Searches for supersymmetry in non-minimal models

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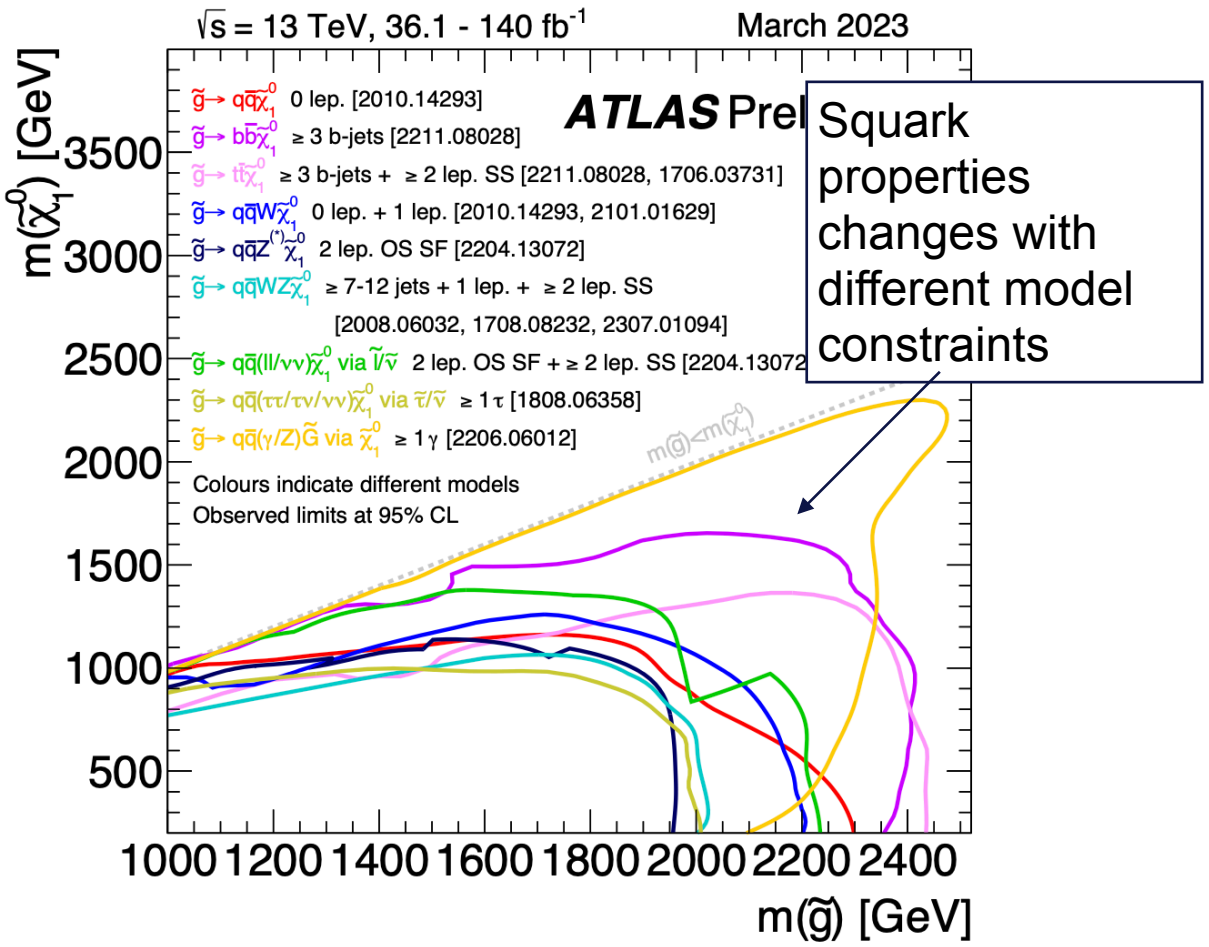
HELMHOLTZ

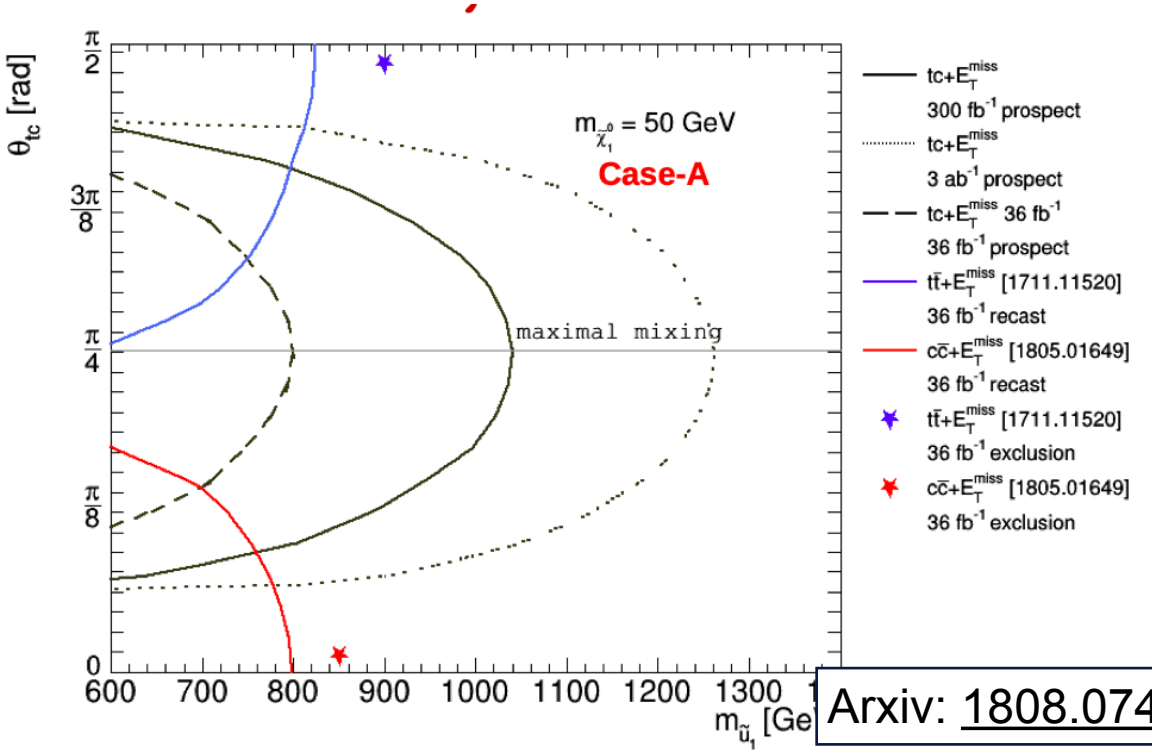
Introduction: Non-Minimal Supersymmetric Models

- SUSY has many parameters (105 parameters+ 19 from SM), educated but ad hoc assumptions are made.
  - R-parity conservation
  - Minimal flavor violation
  - No additional CP violation sources
- Other models with loosened requirements are still well-motivated. E.G. non-minimal flavor violation, R-Parity Violating
- This talk will discuss a list of analyses recently published within ATLAS in this class
  - Long-lived particle signature ATLAS results will be covered in a dedicated talk by Vasiliki Mitsou
- Non-minimal SUSY model argues that limits on simplified models **are not** limits of SUSY!



Flavor Violating Non-minimal Model

- **Mixed top-charm quark**
- Vanilla simplified MSSM assumes minimum flavor violation: Yukawa couplings -> Well Constrained
  - Super-CKM: allow for generational mixing between squark /quark terms
    - Terms constrained by precise measurement in K, B, D physics and Higgs data
    - Possible decay terms $\tilde{u}_i \to t\tilde{\chi}_1^0\,, \qquad \tilde{u}_i \to c\tilde{\chi}_1^0 \qquad \text{with} \;\; i = 1, 2\,,$
  - Final states: tc+MET presented in the previous talk in strong production talk by Edmund Ting, ttMET, ccMET



Arxiv: 1808.07488

top-charm mixing parameter phase space from flavor violating SUSY

R-Parity Violating Non-minimal Models

- R-Parity Conservation is introduced to prevent rapid proton decay
- R-Parity Violation can do the same if some interaction strength is small or forbidden
  E.G. B-L symmetry
- RPV changes the landscape for SUSY
  - Single SUSY particles production
  - The lightest SUSY particle (LSP) decays into SM particles
  - SUSY particles with a lifetime (Long lived particles)
  - Dark matter candidate particles: axions, axino or gravitinos

R-parity violating terms in MSSM

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

Lepton Number Violation Baryon Number Violation

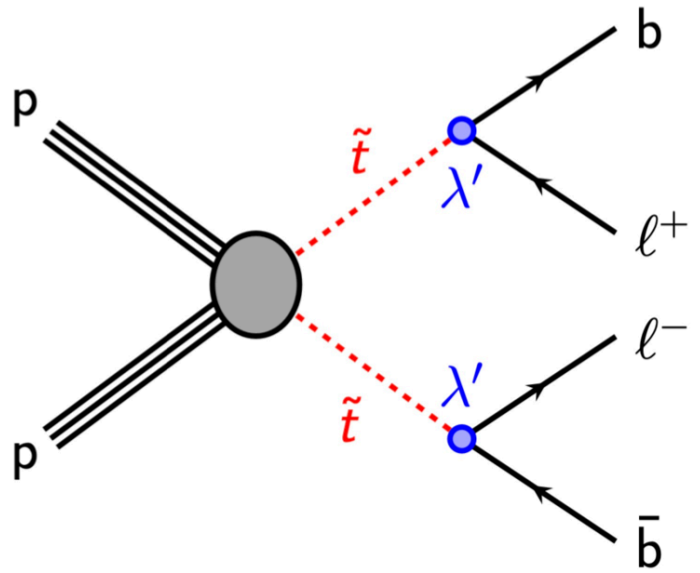
$$R=(-1)^{3(B-L)+2s}$$

R parity is directly related to Baryon/lepton number

RPV Stop Search with B-L Symmetry

SUSY-2018-37

- Final state: direct pair production of the stop decaying through an R-parity violating two 2 charged leptons and two b-jets
- Minimal Supersymmetric Standard Model (MSSM) with an additional B-L gauge symmetry. -> Consistent on proton stability and the bounds on lepton violation observed.
- LSP stop predicted from the model and searched for.
- First full run 2 result(139fb-1)!

