Search for lepton-flavor violation in high-mass dilepton final states with the ATLAS detector

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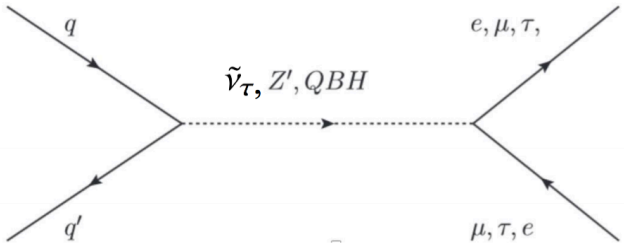
Introduction

- Direct charged-lepton flavor violation (LFV) is forbidden in the Standard Model

- Hypothetic new physics models
- Scalar particle: R-Parity Violating (RPV) SUSY $\tilde{\nu}_\tau$
- Vector particle: Sequential Standard Model (SSM) Z'
- Tensor particle: Quantum Black Hole (QBH)



- Aim of this analysis: search for a new resonance with two leptons of different flavor(eμ,eτ,μτ) in high mass region. Otherwise, set limits on the parameters of new physics models

- Clear experimental signature
- Low background from SM processes
- The invariant mass of the heavy neutral particle can be reconstructed

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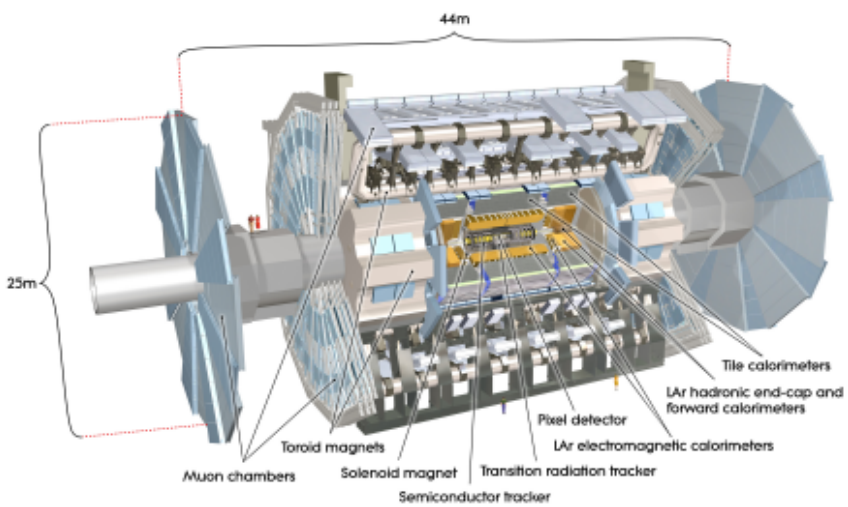
Data and signal simulation samples

- Dataset recorded with the ATLAS detector in 2015 and 2016 at $\sqrt{s}$= 13 TeV, corresponding to an integrated luminosity of 36.1 fb^{-1}

- Signal MC Samples
- Z': Pythia8
- QBH: QBH+Pythia8
- SUSY $\tilde{\nu}_\tau$: MadGraph + Pythia8



ATLAS Detector

Object and Event selection

- **Muon**
- P_T > 65GeV;|η| < 2.5
- ID: high-pT operating point
- Isolation: track-based
- Track: $|d_0/\sigma_{d_0}|$ <3; $|\Delta z_0 \sin\theta|$<0.5 mm

- **Electron**
- P_T > 65GeV;|η| < 2.5 except 1.37 ~ 1.52
- ID: likelihood Tight
- Isolation: calorimeter-based
- Track:$|d_0/\sigma_{d_0}|$<5; $|\Delta z_0 \sin\theta|$<0.5 mm

