Search for LFV at ATLAS

Quanyin Li(USTC)
on behalf of LFV analysis team

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History of ATLAS LFV analysis

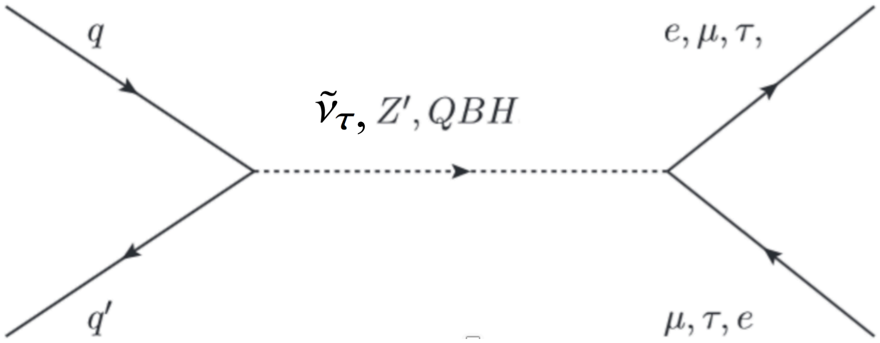
- 2011: **ATLAS** experiment search for $\tilde{\nu}_\tau, Z'$ decaying to **eμ** final states with **35 pb^{-1}** data of pp collision at sqrt(s)=**7** TeV
  Phys.Rev.Lett.106,251801,2011
- 2011: **ATLAS** experiment search for $\tilde{\nu}_\tau, Z'$ decaying to **eμ** final states with **1.07 fb^{-1}** data of pp collision at sqrt(s)=**7** TeV
  Eur.Phys.J.C 71 (2011) 1809
- 2012: **ATLAS** experiment search for $\tilde{\nu}_\tau$ decaying to **eμ,eτ,μτ** final states with **4.6 fb^{-1}** data of pp collision at sqrt(s)=**7** TeV
  Phys.Lett. B723 (2013) 15-32
- 2015: **ATLAS** experiment search for $\tilde{\nu}_\tau, Z'$ decaying to **eμ,eτ,μτ** final states with **20.3 fb^{-1}** data of pp collision at sqrt(s)=**8** TeV
  Phys. Rev. Lett. 115, 031801 (2015)
- 2016: **ATLAS** experiment search for $\tilde{\nu}_\tau, Z', QBH$ decaying to **eμ,eτ,μτ** final states with **3.2 fb^{-1}** data of pp collision at sqrt(s)=**13** TeV
  Eur. Phys. J. C76 (2016) 541
- 2018: **ATLAS** experiment search for $\tilde{\nu}_\tau, Z', QBH$ decaying to **eμ,eτ,μτ** final states with **36.1 fb^{-1}** data of pp collision at sqrt(s)=**13** TeV
  Preparing to submit to PRD

1 model →3 models **1 channel →3 channels** **7TeV →8TeV →13TeV**

Analysis team include USTC(Liang Han, Minghui Liu, Quanyin Li)&SJTU(Haijun Yang, Jun Guo, Marc Cano Bret)

Introduction

- Motivation: Neutrino oscillation → lepton flavor violation(LFV) in neutral particles



- Physics process: pp collision with final states eμ/eτ/μτ

- 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)

- Purpose: Try to find a new resonance in high mass region. Otherwise, set limits on the parameters of new physics models.

New Physics theories

Quantum Black Hole

- Produce QBHs when the extradimensional Planck Scale is reached
- Quantum Gravity might violate Lepton Flavour conservation $\rightarrow e\mu$, $e\tau$ 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 $\sigma(Z' \rightarrow l_i l_j') \sim \frac{Q_{ij}^2 M_{ll'}^2}{M_{ll'}^2 - M_{Z'}^2}$

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)
- Assume only lepton-flavour violating decay at the same time. As such, choose the Yukawa couplings as following:

  $e\mu$: $\lambda_{312}=\lambda_{321} = 0.07$ $e\tau$: $\lambda_{313}=\lambda_{331} = 0.07$
  $\mu\tau$: $\lambda_{323}=\lambda_{332} = 0.07$

Object and event selection

Muons:

- P_T>65GeV; $|\eta|$<2.5
- ID: HighPt
- Isolation: LooseTrackOnly
- Track: $|{}^{d_0}/_{\sigma_{d_0}}|$<3; $|Z_0 Sin\theta|$<0.5mm

Electrons:

- P_T>65GeV; $|\eta|$<2.47 except 1.37~1.52
- ID: LH-Tight
- Isolation: Loose
- Track: $|{}^{d_0}/_{\sigma_{d_0}}|$<5; $|Z_0 Sin\theta|$<0.5mm

Tau:

- P_T>65GeV; $|\eta|$<2.5 except 1.37~1.52
- ID: Tau JetBDTLoose
- Track: 1 or 3 prongs
- Charge: +-1

Event selection:

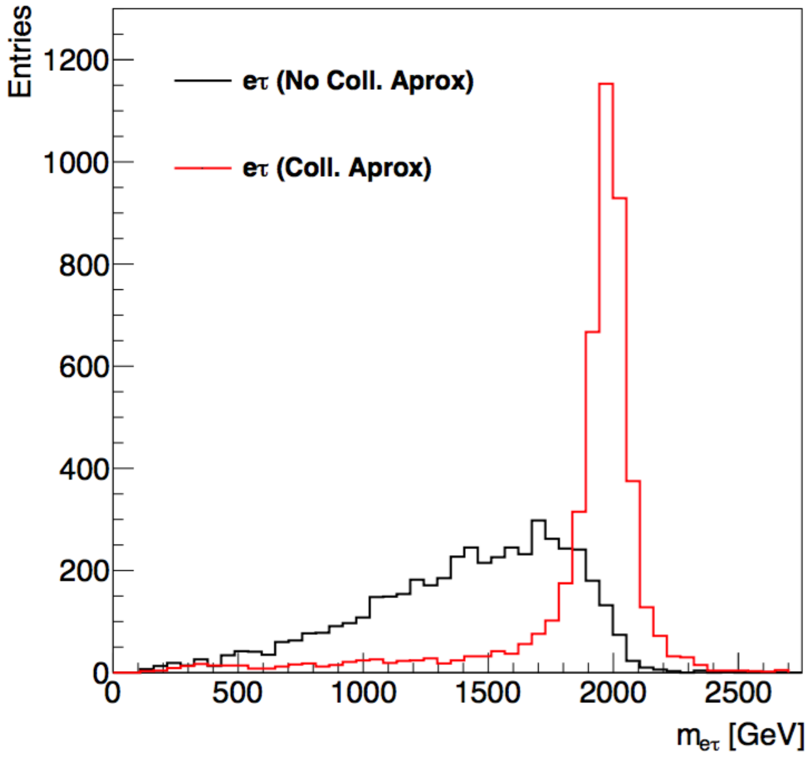
- Pre-selection: remove events with error status flag on detectors
- Primary Vertex: at least two tracks associated with pT > 400 MeV
- Trigger:

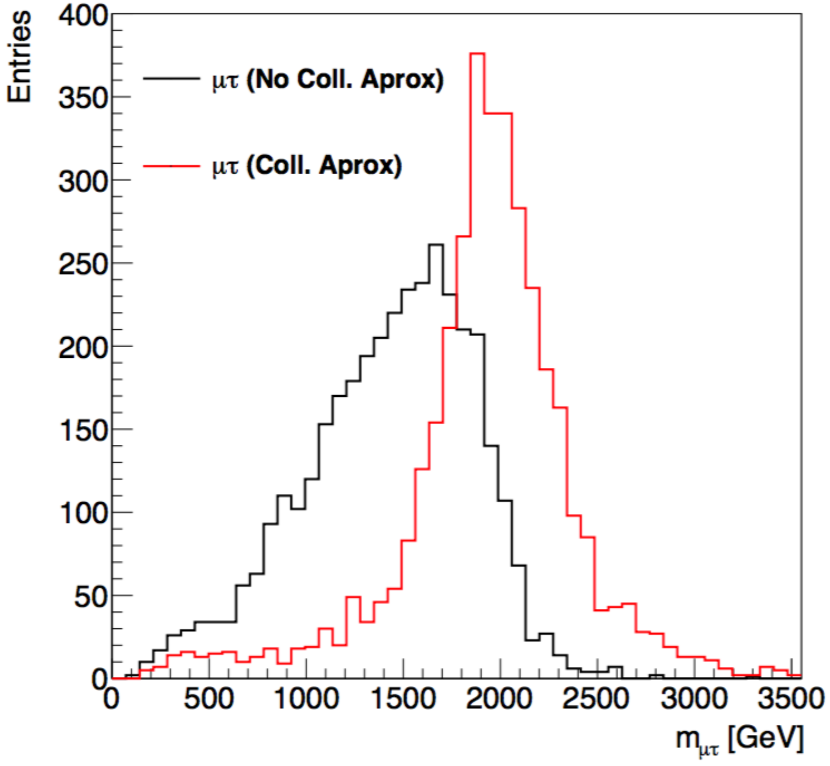
  HLT mu50 || HLT e60 lhmedium || HLT e120 lhloose (2015 data)

  HLT mu50 || HLT e60 lhmedium nod0 || HLT e140 lhloose nod0 (2016 data)
- Event quality: veto event with bad muon/jet
- 3rd lepton veto: events with redundant good leptons are rejected.
- Trig. Match: At least 1 trigger matched lepton
- DeltaPhi: $\Delta\phi(ll') > 2.7$

Optimization: Neutrino 4-vector approximation

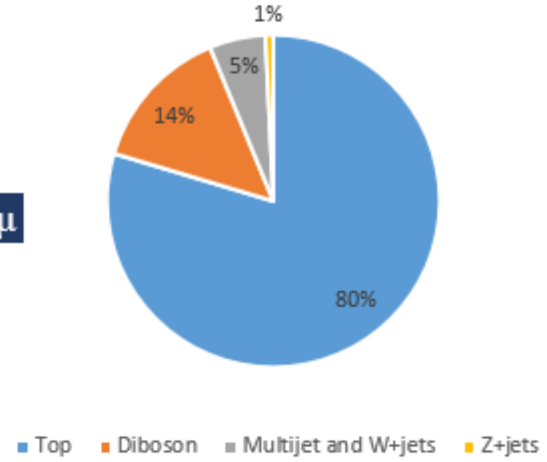
- τ decays finals are heavily boosted due to large resonance mass
- neutrino and the resulting jet are approximately collinear ($\eta_{\nu}=\eta_{\tau}$)
- Leads to improved peak resolution



