



SUSY searches at the ATLAS and CMS experiments

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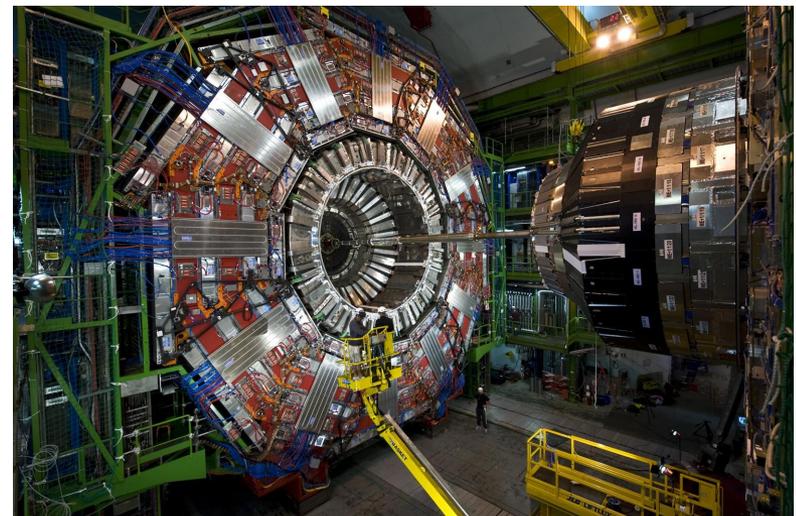
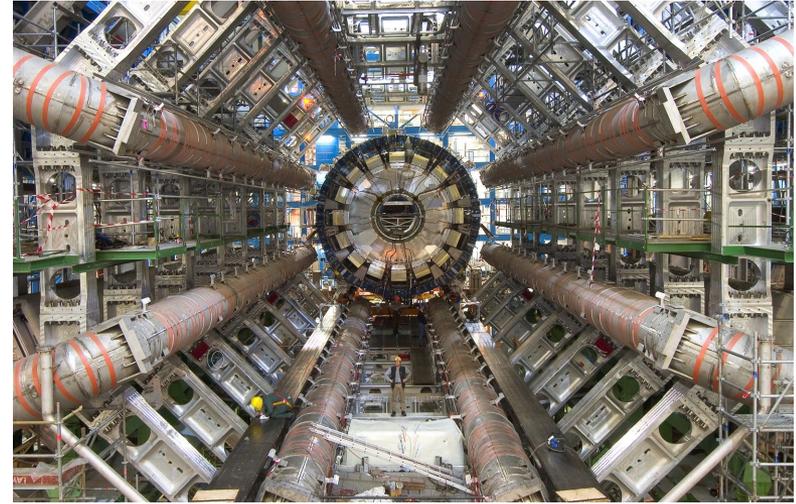
September 05th, 2021



Outline of the talk

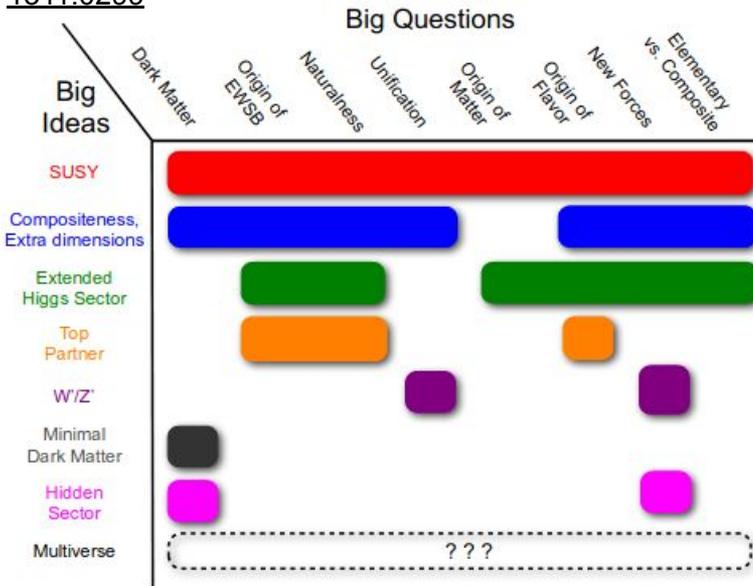
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- ▶ Introduction to SUSY
- ▶ Latest SUSY results:
 - Gluino/squark searches
 - Stop and sbottom searches
 - Chargino and neutralino searches (electroweakino)
 - Slepton searches
 - RPV and LLP searches
- ▶ Summary and Outlook



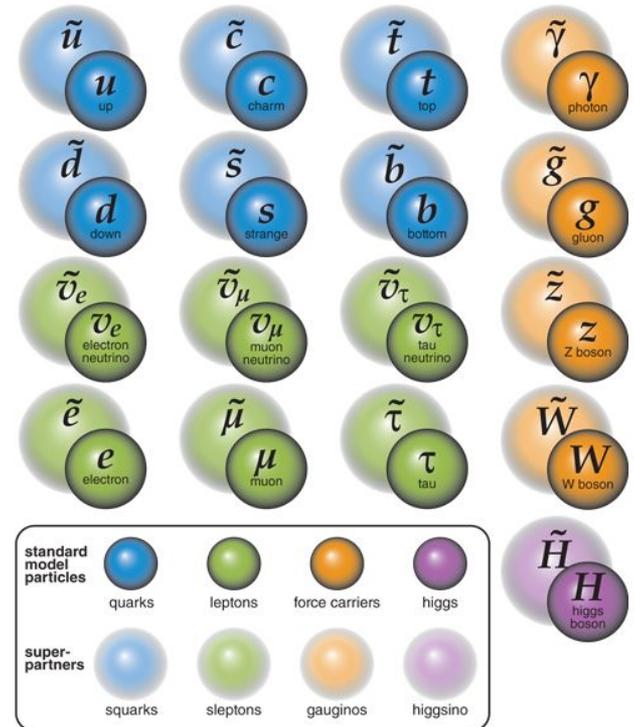
Supersymmetry: why, what?

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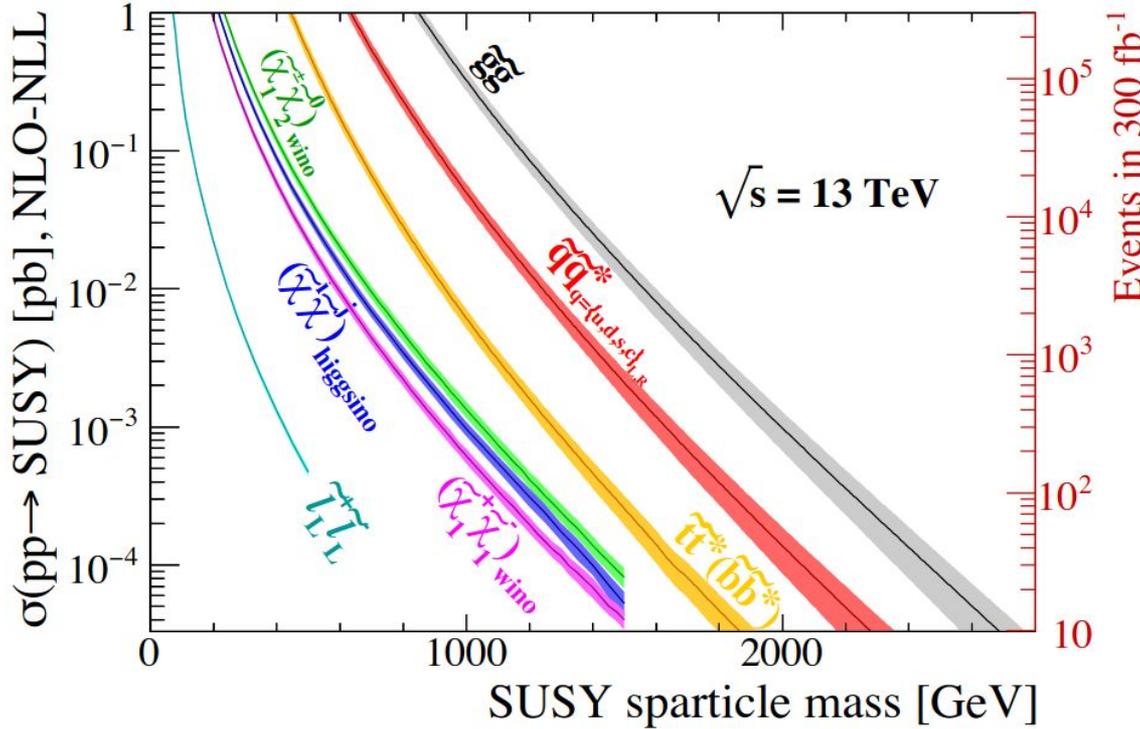
- ▶ Supersymmetry (SUSY) can solve multiple open questions both theoretical (great unification theory) or experimental (dark matter candidate)

- ▶ A new space time symmetry → one superpartner companion per standard model (SM) particle.
- ▶ If R parity conserved → produced in pairs, Lightest supersymmetric particle (LSP) stable
- ▶ Naturalness → gluinos, top squark (stop), charginos and neutralinos at TeV scale



Supersymmetry: where?

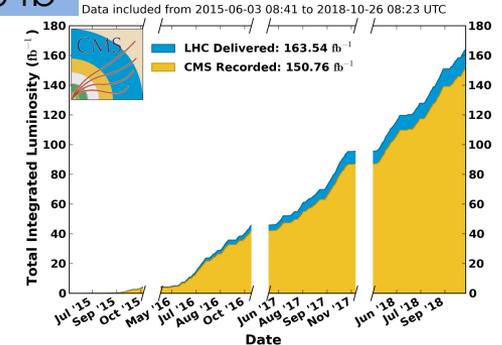
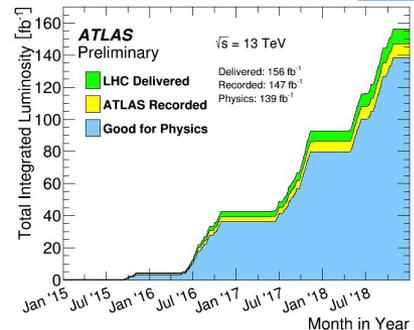
LPCC SUSY Cross Section WG



- ▶ If SUSY to exist, loads of particles should have been produced at the LHC
- ▶ So far, no significant deviations have been found...

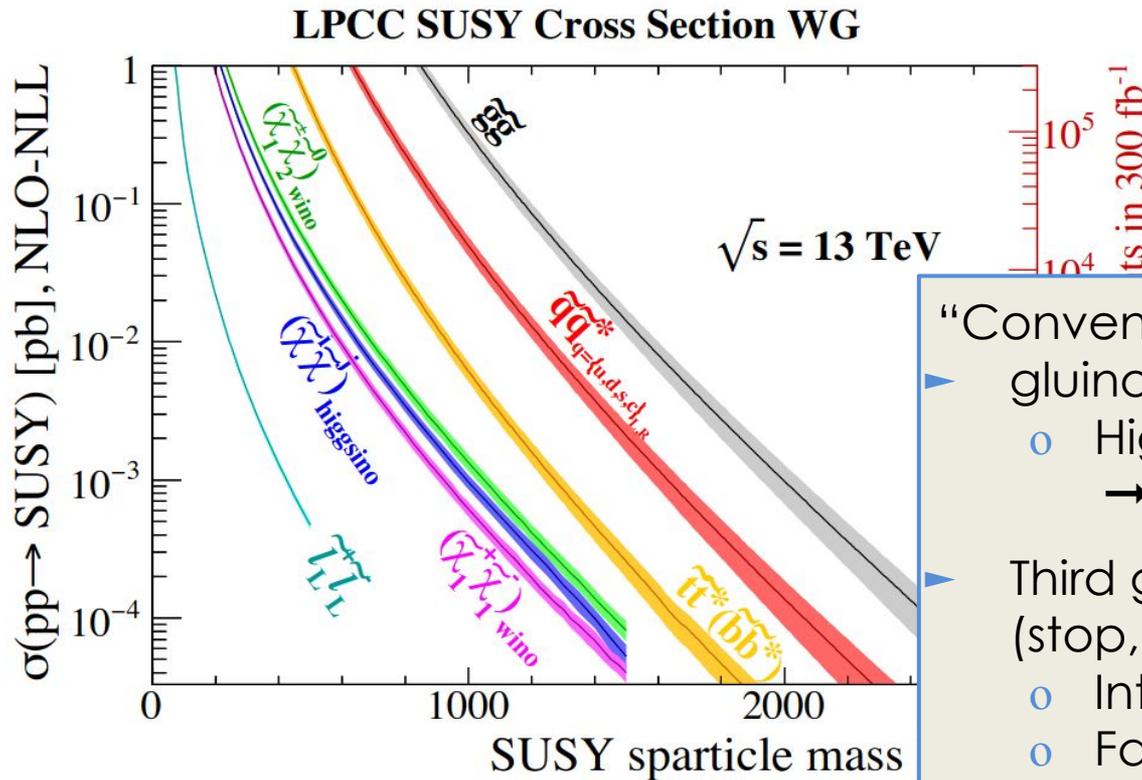
➔ Look for SUSY in challenging regions of the parameter space

Run2~150 fb⁻¹ CMS Integrated Luminosity, pp, $\sqrt{s} = 13$ TeV



Supersymmetry: where?

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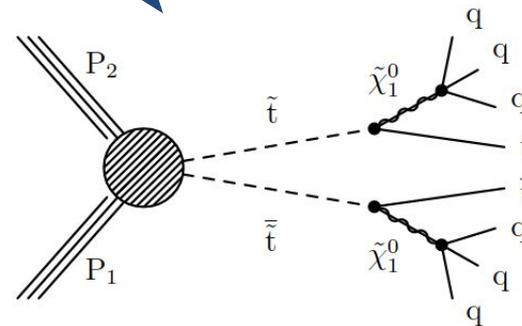
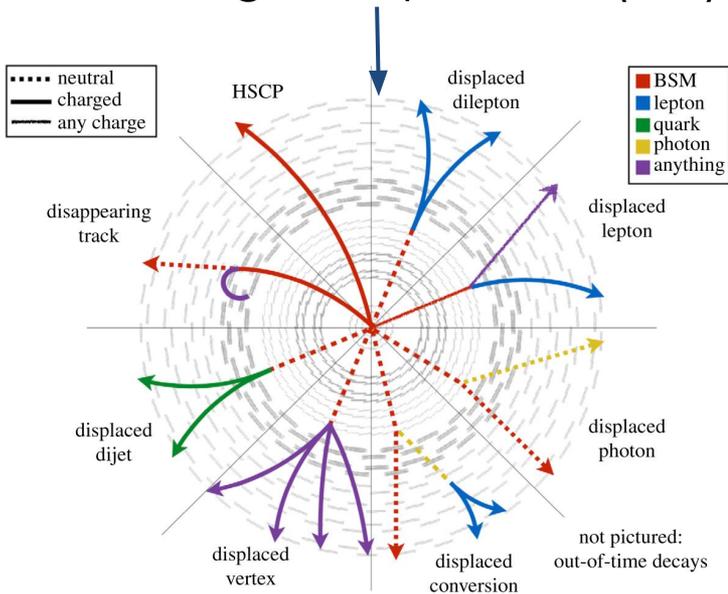
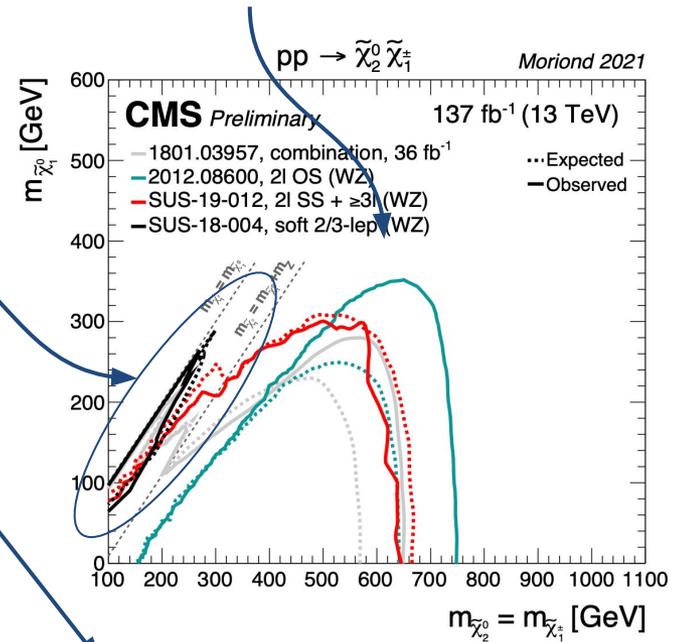


“Conventional” SUSY searches:

- ▶ gluino/squark searches:
 - High cross-sections
 - High mass sensitivity
- ▶ Third generation quarks: (stop, sbottom)
 - Intermediate cross-sections
 - Favoured for naturalness.
- ▶ Electroweak production: (Charginos/neutralinos & sleptons)
 - Lower cross-sections
 - Higher branching fractions to leptons

Supersymmetry: how?

