



R-Parity Violating SUSY searches at ATLAS and CMS

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on behalf of the ATLAS and the CMS Collaborations



RPV - Introduction

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

- R-Parity often assumed conserved in SUSY (RPC)

◀ Provides stable LSP – Dark matter candidate

No signal of SUSY observed!

→ Currently strong exclusions are placed on SUSY ←

- R-Parity violation (RPV)

SUSY hiding behind RPV?!

◀ Baryon-number (BN) and lepton-number (LN) violating terms

LSP decay allowed! No stable SUSY particle
Expected significantly less Missing Transverse Energy (MET)

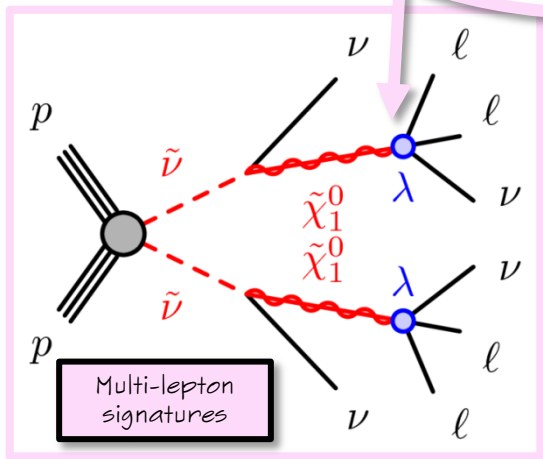
◀ Less stringent limits on RPV scenarios

◀ Individually violated BN/LN avoids rapid proton decays

RPV - Introduction

Lepton number violating terms

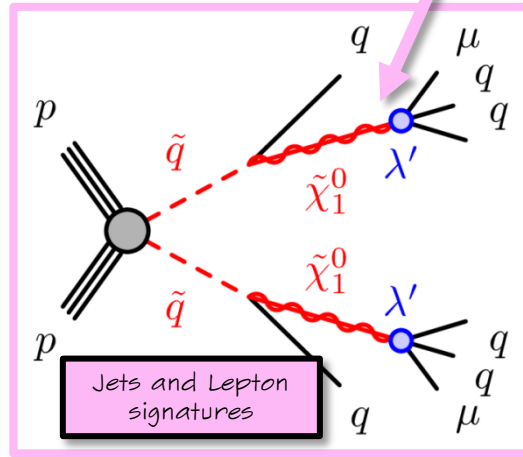
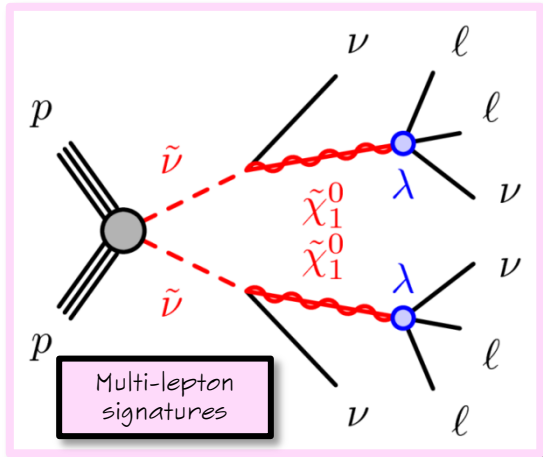
$$\mathcal{L}_{\Delta L=1} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}^k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u$$



RPV - Introduction

Lepton number violating terms

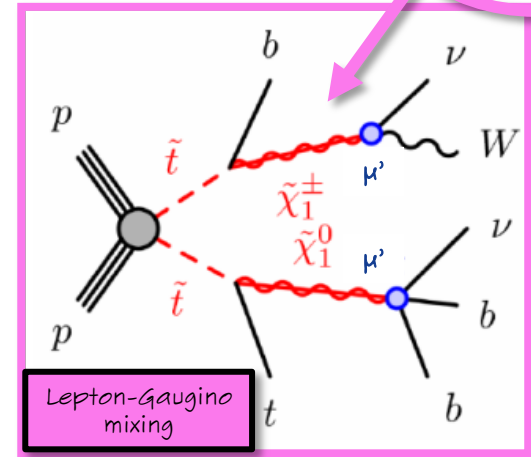
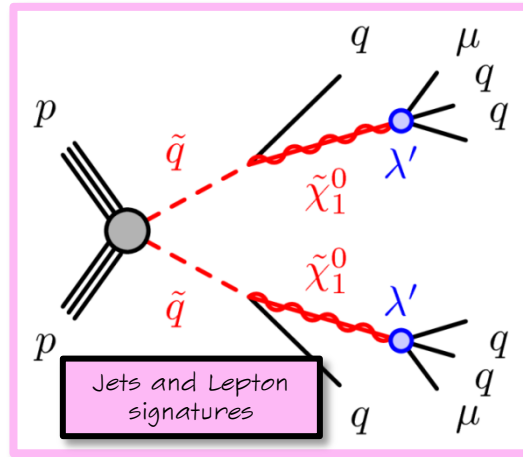
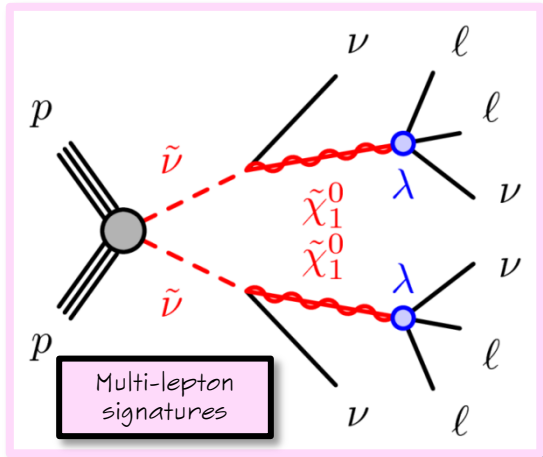
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RPV - Introduction

Lepton number violating terms

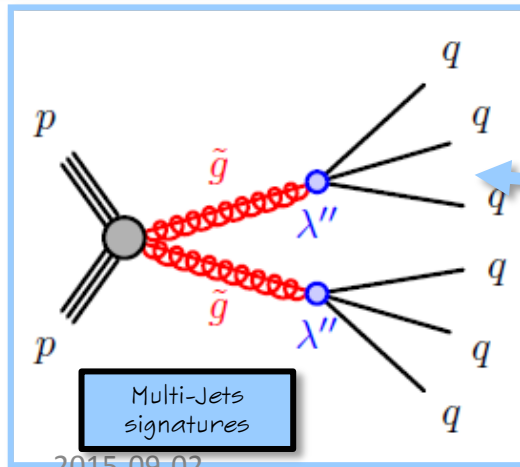
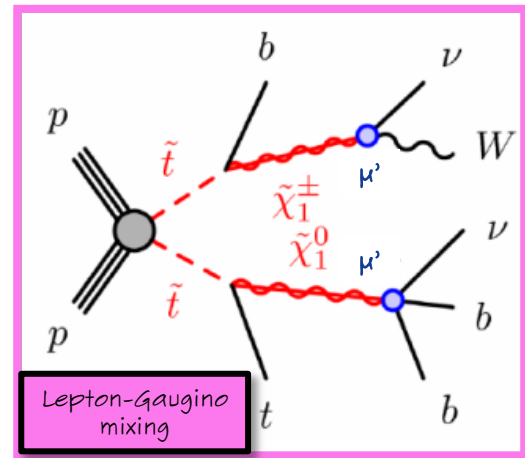
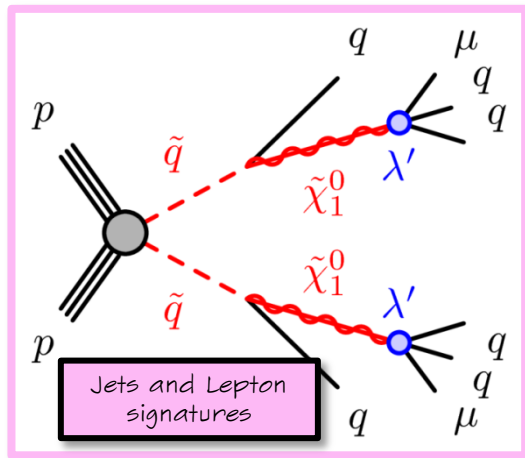
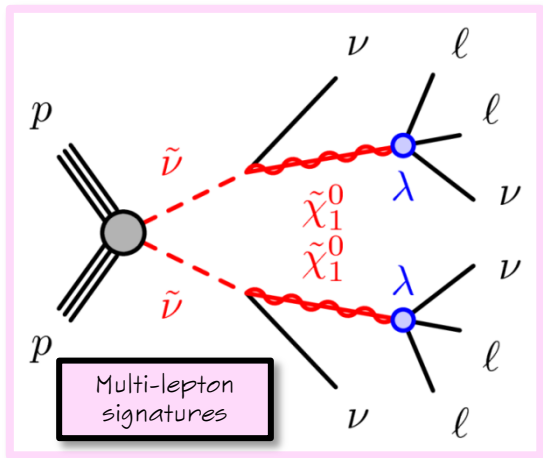
$$\mathcal{L}_{\Delta L=1} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}^k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu^i L_i H_u$$



RPV - Introduction

Lepton number violating terms

$$\mathcal{L}_{\Delta L=1} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}^k + \lambda''^{ijk} L_i Q_j \bar{d}_k + \mu^i L_i H_u$$



Baryon number violating term

$$\mathcal{L}_{\Delta B=1} = \frac{1}{2} \lambda'''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

Least constrained due to difficult all-hadronic states

RPV - Introduction

- Only showing a few examples in this talk

◀ Table shows the searches by search strategy

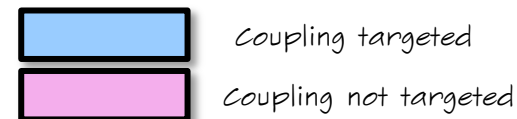
◀ Sorted by targeted RPV couplings

Not an exhaustive list!!