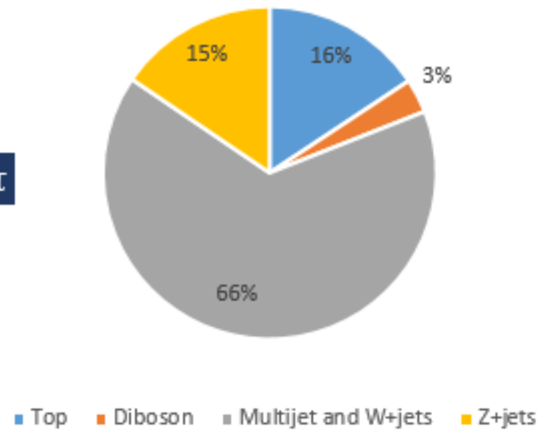


Background

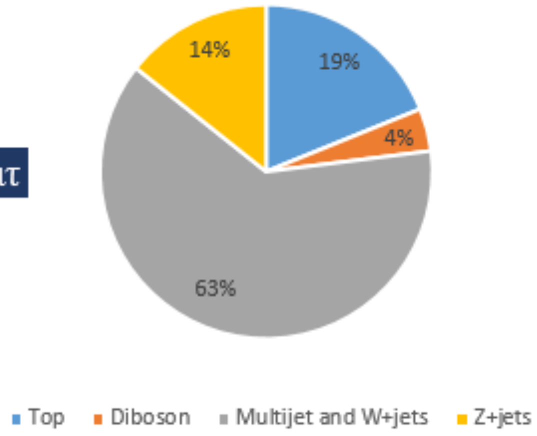
Background in eμ



Background in eτ



Background in μτ



eμ final states

Dominated by： Top + Dibosn
Method:
- **MC simulation + Extrapolation for Top**
- **Matrix method for jet faked background**

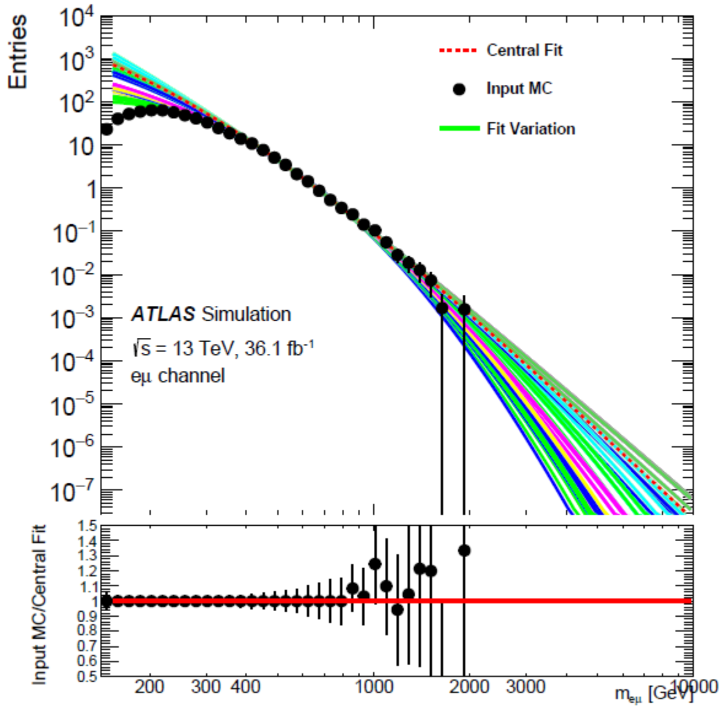
eτ/μτ final states

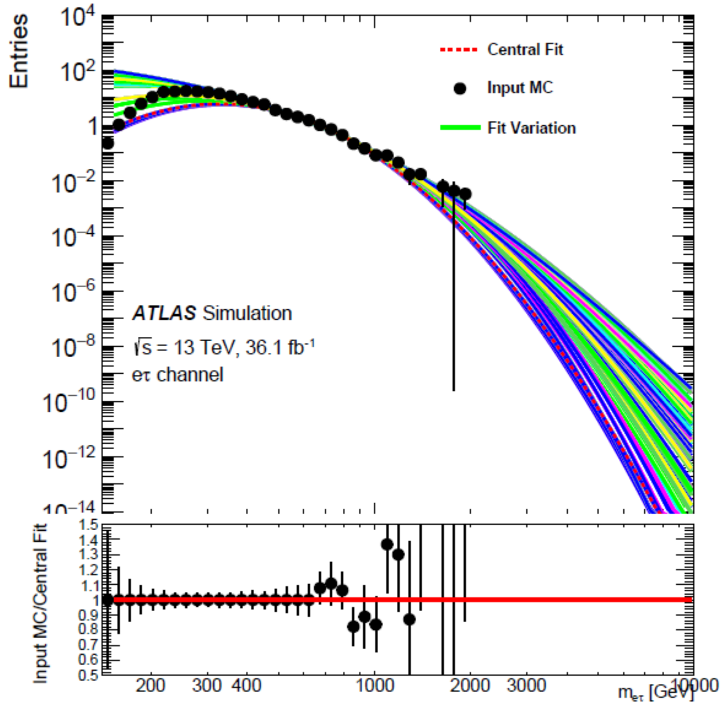
Dominated by: Wjet + QCD
Method:
- **data-driven**

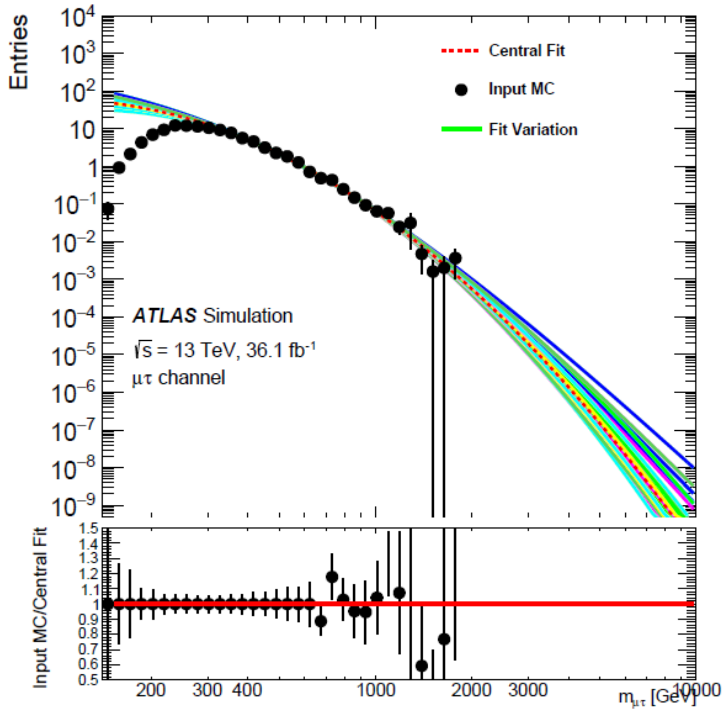
Top background in 3 channels

- Statistic of Top MC samples are not enough in high mass region(>1.5 TeV)
- Extrapolation are applied to get a precise result
- Two functions are used:

Dijet function : $a \cdot x^{b} \cdot x^{c\ln(x)}$ Inverse Monomial function : $\frac{a}{(x+b)^{c}}$







Background in eμ: faked background

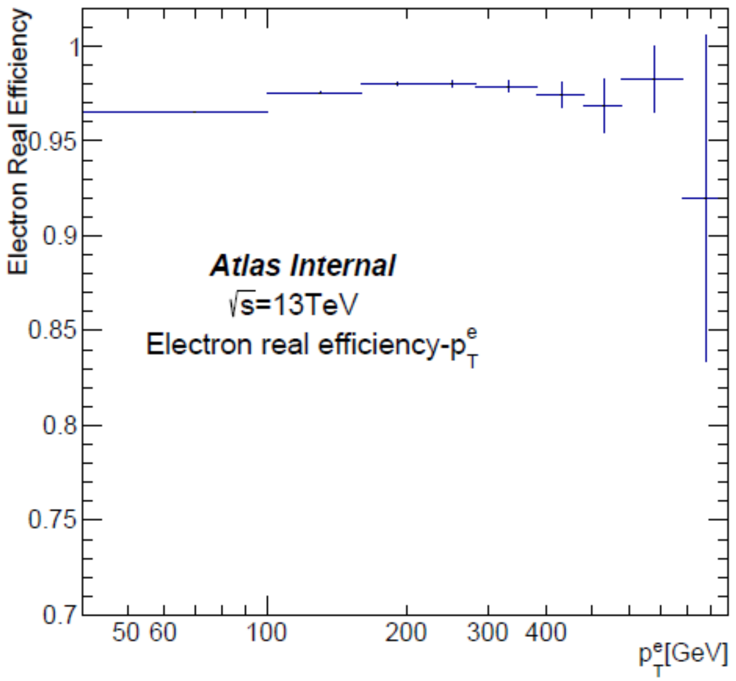
- A 2 X 2 Matrix Method is performed to estimate the jet faked background in eμ channel.

