Searches for supersymmetry in R-parity violating signatures at the LHC

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SUSY 2019, May 18th

Introduction

- We don't know what SUSY looks like → leave no stone unturned
- The most general renormalizable, gauge-invariant superpotential **contains RPV terms**

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

- **RPV is a possible SUSY scenario, we should be looking for it**
- In general combinations of lepton+baryon number violating couplings are highly constrained by proton and neutron decays
  - Limits on only lepton- or only baryon-number violating couplings are much weaker
  - Constrains on third generation couplings are generally much weaker
- **RPV couplings make the LSP decay to SM, trade MET for more visible particles**
- For small enough couplings and/or heavy mediating sparticles the LSP can become long-lived
  - This talk focuses only on prompt decay
  - Dedicated talks for long-lived scenarios:
    - Hidden Sectors and Long-Lived Particle Signatures
    - Searches for long-lived particles with the CMS detector
    - Search for long-lived SUSY decays - CMS Experiment
    - Detecting hidden sector dark matter via long-lived stau decays

RPV searches at the LHC

- Extensive search program for RPV SUSY in both ATLAS and CMS, also inclusive searches with RPV interpretations
- Will discuss only a subset, covering the three trilinear couplings: LLE, LQD, UDD

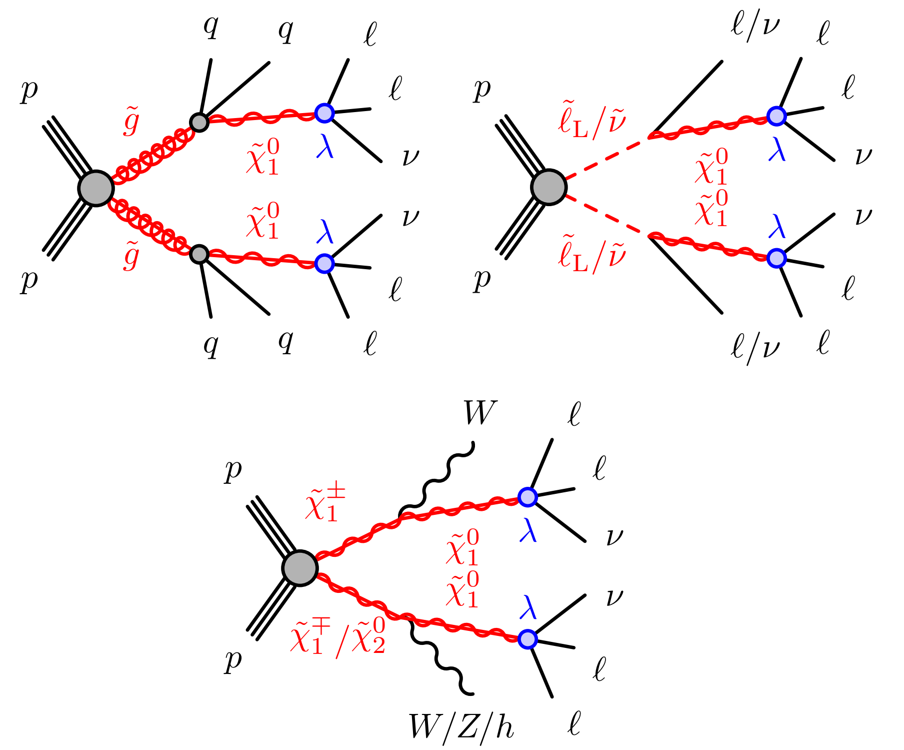
- **ATLAS**
  - Same-sign or three leptons (139 fb^{-1}) ATLAS-CONF-2019-015 (see Giordon's talk)
  - Displaced vertex + muon (136 fb^{-1}) ATLAS-CONF-2019-006 (see Hidetoshi's talk)
  - **RPC to RPV reinterpretation (36.1 fb^{-1}) ATLAS-CONF-2018-003**
  - **RPV all-hadronic (36.1 fb^{-1}) Phys. Lett. B 785 (2018) 136**
  - **RPV four leptons (36.1 fb^{-1}) Phys. Rev. D 98 (2018) 032009**
  - Dijet pairs (36.1 fb^{-1}) Eur. Phys. J. C 78 (2018) 250
  - Stop B-L (36.1 fb^{-1}) Phys. Rev. D 97 (2018) 032003
  - RPV lepton + many jets (36.1 fb^{-1}) JHEP 09 (2017) 88

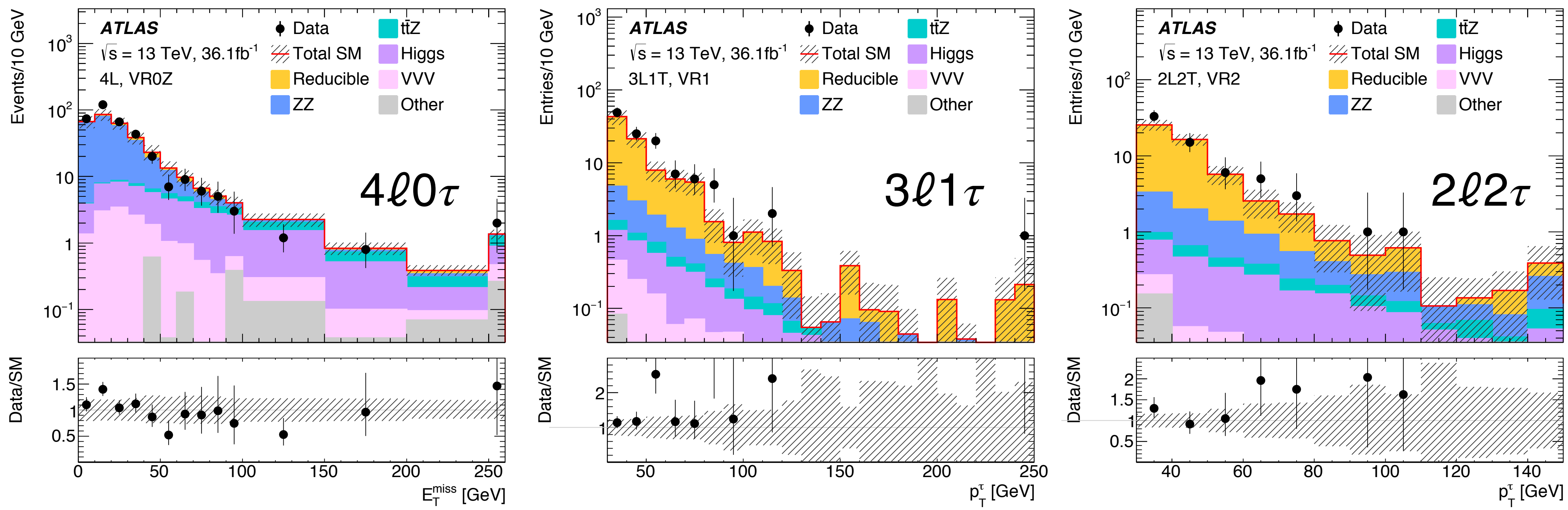
- **CMS**
  - Same-sign or three leptons (137 fb^{-1}) CMS-PAS-SUS-19-008 (see Andrew's talk)
  - **Resonant slepton (35.9 fb^{-1}) Eur. Phys. J. C 79 (2019) 305**
  - Displaced jets (35.9 fb^{-1}) Phys. Rev. D 99 (2019) 032011
  - **Tri-jet pairs (35.9 fb^{-1}) Phys. Rev. D 99 (2019) 012010**
  - Displaced vertex + jets (35.9 fb^{-1}) Phys. Rev. D 98 (2018) 092011
  - RPV lepton + many jets (35.9 fb^{-1}) Phys. Lett. B 783 (2018) 114
  - Dijet pairs (35.9 fb^{-1}) Phys. Rev. D 98 (2018) 112014
  - RPV all-hadronic (38.2 fb^{-1}) Phys. Rev. Lett. 121 (2018) 141802

RPV four leptons, ATLAS

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

- Search for wino, slepton or gluino production with LSP decay via LLE coupling, to **at least four leptons**
- Three search channels with **0, 1 or 2 hadronic taus**
- Sensitivity to all LLE couplings, interpret in the two extremes with most/least taus: λ_{i33} / λ_{12k}, (i,k ∈ 1,2)
- Background in 0-tau regions estimated from MC, dominated by prompt leptons (ZZ, ttZ, triboson)
- Background in 1- and 2-tau regions dominated by fake taus, estimated with data-driven method



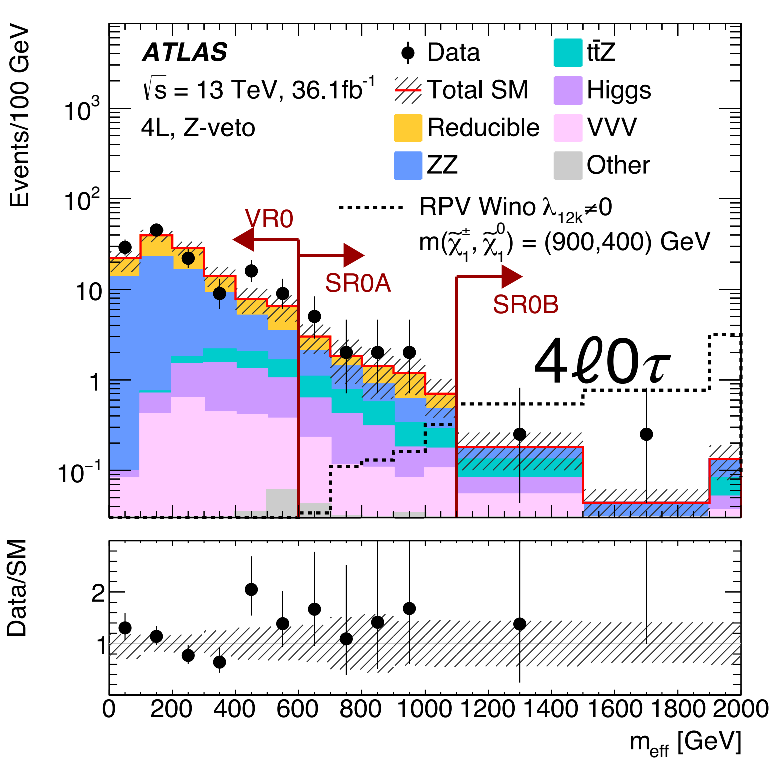


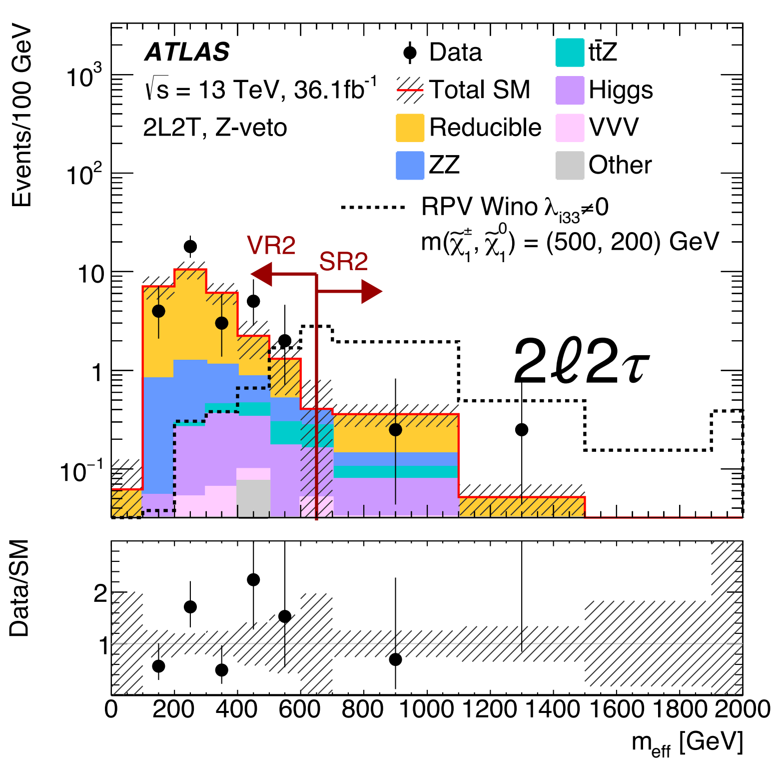
RPV four leptons, ATLAS

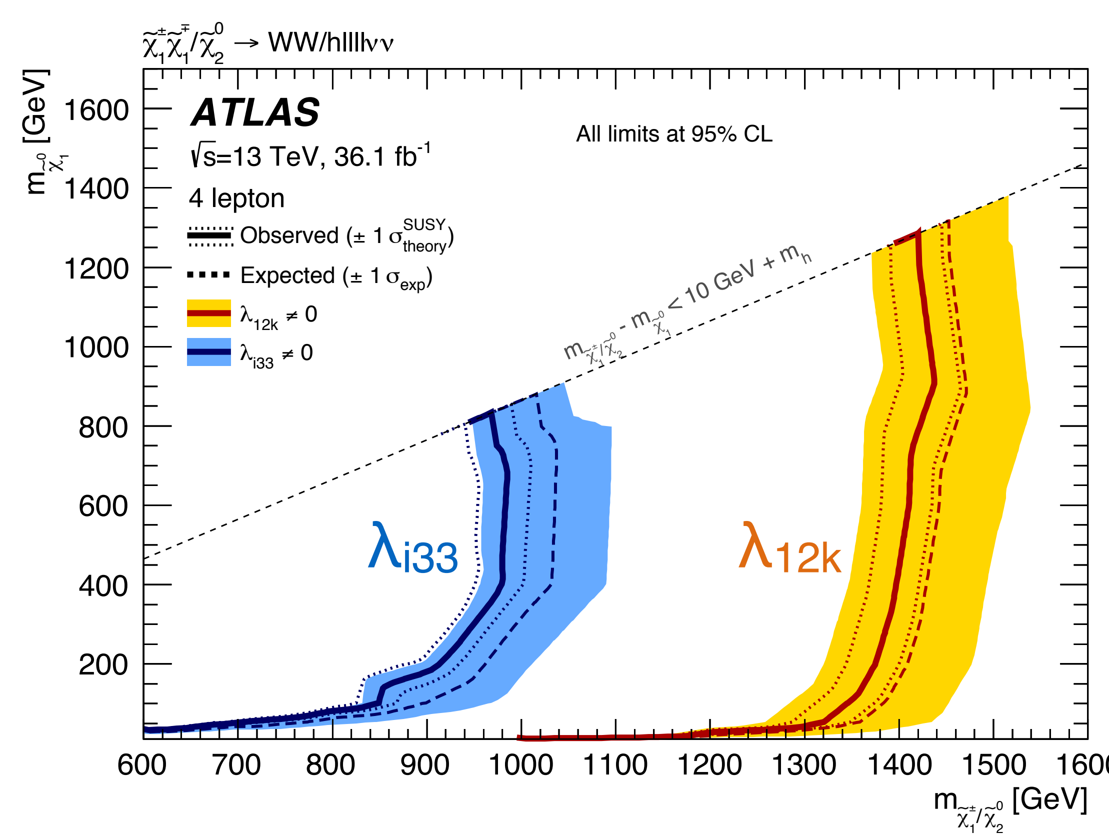
$$\frac{1}{2}\lambda_{ijk} L_i L_j E^c_k$$

- Reducible background estimated via fake-factor method
- Fake-factor extracted from simulation and corrected to data where possible
- FF split per lepton type (light/heavy flavour, gluon-jet, photon conversion), process (ttbar, Z+jets, …) and binned in p_T, eta, and number of prongs for taus
- FF applied to data as a weighted average of lepton type and process fraction

- No significant excess observed, limits are set for each production mode for two couplings: λ_{i33} / λ_{12k}, (i,k ∊ 1,2)



