Search for lepton-flavour-violating Z decays with the ATLAS detector

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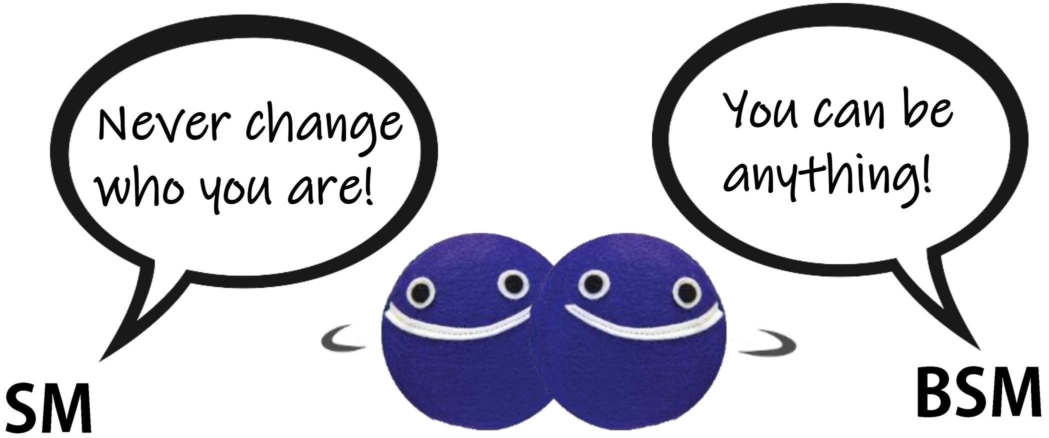
ATLAS EXPERIMENT Nikhef

What is lepton flavour violation (LFV)?

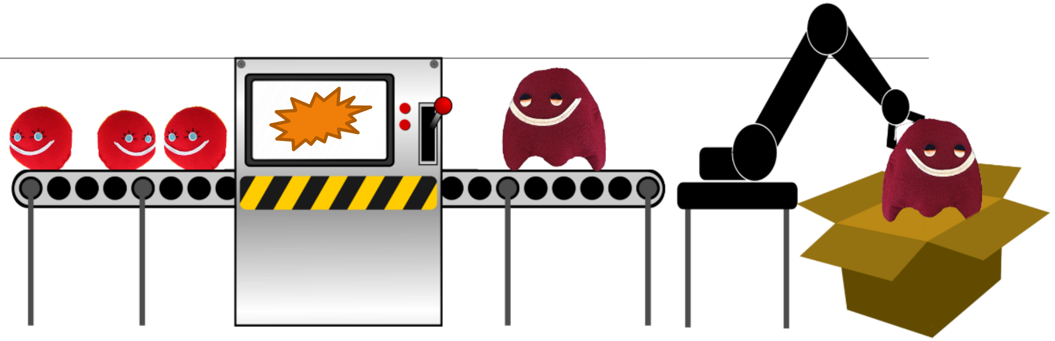
- Flavour symmetry is **not** a fundamental symmetry in the Standard Model
- Indeed, fermions do change flavour:
  - Quark mixing has been observed (CKM matrix)
  - Neutrino mixing has been observed (PMNS matrix)

- How about charged lepton?
  - Possible in the SM (with neutrino oscillations), but with vanishingly small branching ratios ($\ll 10^{-50}$) → Impossible to detect
  - Some BSM theories predict much higher rates → Unambiguous signal of BSM phenomena
  - Not observed yet → Keep searching!

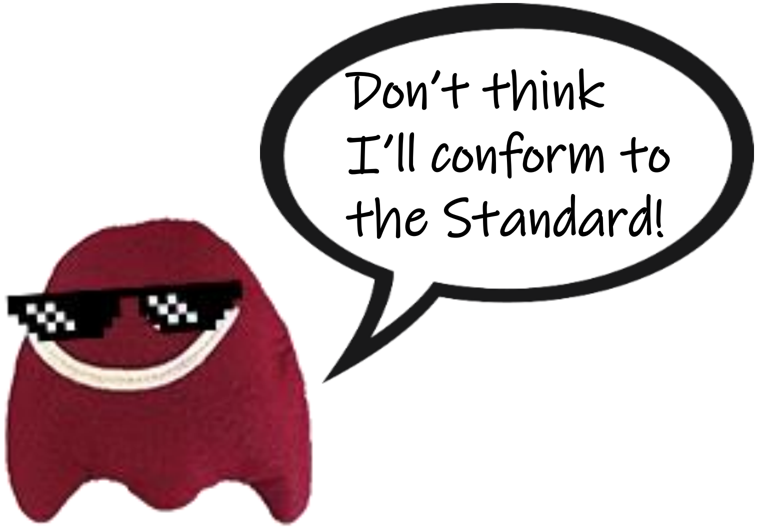


(τ-lepton in an existential crisis)

Why LFV Z decays?

