Search for lepton-flavor violation in different-flavor, high-mass final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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WARNING
STRANGE PHYSICS
AHEAD

Introduction: Motivations and BSM Models

Standard Model processes are expected to conserve lepton flavour → Therefore, a lepton-flavour violating (LFV) decay would be a clear indication of New Physics. Many extensions to the SM include LFV decays:

Quantum Black Hole

- Produce QBHs when the extradimensional Planck Scale is reached
- Quantum Gravity might violate Lepton Flavour conservation → $e\mu$, $e\tau$ and $\mu\tau$ final states

LFV Z'

- Heavy gauge boson with the same couplings as the SM Z
- Model can be extended to allow for LFV couplings ($\mathcal{Q}_{12}$, $\mathcal{Q}_{13}$ and $\mathcal{Q}_{23}$)
- Cross section takes the form $\sigma(Z' \to l_i l_j') \sim \frac{Q_{ij}^2 M_{ll'}^2}{(M_{ll'}^2 - M_{Z'}^2)^2}$

R-Parity Violating SUSY

- R-Parity introduced to avoid the decay of the proton
- SUSY particles have an R-parity of -1 while SM particles have +1
- Can violate either lepton or baryon number but not both at the same time (which would lead to proton decay)

Object and event selection

Muons

p_T, $|\eta|$: > 65 GeV, < 2.5

ID: HighPT

Track: $|d_0/\sigma_{d_0}| < 3$, $|z_0 \sin\theta| < 0.5$ mm

Only Prompt muons considered

Electrons

p_T, $|\eta|$: > 65 GeV, < 2.47

ID: Tightest possible

Track: $|d_0/\sigma_{d_0}| < 5$, $|z_0 \sin\theta| < 0.5$ mm

Only Prompt electrons considered

Taus

p_T, $|\eta|$: > 65 GeV, < 2.5

Track: 1 or 3 prong(s)

Charge: ± 1

ID: Loosest possible

Jets

p_T, $|\eta|$: > 25 GeV, < 2.5

Look for b-jets (Only $e\mu$ channel, where Top Quark background is dominant)

For electron and taus crack region ($1.37 < |\eta| < 1.52$) excluded

Selection Criteria

Primary Vertex : at least to tracks associated with $p_T > 400$ MeV

3rd Lepton Veto: events with an additional good lepton are rejected.

DeltaPhi: $\Delta\phi_{\ell\ell'} > 2.7$

Look for events with masses above 120 GeV

Use Neutrino Collinear approximation to improve resolution in the τ channels

[1] muon satisfying standard selection cuts ad exception of isolation cut
[2] electron satisfying LH-Medium and not checking the isolation requirement

SM background processes

Process	**Generator**	**Estimation method**
Drell-Yan	Powheg	MC simulation
Top Quarks	Powheg	MC simulation + Extrapolation
Di-Boson	Sherpa	MC simulation
W+jets	Sherpa	MC simulation + Data-driven
Multijets	-	Data-driven

- **Top quarks**: estimated using MC simulation plus extrapolation at high mass regime[1]
- **Fake background** (W+jets and multijets)
  - $e\mu$ channel: estimated simultaneously using the Matrix Method
  - $e\tau/\mu\tau$ channels: W+jets and multijets estimated separately

W+jets and multijets contribution estimated separately using background enriched CRs.

W+jets estimation

- evaluate tau fake rate (τ_{FR})
- select events in W+jets simulation without ID requirement applied to taus, in a W+jets control region data sample
- weight events according to τ_{FR}
- systematic uncertainties related to tau fake rate include difference between signal and control regions fake rate (MC-based) & statistical uncertainties

Multijets estimation

R1: SS pairs with non-isolated e/μ and good τ OR with non-isolated e/μ and fake τ

