Natural SUSY Phenomenology

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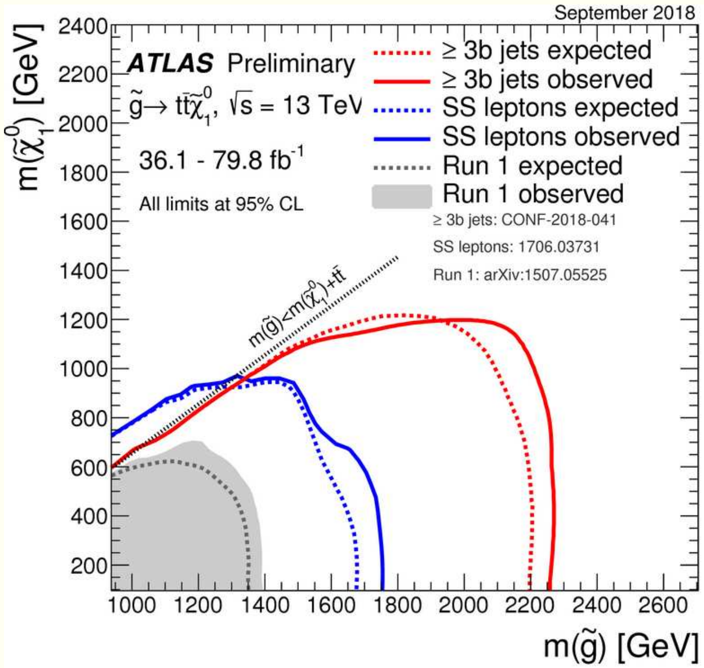
- ⋆ SUSY has been an active area of phenomenological research since the early 1980s.
- ⋆ The search for superpartners has also been an important item on the agenda of every high energy collider experiment in the last 35 years.
- ⋆ This enormous effort has been driven by the beautiful theoretical properties of SUSY theories.

Measured gauge couplings at LEP unify in MSSM but not in SM if SUSY is at the weak scale

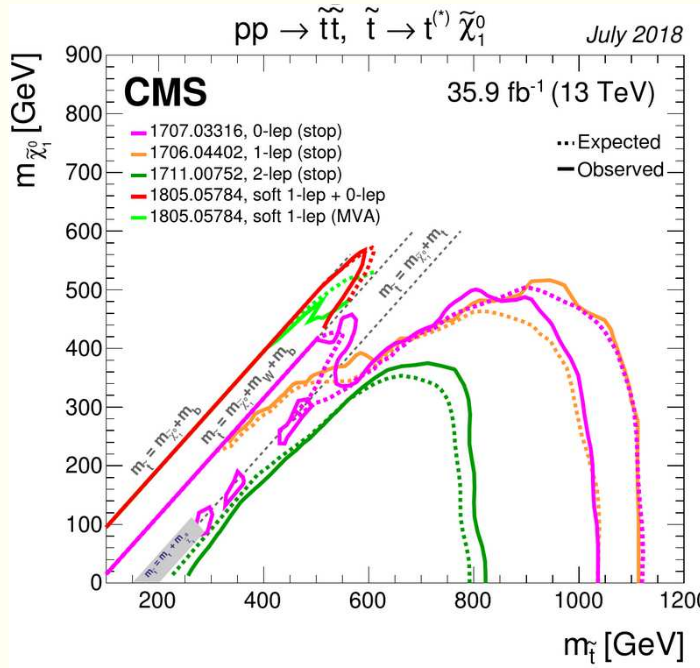
The Higgs boson mass comes out in the narrow window predicted by the simplest SUSY models, and the top quark Yukawa coupling is large enough to drive electroweak symmetry breaking radiatively.

No direct SUSY signals in the LHC data.

