $\Delta_{\rm EW}$ yields the "minimal fine-tuning" for a given SUSY sparticle spectrum, it seems fruitful to pursue the phenomenology of these low $\Delta_{\rm EW}$ theories, and await the construction of a top down model with the required parameter correlations to yield low fine-tuning. IGNORING THIS POSSIBILITY MAY THROW THE BABY OUT WITH THE BATHWATER.

Underlying philosophy is that if we find an underlying theory of SUSY breaking parameters with low $\Delta_{\rm BG}$ that yields essentially the same spectrum, it will have the same phenomenological implications since these are mostly determined by the spectrum. The NUHM2 model with low $\Delta_{\rm EW}$ is a surrogate for exploring the phenomenology of this (as yet unknown) theory with low fine-tuning.

We will regard spectra with $\Delta_{\rm EW} < 30$ as natural. The corresponding $\Delta_{\rm BG}$ (naively evaluated) may be two orders of magnitude larger.

RNS Spectrum characteristics in NUHM2 model

- ⋆ Four light higgsino-like inos, $\widetilde{Z}_{1,2}$, $\widetilde{W}_1^{\pm}$;
- ⋆ $m_{\tilde{t}_1} = 1 - 3$ TeV;
- ⋆ $m_{\tilde{g}} = 2 - 5$ TeV (else $\tilde{t}$s becomes too heavy and make Σ_u^u too large); (Resulting bino and wino mass parameters consistent with low $\Delta_{\rm EW}$.)
- ⋆ The splitting between the higgsinos and the LSP is typically 10-25 GeV if $\Delta_{\rm EW} < 30$. Note that the higgsino splitting is bounded by 10 GeV.
- ⋆ Split the generations and choose $m_0(1,2)$ large to ameliorate flavour and CP issues (This is separate from getting small $\Delta_{\rm EW}$).

Large intra-generation splittings among heavy first/second generation squarks leads to large $\Delta_{\rm EW}$ except for specific mass patterns.

The NUHM3 RNS model where third generation scalar mass parameter is taken to be independent of that for the first two generations allows gluino masses up to about 6 TeV for $\Delta_{\rm EW} < 30$.

The NUHM2 RNS model is the prototypical model with low $\Delta_{\rm EW}$. Note, however that it assumes gaugino mass unification. Relaxing this constraint will have important phenomenological implications.

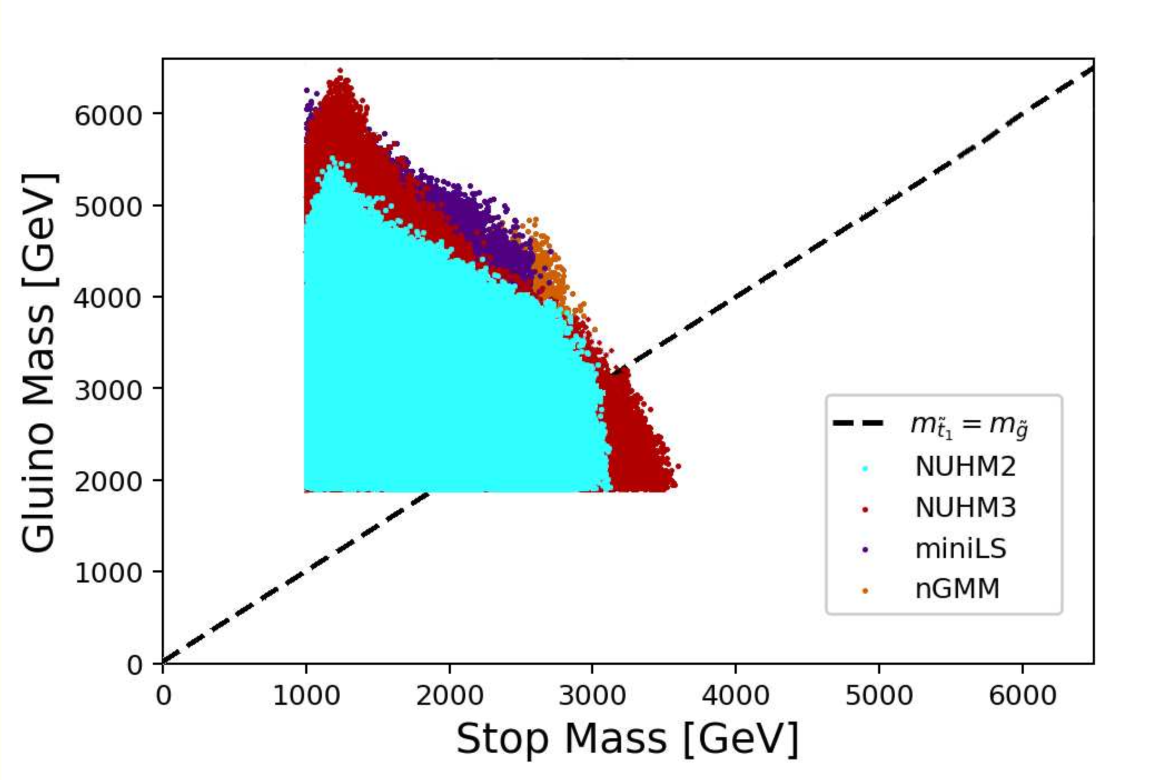
Indeed, there are well-motivated models where the gaugino mass pattern is altered; *e.g.* Models with mirage unification, where gauginos receive comparable contributions from modulus and anomaly contributions to SUSY breaking, and the sparticle mass pattern is quite different. KKLT, Choi, Nilles, Falkowski, Pokorski,Dudas..... The gaugino mass spectrum may be very compressed, with binos and winos amost as heavy as the gluino. Generalized mirage mediation models where scalar mass parameters are generalized from original pattern can have low values of Δ_{EW}.

