Exploring the frontier of R-parity-violating supersymmetry with the ATLAS detector

EPS-HEP Conference 2021

on behalf of the ATLAS Collaboration
Michael Holzbock (MPP)

July 26, 2021

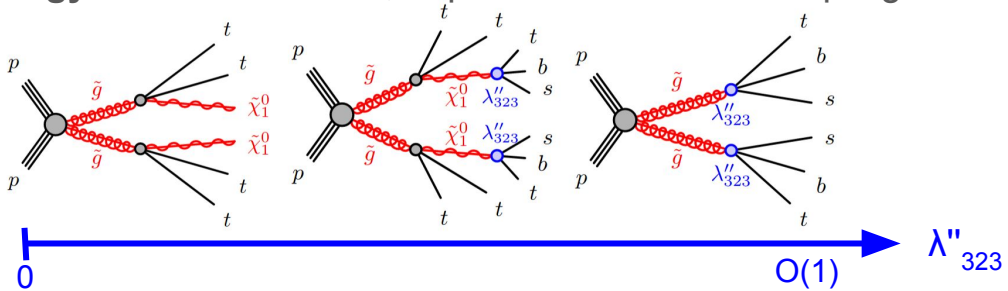
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Introduction

- Most general, renormalizable superpotential contains lepton- and baryon-number violating terms

$$W_{\not R_p} = \underbrace{\mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k}_{\text{L-violating}} + \underbrace{\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k}_{\text{B-violating}}$$

  Simultaneous violation of L and B strongly constrained from proton and neutron decays
  - SUSY models often *ad-hoc* impose conservation of ***R*-parity**: $R_p = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$
  - *R*-parity violation (RPV) scenarios as justified as RPC models by imposing other conditions or discrete symmetries
- Much weaker limits on couplings violating L/B-only (in particular for third generation)
- **Rich phenomenology** in RPV scenarios, dependent on size of couplings



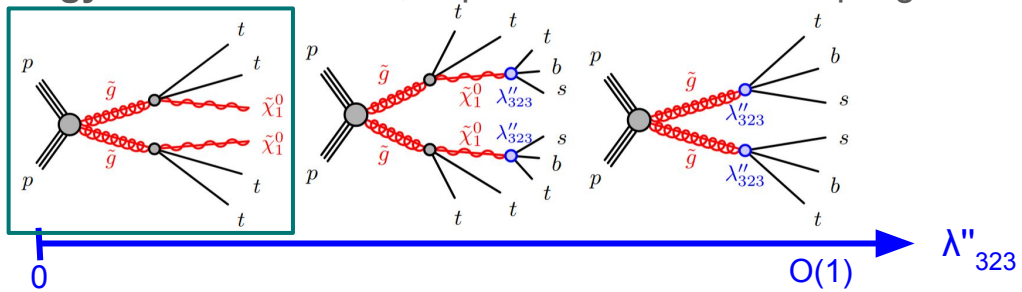
Introduction

- Most general, renormalizable superpotential contains lepton- and baryon-number violating terms

$$W_{\not R_p} = \underbrace{\mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k}_{\text{L-violating}} + \underbrace{\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k}_{\text{B-violating}}$$

  Simultaneous violation of L and B strongly constrained from proton and neutron decays
  - SUSY models often *ad-hoc* impose conservation of ***R*-parity**: $R_p = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$
  - *R*-parity violation (RPV) scenarios as justified as RPC models by imposing other conditions or discrete symmetries
- Much weaker limits on couplings violating L/B-only (in particular for third generation)
- **Rich phenomenology** in RPV scenarios, dependent on size of couplings

Stable LSP (RPC)



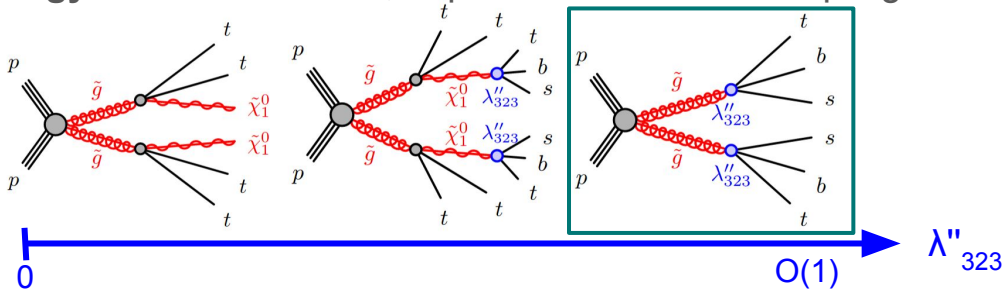
Introduction

- Most general, renormalizable superpotential contains lepton- and baryon-number violating terms

$$W_{\not R_p} = \underbrace{\mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k}_{\text{L-violating}} + \underbrace{\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k}_{\text{B-violating}}$$

  Simultaneous violation of L and B strongly constrained from proton and neutron decays
  - SUSY models often *ad-hoc* impose conservation of ***R*-parity**: $R_p = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$
  - *R*-parity violation (RPV) scenarios as justified as RPC models by imposing other conditions or discrete symmetries
- Much weaker limits on couplings violating L/B-only (in particular for third generation)
- **Rich phenomenology** in RPV scenarios, dependent on size of couplings

