Status and Future of Supersymmetry

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Thanks and congratulations to the organizers for a wonderful conference, with ~ 200 talks.

Not just supersymmetry and unification!

SUSY lives in an ecosystem of Beyond Standard Models and has implications for cosmology, astrophysics, inflation, neutrinos, Higgs physics, flavor physics, precision tests in low-energy physics, unification, proton decay, string/M-theory, the swampland, and formal ideas.

"We are, I think, in the right Road of Improvement, for we are making Experiments."

– Benjamin Franklin

(1786 letter to Jonathan Shipley, Dean of Winchester)

Experimentally, SUSY is a consistent framework and existence proof for a huge variety of new physics signatures for LHC and beyond:

- missing energy $+X$
- multi-leptons, multi-jets without missing energy (R_p violation)
- 125 GeV Higgs $+X$
- b-rich, τ-rich final states
- isolated photons (gauge mediation)
- quasi-stable particles (GMSB, RpV, split SUSY, hidden sectors, stealth SUSY)
  - anomalous $dE/dx =$ highly ionizing particles, timing
  - disappearing tracks
  - appearing tracks
  - displaced vertices
  - non-pointing photons, leptons, jets
  - kinks in tracks

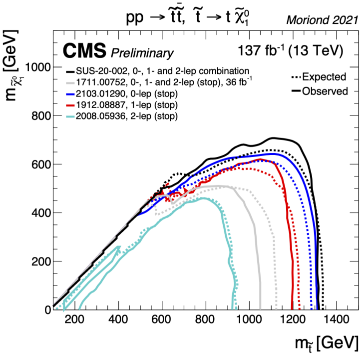
A comprehensive program of searches for SUSY is also an exploration of more general Beyond the Standard Model physics.

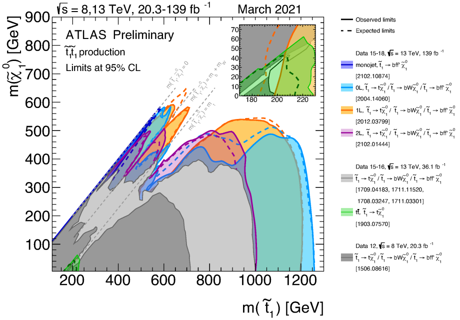
The LHC vs. Supersymmetric Models

However, constraints on SUSY are sometimes colloquially overstated, perhaps due to temptation to make grand statements.

Limits on top squarks

See Vellidis (CMS) and Maurer (ATLAS) talks for details.



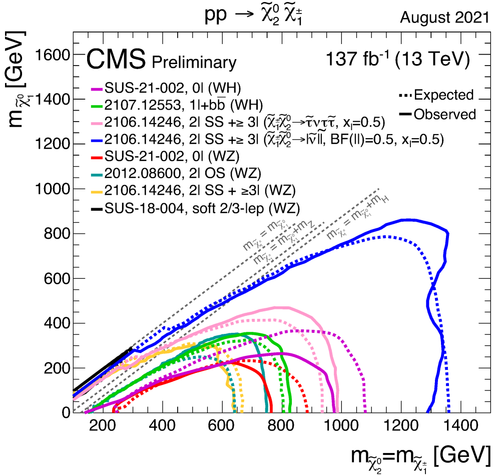


Pessimist: Exclusion of top-squark masses now up to 1300 GeV!

Optimist: No constraints at all on direct pair production of top squarks, if LSP mass exceeds 700 GeV.

More generally, "Compressed SUSY" models with small mass differences are more difficult because visible energy in each event is smaller.

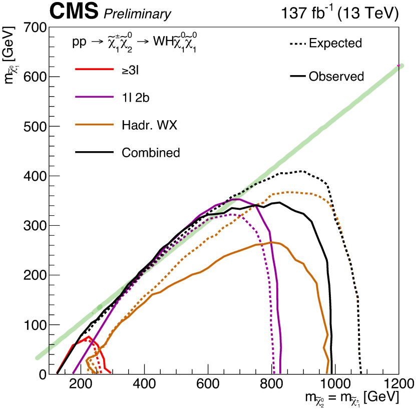
Constraints on wino-like charginos and neutralinos that decay through sleptons: $pp \to \tilde{C}_1 \tilde{N}_2 \to \text{leptons} + \not{E}_T$



Pessimist: Exclusion of electroweakinos above 1300 GeV!

Optimist: Constraints on decays through staus are much weaker, with no exclusion for $m_{\tilde{C}_1} > 1000$ GeV or LSP mass $>$ 450 GeV. Furthermore. . .

Constraints on wino-like charginos and neutralinos decaying through W, h:



Giovanna Salvi, Pablo Matorras-Cuevas talks.

The decay $\tilde{N}_2 \to h\tilde{N}_1$ dominates in SUSY models. In older papers this was known as the "spoiler mode", but after improvements in the last few years, it now gives the best reach!

