Is SUSY hiding from us?

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SUSY continues to be an active area of phenomenological research since the early 1980s. Many attractive features.

- 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).

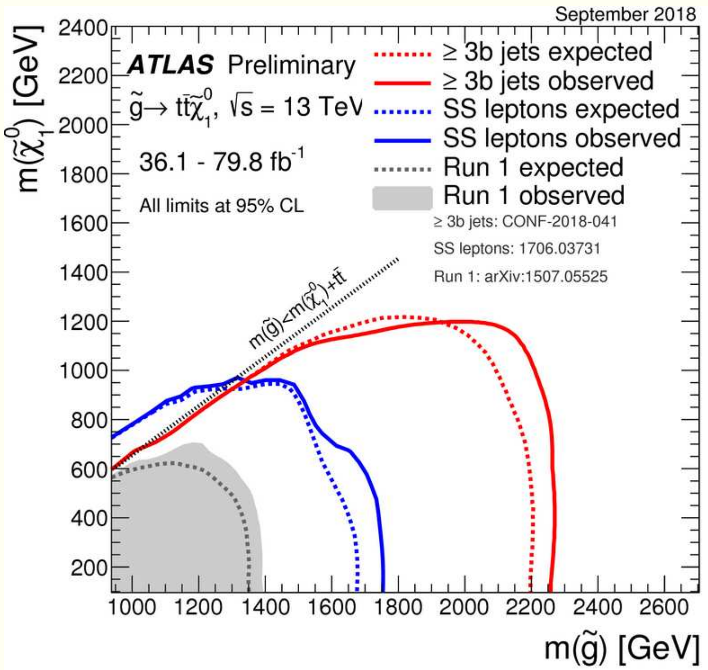
⋆ SUSY solves the big hierarchy problem. Low scale physics does not have quadratic sensitivity to high scales if the low scale theory is embedded into a bigger framework with a high mass scale, Λ. (Kaul-Majumdar, Witten)

Only reason for superpartners at the TeV scale.

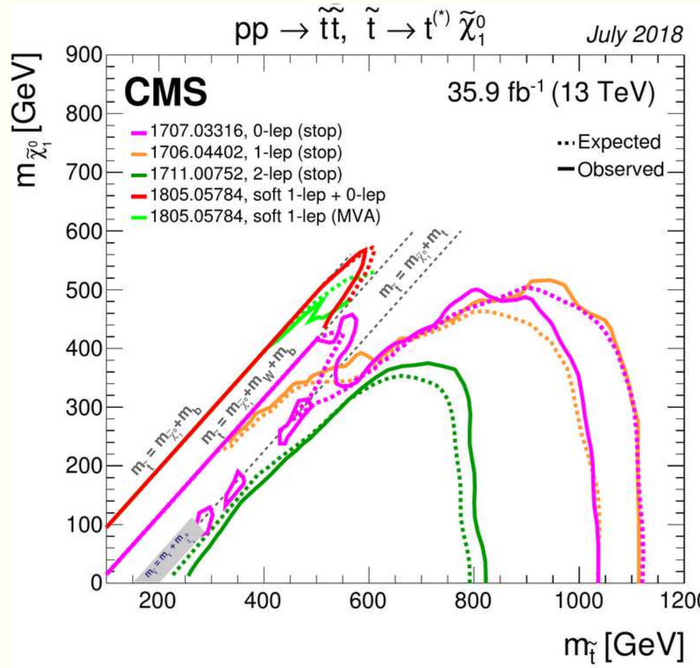
Bonus: Measured gauge couplings at LEP unify in MSSM but not in SM

However, there are no direct SUSY signals in the LHC data.

ATLAS



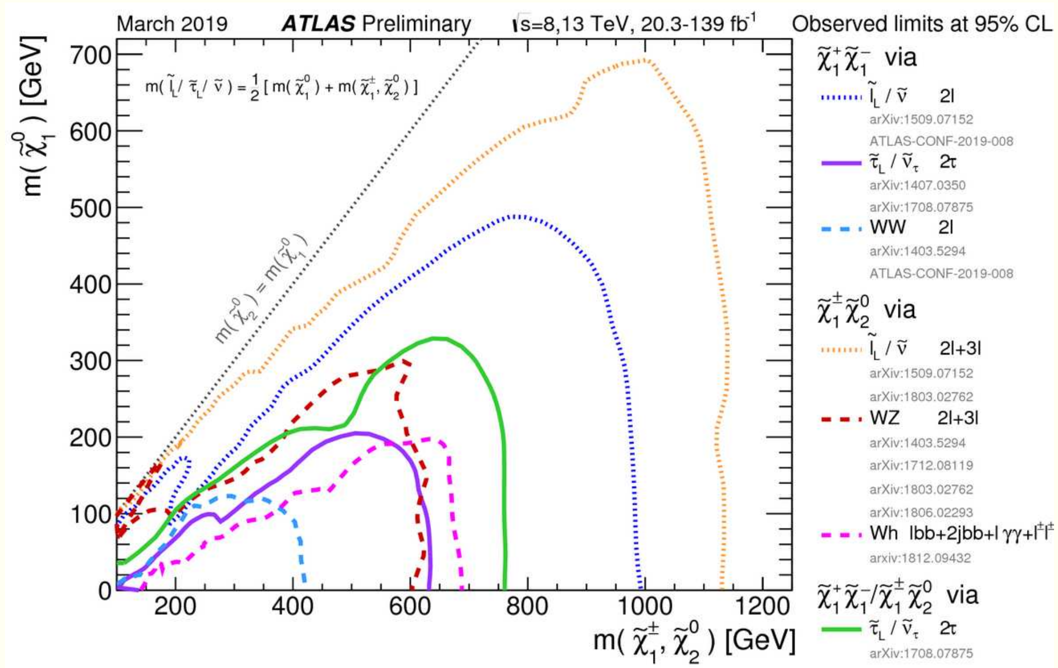
CMS



$m_{\tilde{g}} > 1900 - 2200$ GeV if squarks are heavy, and gluinos decay to third generation.

