Searches for new physics with leptons

using the ATLAS detector

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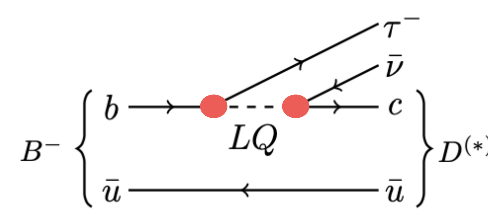
on behalf of the ATLAS Collaboration

EPS-HEP, 27/07/21

New physics with leptons?

- Many **open questions** related to lepton properties and interactions, e.g.
  - Origin of neutrino mass
  - Origin of flavour pattern of Yukawa interactions
- Hints of **lepton anomalies**, e.g.
  - Hints of the violation of lepton flavour universality (LFU) in B-meson decays
  - Discrepancy between measured and predicted values of muon anomalous magnetic moment $(g-2)_\mu$
- Possible explanations with UV-complete models predict existence of **new particles at the TeV scale**, e.g.
  - **Leptoquarks**, **heavy leptons**, new gauge bosons, **SUSY smuons**, …

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$



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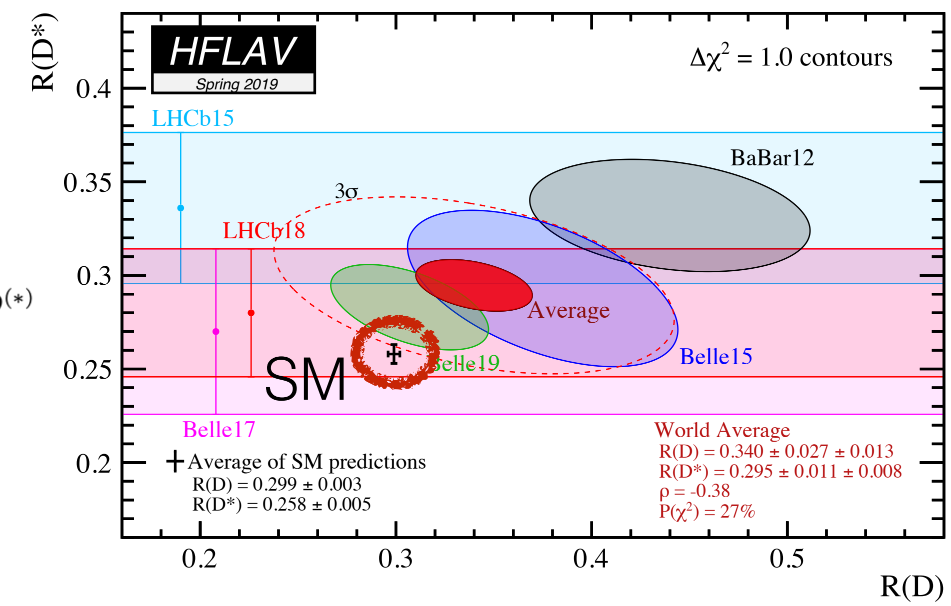
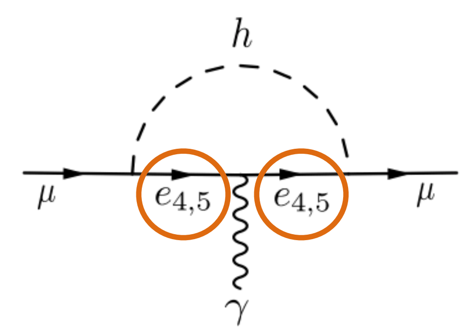
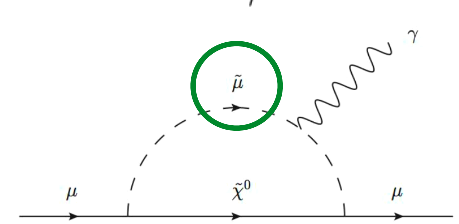
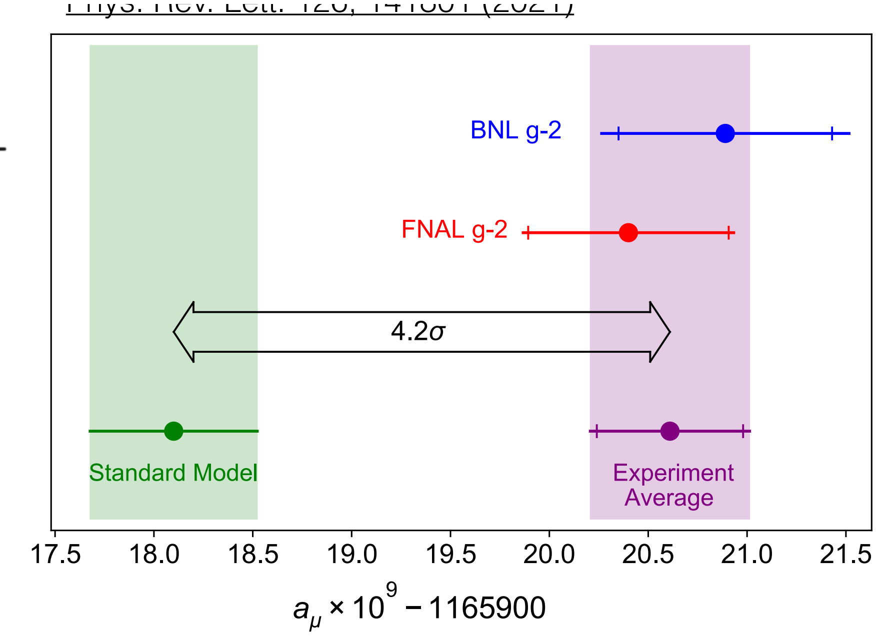






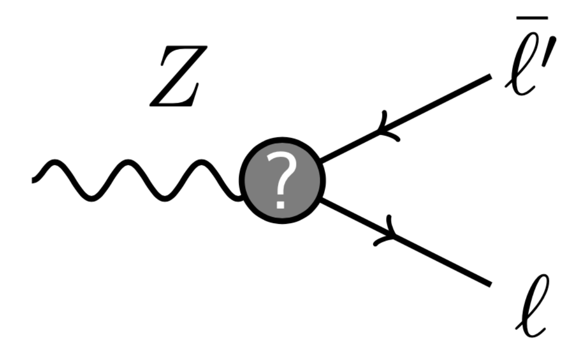
Phys. Rev. Lett. 126, 141801 (2021)

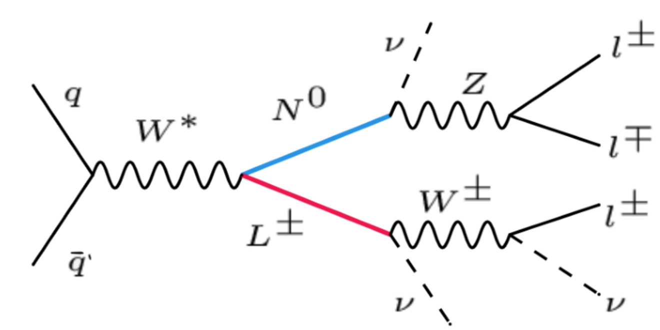


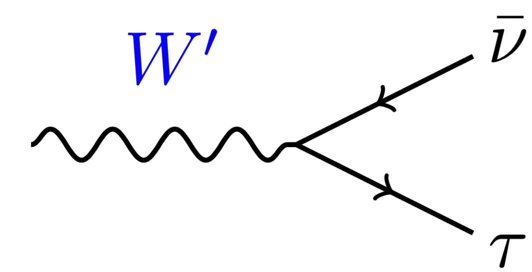
Outline

$$\frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)}$$

- More experimental inputs from different fronts are needed to identify a possible common explanation
- ATLAS is addressing this puzzle with a broad range of searches
- Test of SM symmetries
  - **[NEW] Search for charge flavour symmetry violation**
  - **Search for $Z \to \ell\tau\,(\ell = e, \mu)$ decays**
  - **[NEW] Search for $Z \to e\mu$ decays**
- Search for new heavy particles predicted in UV-complete SM extensions
  - **Search for type-III seesaw heavy leptons**
  - **Search for $W' \to \tau\nu$**





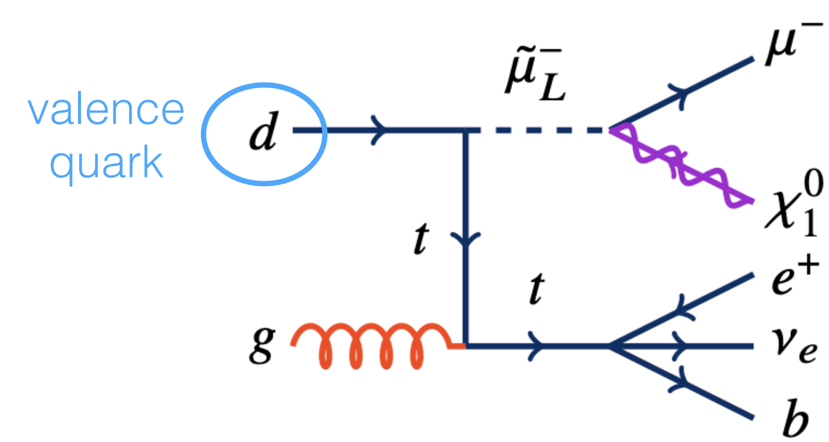


$e^+\mu^- / e^-\mu^+$ Measurement [NEW!]

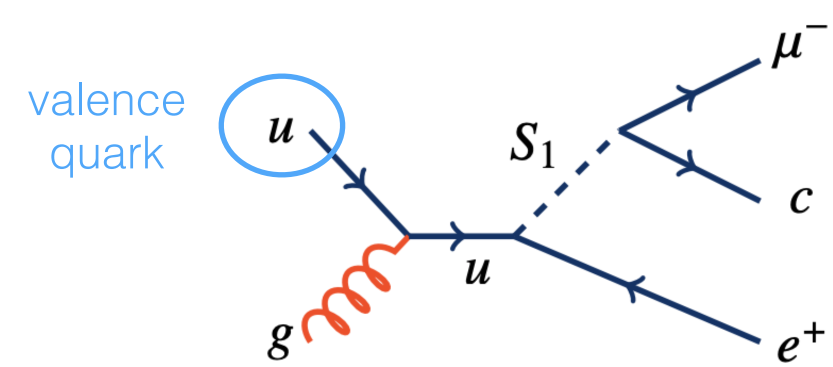
- $\rho_{\text{SM}} = 1$, but new physics can lead to $\rho \neq 1$, for example:
  - R-parity violating (RPV) SUSY models with **smuons** $\tilde{\mu}_L$
  - **Scalar LQ** models with couplings $S_1 \to c\mu^-, ue^-$
  - New physics connected to **B-anomalies** and $(g-2)_\mu$

$$\rho = \frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)}$$

- Search for charge-flavour symmetry violation $\rho > 1$
  - Search for $\rho < 1$ more challenging since experimental effects tend to bias to $\rho < 1$, e.g. $\sigma(W^+j) > \sigma(W^-j)$ and mis-identification probability $P^{\text{mis-ID}}(j \to e) > P^{\text{mis-ID}}(j \to \mu)$



- Analysis almost completely data-driven
  - Data-driven estimate of events with mis-identified leptons
  - Charge-dependent detector effects in muon reconstruction corrected for



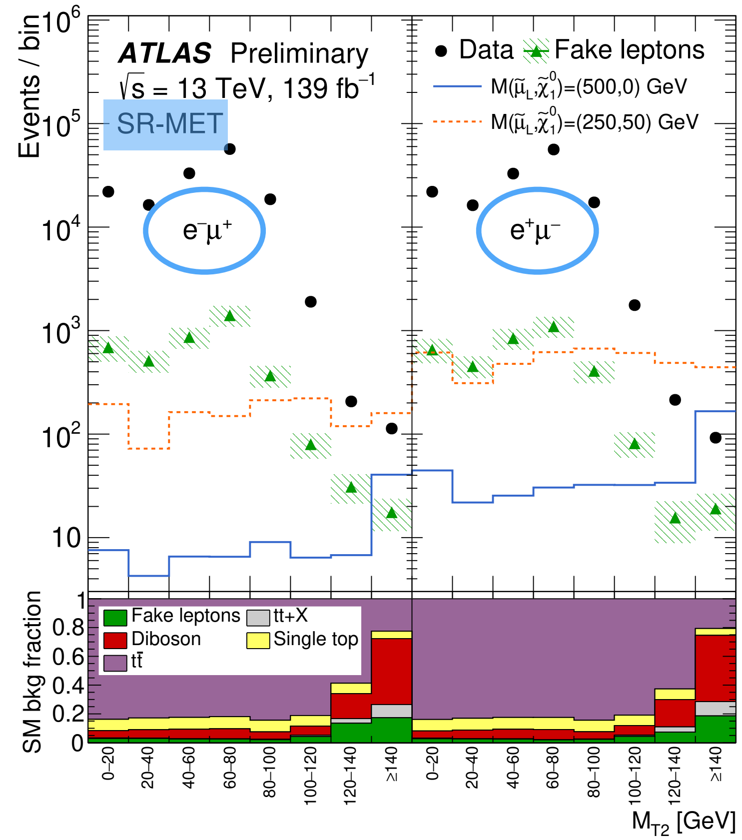
- Measurement in event categories sensitive to events with invisible particles (**SR-MET** and **SR-RPV**) and to events produced with jets (**SR-JET** and **SR-LQ**)