$$N_{TT} = N_{RR} \cdot r_e + N_{FR} \cdot f_e$$
$$N_{LT} = N_{RR} + N_{FR}$$

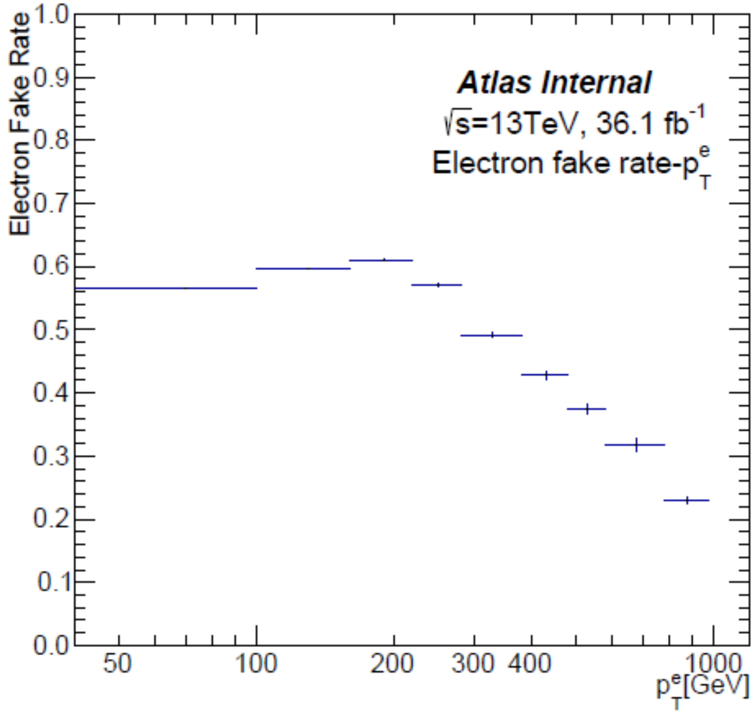
- 'Tight' electrons: fulfill all electron selection cuts
- 'Loose' electrons: all cuts except LH-Medium and no isolation cut
- r_e: real efficiency, estimated by Zee MC samples
- f_e: fake rate, estimated in a dijet CR
- Third lepton veto is very important for this method
- Final calculation:

$$N_{fake} = N_{FR} \cdot f_e = \frac{f_e \cdot (N_{TT} - N_{LT} \cdot r_e)}{f_e - r_e}$$

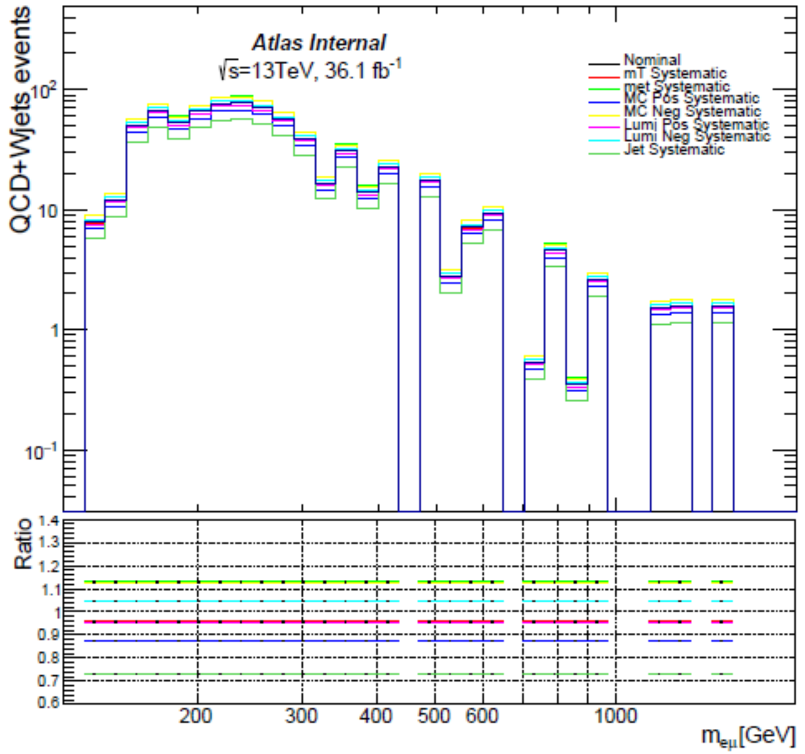
Background in eμ: faked background result



Real efficiency:
MC truth match



Fake rate:
estimated in a QCD enriched sample



Jet faked background and systematic uncertainties

Background in eτ/μτ: W+Jets estimation

➢ Process:

- Evaluate tau fake rate (τ_{FR})
- Select event in Wjets MC with TauJetBDT>0.4 instead ID loose applied to taus
- Weight event according to τ_{FR}: $N_{W\,jets} = N_{tot}^{MC} \cdot \frac{N_{BDTLoose}^{CR}}{N_{tot}^{CR}}$
- Systematic uncertainties related to τ_{FR}

➢ W+jets Control region to calculate τ_{FR}

- Only 1 electron or 1 muon pass object selection
- Tau object with TauJetBDT>0.4 instead loose
- Veto events with invariant mass $80 < m_{l\tau} < 110$ GeV
- $\Delta\varphi(l, \tau) < 2.7$ to ensure orthogonality with the signal region
- $m_T(l, E^T_{miss}) > 80$ GeV
- MC subtraction

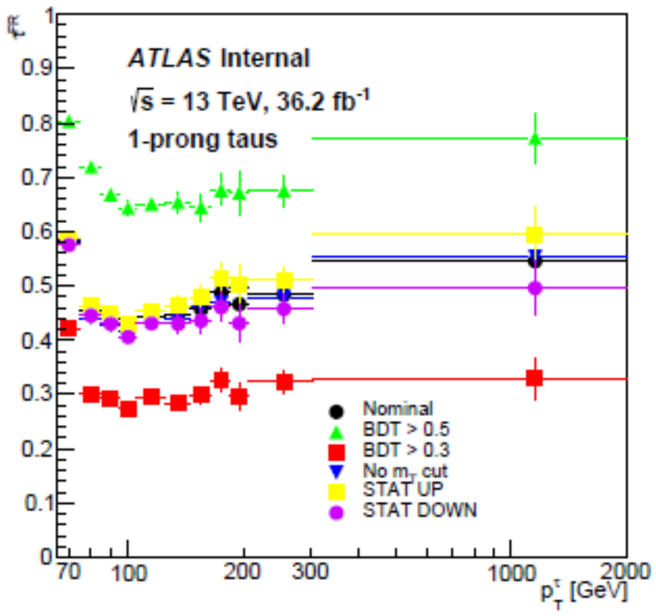
Background in eτ/μτ: τ fake factor

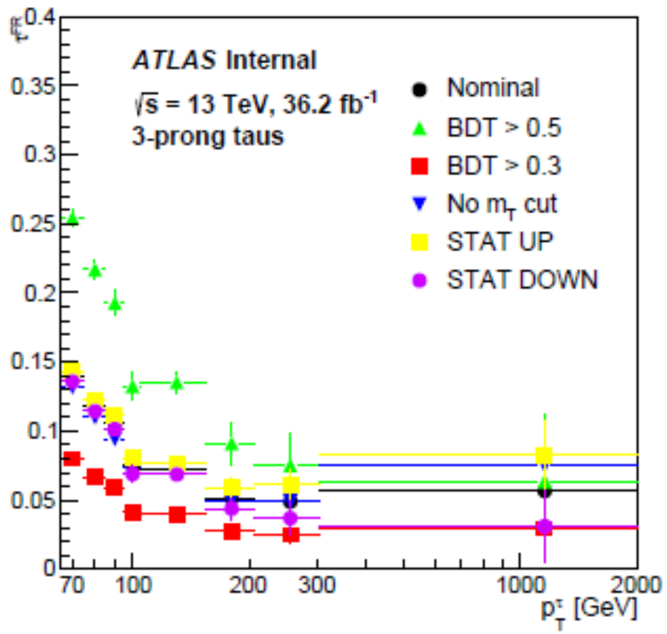
- The tau fake factor is derived:

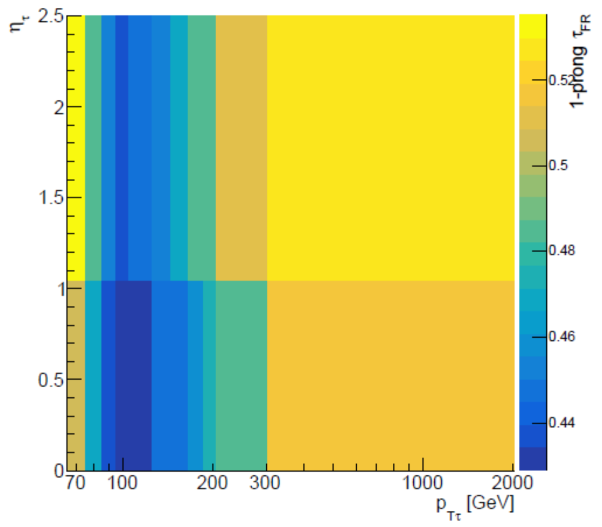
i) directly from data in W + jets CR and defined as $\tau_{FR} = N^{PassID} / N^{tot\ \tau}$