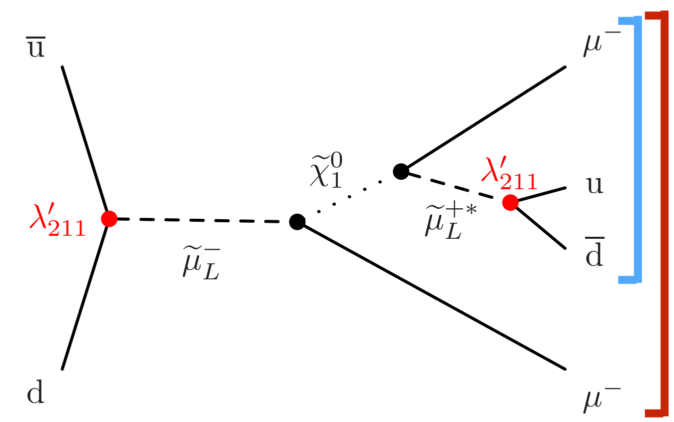


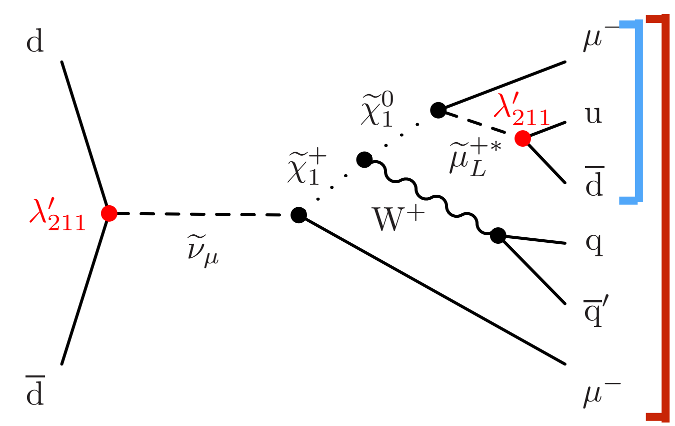


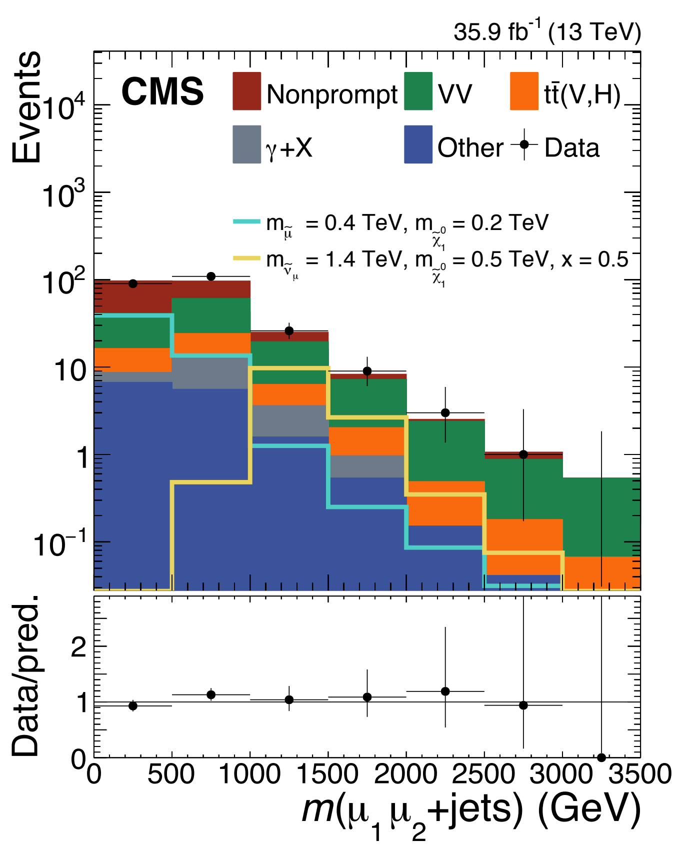
Resonant slepton, CMS

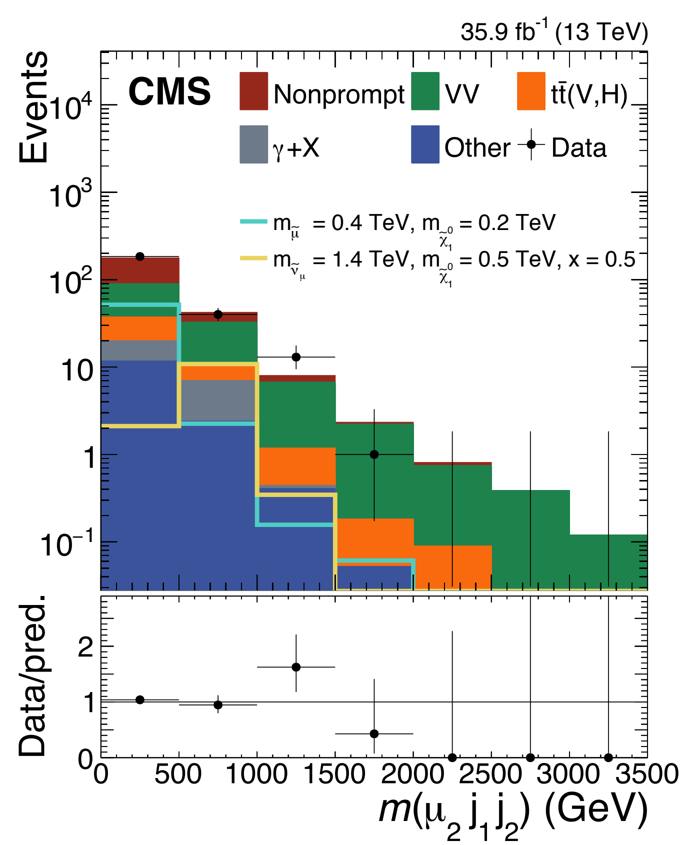
$\lambda'_{ijk} L_i Q_j D^c_k$

- Search for resonant slepton production decaying to **same-sign muons** via λ'$_{211}$ (both production and decay)
- SR is binned in the 2D plane of $m(\mu_1\mu_2$+jets$)\approx m_{\tilde{\mu}_L^-/\tilde{\nu}_\mu}$ and $m(\mu_2 j_1 j_2)\approx m_{\tilde{\chi}_1^0}$
- Background dominated by diboson ($W^\pm W^\pm$, WZ, ZZ) and fake leptons in the low mass bins (mainly ttbar with a muon from b-hadron decay)





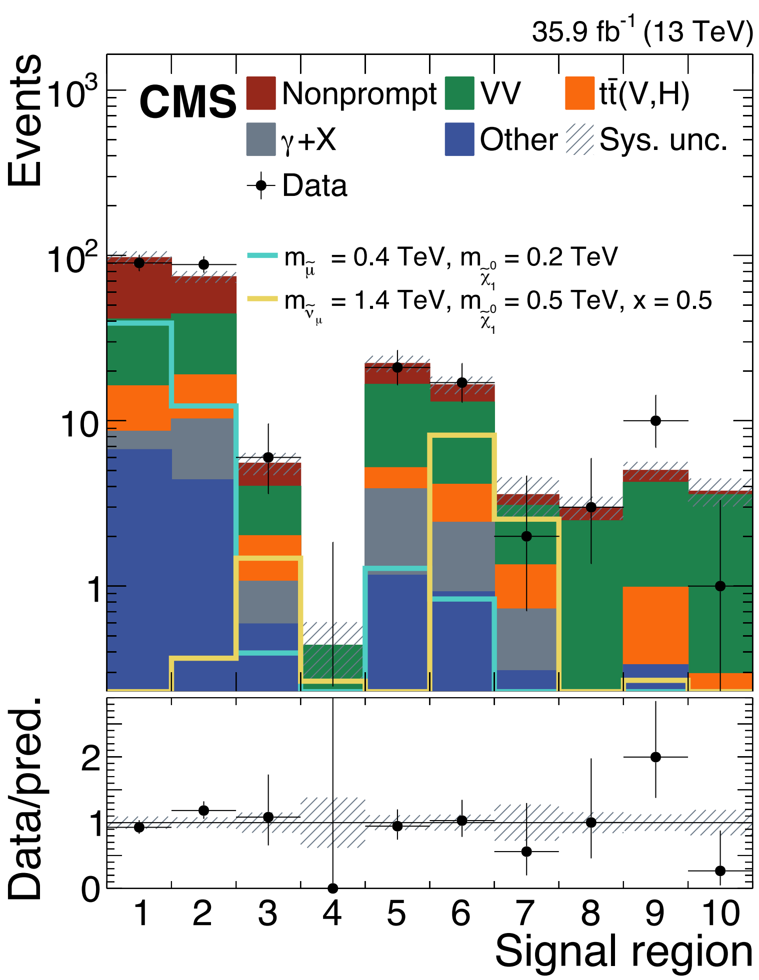


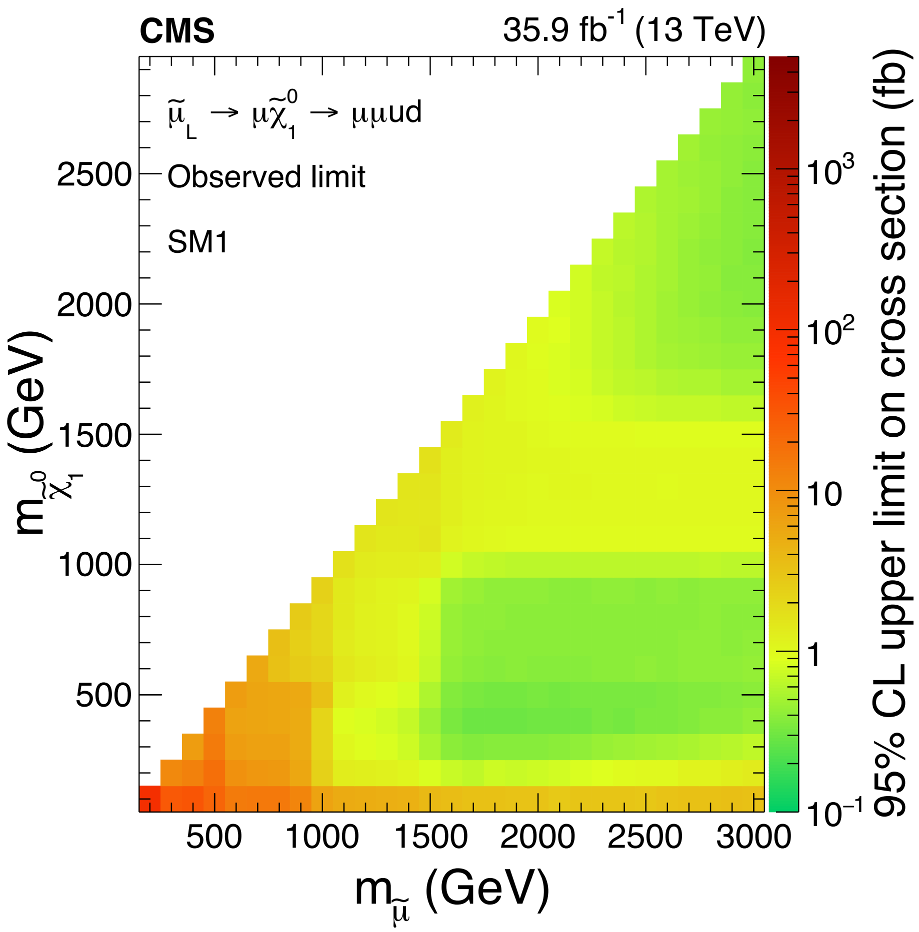


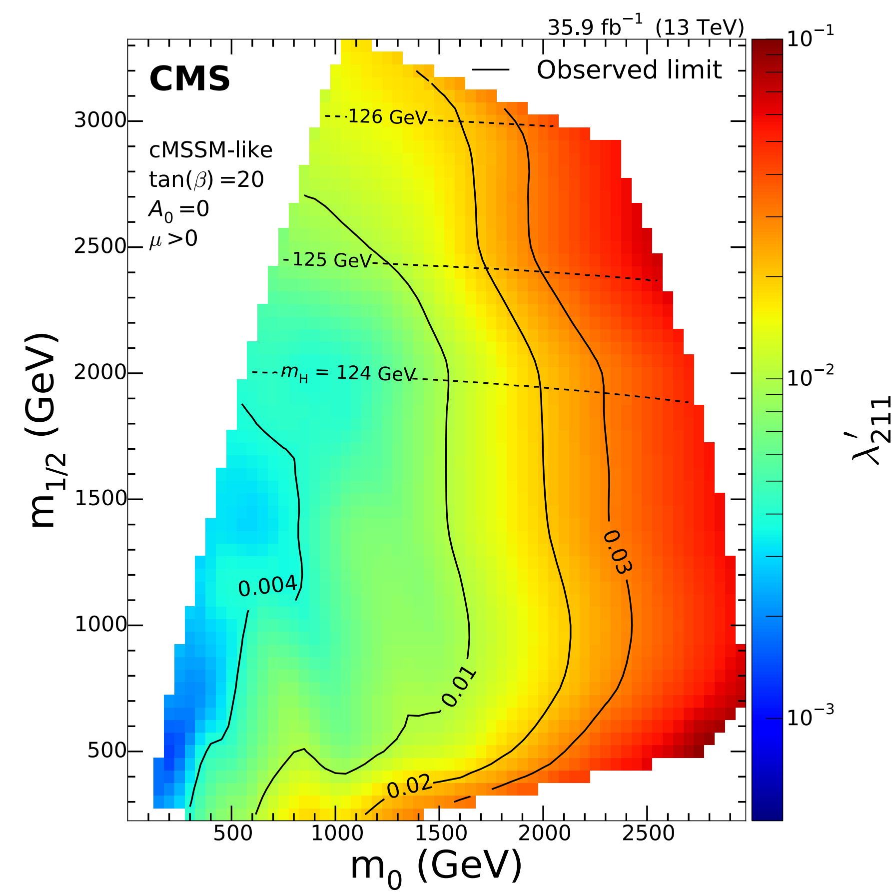
Resonant slepton, CMS

$\lambda'_{ijk} L_i Q_j D^c_k$

- WZ and ttZ normalised via a fit to the b-tag distribution in a 3-muon CR with $|m_{\mu\mu} - m_Z| < 15$ GeV
- Fake muon contribution estimated with tight-to-loose ratio method
- Contribution from photon conversion taken from MC and validated in 3-muon CR with $|m_{\mu\mu\mu} - m_Z| < 15$ GeV
- No significant excess is observed, limits are set on the cross section and on a modified cMSSM model with an additional λ'_{211} coupling



