Searches for supersymmetry in non-minimal models

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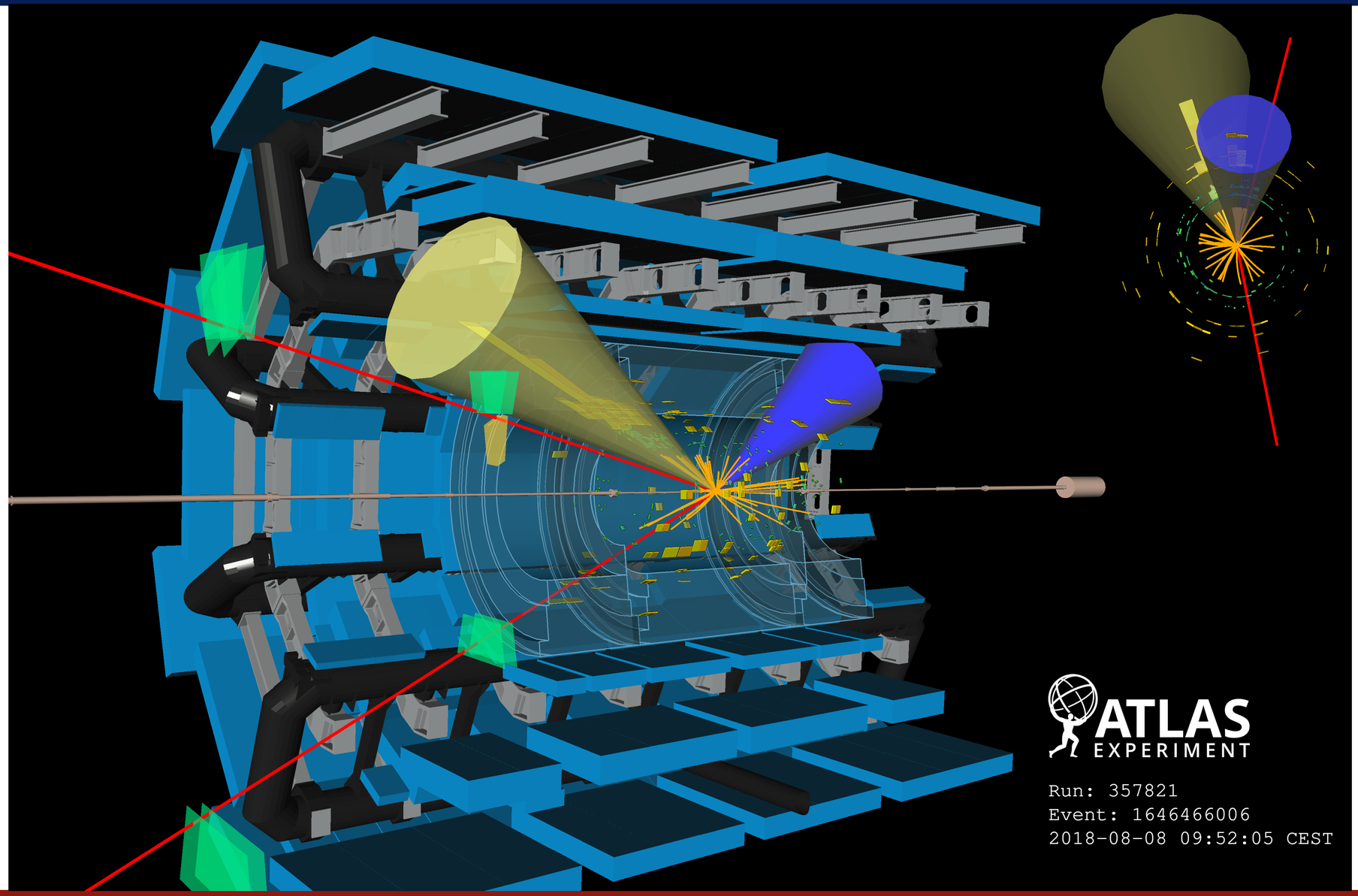
On behalf of the ATLAS Collaboration

Outline

- ATLAS and Large Hadron Collider (LHC)
- Supersymmetry (SUSY)
- *R*-parity violation
- *B* - *L* stop analysis: arxiv
- Multi-jet analysis: JHEP
- Conclusion