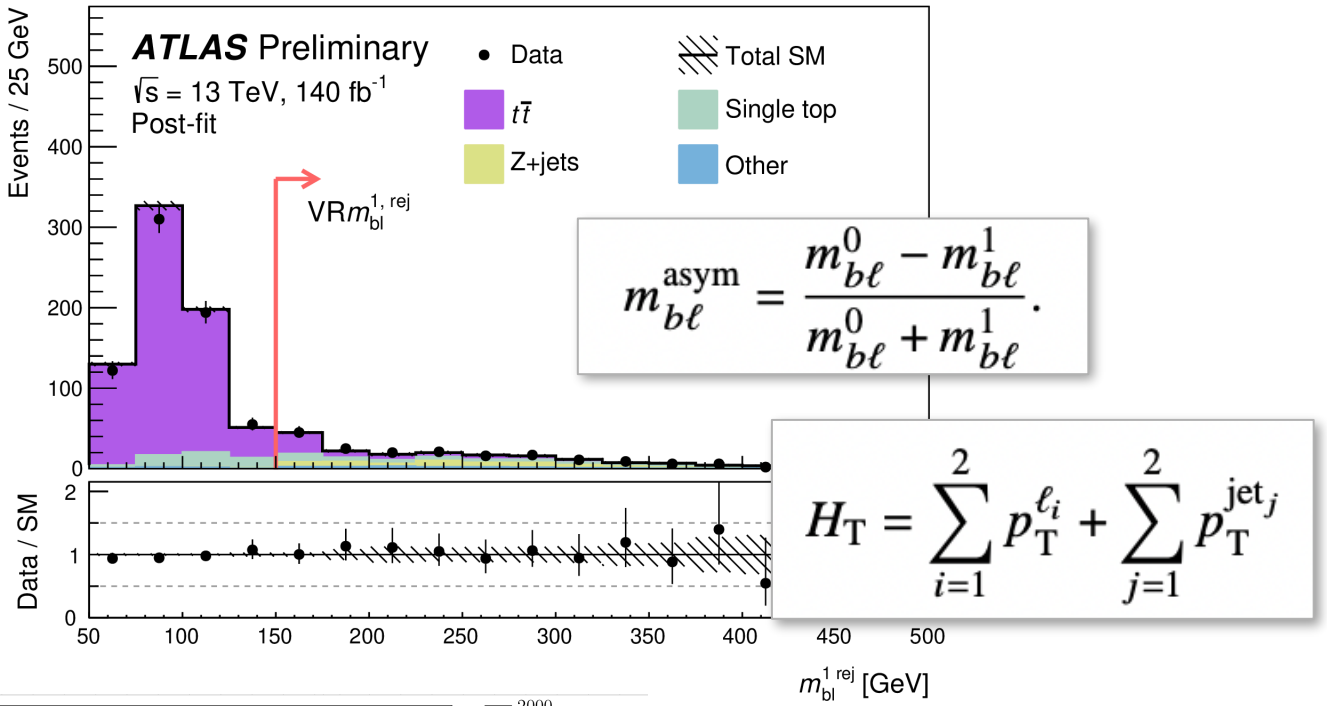


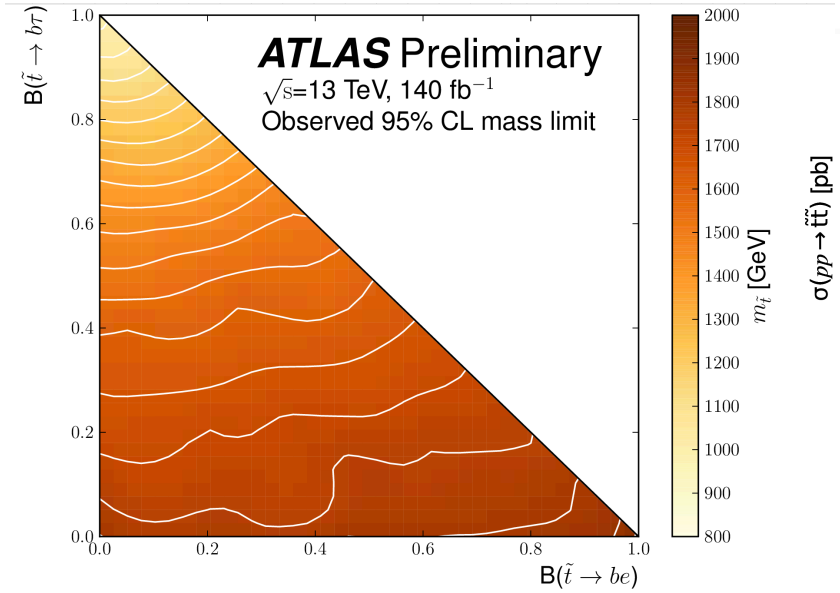
$\tilde{t}$ and anti-$\tilde{t}$ ($\tilde{t}^*$) decay to charged lepton and b quark through RPV coupling (λ)

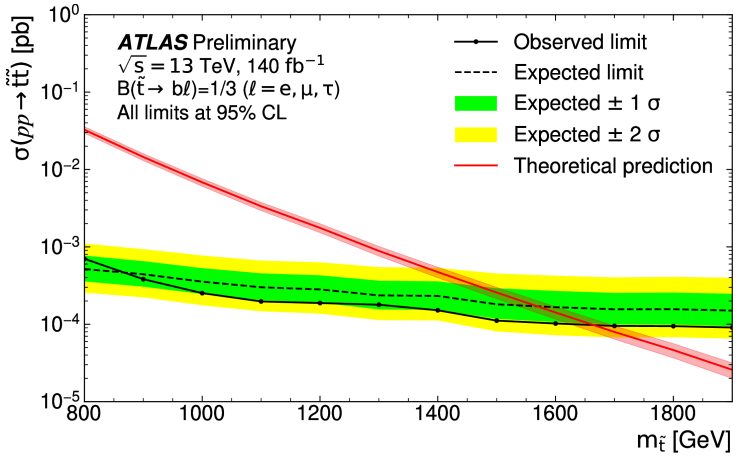
Results

- Cuts on kinematic variables: HT m_{ll} m_{asym} m_{bl} to improve signal sensitivity
- Variable bin-width signal region
- Two exclusion fits for each stop mass + lepton BR combination
- Result: No excess found, but mass limit improved upon early run 2 results

1400 GeV →1800 GeV for BR(t̃ → μ) =100%
1500 GeV → 1900 GeV for BR(t̃ → e)=100%
600 GeV → 1100 GeV for BR(t̃ → τ)=90%



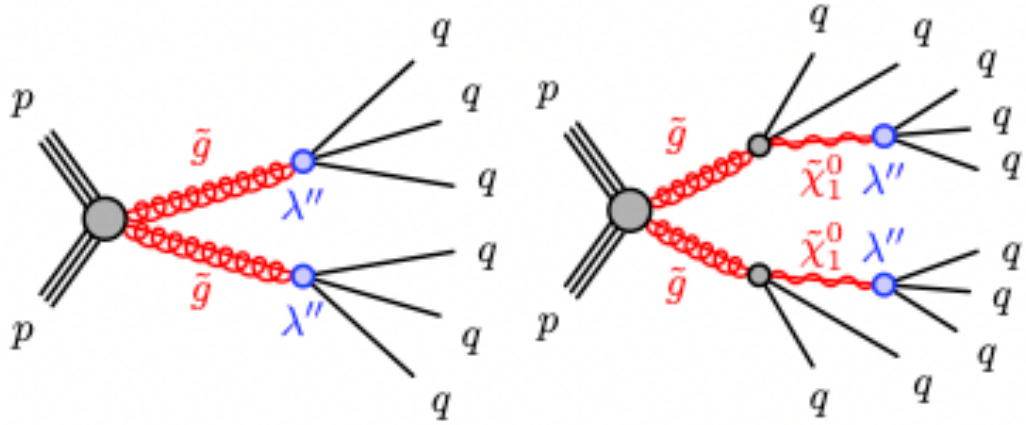




RPV in Many Jets final state

SUSY-2019-24

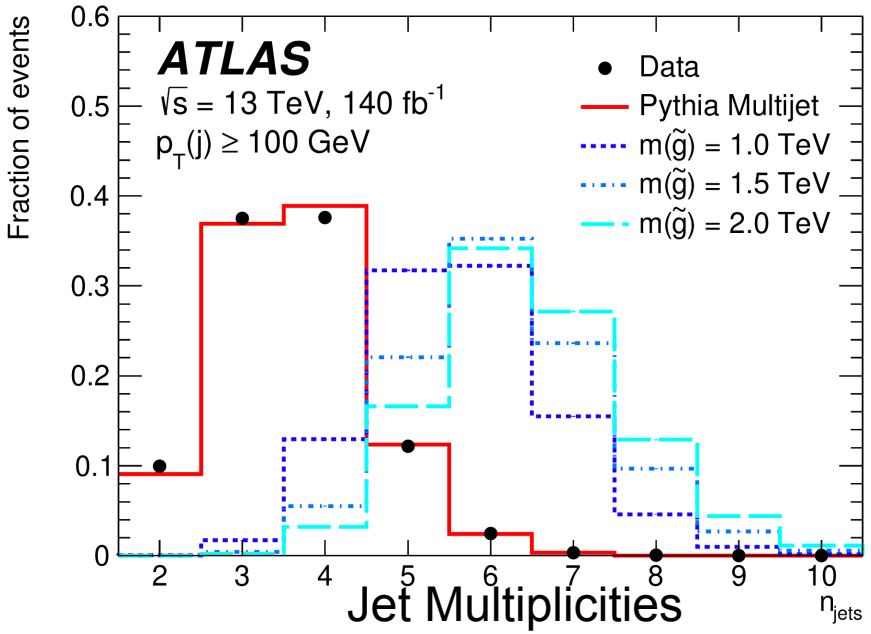
- R-parity Violating have looser limits compared to similar RPC searches.
- Prompt gluino-pair production using simplified models
  - 1. Direct decay into 3 jets
  - 2. Cascade decay via neutralino to 5 jets
  - All jet originated from either light quark(UDS) or can contain a heavy flavor jet(UDB)
- Dominant SM background: multijet prodution
- Two methods to improve S/B ratio:
  - "Jet Counting": requiring many high PT jets
  - "Mass resonance" aims to reconstruct the gluino mass with machine-learning methods



1. Gluino Decay 2. Cascade Decay

Results: Jet Counting Method

- Background is estimated by extrapolation from the low jet multiplicity region to a high jet multiplicity region.
- Cuts to improve sensitivity:
  1. C-parameter: a measure of isotropy of the energy distribution in events.
  2. Number of b-tags, Giving sensitivity to models including b-jets in the decays
- Multiple signal region for different b-tag selections based on signal contamination



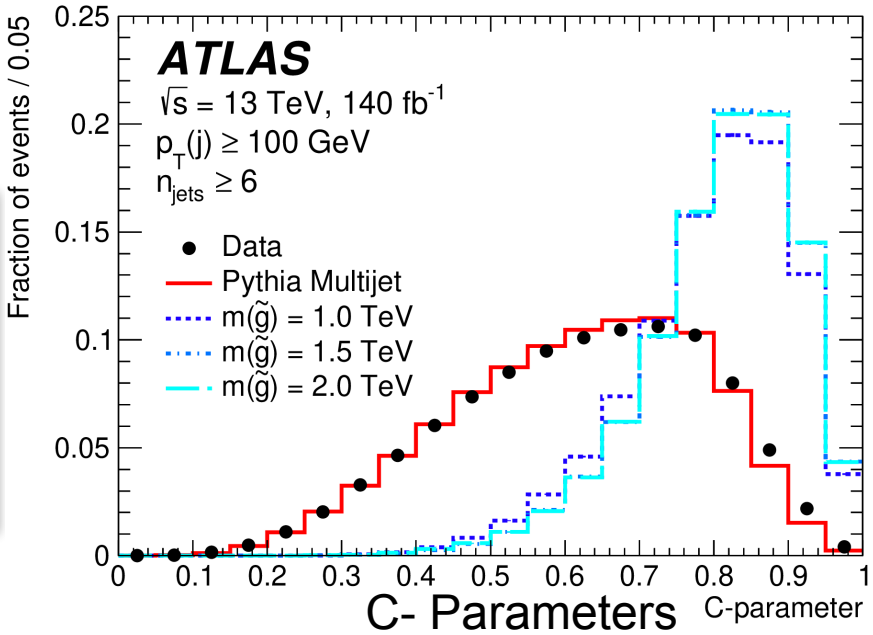
Multiple Signal Regions

	n_{jets}	$p_{\text{T}}(j)$ [GeV]	C	$n_{b-\text{jets}}$
SR1		180		-
SR2	≥ 7	220	≥ 0.90	-
SR3		240		-
SR4	≥ 8	180	≥ 0.85	-
SR5	≥ 8	210	≥ 0.85	-
SR1bj	≥ 7	180	≥ 0.85	≥ 2
SR2bj	≥ 8	180	≥ 0.85	≥ 2

