Search for lepton flavour violation with the ATLAS detector

16-Aug-2018 NuFACT 2018 Blacksburg

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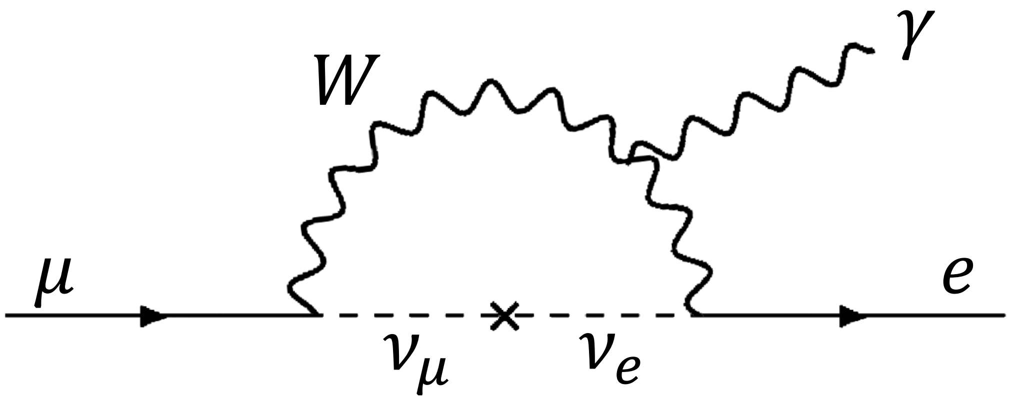
- Introduction
- LHC and the ATLAS detector
- Searches:
  - Decays of Standard-Model (SM) particles
  - Decays of hypothetical particles / objects
- Summary

Introduction – Lepton Flavour Violation

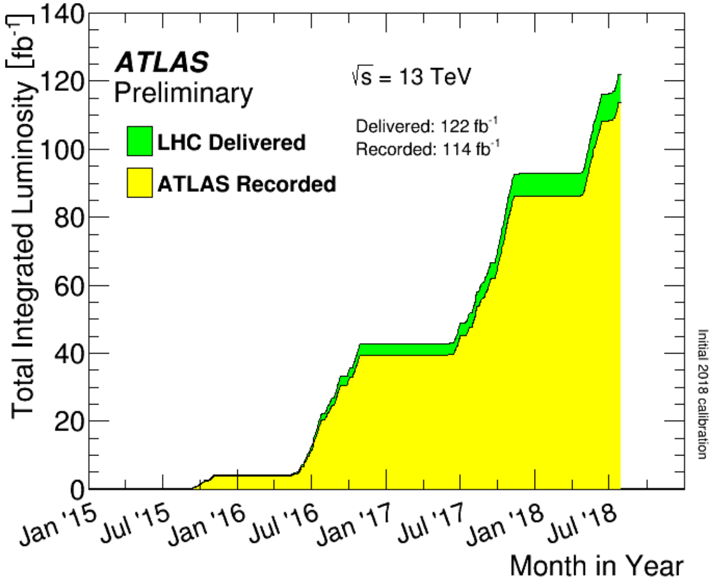
- Flavour conservation is **not** a fundamental symmetry in the SM
- Fermions do change flavour:
  - Quarks: CKM matrix → quark mixing observed
  - Leptons: PMNS matrix → neutrino mixing observed
- How about charged leptons?
  - → (charged) Lepton Flavour Violation (cLFV)
  - Not observed yet
- In the SM
  - Loop with neutrino oscillations
  - Vanishingly small branching ratios



- BSM
  - Various models: Supersymmetry, extended gauge models, heavy neutrinos, etc.
  - Some predict LFV couplings to be tested at the LHC
  - Unambiguous signal: observation = new physics phenomena!

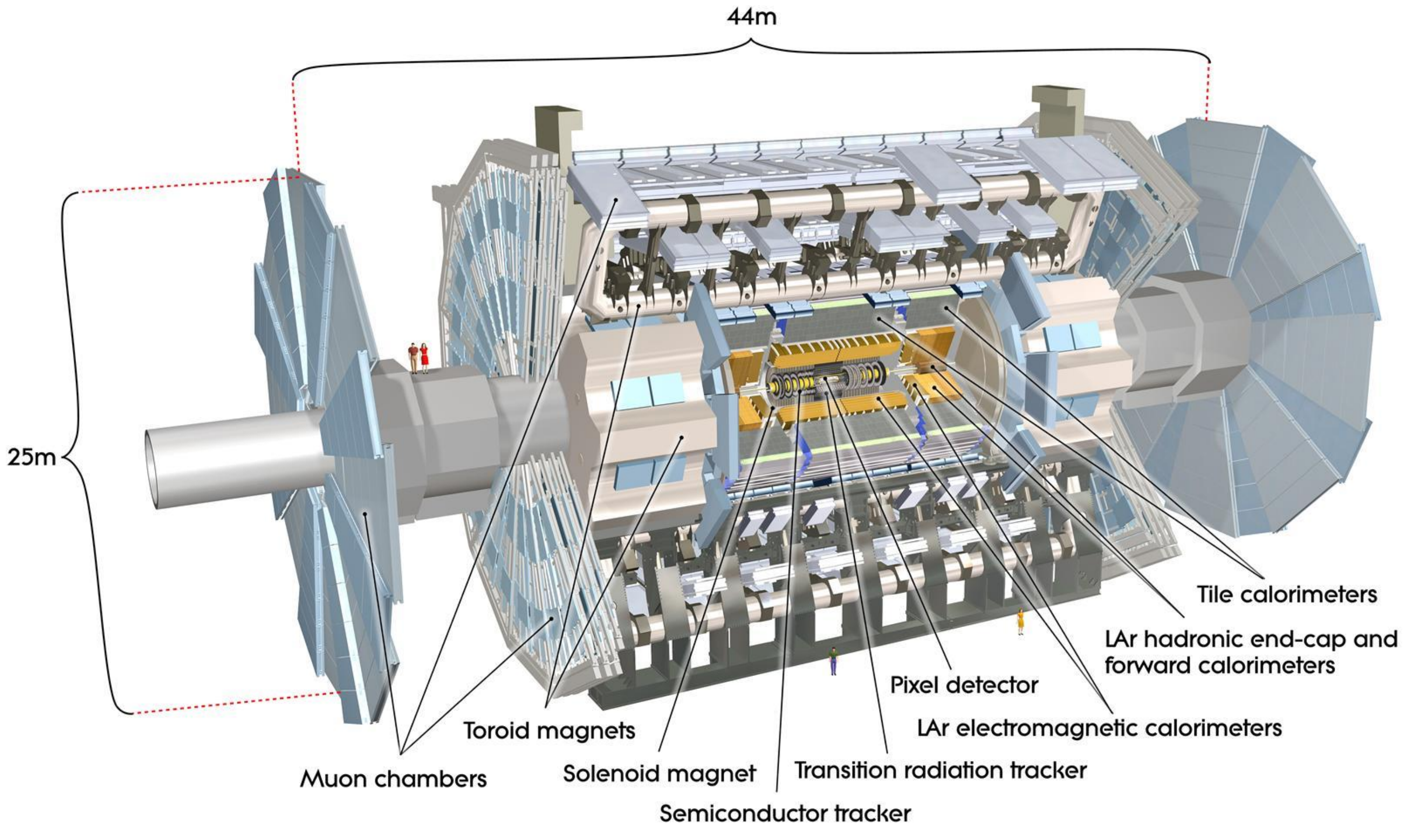
The Large Hadron Collider (LHC)

- World's largest and most powerful particle accelerator
  - 27-km ring near Geneva, Switzerland
  - Completed first operational run ("Run 1"):
    - 2010-2011: pp collisions at $\sqrt{s} = 7$ TeV ($5\ \mathrm{fb}^{-1}$)
    - 2012: pp collisions at $\sqrt{s} = 8$ TeV ($21\ \mathrm{fb}^{-1}$)
  - Currently in second operational run ("Run 2"):
    - 2015-2018: pp collisions at $\sqrt{s} = 13$ TeV (expecting $\sim 150\ \mathrm{fb}^{-1}$)



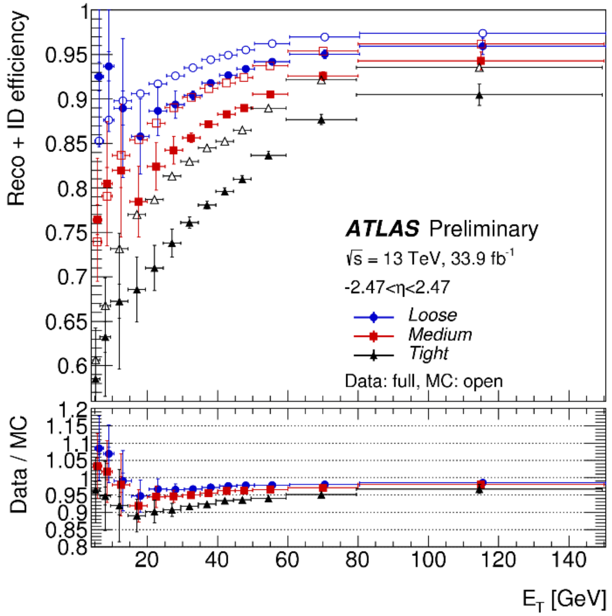
The ATLAS detector

- General-purpose particle detector at the LHC
- Inner detector (ID)
  - High-precision tracking
  - Silicon pixels / strips + transition radiation trackers
- Calorimeters
  - EM: liquid argon (LAr)
  - Hadronic: scintillating tiles + LAr endcaps
- Muon spectrometer (MS)
  - Muon identification and tracking
- Magnet systems
  - Solenoidal (ID)
  - Toroidal (MS)

