Aspirations and Prospects for Supersymmetry in Light of LHC Data

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SUSY continues to be an area of phenomenological research since the early 1980s though enthusiasm seems to have abated. 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-ish scale.

Bonus: Measured gauge couplings at LEP unify in MSSM but not in SM (Really a statement about $\sin^2\theta_W$)[a]

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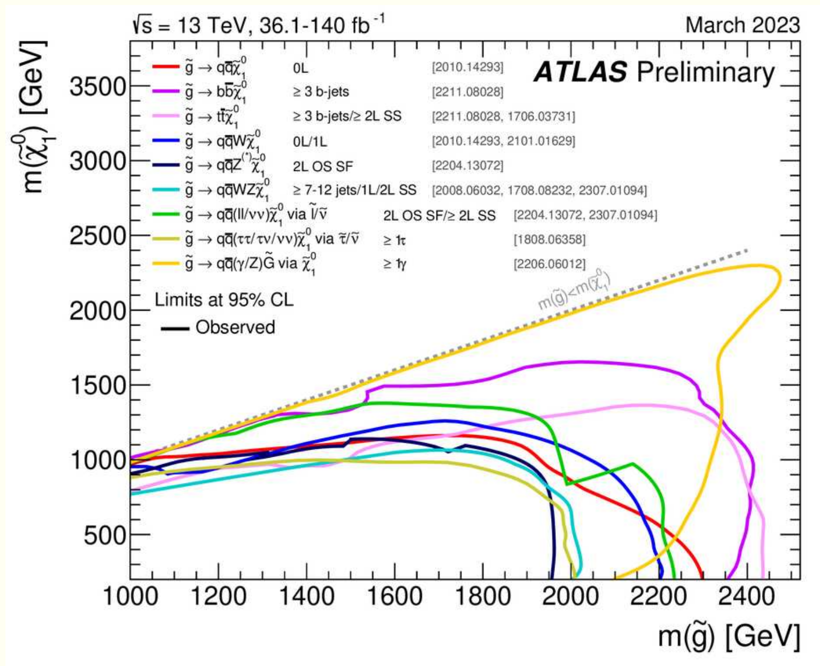
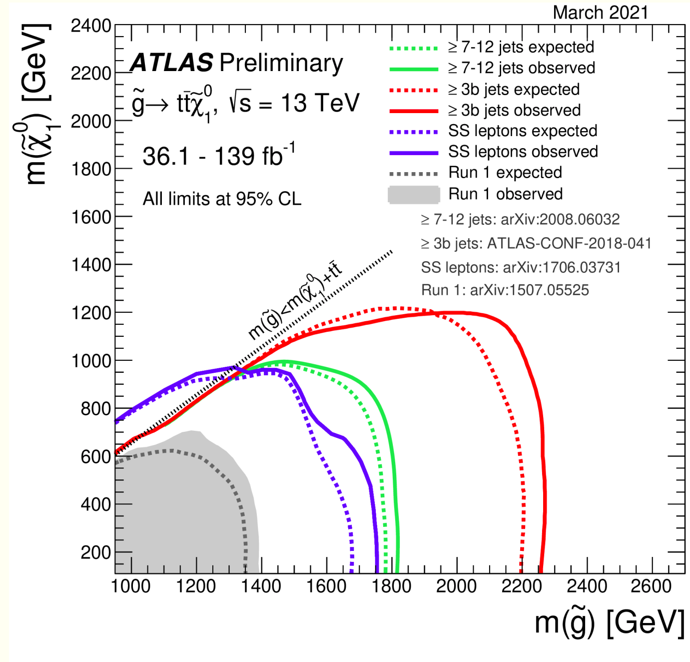
[a]Early prediction of heavy top for suitable $sin^2\theta_W$, Marciano and Senjanovic, PRD25 (1982) 3092.

However, there is yet no direct SUSY signal in the LHC data.

