SUSY searches with the ATLAS detector

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CONICET

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ATLAS EXPERIMENT

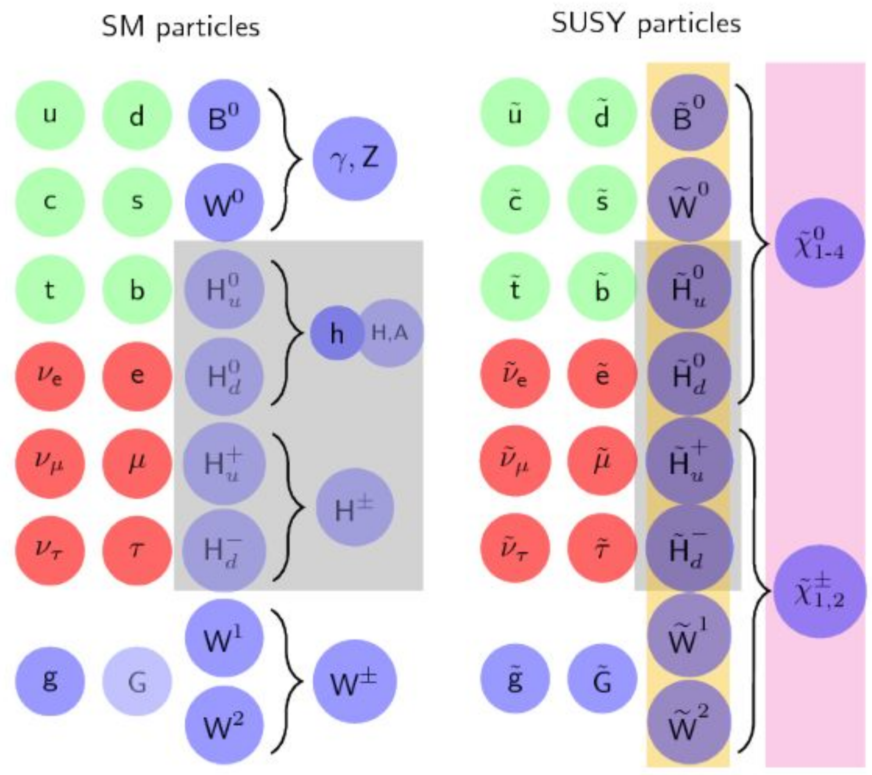
6th ComHEP: Colombian Meeting on High Energy Physics

29 November 2021 to 3 December 2021

Supersymmetry

SUSY: additional symmetry between fermions and bosons on top of SM

- Supersymmetric partner for every SM particle including an extended Higgs sector
- Results in many partner particles, ideally at an LHC-reachable scale
- Many desirable properties, can provide solutions to the open problems:
  - R-parity conserving SUSY→ LSP is a dark matter candidate*
  - Stops cancel divergences in Higgs boson mass loops
  - High scale gauge coupling unification
- LHC is the only place for direct searches for new heavy particles



Neutralinos χ^0 / Charginos $\chi^{\pm}$, are mass eigenstates with a mixture of Bino/ Wino/ Higgsino.

** See Steven Lowette this conference for other DM scenarios at LHC*

General Scenarios

- Strong Production
  - Searches focusing on gluino & squark production
  - Many particles in the final states (jets, leptons, photons)
  - Dedicated 3G SUSY searches (top- and bottom-squarks)
  - Unique phenomenology & final states with heavy fermions
- Electroweek Production
  - Rare but clean signatures
  - Less well-constrained than Strong SUSY
  - Sleptons/Neutralinos affect g-2

- R-Parity Conservation (RPC)
  - Prevents Proton decay
  - Conserves Baryon & Lepton number
  - Lightest SUSY particle (LSP) is stable and non-interacting (DM candidate)
  - Final states containing large Missing Transverse momentum
- R-Parity Violation (RPV)
  - Most general super-potential contains B&L -number violating terms (non-zero lambda terms)
  - Other conditions (not just R-parity) can prevent proton decay
  - More weakly constrained than RPC
  - Very rich phenomenology, final states with many particles (and small missing transverse momentum)

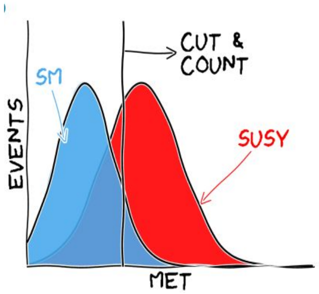
$$\mathcal{W}_{\mathrm{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u$$

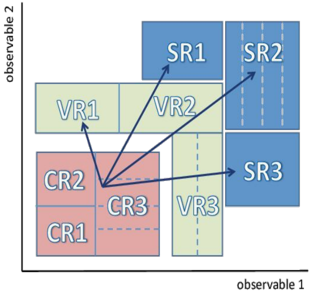
Search for Supersymmetry

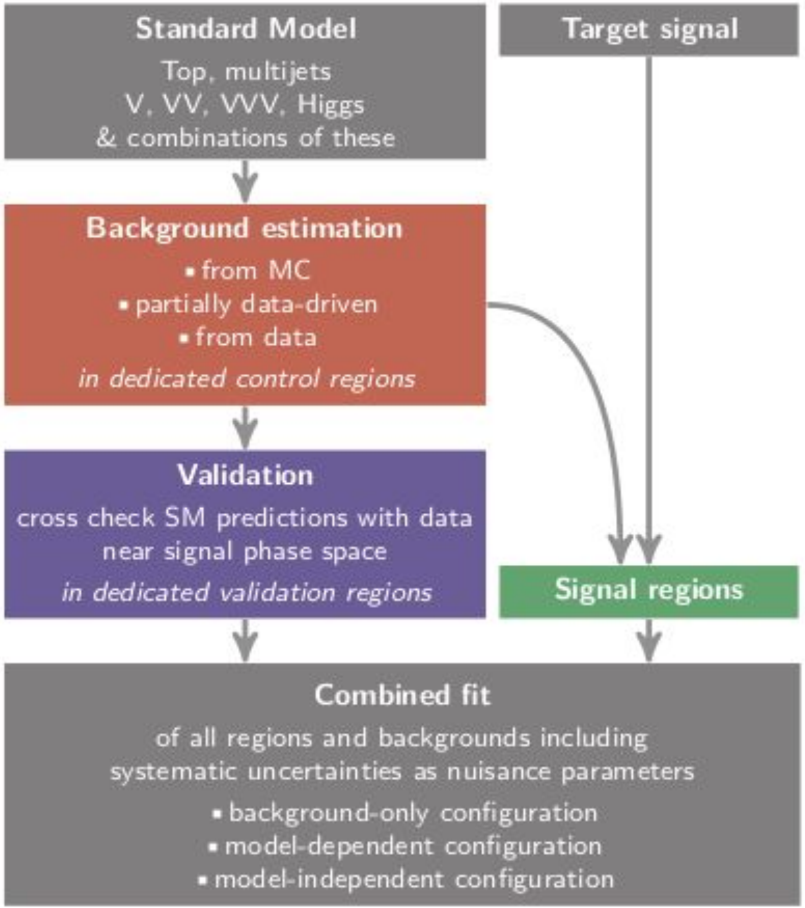
Generally searching for events with jets, missing transverse momentum (MET), and sometimes other high momentum objects.

Interpret with simplified models and perform additional model-independent tests.

Focus on simplified models to systematically cover large phase space,
but moving to also include more general interpretations.







Selection

Typical objects selection:

- Electrons: Medium selection criteria and isolated, p_T > ~10 GeV, η<2.47
- Photons: tight selection criteria and isolated, p_T > ~25 GeV, η<2.37
- Muons: Medium selection criteria and isolated, p_T > ~10 GeV, η<2.5
- Jets: anti-kt, p_T > ~30 GeV, η<2.5. b-jets selection at 77% efficiency for tagging

$$(E_{\mathrm{T}}^{\mathrm{miss}})_{x(y)} = (E_{\mathrm{T}}^{\mathrm{miss}})_{x(y)}^{e} + (E_{\mathrm{T}}^{\mathrm{miss}})_{x(y)}^{\gamma} + (E_{\mathrm{T}}^{\mathrm{miss}})_{x(y)}^{\mathrm{jet}} + (E_{\mathrm{T}}^{\mathrm{miss}})_{x(y)}^{\mu} + (E_{\mathrm{T}}^{\mathrm{miss}})_{x(y)}^{\mathrm{Soft\ Term}}$$

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \{1 - \cos[\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\ell})]\}}$$

Reduce the ttbar and W+jets background events in which a W boson decays leptonically

$$m_{\mathrm{T2}}^{\tau\tau} = \sqrt{\min_{\vec{p}_{\mathrm{T}}^{a} + \vec{p}_{\mathrm{T}}^{b} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left(\max \left[m_{\mathrm{T}}^{2}(\tau_1, \vec{p}_{\mathrm{T}}^{a}), m_{\mathrm{T}}^{2}(\tau_2, \vec{p}_{\mathrm{T}}^{b}) \right] \right)}$$

High values for rejecting ttbar background

$$H_{\mathrm{T}} = \sum_{\mathrm{visible}} |p_{\mathrm{T}}|$$

Signal models with large visible activity

$$m_{\mathrm{eff}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

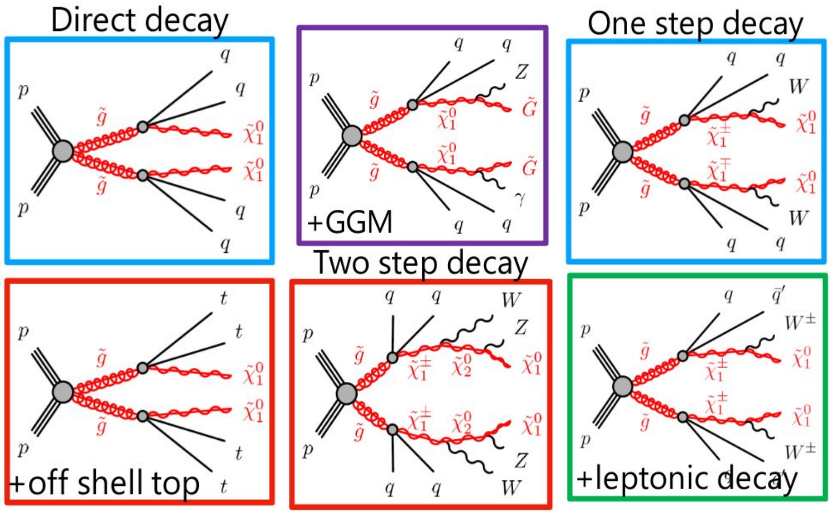
Signal models with large hadronic activity together with large MET

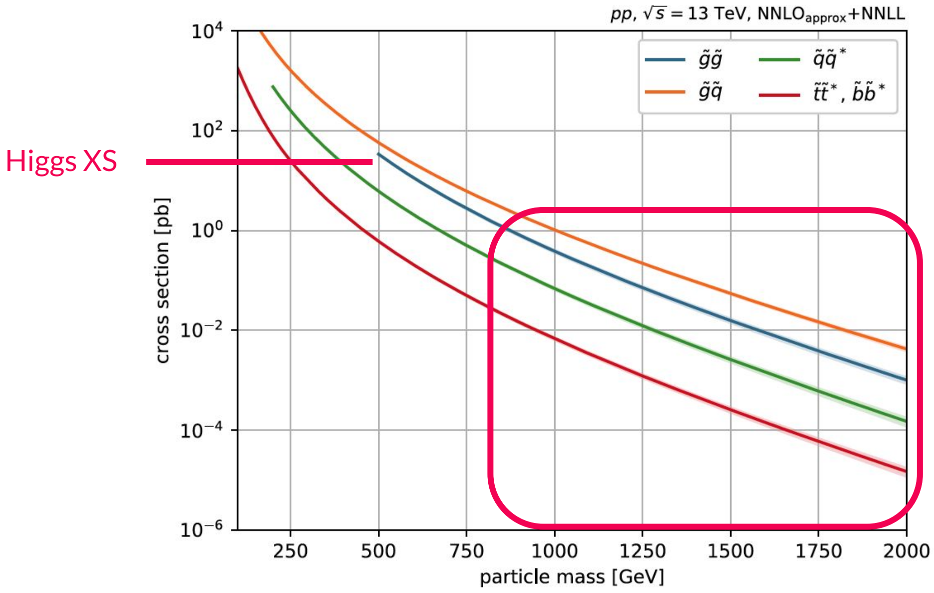
$$\Delta\phi(\mathrm{jet}_{12}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})$$

Remove events with MET arising from jet mismeasurements

Strong production

Generally searching for events with jets, missing transverse momentum (MET), and sometimes other high momentum objects.