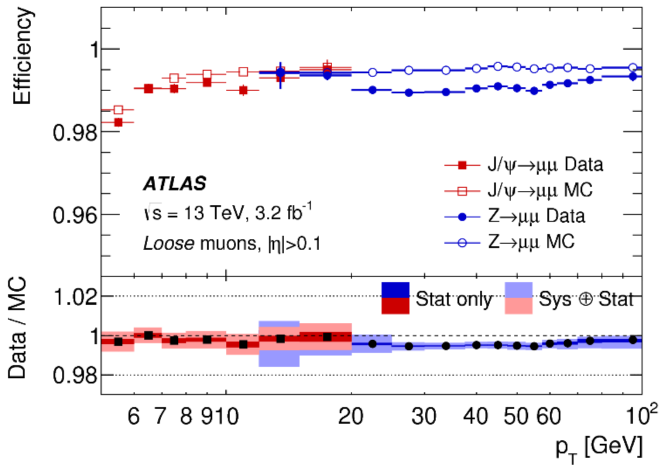


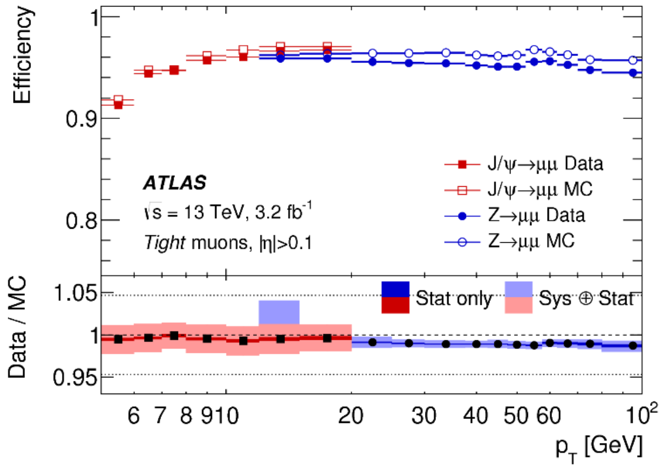
The ATLAS detector – Lepton efficiencies

Loose/*Medium*/*Tight* electrons

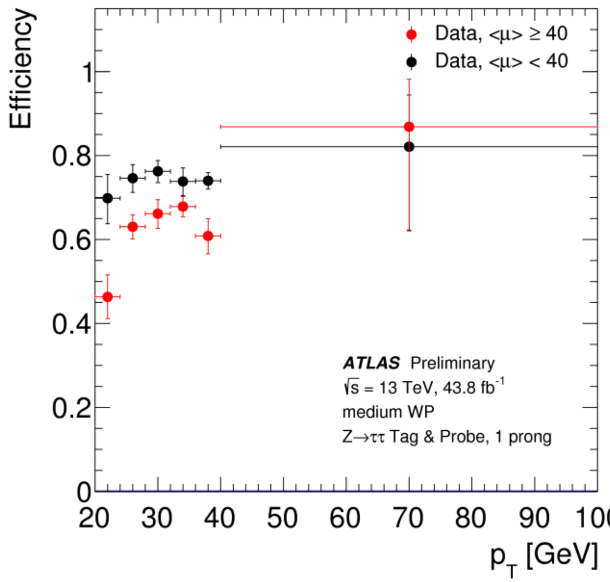


Loose (top) / *Tight* (bottom) muons





Medium 1-prong τ-leptons



Searches with the ATLAS detector

- Decays of Standard-Model particles:
  - $Z \to e\mu$; $Z \to e\tau/\mu\tau$ New update!! arXiv:1804.09568
  - $H \to e\tau/\mu\tau$
  - $\tau \to 3\mu$
- Decays of hypothetical particles / objects: New update!! arXiv:1807.06573
  - Z' – Heavy gauge boson
  - $\tilde{\nu}$ – R-parity violating supersymmetry (RPV SUSY) sneutrino
  - QBH – Quantum black hole

$Z \to e\mu$

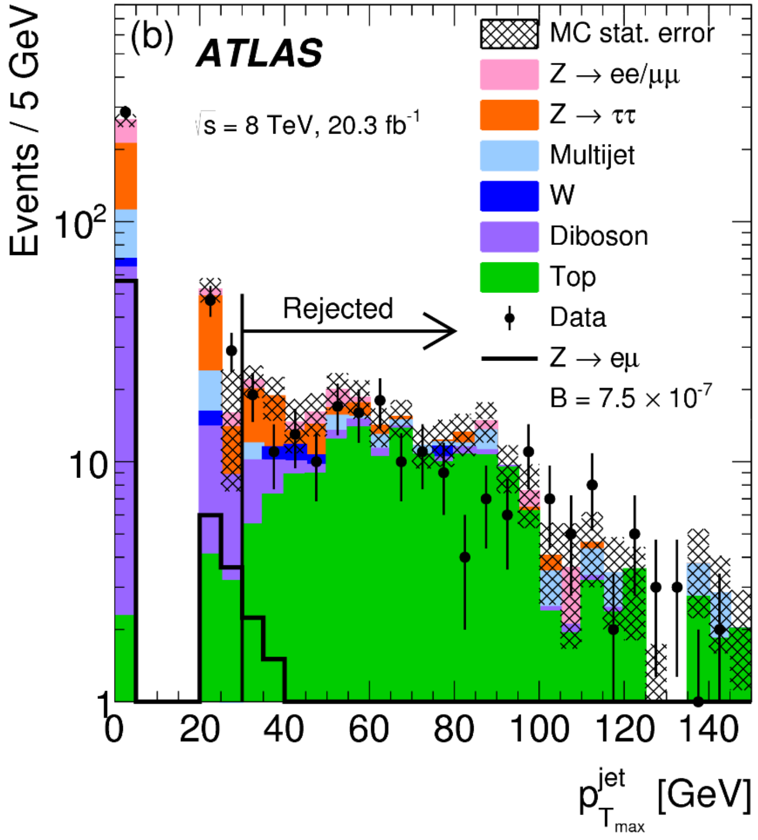
arXiv:1408.5774

- Dataset
  - $20.3\ \mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 8\ \mathrm{TeV}$ (2012)
- Major backgrounds
  - $Z \to \tau\tau \to e\mu\nu\bar{\nu}\nu\bar{\nu}$
  - $WW \to e\mu\nu\bar{\nu}$
  - $t\bar{t} \to e\mu\nu\bar{\nu}b\bar{b}$
- Strategy
  - Reject events with high-energy jets → suppress $t\bar{t}$
  - Reject events with large transverse missing energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) → suppress WW
  - Fit $e\mu$ invariant mass spectrum → search for signal peaking near the Z mass

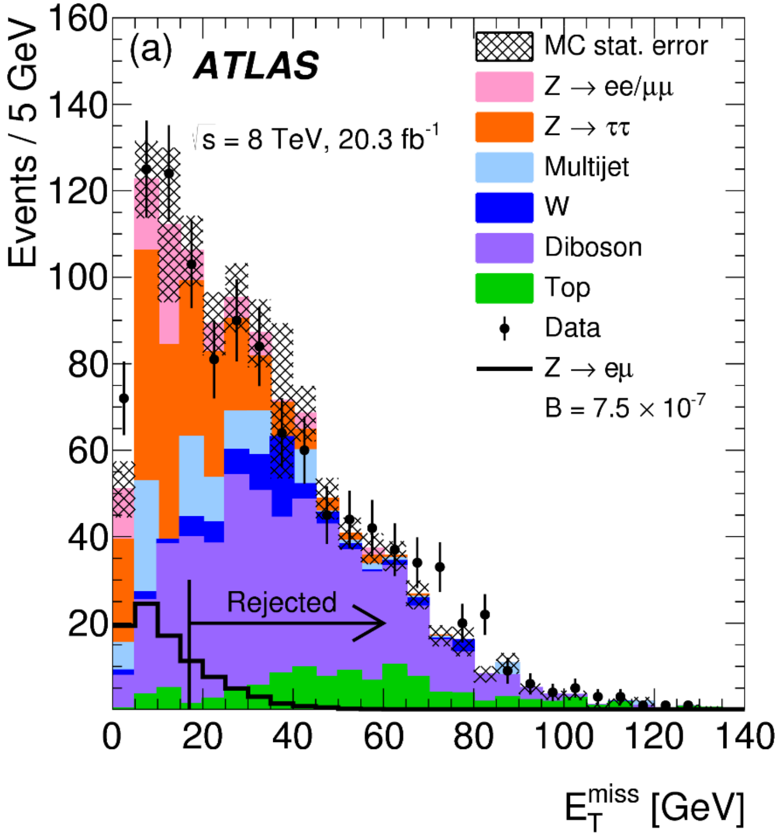
$Z \rightarrow e\mu$

arXiv:1408.5774

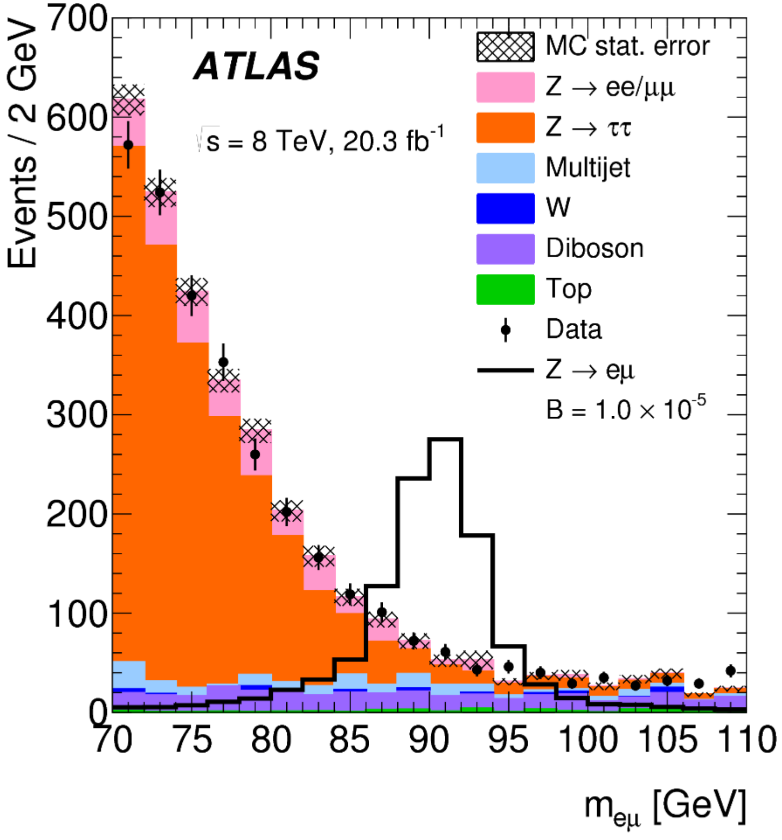
Rejection of events with high-energy jets ($p_{\mathrm{T}_{\max}}^{\mathrm{jet}}$)