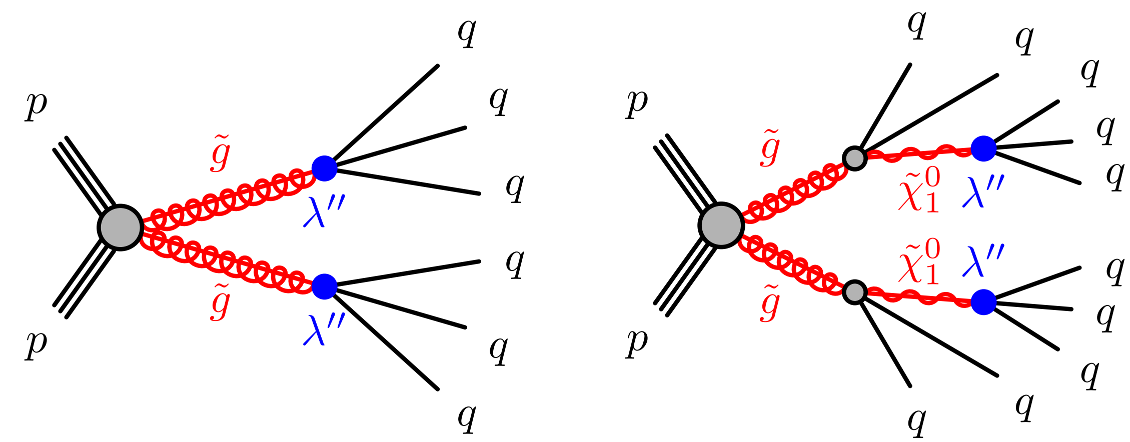




RPV all-hadronic, ATLAS

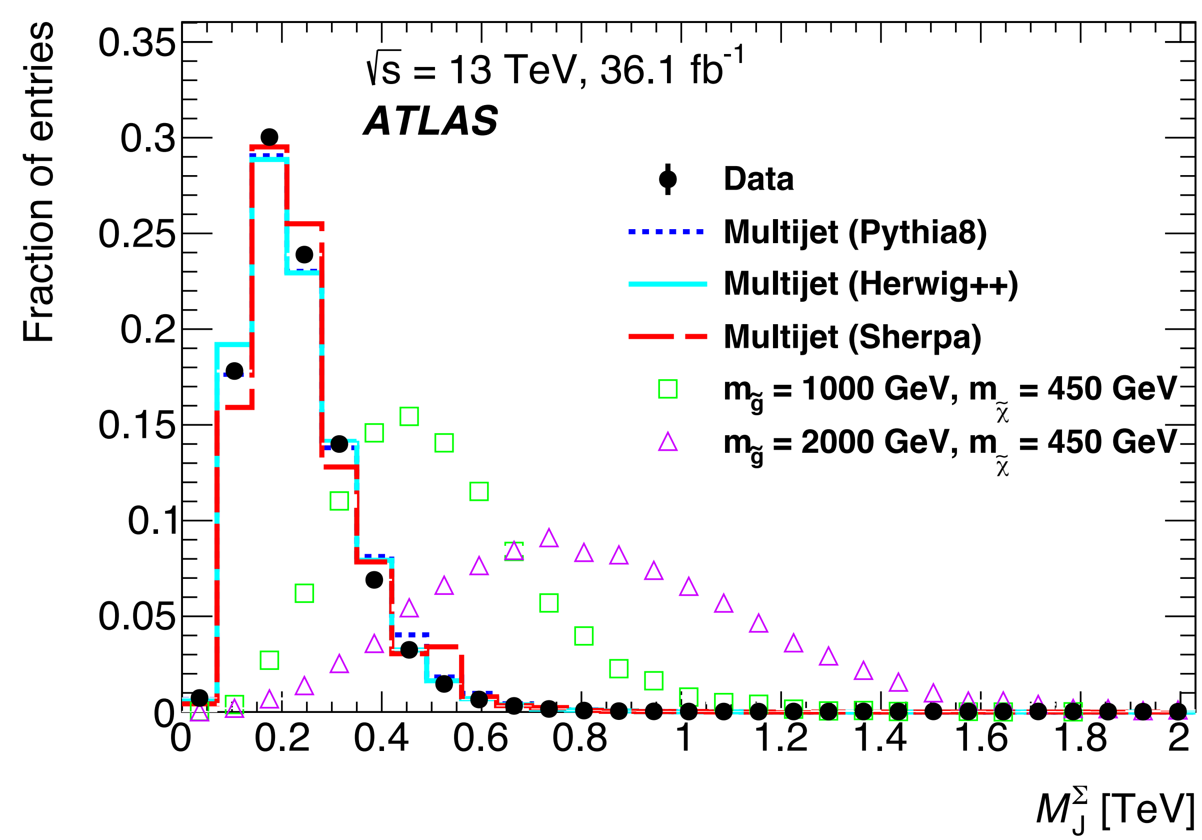
$\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$

- Search for gluino production decaying to 3 or 5 jets via UDD coupling
  - gluino → 3 jets
  - gluino → 2 jets + LSP → 5 jets



- Discriminant variable is sum of large-R jet masses: $\mathbf{M_J^\Sigma}$

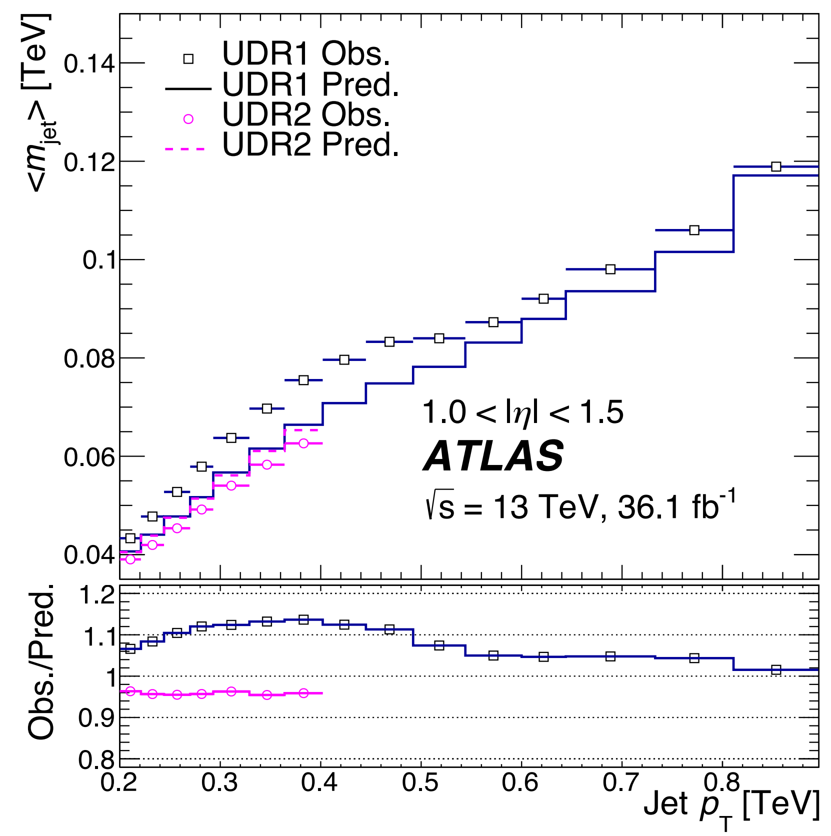
- Individual jet masses predicted by sampling a PDF
  - Build PDF in a control region (N_{jet} =3) as a function of jet p_T/eta/b-tagged
  - **Sample PDF in signal region** ($N_{jet} \geq 4$, $N_{jet} \geq 5$)
- Uncorrelated discriminating variable $|\Delta\eta_{12}|$ used to enhance SR sensitivity and define validation regions

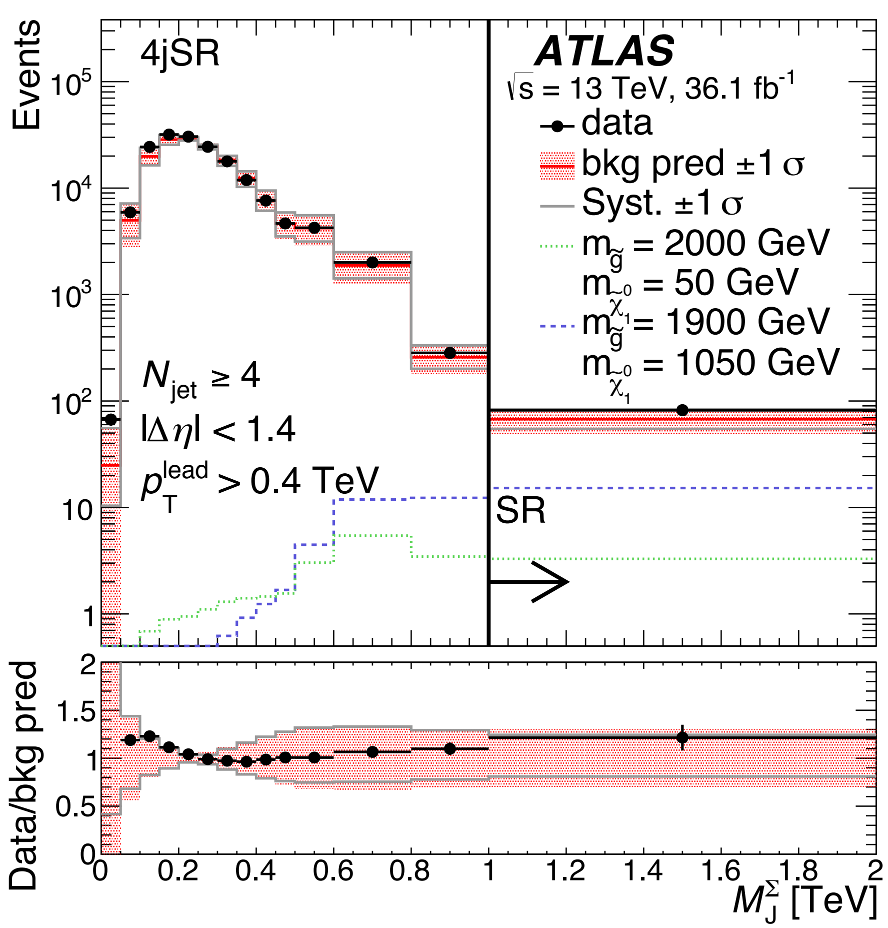


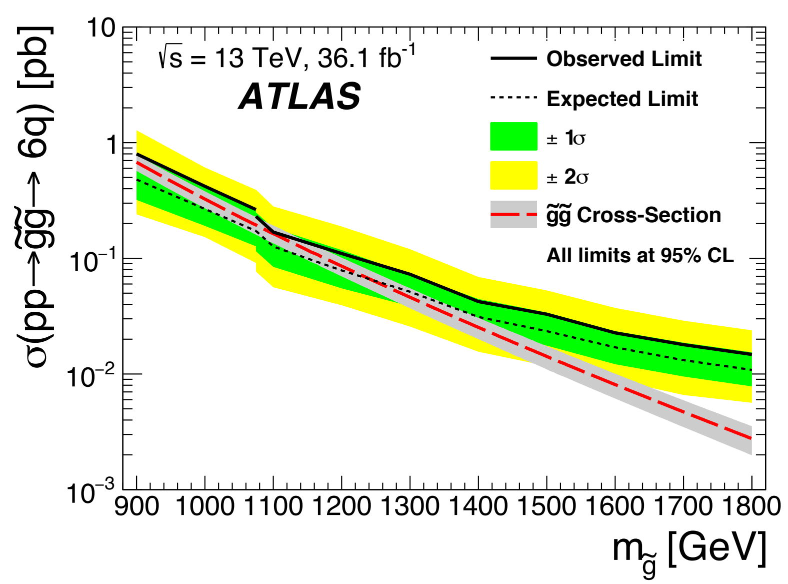
RPV all-hadronic, ATLAS

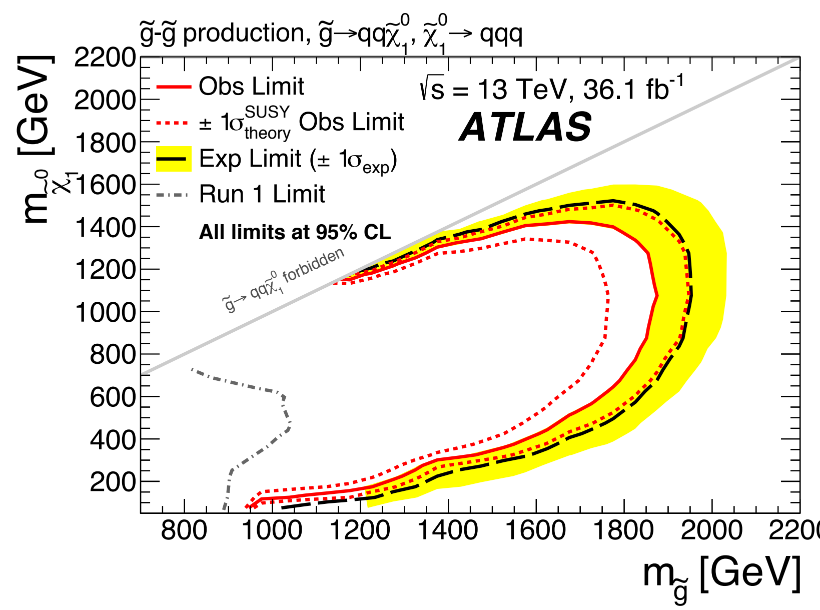
$$\frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

- A systematic uncertainty on the method is derived by looking at the closure in extreme regions of phase space
- No significant excess is observed, and limits are set on the two simplified models





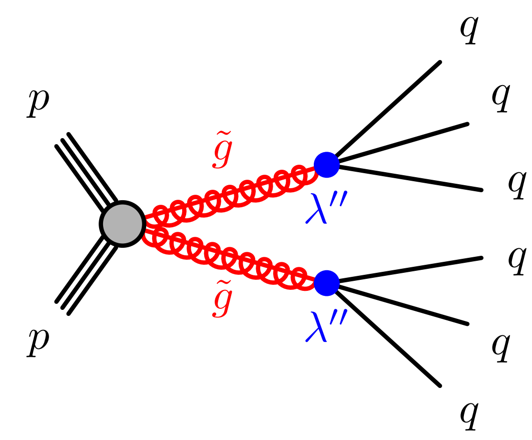




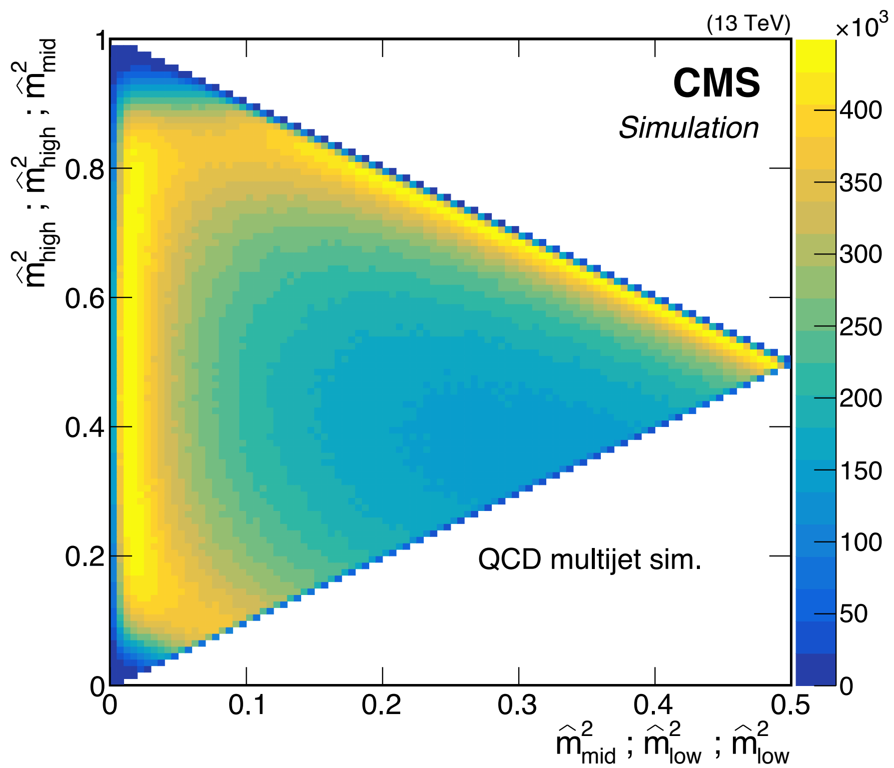
Tri-jet pairs, CMS

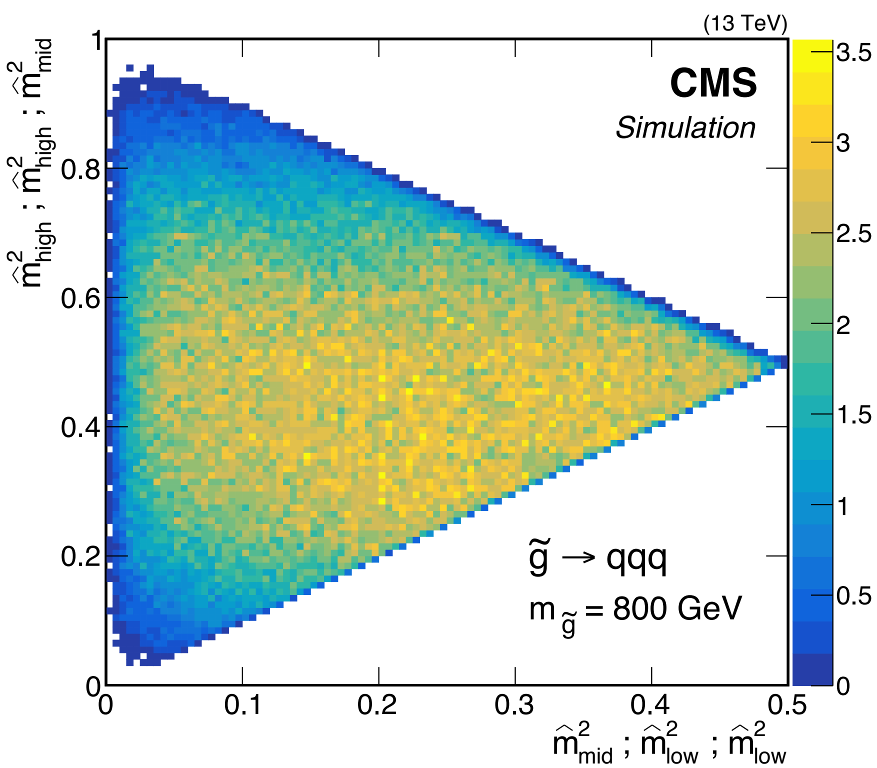
$$\frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