R2: SS pairs with isolated e/μ and good τ

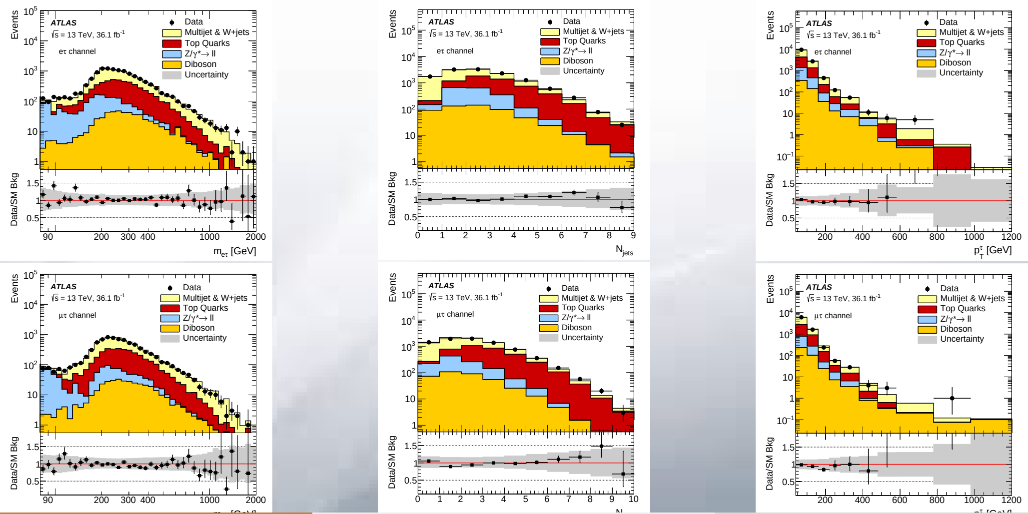
R3: OS+SS pairs with non isolated e/μ and good τ OR with non-isolated e/μ and fake τ

Shape taken from R3 and Yield $\rightarrow N_{\mathrm{Multijets}} = N^{\mathrm{R3}}_{\mathrm{Multijets}} \cdot k_{\mathrm{Multijets}} = N^{\mathrm{R3}}_{\mathrm{Multijets}} \cdot \frac{N^{\mathrm{R2}}_{\mathrm{Multijets}}}{N^{\mathrm{R1}}_{\mathrm{Multijets}}}$

$p_T^{\mathrm{lep}} < 200$ GeV in R1 and R2 is used to avoid any possible signal contamination

Background estimation: Fake background validation for $e\tau/\mu\tau$ channels

The validation of the fake background is done in a CR defined as $\Delta\phi < 2.7$ and $MET > 30$ GeV



Systematics Uncertainties

Theoretical systematics:

- PDF eigenvector variation
- Top Scale variation

Experimental uncertainties:

- Electron/Muon/Tau reconstruction efficiency
- Electron/Muon isolation efficiency
- Electron/Muon trigger efficiency
- Electron/Tau identification efficiency
- Electron/Muon scale and resolution
- Muon track-to-vertex-association
- Muon sagitta
- Tau electron-overlap

Background estimation systematics:

- tau fake rate
- $k_{\text{Multijets}}$

- Jet Jvt Efficiency
- Jet Scale/Resolution
- Jet Uncertainties
- Jet Eta Intercalibration
- b-tag Efficiency (5 systematics)
- MET resolution
- MET Scale
- Pile-up reweighting
- Luminosity uncertainty (2.1%)

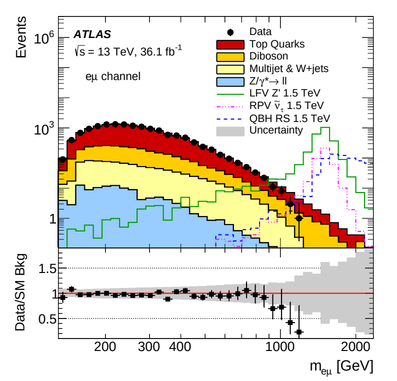
Systematics: % Summary

Source	1 TeV $e\mu$	1 TeV $e\mu$ b-jet veto	1 TeV $e\tau$	1 TeV $\mu\tau$	2 TeV $e\mu$	2 TeV $e\mu$ b-jet veto	2 TeV $e\tau$	2 TeV $\mu\tau$	3 TeV $e\mu$	3 TeV $e\mu$ b-jet veto	3 TeV $e\tau$	3 TeV $\mu\tau$
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