Direct decays of (N)LSP



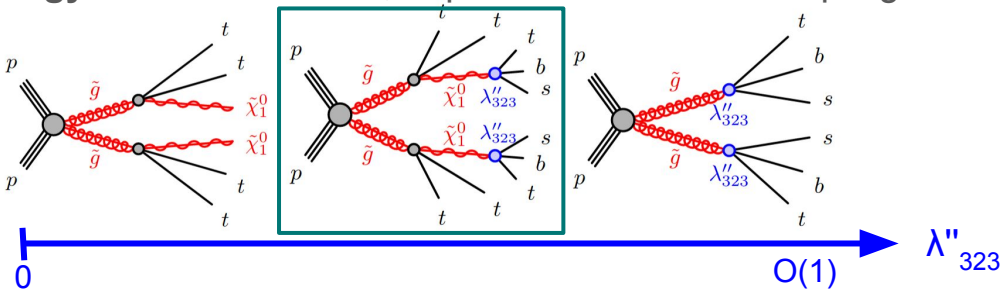
Introduction

- Most general, renormalizable superpotential contains lepton- and baryon-number violating terms

$$W_{\not R_p} = \underbrace{\mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k}_{\text{L-violating}} + \underbrace{\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k}_{\text{B-violating}}$$

  Simultaneous violation of L and B strongly constrained from proton and neutron decays
  - SUSY models often *ad-hoc* impose conservation of ***R*-parity**: $R_p = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$
  - *R*-parity violation (RPV) scenarios as justified as RPC models by imposing other conditions or discrete symmetries
- Much weaker limits on couplings violating L/B-only (in particular for third generation)
- **Rich phenomenology** in RPV scenarios, dependent on size of couplings

Decays of LSP
→ This talk!



RPV Searches at ATLAS

- LSP not stable but decays in RPV scenarios
  ➜ "Trade" E_T^{miss} for **high object multiplicities**
- Extensive RPV search program in ATLAS, presenting here only a subset

High Jet Multiplicities

- Multijet 1-lepton search: arXiv:2106.09609
- Multi b-jet search: Eur. Phys. J. C 81 (2021) 11

High Lepton Multiplicities

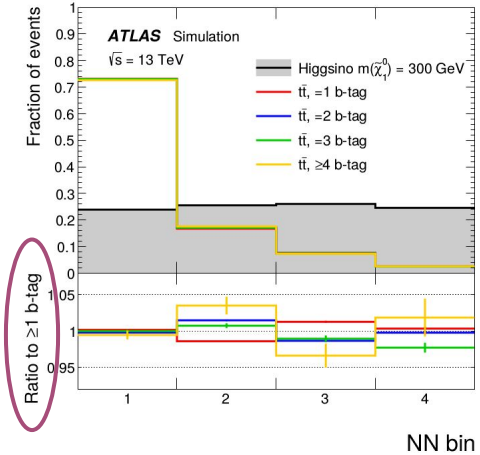
- 3L resonance search: Phys. Rev. D 103, (2021) 112003
- Multilepton search: arXiv:2103.11684

Multijet 1-Lepton Search

$$\lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k$$

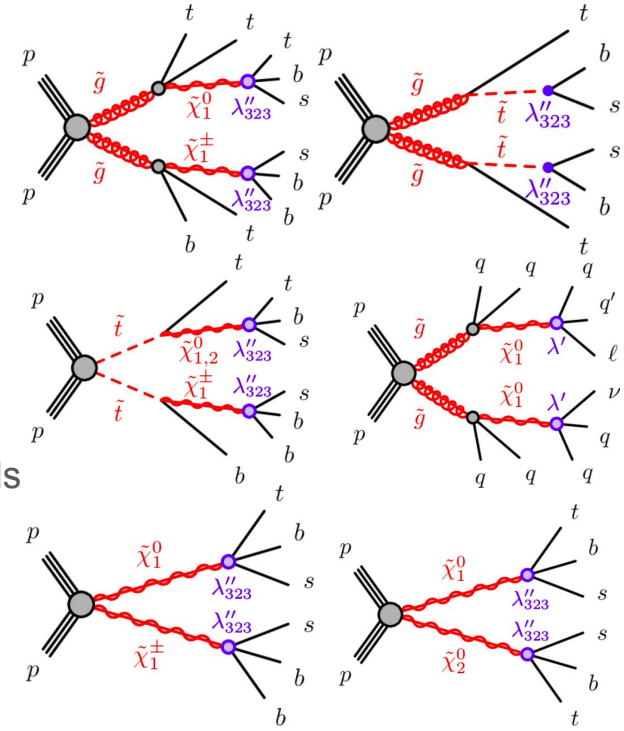
ATLAS-SUSY-2019-04

- Consider SUSY spectrum with **gluinos, stops and ewkinos**
- Inspired by natural RPV model with minimal flavor violation
- Select events with at least **1 isolated *e*/μ** (trigger) and at least **8 to 15 jets**, of which several can be *b*-tagged
- Split into disjoint 1L and 2L^{SC} categories
- Sensitivity extracted via multi-bin fit on jet and b-jet multiplicities



Analysis strategy depends on production:

- Strong: "jet counting" with 5 thresholds p_T > 20, 40, 60, 80, 100 GeV
- Ewk: NN discriminant (1L only) trained on lepton and jet variables, independent of *b*-jet multiplicity



Multijet 1-Lepton Search

$$\lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k$$

ATLAS-SUSY-2019-04

- Dominant backgrounds: tt/V+jets (1L) and ttW, tt+fake, VV ($2L^{SC}$)
- Large modeling uncertainties at large jet multiplicities
  - ➜ Backgrounds estimated from data by extrapolation from moderate to high (*b*-)jet multiplicities
- Describe evolution of event counts with jet multiplicities as