- ▶ Are SUSY particles just heavier or its cross-section smaller than what's been probed? → "Conventional" SUSY searches (with high p_T^{miss} from LSPs)
- ▶ Perhaps SUSY signatures are very "soft"? → Compressed searches
- ▶ R-Parity not conserved? → RPV SUSY
- ▶ New particles with longer lifetimes? → Long lived particles (LLP)



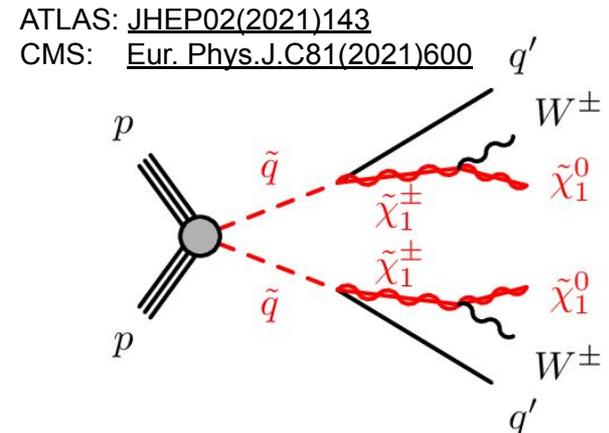
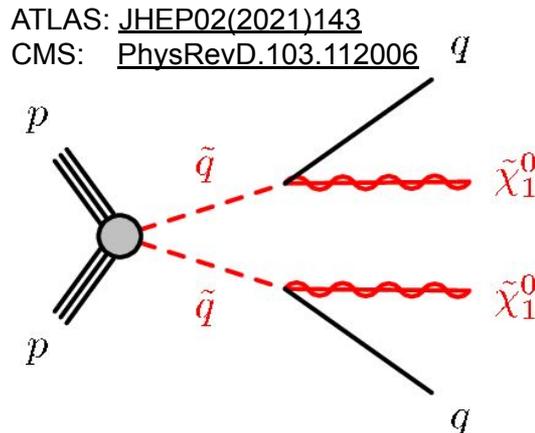
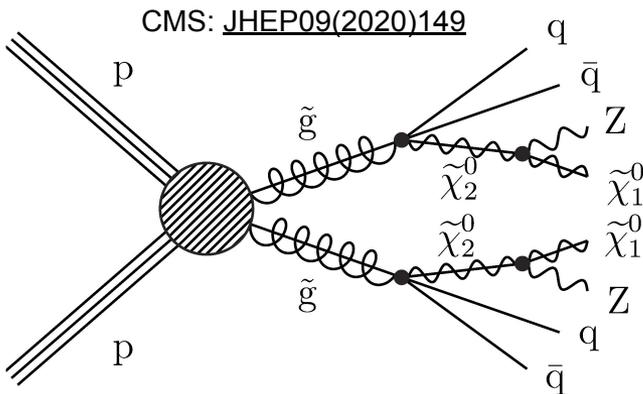
- ▶ Impossible to cover them all analyses in one talk
 - A selection of current analyses have been made, trying to englobe most recent analyses of each search type
 - ▶ New analyses are continuously being published, many applying Machine Learning techniques such as Deep Neural Networks (DNNs).
- Latest updated results in:
- ATLAS:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>
 - CMS :
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

Glino and light squark production in topologies with presence of jets

- ▶ Most analyses exploit fully hadronic final states:
 - Decay chains involving light quarks, b-quarks or top quarks.
 - Large sensitivity due to due to lower high p_T^{miss} backgrounds
- ▶ Additional final states with leptons from the next to LSP (NLSP) neutralinos/charginos in the decay chain
 - Single lepton signature when chargino decays to W bosons
→ **ATLAS: Eur. Phys. J. C 81 (2021) 600**

Current analyses sensitive to very high mass particle production due to high cross-sections

- ▶ Main challenge: reconstruct large-cone jets from boosted object decays



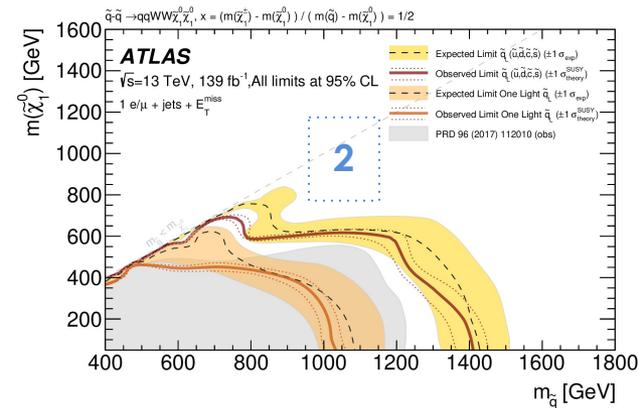
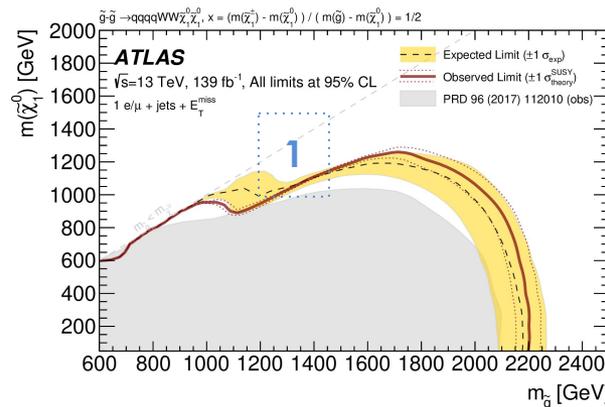
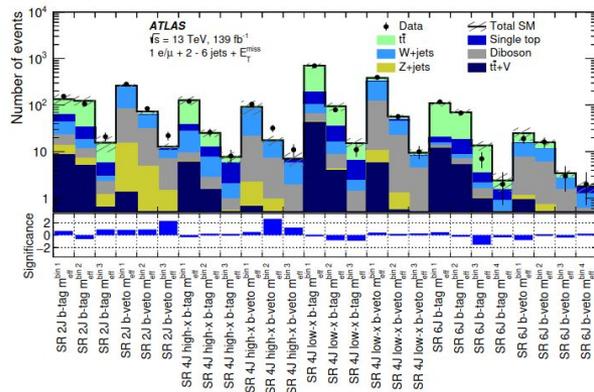
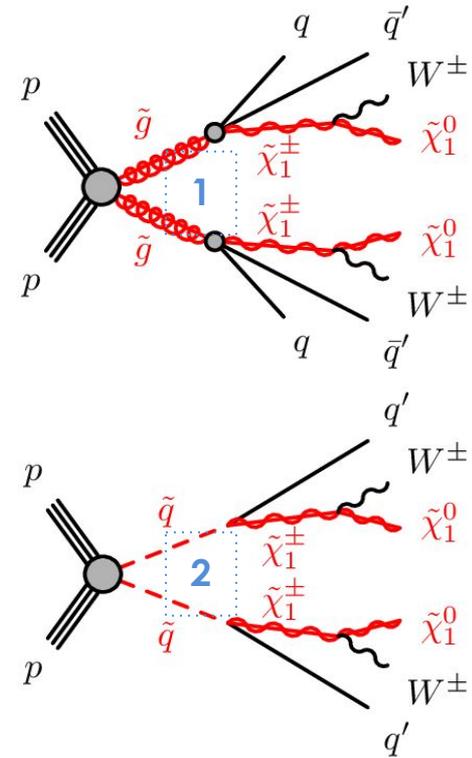
Glino/squark searches: 1ℓ

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ATLAS: *Eur. Phys. J. C* 81 (2021) 600

Glino (1) /squark (2) production decaying to two W bosons, LSPs and quarks, with the chargino assumed to be wino like and the LSP assumed to be bino like.

- ▶ Different signal regions (SR), split by the number of jets and $m_T(\ell, p_T^{\text{miss}})$ values.
- ▶ Control and validation regions (CR, VR) defined in the same phase space but with lower $m_T(\ell, p_T^{\text{miss}})$
- ▶ Limiting up to 2200 GeV (gluino), 1400 GeV (squark if 2 generations are mass degenerate) and 1000 GeV if only one quark accessible.



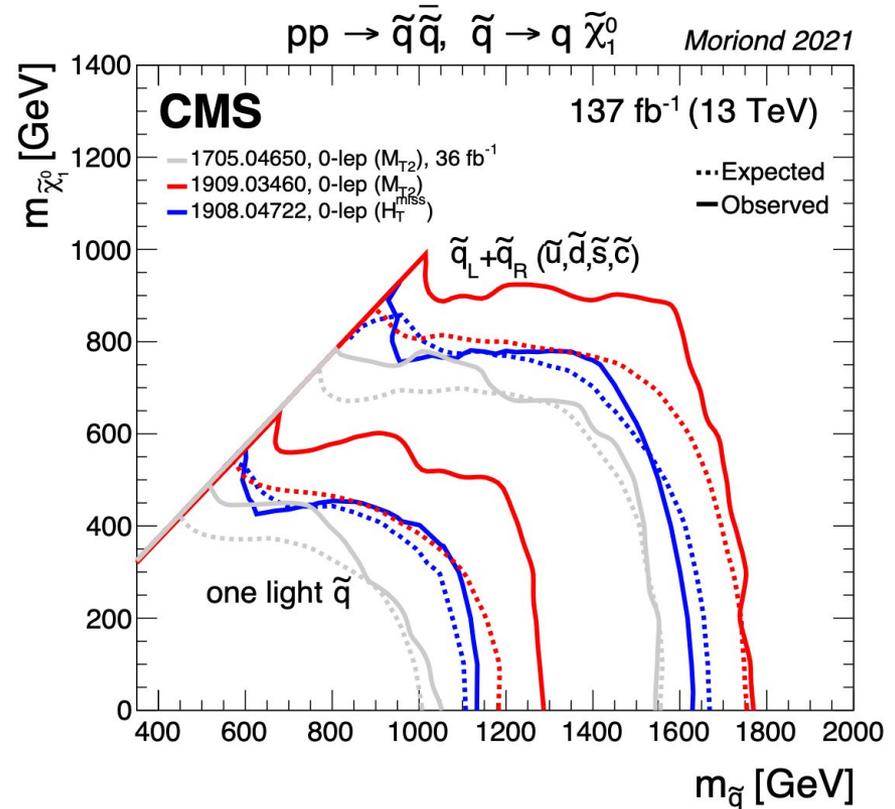
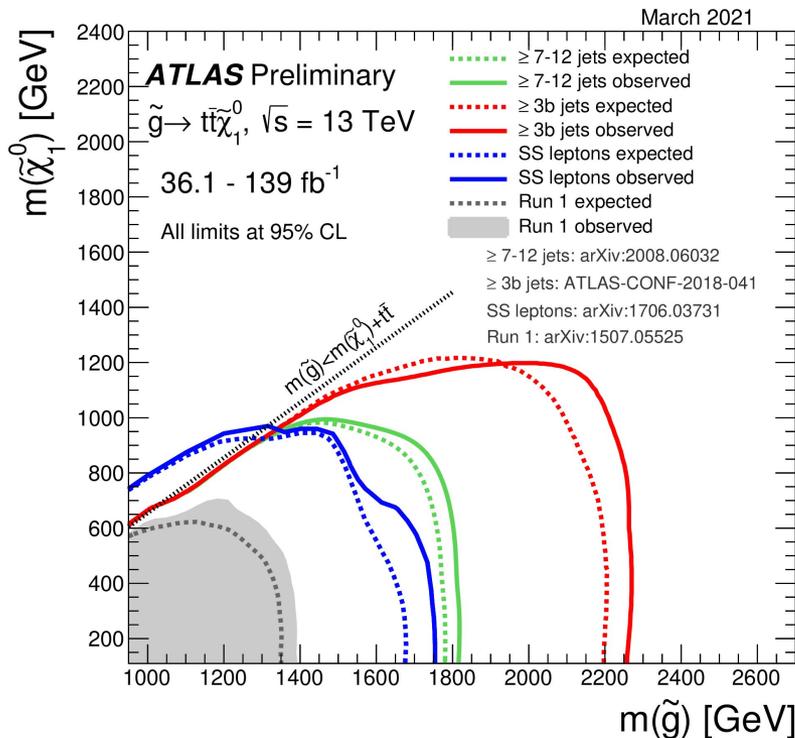
Glino/squark searches: Summary

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Limits at:

- ▶ Glino to qq +LSP: 2100-2300 GeV
- ▶ Glino to top+LSP: 2200 GeV
- ▶ Squark limits: 1800-1900 GeV

→ Naturalness starts being challenged...