ATLAS



CMS

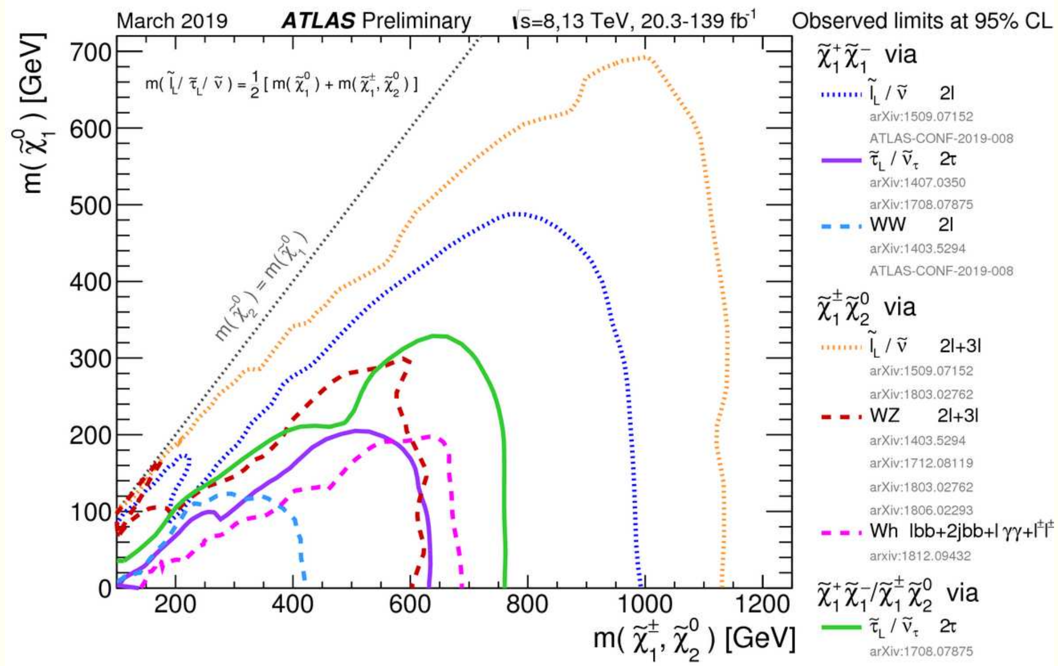


$m_{\tilde{g}} > 1900 - 2000$ GeV if squarks are heavy, and gluinos decay to third generation.

Top and sbottom squarks are heavier than 1.1-1.2 TeV.

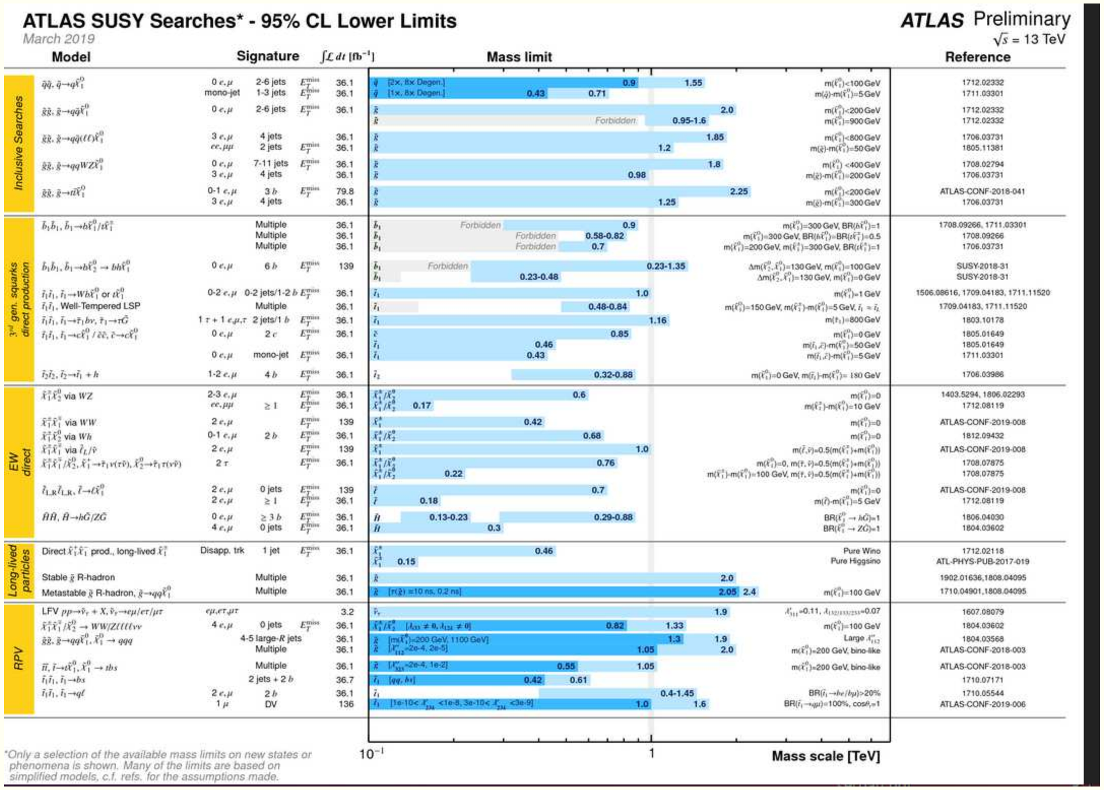
All bounds consistent with models with split first/second and third generation squarks.