Background Estimation by Extrapolation

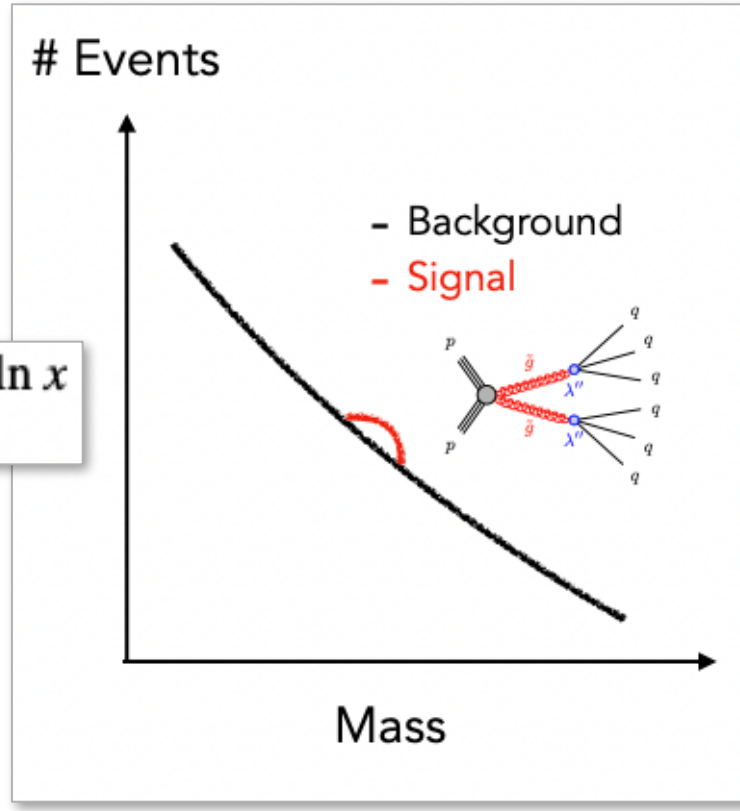
$$N^{\text{extr.}}_{\geq 7\text{jets}} = \sum_{i=7}^{9} w_{5i} \cdot N^{\text{Data}}_{5-\text{jets}} \cdot \frac{N^{\text{MC}}_{i-\text{jets}}}{N^{\text{MC}}_{5-\text{jets}}}$$

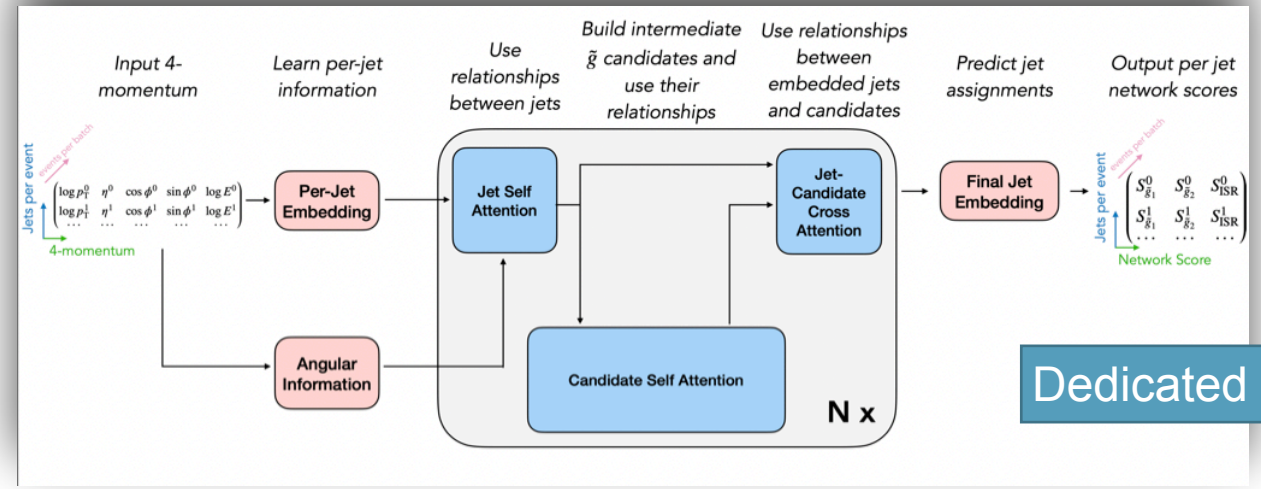
$$w_{5i} = \frac{s_i}{s_5}; \qquad s_i = \left.\frac{N^{\text{Data}}_{i-\text{jets}}}{N^{\text{MC}}_{i-\text{jets}}}\right|_{p_{\text{T}} \geq 60\ \text{GeV}}$$



Mass Resonance Method

- Dedicated neural network to reconstruct gluino from four momenta.
  - Training on all 5 mass points simultaneously.
    - Uses ML to identify 3 jets from the direct gluino decay and reconstruct the gluino mass from the grouped jets.
- Background estimation with fit functions $f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x}$
- Bumphunt to search for signal