[ATLAS-CONF-2021-045]

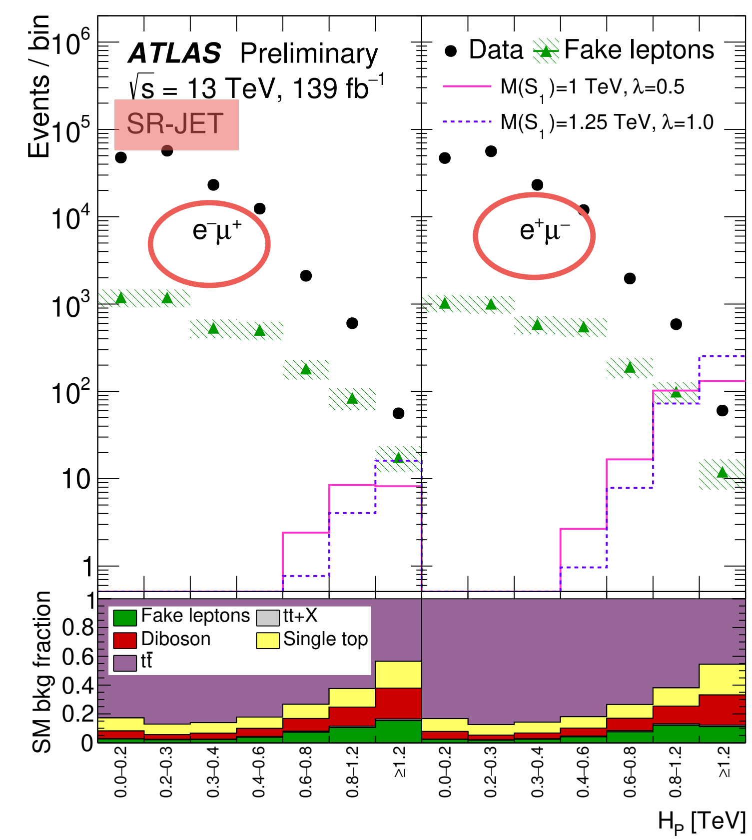
$e^+\mu^- / e^-\mu^+$ Measurement [NEW!]

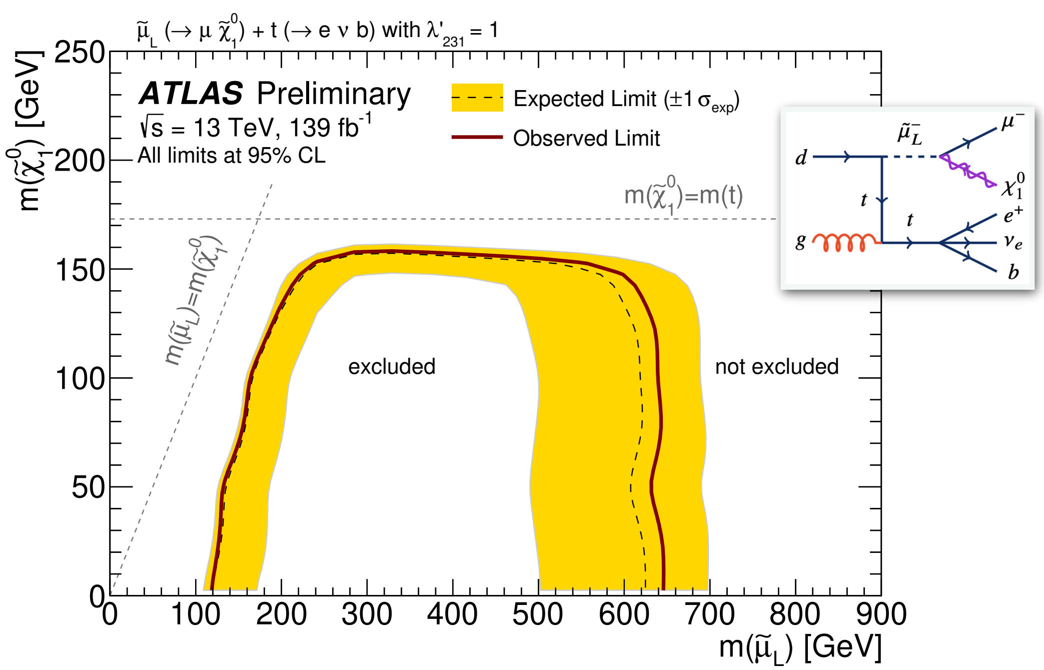
- No significant evidence for $\rho > 1$ observed
- Upper limits set on RPV SUSY and LQ models

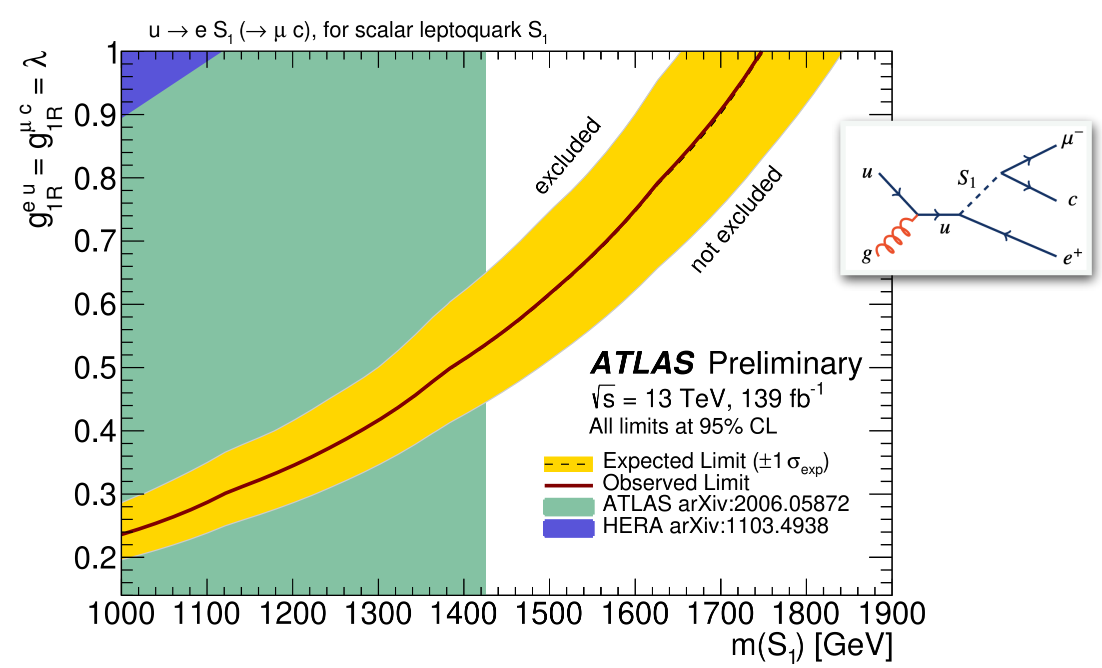
$$M_{T2} = \min_{\vec{a}+\vec{b}=\vec{p}_T^{\,\rm miss}} \max[m_T(e,\vec{a}), m_T(\mu,\vec{b})]$$



$$H_P = |p_T^{\mu}| + |p_T^{e}||p_T^{j1}|$$

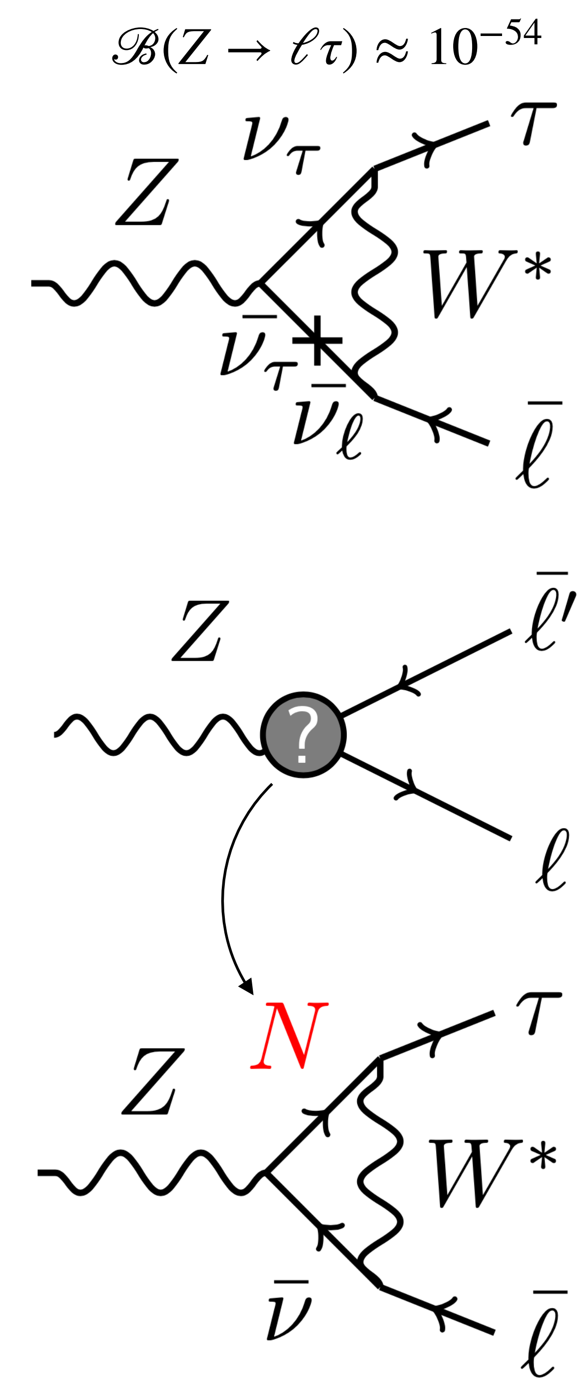






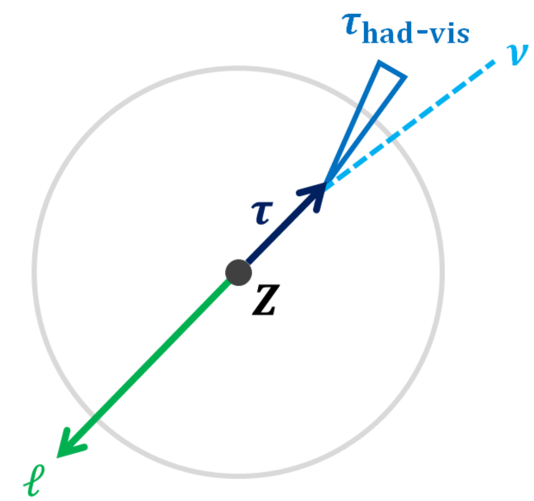
LFV in Z decays

- Lepton flavour conservation is an accidental symmetry in SM
- Violation of lepton flavour conservation (LFV) not forbidden by any fundamental symmetry
- **Any observation is a clear indication of NP!**
- Search for $Z \rightarrow \ell\ell'$ complementary to low-energy searches, e.g. $\tau \rightarrow \gamma\mu$ and $\mu \rightarrow \gamma e$ (eff vertices at different energies)
- Challenge: look for tiny signal in huge background

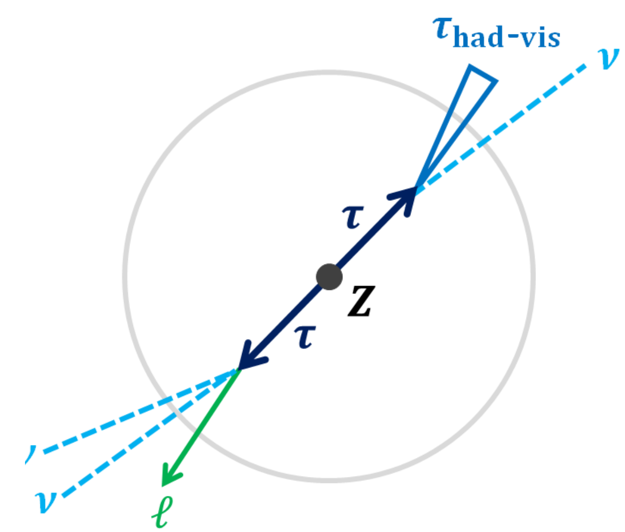


Search for $Z \to \ell\tau$

- Search for $Z \to \ell\tau\, (\ell = e, \mu)$ in final states with both hadronic and leptonic τ decays [Nature Physics 17, 819 (2021), 2105.12491 submitted to PRL]
- **Event classification** with Neural Networks
- **Theory and experimental systematic uncertainties** on signal and $Z \to \tau\tau$ events reduced via data-driven techniques
- Measurement dominated by statistical uncertainties



