Searches for R-Parity violating SUSY with lepton number violation

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ATLAS EXPERIMENT

Introduction

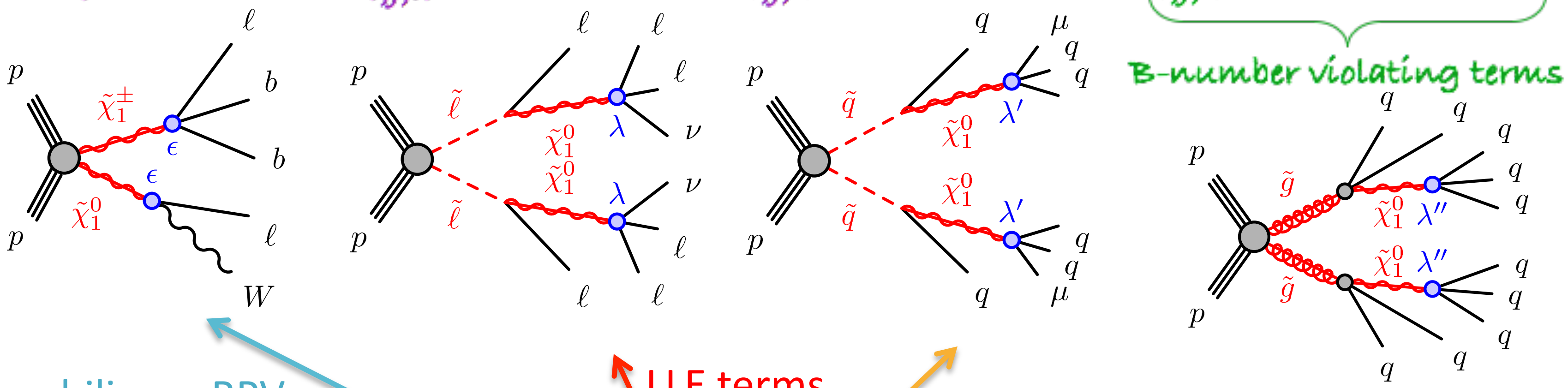
$R = (-1)^{3(B-L)+2s} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for SUSY particles} \end{cases}$

- Lepton (L) and baryon (B) number violation are experimentally constrained but not forbidden by any fundamental reason.
- Standard SUSY searches assume R-Parity Conservation (RPC).
- Introducing non-zero RPV couplings → rich phenomenology, can weaken mass and cross-section limits from collider experiments.

L-number violating terms

$$W^{MSSM}_{\not{R}_P} = \sum_i \varepsilon_i \hat{L}_i \hat{H}_u + \sum_{i,j,k} \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k + \sum_{i,j,k} \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k + \sum_{i,j,k} \lambda''_{ijk} \hat{U}^c_i \hat{D}^c_j \hat{D}^c_k$$

B-number violating terms



bilinear RPV terms (bRPV)

LLE terms

LQD terms

For BNV see next talk by B. Jackson

- In this talk only Lepton Flavour Violating terms (LFV) are considered.

Introduction

- This talk presents the latest results from the ATLAS experiment:
  - 20 fb^{-1} of pp LHC collision data at 8 TeV
  - searches for RPV SUSY with LSPs decaying promptly through LFV couplings for:

RPV summary paper: ATLAS-CONF-2015-018

	Simplified models				pMSSM	Ref.
Analysis short name	LLE $(\tilde{g}\tilde{g})$	LQD $(\tilde{g}\tilde{g})$	LQD $(\tilde{q}\tilde{q})$	LLE + LQD	bRPV	
4L	✓					Phys. Rev. D. 90, 052001 (2014)
SS/3L	✓				✓	JHEP 06 (2014) 035
1L		✓	✓			Phys. Rev. Lett. 114, 161801 (2015)
0L 2-6 jets		✓	✓			JHEP 09 (2014) 176
0L 7-10 jets		✓				J. High Energy Phys. 10 (2013) 130
eμ, eτ, μτ				✓		Phys. Rev. Lett. 115, 031801 (2015)
B-L (Not covered in this talk. See backup for summary)						ATLAS-CONF-2015-015

- Dedicated analysis searching for heavy resonances

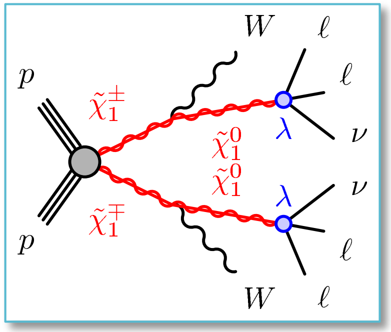
- Reinterpretation in terms of LFV-RPV of searches originally developed to target RPC models.
- This talk will focus more on the model description and interpretation of final results than on the analyses.

RPV summary paper

Analyses considered for the RPV summary paper

4L

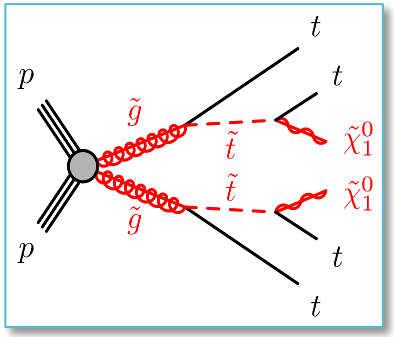
≥ 4 leptons
(≥ 2 e or μ)
no jet selection



- ttZ, ZZ (MC)
- Non-prompt and fake leptons (data driven)

SS/3L

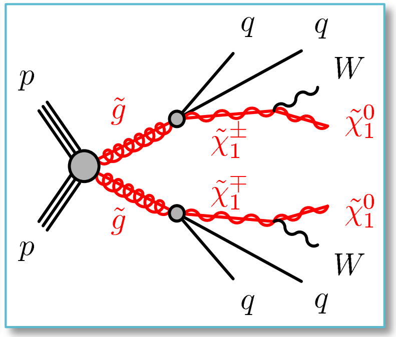
2 SS OR 3 leptons
0 – 3 b-jets



- ttW, ttZ WW, WZ, ZZ + jets (MC)
- Fake leptons, charge-flip (data-driven)

1L

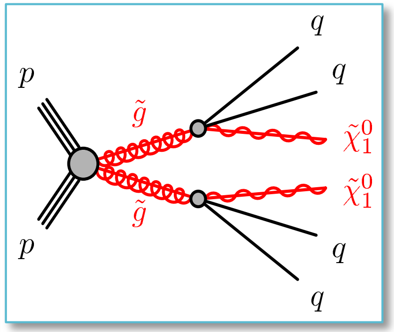
1 lepton
3 – 6 jets



- ttbar and W +jets (Normalize MC to data in CRs)

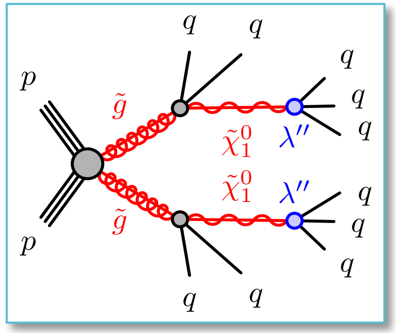
0L

no iso leptons
≥ 5 - 6 jets
$p_T(jet_1)$ >160 GeV

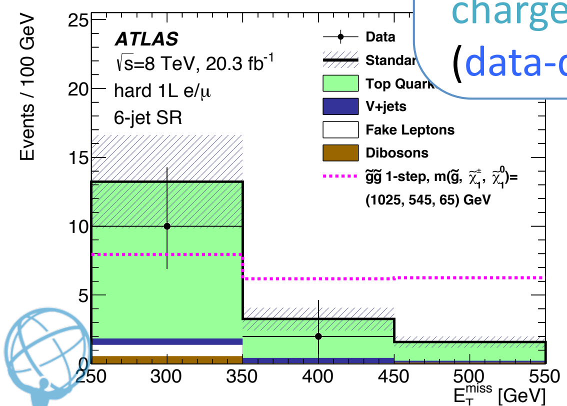


- W+jets, ttbar + single top, Z(νν) + jets, multijets. (Normalize MC to data in CRs)

no iso leptons
7 - 10 jets
p_T > 50 or 80 GeV



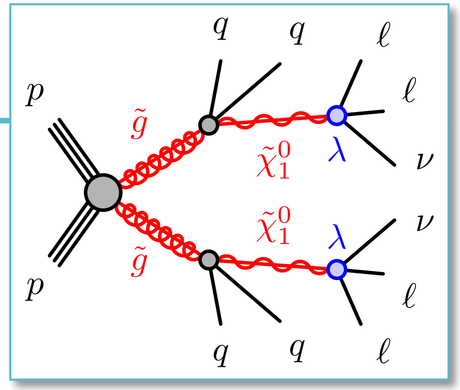
- multijets (matrix method)
- ttbar and W +jets (Normalize MC to data in CR)
- Z+jets, ttV, st (MC)



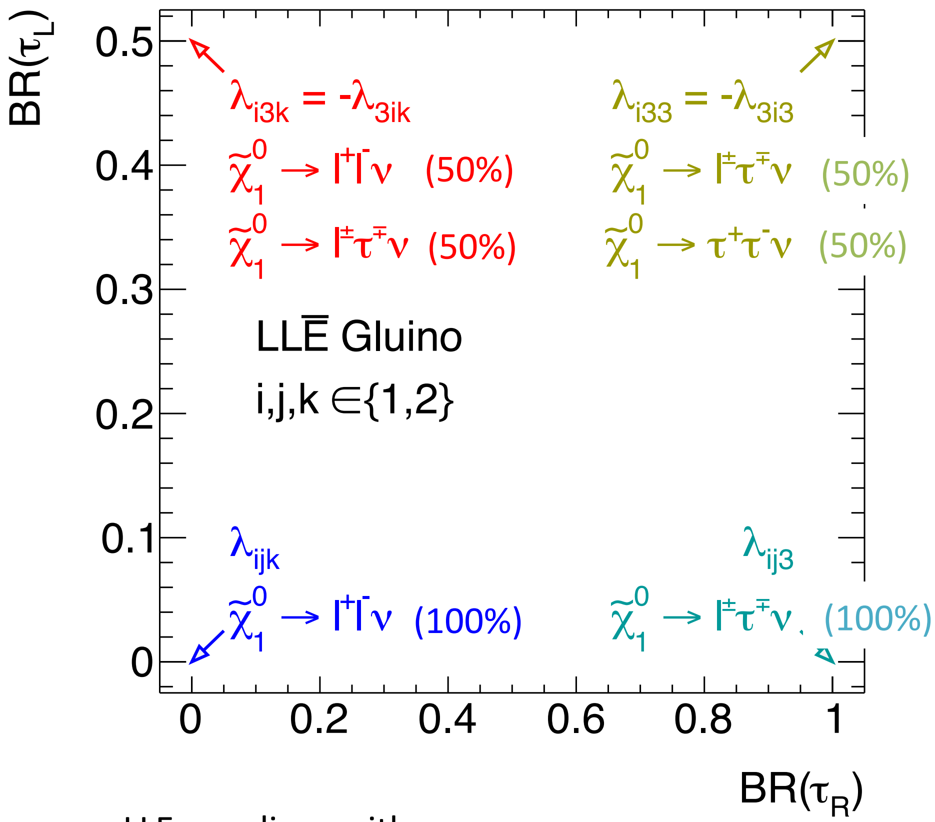
- Good agreement between expected and observed events in VRs and in SRs in all analyses.

- See more details on every analysis in backup slides

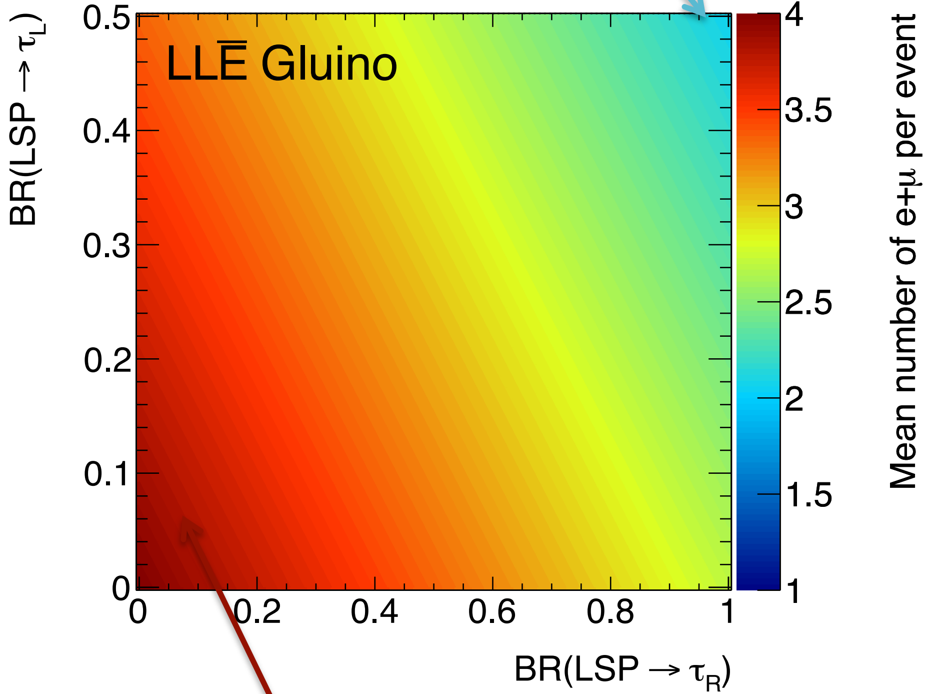
Models: LLE terms



- Simplified model: neutralino LSP decays into two charged leptons and a neutrino
- All possible combinations of e, μ, τ simulated with LSP BRs varying among 4 extreme cases (l = e, μ):