The mirage gaugino mass pattern is also seen in the string-motivated motivated mini-landscape models where third generation masses are hierarchically smaller than those of the first two generations. Championed by Nilles, Vaudrewange and collaborators. These are a hybrid between mirage mediation and NUHM3 models.

Very heavy binos and winos $\Longrightarrow$ higgsino splittings as small as 4 GeV compared to 10-25 GeV in NUHM2. Phenomenologically very important, as we will see.

Gluino and Stop Masses with $\Delta_{\rm EW} < 30$

Examine $m_{\tilde{t}_1}$ and $m_{\tilde{g}}$ as stops and gluinos most copiously produced at the LHC.



Natural spectra with gluinos and stops beyond the high luminosity LHC reach easily possible.

We see that gluinos may be as heavy as 6 TeV and stops as heavy as 3.5 TeV.

However, gluinos are heavier than 5 TeV only if $\tilde{t}_1$ is below ~ 2 TeV.

Natural SUSY ($\Delta_{\rm EW} < 30$) Phenomenology

Monojet Signals from light higgsinos at the LHC

There has been much talk about detecting natural SUSY via inclusive $\not{E}_T$ + monojet events from $pp \to \widetilde{W}_1\widetilde{W}_1, \widetilde{W}_1\widetilde{Z}_{1,2}, \widetilde{Z}_{1,2}\widetilde{Z}_{1,2} + jet$ production, where the jet comes from QCD radiation.

- ⋆ Many analyses done using effective 4-fermion operators. This approximation is invalid because higgsino production dominantly occurs via s-channel Z exchange.
- ⋆ Although there is an observable rate, even after hard cuts, the signal to background ratio is typically at the percent level. We are pessimistic that the backgrounds can be controlled/measured at the subpercent level needed to extract the signal in the inclusive $\not{E}_T$ + monojet channel. Baer, Mustafayev, XT arXiv:1401.1162; C. Han *et al.*, arXiv:1310.4274; P. Schwaller and J. Zurita, arXiv:1312.7350

★ However, as first noted by G. Giudice, T. Han, K. Wang and L-T. Wang, and elaborated on by Z. Han, G. Kribs, A. Martin and A. Menon that backgrounds may be controllable by identifying soft leptons in events triggered by a hard monojet.

OS/SF dilepton pair with $m_{\ell\ell} < m_{\ell\ell}^{\rm cut}$ analysis with $m_{\ell\ell}^{\rm cut}$ as an analysis variable.

Alternatively, examine dilepton flavour asymmetry $\frac{N(SF)-N(OF)}{N(SF)+N(OF)}$ in monojet plus OS dilepton events.