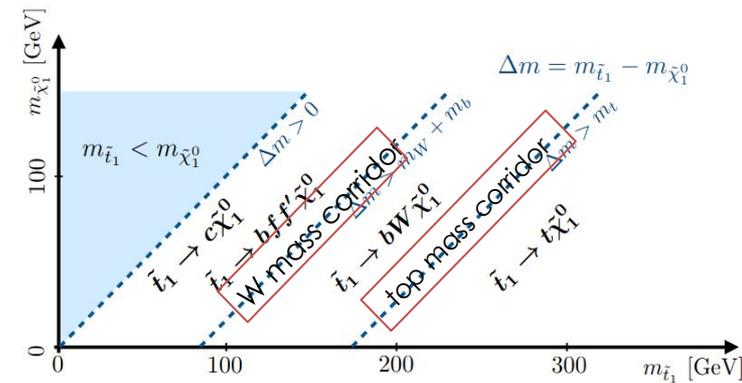
Stop searches

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Naturalness \rightarrow top squark (stop) often lightest squark

Searches with different kinematics depending on mass splitting (Δm) between top squark and LSP:

- ▶ High mass region ($\Delta m > m_{\text{top}}$):
 - \rightarrow Decays with high $p_{\text{T}}^{\text{miss}}$
- ▶ Intermediate mass region ($m_{\text{W}} + m_{\text{b}} < \Delta m < m_{\text{top}}$):
 - \rightarrow 3 body decays
- ▶ Compressed region ($\Delta m < m_{\text{W}} + m_{\text{b}}$):
 - \rightarrow 4 body decays



Searches in this presentation:

- ▶ All hadronic final states: traditionally show the most sensitivity for high Δm (thanks to customised boosted object reconstructions):
 - \rightarrow **CMS: 2103.01290**
- ▶ Other signatures: stop decaying to stau (cleaner due to lack of neutrinos)
 - \rightarrow **ATLAS: 2108.07665**

Stop searches: hadronic final state

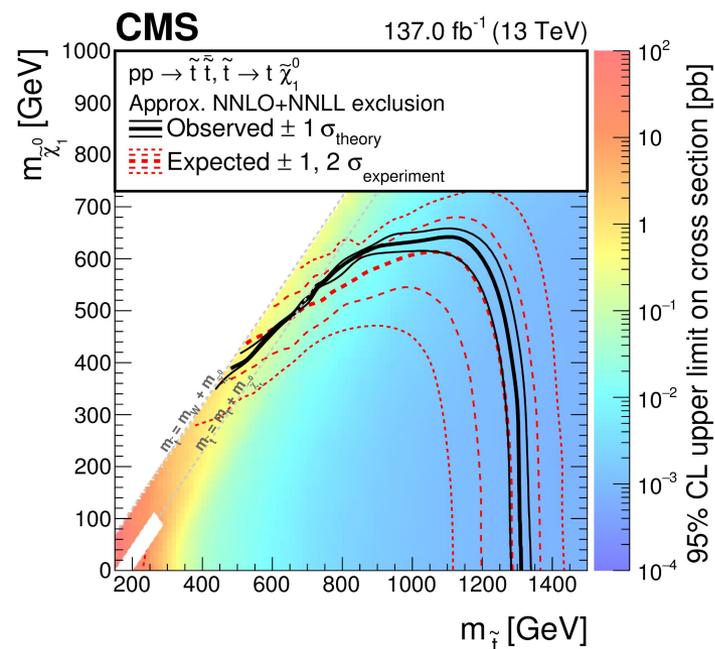
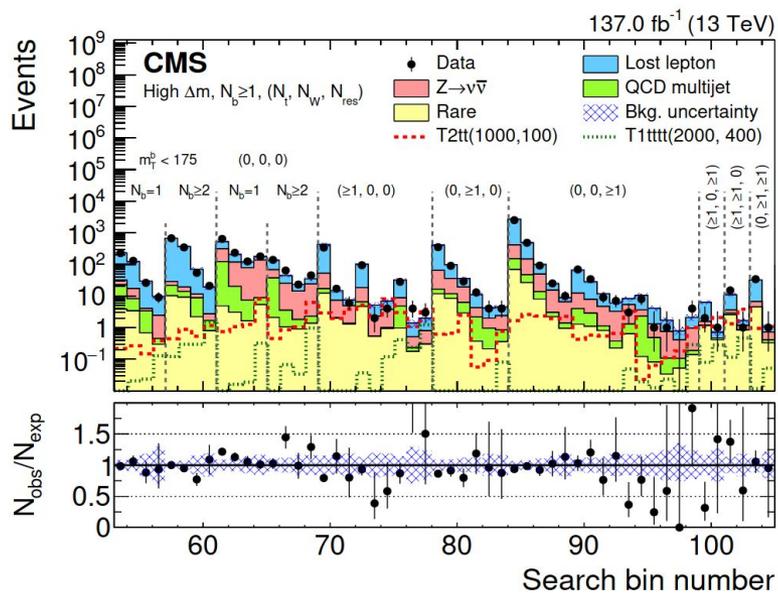
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CMS: 2103.01290

Targeting events with multiple jets, high p_T^{miss} and veto on leptons.
Dedicated object reconstructions Δm regions:

- ▶ Low mass: soft b-tagging+initial state radiation (ISR) jets
- ▶ High mass: DNN to identify boosted top quarks or W bosons

Signal regions defined in bins of several event kinematic variables and multiplicities of dedicated objects



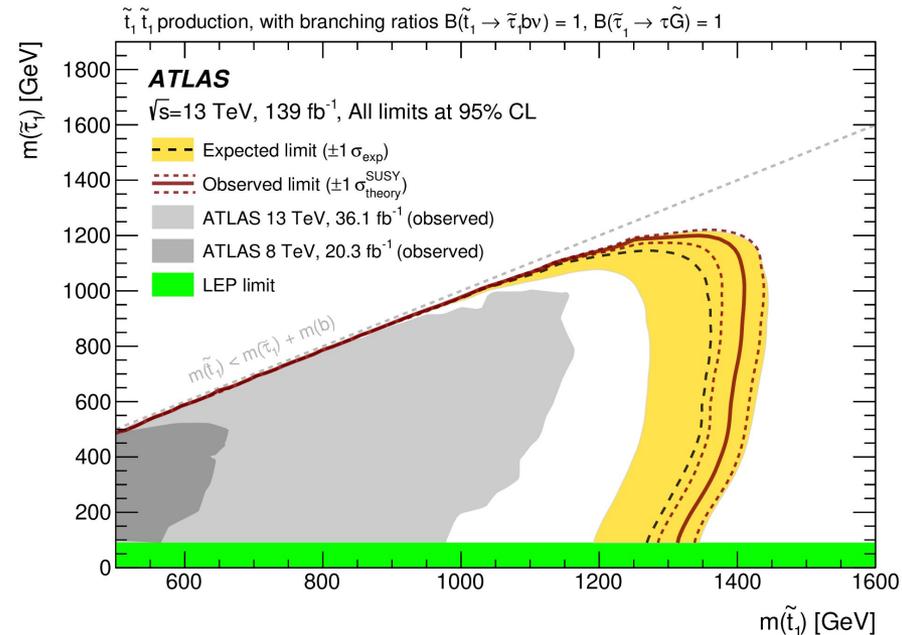
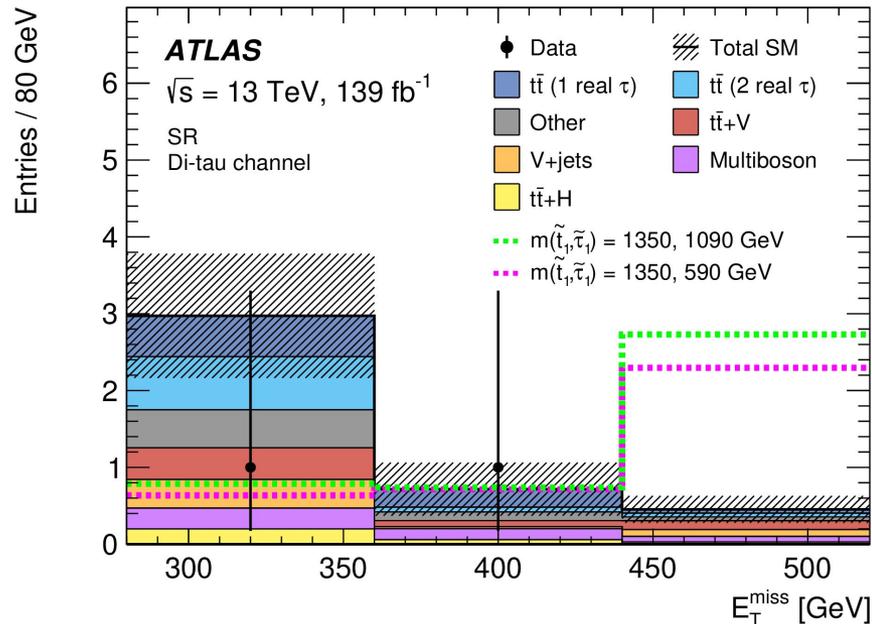
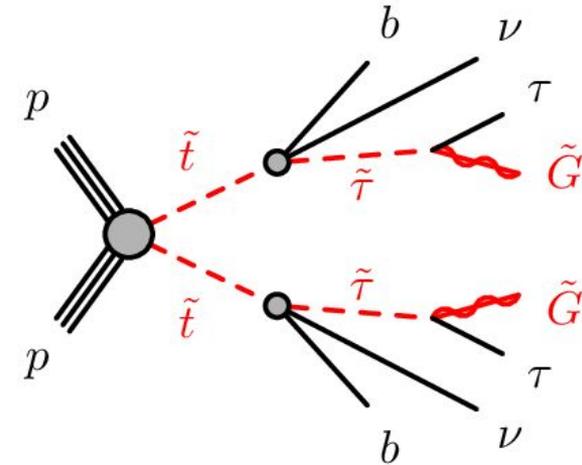
Stop searches: decays into staus

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ATLAS: 2108.07665

Events with $p_T^{\text{miss}} > 250$ GeV, 2 jets (at least one b-tagged), and no e/ μ

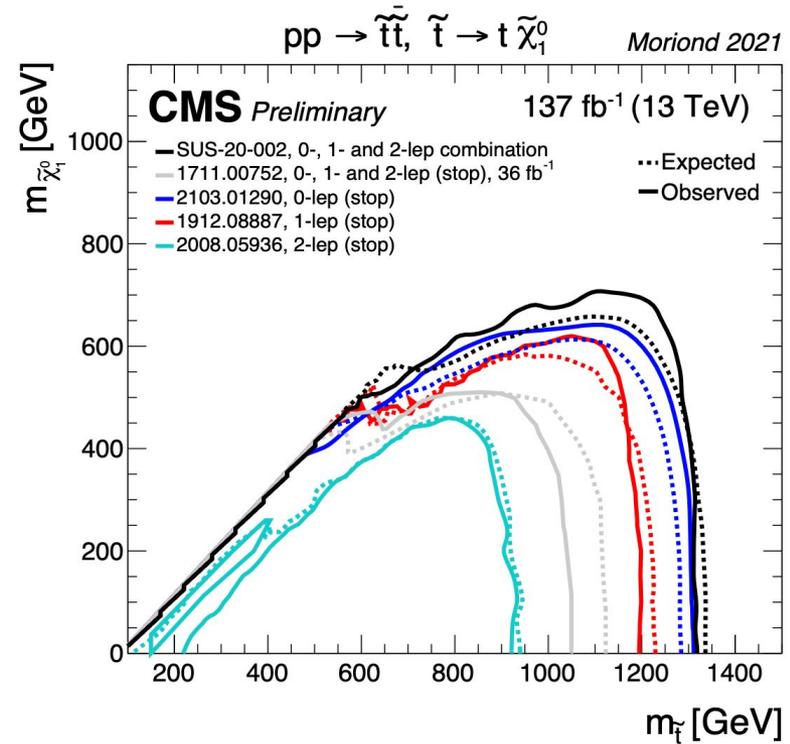
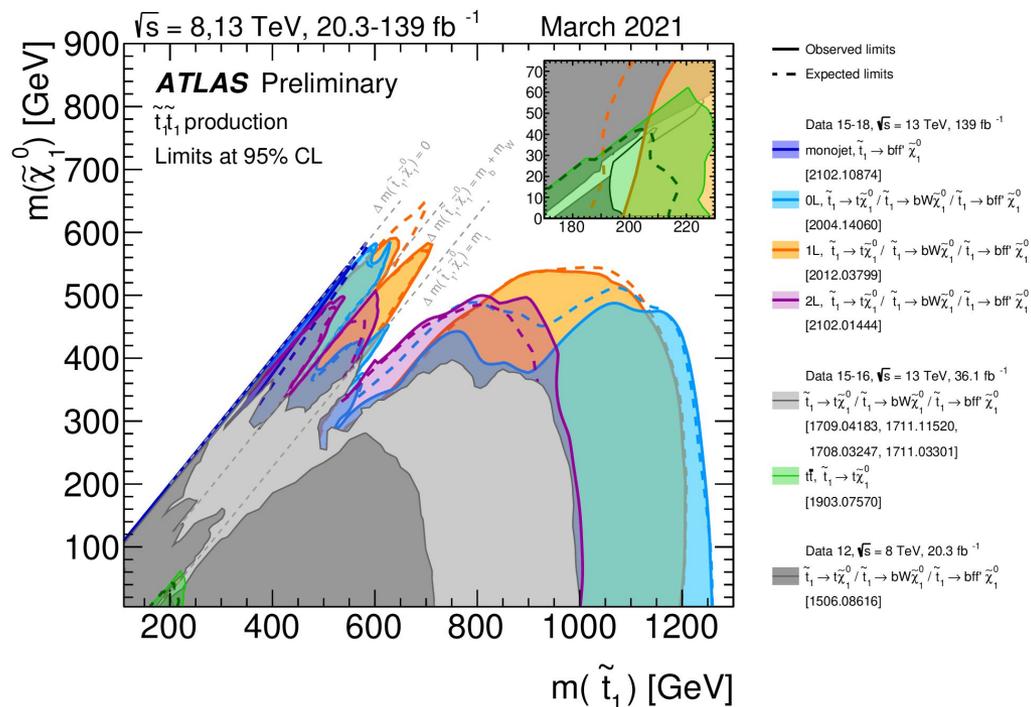
- ▶ Two SR, one with 2 hadronic taus (τ_h), and another with 1 τ_h and at least two b-jets
- ▶ Limits on m_{stop} up to 1400 GeV



Stop searches: Summary

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- ▶ Stop masses excluded up to 1300 GeV for low LSP masses
- ▶ Compressed regions excluded to up to 600 GeV
- ▶ $\Delta m \approx m_{\text{top}}$ region also now excluded by both experiments



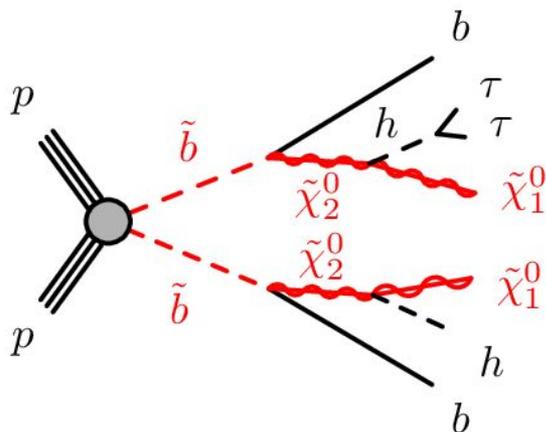
Other squark searches: sbottom

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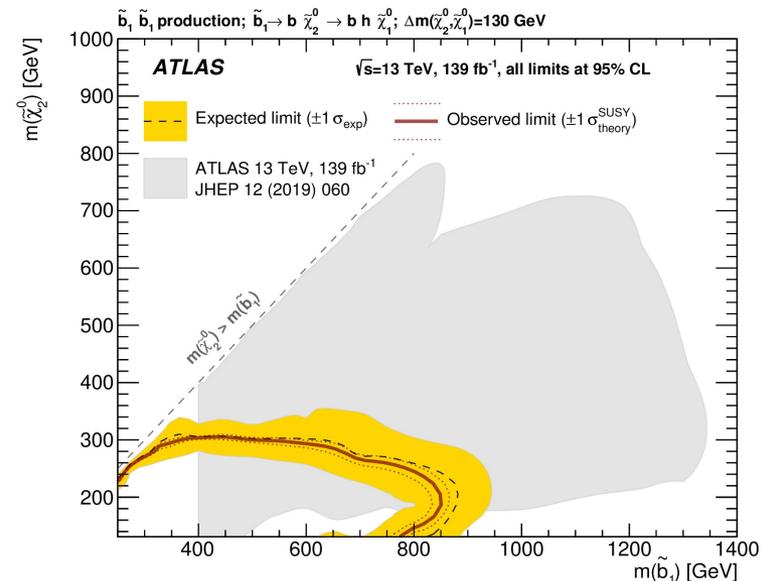
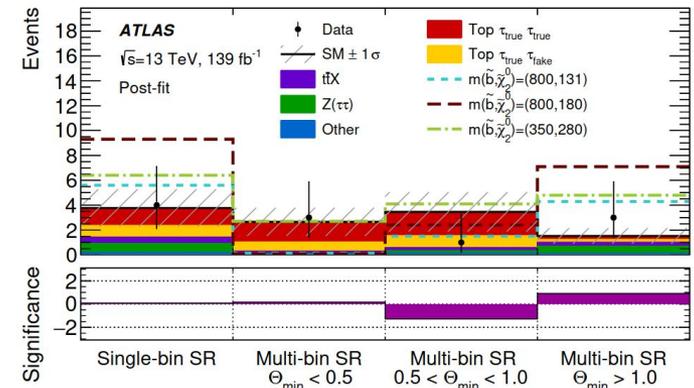
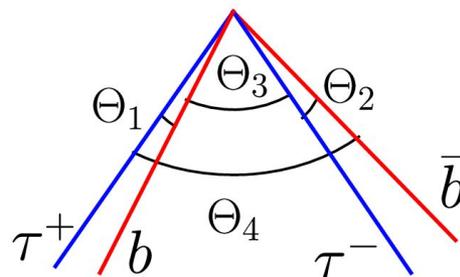
ATLAS: 2103.08189