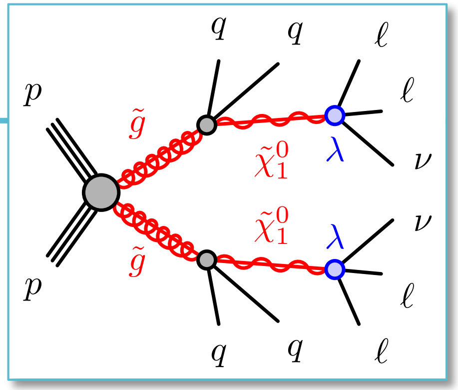
at least 2 light leptons



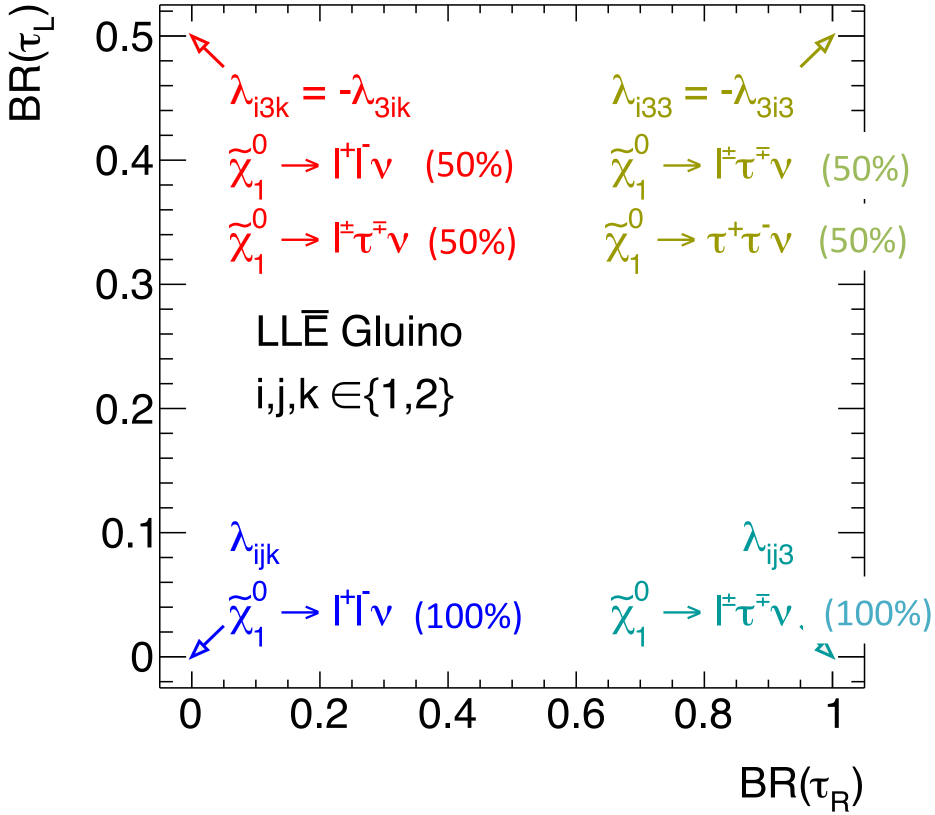
at least 4 light leptons

LLE couplings with 1st- and 2nd-generation leptons dominate → LLE couplings with 3rd-generation leptons dominate

Models: LLE terms



- Simplified model: neutralino LSP decays into two charged leptons and a neutrino
- All possible combinations of e, μ, τ simulated with LSP BRs varying among 4 extreme cases (l = e, μ):



- Each simulated LLE and LQD sample is generated with a fixed mass ratio:

$$R = \frac{m(\tilde{\chi}_1^0)}{m(\text{NLSP})} = 0.1, 0.5 \text{ or } 0.9$$

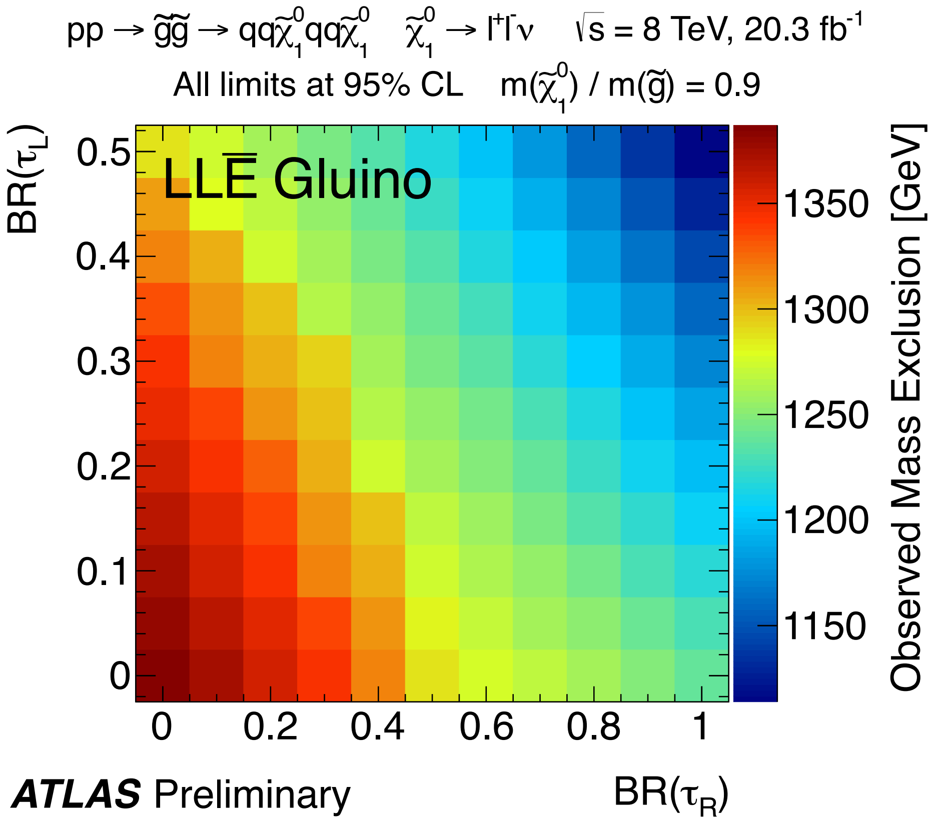
- R determines how the available energy is shared between the final-state objects

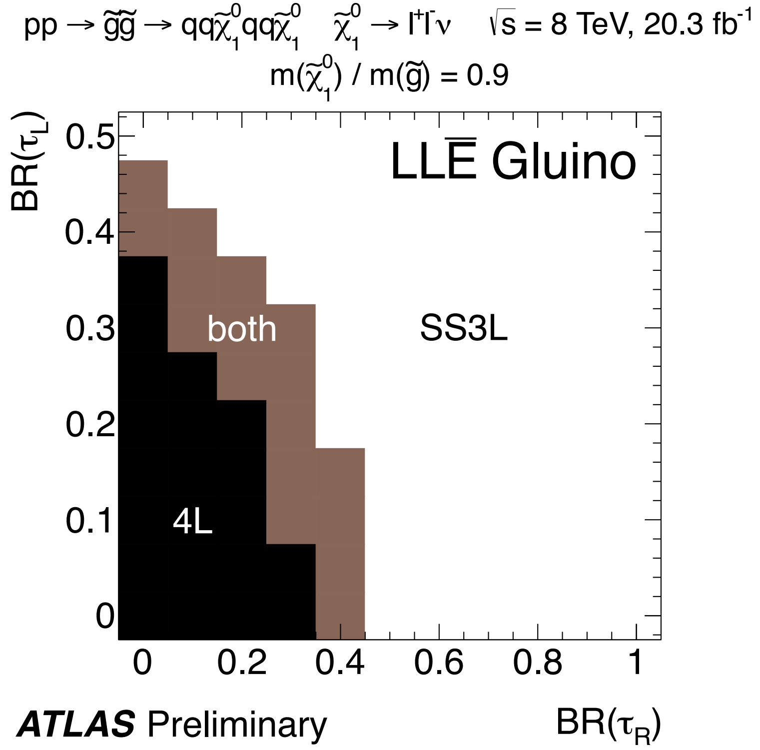
Lower R → softer LSP decay products
→ more energetic particles from the NLSP decays

- May affect the choice of the best-performing signal region for a given model.

Results on LLE

ATLAS-CONF-2015-018

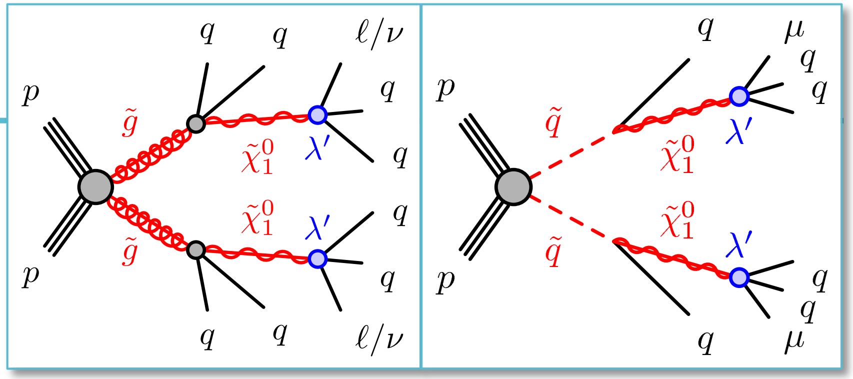




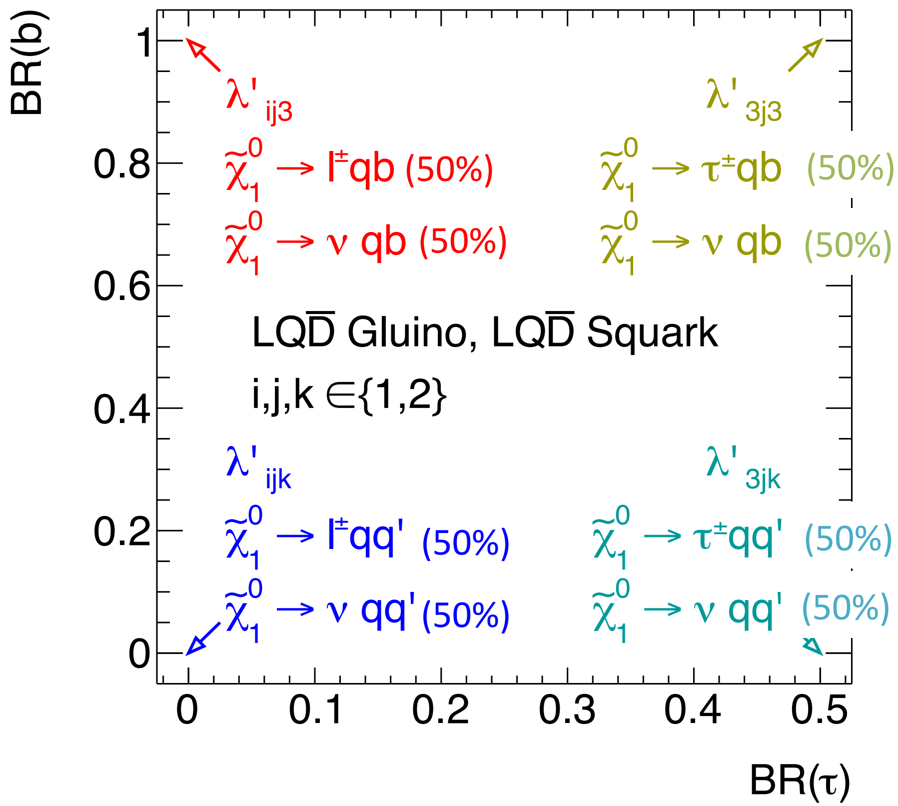
- Lower limits on the gluino mass for R=0.9, set from:
  - 4L analysis (SR0noZb: at least 4 light leptons): strongest limits: $m(\tilde{g}) > 1350$ GeV
  - SS/3L analysis (SR3Lhigh: at least 3 light leptons): weaker limits: $m(\tilde{g}) > 1140$ GeV
  - Combination 4L + SS/3L
  - Limits weaken as the number of light leptons per event decreases

- Cases R=0.1, 0.5 similar results, see backup.