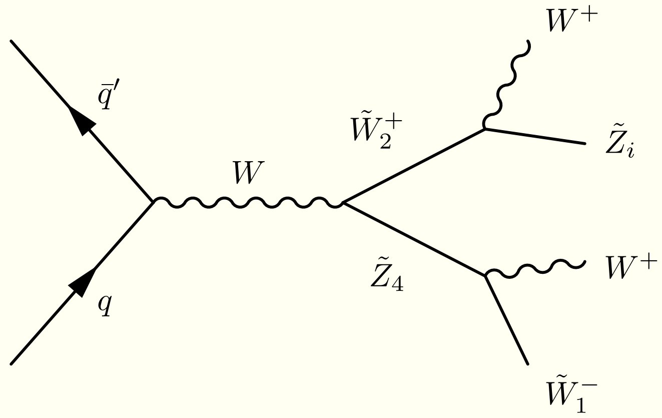
LHC14 reach extends to about $|\mu| = 170$ (210) GeV for integrated luminosity of 300 (1000) $\rm fb^{-1}$. Baer, Mustafayev and XT

If yet higher integrated luminosity is available, we will probably probe much of the $\Delta_{\rm EW} < 30$ parameter space!

LHC analyses in this channel (Sphicas talk).

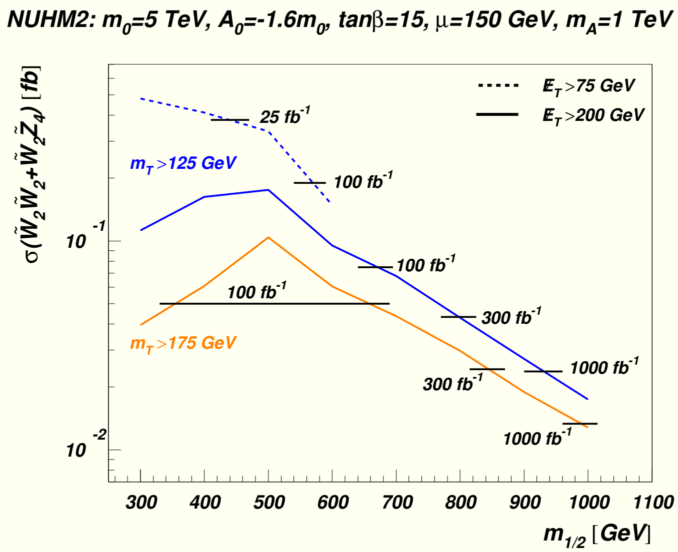
Light higgsinos at the LHC

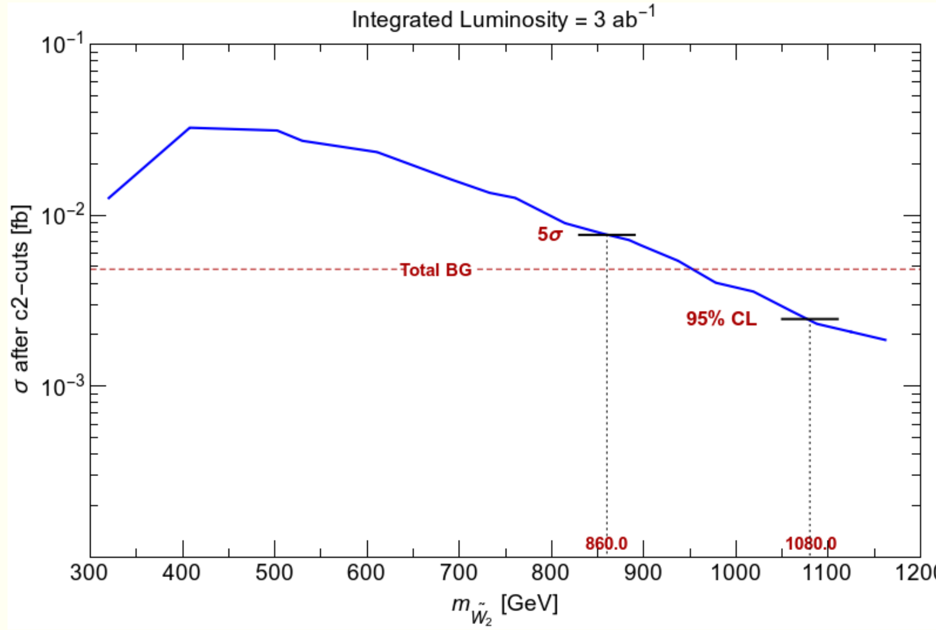
- ⋆ A novel signal is possible at the LHC if $|M_2| \lesssim 0.8 - 1$ TeV, something that is possible, though not compulsory, for low $\Delta_{\rm EW}$ models.