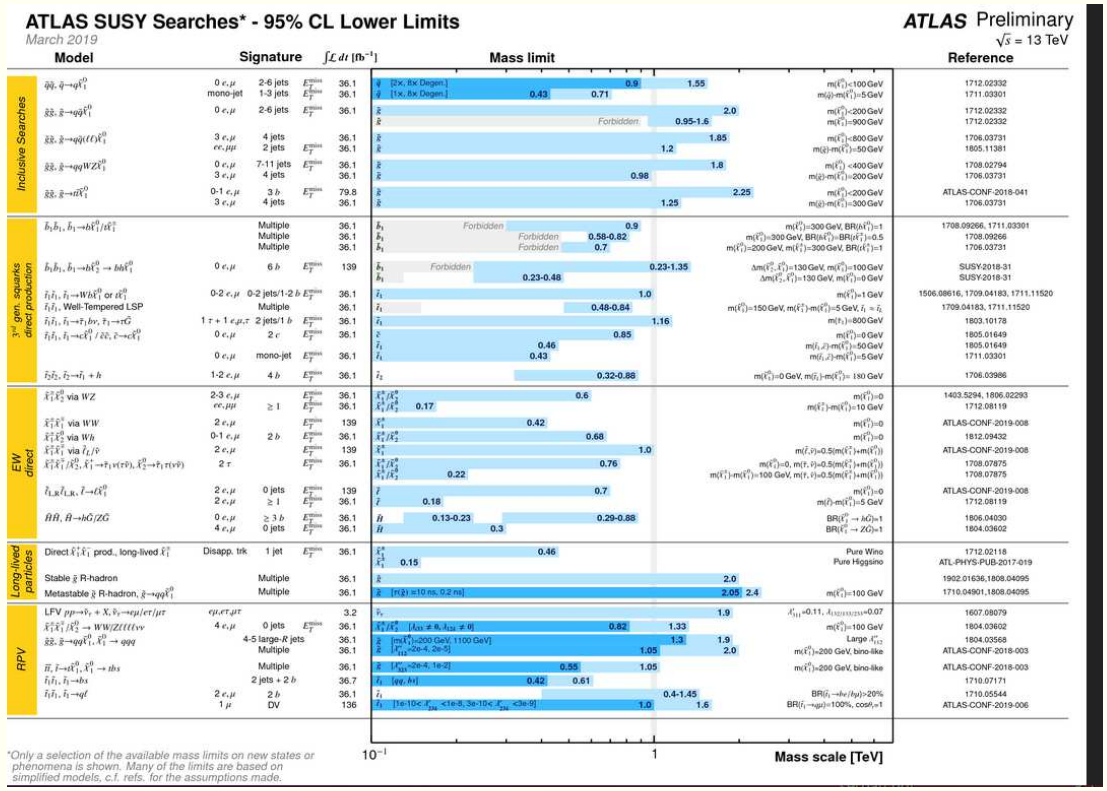
Top and sbottom squarks are heavier than 1.1 TeV.

Electroweak ino-Searches



Interesting electroweak-ino mass limits around 500-600 GeV. Bounds are less stringent as these are produced with smaller cross sections, by electroweak interactions.

Many other searches also, but no signal!



I remark that for the most part under simplified model assumptions. Bounds will change under other scenarios.

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

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.

Absence of superparticle signatures led some groups to suggest that SUSY may be hidden from the usual SUSY analyses that rely strongly on $\not{E}_T$ to pull out the signal.

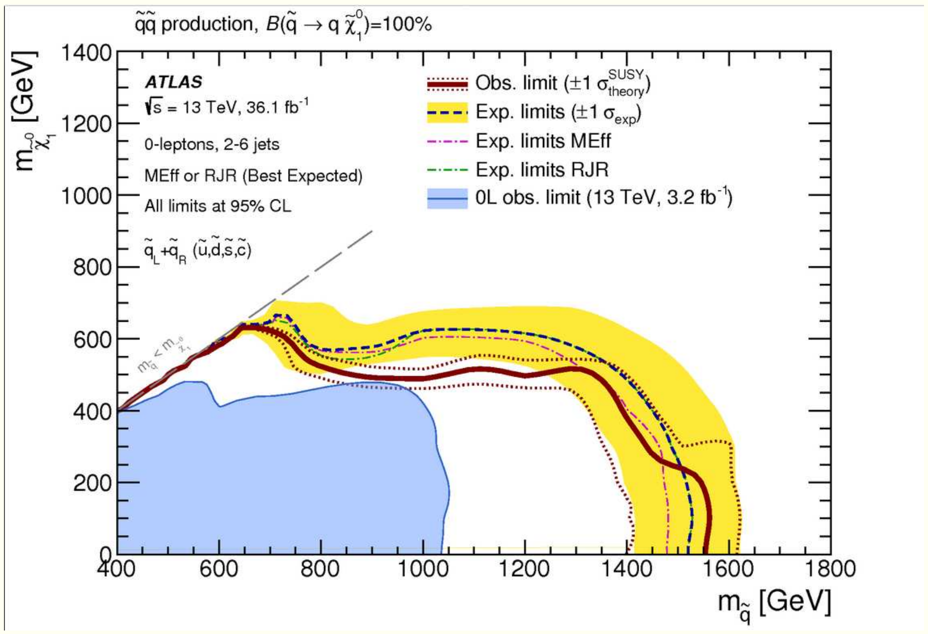
HIDING THE $\not{E}_T$ SIGNAL

- ⋆ Compress the SUSY spectrum. If the parent particle and the LSP are close in mass, the energy released and $\not{E}_T$ is reduced, and signal is harder to distinguish from background.
- ⋆ Make the LSP unstable on collider time scales (RPV). If the LSP decays hadronically, the SUSY signal is harder to detect at the LHC. We will lose SUSY DM, but so what?
- ⋆ Reduce the $\not{E}_T$ by having a theoretically motivated compression in a secluded sector. Stealth SUSY

