Natural Supersymmetry Phenomenology at the LHC

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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.
Only reason for superpartners at the TeV scale.

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

Tremendous effort to search for superpartners

Earlier searches at the LEP, Tevatron and at even earlier machines!

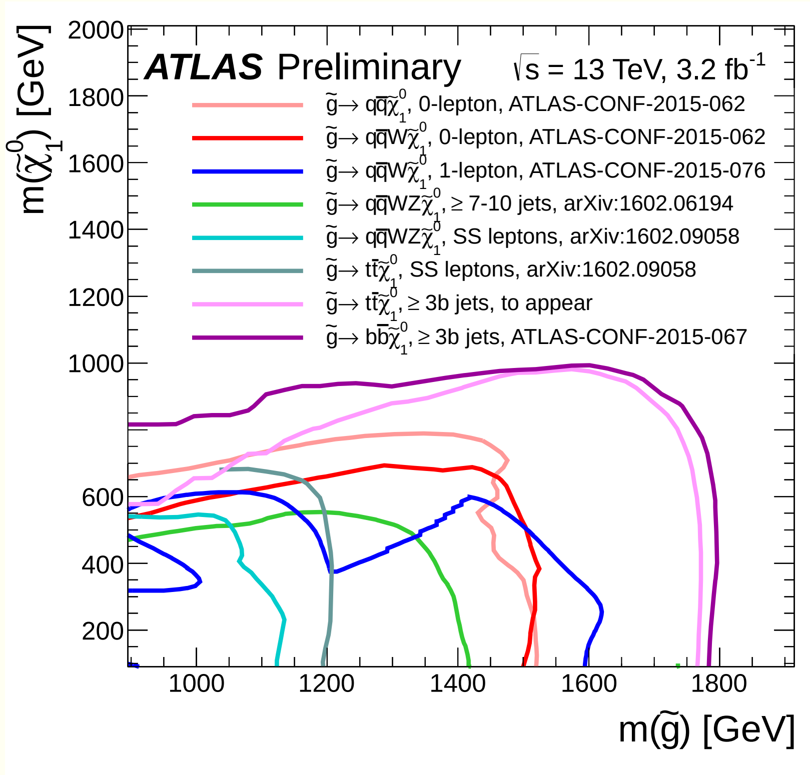
315 Physicists Report Failure in Search for Supersymmetry (Malcolm Browne, NYT Jan. 5, 1993).

Heroic efforts at the LHC to find new physics.

I will just flash results from some SUSY searches. Not a comprehensive review.

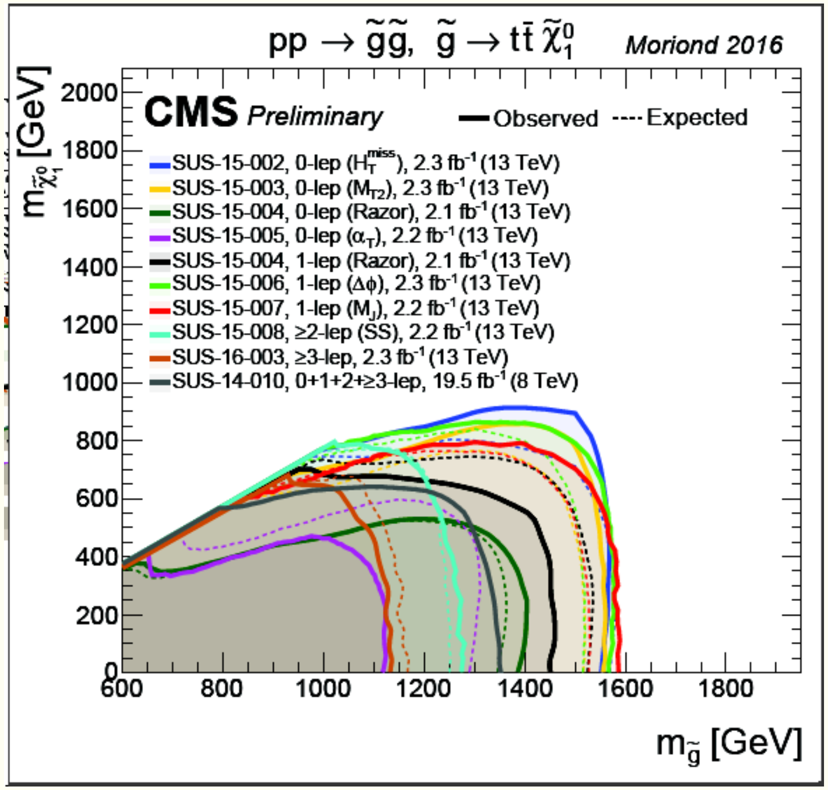
See talks by Davide Costanzo (ATLAS) and Andrew Askew (CMS) plus parallel session reports at SUSY 2016 for an update.

