Search for lepton-flavor violation in high-mass dilepton final states in *pp* collisions at sqrt(*s*) = 13 TeV with the ATLAS detector

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Lepton Flavor Violation Search

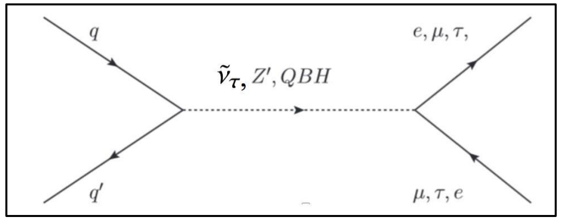
Neutrino oscillations $\Longrightarrow$ neutral lepton flavor violation

What about the charged leptons?

- Many new physics model involve new mechanism to explain neutrino oscillation, at the same time induce new interaction with CLFV
- LHC provides a unique chance to **directly** search for CLFV at TeV scale

High energy, high luminosity $\Longrightarrow$ direct search on new resonance $\Longrightarrow$ high sensitivity on new physics

- Search for new heavy resonance in different flavor, **high-mass** dilepton final state: $e\mu, e\tau, \mu\tau$
  - ATLAS full RunII, 13 TeV, 139 fb^{-1}
  - Search for excess on dilepton mass **m_{ll}, spectrum at TeV**
  - Simultaneous fit with SR and CRs performed independently for each channel



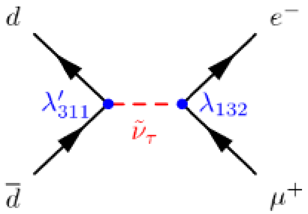
Results interpreted under three signal models: RPV τ-sneutrino, Z' vector boson and QBH

Signal Model

RPV SUSY Model

A scalar particle $\tilde{\nu}_\tau$ resonance is introduced under SUSY RPV model

- R-parity, $R = (-1)^{3(B-L)+2s}$
  - Conserved R-parity: stable Lightest Supersymmetric Particle ……
  - R-parity violation: new mechanism, superpartners could decay into ordinary particles
- RPV Superpotential $\frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k,$
- $\lambda_{ijk} = -\lambda_{jik}, \sigma_{e\mu} \cong 2 \times \sigma_{e(\mu)\tau}$



LFV Z' Model

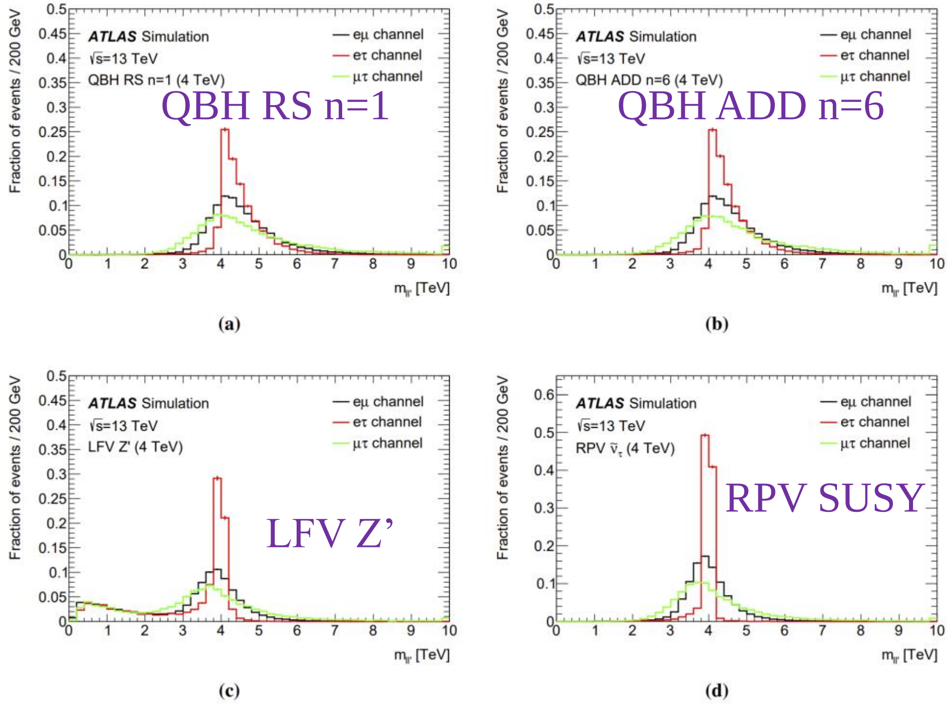
A vector particle Z' is introduced in this search

- Sequential Standard Model Z'
- Model extended to allow CLFV couplings
- Cross section takes the form $\sigma(q\bar{q} \to Z' \to l_i^- l_j^+) \propto \frac{(Q_{ij}^l)^2 M^2}{(M^2 - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$

Quantum Black Hole (QBH) Model

Two basic QBH models are introduced in this search

- pp collision may produce QBHs when the extra-dimensional Planck Scale is reached