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.

Naturalness implies light higgsinos

Not time to discuss naturalness and its implications in detail, but the basic reason for light higgsinos is the well known expression for M_Z^2 in the MSSM:

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

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

Large (compared to M_Z^2) μ^2 or large $|m_{H_u}^2|$ will mean necessity of fine-tuning to get observed value of M_Z^2.

To avoid this, higgsinos cannot be hierarchically heavier than M_Z.[a]

[a]This is not a theorem, but is true with reasonable physical assumptions. Indeed natural models with heavy higgsinos can be constructed, but these typically have many additional TeV scale fields, or have a soft-SUSY breaking higgsino mass term.

The idea behind naturalness is that the corrections to Higgs (or Z) boson masses should not be too large, else we need adjustment of model parameters that have seemingly independent origins.

In SUSY theories, $\delta m_h^2 \sim O(1)\frac{g^2}{16\pi^2} m_{\rm SUSY}^2 \times \log\left(\Lambda^2/m_{\rm SUSY}^2\right) \sim m_{\rm SUSY}^2$, if the weak SUSY theory is coupled to a theory with heavy particles with masses $\sim \Lambda$, *e.g.* in a SUSY GUT, $\Lambda \sim M_{\rm GUT}$. There is no Λ^2 correction because softly broken SUSY has no big hierarchy problem.

Since the log ~ 30, 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.

This is fine if the various contributions to δm_h^2 (*i.e.* from different superpartner loops) are truly independent. However, this will almost certainly not be the case because SUSY breaking parameters will be correlated by the underlying (but as yet unknown) SUSY breaking mechanism.

For appropriately correlated values of SUSY breaking parameters, the large logs almost completely cancel. Ignoring this may lead us to prematurely conclude a model is fine-tuned.

This led us to introduce the electroweak fine-tuning measure $\Delta_{\rm EW}$ that depends only on the weak scale parameters (or essentially only on the SUSY spectrum), and requires no large cancellation between various terms in the usual weak scale expression for M_Z^2. (PRL,109,161802 (2012))

Since $\Delta_{\rm EW}$ contains no $\log\Lambda$ terms, $\Delta_{\rm EW} < \Delta_{\rm BG}$ ($\Delta_{\rm BG}$ is the traditional fine-tuning measure popularized by Barbieri and Giudice).

While I am not saying $\Delta_{\rm EW}$ is a fine-tuning measure, certainly a model with too large a $\Delta_{\rm EW}$ is fine-tuned. (Interpretation different from arXiv:1309.2984)

In the absence of an understanding of how SUSY is broken, we conservatively advocate the use of $\Delta_{\rm EW}$ to avoid discarding viable models prematurely on naturalness considerations. (Indeed, $\Delta_{\rm BG} \rightarrow \Delta_{\rm EW}$ once parameter correlations are properly implemented.)

We adopt $\Delta_{\rm EW} < 30$ as our limit for naturalness. The corresponding $\Delta_{\rm BG}$ may be more than two orders of magnitude larger. (Mustafayev, XT)

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

To get low $\Delta_{\rm EW}$, $m^2_{H_u}$ must be radiatively driven from its value at the high scale to small negative values $\sim -M_Z^2$ at the weak scale.

Underlying philosophy is that any 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 where the soft SUSY breaking parameters are appropriately correlated so that the $\log\lambda$ terms cancel, and $\Delta_{\rm BG} \simeq \Delta_{\rm EW}$.

(Examples later)

- ⋆ Four light higgsino-like inos, $\widetilde{Z}_{1,2}$, $\widetilde{W}_1^\pm$;
- ⋆ $m_{\tilde{t}_1} = 1 - 3.5$ 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

LHC signals for light higgsinos

EW production cross section for 150 GeV higgsino pairs is $\mathcal{O}(1\text{ pb})$. However, the $\widetilde{W}_1 - \widetilde{Z}_1$ and $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gaps are typically below ~ 25 GeV, so the visible higgsino decay products are soft and the signal is swamped by SM backgrounds.