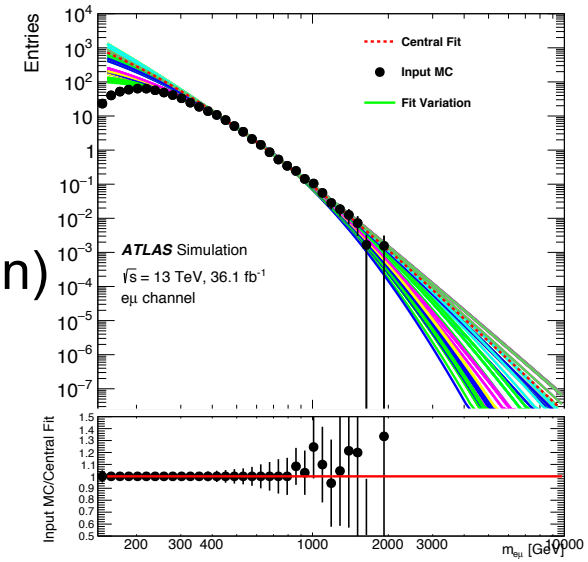
- **Tau**
- P_T > 65GeV;|η| < 2.5 except 1.37 ~ 1.52
- ID:BDT Loose
- Track: 1 or 3 prongs
- Charge: ±1

- **Event selection**
- Pre-selection: remove events with error status flag on detectors
- Pass single-electron or single-muon triggers and at least 1 trigger matched lepton (P_T threshold of 50 GeV for muons and 60 or 120 GeV for electrons)
- 3rd lepton veto: events with an additional good lepton are rejected.
- DeltaPhi: $\Delta\phi$ (ll′) > 2.7
- Look for events with masses above 120 GeV

Background estimation

- **Irreducible background**(processes produce two different-flavor prompt leptons)
- $Z/\gamma^{\star} \rightarrow \tau\tau$: Powheg
- Diboson: Sherpa
- Top($t\bar{t}$, single Top): Powheg + Pythia and Sherpa (limited for dilepton invariant masses above 1TeV)
- Extrapolation is applied with 2 functions on the Top background.

1) $$\frac{a}{(m_{\ell\ell'} + b)^c}$$ 2) $$a \cdot m_{\ell\ell'}^{b} \cdot m_{\ell\ell'}^{c \cdot \ln(m_{\ell\ell'})}$$



- **Reducible background** (estimated by data-driven)
- W+jets and multi-jet processes
- eμ ~ 5%
- $e\tau/\mu\tau$ ~ 50-60%

Reducible background estimation in eμ

- A 2 X 2 Matrix Method is performed to estimate the jet faked background in eμ channel

$$\begin{bmatrix} N_{\mathrm{TT}} \\ N_{\mathrm{LT}} \end{bmatrix} = \begin{bmatrix} r_e & f_e \\ 1 & 1 \end{bmatrix} \begin{bmatrix} N_{\mathrm{RR}} \\ N_{\mathrm{FR}} \end{bmatrix}$$

- N_{TT}: sample where both the electron and the muon pass the tight cut
- N_{LT}: sample where electron loose and the muon pass the tight cut

- r_e: real electron efficiency
- The probability of a “loose” electron(looser ID and without isolation requirement) matched to a generated electron to pass the full object selection
- Estimated by Zee MC samples

- f_e: electron fake rate
- The probability that a jet is misidentified as an electron
- Estimated in a multi-jet CR

Reducible background estimation in $e\tau/\mu\tau$

- **W+jets estimation** (jet misidentified as τ)
- Weight simulated W+jets events with the τ fake rate
- The τ fake rate is measured in a W+jets control region, using the same selection as the signal region, but reverses the back-to-back criterion
- Contributions from non-W+jets processes are subtracted using simulation

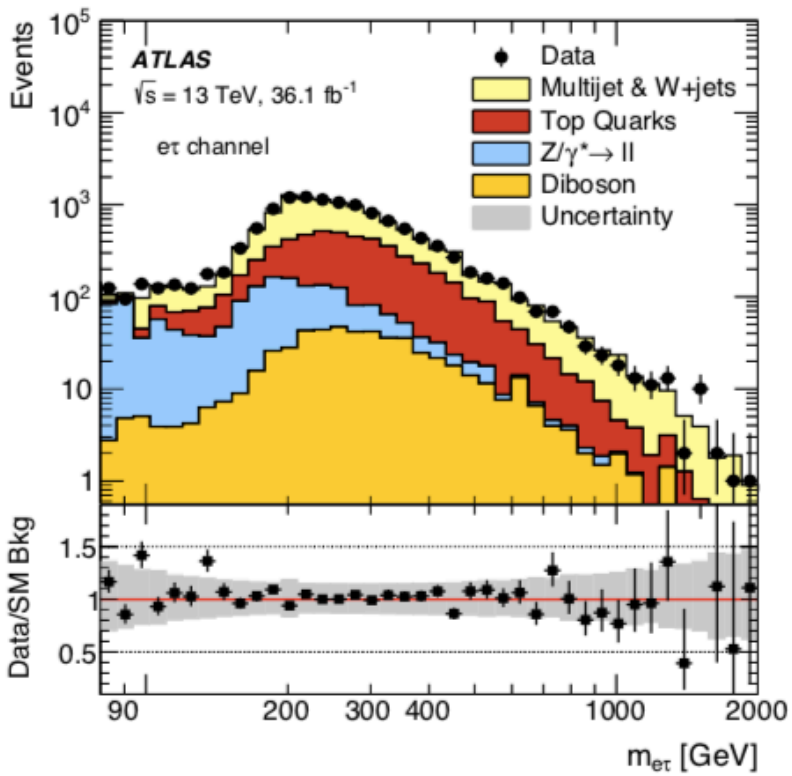
- **Multi-jet estimation**
- Use the events in three control regions to evaluate the contribution