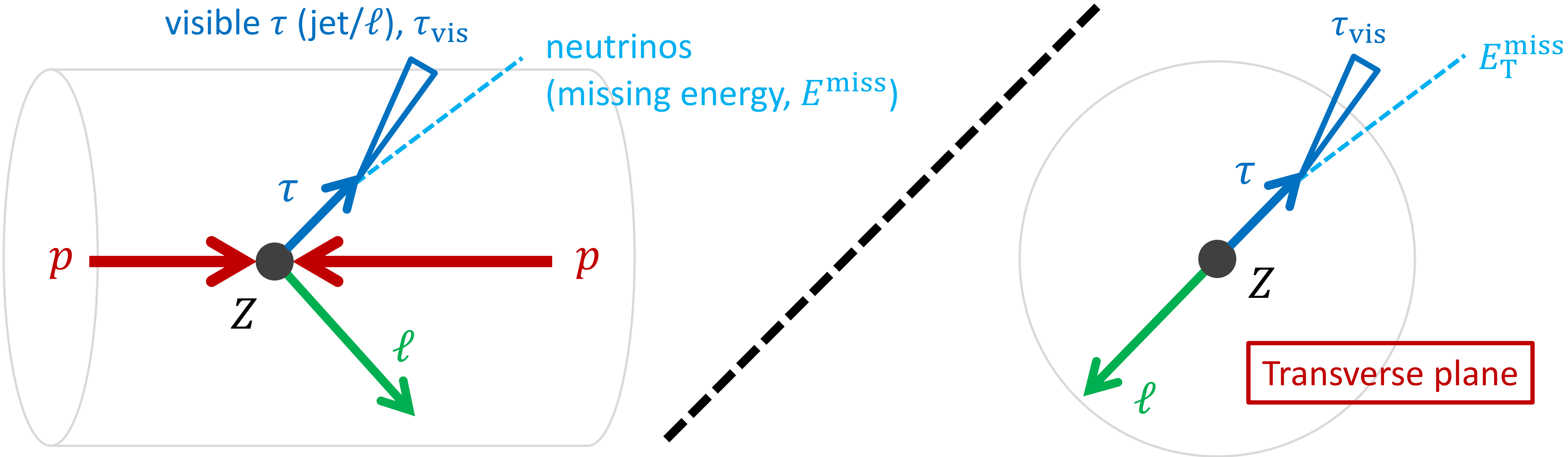


- LHC is basically a Z factory
  - cross section × integrated luminosity (Run-2) $\approx 60\ \text{nb} \times 160\ \text{fb}^{-1} \approx 10^{10}$
- Also, Z boson properties have been very well measured
  - which allows more precise analysis
- Lepton-flavour-violating Z boson decays
  - In the SM, $\text{BR}(Z \to \ell\ell') \sim O(10^{-54})$
  - BSM scenarios with much higher LFV BR predicted, e.g.:
    - Supersymmetry
    - Extended gauge
    - Heavy neutrino



- In particular, we (Nikhef) focus on $Z \to e\tau/\mu\tau$ searches in ATLAS
  - ($Z \to e\mu$ has more stringent indirect limits from low-energy $\mu \to e$ experiments)

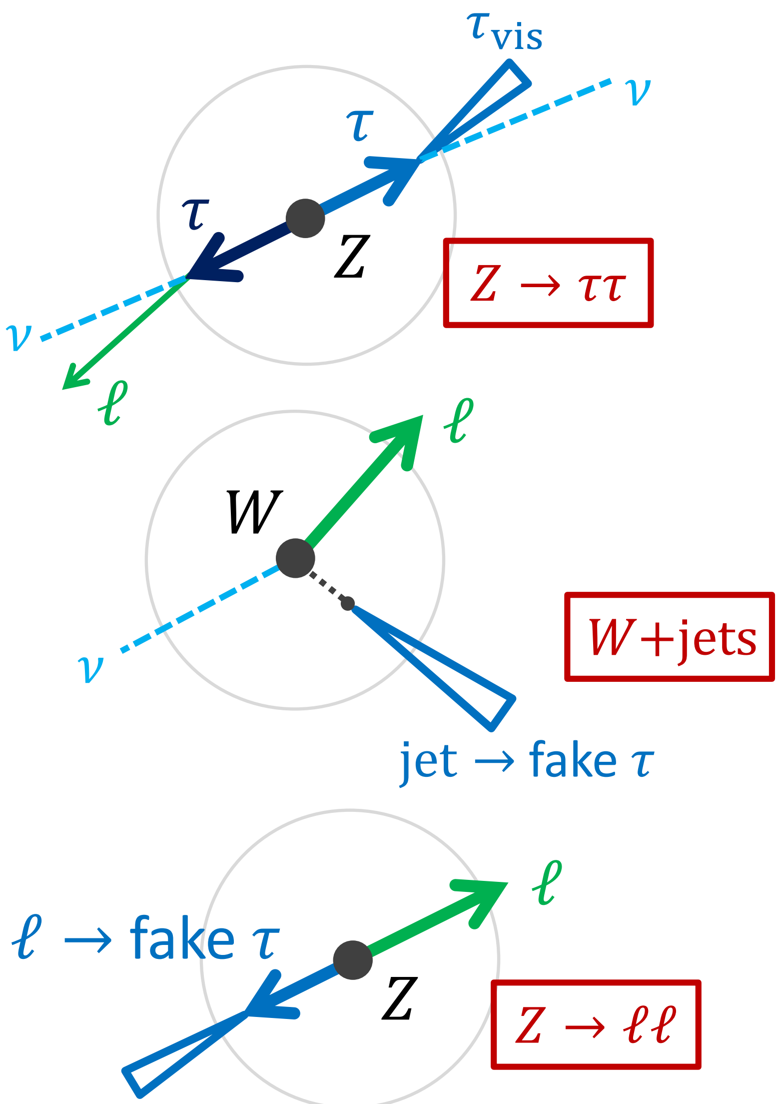
Unique features of the $Z \to \ell\tau$ signal events