LHC


ATLAS
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SUSY

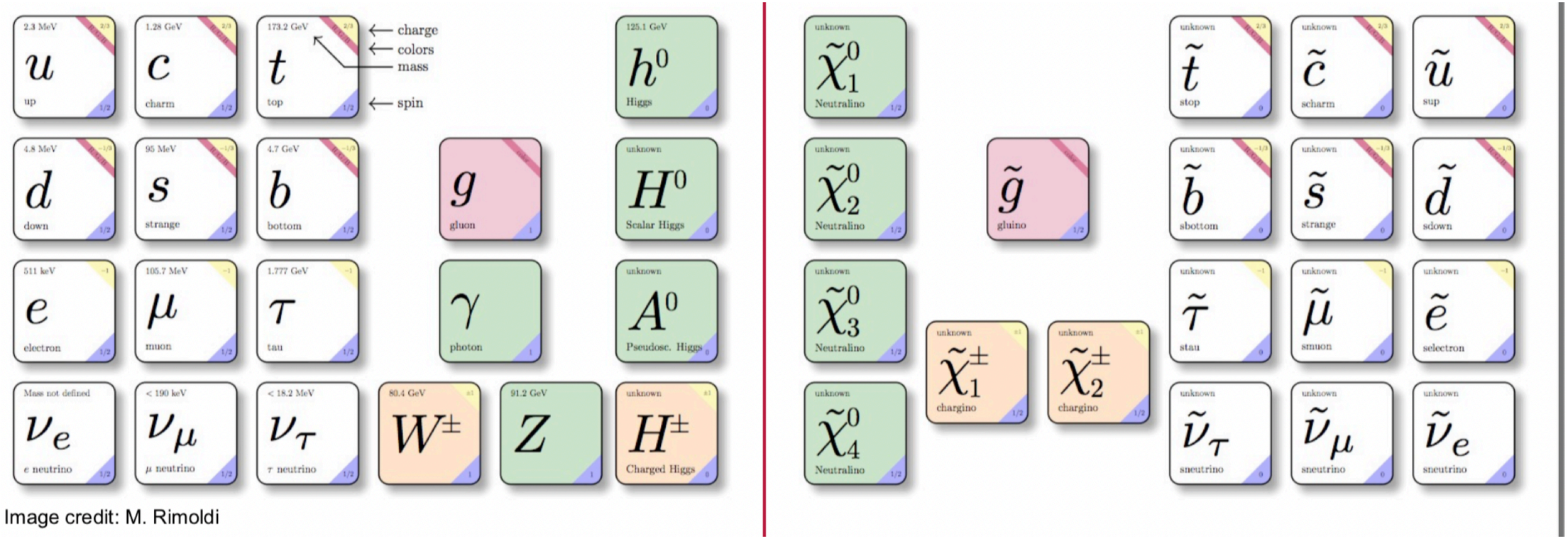
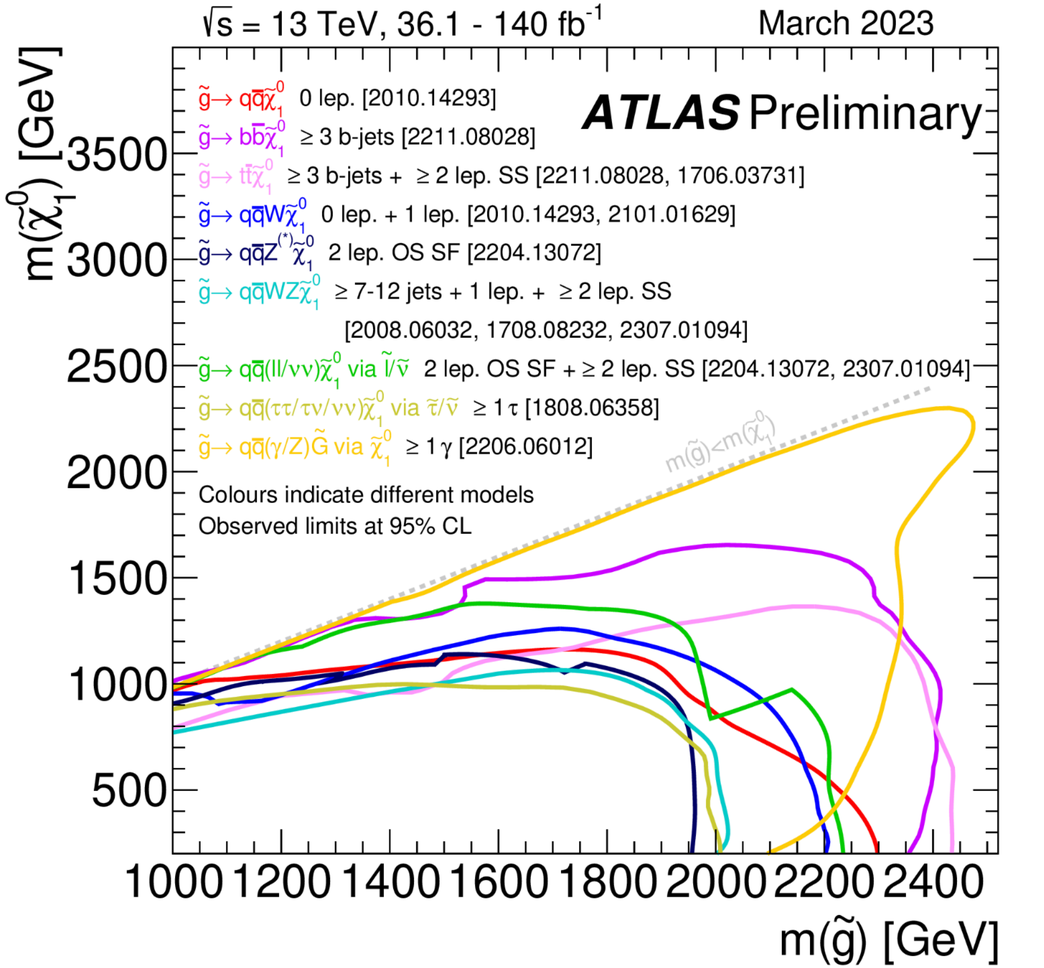


Image credit: M. Rimoldi

Motivation for SUSY: the hierarchy problem, gauge coupling unification, dark matter, baryogensis, etc.

Non-minimal SUSY

- SUSY provides elegant solutions to several problems of the Standard Model
- SUSY is an important component of LHC physics program
- Limits on MSSM do not equate to limits on all of SUSY
- It is important and interesting to explore non-minimal SUSY models (*R*-parity violation, non-minimal-flavour-violating, etc.)



R-parity in SUSY

- Baryon (B) and lepton (L) number violating couplings arise naturally from SUSY
- ***R*-parity:** $R = (-1)^{3(B-L)+2s}$
- The most general gauge invariant and renormalizable SUSY super potential (W) would include *R*-parity violating (RPV) terms
- RPV may explain generation of neutrino masses and mixings as well as flavor anomalies

$$
\begin{aligned}
W &= W_{MSSM} + W_{\not{R}_p}, \\
W_{MSSM} &= h^e_{ij} L_i H_1 \bar{E}_j + h^d_{ij} Q_i H_1 \bar{D}_j + h^u_{ij} Q_i H_2 \bar{U}_j + \mu H_1 H_2, \\
W_{\not{R}_p} &= \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2.
\end{aligned}
$$

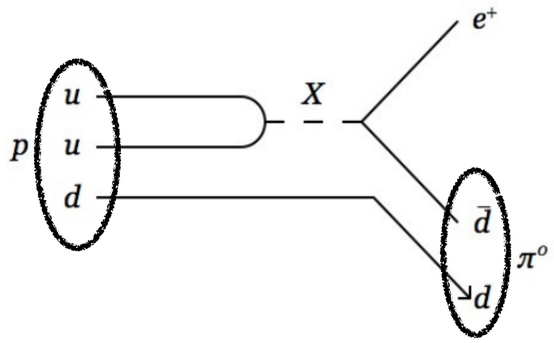
Lepton Number Violating **Baryon number violating**