<i>RPV coupling</i>	λ (LLE)	λ' (LQD)	μ' (bRPV)	λ'' (UDD)
Run-1 LNV Re-Interpretation	[1]	[1]	[1]	
Resonance Searches	[4]	[4]		
Lepton+Jets Searches	[2][13]	[2][3][5][6][12][13]		[7][8]
Multi-Lepton Searches	[14]			
Multi-Jet Searches				[15][16][17]
Long-Lived Searches	[9]	[9][10][11]		

[X] is ATLAS and [X] is CMS

Will not go through all them due to lack of time
(few searches included in the back-up slides)



RUN-1 RE-INTERPRETATION



Short name	Ref.	λ	Simplified models		μ'
		$LL\bar{E}$ $\tilde{g}\tilde{g}$	$LQ\bar{D}$ $\tilde{g}\tilde{g}$	$LQ\bar{D}$ $\tilde{q}\tilde{q}$	pMSSM $bRPV$
		$4q, 4\ell, 2\nu$	$8q, 2(\ell/\nu)$	$6q, 2(\ell/\nu)$	
4L		✓			
SS/3L		✓	◇		✓
1L			✓	✓	◇
0L 2–6 jets			✓	✓	
0L 7–10 jets			✓		

✓ Limits obtained by the analysis
 ◇ Other channel suppress the results from this analysis

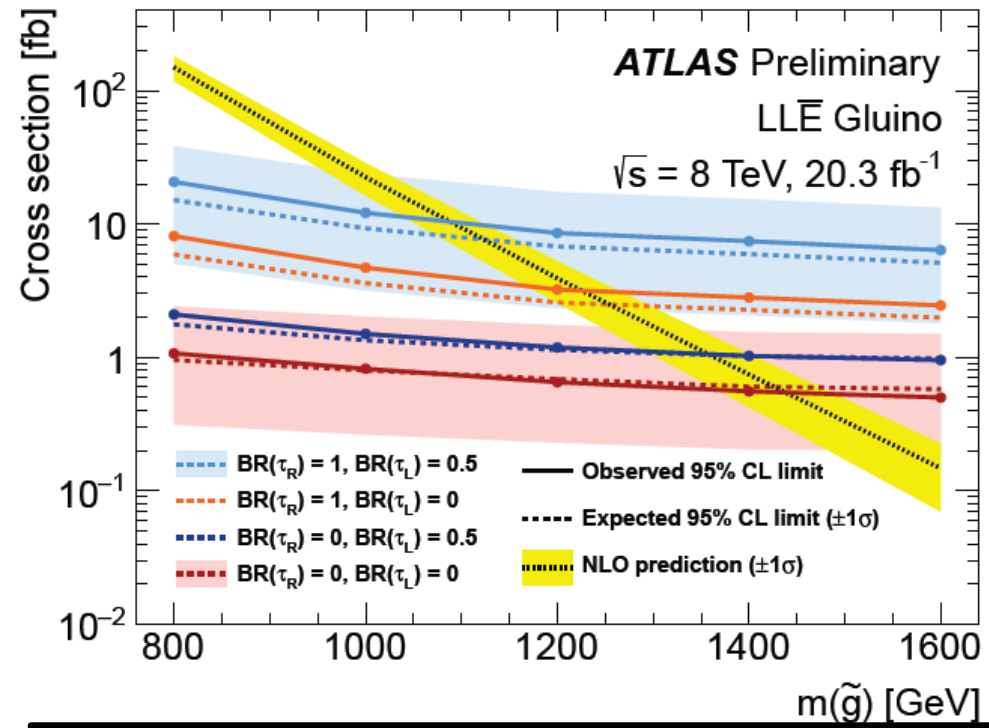
- Combined analyses – stricter exclusions
 - ◀ Gluino- and squark-production
 - ◀ Considering only $\tilde{\chi}_1^0$ LSP
 - ◀ LNV RPV couplings: λ, λ', μ'
- Limits set depending on dominant coupling
 - ◀ BR planes defined to show dependence on dominant couplings
 - ◀ Function of heavy and light flavours
- Looks at three different ratios R between mLSP and mNLSP
 - ◀ R = 0.1, 0.5, 0.9



$$\lambda_{ijk}$$

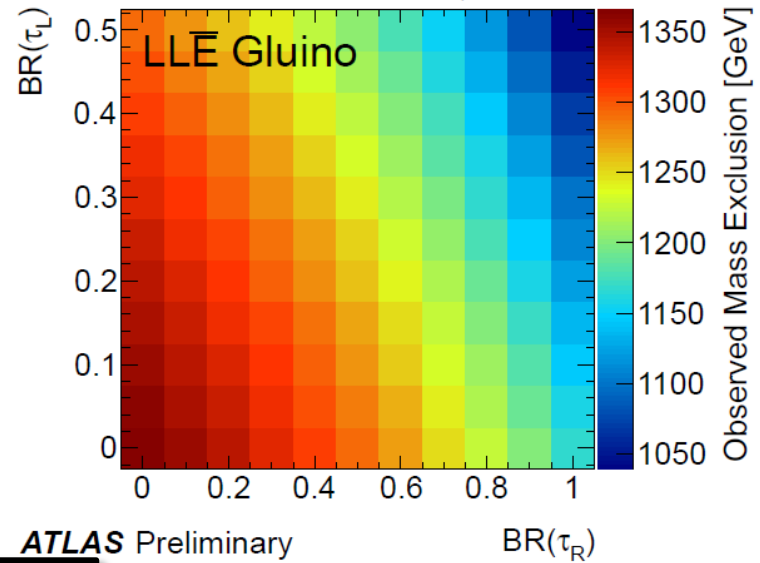
- Gluino-production
- Three types of LSP decay: $ll\nu, l\tau\nu, \tau\tau\nu$
 - Final states with 4 leptons and 2 neutrinos
- 3L signatures most sensitive for $R = 0.1$

$pp \rightarrow \tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}_1^u qq\tilde{\chi}_1^u \quad \tilde{\chi}_1^u \rightarrow l\bar{l}\nu \quad m(\tilde{\chi}_1^u) / m(\tilde{g}) = 0.1$



Excluded mass dependent on BR and kinematics of LSP/NLSP

$pp \rightarrow \tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}_1^0 qq\tilde{\chi}_1^0 \quad \tilde{\chi}_1^0 \rightarrow l\bar{l}\nu \quad \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$
All limits at 95% CL $m(\tilde{\chi}_1^0) / m(\tilde{g}) = 0.1$



Excluded $m_{\text{gluino}} < 1040 \text{ GeV}$ (worst case)

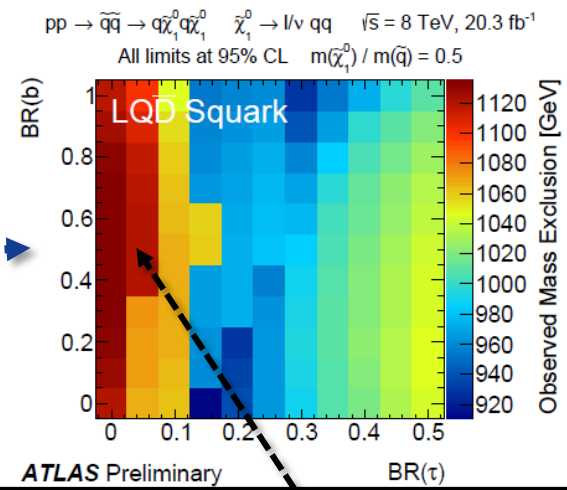
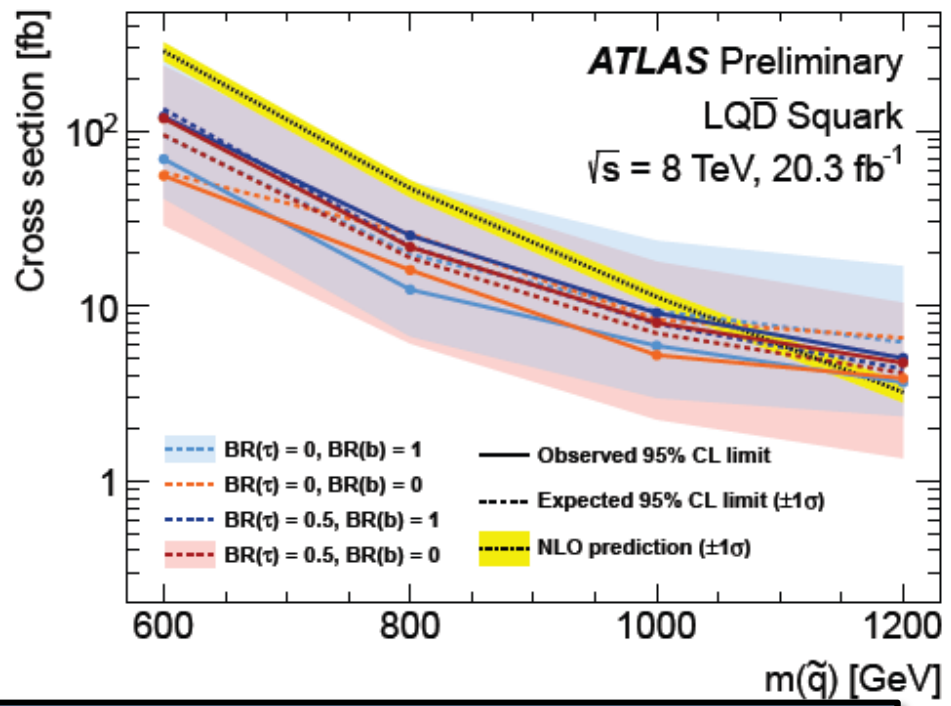
Run-1 Re-interpretations on LNV RPV