Models: LQD terms

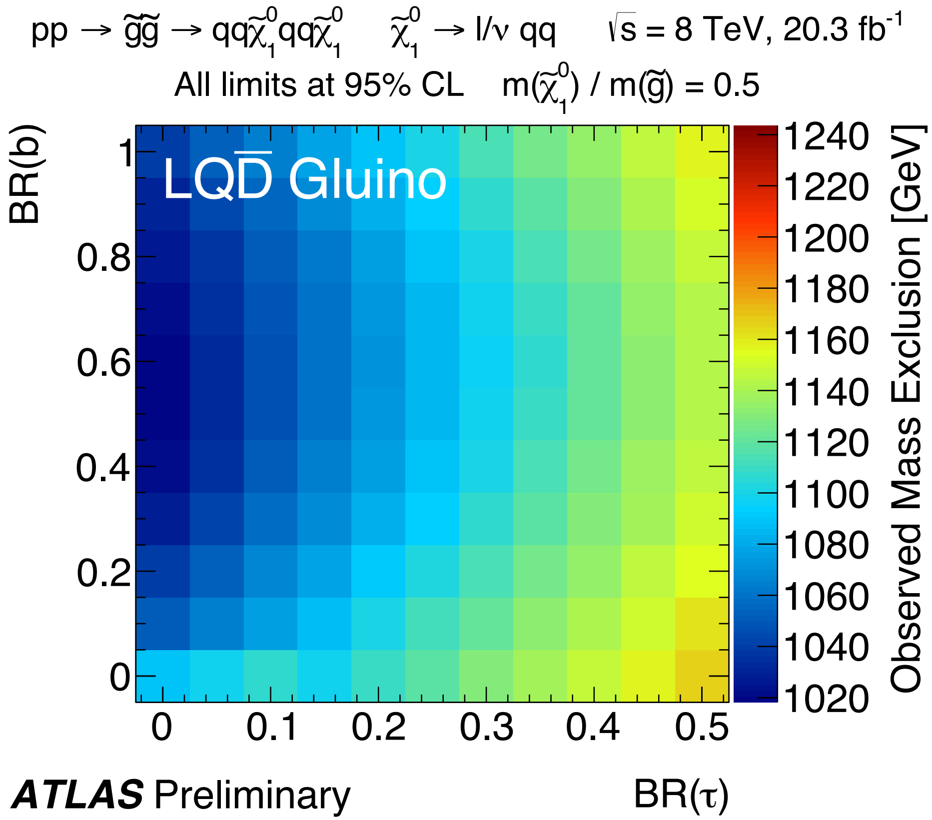


- 2 Simplified models: LQD gluino; LQD squark: neutralino LSP decays into two quarks and a lepton
- A specific λ'_{ijk} allows $\tilde{\chi}_1^0 \rightarrow \ell_i u_j d_k$ and $\tilde{\chi}_1^0 \rightarrow \nu_i d_j d_k$
- All possible combinations of e, μ, τ simulated with LSP BRs varying among 4 extreme cases:

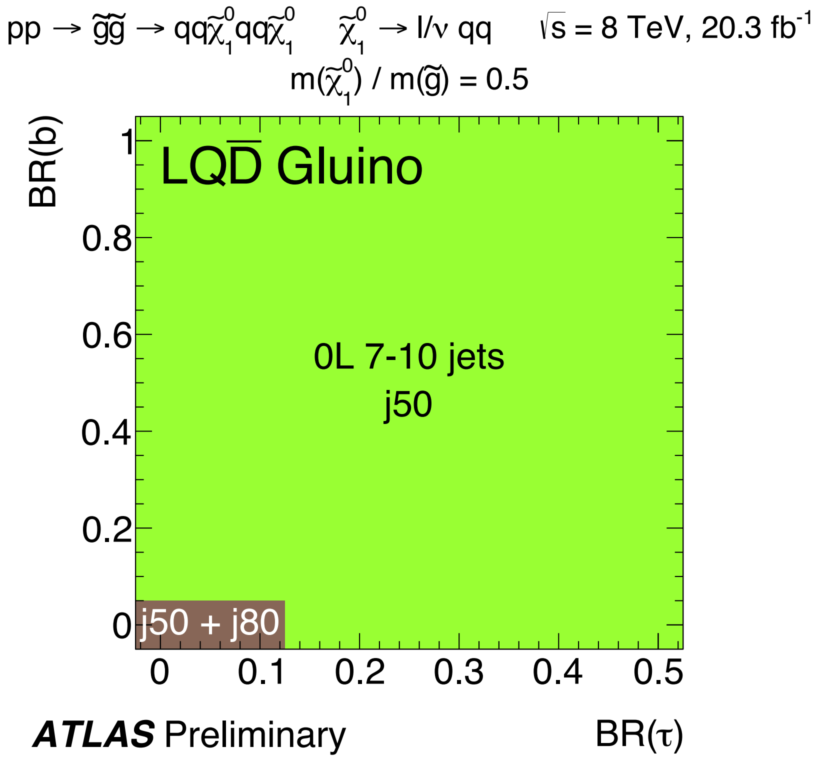


Results on LQD gluino

ATLAS-CONF-2015-018



R=0.5

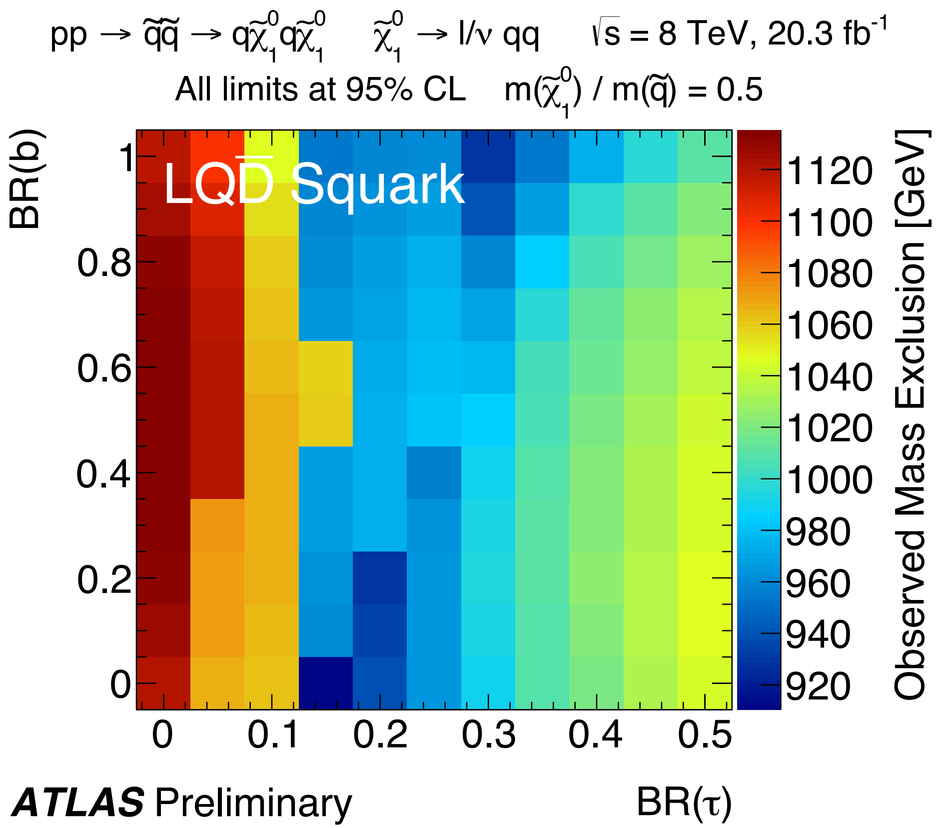


- Model nominally produces 8 jets → strongest constraints for R=0.1, 0.5 set by 0L + 7-10 jets analysis: $m(\tilde{g}) > 1180$ GeV
- Statistical combination of SR with/without b-jets → mass limits shows dependence on BR(b)
- Veto on light leptons → weaker limits in low BR(τ)

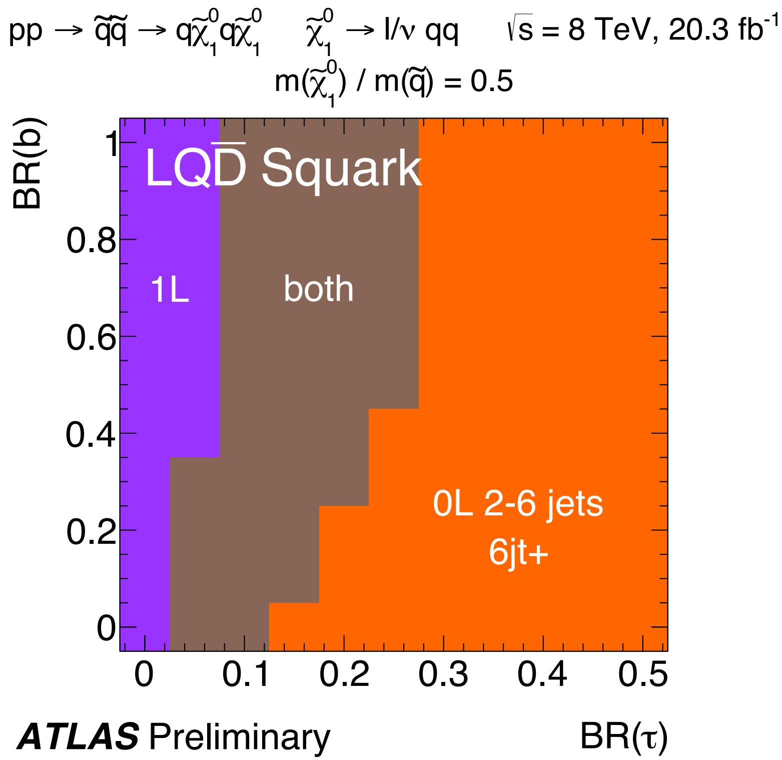
- R=0.9: compressed SUSY spectrum → 0L + 7-10 no longer produces best results.
- More powerful results for 1L and 0L + 2-6 jets analyses. See backup.

Results on LQD squark

ATLAS-CONF-2015-018



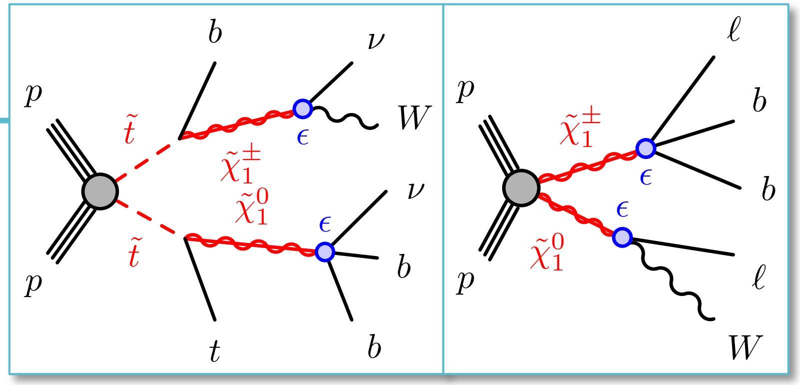
R=0.5



- Model nominally produces 6 jets → strongest constraints set by:
  - 1L for BR(τ) < 0.1: m(g̃) > 1120 GeV
  - 0L + 2-6 jets analysis for BR(τ) > 0.3: m(g̃) > 1050 - 920 GeV
  - combination of both in BR(τ) = (0.1, 0.3): m(g̃) > 1060 – 980 GeV

- No dependency on BR(b) since neither analysis requires/vetoes on b-jets.
- Similar result obtained for R=0.9 (see backup).

Models: bRPV terms

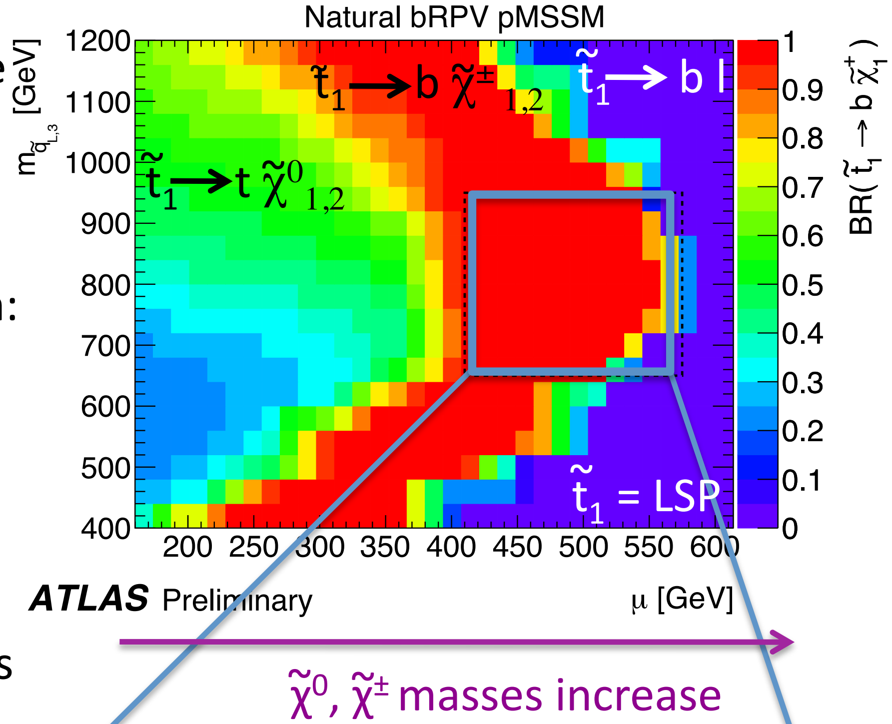


- ATLAS searches have set limits on mSUGRA bRPV: m($\tilde{g}$) ≥ 1.35 TeV, comparable to RPC limits.

- Here first time to explore bRPV Natural SUSY:
  - $\tilde{t}$ and higgsinos mass < 1 TeV
  - Other masses: less stringent constraints survive previous limits

- phenomenological MSSM (pMSSM) compatible with:
  - Observed Higgs mass
  - Measurements of ν oscillations
  - Main production processes: $\tilde{t}\,\tilde{t}$, $\tilde{\chi}^0$, $\tilde{\chi}^{\pm}$
  - Free parameters:
    - μ (higgsino mass parameter)
    - $m_{\tilde{q}L,3}$ (left- handed top and bottom squarks mass → light for naturalness).

- See further details in backup.



