Searches for Charged Lepton Flavour Violation with the ATLAS Experiment

Julia Iturbe

KAON2019
Perugia, Italy

12/September/2019

香港中文大學
The Chinese University of Hong Kong

Motivation for LFV searches

- Lepton flavour violation (LFV) occurs in nature (neutrino oscillations) but LFV in the charged sector (cLFV) is extremely suppressed in the SM: BR($\mu \rightarrow e\gamma$)$<10^{-48}$
- However, many BSM models predict cLFV decays of the Higgs, Z boson, top quark and other high-mass resonances
- Low-energy results provide indirect constraints
- *ATLAS can complement these results*

cLFV searches at ATLAS with $\sqrt{s}$ = 13 TeV

- This talk will touch on 6 searches:
  - H→eμ ATLAS-CONF-2019-037
  - H→τe, H→τμ arXiv:1907.06131
  - Z→τe, Z→τμ Phys. Rev. D 98 (2018) 092010
  - Heavy particle →$\ell\ell'$ Phys. Rev. D 98 (2018) 092008
  - $H^{\pm\pm}\rightarrow e^{\pm}\mu^{\pm}$ Eur. Phys. J. C 78 (2018) 199
  - $t\rightarrow \ell^{\pm}\ell'^{\mp}q$ ATLAS-CONF-2018-044
- **Spoiler alert!** No significant excesses found **but** limits are set which are improvements to previous searches

$H \to e\mu$

ATLAS-CONF-2019-037

Higgs decaying to e+μ (1)

- Using data collected in full Run2 ⇒

  $\mathscr{L} = 139$ fb^{-1}

- **Event selection:**

  - Exactly 1 e and 1 μ with opposite charge

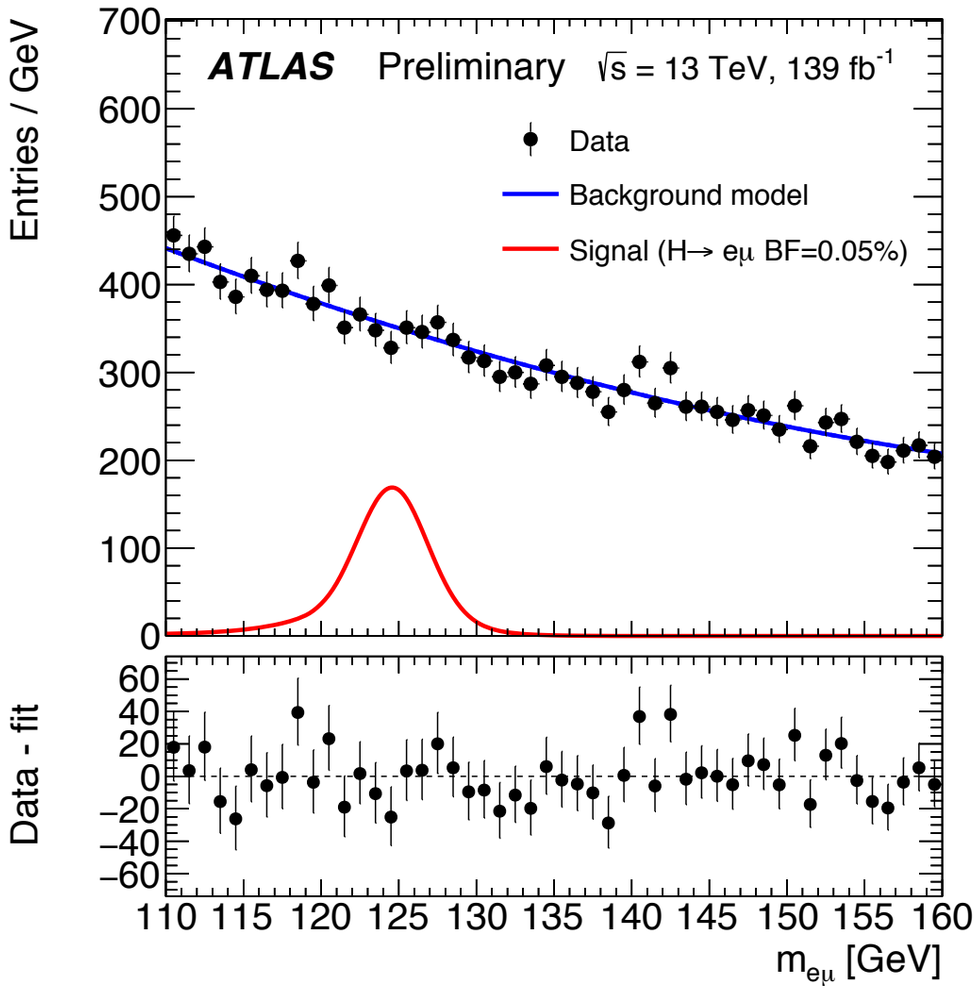
  - Reject events containing b-jets and $E_T^{miss}/\sqrt{H_T} < 1.75$ GeV$^{1/2}$ (to suppress Top bkg)