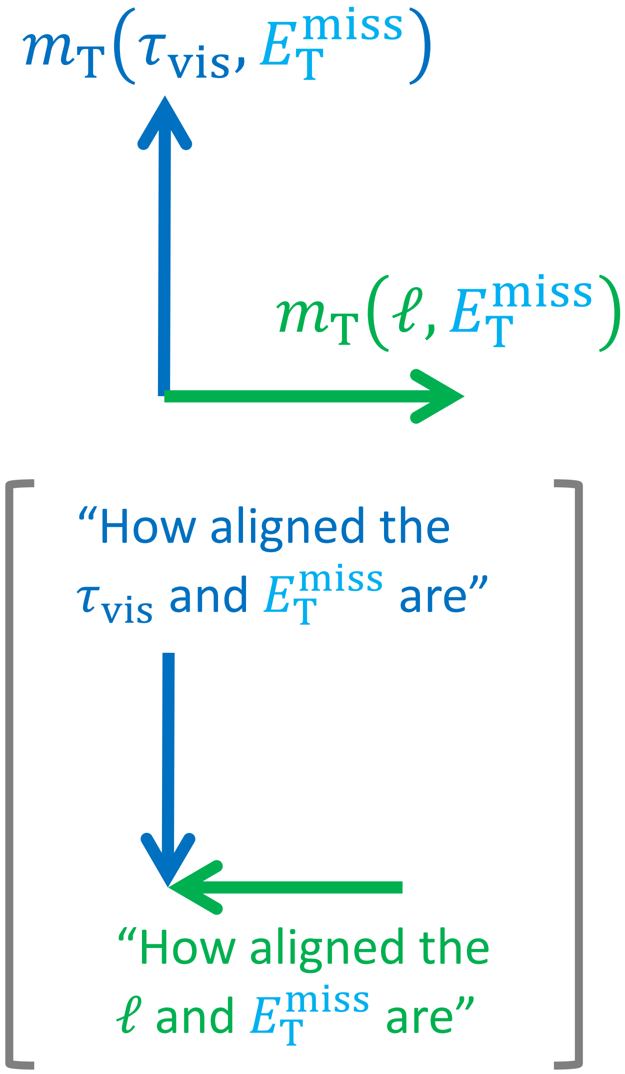
- Resonance at Z rest mass (with E^{miss} considered)
- Z is heavy → boosted τ and ℓ
- $\ell\tau$ pair: opposite-sign charges; almost back-to-back in transverse plane
- E^{miss} almost collinear with τ_{vis} and almost back-to-back with ℓ