ii) as a function of τ pT and η , separately for 1 and 3 prong taus

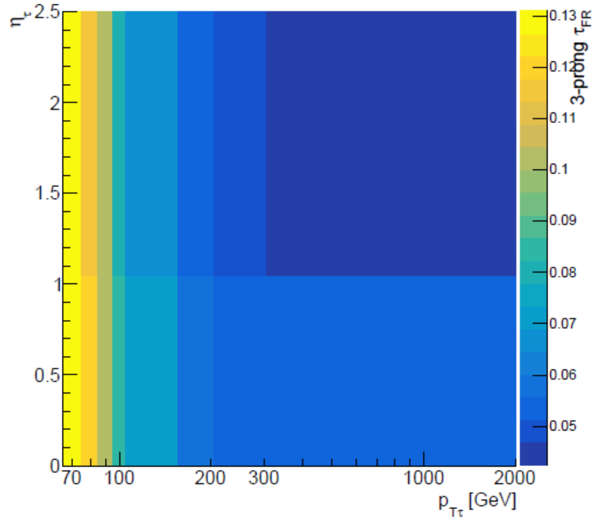
iii) pT-η 2D plots for the τ_{FR}







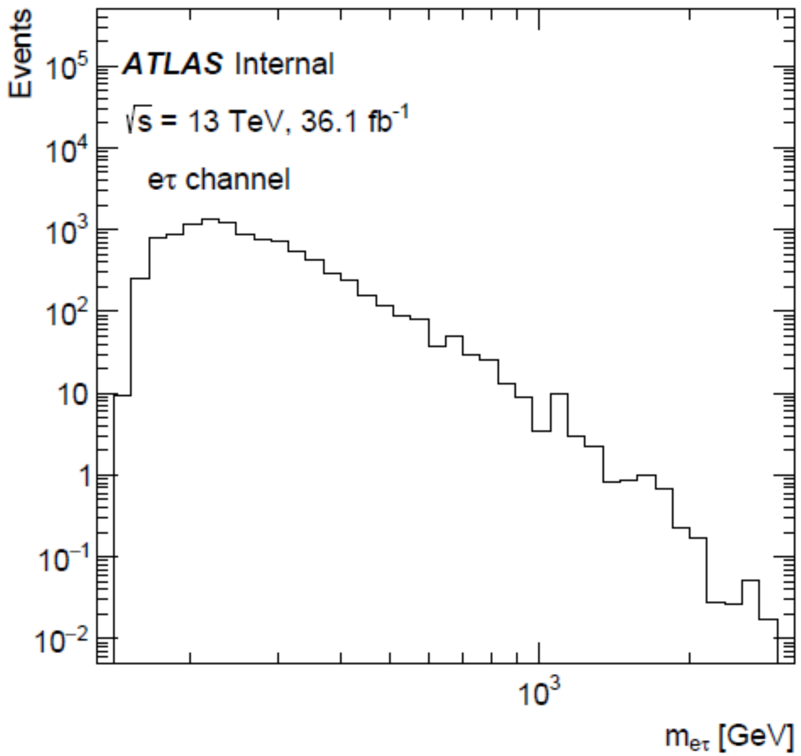
(a) 1-prong taus



(b) 3-prongs taus

Background in eτ/μτ: Wjets result

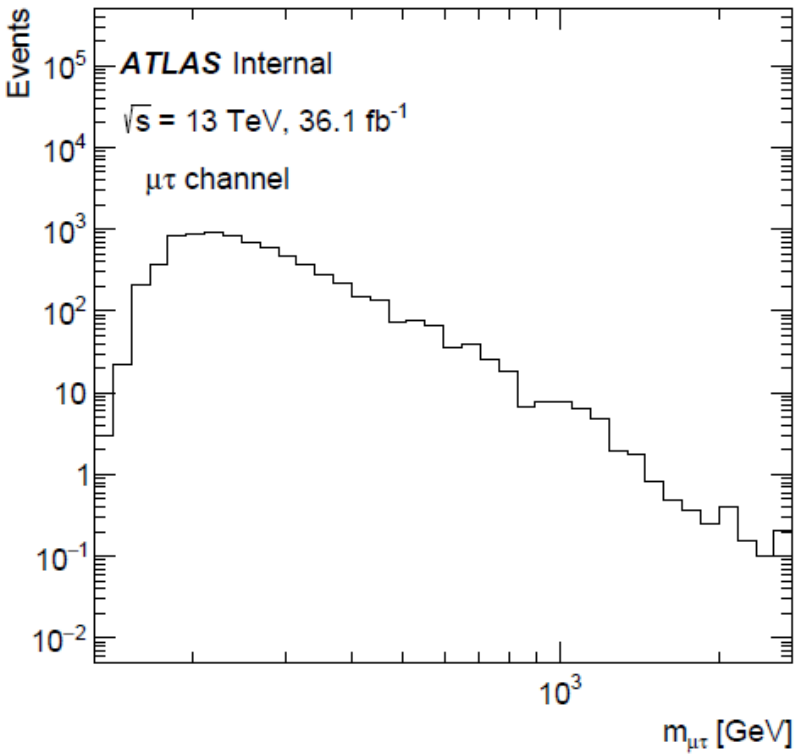
- The Wjets background is evaluated by applying the 2D τ_{FR} to the MC simulation.



(a) *eτ* channel

$N^{e\tau}_{Wjets}$=10159.3

~40% of total background



(b) *μτ* channel

$N^{\mu\tau}_{Wjets}$=7335.44

~40% of total background

Background in eτ/μτ: QCD estimation

➢ QCD Multijet estimation:

Region 1: Same-sign pairs with a non-isolated electron/muon and a tau without Loose ID cut(lepton $p_T < 200$ GeV)

Region 2: Same-sign pairs with a isolated electron/muon and a tau with Loose ID cut(lepton $p_T < 200$ GeV)

Region 3: Opp+Same sign pairs with a non-isolated electron/muon and a tau without Loose ID cut

	Pass Cut1	Fail Cut1
Pass Cut2	A	C
Fail Cut2	B	D

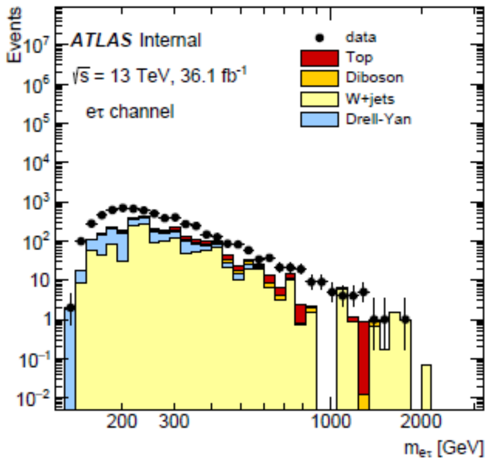
Cut1 and Cut2 are independent

$$\frac{N_A}{N_B} = \frac{N_C}{N_D}$$

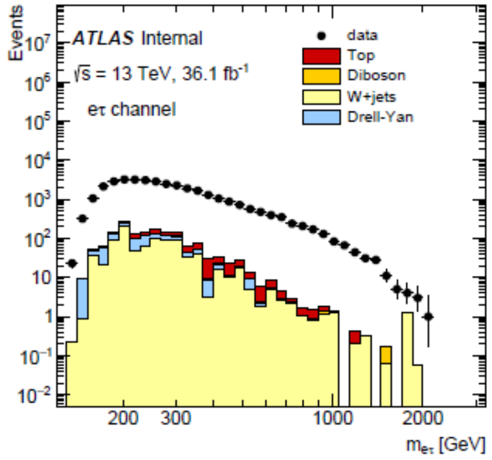
$$\frac{N_{QCD}^{SR}}{N_{QCD}^{Reg3}} = \frac{N_{QCD}^{Reg2}}{N_{QCD}^{Reg1}}$$

$$N_{QCD}^{SR} = N_{QCD}^{Reg3} \cdot \frac{N_{QCD}^{Reg2}}{N_{QCD}^{Reg1}} = (N_{Data}^{Reg3} - N_{MC}^{Reg3}) \cdot \frac{N_{Data}^{Reg2} - N_{MC}^{Reg2}}{N_{Data}^{Reg1} - N_{MC}^{Reg1}}$$