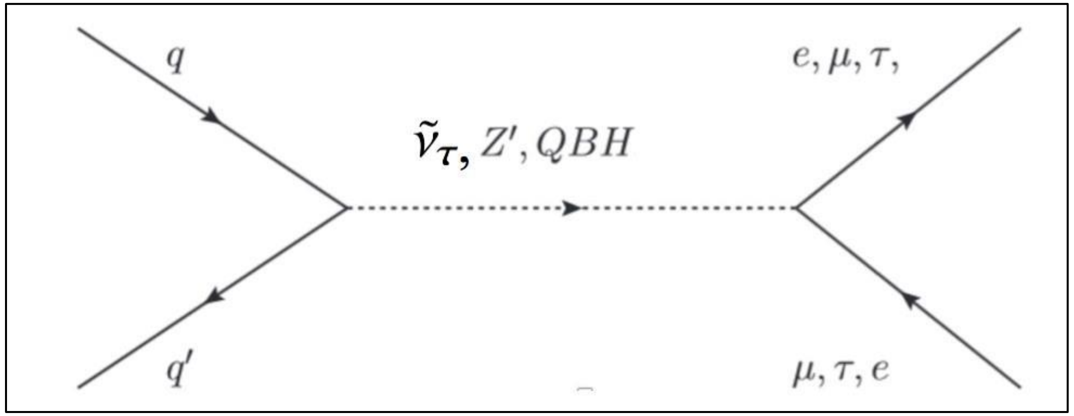
Signal mass distribution at 4 TeV

Introduction

Search for deviations from SM on $m_{ll'}$ spectrum

- 3 channels: $e\mu, e\tau_{had}, \mu\tau_{\text{had}}$
- SR, CRs: $m_{ll'} > 600\ GeV$
- Selection: clear signal feature
  - 3rd lepton veto, OS pair, $|\Delta\phi_{ll'}| > 2.7\ldots$
  - Also lepton quality cuts, isolation……
  - Main improvement on performance for this round:
    - τ RNN ID: fake background
    - b-veto: top background

$$qq \rightarrow X(Z', \widetilde{\nu_\tau}, QBH) \rightarrow ll'(e\mu, e\tau, \mu\tau)$$



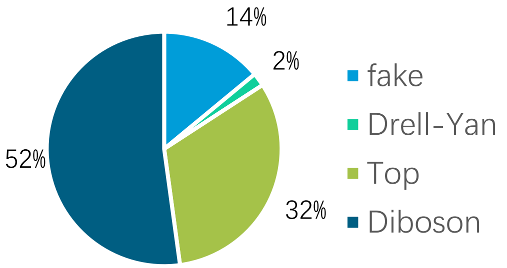
- Mass Reconstruction: suppose ν and the τ_{had} are nearly collinear : $\eta_\nu = \eta_{\tau_{had}}$

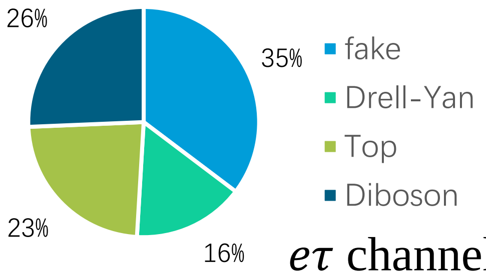
Background estimation

- **Irreducible background:** Top ($t\bar{t}$, tW), Diboson (mainly WW), Drell-Yan ($Z \rightarrow ll$) MC simulation, CR correction
- **Reducible background:** Mainly refers to W+jets and multi-jets backgrounds Data driven method

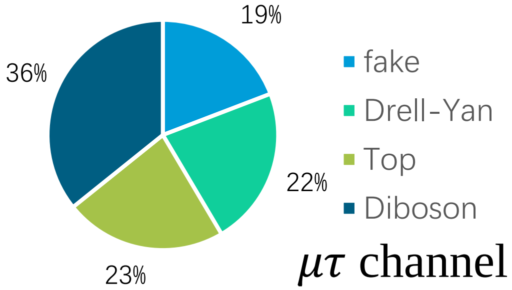
Background component different in each final state

$e\mu$ channel





$e\tau$ channel



$\mu\tau$ channel

- Fake: 4×4 matrix method
- Top, Diboson: Main background
  - Discrepancy found in CRs
  - Fit norm-factors $k_{\bar{t}t}, k_{WW}$ for Top and Diboson with CRs

- Fake: "Charge method"
  - A kind of 2-D side-band method for W+jets
  - Charge symmetry method for multi-jets
- Fake: Additional high mass extrapolation
- Top, Diboson:
  - Fit $k_{\bar{t}t}$ with CR, extrapolate k_{WW} from $e\mu$