There has been much talk about detecting light higgsinos 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 a "5σ signal", 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

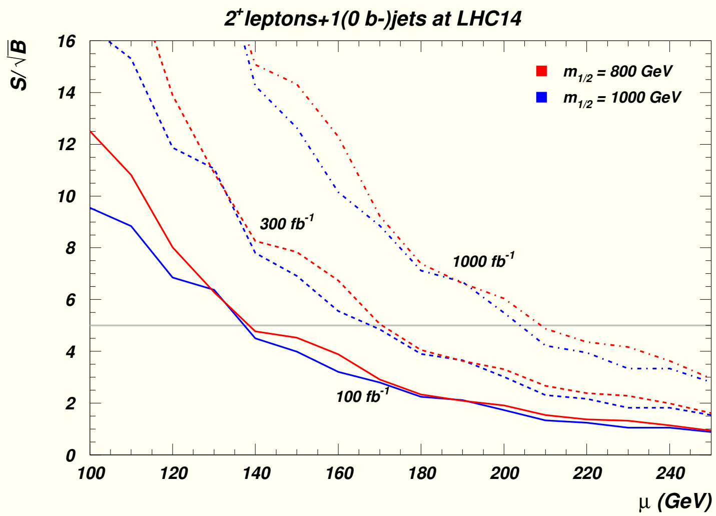
- ⋆ However, as first noted by G. Giudice, T. Han, K. Wang and L-T. Wang, and elaborated on by Z. Han, G. Kribs, A. Martin and A. Menon that backgrounds may be controllable by identifying soft leptons in events triggered by a hard monojet.

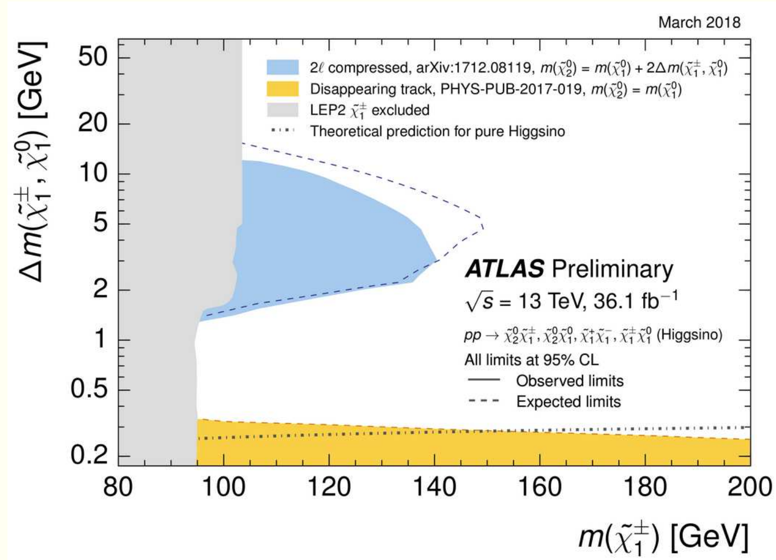
  Hard monojet + soft OS/SF dilepton pair ($m_{\ell\ell} < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$) in the event.

  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. (Gives better control on systematics as normalization uncertainty cancels.)

No time to describe details of the analysis here.

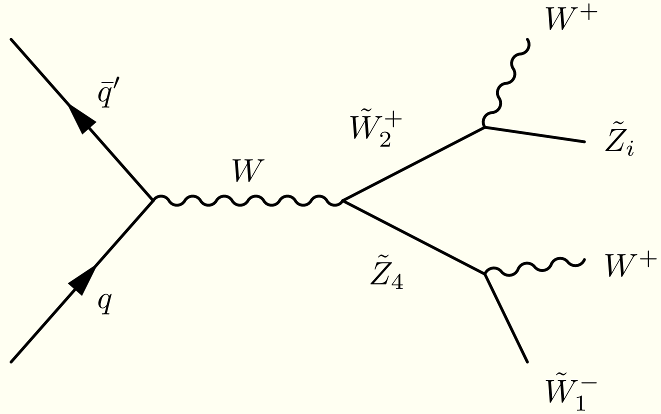




LHC14 reach extends to about $|\mu| = 170$ (210) GeV for integrated luminosity of 300 (1000) fb^{-1}. Baer, Mustafayev and XT

Recent ATLAS analysis gives reassurance that this is doable, but the issue is how low a ΔM they will cover, as M goes up.

