

Search for lepton-flavour-violating decays of the Z boson into a τ -lepton and a light lepton with the ATLAS detector



Wing Sheung Chan (Nikhef) on behalf of the ATLAS collaboration
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Lepton-flavour-violating (LFV) decays of the Z boson

- Flavour conservation is **not** a fundamental symmetry in the SM
- Flavour-changing processes have been observed in the quark and neutrino sectors:
 - CKM matrix \rightarrow quark mixing
 - PMNS matrix \rightarrow neutrino mixing
- How about charged leptons?
 - Charged lepton flavour violation – not observed yet
 - In the Standard model (SM): Possible beyond tree level with neutrino oscillations (fig. 1), but with vanishingly small branching ratios
- LFV Z boson decays
 - Z boson is a well-measured SM particle and has a large production rate at the LHC
 - While the $Z \rightarrow e\mu$ channel is heavily constrained by low-energy experiments, $Z \rightarrow e\tau$ and $Z \rightarrow \mu\tau$ are excellent channels to search for lepton flavour violation
 - In the SM, $\text{BR}(Z \rightarrow \ell\tau) \sim \mathcal{O}(10^{-54})$ ($\ell = e/\mu$)
 \rightarrow Unambiguous signal of Beyond-the-Standard-Model phenomena!

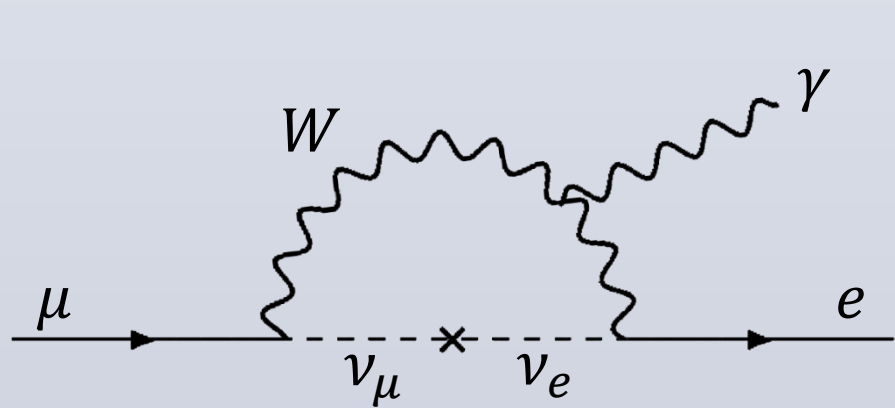


Fig. 1 Example of LFV process in the SM beyond the tree level with neutrino oscillation.

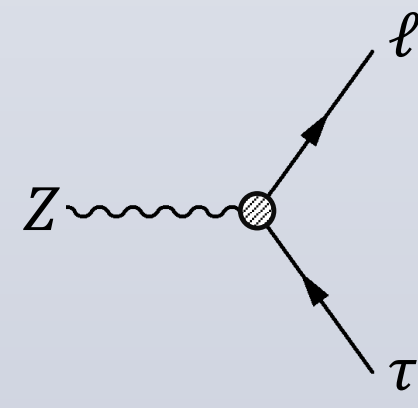


Fig. 2 LFV decay of a Z boson into a τ -lepton and a light lepton, a BSM signal.

Unique features of the $Z \rightarrow \ell\tau$ signal events

- Final state with one **light lepton** and one **τ -lepton** (\rightarrow visible decay products $\tau_{\text{vis}} +$ missing energy $E_{\text{T}}^{\text{miss}}$)
- Resonance at the Z boson rest mass
- Opposite-sign charged $\ell\tau$ pair whose momenta are back-to-back in the transverse plane
- Boosted ℓ and τ due to the heavy mass of Z
- $E_{\text{T}}^{\text{miss}}$ that is almost collinear with the visible τ (due to the boosted nature)
 - Allow the full energy and momentum of the τ -lepton, and thus the invariant mass of the $\ell\tau$ system, to be reconstructed in good approximation (known as the collinear approximation):

$$m_Z = m_{\ell\tau} \approx m_{\text{coll}} = \sqrt{2 p_T^\ell (p_T^{\tau_{\text{vis}}} + E_{\text{T}}^{\text{miss}}) (\cosh \Delta\eta - \cos \Delta\phi)}$$
- Have relatively high $m_T(\ell, E_{\text{T}}^{\text{miss}})$ and low $m_T(\tau_{\text{vis}}, E_{\text{T}}^{\text{miss}})$