Searching for bottom squarks in events with 2 τ_h , 2 b-jets and large p_T^{miss}

- ▶ Uses bins of Θ_{min} , defined as the smallest 3D angle for between the τ_h and the b-jets
- ▶ No significant excess found, and masses up to 850 GeV are excluded assuming: $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}$



$$\Theta_{\text{min}} = \min_{i=1, \dots, 4} (\Theta_i)$$

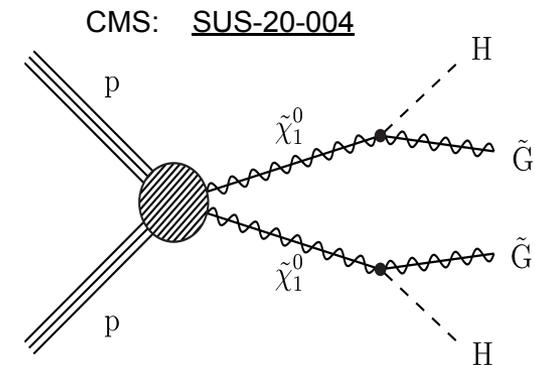
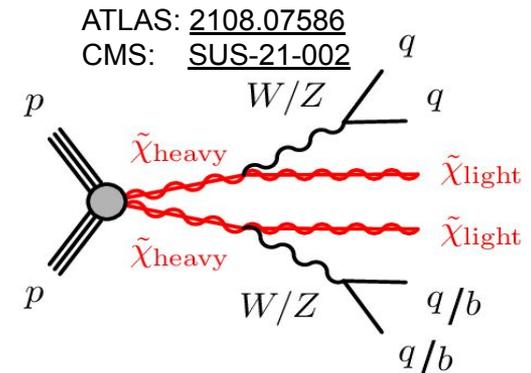
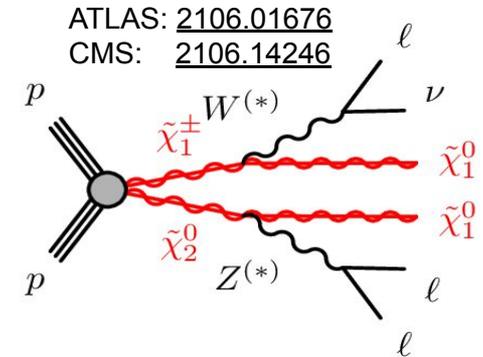


Searches for pair production of charginos and/or neutralinos decaying into the LSP

→ Decay chain can involve W/Z/H bosons or sleptons

Analyses in this presentation:

- ▶ Multilepton searches: Two or more leptons in the final states to reduce SM backgrounds
 - **ATLAS: 2106.01676, CMS: 2106.14246**
- ▶ All Hadronic searches: Take advantage of high branching ratio, and boosted reconstructions objects
 - **ATLAS: 2108.07586, CMS: SUS-21-002**
- ▶ Novel signatures: $H \rightarrow bb$ decay, using boosted techniques for the b-tagging.
 - **CMS: SUS-20-004**



Final states with 3 or more leptons offer a strong rejection of SM backgrounds.

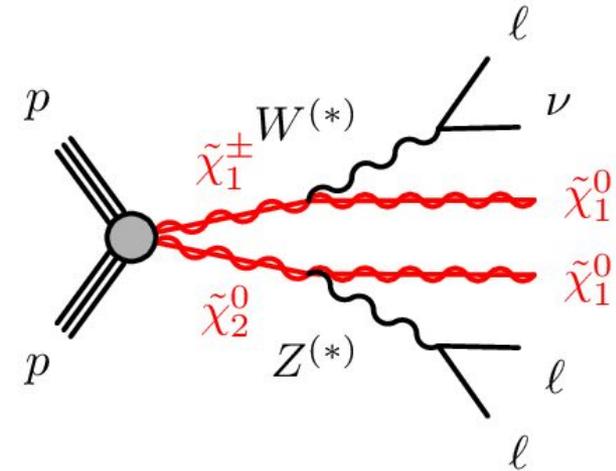
▶ ATLAS:

- Targets bino, wino and higgsino states decaying into W/Z/H bosons
- Events with 3ℓ , different SRs are defined per model, using bins in terms of the m_T and p_T^{miss}

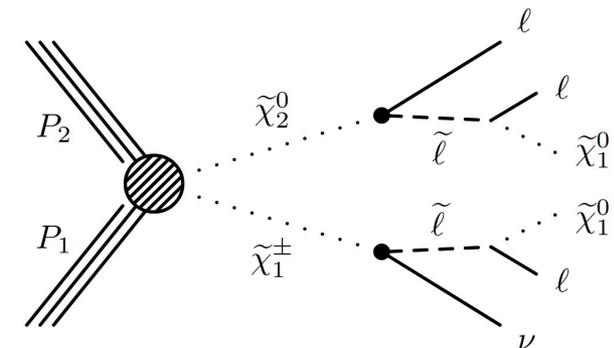
▶ CMS:

- Considers same bino/wino/higgsinos states, including also intermediate slepton decays:
- Events with 3-4 ℓ , with up to $2\tau_h$, further categorized according to the lepton flavors and signs
- using a NN, trained using variables such as $m_{\ell\ell'}$, m_T , $m_T^{3\ell}$, or p_T^{miss}

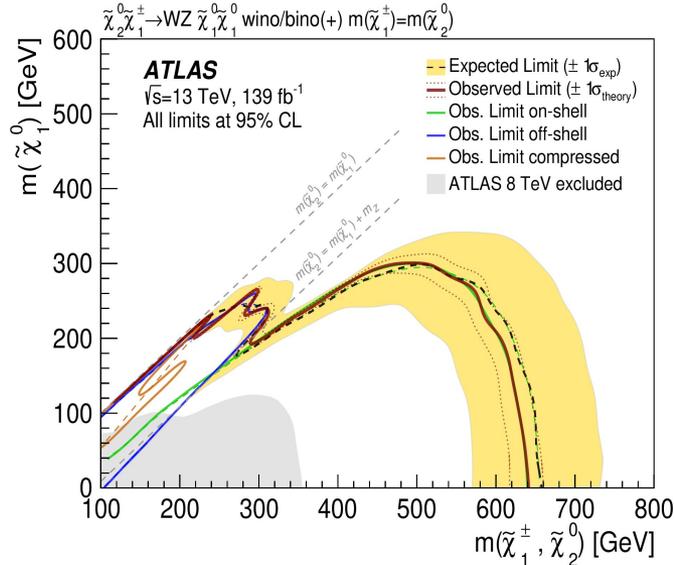
ATLAS: [2106.01676](#)



CMS: [2106.14246](#)

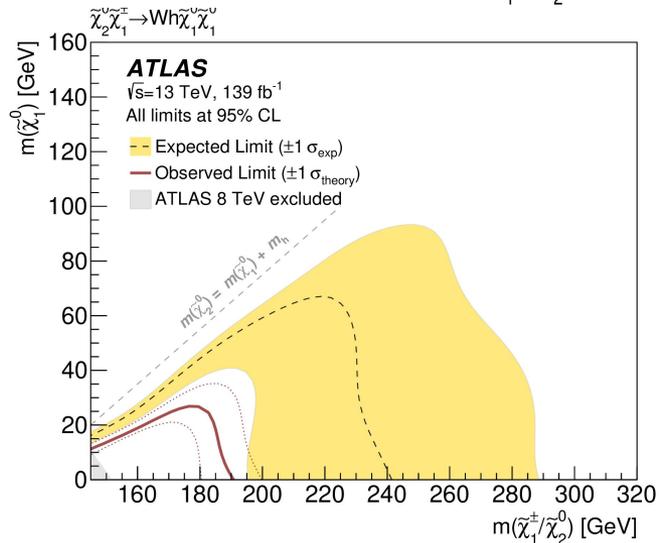
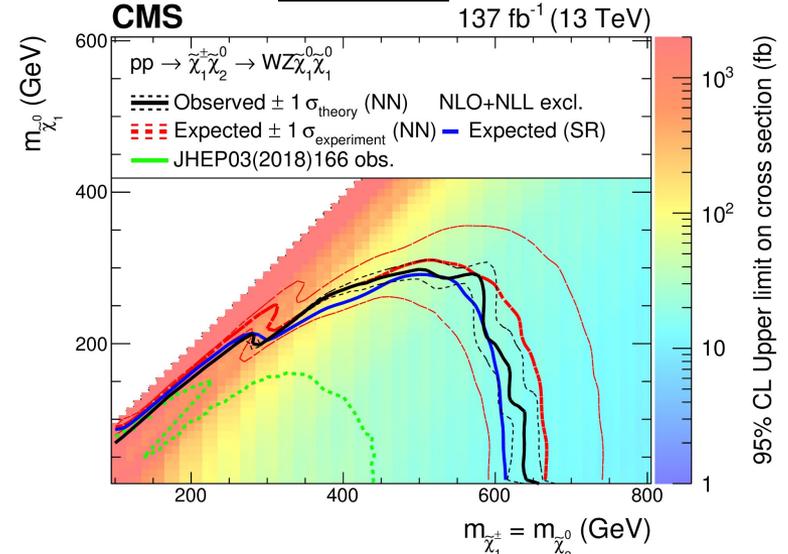


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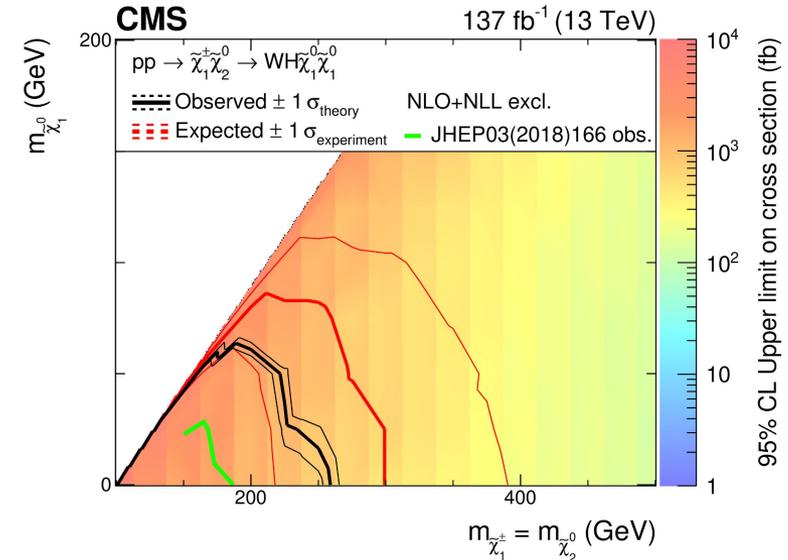


WZ

CMS 2106.14246



WH



Electroweakino searches: all hadronic

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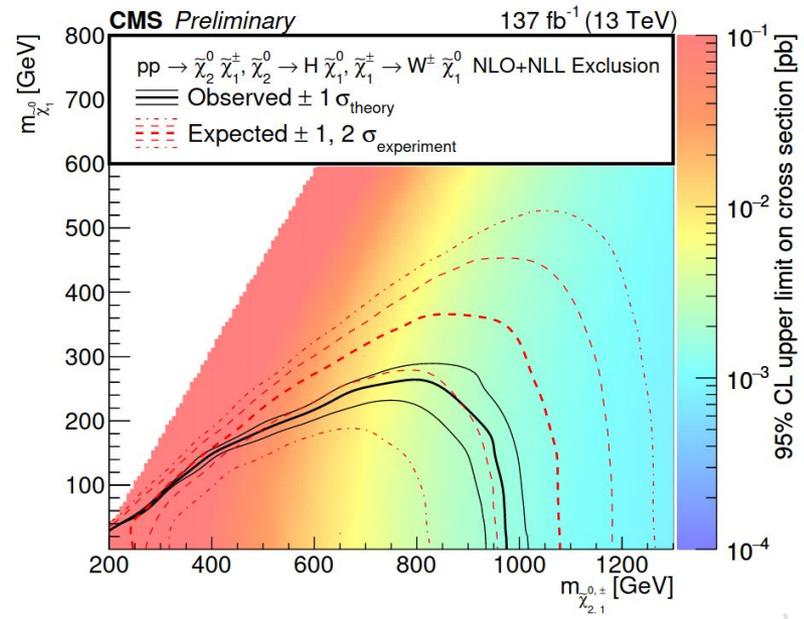
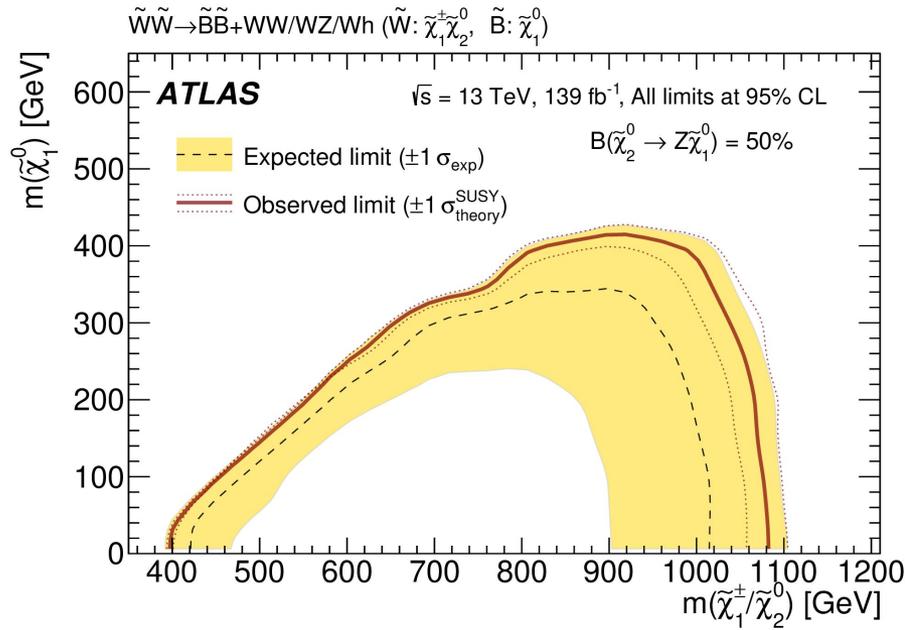
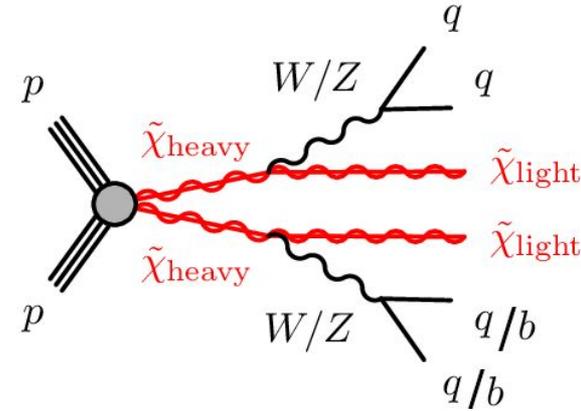
ATLAS: 2108.07586,

CMS: SUS-21-002

New analyses study final states with hadronic topologies, given their high branching ratio, and the possibility of using boosted reconstructions for high mass splitting.