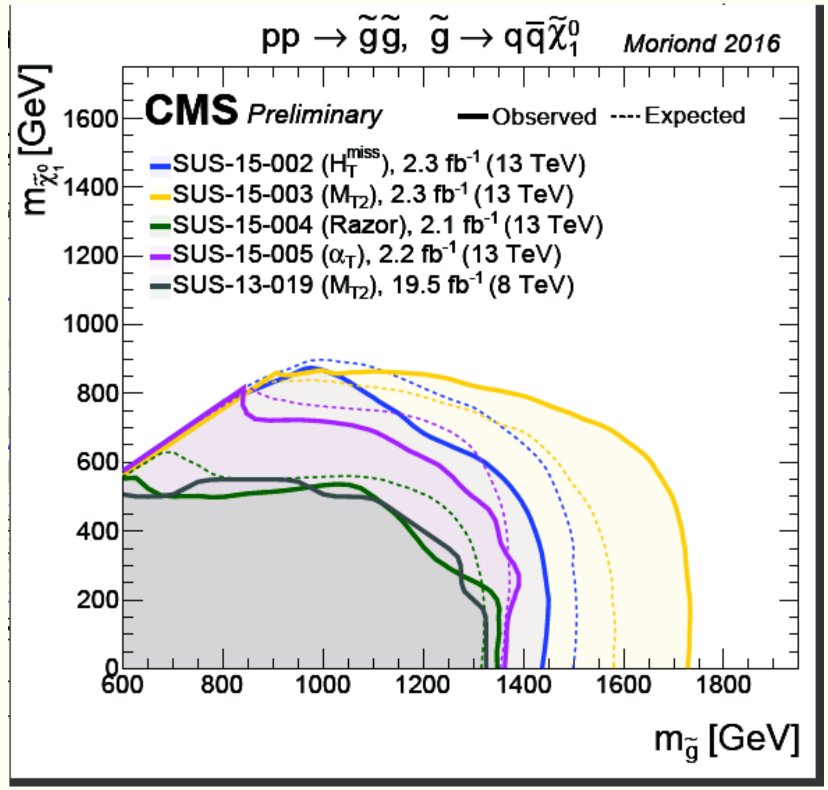
ATLAS gluino search



Gluinos heavier than 1400-1800 GeV.