Rejection of events with large $E_{\mathrm{T}}^{\mathrm{miss}}$



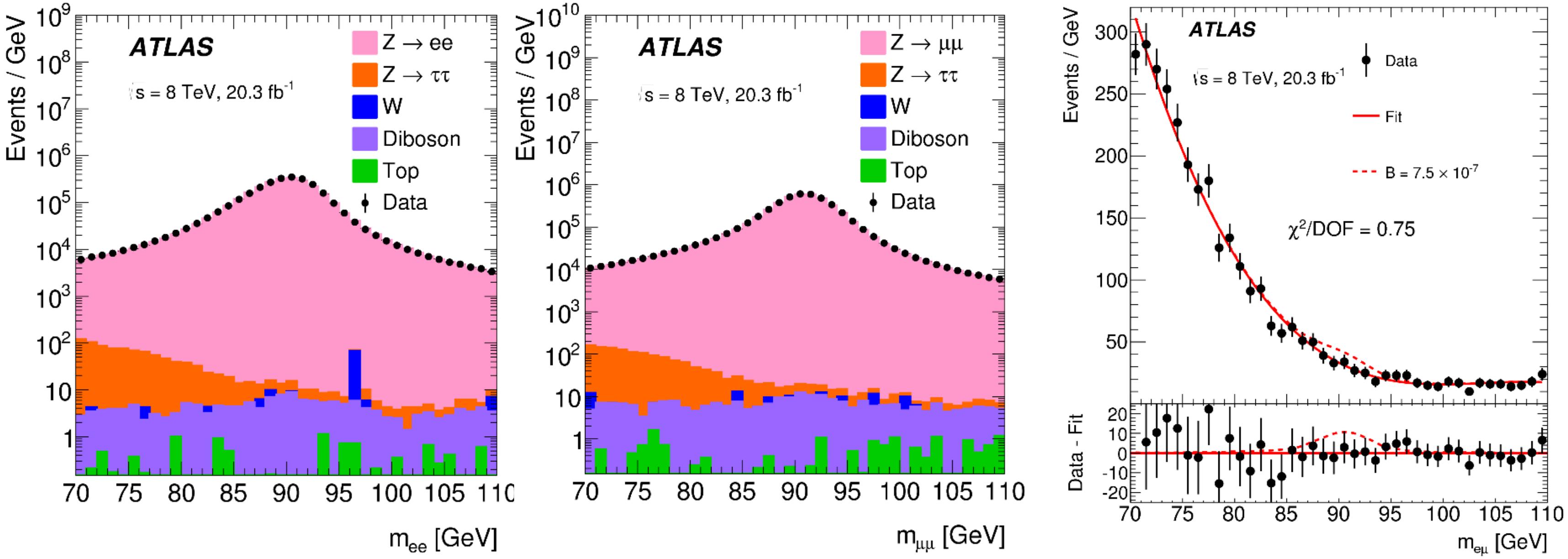
Invariant mass ($m_{e\mu}$) spectrum after all cuts



$Z \to e\mu$

arXiv:1408.5774

- Results and interpretation
  - Upper limit (95% CL) on the branching ratio is calculated by $\mathrm{BR}(Z \to e\mu) < \frac{N_{95\%}}{\epsilon_{e\mu} N_Z}$
  - $N_Z =$ total number of produced Z bosons, estimated by $Z \to ee$ and $Z \to \mu\mu$ measurements
  - $\epsilon_{e\mu}$ = reconstruction efficiency of $e\mu$ events
  - $N_{95\%} =$ upper limit on number of $Z \to e\mu$ events, obtained by fitting $m_{e\mu}$ spectrum
  - Upper limit (95% CL): $\mathrm{BR}(Z \to e\mu) < 7.5 \times 10^{-7}$



$Z \to e\tau/\mu\tau$

New update! arXiv:1804.09568

- Dataset
  - $36.1\ \mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ (2015-2016)
  - Results for $Z \to \mu\tau$ combined with previous analysis with $20.3\ \mathrm{fb}^{-1}$ 8-TeV data (2012)

arXiv:1604.07730

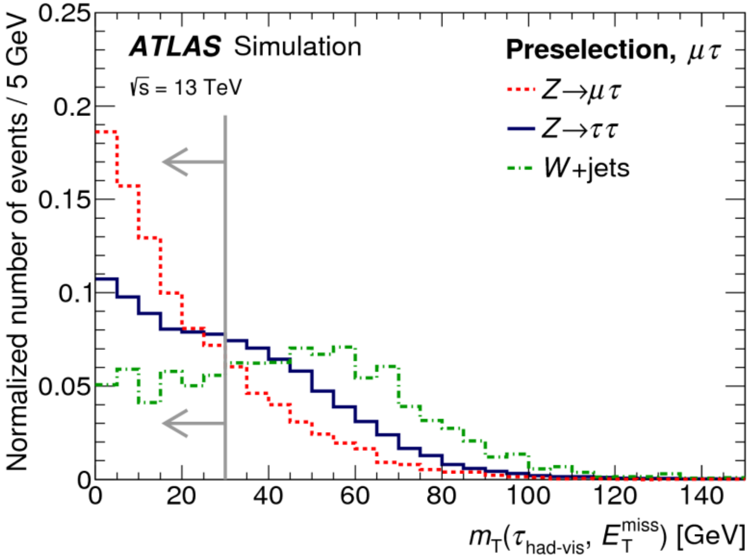
- Focus on channels with hadronically-decaying τ
- Major backgrounds
  - $Z \to \tau\tau \to \ell\tau_{\mathrm{had}}$ ($\ell = e/\mu$; τ_{had} = hadronically-decaying τ)
  - $W(\to \ell\nu) + \mathrm{jets}$ (jets mis-identified as τ_{had}, aka "jet $\to \tau$ fakes")
  - $Z \to \ell\ell$ (e/μ mis-identified as τ_{had}, aka "$\ell \to \tau$ fakes")
- Strategy
  - Reject events with high $m_{\mathrm{T}}\left(\tau_{\mathrm{had\text{-}vis}}, E_{\mathrm{T}}^{\mathrm{miss}}\right)$ → suppress $Z \to \tau\tau$ / W+jets
  - Reject events with visible invariant mass $\approx m_Z$ → suppress $Z \to \ell\ell$
  - Estimate jet $\to \tau$ fakes by data-driven method
  - Discriminate events by neural network (NN) and fit on output

$Z \to e\tau/\mu\tau$

New update!

arXiv:1804.09568

Rejection of events with high $m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}})$



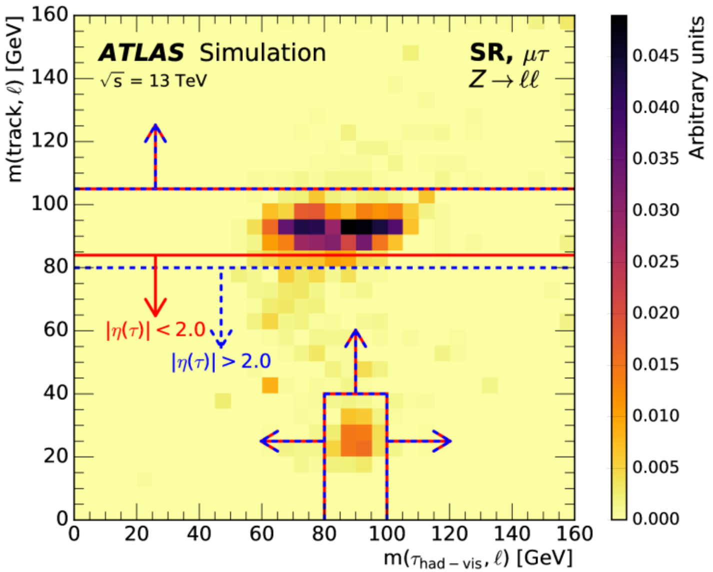
*Plot for the $e\tau$ channel is similar

Rejection of events based on visible invariant mass

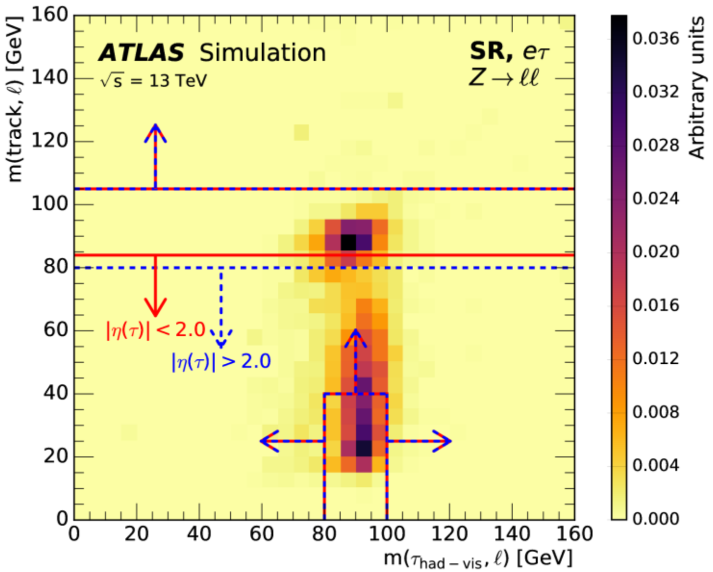
$m(\text{track}, \ell)$: τ energy measured by ID tracking

$m(\tau_{\text{had-vis}}, \ell)$: τ energy measured by calorimeters

$Z \to \mu\mu$



$Z \to ee$



$Z \to e\tau/\mu\tau$

New update!

arXiv:1804.09568

- **Data-driven jet $\to \tau$ fakes estimation**
  - jet $\to \tau$ fakes not well modelled in simulation
  - Measure *fake factors* (FF) in *calibration regions* (CR) using data

1. Measure FF in CR:
FF = ratio of events passing/failing τ identification

2. Apply FF in SR:
Estimation = FF × events failing τ ID

	Signal Region (SR)	Calibration Region (CR)
Passed τ ID	*Estimation*	Data
Failed τ ID	2. Data	1. Data