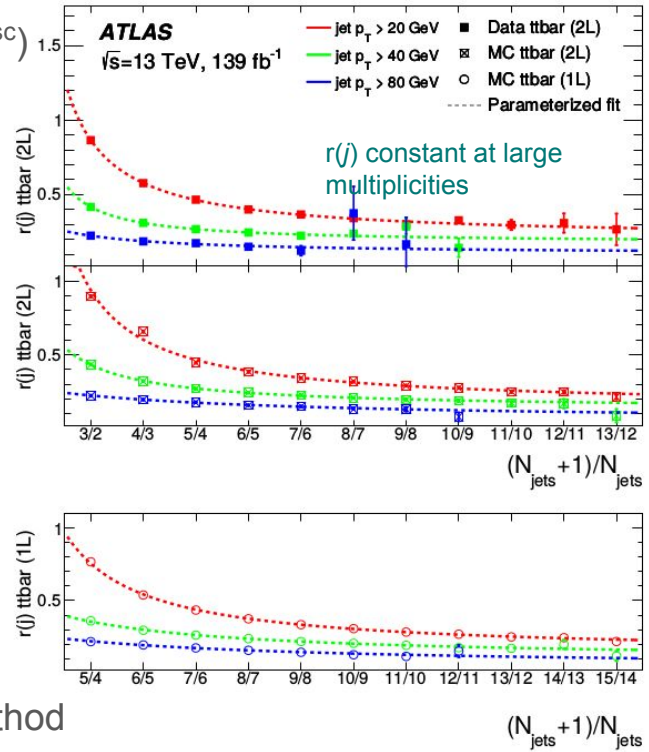
$$r^X(j) \equiv N^X_{j+1}/N^X_j$$

- Parametrize scaling for process *X* and extract c_i^X from data

$$N^X_j = N^X_4 \cdot \prod_{j'=4}^{j'=j-1} r^X(j') \qquad r^X(j) = c^X_0 + c^X_1/(j + c^X_2)$$

Absolute normalization in 4-jet events

- Similar techniques employed for *b*-jet multiplicities and NN output prediction
- Fake/non-prompt lepton background estimated with matrix method



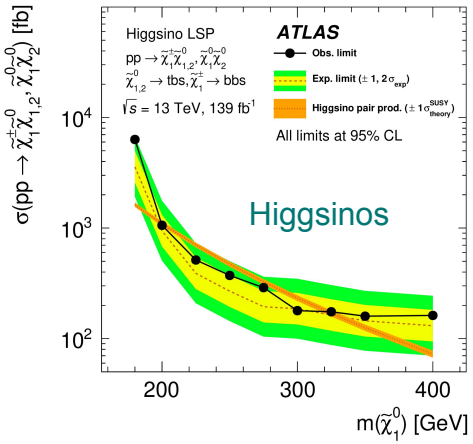
Multijet 1-Lepton Search

$$\lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k$$

ATLAS-SUSY-2019-04

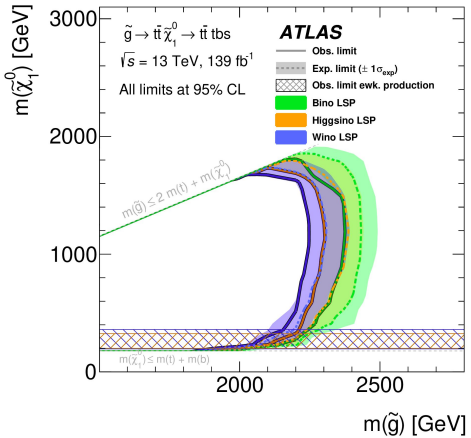
- Excellent agreement of observation with SM predictions
- First LHC search sensitive to ewkino production with prompt RPV decays to quarks

Ewkino Production



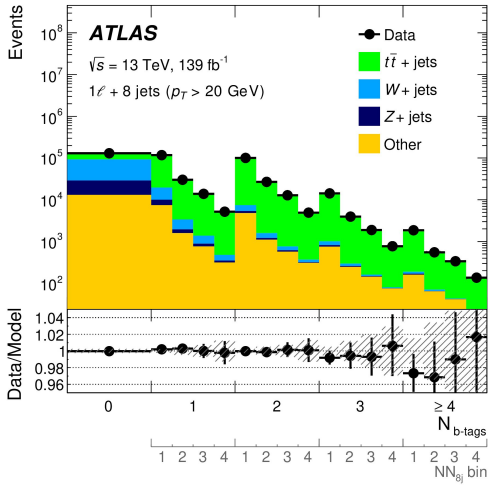
Exclusion of higgsino masses between 200 and 320 GeV

Strong Production



Exclusion of gluino masses up to 2.4 TeV (dependent on LSP nature)

Ewk 1L, 8 jets (p_T > 20 GeV)



Extra: Sensitivity to tttt

Dedicated fit to normalize four-top process:

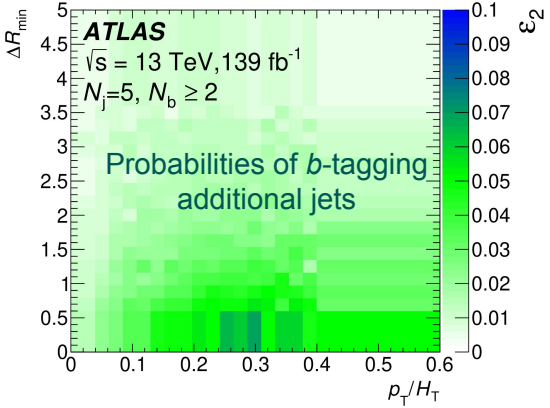
$$\mu_{t\bar{t}t\bar{t}} = 2.0^{+0.9}_{-0.7}$$