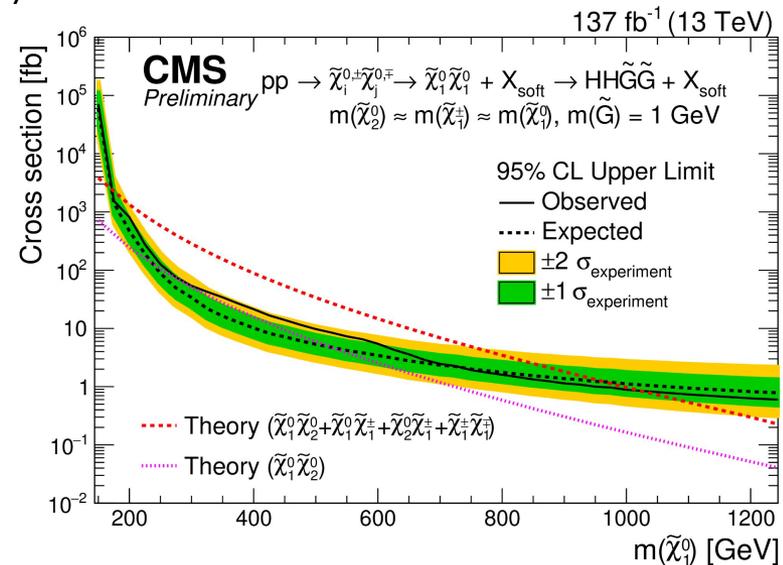
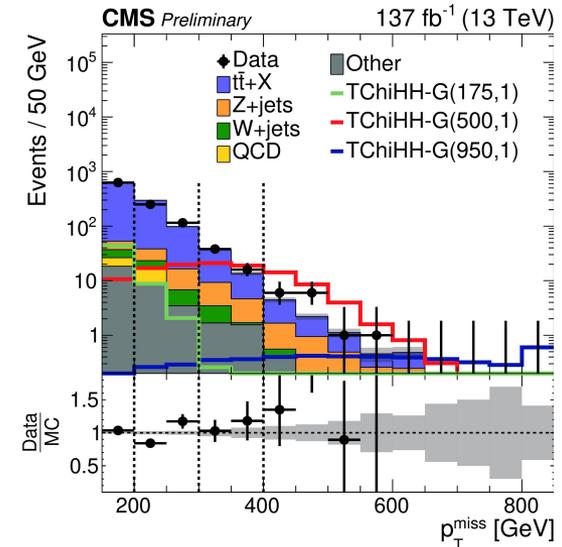
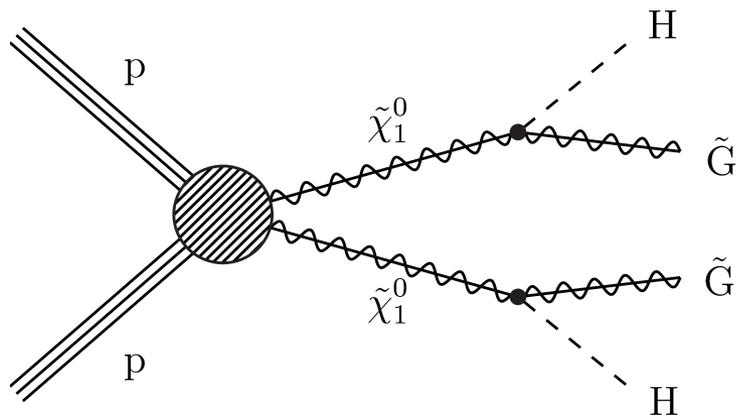
Both ATLAS and CMS search for electroweakino pairs in signal regions with $p_T^{\text{miss}} > 200$ GeV and boosted reconstructed W/Z/H.

Limits are competitive with the leptonic analysis for high mass splitting



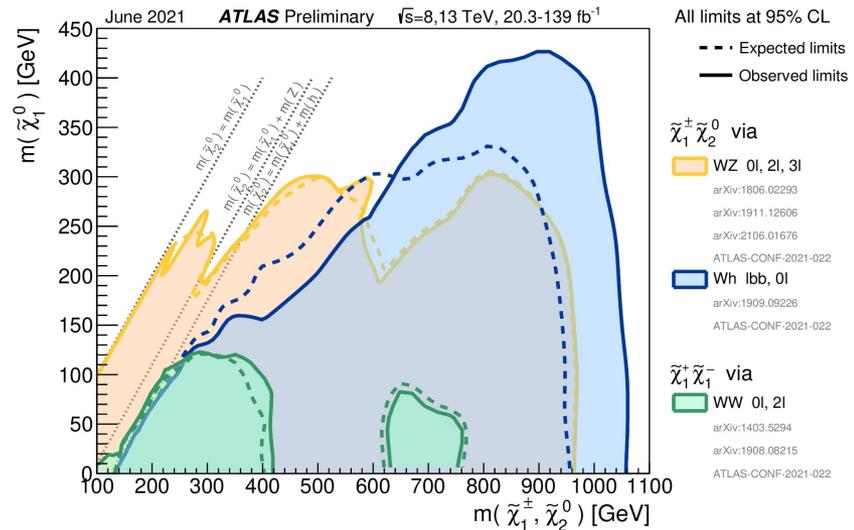
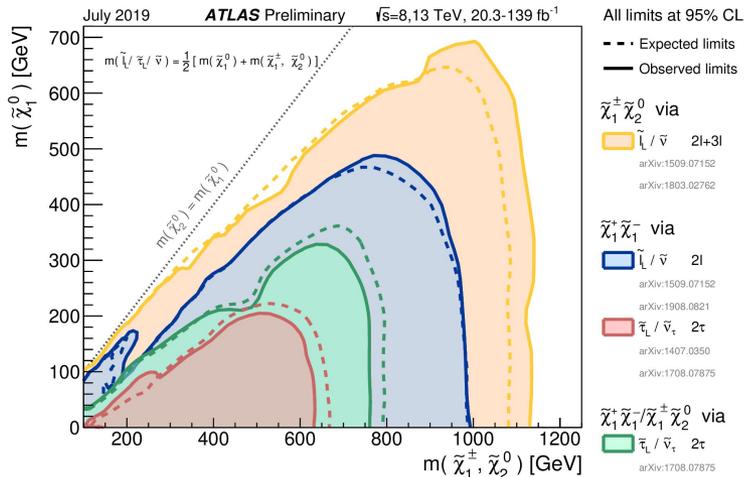
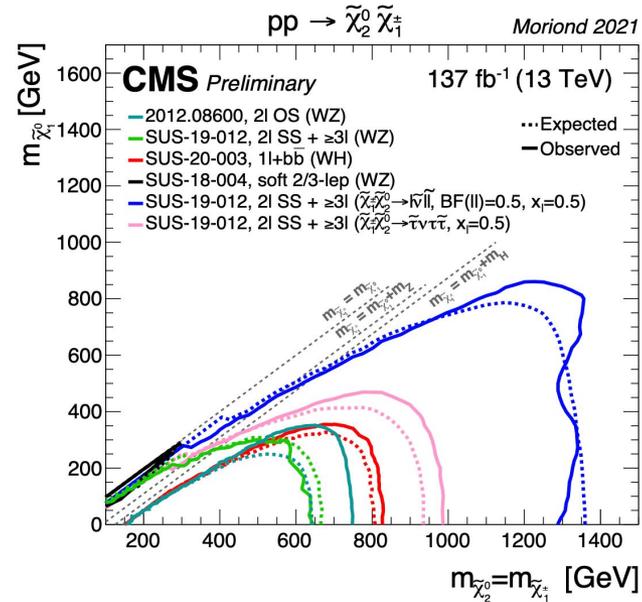
CMS: SUS-20-004

- ▶ Checking final states with two H bosons, each decaying to a bb pair
- ▶ Two different regions defined:
 - Resolved region: $p_T^{\text{miss}} > 150$ GeV, $n_{\text{jets}} = 4-5$ and $n_{\text{bjets}} \geq 2$ with $m_{\text{bb}} > 100$ GeV
 - Boosted region: $p_T^{\text{miss}} > 150$, $n_{\text{jets}} > 2$ with $p_T^{\text{jet}} > 300$ and $95 < m_{\text{jet}} < 145$ GeV
- ▶ Masses excluded from 175 to 1025 GeV for nearly degenerate higgsinos decaying to H and massless Goldstino (GMSB)



Electroweakino searches: Summary

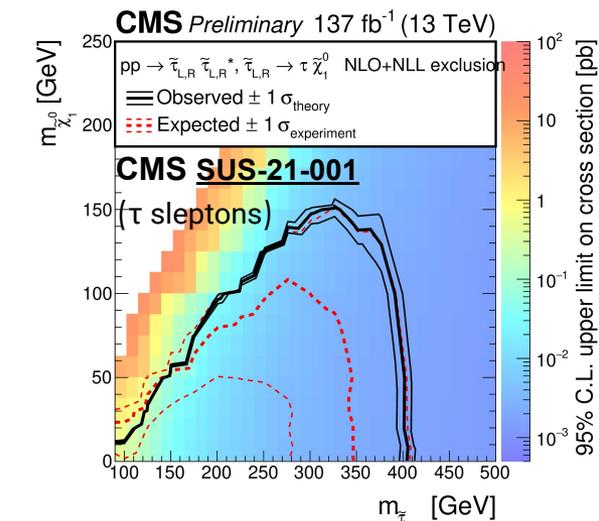
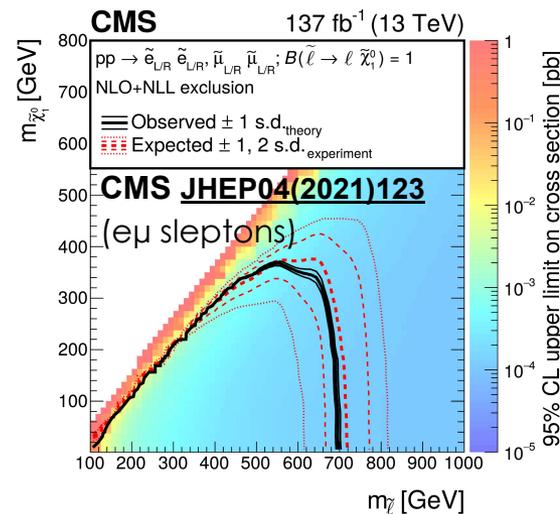
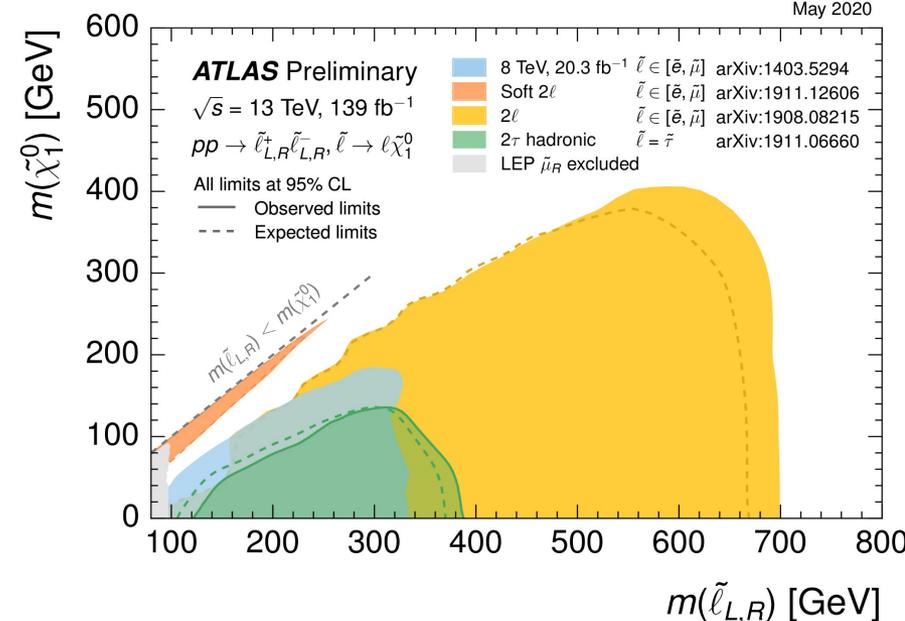
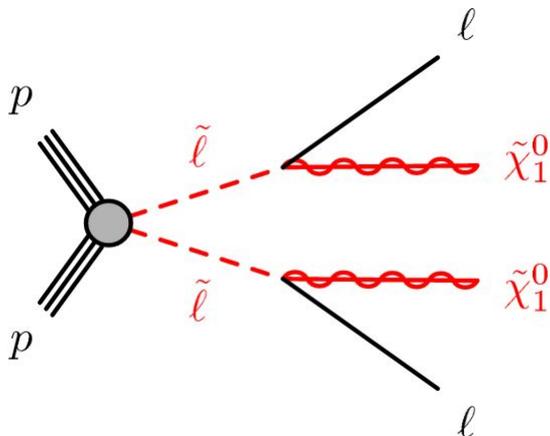
- ▶ Probing Upper limit on electroweakino masses over 1TeV
- ▶ Both collaborations now exploring newer (mostly hadronic) signatures to further constrain the electroweakino production.



Slepton searches

Typically looking for :

- ▶ e, μ slepton pair :
 - 2 OS SF leptons and high p_T^{miss} .
 - Excluding in both ATLAS and CMS up to ~ 700 GeV
- ▶ 2 τ sleptons in hadronic final states:
 - 2 τ_h jets + high p_T^{miss}
 - Exclusion in both ATLAS and CMS ~ 400 GeV



“Non conventional” searches:

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▶ R-Parity Violating SUSY:

- Remove condition of R-parity conservation
- SUSY particles decaying to SM particles:
 - Final states with No p_T^{miss} (besides neutrinos).

○ **ATLAS: [2106.09609](#), CMS: [PhysRevD.104.032006](#)**

▶ Stealth SUSY:

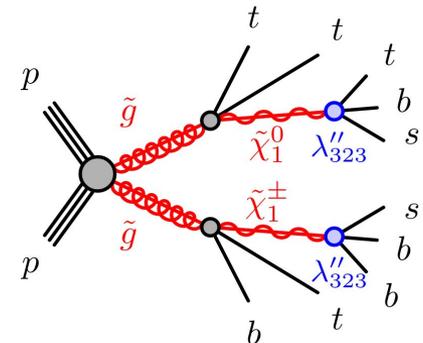
- Stop decays through an hidden SUSY sector
- **CMS: [PhysRevD.104.032006](#)**

▶ Long lived particles:

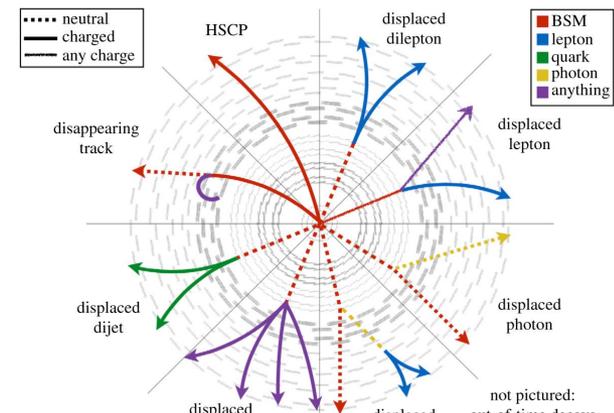
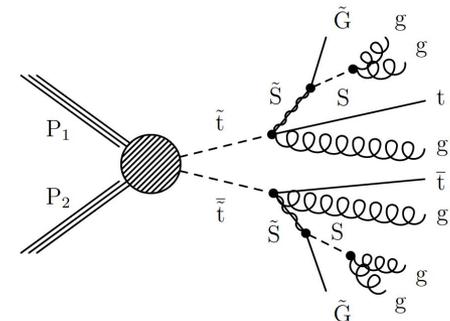
- Small couplings & compressed spectra
- Displaced vertices.
 - Challenging reconstruction & analysis.

