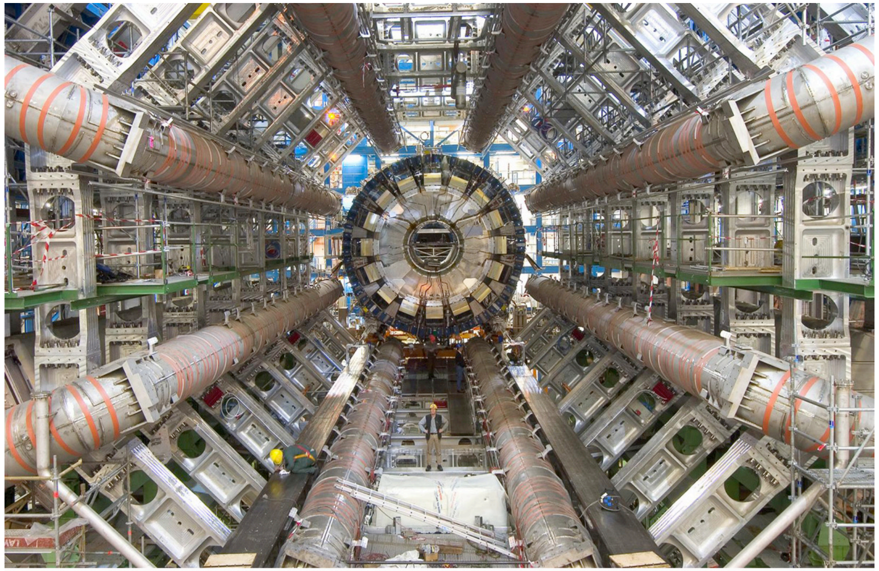


Search for Lepton Flavor Violation in di-lepton channel at ATLAS

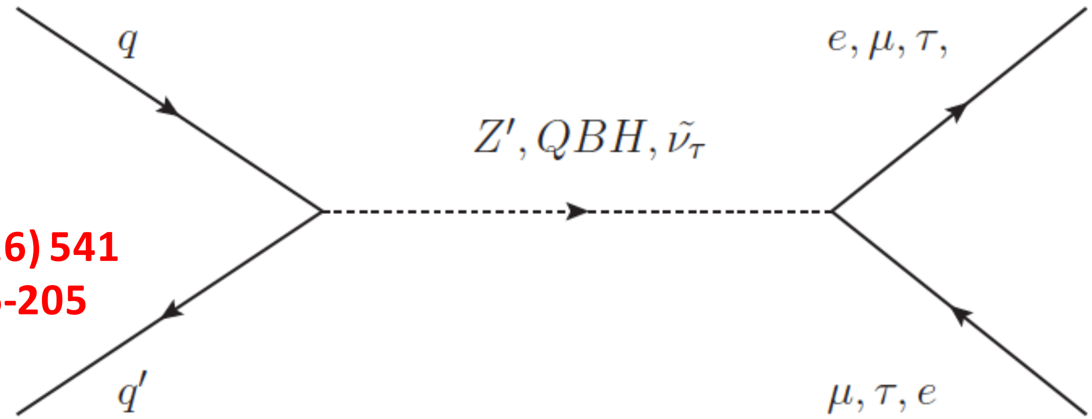
Jun Guo

Shanghai Jiao Tong University

Peking University, Beijing, China, 12/18/2016

Why search for Lepton-Flavour Violation?

- Standard Model processes are expected to conserve lepton flavour. Therefore, a Lepton-Flavour Violating (LFV) decay would be a clear indication of New Physics. LFV is allowed in many extensions of the SM:
  - Predicted by RPV SUSY(τ-sneutrino), QBH and Z', etc.
  - Clear detector signature and low SM background: Drell-Yan process largely suppressed



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ATL-COM-PHYS-2016-205

USTC and SJTU are leading this analysis

Samples

- Data: 3.2fb^{-1}, 13 TeV, collected in 2015

- Background components:
  - MC based:
    - Drell-Yan
    - Top-quark related(pair and single top production)
    - Diboson(WW, WZ and ZZ)
  - Data-driven
    - W+jets
    - QCD Multi-jet

- Signal:
  - Z', ν_τ, QBH

Object Selection

Tau Selection

- $p_T > 40$ GeV & $|\eta| < 2.47$ exc. crack region
- Electron-Muon Overlap removal with tight and loose objects
- 1/3 prong
- $|q|=1$
- JetIDBDTLOOSE

Electron Selection

- $p_T > 65$ GeV & $|\eta| < 2.47$ exc. crack region
- LHTight
- Loose Isolation
- Inner tracking requirements

Muon Selection

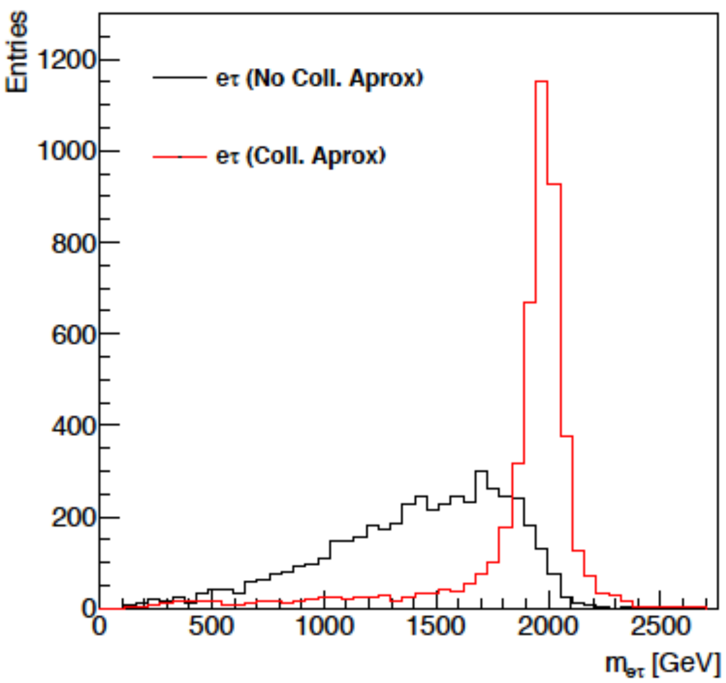
- $p_T > 65$ GeV
- Use only combined muons
- LooseTrackOnly Isolation
- MuonSelectorTools passedHighPtCuts
- Inner tracking requirements

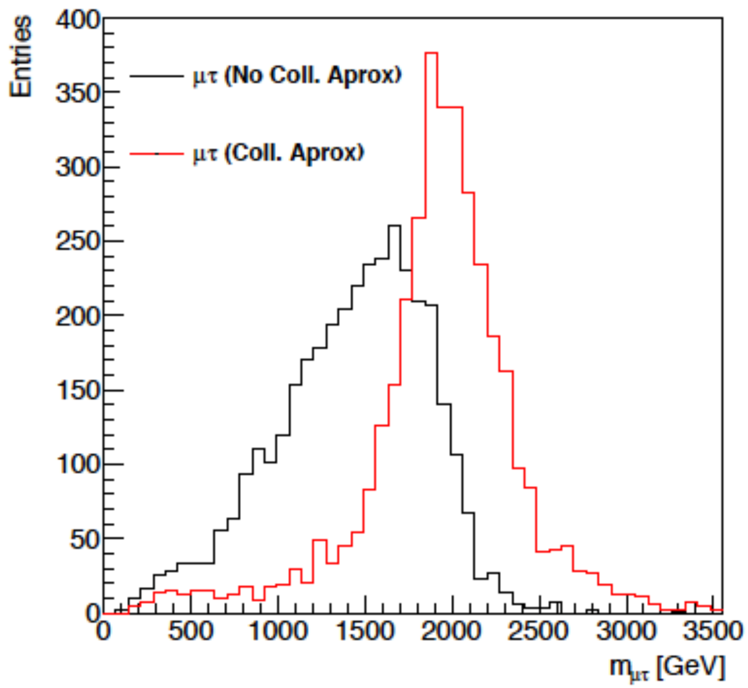
Event Selection

- HLT_mu50 || HLT_e60_lhmedium || HLT_e120_lhloose (no tau trigger used)
- 3rd lepton veto
    i. Check number of good leptons
    ii. Veto events with $N_e = 1$ & $N_\mu = 1$ & $N_\tau = 1$
    iii. Veto events with $N_e > 1 \;||\; N_\mu > 1 \;||\; N_\tau > 1$
    iv. Select channel according to leptons available, but still cut for additional loose leptons
- One trigger matched lepton
- Back-to-back leptons ($\Delta\phi > 2.7$)
- No Opp charge requirement

Neutrino 4-vector determination for hadronic τ's

- τ decay final states are heavily boosted due to large resonance mass
- Neutrino and the resulting jet are approximately collinear
- $\eta_\nu = \eta_{jet}$ approximation leads to improved peak resolution (already used for 8 TeV publication)