Multi b-Jet Search

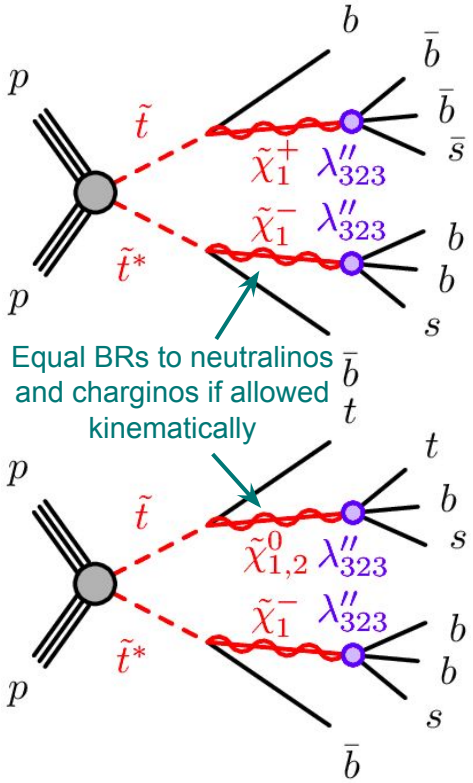
$\frac{1}{2}\lambda''_{ijk}U^c_i D^c_j D^c_k$

ATLAS-SUSY-2018-38

- Considers **light 3rd generation squarks and higgsino triplet** as motivated by naturalness arguments
- Events in SR have at least 6 jets, of which 4 or ≧ 5 are *b*-tagged and no leptonic activity, selected by four-jet triggers
- Dominant backgrounds from **multijet production** and tt+jets events
- Data-driven multijet background estimation using tag-rate function



- Extrapolate *b*-jet multiplicity from N_j = 5 events
- Derive per-jet probability for extra *b*-tags parametrized in p_T/H_T and angular distance to jet with largest *b*-tagging score

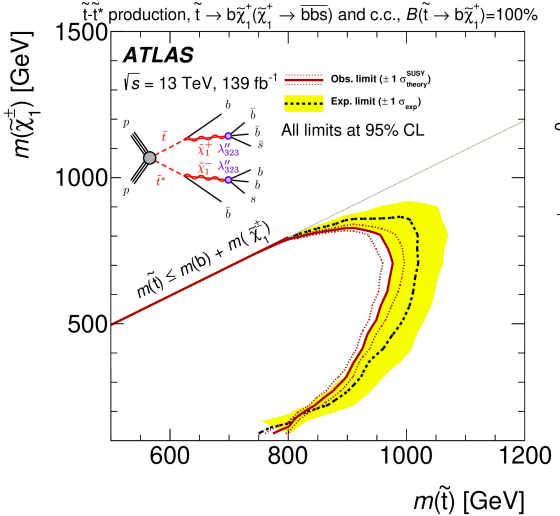


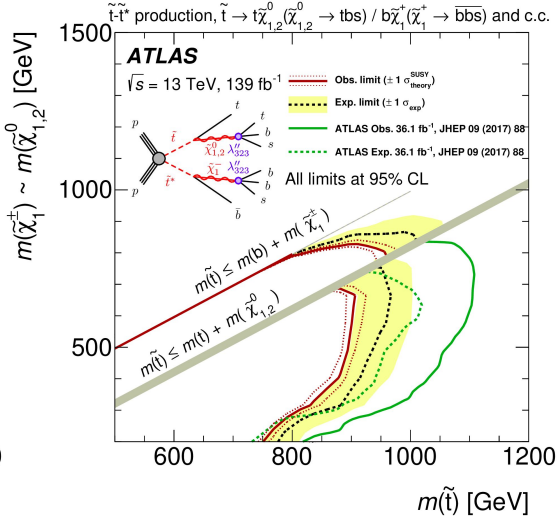
Multi b-Jet Search

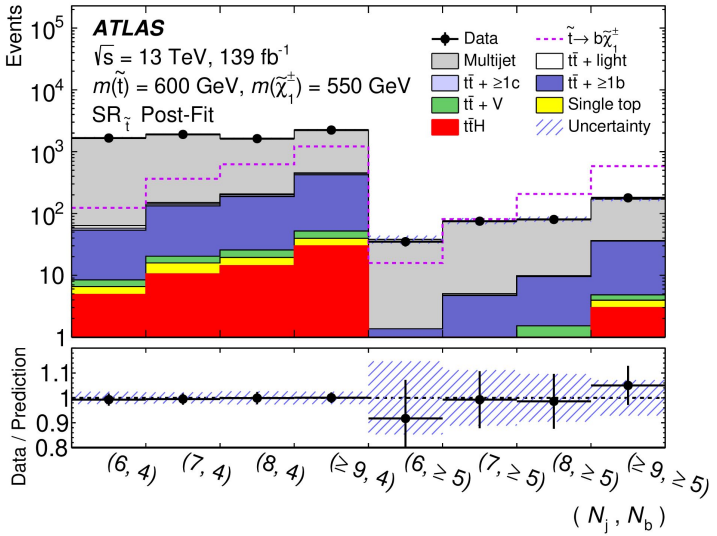
$$\frac{1}{2}\lambda''_{ijk}U_i^c D_j^c D_k^c$$

ATLAS-SUSY-2018-38

- Multi-bin fit in four jet and two *b*-jet (4, ≧ 5) SR bins
- First coverage of ≧ 5 b-jet, 0 lepton final state at LHC
- No significant excess above SM expectations