ATLAS

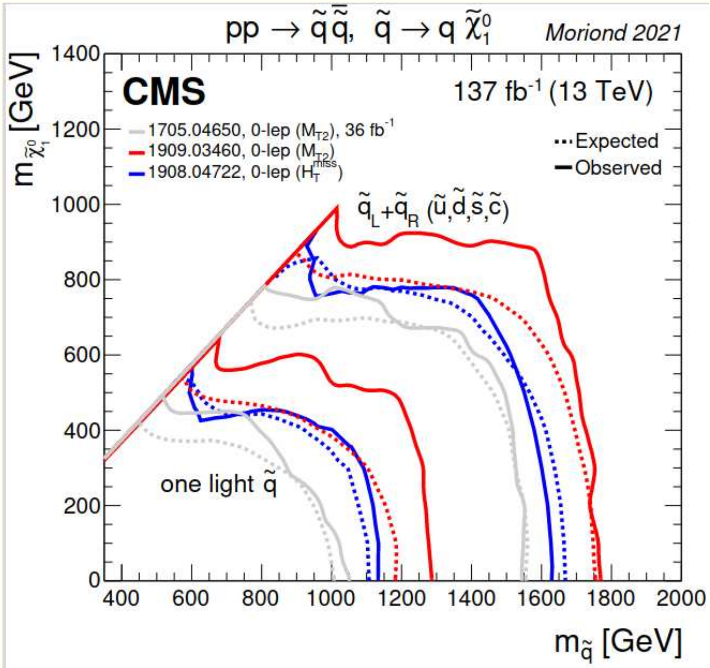


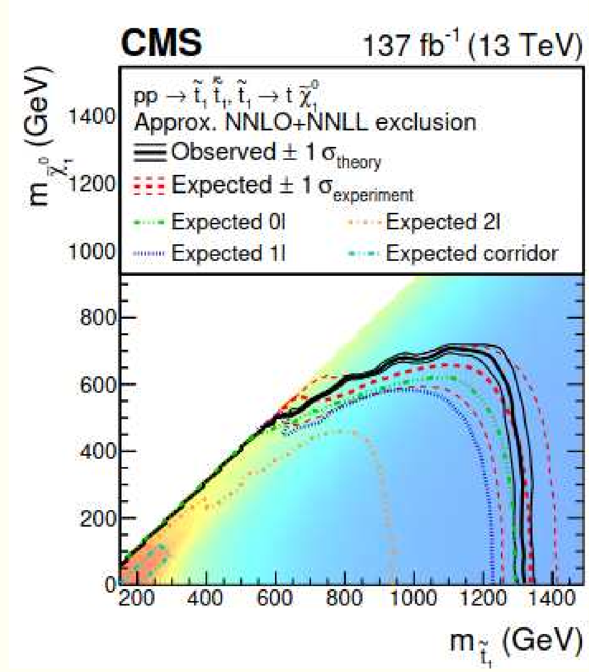
CMS



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

Squark Searches

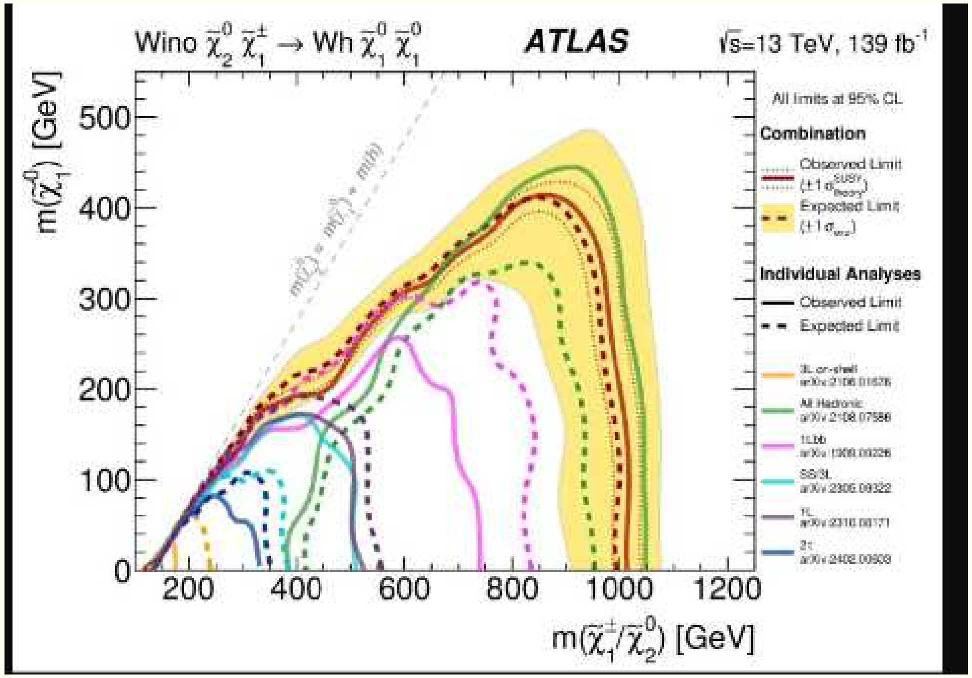




Limits around 1.8 TeV for degenerate squarks decaying to LSPs. Beware $m_{\tilde{g}} = \infty$ for this plot. For $m_{\tilde{g}} \sim m_{\tilde{q}}$, limits strongest on first generation squarks that can be produced from valence quark collisions via t-channel gluino exchange.

Top and bottom squarks are heavier than 1.3 TeV, (except for $m_{\rm LSP} \gtrsim 500$ GeV and a relatively small mass gap).

Electroweak ino-Searches – wino-like states

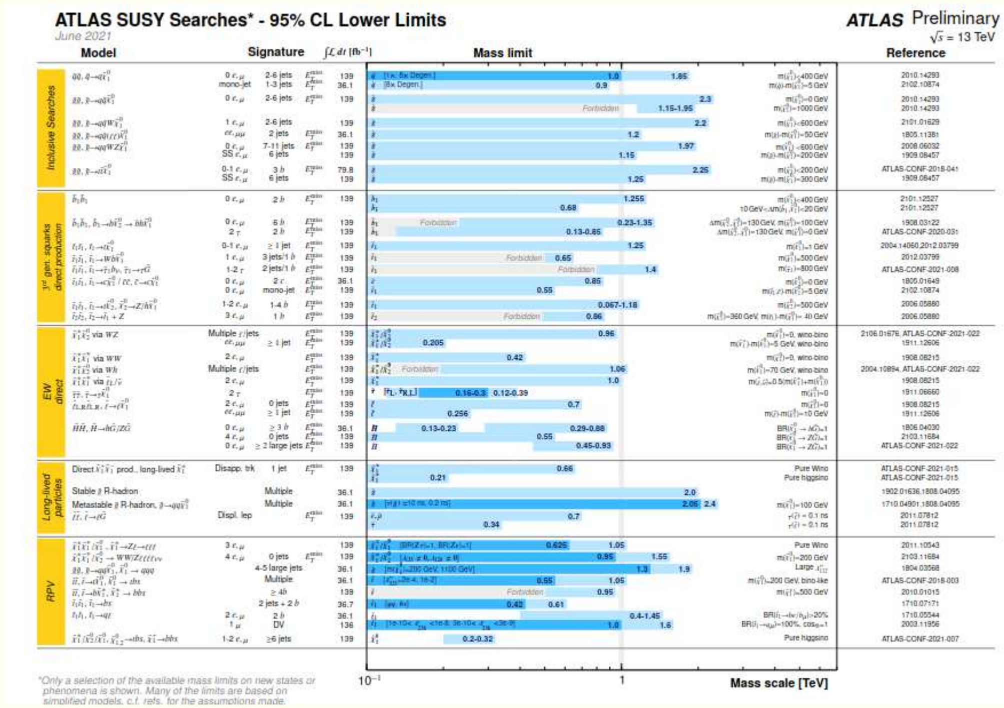


Bounds on wino mass are less stringent than on $m_{\tilde{g}}$ as these are produced with smaller cross sections, by electroweak interactions.

Notice that the most stringent bound (green) is from the hadronic decays of the inos.

Note also the significant $W(\to \ell)h(\to b\bar{b})$ bound (purple curves).

Many other searches also, but no signal!



Notice that for the most part the searches are carried out using simplified model assumptions. Bounds may change under other scenarios.

Information about (model-dependent) inter-relations between searches is absent. Simplified model analysis definitely not okay if we see SUSY signals, as signal channels are correlated.

Instability of Scalar sector to Radiative Corrections

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

$$m_\phi^2 \simeq m_{\phi 0}^2 + C_1 \frac{g^2}{16\pi^2} M_{\rm high}^2 + C_2 \frac{g^2}{16\pi^2} m_{\rm low}^2 \log\left(\frac{M_{\rm high}^2}{m_{\rm low}^2}\right) + C_3 \frac{g^2}{16\pi^2} m_{\rm low}^2 \,.$$

- ★ The quadratic sensitivity to high scale physics destabilizes the SM, if the SM is generically coupled to new physics that has a scale $M_{\rm high}$; *e.g* GUTs.
- ★ Since softly broken SUSY theories have no quadratic sensitivity; *i.e.* $C_1 = 0$, the Higgs sector and also vector boson masses are at most logarithmically sensitive to high scale physics. NO 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 considerable optimism for superpartners at LEP/Tevatron.