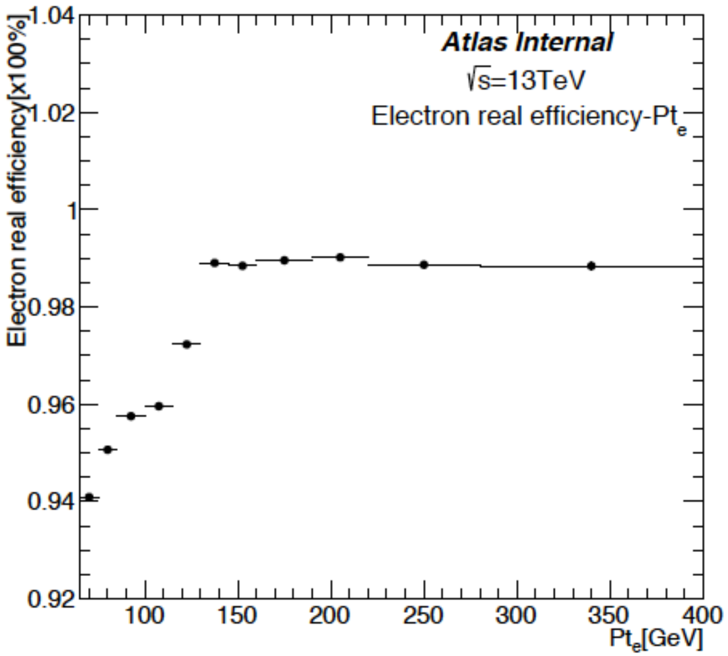


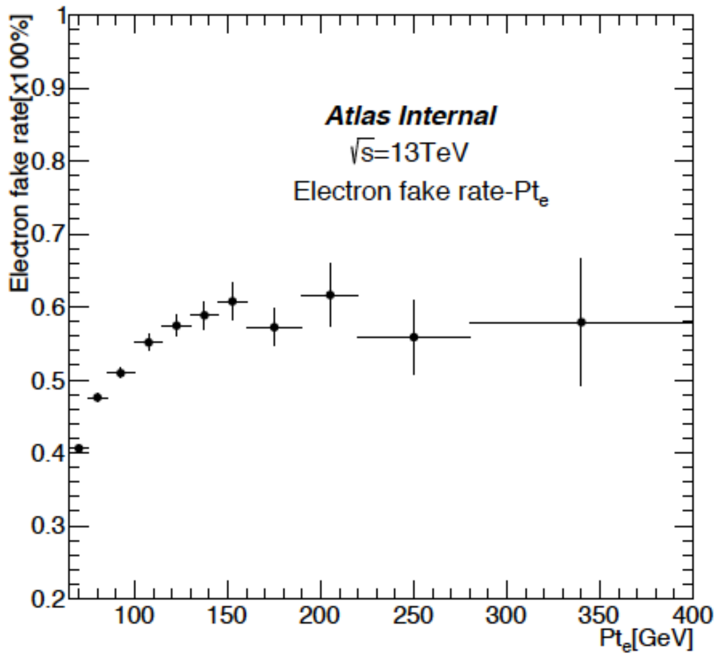
Data-driven Estimation: Matrix method (eμ channel)

- Main source: real muon + fake electron

- Two data samples used:
  - Loose: the electron passed the loose cut and the muon passed the tight cut(N_{LT})
  - Tight: both the electron and the muon pass the tight cut (N_{TT})

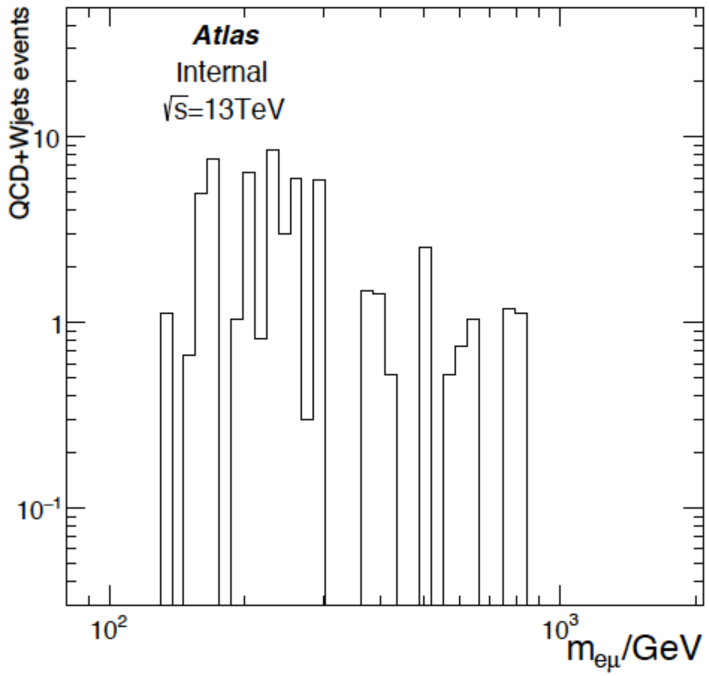
$$\begin{bmatrix} N_{\mathrm{TT}} \\ N_{\mathrm{LT}} \end{bmatrix} = \begin{bmatrix} r_e & f_e \\ 1 & 1 \end{bmatrix} \begin{bmatrix} N_{\mathrm{RR}} \\ N_{\mathrm{FR}} \end{bmatrix}$$

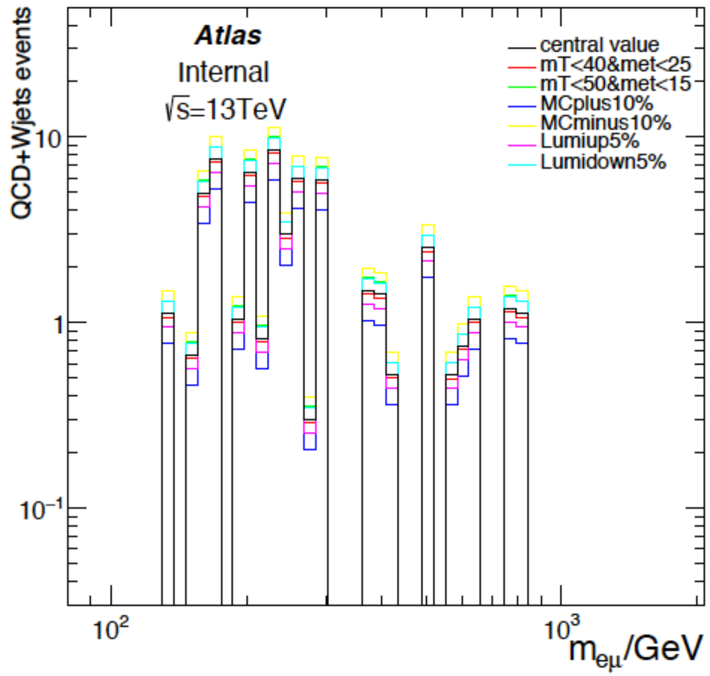




Data-driven Estimation(eμ channel)

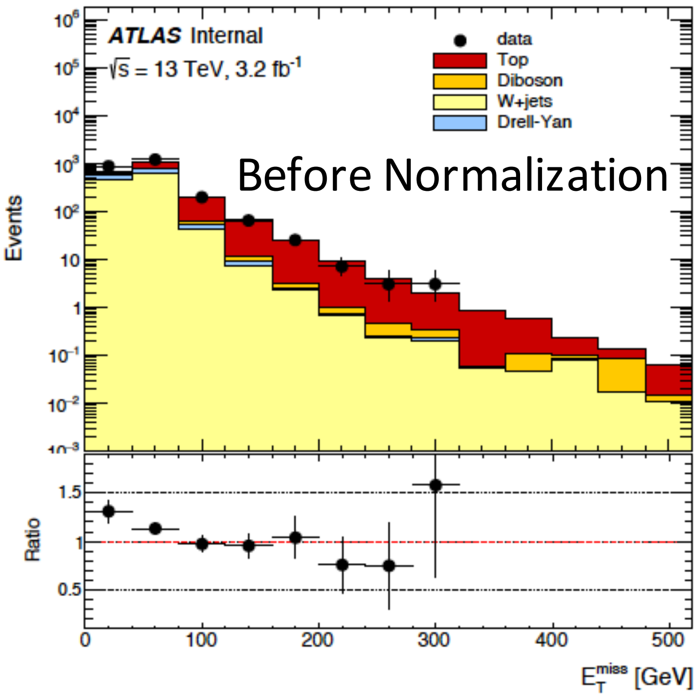
- Applied a smoothing procedure to show the background contribution in the final dilepton invariant mass plots
- Associated systematic uncertainties
  - Variation of definition of control region
  - MC to data discrepancy for W+jets
  - Lumi

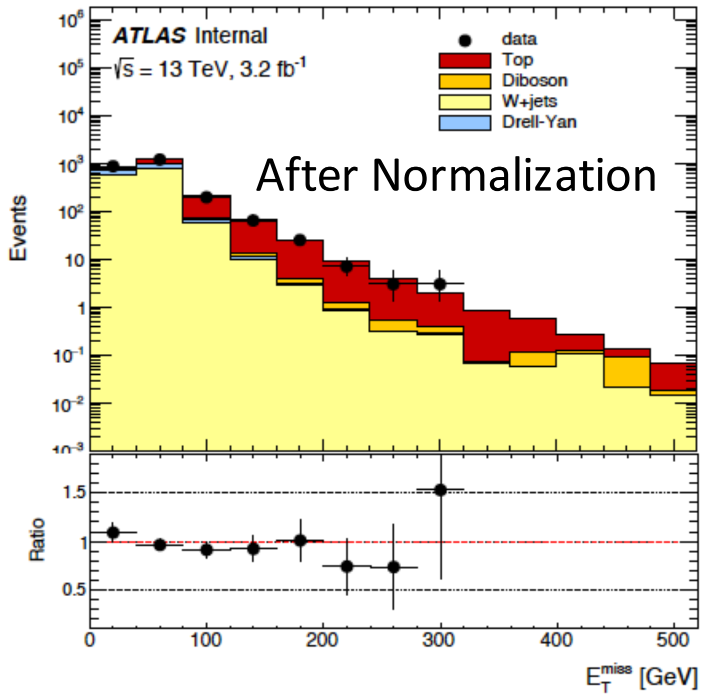




W+jets Estimation(eτ, μτ channel)