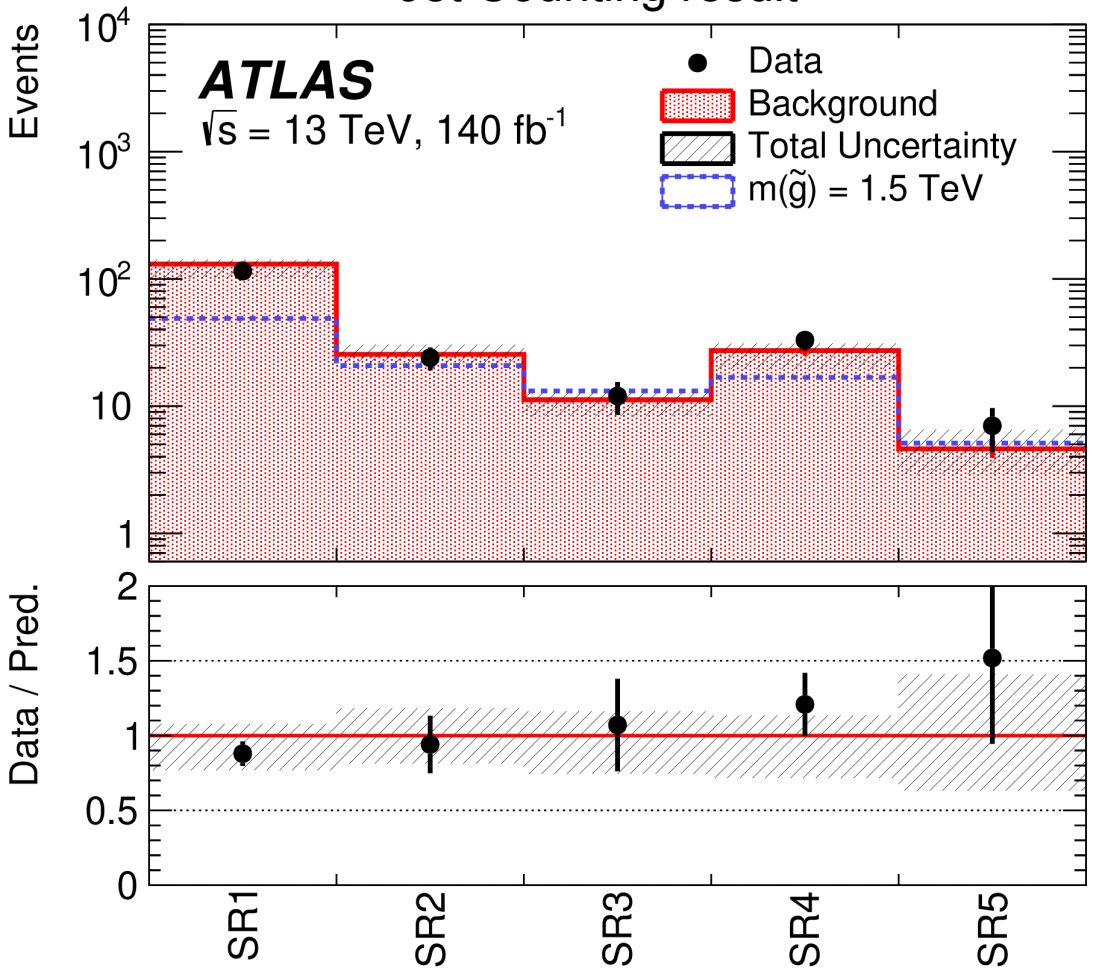


Dedicated Neural Network

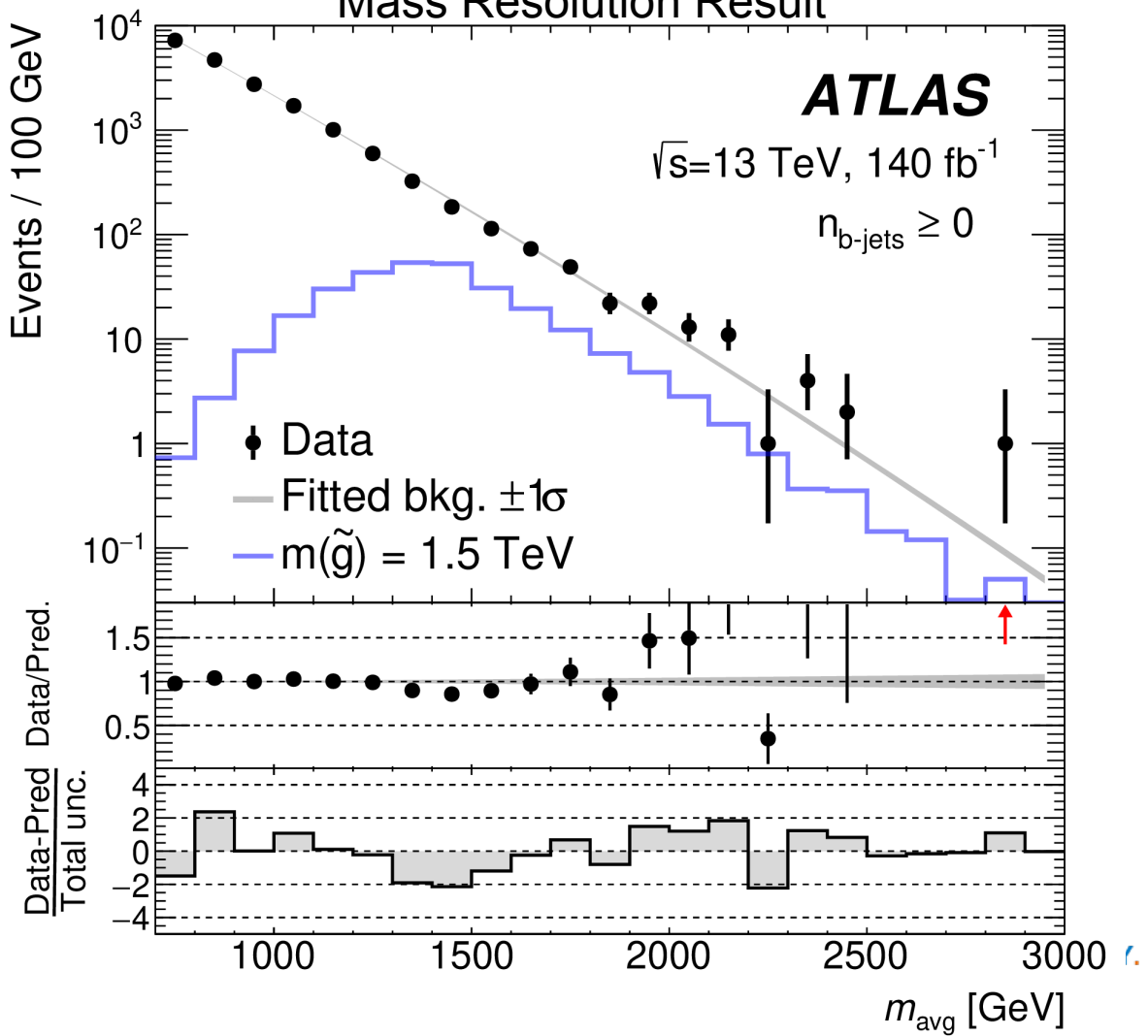
Model Independent Results

No excess observed in the jet counting/ mass resolution results

Jet Counting result

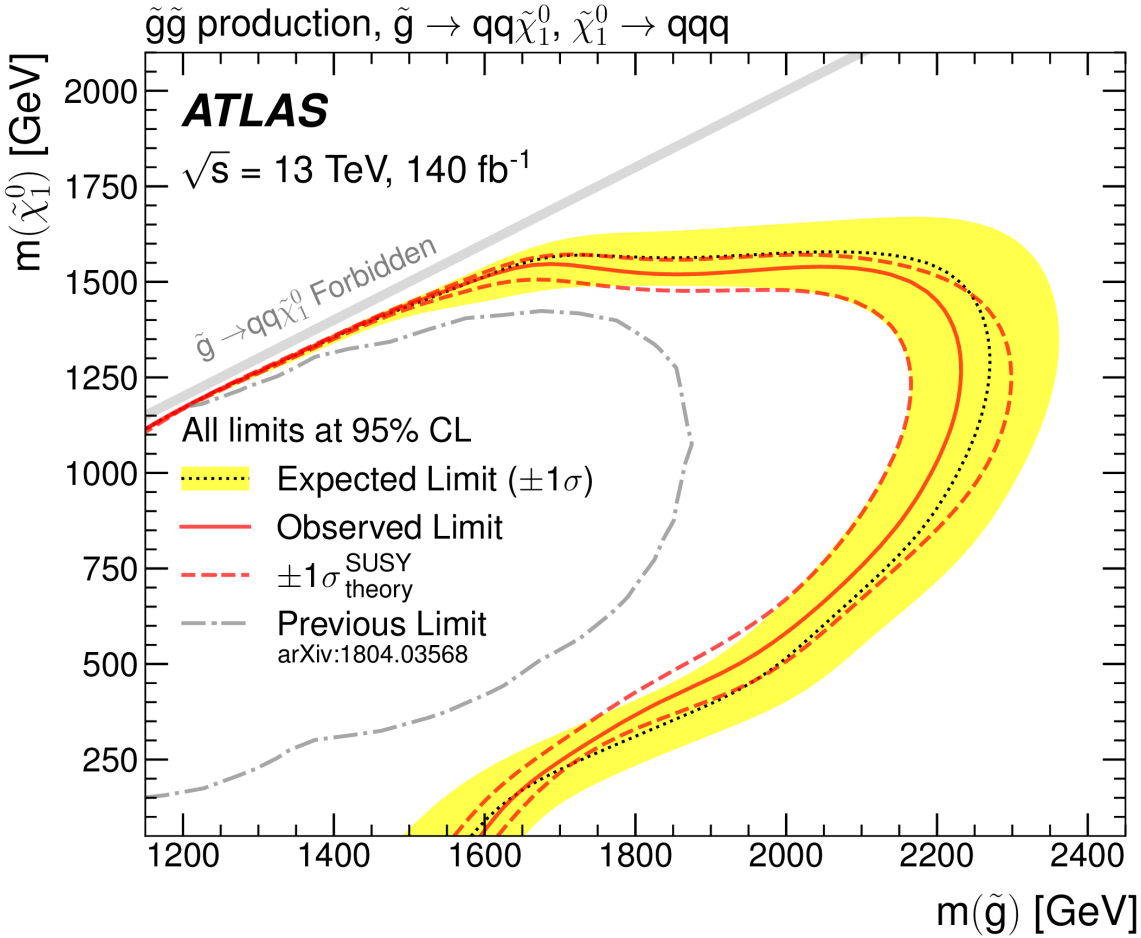


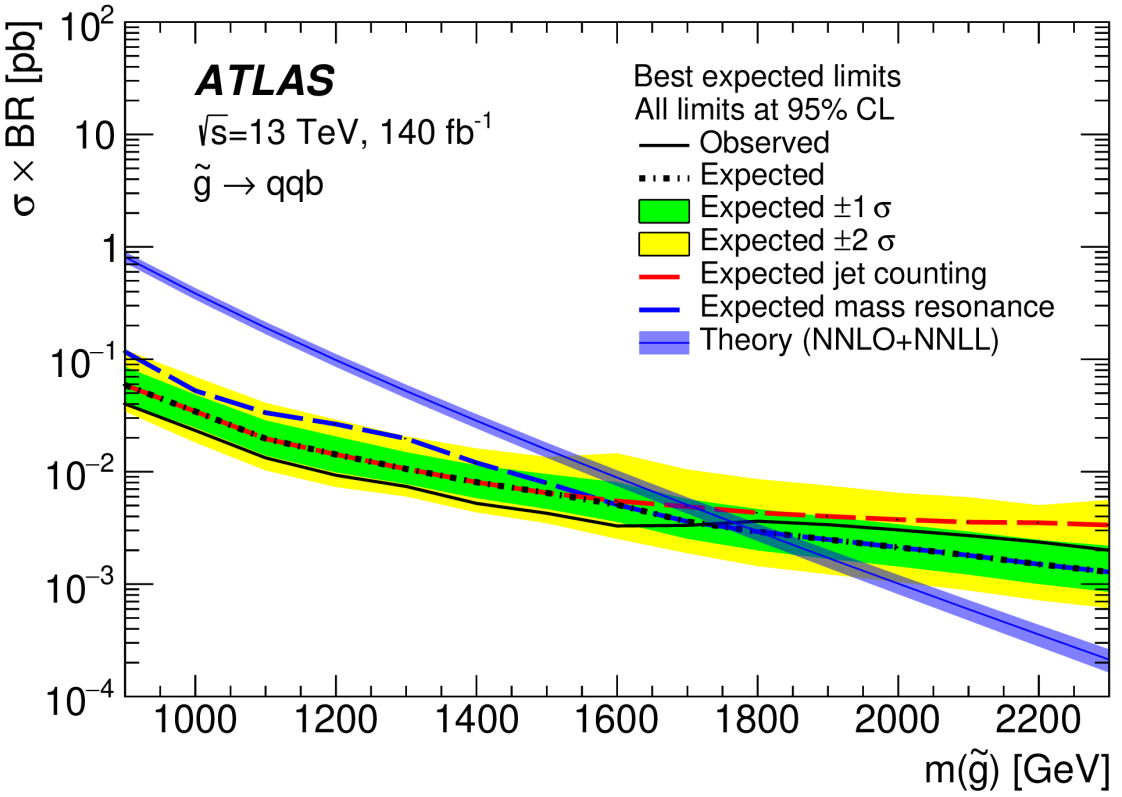
Mass Resolution Result



Model dependent limit

- No excessed found for either mass spectrum or jet counting results
- Improvement from results in Run 1 and early Run 2; No excess is found.

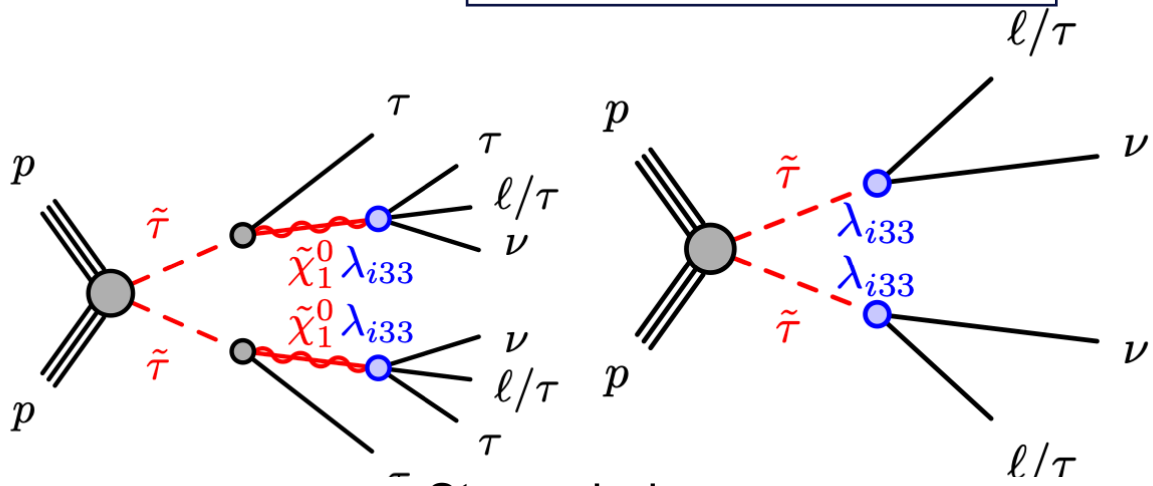




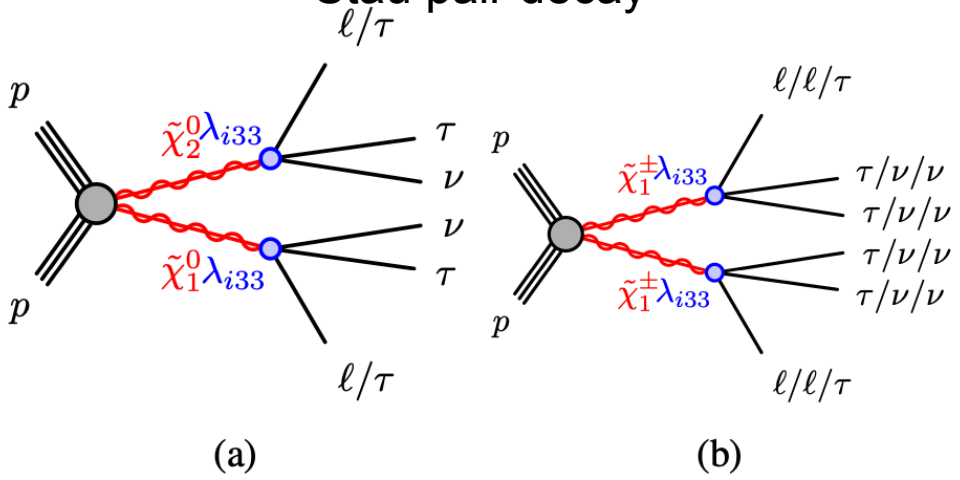
Reinterpretation of RPV SUSY with variable decay length in di-Tau final state

ATL-PHYS-PUB-2024-007

- Reinterpretation of SUSY search with two taus and with four electrons, muons, or taus performed previously.
  Ditau , 4 lepton analysis
- Model reinterpreted for SUSY models with R-parity violating(RPV) couplings with lifetime
- Signal models: Staus/Higgsinos pair decay into SM particles.