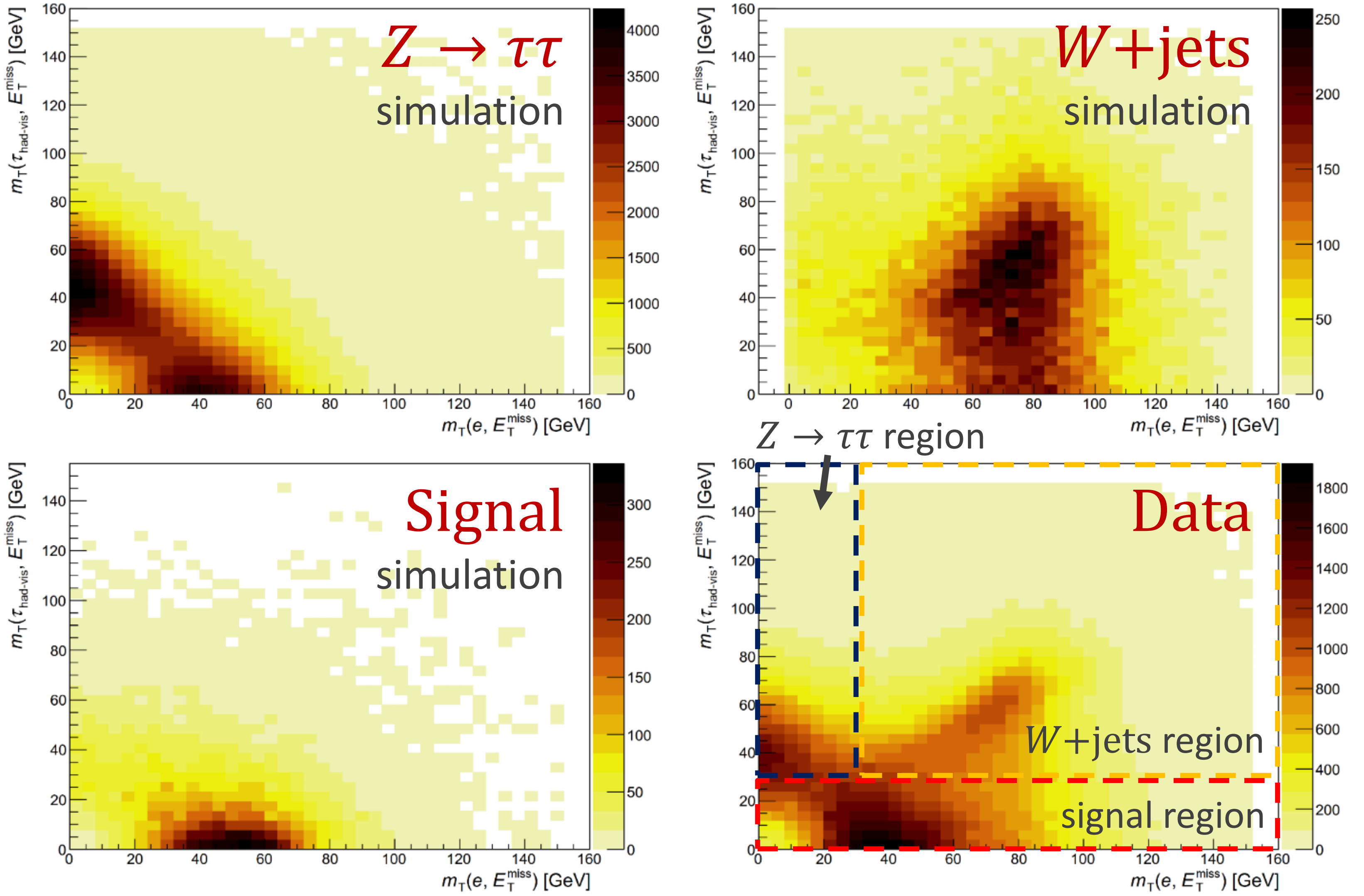
Major backgrounds

- $Z \to \tau\tau(\to \ell)$
  - One τ decays leptonically
  - Both τ decays contribute to the total E^{miss}
    → Partially cancel each other
    → Total E^{miss} can align with ℓ instead of with τ_{vis}
- $W(\to \ell\nu)$+jets
  - Jets mis-identified as hadronically-decaying τ ("fakes")
  - $E^{\text{miss}}(\nu)$ from W decay does not align with the fake τ
- $Z \to \ell\ell(\to \tau)$
  - e/μ mis-identified as τ
  - No E^{miss} expected
    → Visible invariant mass $m_{\text{vis}} \sim m_Z$



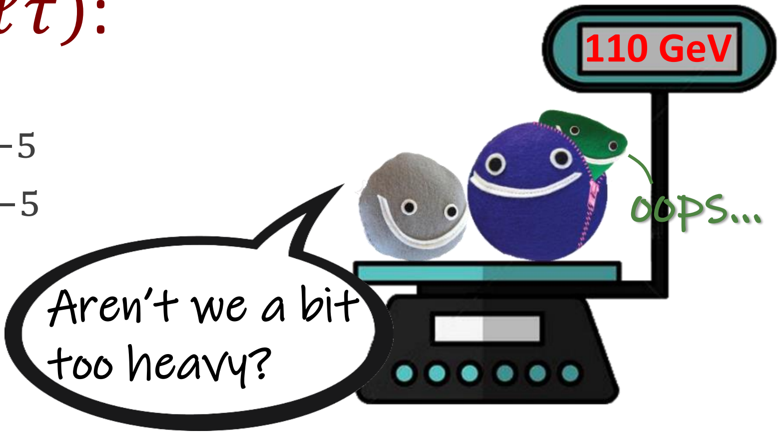
Event selection – $Z \to \tau\tau$ and W+jets rejections