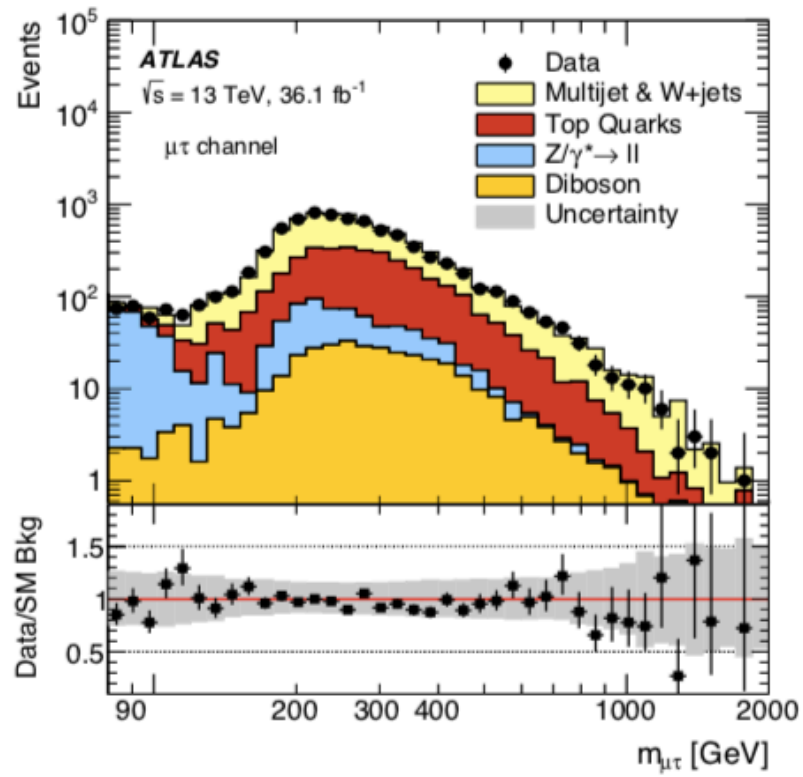
	Object selection	Lepton-pair charges
R_1	Non-isolated e/μ & $\tau_{\text{had-vis}}$ failing τ ID requirements (p_{T_ℓ} & $p_{T_\tau} < 200$ GeV)	Same-charge
R_2	Isolated e/μ & pass ID $\tau_{\text{had-vis}}$ (p_{T_ℓ} & $p_{T_\tau} < 200$ GeV)	Same-charge
R_3	Non-isolated e/μ & $\tau_{\text{had-vis}}$ failing τ ID requirements	Same-charge + Opposite-charge

- The final contribution is estimated as $N_{MJ} = N_{R_3} \times N_{R_2} / N_{R_1}$