λ'_{ijk}

- Squark- and gluino-production
- Assume equal BR for
- BR(b) vs BR(τ)

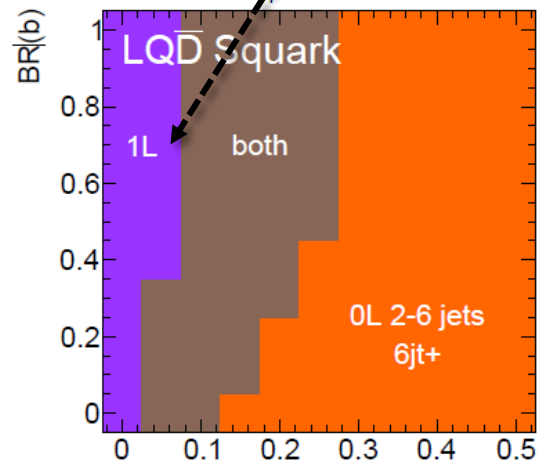
$$\tilde{\chi}_1^0 \rightarrow l_i u_j d_k, \quad \tilde{\chi}_1^0 \rightarrow \nu_i d_j d_k$$

$pp \rightarrow \tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \rightarrow l\nu qq, \quad m(\tilde{\chi}_1^0) / m(\tilde{q}) = 0.5$



Observed excluded mass depends on analyses sensitivity

$pp \rightarrow \tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \rightarrow l\nu qq, \quad \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}, \quad m(\tilde{\chi}_1^0) / m(\tilde{q}) = 0.5$

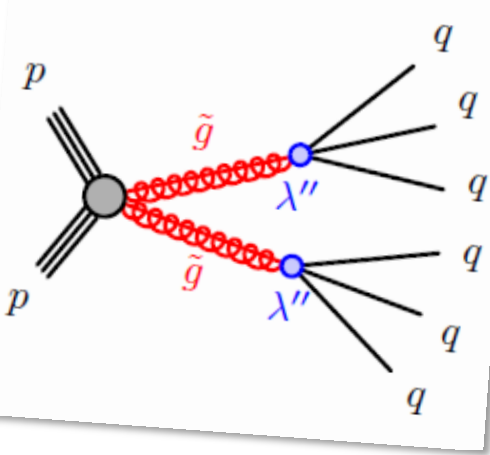


Excluded is $m_{\text{squark}} < 1100 \text{ GeV}$ ($R=0.5$)
 Lower limit for $m_{\text{gluino}} > 910-1220 \text{ GeV}$

RESONANCE SEARCHES

λ''_{ijk}

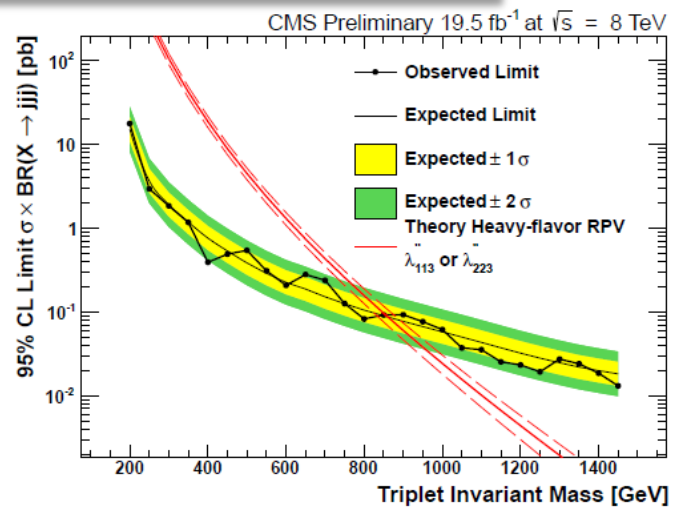
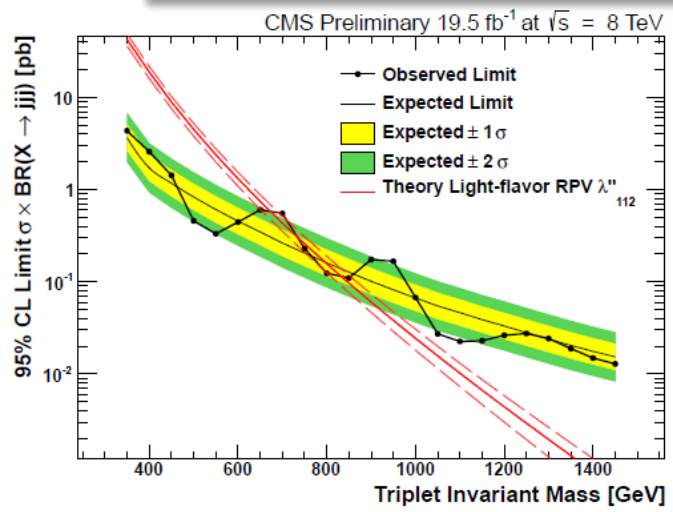
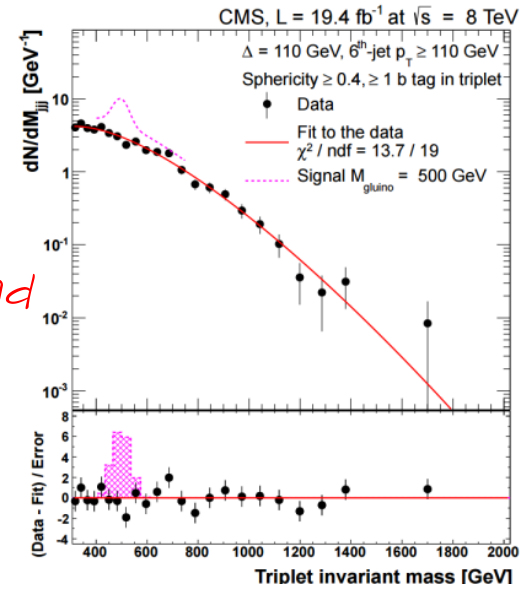
Resonance Searches



- Multi-jet: 6 jets
 - ◀ 3-jet resonances
 - ◀ 0 and 2 b-jets
- Spherical event shape
 - ◀ Veto back-to-back jets

Reduce background

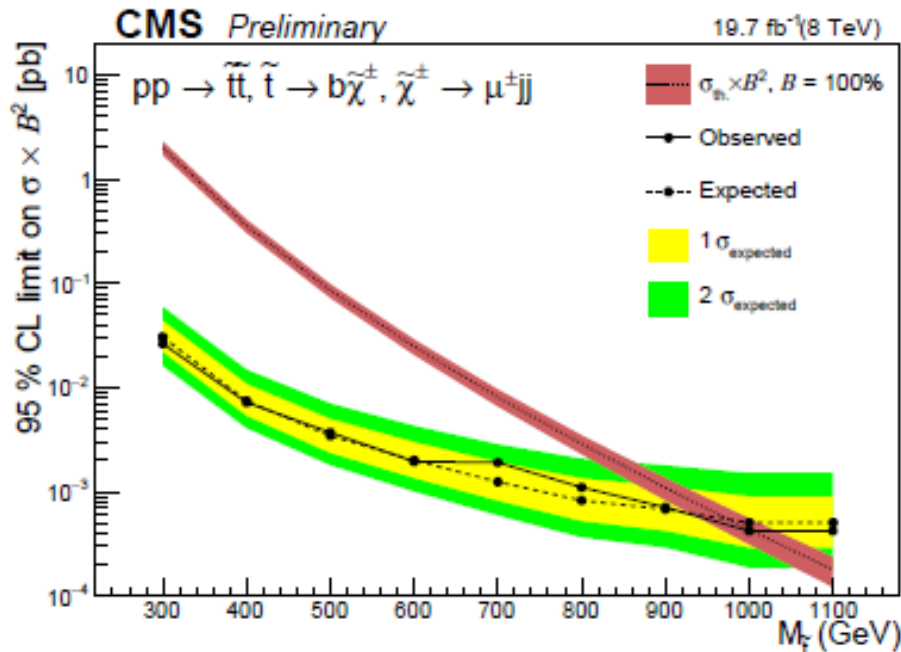
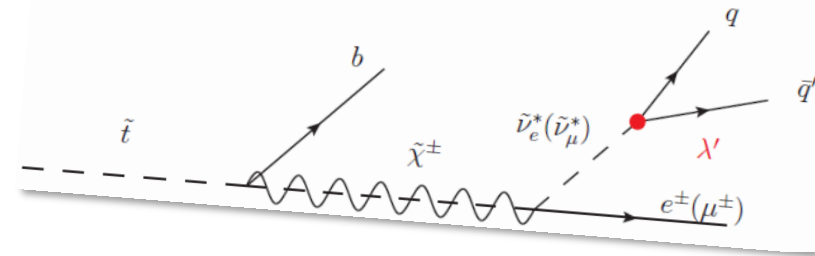
Light-Flavour jets to $m_{\text{gluino}} < 650 \text{ GeV}$
 Heavy-Flavour jet to $m_{\text{gluino}} 200 - 835 \text{ GeV}$