LACK OF SUSY SIGNALS HAS RESULTED IN LOTS OF BAD PRESS FOR SUSY

315 Physicists Report Failure In Search for Supersymmetry

Malcolm Browne, NYT, Jan. 15 1993

Is Supersymmetry Dead?

Davide Castelvecchi, Sci. Am. May 1, 2012

Why Supersymmetry May Be The Greatest Failed

Prediction in Physics History

Ethan Siegel, Science, Feb. 12, 2019

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[a], 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): $\Delta_{\rm BG} = Max_i \frac{p_i}{M_Z^2}\frac{\partial M_Z^2}{\partial p_i}$.

[a]We have known from the start that generic weak scale SUSY is phenomenologically excluded.

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, $\Delta_{\rm EW} \leq \Delta_{\rm BG}$, modulo technical caveats.

For this same reason, Mustafayev and I do not regard it as a measure of fine-tuning in a high scale theory, but as a bound on this.

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).

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

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^2_Z. This is not guaranteed in mSUGRA, but always possible in models where $m^2_{H_u}(\Lambda)$ is an adjustable parameter. Tune $m^2_{H_u}(\Lambda)$ to get small $m^2_{H_u}$(weak). Radiatively-driven Natural SUSY (RNS)

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

(Note that gaugino mass unification is implicitly assumed.)

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.

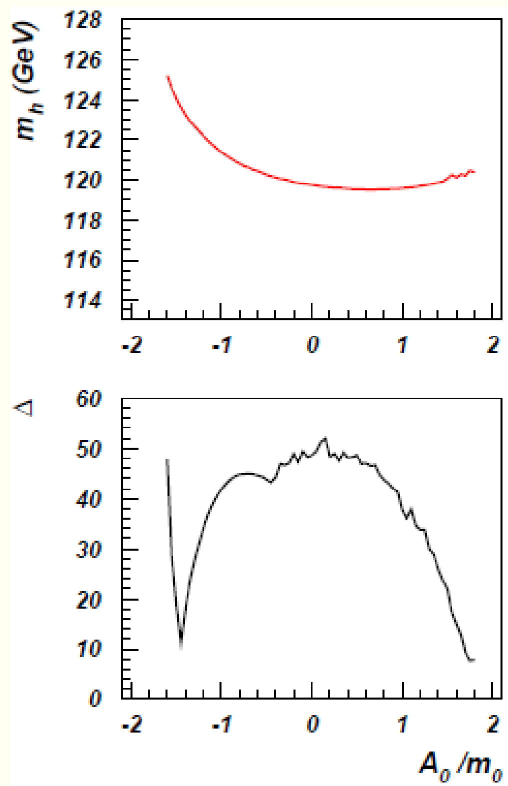
Finally, to get small $\Delta_{\rm EW}$, we also have to ensure that the finite radiative corrections from sparticle loops, Σ^u_u, are small. This requires moderate A_0.

Illustrate with NUHM2 RNS scenario

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 suppressed.

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

However, if we had a theory of soft-parameters that predicted $A_0 \simeq -1.6 m_0$ 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!!!!

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)

LOOKING NAIVELY AT $\Delta_{\rm BG}$ IN NUHM2 WOULD CAUSE US TO DISCARD THE POINT!

Surely we can hope that a smart person may devise a model that predicts the required correlations, or at least not exclude this possibility when we have no idea of how SUSY is broken in nature.

HOW MUCH FINE-TUNING IS TOO MUCH?

Cancellations by an order of magnitide can happen, *e.g.* the orthopositronium decay rate, a part in hundred likely excessive.

We will regard $\Delta_{\rm EW} \lesssim 30$ as "natural" from this point forward.

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 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. Many aspects of the phenomenology depend just on the spectrum, and can be investigated even without knowledge of the underlying high scale theory.

IGNORING THIS POSSIBILITY MAY THROW THE BABY OUT WITH THE BATHWATER.

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). Empasized by Ross, Schmidt-Hoberg, Staub.
- ⋆ The Higgs boson 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.

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

- ⋆ Four higgsino-like inos, $\widetilde{Z}_{1,2}$, $\widetilde{W}_1^{\pm}$ with $m \lesssim 350$ GeV and small mass splittings;
- ⋆ $m_{\tilde{t}_1} = 1 - 3.5$ 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

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

The underlying idea is that phenomenological implications are mostly fixed by the sparticle spectrum. Thus the NUHM2, NUHM3 or some other model with low $\Delta_{\rm EW}$ serves as a surrogate for exploring the phenomenology of an (as yet unknown) theory with a similar spectrum and low 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. which makes electorweak production hard to detect over backgrounds.

- ★ If $|M_{1,2}|$ coincidentally 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.

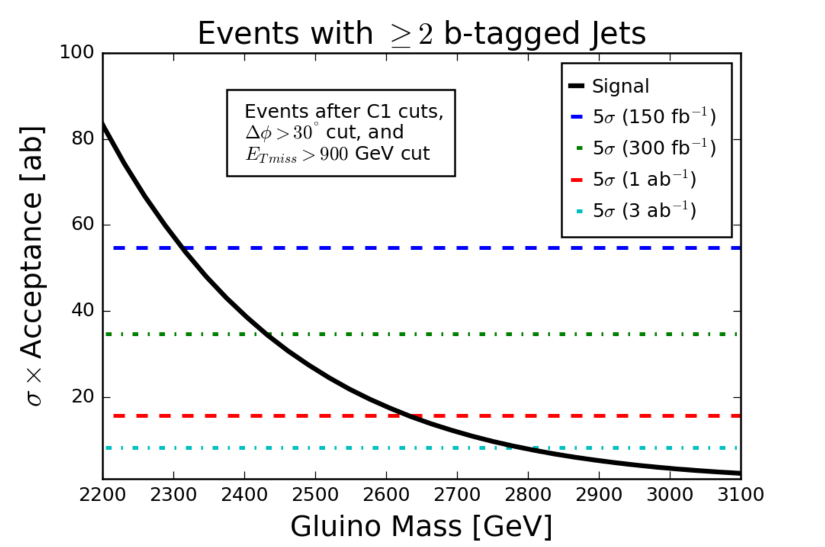
- ★ In the generic case, the small mass gap may makes it difficult to see the signals from electroweak higgsino pair production at the LHC because decay products are very soft (even though the production cross section is in the pb range for 150 GeV higgsinos).