Photon(s) + jets + MET

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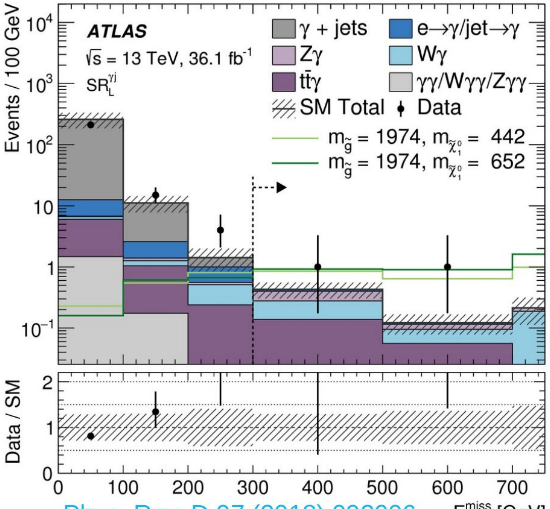
- General Gauge Mediation (GGM) inspiration
- High p_T photon >145 GeV (Trigger on photon)
- MET > 250 GeV, HT>1600 GeV
- Jets and MET, but no leptons
- 3 SRs targeting small to large mass splittings, optimized for full dataset



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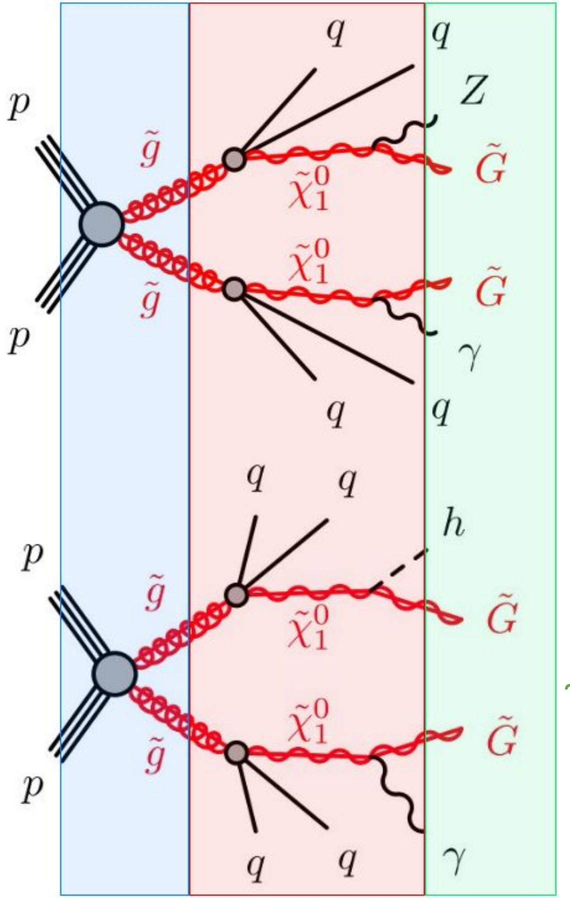
Previous search with 36 fb^{-1} resulted in 2.36σ local excess

Gluino pair production

Many jets

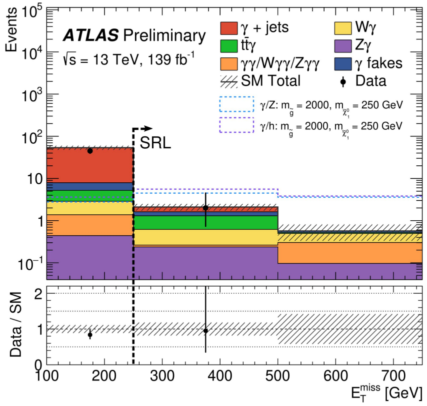
Light LSP



~50/50% Z/γ

~50/50% h/γ

Photon(s) + jets + MET

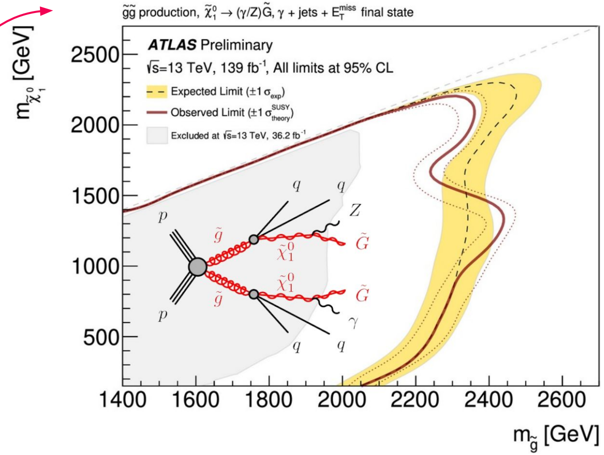


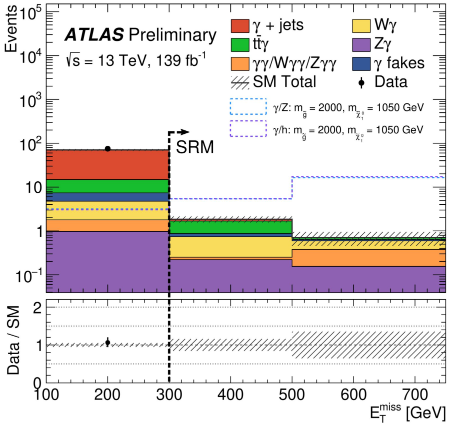
SRL

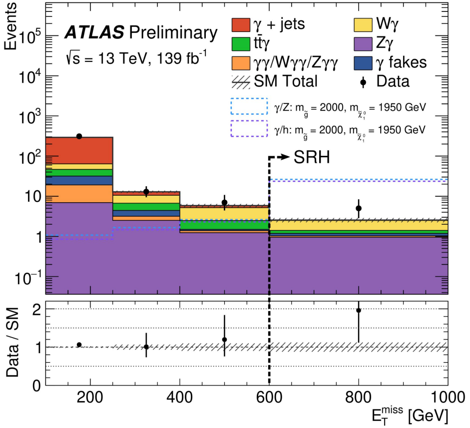
SRM

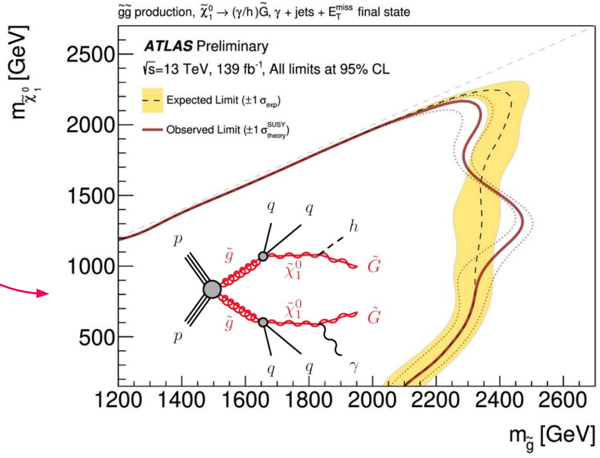
SRH

Result: no significant excess observed. Combined limits with best SR for each model

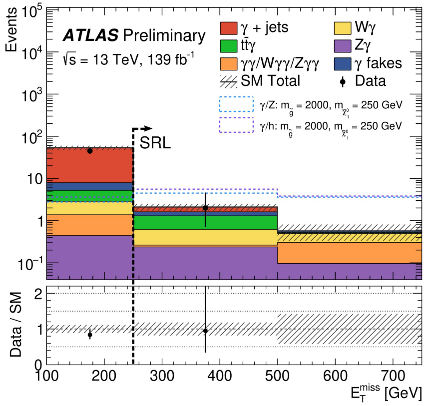








Photon(s) + jets + MET



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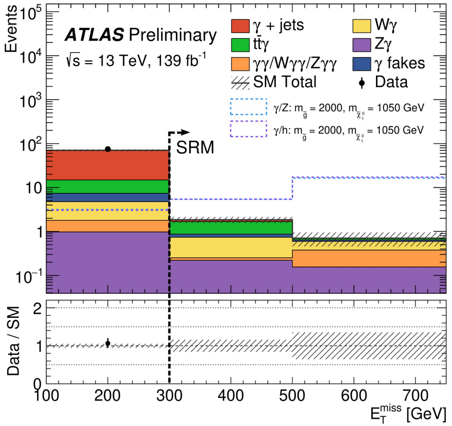

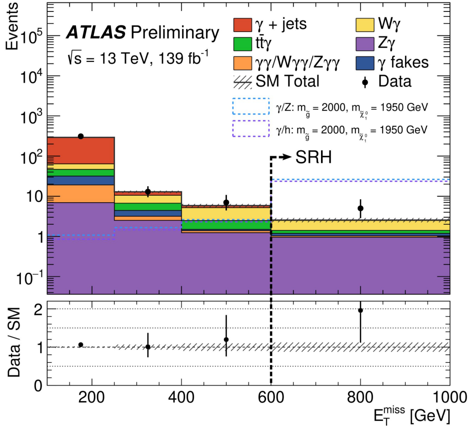

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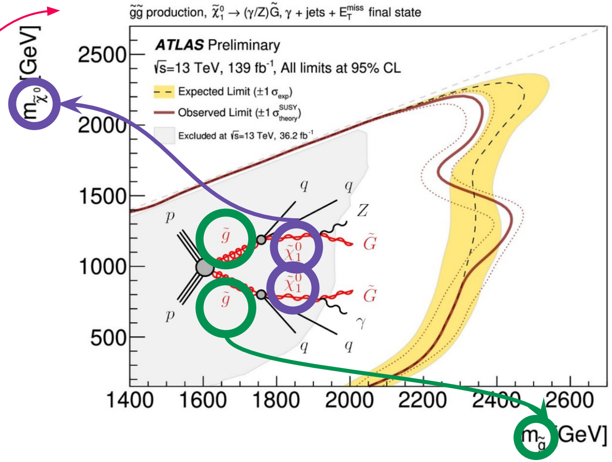

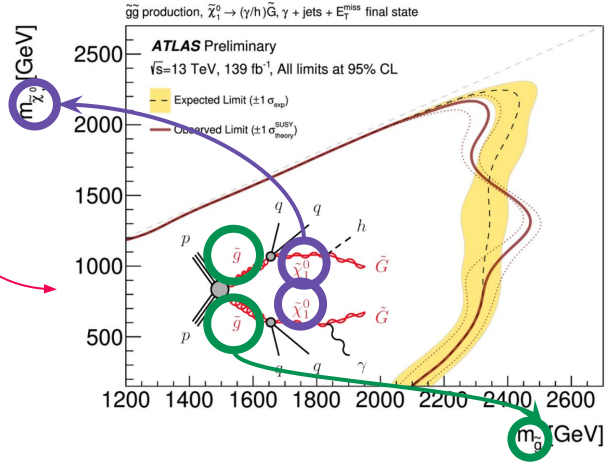

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bb+MET analysis

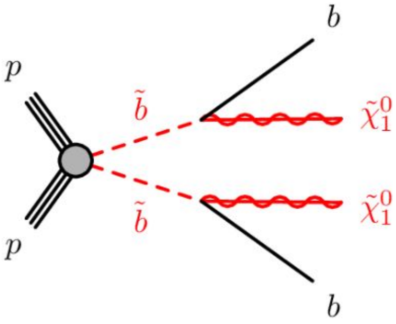
Final state with b-jets and MET, no leptons

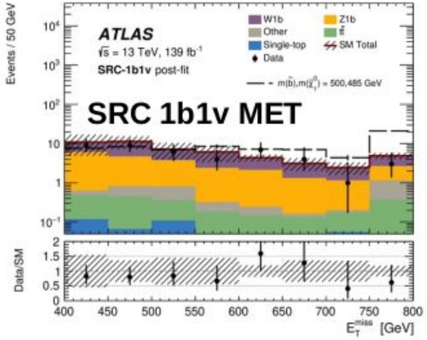
- Trigger on MET (require > 250 GeV)

SRA-C defined for large to small mass splittings

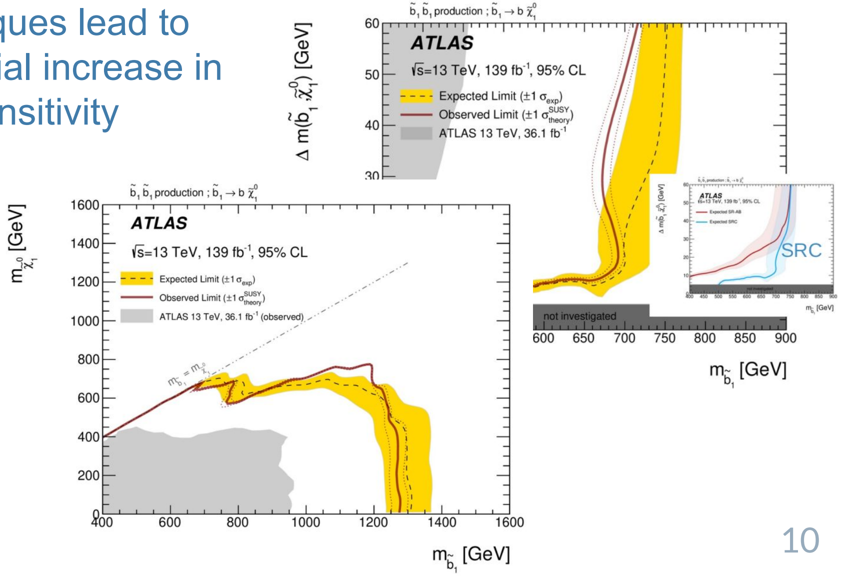
- SRA: m_{CT} to reject ttbar
- SRB: BDT based selection (most important: min m_T (jet1-4,MET), and jet1-3 p_T)
- SRC: Require ISR jet and make use of soft b-tagging improvements to target compressed region. Tags displaced vertices down to 5 GeV