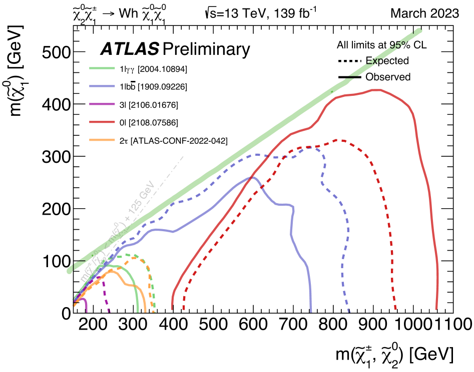
Green line = prediction from gaugino mass unification

Bounds will be weaker if you take into account:

- $\text{BR}(\tilde{N}_2 \to h\tilde{N}_1) < 1$, and
- t-channel u, d squark exchange, even if squark masses are ≥ 2 TeV.

Exclusion is weaker than expected for large $\tilde{C}_1$, but. . .

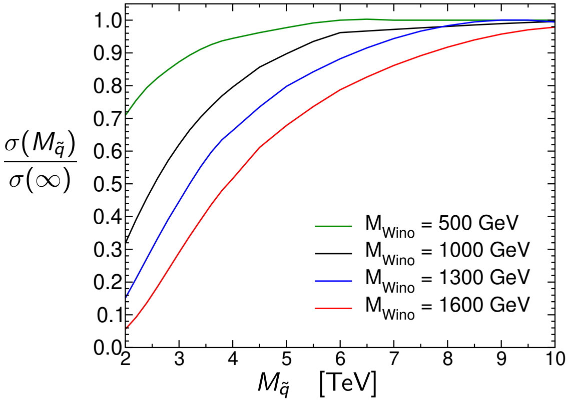
ATLAS (see talk by Shuhui Huang) sees a stronger than expected exclusion at the large $\tilde{C}_1$ region with small $\tilde{N}_2$, but does not touch the gaugino mass unification line:



One can say the words "exclusion for $m_{\tilde{C}_1}$ up to 1060 GeV", but there is no exclusion at all for $m_{\tilde{N}_1} > 425$ GeV, or considerably lower for general masses.

Still plenty of room in the "compressed" region, which includes the entirety of the gaugino mass unification line!

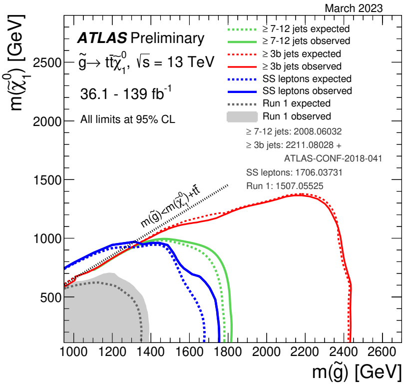
Impact of squarks in the t-channel on wino production $pp \to \tilde{C}_1^{\pm} \tilde{N}_2$.

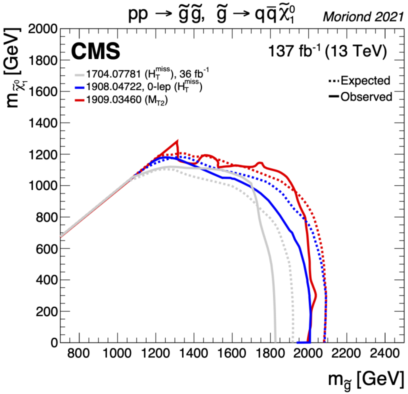


The suppression of cross-section, compared to the simplified model prediction with $M_{\tilde{q}} = \infty$, gets more dramatic for larger wino masses, and can be important even if squarks are well out of the 14 TeV LHC reach.

Discovery of wino-like $\tilde{C}_1, \tilde{N}_2$ could eventually give a handle on squark masses.

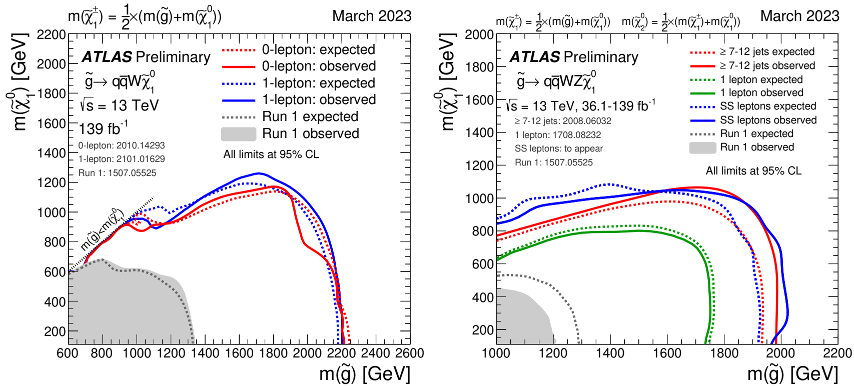
Constraints on gluino pair production tend to have the highest reach:





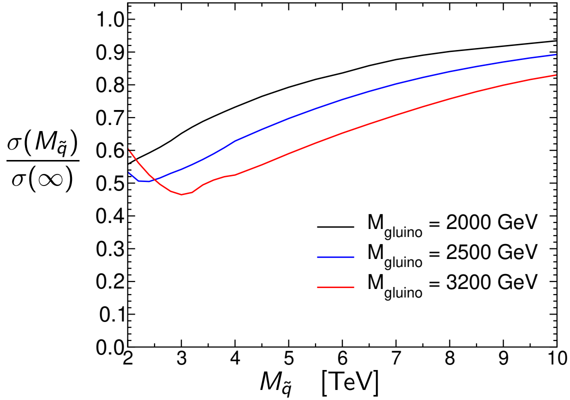
But again, there is no exclusion if the gluino-LSP mass difference is not large.