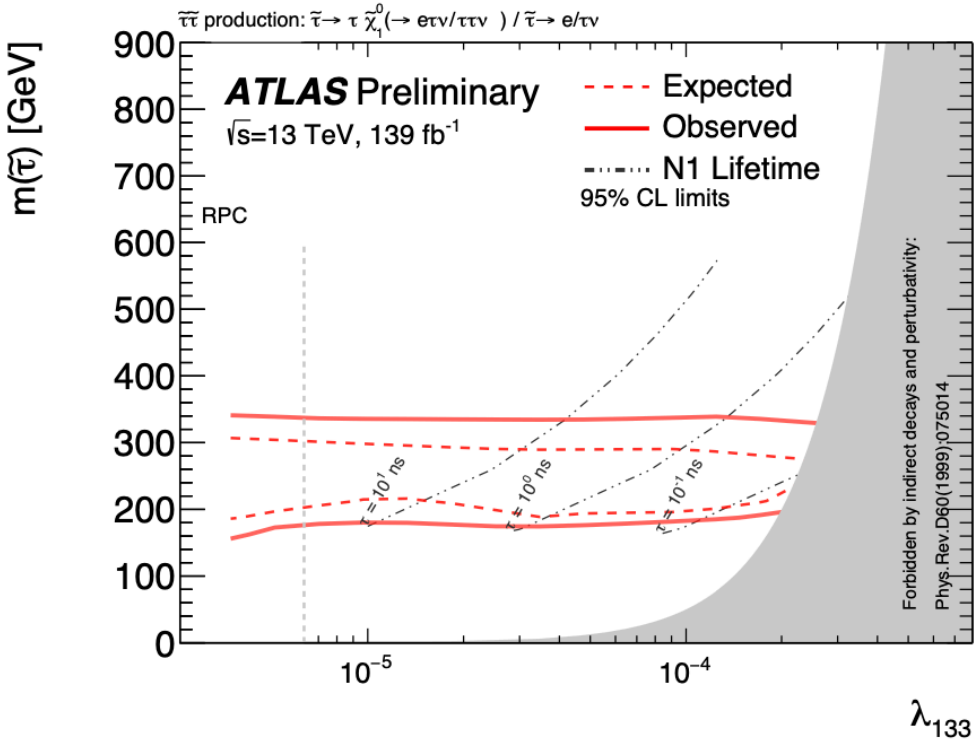
Stau pair decay

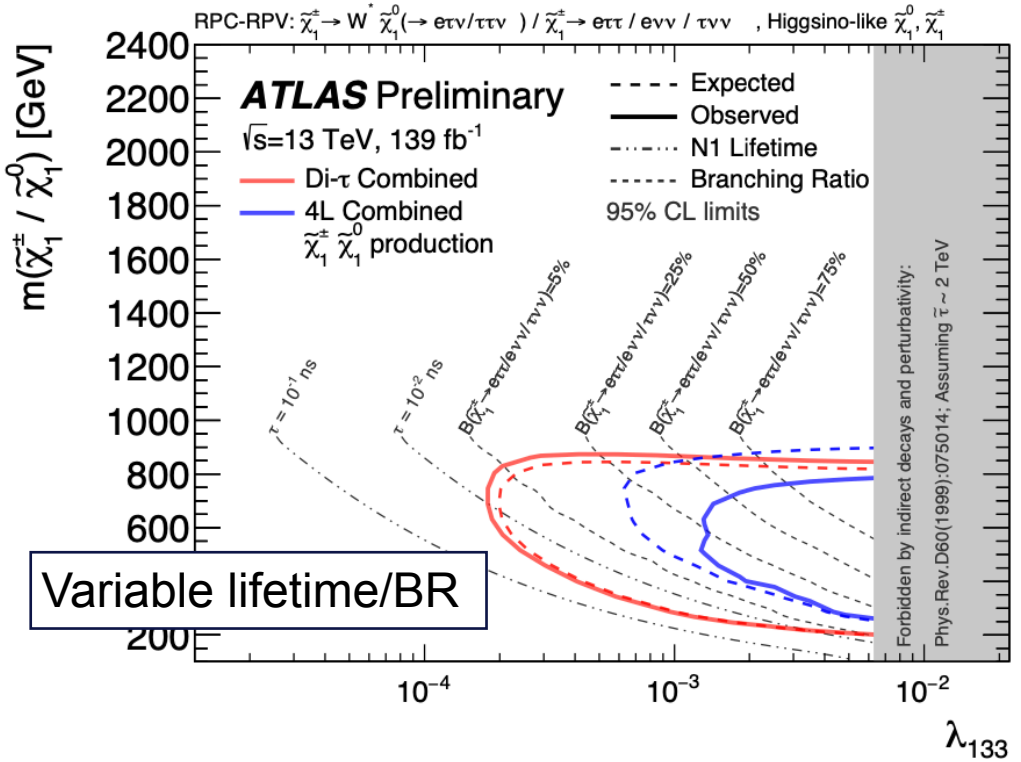


Higgsino pair production

Results

- Limit set on λ_{133} and λ_{233} from the Higgsino and stau decay channels.
- Systematics of displaced taus estimated by Zjet and ttbar samples
- First result in this channel/RPV Model

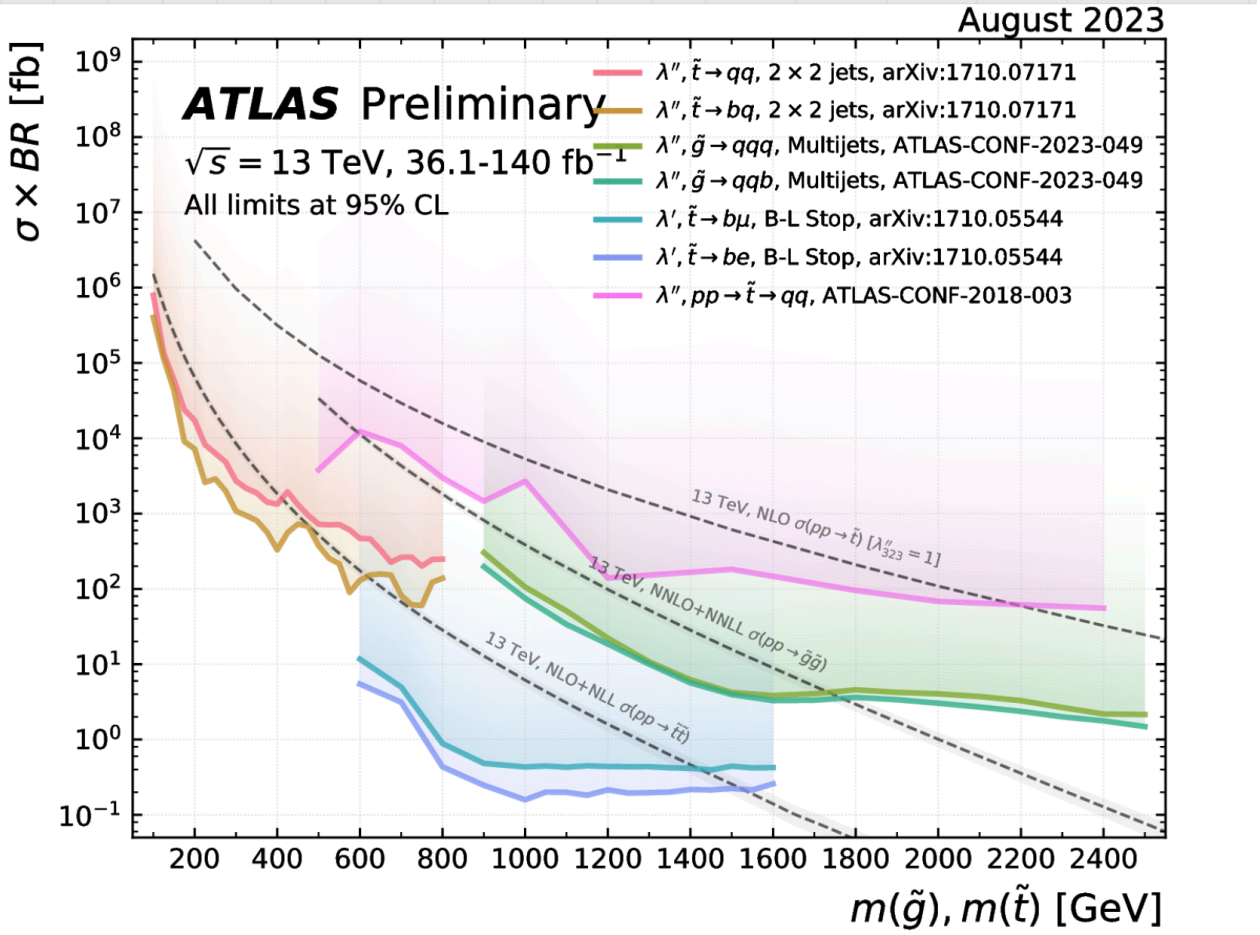




Summary

- 3 latest ATLAS results in non-minimal SUSY model are presented
- Novel ways of challenging existing model
- More full run 2 and early run3 results to be expected soon!