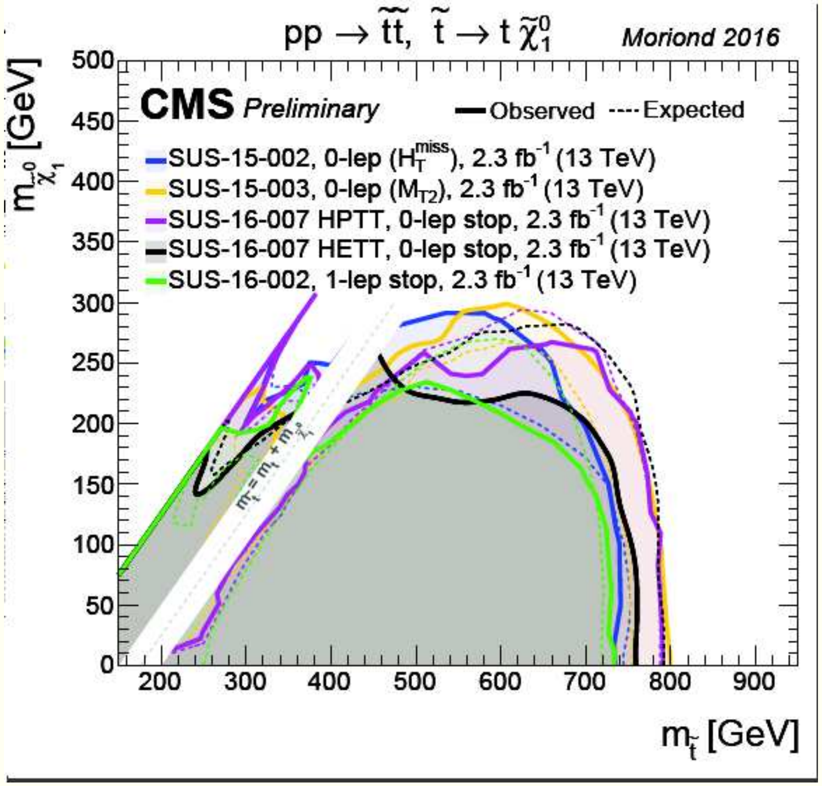
CMS gluino searches





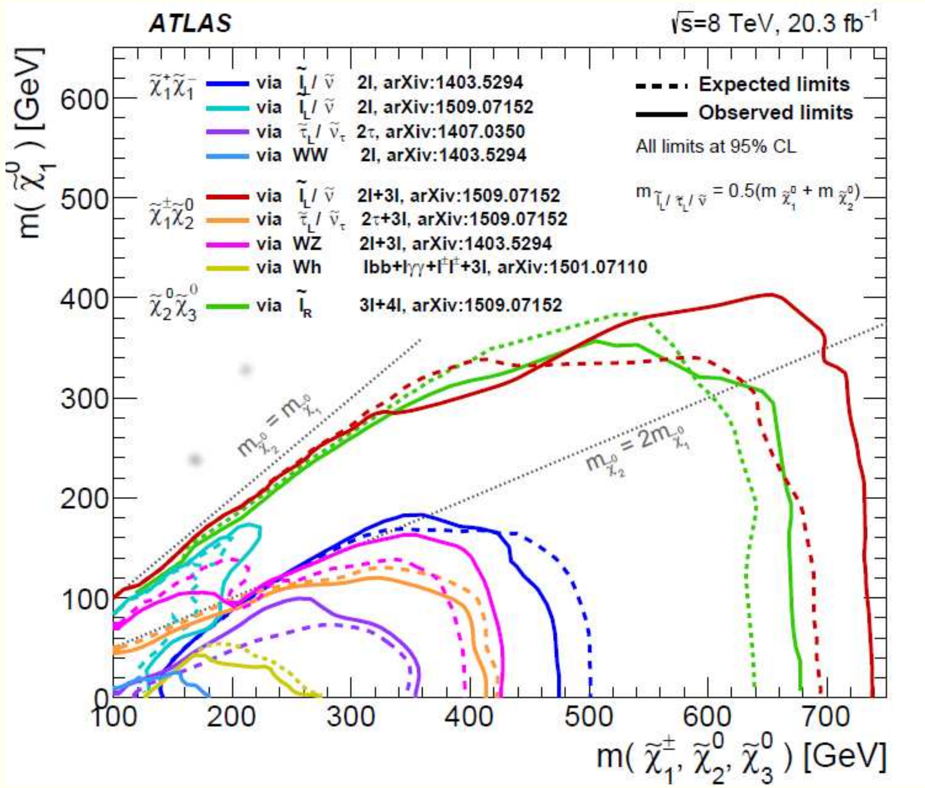
Gluinos heavier than 1400-1700 GeV.

CMS top squark searches



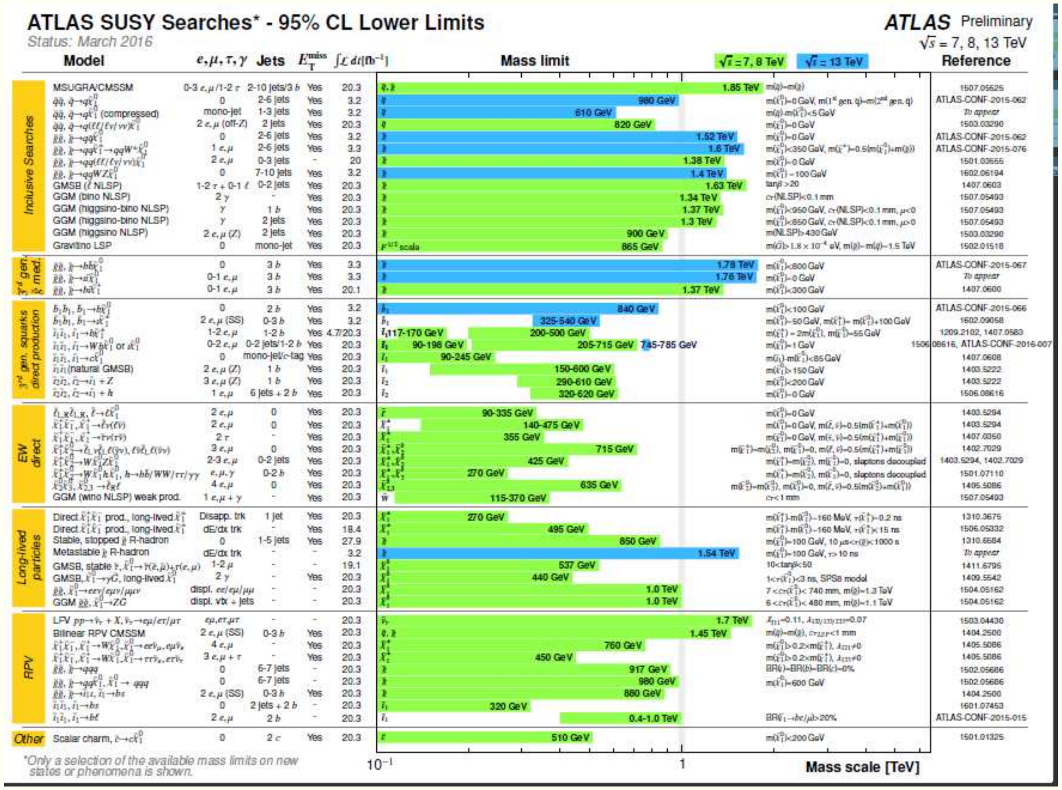
Top squarks heavier than 500-800 GeV; loopholes possible.