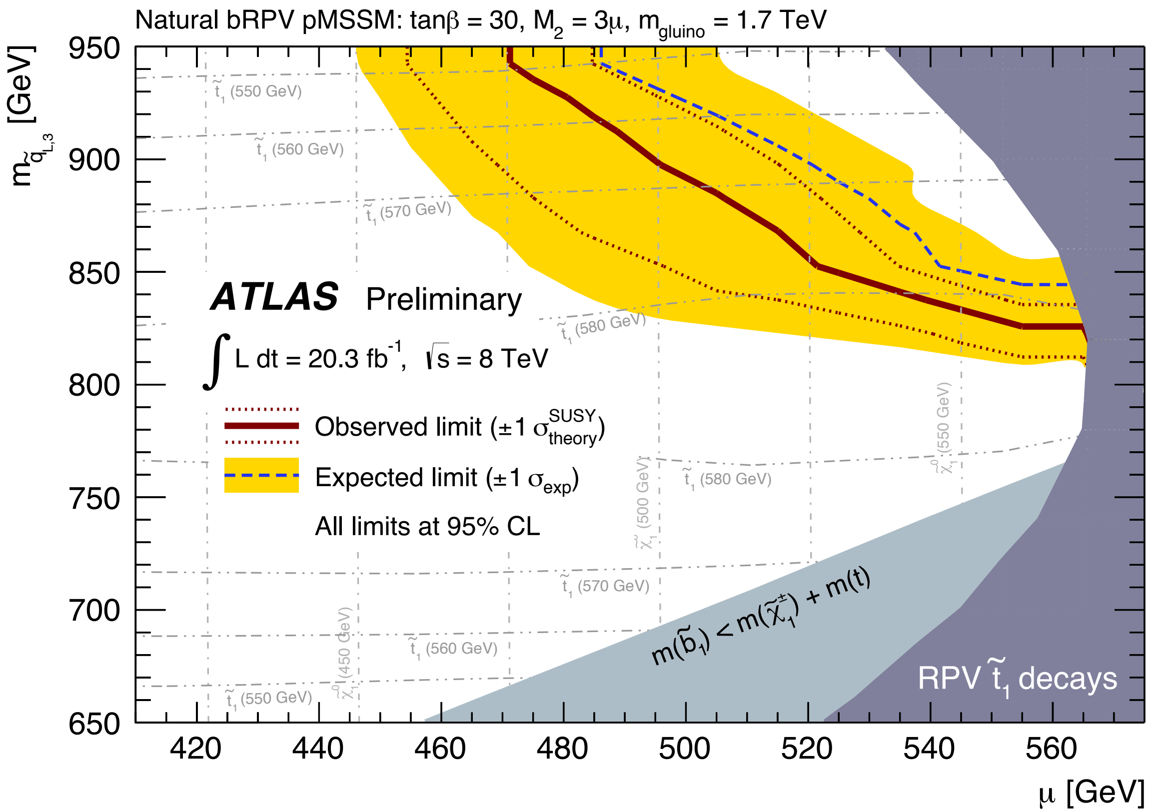
Explored region: large lepton and b-jet multiplicity

$$\tilde{\chi}_1^0 \to Wl \approx 60\%$$

$$\tilde{\chi}_1^{\pm} \to lbb \approx 60\%$$

Results on bRPV

ATLAS-CONF-2015-018



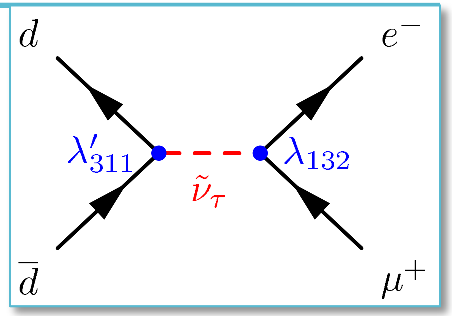
- For $m_{\tilde{q}L,3}$ = 800 GeV, entire range of μ excluded.
- Lower limits of μ < 455 GeV and $m_{\tilde{q}L,3}$ > 810 GeV within explored region.

- Strongest constraints set by SR3b in the SS/3L analysis along the entire plane.
- Limit weakens as $m_{\tilde{q}L,3}$ increases due to:
  - Contribution from $\tilde{b}_1$ pair production is critical: large m_{eff} difficult to produce from $\tilde{t}_1$ decays when $\tilde{t}_1$ and $\tilde{\chi}^{\pm}_1$ degenerate
  - Increasing $\tilde{b}_1$ mass, and corresponding decrease in the $\tilde{b}_1\,\tilde{b}_1$ production cross-section.

eμ, eτ, μτ resonances

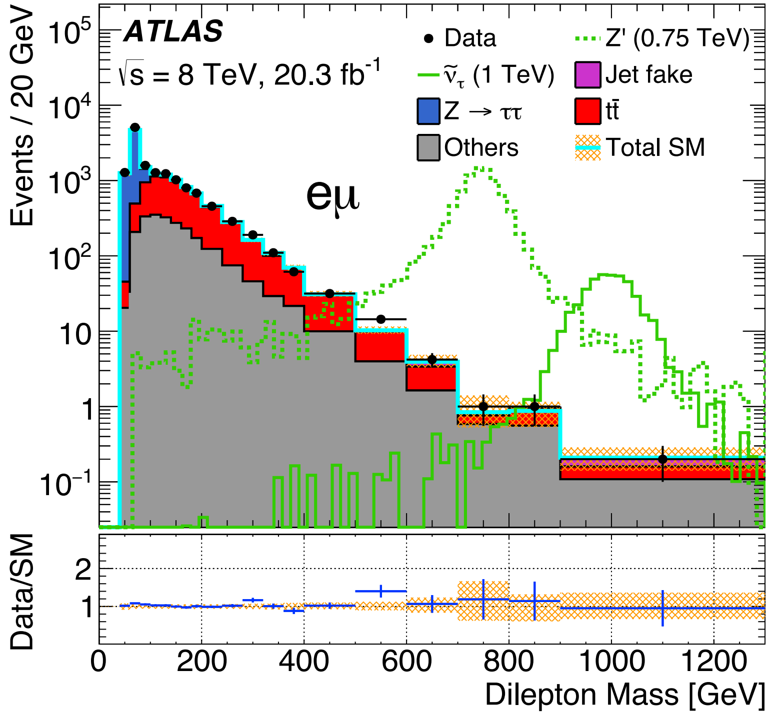
Heavy resonances

[Phys. Rev. Lett. 115, 031801 (2015)]



- Dedicated search for the decay of a heavy neutral particle into a pair of different flavor leptons via LFV couplings.

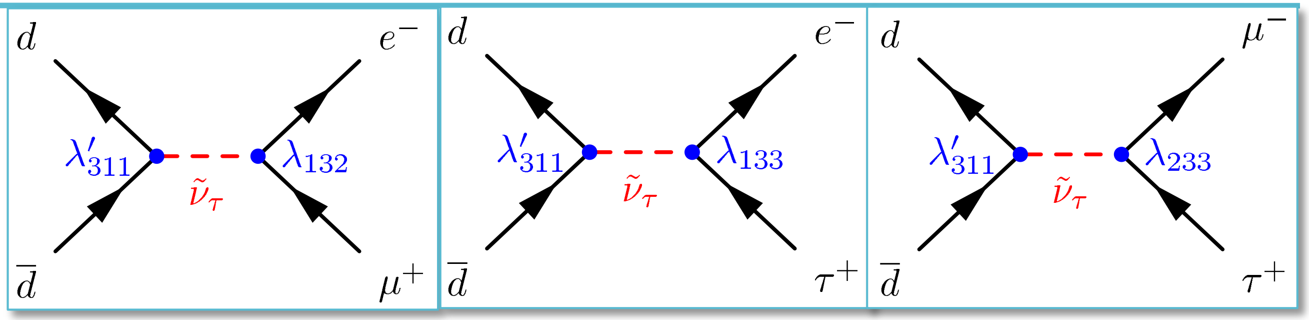
- Aiming RPV combined LLE + LQD terms
- Selection:
  - Trigger on 1 or 2 leptons (e or μ)
  - 0 or 1 τ_{had} candidates with 1 prong
  - Exactly 2 leptons with OSDF
  - Leptons back to back ($\Delta\varphi > 2.7$)
  - $m_{ll} > 200$ GeV ($m_{ll} < 200$ GeV used as VR)



- Main backgrounds:
  - 2 prompt leptons:
    Z/γ* -> ττ, ttbar, st Wt channel, dibosons
    → Estimated using MC
  - Jets misidentified as leptons (fakes):
    W+ jets, multijets
    → Estimated normalizing MC to data in CRs

- Good agreement between expected and observed events in VRs and in SRs.

Models: LQD + LLE terms



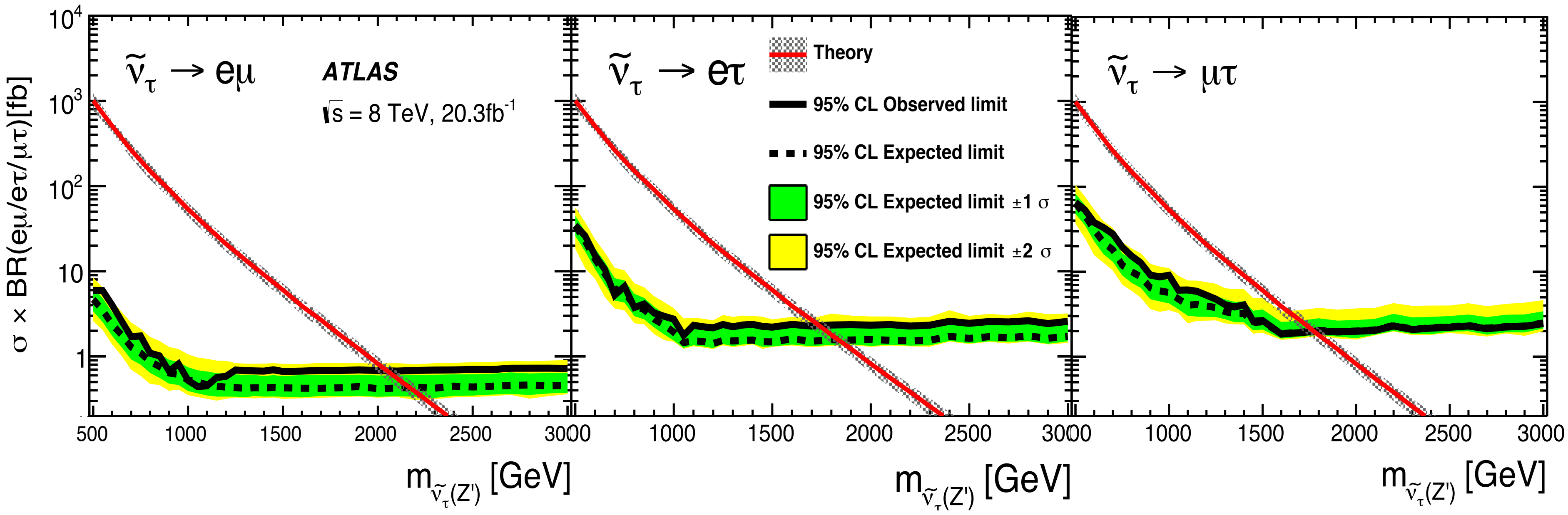
- Simplified model: tau sneutrino ($\tilde{\nu}_\tau$) LSP decays to eμ, eτ, μτ

- In this case RPV couplings are present both at the production and at the decay vertex.

- Only tau sneutrino is considered here in order to compare with previous searches performed at the Tevatron, but...
- The results of this analysis apply to any sneutrino flavour.

Results on LLE + LQD

Phys. Rev. Lett. 115, 031801 (2015)



- Theoretical predictions of σ x BR: assuming λ'_{311} = 0.11 and λ_{i3k} = 0.07
- Lower limits on the $\tilde{\nu}_\tau$ mass are 2.0 TeV, 1.7 TeV, and 1.7 TeV for eμ, eτ and μτ channels.

- The observed lower mass limits are a factor of 3 – 4 higher than the best limits from the Tevatron and also more stringent than the previous limits from ATLAS for the same couplings.

- Not a reinterpretation! Dedicated search for this model

Summary

- *R*-parity violation can be a cause of non-discovery in general searches for new physics at LHC.
- A variety of RPV scenarios are tested either by dedicated searches or by reinterpreting previously published ATLAS searches.

- LLE and LQD cases:
  - Limits on production cross-section and sparticle masses obtained for different LSP mass hypotheses as a function of the LSP BRs to bottom quarks and tau leptons.