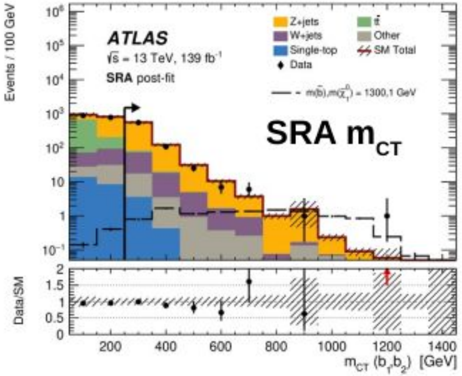
$$m_{CT}^2(v_1,\ v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$$

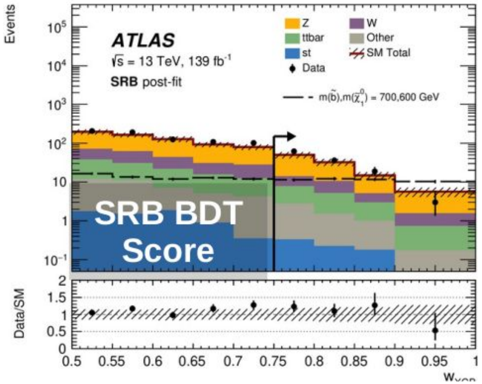




More data, but especially new techniques lead to substantial increase in sensitivity



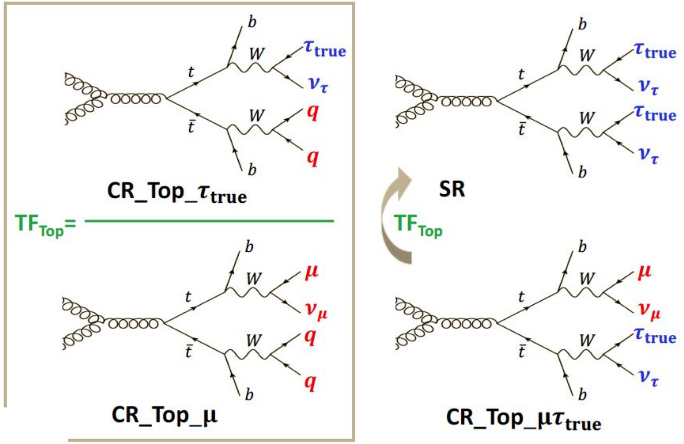


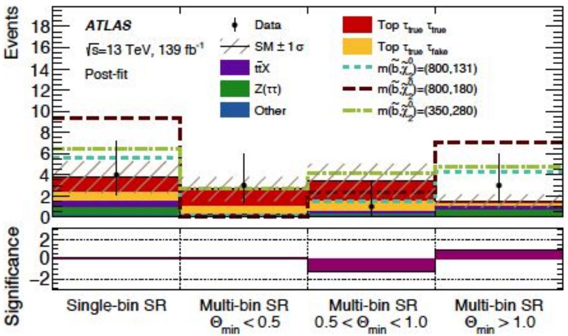


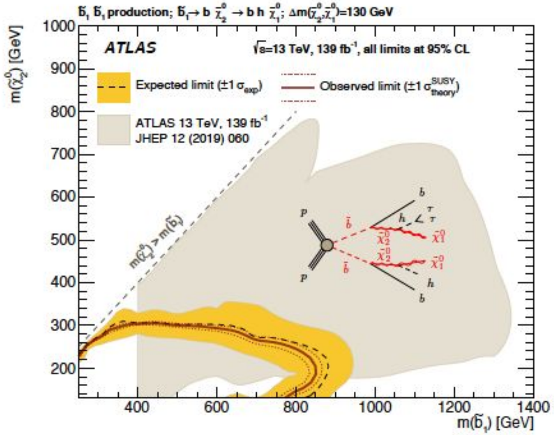
PRD 104, 032014 (2021)

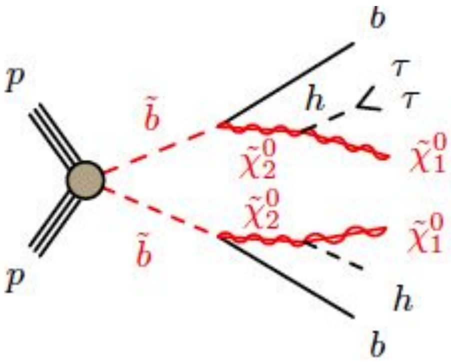
Sbottom with taus, b-jets and MET

- Sbottom search in final states with hadronically decaying taus, b-jets and high E_T^{miss}
- Two-step SUSY decay, with Wino-like NLSP decaying to Bino-like LSP (and Higgs)
- SR defined requiring at least two hadronic-taus and at least two b-jets. Main background arising from top-processes and Z+jets
- Key discriminating variable: Θ_{min} (τ ,b) (minimum angle between tau, and b-jet)



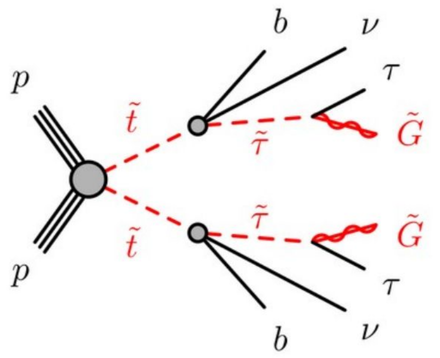




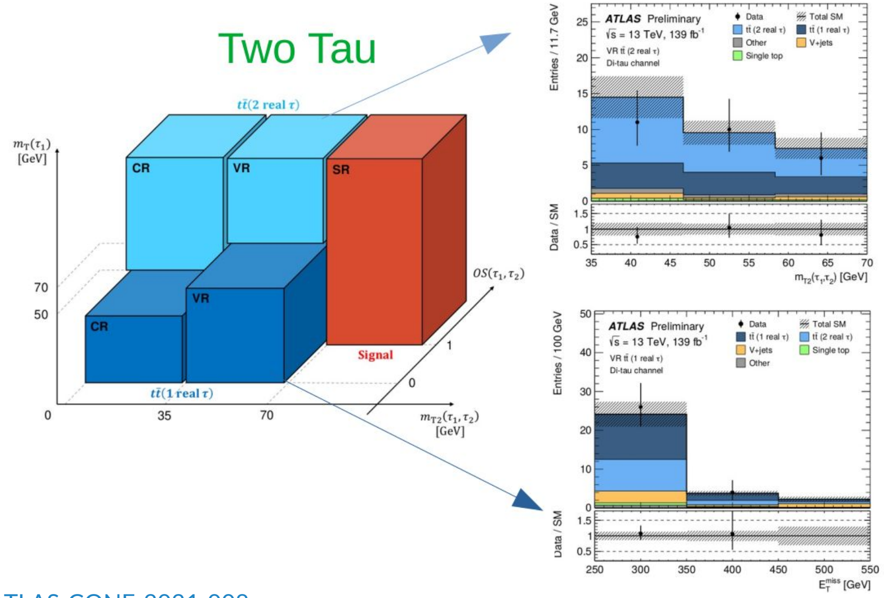


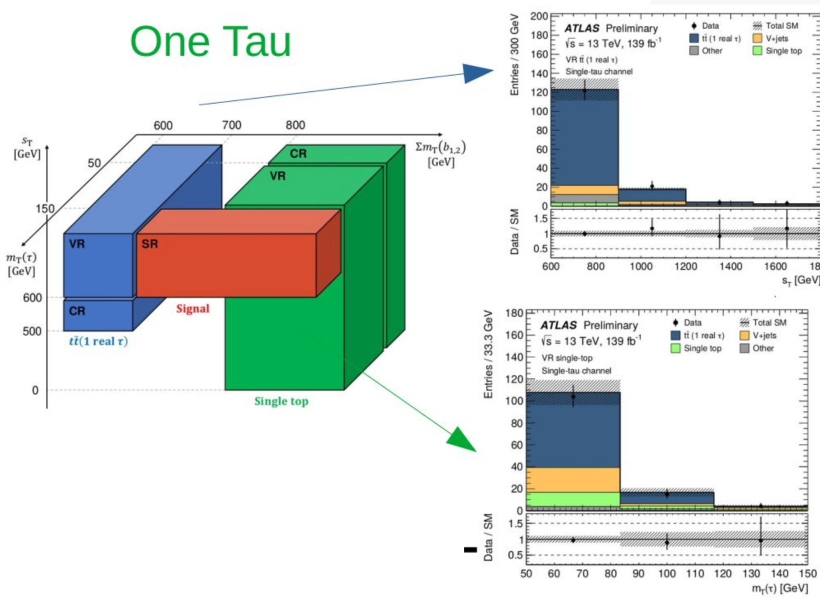
Limits placed in a previously uncovered region of the phase space, benefitting from targeting a different final state with respect to the previous analysis

Stop to staus



- b-jets, hadronic taus, MET, no e/mu
- Trigger on MET (require MET>280 GeV)
- ≥2 τ ≥1b, 1 τ ≥2b channels
- Use endpoint variables and scalar sum (s_T) of tau+jet1+jet2 p_T
- ttbar and tW are most important backgrounds (one or two real taus)





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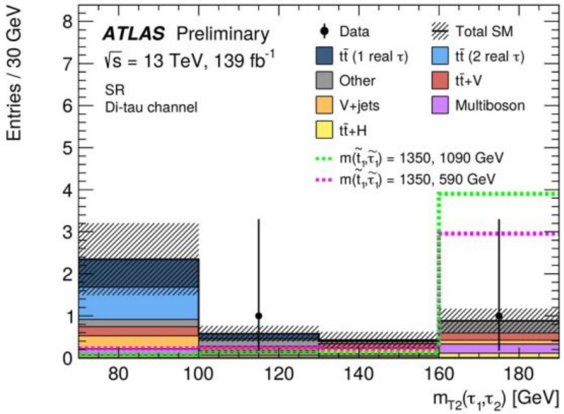
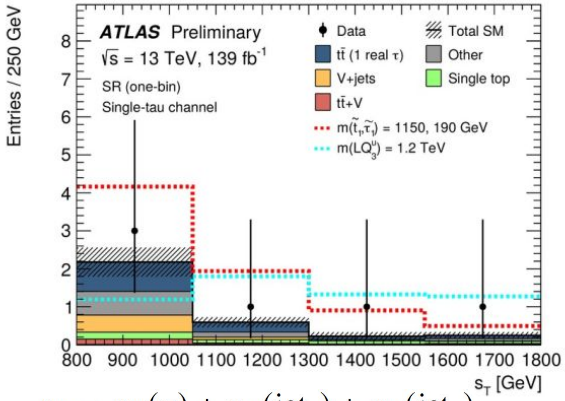
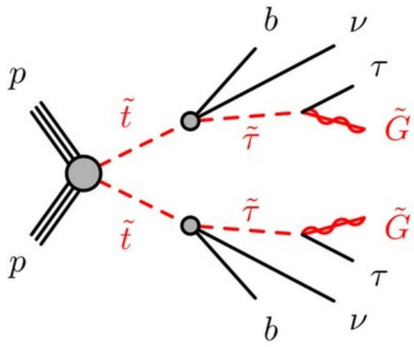
Stop to staus

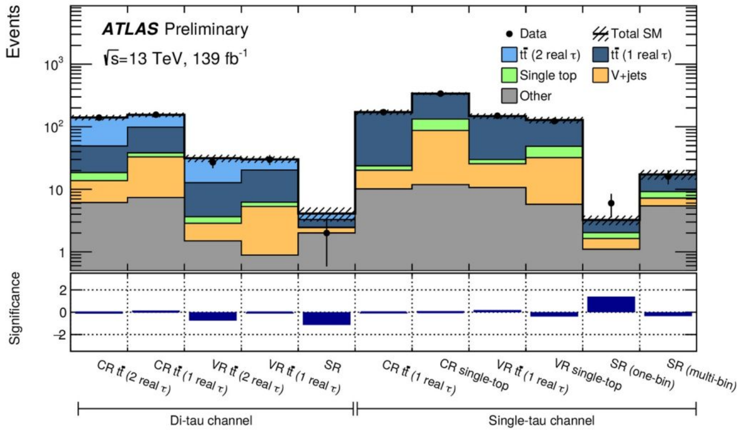


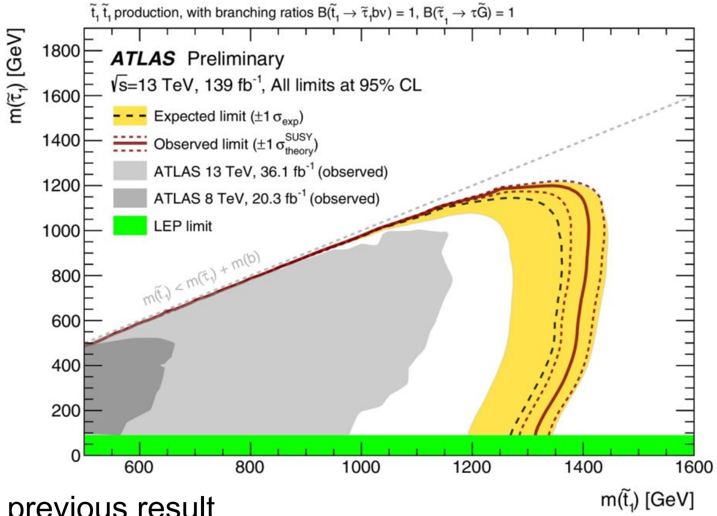


$$s_T = p_T(\tau) + p_T(\text{jet}_1) + p_T(\text{jet}_2)$$



Results: No significant excess observed





Significant gain in analysis reach compared to previous result

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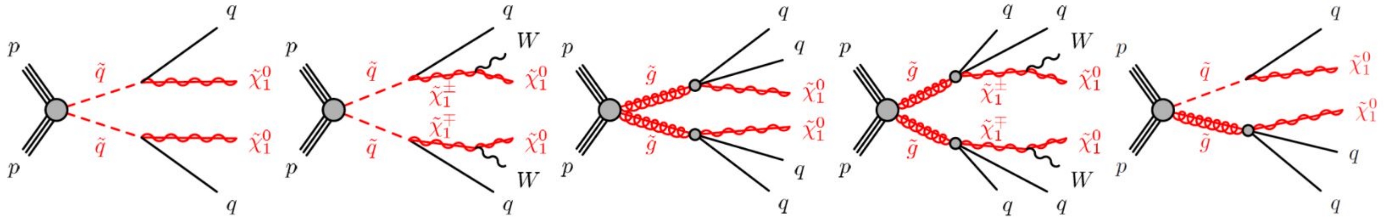
Multijets (2-6)

arxiv.org/abs/2010.14293

- Targeted final states: at least 2 jets and MET but no leptons
- Large signal yields due to high cross section
- Huge irreducible backgrounds
- Two approaches are employed for exclusion of the model:

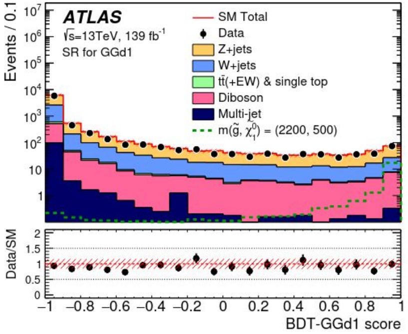


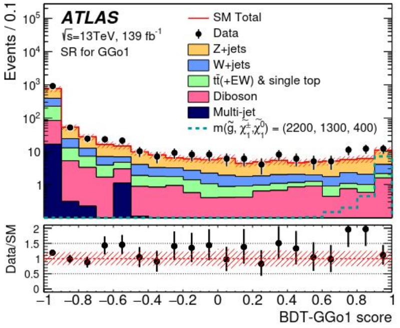
SS direct | SS one step | GG direct | GG one step | inclusive

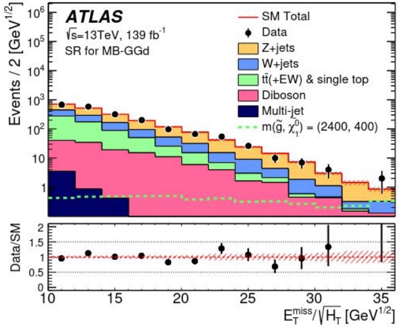
Boosted Decision Tree (BDT) score is used:

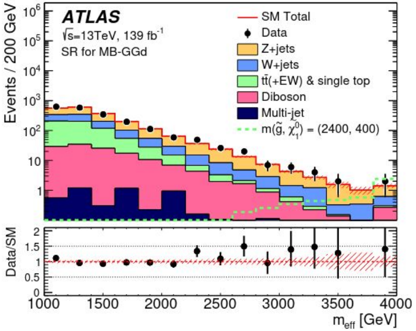
- BDT-GGd: optimized for direct gluino decays
- BDT-GGo: optimized for one step gluino decays
- Each set separated in 4 independent signal regions depending on $\Delta m(g,\chi_1^0)$

Up to 12 variables are selected among MET, meff, aplanarity, p_T and η of selected jets









Three region are optimized:

- MB-SSd: for non compressed squarks
- MB-GGd: for non compressed gluinos
- MB-C: for compressed scenarios

Likelihood is calculated using multiple 2D bins

Multijets (2-6)

arxiv.org/abs/2010.14293

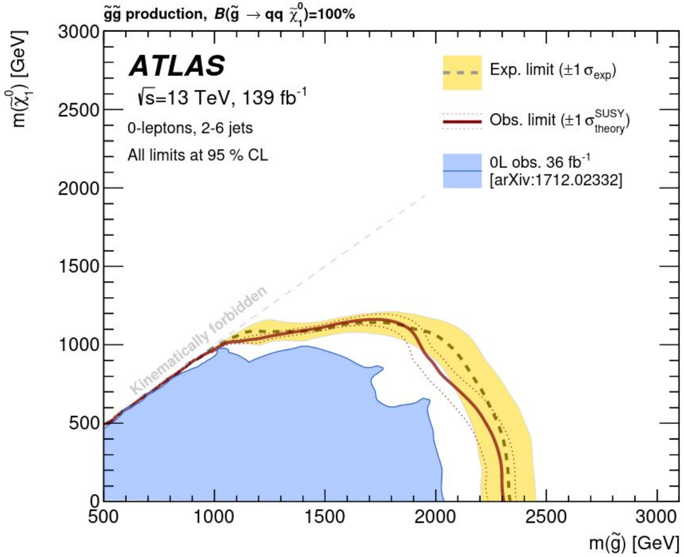
No significant deviations found

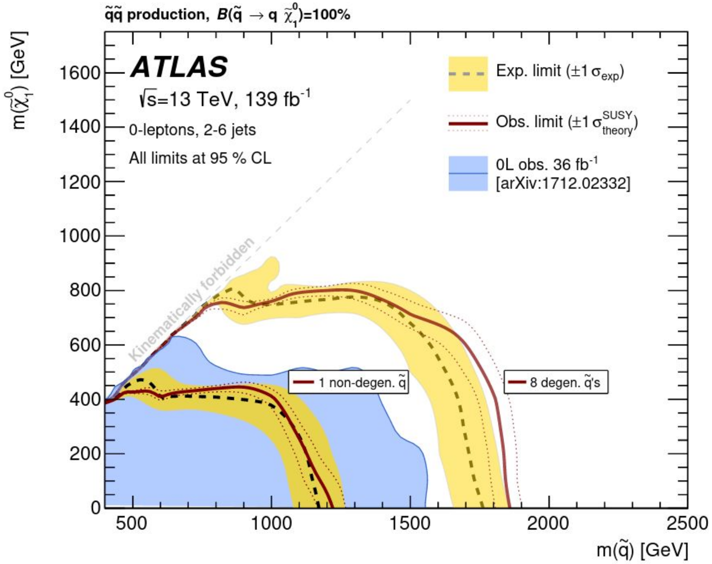
Excluded for:

- GG direct: $m(g)$< 2.35 TeV
- GG one step: $m(g)$< 2.19 TeV
- Inclusive: $m(q)$= $m(g)$< 3000 GeV

Excluded for:

- SS direct: $m(q)$< 1.94TeV
- SS one step: $m(q)$< 1.59 TeV





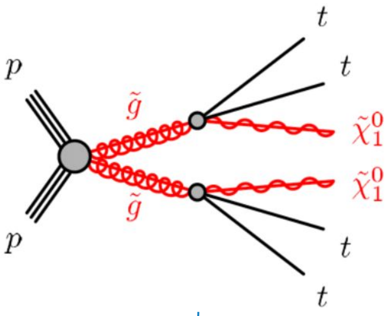
Large jet multiplicities (8-12)

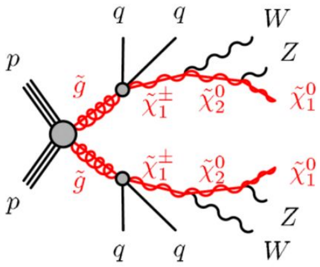
arxiv.org/abs/2008.06032

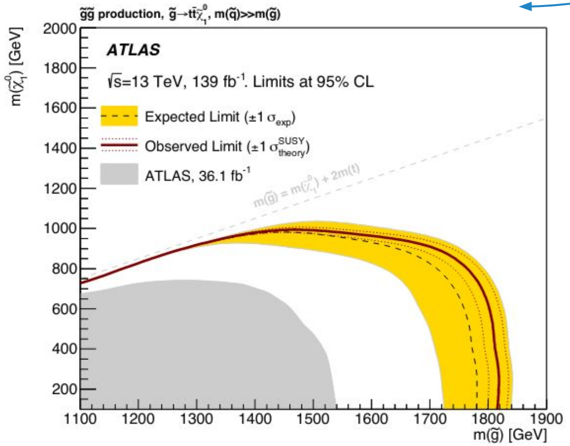
- Targeted Final states: >=8 jets and MET but no leptons
- Unusually high jet multiplicities suppress backgrounds
- Background simulations with large jet multiplicities have large uncertainties
- Data-driven method is employed for major background

Newly improved techniques from the previous study:

- Particle Flow jets and MET reconstruction
- MET significance S(MET)





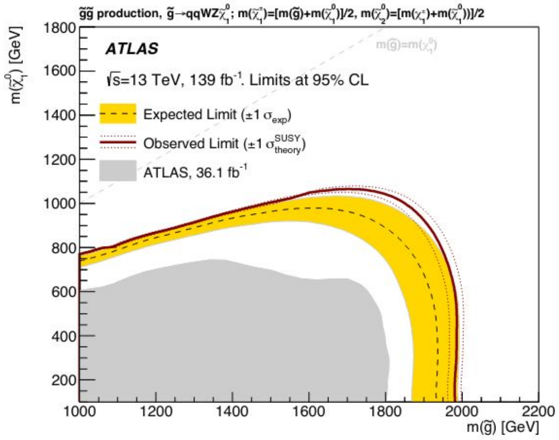


No significant deviation is found

Excluded for:

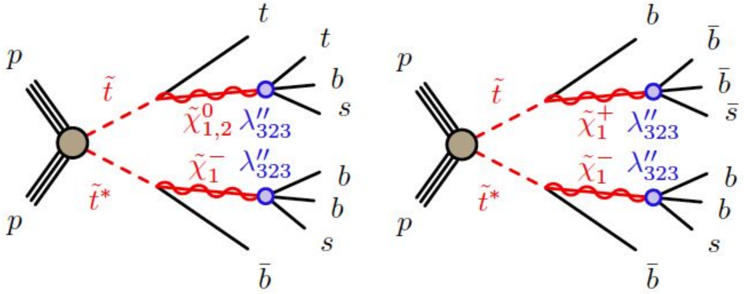
$m(g)$< 2 TeV (two step decay)

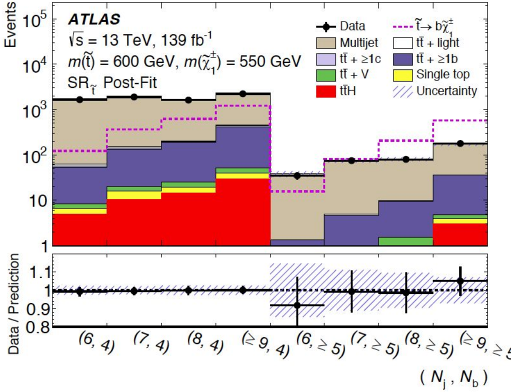
$m(g)$< 1.8 TeV for m_{10} < 700 GeV (direct decay + off shell top)

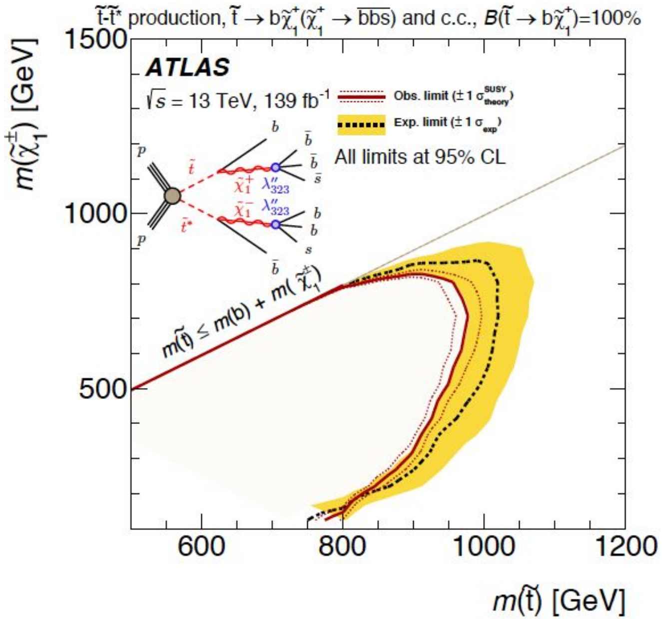


RPV Stop search with many b-jets

- RPV Stop search with non-zero λ_{323}
- Baryon number violating decay leading to final state with many b-jets
- SRs defined with at least 6 jets, 4 of which are b-jets, and 0L
- SRs are split into different njet & nb-jet multiplicities
- Multi-jet production is the main background, and is estimated in a fully data-driven manner using a two-step method
- Extrapolate the number of b-jets from a 5-jet (≥ 2 b-jet) region, to higher b-jet multiplicities using a parameterised probability that an additional b-jet is present in the event
- Probability of additional b-jets is then extended to higher multiplicities
- Sensitivity up to m_{stop} = 1TeV in scenarios with the largest b-jet multiplicities