Decays of the parent $\widetilde{W}_2$ and $\widetilde{Z}_4$ that lead to W boson pairs give the same sign 50% of the time. Novel same sign dilepton events with jet activity essentially only from QCD radiation since decay products of higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_2$ are typically expected to be soft.

This new signal may point to the presence of light higgsinos. PRL 110, 151801 (2013), recently revisited in arXiv:1710.09103





Hard cuts on $\not{E}_T$ and minimum transverse mass $m_T(\ell_{1,2}, \not{E}_T)$ and limiting jet activity is crucial to pull out the signal. Additional cut $n_j \leq 1$ and harder $\not{E}_T$ for HL-LHC.

Urge searches in this channel as the LHC data sample size goes into the 100 fb^{-1} range.

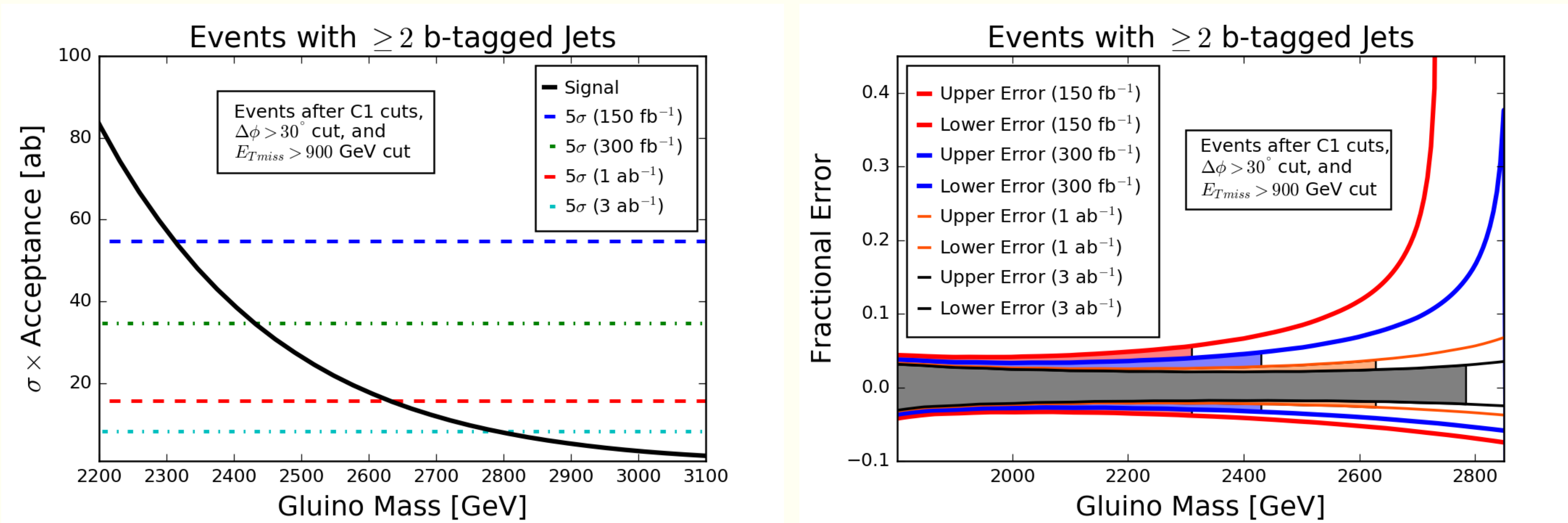
Sengupta's parallel talk for details.

Additional confirmatory signals from 3 and 4 lepton production. JHEP06 (2015) 053.

Gluinos in natural SUSY at the LHC

Likely that third generation squarks are much lighter than those of first two generations, so $\tilde{g} \to t\tilde{t}_1 t$, $\tilde{t}_1 \to t\widetilde{Z}_{1,2}, b\widetilde{W}_1$. Multi-b jet events with large $\not{E}_T$.