LFV $Z \to \ell\tau_{\text{had}}$

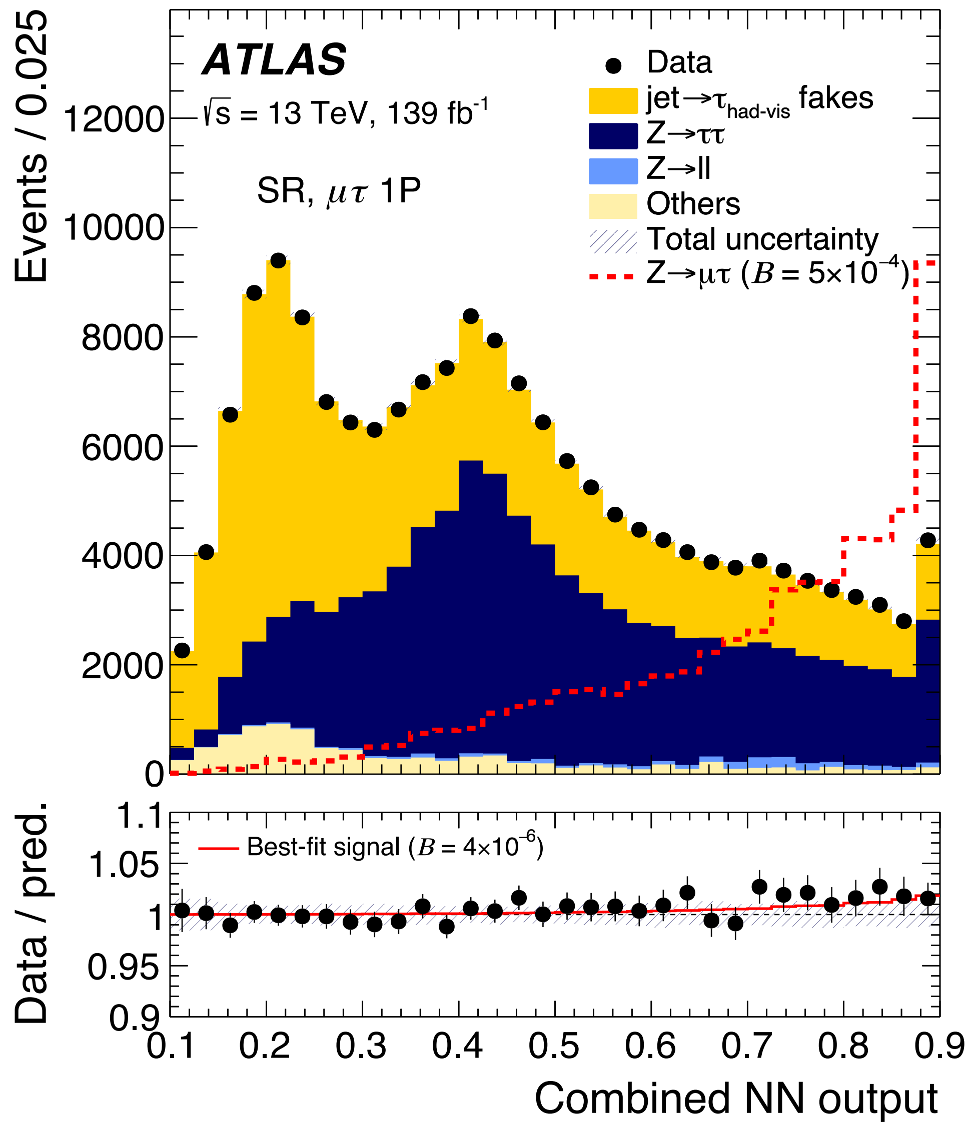


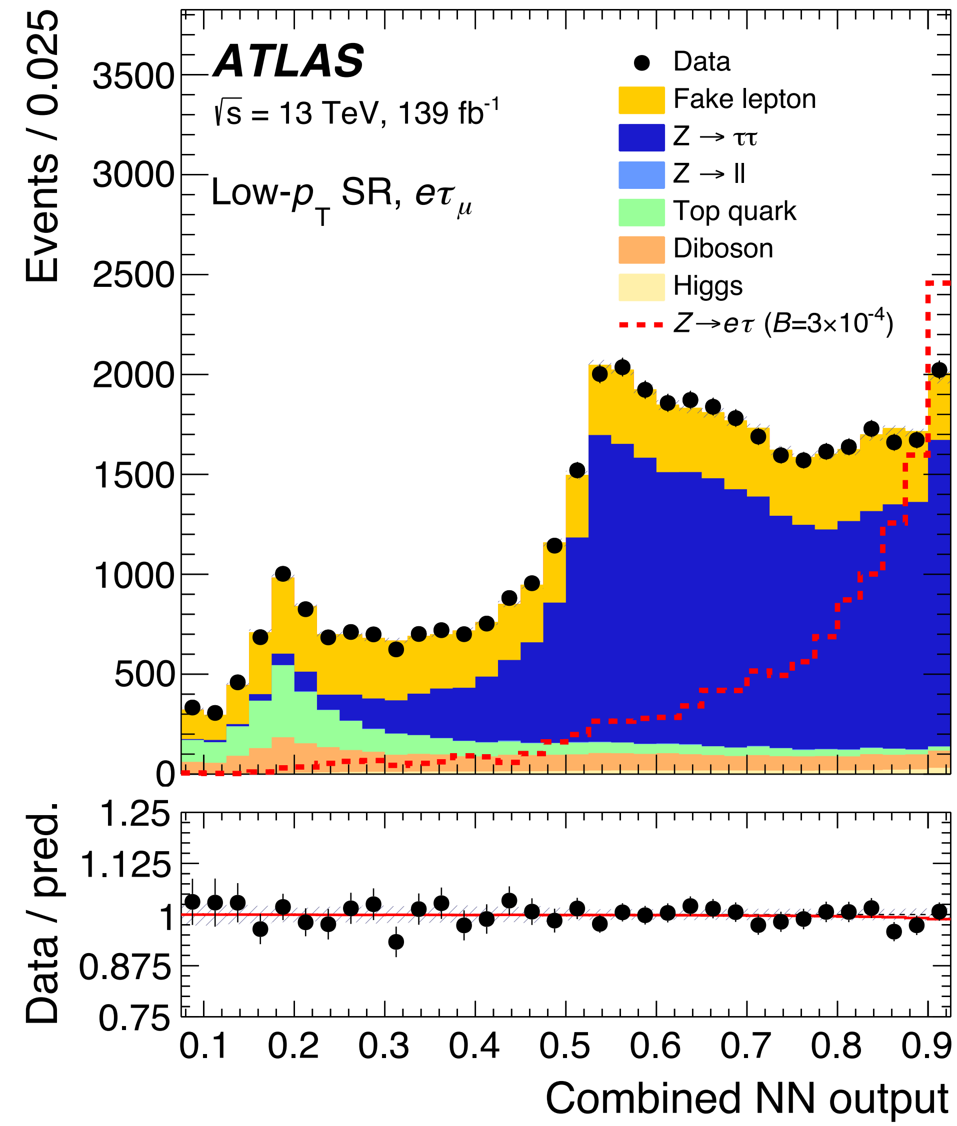
$Z \to \tau_\ell \tau_{\text{had}}$

Hadronic channel

Source of uncertainty	Uncertainty on $\mathcal{B}(Z \to \ell\tau)$ $[\times 10^{-6}]$ $e\tau$	$\mu\tau$
Statistical	±3.5	±2.8
Systematic	±2.3	±1.6
τ-leptons	±1.9	±1.5
Energy calibration	±1.3	±1.4
Jet rejection	±0.3	±0.3
Electron rejection	±1.3	
Light leptons	±0.4	±0.1
$E_{\text{T}}^{\text{miss}}$, jets and flavour tagging	±0.6	±0.5
Z-boson modelling	±0.7	±0.3
Luminosity and other minor backgrounds	±0.8	±0.3
Total	±4.1	±3.2

Search for $Z \to \ell\tau$

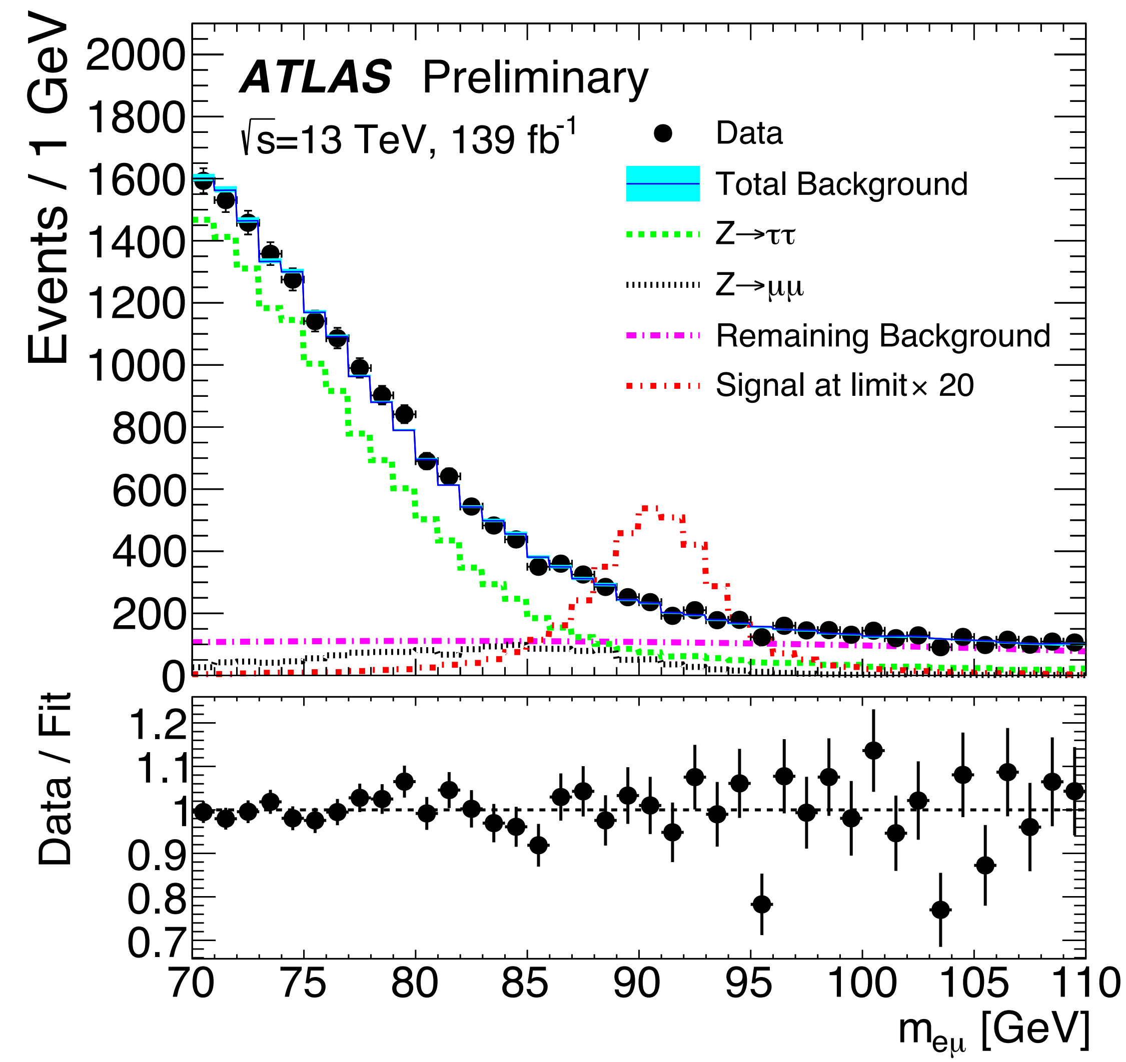




LFV Z decay	New UL @95%CL	Previous UL @95%CL
$\mathcal{B}(Z \to \mu\tau)$	6.5×10^{-6} [ATLAS]	1.2×10^{-5} [DELPHI]
$\mathcal{B}(Z \to e\tau)$	5.0×10^{-6} [ATLAS]	9.8×10^{-6} [OPAL]