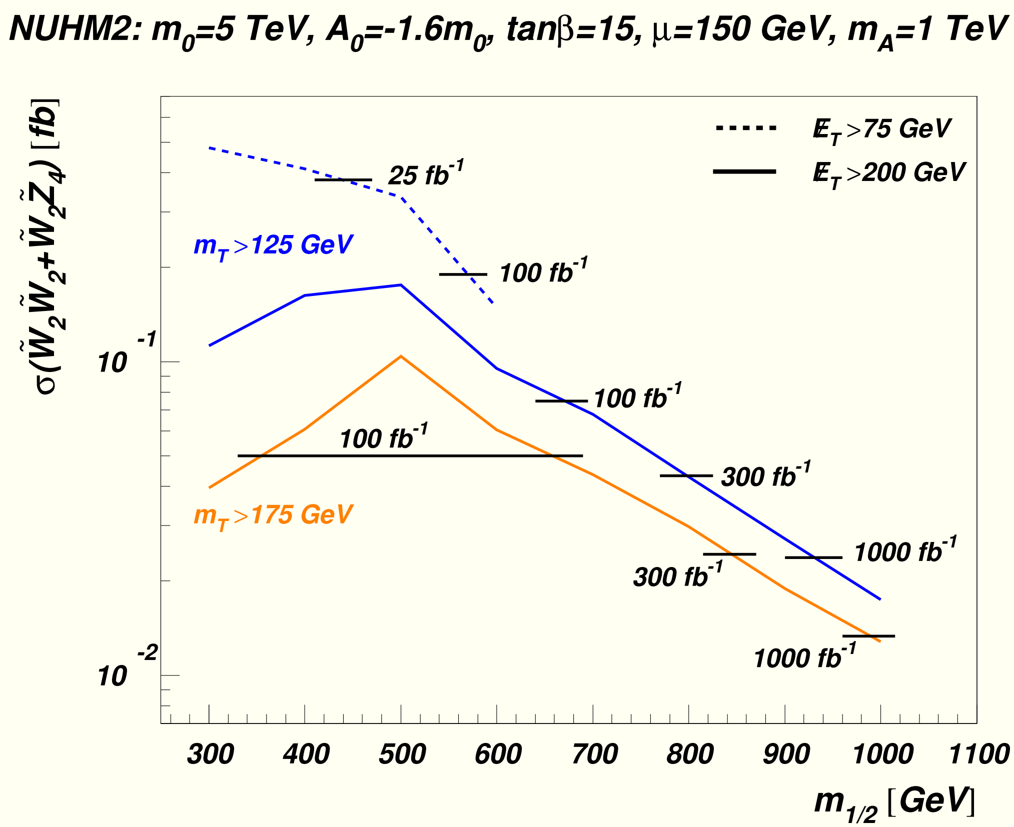
A novel LHC signal for light higgsinos



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.

Leptons from daughter higgsinos may be observable – novel 4ℓ signature in events free from jet activity in addition to the canonical trilepton signal.

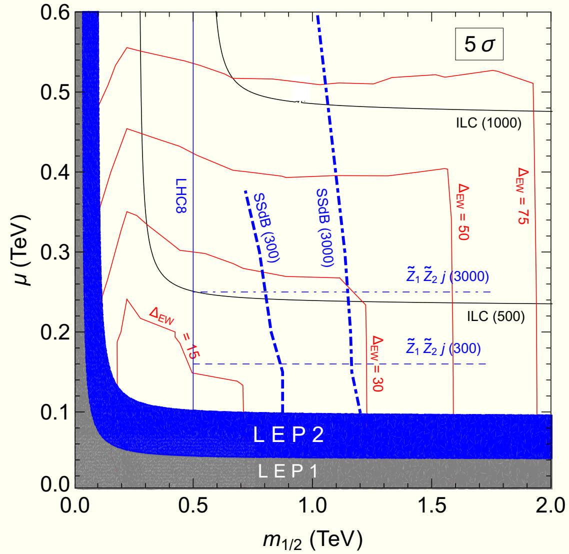
This new SSdB signal may point to the presence of light higgsinos.