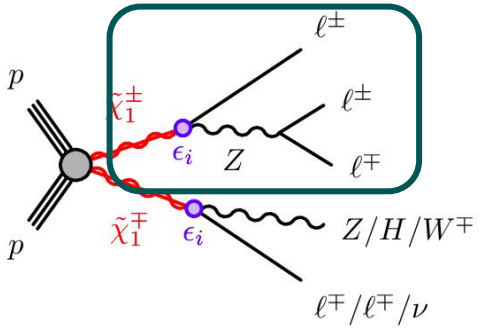
Exclusion of stop masses up to 950 GeV

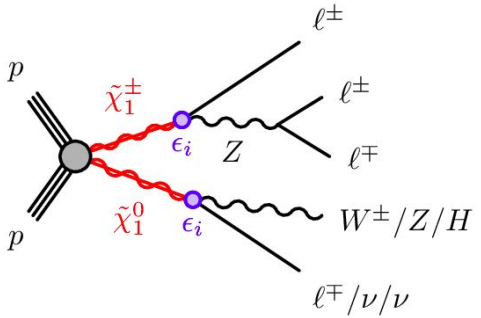
3L Resonance Search

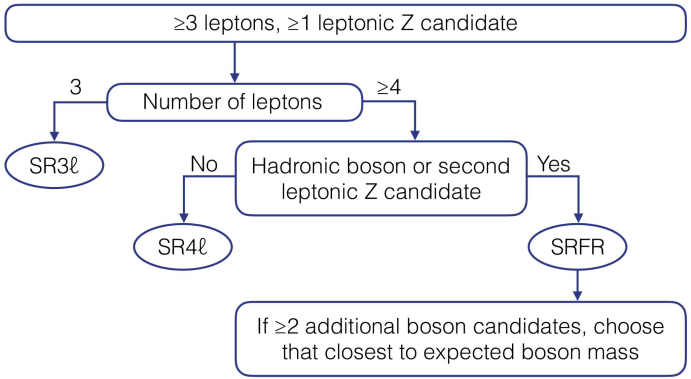
$\mu_i H_u L_i$

ATLAS-SUSY-2018-36

- Motivated by MSSM with additional $U(1)_{B-L}$ gauge group
  - Includes right-handed neutrino supermultiplets to introduce L-violation
- Consider mass-degenerate wino chargino/neutralino production
- Ewkino decays to ℓ+Z/W/H via generalized RPV coupling ε_i
- Target events with $Z\ell \rightarrow \ell\ell\ell$ candidate from chargino decay
- 3 SRs defined to cover possible decays of second leg







- SR3ℓ: 3ℓ + substantial E_T^{miss}
- SR4ℓ: ≧4ℓ + potential E_T^{miss} †
- SRFR: ≧4ℓ + hadronic boson

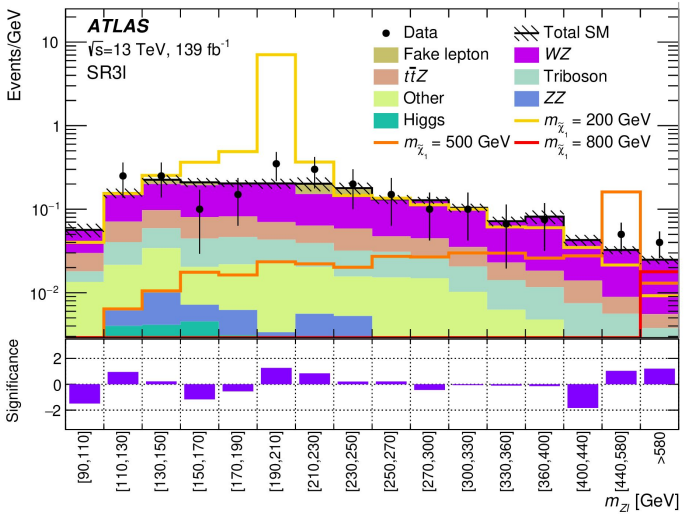
† Only for events with 2 SF lepton pairs

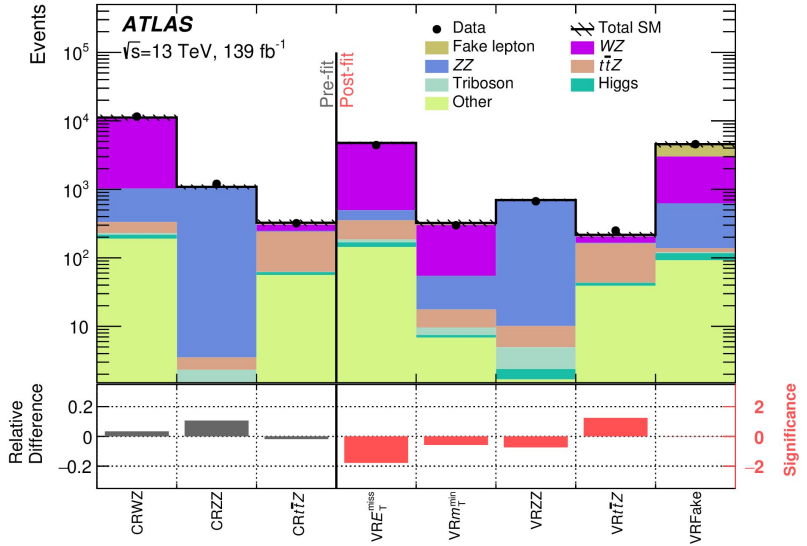
3L Resonance Search

$\mu_i H_u L_i$

ATLAS-SUSY-2018-36

- Dominant background sources from ttZ, ZZ & WZ processes
- Normalized to data in dedicated CRs
- Fake lepton bkg. estimated from sample enriched in ℓ from hadronic decays