- Search for pair-produced three-jet resonances. Interpreted as gluino production decaying to 3 jets via UDD coupling
- At high gluino masses (>700 GeV), trigger on H_T and H_T+jets
- Hard to trigger at low gluino masses, uses **data-scouting technique**: store only HLT-reconstructed objects. Allows much higher trigger rate by recording smaller event size
- Strategy: fit jet-triplet mass distribution, using all jet triplet combinations out of the 6 leading jets (20 triplets)
- Sensitivity improved by using **Dalitz variables**



$$\hat{m}(3,2)^2_{ij} = \frac{m^2_{ij}}{m^2_{ijk} + m^2_i + m^2_j + m^2_k}$$





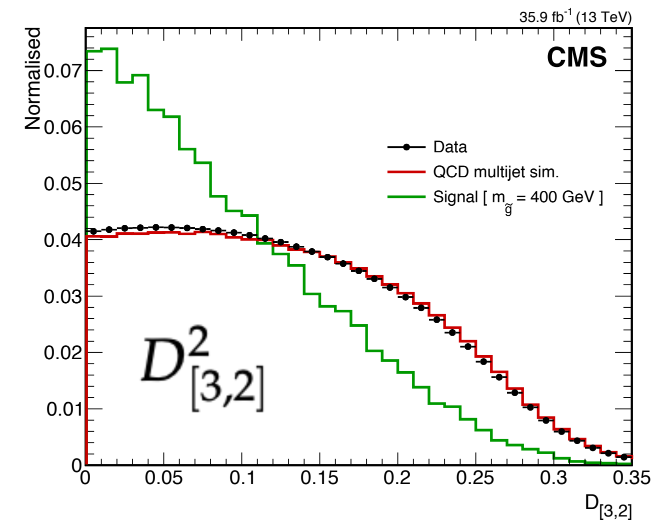
Phys. Rev. D 99 (2019) 012010

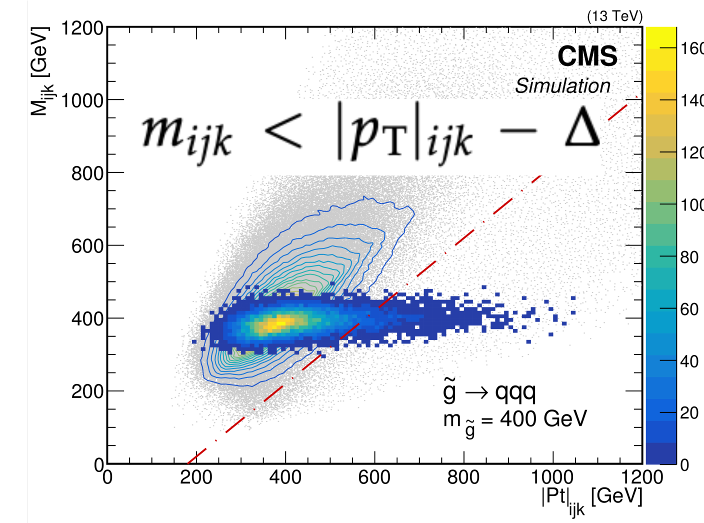
Tri-jet pairs, CMS

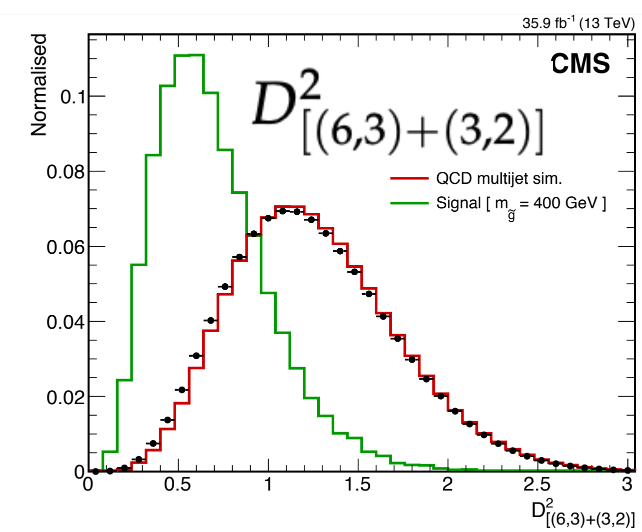
$$\frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

- Sensitivity enhanced building new Dalitz variables:
  - 3 per dijet permutation in a triplet $$\hat{m}(3,2)^2_{ij} = \frac{m^2_{ij}}{m^2_{ijk} + m^2_i + m^2_j + m^2_k}$$
  - 1 per triplet $$D^2_{[3,2]} = \sum_{i>j}\left(\hat{m}(3,2)_{ij} - \frac{1}{\sqrt{3}}\right)^2$$
  - 20 per triplet permutation in the event $$\left\{ \begin{array}{l} \hat{m}(6,3)^2_{ijk} = \dfrac{m^2_{ijk}}{4\, m^2_{ijklmn} + 6\, \sum_i m^2_i} \\ m_{ijk} < |p_{\mathrm{T}}|_{ijk} - \Delta \end{array} \right.$$
  - 10 per triplet-pair permutation in the event $$A_m = \frac{|m_{ijk} - m_{lmn}|}{m_{ijk} + m_{lmn}}$$
  - 1 per event

$$D^2_{[(6,3)+(3,2)]} = \sum_{i<j<k}\left(\sqrt{\hat{m}(6,3)^2_{ijk} + D^2_{[3,2],ijk}} - \frac{1}{\sqrt{20}}\right)^2$$



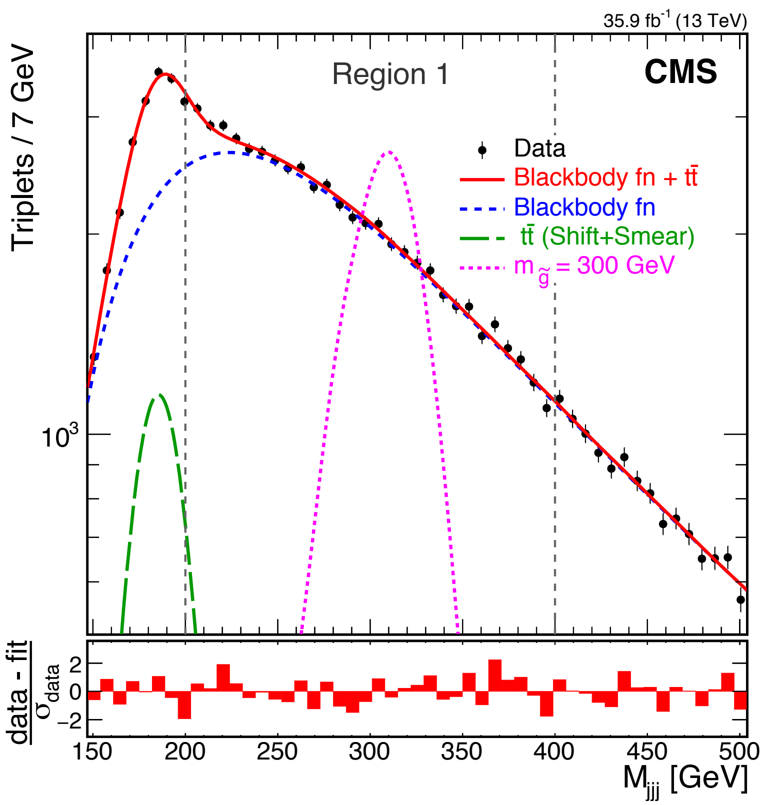


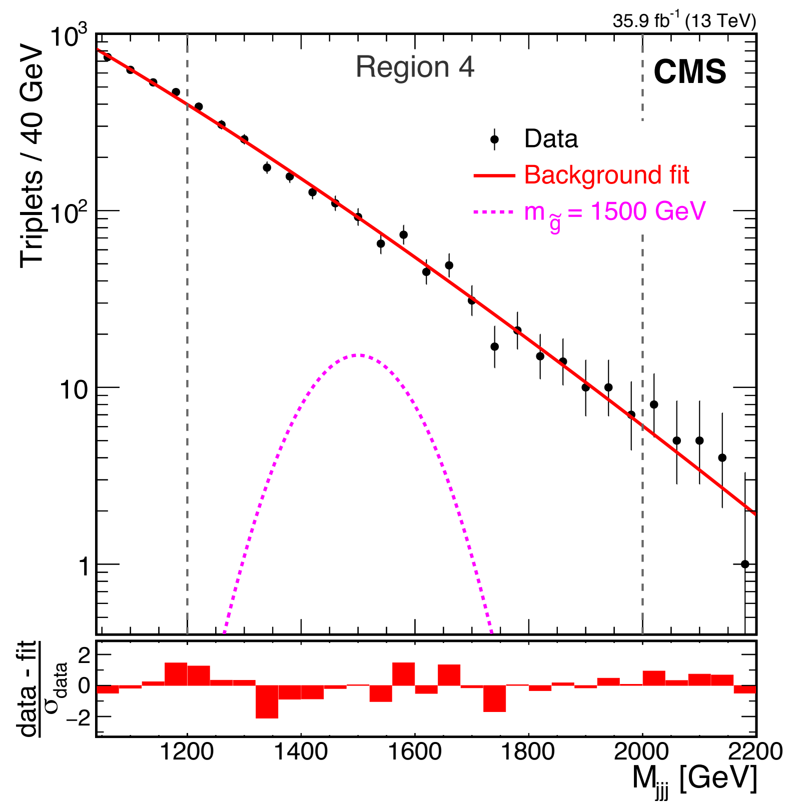


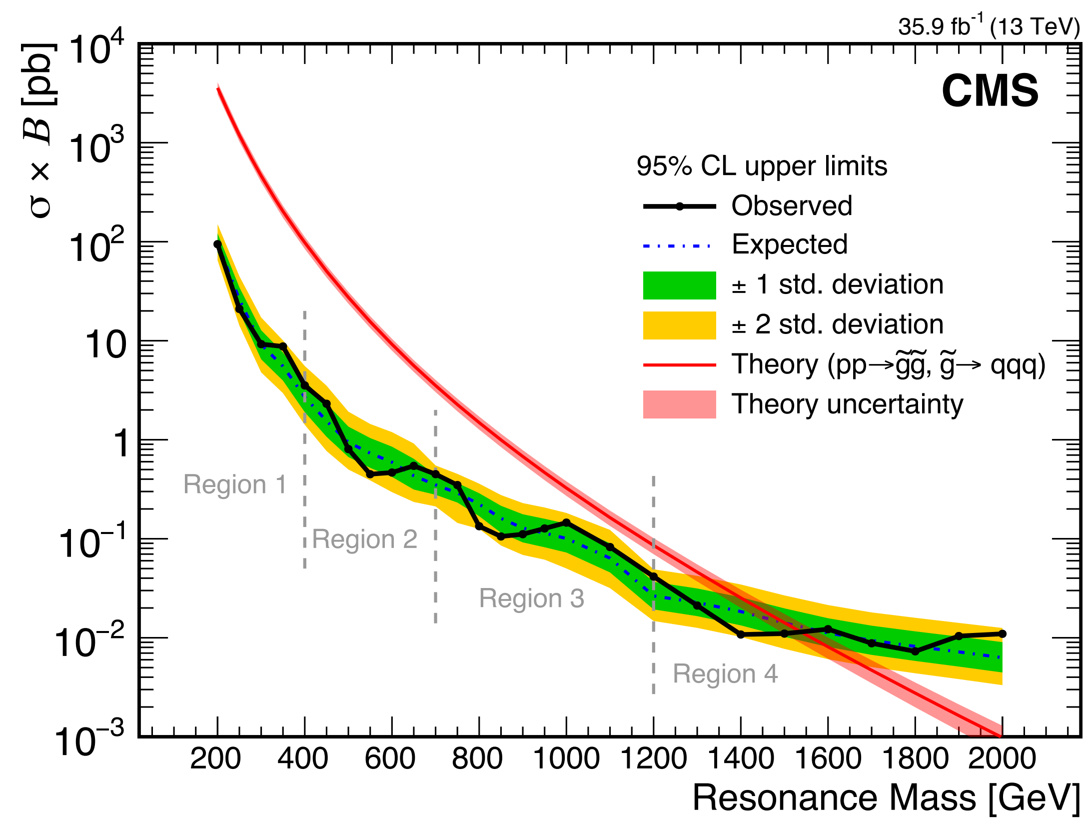
Tri-jet pairs, CMS

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

- Fit jet-triplet mass distribution with analytic function, using all jet triplet combinations that pass the triplet and event selections
- Correction and uncertainties in the regions using data-scouting are derived by **fitting the hadronic top mass**
  - ttbar simulation needs to be smeared and shifted to match data, same correction applied to signal.
- No significant excess observed, set limits on the production of three-jet resonances

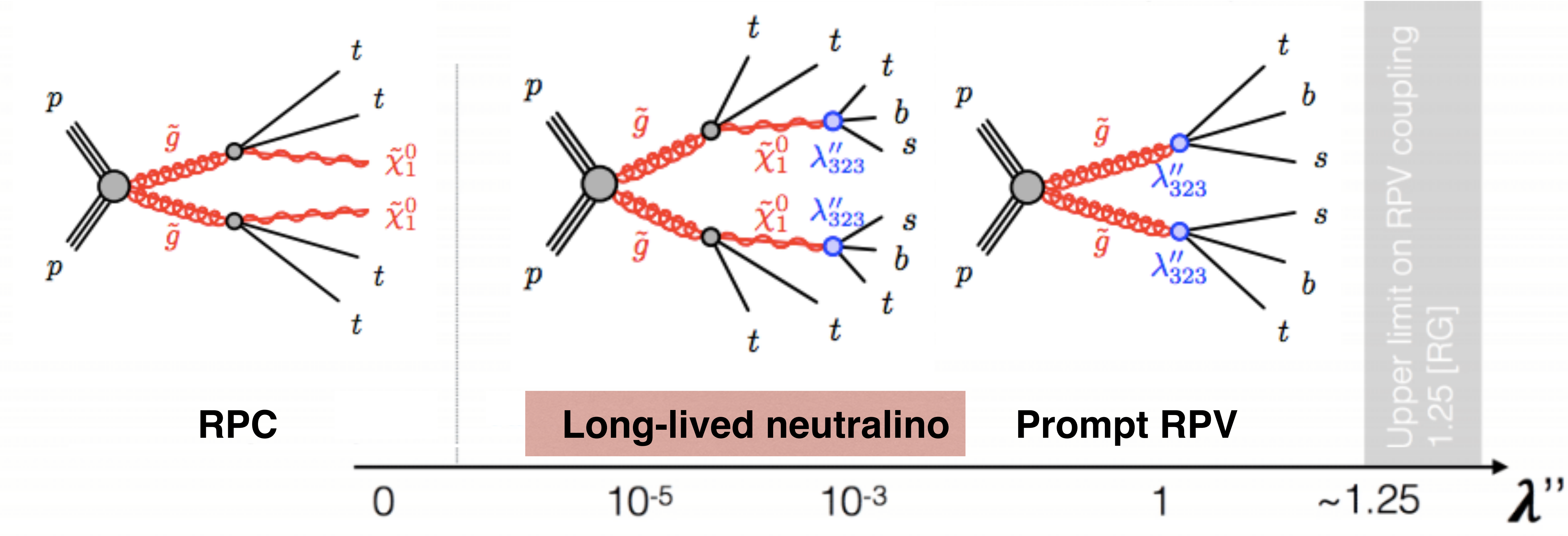






RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$

- Reinterpret RPC and RPV analyses in models with variable RPV coupling, rich phenomenology:
  RPC → long-lived → prompt with cascade to LSP → prompt with direct decay