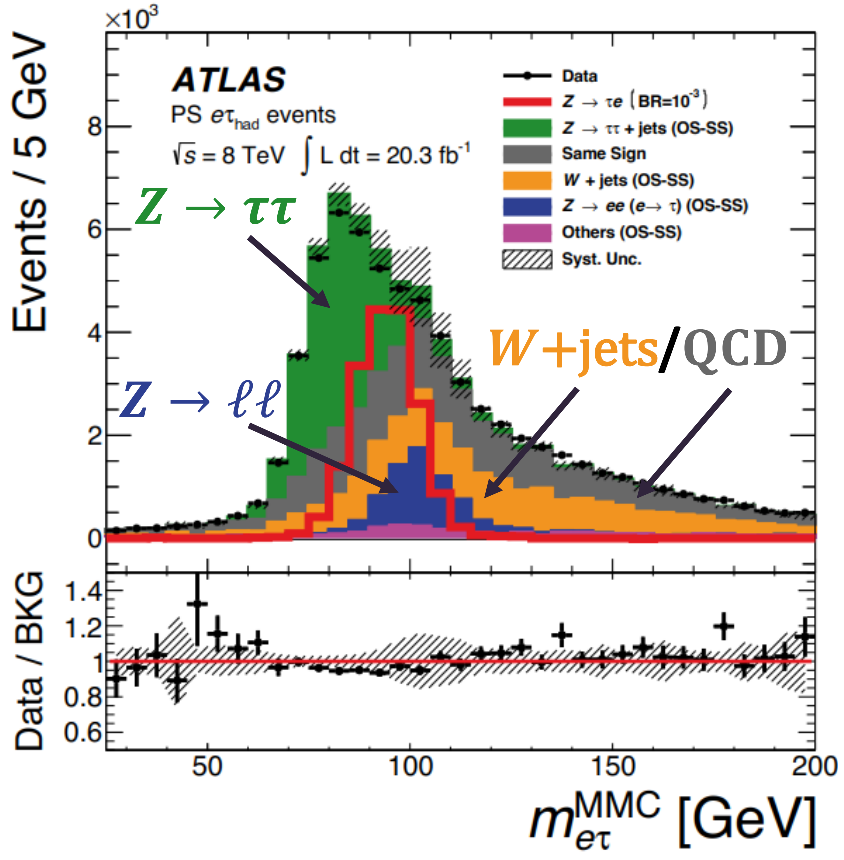




Mass spectrum fitting (Run-1 strategy)

- Even after the event selection, a lot of backgrounds still remain
- The $\ell\tau$ invariant mass spectrum provides us some discriminating power
  - $Z \rightarrow \tau\tau$ peaks *lower* than signal (more E^{miss})
  - $Z \rightarrow \ell\ell$ peaks *higher* than signal (no E^{miss})
  - W+jets/QCD fakes are more flat and has no clear peak (not resonance)
- Fitting the spectrum allows us to measure/ constrain $\mathrm{BR}(Z \rightarrow \ell\tau)$:
  - Run-1 95% CL limits:
    $\mathrm{BR}(Z \rightarrow e\tau) < 4.7 \times 10^{-5}$
    $\mathrm{BR}(Z \rightarrow \mu\tau) < 1.7 \times 10^{-5}$



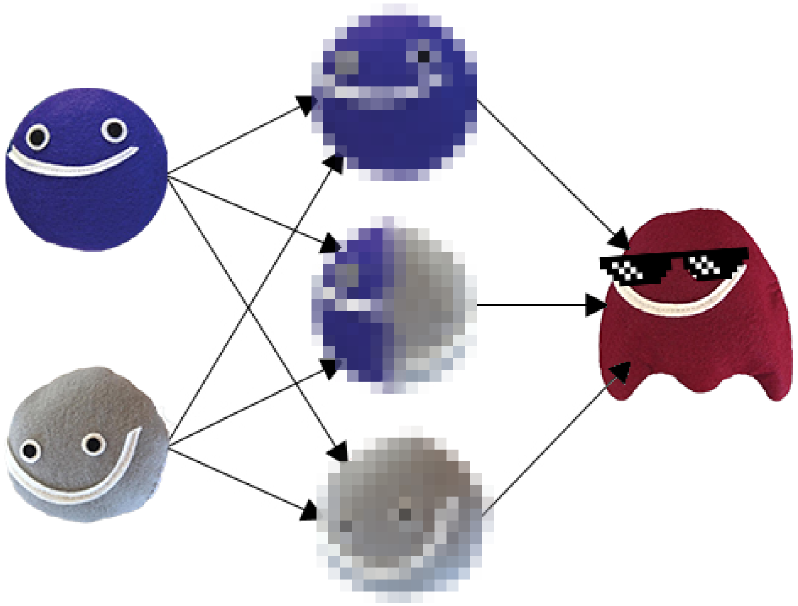


So, limit obtained, end of the story?