RPV decays

- *R*-parity conservation often invoked in SUSY “ad hoc” to prevent Baryon # violating and Lepton # violating terms; also to prevent proton decay

- If *R*-parity is conserved → Lightest Supersymmetric Particle (LSP) is stable → missing energy, dark matter candidate

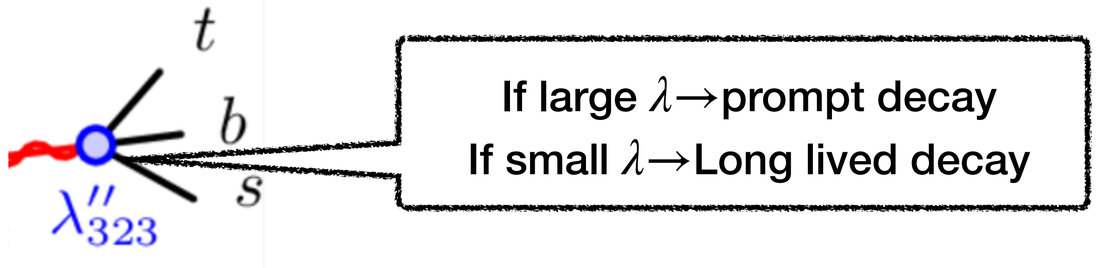
- If *R*-parity is violated → LSP allowed to decay into only SM particles (proton still stable) → reconstructable signatures



Proton decay

$\Delta B = \Delta L = 1$

$\Delta(B - L) = 0$



RPV coupling

$\Delta B = 1, \Delta L = 0$

$\Delta(B - L) = 1$

Overview: stop search

- *B - L* Model for stop motivated by University of Pennsylvania theorists; Marshall, Ovrut, Purves, Spinner, PLB 732 (2014) 325-329 arxiv
- Model adds local U(1) *B – L* symmetry with right-handed neutrinos
- Experimental signature: 2 opposite charged leptons and 2 *b*-jets (fully reconstructable in ATLAS)
- Target Signal:
  - 2 opposite sign leptons (e or μ)
  - 2 jets ($\geq$1 *b*-tag)

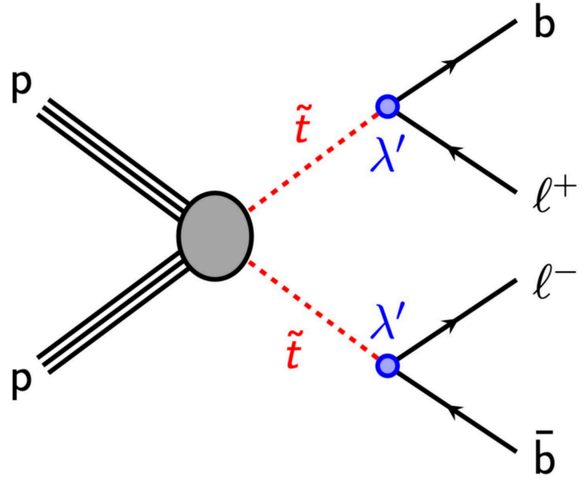
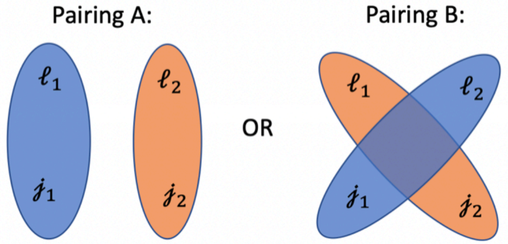


Figure: t̃ and anti-t̃ decay to charged lepton and *b*-quark through *R*-parity violating (RPV) coupling (λ')

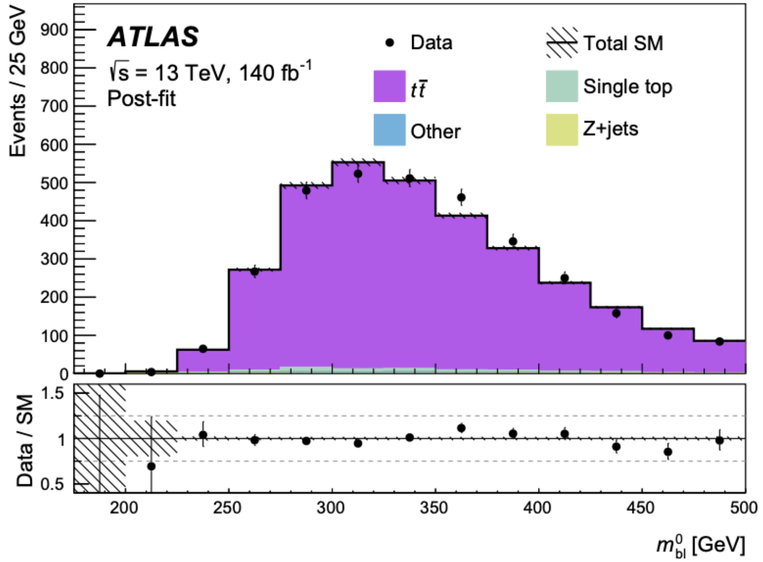
Early Run 2 Analysis: ATLAS Collab, Phys. Rev. D 97 (2018) 032003
Full Run 2 Analysis: arxiv