Background estimation validation

The validation of the background estimation in the W+jets control region



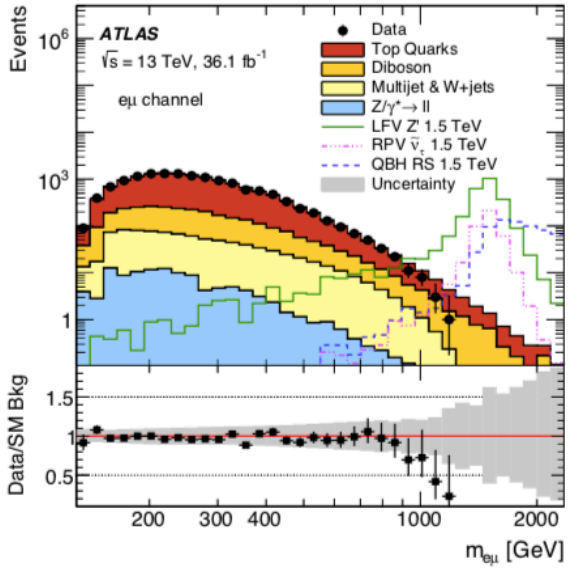


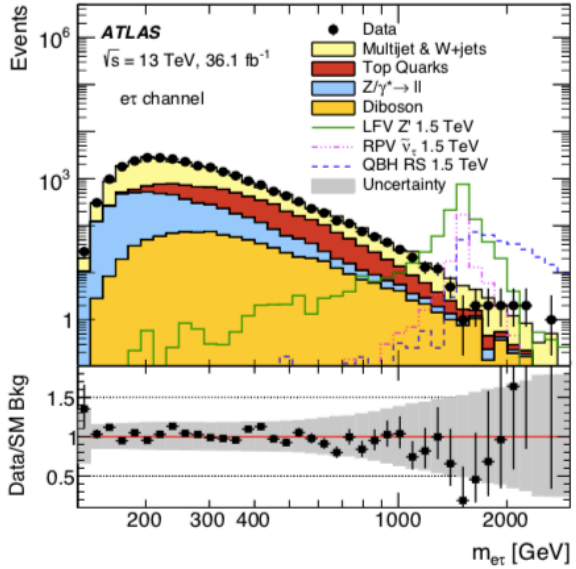
Systematic uncertainties

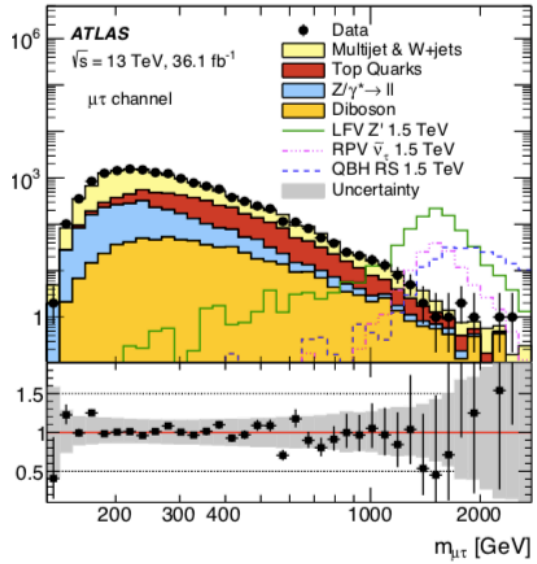
- Summary of the systematic uncertainties as a percentage of the total background
- The PDF uncertainties and the uncertainty on the extrapolation to estimate the top-quark are dominant

Source	1 TeV				2 TeV				3 TeV			
	$e\mu$	$e\mu$ b-jet veto	$e\tau$	$\mu\tau$	$e\mu$	$e\mu$ b-jet veto	$e\tau$	$\mu\tau$	$e\mu$	$e\mu$ b-jet veto	$e\tau$	$\mu\tau$
Luminosity	2	2	2	2	2	2	2	2	2	2	2	2
Top-quark extrapolation	5	3	2	2	32	8	3	4	63	12	3	14
Top scale	7	6	7	8	40	15	1	14	65	15	3	27
PDF	16	15	12	14	32	34	17	20	51	69	16	53
Pile-up	1	1	3	7	9	6	3	13	32	12	2	17
Dilepton p_T modeling	7	4	2	1	11	5	0	1	15	6	0	4
Electron iden. and meas.	4	4	5	-	4	8	6	-	5	11	8	-
Muon iden. and meas.	3	4	-	4	7	7	-	16	17	10	-	18
τ iden. and meas.	-	-	2	2	-	-	1	1	-	-	1	2
τ reconstruction eff.	-	-	2	2	-	-	1	1	-	-	1	3
τ fake rate	-	-	6	9	-	-	5	12	-	-	2	12
Multijet transf. factor	-	-	31	2	-	-	53	0	-	-	64	0
Reducible $e\mu$ estimation	2	-	-	-	2	-	-	-	2	-	-	-
Jet eff. and resol.	1	4	9	8	2	12	17	42	5	17	22	48
b-tagging	-	3	-	-	-	2	-	-	-	2	-	-
E_T^{miss} resol. and scale	-	-	3	4	-	-	5	6	-	-	8	8
Total	19	20	37	25	62	45	61	62	110	79	73	91