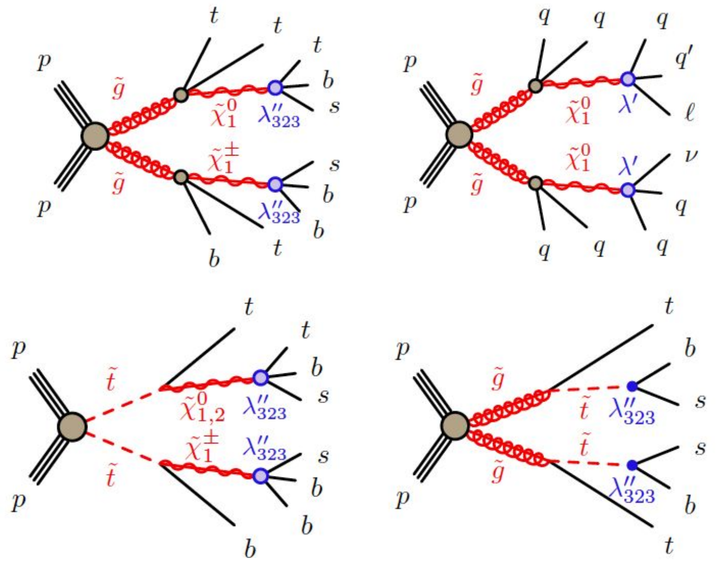


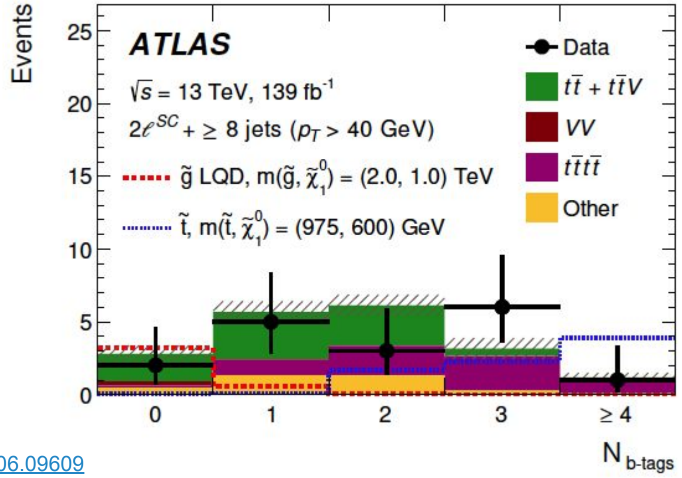


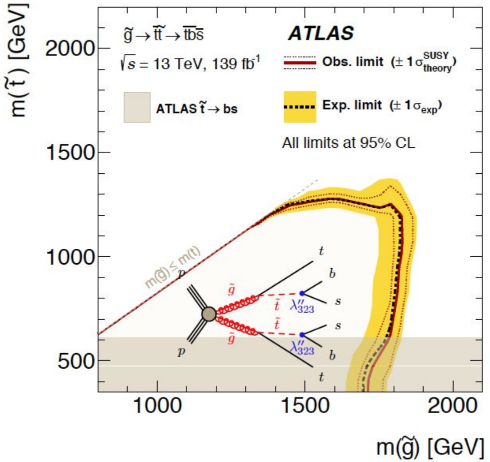


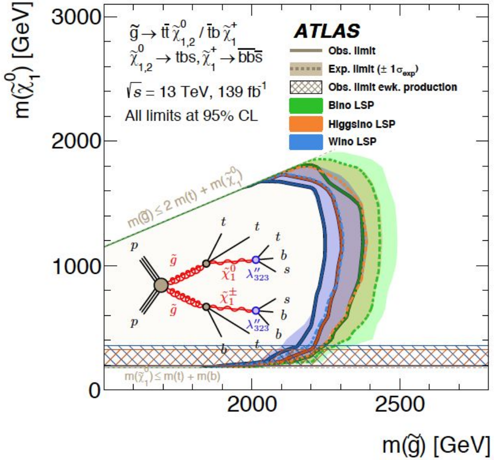
RPV Search with 1L and many jets

- Very powerful search in final states with at least 1L and many jets
- Sensitive to gluino and stop pair production in a variety of RPV scenarios
- Various intermediate decays are considered
- Two sets of SRs with either 1L or 2L (same-charge)
- ‘Jet counting analysis’ using SRs with high jet and b-jet multiplicities
- Significant gain in sensitivity compared to previous results
- Limits also placed using different assumptions on the neutralino composition









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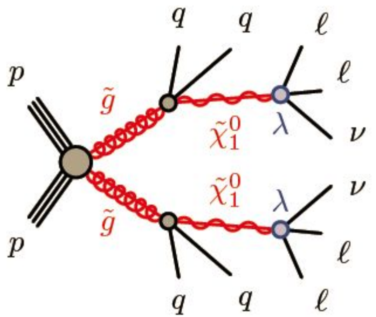
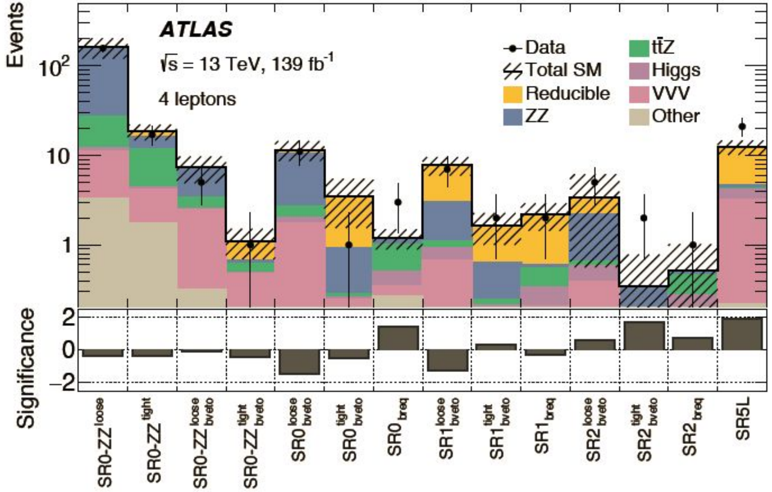
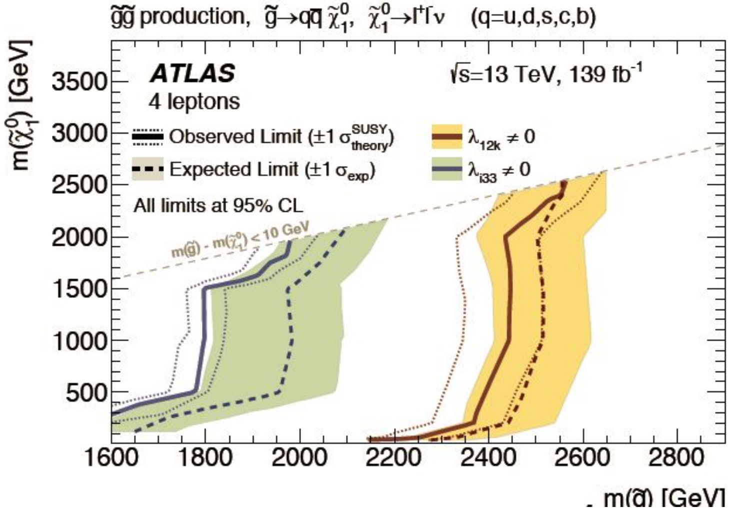
Final states with 4L with RPV

- Search for SUSY in final states with at least 4L
- Targets both strong & EWK, RPC and RPV scenarios
- EWK interpretation discussed on nexts slides
- For strong-production, gluino pair-production with non-zero λ_{12k} or λ_{i33} is considered
- Regions defined requiring at least 1 b-jet and high meff
- Main backgrounds arise from ZZ and ttZ
- Limits placed in the two strong RPV scenarios considered







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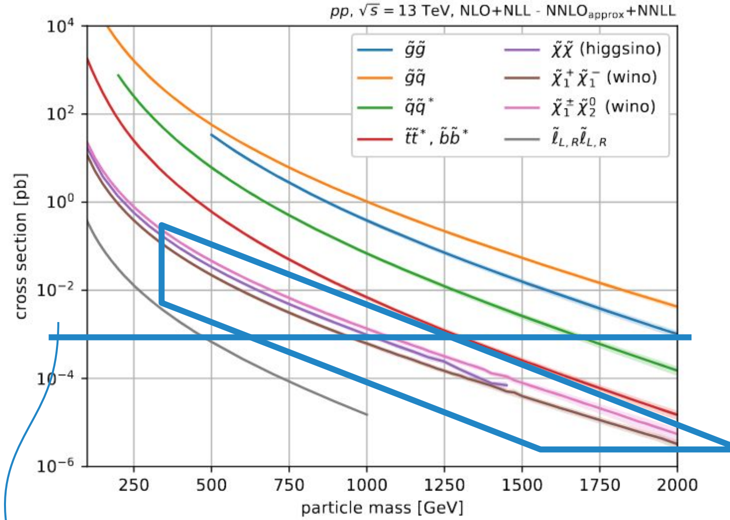
SUSY Electroweak

Electroweakinos with mass ~0.1—1 TeV well motivated

- Neutralino LSP as dark matter, naturalness problem, muon g-2 anomaly

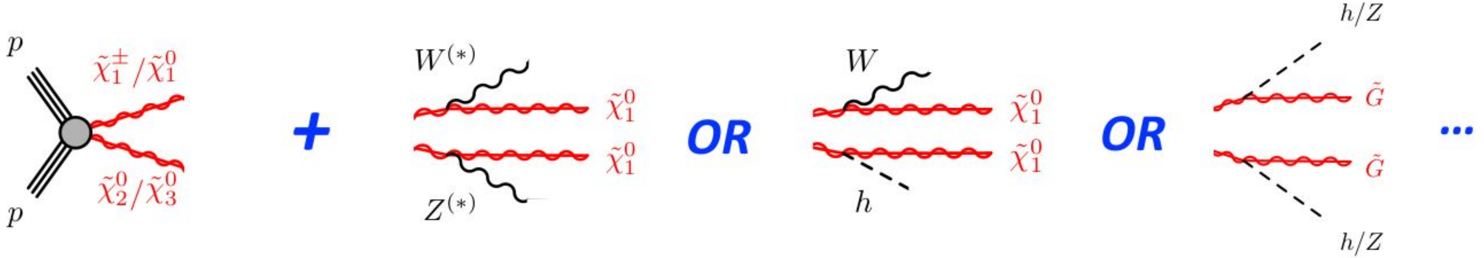
Same strategies from Strong production

- Cleaner signatures
- Process with lower XS → lower masses



Push towards kinematic bounds and statistically challenging regions (decreasing cross section). Develop searches to cover gaps and target unexplored corners of phase space, consider more general models than just the simplified cases.

In account for acc*eff then expect O(100) events in full Run 2 13 TeV dataset



Strategy depends on mass difference of LSP and next LSP : $\Delta m(\chi_2^0/\chi_1^{\pm},/\chi_1^0)$

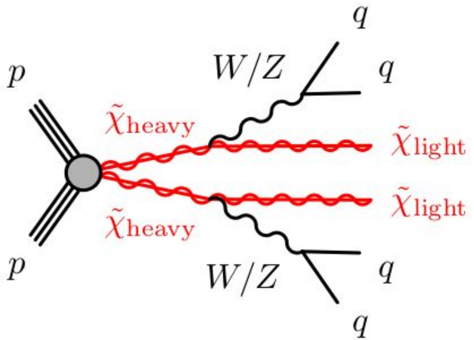
Fully Hadronic

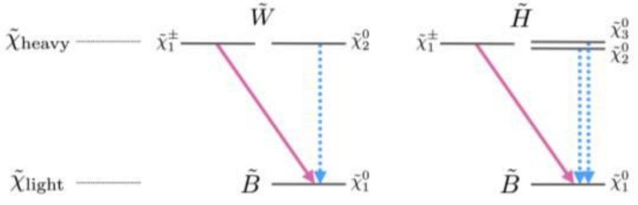
Experimental signature:

- Two hadronically decaying boosted bosons (W, Z, h) and MET
- New search for electroweakino production in full hadronic final states (*qqqq/qqbb*) from W/Z/h
- Large sensitivity to heavier electrowikinos due to large BR
- Large-radius jet
- Target: Δm (χ_{heavy}, χ_{light}) greater than 400 GeV by selecting high p_T kinematics and explicitly reconstructed two boosted SM bosons

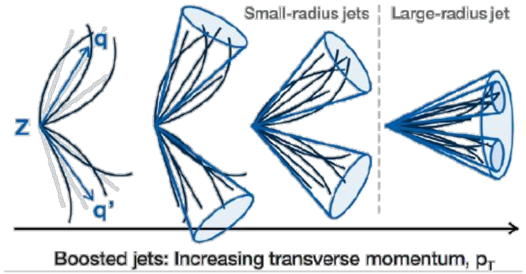
Main backgrounds:

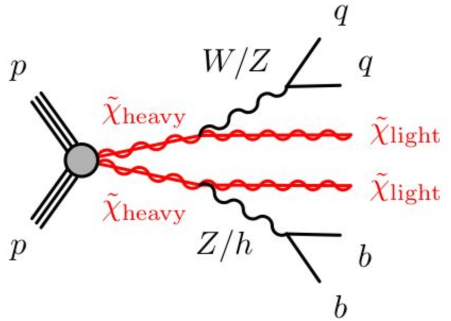
- Reducible: Z+jets and W+jets, "semi-data-driven"
- Irreducible: VVV and A+X, taken from MC