Electroweak ino-Searches



Heavier EW-inos are generically heavier than 300-400 GeV. (Very high limits are exceptions rather than the rule.)

Notice the small exclusion in Wh channel, obtained assuming h decays as in SM. (Only small part comes from $h \to bb$.)



Sadly, only lower bounds on superpartner masses, for the most part under simplified model assumptions.

Bounds will change under other scenarios.

Information about (model-dependent) inter-relations between searches is absent.

While I certainly would have loved it if we had heard about the discovery of superpartners rather than about superpartner mass bounds, let us address whether the non-appearance of new physics at LHC13 should cause us to seriously re-evaluate our hopes and aspirations of the early 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 very high scale physics; *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.

$\Delta_{\log}^{-1} = \frac{m_h^2}{\delta m_h^2}$ 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): $\Delta_{\rm BG} = Max_i \frac{p_i}{M_Z^2}\frac{\partial M_Z^2}{\partial p_i}$,

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

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. But nonetheless it is very useful, as we will see.

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 such a UV theory of SUSY breaking parameters.
- ⋆ 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). Recently re-empasized by Ross, Schmidt-Hoberg, Staub.
- ⋆ 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 and 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).

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

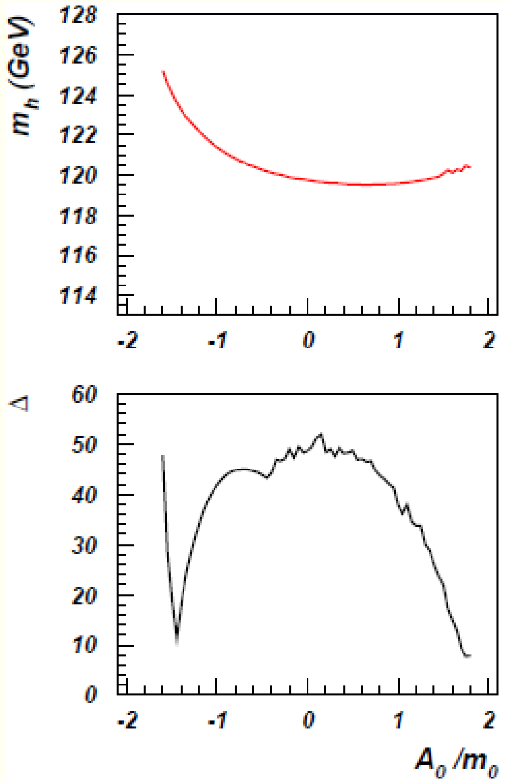
This is not an empty statement. Small $\Delta_{\rm EW}$ cannot be realized in mSUGRA, and also in many other constrained models (Baer, Barger, Mickelson, Padeffke-Kirkland). A large value of $\Delta_{\rm EW}$ signals there must be fine-tuning in the theory.

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.

Contributions dominantly come from top squark loops.

The $\tilde{t}_2$ contribution is $\propto \ln \frac{m_{\tilde{t}_2}}{m_{\tilde{t}_1}} - 1$, and so often small.

The $\tilde{t}_1$ constribution suppressed for large A_t values realized for large, negative A_0.



Thus, $\Delta_{\rm EW}$ falls sharply for $A_0 \sim -1.6 m_0$.

This same A_0 raises the Higgs mass!

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 $m_{H_u}^2$ have to be adjusted to get low $\Delta_{\rm EW}$ says otherwise.

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

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

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

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.

Although this interpretation differs from that of Baer and collaborators (arXiv: 1309.2984, 1404.2277), these differences don't affect the relevance of $\Delta_{\rm EW}$ or the observable implications of these models.