Gluino exclusions can be somewhat weaker if more decay steps, fewer *b*-jets.



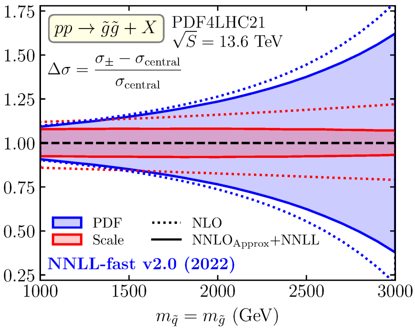
A general lesson: "Simplified SUSY models" are not actually SUSY!
In real SUSY models, things are more complicated.

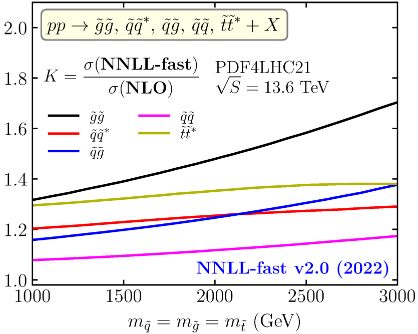
Impact of squarks in the t-channel on gluino production $pp \to \tilde{g}\tilde{g}$.



The suppression of cross-section, compared to the simplified model prediction with $M_{\tilde{q}} = \infty$, is not quite as dramatic as for wino production, but is still important as it can reach a factor of 2.

Uncertainties from PDFs and higher order corrections are a challenge for setting limits in the future, especially since they become more significant as one probes higher masses. Examples from Christoph Borschensky's talk:





PDF uncertainties at large masses can exceed ∼50%.
K-factors from NNLL are quite large.

To address the simplified model problem: **recast**, **reinterpret**, and/or **combine** search results in terms of Real SUSY (or your favorite model). "Do it yourself."

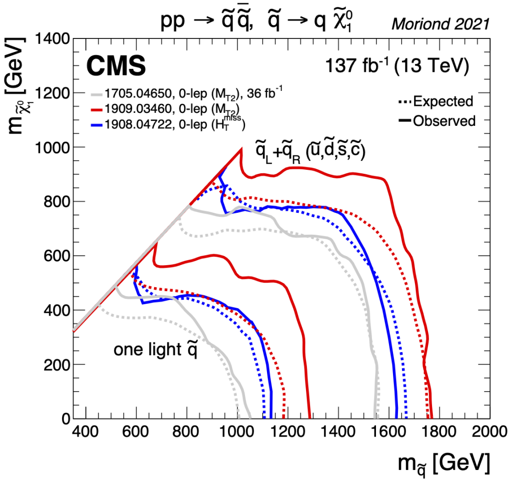
See talk by Alexander Khanov (ATLAS SimpleAnalysis).

Various non-collaboration software tools exist: SModelS (see talks by Sabine Kraml and Timothée Pascal), GAMBIT (see talk by Tomás Gonzalo), CheckMATE, Rivet/Contur, MadAnalysis5, ...

These obviously benefit from cooperation by experimentalists; need information to be public and documented.

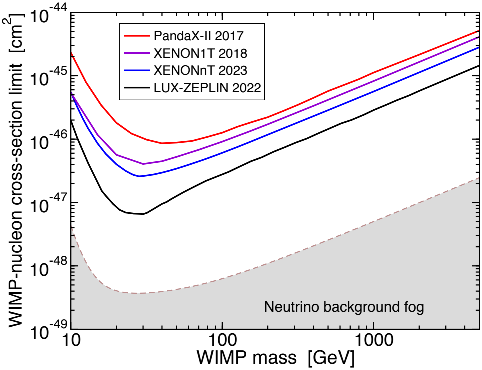
In the future, we should strive to make this open, standardized, routine, transparent, and automatic!

Squark limits tend to be somewhat weaker than for the gluino:



In real SUSY models, squarks often don't decay as assumed in these simplified models. Recall $\tilde{q}_L$ couple more strongly to winos. Exclusions could be stronger or weaker.