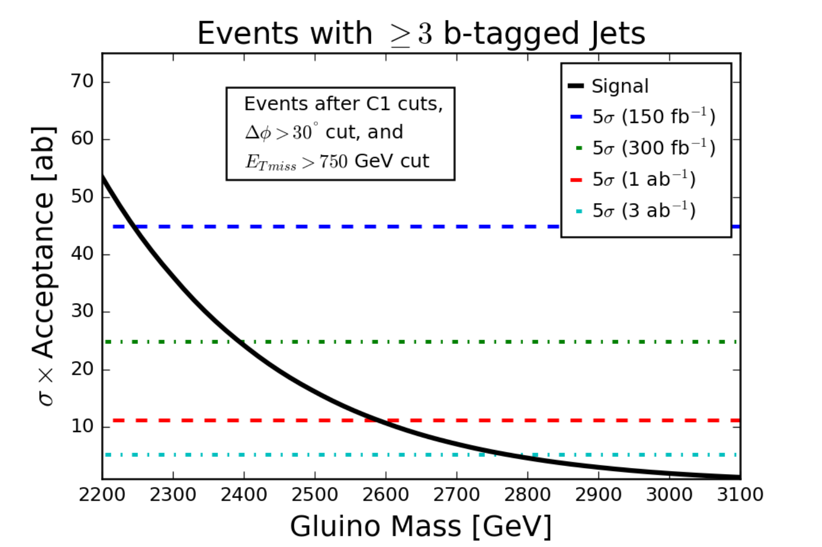
- ★ Monojet/monophoton recoiling against higgsinos also does not work. Can reduce backgrounds by requiring additional soft leptons from higgsino decays.

- ★ 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.

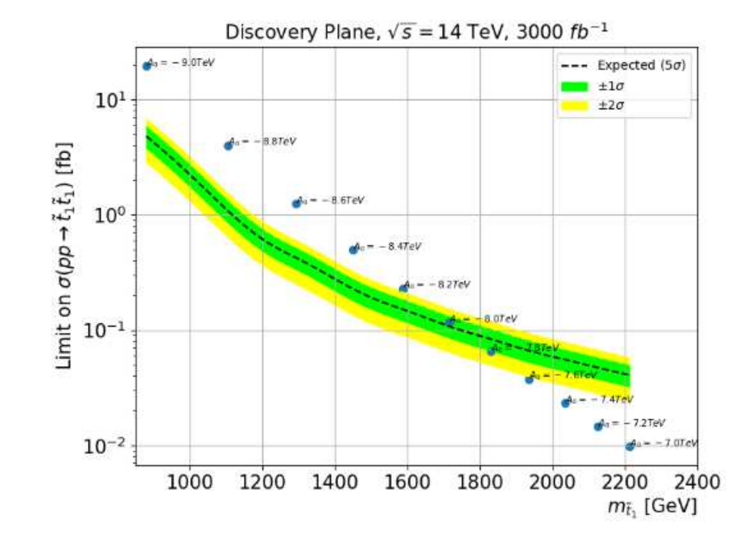




Even with 3 ab^{-1}, gluinos heavier than 2.8 TeV will not be detectable at LHC14.

(arXiv:1612.00795)

Natural SUSY stop reach at LHC14



Baer, Barger, Dutta, Sengupta and Zhang

The discovery reach extends to 1.7 TeV. This number is a bit larger than canonically reported, probably because the higgsino LSP allows both $\tilde{t}_1 \to t\widetilde{Z}_{1,2}$ and $\tilde{t}_1 \to b\widetilde{W}_1$ decays.

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.

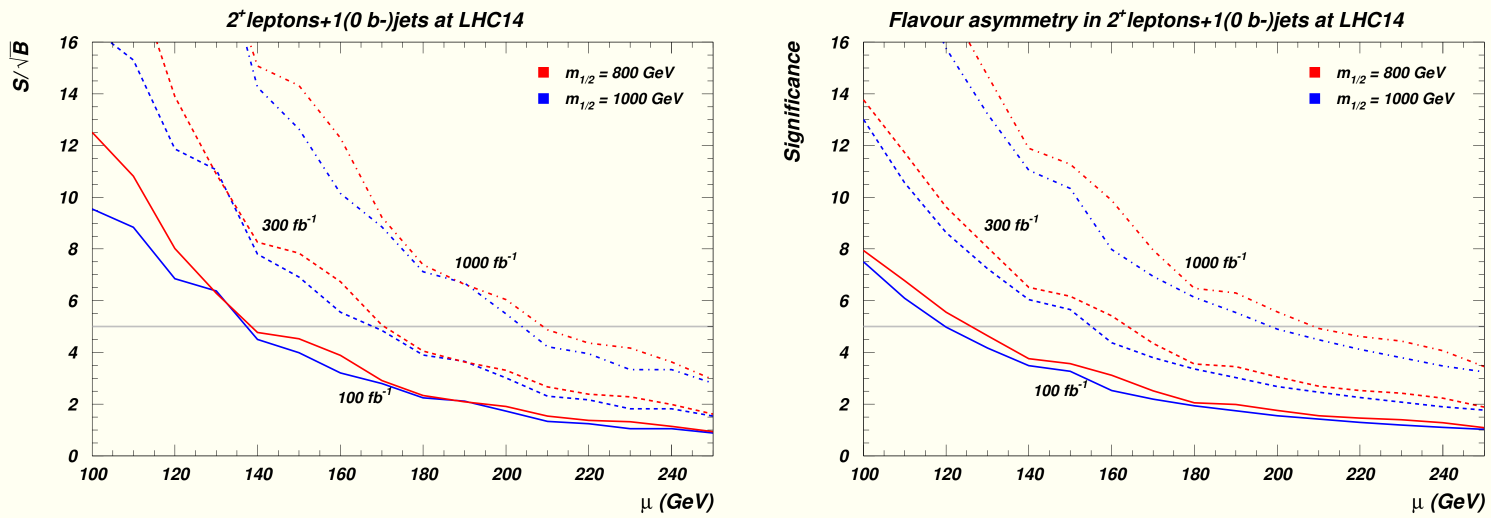
- ★ Although there is an observable rate, even after hard cuts, the signal to background ratio is typically at the percent level. We are pessimistic that the backgrounds can be controlled/measured at the subpercent level needed to extract the signal in the inclusive $\not{E}_T$ + monojet channel. Baer, 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.