	LLE	LQD		LLE + LQD
		gg	qq	
Dominant analysis	SS/3L	1L / 0L	1L / 0L	$e\mu$, $e\tau_{had}$, $\mu\tau_{had}$
mass limit	$m(\tilde{g}) > 1040$ – 1400 GeV	$m(\tilde{g}) > 910$ - 1220 GeV	R > 0.1: $m(\tilde{g}) >$ 910 - 1280 GeV	$m(\tilde{\nu}_\tau) >$ (2.0, 1.7, 1.7) TeV for ($e\mu$, $e\tau$, $\mu\tau$)

reinterpretation of previous ATLAS searches (LLE, LQD)

dedicated ATLAS search (LLE + LQD)

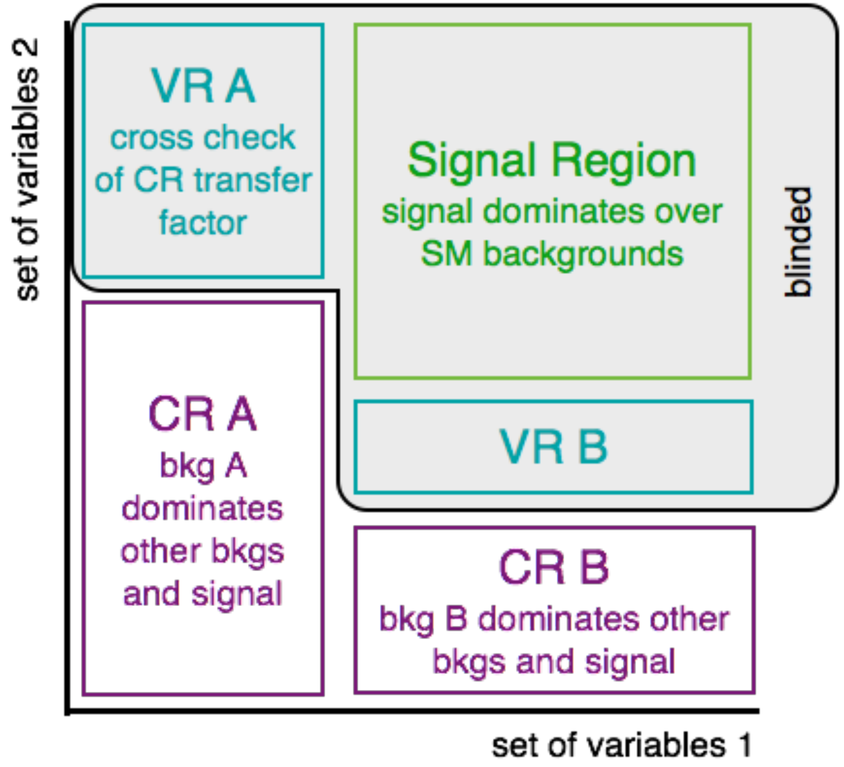
- Bilinear *R*-parity violation in natural pMSSM:
  - Reinterpretation of previous ATLAS searches (SS/3L dominant)
  - μ = (160, 455) GeV excluded at 95%CL; $m_{\tilde{q}_{L,3}}$ = 800 GeV excluded up to μ = 560 GeV
  - Limits in natural SUSY with bRPV complement previous studies of mSUGRA model.

Backup

Search method

- MC used to optimise signal selection in Signal Regions (SR).

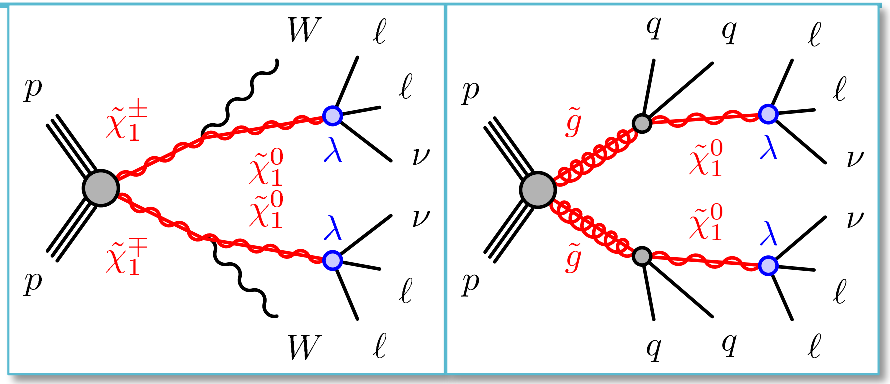
- Searches rely on the understanding of the SM backgrounds:
  - Irreducible bkgs:
    - Dominant sources: Normalise MC to data in Control Regions ⟶ transfer factor.
      Validation regions : transfer factors cross check.
    - Minor sources ⟶ MC estimation.
  - Reducible bkgs:
    - Fake EtMiss ⟶ data-driven
    - Charge mismeasurement ⟶ data-driven
    - Fake leptons ⟶ data-driven



- Interpretation of results using CLs prescriptions.
  - Discovery fit (look for an excess of data wrt SM estimation; no signal considered)
  - Exclusion fit (limit setting; particular model considered)

Four leptons (4L)

Phys. Rev. D. 90, 052001 (2014)



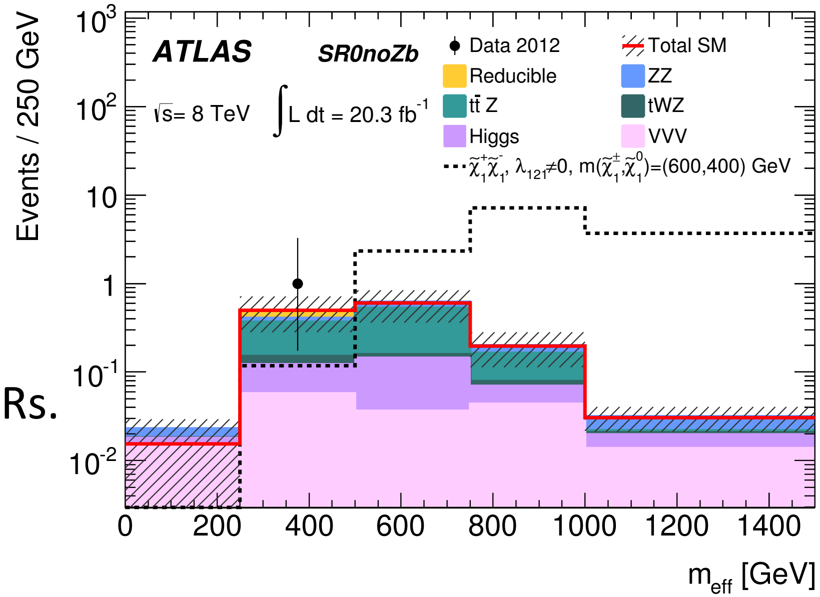
- Aiming RPC and RPV with LLE terms

- Selection:
  - ≥ 4 leptons (at least two of them e or μ)
  - Veto on Z->ll (orthogonal SRs contain Zs)
  - No jet selection: valid for strong and EW

  - 3 SRs relevant for LLE:

SR name	$N(e/\mu)$	$N(\tau)$	E_T^{miss} [GeV] or m_{eff} [GeV]		
SR0noZb	≥ 4	≥ 0	≥ 75	or	≥ 600
SR1noZb	$= 3$	≥ 1	≥ 100	or	≥ 400
SR2noZb	$= 2$	≥ 2	≥ 100	or	≥ 600

- Final result: statistical combination of all considered SRs.

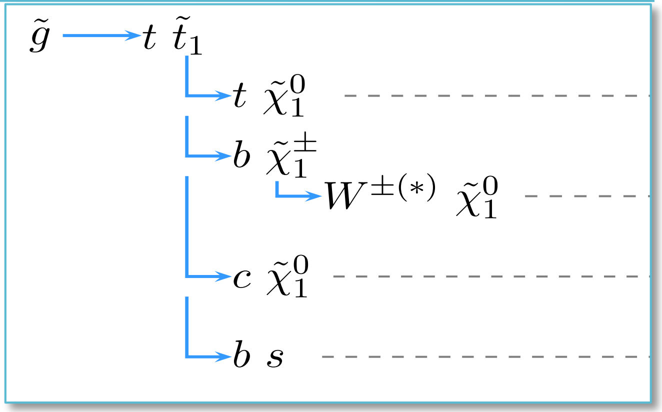


- Good agreement between expected and observed events in VRs and in SRs.

- Main backgrounds:
  - ttZ, ZZ
    → Estimated from MC
  - Non-prompt and fake leptons
    → Estimated with data driven methods, checked in VRs

2 same sign leptons / 3 leptons (SS/3L)

JHEP 06 (2014) 035



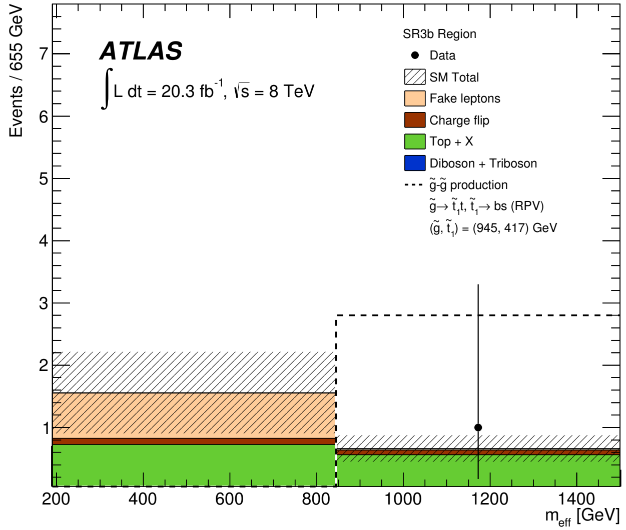
- Aiming RPC models where Majorana particle pairs decay semileptonically .

- Selection:
  - 2 SS leptons OR 3 leptons
  - 3 relevant SRs:

SR	Leptons	$N_{b-\text{jets}}$	Other variables	m_{eff}
SR3b	SS or 3L	≥ 3	$N_{\text{jets}} \geq 5$	$m_{\text{eff}} > 350$ GeV
SR1b	SS	≥ 1	$N_{\text{jets}} \geq 3$, $E_T^{\text{miss}} > 150$ GeV, $m_T > 100$ GeV, SR3b veto	$m_{\text{eff}} > 700$ GeV
SR3Lhigh	3L	-	$N_{\text{jets}} \geq 4$, $E_T^{\text{miss}} > 150$ GeV, SR3b veto	$m_{\text{eff}} > 400$ GeV

- Final result: statistical combination of all considered SRs.

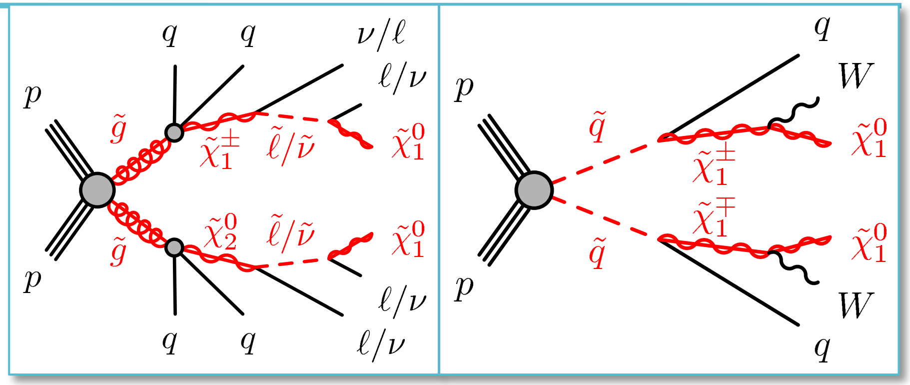
- Main backgrounds:
  - Prompt leptons:
    ttW, ttZ (dominant in SRb), WW, WZ, ZZ + jets (dominant in SRL)
    → Estimated from MC
  - Fake leptons, charge-flip
  → Estimated with data-driven method



- Good agreement between expected and observed events in SRs.

One lepton (1L)

[Phys. Rev. Lett. 114, 161801 (2015)](#)

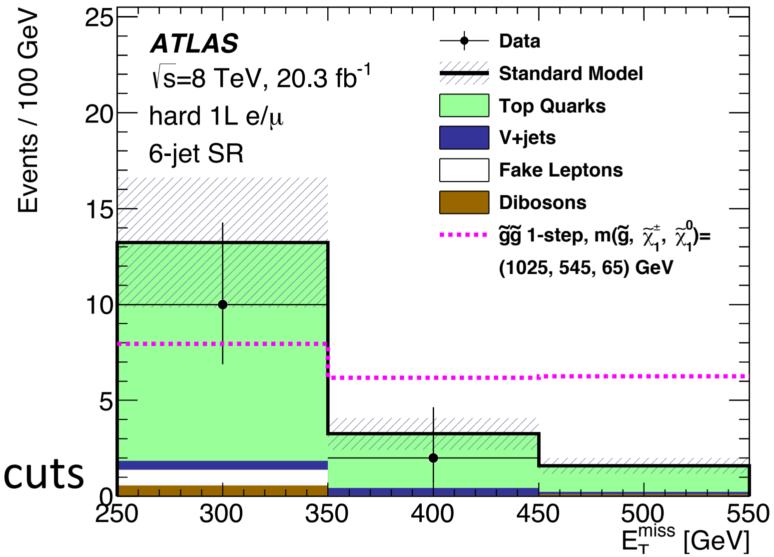


- Aiming a wide variety of models (mSUGRA bRPV among them) with 1L or 2L OS. Here only 1L.

- Selection:
  - 1L + jets
  - 3 relevant SRs:

	3-jet	5-jet	6-jet
N_{lep}	$= 1$	$= 1$	$= 1$
p_T^{lep1} [GeV]	> 25	> 25	> 25
p_T^{lep2} [GeV]	< 10	< 10	< 10
N_{jet}	≥ 3	≥ 5	≥ 6
p_T^{jet} [GeV]	$> 80, 80, 30$ p_T $^{\text{5th jet}} < 40$ GeV	$> 80, 50, 40, 40, 40$ p_T $^{\text{6th jet}} < 40$ GeV	$> 80, 50, 40, 40, 40, 40$
E_T^{miss} [GeV]	> 300	> 300	> 250
m_T [GeV]	> 150	> 150	> 150
$E_T^{\text{miss}}/m_{\text{eff}}^{\text{excl}}$	> 0.3	–	–
$m_{\text{eff}}^{\text{incl}}$ [GeV]	> 800	> 800	> 600

- Good agreement between expected and observed events in SRs.