Strongest current limits on neutralino dark matter from the LUX-ZEPLIN experiment, 2207.03764:



For $m_{\rm LSP} > 100$ GeV, the bound on the spin-independent cross-section is

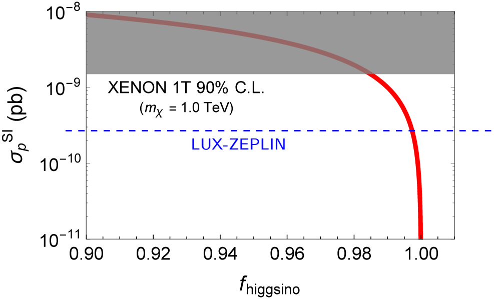
$$\sigma_{\rm SI} \; < \; 2.7 \times 10^{-10}\,\text{pb}\, \left(\frac{m_{\rm LSP}}{1000\,{\rm GeV}}\right)$$

Eventually, the experiments will hit the “neutrino fog”, where astrophysical neutrino backgrounds greatly reduce the sensitivity to dark matter.

Implications of dark matter direct detection

Mixed gaugino-higgsino LSPs are often ruled out, but holes exist in parameter space where destructive interference means a loss of sensitivity.

Nearly pure higgsino (mass 1.1 TeV) or wino (mass 2.8 TeV) can escape direct detection if the mixing is small enough. For example:



Kowalska and Sessolo, 1802.04097

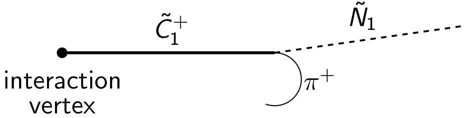
$f_{\rm higgsino}$ = higgsino content of LSP

LZ constraints added

Recall: nearly pure higgsinos have $\tilde{N}_1$, $\tilde{N}_2$, $\tilde{C}_1^\pm$ separated by few hundred MeV. Nearly pure winos similarly have $\tilde{N}_1$, $\tilde{C}_1^\pm$ separated by 160 MeV, but are highly constrained by indirect detection.

Difficult challenges for detection at the LHC!

Disappearing track signal for nearly degenerate higgsinos or winos



The distance traveled by the chargino is macroscopic, perhaps of order millimeters or centimeters. The pion is very soft, so curls up in the magnetic field and is not detected.

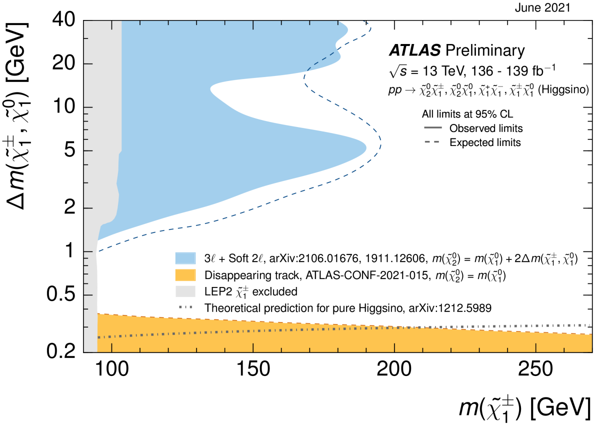
The mass reach is much lower for higgsinos than for winos because:

- track is shorter,
- production cross-section is much smaller.

Longer $\tilde{C}_1$ tracks can also be detected by measuring the anomalous energy deposited per distance traveled in the detector (dE/dx).

Nearly degenerate higgsino-like $\tilde{C}_1^{\pm}$, $\tilde{N}_2$, and $\tilde{N}_1$

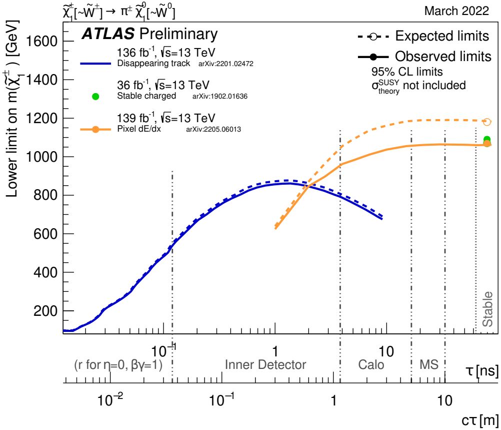
Look for soft leptons if mass difference is large enough, otherwise disappearing tracks if the mass difference is smaller than few hundred MeV. This includes the limit of pure Higgsino.



Exclusion presently limited to 210 GeV. (CMS similar. See Sam Bein's talk.) Recall higgsino-like thermal dark matter has $m_{\tilde{N}_1} \approx 1.1$ TeV.

Nearly degenerate wino-like $\tilde{C}_1^{\pm}$ and $\tilde{N}_1$

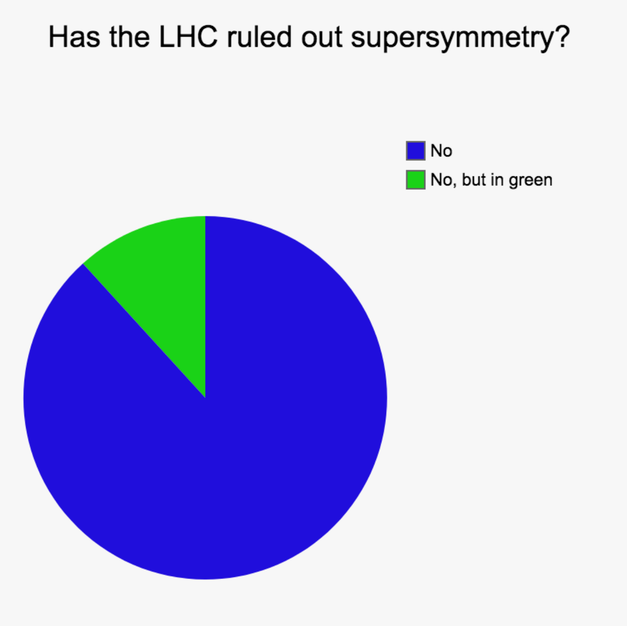
Can use both disappearing track, and anomalous energy deposition dE/dx for longer tracks.