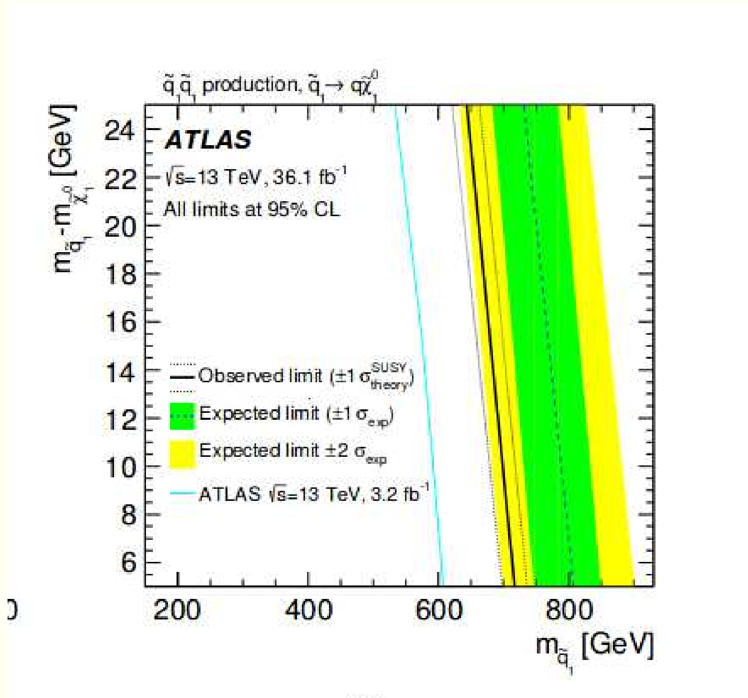
What do LHC experiments say about each of these ideas?

Compressed SUSY Barger, Hagiwara, Woodside, Keung (1984); LeCompte, Martin; Dreiner, Kramer, Tattersall; Barducci et. al.; An, Wang, Chowdhury et al.,......

Usual search

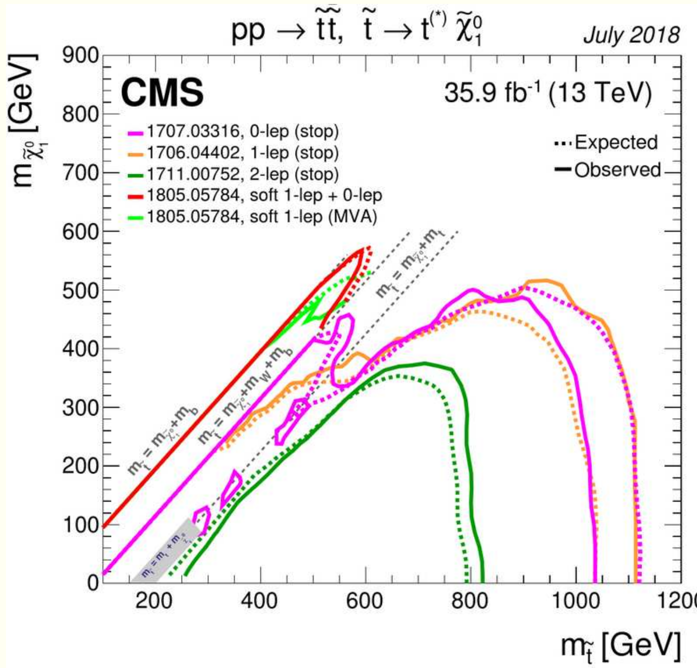


Monojet search



The monojet search for $\tilde{q}\tilde{q}+$ QCD jet production (right frame) kicks in if squark has no visible decay products, and the squarks are essentially invisible.

Our experimental colleagues have worked incredibly hard to explore the compressed stop-LSP spectrum.



This was important for EW baryogenesis considerations.

Notice that some gap remains, and the search does not extend as far in the degenerate stop-LSP case..

R-parity violation

If LSP decays leptonically, many easy signals at LHC. To hide SUSY, make LSP decay hadronically, and avoid third generation. λ''_{112} type superpotential coupling in superpotential, so $\widetilde{Z}_1 \to uds$.

No physics $\not{E}_T$ except from neutrinos in cascade decays, (and no b-jet tag).

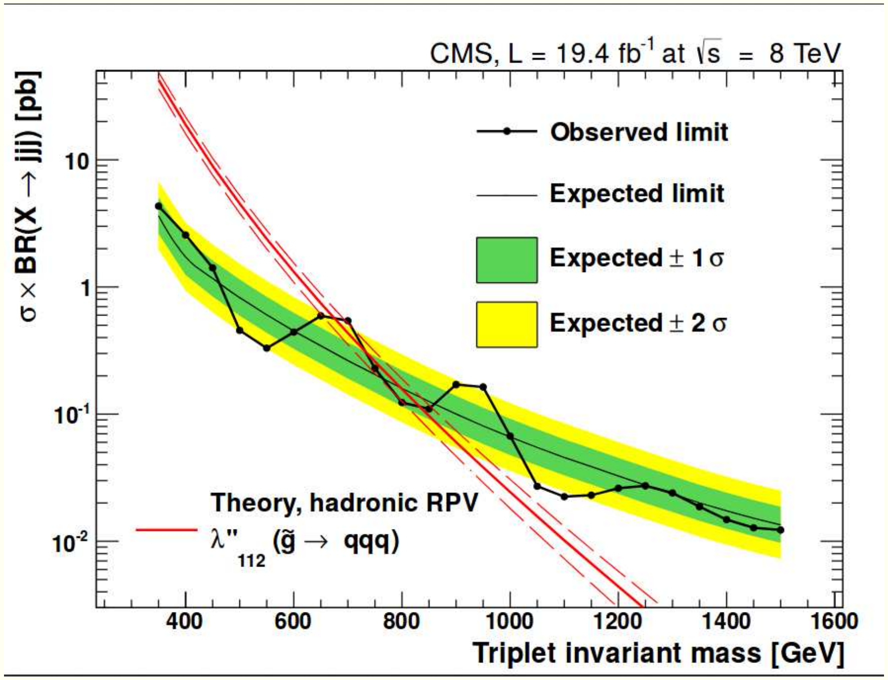
I could not find any experimental analyses of this type of situation.

Ancient mSUGRA analysis of 10 fb^{-1} LHC suggests that gluinos and squarks in excess of 1 TeV would be probed via multilepton channels, to be compared with 1.6-2 TeV in R-parity conserving scenario. Baer, Chen and XT, PRD 55 (1997) 1466

If the RPV coupling is big, $\tilde{g} \to uds$!