- Main backgrounds:
  - ttbar and W+jets
  - → MC normalized to data in CRs with lower met, mT cuts
  - → Extrapolation to SRs tested in VRs

0 leptons + 2-6 jets (0L + 2-6 jets)

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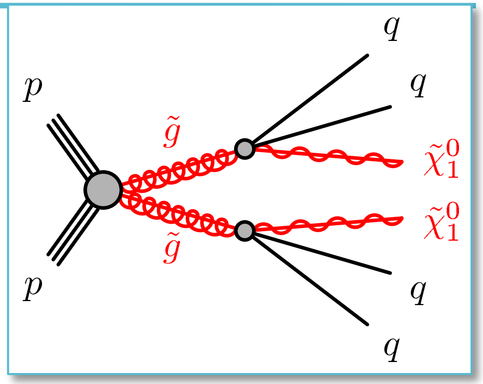


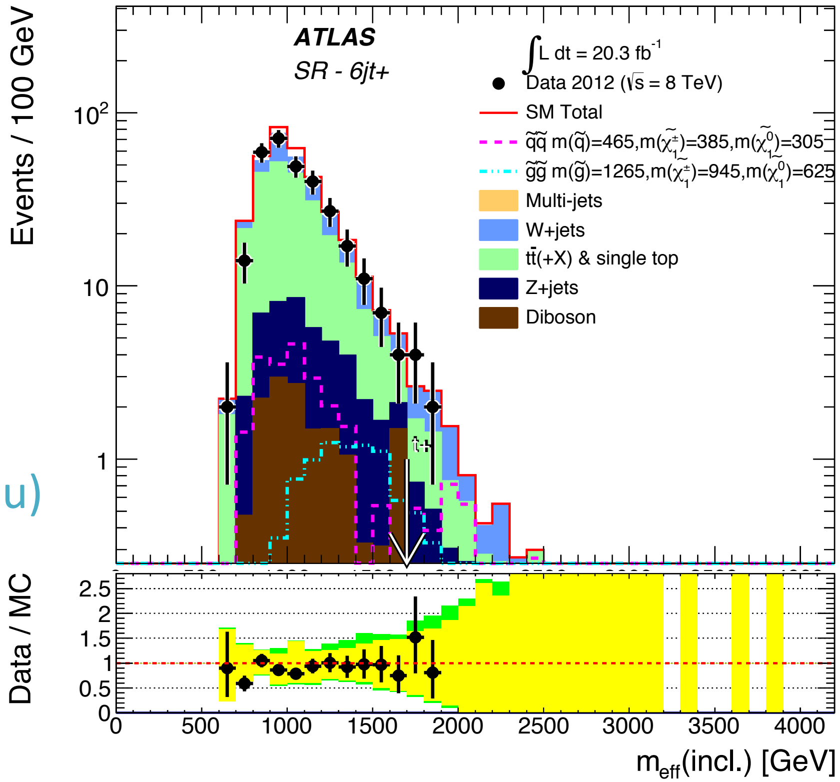
- Aiming a variety of RPC with no leptons in the final state

- Selection:
  - no isolated leptons
  - 4 relevant SR with diff. jet multiplicity :

    >=5 jets with pT>60 GeV,

    at least one jet with pt>160 GeV

Requirement	5j	6jl	6jm	6jt+
$N_{\mathrm{jet}} \geq$	5	6	6	6
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(N_{\mathrm{jet}}) >$	0.2	0.2	0.2	0.15
$m_{\mathrm{eff}}(\mathrm{incl.})$ [GeV] $>$	1200	900	1200	1700

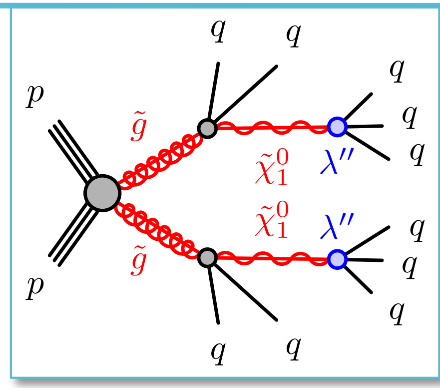


- Main backgrounds
  - W+jets , combined ttbar + single top, Z(->nunu) + jets and multijets .

  → Normalize MC to data in 4 CRs per SR.

  → Checked in several VRs

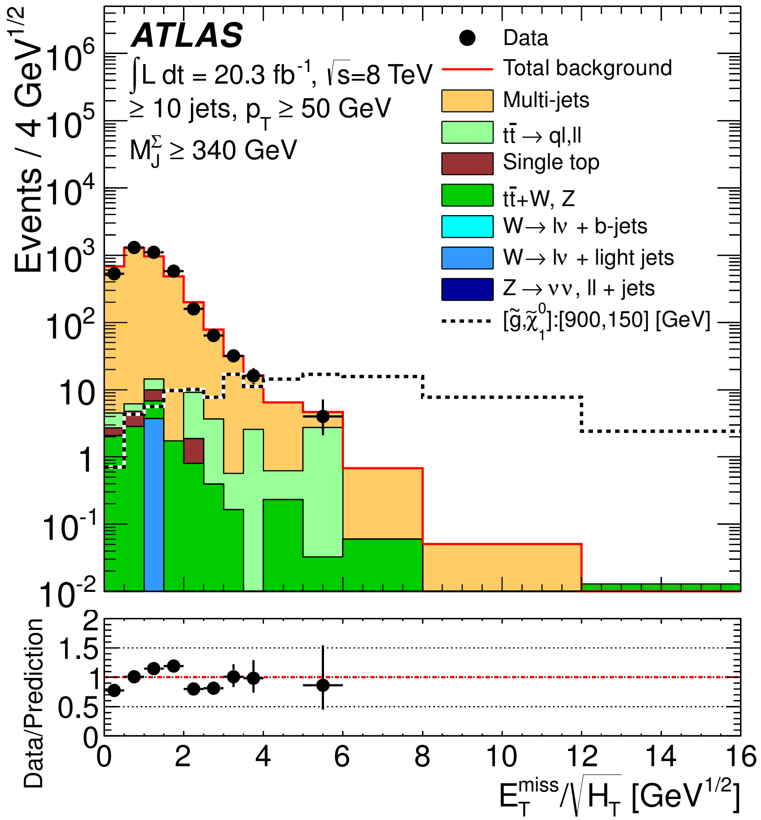
0 leptons + 7-10 jets (0L + 7-10 jets) J. High Energy Phys. 10 (2013) 130



- Aiming RPC models and RPV with BNV

- Selection:
  - No isolated leptons
  - 13 relevant SRs with different jet and b-jet multiplicity:

	j50			j80	
	8j50	9j50	≥ 10j50	7j80	≥ 8j80
Jet $\lvert\eta\rvert$	< 2.0			< 2.0	
Jet p_T	> 50 GeV			> 80 GeV	
N_{jet}	= 8	= 9	≥ 10	= 7	≥ 8
b-jets	0, 1, ≥ 2	0, 1, ≥ 2	—	0, 1, ≥ 2	0, 1, ≥ 2
$E_T^{miss}/\sqrt{H_T}$	≥ 4 GeV$^{1/2}$			≥ 4 GeV$^{1/2}$	



- Main backgrounds:
  - multijets
    → Estimated using matrix method
  - ttbar and W+jets
    → Normalize MC to data in 1 CR per SR
  - Z+jets, ttV, st
    → Estimated using MC

B-L analysis description

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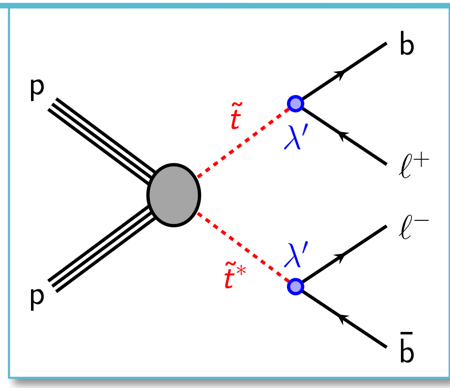


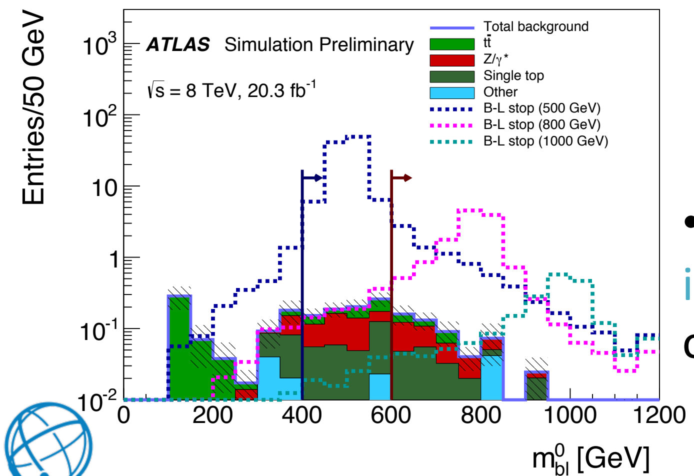
- Impose a U(1)$_{B-L}$ symmetry to the SM with right-handed neutrinos
- Symmetry is spontaneously broken by right-handed sneutrino vev
- Simplified model with stop (LSP) pair production

- Selection:
  - 2 OS leptons (e, μ) + 2 bjets (no E_T^{miss} cut!) + Z veto
  - Check m_{bl} asymmetry for all possible combinations of bl
  - Take the combination with smallest m_{bl} asymmetry
  - Two SRs defined for high sensitivity to different stop masses

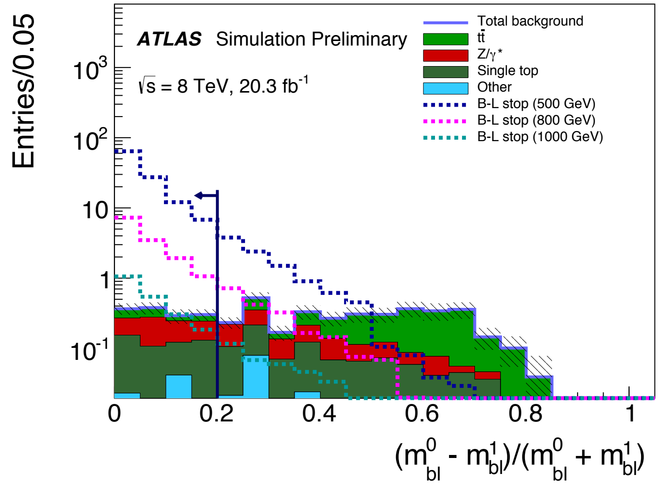
$$m_{b\ell}\text{ asymmetry} = \frac{m^0_{b\ell} - m^1_{b\ell}}{m^0_{b\ell} + m^1_{b\ell}}.$$

Region	$m^0_{b\ell}$ [GeV]	H_T[GeV]	$m_{b\ell}$ asymmetry	Z window
SR 400	≥ 400	≥ 1100	≤ 0.2	Veto
SR 600	≥ 600	≥ 1100	≤ 0.2	Veto

- Signal: small m_{bl}
- SM bkg: flat m_{bl}



- Search for a peak in the invariant mass distribution of (two pairs of) bl



B-L analysis results

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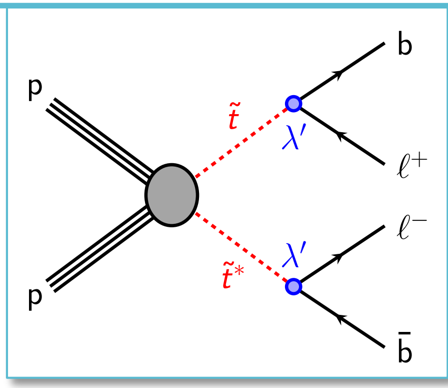
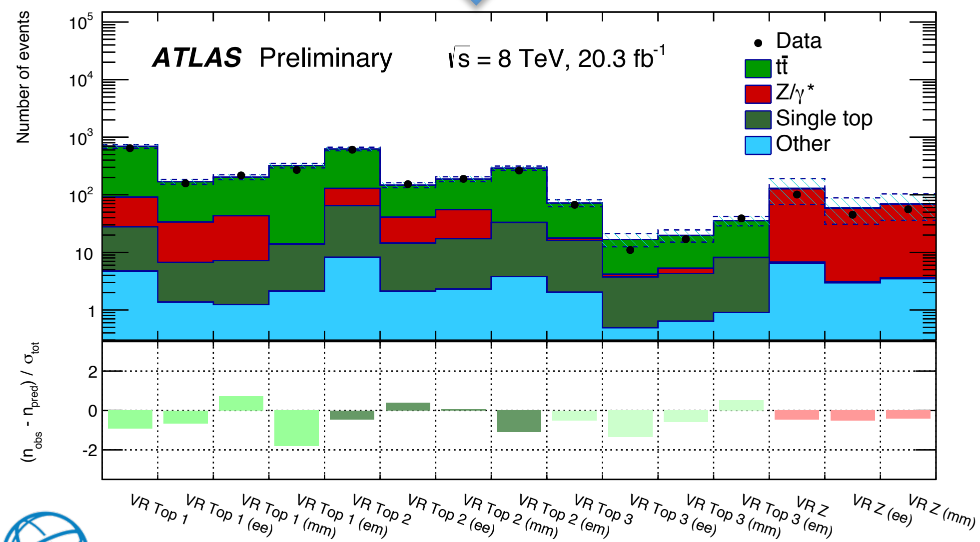
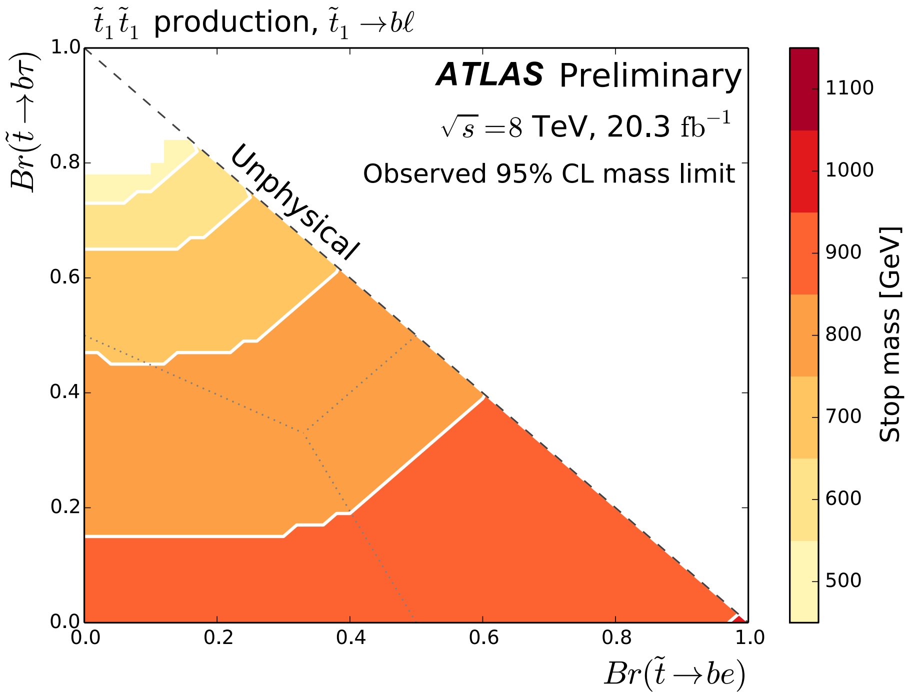