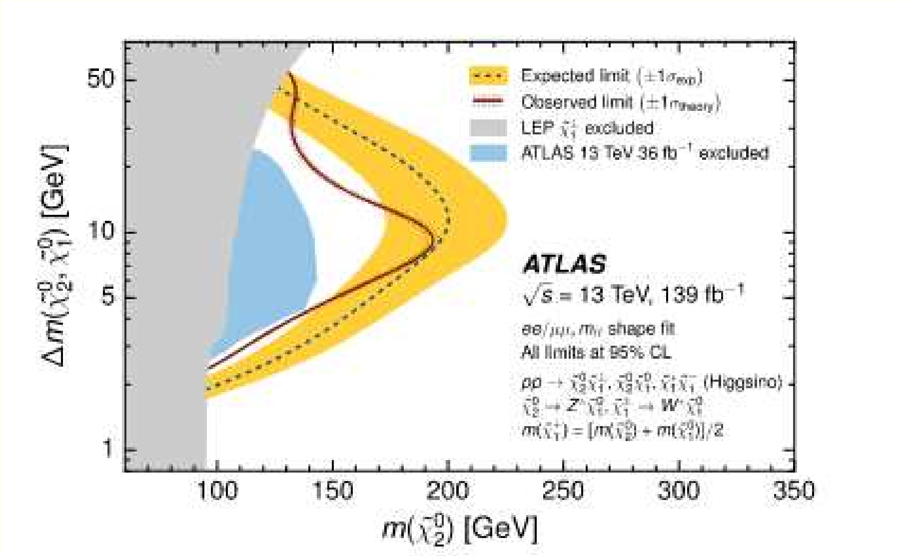
No time to describe details of the analysis here.

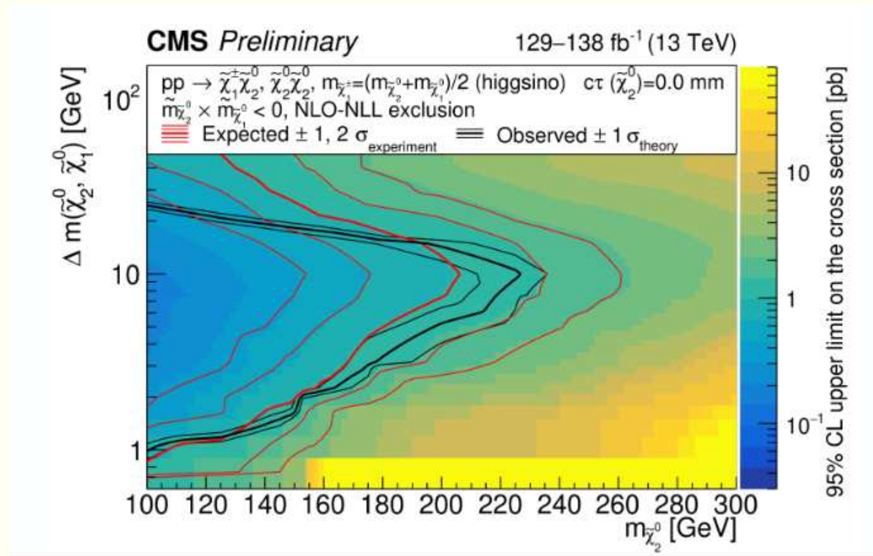


LHC14 discovery reach extends to about $|\mu| = 170$ (210) GeV for integrated luminosity of 300 (1000) fb^{-1}. This analysis used a very conservative 60% detection efficiency for b jets in the evaluation of the $t\bar{t}$ background. Baer, Mustafayev and XT In NUHM2, $\Delta M(\widetilde{Z}_2, \widetilde{Z}_1) \gtrsim 10$ GeV.

How low a ΔM will be covered?

What do the experiments say?



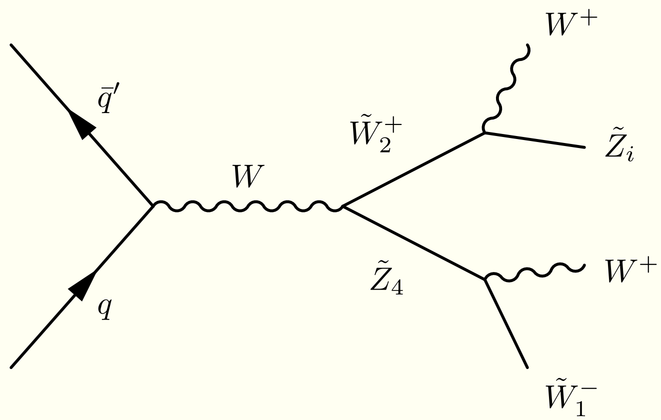


These analyses suggest low ΔM might be doable. The question is to what $\widetilde{Z}_2$ mass values. It will be very interesting to push these analyses as much as possible as we go forward.

We have devised a new analysis to more efficiently reduce the background from $Z(\to\tau\tau)+j$ events using angular cuts. Baer,Barger,Sengupta,XT

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.

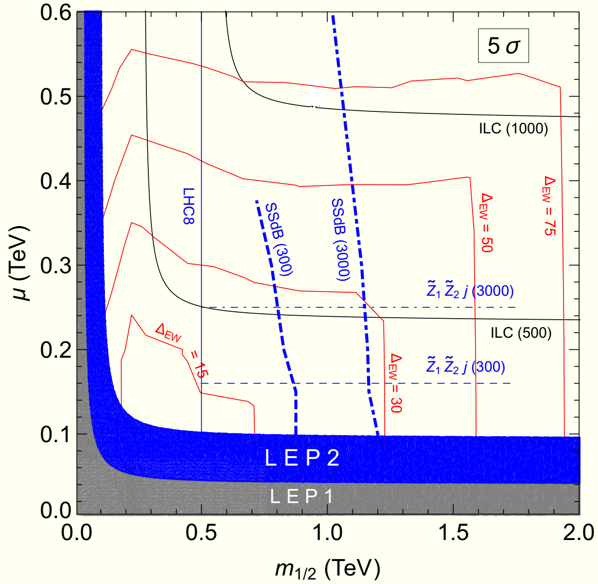


Decays of the parent $\widetilde{W}_2$ and $\widetilde{Z}_4$ that lead to W boson pairs give the same sign 50% of the time. Novel same sign dilepton events with limited jet activity (essentially only from QCD radiation) since decay products of higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_2$ are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

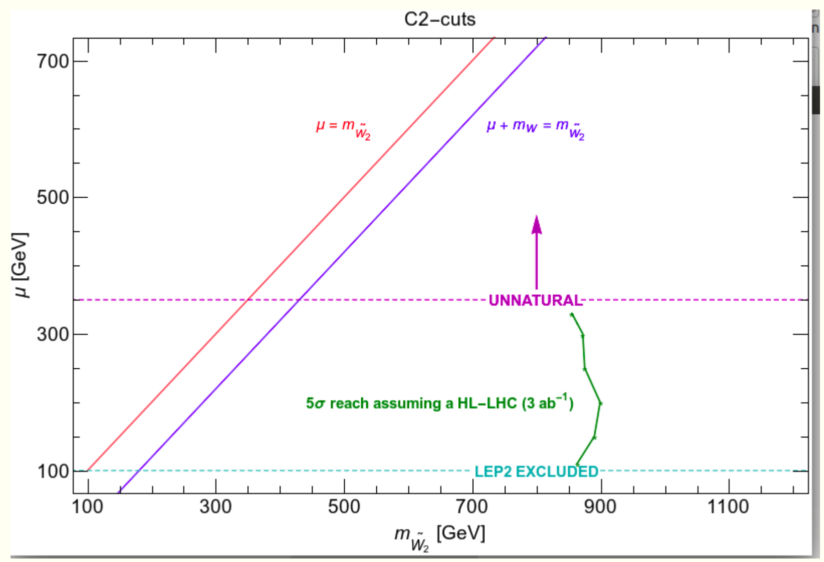
This new signal may point to the presence of light higgsinos.