Background estimation

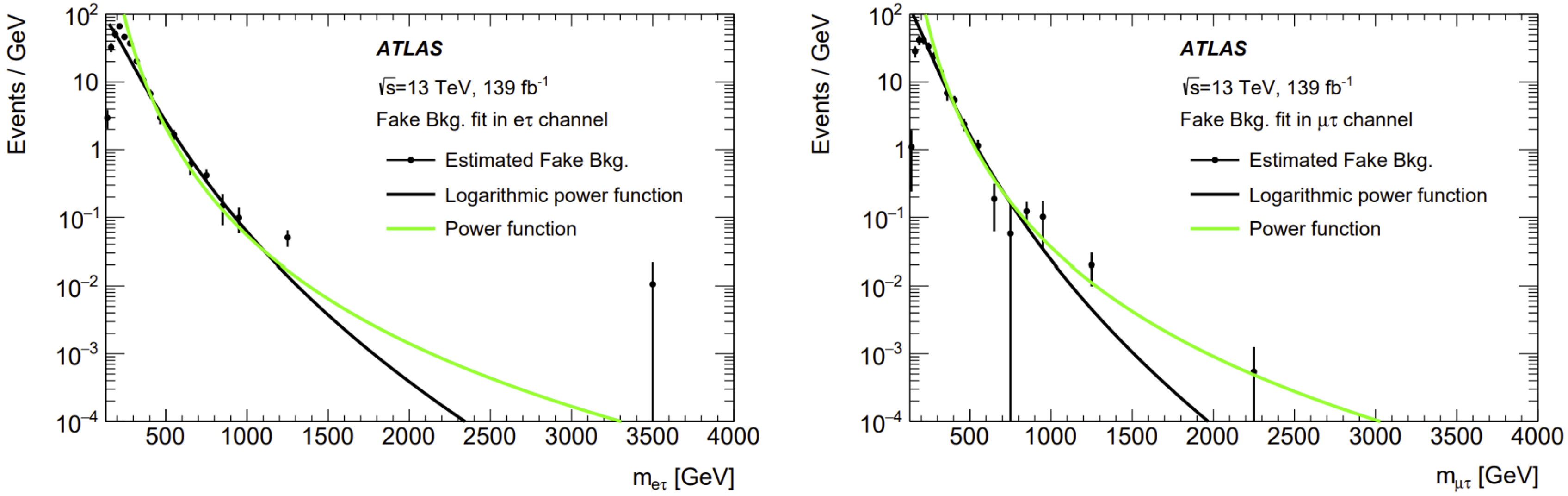
High mass extrapolation in τ channels

The "charge method" is limited by the statistics of the same sign Data and W+jets MC in the high mass

A fit to extrapolate the fake estimation to high mass

- Fit range: [340,3000] GeV;
- Application range: [600,10000] GeV
- Nominal fit function: "logarithmic power function", other as variation

- **The "logarithmic power function" :** $f(x) = Nx^{a+b\log(x)}$, where x is the invariant mass.
- **The "power function" :** $f(x) = Ax^{B}$, where x is the invariant mass.



(a) $e\tau$ channel **(b)** $\mu\tau$ channel

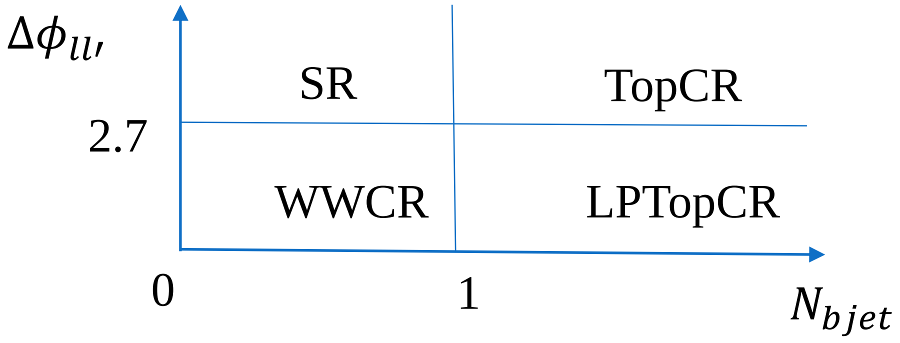
Background estimation

Top, Diboson Correction

Include CRs and normalization factors as free parameters in final simultaneous fit

$e\mu$ channel

Include additional LPTopCR to solve $\Delta\phi$ dependence

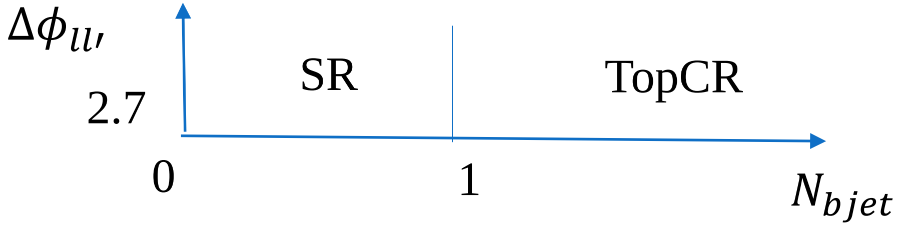


$e\mu$ channel, $m_{ll} > 600$ GeV

τ channels

Difficult to define a high purity WW control region

$k_{\bar{t}t}$ derived from Top CR, k_{WW} extrapolate from $e\mu$ channel



τ channels, $m_{ll} > 600$ GeV

Based on lepton flavor universality:

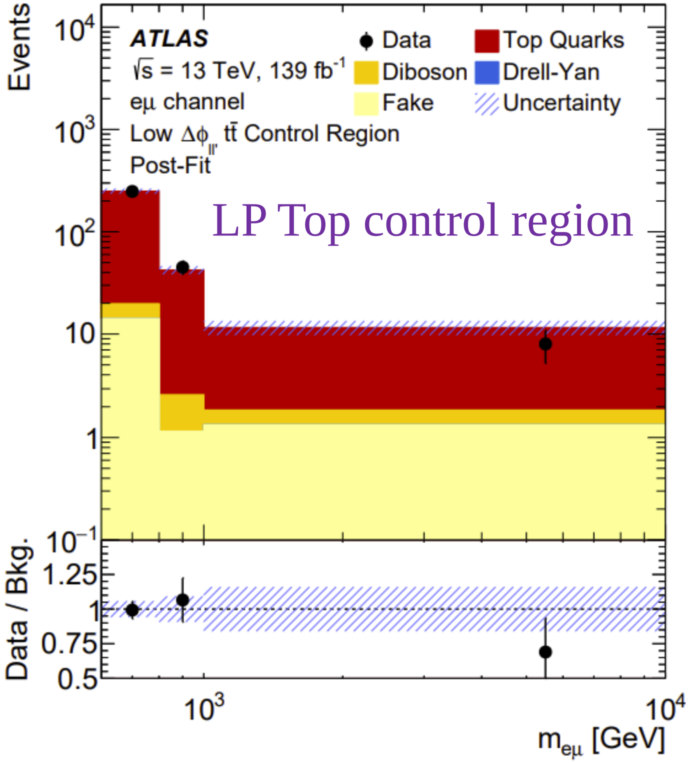
$$\frac{k_{WW}^{e(\mu)\tau}}{k_{WW}^{e\mu}} = \frac{k_{t\bar{t}}^{e(\mu)\tau}}{k_{t\bar{t}}^{e\mu}} \qquad k_{WW}^{e(\mu)\tau} = k_{WW}^{e\mu} \times \frac{k_{t\bar{t}}^{e(\mu)\tau}}{k_{t\bar{t}}^{e\mu}}.$$

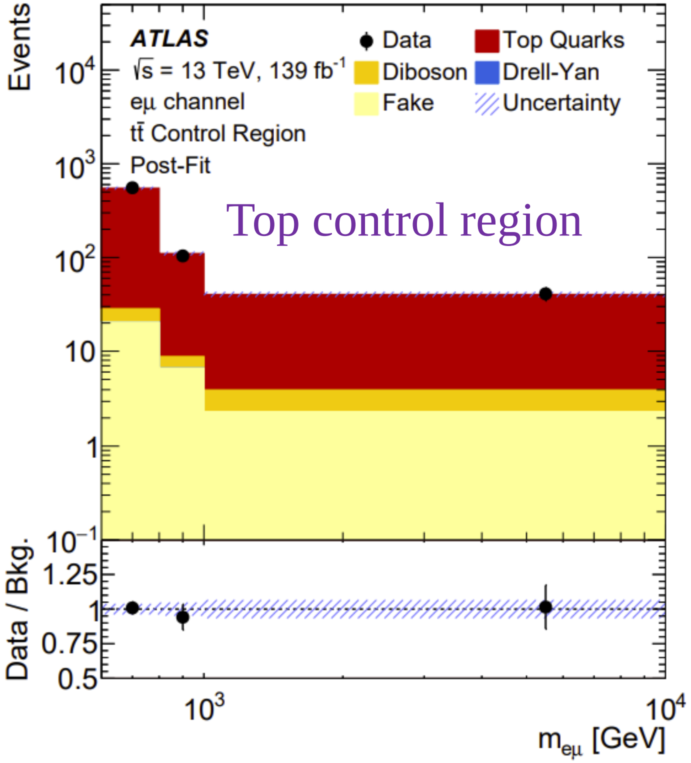
Correction factor	$e\mu$	$e\tau$	$\mu\tau$
Top Quarks	0.89±0.06	0.94±0.11	0.97±0.11
Diboson	0.94±0.11	1.05±0.12	1.00±0.12

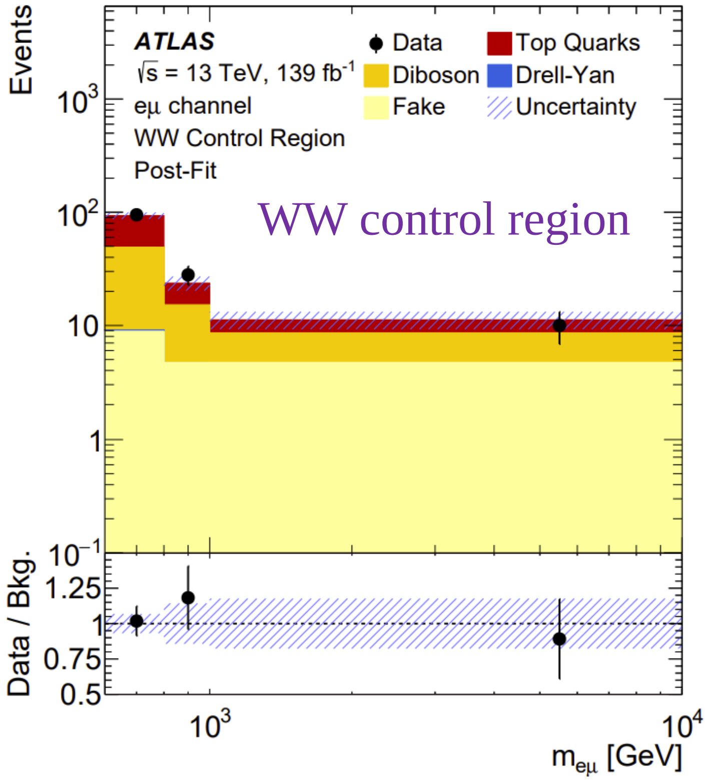
Control Region Agreement: $e\mu$ channel

- The binned profile-likelihood fits are performed, following a modified frequentist method
- The background-only fit result for $e\mu$ channel
- It shows good agreement between data and estimated background in CRs