- Sensitivity via multi-bin fit on $m_{Z\ell}$ in 16 bins for each SR

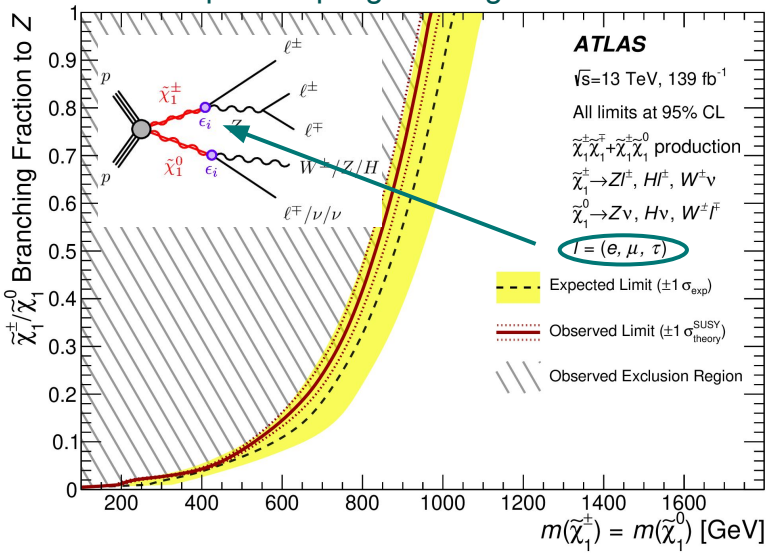
3L Resonance Search

$\mu_i H_u L_i$

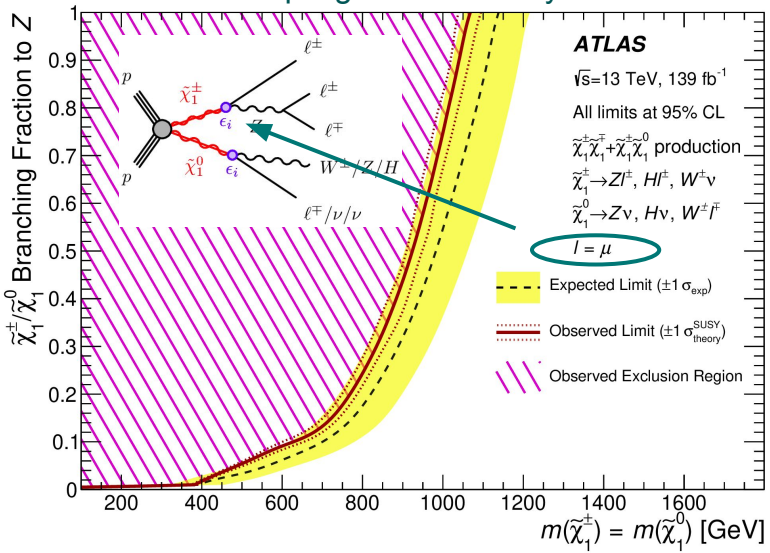
ATLAS-SUSY-2018-36

- Limits have been set depending on the branching fraction to Z and coupling to lepton flavor

Equal couplings to all generations



Coupling to muons only



Exclusion of Wino masses up to 1050 GeV

Multilepton Search

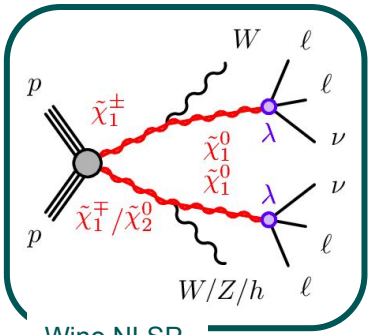
$\frac{1}{2}\lambda_{ijk} L_i L_j E^c_k$

ATLAS-SUSY-2018-02

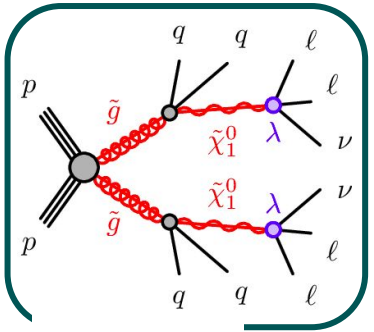
- LLE term allows LSP to decay into 2 charged leptons: $\tilde{\chi}_1^0 \rightarrow \ell_k^{\pm}\ell_{i/j}^{\mp}\nu_{j/i}$
  - Four-lepton final state promising phase space
- Analysis considered two extreme choices of λ_{ijk}
  - $\lambda_{12k} \neq 0$ (k ∈ 1, 2): only decays to *e* and μ
  - $\lambda_{i33} \neq 0$ (i ∈ 1, 2): only decays to τ and *e*/μ
- Winos, gluinos or sleptons/sneutrinos as NLSP
- Three search channels with ≧ 0, 1 or 2 hadronic taus
  - 4L0T: $N_{e/\mu} \geqq 4$, $N_{\tau} \geqq 0$
  - 3L1T: $N_{e/\mu} = 3$, $N_{\tau} \geqq 1$
  - 2L2T: $N_{e/\mu} = 2$, $N_{\tau} \geqq 2$
- Veto of leptonic Z candidate, several thresholds on

$$m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + \sum_{e,\mu,\tau} p_{\text{T}} + \sum_{\text{jets}} p_{\text{T}}$$

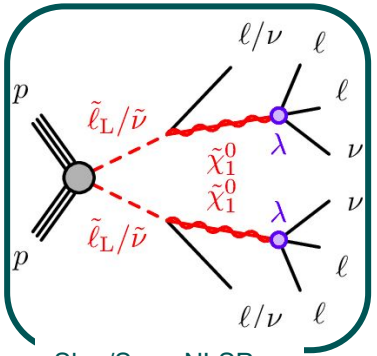
  between 600 and 1300 GeV dependent on N_{τ} and presence of b-tagged jet
- General **5L region** with $N_{e/\mu} \geqq 5$