(a) $(\tilde{W}, \tilde{B})$ (b) $(\tilde{H}, \tilde{B})$





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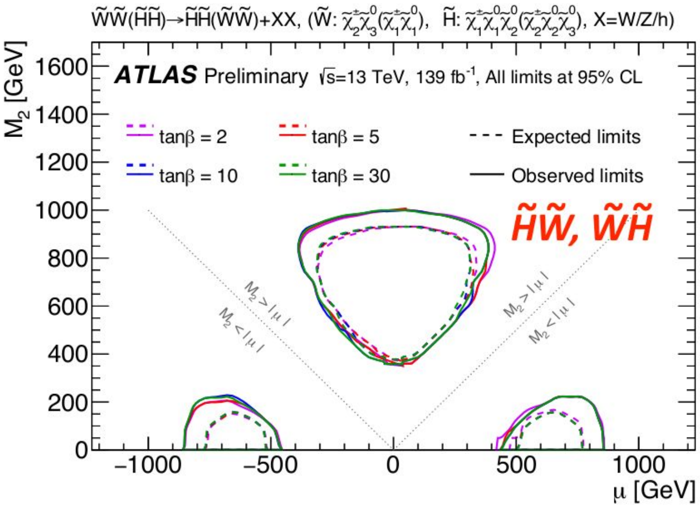
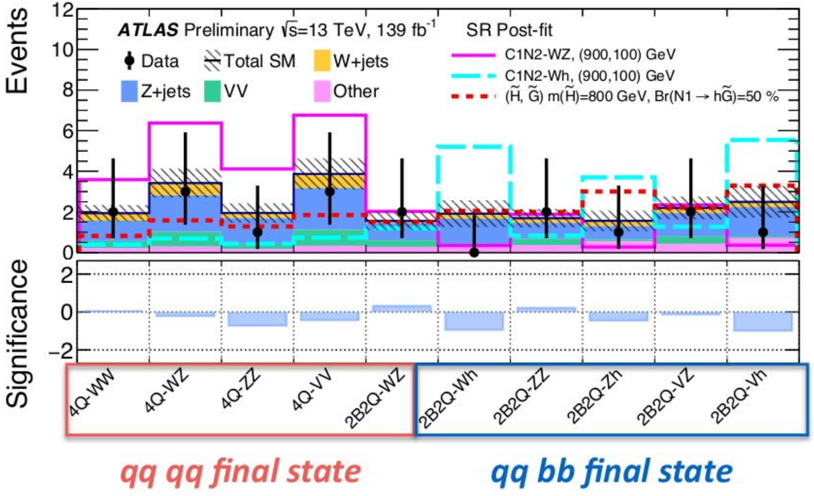
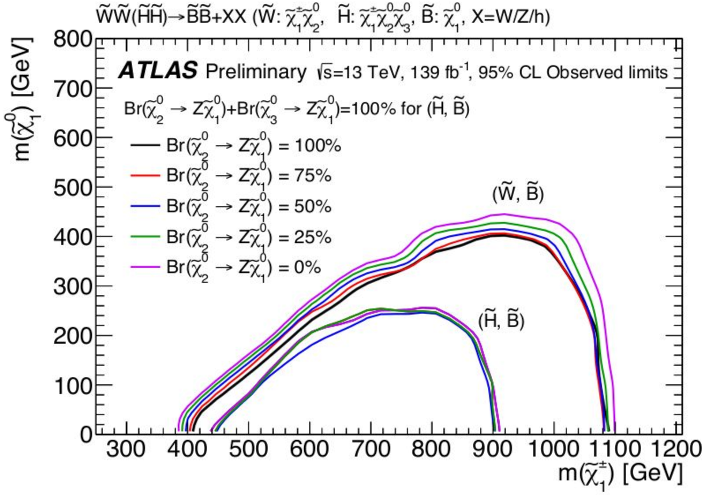
Fully Hadronic

Signal models driven by three physics scenarios

- Baseline MSSM scenario focusing on pairs of Wino, Bino and Higgsino $(X_{heavy}, X_{light}) = (\tilde{W}, \tilde{H}), (\tilde{W}, \tilde{B}), (\tilde{H}, \tilde{B})$, ...
- GGM scenario with light Higgsinos and gravitino LSP $(X_{heavy}, X_{light}) = (\tilde{H}, \tilde{G})$
- Scenario with light Higgsinos and axino LSP $(X_{heavy}, X_{light}) = (\tilde{H}, \tilde{a})$







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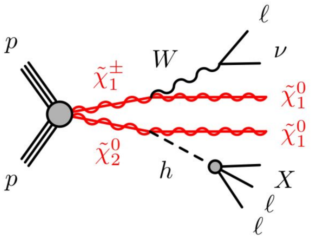
3 leptons

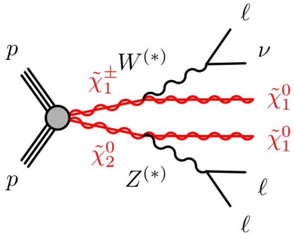
Final state with 3 leptons from chargino + neutralino direct production

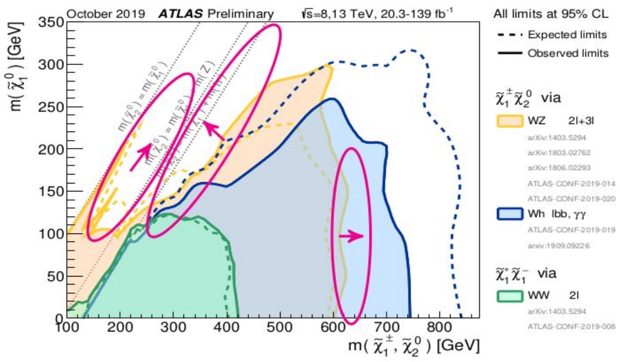
- one lepton stemming from a W (*) decay,
- a pair from either Z (*) or SM h→WW/ZZ/$\tau\tau$

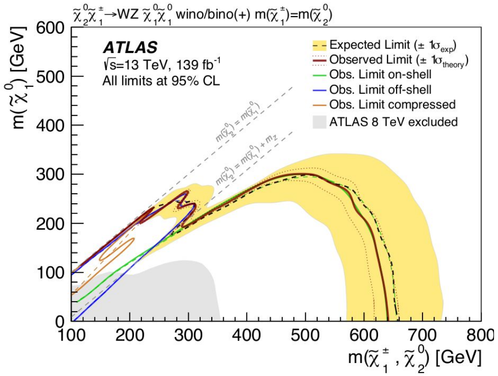
Signal models driven by two different scenarios within MSSM

- |M1|<|M2|<<|μ| resulting in Bino-like stable LSP and Wino-like degenerate C1, N2. DM co-annihilation motivated, slightly higher cross section, important for intermediate & higher mass splittings
- |μ|≈EWK scale and an Higgsino triplet of quasi-degenerate C1 , N2 , N1. Naturalness motivated, smaller cross section, important for smaller mass splittings







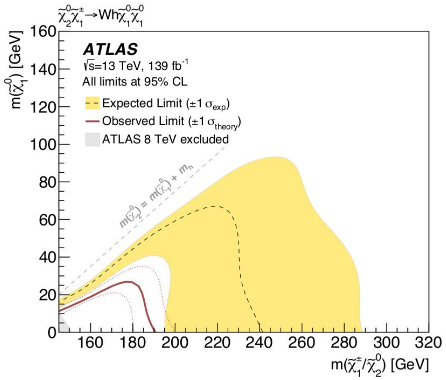


Multi bin SRs to cover different signal scenarios and masses

- Exploiting several observables: jet multiplicity, H_T, m_T (W decay), E_T, mll min, vetoing b-jets

Main backgrounds:

- Irreducible: mainly WZ, and SM Higgs, MC simulation normalized to data in CRs
- Reducible: ≥ 1 misidentified lepton, data-driven, mainly at low E_T



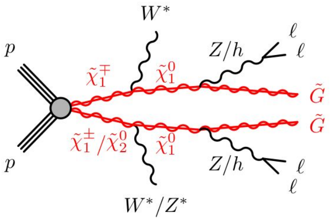
	$\sigma^{95}_{\mathrm{vis}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$\mathrm{CL_b}$	$p(s=0)\ (Z)$
SR3ℓ-Low	0.24	33	30^{+10}_{-8}	0.61	0.39 (0.28)
SR3ℓ-ISR	0.14	19	12^{+5}_{-4}	0.89	0.09 (1.32)

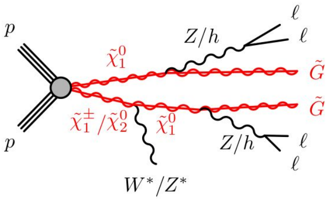
Followed up previous excess (≈3.0σ):

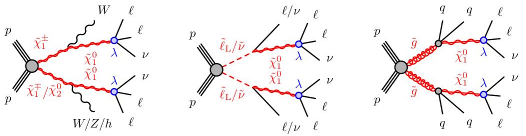
- good agreement now with SM

4 or more leptons

arXiv:2103.11684







C1C1 / C1N1 / C1N2 / N1N2 production considered

- Final states with ≥4 leptons (including ≤2 τhad)

Focus on general gauge mediation (GGM) scenario + RPC

- light mass-degenerate higgsino triplet
- nearly massless gravitino LSP
- same-flavour opposite-sign lepton pairs from Z/h decays, additional leptons from W/h decays too soft for detection

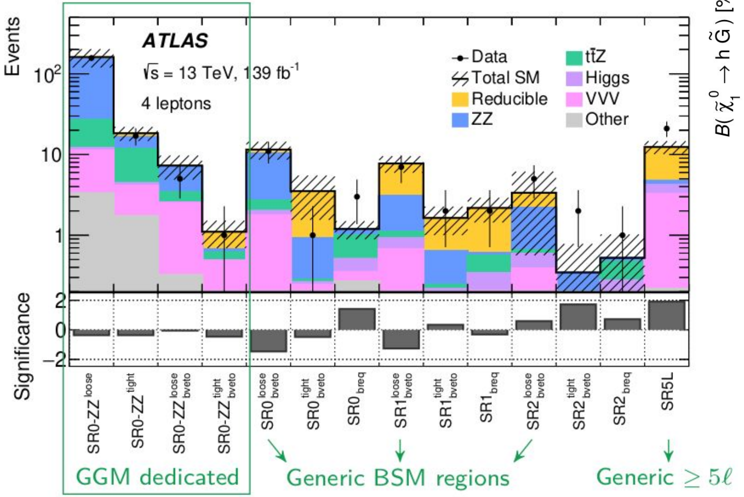
Signal regions separated by

- presence/absence of Z bosons (2Z/0Z)
- τ_{had} and b-jet multiplicity
- MET and meff

Main backgrounds

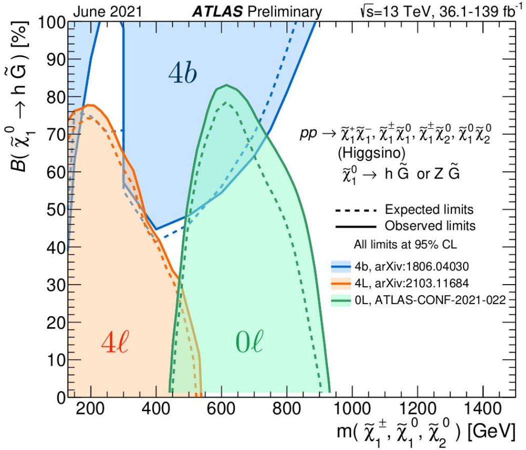
- irreducible: ZZ and tt from MC normalised in CR
- reducible: fake leptons from data-driven measurement

Also target models with RPV. Wino/slepton/gluino NLSP, N1 decays to leptons.