- Contribution from fake τ's is generally not very well modelled in simulation.
- The τ fake rate is estimated and used to weight simulated W+jets events to get W+jets contribution in control region. It is then scaled to signal region
- A normalisation factor for the W+jets background is obtained by taking ratio between the above expected number of W+jets and raw W+jets MC prediction





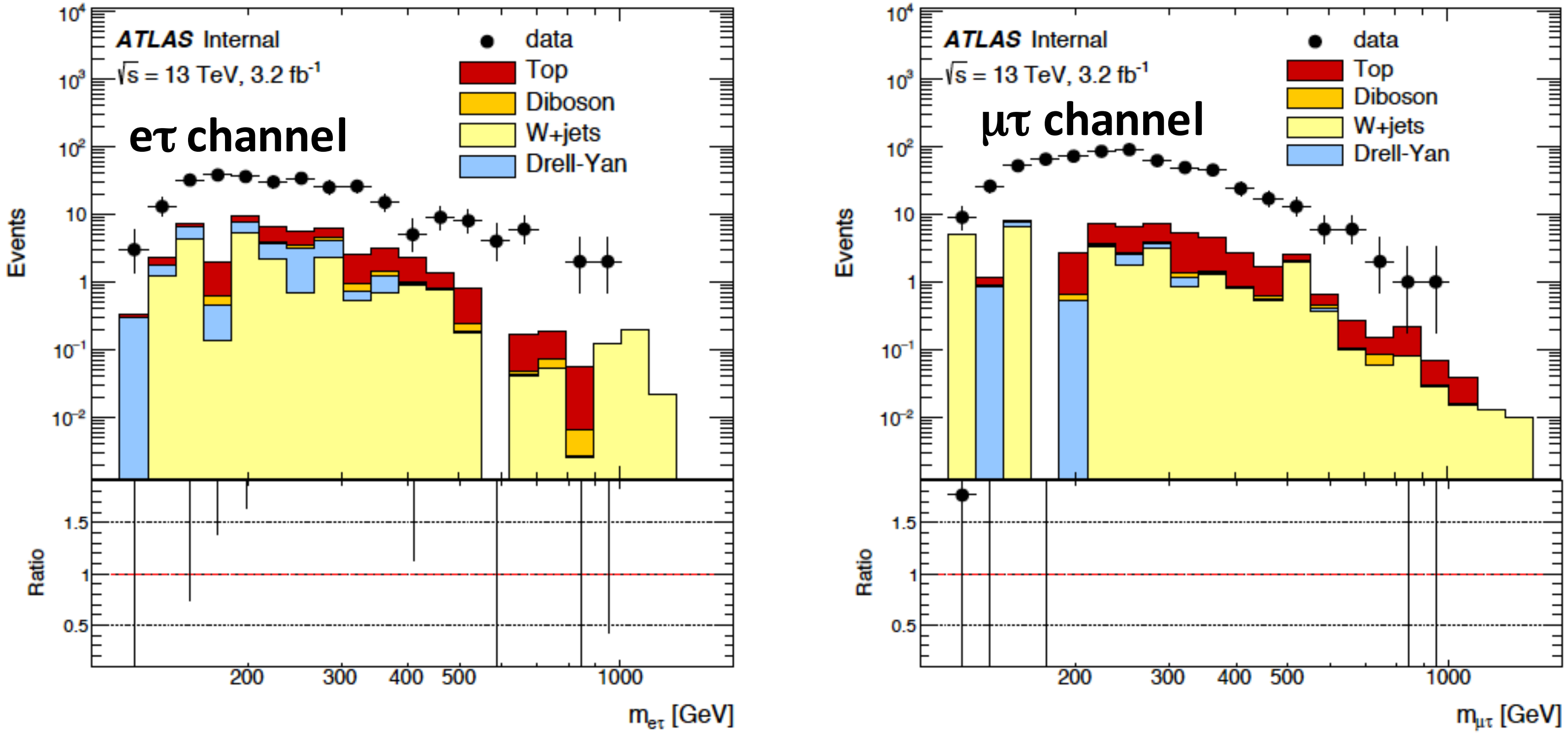
QCD Estimation($e\tau$, $\mu\tau$ channel)

Region 1: Same-sign pairs with non-isolated electrons/muons (lepton p_T < 200 GeV)

Region 2: Same-sign pairs with isolated electrons/muons (lepton $p_T <$ 200 GeV)

Region 3: Opp+Same sign pairs with non-isolated electrons/muons

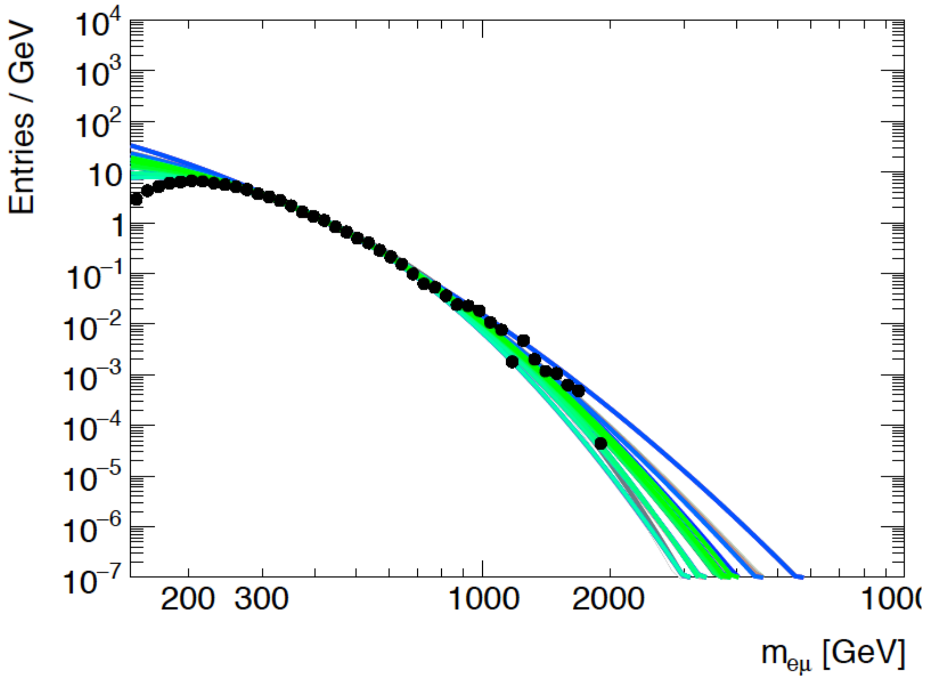
- Obtain QCD shape from region 3 (orthogonal to SR) by taking $N_{QCD}^{Reg} = N_{Data}^{Reg} - N_{Reg}^{AllMC}$
- Normalise using regions 1 and 2: $K_{QCD} = N_{QCD}^{Reg2}/N_{QCD}^{Reg1}$

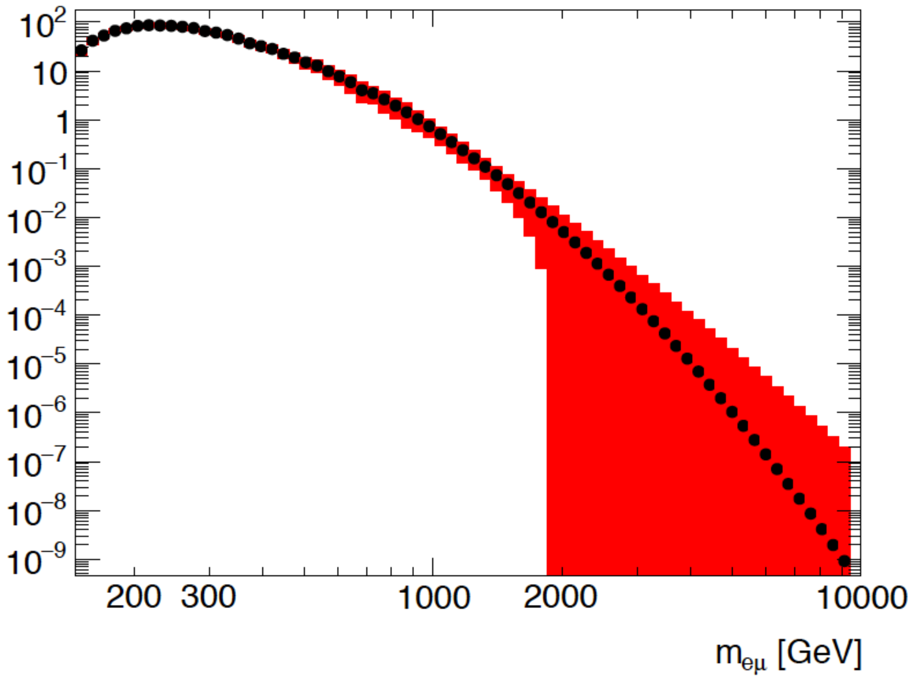


Extrapolation of MC bkgd

- MC samples for pair- and single-top processes are statistically limited beyond 1.0 TeV in $m_{ll'}$. They are added and extrapolated together.
- Two function forms are used; their results are combined together

$$e^{-a} \cdot m_{\ell\ell'}^{b} \cdot m_{\ell\ell'}^{c\cdot\ln(m_{\ell\ell'})} \quad \text{and} \quad \frac{a}{(m_{\ell\ell'}+b)^c}$$