What is the experimental situation?

CMS 8 TeV $\tilde{g}\tilde{g}$ pair search when $\tilde{g} \to uds$

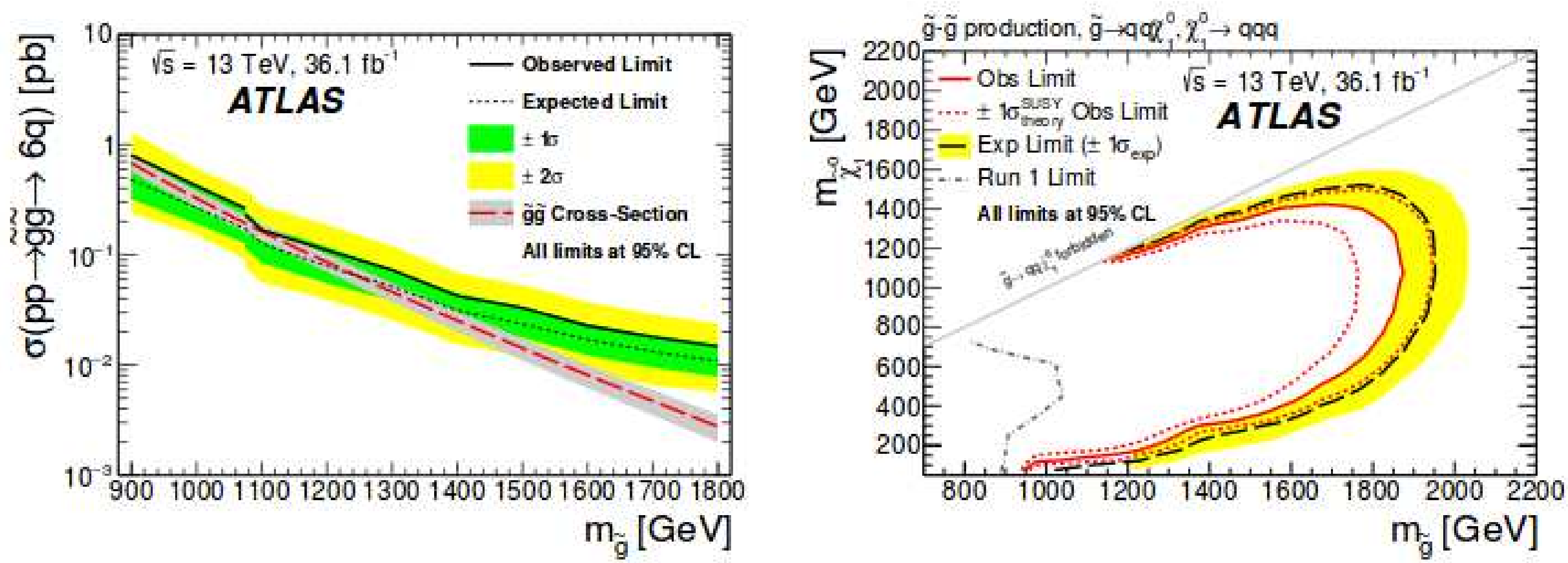


Use mass constraint to separate the signal from $6j$ background. Clearly take a hit in the reach.

LAMP-POST BARYONIC RPV ANALYSES

Flavour democratic RPV, so lots of tops and bottoms, or cascade with leptons!

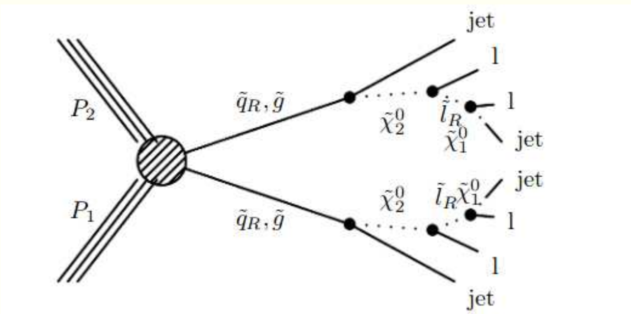
$$\tilde{g} \to qqq$$

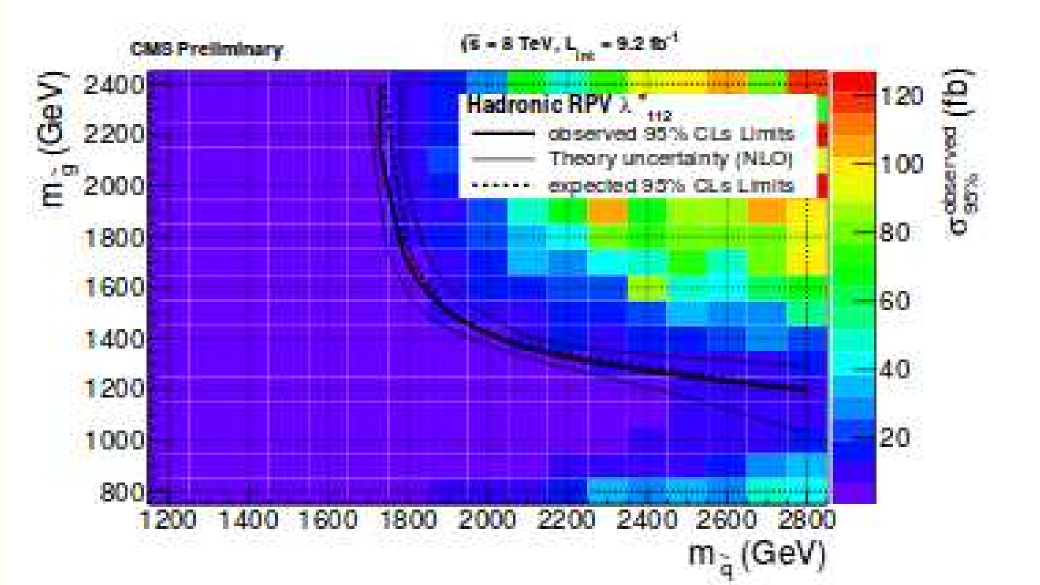


(a) gluino direct decay model (b) gluino cascade decay model

Possibility to tag third generation clearly helps.