Process	$t\bar{t}$ CR	WW CR	Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR
Top Quarks	660±27	55.4±5.9	279±18
Diboson	11.3±2.4	54.3±8.4	7.5±2.3
Fake	29.3±5.9	18.3±3.8	16.6±4.9
Drell–Yan	0.25±0.03	0.26±0.03	0
Total background	701±26	128.2±8.3	304±17
Data	700	133	301



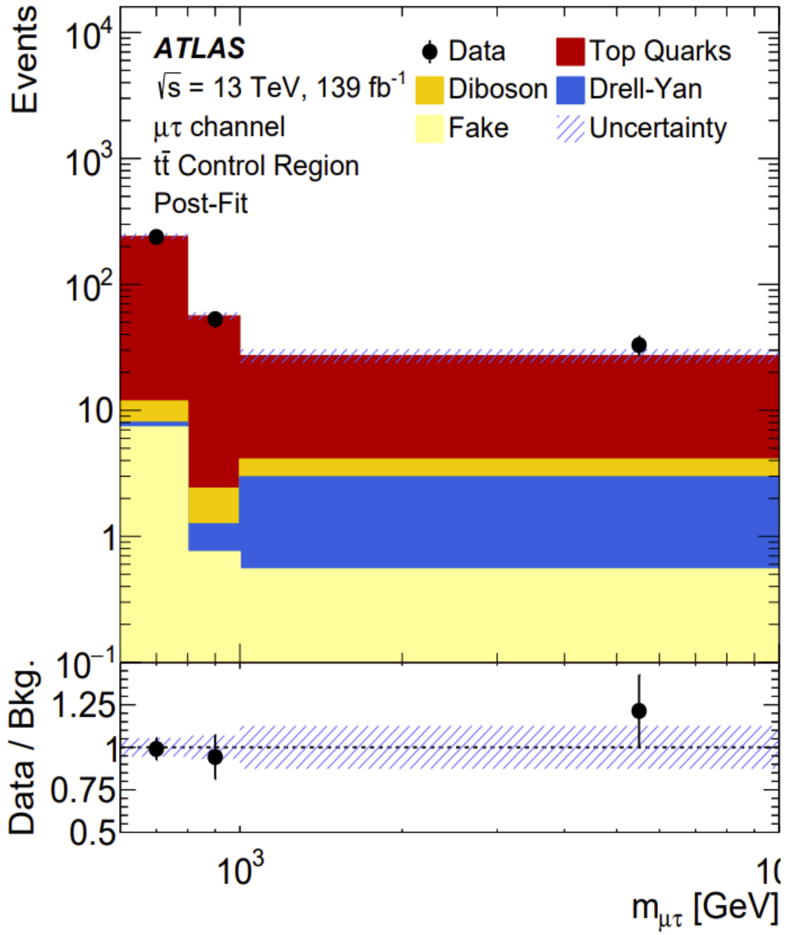




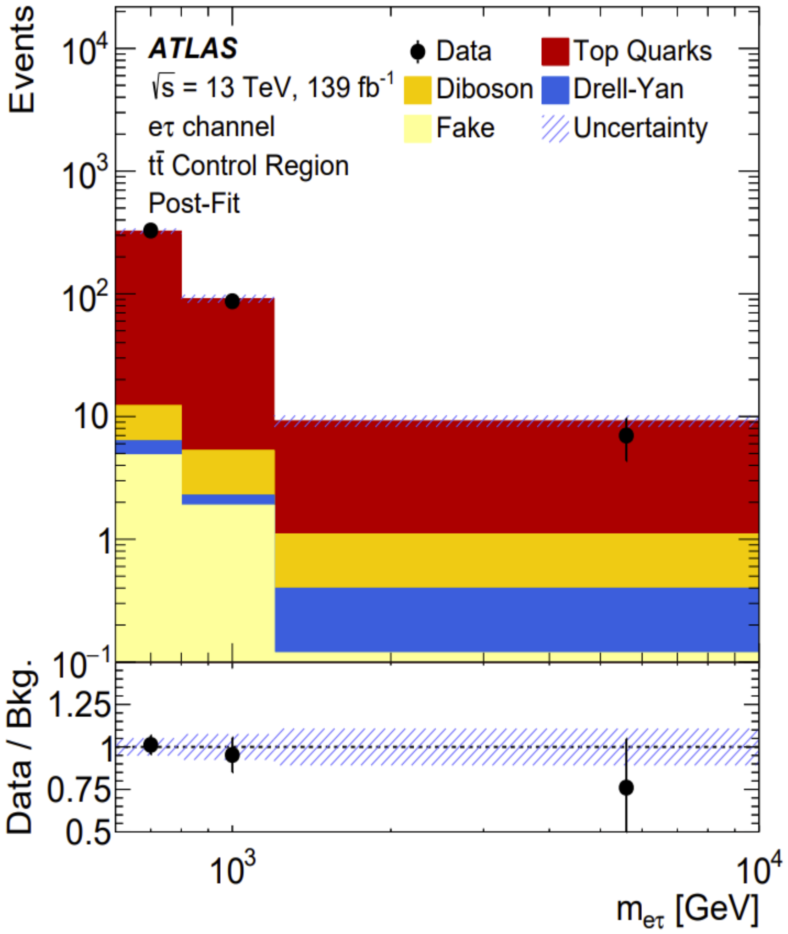
Control Region Agreement: $e\tau, \mu\tau$ channel