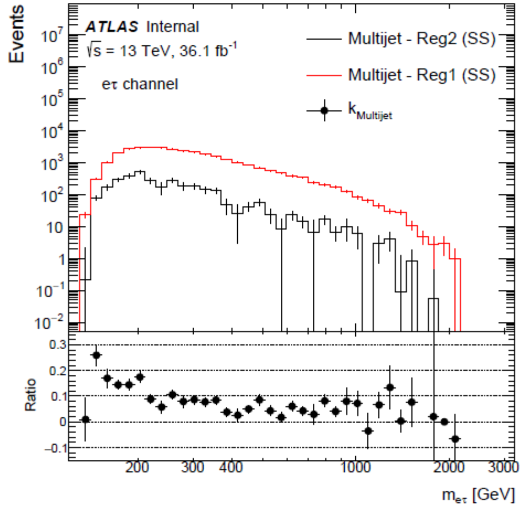
Background in eτ/μτ: QCD Result



(b) $e\tau$ channel: Region 2

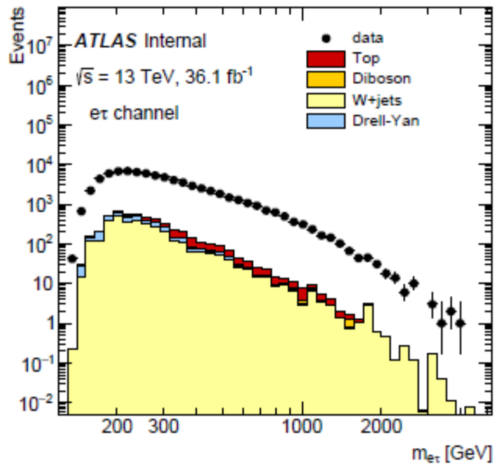


(a) $e\tau$ channel: Region 1

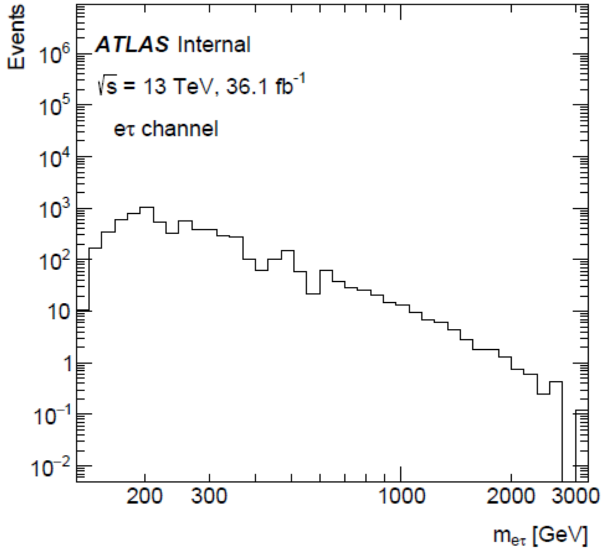


(a) $e\tau$ channel: K_{Multijet}

Applied



(c) $e\tau$ channel: Region 3

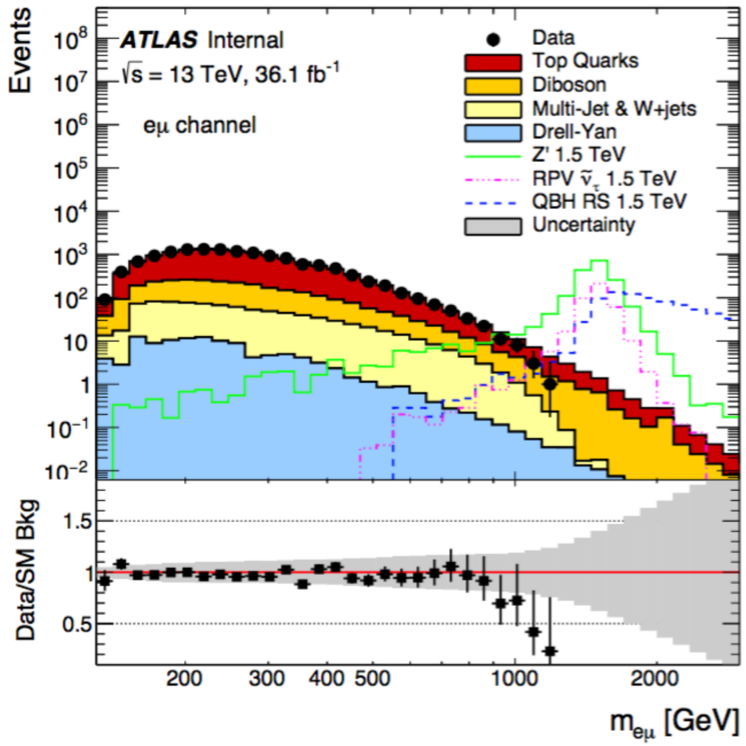


$N^{e\tau}_{QCD}$=6498.18
Almost 25% of total background

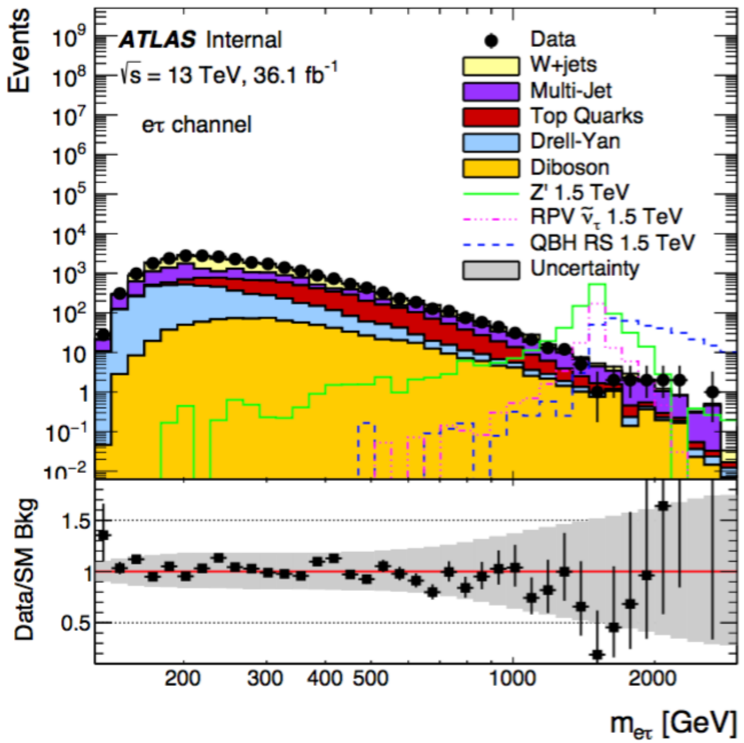
Systematic uncertainties

Source	1 TeV			2 TeV			3 TeV		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
Luminosity	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%
Top background prediction	5.3%	1.7%	1.6%	31.7%	2.6%	3.7%	62.5%	3.2%	14.2%
Top Scale	6.6%	6.7%	8.3%	39.6%	1.1%	13.7%	65.0%	2.7%	26.5%
PDF	16.0%	12.2%	13.9%	31.8%	16.9%	20.0%	50.9%	16.3%	53.4%
Pile-Up reweighting efficiency	0.5%	2.9%	6.5%	9.2%	3.3%	13.0%	31.7%	2.2%	16.9%
Dilepton p_T modelling	7.4%	2.1%	0.5%	11.0%	0.3%	0.6%	15.1%	0.1%	4.0%
Electron trigger efficiency	0.2%	0.1%	N/A	0.2%	0.1%	N/A	0.3%	0.1%	N/A
Electron identification efficiency	1.6%	0.8%	N/A	2.4%	0.5%	N/A	2.9%	0.4%	N/A
Electron reconstruction efficiency	0.2%	0.1%	N/A	0.3%	0.1%	N/A	0.3%	0.1%	N/A
Electron isolation efficiency	1.8%	0.8%	N/A	2.7%	0.6%	N/A	3.0%	0.6%	N/A
Electron energy resolution	0.2%	0.2%	N/A	0.3%	1.3%	N/A	0.4%	1.2%	N/A
Electron energy scale	1.5%	5.2%	N/A	2.0%	5.5%	N/A	1.8%	8.3%	N/A
Muon trigger efficiency	0.7%	N/A	0.6%	0.7%	N/A	0.9%	0.7%	N/A	1.1%
Muon reconstruction efficiency	2.8%	N/A	2.1%	4.2%	N/A	3.7%	5.3%	N/A	5.4%
Muon isolation efficiency	0.5%	N/A	0.2%	1.9%	N/A	0.3%	3.2%	N/A	0.5%
Muon track-to-vertex efficiency	<0.1%	N/A	<0.1%	<0.1%	N/A	<0.1%	<0.1%	N/A	<0.1%
Muon momentum resolution (ID)	1.1%	N/A	1.9%	4.2%	N/A	19.5%	11.1%	N/A	16.3%
Muon momentum resolution (MS)	0.4%	N/A	1.2%	3.7%	N/A	1.2%	12.2%	N/A	1.4%
Muon momentum scale	0.1%	N/A	0.8%	0.3%	N/A	1.9%	0.7%	N/A	6.3%
Muon sagitta	0.7%	N/A	2.2%	1.2%	N/A	11.3%	2.0%	N/A	2.9%
Tau identification efficiency	N/A	1.7%	1.9%	N/A	0.8%	1.3%	N/A	0.6%	2.4%
Tau reconstruction efficiency	N/A	0.7%	0.8%	N/A	0.3%	0.6%	N/A	0.2%	1.3%
Tau-electron OLR efficiency	N/A	0.5%	0.6%	N/A	0.3%	0.5%	N/A	0.2%	1.3%
Tau momentum resolution	N/A	0.1%	0.1%	N/A	0.1%	0.4%	N/A	0.1%	1.9%
Tau fake rate statistical	N/A	1.3%	1.8%	N/A	1.3%	3.4%	N/A	0.8%	5.0%
Tau fake rate systematic	N/A	5.9%	8.5%	N/A	4.5%	11.7%	N/A	2.1%	11.4%
Tau fake rate Control region	N/A	0.2%	0.3%	N/A	0.5%	1.0%	N/A	0.4%	2.5%
Multijet transf. factor statistical	N/A	30.0%	1.6%	N/A	51.3%	0.2%	N/A	61.9%	0.1%
Multijet transf. factor systematic	N/A	7.2%	N/A	N/A	13.1%	N/A	N/A	15.8%	N/A
Jet JVT efficiency	0.4%	0.2%	0.3%	0.4%	0.2%	0.4%	0.4%	0.2%	0.3%
Jet resolution	0.8%	6.7%	6.0%	2.2%	13.1%	35.7%	3.6%	18.3%	45.6%
Jet uncertainty	0.4%	5.0%	4.6%	0.4%	10.5%	20.7%	2.0%	12.7%	13.4%
MET resolution	N/A	2.6%	3.9%	N/A	5.4%	5.7%	N/A	7.5%	3.4%
MET scale	N/A	0.6%	1.2%	N/A	0.6%	2.6%	N/A	1.0%	7.0%
Total	18.9%	37.2%	24.6%	61.9%	60.5%	62.4%	113.3%	73.0%	90.8%

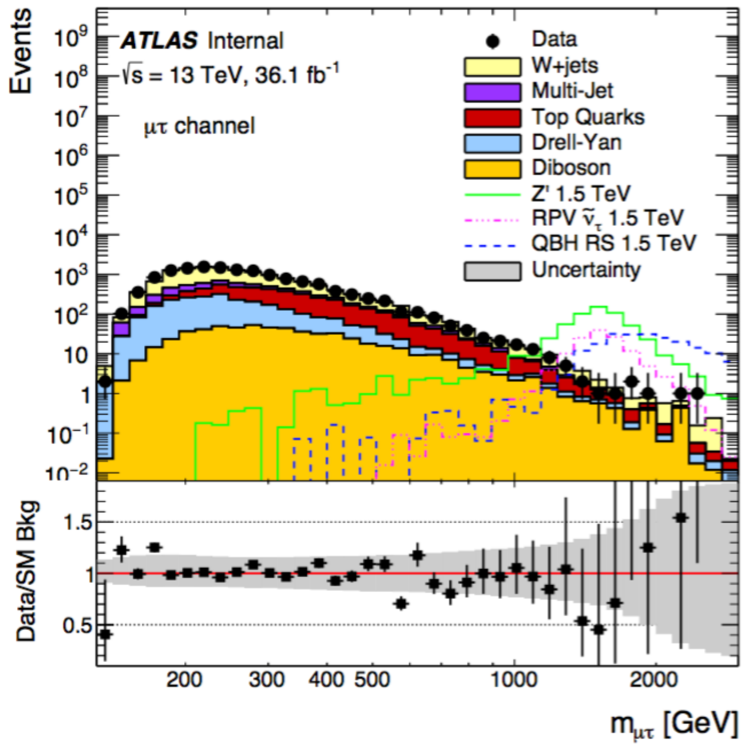
Result:



highest mass event in data at 1.23 TeV



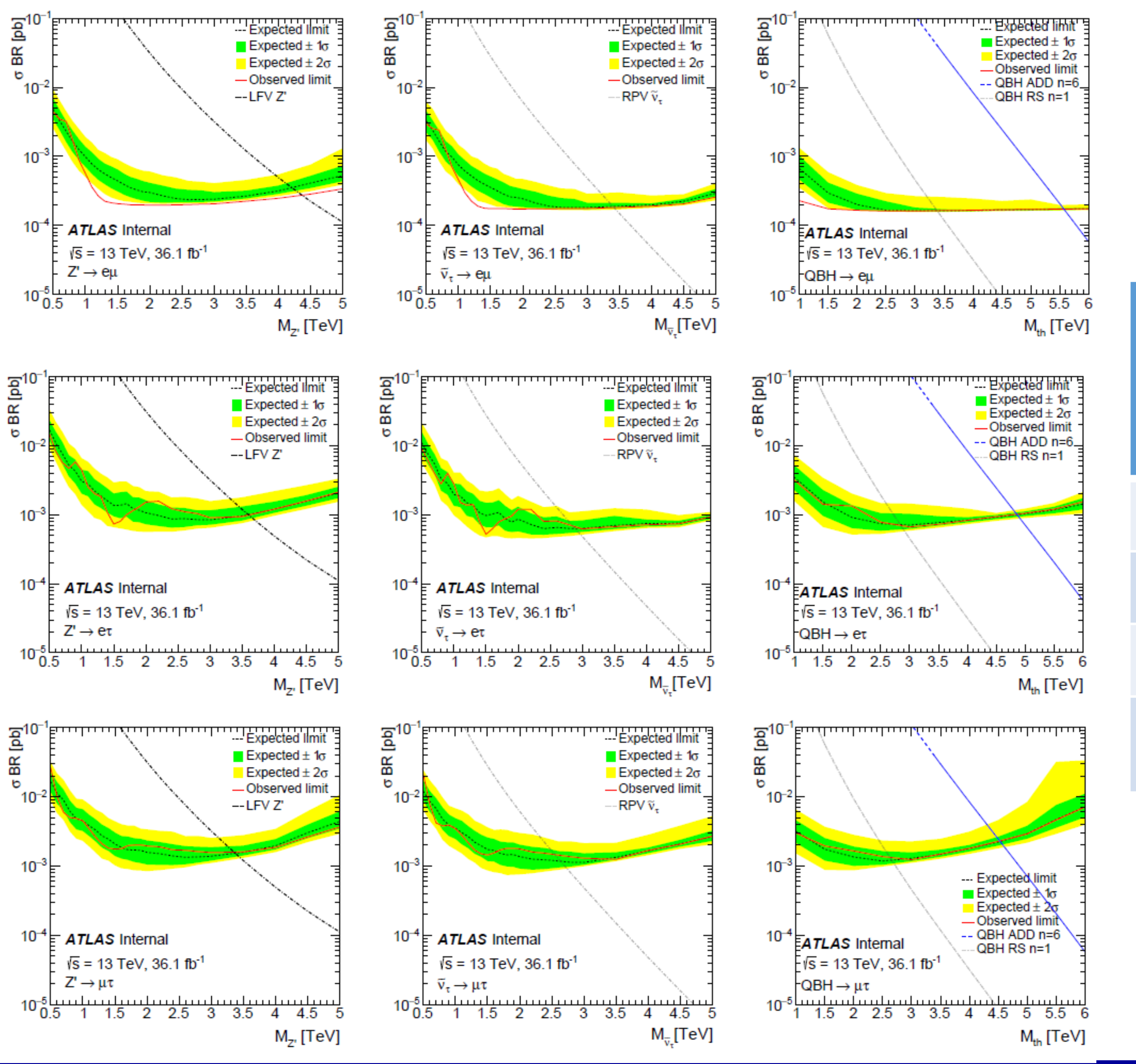
highest mass event in data at 2.58 TeV



highest mass event in data at 2.39 TeV

No significant excess over the SM background expectation found!

Limit setting:



Model	Expected Limit [TeV]			Observed Limit [TeV]		
	eμ	eτ	μτ	eμ	eτ	μτ
LFV Z’	4.21	3.60	3.38	4.37	3.61	3.36
RPC SUSY $\tilde{\nu}_\tau$	3.40	2.89	2.63	3.42	2.85	2.55
QBH ADD n=6	5.55	4.86	4.53	5.55	4.85	4.52
QBH RS n=1	3.34	2.84	2.66	3.35	2.85	2.63

Summary

➢ Summary

- Based on 36.1 fb^{-1} data at 13 TeV
- Several techniques applied to optimize the signal reconstruction
- Background are studied with MC estimation and data-driven method
- No significant excess over the SM background expectation found!
- Limits are better than before

- Paper will be published to PRD soon
- Another same analysis with 3.2 fb^{-1} data das been published in EPJC: Eur. Phys. J. C **76** (2016) 541

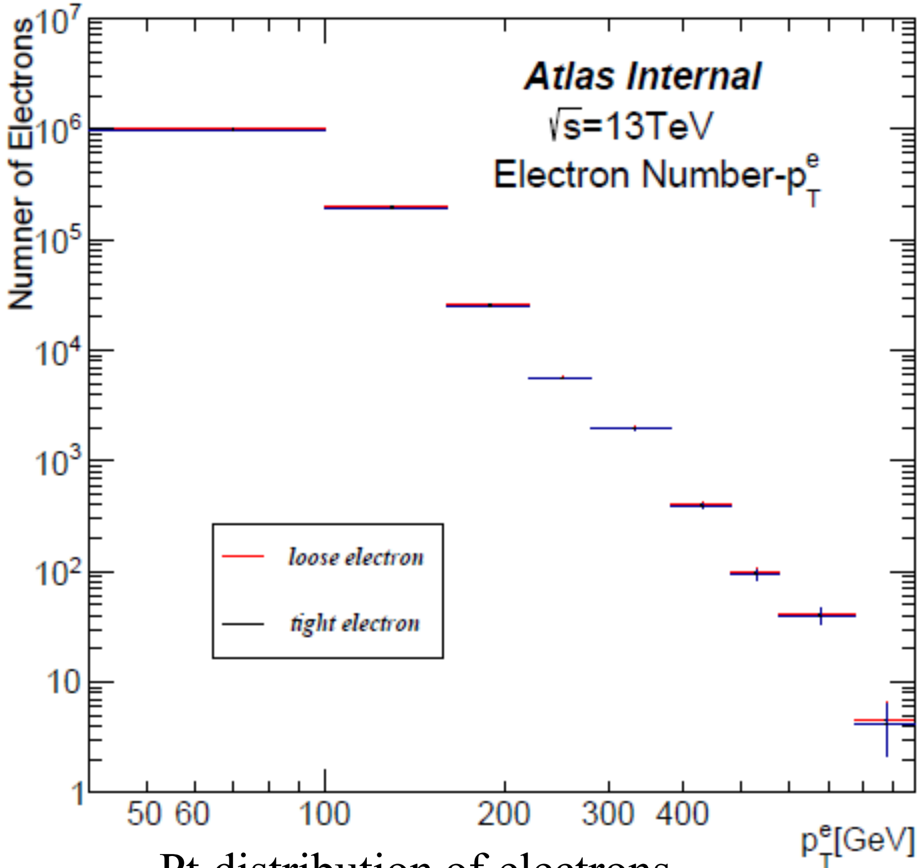
Thank you!

Backup

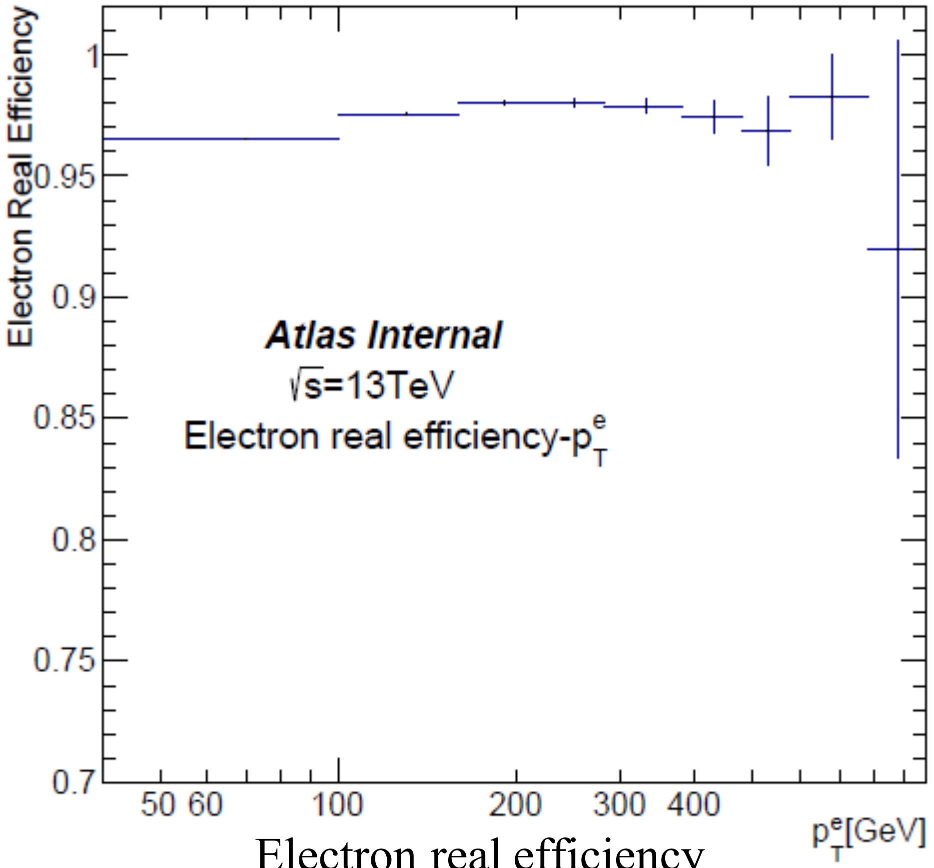
Background in eμ: Real Efficiency

Real efficiency

- Electrons with very high pT and tight Δφ cut
- Extracted from a Zee MC sample by electron truth match