LEPTON + JET SEARCHES



- Chargino-mediated stop decay
 - ◀ Off-shell sneutrino to qq pairs
- Signals of
 - ◀ $\mu^\pm\mu^\mp$ or $e^\pm e^\mp$
 - ◀ with ≥ 5 jets and ≥ 1 b-jet



Excluded masses of
 $M_{\text{stop}} < 1000$ (890) GeV for μ (e)

$$\Delta M_{\text{stop}} - M_{\text{chargino}} = 100 \text{ GeV}$$

Phys.Lett B739 (2014) 229

Complementary search for
 stau neutrino and λ'^2_{zjk}

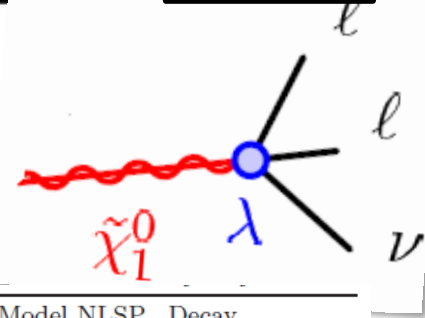


MULTI-LEPTON SEARCHES

λ_{ijk}

Multi-Lepton Searches

Phys.Rev D90, (2014) 052001



RPV Model NLSP	Decay
Chargino	$\tilde{\chi}_1^\pm \rightarrow W^{\pm(*)} \tilde{\chi}_1^0$
L-slepton	$\tilde{\ell}_L \rightarrow \ell \tilde{\chi}_1^0$ $\tilde{\tau}_L \rightarrow \tau \tilde{\chi}_1^0$
R-slepton	$\tilde{\ell}_R \rightarrow \ell \tilde{\chi}_1^0$ $\tilde{\tau}_R \rightarrow \tau \tilde{\chi}_1^0$
Sneutrino	$\tilde{\nu}_e \rightarrow \nu_e \tilde{\chi}_1^0$ $\tilde{\nu}_\tau \rightarrow \nu_\tau \tilde{\chi}_1^0$
Glauino	$\tilde{g} \rightarrow q\bar{q} \tilde{\chi}_1^0$ $q \in u, d, s, c$

- Target final state with four leptons L
 - ◀ Signal regions of $N(L) + N(\tau) \geq 4$
- 4 production channels of LSP
 - ◀ Decay through LNV: $\tilde{\chi}_1^0 \rightarrow llv$

Assuming $LSP \geq 0.2 NLSP$ mass

Limits set on NLSP/LSP

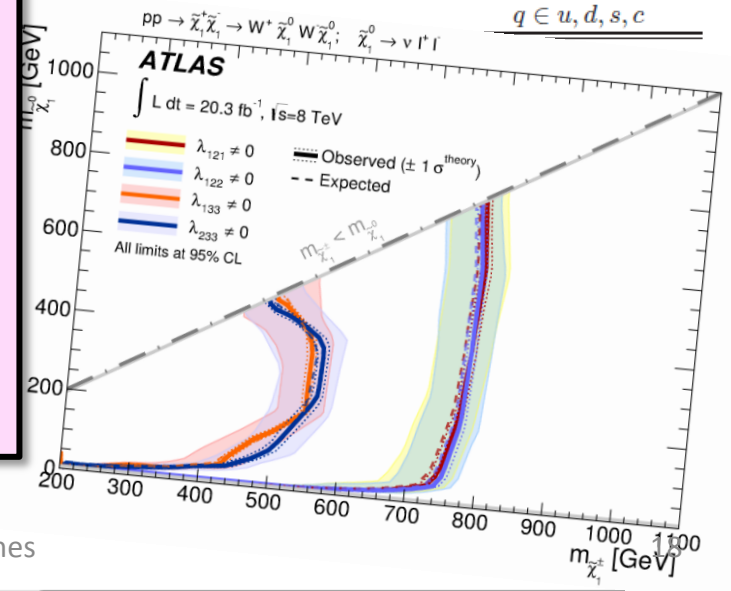
→ Excluded masses are

Glauino < 1350 GeV

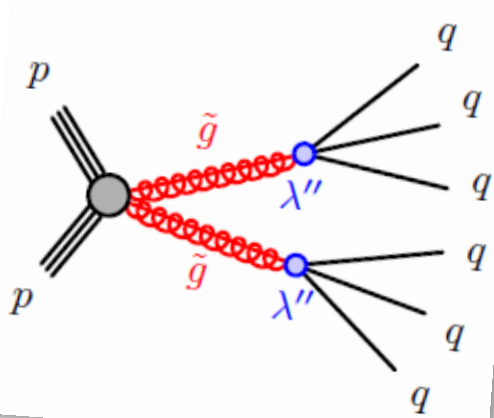
Chargino < 750 GeV

Sleptons < 490 (410) L(R)

Sneutrino < 400 GeV

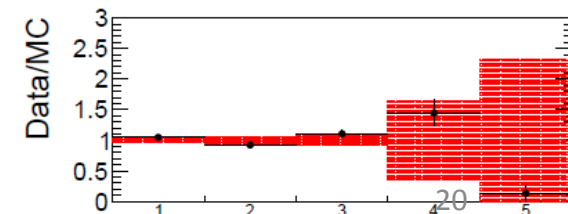
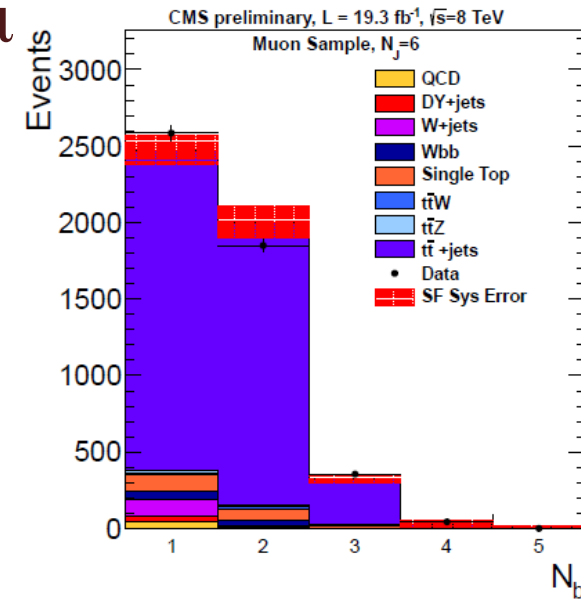
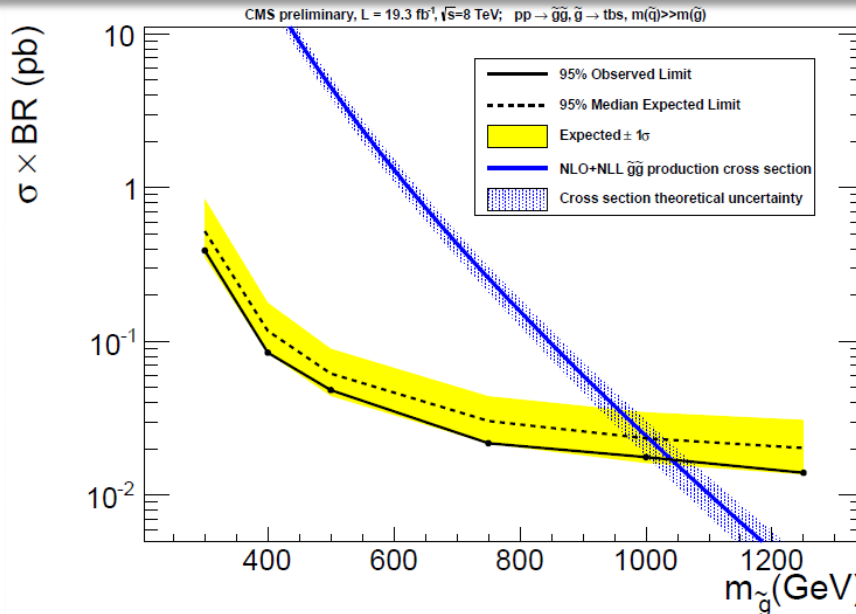


MULTI-JET SEARCHES



- Target especially heavy flavour jets
- Multiple jets and 1 Lepton
 - ◀ Gluino LSP: $\tilde{g} \rightarrow tsb$
 - ◀ 6, 7 or ≥ 8 jets + e/μ

Exclusion on $m_{\text{gluino}} < 1036 \text{ GeV}$ with
 $BR(\tilde{g} \rightarrow tbs) = 100\%$