Excess follow-up: 36fb^{-1} 4l result

- good agreement with SM now

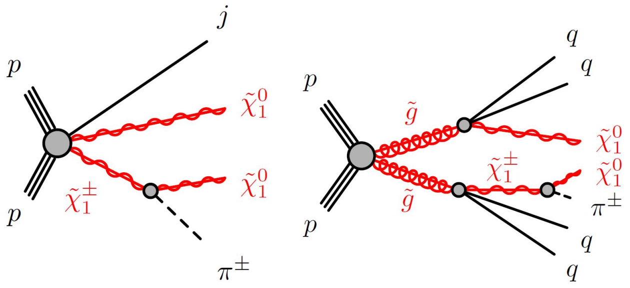


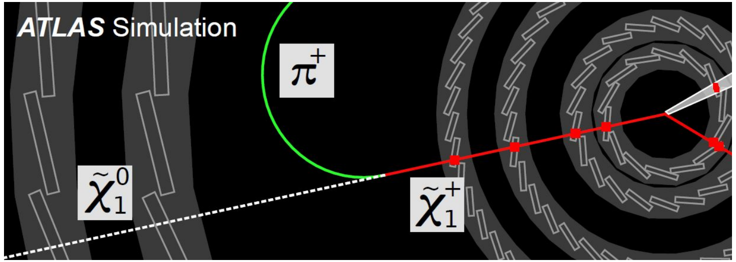
More sensitive to Z decays due to relatively high $Z \rightarrow$ll branching ratio

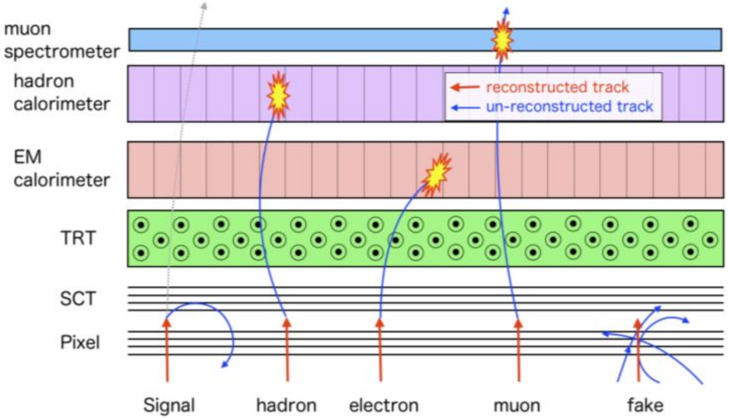
Great complementarity of $4b$ and 0ℓ results, sensitive respectively at higher Higgs BR and at higher higgsino mass

Disappearing track search

- A doublet of wino state ($\chi_1^{\pm}$,χ_1^0) to be LSPs
- Predicted by Anomaly-Mediated Supersymmetry Breaking model (AMSB)
- The lightest states χ_1^0 and $\chi_1^{\pm}$are highly mass-degenerate.
- Δm~160 MeV by radiative SM correction $\chi_1^{\pm}$ lifetime ~ 0.2ns
- $\chi_1^{\pm}$ can have a lifetime long enough that it can reach the detector before decaying ➜ **“Disappearing track”**
- ISR jet to get the system boosted ➜ Large E_T^{miss} to be triggered
- Final state: very-low-momentum p±, E_T^{miss} and disappearing track
- The disappearing tracks are characterized by a lack of hits in the outermost silicon trackers and no calorimeter activity.
- Main background
    - Fake from random combination of pixel hits, estimated using fake enriched CRs with inverted cut of impact parameter







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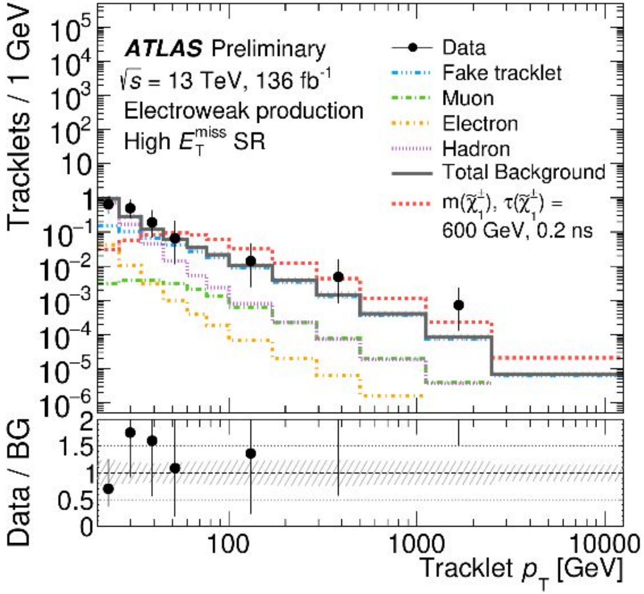
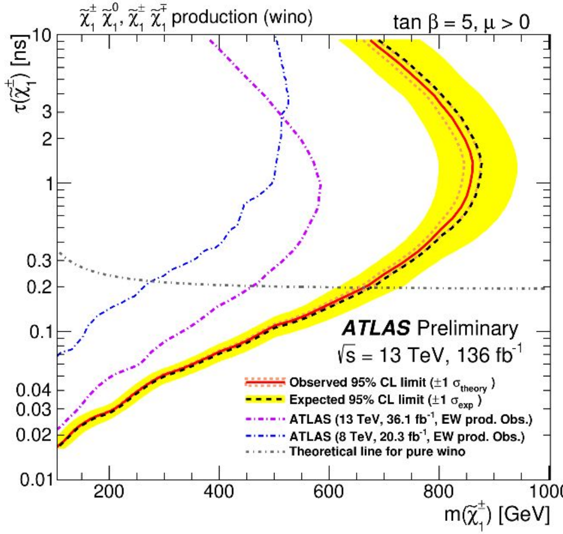
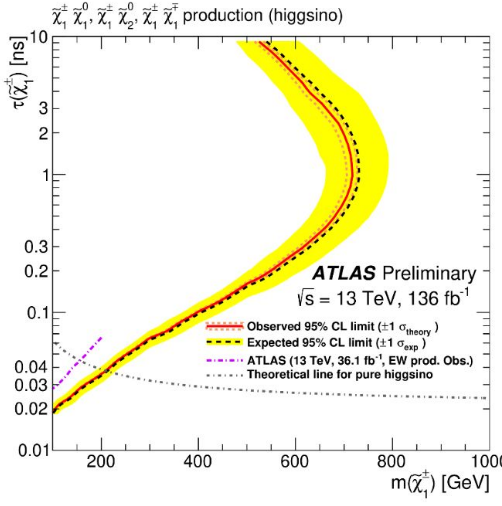
Disappearing track search







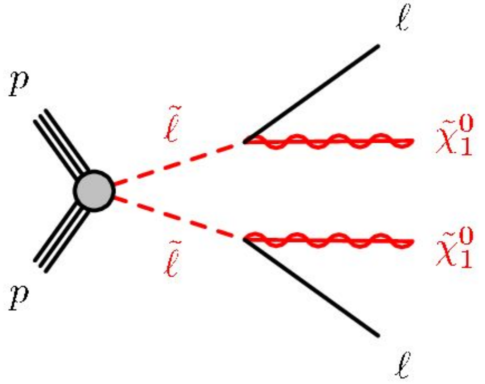
$\chi_1^{\pm}$ masses excluded up to 660 GeV for pure winos

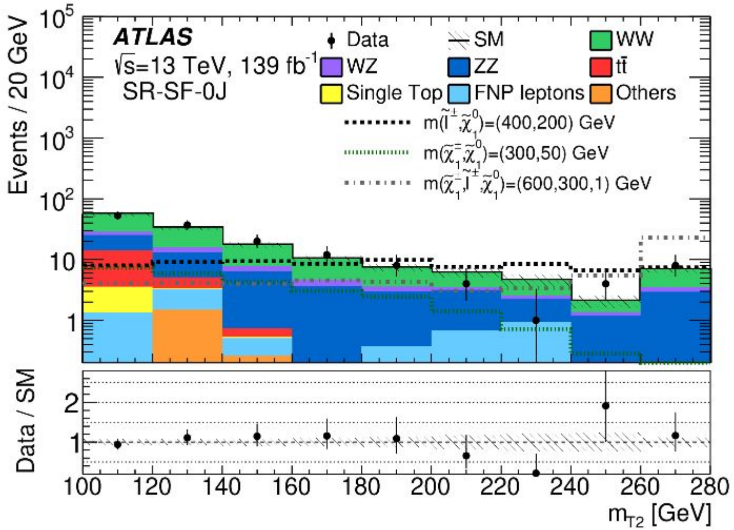
$\chi_1^{\pm}$ masses excluded up to 210 GeV for pure higgsinos

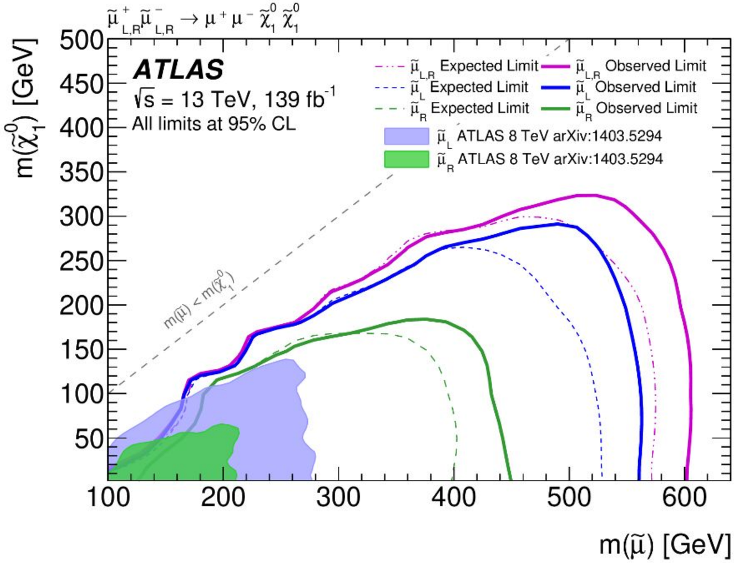
ATLAS-CONF-2021-015

Slepton production search

- Direct pair production of sleptons decaying into final states with two charged leptons and $E_T^{miss}(\chi_1^0)$
- Light smuons are motivated by the muon g-2 anomaly
- Final state: exactly two oppositely charged leptons with p_T>25 GeV and E_T^{miss}
- M_{T2}: mass of a pair of particles that are assumed to have each decayed into one visible and one invisible particle





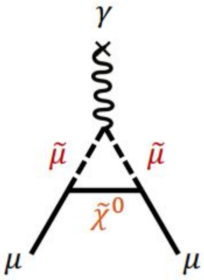


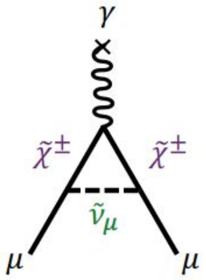
Eur.Phys.J.C80(2020)123

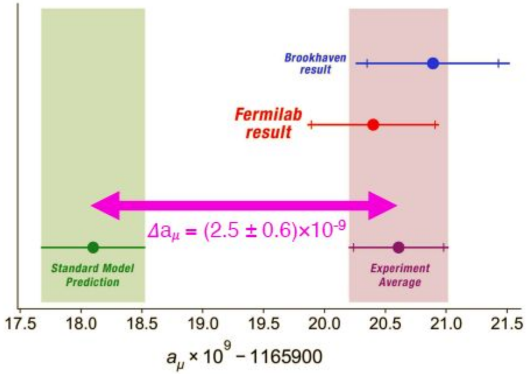
SUSY and g-2 deviation

- SUSY **smuons**, **sneutrinos**, **neutralinos** and **charginos** couple to μ and γ and cause deviations to $a_\mu = (g-2)/2$

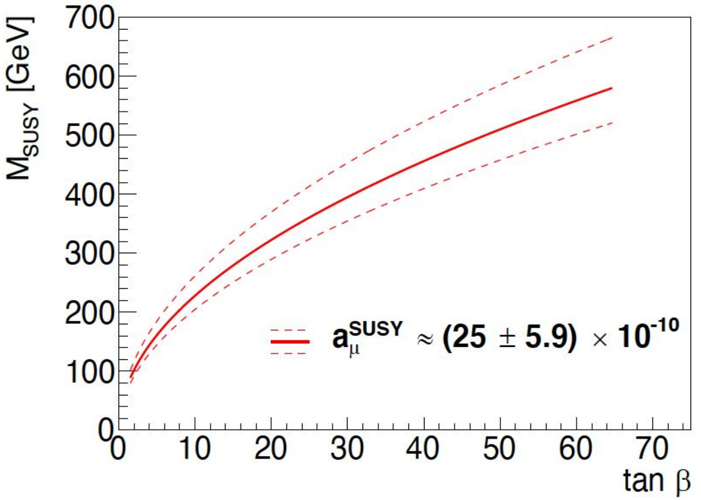
$$a_\mu^{\mathrm{SUSY,1L}} = 13 \times 10^{-10} \left(\frac{100\,\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2 \tan\beta\ \mathrm{sign}(\mu)$$







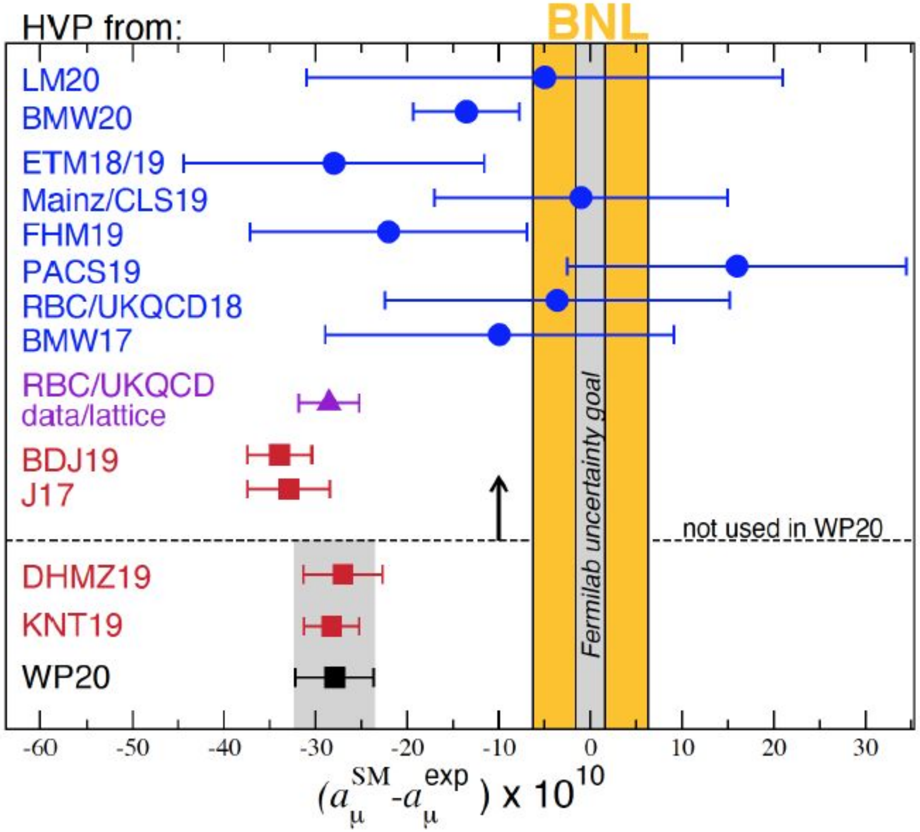
See David Tarazona this conference



- SUSY at electroweak scale can explain the observed g-2 deviation
- Preferred mass range is well-matched to the direct SUSY searches

Heinemeyer, Hollik, Weiglein, Phys. Rept. 425:265-368 (2006)
Endo, Hamaguchi, Iwamoto, Kitahara, Supersymmetric Interpretation of the Muon g-2 Anomaly, 2104.03217

SUSY and g-2 deviation (with a caveat...)