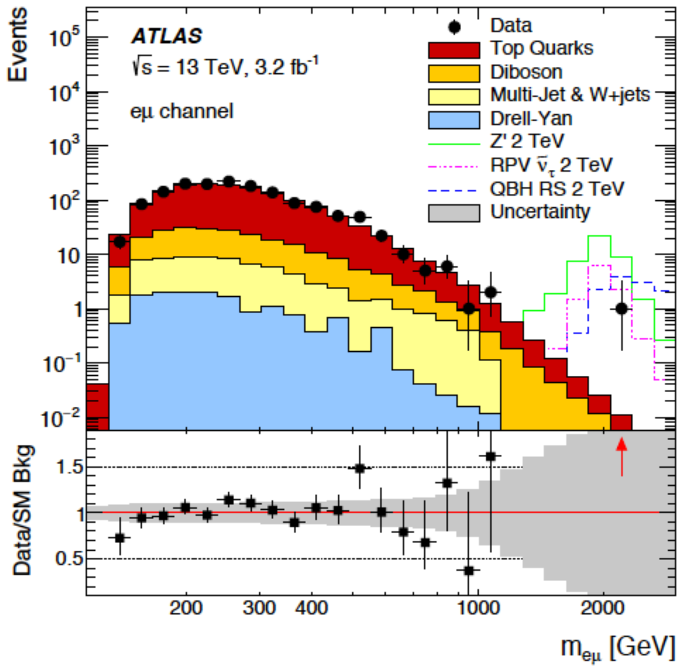




Systematics

Source	$m_{\ell\ell'} = 1$ TeV			$m_{\ell\ell'} = 2$ TeV			$m_{\ell\ell'} = 3$ TeV		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
PDF uncertainty	17%	15%	15%	35%	38%	35%	70%	75%	70%
Luminosity	5%	5%	5%	5%	5%	5%	5%	5%	5%
Statistical	18%	11%	15%	80%	27%	27%	120%	28%	30%
Reducible background	5%	29%	40%	5%	35%	75%	5%	45%	85%
Top quark production modelling	5%	3%	4%	12%	4%	5%	15%	10%	8%
Electron trigger efficiency	1%	1%	N/A	1%	1%	N/A	1%	1%	N/A
Electron identification	2%	2%	N/A	2%	2%	N/A	2%	2%	N/A
Electron energy scale and resolution	3%	3%	N/A	3%	3%	N/A	3%	3%	N/A
Muon reconstruction efficiency	2%	N/A	2%	4%	N/A	4%	6%	N/A	6%
Muon scale and resolution	4%	N/A	4%	12%	N/A	12%	20%	N/A	20%
Muon trigger efficiency	2%	N/A	2%	2%	N/A	2%	2%	N/A	2%
Tau identification	N/A	4%	4%	N/A	5%	5%	N/A	6%	6%
Tau reconstruction	N/A	3%	3%	N/A	4%	4%	N/A	4%	4%
Tau energy calibrations	N/A	2%	2%	N/A	3%	3%	N/A	4%	4%
Total	27%	35%	44%	90%	59%	90%	140%	90%	120%
SM Background in $m_{\ell\ell'} \pm 0.1 \cdot m_{\ell\ell'}$	3.9	11.9	11.4	0.09	0.55	0.49	0.002	0.014	0.017

Invariant mass of eμ

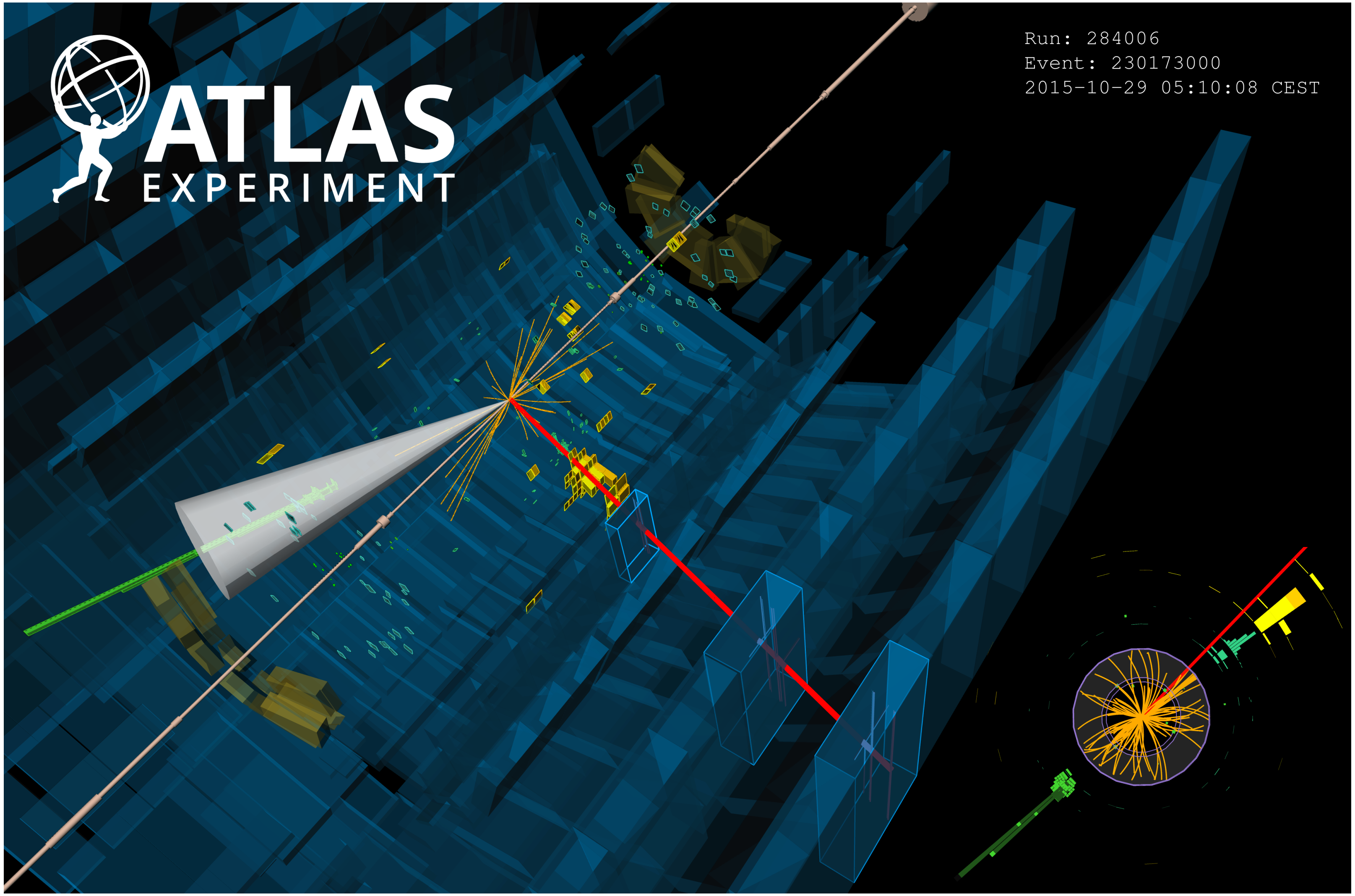


No signal observed

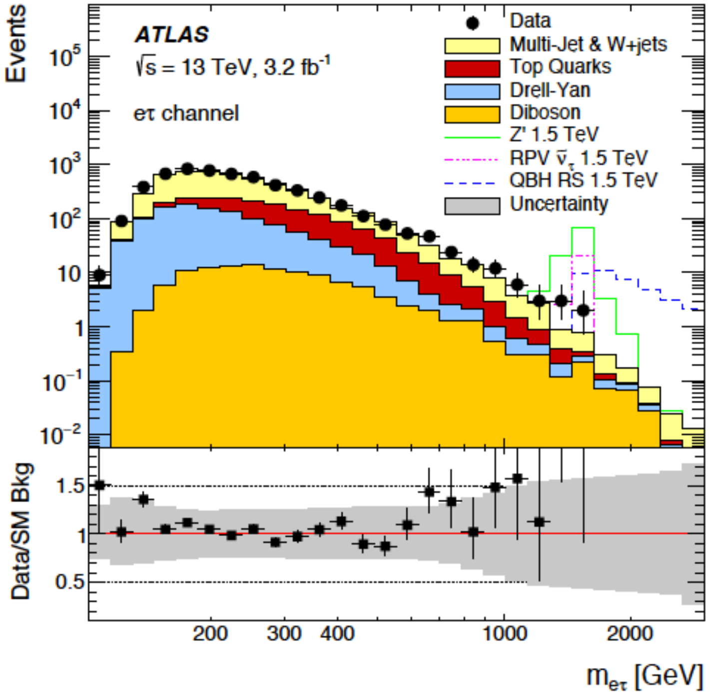
Process	$m_{e\mu} < 600$ GeV	$m_{e\mu} > 600$ GeV
Top quark	1190 ± 140	22 ± 5
Diboson	159 ± 17	4.9 ± 0.9
Multi-jet and W+jets	55 ± 11	2.7 ± 1.7
$Z/\gamma^* \rightarrow \ell\ell$	14.5 ± 2.0	0.18 ± 0.04
Total SM background	1410 ± 150	30 ± 7
SM+Z' ($M_{Z'} = 2$ TeV)	-	75 ± 13
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 2$ TeV)	-	40 ± 8
SM+QBH RS $n = 1$ ($M_{\rm th} = 2$ TeV)	-	44 ± 9
Data	1463	25

$m_{e\mu}$=2.088 TeV

$m_{\ell\ell'}$	Run	Event	E_T^{miss}	Lep ID	p_{T_ℓ}	η_ℓ	ϕ_ℓ
2088.7	284006	230173000	72	-13	617	0.29	0.4
				11	1164	1.64	-2.8