THE LEPTONIC LAMPOST – 8 TeV CMS analysis



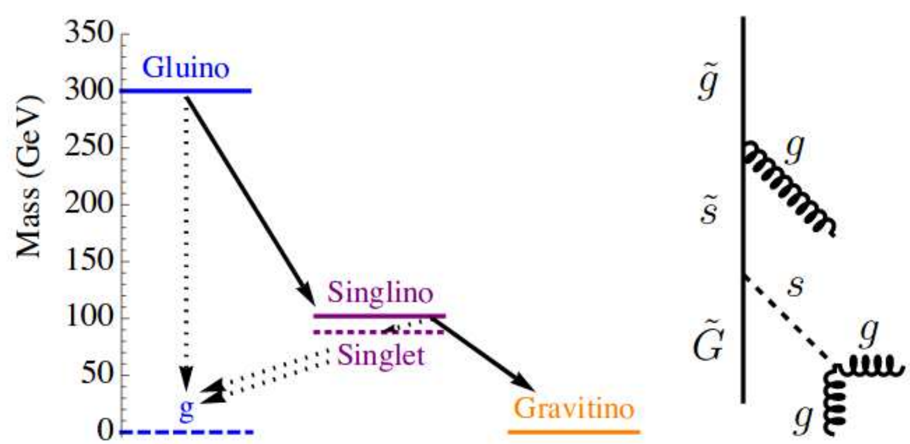


Leptonic lamposts are very bright!!!!

STEALTH SUPERSYMMETRY: An R-parity conserving scenario.

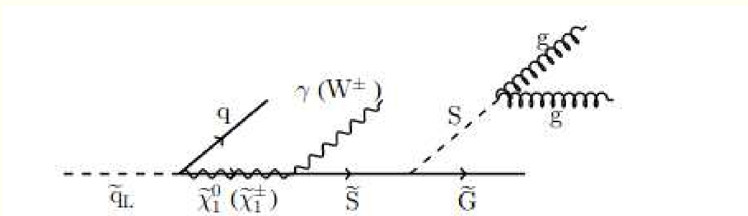
Fan, Reece, Ruderman; Fan, Krall, Pinner, Reece, Ruderman,...

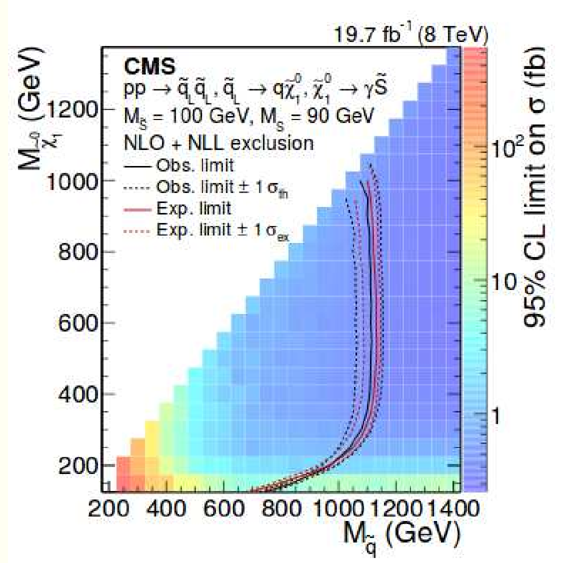
This was motivated by the fact that the assumption of a compressed MSSM spectrum has no compelling theoretical motivation. Compression in a secluded sector may be better motivated if its coupling to the SUSY breaking sector is suppressed.

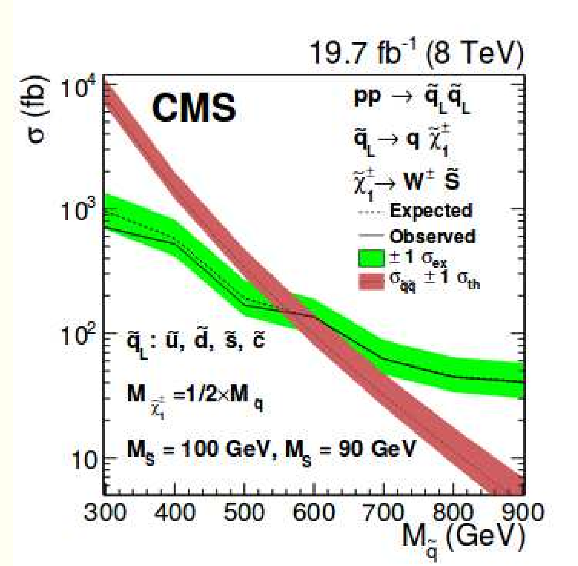


Since $m_{\tilde{S}} - m_S \ll m_{\tilde{g}}$, the $\tilde{G}$ is typically soft, and the $\not{E}_T$ in SUSY events is small.

Again, I could find only lamp-post experimental analyses of stealth SUSY.







Even with the lampost, the LHC reach is considerably reduced.

Is hiding SUSY from LHC really necessary?

We have seen that it is possible to contrive things to hide SUSY from LHC searches, but how crucial is it to build this new bunker?

SUSY undoubtedly solves the big hierarchy problem, but LHC constraints are said to require per mille fine-tuning. This is based on,

$$\delta m_h^2 \sim \Sigma_i C_2(i) \frac{g^2}{16\pi^2} m_{\rm SUSY}^2(i) \times \log \frac{\Lambda^2}{m_{\rm SUSY}^2(i)} \ ,$$

and is is true only if various SUSY contributions are truly independent.

However, it is very plausible (even likely) various soft SUSY-breaking parameters will turn out to be correlated by the yet-to-be-understood SUSY breaking/mediation mechanism. With appropriate correlations, the large logs can cancel, and the degree of fine-tuning (ignoring these correlations) may be greatly over-estimated by the traditional Ellis-Enqvist-Nanopoulos-Zwirner measure popularized by Barbieri and Giudice.

PLEASE DO NOT IGNORE THIS POSSIBILITY EVEN IF WE DO NOT HAVE A TOP-DOWN MODEL THAT GIVES SUCH CORRELATIONS.