Radiatively-driven Natural SUSY (Baer,Barger,Huang,Mickelson,Mustafayev,XT)

These considerations led us to the radiatively-driven natural SUSY framework for generating spectra with low $\Delta_{\rm EW}$ that may be useful for phenomenological analyses.

In the NUHM2 model, perform a scan over;

- $m_0 = 1 - 7$ TeV; $A_0 = -(1-2)m_0$; $\tan\beta = 5 - 50$;
- $\mu = 100 - 300$; m_A= your choice

Find points with $\Delta_{\rm EW} < 30$, consistent with phenomenological constraints.

Examine the phenomenology of these low $\Delta_{\rm EW}$ RNS scenarios.

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.

RNS Spectrum characteristics

- ⋆ Four light higgsino-like inos, $\widetilde{Z}_{1,2}$, $\widetilde{W}_1^{\pm}$;
- ⋆ $m_{\tilde{t}_1} = 1 - 2$ TeV; $m_{\tilde{t}_2} = 2 - 4$ TeV;
- ⋆ $m_{\tilde{g}} = 1 - 4$ TeV (else $\tilde{t}$s becomes too heavy and make Σ_u^u too large);
  (Resulting bino and wino mass parameters consistent with low $\Delta_{\rm EW}$.)
- ⋆ Split the generations and choose $m_0(1,2)$ large to ameliorate flavour and CP issues (This is separate from getting small $\Delta_{\rm EW}$).

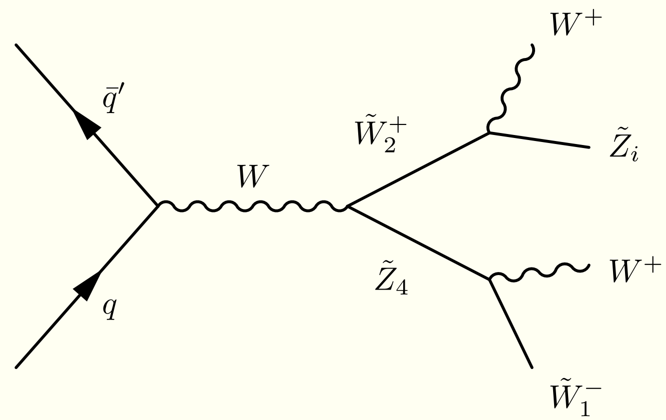
Large intra-generation splittings among heavy first/second generation squarks leads to large $\Delta_{\rm EW}$ except for specific mass patterns.

Broad Brush RNS Phenomenology at the LHC

- ⋆ Light higgsino-like states $\widetilde{W}_1^{\pm}$, $\widetilde{Z}_2$, $\widetilde{Z}_1$ must be present with masses $\sim |\mu| \ll |M_{1,2}|$, and generically small splittings.
- ⋆ If $|M_{1,2}|$ also happens to be comparable to $|\mu|$, these states would be easy to access at the LHC via $\widetilde{W}_1\widetilde{Z}_2$ production, or at a *LC via $\widetilde{W}_1\widetilde{W}_1$, $\widetilde{Z}_1\widetilde{Z}_2$ and $\widetilde{Z}_2\widetilde{Z}_2$ production. Heavier -inos may also be accessible.
- ⋆ In the generic case, the small mass gap may makes it difficult to see the signals from electroweak higgsino pair production at the LHC because decay products are very soft (even though the cross section is in the pb range for 150 GeV higgsinos).
- ⋆ Monojet/monophoton recoiling against higgsinos also does not work. Can reduce backgrounds by requiring additional soft leptons from higgsino decays.
- ⋆ Gluino pair production, if it is accessible at the LHC, will lead to signals rich in b-jets because we have assumed first/second generation squarks are very heavy. However, gluinos may not be accessible.