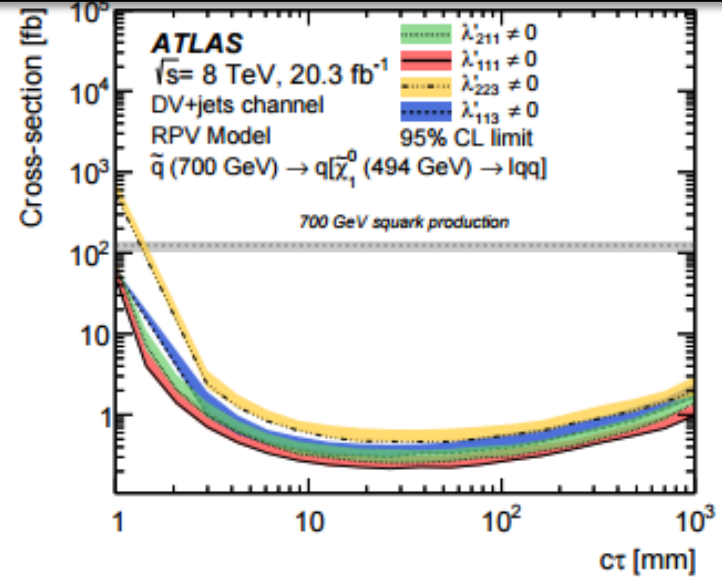
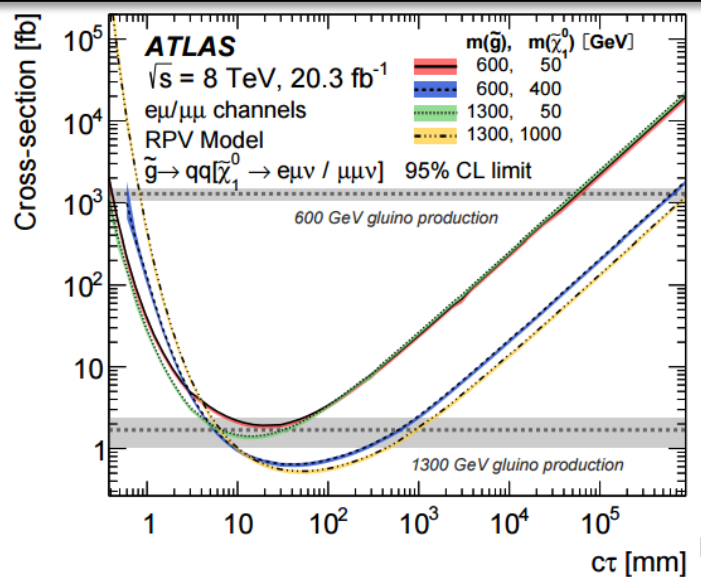


LONG-LIVED SEARCHES

Long-Lived Scenarios

- Several LLP searches targets RPV scenarios
- Ex: Displaced vertex signature
 - ◀ ATLAS: [arXiv:1504.05162](#)
 - ◀ CMS: [Phys.Rev.Lett 114.6 \(2015\) 061801](#)
 - ◀ Details in previous talk by Daniela Salvatore (31st Aug)

Limits set as a function of lifetime!
Here shown limits from the ATLAS Displaced Vertex search for λ and λ'



Conclusion

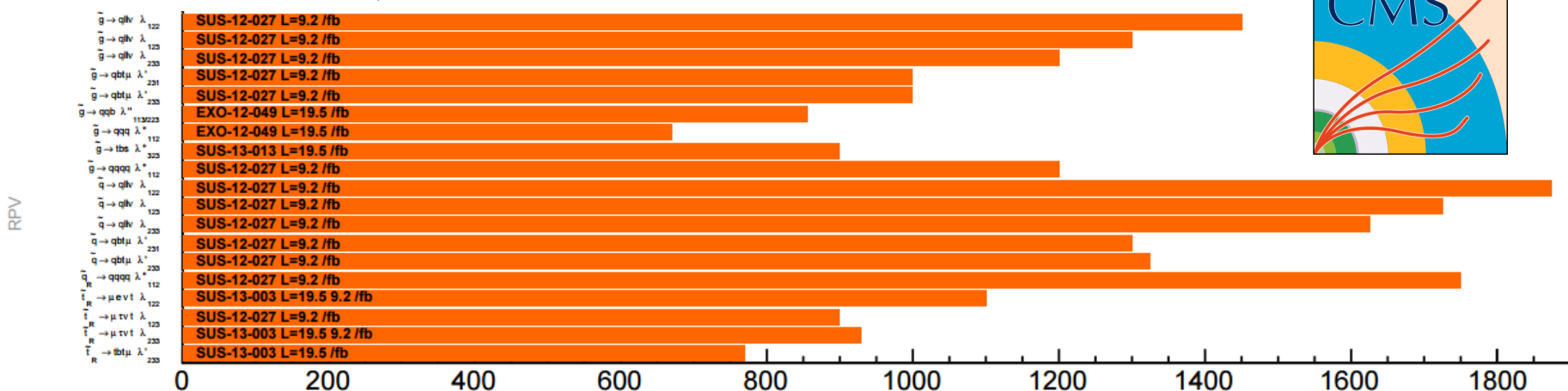


A wide variety of search strategies

Resonances, Multiple jets/leptons or long-lived scenarios
Re-interpretations possible for RPC searches with low MET

Search Strategy	Final State	Signature	Yes	No	20.3	Mass [GeV]	Notes
LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, e\tau, \mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$
Bilinear RPV CMSSM	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$
$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	$4 e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	750 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{121} \neq 0$
$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	$3 e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{133} \neq 0$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq$	0	6-7 jets	-	20.3	\tilde{g}	917 GeV	$BR(j) = BR(b) = BR(c) = 0\%$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$	0	6-7 jets	-	20.3	\tilde{g}	870 GeV	$m(\tilde{\chi}_1^0) = 600 \text{ GeV}$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	\tilde{g}	850 GeV	
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	20.3	\tilde{t}_1	100-308 GeV	
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	$2 e, \mu$	2 b	-	20.3	\tilde{t}_1	0.4-1.0 TeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$
Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	490 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$

Multiple limits set by both experiments covering a large spectrum of RPV decays



*Observed limits, theory uncertainties
Only a selection of available results
2015-09-02

Run-2 will extend on these limits!

BACKUP

References

- [ATLAS-CONF-2015-018](#) [1] The ATLAS collaboration, *Constraints on promptly decaying supersymmetric particles with lepton-number- and R-parity-violating interactions using Run-1 ATLAS data* (2015).
- [CMS-PAS-SUS-12-027](#) [2] *Search for RPV supersymmetry with three or more leptons and b-tags* (2012).
- [arXiv:1306.6643](#) [3] CMS collaboration, *Search for top squarks in R-parity-violating supersymmetry using three or more leptons and b-tagged jets*, *Phys. Rev. Lett.* **111.22** (2013) 221801, arXiv: 1306.6643 [hep-ex].
- [arXiv:1503.04430](#) [4] The ATLAS collaboration, *Search for a Heavy Neutral Particle Decaying to $e\mu$, $e\tau$, or $\mu\tau$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*, *Phys. Rev. Lett.* **115.3** (2015) 031801, arXiv: 1503.04430 [hep-ex].
- [EXO-14-013](#) [5] CMS Collaboration, *Search for top squarks in R-parity violating supersymmetry with dileptons and jets* (2015).
- [arXiv:1408.0806](#) [6] CMS collaboration, *Search for pair production of third-generation scalar leptoquarks and top squarks in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett.* **B739** (2014) 229, arXiv: 1408.0806 [hep-ex].
- [arXiv:1404.2500](#) [7] The ATLAS collaboration, *Search for supersymmetry at $\sqrt{s}=8$ TeV in final states with jets and two same-sign leptons or three leptons with the ATLAS detector*, *JHEP* **06** (2014) 035, arXiv: 1404.2500 [hep-ex].

References

- [arXiv:1311.6736](#) [8] CMS collaboration, *Search for new physics in events with same-sign dileptons and jets in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **01** (2014) 163, [Erratum: *JHEP*01,014(2015)], arXiv: 1311.6736.
- [arXiv:1504.05162](#) [9] The ATLAS collaboration, *Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector* (2015), arXiv: 1504.05162 [hep-ex].
- [arXiv:1411.6530](#) [10] CMS collaboration, *Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev.* **D91.1** (2015) 012007, arXiv: 1411.6530 [hep-ex].
- [arXiv:1409.4789](#) [11] CMS collaboration, *Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters*, *Phys. Rev. Lett.* **114.6** (2015) 061801, arXiv: 1409.4789 [hep-ex].
- [ATLAS-CONF-2015-015](#) [12] The ATLAS collaboration, *A search for $B - L$ R-Parity violating scalar top decays in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS experiment* (2015).
- [arXiv:1306.6643](#) [13] CMS collaboration, *Search for top squarks in R-parity-violating supersymmetry using three or more leptons and b-tagged jets*, *Phys. Rev. Lett.* **111.22** (2013) 221801, arXiv: 1306.6643 [hep-ex].
- [arXiv:1405.5086](#) [14] The ATLAS collaboration, *Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, *Phys. Rev.* **D90.5** (2014) 052001, arXiv: 1405.5086 [hep-ex].