- The background-only fit result for $e\tau, \mu\tau$ channel
- Fake is estimated by W+jets MC
- It shows good agreement between data and estimated background in CRs

Process	$e\tau$ channel $t\bar{t}$ CR	$\mu\tau$ channel $t\bar{t}$ CR
Top Quarks	406±21	305±17
Diboson	9.6±2.8	6.1±1.6
Fake	6.8±1.2	8.6±2.6
Drell–Yan	2.1±0.1	3.6±0.7
Total background	424±20	324±17
Data	422	324



$e\tau$ channel

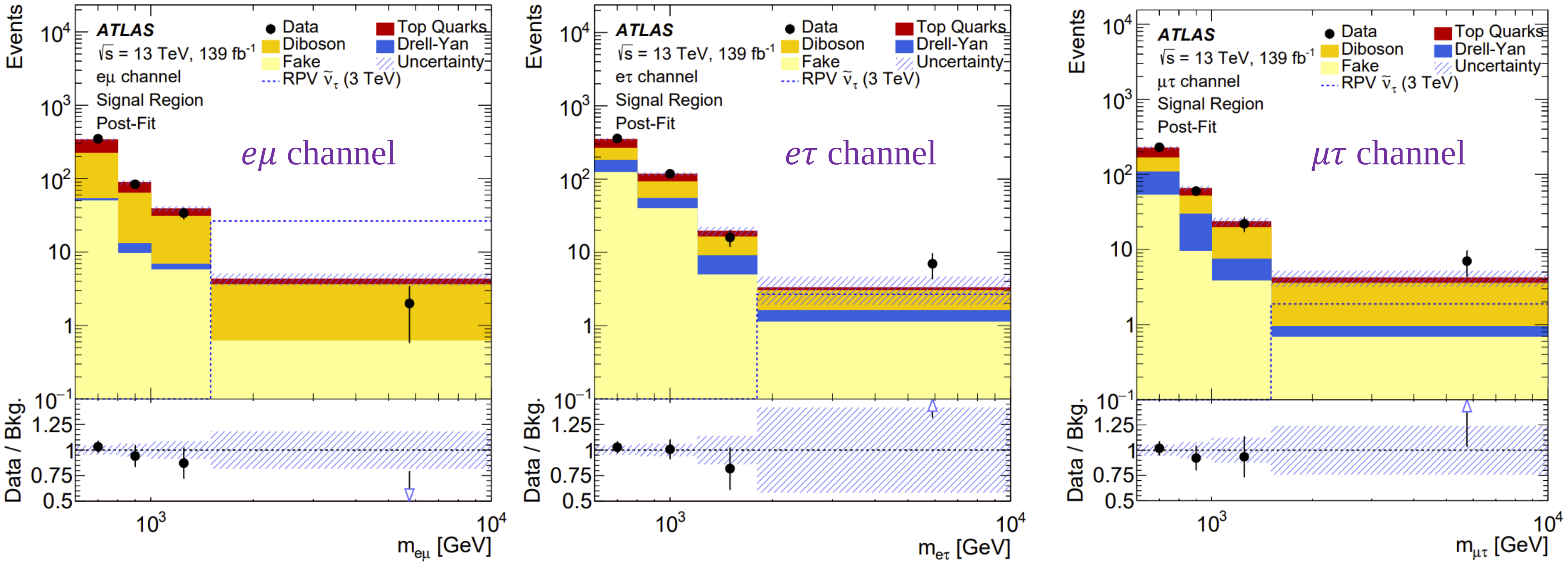


$\mu\tau$ channel

Signal Region Comparison

- The background-only fit result for Signal Region
- In the last bin, SM expectations are statistically consistent with the data within 2σ

Process	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
Top Quarks	151±15	114±10	79.4±6.4
Diboson	246±28	125±27	94±20
Fake	66±11	172±34	67±25
Drell–Yan	8.6±0.5	76.1±8.9	78.0±7.9
Total background	471±21	488±21	319±16
Data	470	499	319