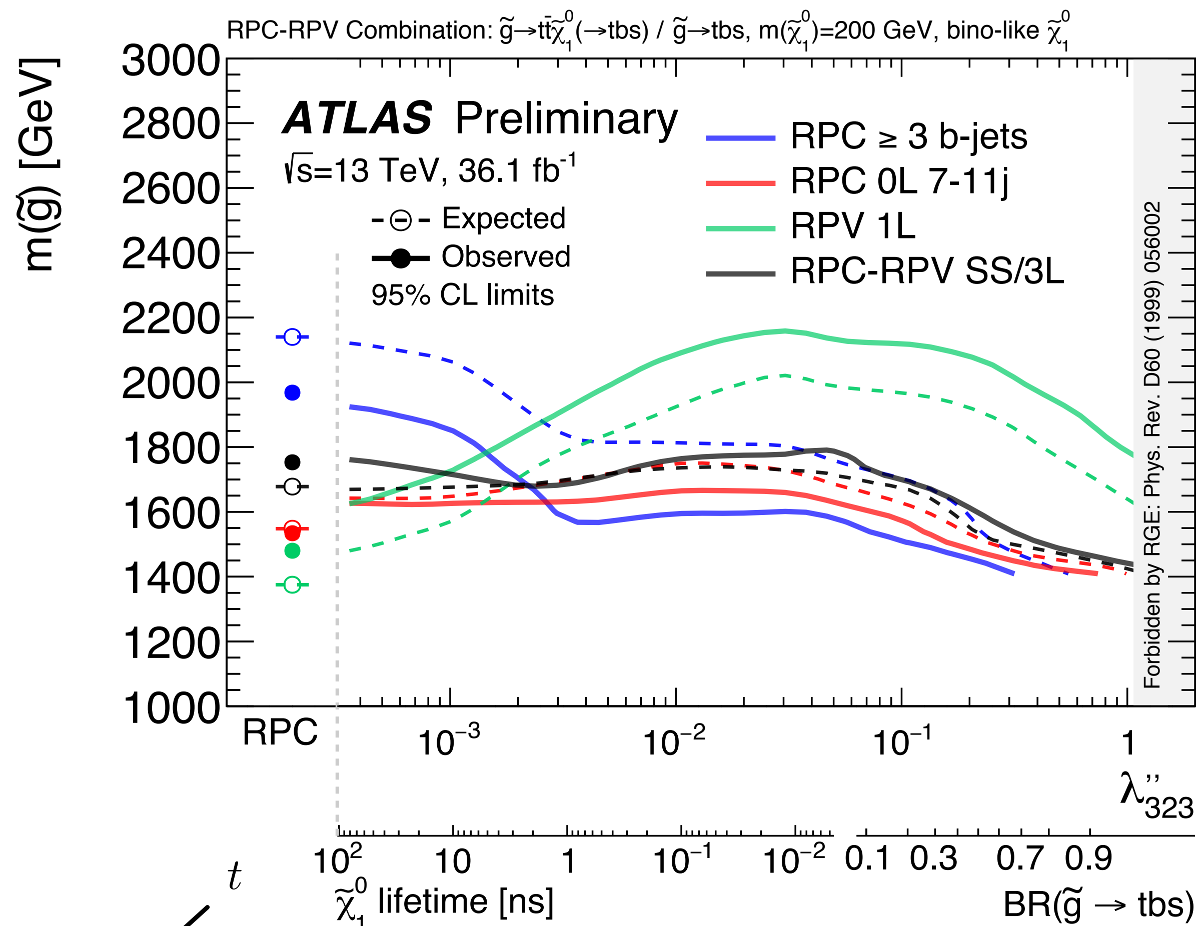


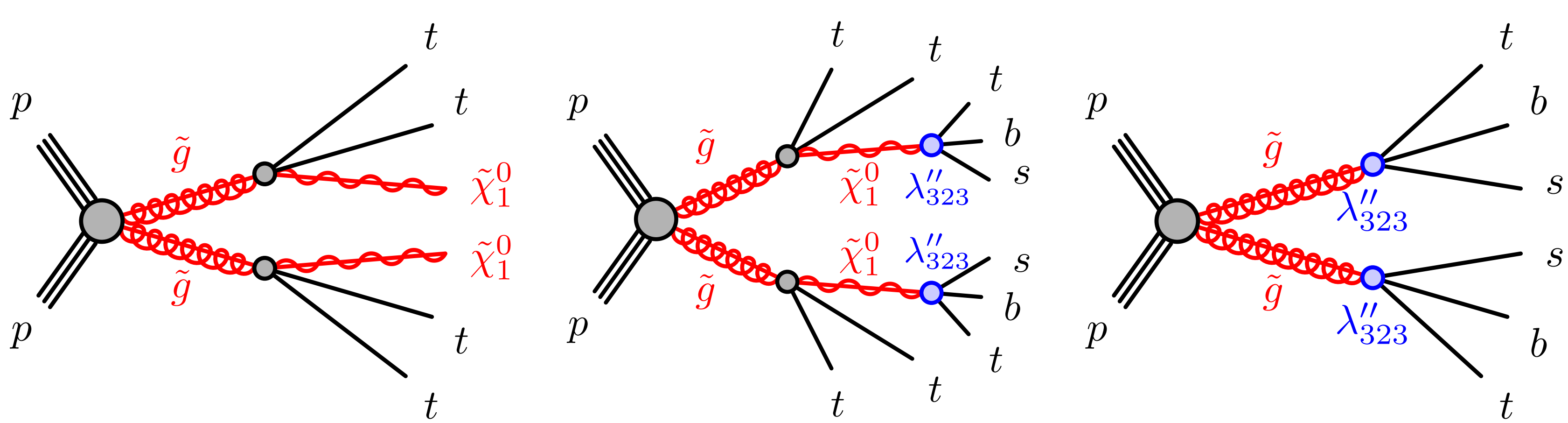
- Searches that don't exploit displaced objects can retain good sensitivity to moderate lifetimes (especially without leptons)

RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk}U^c_i D^c_j D^c_k$

- Nice coverage and complementarity between RPC and RPV searches
- In some cases dedicated long-lived searches are needed to bridge the gaps

- Model with **gluino → tt**$\tilde{\chi}^0_1$ (→tbs via λ''_{323}) is covered over the full RPV coupling range
- Exclusion limit drops by ~400 GeV in the $\tau_{\tilde{\chi}^0_1} \approx$1-10 ns lifetime regime

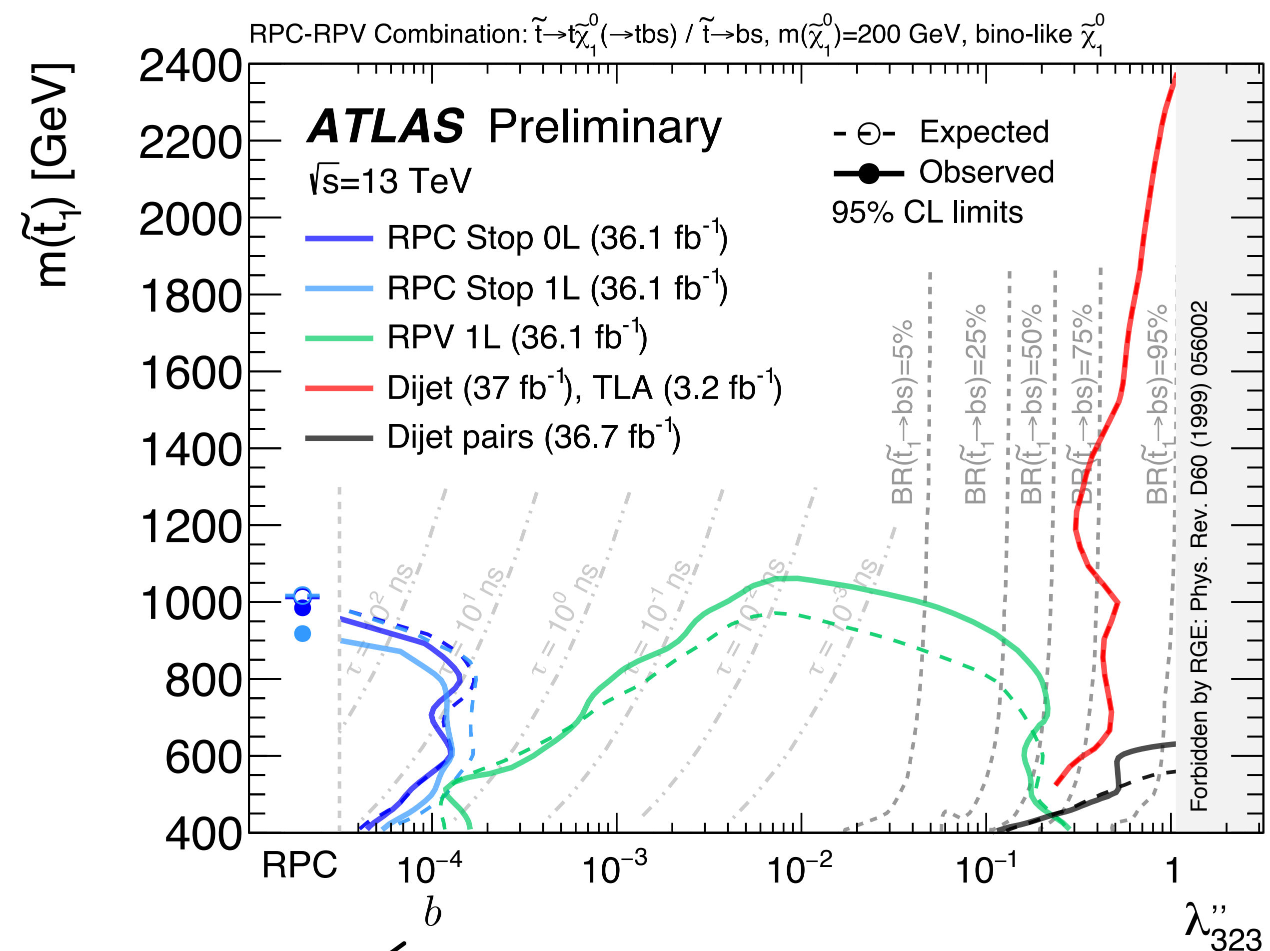


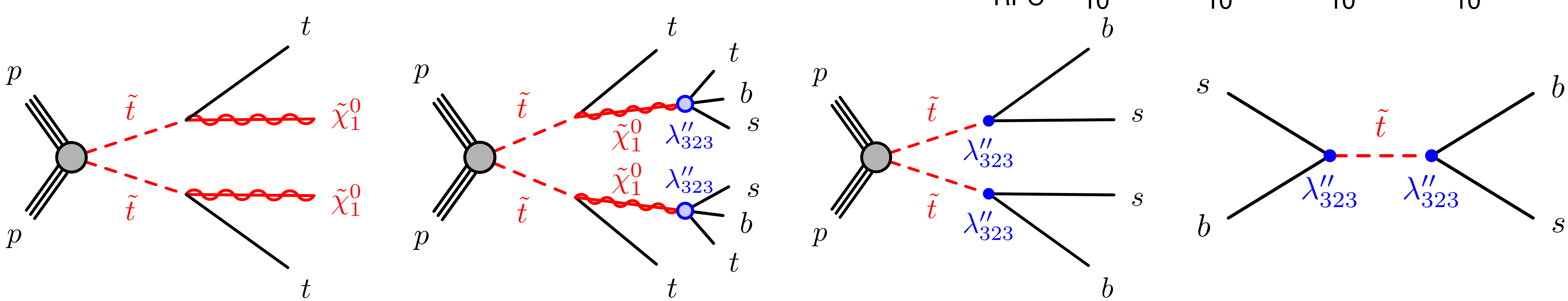


RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$

- Nice coverage and complementarity between RPC and RPV searches
- In some cases dedicated long-lived searches are needed to bridge the gaps

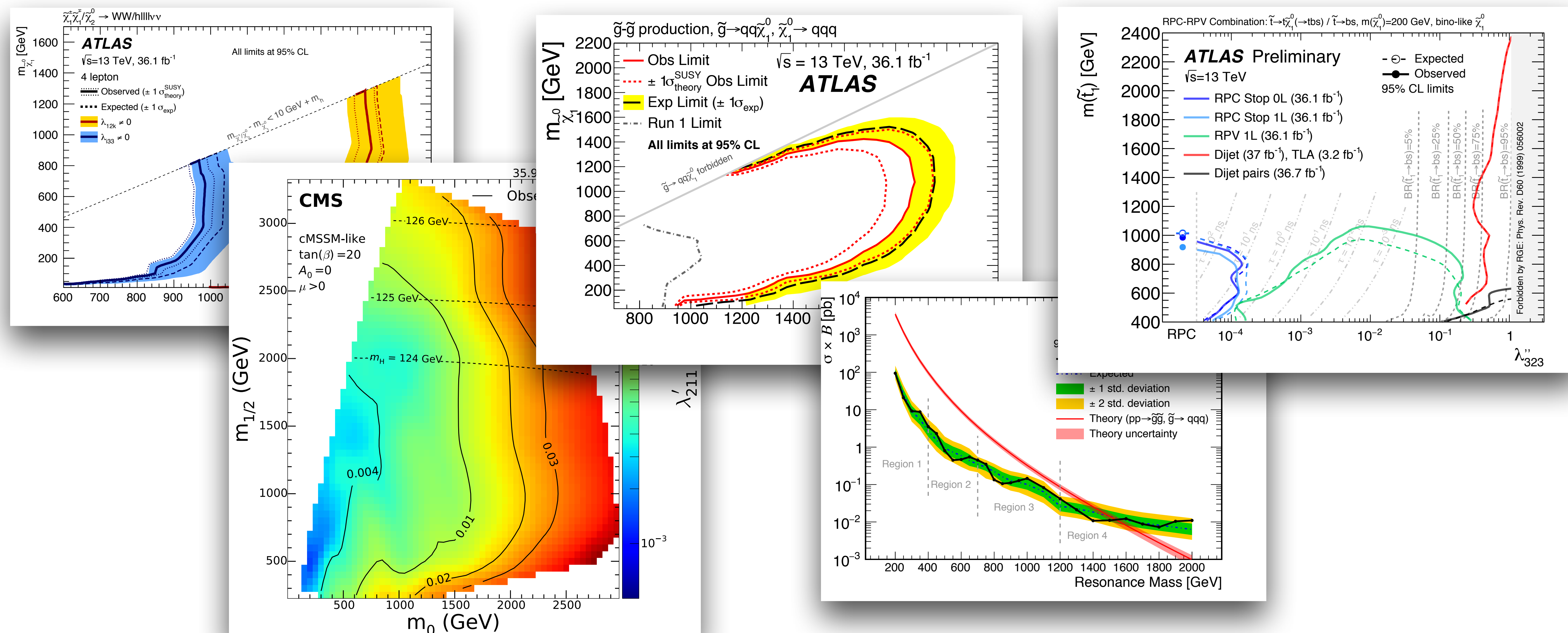
- Model with **stop → t**$\tilde{\chi}_1^0$ (→tbs via λ''$_{323}$) has sensitivity gaps in the $\tau_{\tilde{\chi}_1^0} \approx$1-10 ns lifetime regime
- Drop in sensitivity when direct decay stop→bs dominates over the cascade decay stop → t$\tilde{\chi}_1^0$ (→tbs)
- For large couplings, resonant production becomes relevant and the dijet search can place extremely tight constraints