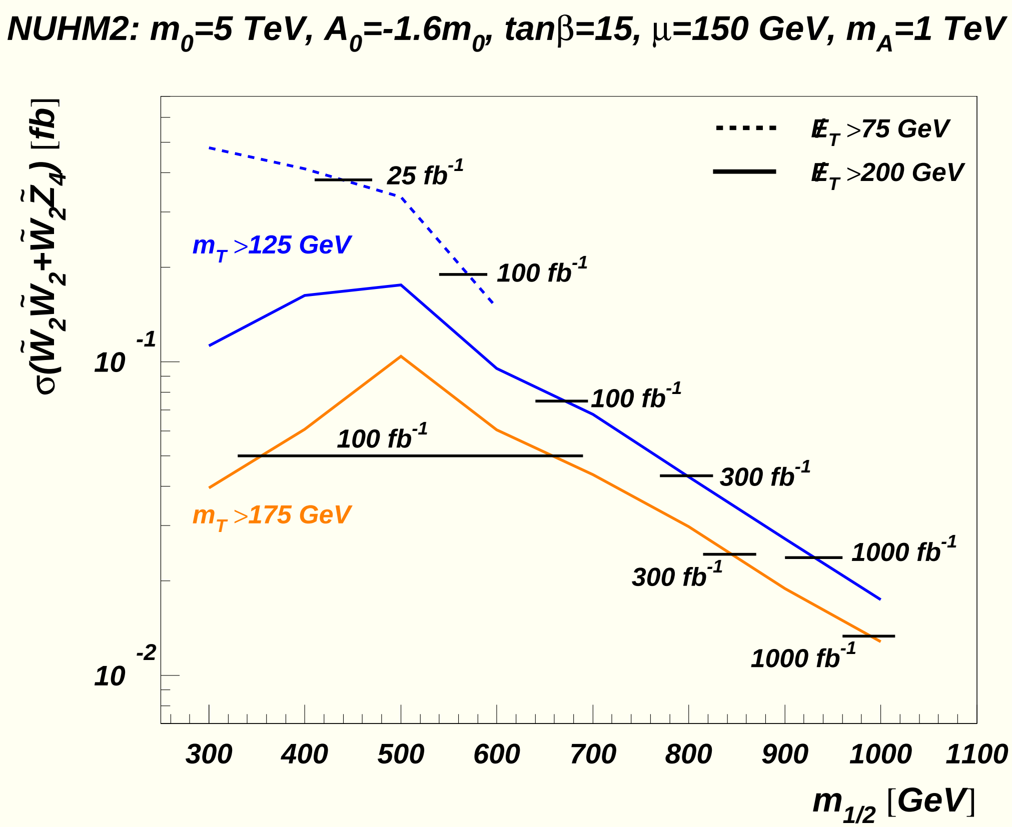
Light higgsinos at the LHC

★ 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.



Hard cuts on $\not{E}_T$ and minimum transverse mass $m_T(\ell_{1,2}, \not{E}_T)$ is crucial to pull out the signal. PRL 110, 151801 (2013)

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

A Recap of the LHC14 Reach for RNS in terms of $m_{\tilde{g}}$/TeV

Int. lum. (fb^{-1})	$\tilde{g}\tilde{g}$	SSdB	$WZ \to 3\ell$	4ℓ
10	1.4	–	–	–
100	1.6	1.6	–	~ 1.2
300	1.7	2.1	1.4	$\gtrsim 1.4$
1000	1.9	2.4	1.6	$\gtrsim 1.6$

The canonical gluino signature yields the highest reach only for integrated luminosities up to 100 fb^{-1}. For higher integrated luminosities, the SSdB channel yields the best reach. The SSdB signal is a generic characteristic of small $|\mu|$ models.

If the SSdB signal is present, there may be confirmatory signals in the 3ℓ and 4ℓ channels.

Can the LHC catch SUSY if $\Delta_{EW} < 30$?

Monojet Signals

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.

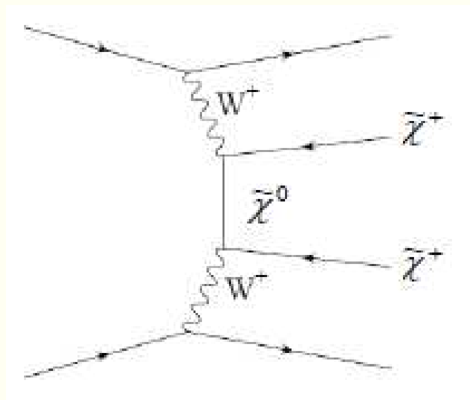
Alternatively, examine dilepton flavour asymmetry $\frac{N(SF)-N(OF)}{N(SF)+N(OF)}$ in monojet plus OS dilepton events.

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!

HOW NOT TO SEARCH FOR LIGHT HIGGSINOS AT THE LHC

Since ATLAS/CMS have been able to probe $W^+W^+ \to W^+W^+$ scattering, it seemed natural to study same sign charged higgsino pair production $pp \to \widetilde{W}_1^\pm \widetilde{W}_1^\pm jjX$ in natural SUSY that occurs via t-channel exchange of neutralinos. Many VBF studies by the Texas A and M group after pioneering work by Hagiwara et. al. (2006) and Giudice et al. (2010).