Results



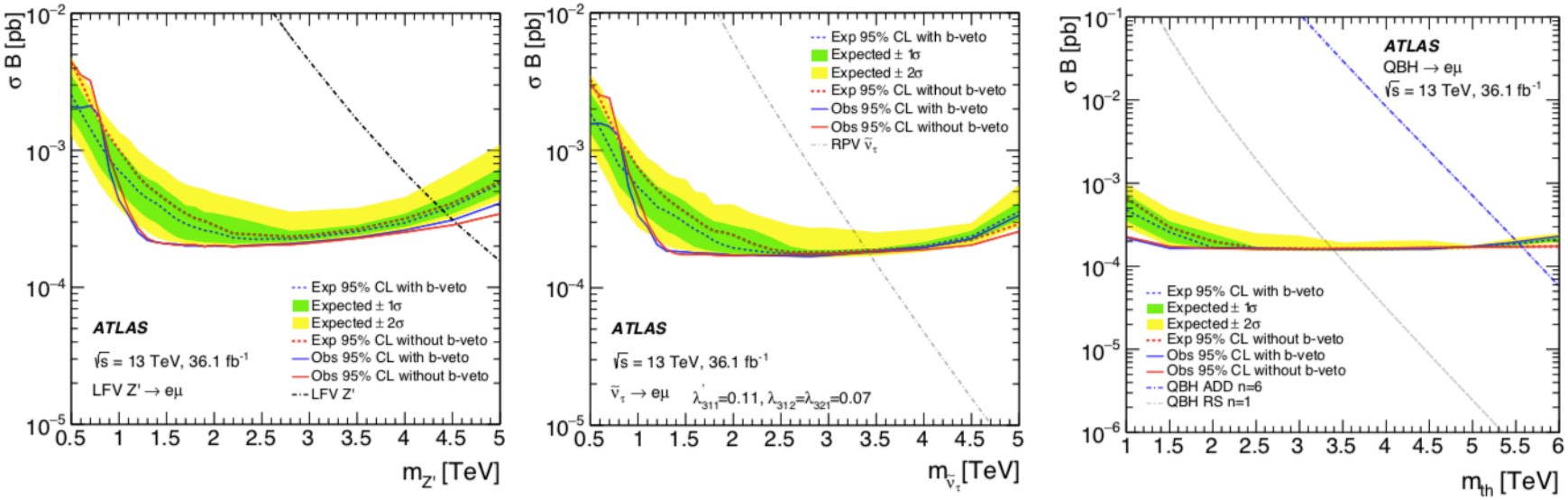




	eμ Signal Region	eτ Signal Region	μτ Signal Region
Top	145.3±28.0	165.9±53.2	98.3±26.6
Diboson	50.7±8.1	53.0±11.3	36.2±9.5
Mutijet and W+jets	24.2±9.5	328.4±139.4	136.1±44.3
Z->ll	1.4±0.3	26.9±6.0	15.2±4.5
Total background	221.6±37.5	575.2±156.4	297.5±116.3
Data	197	509	269