Systematics shown as a fraction of the total background

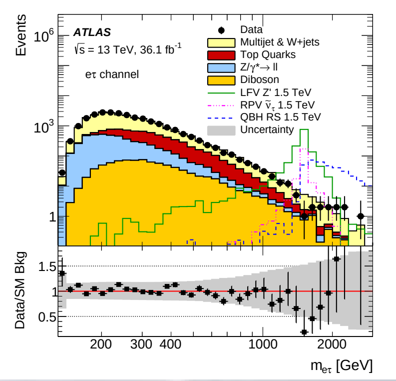
Results: $m_{\ell\ell'}$ distributions

$e\mu$ channel



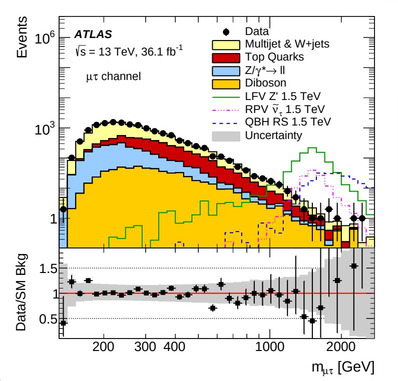
highest mass event in data at 1.23 TeV

$e\tau$ channel



highest mass event in data at 2.58 TeV

$\mu\tau$ channel

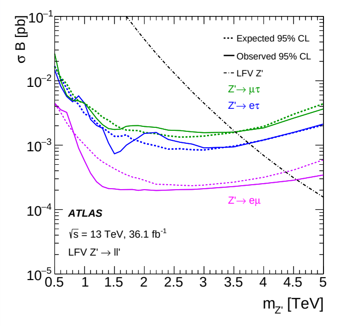


highest mass event in data at 2.39 TeV

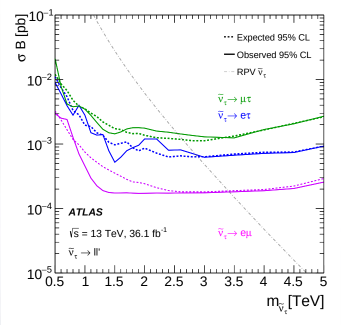
- No significant excess over the SM background expectation found
- $e\mu$ channel: deficit in the region 1.1 - 1.4 TeV of 1.8σ under background only hypothesis

Results: Cross section and mass limits

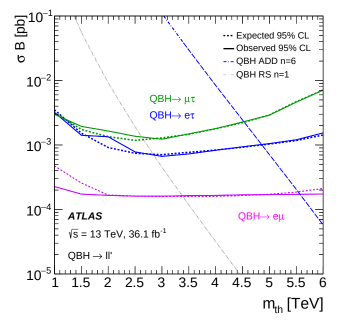
Limits extracted using Bayesian inference using the Bayesian Analysis Toolkit (BAT). Template shape method employed and sources of systematic uncertainty as nuisance parameters



LFV Z'



RPV SUSY $\tilde{\nu}_\tau$



Quantum Black Hole

- For LFV Z' and RPV SUSY, only one LFV coupling is assumed to be non-zero at each given time
- Couplings assumed for RPV SUSY: $\lambda'_{311} = 0.11$, $\lambda_{3XY} = \lambda_{3YX} = 0.07$, where X,Y=1,2,3
- Mass limits improved by $\sim$40% wrt the 3.2 fb^{-1} paper (Eur. Phys. J. C76 (2016) 541)

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.