○ **ATLAS: [2104.03050](#), CMS: [EXO-18-003](#)**

ATLAS: [2106.09609](#)



CMS: [PhysRevD.104.032006](#)



ATLAS: 2106.09609

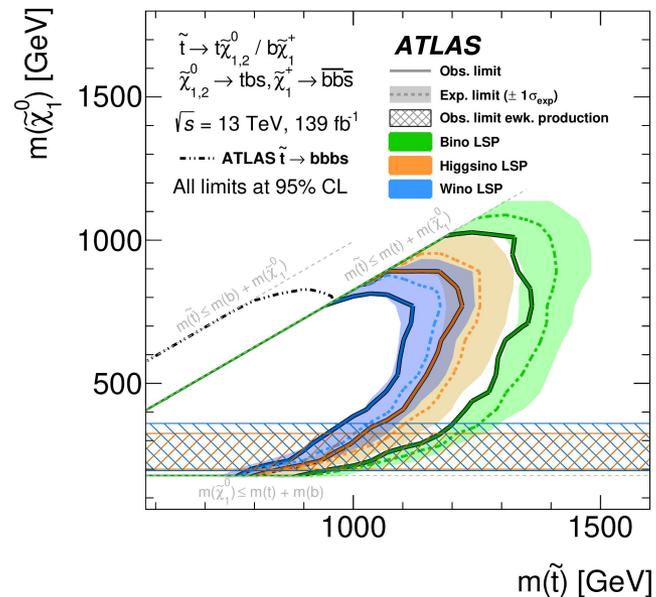
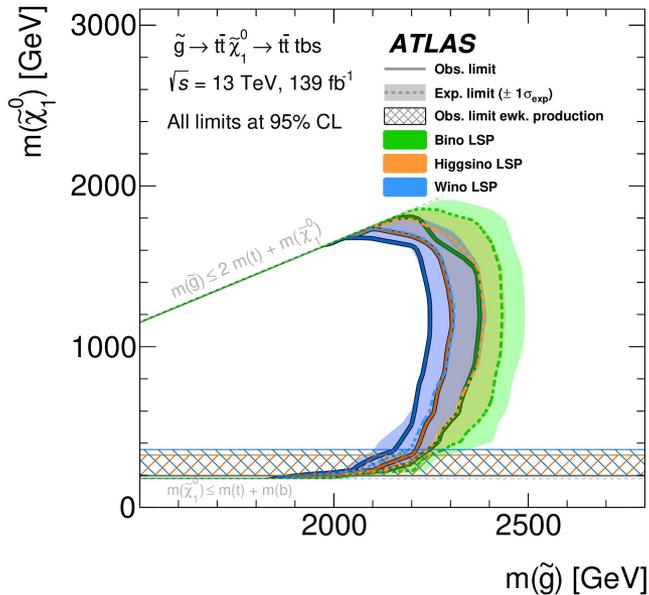
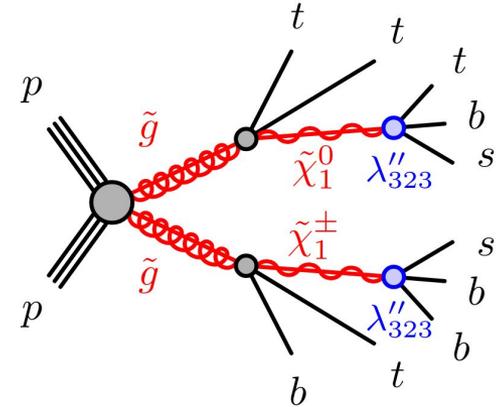
Challenge: if R parity is violated, LSP is not stable and does not contribute to p_T^{miss}

Selecting events with high jet multiplicity:

- ▶ Jet counting in lepton and b-jet multiplicity bins

Various models for gluino/stop production considered:

- ▶ Gluino mass: ~ 2.4 TeV
- ▶ Top squark mass: ~ 1.35 TeV



R-Parity Violation searches at CMS

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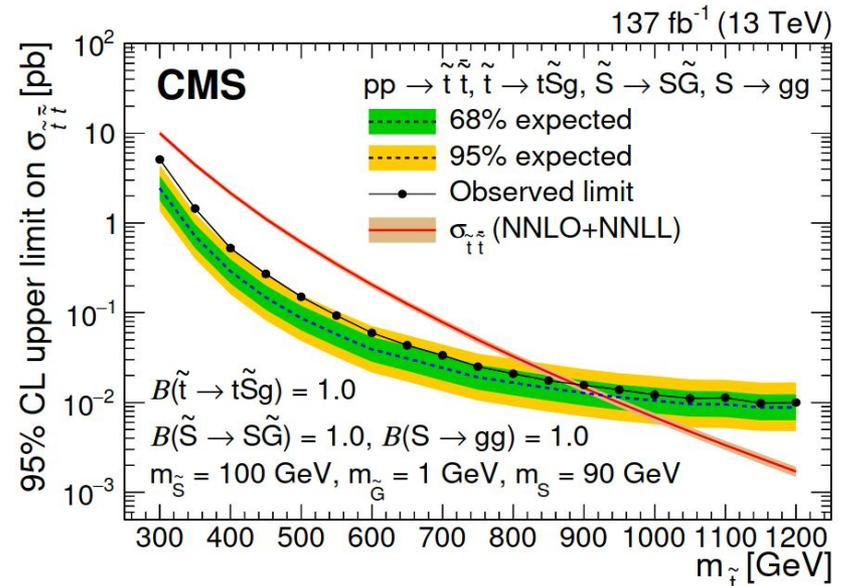
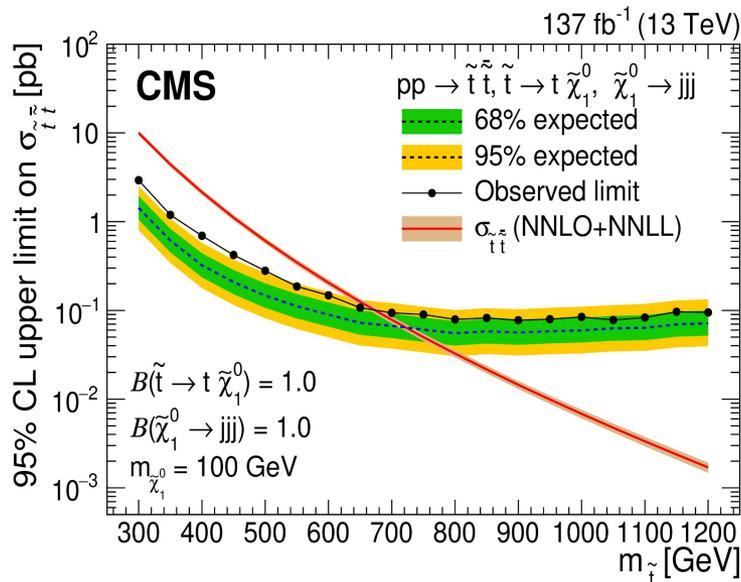
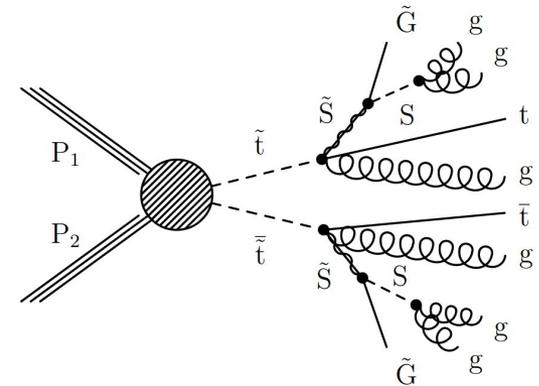
CMS: [PhysRevD.104.032006](#)

Selecting events with 2 top quarks, $n_{\text{jets}} \geq 7$, $n_{\text{bjets}} \geq 1$, $H_T > 300$ GeV, and one lepton:

- ▶ NN with information of 7th highest p_T jets, and lepton given as input

Results also interpreted for a model where the stop decays through an hidden (stealth) SUSY sector

- ▶ Excluded masses up to 670 GeV for RPV and 870 GeV for Stealth SUSY



Stopped long lived particles

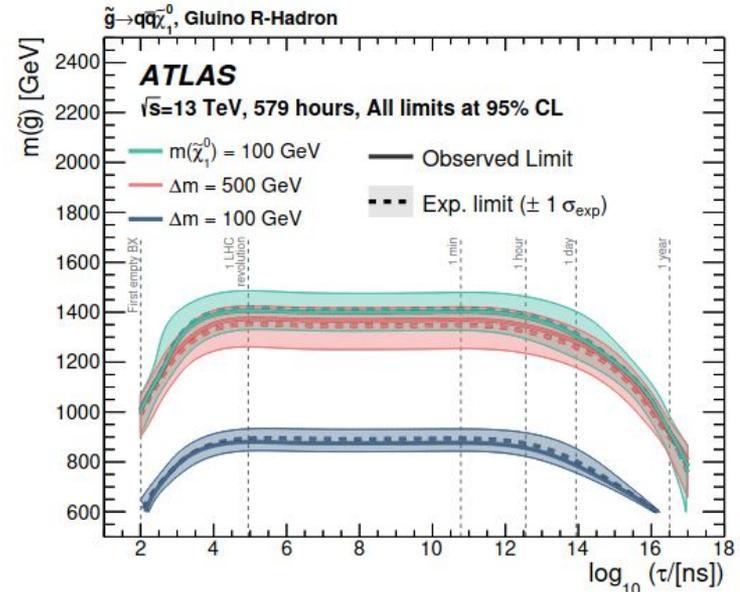
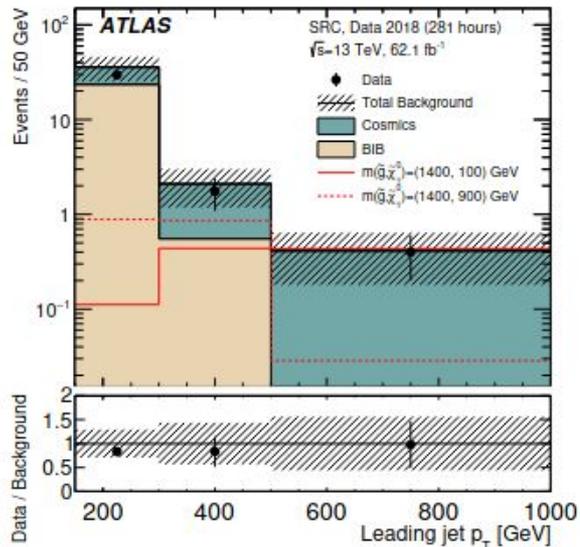
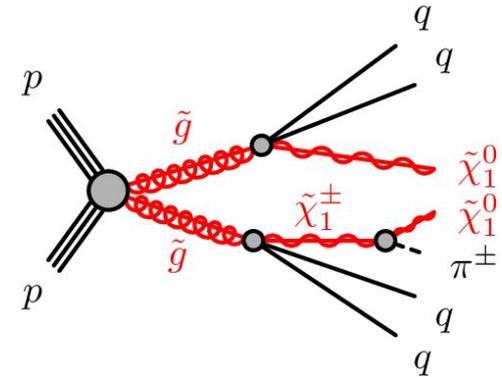
ATLAS: 2104.03050

Search for long lived gluinos, forming R-Hadrons which can stop in the detector

→ Significant deposit in calorimeter.

Looking for events with a high p_T jets in empty data from empty bunch crossings

$m_{\tilde{g}} < 1400$ GeV excluded for $10^{-5} < \tau_{\tilde{g}} < 10^{-3}$ s



LLP: Displaced leptons

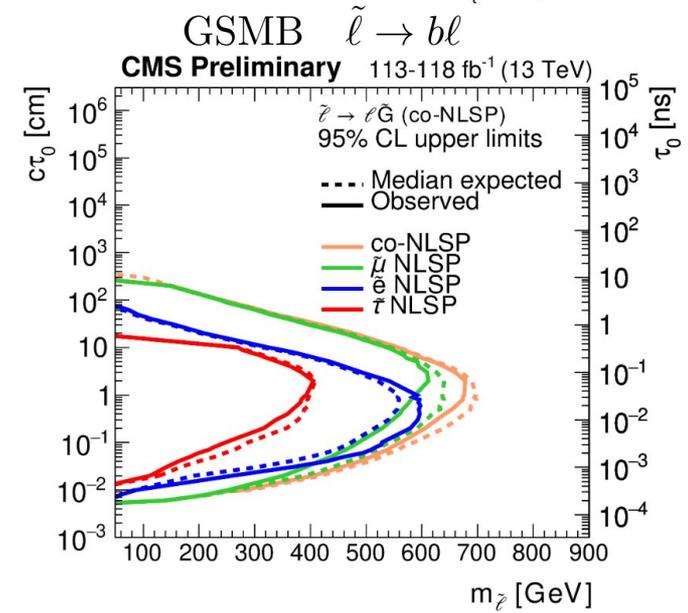
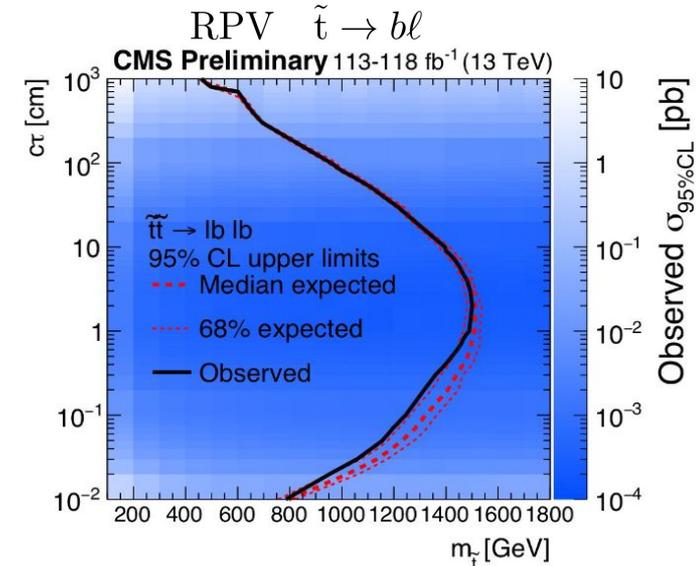
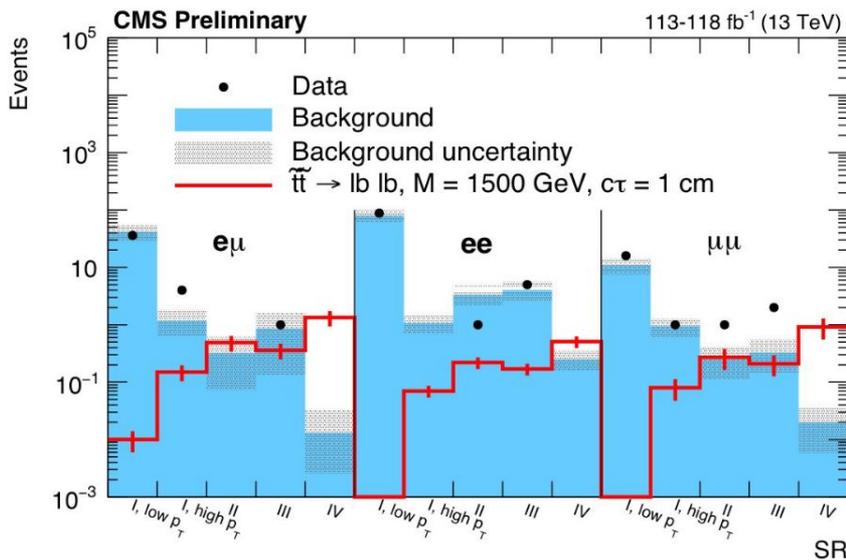
27

CMS: EXO-18-003

+Similar analysis from ATLAS

Search defined to be sensitive to any model whose signature includes 2 displaced leptons ($e\mu$, $\mu\mu$, ee).