Recall wino-like thermal dark matter would have $m_{\tilde{N}_1} \approx 2.8$ TeV, but with strong constraints from indirect detection from annihilations to photons.

Summarizing important things to keep in mind when looking at LHC limits

- Compressed mass spectra (small mass splittings) give weaker limits, or no limit
- "Simplified SUSY models" are not SUSY
- Cascade decays can give weaker limits
- Decays through τ leptons give weaker limits
- Dark matter motivates nearly degenerate and nearly pure higgsinos (or winos?), but with masses well beyond the reach of LHC
- Mass reach for squarks and gluinos will increase slowly with more LHC data in Run 3. Cross-section falls quickly with large masses because of parton distribution functions.
- Mass reach for charginos, neutralinos, sleptons still have some room to grow at LHC


Has the LHC ruled out supersymmetry?
No
No, but in green

Question: **Can** the LHC rule out supersymmetry?

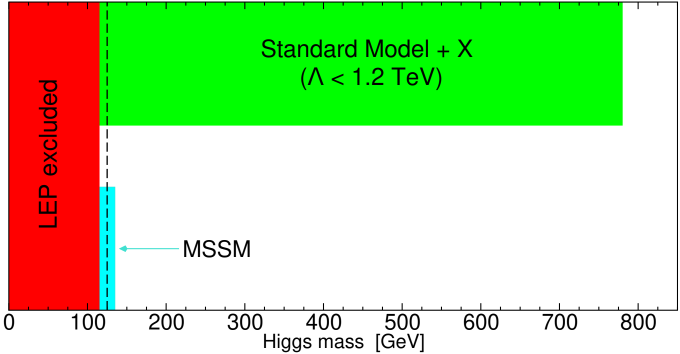
Answer: **No.** Supersymmetry is an example (one of many!) of a decoupling theory; the more you raise the masses of the new particles, the better it agrees with the Standard Model.

Keith Olive's talk: "There is always a best fit point."

Actually, there is one exception to decoupling in SUSY: it was predicted in the 1990's that the Higgs boson had to be light ($M_h \lesssim 135$ GeV) in SUSY. When we discovered the Higgs with mass 125 GeV in 2012, we lost the last chance to rule out SUSY.

The LHC had a real chance to rule out SUSY, but it failed to do so!

The success of the Higgs scalar boson mass in SUSY, illustrated:

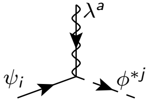


Once we fix the weak scale, a generic theory beyond the Standard Model could have had a Higgs scalar boson mass anywhere up to nearly 800 GeV, consistent with unitarity. It turned out to be in the range predicted by SUSY.

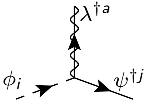
None of the competitor theories to explain the Big Hierarchy problem are being discovered at LHC either! And many are in worse shape than SUSY is, or are now completely dead (technicolor, top-quark condensate models, chiral quarks and leptons. . .).

Those who don't like the fact that SUSY cannot be ruled out by the LHC should remember that **all** theories of physics beyond the Standard Model that remain alive after the LHC are **also** decoupling theories.

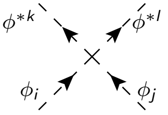
Softly broken SUSY does make predictions: dimensionless couplings