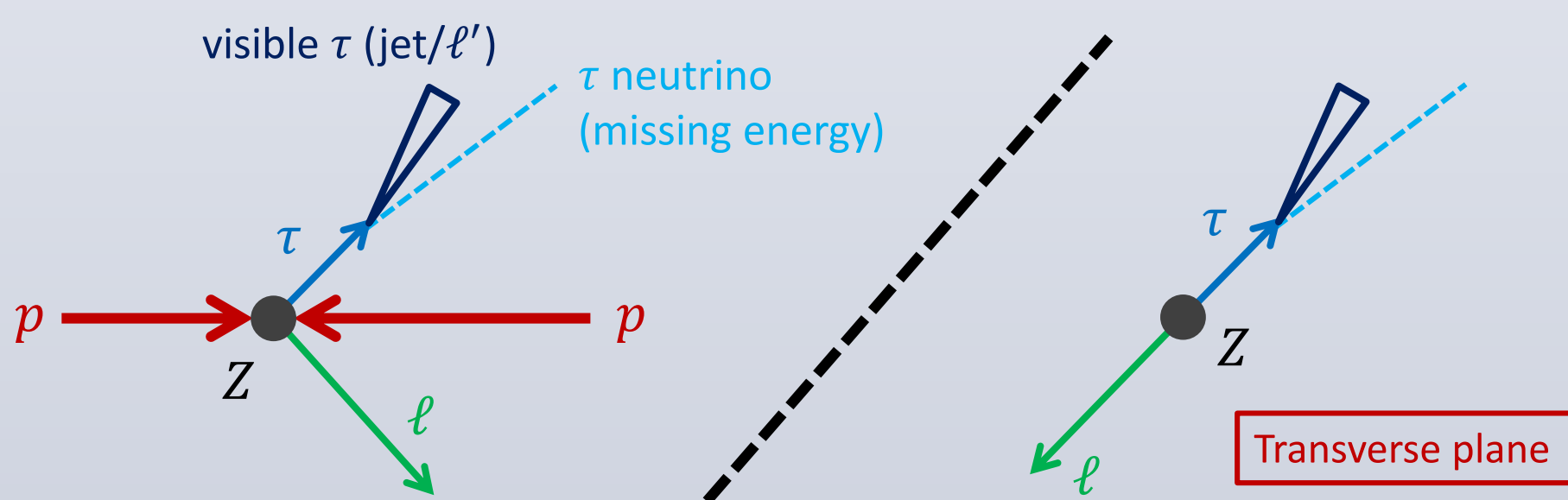


Fig. 3 Schematic diagrams showing the typical spatial configuration of a $Z \rightarrow \ell\tau$ signal event.

Major backgrounds and their estimation

- For this analysis, only channels with a hadronically decaying τ -lepton (τ_{had}) are considered. For these channels, the major backgrounds are:
 - $Z \rightarrow \tau\tau \rightarrow \ell\tau_{\text{had}}$
 - $W(\rightarrow \ell\nu) + \text{jets}$ (jet mis-identified as $\tau_{\text{had-vis}}$, a.k.a. “jet $\rightarrow \tau$ fakes”)
 - $Z \rightarrow \ell\ell$ (ℓ mis-identified as $\tau_{\text{had-vis}}$, a.k.a. “ $\ell \rightarrow \tau$ fakes”)
- Monte Carlo (MC) simulations are used to estimate the $Z \rightarrow \tau\tau$ and $Z \rightarrow \ell\ell$ backgrounds, as well as other minor backgrounds like $H \rightarrow \tau\tau$ and diboson events.
- jet $\rightarrow \tau$ fakes are not well modelled in simulation, therefore their contributions are estimated by a data-driven method known as the fake factor (FF) method (fig. 4)
- To reduce theoretical uncertainties, all of the major backgrounds are normalised to data using events in some background-enriched, signal-free regions

Basic procedures of the fake factor method:

1. Measure FF in calibration regions (CRs):
FF = ratio of observed events passing/failing the τ identification algorithm (τ ID)

2. Apply FF in the signal region (SR):
Estimation = FF \times observed events failing τ ID

	SR	CRs
Passed τ ID	Estimation	Data
Failed τ ID	Data	Data

Fig. 4 The basic concept and procedures of the fake factor method.