- Not yet (as you can guess from the slide numbers)
- As we gather more and more data (now with LHC Run-2, future with HL-LHC), we are not just sitting there waiting
- Many ideas for improvement were studied; most fruitful ones include:
  - 1. Exploiting the data with neural network
  - 2. Rejecting $Z \to \ell\ell$ effectively using track measurements

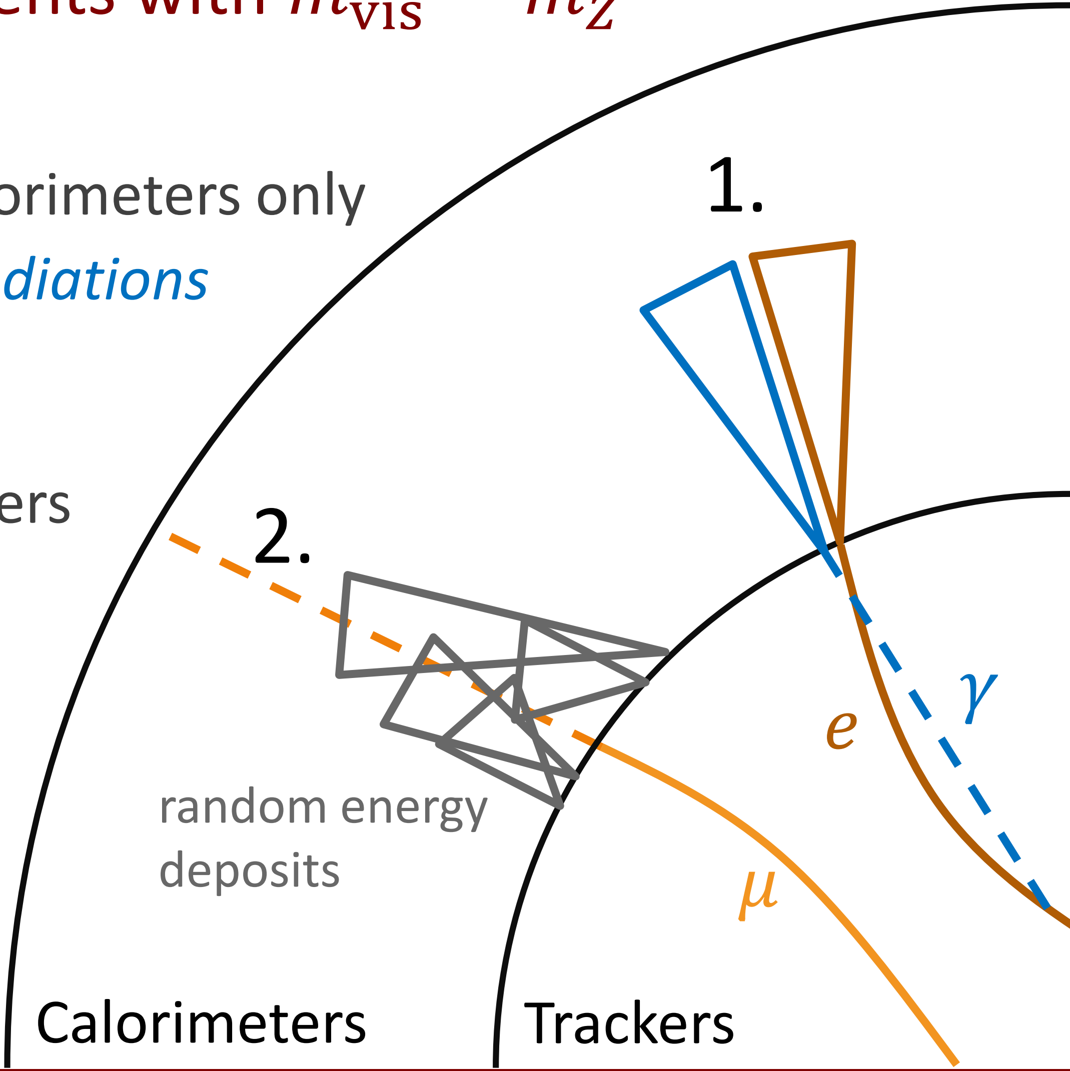
1. Exploiting the data with neural networks

- Many recent developments in neural networks (thanks to industrial usage)
  $\rightarrow$ we are making use of it!
- Use NN to create a kinematic discriminant
- Our NN classifiers:
  - Software: KERAS on top of TENSORFLOW
  - Input: 4-momenta of ℓ, τ_{vis} and $E_{\text{T}}^{\text{miss}}$
    (and variables derived from them)
  - Output: scores to discriminate signal from $Z \rightarrow \tau\tau$, W+jets and $Z \rightarrow \ell\ell$
  - Hyperparameters are optimised by a grid search
- By fitting the NN output, we gained $\sim 50\%$ sensitivity compared to conventional mass fitting!