$t\bar{t}$, $ttbb$, $4t$, bbZ single t backgrounds. Clean sample after very hard cuts.

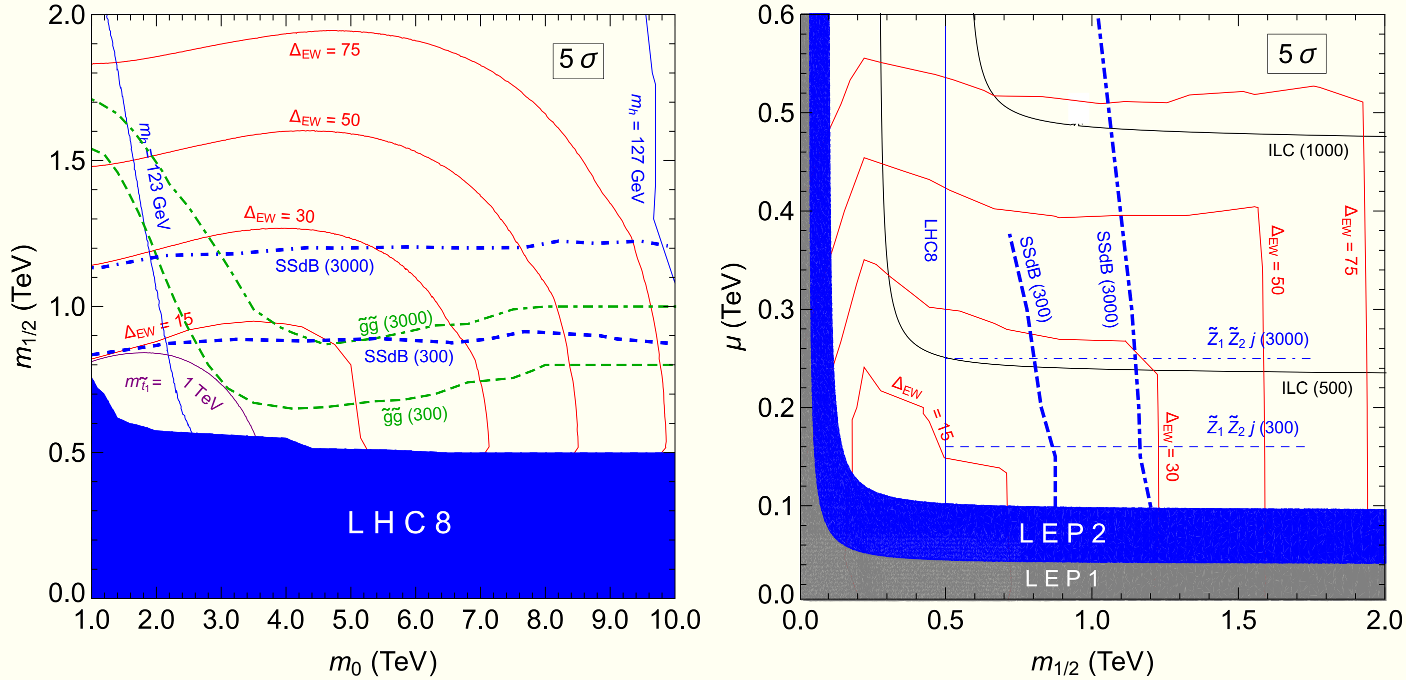


Eur. Phys. J C77 (2017) 499.

HL-LHC 5σ reach out to $m_{\tilde{g}} = 2.8$ TeV Mass measurement from counting possible to 2.5-5% level because background level is $\mathcal{O}$(ab).

Similar results via 3 tagged b-jet channel.

Overview of the High Luminosity LHC reach in nNUHM2 (Baer, Barger, Savoy, XT)



With apologies for not-updated contours of SSdB reach

The high luminosity LHC has the potential to detect a SUSY signal over much of the $\Delta_{EW} \leq 30$ part of RNS parameter space! Possibly more than one signal detectable.

However, this conclusion depends crucially on gaugino mass unification.

What if we don't have gaugino mass unification?