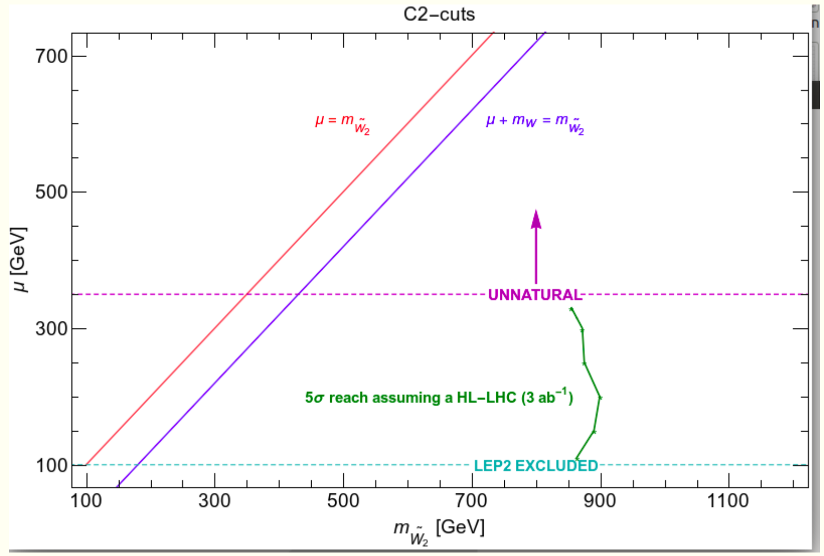


Hard cuts on $\not{E}_T$ and minimum transverse mass $m_T(\ell_{1,2}, \not{E}_T)$ are crucial to pull out the signal. PRL 110, 151801 (2013)

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

Reach for SSdB and monojet+ soft dilepton channels





The SSdB signal requires not too heavy winos (small M_2, or equivalently, $m_{1/2}$).

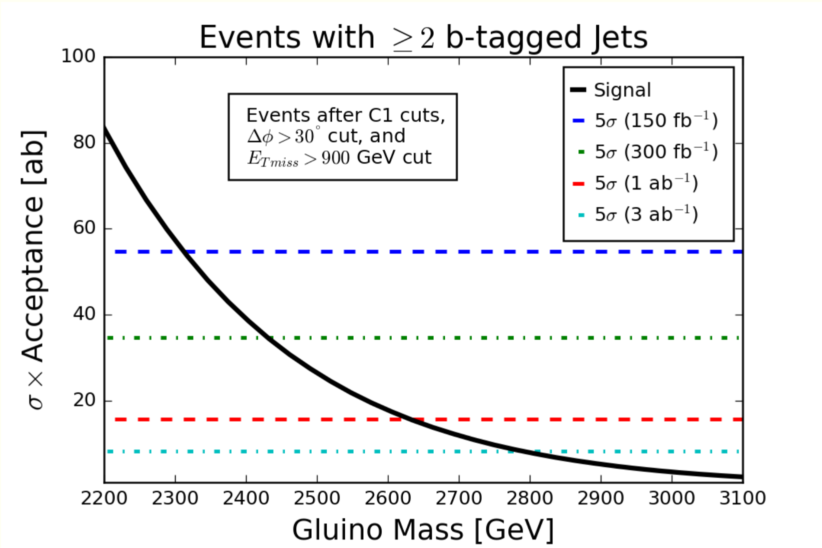
The monojet + soft dilepton signal requires light higgsinos, *i.e.* not too large $|\mu|$.