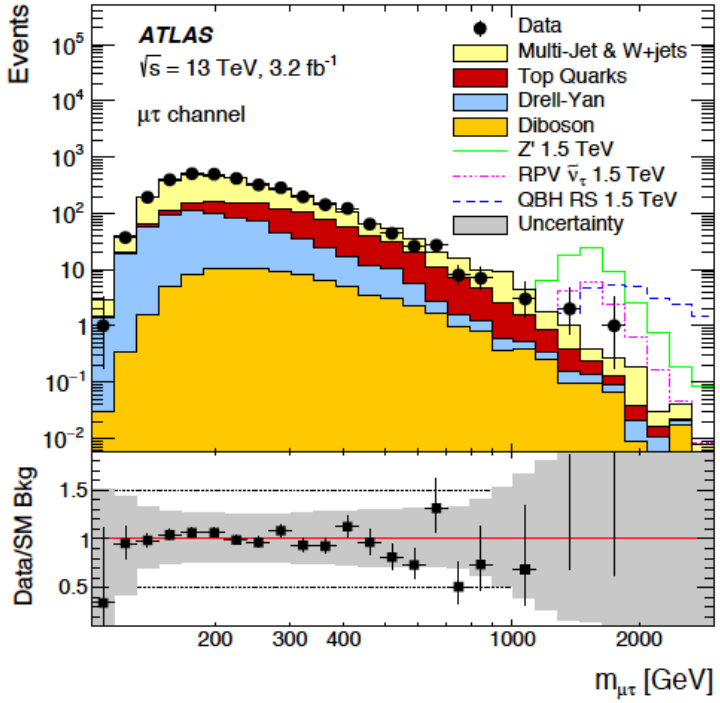
Invariant mass of eτ



No signal observed

Process	$m_{e\tau} < 600$ GeV	$m_{e\tau} > 600$ GeV
Top quark	790 ± 190	25 ± 9
Diboson	109 ± 26	6.2 ± 1.9
Multi-jet and W+jets	3200 ± 800	45 ± 14
$Z/\gamma^* \to \ell\ell$	1030 ± 240	5.2 ± 1.4
Total SM background	5200 ± 1300	81 ± 25
SM+Z' ($M_{Z'}$ = 1.5 TeV)	-	185 ± 34
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau}$ = 1.5 TeV)	-	105 ± 27
SM+QBH RS $n = 1$ (M_{th} = 1.5 TeV)	-	122 ± 28
Data	5416	111

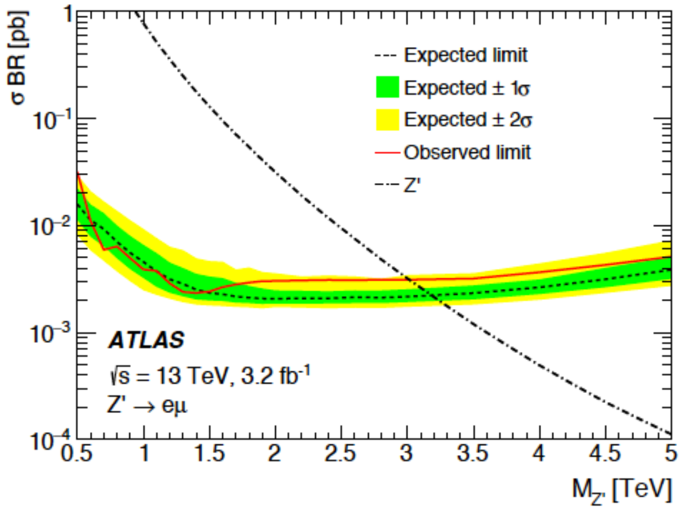
Invariant mass of $\mu\tau$



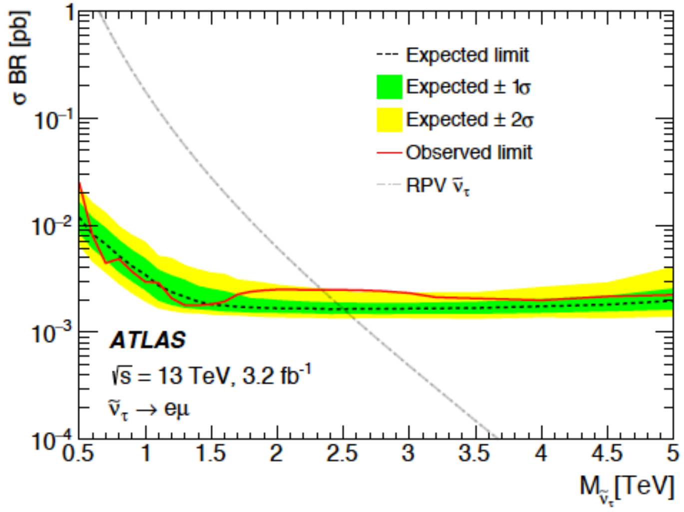
No signal observed

Process	$m_{\mu\tau} < 600$ GeV	$m_{\mu\tau} > 600$ GeV
Top quark	580 ± 140	21 ± 7
Diboson	84 ± 20	4.8 ± 1.4
Multi-jet and W+jets	1900 ± 500	34 ± 12
$Z/\gamma^* \rightarrow \ell\ell$	610 ± 140	2.6 ± 0.7
Total SM background	3200 ± 800	63 ± 20
SM+Z' ($M_{Z'}$ = 1.5 TeV)	-	130 ± 28
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau}$ = 1.5 TeV)	-	78 ± 22
SM+QBH RS $n = 1$ (M_{th} = 1.5 TeV)	-	90 ± 23
Data	3239	48

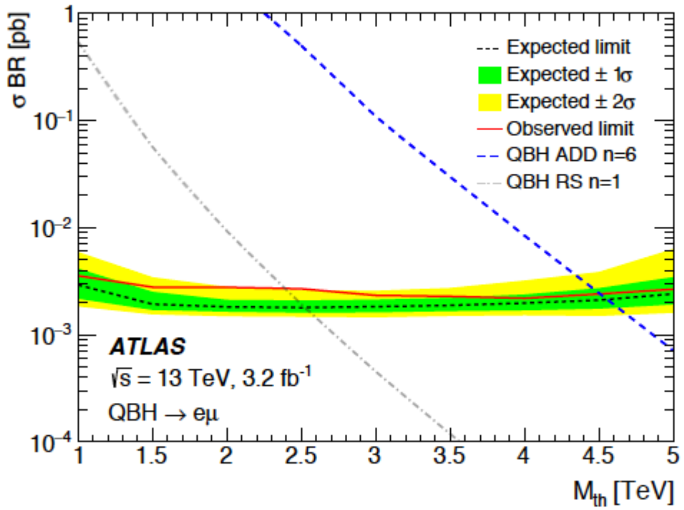
Limit Setting of eμ Channel



(a) *Z′*

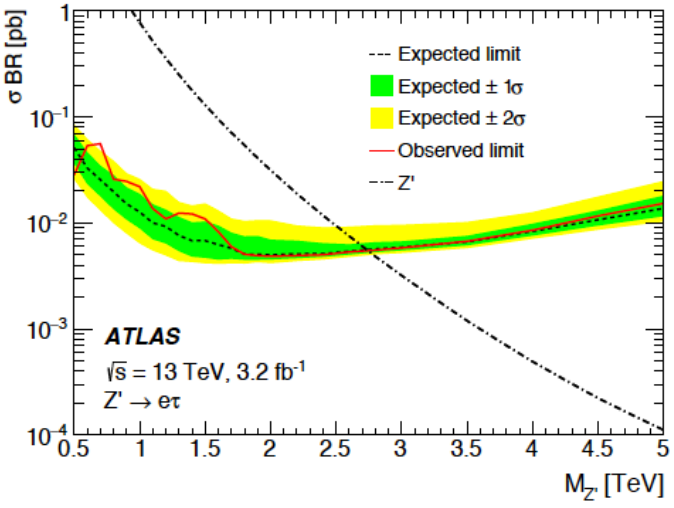


(b) RPV SUSY

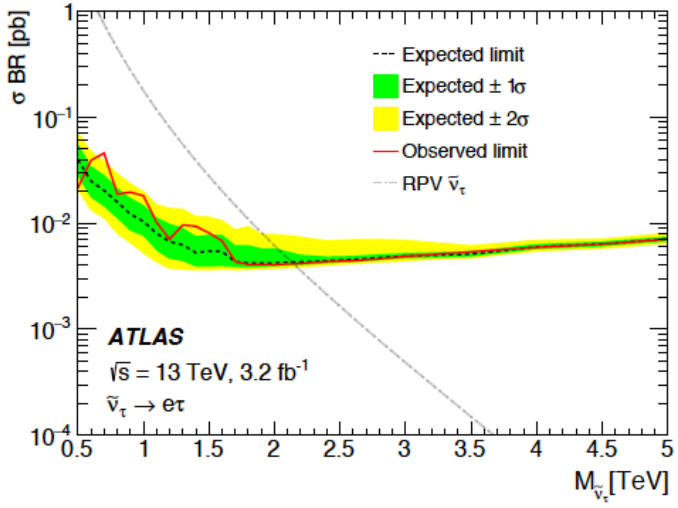


(c) QBH

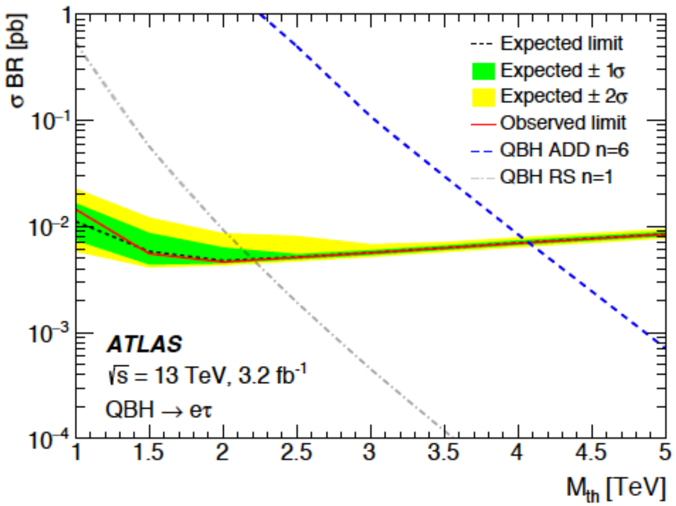
Limit Setting of eτ Channel



(a) Z'