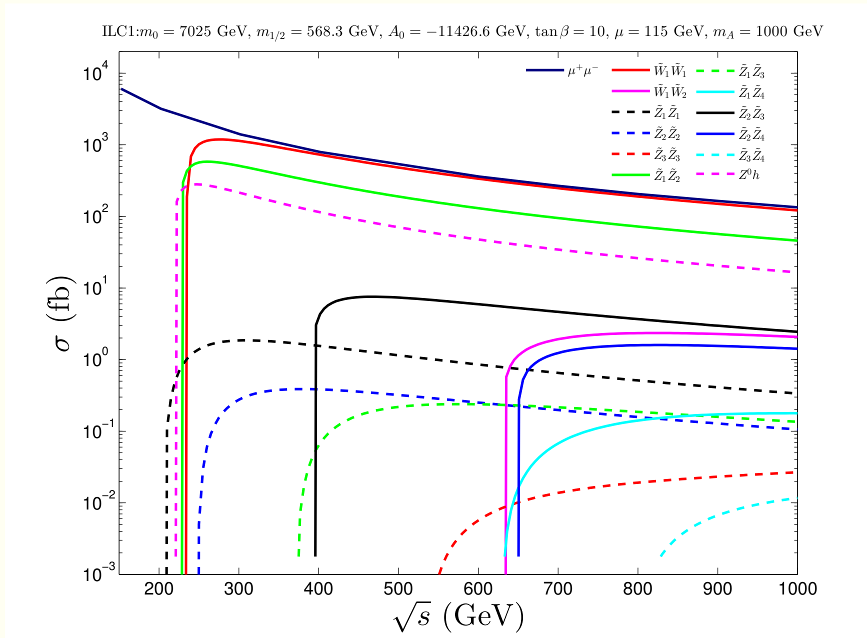
Without gaugino mass unification, the SS di-boson signal and the signal from gluinos may both be inaccessible. Moreover, the leptons from higgsino decays in the monojet + dilepton signal may be too soft to be detectable even at the high luminosity LHC, so no $\widetilde{Z}_1\widetilde{Z}_2 j$ signal either .

What do we do?

Look to future facilities such as: A linear e^+e^- collider, the energy upgrade of the LHC mooted at CERN, a future 100 TeV pp collider.

Natural to study Natural SUSY at e^+e^- colliders

Since higgsinos are electroweak doublets, large production cross sections are expected in e^+e^- collisions.



Electron-positron colliders are higgsino factories. "Easy" to see higgsino signals right up to the threshold for higgsino pair production for higgsino mass gaps $\gtrsim 10$ GeV. With beam polarization even mass measurements possible in this case. (JHEP 1406 (2014) 172)

ILC physics subject of Godbole's talk.

Gluino and stop reach at LHC33 (arXiv:1708.09054)

CERN is considering a plan for an energy upgrade of LHC. arXiv:1108.1617 [phys.acc-ph] suggested a 33 TeV collider to deliver a data sample of ~ 1 ab^{-1} in LEP tunnel. (28 TeV workshops.)

Natural to examine prospects for gluinos and stops of natural SUSY whose masses are bounded above by about 3.5 and 6 TeV, respectively.

Examined the reach of LHC33 assuming $\tilde{g} \to \tilde{t}_1^{(*)} t$, $\tilde{t}_1 \to t\widetilde{Z}_1, b\widetilde{W}_1$.