Conclusions

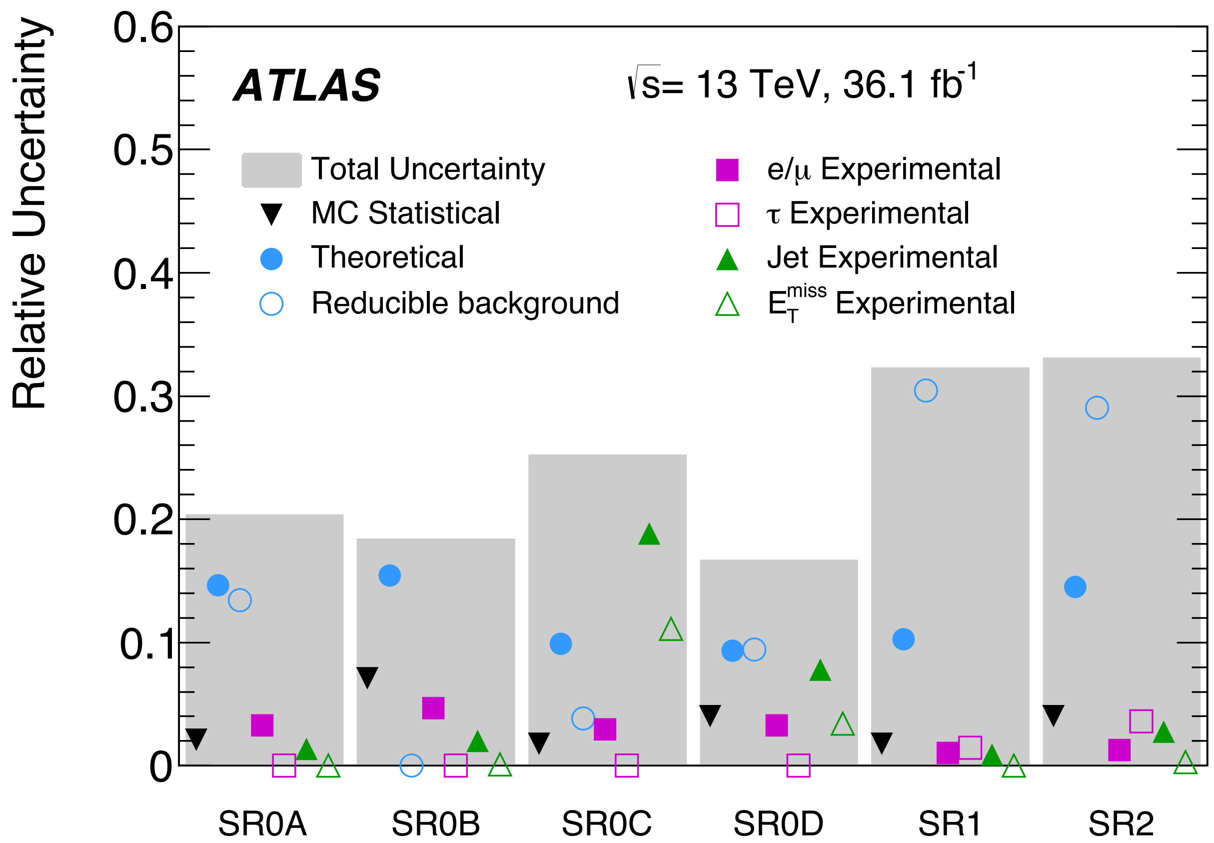
- Extensive search program at the LHC in searches for supersymmetry with R-parity violation
- No significant excess observed
- Large increase in sensitivity still possible from full Run 2 dataset



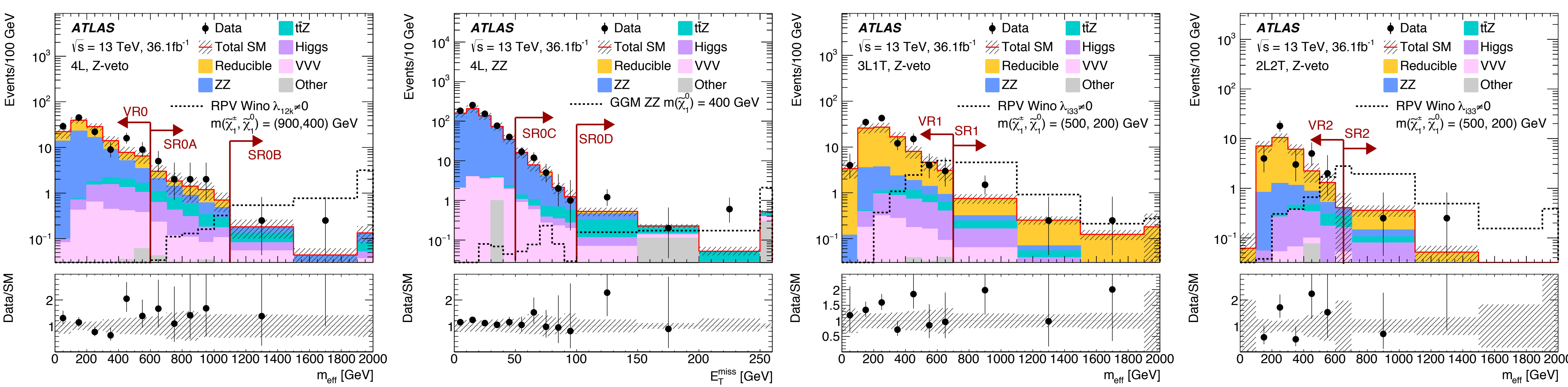
Backup

RPV four leptons, ATLAS

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



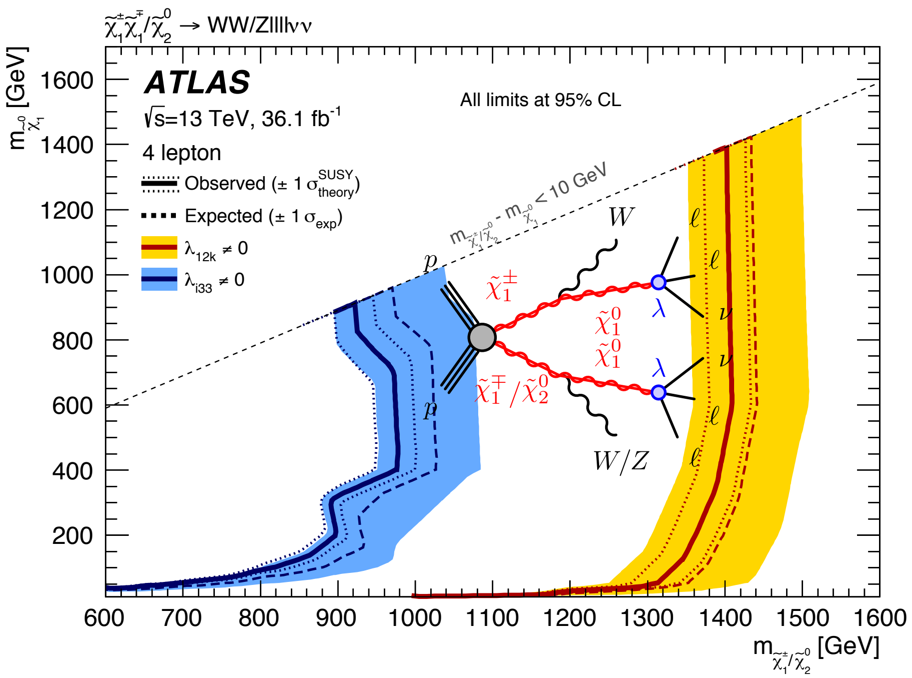
- Breakdown of systematic uncertainties
- SR distributions

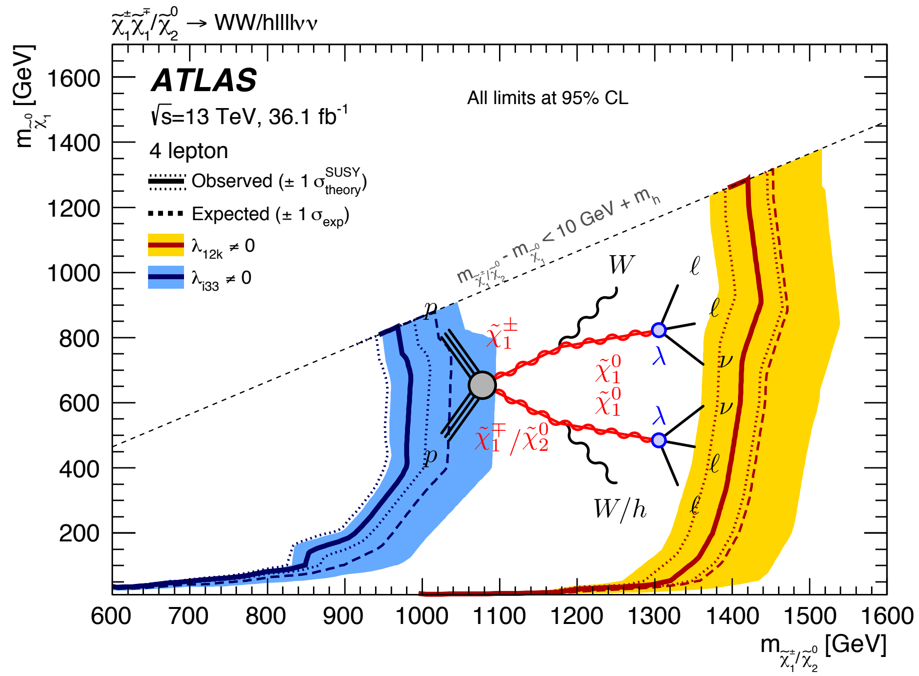


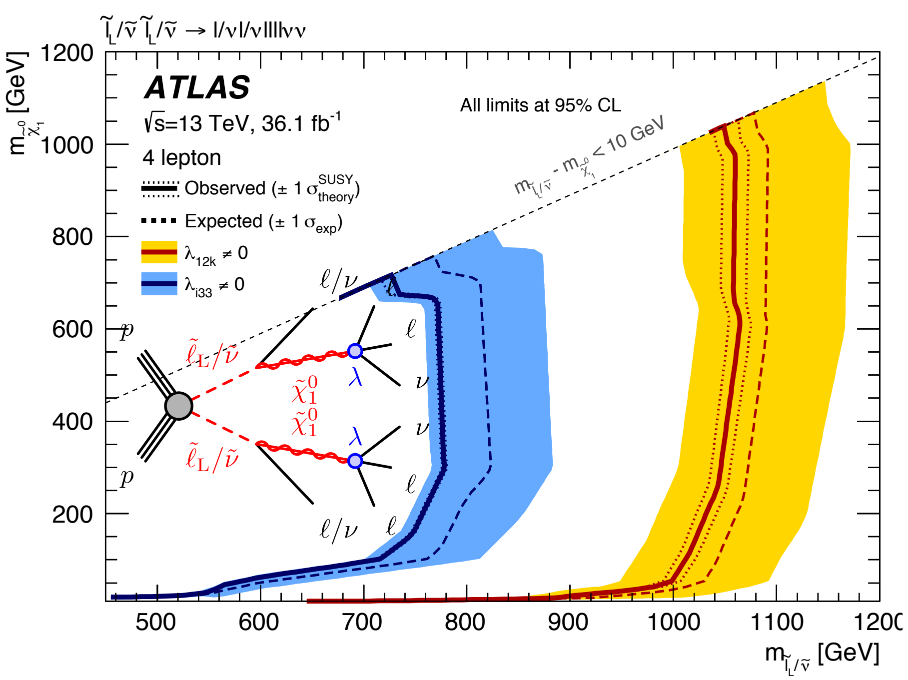
RPV four leptons, ATLAS

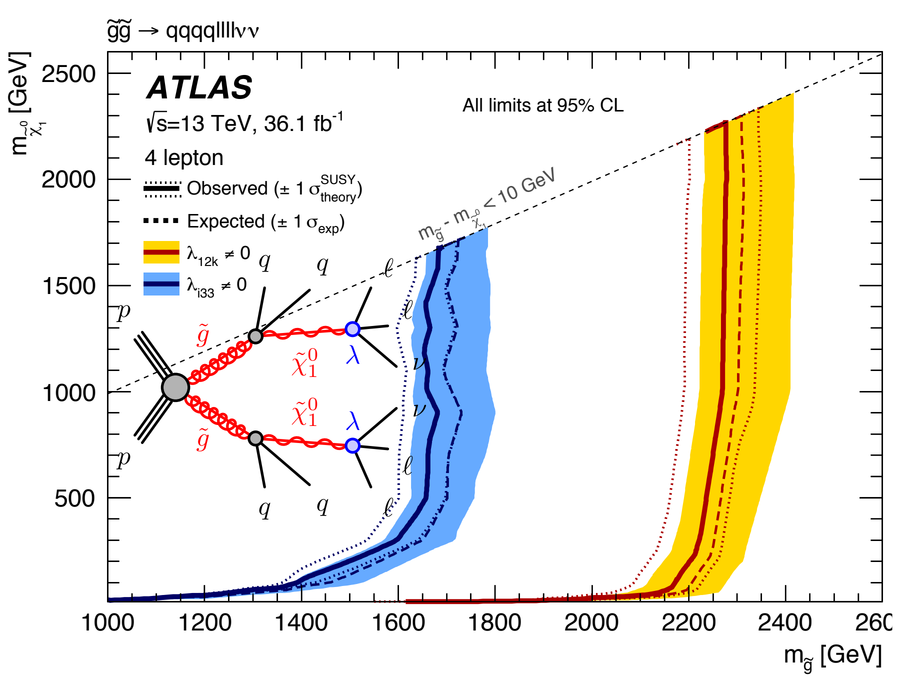
$$\frac{1}{2}\lambda_{ijk} L_i L_j E_k^c$$