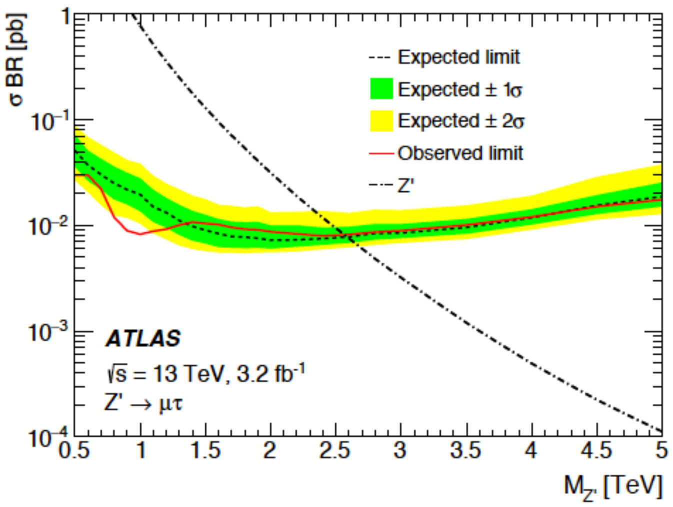


(b) RPV SUSY

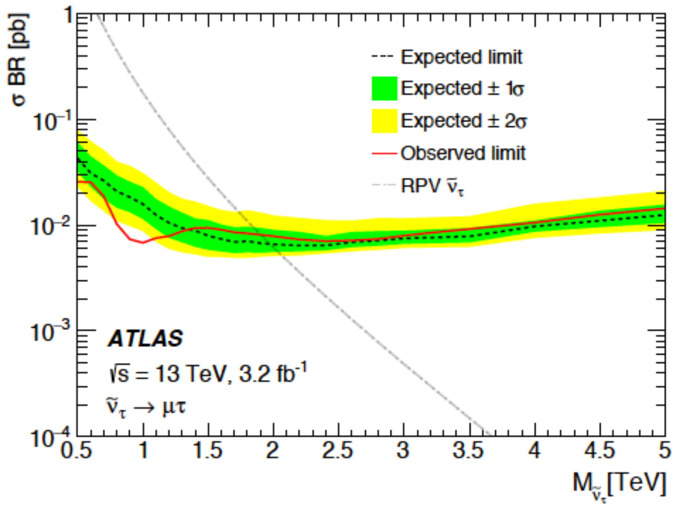


(c) QBH

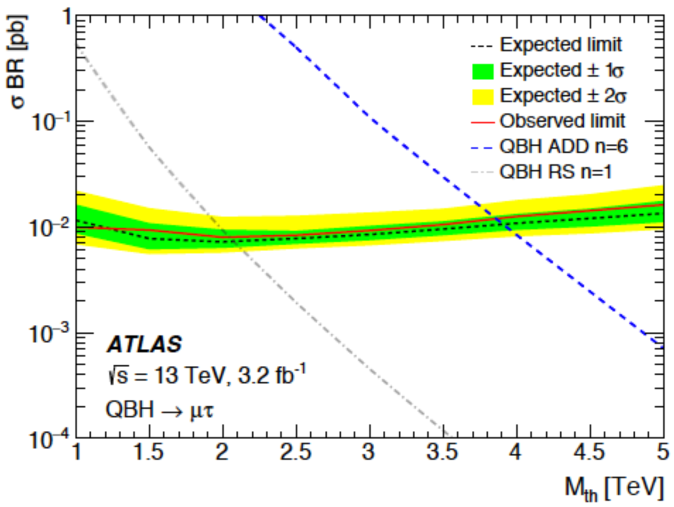
Limit Setting of μτ Channel



(a) Z'



(b) RPV SUSY



(c) QBH

Limit Summary

Model	Expected Limit [TeV]			Observed Limit [TeV]		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
Z'	3.2	2.7	2.6	3.0	2.7	2.6
RPV SUSY $\tilde{\nu}_\tau$	2.5	2.1	2.0	2.3	2.2	1.9
QBH ADD $n = 6$	4.6	4.1	3.9	4.5	4.1	3.9
QBH RS $n = 1$	2.5	2.2	2.1	2.4	2.2	2.1

Summary

- Search for Lepton-Flavor Violation was carried out in dilepton channel at ATLAS in Run II, using 13 TeV data collected in 2015
- Strategies were optimized accordingly for different decay channels. ATLAS result on LFV search has been submitted to EPJC recently. No LFV has been observed so far
- 13 TeV data in 2016 is being analyzed. Stay tuned for more exciting physics!

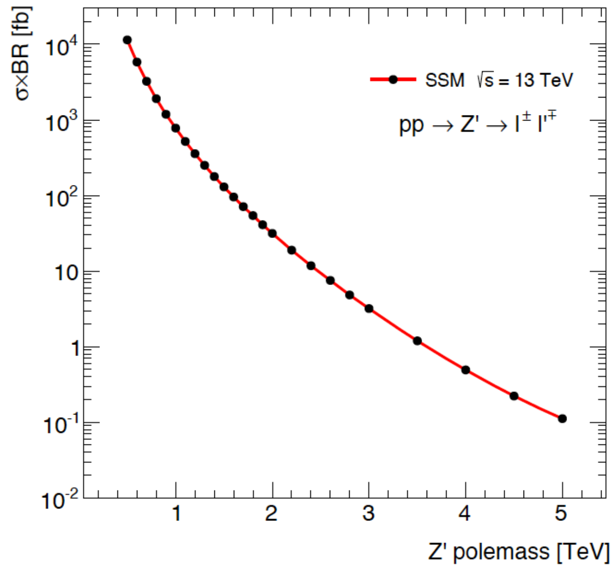
backup

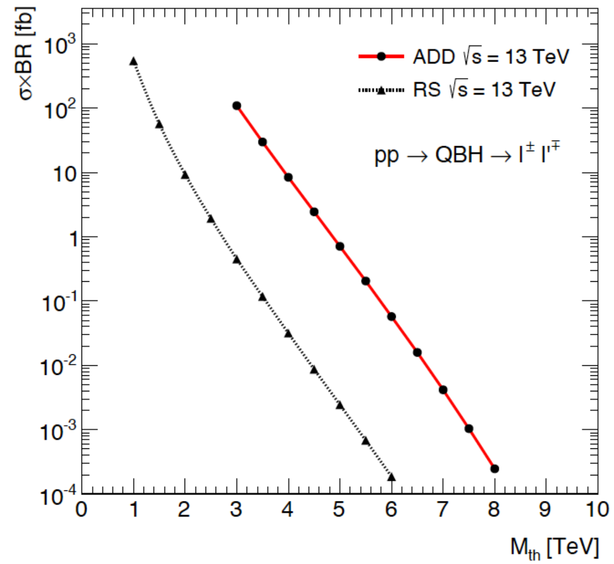
Analysis Strategy

- Aim to find excess in the dilepton invariant mass spectrum from SM expectation
- Select events from data with exactly two different flavour leptons
- Look for deviations from SM expectation in the $m_{e\mu}/m_{e\tau}/m_{\mu\tau}$ spectrum. In case deviations are found, quantify them
- If no significant deviations are found, proceed to extract limits based on BSM models

Beyond-SM Models

- LFV Z':
  - Heavy gauge boson with the same quark couplings as the SM Z
  - LFV couplings are introduced: (Q_{12}, Q_{13} and Q_{23})
- RPV 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)
- QBH:
  - Produce QBHs when the extra dimensional Planck Scale is reached
  - Quantum Gravity might violate Lepton Flavour conservation $e\mu$, $e\tau$ and $\mu\tau$ states





SM backgrounds and Signal

Background	Estimation Method	Generator	Available?
$DY \rightarrow ll$	MC Simulation	Pythia	Yes
$t\bar{t}$	MC Simulation	Powheg	Yes
Single Top	MC Simulation	Powheg	Yes
Diboson	MC Simulation	Sherpa	Yes
W+Jets	MC+Data-driven	Powheg	Yes
Multi-jet	Data-driven	-	Yes

Signal process	PDF	Generator	Available?
QBH	CTEQ6L1	QBH	Yes
Z'	NNPDF2.3	Pythia8	Yes
$\tilde{\nu}_\tau$	NNPDF2.3	Madgraph	Yes

QCD & W+jets Estimation(eτ, μτ channel)

Define control regions for each background:

- W+Jets:
  - MET> 30 & Lepton $p_T < 150$ GeV
  - Take shape from MC and scale according to CR:
    $N^{\mathrm{SR}}_{\mathrm{W+jets}} = (N^{\mathrm{CR}}_{\mathrm{Data}} - N^{\mathrm{CR}}_{\mathrm{Others}}) \cdot K_{\mathrm{W+jets}}$
    where $K_{\mathrm{W+jets}} = \frac{N^{\mathrm{SR}}_{\mathrm{W+jets\,MC}}}{N^{\mathrm{CR}}_{\mathrm{W+jets\,MC}}}$
- QCD Multijet estimation:

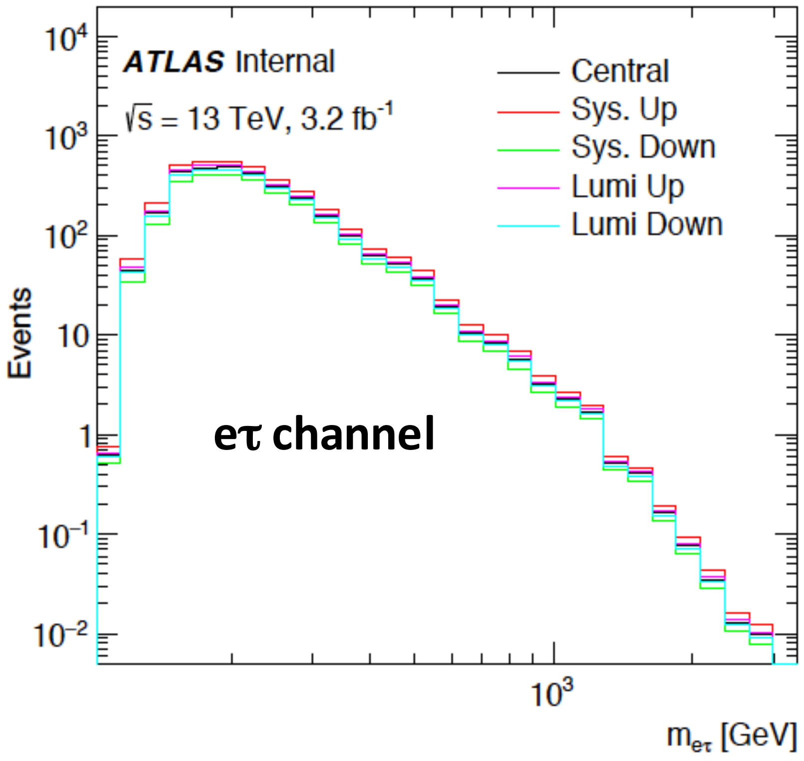
Region 1: Same-sign pairs with non-isolated electrons/muons (lepton p_T < 200 GeV)

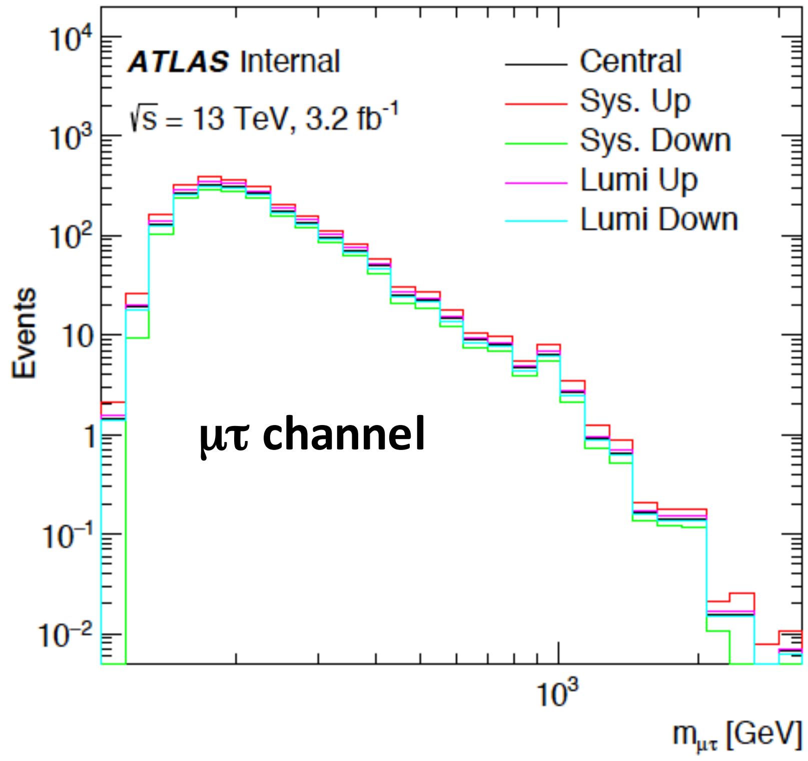
Region 2: Same-sign pairs with isolated electrons/muons (lepton $p_T <$ 200 GeV)

Region 3: Opp+Same sign pairs with non-isolated electrons/muons

- Obtain QCD shape from region 3 (orthogonal to SR) by taking
  $N^{Reg}_{QCD} = N^{Reg}_{Data} - N^{AllMC}_{Reg}$
- Normalise using regions 1 and 2: $K_{QCD} = N^{Reg2}_{QCD} / N^{Reg1}_{QCD}$

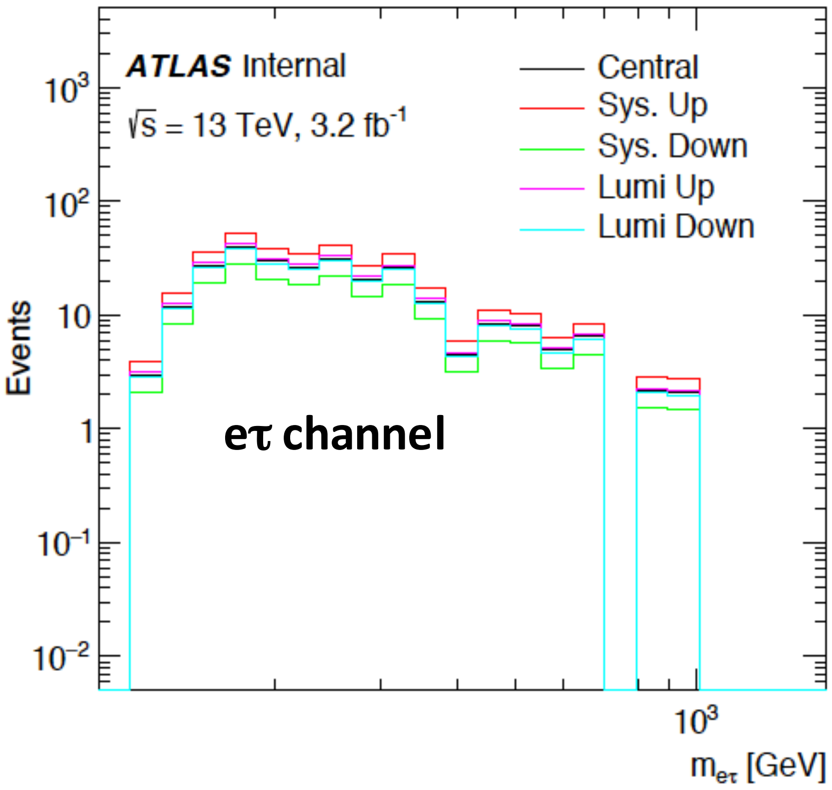
W+jets Estimation(eτ, μτ channel)

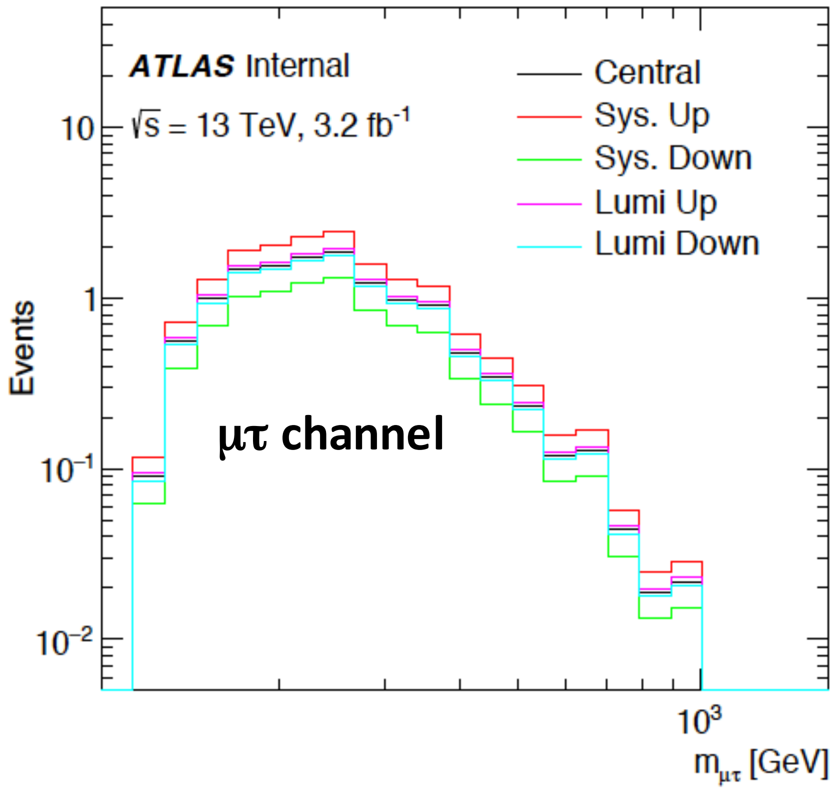




channel	Normalisation Factor (CR to SR)	Contribution
$e\tau$	$1.30 \pm 0.09 \pm 0.20$	3020.44 ± 531.98
$\mu\tau$	$1.04 \pm 0.08 \pm 0.17$	1951.25 ± 342.58