- See SUSY Public Result Page and ATLAS Summary Plots for more information



Back up slides

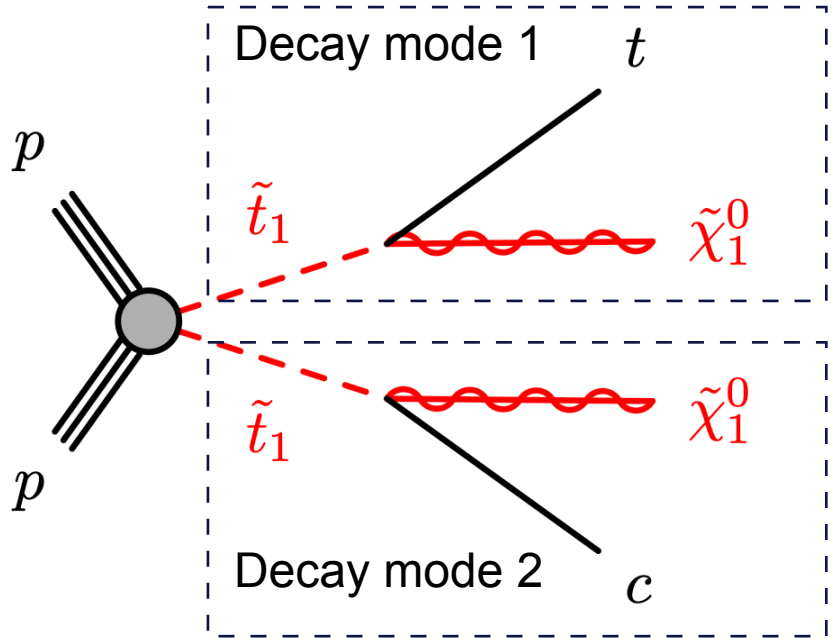
Mass Resonance Method

Stop to t c MET

SUSY-2019-23

ANA-SUSY-2018-37

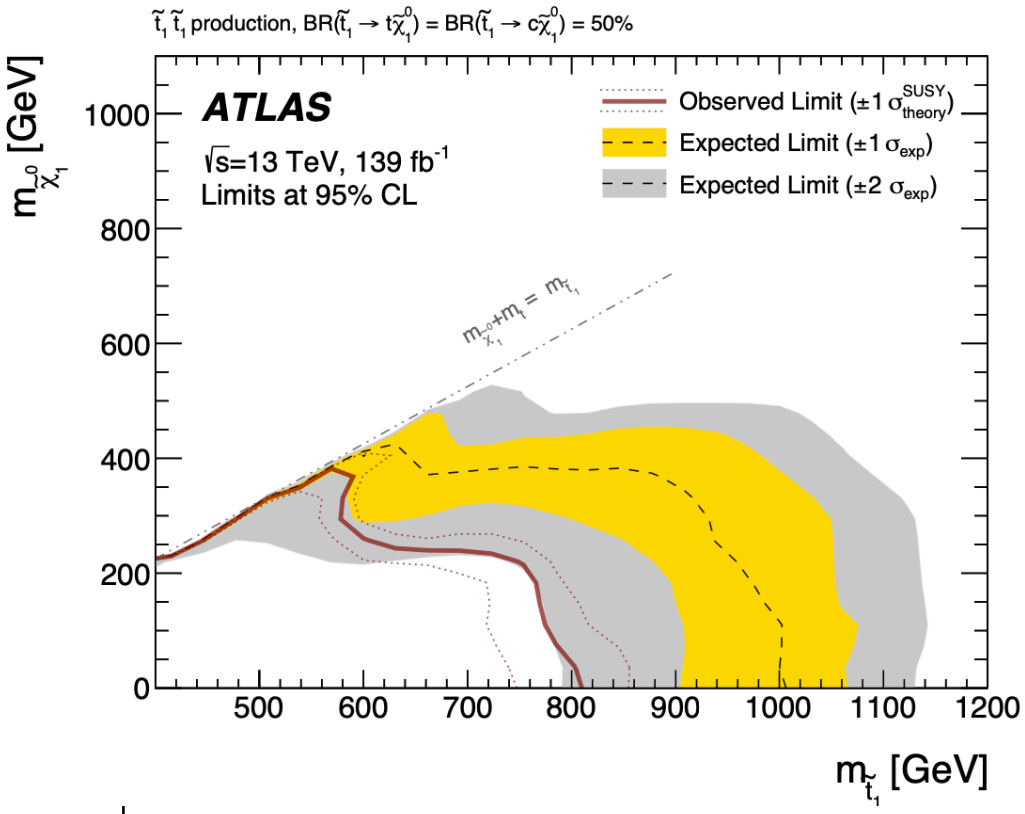
- Final state of two top-squark production to top/neutralino production
- Motivated by: extended MSSM, non-minimal flavor violation in the 2nd and 3rd squark sector.
- Long list of variables to help with signal/background optimization
- Different Signal region defined by differnet mass splitting of the top-squark/neutralino pair
  - Bulk (SRA): large mass difference between stop and neutralino
  - Intermediate (SRB, SRC): small mass difference between stop and neutralino
  - Compressed (SRD with ISR): mass difference between stop and neutralino=top mass

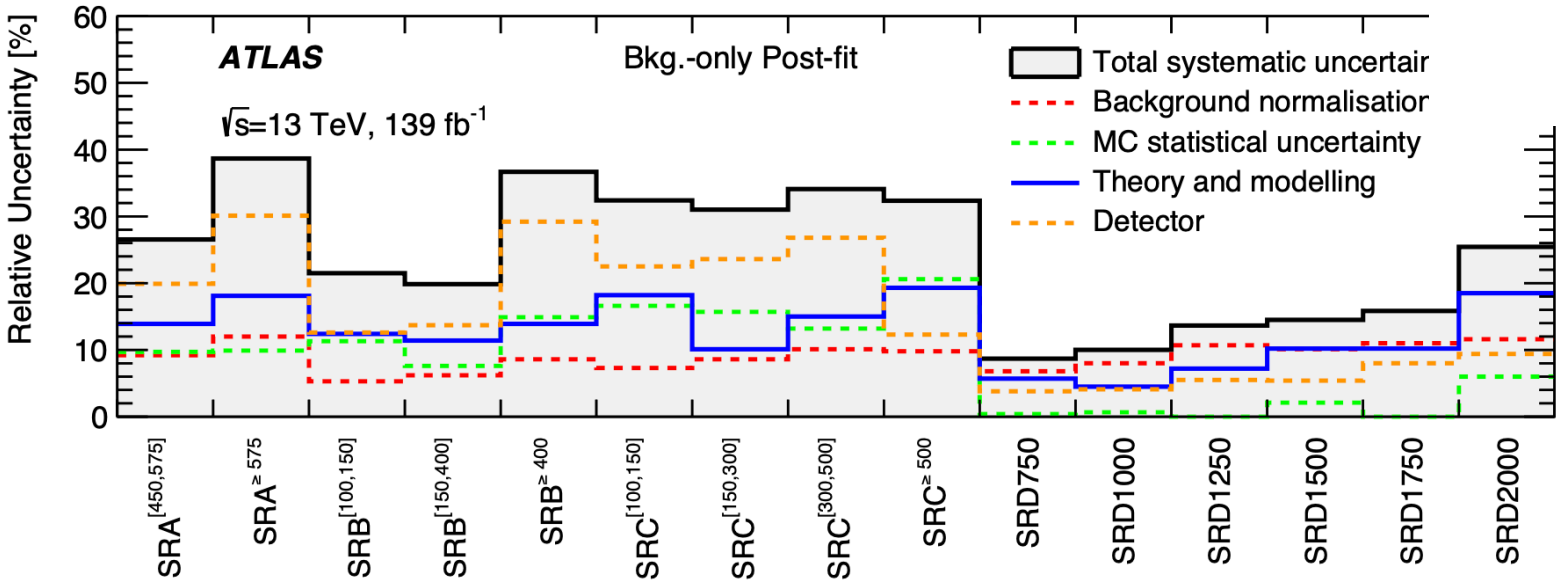


3 different decay channels of different top-squark decaying mode combinations

Results

- No excess seen.
- Tightest limit set for the final state seen





RPV SUSY with leptons and jets final state

- Setting limit on R-parity violating SUSY models on RPV decay with at least 1 isolated lepton
- RPV decay with at least 1 isolated lepton (electron/muon) and 8-15 jets of various on the transverse momentum threshold.
- These final states are common in baryon number violating(2 leptons of the same charge) or baryon-number violating RPV models (1 lepton event)
- Multi-variate discriminants used.
- This is the first RPV SUSY electroweak production decaying to quarks.
- Bkg estimation sensitive to the normalization of the 4 top quark production

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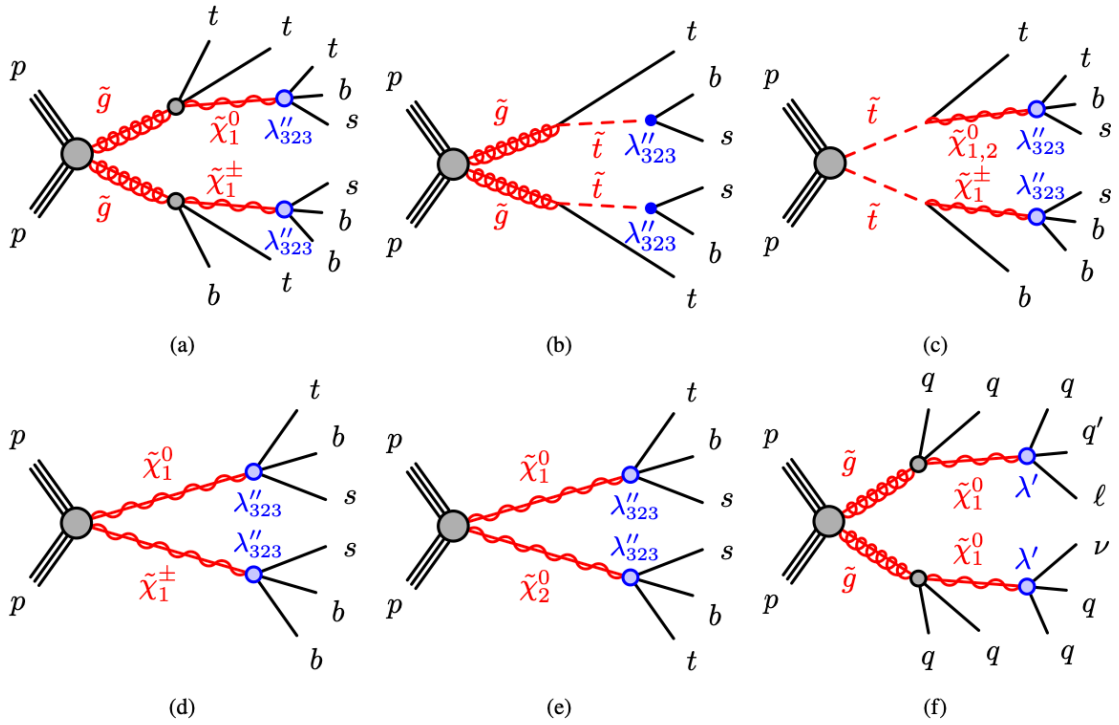


Possible decay channels

Methods and Results

- Signal regions
  A. 1 lepton category: 1 isolated muon/electron
  B. 2 leptons same charge category: suppressed electron charge flip by a BDT.

  Two ways of doing the analysis:
  1. jet counting analysis(Strong production)
  2. Electroweak analysis(Electroweak production)

  NN was introduced for the Electroweak analysis for improved signal/background discrimination. Two-level (high level/ low level) distance correlation training ensures b-jet multiplicity invariance is achieved.

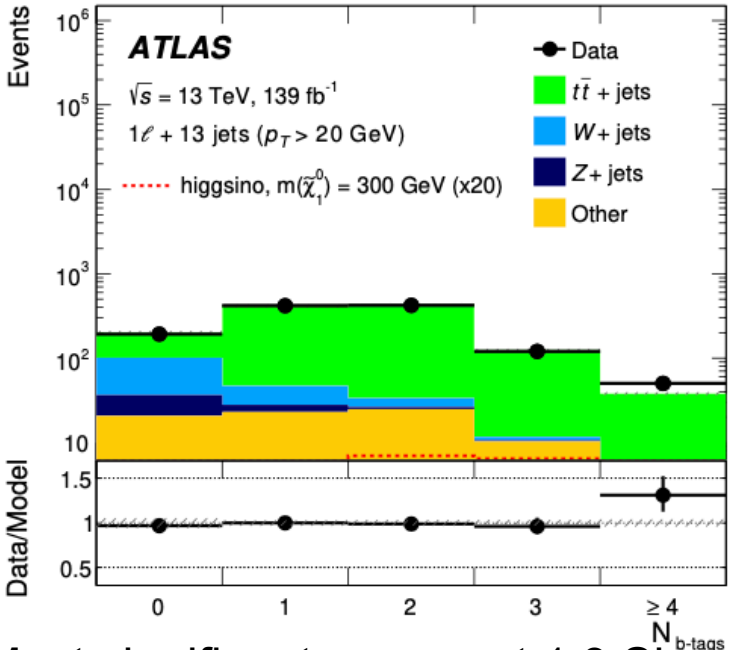
- SM-> 4 top measured as a background process.