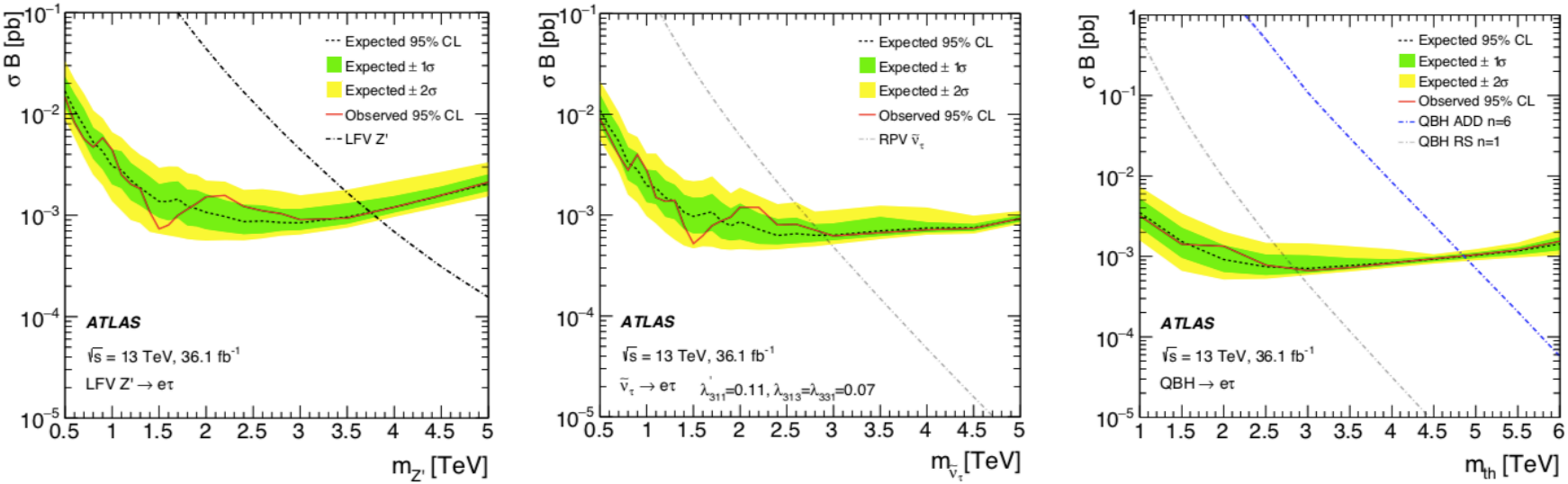
No significant excess beyond SM expectation observed

Limit setting: eμ channel



Model	Expected limit [TeV]				Observed limit [TeV]			
	$e\mu$	$e\mu$ (b-veto)	$e\tau$	$\mu\tau$	$e\mu$	$e\mu$ (b-veto)	$e\tau$	$\mu\tau$
LFV Z'	4.3	4.3	3.7	3.5	4.5	4.4	3.7	3.5
RPV SUSY $\tilde{\nu}_\tau$	3.4	3.4	2.9	2.6	3.4	3.4	2.9	2.6
QBH ADD $n = 6$	5.6	5.5	4.9	4.5	5.6	5.5	4.9	4.5
QBH RS $n = 1$	3.3	3.4	2.8	2.7	3.4	3.4	2.9	2.6

Limit setting: eτ channel



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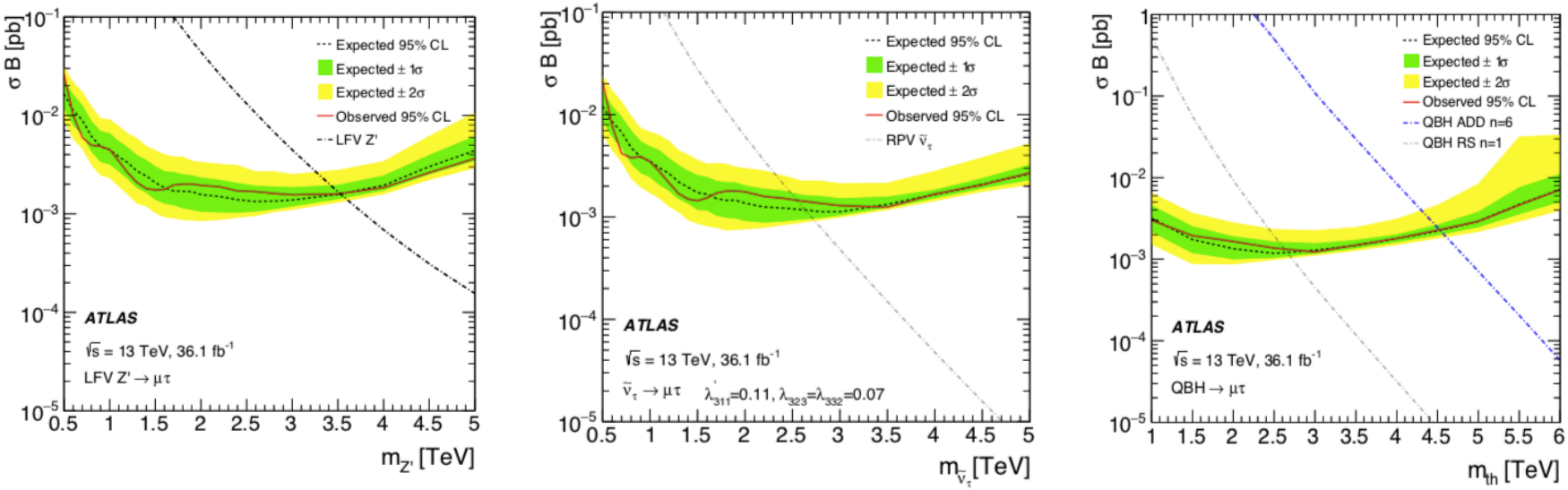
Limit setting: μτ channel