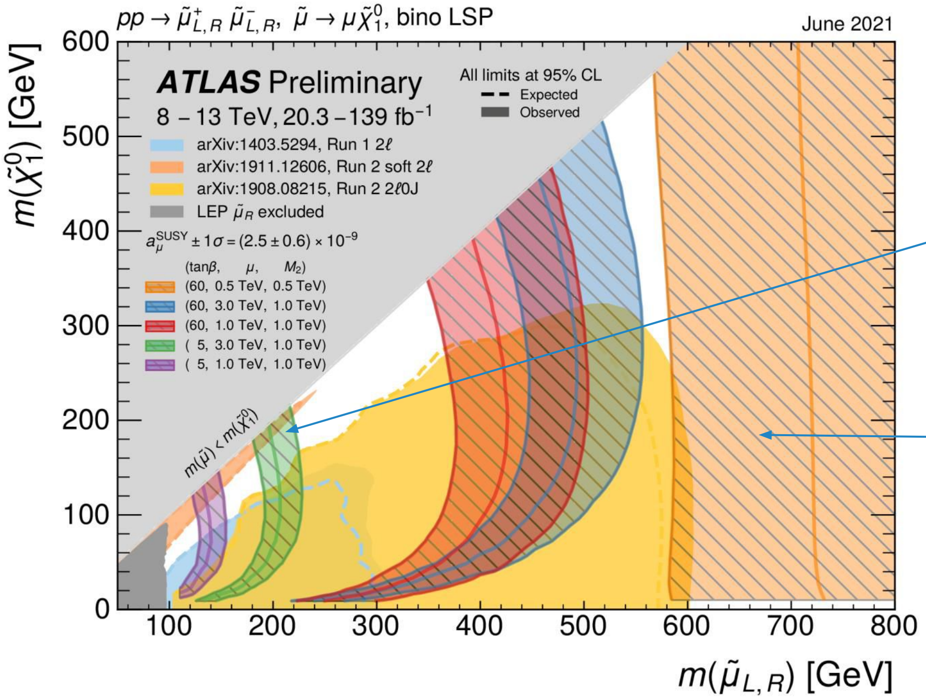


$\Rightarrow$ BMW20: difference to experimental data $\sim 1.5\,\sigma$

https://indico.cern.ch/event/1019685/

SUSY and g-2 deviation

Light smuons and light neutralino required to explain g-2 anomaly
– If R-parity is conserved, light smuon guarantees light neutralino (
– The neutralino can be bino, bino / higgsino, or wino / higgsino



Compressed region

– Clever techniques (e.g. shape analyses, machine learning, etc.) help to enhance discovery reach ⟶ excellent **Run 2 / 3** targets

Large mass region

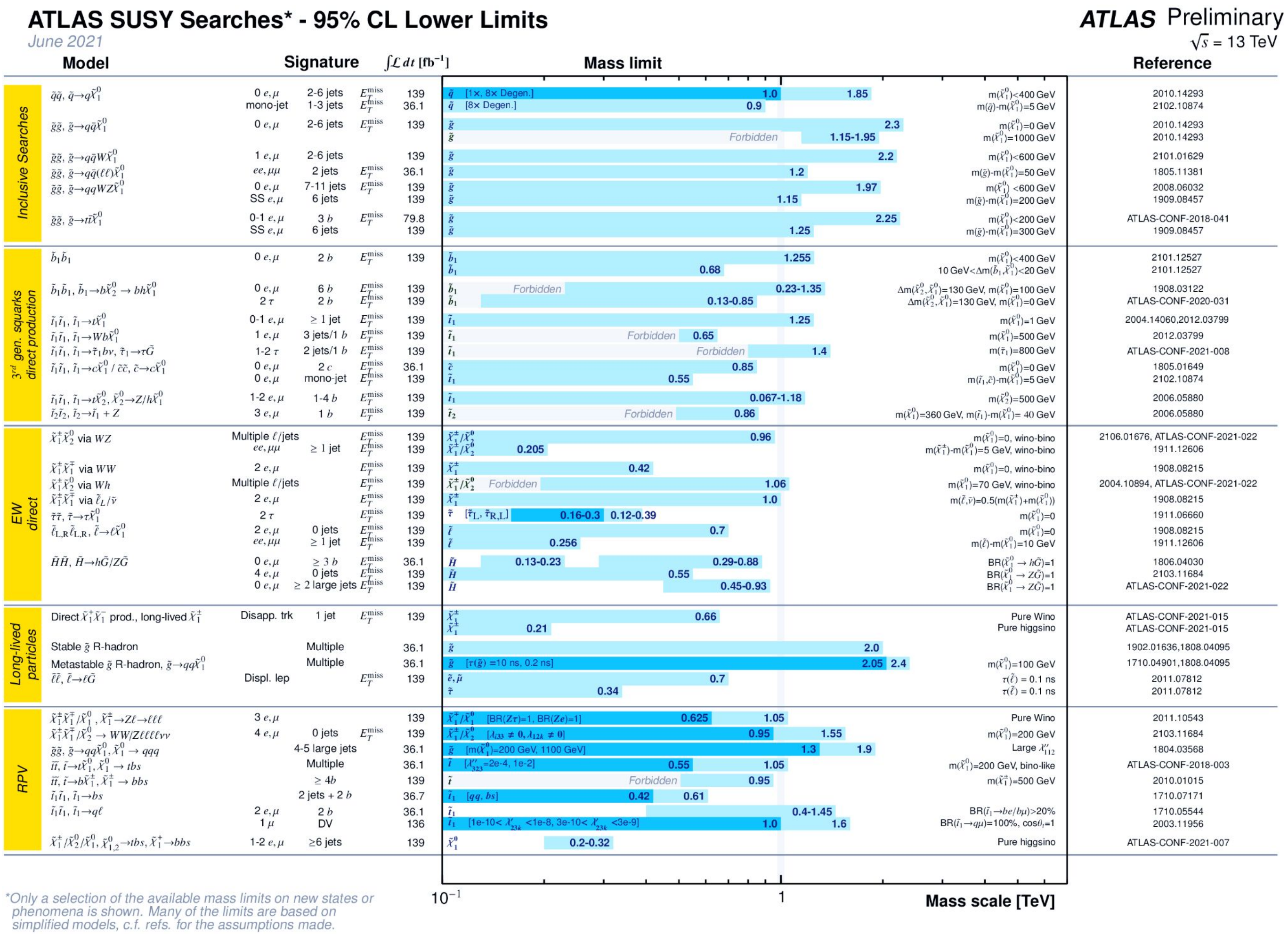
– Cross-section limited ⟶ more data needed ⟶ excellent targets for **Run 3 and HL-LHC**

Shaded bands indicate regions compatible with g-2 anomaly for different choices for mu and tan β

Mass reach of the ATLAS searches for Supersymmetry

Simplified models limits exploiting 2015-2018 Run 2 dataset

- Up to 2.3 TeV exclusion for gluinos at low LSP mass
- Up to 1.85 TeV for squarks (8-fold degeneracy)
- Some scenarios excluding 1.4 TeV stops
- Up to 1 TeV limits for gauginos and 0.7 TeV for sleptons



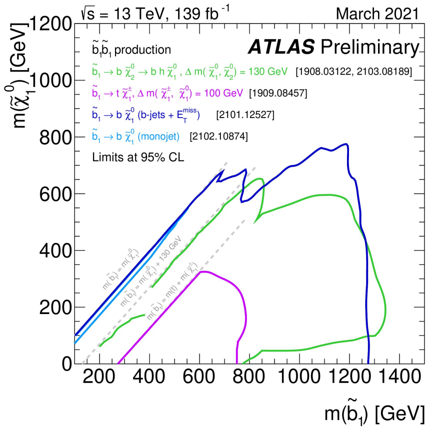
Summary

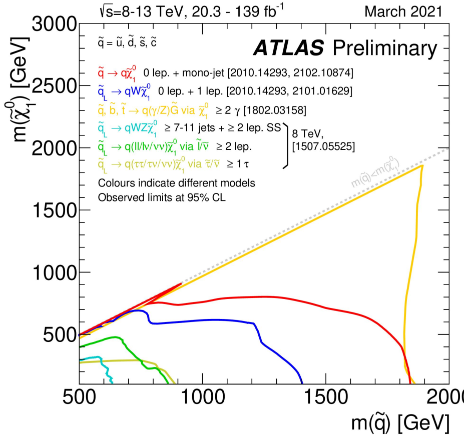
- Comprehensive ATLAS search program targeting strongly and weakly produced particles (in both RPC and RPV scenarios) with full Run 2 dataset (a review of ATLAS and CMS* results could be found in arXiv:2111.10180)
- Greatly enhanced sensitivity compared to early Run 2 results
  - Due to the increased data, but also more complex analysis methods.
  - Data-driven estimates of key backgrounds.
- Latest searches expand excluded susy phase space ever further for many final states, but still lots of well-motivated phase space to explore, e.g. models consistent with g-2 anomaly and slepton searches.
- Further searches are ongoing to fully exploit the Run 2 dataset in addition to the on-going work preparing for Run 3 and beyond!

** See Seema Sharma this conference*

Backup slides

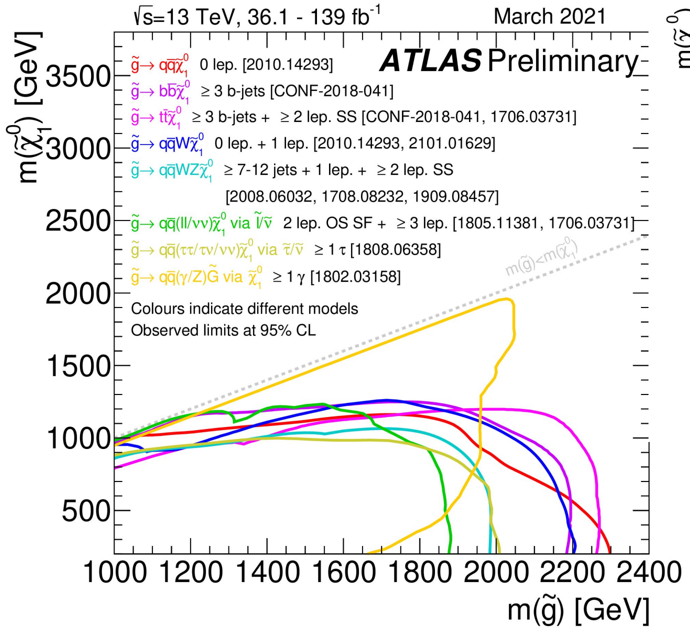
SUSY Strong Summary



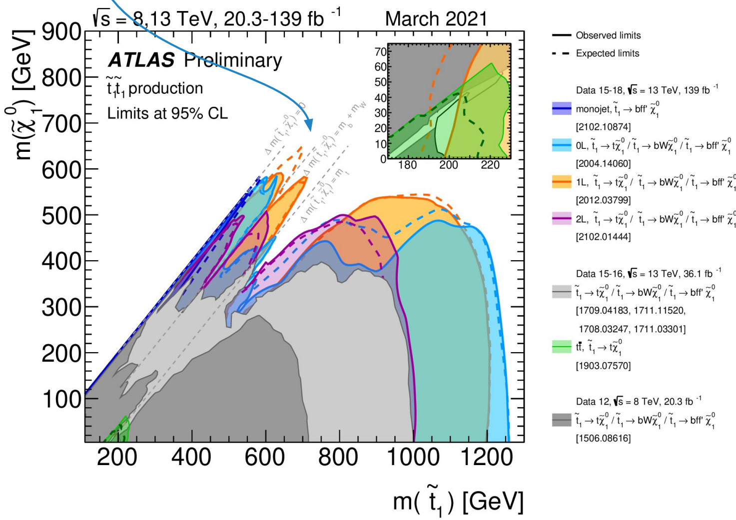


[Supersymmetry Public Results]

[Supersymmetry Summary Plot]



Weaker limits in regions close to and below Δm=m_top
Difficult to distinguish from backgrounds



Small mass splittings are difficult, need dedicated analysis design and/or techniques to cover, e.g. bb+MET and monojet