Pt distribution of electrons

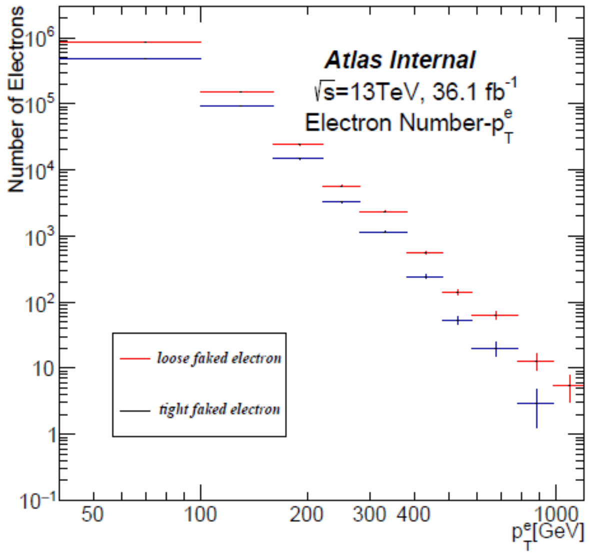


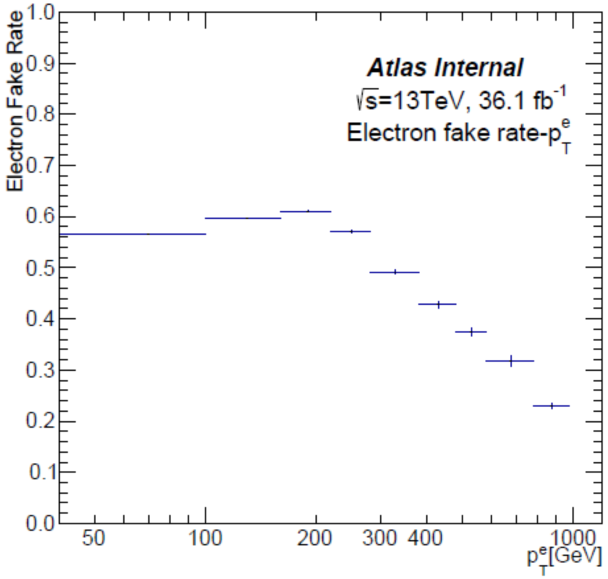
Electron real efficiency

Background in eμ: Fake Rate

Fake rate

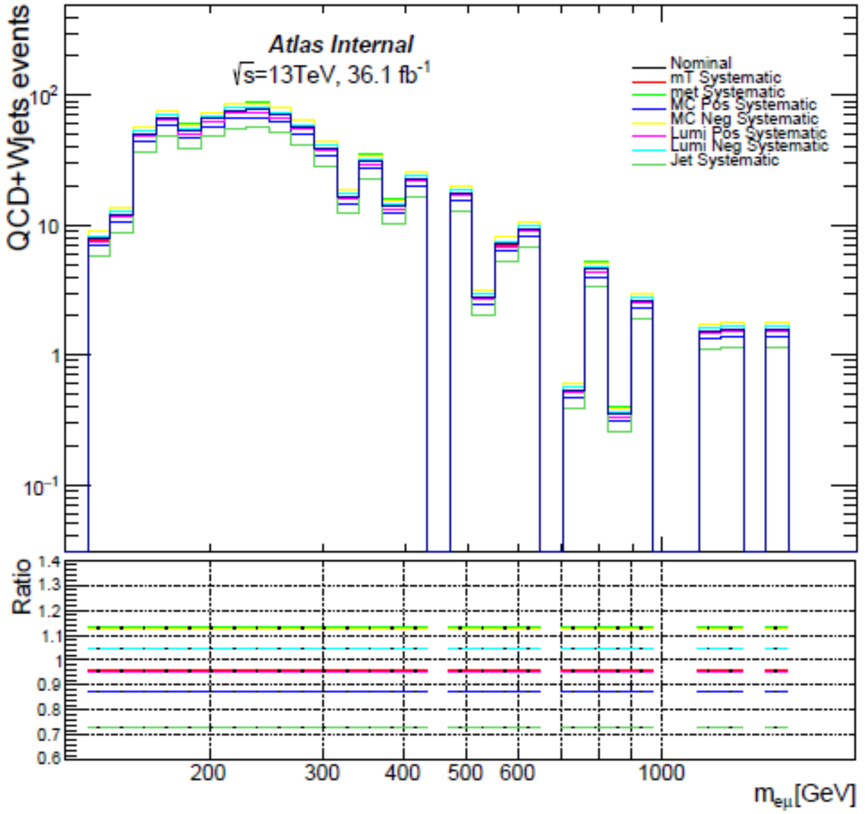
- ➢ Construct a QCD enriched sample
- Select events with only 1 good loose electron and several good jets from data
- dPhi between the electron and the jet with largest pt > 2.7
- MET < 25 GeV
- mT(e,met) < 50 GeV
- ➢ Subtract the contribution from EW process by MC
- ➢ Ratio of tight and loose electrons





Background in eμ: faked background result

- Result
  - In electron pt spectrum, contribution of jet faked background is calculated bin by bin
  - Number of faked background normalized to the value in pt spectrum
- systematic uncertainties
  - Luminosity uncertainty
  - Vary the met and mT cut in fake rate calculation
  - Use second highest pt jet in fake rate calculation
  - 10% Wjets MC sample uncertainty in fake rate calculation



W+Jets/QCD estimation in eτ/μτ

➢ W+jets:

- Evaluate tau fake rate (τ_{FR})
- Select event in Wjets MC with TauJetBDT>0.4 instead ID loose applied to taus
- Weight event according to τ_{FR} $N_{W\,jets} = N_{tot}^{MC} \cdot \frac{N_{BDTLoose}^{CR}}{N_{tot}^{CR}}$
- Systematic uncertainties related to τ_{FR}

➢ QCD :

Region 1: Same-sign pairs with a non-isolated electron/muon and a tau without Loose ID cut(lepton p_T < 200 GeV)

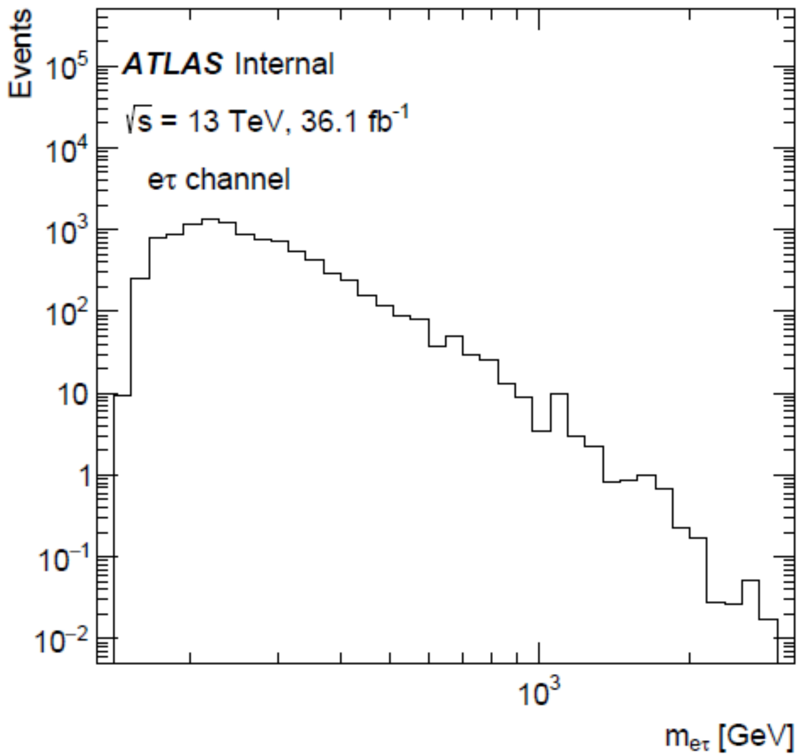
Region 2: Same-sign pairs with a isolated electron/muon and a tau with Loose ID cut(lepton p_T < 200 GeV)

Region 3: Opp+Same sign pairs with a non-isolated electron/muon and a tau without Loose ID cut

$$N_{QCD}^{SR} = N_{QCD}^{Reg3} \cdot \frac{N_{QCD}^{Reg2}}{N_{QCD}^{Reg1}} = (N_{Data}^{Reg3} - N_{MC}^{Reg3}) \cdot \frac{N_{Data}^{Reg2} - N_{MC}^{Reg2}}{N_{Data}^{Reg1} - N_{MC}^{Reg1}}$$

Background in eτ/μτ: Wjets result

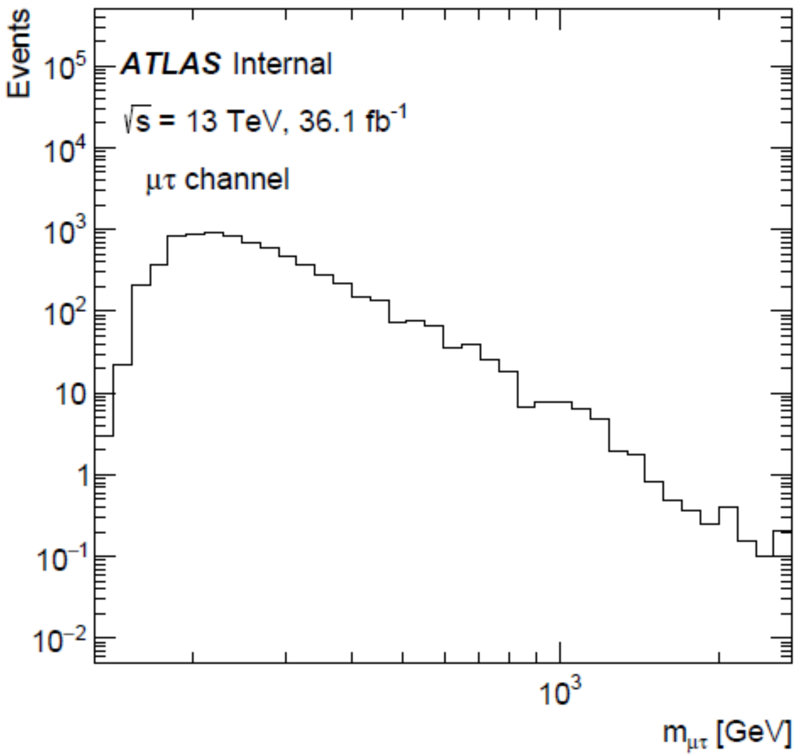
- The Wjets background is evaluated by applying the 2D τ_{FR} to the MC simulation.