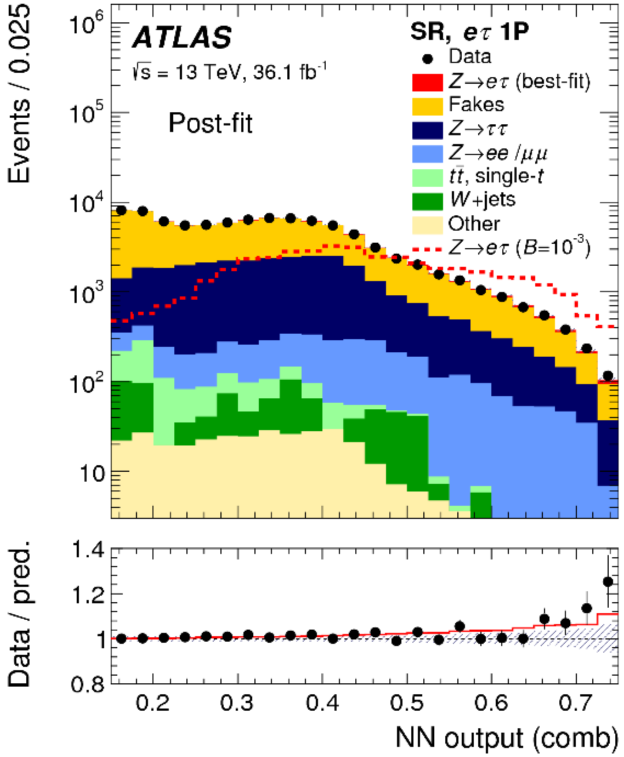
2. $Z \to \ell\ell$ rejections using track measurements

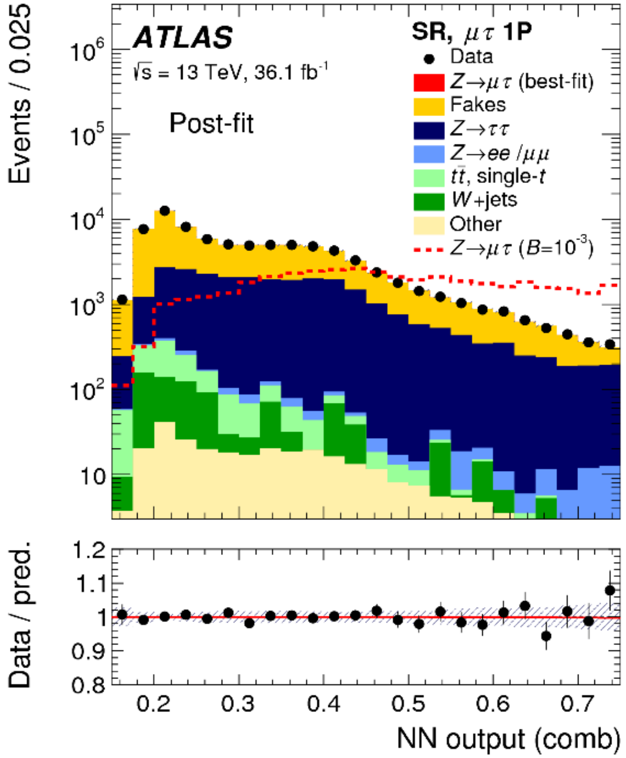
- $Z \to \ell\ell$ can be suppressed by rejecting events with $m_{\text{vis}} \sim m_Z$
- But there is more to it
  - Normally, $p(\tau_{\text{vis}}\ \text{candidate})$ is measured by calorimeters only
  - 1. *Electrons/Muons* can emit *Bremsstrahlung radiations*
    tracker measurement: $p_{\text{reco}} < p_{\text{truth}}$
    calorimeter measurement: $p_{\text{reco}} \approx p_{\text{truth}}$
  - 2. Muons detected by tracker but not calorimeters
    → fake taus with random energy deposits
    tracker measurement: $p_{\text{reco}} \approx p_{\text{truth}}$
    calorimeter measurement: random p_{reco}
  - Allow very specific cuts against $Z \to \ell\ell$!
- Make full use of the ATLAS detector
  → say goodbye to $Z \to \ell\ell$ backgrounds



Mid-Run-2 results (36.1 fb^{-1} of data)

- Only channels with hadronically-decaying τ's considered





- $Z \to e\tau$:
  - 2.3σ excess observed
  - 95% CL limit: $\mathrm{BR}(Z \to e\tau) < 5.8 \times 10^{-5}$
- $Z \to \mu\tau$:
  - No excess observed
  - 95% CL limit: $\mathrm{BR}(Z \to \mu\tau) < 1.3 \times 10^{-5}$ (combined with Run-1 data)