Model	Expected limit [TeV]				Observed limit [TeV]			
	$e\mu$	$e\mu$ (b-veto)	$e\tau$	$\mu\tau$	$e\mu$	$e\mu$ (b-veto)	$e\tau$	$\mu\tau$
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Summary

- Presented search for a heavy particle decaying into an eμ, eτ or μτ final state using 36.1 fb^{-1} of $\sqrt{s}$ = 13 TeV pp data collected by the ATLAS experiment at the LHC during the 2015 and 2016 run periods.

- Bayesian lower limits at 95% credibility level are set on the mass of a *Z'* vector boson, supersymmetric τ-sneutrino and the threshold mass for quantum black-hole production, reaching out to the TeV regime

- For the second round, a full run-II analysis is ongoing with almost 4 times the integrated luminosity.

BACKUP

Coupling limits Z'

- For LFV Z' and RPV SUSY $\tilde{\nu}_\tau$,$\sigma \times BR$ limits can be converted to coupling limits to facilitate comparison with low-energy precision measurements.

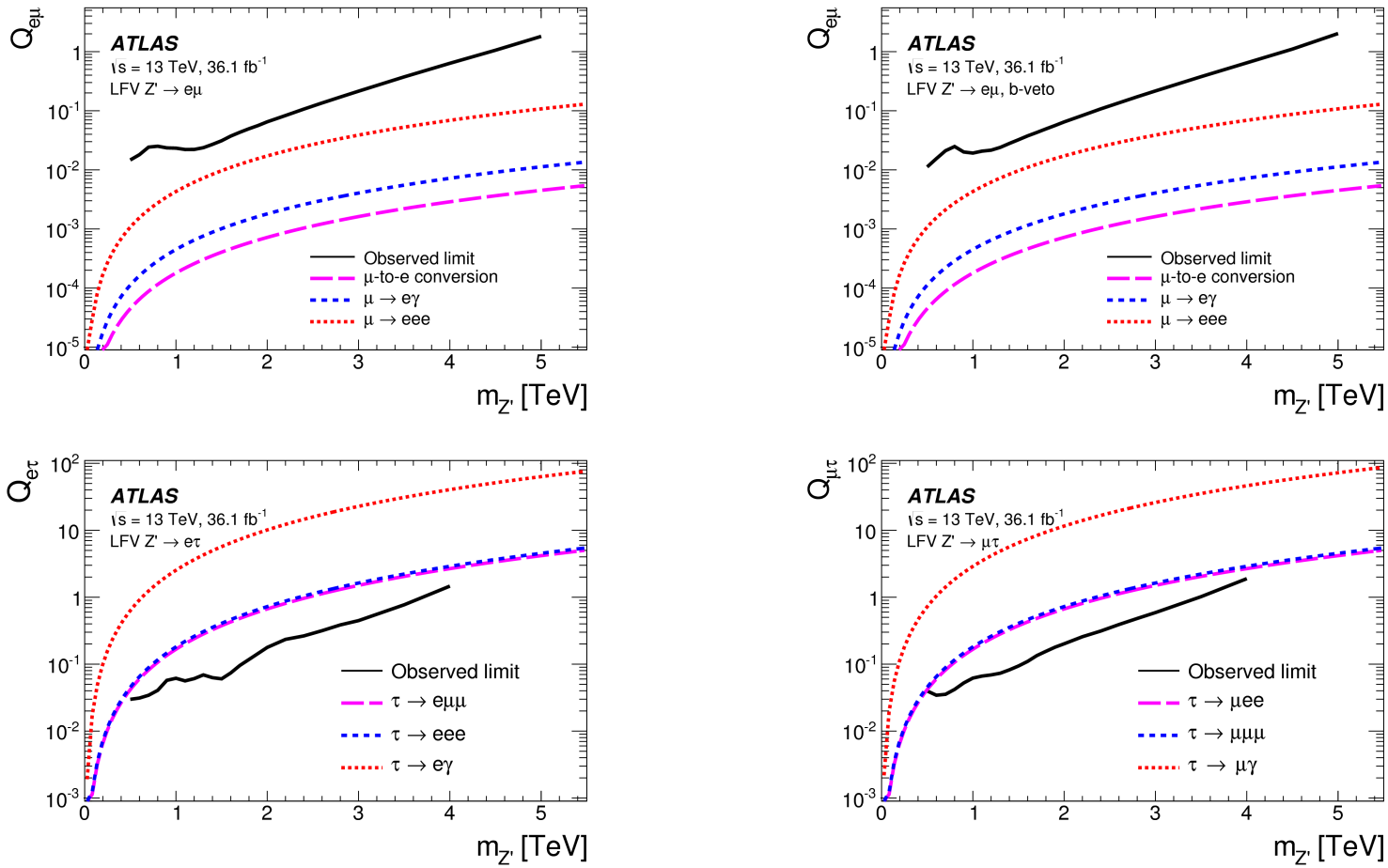
- ATLAS limits
- Assumed a Sequential Standard Model (SSM) Z' with additon LFV coupling
- LFV terms are assumed to have V-A structure as SM Z coupling to lepton pairs: $Q_{ll'}$ is the ratio of the LFV Z' coupling to ll' compare to the Z coupling to ll
- The limit on $Q_{ll'}$ is $(\sigma \times BR)_{ll'}^{\lim} / (\sigma \times BR)_{ll'}^{theory}$