QCD Estimation($e\tau$, $\mu\tau$ channel)





Channel	K_{QCD}	$N_{\mathrm{QCD}}^{\mathrm{Reg.\ 1}}$	$N_{\mathrm{QCD}}^{\mathrm{Reg.\ 2}}$	$N_{\mathrm{QCD}}^{\mathrm{Reg.\ 3}}$	$N_{\mathrm{QCD}}^{\mathrm{SR}}$
$e\tau$	$1.12 \pm 0.47 \pm 0.17$	110.09	123.77	237.91	267.47 ± 80.24
$\mu\tau$	$0.02 \pm 0.13 \pm 0.01$	272.77	6.11	569.02	12.77 ± 3.83

Highest mass events of eμ, eτ, μτ

$e\mu$ channel:

$m_{\ell\ell'}$	Run	Event	$E_T^{\rm miss}$	Lep ID	p_{T_ℓ}	η_ℓ	ϕ_ℓ
2088.7	284006	230173000	72	-13	617	0.29	0.4
				11	1164	1.64	-2.8

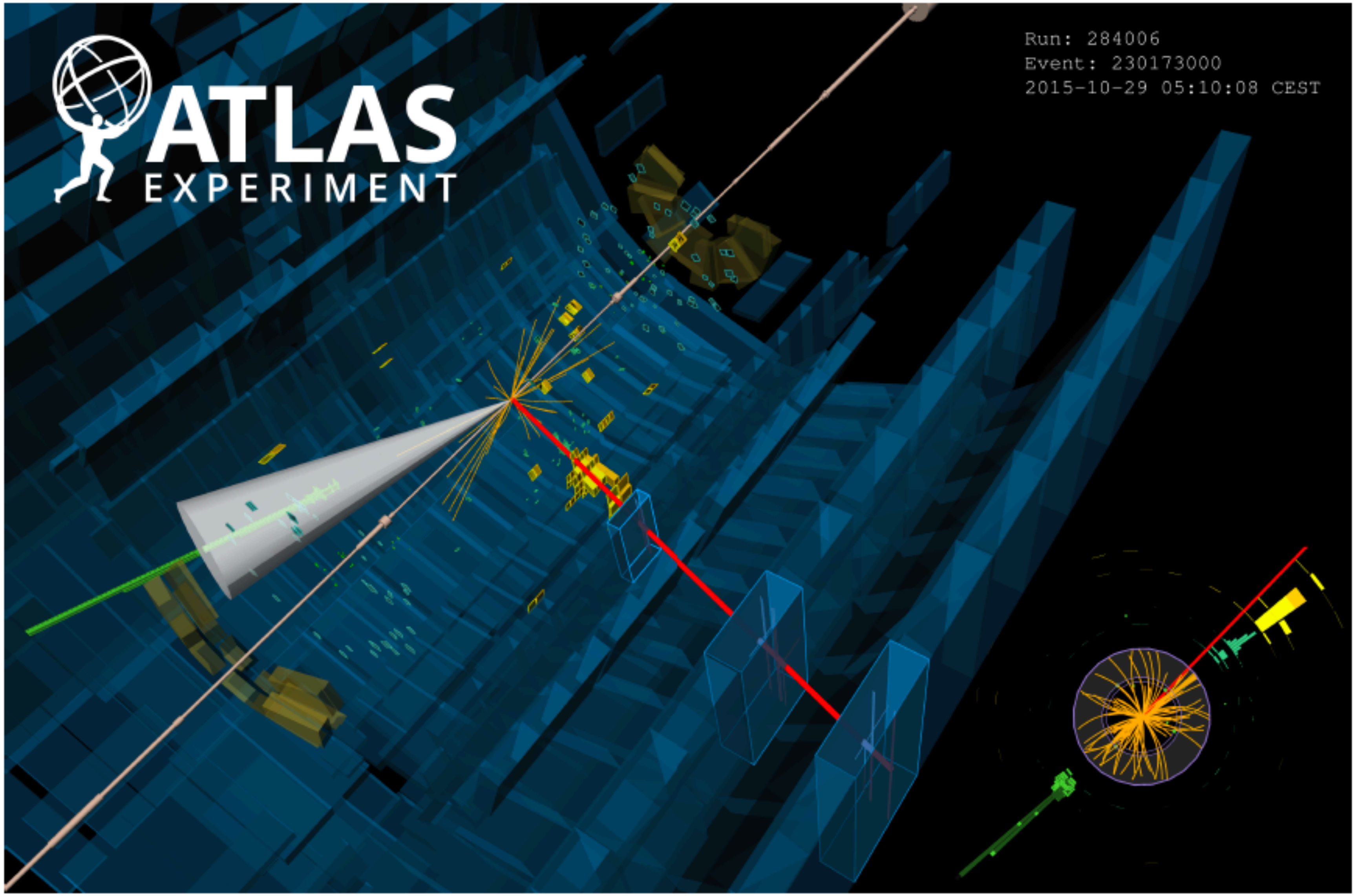
$e\tau$ channel:

$m_{\ell\ell'}$	Run	Event	$E_T^{\rm miss}$	Lep ID	p_{T_ℓ}	η_ℓ	ϕ_ℓ
1633.8	281411	741678308	8.5	11	412	-1.26	1.8
				-15	409	1.33	-1.5

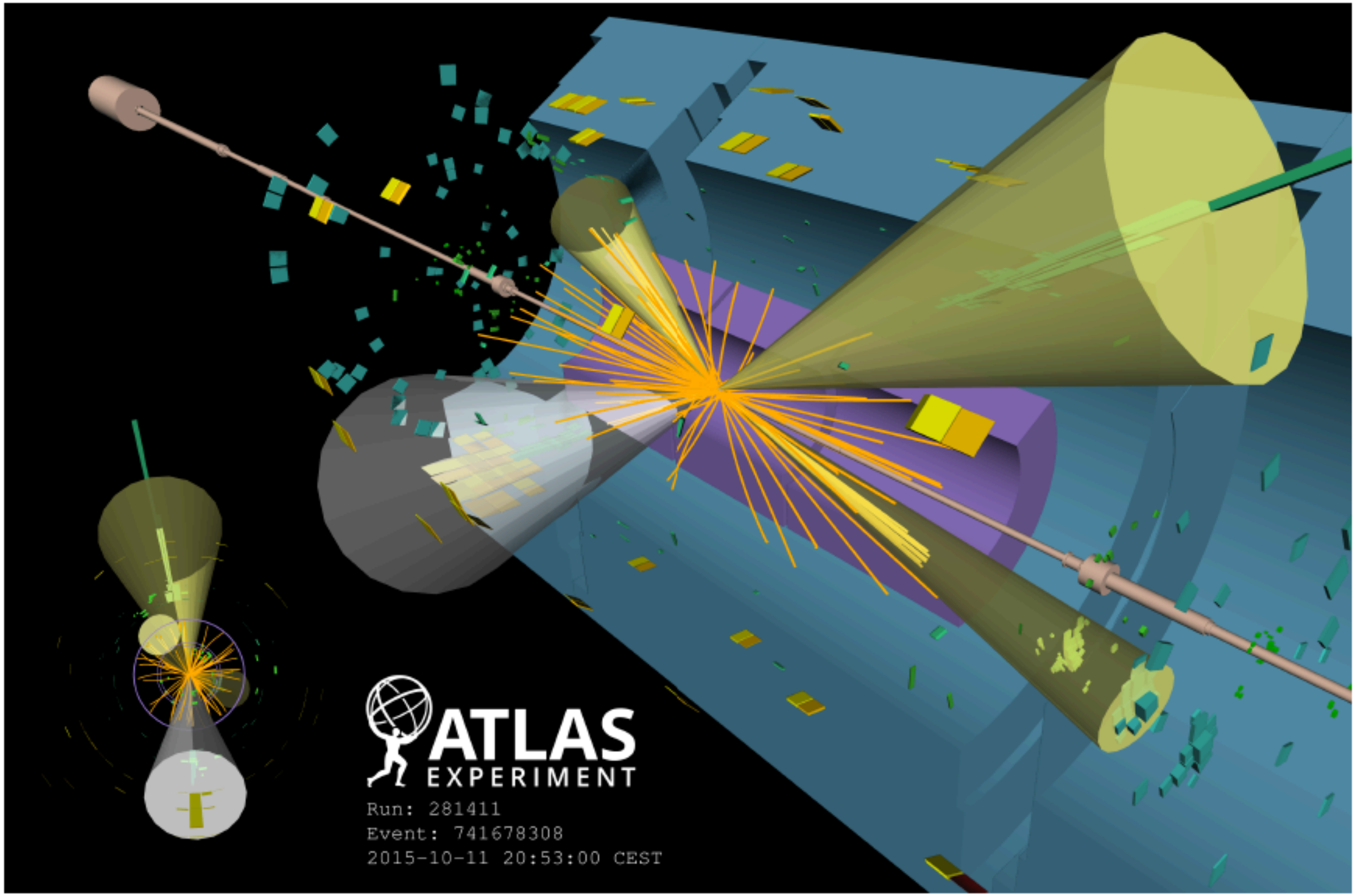
$\mu\tau$ channel:

$m_{\ell\ell'}$	Run	Event	$E_T^{\rm miss}$	Lep ID	p_{T_ℓ}	η_ℓ	ϕ_ℓ
1665.7	284285	507432681	130.8	-13	159	2.20	2.7
				15	81	-2.19	-0.5

3-D event display $m_{e\mu} = 2.088$ TeV



3-D event display $m_{e\tau} = 1.634$ TeV



3-D event display $m_{\mu\tau} = 1.665$ TeV