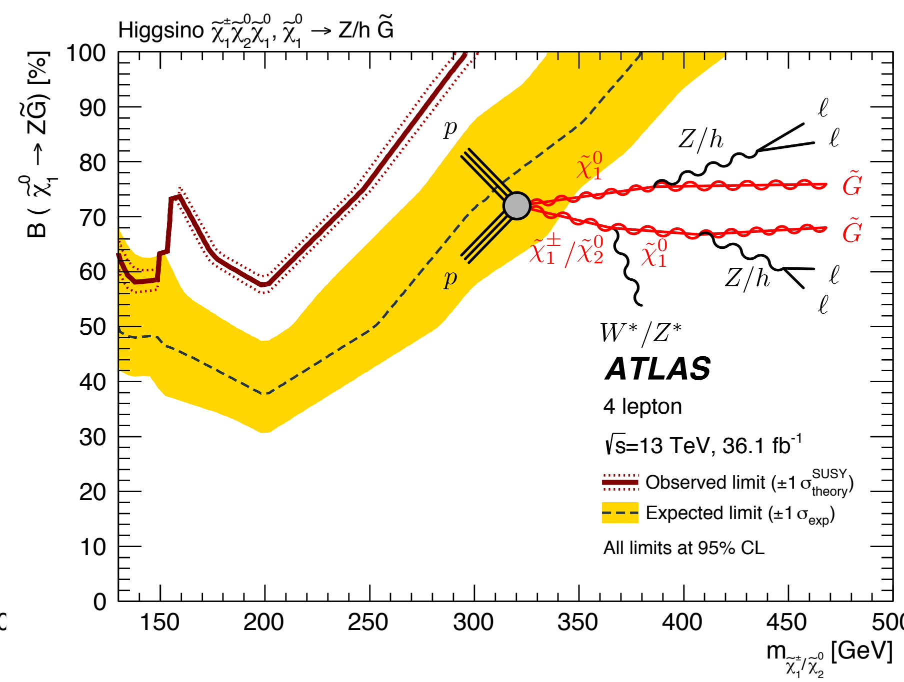
- Exclusion limits per model







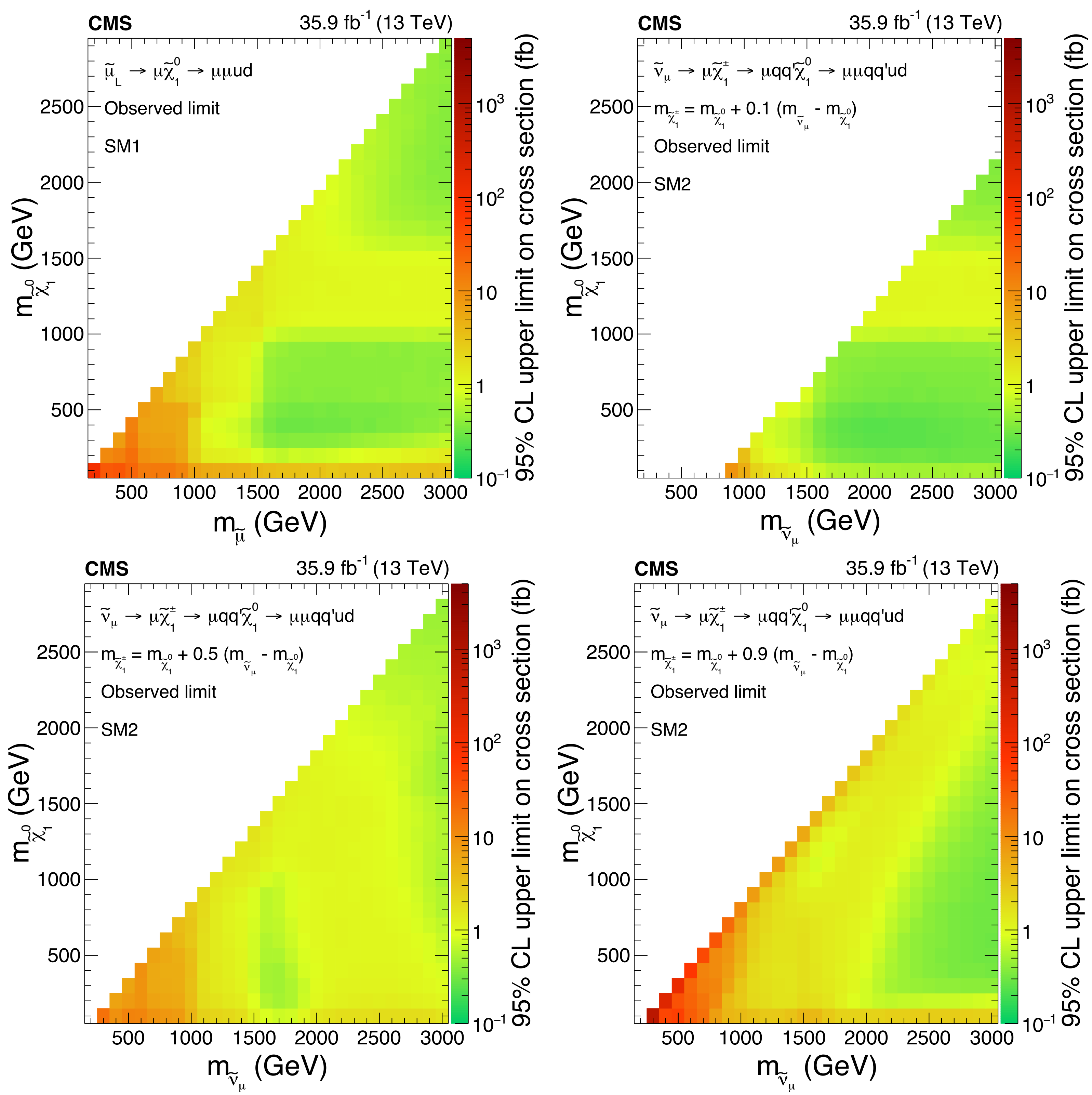




Resonant slepton, CMS

$\lambda'_{ijk} L_i Q_j D^c_k$

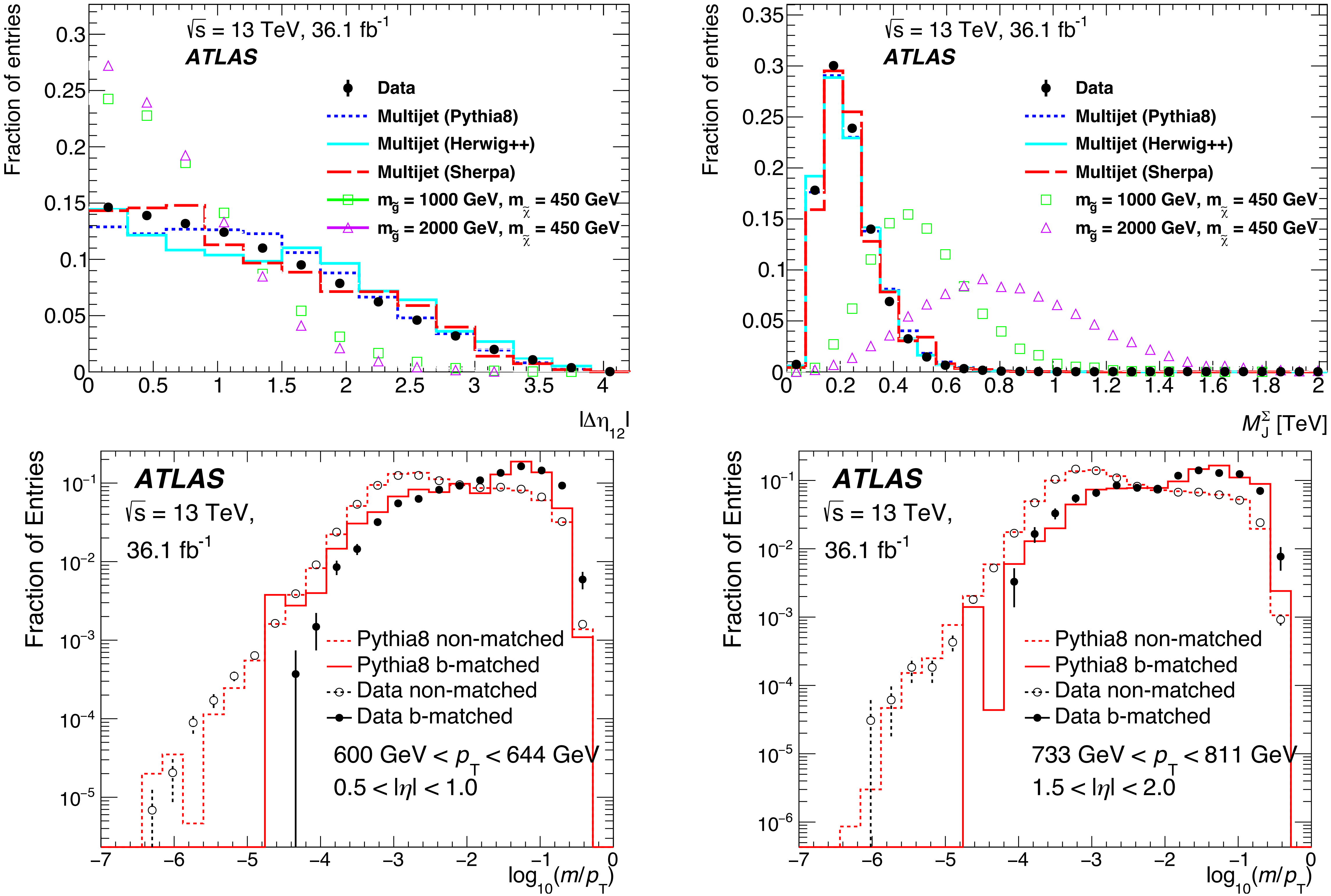
- Cross section limits



Eur. Phys. J. C 79 (2019) 305

RPV all-hadronic, ATLAS

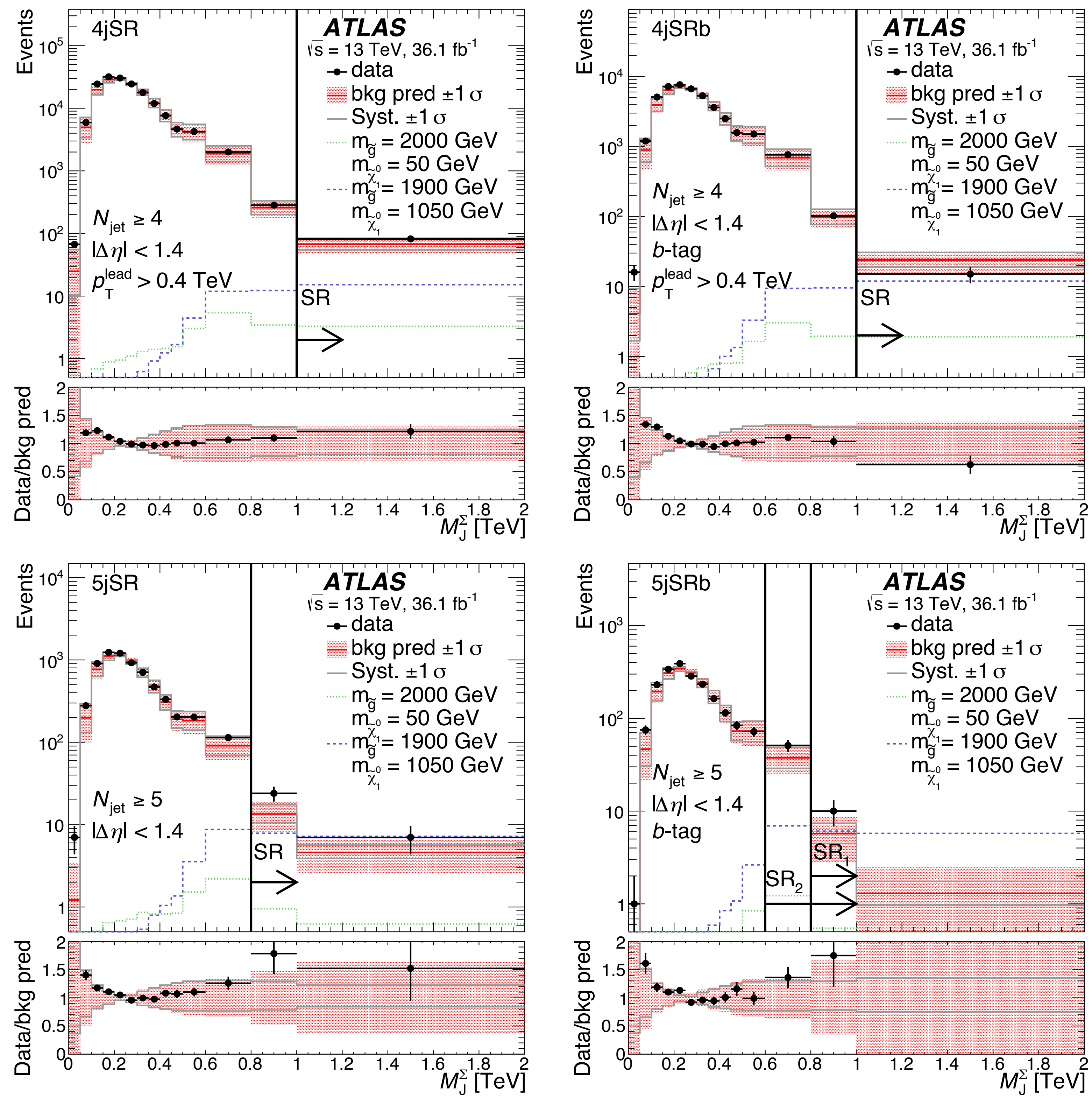
$$\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$