- ▶ Uses transverse impact parameters (d_0) as the discriminant variable, with $10\mu\text{m} < |d_0| < 10\text{cm}$.

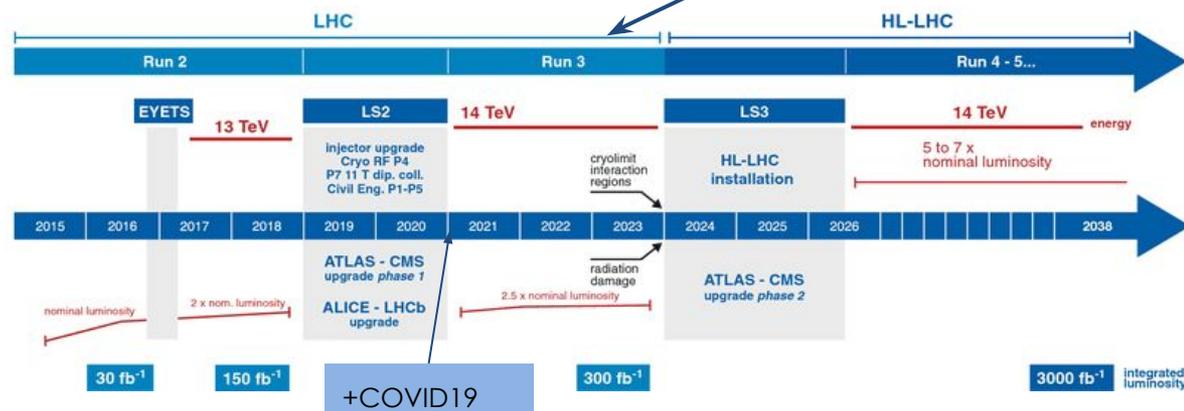


Summary and outlook

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- ▶ SUSY has been searched in loads of challenging analyses both at ATLAS and CMS:
 - Tackling challenging phase space regions (eg boosted scenarios)
 - Studying non classical signatures (RPV, Long lived...)
 - ▶ So far, only mass limits have been observed...
 - The Run3 around the corner: more data, upgraded detectors are coming!
 - New techniques and refined searches are keep appearing
 - SUSY can still be the solution for many SM problems.
- The best is yet to come

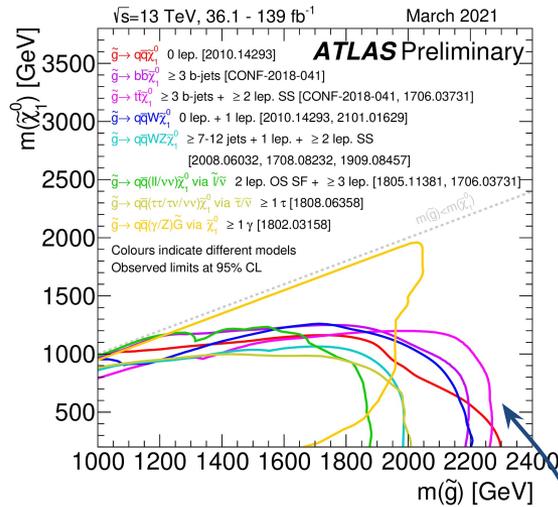
SUSY is dead, long live SUSY!



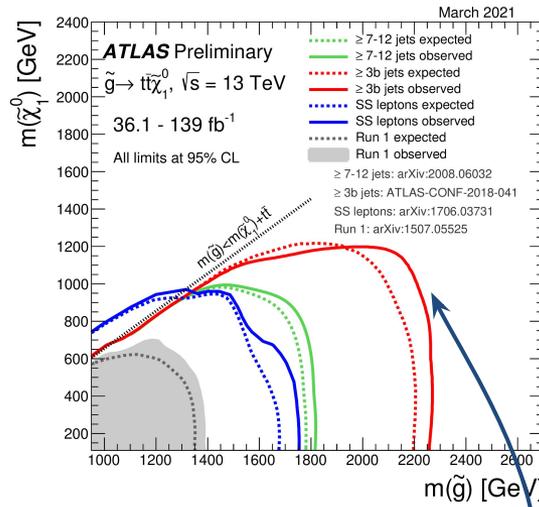
Additional material

Glino/squark searches: Summary

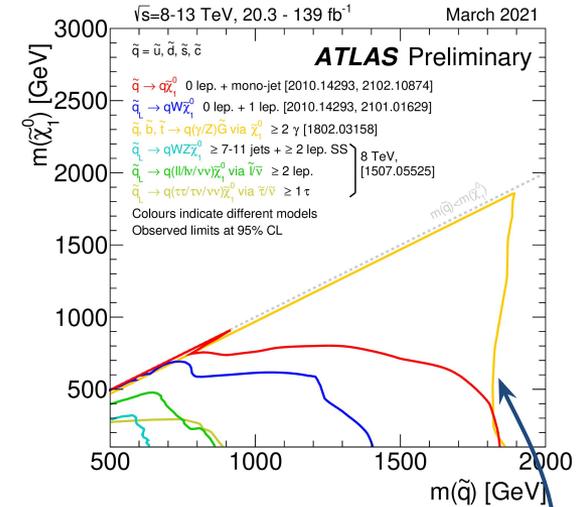
30



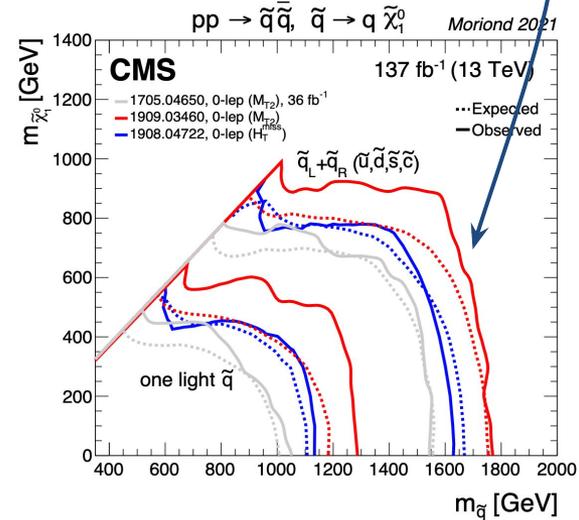
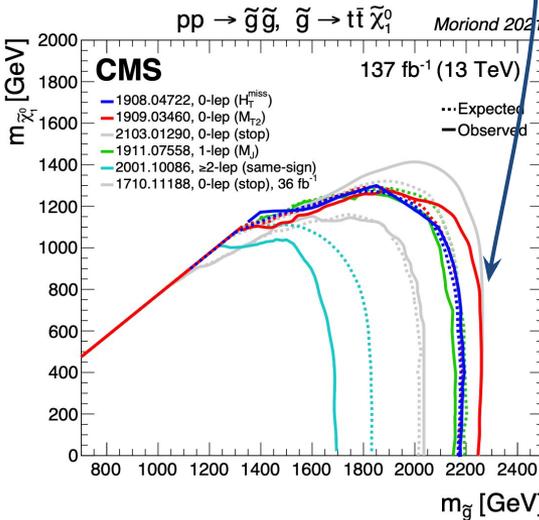
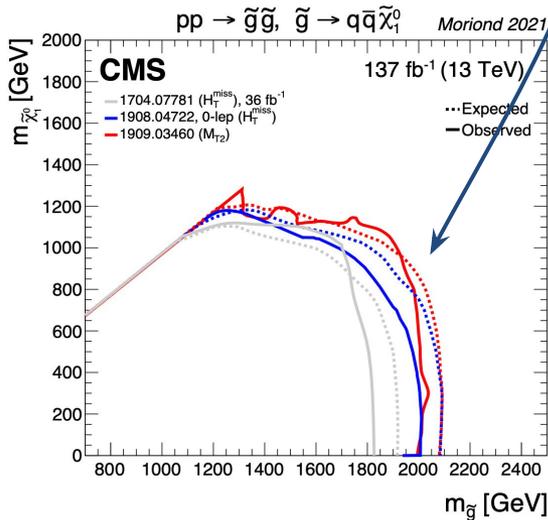
gluino to qq+LSP limit at 2100-2300 GeV



gluino to top+LSP limits at 2200 GeV



squark limits at 1800-1900 GeV



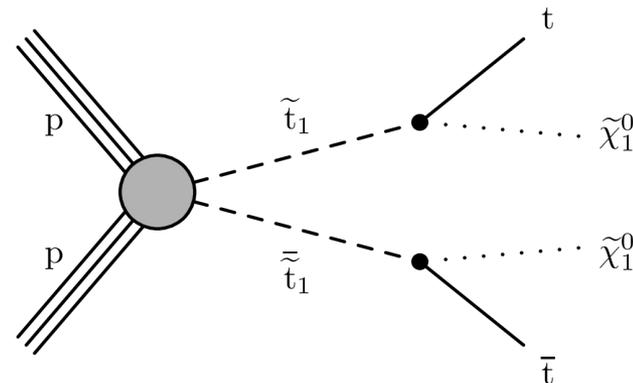
Stop searches: $\Delta m \approx m_{\text{top}}$

CMS: 2107.10892

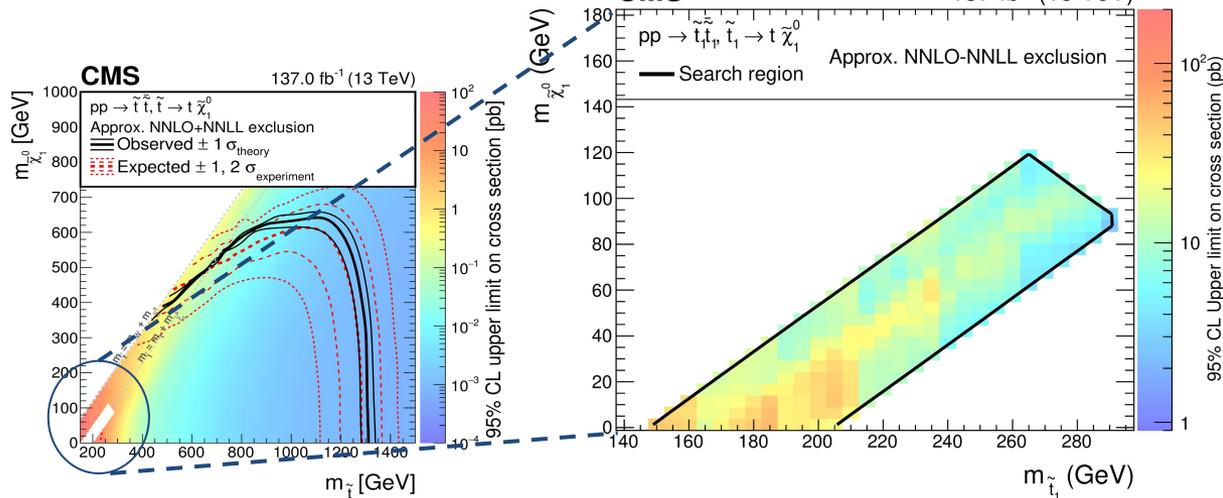
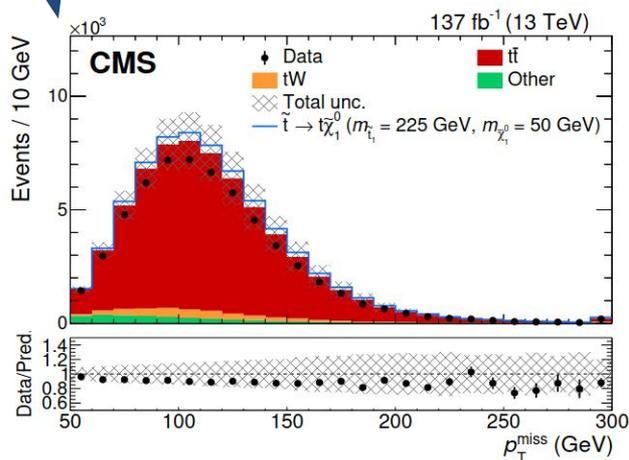
Very challenging since the signal kinematics similar to SM $t\bar{t}$ events

- ▶ DNN to differentiate signal from bkg
 - At least 2 jets (at least 1 b-tagged), $p_T^{\text{miss}} > 50$ GeV and 2 leptons.
 - Stop/neutralino masses included in the training, with optimised weights per mass point

Whole corridor excluded for the 1st time in CMS

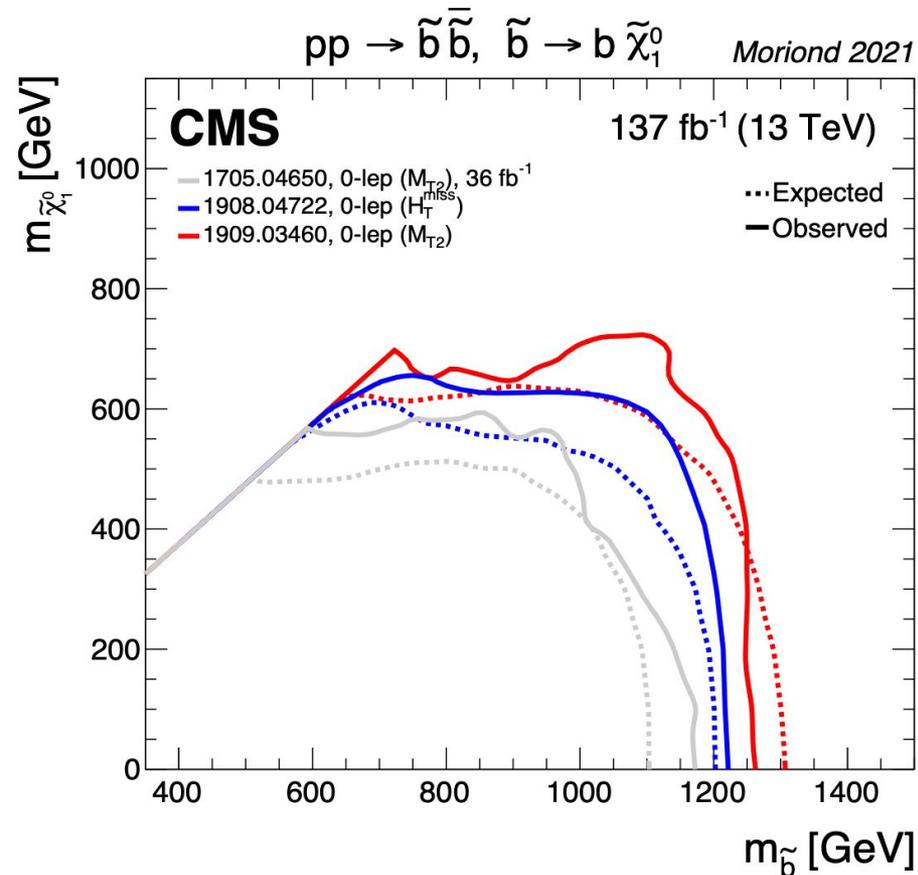
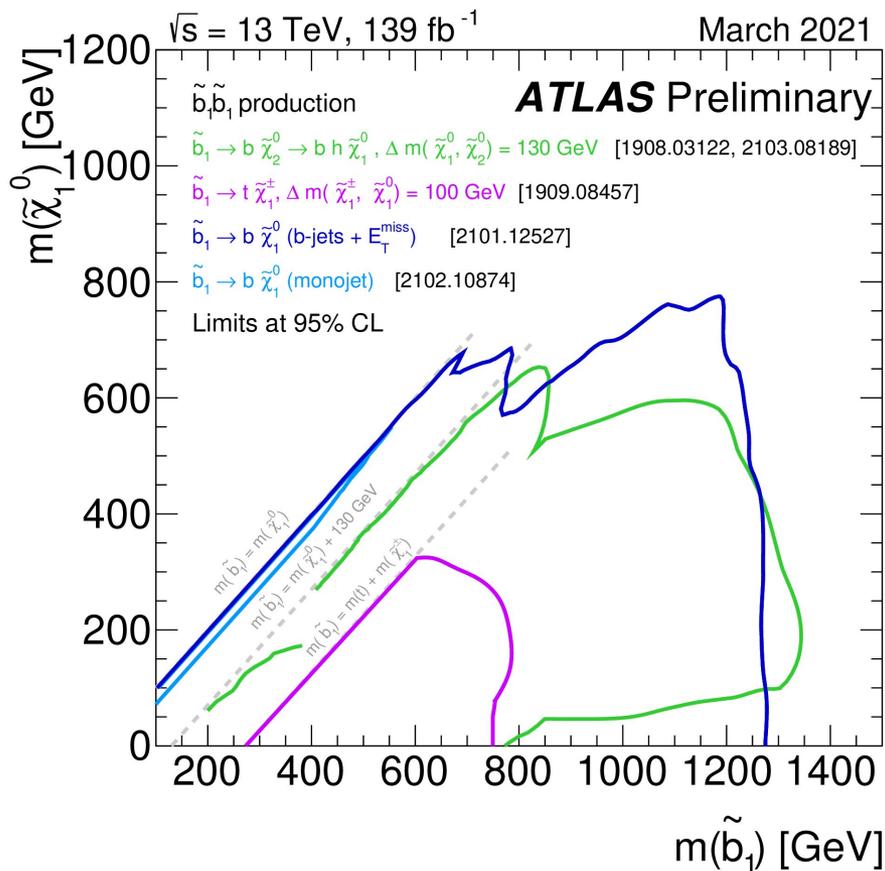