- **Neural network classifiers**
  - 3 classifiers: signal against $Z \to \tau\tau$, W+jets, and $Z \to \ell\ell$ backgrounds
  - Trained with simulated events
  - Inputs: 4-momenta of ℓ, τ and $E_{\mathrm{T}}^{\mathrm{miss}}$ + few high-level variables like inv. mass
  - Combined into one powerful classifier

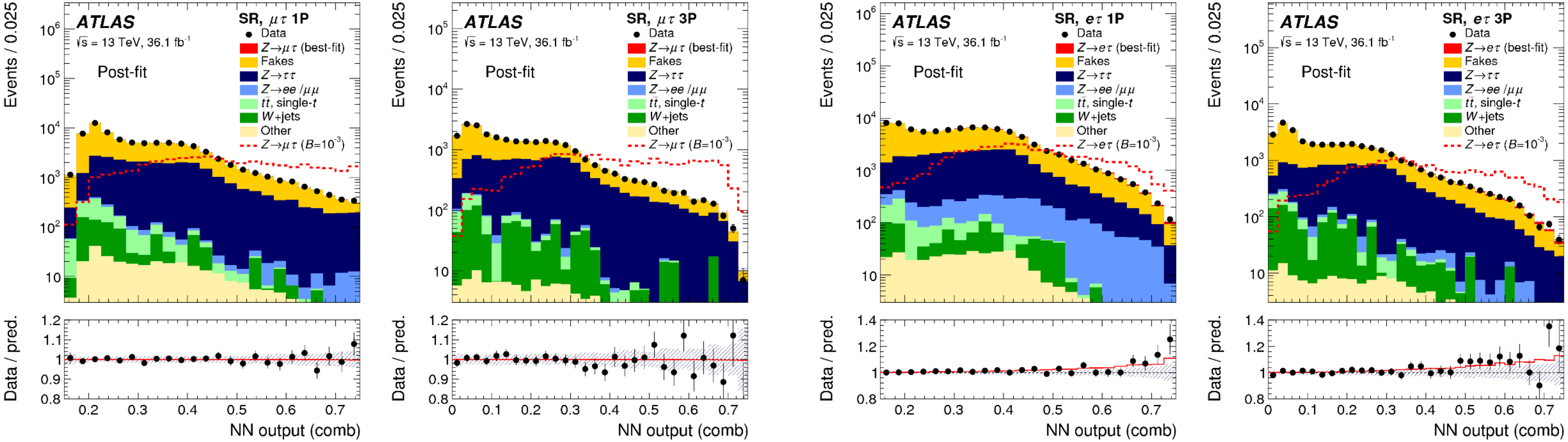
$Z \to e\tau/\mu\tau$

New update!

arXiv:1804.09568

- Results and interpretation
  - Predicted NN output distributions are fit to data
  - Free parameters: $\mathrm{BR}(Z \to \ell\tau)$ and normalisations of Z and jet $\to \tau$ fakes
  - Events with 1-prong and 3-prong τ_{had} are fit separately (but simultaneously)
  - Upper limits (95% CL): $\mathrm{BR}(Z \to e\tau) < 5.8 \times 10^{-5}$
    $\mathrm{BR}(Z \to \mu\tau) < 2.4 \times 10^{-5}$
  - Combined with 8-TeV data*: $\mathrm{BR}(Z \to \mu\tau) < 1.3 \times 10^{-5}$

*no 8-TeV ATLAS results on $Z \to e\tau$



$H \to e\tau/\mu\tau$

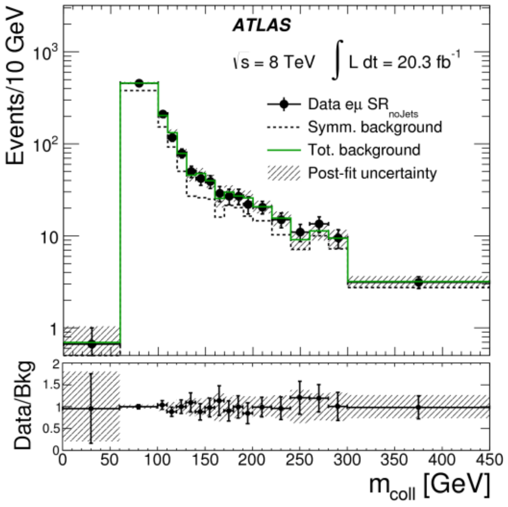
arXiv:1508.03372
arXiv:1604.07730

- Dataset
  - $20.3\ \mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 8\ \mathrm{TeV}$ (2012)
- Consider both leptonically- and hadronically-decaying τ
- Major backgrounds
  - $\ell\tau_{\mathrm{lep}}$ channels: Z+jets, WW, $t\bar{t}$
  - $\ell\tau_{\mathrm{had}}$ channels: Z+jets, W+jets, QCD multi-jet (jet $\to \tau$ fakes)
- Strategy
  - $\ell\tau_{\mathrm{lep}}$ channels:
    - Focus on $e\mu$ final state – exploit $e \leftrightarrow \mu$ symmetry in SM, asymmetry for LFV signal
  - $\ell\tau_{\mathrm{had}}$ channels:
    - Make use of signal characteristics in $m_{\mathrm{T}}\left(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\mathrm{miss}}\right)$ and $m_{\mathrm{T}}\left(\ell, E_{\mathrm{T}}^{\mathrm{miss}}\right)$ (similar to $Z \to \ell\tau_{\mathrm{had}}$)

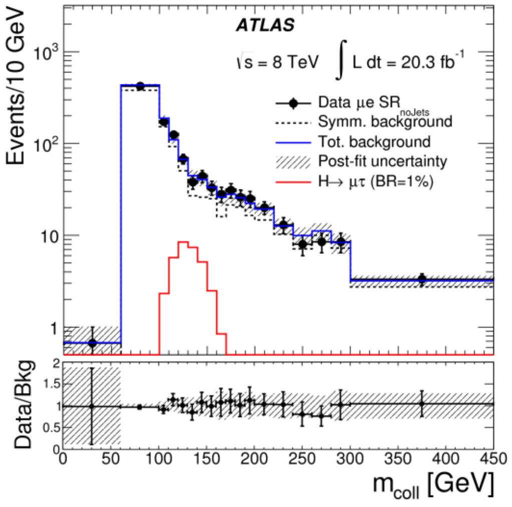
$H \to e\tau/\mu\tau$

arXiv:1508.03372
arXiv:1604.07730

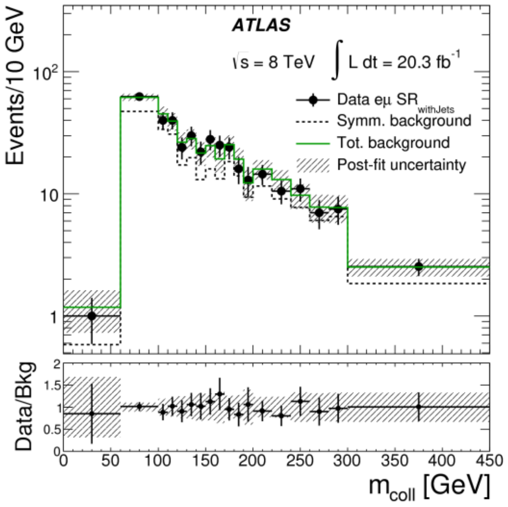
- $\ell\tau_{\text{lep}}$ channels ($e\mu$ final state)
  - Two categories: one for $p_{\mathrm{T}}^{e} > p_{\mathrm{T}}^{\mu}$ ($e\mu$) and one for $p_{\mathrm{T}}^{e} < p_{\mathrm{T}}^{\mu}$ (μe)
  - $e\mu \leftrightarrow \mu e$ symmetric in SM, asymmetric for LFV signal (e/μ from τ is softer)
  - Fit mass spectrum after correcting for asymmetry from trigger/reco. efficiencies and mis-identifications



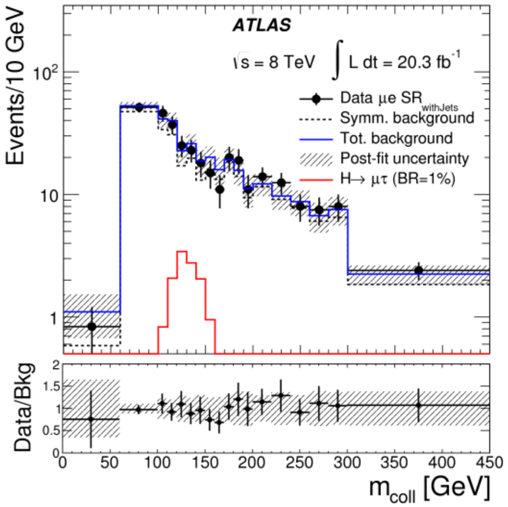
$e\mu$, SR (no jets)



μe, SR (no jets)



$e\mu$, SR (with jets)