- **Signal regions:** baseline selection + 8 categories with different S/B (to improve sensitivity)

1	Low p_T^{ℓ}	$p_T^{\ell 2} < 27$ GeV
2	VBF	2 jets opposite hemisphere, |njj|>3, mjj > 500 GeV
3	Central	$\|\eta^{\ell}\| < 1$
4	Non-central	$\|\eta^{\ell}\| \geq 1$
3 and 4 are further split into:		
	Low $p_T^{\ell\ell}$	$p_T^{\ell\ell} \leq 15$ GeV
	Mid $p_T^{\ell\ell}$	15 GeV $< p_T^{\ell\ell} \leq 50$
	High $p_T^{\ell\ell}$	$p_T^{\ell\ell} > 50$ GeV

Higgs decaying to e+μ (2)

- The $m_{e\mu}$ distribution for signal and bkg is modelled by analytical functions
- **Signal**: Narrow resonance with m_H = 125 GeV, MC fitted with **Crystal Ball + Gaussian**
- **Bkg:** $Z/\gamma^* \rightarrow \tau\tau$, top quarks, diboson, jets mis-id as leptons. Data fitted with **Bernstein polynomial 2nd degree**
- Fit performed with S+B model in all categories simultaneously, in the region 110 GeV < $m_{e\mu}$ < 160 GeV
- **RESULTS**:



Observed (expected) limit on BR(H→eμ)<6.1x10^{-5} (5.8x10^{-5})

First result of this kind for ATLAS, improvement over the previous result from CMS

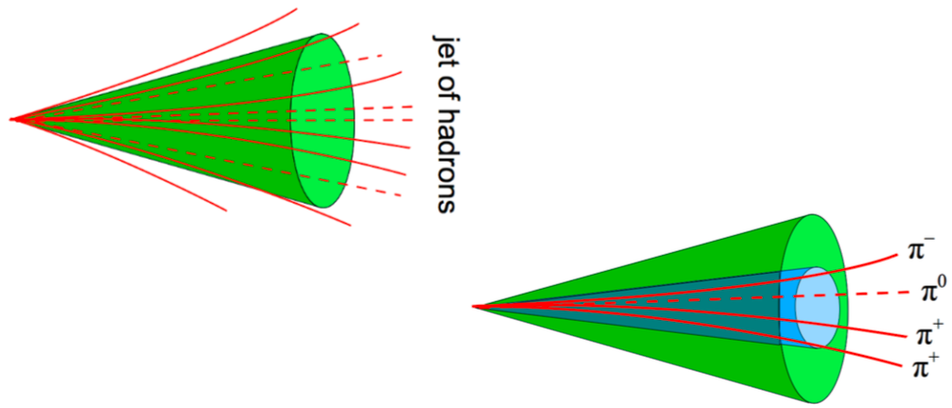
$H \to \tau e$, $H \to \tau \mu$

arXiv:1907.06131

Higgs decaying to τ + (e or μ) (1)

- Using data collected in 2015-2016
  $\Rightarrow \mathscr{L} = 36\ fb^{-1}$
- Two searches performed:
  $H \rightarrow \tau e$, $H \rightarrow \tau \mu$
- Each search has two channels:
  - tau decaying leptonically
    ($\ell\tau_{lep}$: $e\tau_{\mu}$, $\mu\tau_{e}$)
  - tau decaying hadronically
    ($\ell\tau_{had}$: $e\tau_{had}$, $\mu\tau_{had}$)
- **Leptonic taus:** reconstructed as electrons or muons

- **Hadronic taus:**
  - Typically 1 (1-prong) or 3 (3-prong) $\pi^{\pm}$ plus ≤2 π^{0}
  - Reconstructed as narrow jets: Seeded by jets (anti-kT, R=0.4) + info from ID tracks and energy deposits in calorimeter
  - Separated from mis-id jets or hadron decays using a BDT
  - eVeto: removes τ_{had} candidate with a track overlapping with a highId electron candidate (BDT-based)
  - 1 and 3 prong taus used in the following analyses