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 $\Delta_{EW} \leq 30$ part of RNS parameter space! Possibly more than one signal detectable.

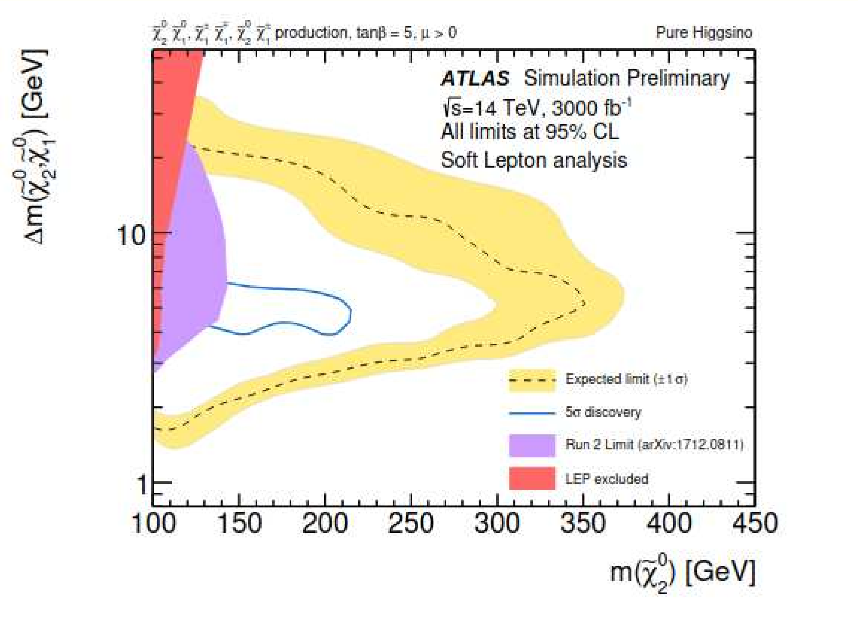
However, this conclusion depends crucially on gaugino mass unification.

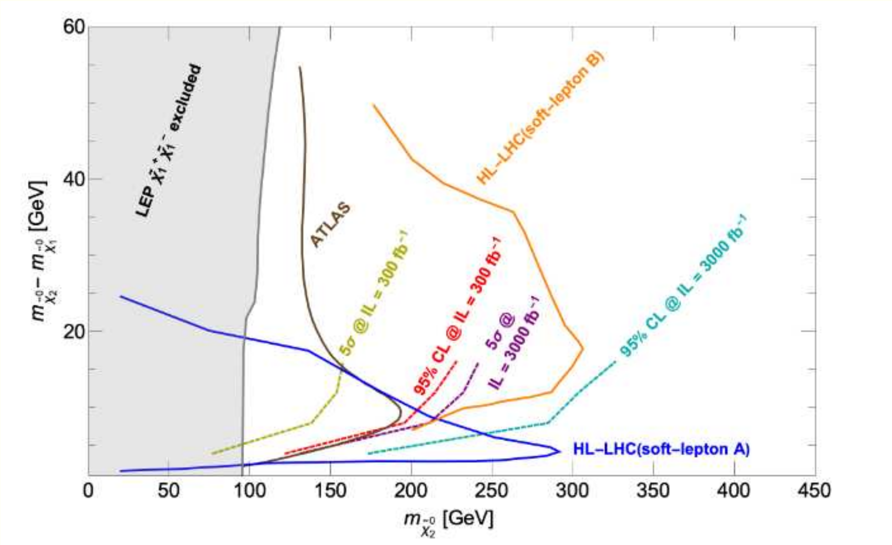
What if we don't have gaugino mass unification?

Indeed 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? Urge dedicated studies along these lines, probaby down to $\Delta m \simeq 3$ or 4 GeV in $\Delta_{\rm EW} \lesssim 30$ models. Both ATLAS and CMS collaborations have shown amazing results.





arXiv:2109.14030

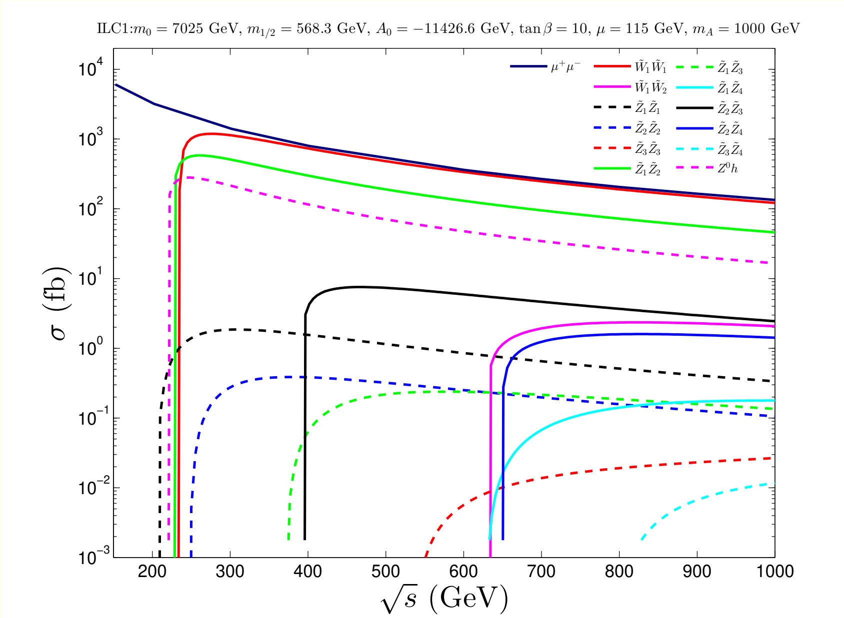
The projection for the ATLAS discovery contour (left frame) is very puzzling because our updated theorists' projections (right frame) for the 5σ reach (optimized for $\Delta m \lesssim 20$) do not cut off when Δm exceeds a few GeV.