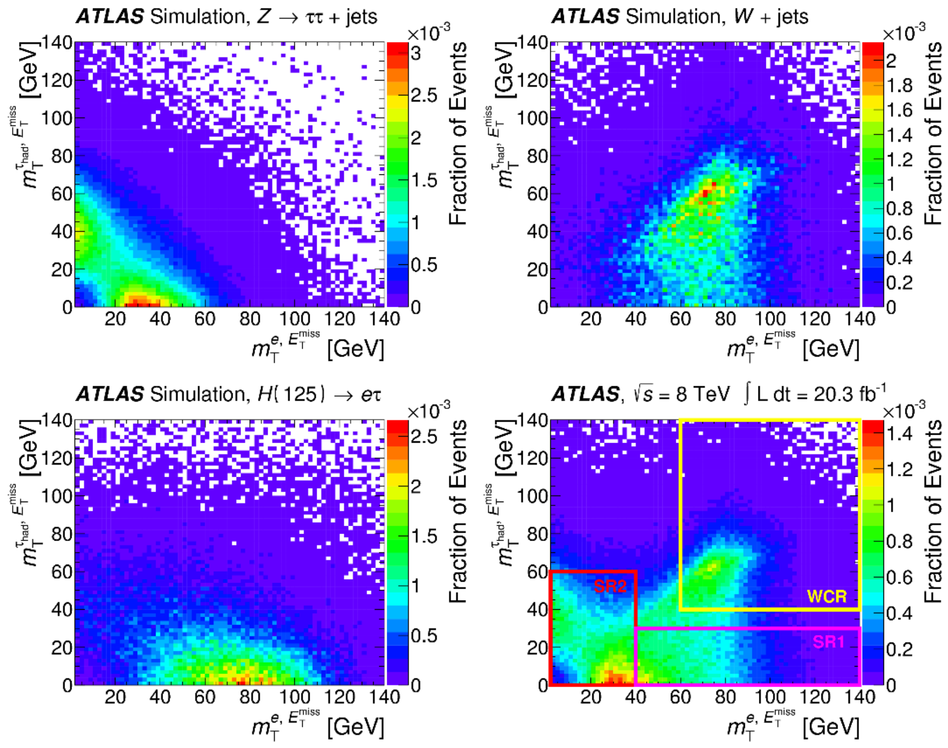


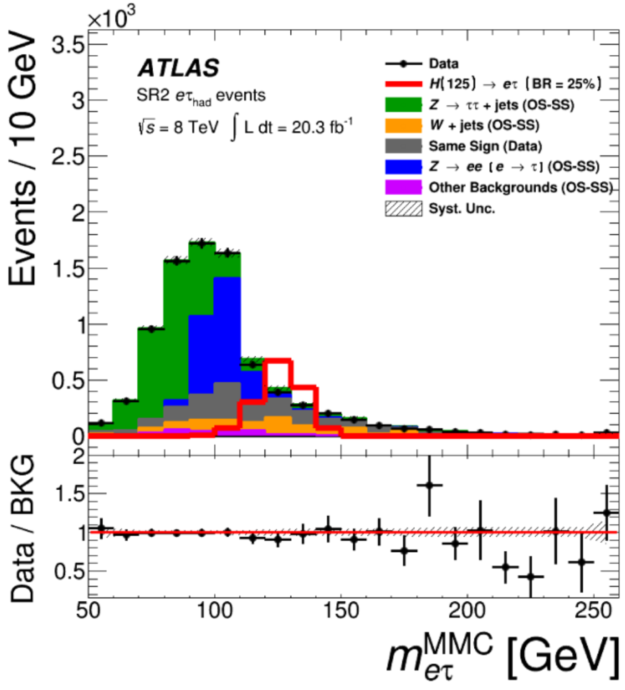
μe, SR (with jets)

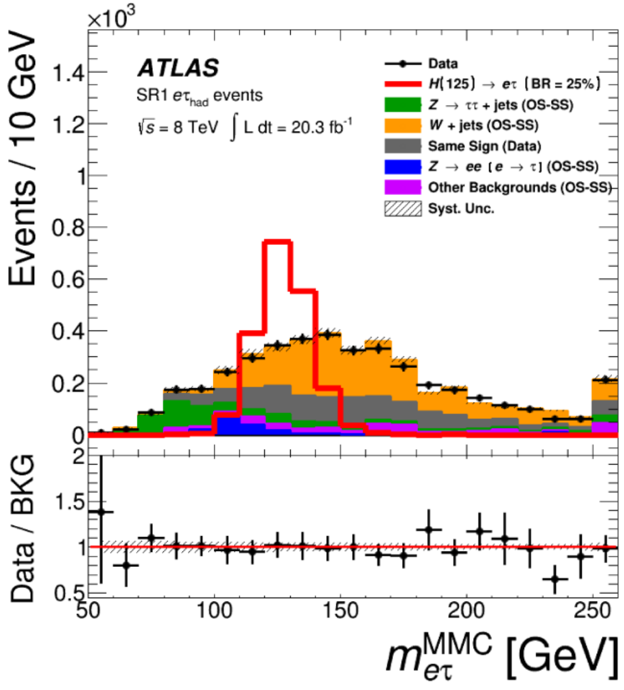
$H \to e\tau/\mu\tau$

arXiv:1508.03372
arXiv:1604.07730

- $\ell\tau_{\text{had}}$ channels
  - Two SRs: different background composition (W+jets or $Z \to \tau\tau$ dominating)
  - Event selection mainly based on $m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}})$ and $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\text{miss}})$



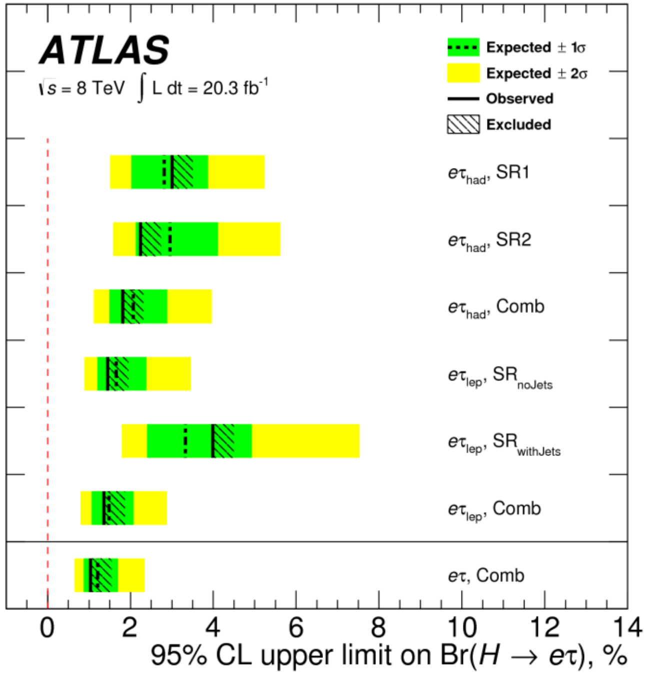


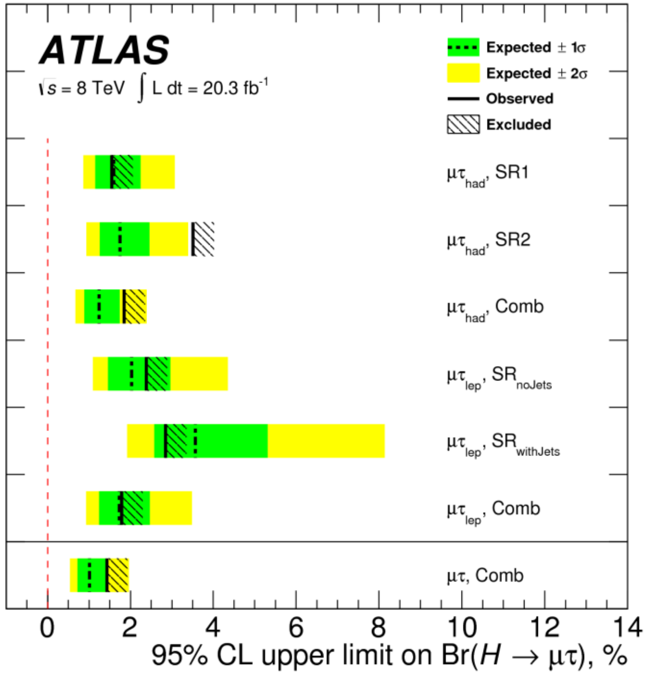


$H \to e\tau/\mu\tau$

arXiv:1508.03372
arXiv:1604.07730

- Results and interpretation
  - All channels are statistically combined
  - Limit on $\mathrm{BR}(H \to e\tau)$ obtained under the assumption $\mathrm{BR}(H \to \mu\tau) = 0$, and vice versa
  - Upper limits (95% CL): $\mathrm{BR}(H \to e\tau) < 1.04 \times 10^{-2}$
    $\mathrm{BR}(H \to \mu\tau) < 1.43 \times 10^{-2}$





$\tau \to 3\mu$

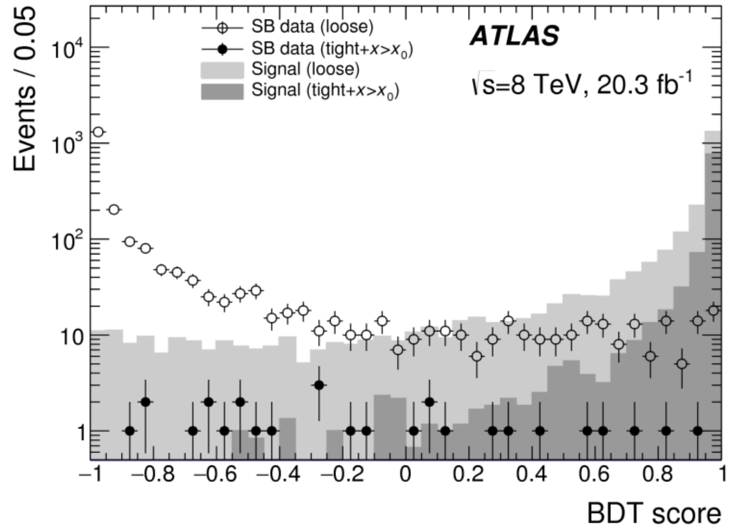
arXiv:1601.03567

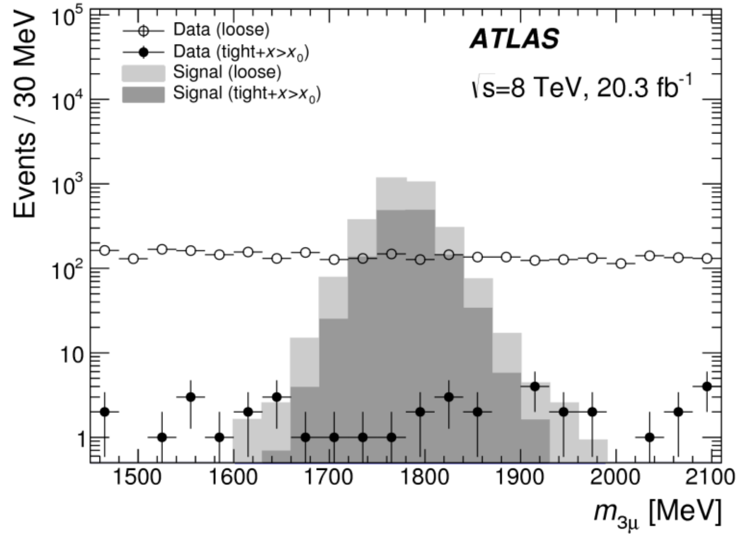
- Dataset
  - $20.3\ \mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 8\ \mathrm{TeV}$ (2012)
- Major backgrounds / challenges
  - Almost background-free
  - Challenging for ATLAS (very low-energy and close-by muons)
- Strategy
  - Use τ from $W \to \tau\nu$ (large $p_{\mathrm{T}}^{\tau} \to$ muons close in angle; large recoil $E_{\mathrm{T}}^{\mathrm{miss}}$)
  - Select events with 3 muons with common vertex and $m_{3\mu} \approx m_{\tau}$
  - Event selection mainly based on muon kinematics and vertex displacement
    - *Loose* selection for Boosted Decision Trees (BDT) training
    - *Tight* selection for BDT cut optimization
  - Regions are defined according to how close $m_{3\mu}$ is to m_{τ}:
    - (close to m_{τ}) signal region < blinded region < sideband region < training region (far from m_{τ})