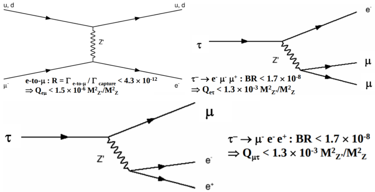
LFV Z′ couplings limits

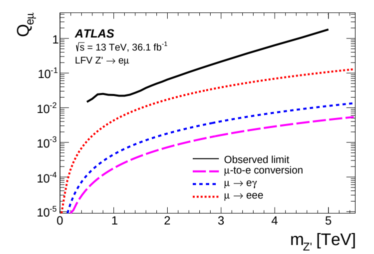
ATLAS limits

- Assumed a Sequential Standard Model (SSM) Z′ with addition LFV couplings
- LFV terms are assumed to have the V-A structure as SM Z couplings to lepton pairs: $Q_{\ell\ell'}$ is the ratio of the LFV Z′ couplings to $\ell\ell'$ compare to the Z coupling to $\ell\ell$
- The limit on $Q^2_{\ell\ell'}$ is $(\sigma \times BR)^{\mathrm{lim}}_{\ell\ell'}/(\sigma \times BR)^{\mathrm{theory}}_{\ell\ell'}$

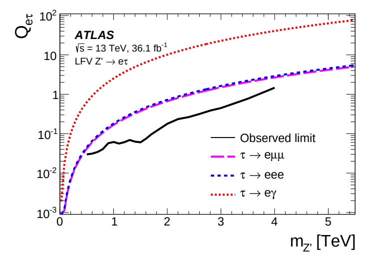
Low energy limits

- ***eμ* channel**: most significant limits are from $\mu \to e$ conversion
- ***eτ* channel**: most significant limits are from $\tau \to eee$ and $e\mu\mu$
- ***μτ* channel**: most significant limits are from $\tau \to \mu\mu\mu$ and μee

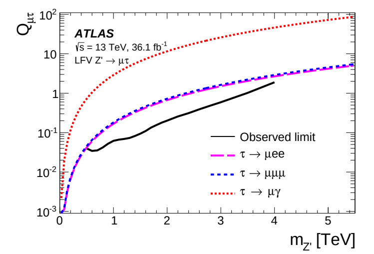




$e\mu$ channel



$e\tau$ channel



$\mu\tau$ channel

- $e\mu$ channel: low-energy limits are significantly more stringent, but there are model dependencies (different for low-energy and ATLAS)

- $e\tau/\mu\tau$ channels: ATLAS limits are better than those from low-energy experiments, but, as before, there are different model dependencies

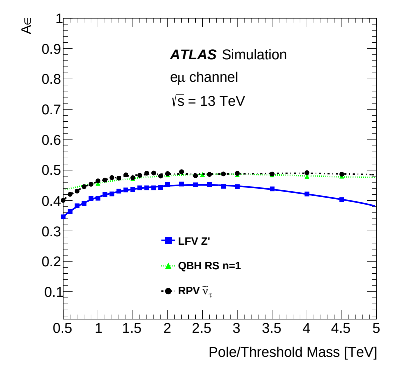
Summary

- LFV search performed with 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV, no significant deviations found over SM expectation
- Paper can be found in arXiv:1807.06573 & Phys. Rev. D 98 (2018) 092008
- Aim for a full Run-2 paper