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, $\Delta_{\rm EW} \leq \Delta_{\rm BG}$.

However, we will see that if UV scale parameters of the model 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).

We suggest $\Delta_{\rm EW} < 30$ – right between one and two orders of magnitude FT – is a reasonable conservative bound.

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

Features of $\Delta_{\rm EW} < 30$ models

- ⋆ Four light higgsino-like inos, $\widetilde{Z}_{1,2}$, $\widetilde{W}_1^\pm$, typically with small mass splittings as binos and winos at the TeV scale;
- ⋆ $m_{\tilde{t}_1} = 1 - 3.5$ TeV
- ⋆ Typically, $m_{\tilde{g}} = 1 - 6$ TeV (else $m_{\tilde{t}_1}$ increases and makes Σ_u^u too large).
- ⋆ Split the generations and choose $m_0(1,2)$ large to ameliorate flavour and CP issues. This is separate from getting small $\Delta_{\rm EW}$. NUHM3 model

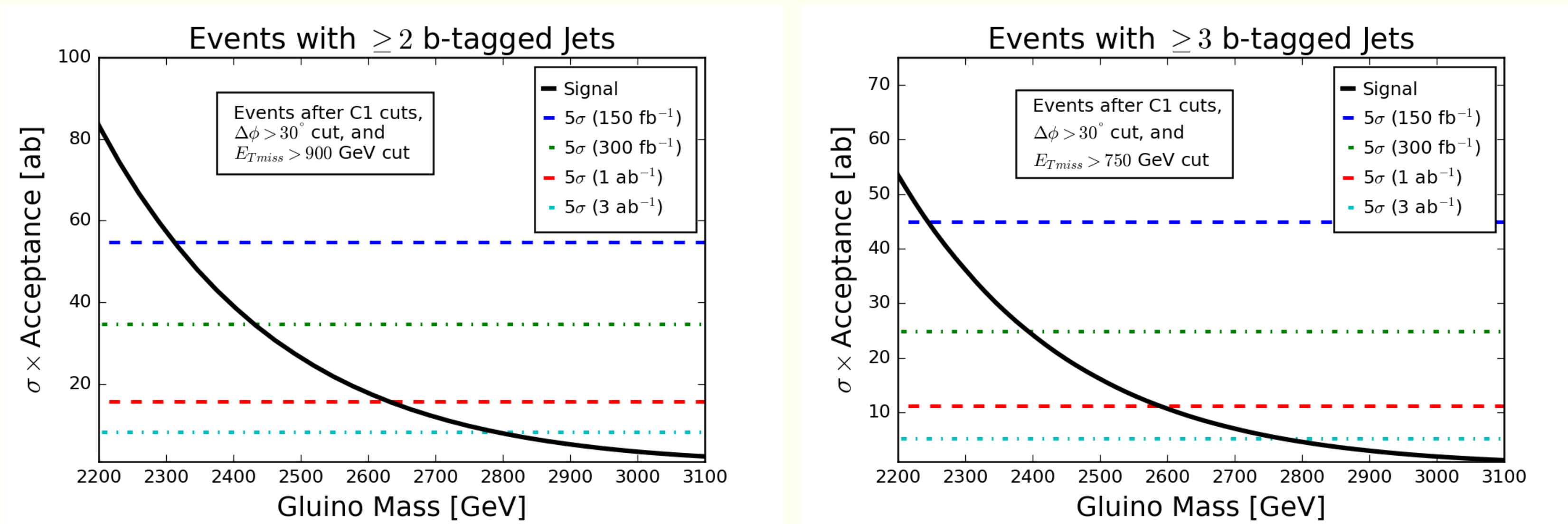
Underlying philosophy is that if we find an underlying theory of SUSY breaking parameters with low $\Delta_{\rm BG}$ that yields essentially the same spectrum, it will have the same phenomenological implications since these are mostly determined by the spectrum. The NUHM2, or some other top-down model with low $\Delta_{\rm EW}$ is a surrogate for exploring the phenomenology of this (as yet unknown) theory with low ($\Delta_{\rm EW} < 30$) fine-tuning. (Examples later)

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.

Natural SUSY gluino reach at LHC14

Since stops are light, gluinos typically decay via $\tilde{g} \to t\tilde{t}_1$, with $\tilde{t}_1 \to t\widetilde{Z}_{1,2}$ and $\tilde{t}_1 \to b\widetilde{W}_1$. Decay products of the daughter higgsinos are too soft for efficient detection.



Even with 3 ab^{-1}, gluinos heavier than 2.8 TeV will not be detectable at LHC14.

(arXiv:1612.00795)

Light Higgsinos at the LHC

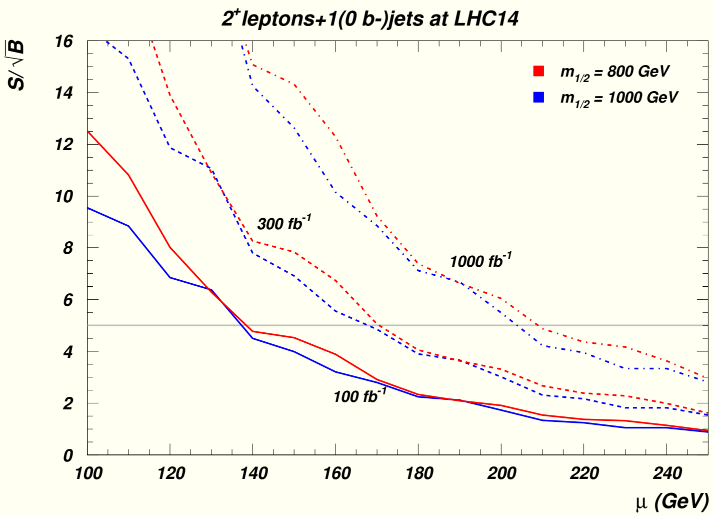
There has been much talk about detecting natural SUSY via inclusive $\not\!\!E_T$ + monojet events from $pp \to \widetilde{W}_1\widetilde{W}_1, \widetilde{W}_1\widetilde{Z}_{1,2}, \widetilde{Z}_{1,2}\widetilde{Z}_{1,2} + jet$ production, where the jet comes from QCD radiation.