To our surprise, we found that the cross section for $pp \to \widetilde{W}_1^\pm \widetilde{W}_1^\pm jjX$ production falls of very fast with increasing $m_{1/2}$ even if chargino mass is not changed!

(Stengel, XT)

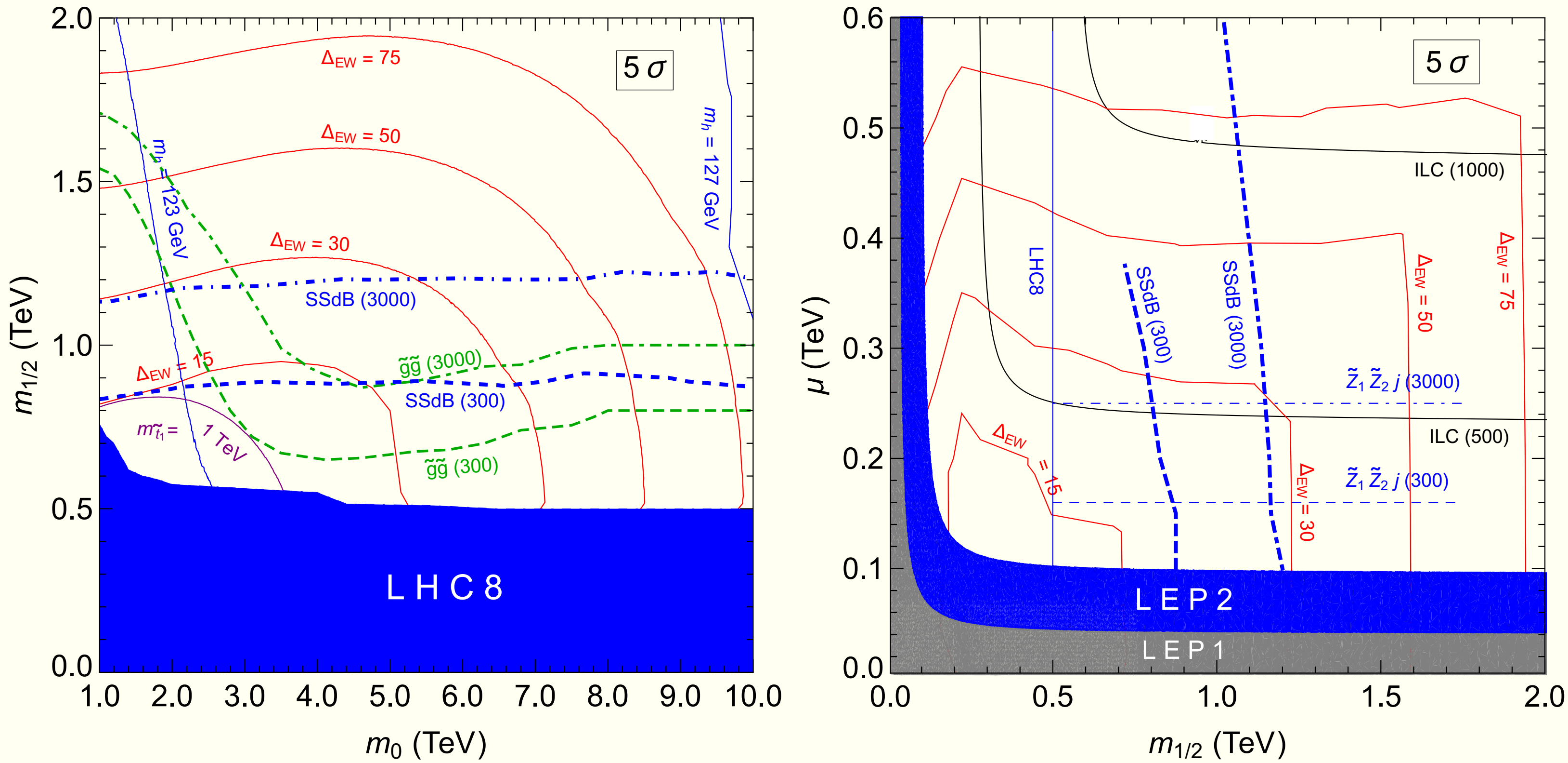
To understand this, we focussed on $W^+W^+ \to \widetilde{W}_1^+\widetilde{W}_1^+$.

We realized that in the $M_{1,2} \to \infty$ limit, the two degenerate neutral higgsinos can be written as one Dirac higgsino ($\widetilde{Z}_D$) and then, the $W\overline{\widetilde{W}_1}\widetilde{Z}_D$ coupling has an extra conserved $U(1)$ charge where $\widetilde{W}_1^+$ and $\widetilde{W}_1^-$ have equal and opposite charges, as do $\widetilde{Z}_D$ and $\overline{\widetilde{Z}_D}$ (gaugino number). Exact symmetry if sfermions decouple.