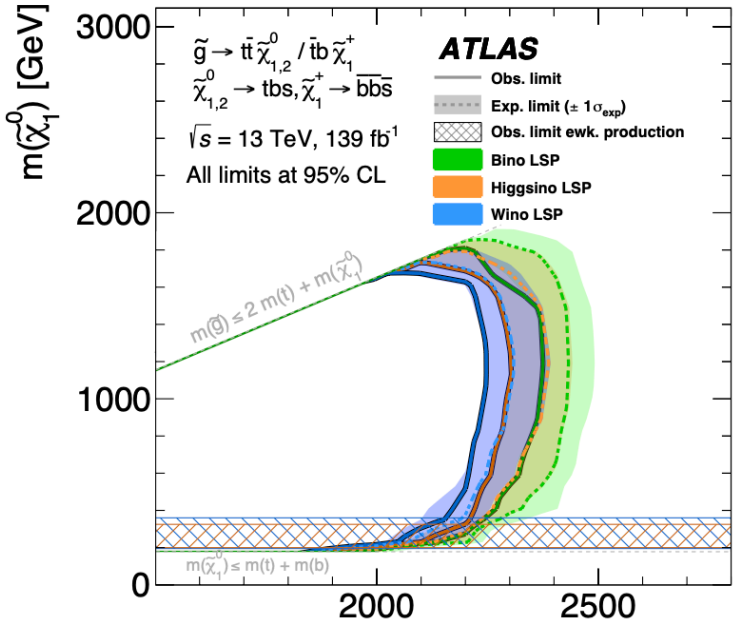
- Results: No significant excess.

- Interpreted results featuring gluino, stop, or electrowekino pair production in PRV supersymmetry scenarios.

LSP type	Branching ratios: stop $t\tilde{\chi}^0_{1,2}$	stop $b\tilde{\chi}^\pm_1$	gluino $tt\tilde{\chi}^0_{1,2}$	gluino $bb\tilde{\chi}^0_{1,2}$	gluino $tb\tilde{\chi}^\pm_1$	Cross-section [fb] for direct production $\tilde{\chi}^\pm_1\tilde{\chi}^0_1$	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$	$\tilde{\chi}^0_2\tilde{\chi}^0_1$
Bino	100%	0%	100%	0%	0%	0	0	0
Wino	33%	67%	17%	17%	66%	387	0	0
Higgsino	50%	50%	50%	0%	50%	91	91	52

Different LSP type, branching ratio of models
26 floating parameters in the background model; 41 in EWK analysis





Most significant excess at 1.3 Sigma(Local).

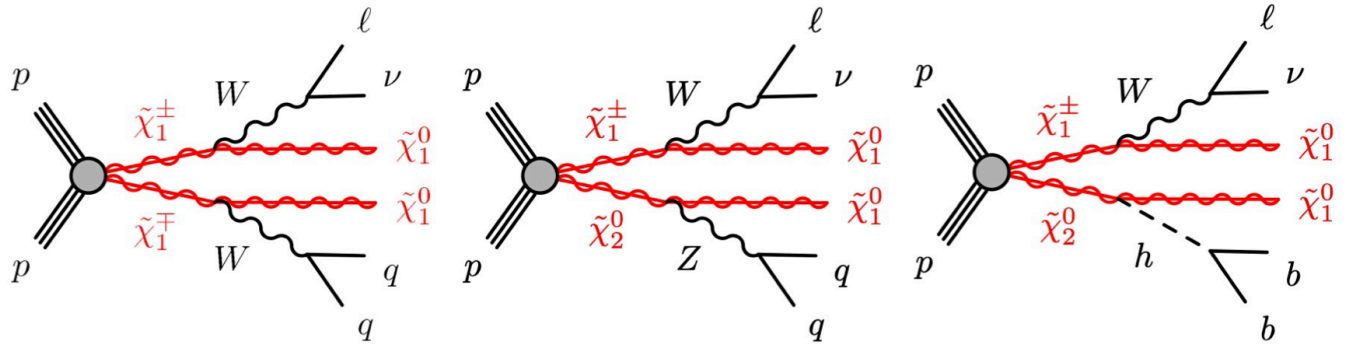
Gluino, Stop, Bino, Wino electroweak RPV limits

ANA-SUSY-2018-37

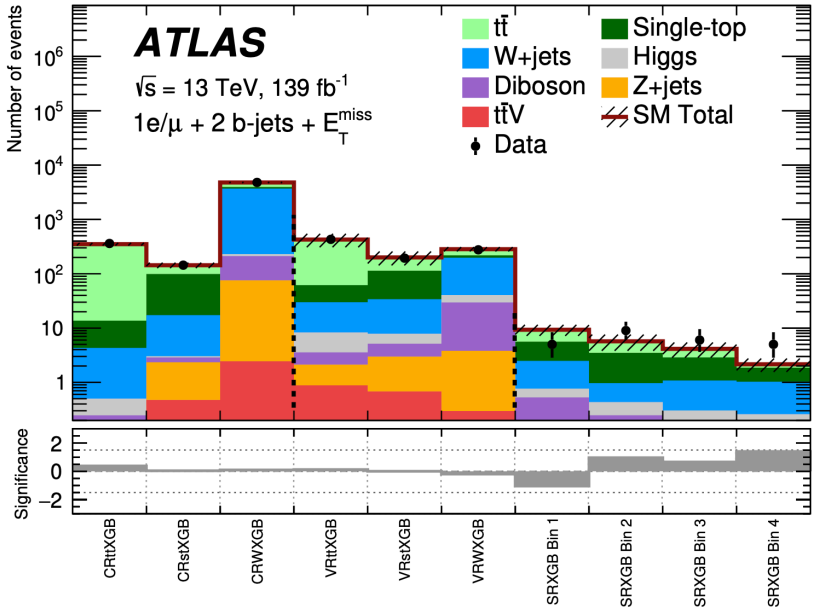
Search for direct production of electroweakinos in final states with one lepton, jets and missing transverse momentum

- Final state: electroweakinos decay into 1 lepton, jets and MET
- Targeting direct EWK production of chargino-neutralino pairs and chargino pairs, decaying into LSP via W/Z and on-shell Higgs bosons.
- LSPs (Lightest SUSY Particles), specifically the lightest neutralino χ^0 and its decay mechanisms, in the adopted simplified SUSY model, could explain the observed discrepancy in the g-2 measurement with respect to the SM predictions and itself plays an important role as a Dark Matter candidate