Event selection and classification

- Event selection is performed based on reconstructed kinematic variables of the ℓ and $\tau_{\text{had-vis}}$ candidates, together with the $E_{\text{T}}^{\text{miss}}$
- Suppressing W +jets and $Z \rightarrow \tau\tau$ events:
 - Signal** – low $m_T(\tau_{\text{vis}}, E_{\text{T}}^{\text{miss}})$ due to boosted τ -lepton decay
 - W +jets** – high $m_T(\tau_{\text{vis}}, E_{\text{T}}^{\text{miss}})$ due to large jet p_T and large opening angle between neutrino and jet ($\rightarrow \tau$ fake)
 - $Z \rightarrow \tau\tau$** – high $m_T(\tau_{\text{vis}}, E_{\text{T}}^{\text{miss}})$ on average due to two τ -leptons decaying in opposite directions
 \rightarrow Making use of these characteristics, a cut is placed on $m_T(\tau_{\text{vis}}, E_{\text{T}}^{\text{miss}})$ to divide up the background control regions and the signal region
- Suppressing $Z \rightarrow \ell\ell$ events:
 - Signal** – reconstructed visible invariant mass m_{vis} does not resemble the Z rest mass in general due to missing energy from τ neutrinos
 - $Z \rightarrow \ell\ell$** – m_{vis} resembles the Z rest mass since there is no missing energy in the events
 \rightarrow Cuts are placed to reject events with $m_{\text{vis}} \approx m_Z$
- After the event selection, events within the signal region are classified using neural network (NN) classifiers
- Three binary classifiers are trained for each channel, with each classifier trained against one of the major backgrounds ($Z \rightarrow \tau\tau$, W +jets and $Z \rightarrow \ell\ell$)
 - Simple network: 2 hidden layers, 16 nodes per layer; optimised to reduce cross entropy
 - Training samples: MC simulated events
 - Inputs: 4-momenta of the reconstructed ℓ , $\tau_{\text{had-vis}}$ and $E_{\text{T}}^{\text{miss}}$, along with a few high-level kinematic variables, including m_{coll} and m_{vis}
 - The different classifiers are then combined into one single powerful classifier, whose output is used for final statistical interpretations

Results, interpretations and outlook

- The expected distributions of the combined NN classifier output are fit to data in the signal region (fig. 5)
 - Data: $\sqrt{s} = 13$ TeV pp collisions, collected by ATLAS in 2015-2016 ($L = 36.1 \text{ fb}^{-1}$)
 - Free parameters of the fit include the LFV decay branching ratio $\text{BR}(Z \rightarrow \ell\tau)$ and the normalisations of the $Z \rightarrow \tau\tau$ and jet $\rightarrow \tau$ fakes backgrounds
 - Fits for the $Z \rightarrow e\tau$ and $Z \rightarrow \mu\tau$ channels are performed separately, since the branching ratios of the two LFV decays are not necessarily correlated
 - Due to the difference in background compositions, events with 1-prong and 3-prong $\tau_{\text{had-vis}}$ candidates are fit separately but simultaneously
- No significant excess ($> 3\sigma$) of events above the expected background is observed
 - An excess in the $e\tau$ final state with a significance of 2.3σ is observed
- CL_S upper limits at 95% confidence level are set:
 - $\text{BR}(Z \rightarrow e\tau) < 5.8 \times 10^{-5}$** (expected: 2.8×10^{-5})
 - $\text{BR}(Z \rightarrow \mu\tau) < 2.4 \times 10^{-5}$** (expected: 2.4×10^{-5})
- When combined with previous ATLAS result on the $Z \rightarrow \mu\tau$ channel, the limit reached:
 - $\text{BR}(Z \rightarrow \mu\tau) < 1.3 \times 10^{-5}$** (to be compared with LEP most stringent limit at 1.2×10^{-5})
- Outlook:
 - More data is coming! (Expecting $\sim 150 \text{ fb}^{-1}$ of data collected by the end of 2018)
 - Expect much improved upper limits and stay tuned!