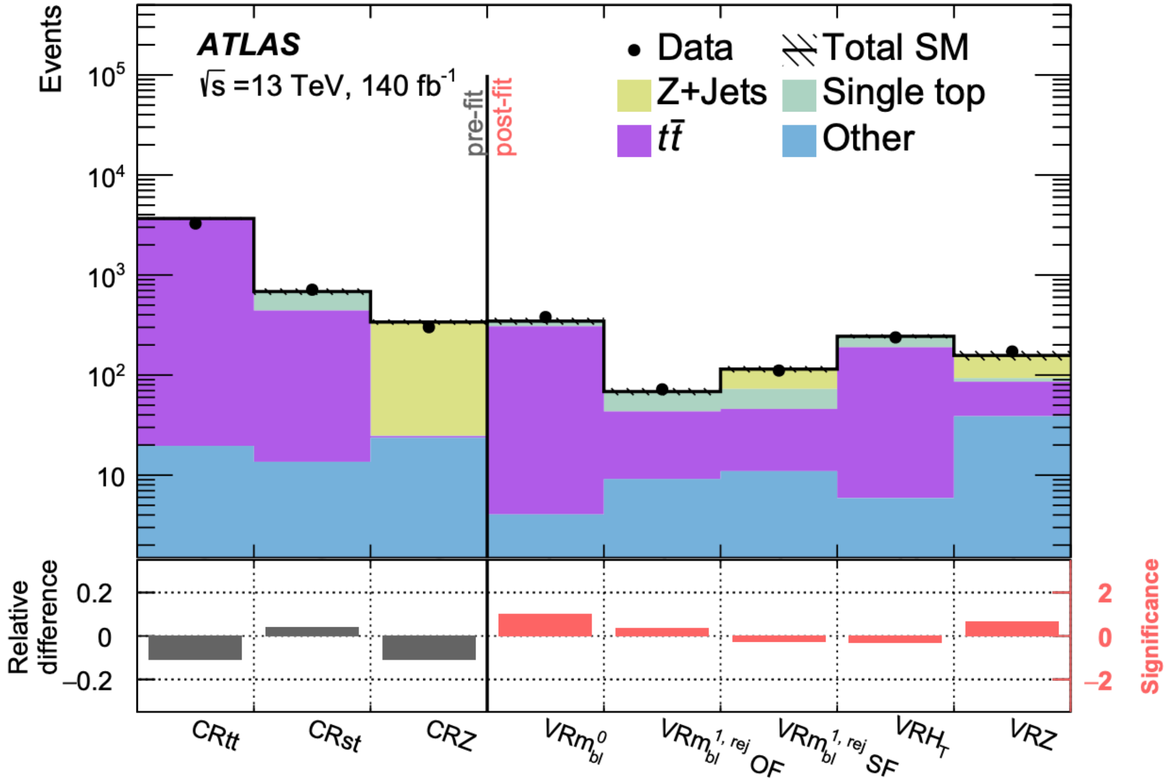
Analysis Strategy: stop search

- Kinematic variables: H_T , m_{ll} , m_{asym} , m_{bl}
- H_T is scalar sum of decay products
- Search for resonance in *b*-jet + lepton invariant mass distribution m_{bl}
- We utilize the *b*-jet + lepton pair's leading mass, sub-leading mass and rejected pairing



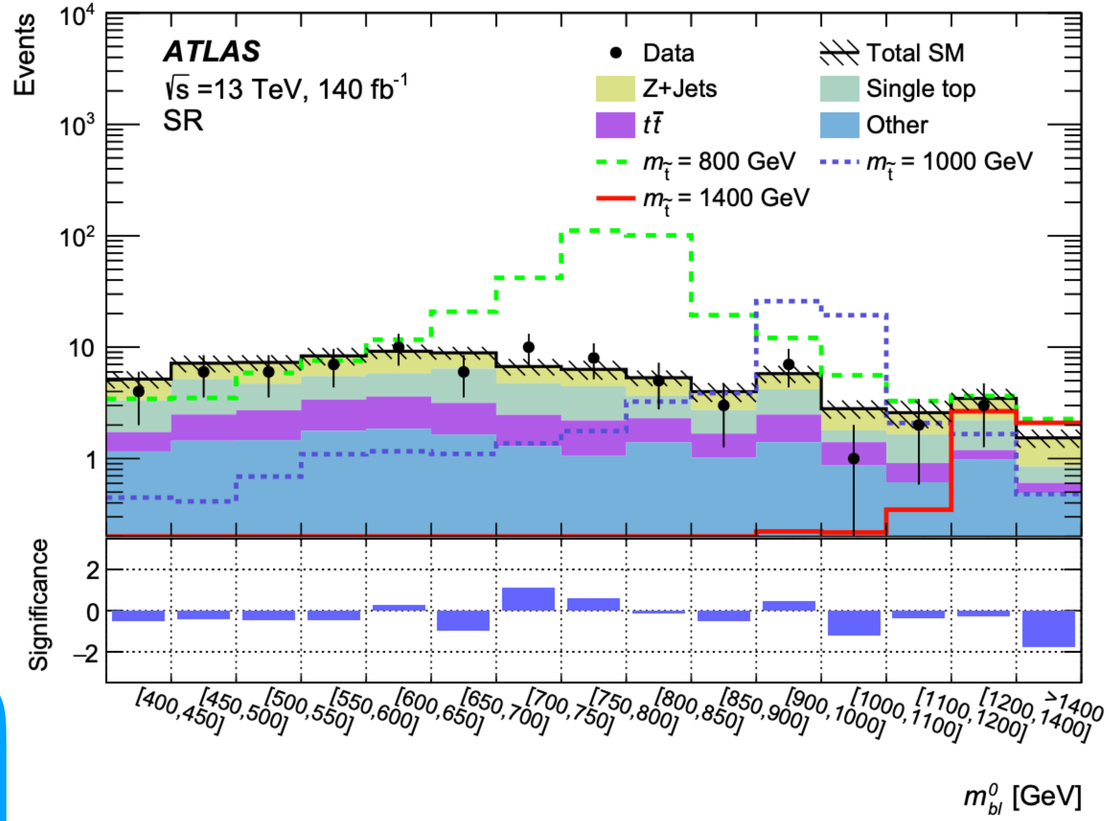
$$m_{b\ell}\ \text{asymmetry} = \frac{\left(m^0_{b\ell} - m^1_{b\ell}\right)}{\left(m^0_{b\ell} + m^1_{b\ell}\right)}$$





Fitting methods: stop search

- Variable bin-width signal region from optimization studies
- Two exclusion fits for each stop mass + lepton branching ratio combination: 15 bin flavor agnostic fit and 45 bin flavor aware