Wino NLSP



Gluino NLSP



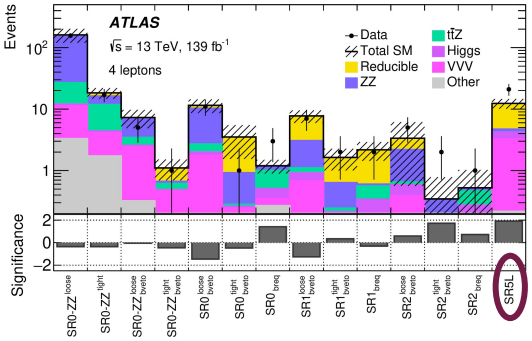
Slep/Sneu NLSP

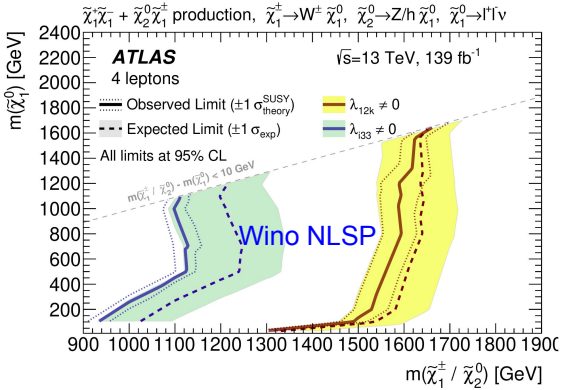
Multilepton Search

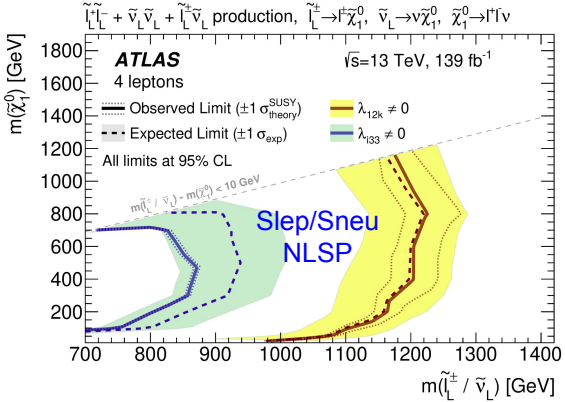
$$\frac{1}{2}\lambda_{ijk} L_i L_j E^c_k$$

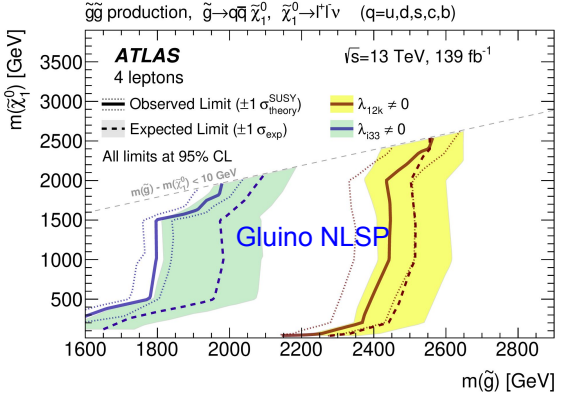
ATLAS-SUSY-2018-02

- Dominant backgrounds:
  - ZZ and ttZ estimated from MC, normalized to data in CRs
  - Reducible background estimated in data enriched in non-prompt lepton decays
- Data consistent with SM expectations
- Highest excess of ~2σ in 5L SR





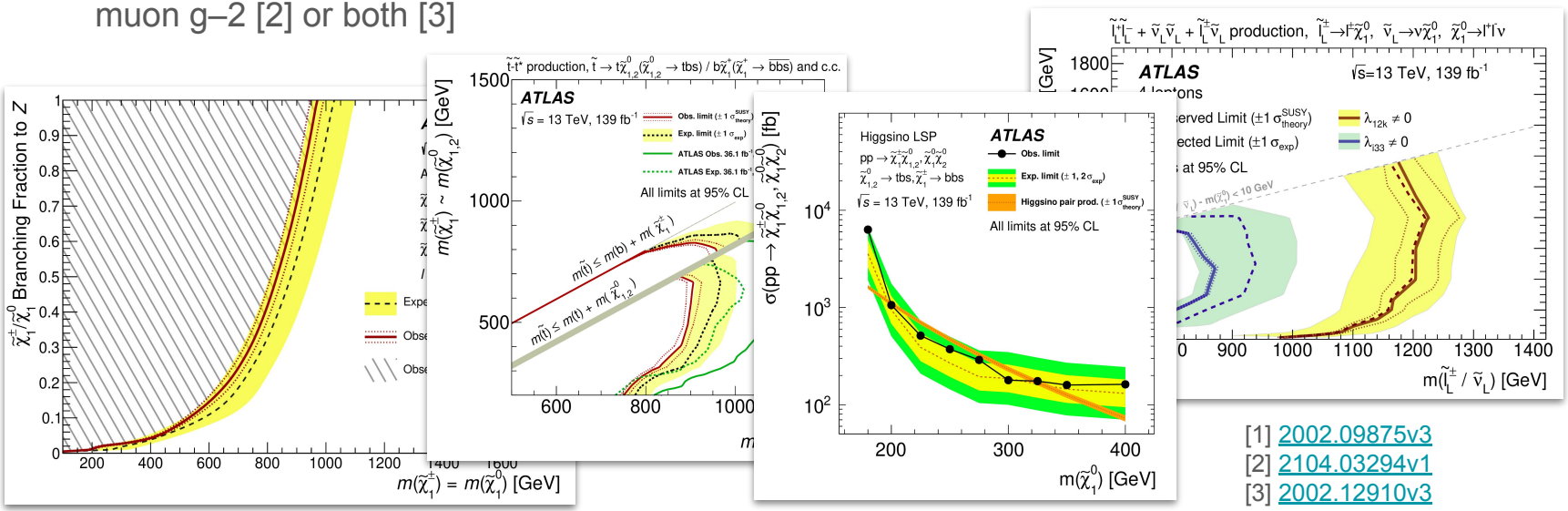




Exclusion of Wino, slepton/sneutrino and gluino masses up to 1.6 TeV, 1.2 TeV & 2.6 TeV