WHAT IF THE HL LHC CANNOT DISCOVER LIGHT HIGGSINOS AND STOPS, GLUINOS AND WINOS ARE BEYOND ITS REACH IN NATURAL SUSY MODELS?

Studying higgsinos at e^+e^- colliders (JHEP 1406 (2014) 172)

Follow ups by ILC study groups.

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



Electron-positron colliders are higgsino factories.

Detailed studies show natural SUSY accessible at a 600 GeV e^+e^- collider.

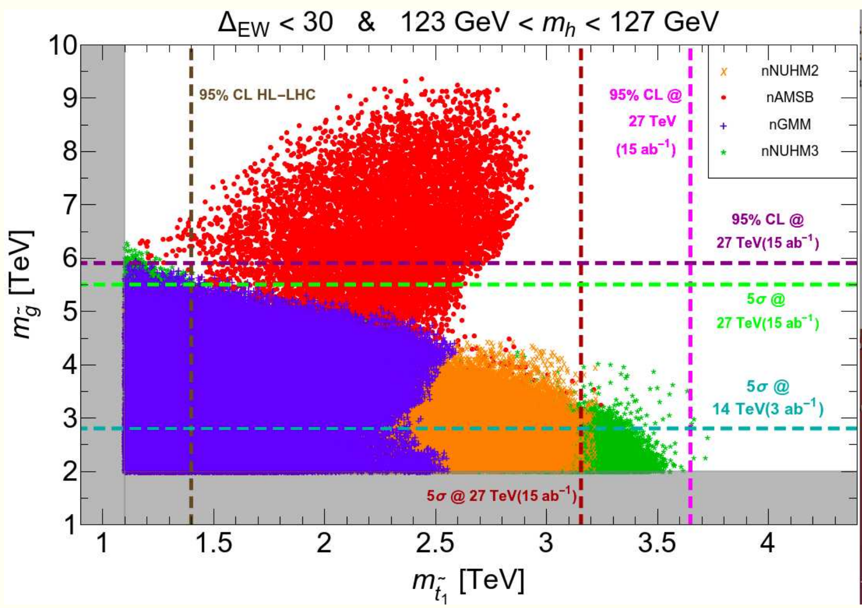
However, such a machine may never exist!!!

Motivation to look at hadron colliders beyond the LHC.

For a while, CERN was considering an energy upgrade of the LHC to 27 TeV with an integrated luminosity of 15 ab^{-1}. (This is, however, not going to happen as we all know.)

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

$\tilde{g} \to t\tilde{t}_1^{(*)}$, $\tilde{t}_1 \to t\widetilde{Z}_{1,2}, b\widetilde{W}_1$. 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 ab^{-1}.



LHC27 would have had 5σ sensitivity 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.

Today, HE $\Longrightarrow$ FCC-hh

Sparticle	HE-LHC	FCC-hh
gluinos	5 TeV (5σ)	10 TeV (5σ, 3/ab)
stops	3 TeV (95% C.L)	10 TeV (5σ, 30/ab)
higgsinos	0.5 TeV (5σ)	0.8 TeV (5σ)
winos	1.5 TeV (5σ)	4.0 TeV (5σ)
staus	0.8 TeV (5σ)	3-4 TeV (5σ extrap.)

Conservative scenarios

Anadi Canepa, SUSY 2019

Of course a 100 TeV *pp* collider will not only assure the discovery of natural SUSY, but also of other new states associated with the picture.

Higgsinos as Dark Matter

Higgsinos annihilate efficiently via Z exchange.

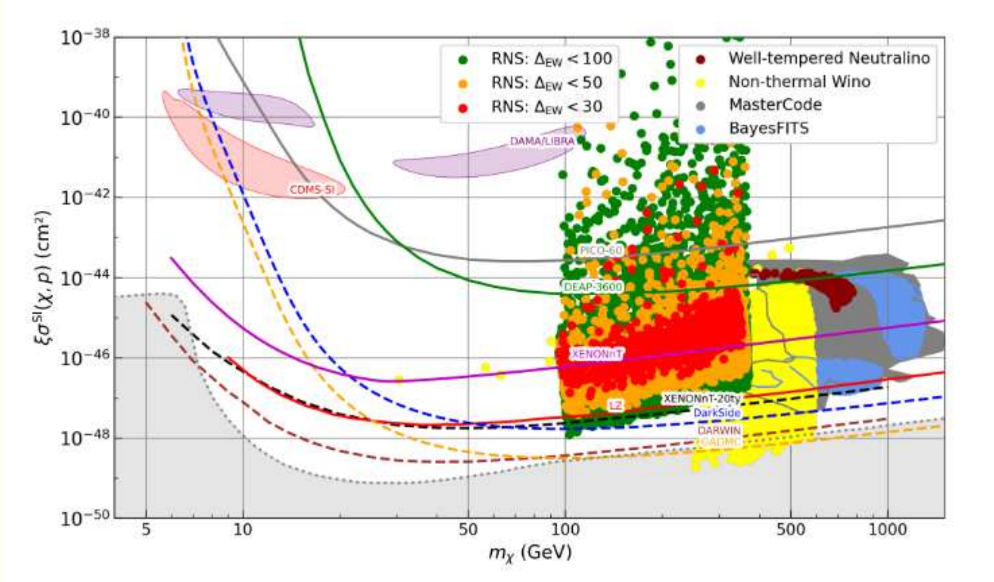
As a result, thermally produced higgsinos saturate the observed CDM relic density only if they are heavy enough (since the annihilation rate $\sim 1/m^2_{higgsino}$) — 1.2 TeV

Themally produced higgsinos of natural SUSY can produce only about $\sim 10 \pm 5\%$ of the observed CDM. The rest would have to be something else; *e.g.* axions is another motivated possibility.[a] Multi-component dark sector would then be like our observed sector in this respect.

If higgsinos are such a small fraction of DM, their signals in direct detection experiments will reduce making them harder to observe. Do we lose a handle on accessing them?

[a] All higgsino DM with light higgsinos is excluded: EPJC 78 (2018) 838.

THIS IS VERY FAR FROM THE TRUTH!



arXiv:2502.10879

The red dots, which should actually extend to somewhat lower values than shown here, show the expectation for the spin-independent WIMP-nucleon scattering cross section in natural SUSY models. The cross section cannot be arbitrarily small because the wino mass parameter is bounded by naturalness.