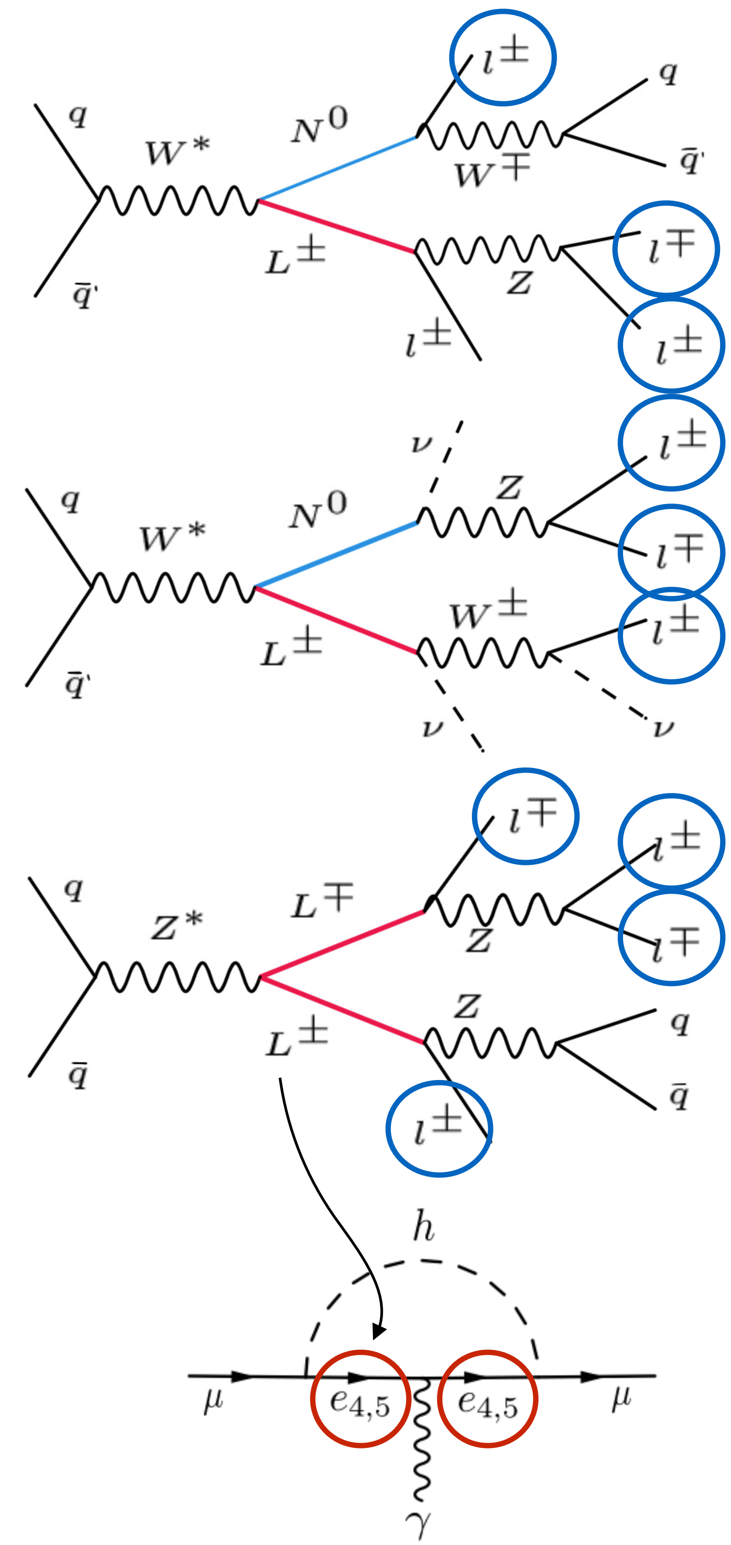
Search for $Z \to e\mu$ [NEW!]

- Search for $Z \to e\mu$ peak in the $m_{e\mu}$ invariant mass distribution
- Background events with opposite-sign $e\mu$ pair: $Z \to \tau\tau, \mu\mu(\to e)$, $t\bar{t}$ and WW
- To reduce backgrounds, events with high-p_T jet and large E_T^{miss} are vetoed. BDT to further improve background rejection
- Total number of Z decays determined from sample of $Z \to ee, \mu\mu$ decays
- Analysis limited by statistical uncertainties in data and in simulation
- Upper limit set at $\mathscr{B}(Z \to e\mu) < 3.0 \times 10^{-7}$

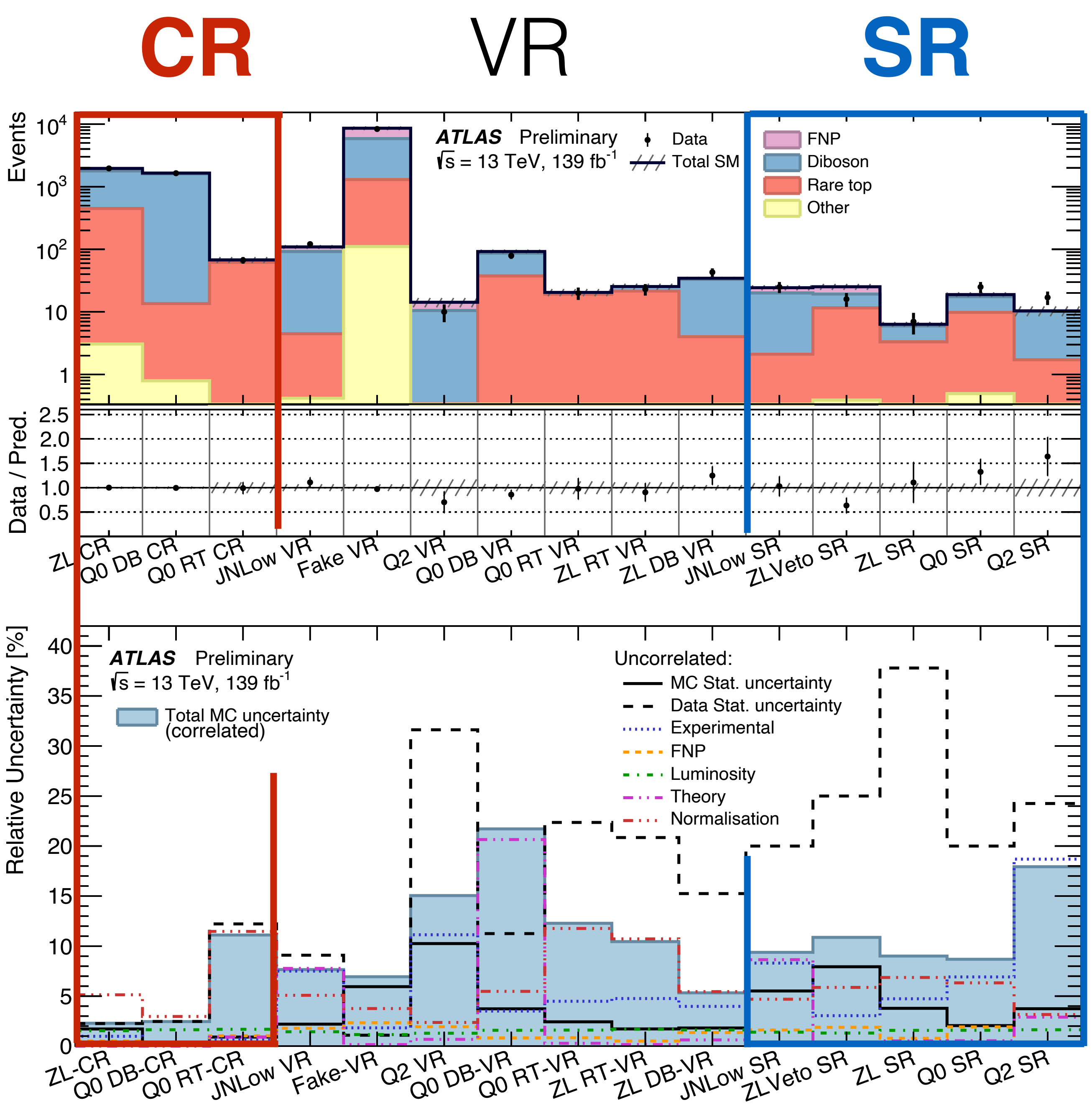


Search for Heavy Leptons

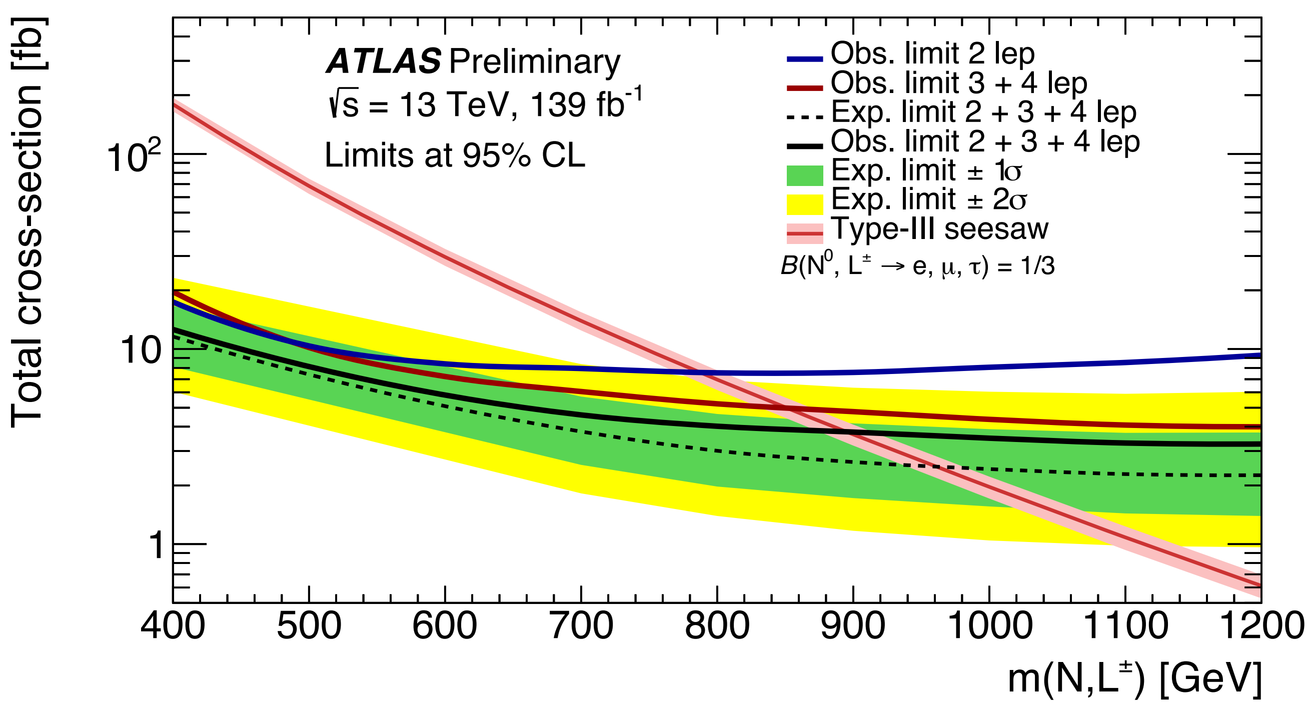
- Search for heavy leptons in events with 3/4 leptons
- Benchmark model: **Type-III seesaw model** which provides a heavy Majorana neutrino that could explain small neutrino mass
- Phenomenology similar to other models with heavy leptons, like **Vector-Like Lepton** triplets that could be linked to $(g-2)_\mu$ anomaly



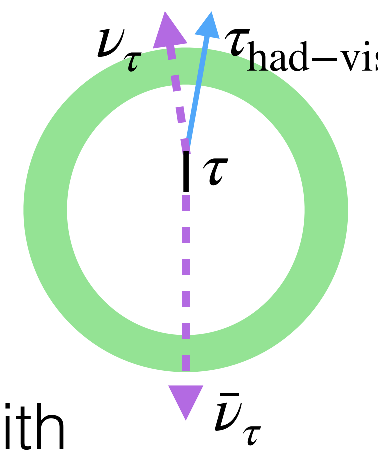
Search for Heavy Leptons

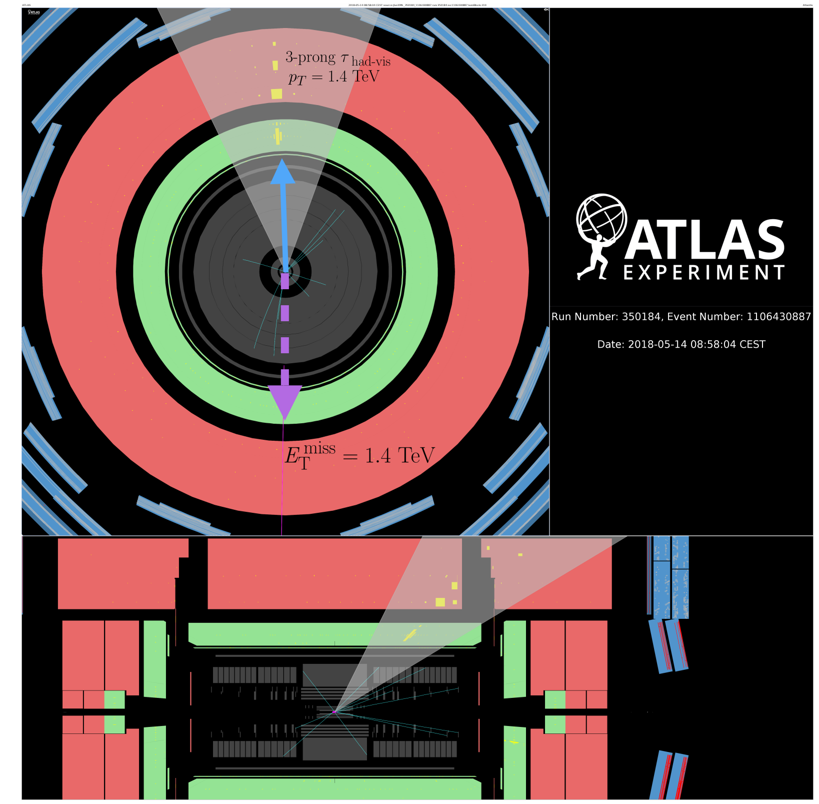


- Statistical uncertainties dominant in SRs
- Results combined with similar search in 2-lepton events [Eur. Phys. J. C 81 (2021) 218]
- Exclusion limits at $m(N, L^{\pm}) > 910$ GeV
- Most stringent limits on type-III seesaw models at LHC