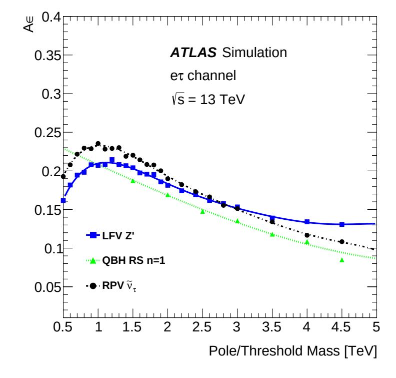
BACKUP SLIDES

Acc × Efficiency

$e\mu$ channel



$e\tau$ channel



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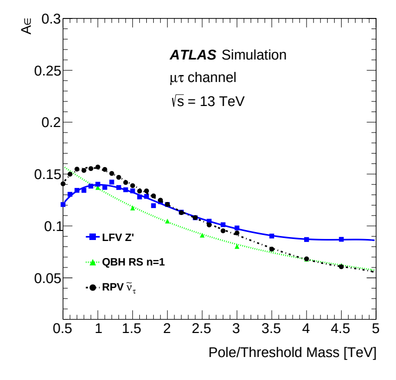
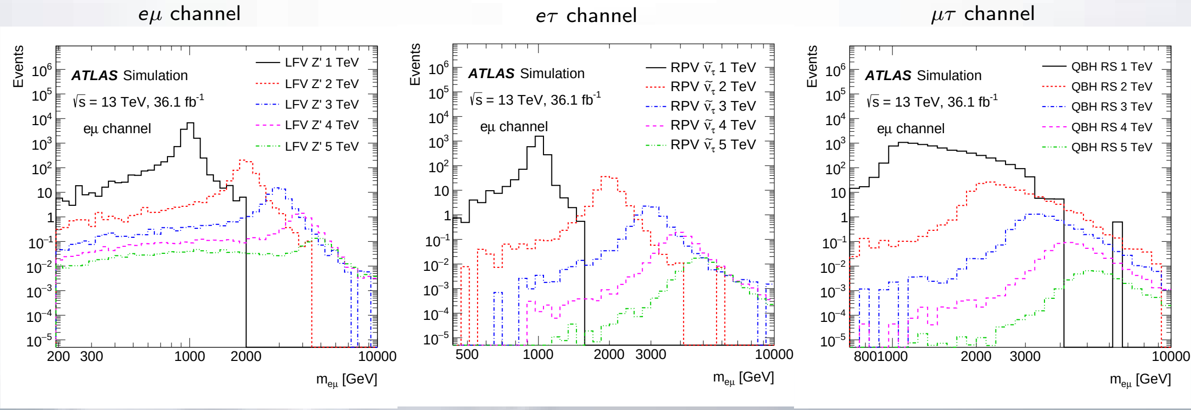
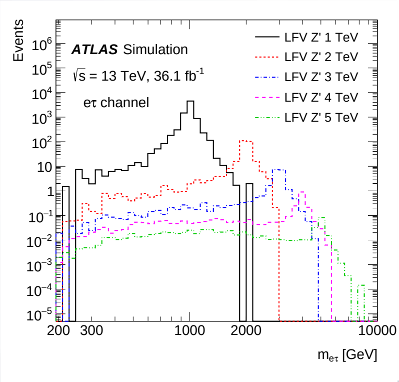