45 Bin Configuration

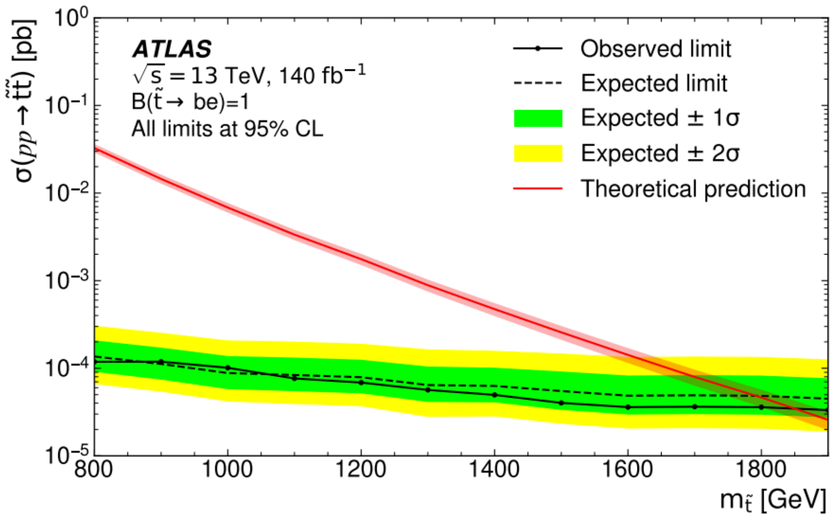
- *ee* Channel: 15 bins
- $e\mu$ Channel: 15 bins
- $\mu\mu$ Channel: 15 bins

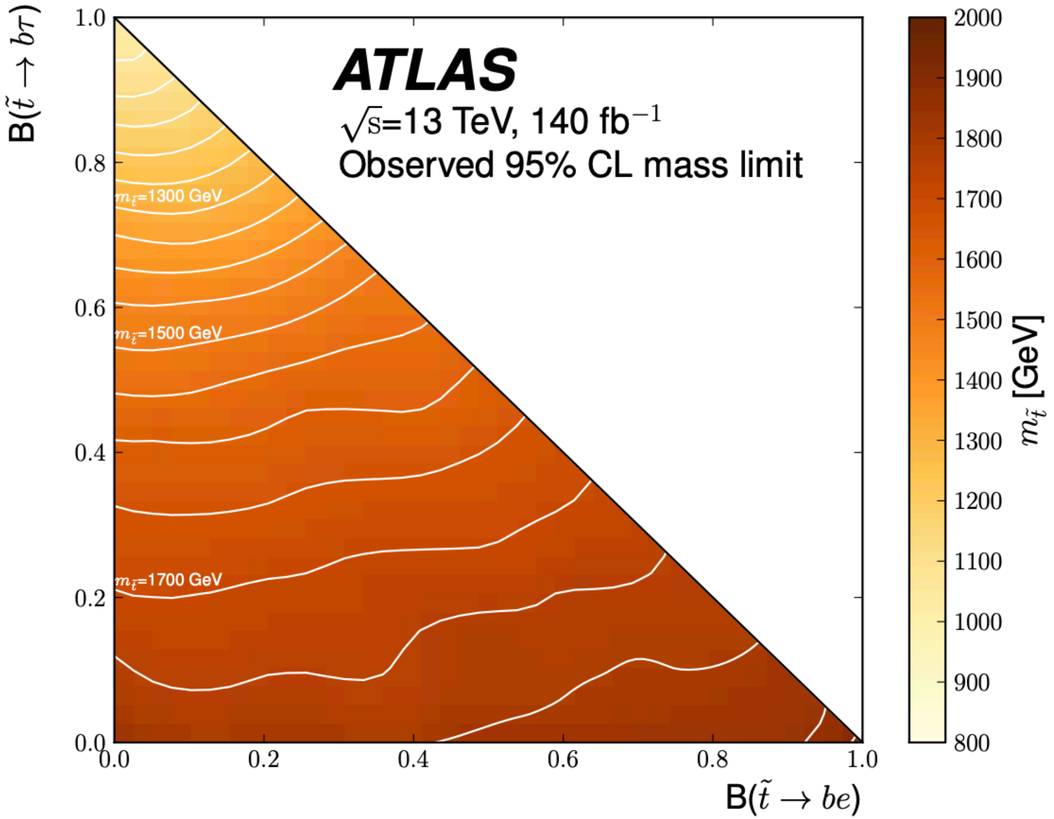
15 Bin Configuration

ee Channel + $e\mu$ Channel + $\mu\mu$ Channel

Results: stop search

- No excess above Standard Model found
- Improved from Early Run 2 limits:
  - 1400 GeV →1800 GeV for $\mathcal{B}(\tilde{t} \rightarrow b\mu) = 100\%$
  - 1500 GeV → 1900 GeV for $\mathcal{B}(\tilde{t} \rightarrow be) = 100\%$
  - 600 GeV → 1100 GeV for $\mathcal{B}(\tilde{t} \rightarrow b\tau) = 90\%$





Overview: multi-jet search

- Experimental signature: 6 jets for direct decay model and 10 jets for cascade decay (fully reconstructable in ATLAS)
- Target Signal: at least 4 jets with $p_T > 50$ GeV and no leptons; events must pass H_T trigger
- Main background is QCD multi-jet which requires strong background suppression
- *b*-tagging selections are used to target third generation couplings