In fact, the recent 95%CL bound from the LZ collaboration exclude the $\Delta_{\rm EW} < 30$ models.

DOES THIS MESS UP THE WHOLE PICTURE?

It sure does if higgsinos are light enough for $\Delta_{\rm EW} < 30$, thermally produced, stable and we assume standard Big Bang cosmology (modulo the $\mu > 0$ caveat).

We know relatively little about cosmology before BBN and late decays of long-lived particles to SM particles can reduce the relative abundance of the higgsinos. We would have to be careful of the photons injected though.

The higgsino LSP, while stable on the length scale of collider experiments, may decay on the length scale of the lifetime of the Universe, so the DM constraint is evaded. R-parity violating couplings natural to think about for this, but then one would ask why these couplings are so small. In this case, the DM would have to be something else unless "just the right amount of higgsinos decayed via RPV couplings".

Cute, recent proposal by Baer, Barger, Bolich, Sengupta and Zhang, arXiv:2505.09785.

THE BBBSZ PROPOSAL

No higgsino DM because of RPV, but no RPV signals at colliders either for symmetry reasons.

Assume a Z_N^R symmetry of the MSSM superpotential that is augmented by gauge singlet superfields, $\hat{X}$ and $\hat{Y}$, that couple to MSSM superfields and to themselves only via non-renormalizable superpotential ineractions, suppressed by powers of M_P. The scalar components X and Y acquire intermediate scale vevs $M_I \sim 10^{11}$ GeV when coupled via supergravity, and generate a TeV scale μ term (otherwise forbidden) for the MSSM via the Kim-Nilles mechanism.

Renormalizable R-parity conserving Yukawa couplings are allowed by Z_N^R but renormalizable R-parity violating bilinear superpotential interactions $\hat{L}\hat{h}_u$, and the trilinear $\hat{L}\hat{L}\hat{E}^c$, $\hat{L}\hat{Q}\hat{D}^c$ and $\hat{U}\hat{D}^c\hat{D}^c$ are forbidden.

Of course, these RPV couplings, suppressed by sufficient powers of M_P, can be generated via non-renormalizable interactions of MSSM fields with $\hat{x}$ and $\hat{Y}$.

BBBSZ require

The $\hat{L}\hat{h}_u$ mass needs to be smaller than ~ 1 MeV for a higgsino at the few hundred GeV scale, i.e. $< M_I(M_I/M_P)^2$, to satisfy the neutrino mass constraint.

They want the higgsino to decay before BBN for which the need the trilinear RPV interactions to be suppresed by $\sim 10^{-7} \sim \frac{M_I}{M_P}$.

A suppression of the non-renormalizable matter superpotential quartic interaction by $\sim \frac{M_I}{M_P} \sim 10^{-7}$ suffices for proton decay.

<u>BBBSZ Results</u>

BBBSZ exhibit five Z_N^R charge assignments where:

Trilinear RPV couplings are suppressed by $\frac{M_I}{M_P}$ allowing the LGP to decay before BBN. In each of these cases, the dangerous quartic superpotential interaction is suppressed by one or more powers of $\frac{M_I}{M_P}$, so proton decay is safe from these. They find that the bilinear is <u>always</u> suppressed by exactly two powers of $\frac{M_I}{M_P}$, consistent with neutrino mass constraint.

However, they point out that all is not well since the proton may decay by two trilinears, each with 10^{-7} if both baryon and lepton number violation is present.

An additional problem is that a higgsino-neutrino MeV scale mass term implies a mixing angle $\sim 10^{-5}$ for a 100 GeV higgsino, so this term induces two-body decays $\widetilde{Z}_1 \to \ell W$ and $\widetilde{Z}_1 \to \nu Z$ with partial lifetimes $\sim 10^{-14}$ s, so LSP is not stable at the LHC, and would have already lead to spectacular signatures.

They definitely require additional RPV suppressions to make their idea work, perhaps a more complicated hidden sector.

I have, hopefully, convinced you that though natural SUSY models (defined by $\Delta_{\rm EW} < 30$) may elude detection at the LHC, they would reveal themselves at an e^+e^- collider with $\sqrt{s} = 600$ GeV and surely at FCC-hh.

The spectra of these models satisfy our aspirations for SUSY since the early 1980s, except perhaps we have to rethink what CDM is, and/or resort to more elaborate scenarios for early universe cosmology than a thermal WIMP.

We do not yet have an explicit top-down model that yields the required sparticle spectra and would have $\Delta_{BG} \simeq \Delta_{\rm EW}$. However, this does not mean that such models do not exist. Their construction probably awaits a better understanding of how SUSY breaking is felt by MSSM superpartners.To abandon SUSY saying it is fine-tuned because LHC has not yet seen new physics seems premature.

The non-observation of new physics at the LHC constrains all new physics, not just SUSY. In the absence of experimental guidance, we should continue to explore the most promising theoretical ideas. IMO, EFT with an intractably large number of operators is not the right direction.

Pluses and Minuses of Supersymmetry

- ⋆ Synthesis of bosons and fermions, although not of known bosons and fermions.
- ⋆ Possible Grand Unification of gauge interactions.
- ⋆ Prediction that top is heavy, in an era when people were talking about tops of 20-25 GeV.
- ⋆ Radiative corrections driving electroweak symmetry breaking.
- ⋆ The simplest ideas do not seem to work for a SUSY DM candidate (unless it is uncomfortably – to me – heavy).
- ⋆ Generic weak scale SUSY has a plethora of problems (p-decay, FCNC, CP violation), but this is a guide for deciphering the mechanism by which superpartners acquire masses.

Final Remarks

- ⋆ It is certainly possible that even in the MSSM, natural SUSY remains hidden from LHC searches.
- ⋆ 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. May need colliders beyond the HL-LHC.
- ⋆ Light higgsinos seem to be the best bet for naturalness, and may yield the novel LHC signals: the monojet plus soft dileptons with $m_{\ell\ell} < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ is being explored. The $W^\pm W^\pm$ signal will likely not be at the discovery level if current wino bounds hold up.
- ⋆ A 600 GeV electron-positron collider or FCC-hh will decisively probe natural SUSY scenarios I have been talking about.

- ⋆ Our original (from the 1980s) aspirations for SUSY remain unchanged if we accept that "accidental cancellations" at the few percent level are ubiquitous, though we may have to re-think the physics of DM.

In my opinion, weak scale SUSY remains the best resolution of the big hierarchy problem, and offers us the best prospects of writing down calculable theories that may be valid up to very high scales. There may well be viable theories, with just the MSSM particle content at the TeV-ish scale, where the fine-tuning is no worse than a few percent.