- Main backgrounds:
  - ttbar and Z+jets
    → Normalize MC to data in CRs
  - others
    → Estimated using MC

- Good agreement between data and SM expectations in all VRs and SRs

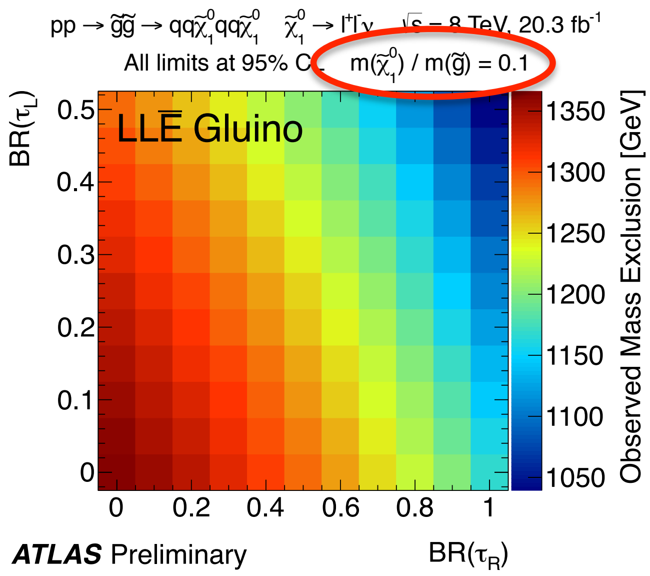




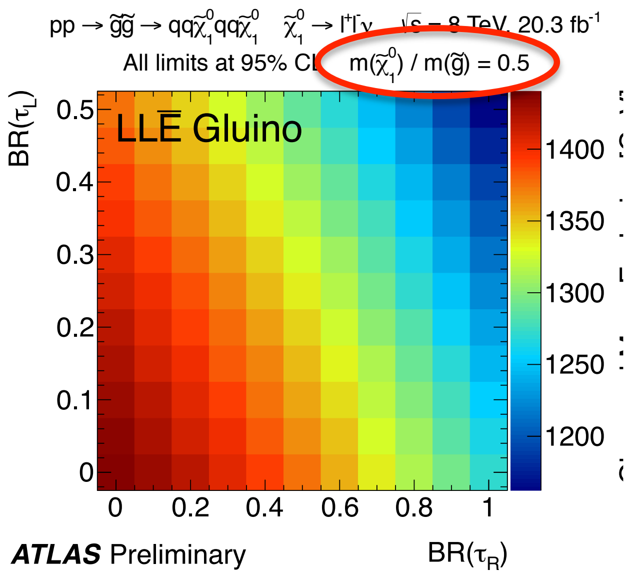
- Limits set on the stop mass range (1.1, 0.5) TeV