SS higgsino production is strongly suppressed because it does not conserve gaugino

With hindsight, we can also see suppression of the cross-section by examining MSSM amplitudes; the contribution from $\widetilde{Z}_1$ and $\widetilde{Z}_2$ exchanges cancel exactly in the limit that the winos and binos are very heavy.

An overview of the High Luminosity LHC reach in RNS (Baer, Barger, Savoy, XT)

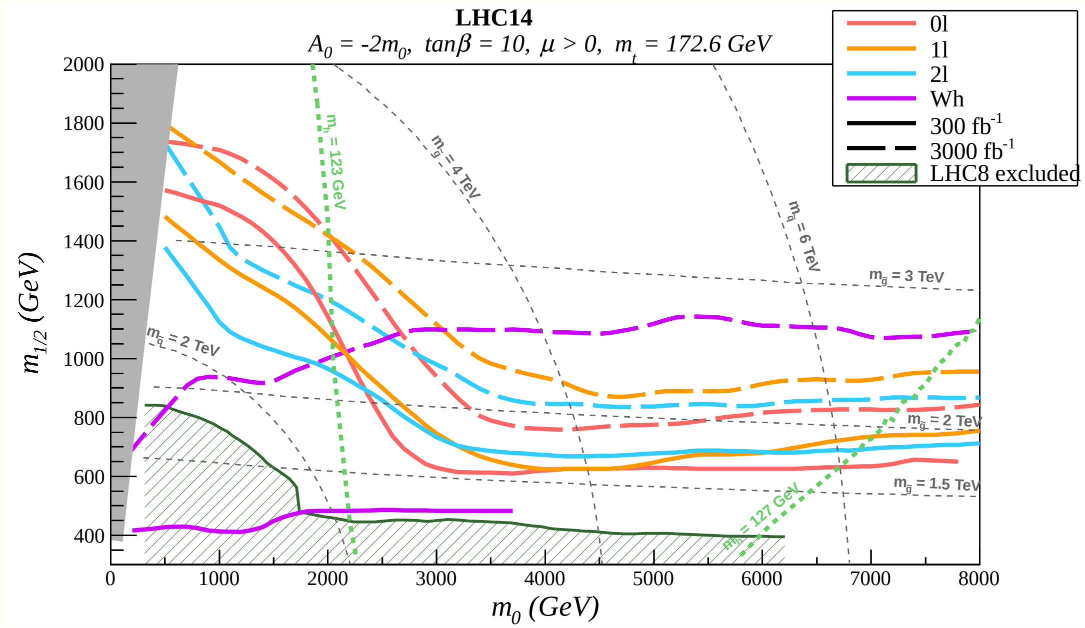


The high luminosity LHC has the potential to detect a SUSY signal over most of the $\Delta_{EW} \leq 30$ part of RNS parameter space!

Possibly more than one signal detectable.

Gaugino production yields a bigger reach than gluino production.

The higher reach via winos vs. gluinos seems generic in models with gaugino mass unification, as shown also by High Luminosity LHC: mSUGRA.



Baer,Barger,Lessa,XT

Notice again that at very high integrated luminosity, and very high m_0 the reach in $m_{1/2}$ is dominated by the $Wh+ \not{E}_T$ channel.

This is because gluino and squark production is kinematically suppressed and $\widetilde{W}_1\widetilde{W}_1$ and $\widetilde{W}_1\widetilde{Z}_2$ production are the dominant production mechanisms. Since $B(\widetilde{Z}_2 \to \widetilde{Z}_1 h)$ and $B(\widetilde{W}_1 \to W\widetilde{Z}_1)$ are essentially 100%, this channel dominates at very high integrated luminosity.

Final Remarks

- ⋆ Dismay at the non-appearance of SUSY seems premature. We were over-optimistic in our expectations. The LHC13 run has just begun.
- ⋆ 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.
- ⋆ Light higgsinos seem necessary for naturalness, and will likely yield novel LHC signals via soft leptons in triggered events.
- ⋆ At the high luminosity LHC, the best reach may be obtained via wino rather than gluino pair production.
- ⋆ Light higgsino scenarios cannot saturate the total CDM; nonetheless, assuming gaugino mass unification, there is enough thermal higgsino DM fraction that will reveal itself in direct DM searches at ton size detectors.

  (Baer, Barger, Mickelson)

- ⋆ 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.
- ⋆ 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.