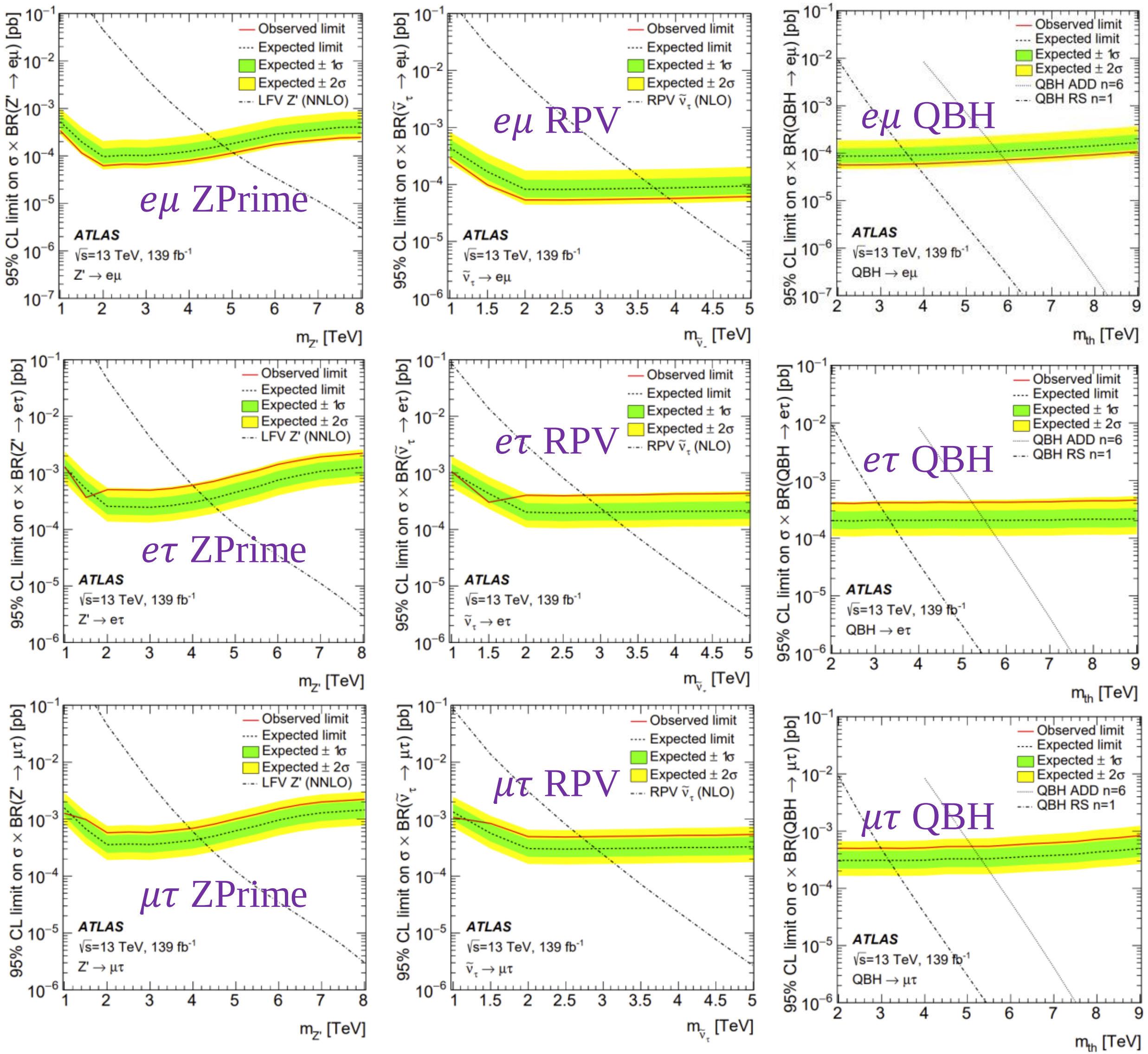
Uncertainties

- Summary of the different sources of uncertainty on the post-fit observed signal strength
  - RPV SUSY model at 3 TeV as an example, other signals have similar results
  - The total uncertainties are dominated by the data (and MC) statistics in all three channels.
  - In $e\mu$, major systematic uncertainty comes from theory and normalization factor
  - In $e\tau$ and $\mu\tau$, major systematic uncertainty comes from τ performance and fake estimation

Source of uncertainty (in percent)	Impact on observed $\mu_{\mathrm{RPV}}^{e\mu}$	Impact on observed $\mu_{\mathrm{RPV}}^{e\tau}$	Impact on observed $\mu_{\mathrm{RPV}}^{\mu\tau}$
Electrons	2.2	0.85	NA
Muons	2.8	NA	4.4
τ-leptons	NA	9.7	11
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1	0.8	0.8
Flavour tagging	2.1	<0.1	0.1
Other (luminosity, JVT, pile-up)	0.6	0.4	0.7
Fake backgrounds	0.6	3.2	9.7
Background modelling	9.6	2.1	7.3
Top and Diboson normalisations	8.7	1.6	1.8
Simulation statistical uncertainty	28	9.6	15
Total systematic uncertainty	32	14	23
Data statistical uncertainty	53	48	71
Total uncertainty	62	50	74

Results

No significant excess observed, 95% CL upper limits on the production cross-section and signal mass are set for each model



- The upper limits are computed in the CL_S method with the asymptotic approximation
- Mass limits improved by about 0.5 TeV compared to 36.1 fb-1 results for Z' model

Model	Observed (expected) 95% CL lower limit [TeV]		
	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
LFV Z'	5.0 (4.8)	4.0 (4.3)	3.9 (4.2)
RPV SUSY $\tilde{\nu}_\tau$	3.9 (3.7)	2.8 (3.0)	2.7 (2.9)
QBH ADD $n = 6$	5.9 (5.7)	5.2 (5.5)	5.1 (5.2)
QBH RS $n = 1$	3.8 (3.6)	3.0 (3.3)	3.0 (3.1)