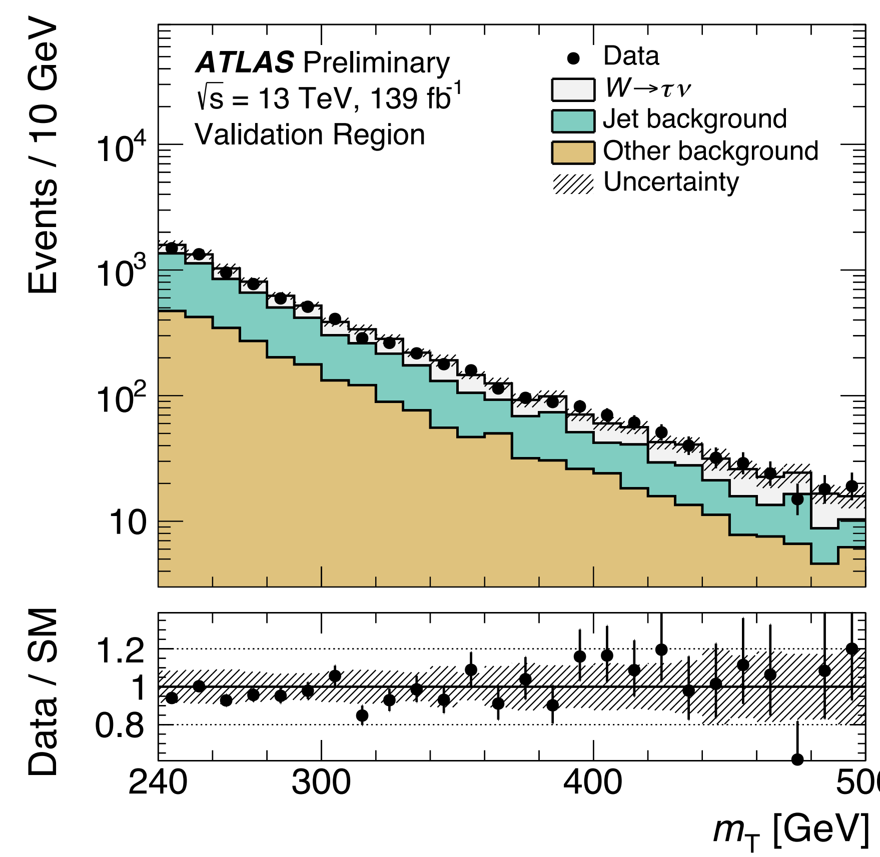


Search for $W' \to \tau\nu$



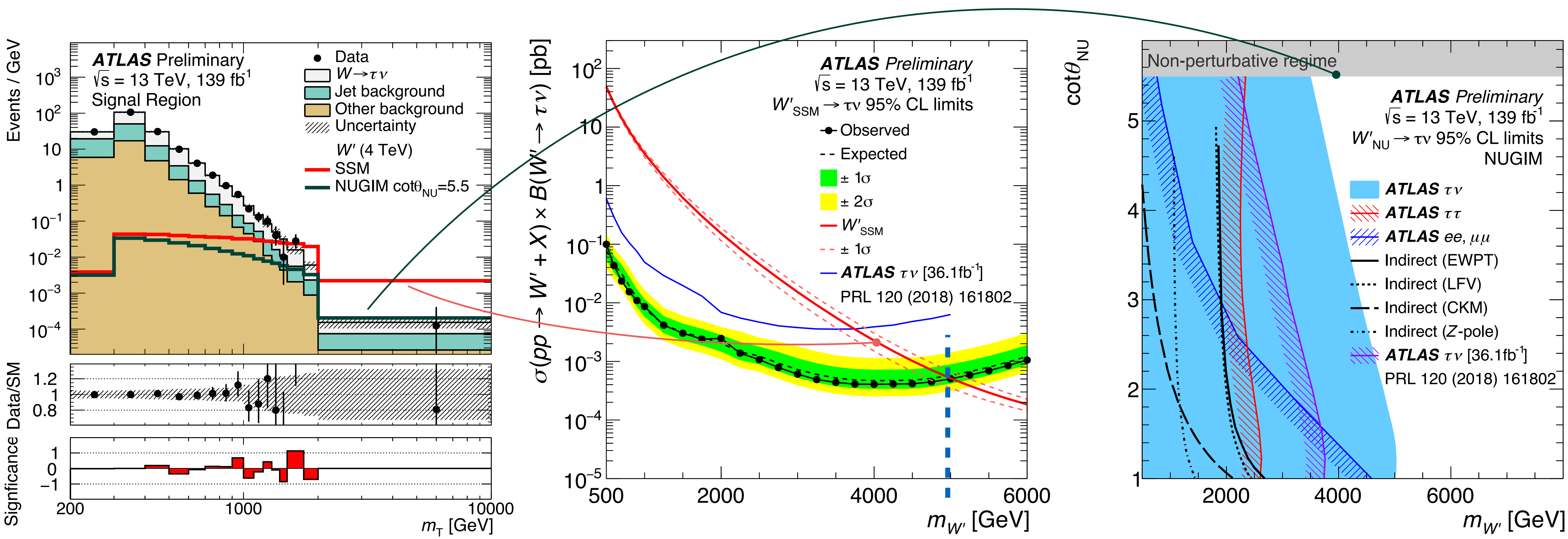


- Search for high-mass resonances in events with hadronically decaying τ lepton and missing transverse energy E_T^{miss}
  - Motivated by extensions of SM with heavy gauge bosons that violate LFU
- Signal events expected to have:
  - back-to-back and p_T-balanced E_T^{miss} and $\tau_{\text{had-vis}}$
  - high $m_T = \sqrt{2E_T^{\text{miss}} p_T (1 - \cos\Delta\phi)}$
- Dominant backgrounds:
  - $W \to \tau\nu$: $W - W'$ interference model dependent and neglected
  - events with mis-identified $\tau_{\text{had-vis}}$ ("jet background") estimated from data



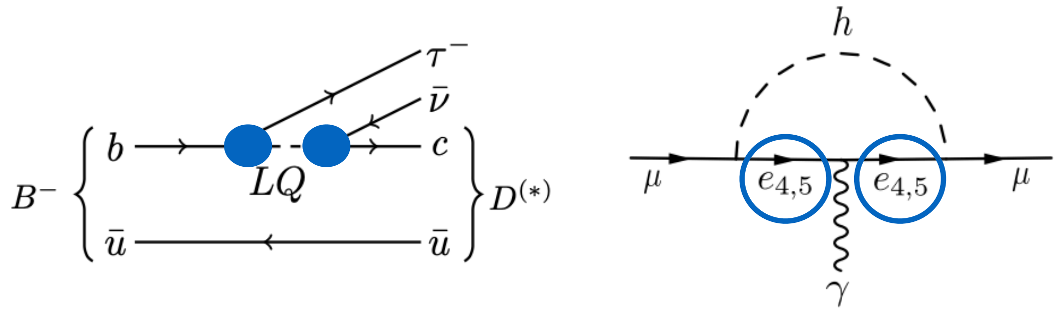
[ATLAS-CONF-2021-025]

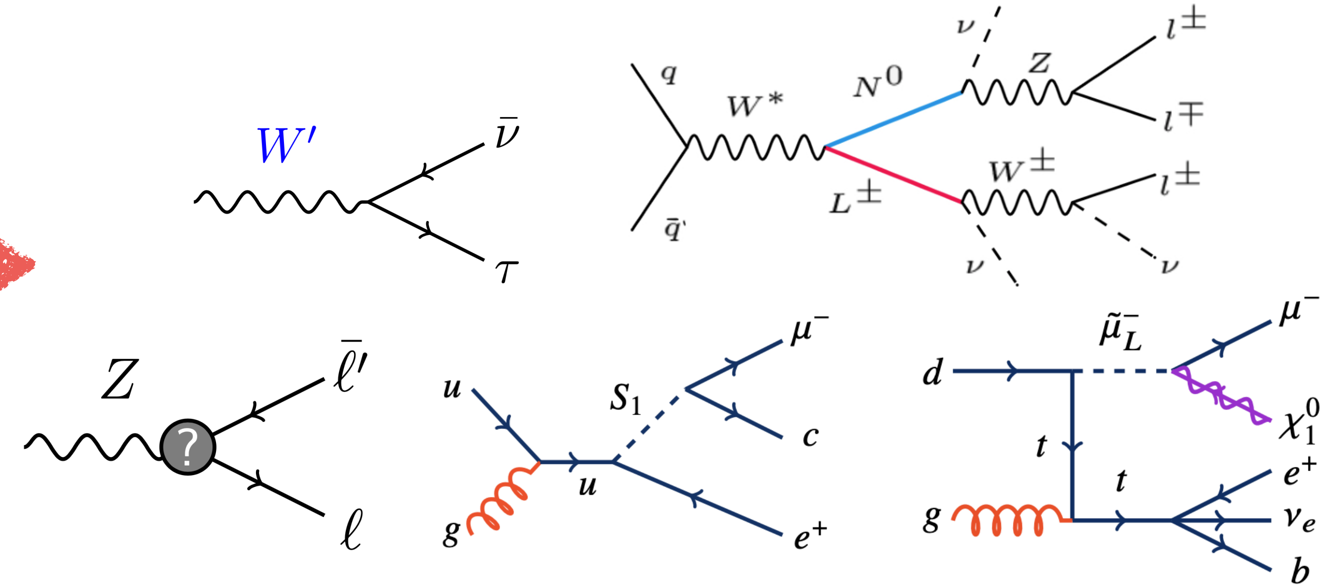
Search for $W' \to \tau\nu$



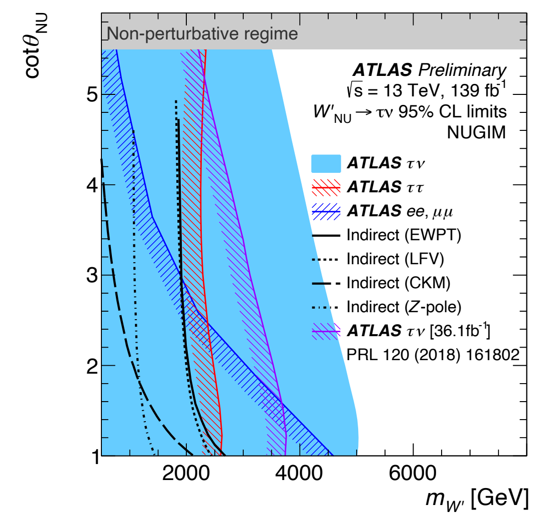
- Upper limits on model-independent cross-section as well as for:
  - **Sequential Standard Model** (SSM) where W' has same flavour-universal coupling as W
  - **Non-Universal Gauge Interaction Model** (NUGIM) with enhanced couplings to third generation fermions ($\cot\theta_{\rm NU} > 1$)

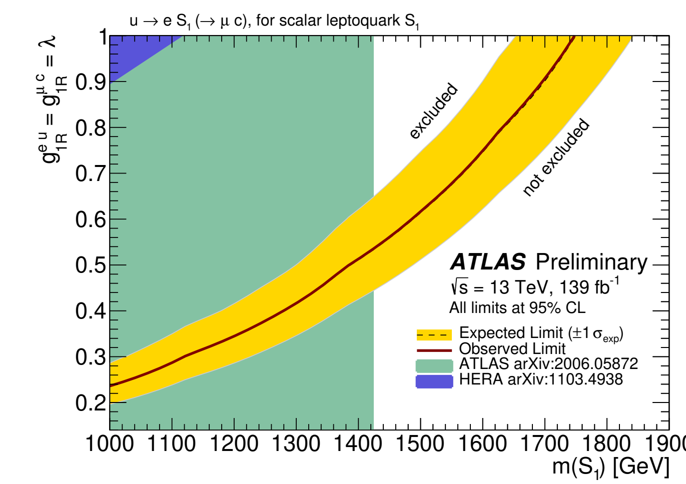
Summary





- **Growing evidence for anomalies in lepton interactions**
- **New experimental data needed from complementary frontiers**
- ATLAS is pushing the search for new phenomena in lepton interactions on several fronts





LFV Z decay	New UL @95%CL	Previous UL @95%CL
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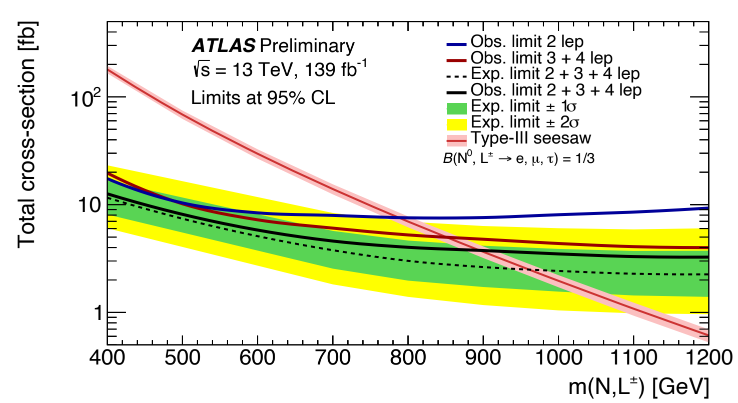
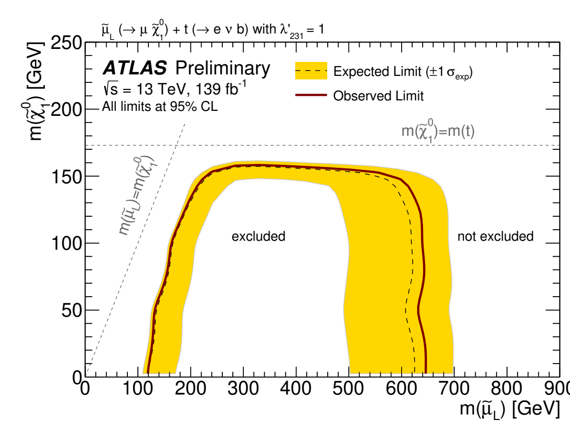
$\mathcal{B}(Z\to e\tau)$	5.0×10^{-6} [ATLAS]	9.8×10^{-6} [OPAL]
$\mathcal{B}(Z\to e\mu)$	3.0×10^{-7} [ATLAS]	7.5×10^{-7} [ATLAS]