Further results on LLE

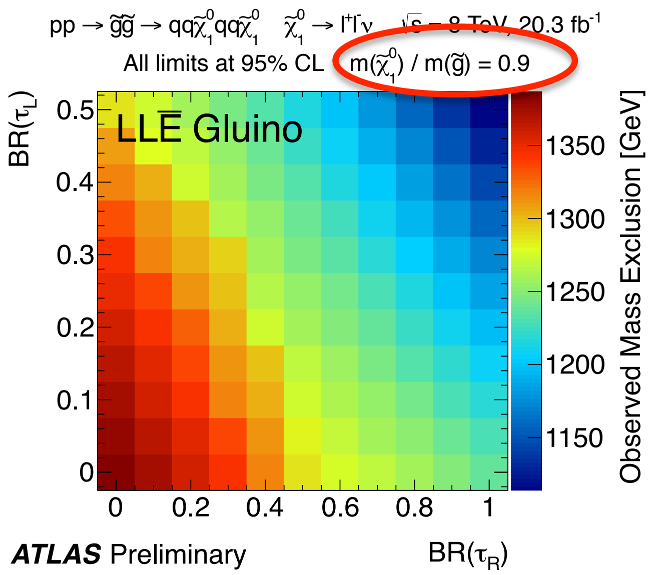
R=0.1



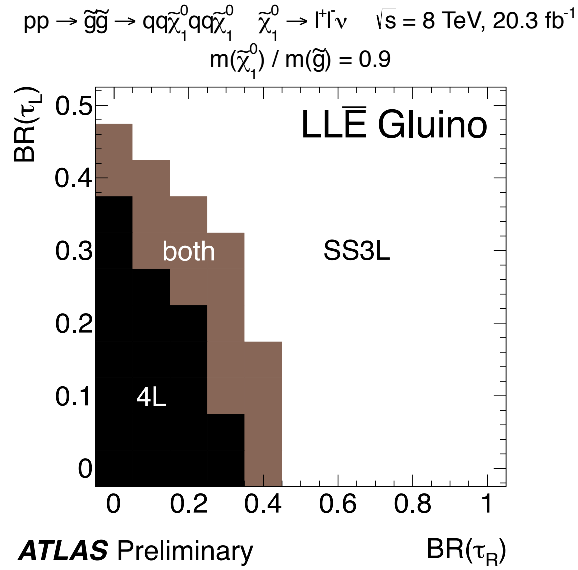
R=0.5



R=0.9



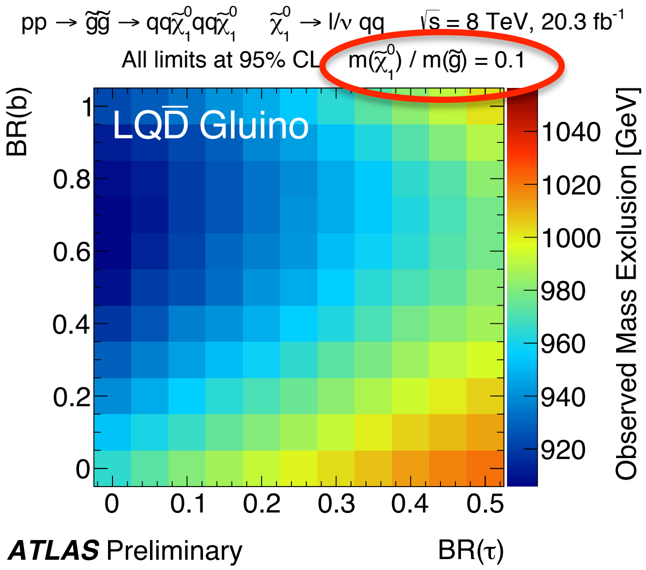
limits driven by the SS/3L analysis

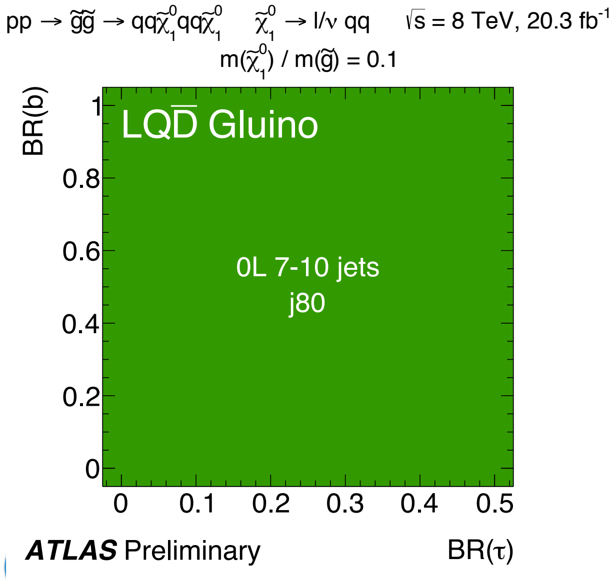


Further results on LQD gluino

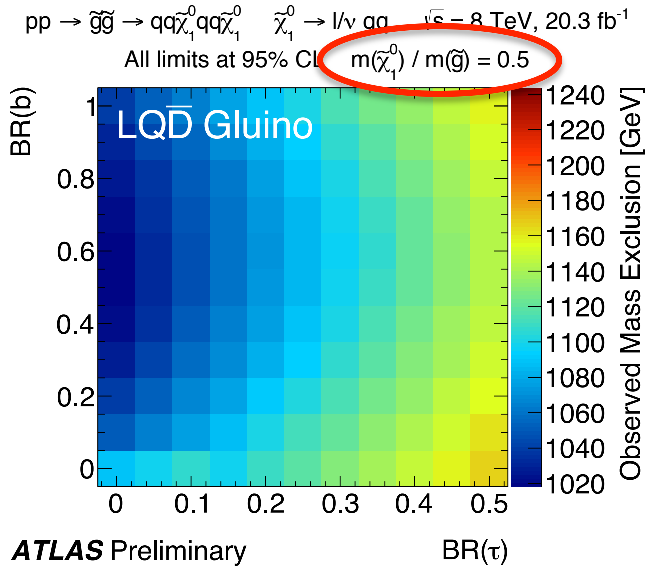
ATLAS-CONF-2015-018

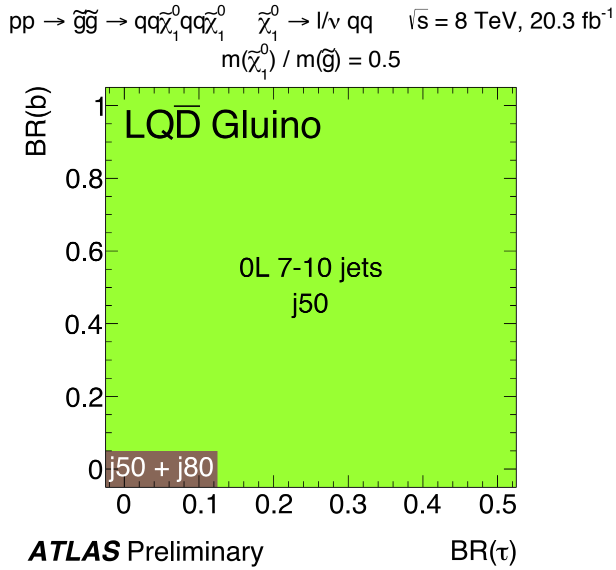
R=0.1



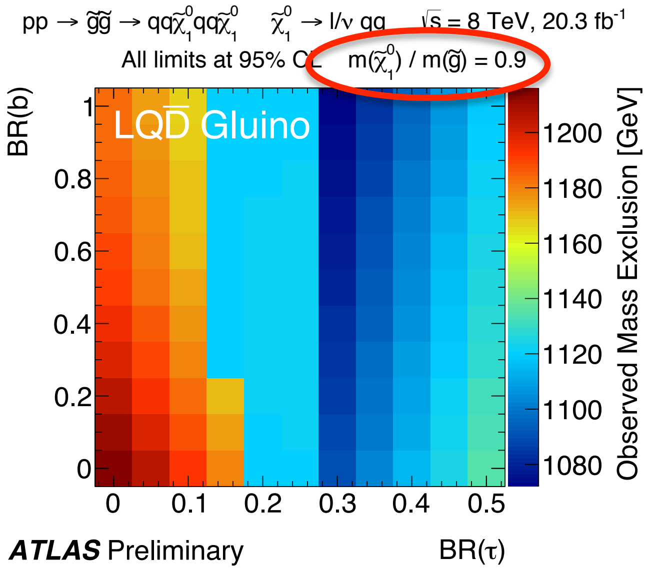


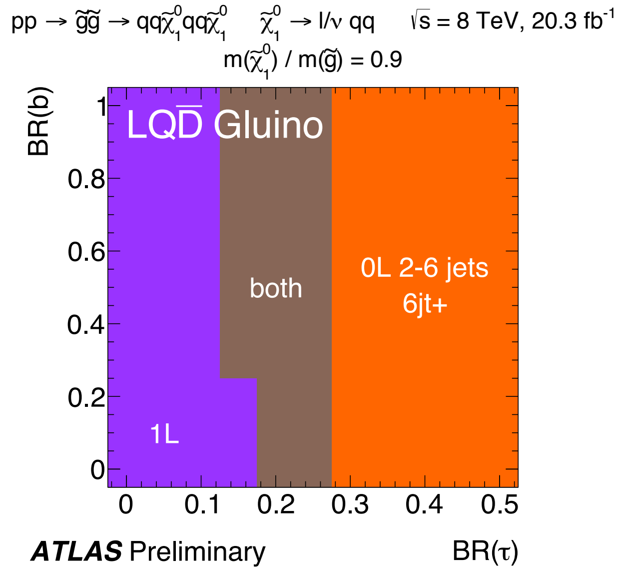
R=0.5





R=0.9

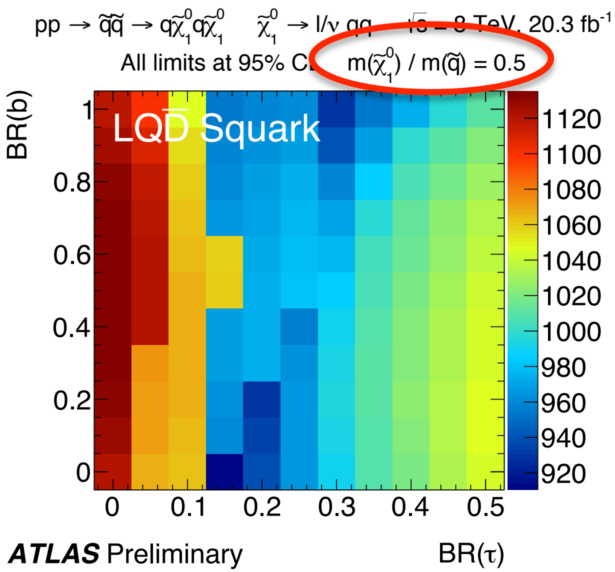


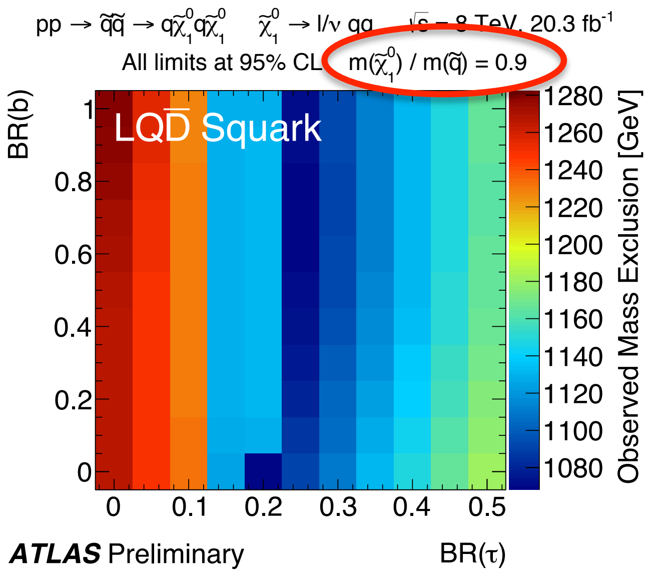


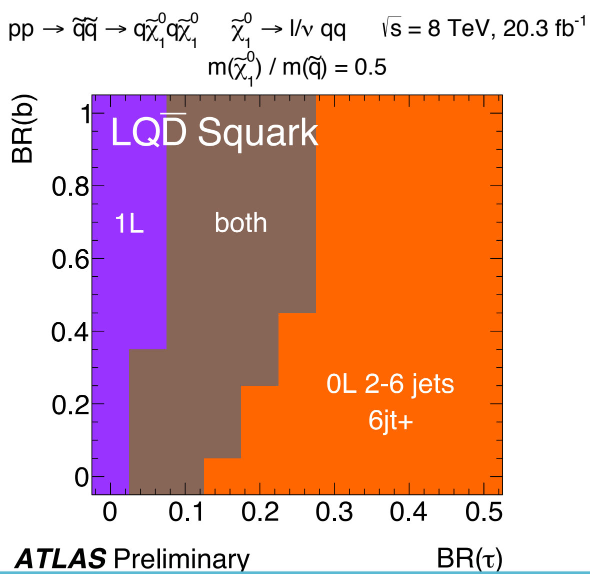
Further results on LQD squark

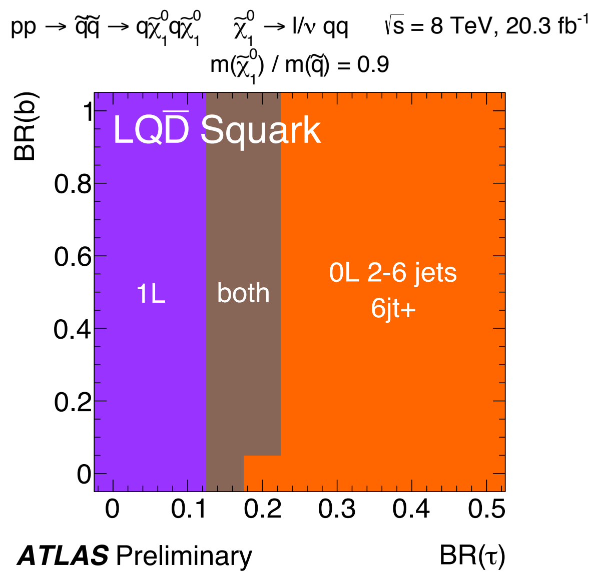
[ATLAS-CONF-2015-018]

R=0.5 | R=0.9



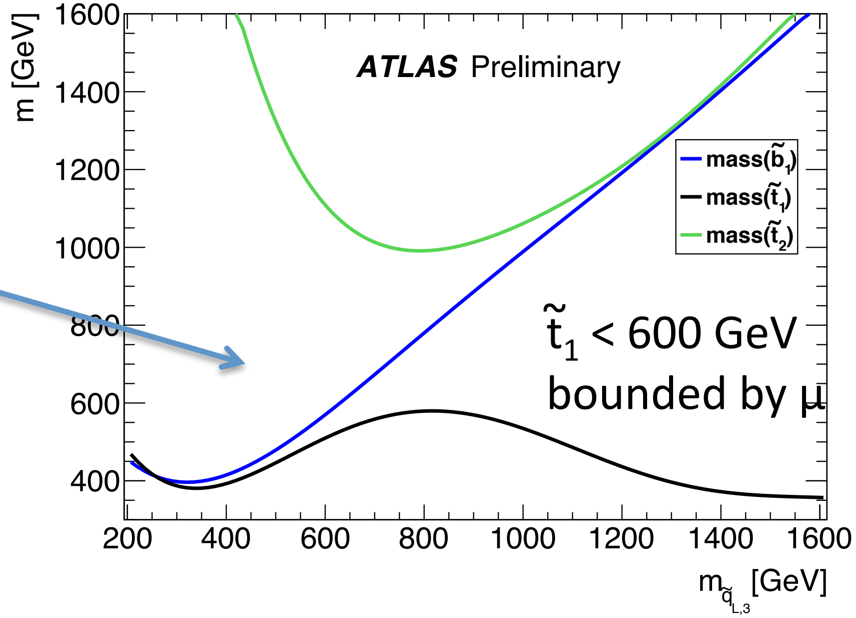




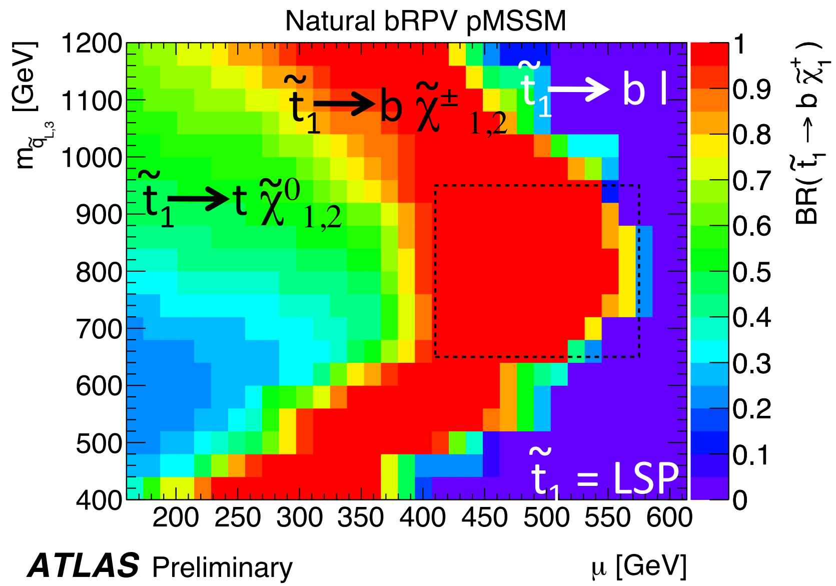


Exploring bRPV in pMSSM

- Complex phenomenology, discussed for the first time in [RPV summary paper: ATLAS-CONF-2015-018]
- $m(\tilde{t}, \tilde{b})$ vary with $m_{qL,3}$, almost independent of μ.



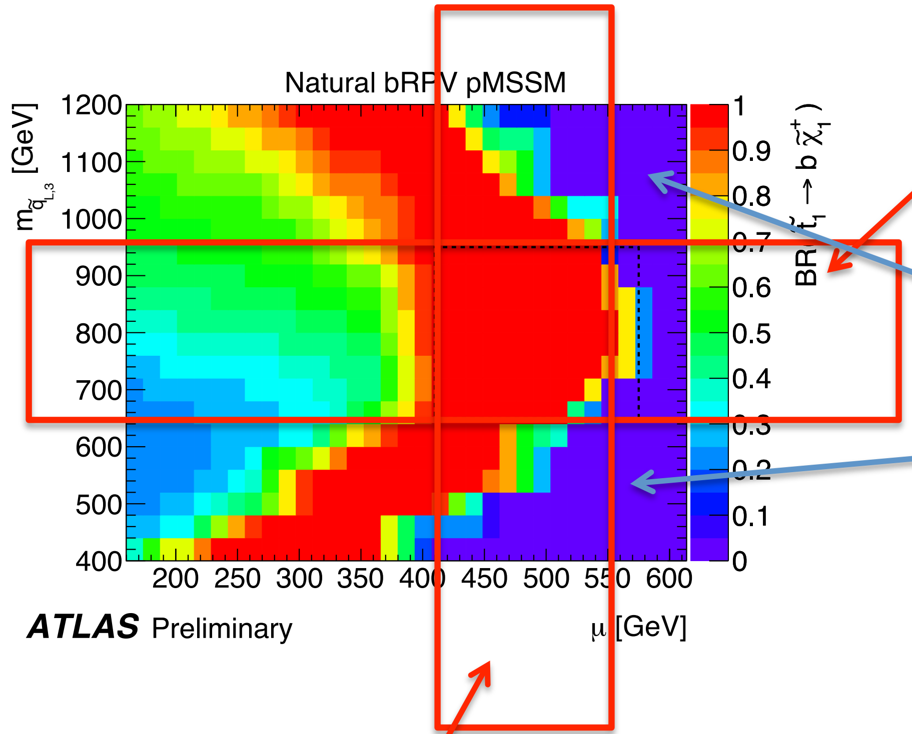
- $\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^\pm_1$ masses increase with μ.
  - μ>570 GeV → LPS = stop1.
  - Different phenomenology, not considered here



neutr, chi masses increase

Exploring bRPV in pMSSM

- Interesting region around μ = 550 GeV and $m_{qL,3}$ = 800 GeV:
    - $m(t_1) \sim m(\chi^{\pm}_1) \sim m(\chi^0_1)$.
    - $\tilde{t}_1 \rightarrow b\, \tilde{\chi}^{\pm}_{1,2}$ ~100%

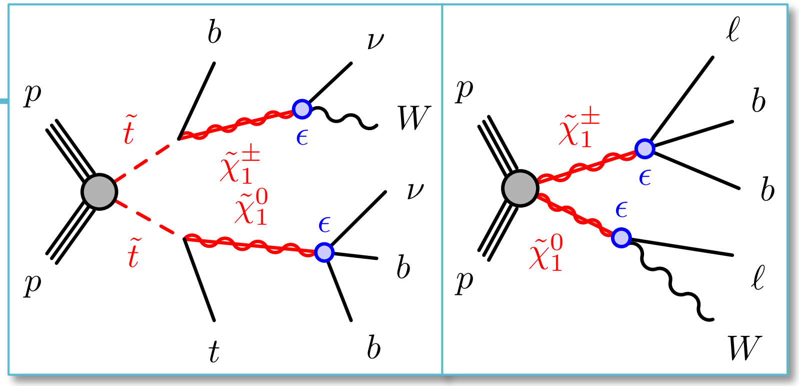


$\tilde{t}_1$ takes largest mass available for natural pMSSM scenario ($m(t\ \ )$ < 580 GeV). Maximum possible Δm($\tilde{t}_1$, LSP)

- other regions: more compressed spectrum reduces the momentum of particles from the t_1 and b_1 decays and increases signal contaminating the validation regions of the SS/3L analysis

- neutralino LSP
- $\tilde{t}_1 \rightarrow b\, \tilde{\chi}^{\pm}_{1,2}$ kinematically accessible to avoid discontinuities in the sparticle decay patterns

Exploring bRPV in pMSSM



•Search channels requiring at least one lepton are used to constrain the natural *b*RPV model.
• The lepton requirement is motivated by the high branching ratios of the χ^0_1 and $\chi^\pm_1$ to leptons, together with the possibility of additional leptons from RPC SUSY cascades.

•L1 search: too tight met cut → low sensitivity BUT
•since neutralino LSP is majorana→ two LSP can decay to SS leptons

• Sparticle decays determined by bRPV params ε.
• RPV can happen before LPS decay