Summary

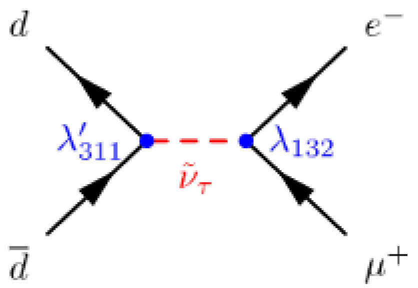
- A search for new heavy particle decaying into $e\mu, e\tau_{had}, \mu\tau_{had}$ final states aiming for lepton flavor violation
  - Using ATLAS full RunII Data, 13 TeV, 139 fb^{-1}
  - No significant deviation from standard model was found
  - 95% CL upper limits on the production cross-section and signal mass are set for each model: Z’, RPV SUSY and QBH
- Main improvement:
  - ~4 times larger statistics
  - Background estimation update: high mass extrapolation fit in tau channel, simultaneous fit for Top and Diboson correction, matrix method……
  - Application of b-jet veto and tau RNN ID
- This result has been published in JHEP10(2023)082

Backup

Signal Model

RPV SUSY Model

A scalar particle $\tilde{\nu}_\tau$ resonance is introduced under SUSY RPV model



- R-parity, $R = (-1)^{3(B-L)+2s}$ is introduced in the SUSY model
  - Conserved R-parity: stable Lightest Supersymmetric Particle ……
  - R-parity violation: new mechanism, superpartners could decay into ordinary particles
- RPV Superpotential:

$$\mathcal{W}_{\not{R}_p} = \frac{1}{2}\epsilon_{ab}\lambda_{ijk}\hat{L}_i^a\hat{L}_j^b\hat{E}_k + \epsilon_{ab}\lambda'_{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{D}_k + \frac{1}{2}\epsilon_{\alpha\beta\gamma}\lambda''_{ijk}\hat{U}_i^\alpha\hat{D}_j^\beta\hat{D}_k^\gamma + \epsilon_{ab}\delta_i\hat{L}_i^a\hat{H}_2^b$$

- In hadron colliders, single sneutrino can produce by $\hat{L}\hat{Q}\hat{D}$ coupling and decay by $\hat{L}\hat{L}\hat{E}$ coupling to dilepton final state
- λ_{ijk} should be antisymmetric with i, j due to the gauge invariance, that means $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda_{iik} = 0$ *
- As our signal is τ-sneutrino, we only have LFV terms $\lambda_{132}(e\mu), \lambda_{231}(e\mu), \lambda_{133}(e\tau), \lambda_{233}(\mu\tau)$ and $\lambda_{331}(e\tau), \lambda_{332}(\mu\tau)$ is forbidden. So $e\mu$ cross section is 2 times larger than τ channels. **
  - Each LFV final state is considered separately

* RPV Report: R-Parity-violating supersymmetry – ScienceDirect, arXiv: hep- ph/0406039
** Pervious result do not consider the antisymmetry and then have nonzero λ331 and λ332 in the model files, detail in: https://its.cern.ch/jira/browse/AGENE-1853.

Objects and event selection

Muon

$P_T, |\eta|: > 65\ GeV, < 2.5$
ID: HighPT
Track: $|d_0/\sigma_{d_0}| < 3$
$|z_0 sin\theta| < 0.5\ mm$
Isolation: FCLoose

Electron

$P_T, |\eta|: > 65\ GeV, < 2.47$
ID: LH-Tight
Track: $|d_0/\sigma_{d_0}| < 5$
$|z_0 sin\theta| < 0.5\ mm$
Isolation: FCTight

Tau

$P_T, |\eta|: > 65\ GeV, < 2.5$
ID: RNN Medium
Track: 1 or 3 prong(s)
Veto: $e - \tau$ BDT-based veto

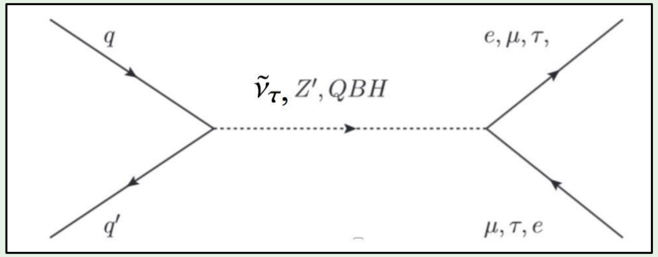
Jet

$P_T, |\eta|: > 30\ GeV, < 2.5$
DL1R: 85% eff WP

For electron and taus crack region ($1.37 < |\eta| < 1.52$) excluded
Overlapping objects removed using OLR Tool

Selection Criteria

Pre-selection : remove events with error status flag on detectors
Primary Vertex : at least to tracks associated with $p_T > 400$ MeV
Trigger: Combination of single electron/muon triggers
Bad muon veto : remove events with muon flagged as 'bad'
Jet-cleaning : remove events with at least one jet flagged as 'bad'



3rd Lepton Veto: events with an good lepton are rejected. For $e\mu$ also events with additional 'Loose' muon or electron are rejected.
Trig. Match: At least one trigger matched lepton
DeltaPhi: $\Delta\phi_{\ell\ell'} > 2.7$
Opposite-sign pairs

Data-driven method systematics

$e\mu$ channel

4×4 matrix method:

- Real efficiency measurement:
  - Overall Unc: Comparing Z+0jets and Z+njets
- Fake efficiency measurement:
  - CR definition: MET, MT, TTVA (for muon)
  - Jet kinematics: covered by

$e\tau, \mu\tau$ channel

Charge method:

- Experimental efficiency/calibration propagation
- W+jets CR definition
- Theoretical uncertainty on W+jets MC shape
- Method agreement: 20% based on a validation CR

Fit method:

- Fit function: "power function" as variation
- Fit statistics: calculate by the correlation matrix from Minuit2