$\tau \to 3\mu$

arXiv:1601.03567

- Analysis procedures
  - Obtain background samples (*loose* selection in training region)
  - Train BDT – input features:
    - 3μ and $E_{\mathrm{T}}^{\mathrm{miss}}$ kinematics
    - Vertex/track fitting probability/significance
  - Study rejection (*tight* selection in sideband region)
  - Define optimal BDT cut
  - Count events in the signal region for interpretation

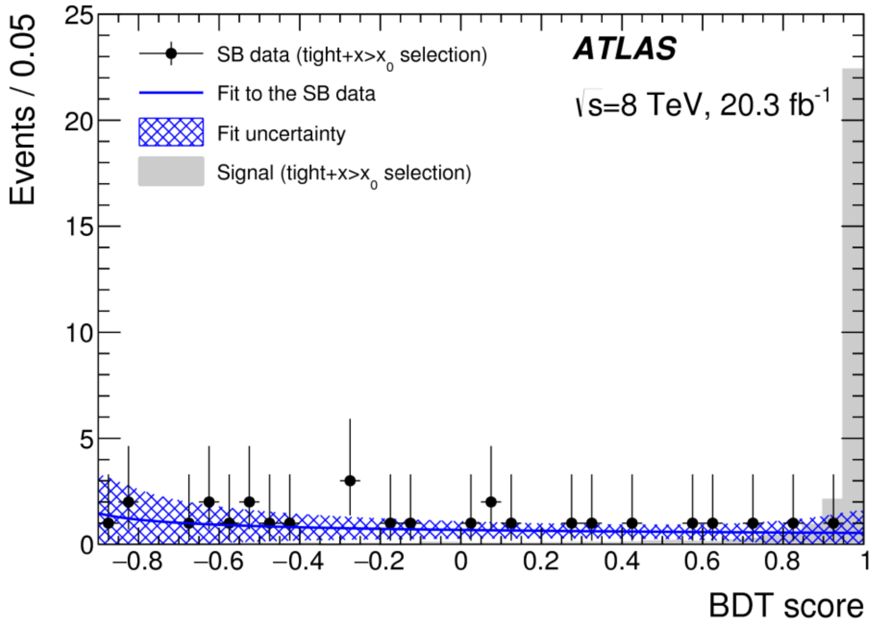


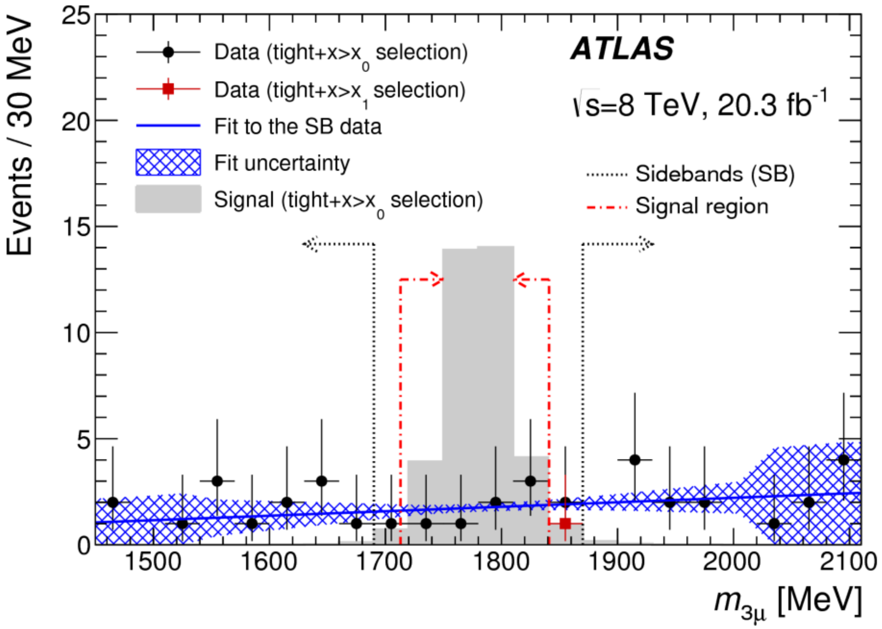


$\tau \to 3\mu$

arXiv:1601.03567

- Results and interpretation
  - One event observed at 1860 MeV
  - Upper limit (90% CL): $\mathrm{BR}(\tau \to 3\mu) < 3.76 \times 10^{-7}$





$Z'/\tilde{\nu}/\mathrm{QBH} \to e\mu/e\tau/\mu\tau$

New update!

arXiv:1807.06573

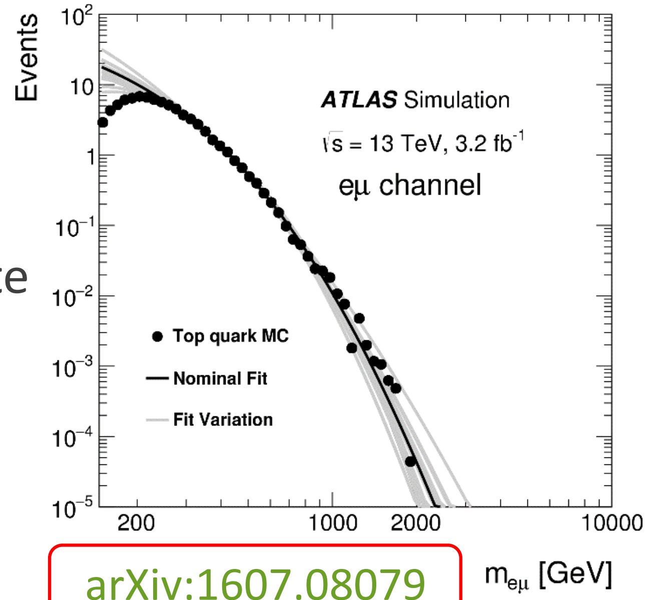
- Dataset
  - $36.1\ \mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ (2015-2016)
- Major backgrounds
  - $t\bar{t}$ and single-top
  - W+jets and QCD multi-jet (channels with τ)
- Strategy
  - Select events with high-mass $e\mu/e\tau_{\mathrm{had}}/\mu\tau_{\mathrm{had}}$ final state
  - Construct invariant mass
  - Estimate top background by extrapolating from low-mass regions
  - Estimate W+jets and QCD multi-jet by data-driven methods
  - Interpretations in three types of models ($Z'/\tilde{\nu}/\mathrm{QBH}$) using Bayesian method

$Z'/\tilde{\nu}/\mathrm{QBH} \rightarrow e\mu/e\tau/\mu\tau$

New update!

arXiv:1807.06573

- Background estimation
  - Top background:
    - Very limited number of simulated events at high-mass
    - Fit smooth functions (3 parameters) in low-mass regions and extrapolate (vary fit parameters and fit range → uncertainty estimate)
  - W+jets (channels with τ):
    - Measure jet $\rightarrow \tau$ fake rate in W+jets-enriched control region
    - Apply to simulated jets in signal region
  - QCD multi-jet (channels with τ):
    - Idea similar to $Z \rightarrow \ell\tau$ Fake Factor method
    - Measure "pass"/"fail" ratio using events in CR (low-p_{T}, same-charge $\ell\tau$ pairs) ("pass"/"fail" referring to lepton isolation and τ identification criteria)
    - Multiply observed "fail" events in signal region by the ratio



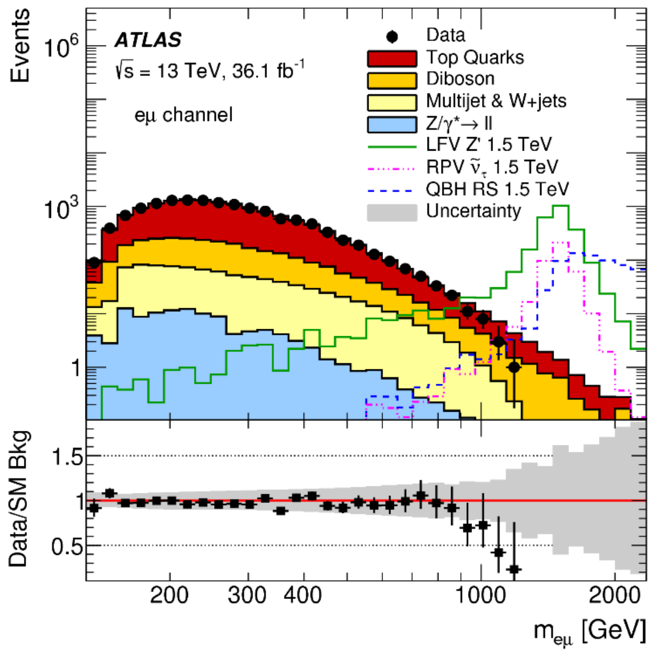
arXiv:1607.08079

$Z'/\tilde{\nu}/\text{QBH} \rightarrow e\mu/e\tau/\mu\tau$

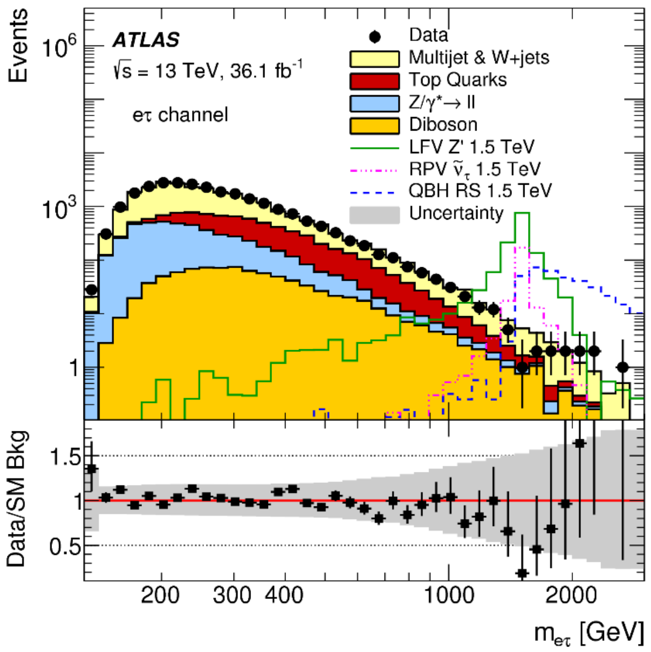
New update!