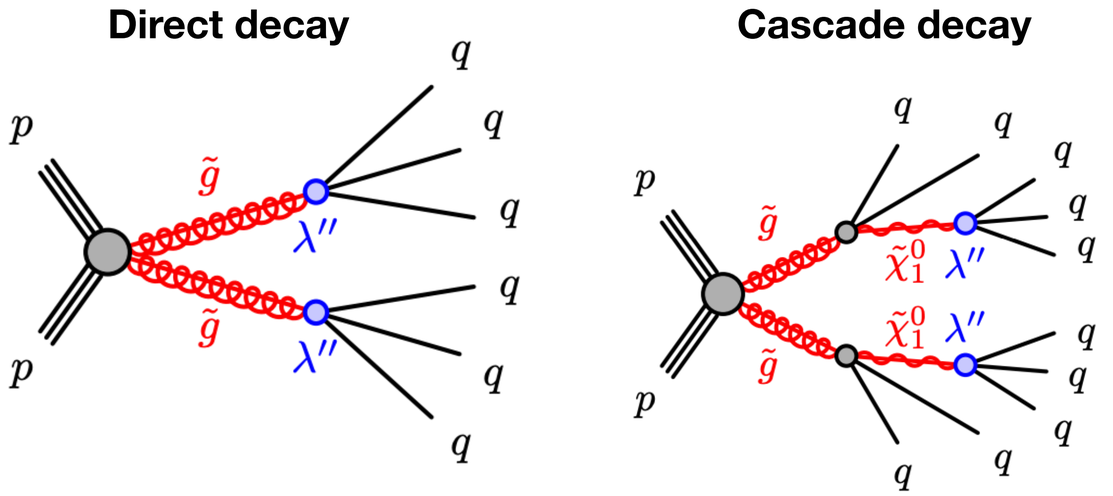
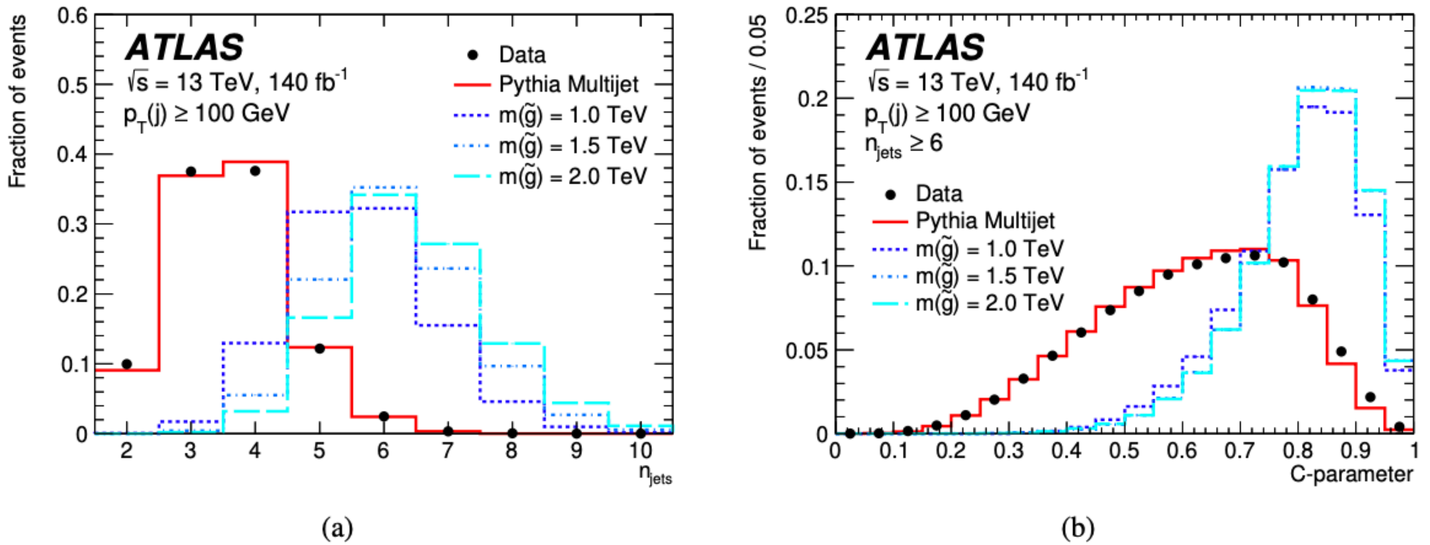


Figure: g˜ and anti-g˜ direct decay to 6 jets (left) and cascade decay to at least 10 jets (right) through RPV coupling (λ")

Run 1 Analysis: ATLAS Collab, Phys. Rev. D 93 (2016) 039901
Early Run 2 Analysis: Atlas Collab, Phys. Lett. B 785 (2018)
Full Run 2 Analysis: Atlas Collab, JHEP 05 (2024) 003

Jet counting method: multi-jet search



Jet Counting Method: (both decays)

- 7 SRs requiring at least 7 high p_T jets create more more-model independent search strategy
- Background estimation of data and simulation from low jet p_T and low jet multiplicity → extrapolated to high
- C event-shape variable derived from linearized sphericity tensor to distinguish between signal and background

Mass resonance method: multi-jet search

Mass Resonance Method: (direct decay only)

- Reconstruct gluino mass with machine learning (ML) techniques
- Assign jets to correct gluino
- Mass resonance search in gluino mass spectrum
- Data-driven approach to estimate background