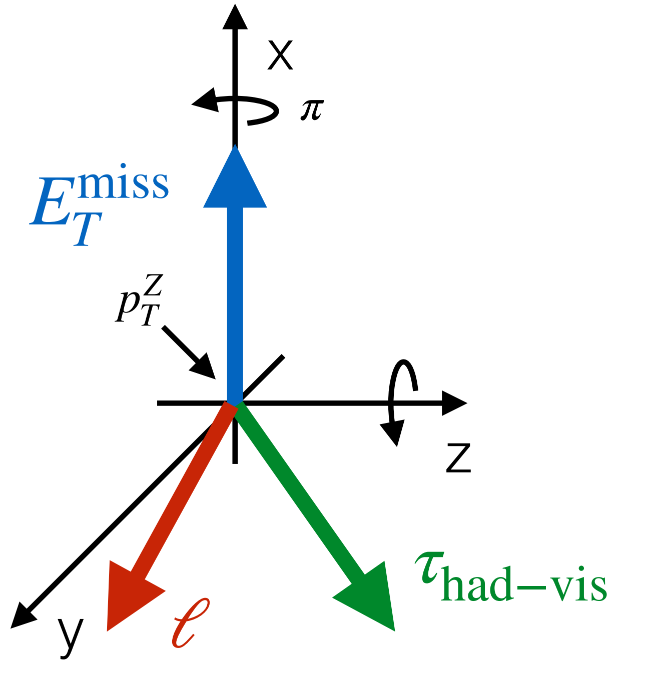
Additional Material

Search for $Z \to \ell\tau$

- Deep neural networks with **full kinematic information** (4-momentum components) of particles
- Inputs:
  - Removal of physical symmetries via rotation and Lorentz-boost. Reduction from 12 to **6 independent momentum components**, hence reduced set of NN inputs (smaller network, good given limited statistics for training)
  - Addition of **high-level variables** (eg masses) to aid training

Variable	Description	
$p_z(\ell)$	z-component of the light lepton's momentum.	In transformed frame
$E(\ell)$	Energy of the light lepton.	
$p_x(\tau_{\text{had-vis}})$	x-component of the $\tau_{\text{had-vis}}$ candidate's momentum.	
$p_z(\tau_{\text{had-vis}})$	z-component of the $\tau_{\text{had-vis}}$ candidate's momentum.	
$E(\tau_{\text{had-vis}})$	Energy of the $\tau_{\text{had-vis}}$ candidate.	
$E_{\text{T}}^{\text{miss}}$	The missing transverse momentum.	
$m_{\text{vis}}(\ell,\tau)$	The visible mass: the invariant mass of the ℓ–$\tau_{\text{had-vis}}$ system.	
$m_{\text{coll}}(\ell,\tau)$	The collinear mass: the invariant mass of the ℓ–$\tau_{\text{had-vis}}$–ν system, where the ν is assumed to have a momentum that is equal in the transverse plane to the measured $E_{\text{T}}^{\text{miss}}$ and collinear in η with the $\tau_{\text{had-vis}}$ candidate.	
$m(\ell,\tau \text{ track})$	The invariant mass of the light lepton and the track associated with the $\tau_{\text{had-vis}}$ candidate (only used by the $Z \to \ell\ell$ classifier).	
$\Delta\alpha$	A kinematic discriminant sensitive to the different fractions of τ-lepton four-momentum carried by neutrinos in signal and background [7].	

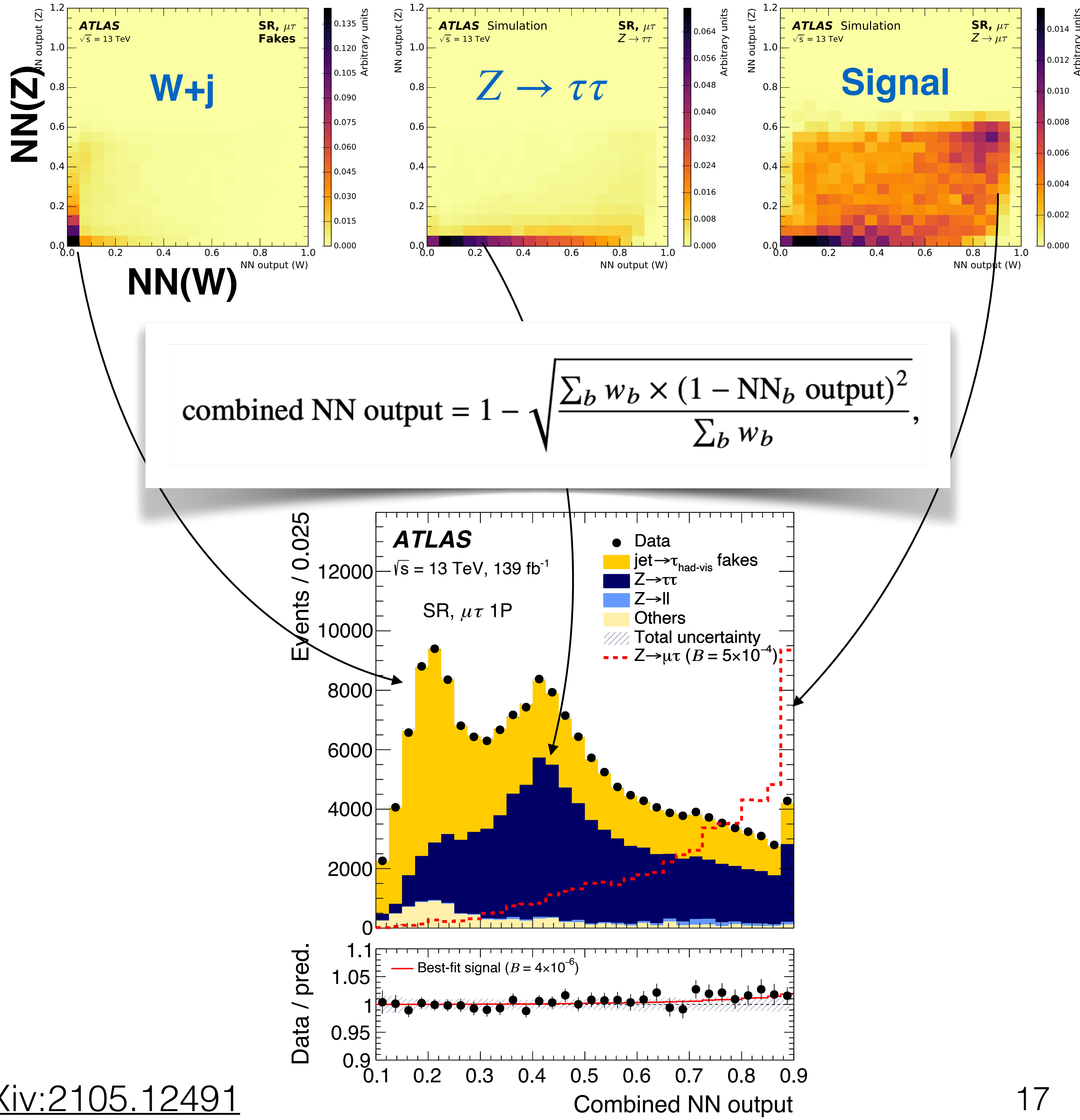
Similar set for leptonic channel



Search for $Z \to \ell\tau$

[Phys. Rev. D 98 (2018) 092010]

- One binary NN classifier trained against each main background
  - Had channel: $Z \to \tau\tau$, $W + j$, $Z \to \ell\ell$
  - Lep channel: $Z \to \tau\tau$, $t\bar{t}$, VV
- **NN outputs combined** exploiting different correlations of these for different processes
- Different source of backgrounds separated from signal but also among themselves
- Shape fit of full combined NN output spectrum able to **better constrain each individual background contribution**, hence better sensitivity



$$\text{combined NN output} = 1 - \sqrt{\frac{\sum_b w_b \times (1 - \text{NN}_b\ \text{output})^2}{\sum_b w_b}},$$

Search for $Z \to \ell\tau$

- Modelling of **Z production**:
  - Signal (Pythia) and $Z \to \tau\tau$ (Sherpa) events reweighed to fiducial Z production cross section measurement by ATLAS to reduce theory uncertainties
- **Common normalisation factor** on signal and $Z \to \tau\tau$ determines $\sigma_Z \times A(\ell\tau)$ from data and reduces experimental systematics uncertainties
- Events with mis-identified objects ($j \to \tau_{\mathrm{had-vis}}$ fakes and non-prompt electrons and muons) modelled from data

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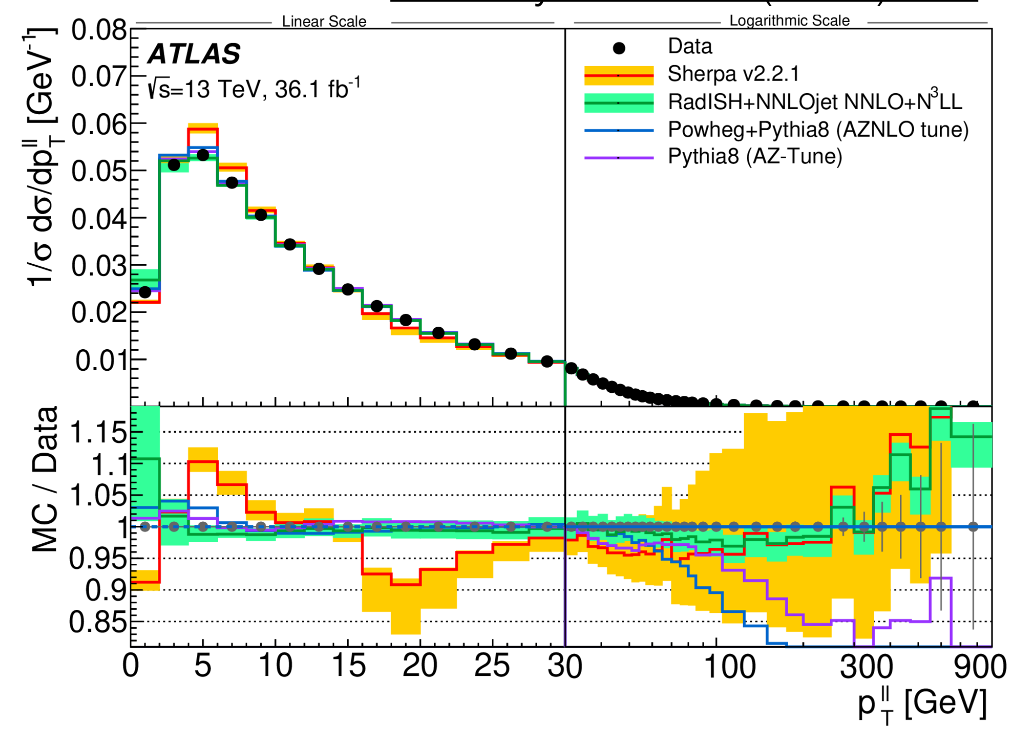


Hadronic channel

Source of uncertainty	Uncertainty on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±2.8
Systematic	±2.3	±1.6
τ-leptons	±1.9	±1.5
Energy calibration	±1.3	±1.4
Jet rejection	±0.3	±0.3
Electron rejection	±1.3	
Light leptons	±0.4	±0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$, jets and flavour tagging	±0.6	±0.5
Z-boson modelling	±0.7	±0.3
Luminosity and other minor backgrounds	±0.8	±0.3
Total	±4.1	±3.2