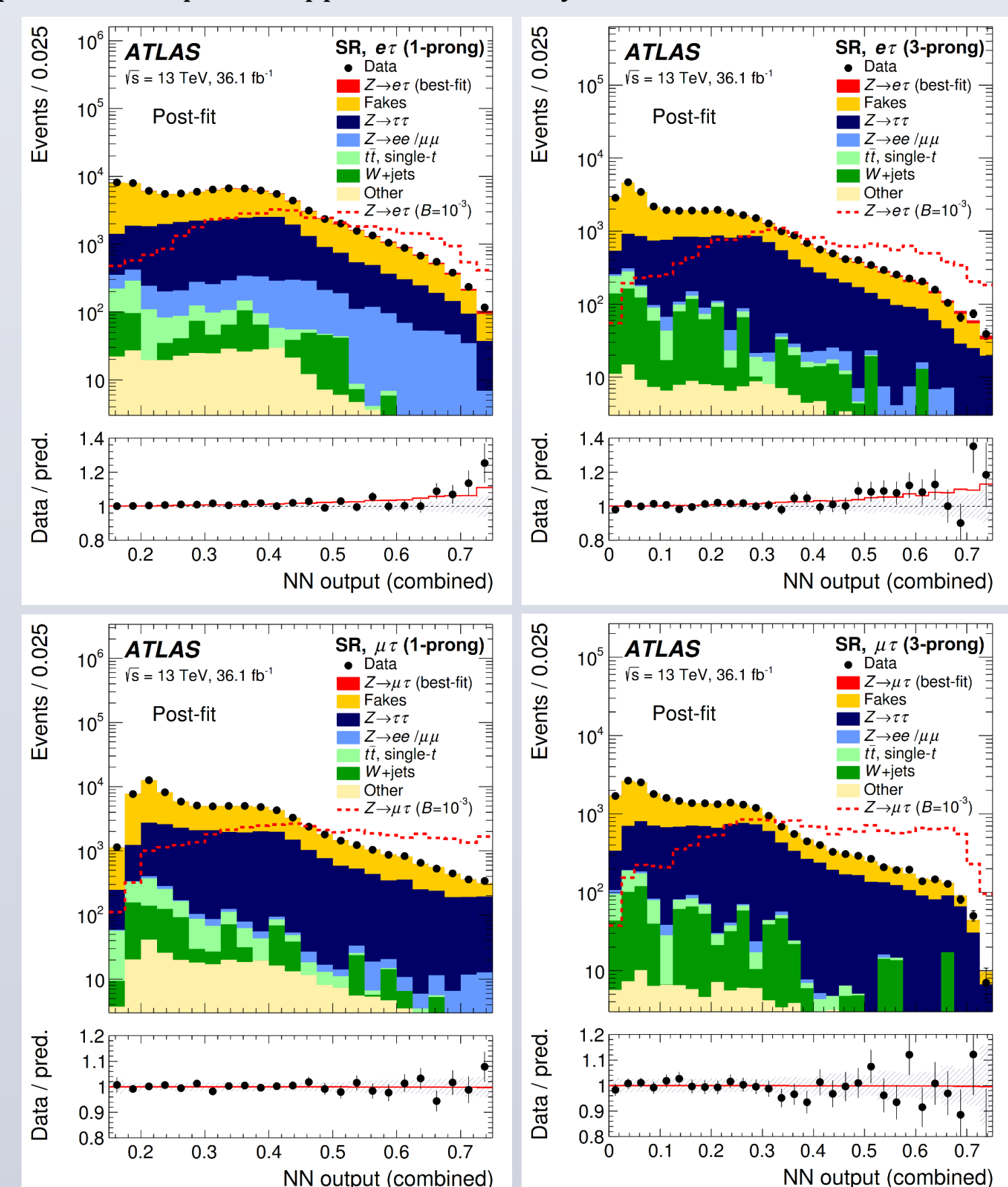


Fig. 5 Post-fit expected and observed distributions of the combined NN classifier output.