Final state $t\bar{t}$ + low mass neutralinos
 → Relatively low p_T^{miss}



Sbottom summary plots

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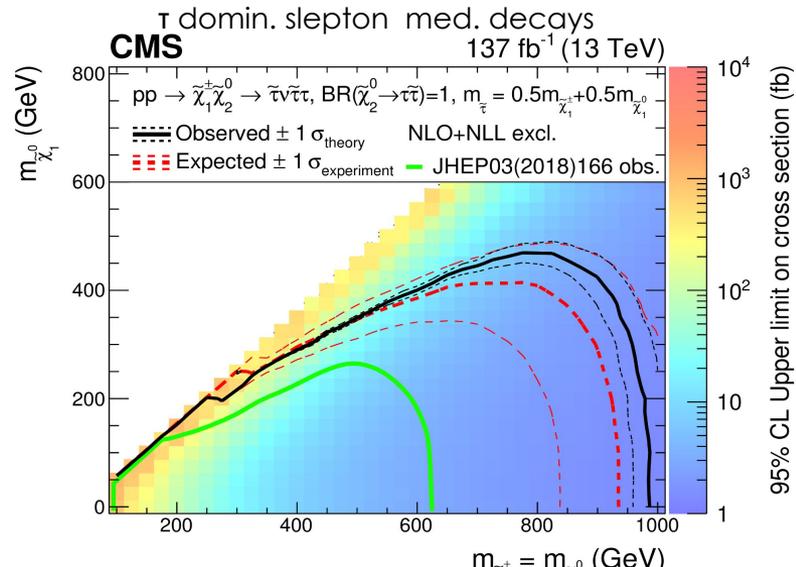
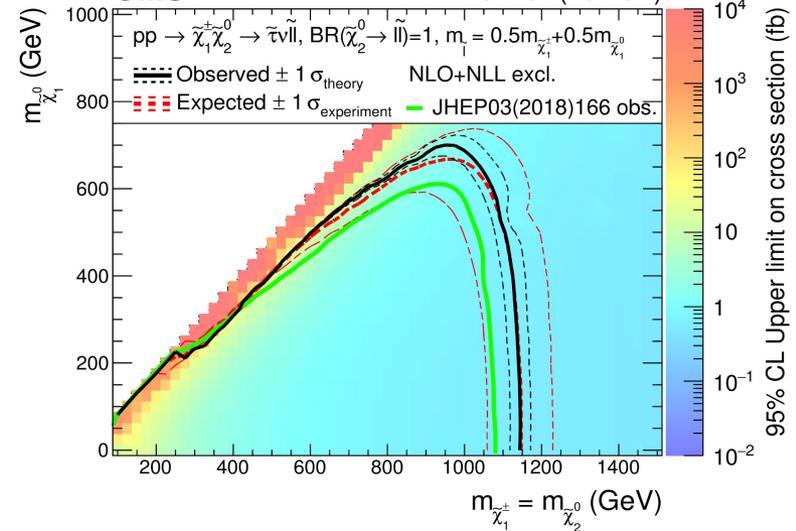
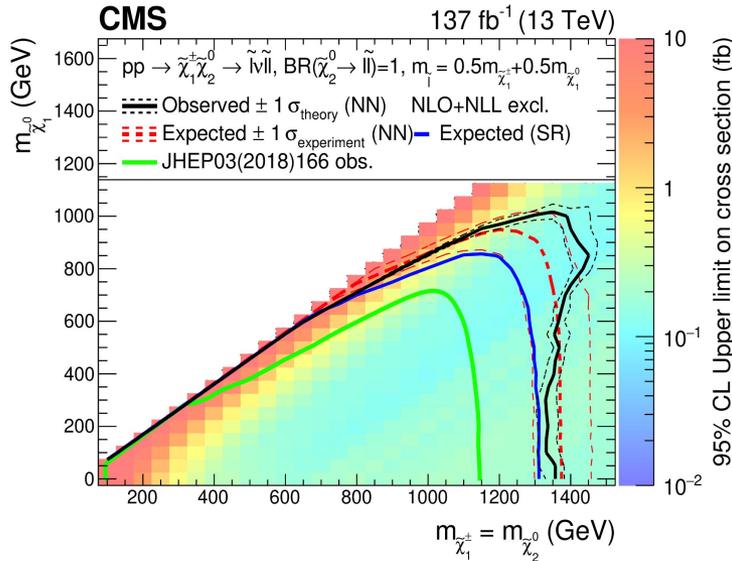


Electroweakino searches: multileptons

slepton med. decays

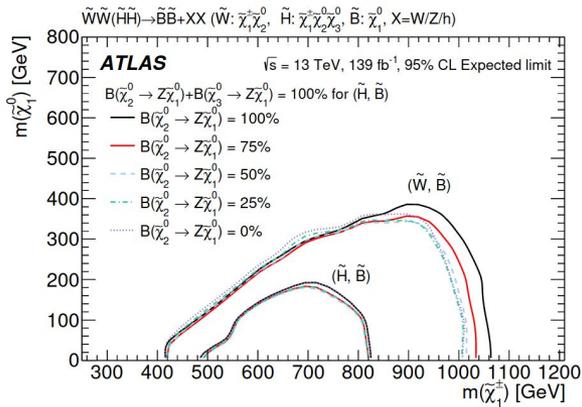
CMS 2106.14246

τ enriched slepton med. decays
137 fb⁻¹ (13 TeV)

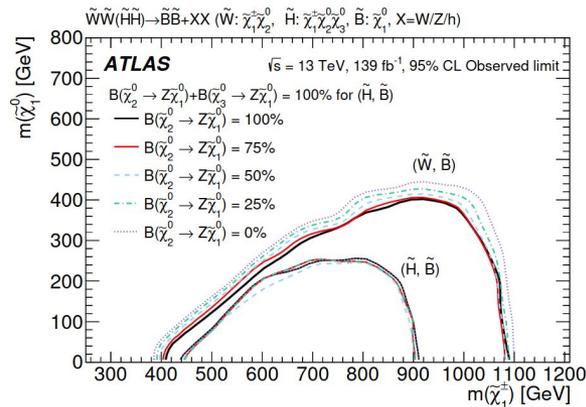


ATLAS: 2108.07586

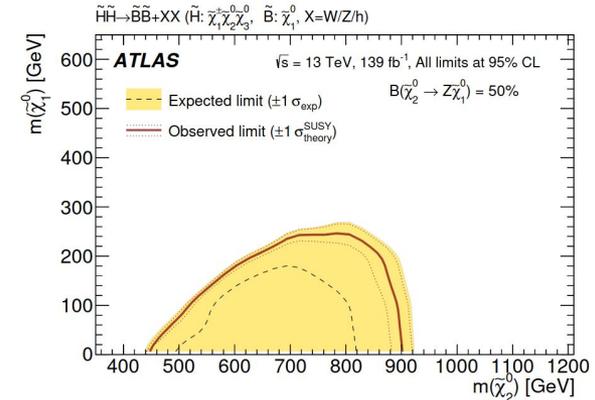
Expected limits with various $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)$



Observed limits with various $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)$

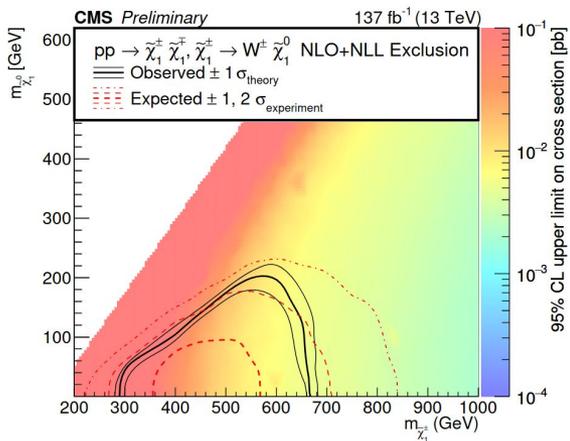


(\tilde{H}, \tilde{B}) with $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0) = 50\%$

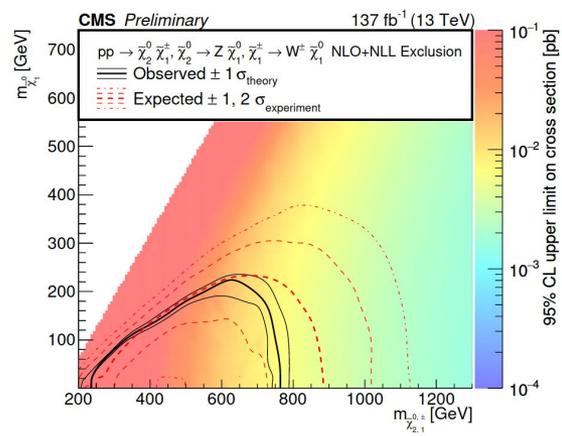


CMS: SUS-21-002

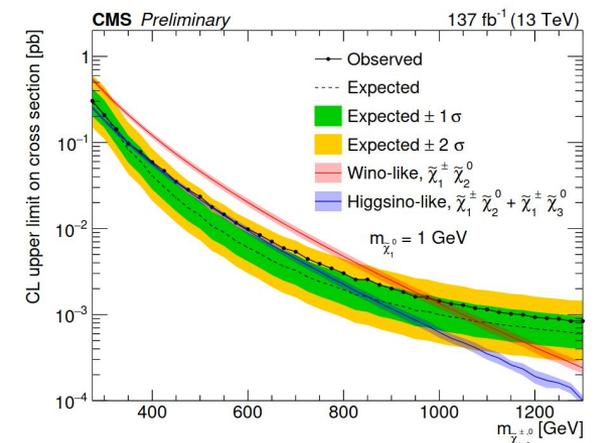
Limits for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$



Limits for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow W^\pm \tilde{\chi}_1^0$



Mass exclusions for Wino/Higgsino like particles

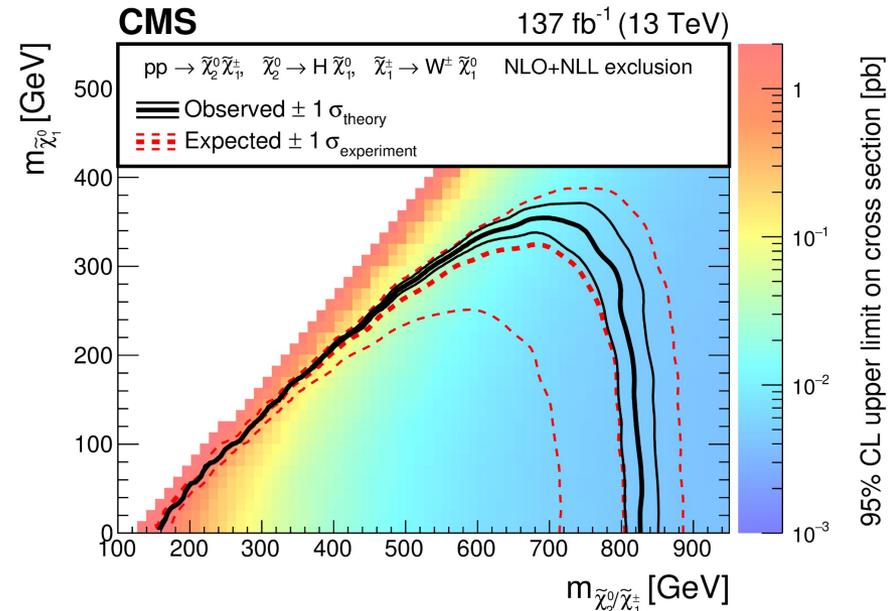
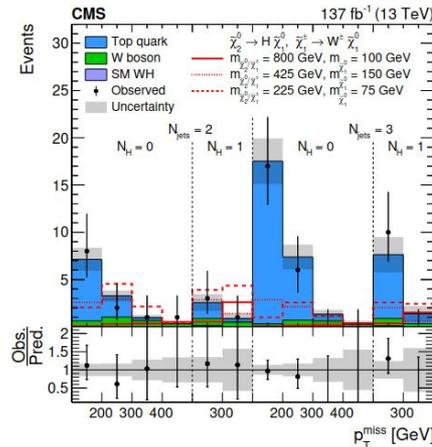
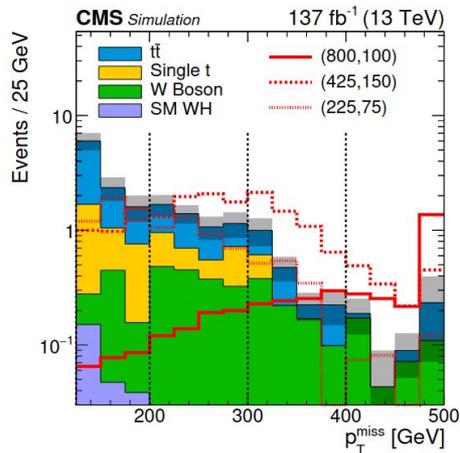
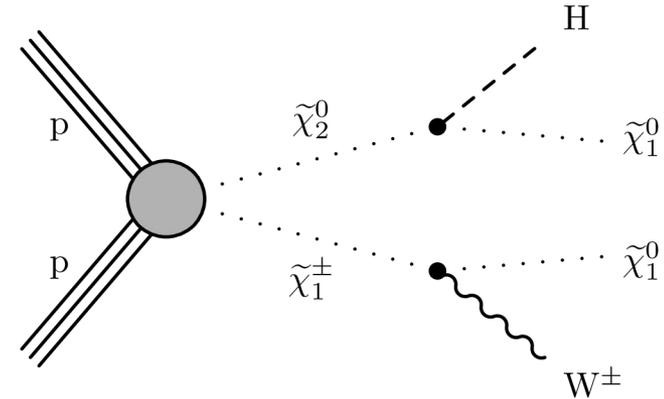


CMS: 2107.12553

Exploits final states with $H \rightarrow bb$ decays with dedicated NN tagging technique.

W boson decaying leptonically

- ▶ Exactly 1 leptons (e, μ), two b jets and $p_T^{\text{miss}} > 125$ GeV
- ▶ SRs are defined in terms of N_{jets} and the number of H-tagged large-R jets (N_H)



R-Parity Violation searches

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ATLAS: 2106.09609

CMS: PhysRevD.104.032006