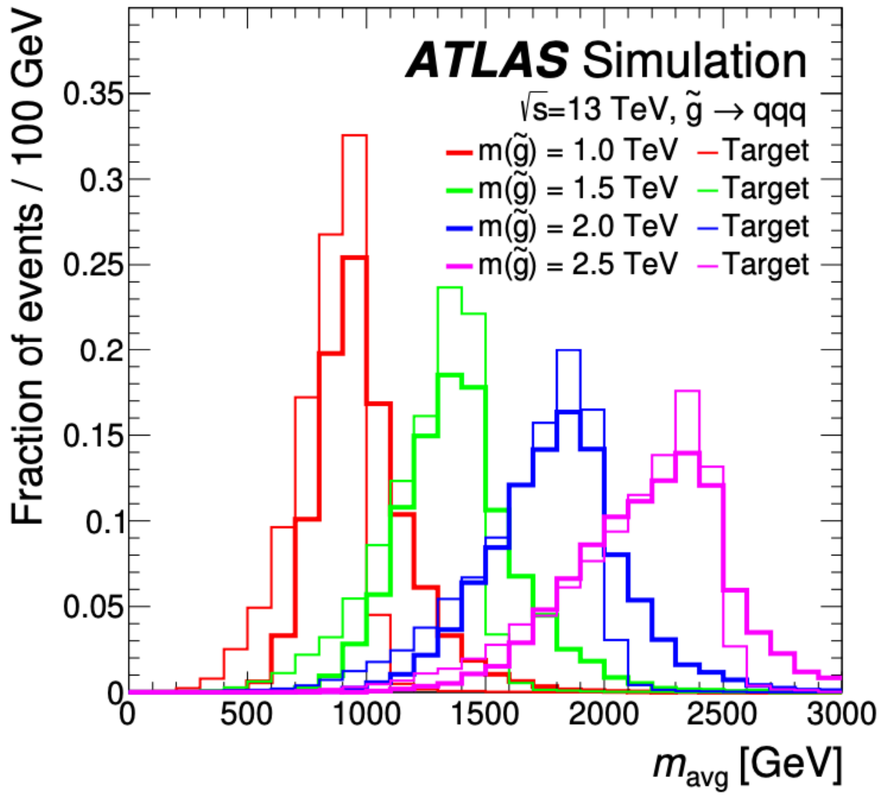
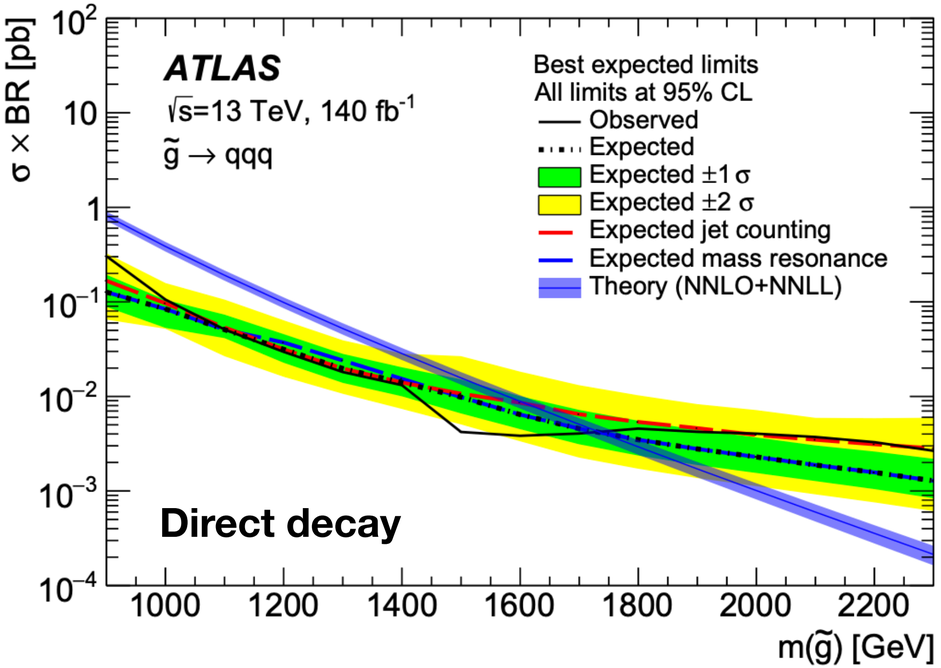
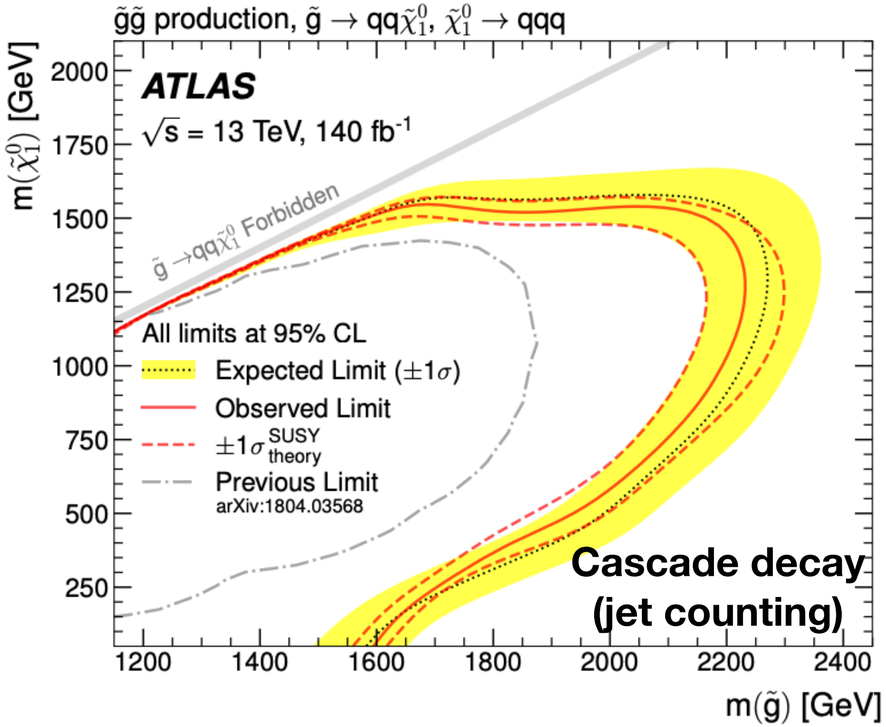


Figure: normalized average mass spectrum (m_{avg}) comparing the shapes of the reconstructed ML (solid) and target Monte-Carlo generated label (light) distributions.