References

- [arXiv:1502.05686](#) [15] The ATLAS collaboration,
Search for massive supersymmetric particles decaying to many jets using the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV,
Phys. Rev. D **91.11** (2015) 112016, arXiv: [1502.05686](#) [hep-ex].
- [ATLAS-CONF-2015-026](#) [16] The ATLAS collaboration,
*A search for **R**-parity violating scalar top decays in all-hadronic final states with the ATLAS detector in $\sqrt{s} = 8$ TeV pp collisions* (2015).
- [SUS-12-015](#) [17] CMS Collaboration, *A search for new physics in events with high jet and b-tagged jet multiplicities and one lepton* (2013).

Run-1 Re-interpretations on LFV RPV

μ'_i

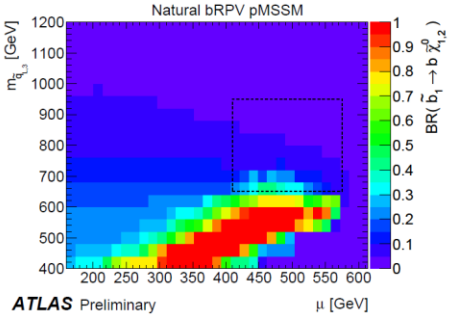
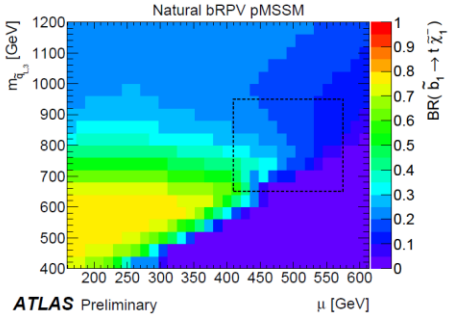
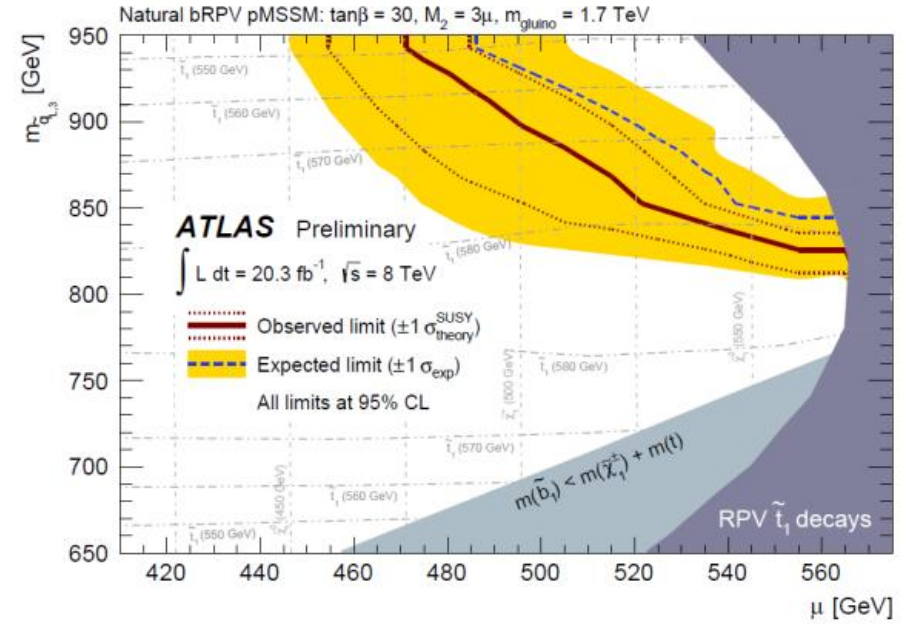
- Bilinear RPV natural pMSSM models
- 3rd-gen squarks and higgsino-like LSP
- \tilde{t}, \tilde{b} / mass-degen χ_1^\pm, χ_1^0 - production

First time!

Difficult phenomenology

EW symmetry breaking
Neutrino-Neutralino
mixing

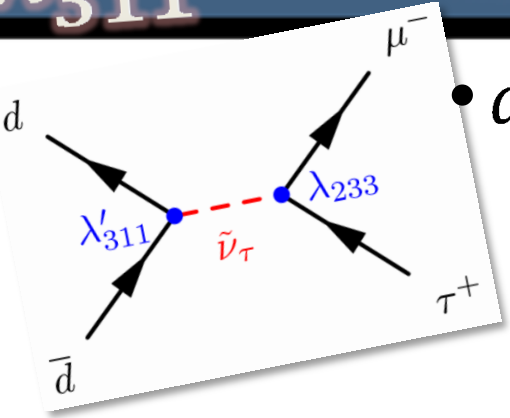
Many different channels
targeted



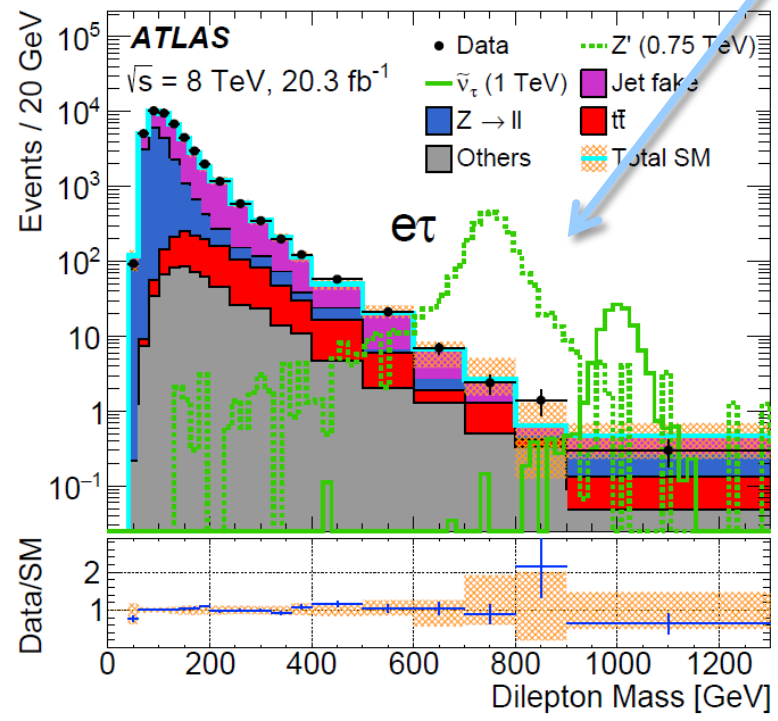
Constrained criteria, stop $\sim 550-580$ GeV
Higgsino-like LSP gives μ 160-455 GeV
For 3rd-gen L-handed squarks (top and b)
 $m = 800$ GeV $\mu < 560$ GeV

λ'_{311} λ_{i3k}

Resonance Searches

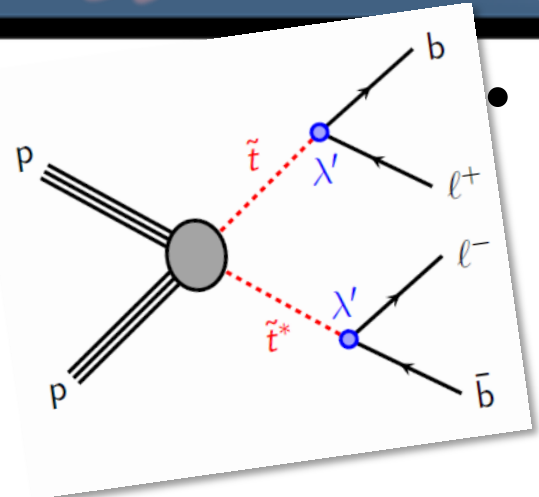


- $d\bar{d}$ annihilation producing $\tilde{\nu}_\tau$
 - ◀ Decay to $e^\pm \mu^\mp, e^\pm \tau^\mp, \mu^\pm \tau^\mp$
 - ◀ Search for resonance in dilepton mass

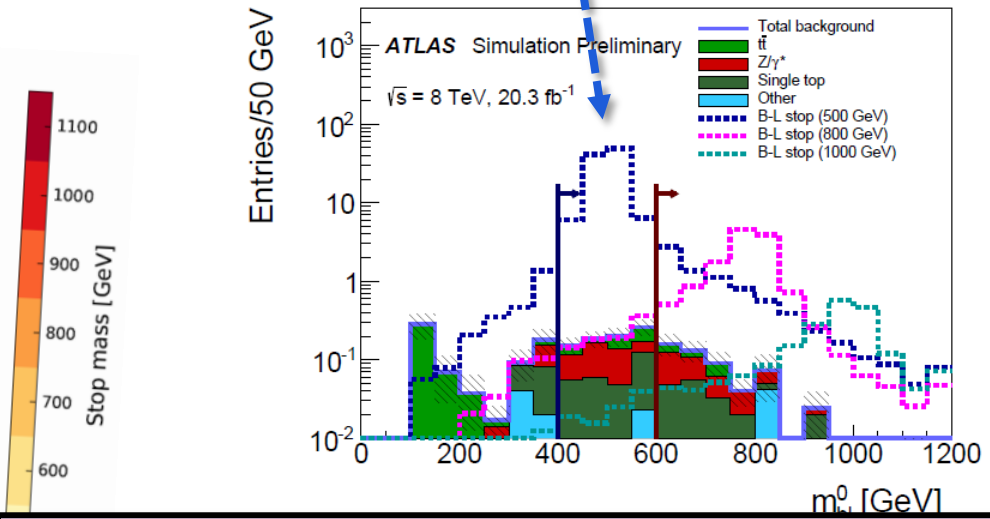
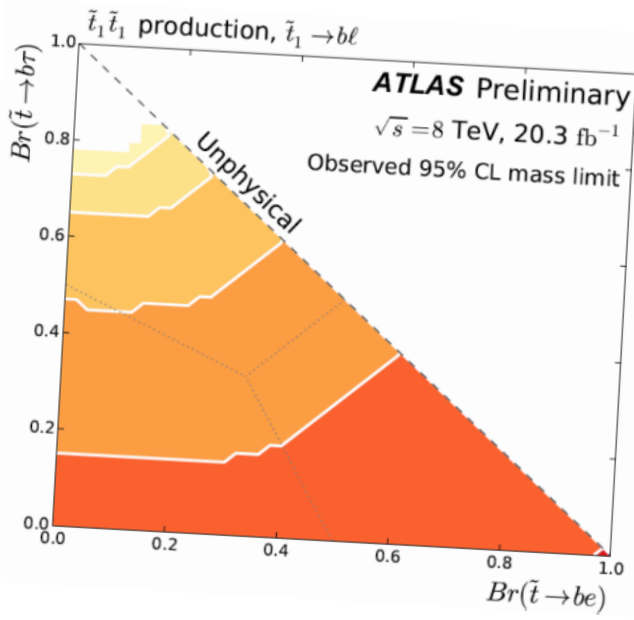