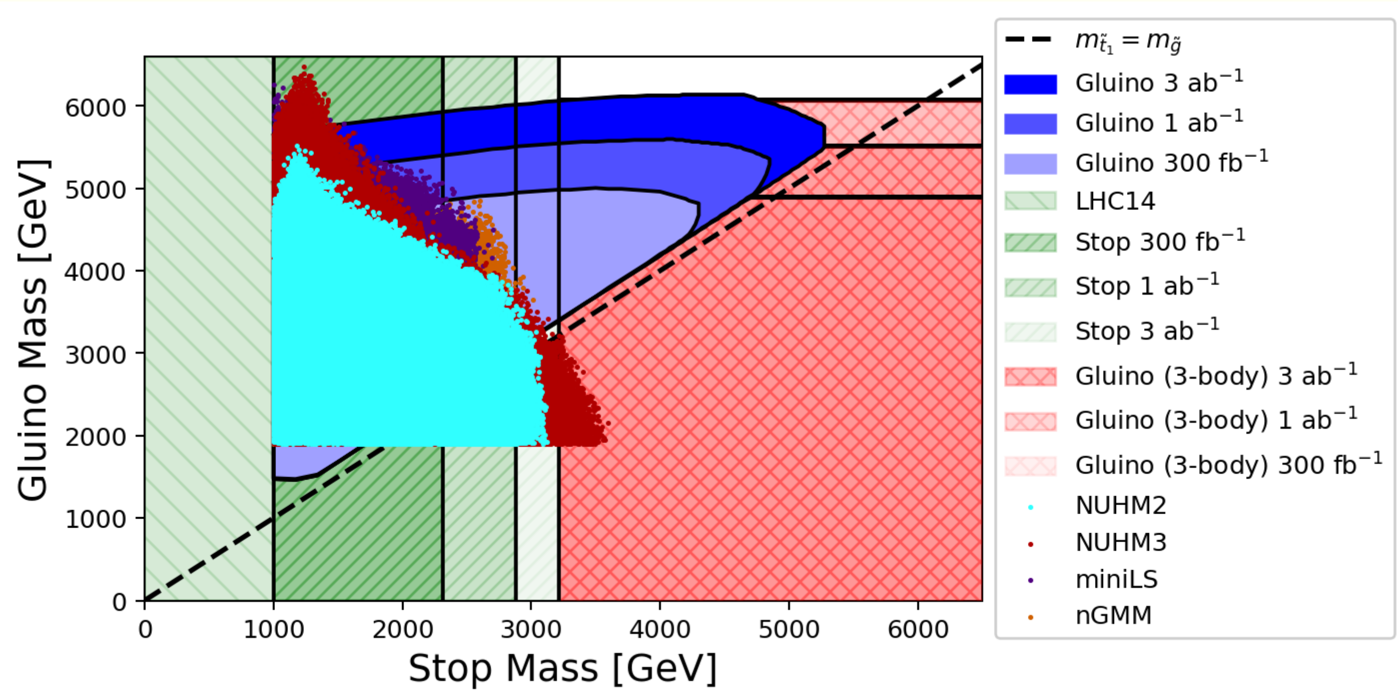
Again, used very hard cuts to get the maximal reach.

Gluino: $n_b \geq 2$, isolated lepton veto, $\not{E}_T > Max(1900\ \mathrm{GeV}, 0.2M_{\rm eff})$, $n_j \geq 4$ with $E_{Tji} > 1300, 900, 200, 200$ GeV, $S_T > 0.1$, $\Delta\phi > 10$ degrees.

Stop: $n_b \geq 2$, isolated lepton veto, $\not{E}_T > Max(1500\ \mathrm{GeV}, 0.2M_{\rm eff})$
$E_{Tj_i} > 1000, 600$ GeV, $S_T > 0.1$, $\Delta\phi > 30$ degrees.

LHC33 reach for gluinos and squarks

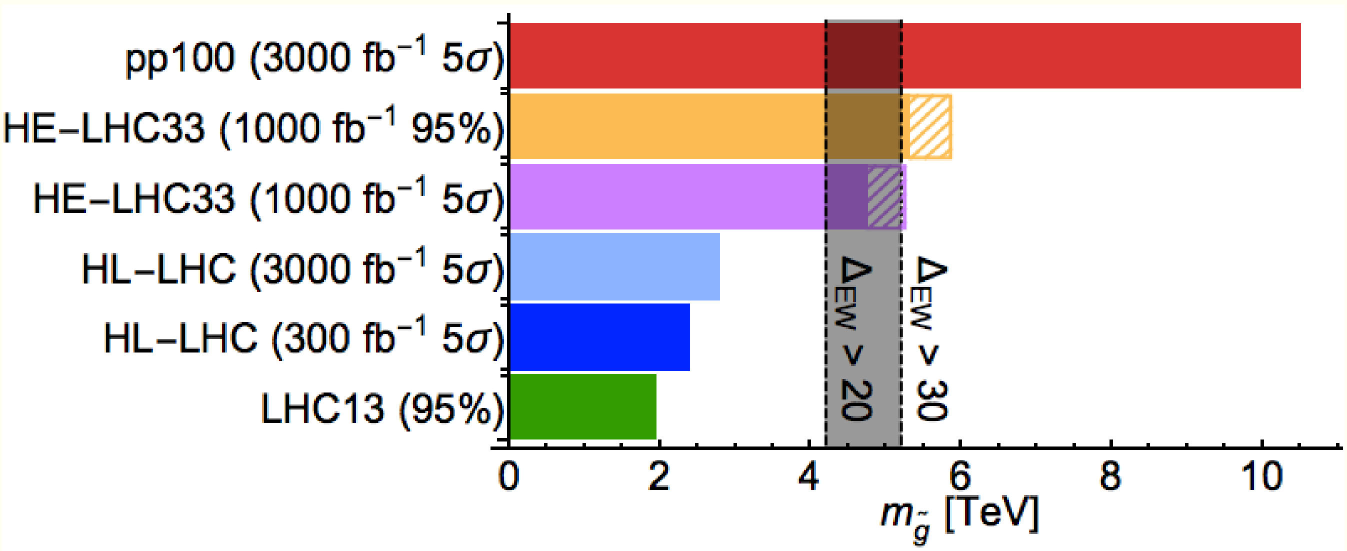
The various dots denote gluino and stop masses in various models with $\Delta_{EW} < 30$ that I showed you earlier. The vertical regions are our projections for the stop reach for integrated luminosities of 0.3, 1 and 3 ab^{-1}. The other shaded regions are the gluino reach.