Signal Templates $e\mu$

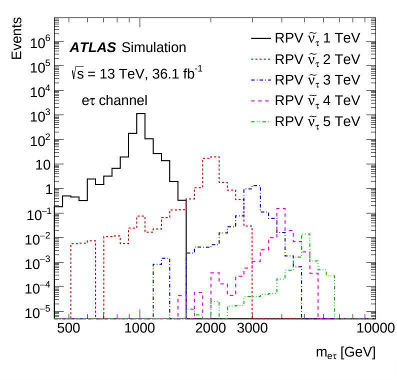


Signal Templates $e\tau$

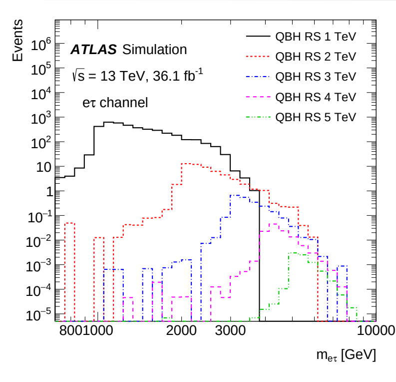
$e\mu$ channel



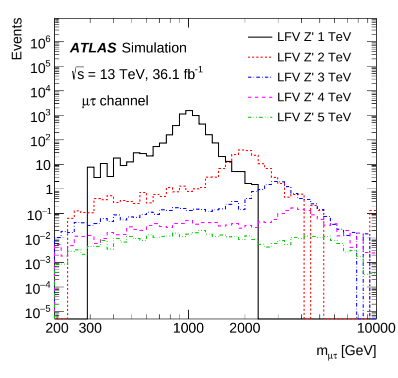
$e\tau$ channel



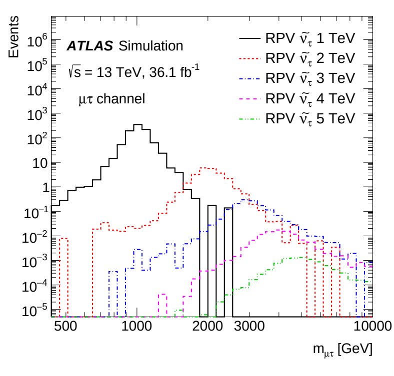
$\mu\tau$ channel



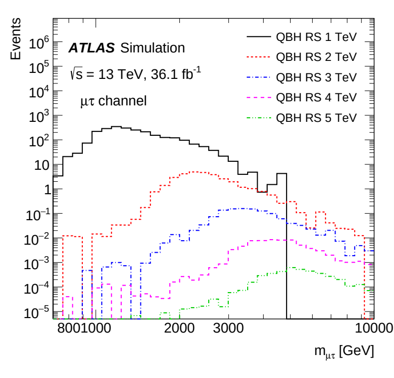
$e\mu$ channel



$e\tau$ channel



$\mu\tau$ channel



Results: Cross section and mass limits - Summary

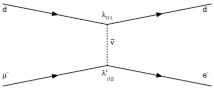
Model	Expected limit [TeV]				Observed limit [TeV]			
	$e\mu$	$e\mu$ (b-veto)	$e\tau$	$\mu\tau$	$e\mu$	$e\mu$ (b-veto)	$e\tau$	$\mu\tau$
LFV Z'	4.3	4.3	3.7	3.5	4.5	4.4	3.7	3.5
RPV SUSY $\tilde{\nu}_\tau$	3.4	3.4	2.9	2.6	3.4	3.4	2.9	2.6
QBH ADD $n = 6$	5.6	5.5	4.9	4.5	5.6	5.5	4.9	4.5
QBH RS $n = 1$	3.3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

ATLAS limits

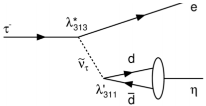
- Assumed only couplings to $\ell\ell'$ and $d\bar{d}$
- $\sigma \propto |\lambda'|^2$ and $BR(\ell\ell') = \frac{\Gamma_{\ell\ell'}}{\Gamma_{\ell\ell'}+\Gamma_{d\bar{d}}} = \frac{2|\lambda|^2}{2|\lambda|^2+3|\lambda'|^2}$
- $\left(\frac{|\lambda|^2|\lambda'|^2}{2|\lambda|^2+3|\lambda'|^2}\right) < \frac{\sigma\times BR_{\rm lim}}{\sigma\times BR_{\rm MC}} \left(\frac{|\lambda|^2|\lambda'|^2}{2|\lambda|^2+3|\lambda'|^2}\right)_{\rm MC}$ where $\lambda_{\rm MC} = 0.07$ and $\lambda'_{\rm MC} = 0.11$

Low energy limits

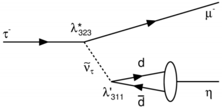
- ***eμ* channel**: most significant limits are from $\mu \to e$ conversion
- ***eτ* channel**: most significant limits are from $\tau \to e\eta$
- ***μτ* channel**: most significant limits are from $\tau \to \mu\eta$



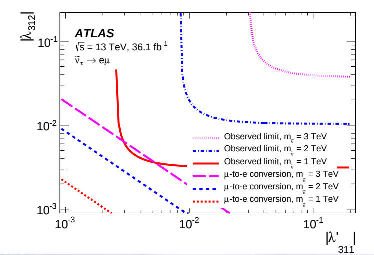
$|\lambda'_{311}\lambda_{312}| < 2.1 \times 10^{-8}\left(\frac{m_{\tilde{\nu}}}{100\ GeV}\right)^2$