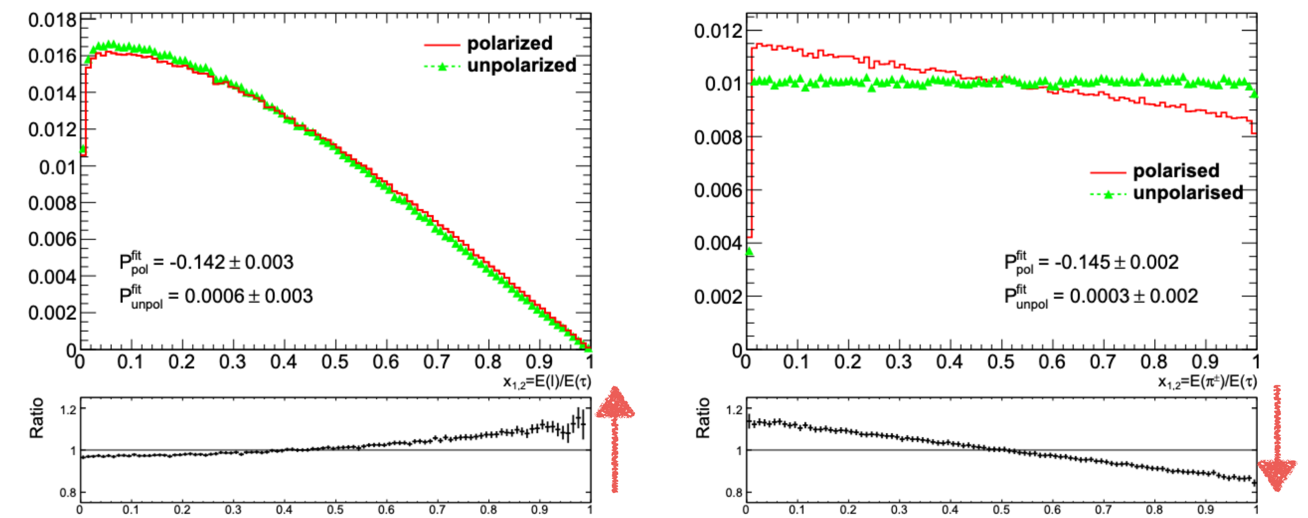
Leptonic channel

Source of uncertainty	Uncertainty in $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	±0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$, jets and flavor tagging	±2.1	±2.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	±0.4	±0.8
Jets	±1.9	±2.2
Flavor tagging	±0.5	±0.9
Z-boson modeling	<0.1	±0.1
$Z \to \mu\mu$ yield	–	±0.8
Other backgrounds	±0.1	±0.6
Fake leptons (systematic)	±0.4	±0.9
Total	±4.4	±5.2

Search for $Z \to \ell\tau$

- Limits on $\mathscr{B}(Z \to \ell\tau)$ for unpolarised and maximally polarised τ leptons
- Due to spin correlations, same polarisation has opposite effects on the energy fraction of the visible decay products in leptonic and hadronic decays
- **Combined results are almost independent of polarisation hypothesis**

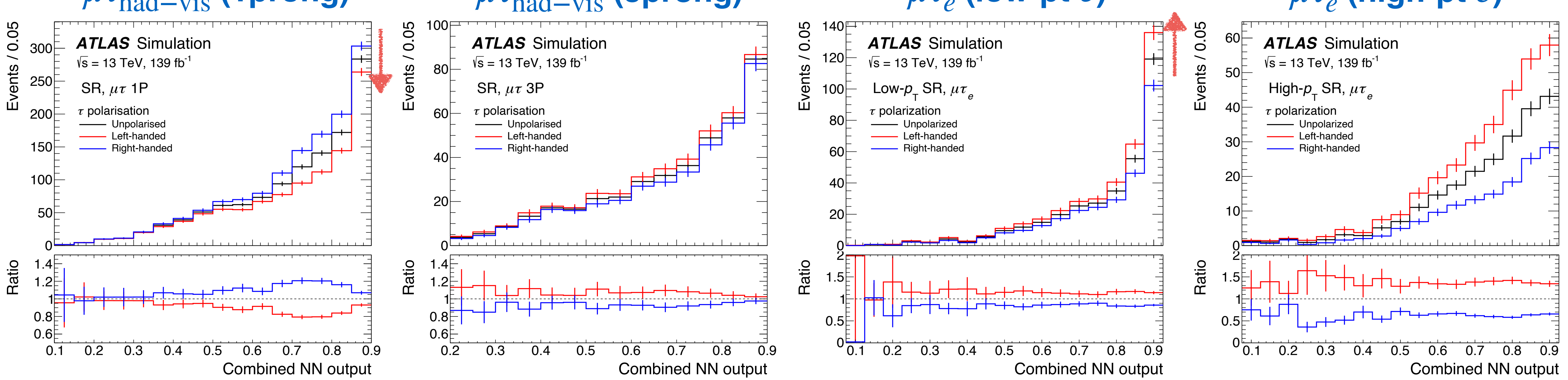
$\tau \to \ell\nu\nu$ $\tau \to \pi\nu$



(a) $\tau \to l\nu_l\nu_\tau$ (b) $\tau \to \pi\nu_\tau$

Acta Phys.Polon.B 45 (2014) 10, 1921-1946

$\mu\tau_{\mathrm{had-vis}}$ **(1prong)** $\mu\tau_{\mathrm{had-vis}}$ **(3prong)** $\mu\tau_e$ **(low-pt e)** $\mu\tau_e$ **(high-pt e)**



D. Zanzi

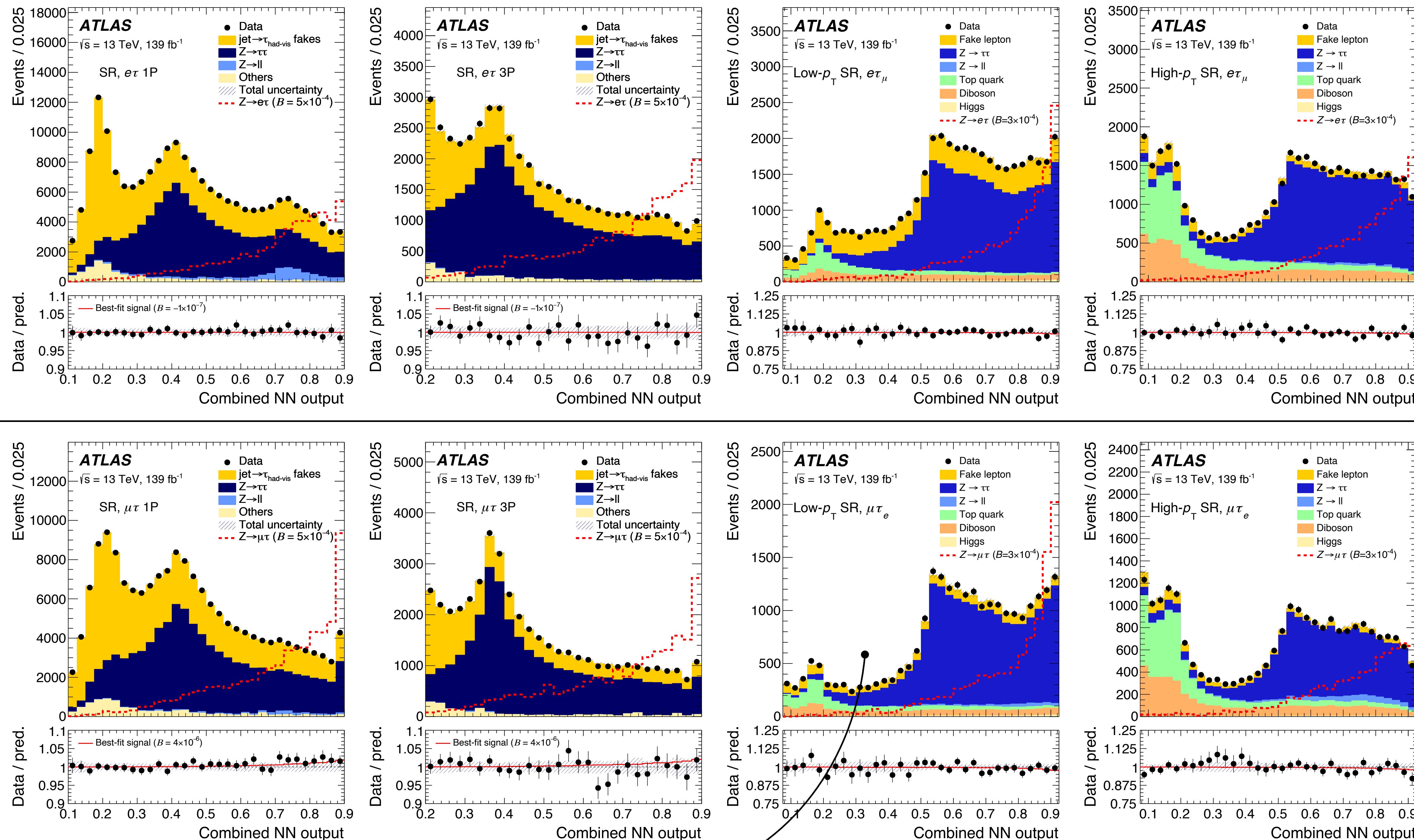
Nature Physics 17, 819 (2021), arXiv:2105.12491

Search for $Z \to \ell\tau$

	$\ell\tau_{\text{had-vis}}$ **(1prong)**	$\ell\tau_{\text{had-vis}}$ **(3prong)**	$\ell\tau_{\ell'}$ **(low-pt l')**	$\ell\tau_{\ell'}$ **(high-pt l')**

Search for $Z \to e\tau$

Search for $Z \to \mu\tau$



Bulk of $Z \to \tau\tau$ events fitted in separate Z-CRs

SRs divided by p_T of subleading lepton to improve categorisation of fakes background

D. Zanzi

Search for $Z \to \ell\tau$

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

- Best-fit:
  - $\mathcal{B}(Z \to e\tau) = (-1.4 \pm 2.5(\text{stat}) \pm 1.8(\text{sys})) \times 10^{-6}$
  - $\mathcal{B}(Z \to \mu\tau) = (+1.7 \pm 2.2(\text{stat}) \pm 1.6(\text{sys})) \times 10^{-6}$
- World-best upper limits, **2x** improvement on limits by LEP!

Search for Heavy Leptons

3ℓ Events:

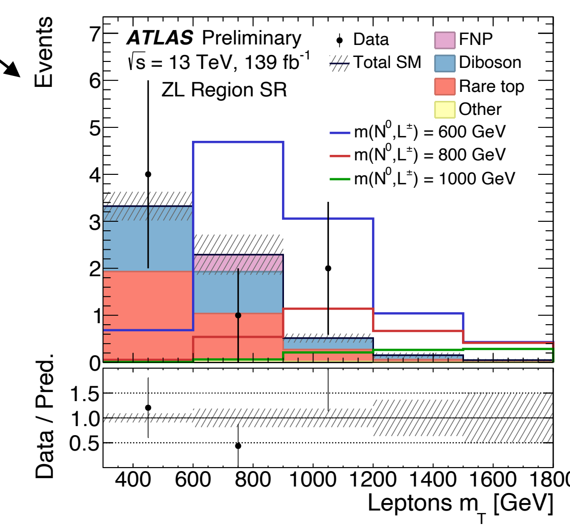
Table 2: Summary of the selection criteria used to define relevant regions in the three-lepton analysis.

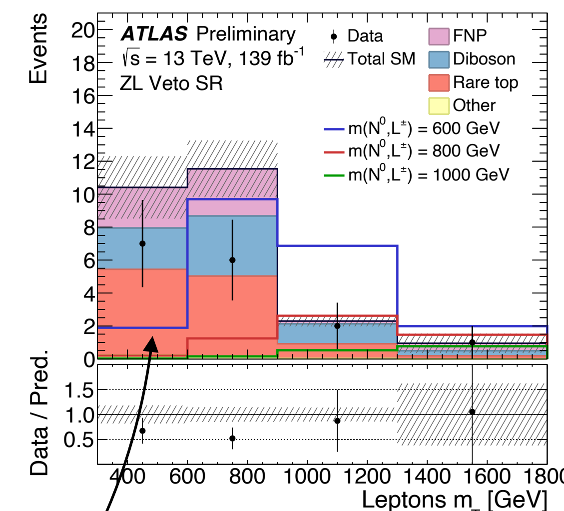
		ZL				ZLveto	JNLow	
	Fake-VR	CR	DB-VR	RT-VR	SR	SR	VR	SR
	$p_T(l_1) > 40$ GeV $p_T(l_2) > 40$ GeV $p_T(l_3) > 15$ GeV							
$S(E_T^{miss})$	< 5	≥ 5						
$N(jet)$		≥ 2				≥ 2	≤ 1	
$N(bjet)$		-	0	≥ 1	-			
$m_{ll}(OSSF)$ [GeV]		$80 - 100$				≥ 115	≥ 80	
$H_T + E_T^{miss}$ [GeV]						≥ 600		
m_{lll} [GeV]		-	≥ 300			≥ 300		
m_{jj} [GeV]						< 300		
$H_T(SS)$ [GeV]						≥ 300		
$H_T(lll)$ [GeV]							≥ 230	
$m_T(l_1)$ [GeV]			≥ 200				< 240	≥ 240
$m_T(l_2)$ [GeV]		< 200	≥ 200				≥ 150	
$\Delta R(l_1, l_2)$			< 1.2		$1.2 - 3.5$		≥ 1.3	