$-i\sqrt{2}g_a(T^a)_i{}^j$



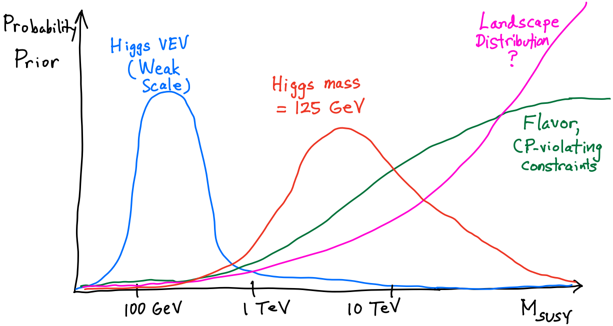
$-i\sqrt{2}g_a(T^a)_i{}^j$



$-ig_a^2(T_i^{ak}T_j^{al}+T_i^{al}T_j^{ak})$

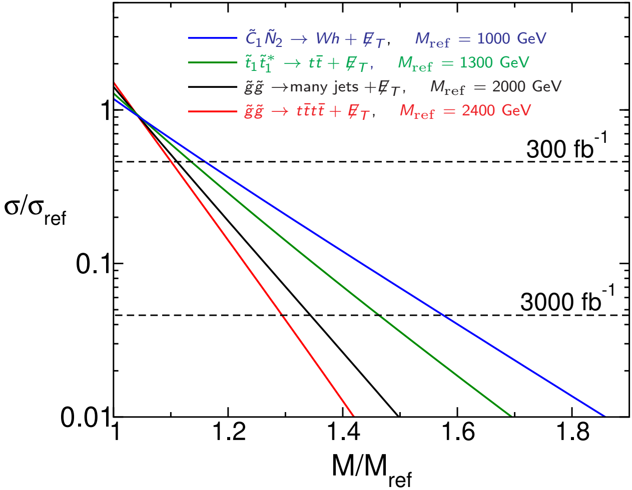
With all of that taken into account, the smart money might favor betting on heavier superpartners, and not just because of direct constraints from LHC.

Cartoon of probability priors for superpartner mass scale M_{SUSY}:



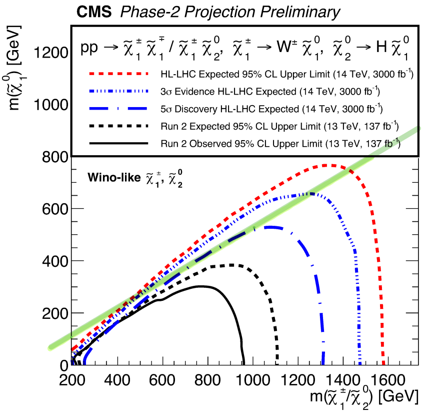
- Electroweak scale of 174 GeV would favor light superpartners, especially higginos, stops, and gluino. (But more on this later.)
- In July 2012, we learned $M_h = 125$ GeV, which favors much heavier stops.
- Flavor- and CP-violation bounds favor heavier superpartners.
- More speculatively (in my opinion), landscape distribution of vacua could favor large supersymmetry breaking

Road of Improvement for HL-LHC: relative decrease in cross-section at $\sqrt{s} = 13.6$ TeV as a function of relative increase in mass. [For this graph, chose reference mass $M_{\rm ref}$ near present mass limit, with a light LSP.]



For increasing superpartner mass, cross-sections for electroweakinos decrease much more slowly than those for squarks, gluino.

Projections for HL-LHC with $\sqrt{s} = 14$ TeV and 3000 fb^{-1}, for wino-like charginos and neutralinos decaying through W, h:

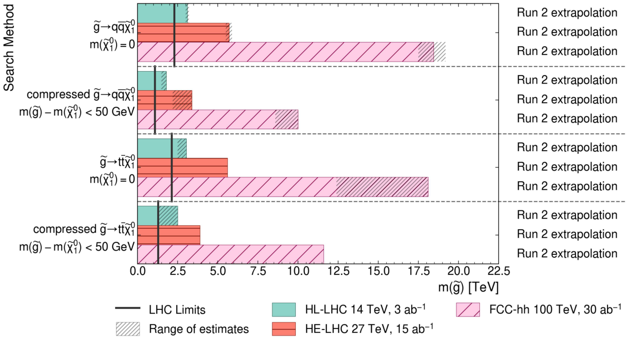


From *Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors*

According to this projection, the expected 5σ exclusion almost coincides with the gaugino mass unification line. Can this be improved?

The 95% exclusion reach is equivalent of $\gtrsim$ 5000 GeV in gluino mass, for models with gaugino mass unification. This is far beyond what can be done for direct gluino pair searches at HL-LHC.

For future explorations of SUSY there is no substitute for energy:



Snowmass BSM Energy Frontier report 2209.13128, and references therein. There is ample opportunity for more work in the area of projections for future colliders.

Why did we think superpartners should be light?

Minimizing the Higgs potential, we find:

$$M_Z^2 = -2(|\mu|^2 + m_{H_u}^2) + \mathcal{O}(1/\tan^2\beta) + \text{loop corrections}$$

So avoiding fine-tuning suggests that **Higgsinos should be light:** $\mu^2 \sim -m_{H_u}^2 \sim M_Z^2$.

Other superpartners should be light only if their masses are correlated with, or feed into, $m_{H_u}^2$.

Corrections from loop diagrams give:

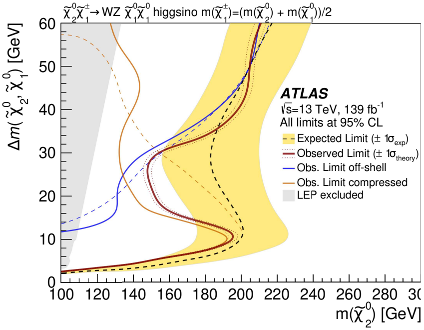
$$\Delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)\ln(\Lambda/\text{TeV}) - \frac{\alpha_S y_t^2}{\pi^3} M_{\tilde{g}}^2 \ln^2(\Lambda/\text{TeV}) + \text{small.}$$

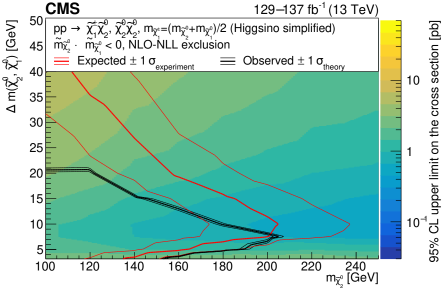
So the **top squarks and gluino should also not be too heavy**.