We see that the LHC33 reach will be sensitive to at least one of the stop, or the gluino, and over most of the parameter range to both!

One Sentence Message about LHC33 Reach

Even with 1 ab^{-1} at LHC33 gluino reach, assuming $\tilde{g} \to t\tilde{t}_1$ extends to 5.5 TeV for heavy stops, and the stop reach extends to 2.9 TeV assuming that stops decay to light higgsinos. (Baer,Barger,Gainer,Savoy,Serce,XT.)



For natural SUSY, when gluino becomes too heavy to be detectable at LHC33, the stop is light enough to be readily detectable.

Conclusions for natural SUSY models at future facilities

Even our very conservative version[a] of natural SUSY will find it very hard to remain hidden at LHC33.

If a signal is found, there will be a strong case for the 100 TeV machine to look for other superpartners.

The ILC, via a study of the light higgsinos, will be able to elucidate the natural origin of W, Z and h masses. (Godbole talk.)

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[a] I say conservative because with the naive use of Δ_{BG} these models will appear to have large fine-tuning because the possibility that parameters may turn out to be correlated in the underlying theory has been ignored.

Final Remarks

- ⋆ Dismay at the non-appearance of SUSY seems premature. We were over-optimistic in our expectations. The LHC run has a long way to go.
- ⋆ Viable natural spectra exist without a need for superpartners beyond MSSM. We do not understand SSB parameters, and ignoring potential correlations among these in discussing fine-tuning may throw the baby out with the bathwater. Encourage the use of $\Delta_{\rm EW}$ for conservatively evaluating whether or not a spectrum is fine-tuned.
- ⋆ Light higgsinos seem necessary for naturalness, and will likely yield the novel LHC signals: same sign dibosons, monojet plus soft dileptons with $m_{\ell\ell} < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$.
- ⋆ Light higgsino scenarios cannot saturate the total CDM; nonetheless, there is enough thermal higgsino DM fraction that will reveal itself in direct DM searches at ton-size detectors; Xenon1t, Xenon-nT, LZ (Baer, Barger, Mickelson, and also JHEP 1705 (2017) 101)

- ★ An e^+e^- collider with $\sqrt{s} \gtrsim 600$ GeV could be a discovery machine for light higgsinos for $\Delta_{\rm EW} \lesssim 30$; *i.e.* no worse than 3% electroweak fine-tuning, and would serve to elucidate the nature of the higgsinos, suggesting a link between them and a natural origin of W, Z and h masses.
- ★ The high energy LHC, a 33 TeV pp collider would definitively probe SUSY models with no worse than a part in thirty electroweak fine-tuning. Very likely, both gluinos and top squark should be discoverable in such scenarios.
- ★ Our original (from the 1980s) aspirations for SUSY remain unchanged if we accept that "accidental cancellations" at the few percent level are ubiquitous, and that DM may be multi-component.

In my opinion, weak scale SUSY still offers the best resolution of the big hierarchy problem, and there may well be viable models with just the MSSM spectrum where the fine-tuning is no worse than a few percent.