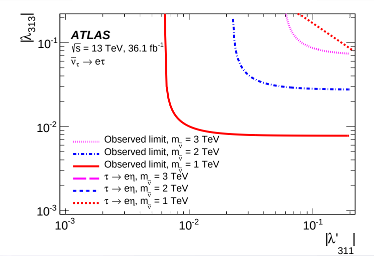
$|\lambda'_{311}\lambda_{313}| < 1.7 \times 10^{-4}\left(\frac{m_{\tilde{\nu}}}{100\ GeV}\right)^2$



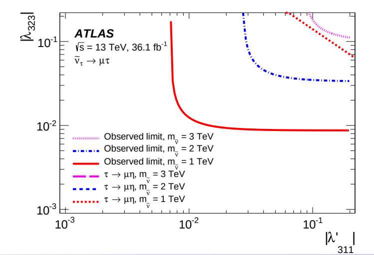
$|\lambda'_{311}\lambda_{323}| < 1.6 \times 10^{-4}\left(\frac{m_{\tilde{\nu}}}{100\ GeV}\right)^2$



$e\mu$ channel



$e\tau$ channel



$\mu\tau$ channel

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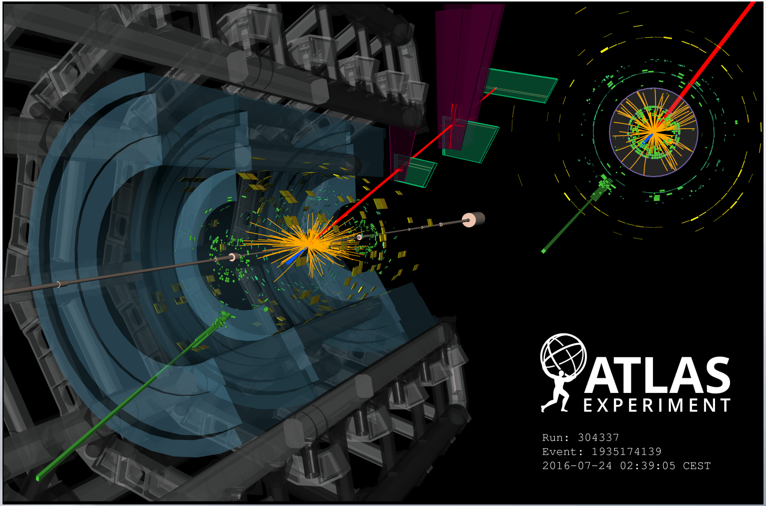
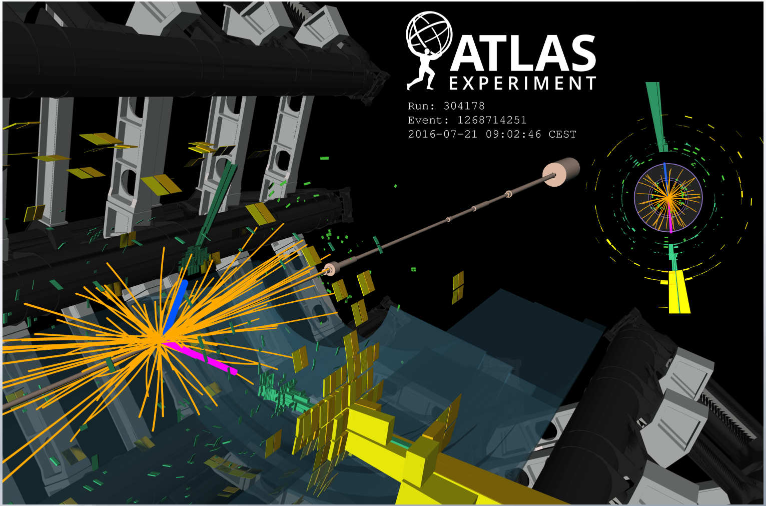
Event display: $e\mu$ channel



Event display: $e\tau$ channel



Event display: $\mu\tau$ channel