The three decay channels studied



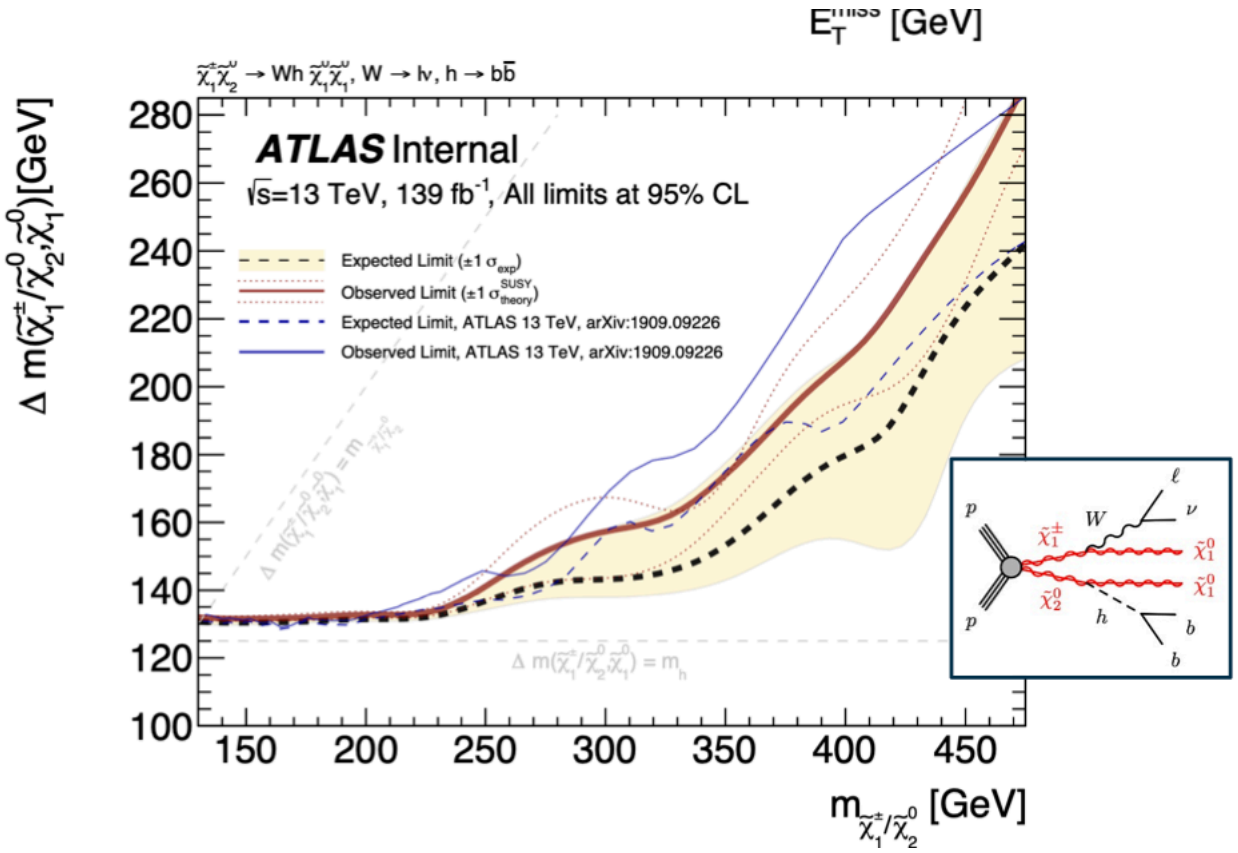
C1C1_WW **C1N2_WZ** **C1N2_Wh**



Data-driven bkg estimation from CR

Results

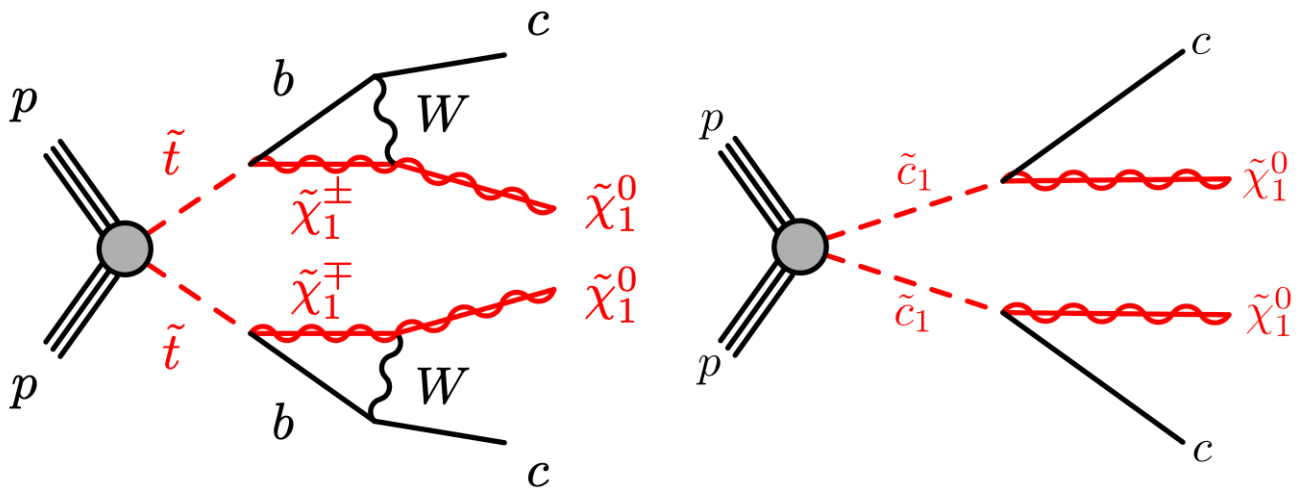
- BDT-based C1N2$_{Wh}$ search for LSP exceeds previous constraints by up to 40 GeV in the range of 200 − 260 GeV and 280 − 470 GeV in $\tilde{\chi}1\pm/\tilde{\chi}20$ mass.
- Searches exploiting large radius jets to identify hadronically decaying W and Z bosons improve on the previous ATLAS limits by around 100 GeV in $m(\tilde{\chi}1\pm)$ for a massless $\tilde{\chi}10$.
- No excess identified



Search for supersymmetry in final states with missing transverse momentum and charm-tagged jets

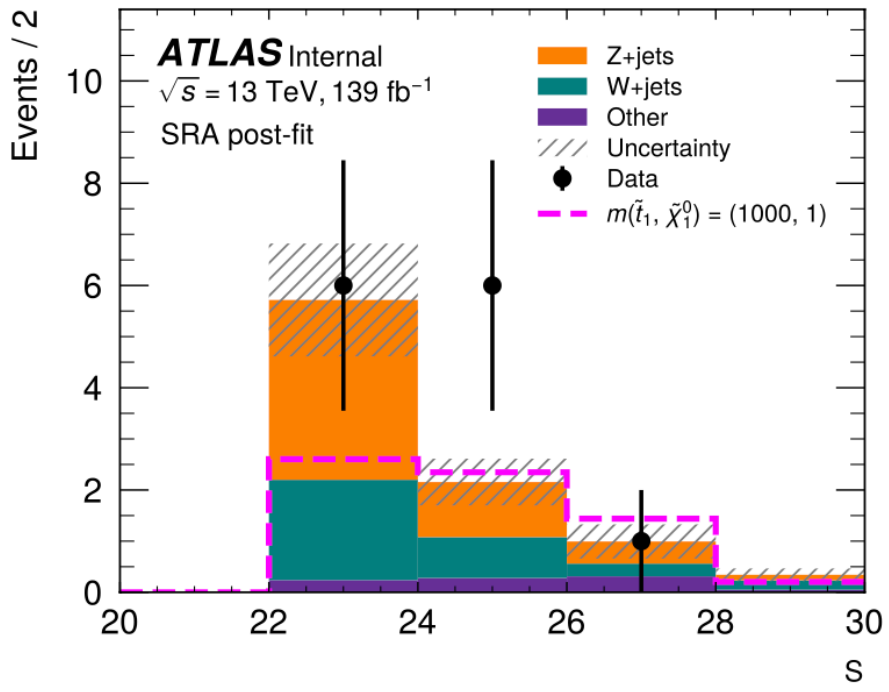
ANA-SUSY-2018-25

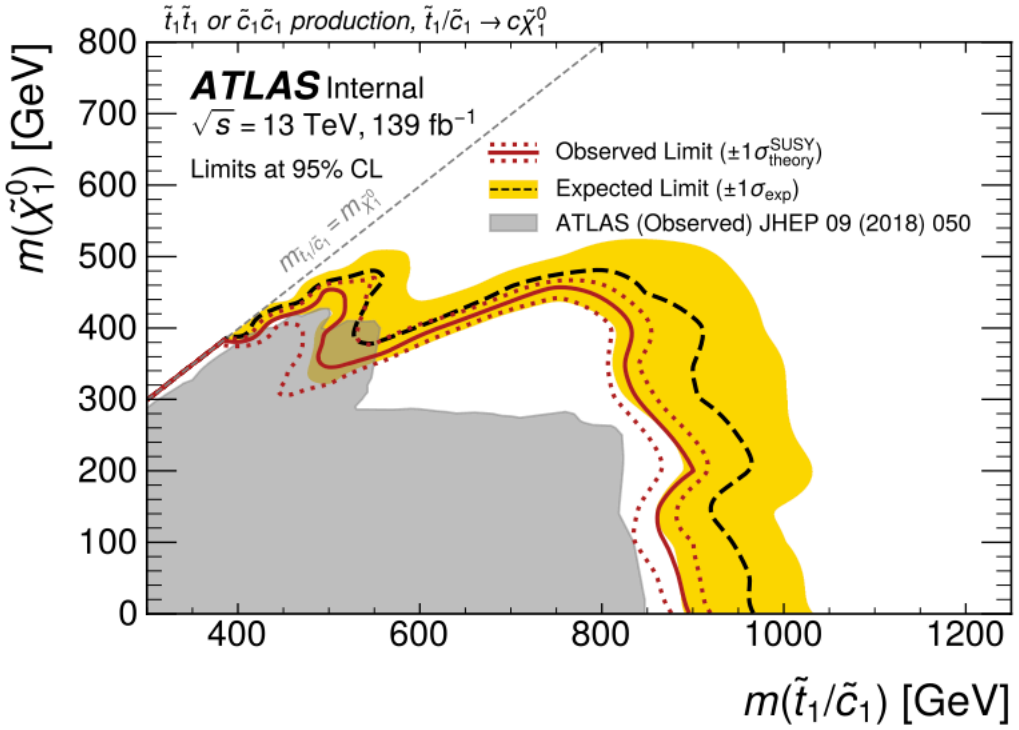
- Final state of charm and MET
- Looking at SUSY models where top or charm squarks ($\tilde{t}/\tilde{c}$) are the lightest squarks with masses less than about one TeV
- 2 signal regions: High-Mass and Compressed
- Recursive Jigsaw Reconstruction for top/ charm pair production improvement



Results

- No excess found
- Stringent limit set on the model





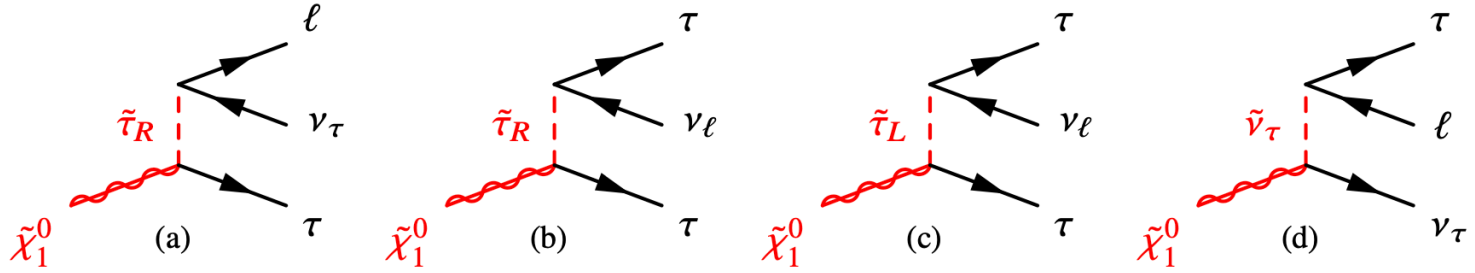


Figure 1: LSP possible decay channels

SR-C1C1-LM	SR-C1C1-HM	SR-C1N2OS-LM	SR-C1N2OS-HM
b-jet veto			
Z/h veto			
= 2 "medium" τ_{had} (OS)		≥ 2 "medium" τ_{had} (OS)	
≥ 1 "tight" τ_{had}	-	≥ 1 "tight" τ_{had}	-
60 GeV < $E_{\text{T}}^{\text{miss}}$ < 150 GeV	$E_{\text{T}}^{\text{miss}}$ > 150 GeV	60 GeV < $E_{\text{T}}^{\text{miss}}$ < 150 GeV	$E_{\text{T}}^{\text{miss}}$ > 150 GeV
m_{T2} > 80 GeV	m_{T2} > 85 GeV	m_{T2} > 70 GeV	m_{T2} > 85 GeV
$\lvert\Delta\Phi(\tau_1,\tau_2)\rvert$ > 1.6	m_{Tsum} > 400 GeV	N_{jets} < 3	m_{Tsum} > 400 GeV

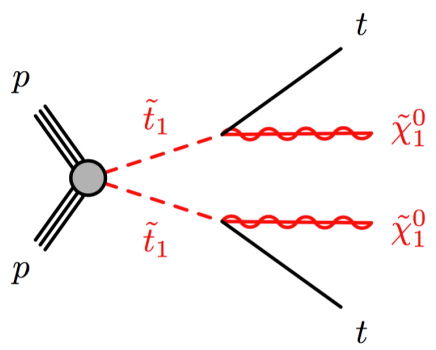
R-Parity Conservation (RPC) SUSY vs R-Parity Violation (RPV) SUSY

- ATLAS usually uses simplified models where the LSP is either stable (RPC) or decay promptly to SM particles (RPV)
- Both allows for searches for promptly decay final state objects
- R-partity Violation terms allowed for tuning -> LSP with a life time

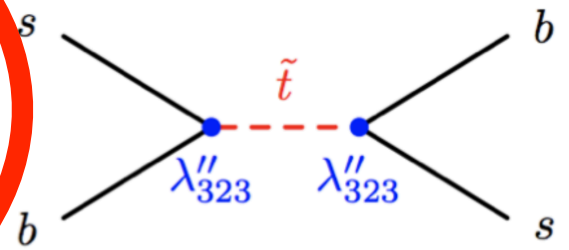
Between R-parity conservation/Maximal Violation….

Lepton Number Violation Baryon Number Violation

Stop -> neutralino decay example



A gap where RPC and RPV meets (Our Effort)



RPC: Stable LSP

0

RPV: LSP prompt decay to SM particle

O(1) λ''_{323}

*λ and λ' are assumed to be 0

DESY.

SUSY-2018-37

A search for R-parity violating supersymmetric decays of the top squark to a b-jet and a lepton in ATLAS experiment
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https://cds.cern.ch/record/2897962/files/SUSY-2018-37-002.pdf

A search is presented for direct pair production of the stop, the supersymmetric partner of the top quark, in a decay through a R-parity-violating coupling to a charged lepton and a b-jet. The final state has two charged leptons and two b-jets. Limits are set on this production in a Minimal Supersymmetric Standard Model with an additional $B - L$ gauge symmetry. This model violates lepton number but not baryon number, and is consistent with proton stability and the bounds on lepton number violation

SUSY-2022-07