RPV all-hadronic, ATLAS

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

- Signal region distributions

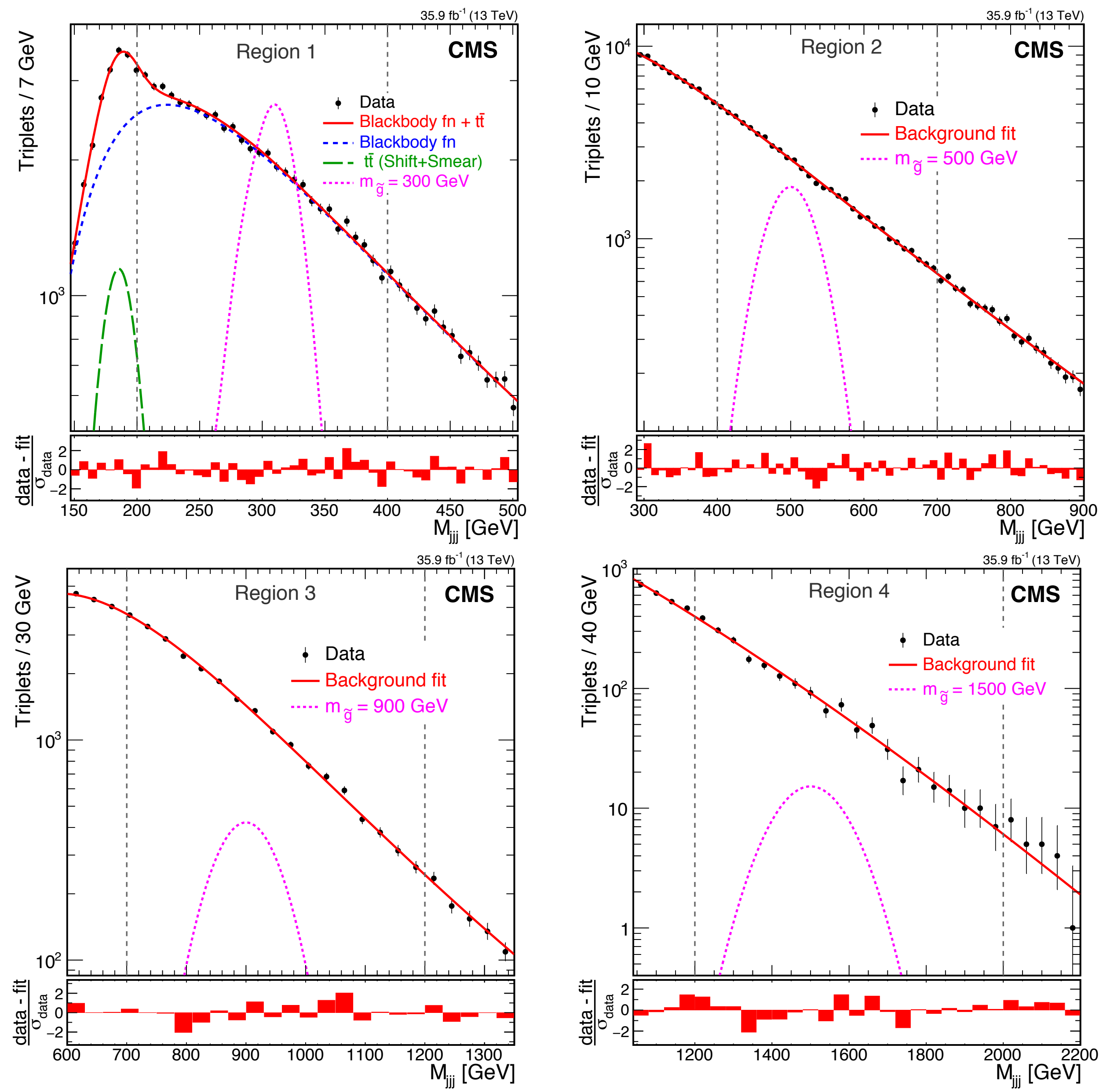


Phys. Lett. B 785 (2018) 136

Tri-jet pairs, CMS

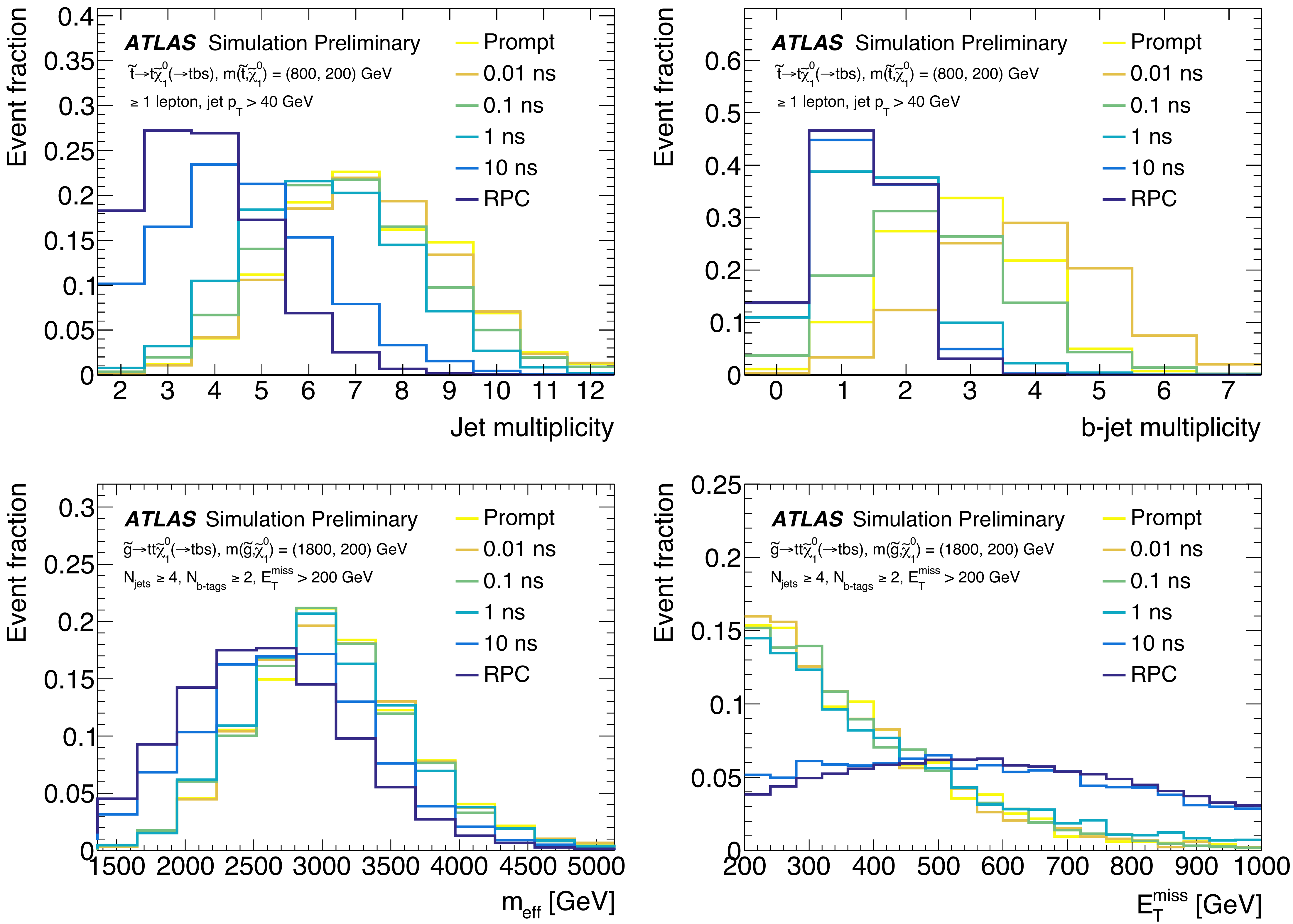
$$\frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k$$

- Signal region distributions
- Event selection



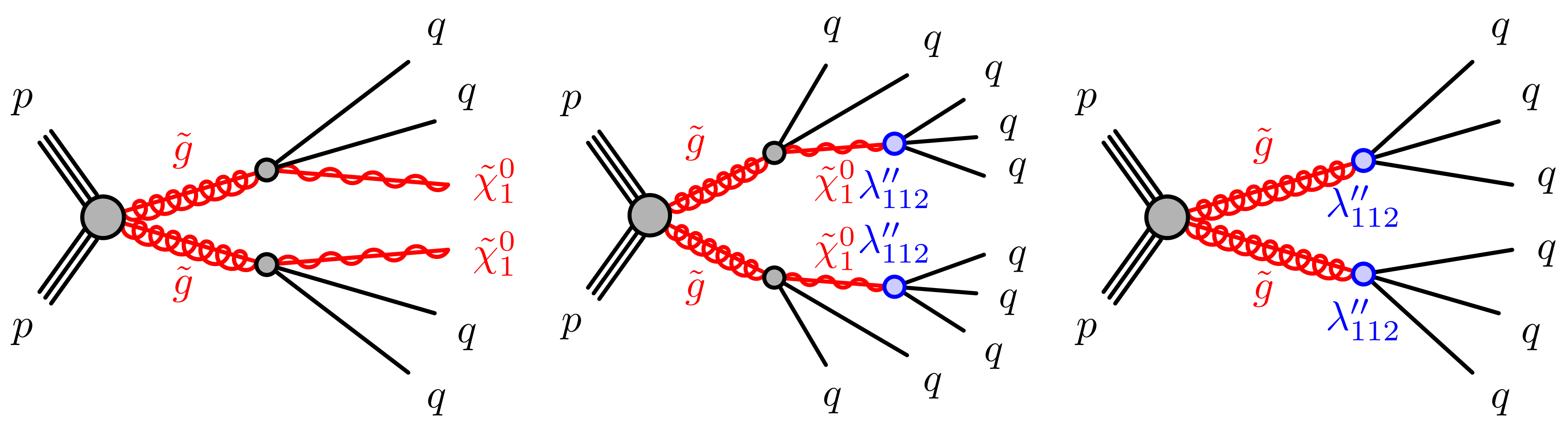
Region	Gluino mass range	Jet p_T	H_T	sixth jet p_T	$D^2_{[(6,3)+(3,2)]}$	A_m	Δ	$D^2_{[3,2]}$
1	200–400 GeV	>30 GeV	>650 GeV	>40 GeV	<1.25	<0.25	>250 GeV	<0.05
2	400–700 GeV	>30 GeV	>650 GeV	>50 GeV	<1.00	<0.175	>180 GeV	<0.175
3	700–1200 GeV	>50 GeV	>900 GeV	>125 GeV	<0.9	<0.15	>20 GeV	<0.2
4	1200–2000 GeV	>50 GeV	>900 GeV	>175 GeV	<0.75	<0.15	>-120 GeV	<0.25

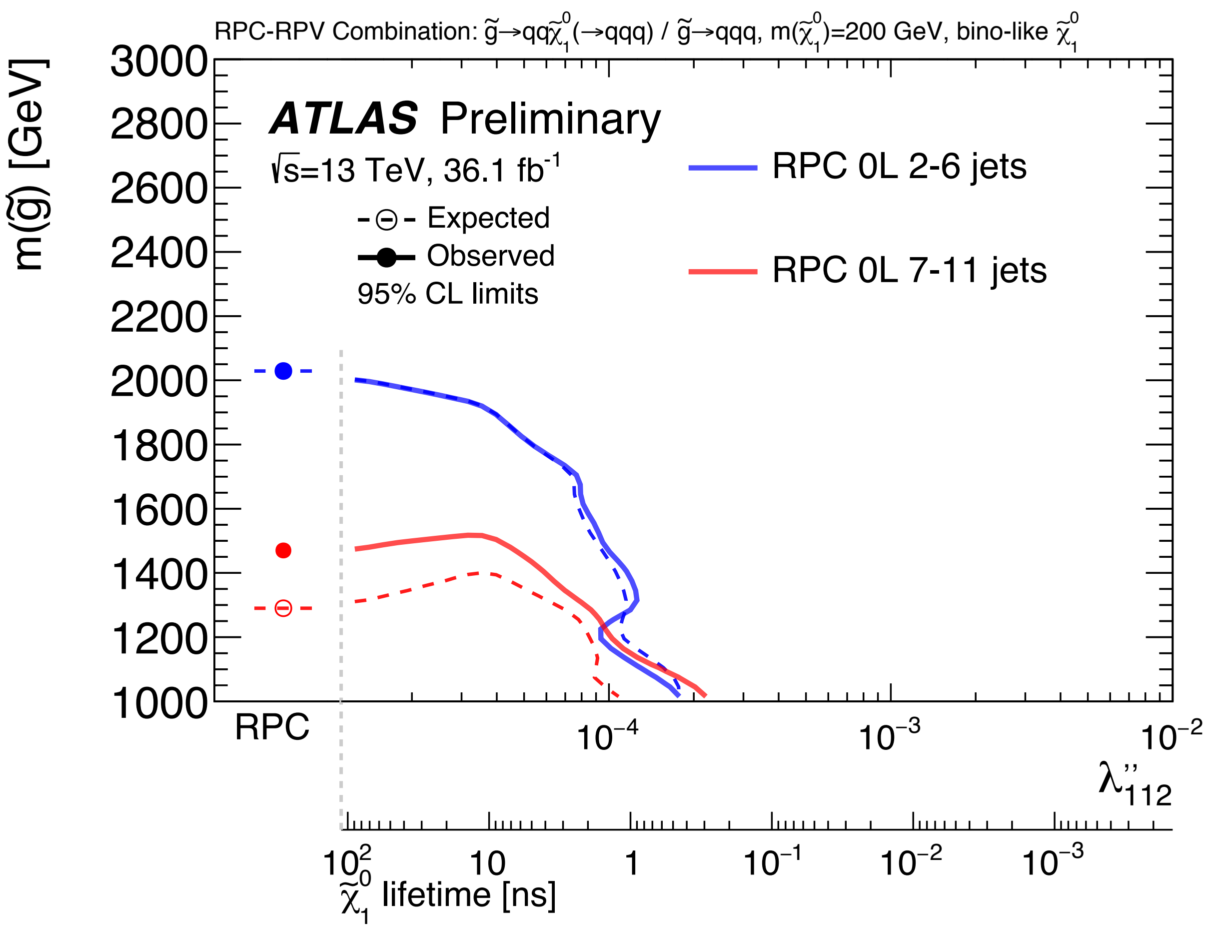
RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k$

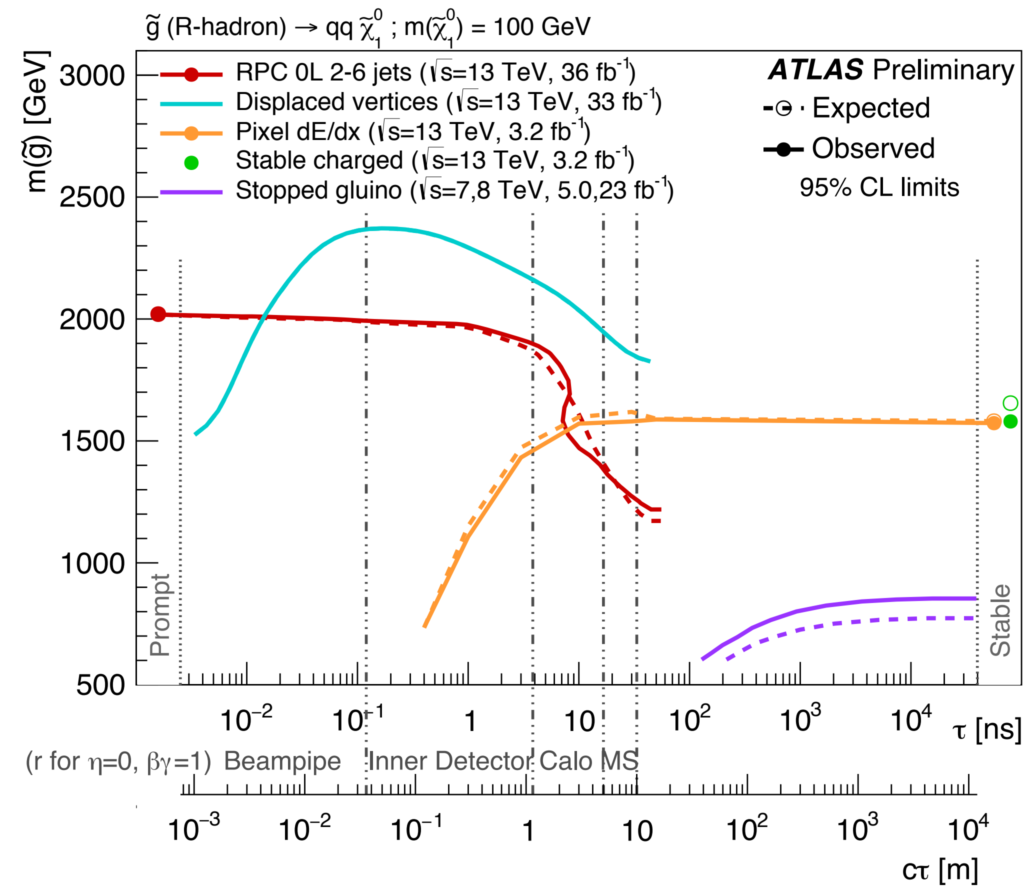


RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k$

- Gluino → qq+LSP model







RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$

- Model summary

Model name	Gqq	Gtt	Stop	R-hadron
Coupling	λ''_{112}	λ''_{323}	λ''_{323}	–
Decay	$\tilde{g} \to qq\tilde{\chi}_1^0$ $\tilde{g} \to qq\tilde{\chi}_1^0(\to qqq)$ $\tilde{g} \to qqq$	$\tilde{g} \to tt\tilde{\chi}_1^0$ $\tilde{g} \to tt\tilde{\chi}_1^0(\to tbs)$ $\tilde{g} \to tbs$	$\tilde{t}_1 \to t\tilde{\chi}_1^0$ $\tilde{t}_1 \to t\tilde{\chi}_1^0(\to tbs)$ $\tilde{t}_1 \to bs$	$\tilde{g} \to qq\tilde{\chi}_1^0$
Other colored sparticle masses	$m(\tilde{q}) = 3$ TeV $m(\tilde{t}, \tilde{b}) = 5$ TeV	$m(\tilde{q}) = 5$ TeV $m(\tilde{t}, \tilde{b}) = 2.4$ TeV	$m(\tilde{q}, \tilde{g}) = 3$ TeV $m(\tilde{t}_2, \tilde{b}) = 3$ TeV	$m(\tilde{q}, \tilde{t}, \tilde{b}) \approx$ PeV
LSP	The LSP is bino-like, $m(\tilde{\chi}_1^0) = 200$ GeV			$m(\tilde{\chi}_1^0) = 100$ GeV

RPV-RPC reinterpretation, ATLAS $\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$

- Analyses summary

Analysis name	Leptons	Jets / b-tags	$E_{\mathrm{T}}^{\mathrm{miss}}$ requirement	Representative cuts	Model targeted
RPC 0-lepton, 2-6 jets [53]	0	≥ 4 / –	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.2$	$m_{\mathrm{eff}} > 3000$ GeV	Gqq, R-hadron
RPC 0-lepton, 7-11 jets [55]	0	≥ 7 / – ≥ 11 / ≥ 2	$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 5$ GeV$^{1/2}$	–	Gqq Gtt
RPC multi-b [56]	0 1	≥ 7 / ≥ 3 ≥ 5 / ≥ 3	$E_{\mathrm{T}}^{\mathrm{miss}} > 350$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV	$m_{\mathrm{eff}} > 2600$ GeV $m_{\mathrm{eff}} > 2200$ GeV	Gtt
RPV 1-lepton [57]	1	≥ 10 / ≥ 4	–	–	Gtt, stop
RPC Stop 0-lepton [58]	0	≥ 4 / ≥ 2	$E_{\mathrm{T}}^{\mathrm{miss}} > 400$ GeV	$m_{\mathrm{jet,R=1.2}} > 120$ GeV	stop
RPC Stop 1-lepton [59]	1	≥ 4 / ≥ 1	$E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV	$m_T > 160$ GeV	stop
RPC and RPV same-sign and three leptons [60]	2 SS or 3	≥ 6 / ≥ 2 ≥ 6 / ≥ 2	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$¿0.15 –	$m_{\mathrm{eff}} > 1800$ GeV $m_{\mathrm{eff}} > 2000$ GeV	Gtt, stop
RPV stop dijet pairs [61]	–	≥ 4 / ≥ 2	–	$\mathcal{A} < 0.05$	stop
Dijet and TLA [62,63]	–	≥ 2 / –	–	$\lvert y^* \rvert < 0.6$	stop