(a) *eτ* channel

$N^{e\tau}_{Wjets}$=10159.3

~40% of total background

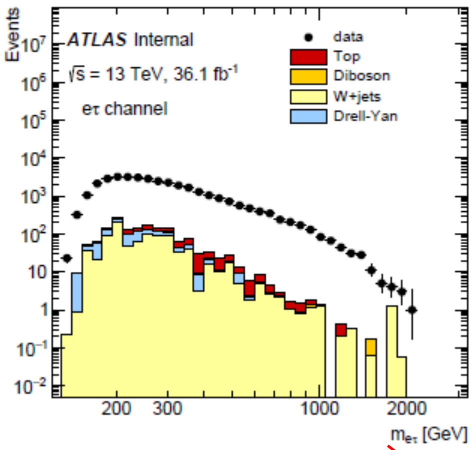


(b) *μτ* channel

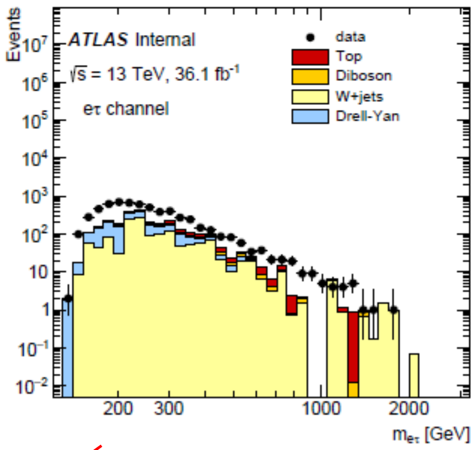
$N^{\mu\tau}_{Wjets}$=7335.44

~40% of total background

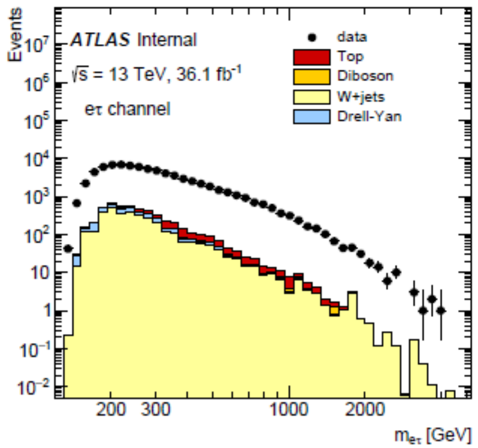
QCD estimation for eτ/μτ



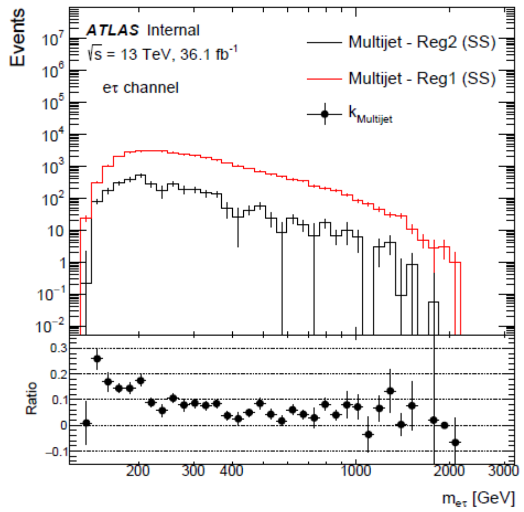
(a) $e\tau$ channel: Region 1



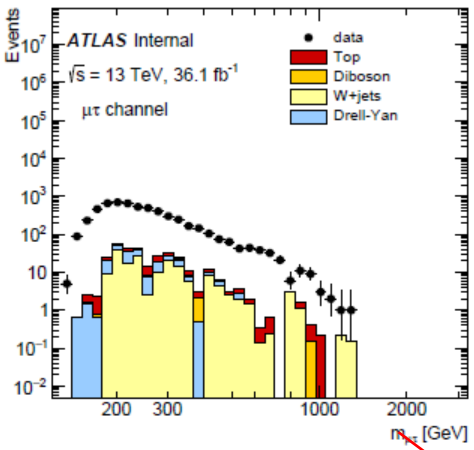
(b) $e\tau$ channel: Region 2



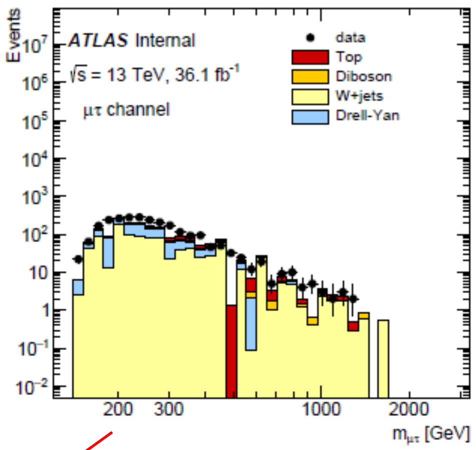
(c) $e\tau$ channel: Region 3



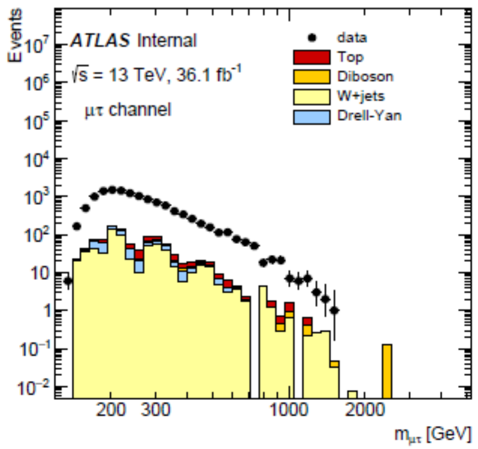
(a) $e\tau$ channel: K_{Multijet}



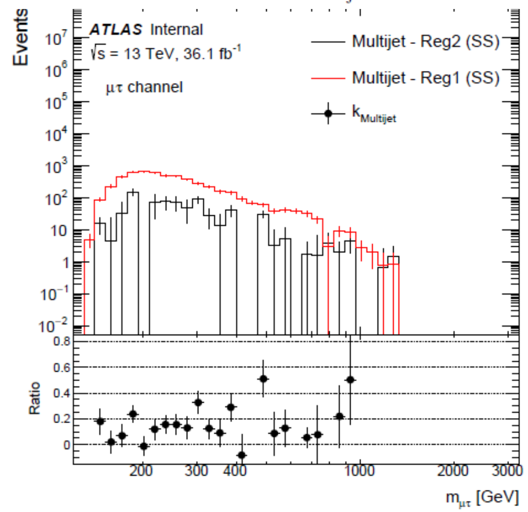
(d) $\mu\tau$ channel: Region 1



(e) $\mu\tau$ channel: Region 2



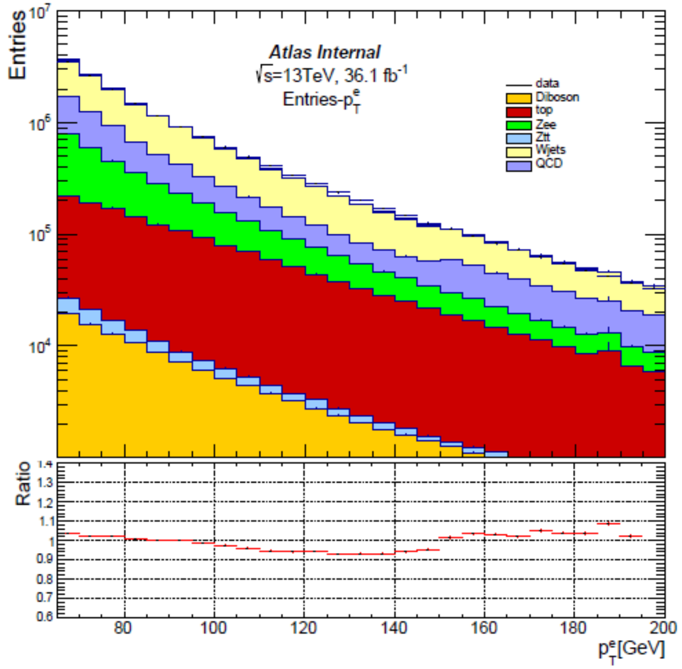
(f) $\mu\tau$ channel: Region 3



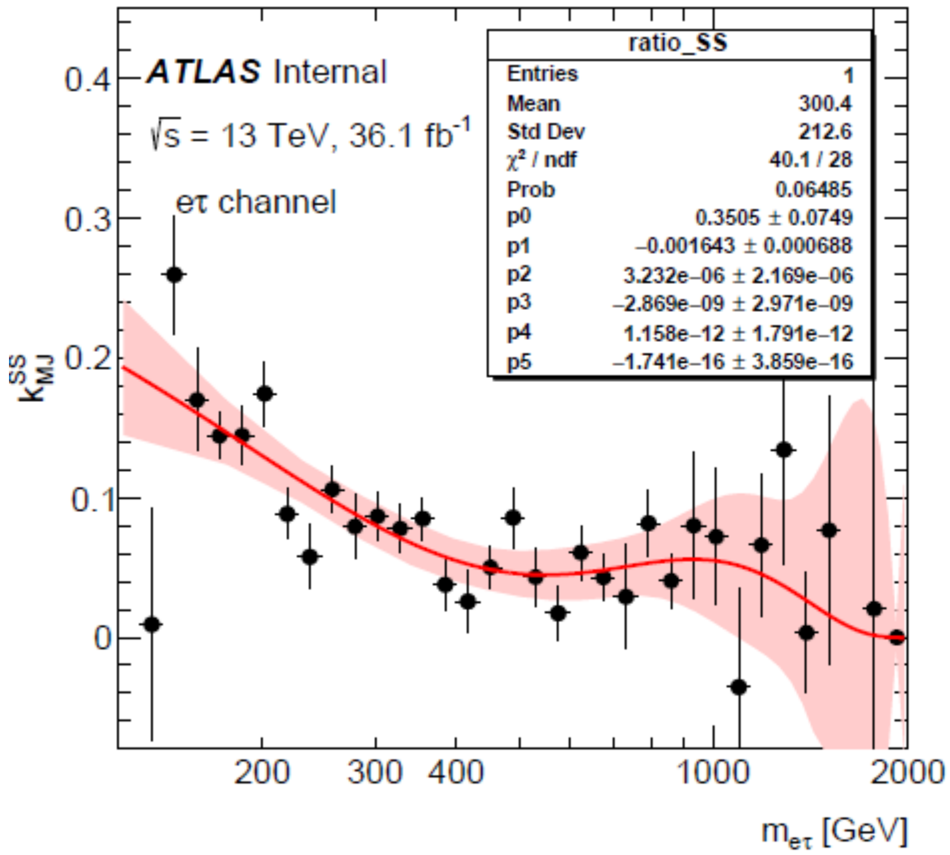
(b) $\mu\tau$ channel: K_{Multijet}

Wjet uncertainty

the electron fake rate is calculated in a multijet control region, but it is expected that the fake background is composed of a mixture of W+jets and multijet. As such, the jet to electron fake rate is recalculated using the subleading jet in the event instead of the leading one. This change in the kinematic definition of the jet is expected to account for the difference with the W+jets fake rate. The difference between the multijet and W+jets fake rates arises from the differences in the jet kinematics and flavour contributions of the processes. Both contributions will change when the jet kinematic definition is modified. This difference is expected to cover the difference between the fake rate in the two processes (W+jets and multijet)



QCD k factor


ATLAS Internal
√s = 13 TeV, 36.1 fb-1
eτ channel
ratio_SS
Entries 1
Mean 300.4
Std Dev 212.6
χ² / ndf 40.1 / 28
Prob 0.06485
p0 0.3505 ± 0.0749
p1 −0.001643 ± 0.000688
p2 3.232e−06 ± 2.169e−06
p3 −2.869e−09 ± 2.971e−09
p4 1.158e−12 ± 1.791e−12
p5 −1.741e−16 ± 3.859e−16
k^SS_MJ
m_eτ [GeV]
0.4
0.3
0.2
0.1
0
200
300
400
1000
2000