But, “not too heavy” is a notoriously fuzzy statement.

From ATLAS and CMS (see talks of Judita Mamužić, Sam Bein, and Costas Vellidis, and papers 2106.01676 and 2111.06296), we see slight excesses in soft leptons, as weaker-than-expected exclusions for Higgsinos:

$$m_{\tilde{H}} \approx m_{\tilde{N}_1} \approx m_{\tilde{C}_1} \approx m_{\tilde{N}_2} \qquad \text{with}$$
$$\Delta m = m_{\tilde{N}_2} - m_{\tilde{N}_1} = 12 \text{ to } 32 \text{ GeV or so.}$$





This region is well-motivated by "small μ natural supersymmetry", so it will be interesting to see what becomes of it in the future. Can also interpret in terms of wino/bino models, but the slight excesses are the same ones.

Can natural SUSY (no little hierarchy problem) work without small $|\mu|$?

All we really need is that the particular combination:

$$m^2_{H_u} + |\mu|^2 \quad \equiv \quad \widehat{m}^2_{H_u}$$

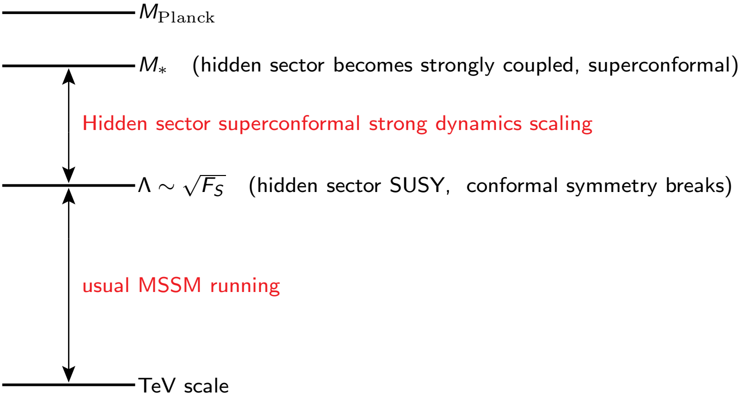
is small, even if $|\mu|^2$ and $m^2_{H_u}$ are individually large. Can renormalization group running do this?

If Q is the renormalization scale, then near a conformal fixed point, could have power-law renormalization group running:

$$\widehat{m}^2_{H_u}(Q) \quad = \quad \left(\frac{Q}{M_*}\right)^{\Gamma} \widehat{m}^2_{H_u}(M_*),$$

where M_* is some very large input scale (perhaps the GUT or Planck scale). Prefer a scaling dimension Γ that is positive and large.

Scalar sequestering, invented for other reasons by Roy and Schmaltz 0708.3593, Murayama, Nomura, Poland 0709.0775, Perez, Roy, Schmaltz 0811.3206, suggests a way of realizing this. The big picture:



Scalar squared masses obtain a relative suppression factor $(\Lambda/M_*)^\Gamma$ compared to gaugino masses.

Communication of supersymmetry breaking to the MSSM sector:

$$
\begin{aligned}
\mathcal{L}_{\text{gaugino masses}} &= -\frac{c_a}{2M_*}\int d^2\theta\, S\, \mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha + \text{c.c.} \\
\mathcal{L}_{a\text{ terms}} &= -\frac{c^{ijk}}{6M_*}\int d^2\theta\, S\phi_i\phi_j\phi_k + \text{c.c.} \\
\mathcal{L}_{\mu\text{ term}} &= \frac{c_\mu}{M_*}\int d^4\theta\, S^* H_u H_d + \text{c.c.} \\
\mathcal{L}_{b\text{ term}} &= \frac{c_b}{M_*^2} Z_{S^*S}\int d^4\theta\, S^*S H_u H_d + \text{c.c.} \\
\mathcal{L}_{m^2\text{ terms}} &= -\frac{c_i^j}{M_*^2} Z_{S^*S}\int d^4\theta\, S^*S\phi^{*i}\phi_j,
\end{aligned}
$$

Key feature: the last two terms are **non-holomorphic** in S, so they have an additional scaling factor $Z_{S^*S} \sim (Q/Q_0)^\Gamma$.

Dimension-2 terms (scalar squared masses) have extra power-law suppression compared to dimension-1 (gaugino masses, scalar cubic couplings, μ term).