Analysis will covered in details by Aliaksandr Pranko (2nd Sept)
“Search for heavy neutrinos, lepton flavor violation and multilepton signatures in high mass final states”

Lepton+Jet Searches



- Top squark LSP
 - ◀ Final states: $ee, e\mu, \mu\mu$ and 2 b-jets
- Resonance search
 - ◀ Lepton-b pair require
 - ◀ mass ≥ 400 and ≥ 600



Mass exclusions decreases with $BR(b\tau)$
 Number of expected e/μ decrease with $BR(b\tau)$
 Lose signal efficiency



$\lambda_{ijk} \lambda'_{ijk}$ Lepton+Jet searches

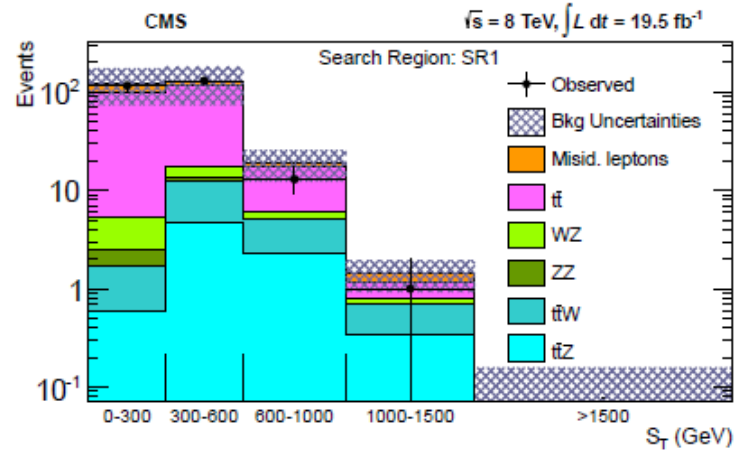
• Target: $\tilde{t}_1 \rightarrow \tilde{\chi}_1^{0*} + t$ *Bino-like LSP*

◀ Decay through λ or λ'
 ▶ to $ll\nu, lqq, \nu qq$

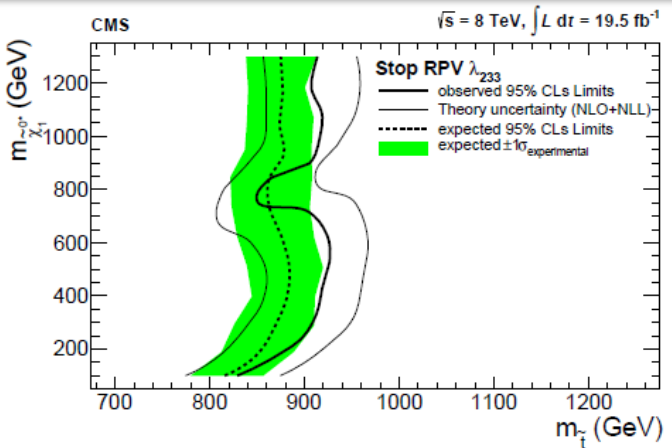
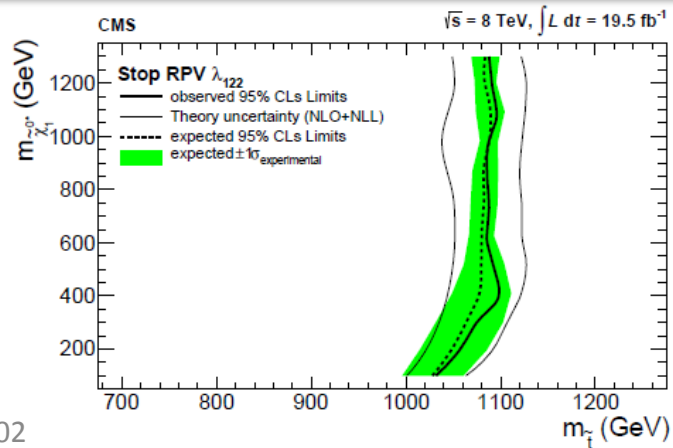
• Search Strategy

◀ Three or Four leptons

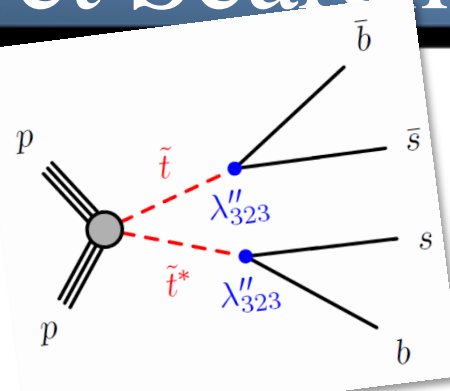
◀ Bin in S_T 0-1500 GeV Scalar sum of Missing E_T



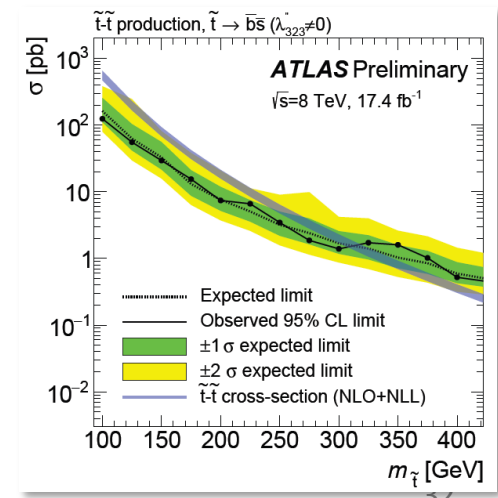
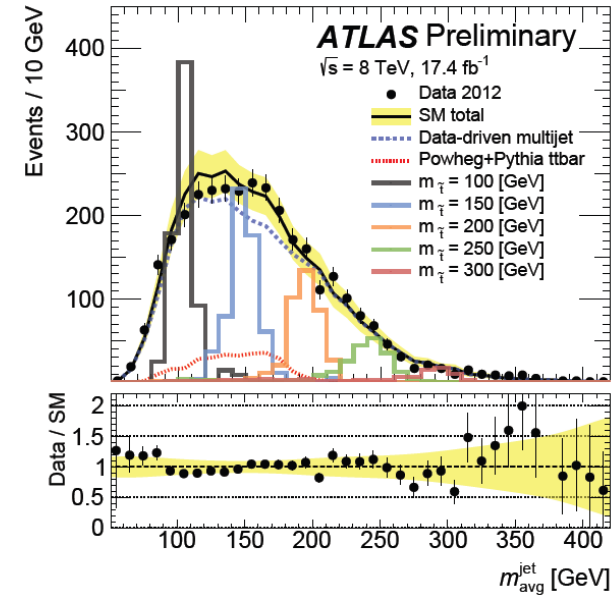
$\lambda_{122}, \lambda_{233}$ for LSP 200 GeV stop excluded up to 1020 GeV and 820 GeV