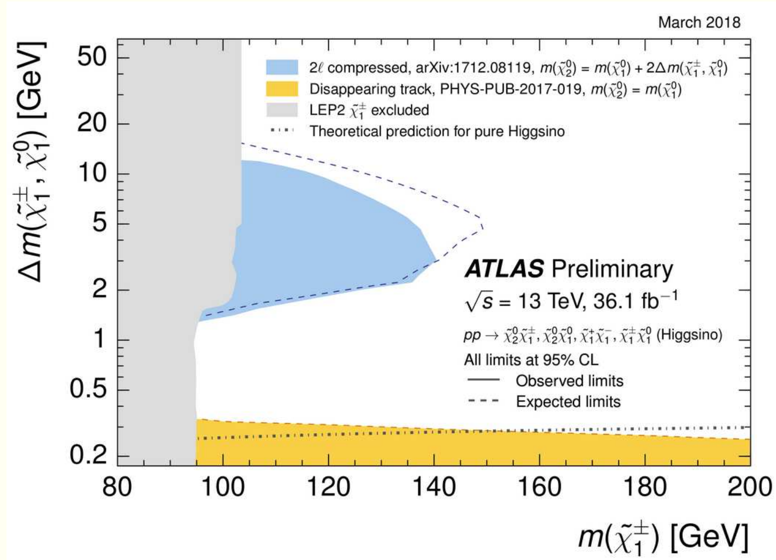
- ⋆ Although there is an observable rate, even after hard cuts, the signal to background ratio is typically at the percent level. We are pessimistic that the backgrounds can be controlled/measured at the subpercent level needed to extract the signal in the inclusive $\not\!\!E_T$ + monojet channel. Baer, 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 $m_{\ell\ell} < m_{\ell\ell}^{\rm cut}$ 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.

No time to describe details of the analysis here.



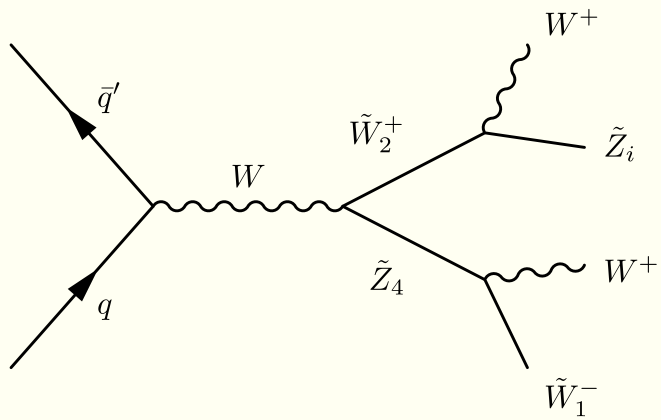


LHC14 reach extends to about $|\mu| = 170$ (210) GeV for integrated luminosity of 300 (1000) fb^{-1}. Baer, Mustafayev and XT How low a ΔM will be covered?

Recent ATLAS analysis gives reassurance that low ΔM is doable, but the issue is how low a ΔM they will cover, as M goes up. CMS cut off at $\Delta M = 7.5$ GeV.

Light higgsinos at the LHC II

★ 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.

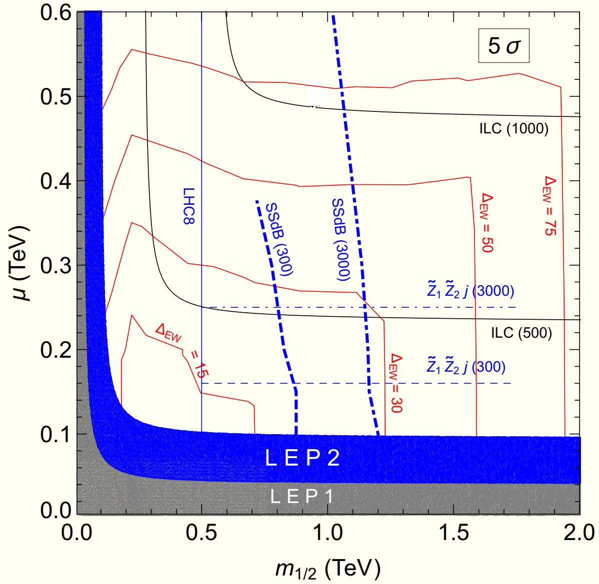


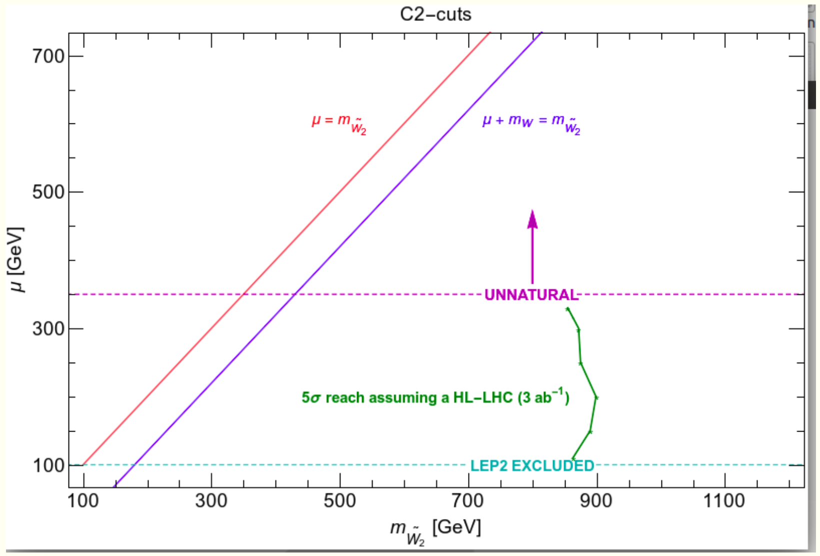
Decays of the parent $\widetilde{W}_2$ and $\widetilde{Z}_4$ that lead to W boson pairs give the same sign 50% of the time. Novel same sign dilepton events with jet activity essentially only from QCD radiation since decay products of higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_2$ are typically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

This new signal may point to the presence of light higgsinos.