- Low energy limits
- eμ channel: most significant limits are from μ to e conversion
- eτ channel: most significant limits are from $\tau \rightarrow$ eee and eμμ
- μτ channel: most significant limits are from $\tau \rightarrow$ μμμ and μee

- eμ channel: low-energy limits are significantly more stringent, but there are model dependencies (different for low-energy and ATLAS)
- eτ/μτ channels: ATLAS limits are better than those from low-energy experiments, but, as before, there are different model dependencies

Coupling limits Z’

The 95% CL upper limits on the couplings as a from the cross-section times branching ratio (solid lines) and from low-energy experiments (dashed lines).

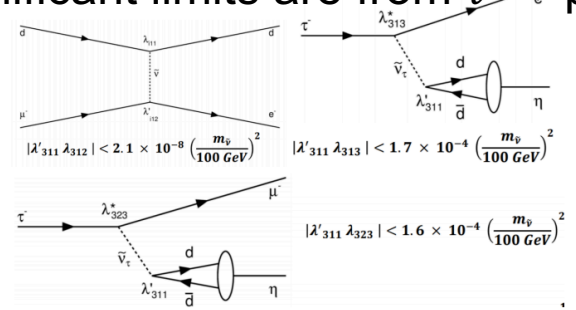


Coupling limits RPV

- For LFV Z' and RPV SUSY $\tilde{\nu}_\tau$,$\sigma \times BR$ limits can be converted to coupling limits to facilitate comparison with low-energy precision measurements.

- ATLAS limits
- Assumed only coupling to ll' and $d\bar{d}$
- $\sigma \propto |\lambda'|^2$ and $BR(\ell\ell') = \frac{\Gamma_{\ell\ell'}}{\Gamma_{\ell\ell'}+\Gamma_{d\bar{d}}} = \frac{2|\lambda|^2}{2|\lambda|^2+3|\lambda'|^2}$
- $\left(\frac{|\lambda|^2|\lambda'|^2}{2|\lambda|^2+3|\lambda'|^2}\right) < \frac{\sigma \times BR_{\mathrm{lim}}}{\sigma \times BR_{\mathrm{MC}}} \left(\frac{|\lambda|^2|\lambda'|^2}{2|\lambda|^2+3|\lambda'|^2}\right)_{\mathrm{MC}}$, where λ_{MC} = 0.07 and λ'_{MC} = 0.11

- Low energy limits
- eμ channel: most significant limits are from μ to e conversion
- eτ channel: most significant limits are from $\tau \rightarrow e\eta$
- μτ channel: most significant limits are from $\tau \rightarrow \mu\eta$



Coupling limits RPV

The 95% CL upper limits on the couplings as a from the cross-section times branching ratio limits and from low-energy experiments .