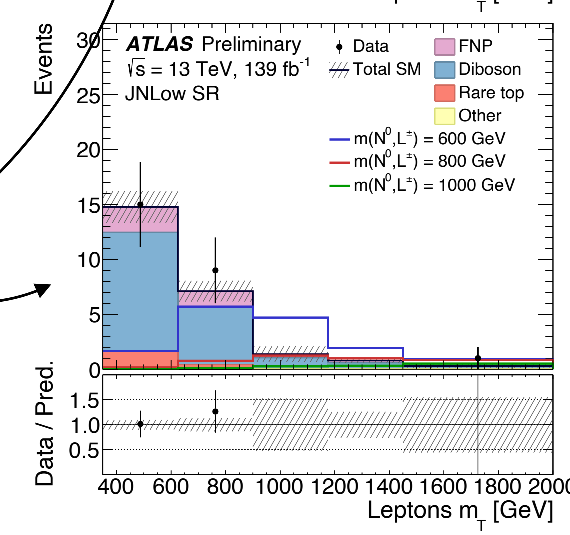
$$m_T(i) = \sqrt{2p_T(i)E_T^{miss}(1 - \cos\Delta\phi(i, E_T^{miss}))}$$

$$H_T = \Sigma_i p_T(i)$$

$$m_T = |\Sigma_i^{3\ell}\overrightarrow{p}_{T,i} + \overrightarrow{p}_T^{miss}|$$





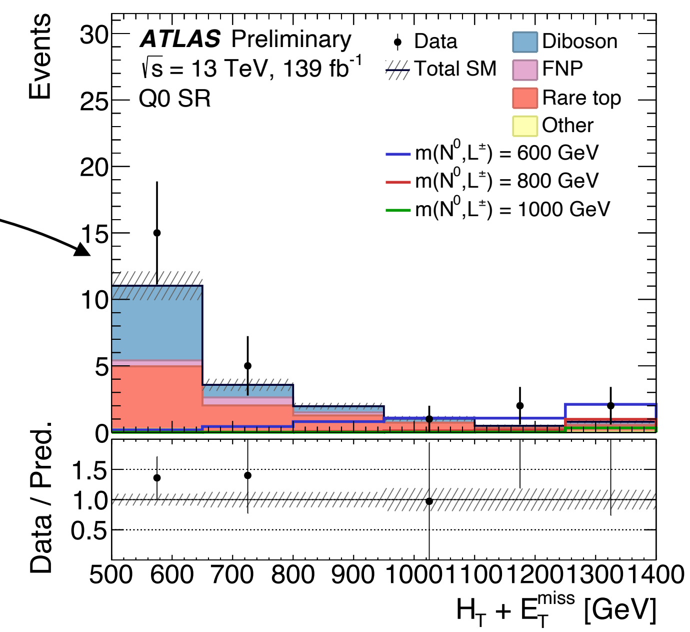


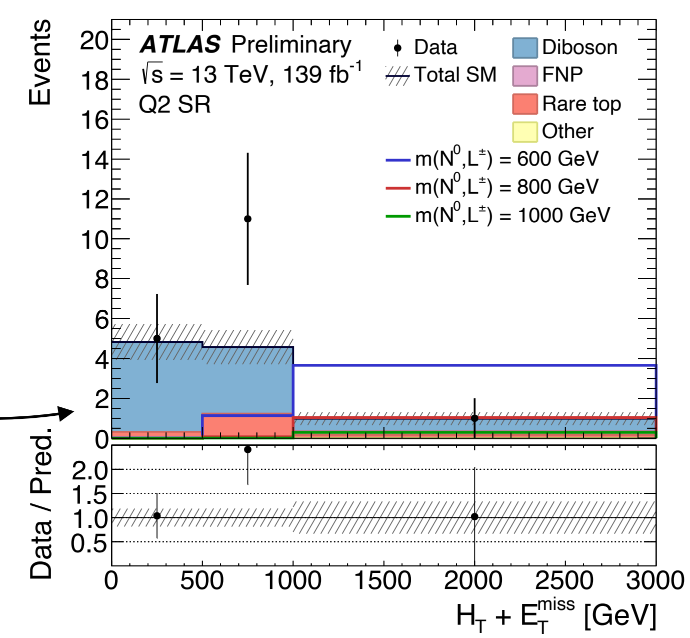
Search for Heavy Leptons

4ℓ Events:

Table 3: Summary of the selection criteria used to define relevant regions in the four-lepton analysis. N_Z is the number of leptonically reconstructed Z, using opposite sign same flavour leptons.

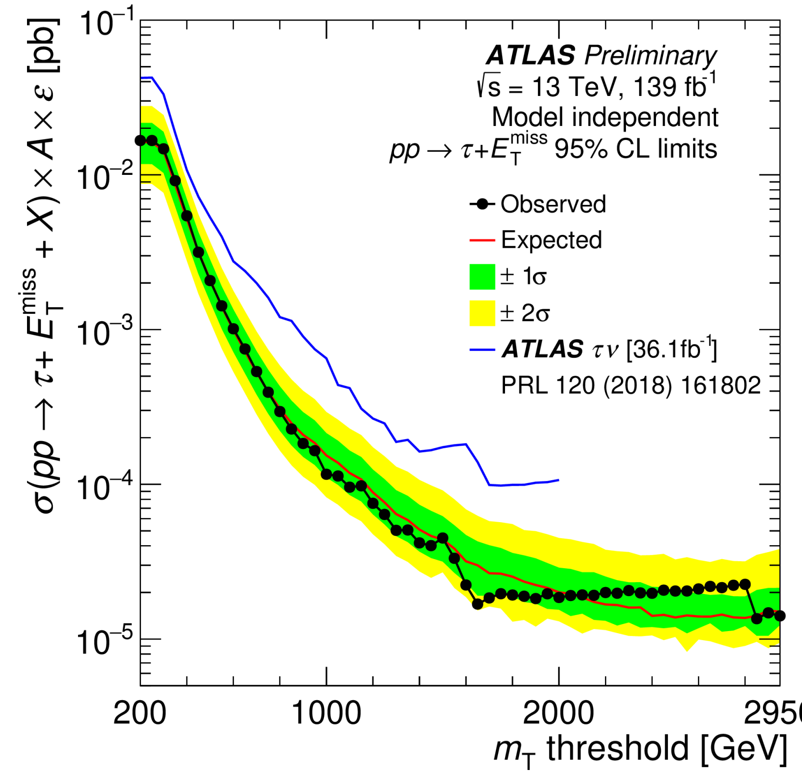
	Q0					Q2	
	DB-VR	RT-VR	DB-CR	RT-CR	SR	VR	SR
$\lvert\sum q_\ell\rvert$	0					2	
$N_{b\text{-jet}}$	1	1	0	≥ 2	0		
m_{llll} [GeV]	170 – 300	300 – 500	170 – 300	< 500	≥ 300	< 200	≥ 300
						OR	
$H_T + E_T^{\text{miss}}$ [GeV]		≥ 400			≥ 300	< 300	≥ 300
N_Z					≤ 1		
$\mathcal{S}(E_T^{\text{miss}})$		≥ 5			≥ 5		

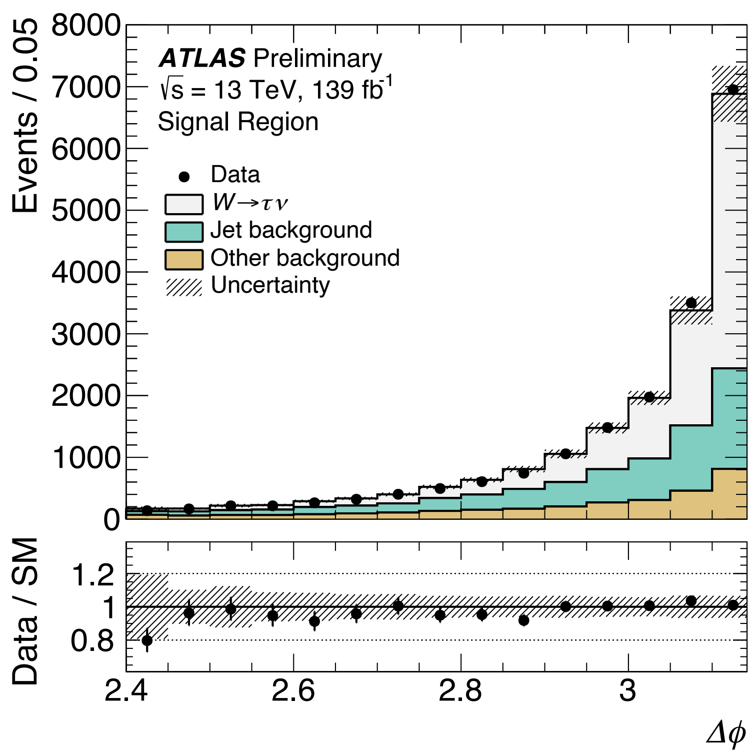


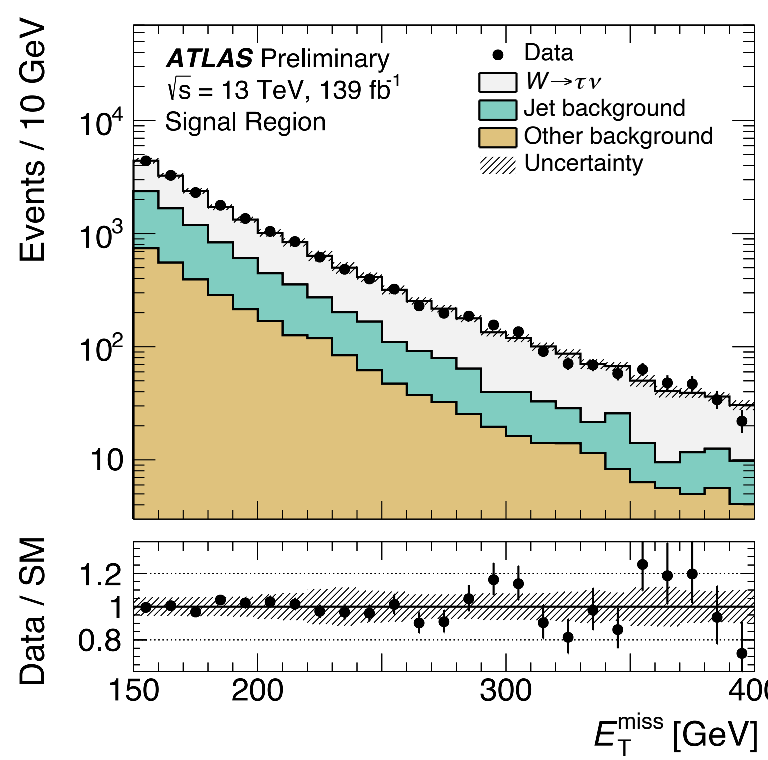


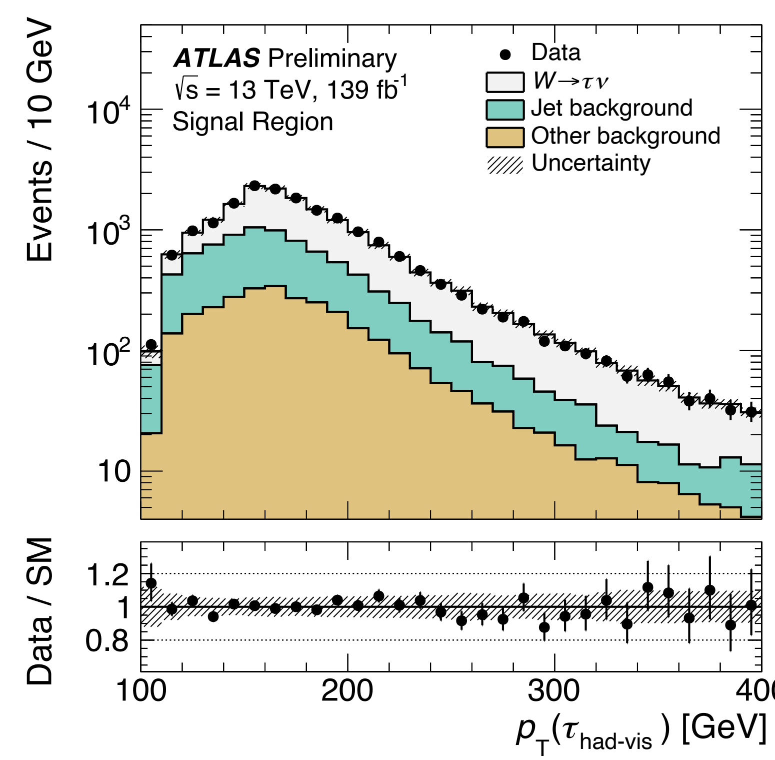
Search for $W' \to \tau\nu$

	Preselection				
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	70, 90, 110 GeV				
Event cleaning	applied				
$\tau_{\text{had-vis}}$ tracks	1 or 3				
$\tau_{\text{had-vis}}$ charge	± 1				
$\tau_{\text{had-vis}}$ p_{T}	> 30 GeV				
$\tau_{\text{had-vis}}$ $p_{\mathrm{T}}^{\text{leadTrack}}$	> 10 GeV				
Lepton veto	applied				
$\Delta\phi(\tau_{\text{had-vis}}\ p_{\mathrm{T}}, E_{\mathrm{T}}^{\mathrm{miss}})$	> 2.4 rad				
	Region requirements				
	SR	**CR1**	**CR2**	**CR3**	**VR**
Tau identification	L	VL \ L	L	VL \ L	L
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 150 GeV	< 100 GeV	< 100 GeV	> 150 GeV
$p_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}}$	$\in [0.7, 1.3]$	$\in [0.7, 1.3]$	–	–	< 0.7
m_{T}	–	–	–	–	> 240 GeV









[ATLAS-CONF-2021-025]

$e^+\mu^- / e^-\mu^+$ Measurement [NEW!]