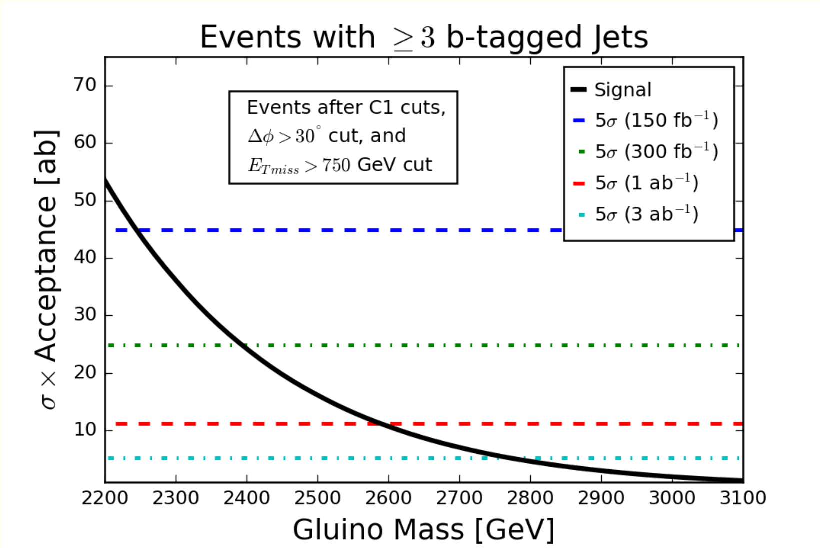
This picture misleadingly rosy as we implicitly assumed gaugino mass unification! Winos can be heavy without jeopardizing naturalness. WHAT ELSE CAN WE DO?

Gluino reach at LHC14 with lighter stops

Present stop limits $\sim 0.9 - 1$ TeV; Snowmass studies project that HL-LHC may cover stops out to 1.4 TeV.

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. Else even more handles on the signal.

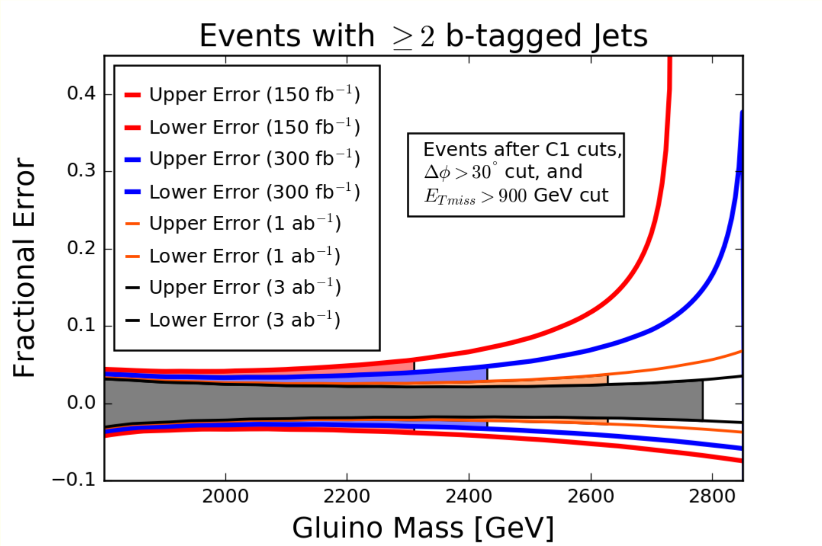


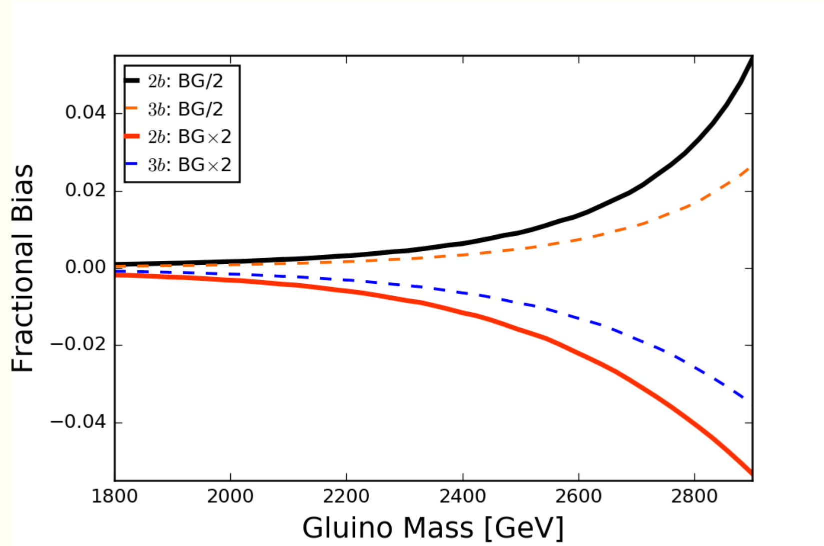


Even with 3 ab^{-1}, gluinos heavier than 2.8 TeV will not be detectable at LHC14. (arXiv:1612.00795)

In extracting the signal, we had made very hard cuts to get large S/B ratios: > 5 (10) in 2- (3-) tagged b-jet channels.