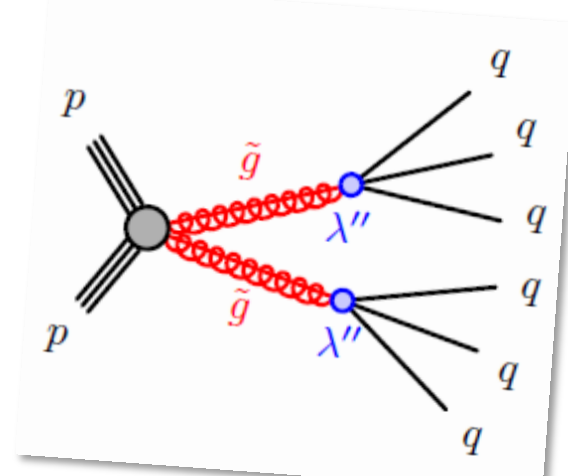
Limits also set for λ'_{233}



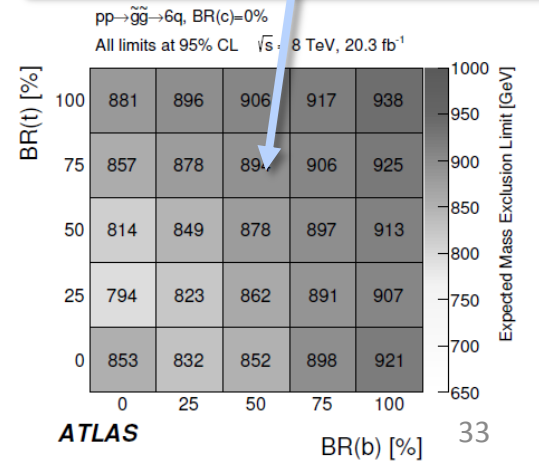
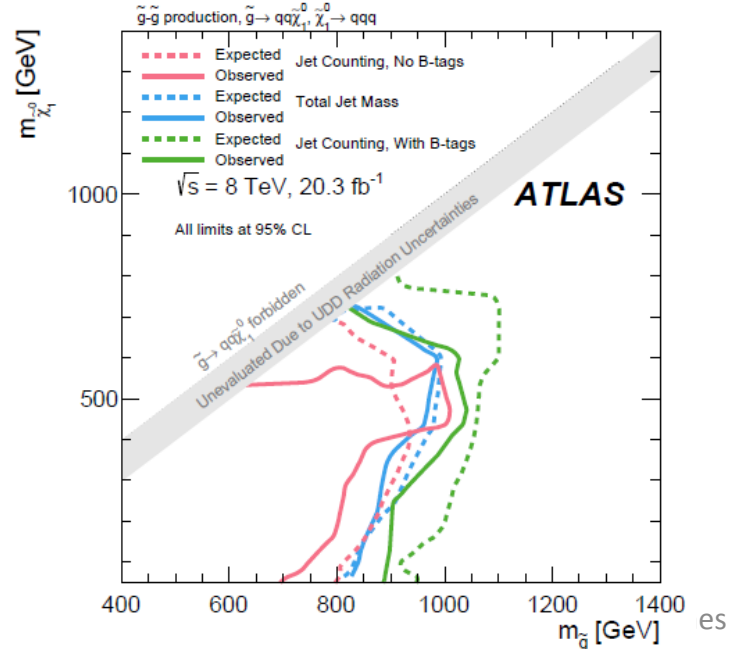
- Top squark LSP
- Search strategy of merged bs-jets
 - ◀ Boosted jets, high p_T and low mass
 - ◀ Two jets inside a large cone
- Kinematic variables suppress background
 - ◀ jet symmetry, similar angles and p_T
- Exclude mass of \tilde{t} 100-310 GeV



- \tilde{g} and $\tilde{\chi}_1^0$ LSP
 - ◀ B-RPV to numerous jets
- Two strategies
 - ◀ Jet-counting ≥ 6 -, ≥ 7 -jets
 - ◀ Total-jet-mass of large-R jets
- Exclude up to $m_{\text{gluino}} < 917 \text{ GeV}$

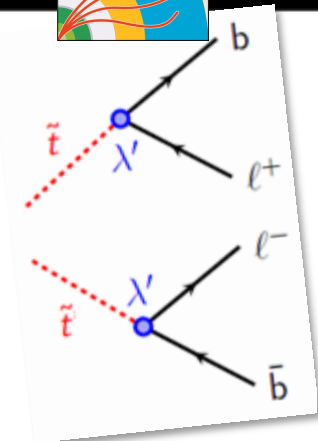


Jet-counting:
Limit m on RPV decay to t, b and c $BR(t)$, $BR(b)$ and $BR(c)$



λ'_{ijk}

Long-Lived Scenarios

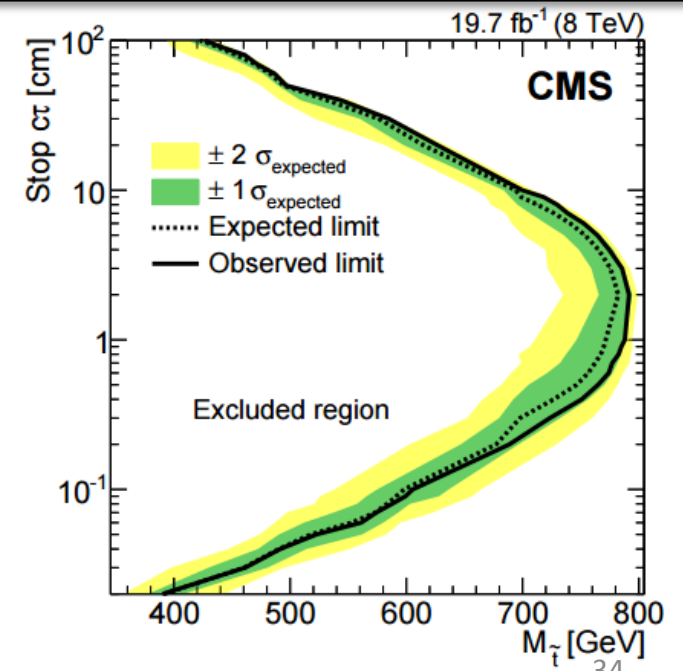
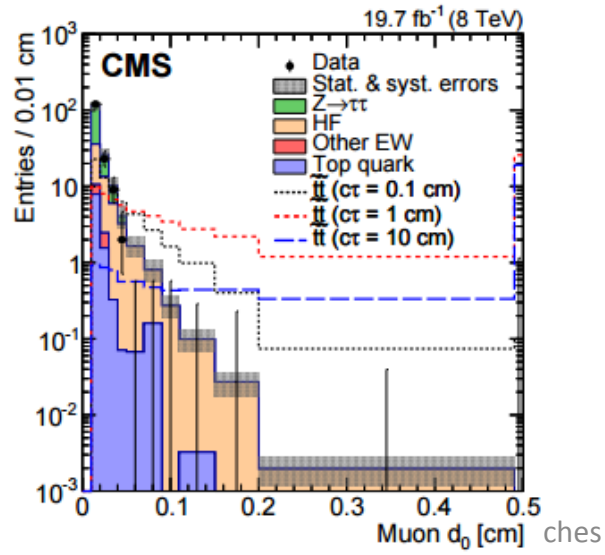
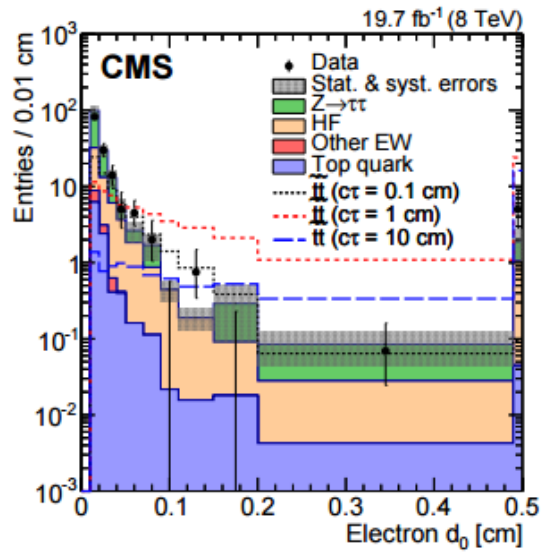


No further requirements!

- Stop LSP decaying to b-quark lepton pairs
- Require isolate e^\pm and μ^\mp
 - ◀ Displaced tracks from LLP
 - ◀ Transverse impact parameter d_0 0.02 cm to 2 cm

Background reduced rapidly with d_0 requirement

Exclude stop mass < 790 GeV for $\tau = 2$ cm

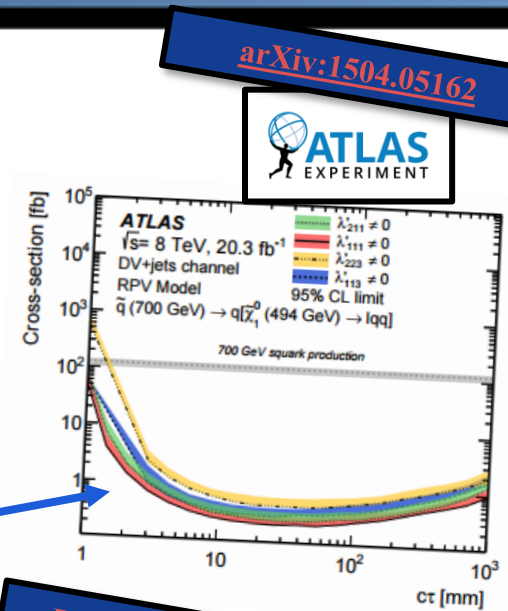


$\lambda'_{ijk} \lambda_{ijk}$

Long-Lived Scenarios

- Displaced Vertices from LLP

- ◀ Squark production
- ◀ Small RPV couplings give LLP LSP
 - ◀ L-RPV: $\chi_1^0 \rightarrow qql$, $\chi_1^0 \rightarrow llv$
- ◀ Mult-track and Dilepton channels
- ◀ No SM background (< 1 event)
- ◀ Limits on RPV couplings vs $c\tau$



- Neutral LLP decaying to quark-antiquark

- ◀ Search for jets from a Secondary Vertex
 - ◀ Tracker volume
- ◀ Jet-Track/vertexing selection