Results: multi-jet search

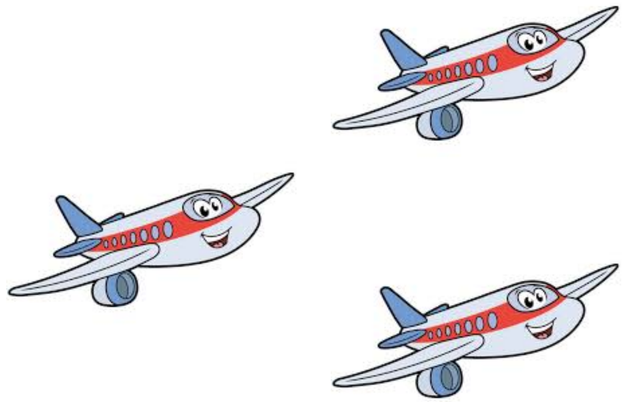
- No excess above Standard Model found.
  - Direct gluino decay → excluded up to 1800 GeV
  - Cascade gluino decay → excluded up to 2340 GeV for a neutralino with 1250 GeV mass
  - Mass resonance method extends limits compared to jet counting method by ~200 GeV





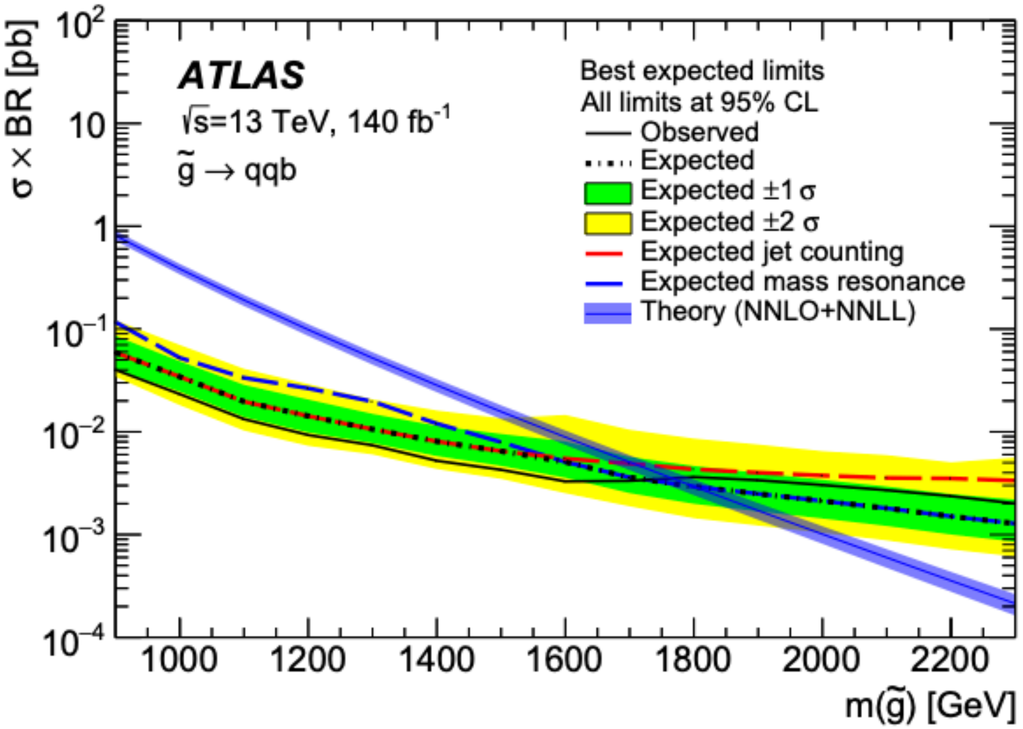
Conclusions

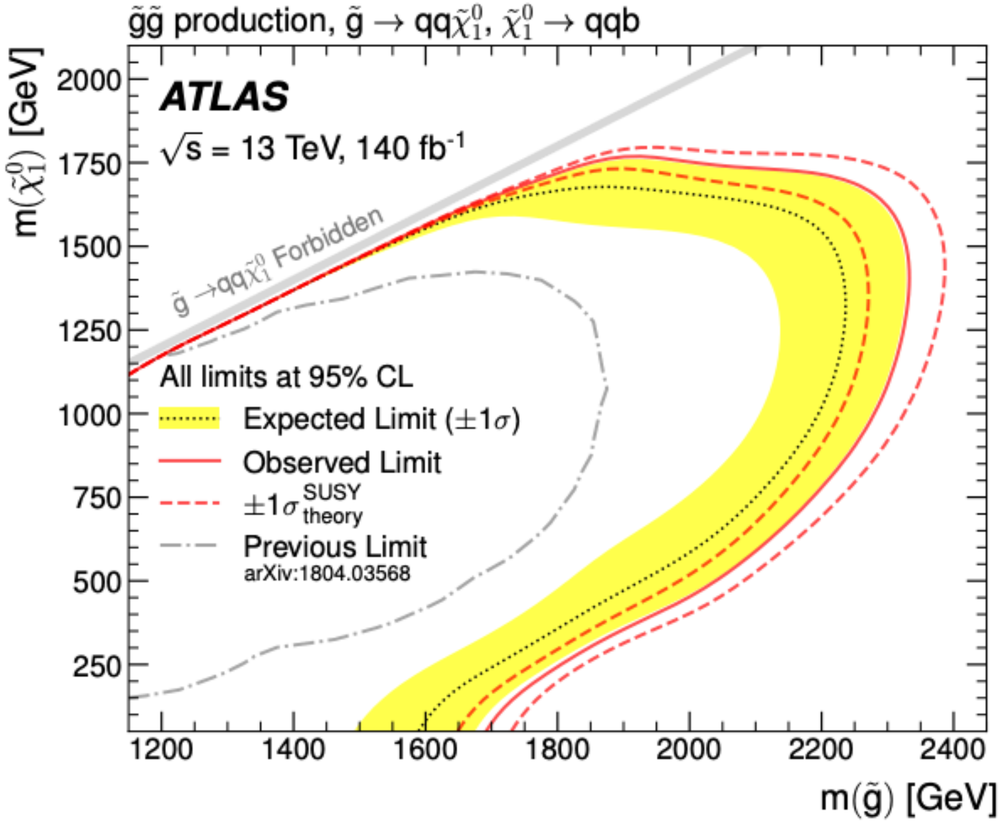
- RPV SUSY models search in new areas of SUSY not previously explored in minimal models
- Limits improved with respect to previous iterations of these analyses
- Significant gain beyond increased data due to new analyses techniques
- New techniques (mass-resonance method) can be applied to future analyses, even beyond the demonstrated finals states!



Backup

UDB model: multi-jet search





Alternate Lepton flavors: stop analysis