arXiv:1807.06573

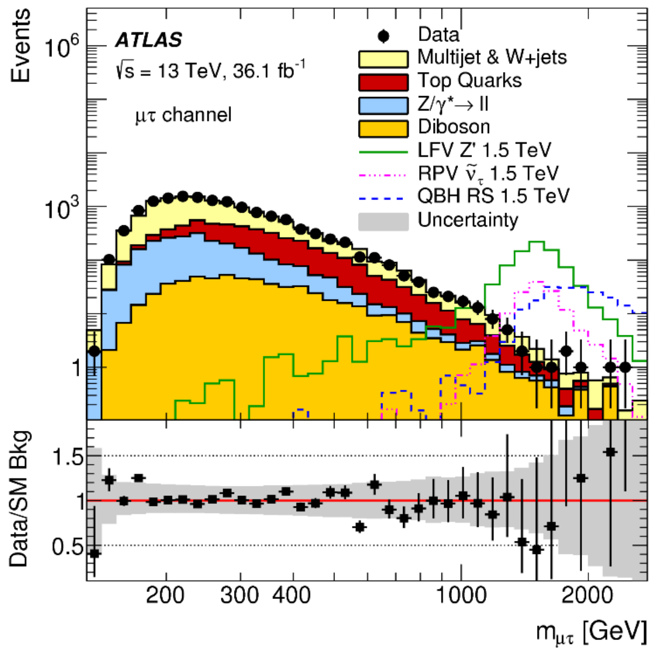
$m_{e\mu}$



$m_{e\tau}$



$m_{\mu\tau}$



$Z'/\tilde{\nu}/\mathrm{QBH} \rightarrow e\mu/e\tau/\mu\tau$

New update!

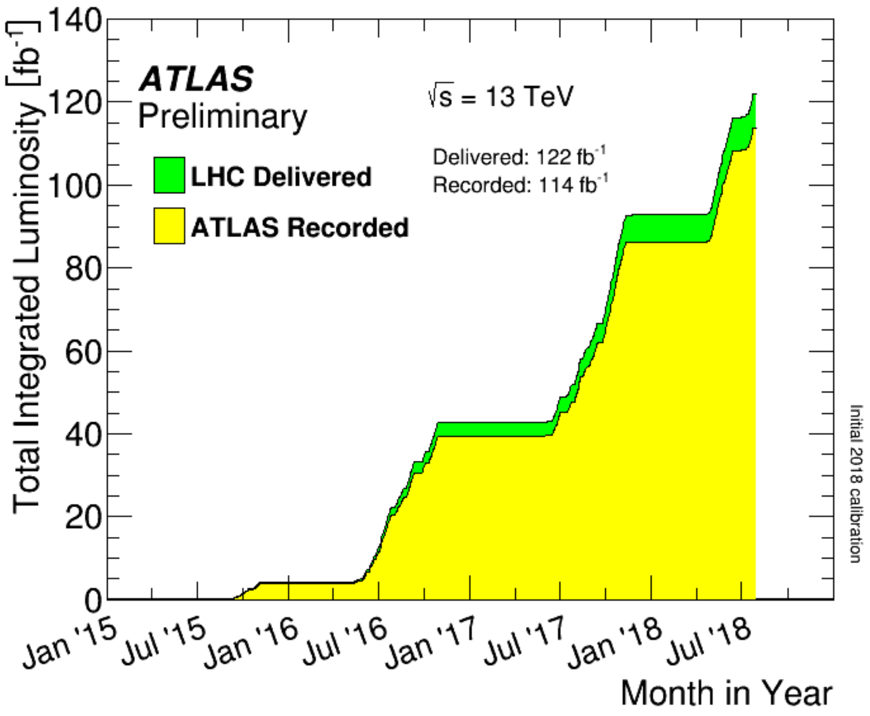
arXiv:1807.06573

- Results and interpretations
  - Three models
    - Z': SM quark couplings; no SM lepton couplings. Upper limit set on $m_{Z'}$
    - $\tilde{\nu}$: RPV SUSY sneutrino. Upper limit set on $m_{\tilde{\nu}}$
    - QBH: Considered two extra-dimension models – ADD (*n*=6) and RS (*n*=1). Upper limit set on threshold mass m_{th}
  - Only one LFV coupling ($e\mu/e\tau/\mu\tau$) allowed at a time
  - Upper limits on $m_{Z'}/m_{\tilde{\nu}}/m_{\mathrm{th}}$ (95% CL, Bayesian):

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

Summary

- LFV searches performed in ATLAS:
  - Decays of SM Z, H and τ
  - Decays of hypothetical Z', $\tilde{\nu}$ and QBH
- No evidence or discovery of LFV processes
- Upper limits set on considered models
- Ongoing analyses with full Run-2 data
  - Data taking complete this year (2018)
  - Can expect luminosity $\sim 150\ \mathrm{fb}^{-1}$
- Stay tuned!!



Thank you!

Backup

$Z \to e\mu$: Event selections, reconstruction efficiencies

Z decay	Efficiency (%)	N_Z (10^8)
ee	10.8 ± 0.3	7.85 ± 0.24
$\mu\mu$	17.8 ± 0.4	7.79 ± 0.17
$\langle ee, \mu\mu \rangle$		7.80 ± 0.15
$e\mu$	14.2 ± 0.4	

Sources	MC			Data					
Channels	ee	$\mu\mu$	$e\mu$	ee		$\mu\mu$		$e\mu$	
—	Eff. (%)	Eff. (%)	Eff. (%)	Events	Eff. (%)	Events	Eff. (%)	Events	Eff. (%)
Initial	—	—	—	242,852,345	—	242,852,345	—	242,852,345	—
Triggered	62.5	65.7	64.8	76,840,946	31.6	76,840,946	31.6	76,840,946	31.6
Two Lepton, η and p_T cuts	31.1	51.6	40.6	4,908,037	6.4	8,129,937	10.6	76,657	0.1
$E_\mathrm{T}^\mathrm{miss} < 17$ GeV	67.9	66.9	68.0	3,384,179	69.0	5,547,293	68.2	12,189	15.9
$p_{\mathrm{T}\,\mathrm{max}}^{\mathrm{jet}} < 30$ GeV	84.9	81.7	81.8	2,965,933	87.6	4,869,110	87.8	8,744	71.7
$70 < m_{\ell\ell} < 110$ GeV	96.4	96.3	97.1	2,847,689	96.0	4,670,014	95.9	3,163	36.2
$85 < m_{\ell\ell} < 95$ GeV	81.8	86.5	86.2	2,248,034	78.9	3,702,598	79.3	362	11.4

$Z \to \ell\tau$: Event selections, CR definitions

Preselection	one isolated tight light lepton with $p_{\mathrm{T}} > 30$ GeV matched to a lepton selected at trigger level leading $\tau_{\text{had-vis}}$ with $p_{\mathrm{T}} > 20$ GeV, $N_\tau^{\text{tracks}} = 1$ or 3 and passing tight identification if $N_\tau^{\text{tracks}} = 1$: $0.0(0.1) < \lvert\eta_\tau\rvert < 1.37$ or $1.52 < \lvert\eta_\tau\rvert < 2.2(2.5)$ in $e\tau(\mu\tau)$ events if $N_\tau^{\text{tracks}} = 3$: $0.0 < \lvert\eta_\tau\rvert < 1.37$ or $1.52 < \lvert\eta_\tau\rvert < 2.5$ $q_\ell \times q_\tau = -1$ no b-jet, no additional light lepton
Signal Region	$m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}}) < 35(30)$ GeV in $e\tau$ ($\mu\tau$) events if $N_\tau^{\text{tracks}} = 1$ and $\lvert\eta_\tau\rvert < 2.0$: $m(\text{track}, \ell) < 84$ GeV or $m(\text{track}, \ell) > 105$ GeV if $N_\tau^{\text{tracks}} = 1$ and $\lvert\eta_\tau\rvert > 2.0$: $m(\text{track}, \ell) < 80$ GeV or $m(\text{track}, \ell) > 105$ GeV if $N_\tau^{\text{tracks}} = 1$ and $80 < m(\tau_{\text{had-vis}}, \ell) < 100$ GeV: $m(\text{track}, \ell) > 40$ GeV

Region	**Change relative to SR selection**	**Purity [%]**	
		$e\tau$	$\mu\tau$
CRZll	Two same-flavor opposite-charge light leptons with $81 < m_{\ell\ell} < 101$ GeV	98	98
CRW	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\text{miss}}) > 40$ GeV and $m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}}) > 35(30)$ GeV in $e\tau$ ($\mu\tau$) events	84	85
CRT	$N_{b\text{-jets}} \geq 2$	98	98
CRQ	Inverted light-lepton isolation	75	37