This suggests the possibility of extracting the gluino mass via counting experiments.





Mass measurements at the 2.5-5% level may be possible at least in models where the assumed decay patterns may be confirmed via other signals. (arXiv:1612.00795)

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

Int. lum. (fb^{-1})	$\tilde{g}\tilde{g}$ (can)	SSdB	$WZ \to 3\ell$	4ℓ	$\tilde{g} \to \tilde{t}$
10	1.4	–	–	–	
100	1.6	1.6	–	~ 1.2	2.2
300	1.7	2.1	1.4	$\gtrsim 1.4$	2.4
1000	1.9	2.4	1.6	$\gtrsim 1.6$	2.6

Gaugino mass unification is assumed when correlating SSdB signal with $m_{\tilde{g}}$.

The canonical gluino signature yields the highest reach only for integrated luminosities up to 100 fb^{-1}. (Higher $\tilde{g}$ reach if $\tilde{g} \to tt, tb + X$.) 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.

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)

Motivation to look at energy upgrades of the LHC

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 33 TeV collider to deliver a data sample of ~ 1 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 LHC33 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.

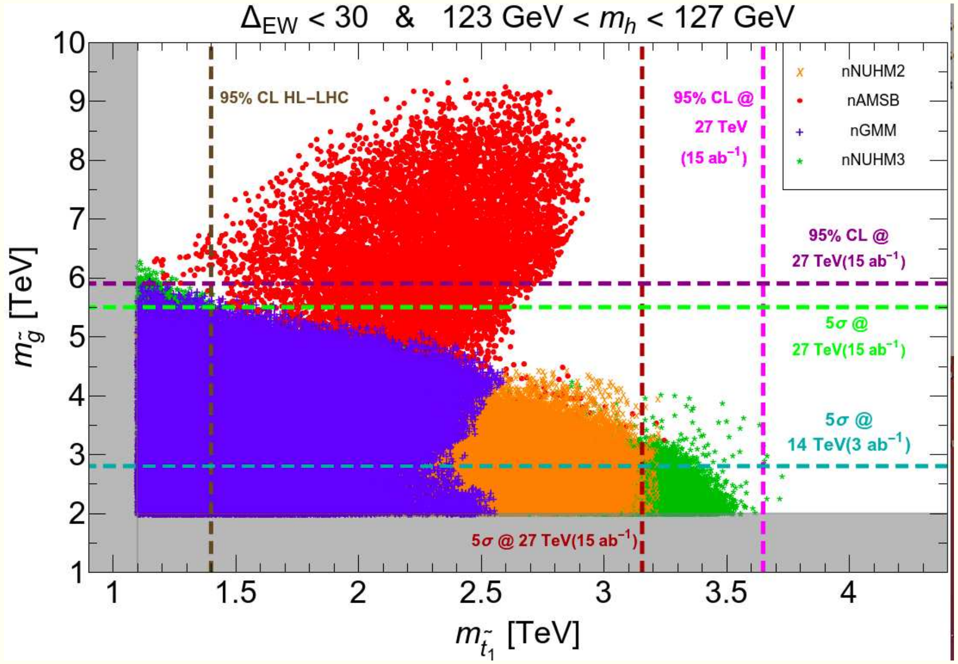
Gluino: $n_b \geq 2$, isolated lepton veto, $\not{E}_T > Max(1900 \text{ GeV}, 0.2M_{\text{eff}})$, $n_j \geq 4$ with $E_{Tji} > 1300, 900, 200, 200$ GeV, $S_T > 0.1$, $\Delta\phi > 10$ degrees.

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 $\Delta_{\rm EW} < 30$ 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 $\rm ab^{-1}$.



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

- ⋆ Dismay at the non-appearance of SUSY seems premature. We were over-optimistic in our expectations from naturalness. 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 $m_{\ell\ell} < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$. Lovely analyses from ATLAS.
- ⋆ 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. (Baer, Barger, Mickelson, and also arXiv:1705.01578)

- ⋆ 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 27 TeV pp collider with 15 ab^{-1} 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 aspirations for SUSY dating back to early 1980s 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. The discovery potential is enormous, and we should not be discouraged.