An important subtlety: it was argued by Murayama, Nomura, Poland, 0709.0775 and Perez, Roy, Schmaltz, 0811.3206 that the Higgs squared masses that have hidden-sector superconformal scaling are the **combined** SUSY-breaking and SUSY-preserving ones:

$$\begin{aligned} \widehat{m}^2_{H_u} &\equiv m^2_{H_u} + |\mu|^2, \\ \widehat{m}^2_{H_d} &\equiv m^2_{H_d} + |\mu|^2 \end{aligned}$$

This seems great; just what we want to cure the SUSY little hierarchy problem!

Even if $|\mu|^2$ and $m^2_{H_u}$ are individually large, the renormalization group fixed running due to the strongly coupled superconformal sector should drive the right combination towards very small values.

Challenges for this scenario:

- It is not known whether an appropriate superconformal field theory actually exists.
- Results from the superconformal bootstrap show that the relative scaling exponent is constrained to be not too big: $\Gamma \lesssim 0.3$.

  Poland, Simmons-Duffin, Vichi, 1109.5176, Poland and Stergiou, 1509.06368
- Must exit superconformal scaling regime at high enough scale to allow for suitable gaugino masses. This limits how small one can drive $\widehat{m}^2_{H_u}$.

  Knapen and Shih, 1311.7107
- The IR fixed point for $\widehat{m}^2_{H_u}$ may not actually be at 0, because of:
  - Possible hidden sector effects

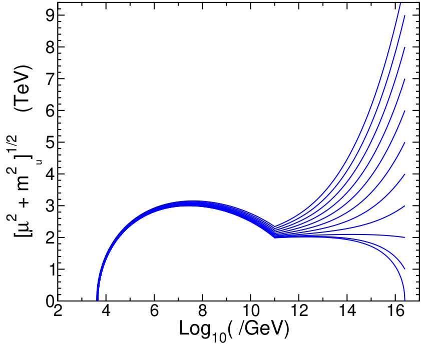
    Nathaniel J. Craig, Daniel Green, 0905.4088
  - Definitely visible sector effects

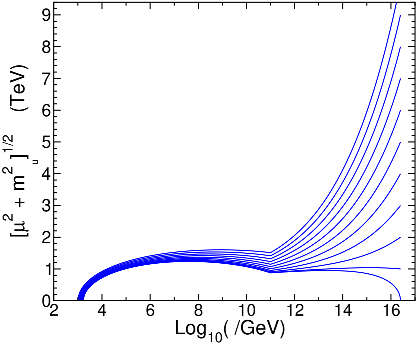
    SPM, 1712.05806

    $$Q\frac{d}{dQ}m^2_{H_u} = \Gamma m^2_{H_u} + \beta^{\text{MSSM}}_{m^2_{H_u}}$$

    Quasi-fixed point, rather than power-law running.

Renormalization group running of $\widehat{m}_{H_u}^2 = \mu^2 + m_{H_u}^2$ with (left) and without (right) gaugino mass unification:





I wouldn't claim a complete solution to the SUSY little hierarchy problem, but subjectively, the smaller $m_{H_u}^2 + \mu^2$ at the quasi-fixed point suggests slightly less "tuning" than in traditional models.

The Dream: can a robust dynamical reason for $m_{H_u}^2 + |\mu|^2 \ll M_{\mathrm{SUSY}}^2$, perhaps due to RG running, be found?

Opportunities/challenges for experimentalists

- Push harder into the compressed regions
- Exploit other hard-to-access signals
- Continue the recent impressive progress in exploiting 125 GeV Higgs
- Leverage machine learning opportunities
- Explore the capabilities for future colliders!
- Full and open documentation of search results (assumptions, likelihoods, acceptances and efficiencies)

Opportunities/challenges for theorists

- The classic question: How does supersymmetry get broken?
- The modern corollary: Is there a good explanation for the little hierarchy M_{SUSY}/M_Z ?
- Continue improvement of tools for evaluation of signals and backgrounds
- Identify new signals that might be missed or underexploited
- Explore the capabilities for future colliders!

Let us heed Ben Franklin, and stay on the Road to Improvement by continuing to make Experiments.

Conclusion

The future of supersymmetry as a research program holds both exciting challenges and potential breakthroughs. While the LHC experiments have yet to observe direct evidence of supersymmetric particles, ongoing theoretical advancements and refined experimental techniques offer renewed hope. The future of supersymmetry research lies in two key directions. Firstly, novel theoretical models are being explored, including new variants of supersymmetry that incorporate dark matter candidates or non-linear realizations. These approaches push the boundaries of our understanding and allow for further exploration of the particle zoo. Secondly, upcoming experiments, such as the High-Luminosity LHC and future colliders, aim to explore higher energy scales and increase the sensitivity to supersymmetric signals. With these advancements, the quest for supersymmetry will continue to shape the field of particle physics, inspiring new theoretical insights and propelling experimental discoveries.

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Thanks again to the organizers of SUSY23. Let's hear about SUSY24!

My view on fine-tuning and naturalness:

- There is no way of objectively defining, let alone measuring, "fine-tuning", or "naturalness".
- Naturalness is personal and subjective, rather than scientific.
- **However**, naturalness is useful, and even crucial, for scientists. We are constantly making practical decisions about which research directions to pursue, given finite time and money.