Conclusions

- Rich search program for RPV SUSY at ATLAS using full Run 2 data
- Dedicated, **non-standard background estimation** techniques for **high-multiplicity final states**
- No significant excess beyond SM expectations observed yet
- Nevertheless **strong interest in RPV SUSY** due to solutions for flavor anomalies R(K$^{(*)}$) [1], muon g–2 [2] or both [3]

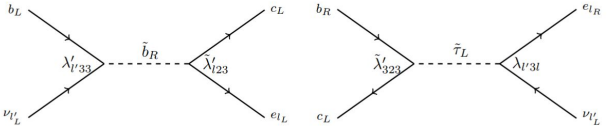


[1] 2002.09875v3
[2] 2104.03294v1
[3] 2002.12910v3

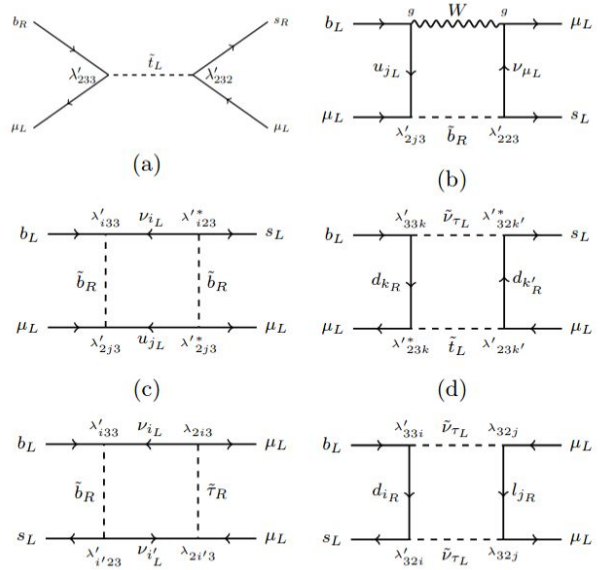
Backup

Extra: Addressing Anomalies with RPV SUSY

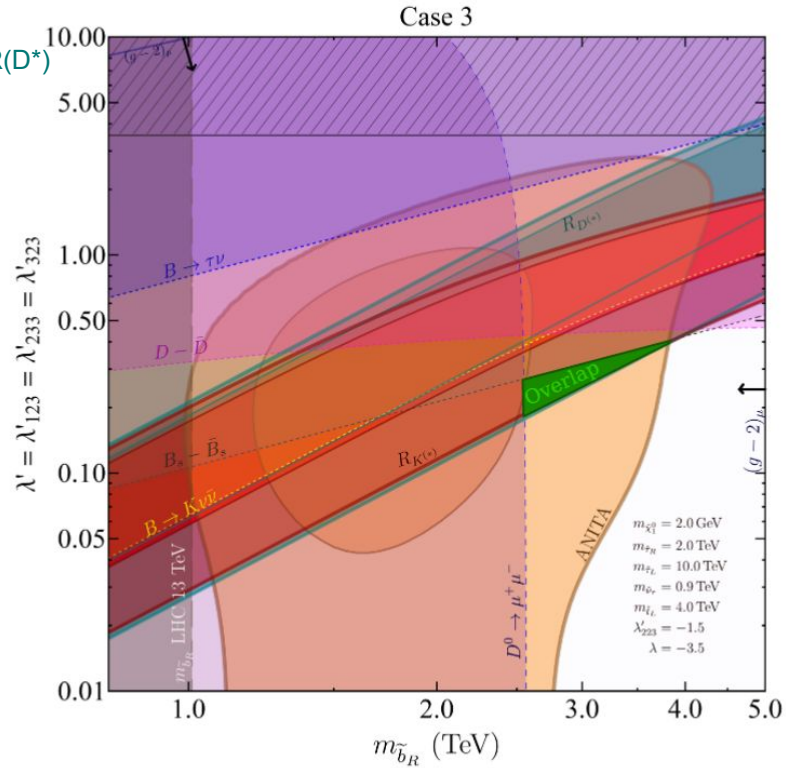
2002.12910v3



Contributions to R(D) and R(D*)

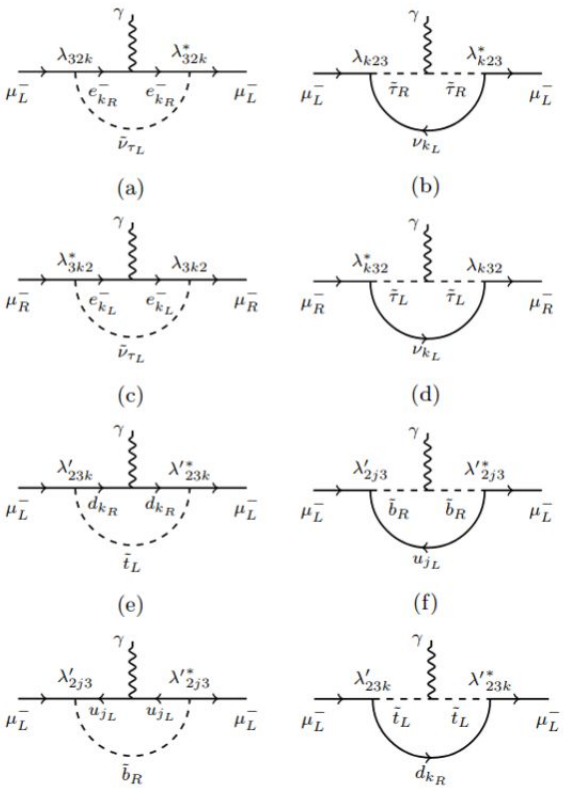


Contributions to b→sμμ



Extra: Addressing Anomalies with RPV SUSY

2002.12910v3



Contributions to Muon g-2