LEP limit: 1.2×10^{-5}

Future expectations

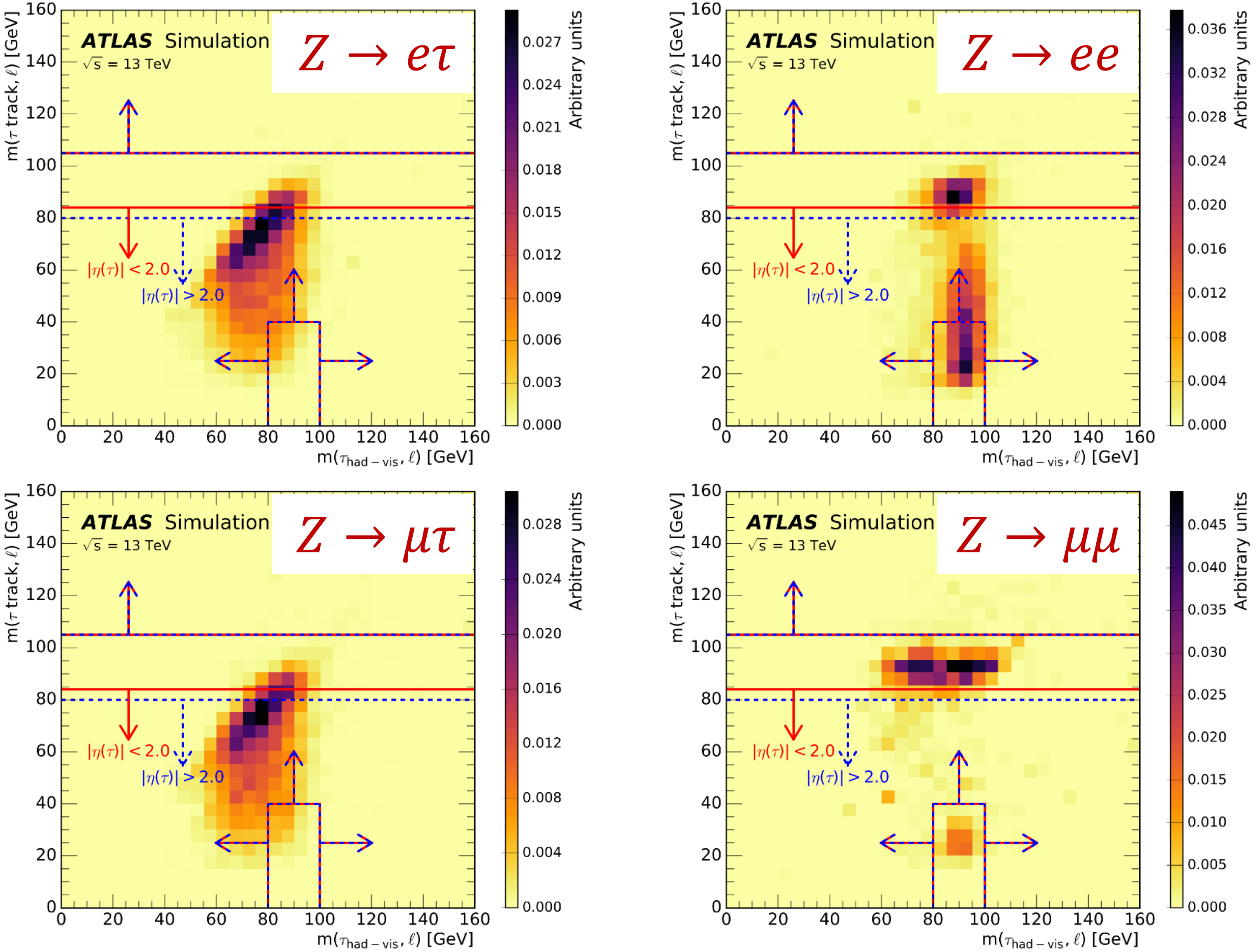
- With full-Run-2 data ($\sim 150\ \mathrm{fb}^{-1}$), projected expected limits:
  - $\mathrm{BR}(Z \rightarrow e\tau) < \sim 1.0 \times 10^{-5}$ current limit (LEP): 9.8×10^{-6}
  - $\mathrm{BR}(Z \rightarrow \mu\tau) < \sim 8.9 \times 10^{-6}$ current limit (LEP): 1.2×10^{-5}
- With HL-LHC data ($\sim 3000\ \mathrm{fb}^{-1}$), projected expected limits :
  - $\mathrm{BR}(Z \rightarrow e\tau) < \sim 2.2 \times 10^{-6}$
  - $\mathrm{BR}(Z \rightarrow \mu\tau) < \sim 2.0 \times 10^{-6}$
- So far limits shown are with hadronic taus only
  - Expect another factor of $\sim 1/\sqrt{2}$ improvement with leptonic taus considered!

Conclusion

- The $Z \rightarrow e\tau/\mu\tau$ LFV decays are interesting signals of BSM phenomena
- By making use of the signal's unique features, we are able to set stringent limits on the LFV branching ratios with ATLAS
- With improved methods and more and more data, we really expect to push the limits even further
- Stay tuned for the full-Run-2 analysis results!

Backup

Event selection against $Z \to \ell\ell$



Run-1 $H \to \ell\tau$ limits

- Hadronic and leptonic tau channels have similar sensitivities
  - Statistically combined → improve limit by a factor of $\sim 1/\sqrt{2}$
  - As a very rough estimate, can expect the same for $Z \to \ell\tau$