Overview of the High Luminosity LHC Reach in nNUHM2 Model

arXiv:1604.07438 arXiv:1710.09103





The high luminosity LHC has the potential to detect a SUSY signal over much of the $\Delta_{\rm EW} \leq 30$ 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?

The cross section for $e^+e^- \to higgsinos$ exceeds that for $e^+e^- \to Zh$, so electron positron colliders are higgsino factories. Detection of higgsinos with mass gaps down to 10 GeV explored in JHEP 1406 (2014) 172 where it is shown precision studies are possible. Follow ups by ILC study groups.
600 GeV CM energy needed for definitive exploration.

But such a machine may never exist!!! Motivation to look at energy upgrades of the LHC

We had seen that assuming gaugino mass unification, experiments at the HL-LHC seemed to cover essentially all the "natural" SUSY region via the SSdB and monojet+ soft lepton channels.

But this is not good enough because gaugino mass unification is not expected in many well-motivated SUSY GUT models maintaining naturalness.

- ⋆ Mirage unification (KKLT, Choi et. al., Falkowski et al.)
- ⋆ The mini-landscape picture (Nilles and collaborators.)
- ⋆ Non-universality is generic if the field that breaks SUSY transforms non-trivially under the GUT gauge group.

In such scenarios, we may have low $\Delta_{\rm EW}$, but no observable signals at even the HL-LHC. How small a ΔM is accessible at the HL-LHC? (under examination)

Gluino and stop reach at LHC27 (arXiv:1708.09054 and arXiv:1808.04844)

CERN is considering a plan for an energy upgrade of LHC. arXiv:1108.1617 [phys.acc-ph] suggested a 27 TeV collider to deliver a data sample of ~ 15 ab^{-1} in LEP tunnel. (HE-LHC study at 27 TeV, 15 ab^{-1}, arXiv:1812.07831.)

Natural to examine prospects for gluinos and stops of natural SUSY whose masses are bounded above by about 3.5 and 6 TeV/9 TeV, respectively.

Examined the reach of LHC27 assuming $\tilde{g} \to \tilde{t}_1^{(*)} t$, $\tilde{t}_1 \to t\widetilde{Z}_1, b\widetilde{W}_1$.

Used very hard cuts to get the maximal reach.

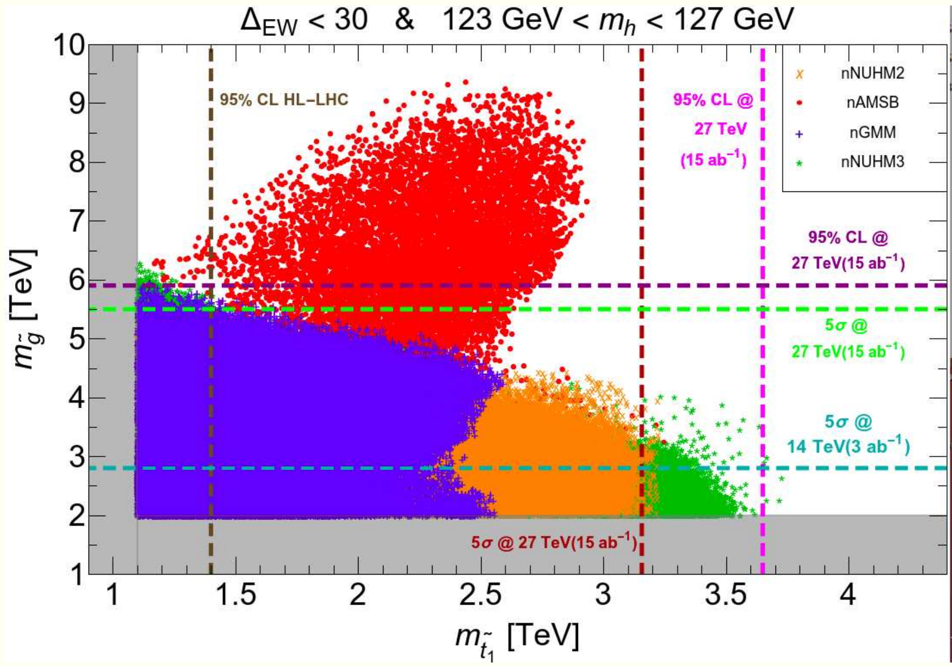
Gluino: $n_b \geq 2$, isolated lepton veto, $\not{E}_T > Max(1900\text{ GeV}, 0.2M_{\text{eff}})$, $n_j \geq 4$ with $E_{Tji} > 1300, 900, 200, 200$ GeV, $S_T > 0.1$, $\Delta\phi > 10$ degrees.

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

Main SM backgrounds from $t\bar{t}$, $b\bar{b}Z$, $t\bar{t}b\bar{b}$, $4t$ and single t production.

LHC27 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 (horizontal) lines are our projections for the stop (gluino) reach/exclusion region for an integrated luminosity of 15 ab^{-1}.



We see that the LHC27 reach will be sensitive to at least one of the stop, or the gluino, and over most of the parameter range to both! Independent analysis by Han, Ismail and Haghi with 4.7 TeV reach in gluino and 2.8 TeV in stop (arXiv:1902.05109). They find larger backgrounds, but have softer cuts.

Final Remarks

- ⋆ It is certainly possible to contrive of ways to hide SUSY signals from revealing themselves via the standard SUSY searches. In this case our experimental colleagues will have to work extra hard to dig these out as they have done for stop nearly degenerate with the LSP.
- ⋆ To me, the dismay at the non-appearance of SUSY seems premature. We were over-optimistic in our expectations from naturalness, and we may not (yet) need to take refuge in models constructed to deliberately hide the $\not{E}_T$ signals. Remember also that the LHC run has a long way to go.
- ⋆ Light higgsinos seem to be the best bet for naturalness, and will likely yield the novel LHC signals: same sign dibosons, monojet plus soft dileptons with $m_{\ell\ell} < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$.
- ⋆ A 600 GeV electron-positron collider or the high energy LHC, a 27 TeV pp collider would definitively probe SUSY models with acceptable fine-tuning.

- ⋆ 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.