$Z \to \ell\tau$: Observed/post-fit events, NN inputs

	1-prong	3-prong
Total observed $e\tau$ events	89 294	35 148
Total post-fit $e\tau$ events	89 300±300	35 200±200
Fakes	57 000±1000	21 500±500
$Z \to \tau\tau$	26 000±1000	11 500±500
$Z \to \ell\ell$	3200±100	250±150
Top	770±120	440±70
W+jets	540±100	950±180
Other	340±70	150±30
$Z \to \tau e$ signal	900±400	390±160
Total observed $\mu\tau$ events	79 744	25 050
Total post-fit $\mu\tau$ events	79 700±500	25 100±700
Fakes	52 000±1000	13 600±800
$Z \to \tau\tau$	26 000±1000	10 300±300
$Z \to \ell\ell$	240±110	80±40
Top	890±140	360±60
W+jets	610±120	680±130
Other	290±70	110±20
$Z \to \tau\mu$ signal	−20±360	−10±140

Variable	**Description**	**Z NN**	**Zll NN**	**W NN**
$\hat{E}^{\text{lep}}$	light-lepton energy	✓	✓	✓
$\hat{p}_x^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_x	✓	✓	✓
$\hat{p}_z^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_z	✓	✓	✓
$\hat{E}^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ energy	✓	✓	✓
$\hat{p}_z^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$ component along z-axis	✓	✓	✓
$\hat{E}^{\text{miss}}$	magnitude of $E_{\text{T}}^{\text{miss}}$	✓	✓	✓
$p_{\text{T}}^{\text{tot}}$	transverse component of total momentum	✓	✓	✓
m_{coll}	collinear mass	✓	✓	✓
$\Delta\alpha$	see Eq. (1) [47]	✓	✓	✓
$m(\ell, \tau_{\text{had-vis}})$	invariant mass of light lepton and $\tau_{\text{had-vis}}$		✓	

$H \to \ell\tau$: Event selections, region definitions

$\ell\tau_{\mathrm{had}}$

Criterion	SR1	SR2	WCR	TCR
$E_{\mathrm{T}}(e)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$\lvert\eta(e) - \eta(\tau_{\mathrm{had}})\rvert$	<2	<2	<2	<2
$m_{\mathrm{T}}^{e,E_{\mathrm{T}}^{\mathrm{miss}}}$	>40 GeV	<40 GeV	>60 GeV	–
$m_{\mathrm{T}}^{\tau_{\mathrm{had}},E_{\mathrm{T}}^{\mathrm{miss}}}$	<30 GeV	<60 GeV	>40 GeV	–
N_{jet}	–	–	–	≥2
$N_{b-\mathrm{jet}}$	0	0	0	≥1

$\ell\tau_{\mathrm{lep}}$

	$\mathrm{SR}_{\mathrm{noJets}}$	$\mathrm{SR}_{\mathrm{withJets}}$
Light leptons	$e^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$
τ leptons	veto	veto
Central jets	0	≥ 1
b-jets	0	0
$p_{\mathrm{T}}^{\ell_1}$	$\geq 35 GeV$	$\geq 35 GeV$
$p_{\mathrm{T}}^{\ell_2}$	$\geq 12 GeV$	$\geq 12 GeV$
$\lvert\eta^{e}\rvert$	≤ 2.4	≤ 2.4
$\lvert\eta^{\mu}\rvert$	≤ 2.4	≤ 2.4
$\Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	≤ 0.7	≤ 0.5
$\Delta\phi(\ell_1, \ell_2)$	≥ 2.3	≥ 1.0
$\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$	≥ 2.5	≥ 1.0
$\Delta p_{\mathrm{T}}(\ell_1, \ell_2)$	$\geq 7 GeV$	$\geq 1 GeV$

$\tau \to 3\mu$: Region definitions, event counts

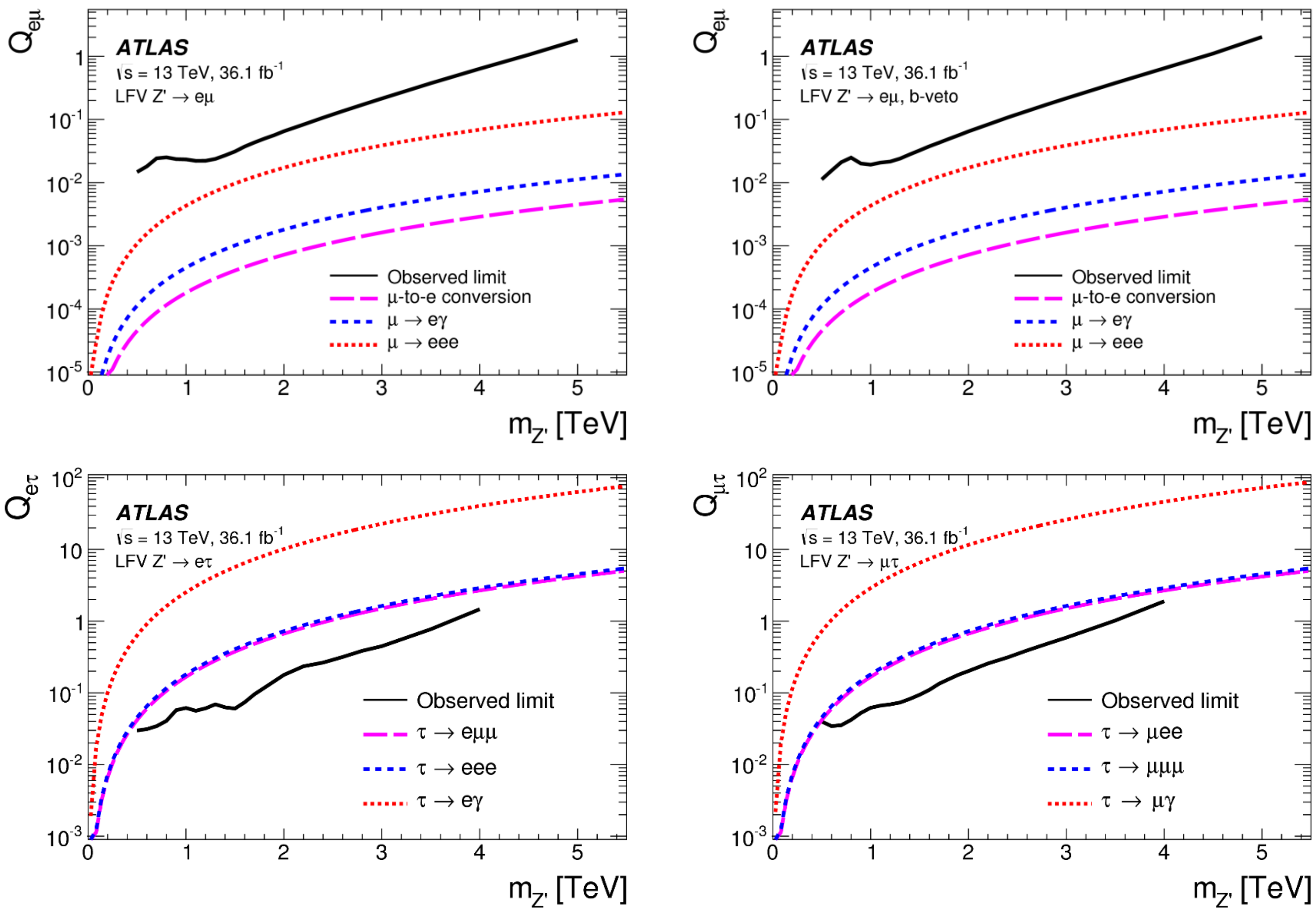
Region	Range in $m_{3\mu}$ [MeV]
Signal region	$[1713, 1841]$
Blinded region	$[1690, 1870]$
Sideband region	$[1450, 1690]$ and $[1870, 2110]$
Training region	$[750, 1450]$ and $[2110, 2500]$

Phase	Data SB	Data SR	Signal MC SR [out of 2×10^5]
loose	2248	580	12672
loose$+x>x_0$	736	203	12557
tight	42	9	5503
tight$+x>x_0$	28	7	5501
tight$+x>x_1$	0	0	4616

$\tau \rightarrow 3\mu$: BDT input features

1. The calorimeter-based transverse mass, $m_{\mathrm{T}}^{\mathrm{cal}}$.
2. The track-based missing transverse momentum, $E_{\mathrm{T,trk}}^{\mathrm{miss}}$.
3. The isolation variable, $\Sigma p_{\mathrm{T}}^{\mathrm{trk}}(\Delta R_{\mathrm{max}}^{3\mu} + 0.20)/p_{\mathrm{T}}^{3\mu}$.
4. The transverse component of the vector sum of the three-muon and leading jet momenta, Σ_{T}.
5. The track-based transverse mass, $m_{\mathrm{T}}^{\mathrm{trk}}$.
6. The difference between the $E_{\mathrm{T,cal}}^{\mathrm{miss}}$ and $E_{\mathrm{T,trk}}^{\mathrm{miss}}$ directions, $\Delta\phi_{\mathrm{trk}}^{\mathrm{cal}}$.
7. The calorimeter-based missing transverse momentum, $E_{\mathrm{T,cal}}^{\mathrm{miss}}$.
8. The track-based missing transverse momentum balance $p_{\mathrm{T}}^{3\mu}/E_{\mathrm{T,trk}}^{\mathrm{miss}} - 1$.
9. The difference between the three-muon and $E_{\mathrm{T,cal}}^{\mathrm{miss}}$ directions, $\Delta\phi_{3\mu}^{\mathrm{cal}}$.
10. Three-muon vertex fit probability, p-value.
11. The three-muon vertex fit a_{xy}^{0} significance, $S(a_{xy}^{0})$.
12. The track fit probability product, $\mathcal{P}_{\mathrm{trks}}$.
13. The three-muon transverse momentum, $p_{\mathrm{T}}^{3\mu}$.
14. The number of tracks associated with the PV (after refitting the PV while excluding the three-muon tracks), $N_{\mathrm{trk}}^{\mathrm{PV}}$.
15. The three-muon vertex fit L_{xy} significance, $S(L_{xy})$.
16. The calorimeter-based missing transverse momentum balance, $p_{\mathrm{T}}^{3\mu}/E_{\mathrm{T,cal}}^{\mathrm{miss}} - 1$.

$Z' \to \ell\ell'$: Limit conversion from low-energy experiments



$\tilde{\nu} \to \ell\ell'$: Limit conversion from low-energy experiments