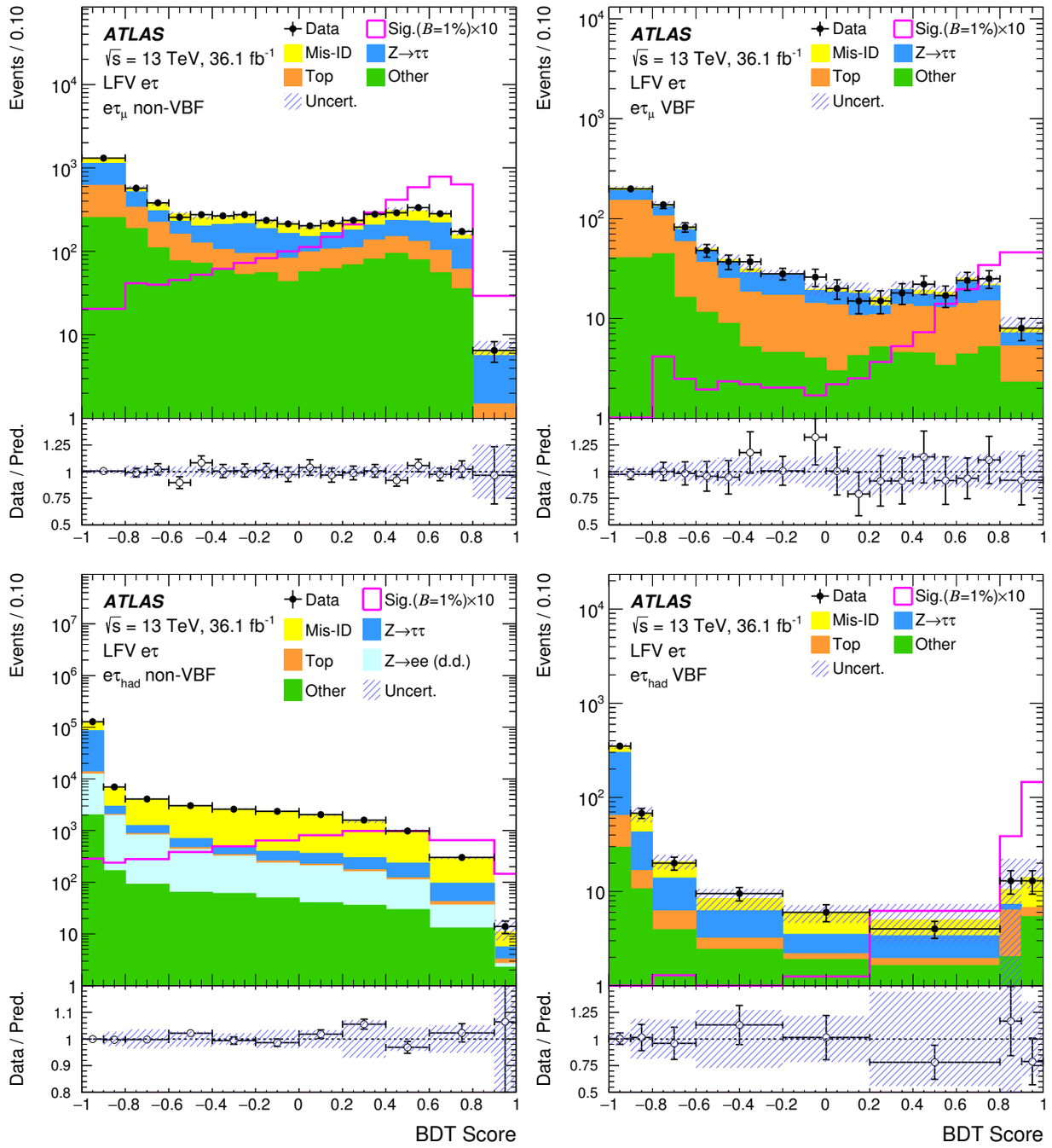


Higgs decaying to τ + (e or μ) (2)

- **Signal**: Assuming m_H = 125 GeV, SM production cross-sections. Inclusive wrt τ decay modes.
- **Backgrounds**:
  - Z→ττ (1st for both channels), Top (2nd for $\ell\tau_{lep}$), Diboson, SM H→ττ and Z→$\ell\ell$ (from MC)
  - Fake bkg (jets mis-id as τ_{had} or ℓ) (2nd for $\ell\tau_{had}$). Calculated from data (Fake Factor method)
- **Event selection:**
  - $\ell\tau_{lep}$: exactly 2 light-leptons of different flavour and opposite charge
  - $\ell\tau_{had}$: exactly 1 τ_{had} and 1 light-lepton, with opposite charge
  - Reject events containing b-jets (suppress Top bkg)
  - Baseline selection includes other cuts to reduce other bkgs (BU slides)

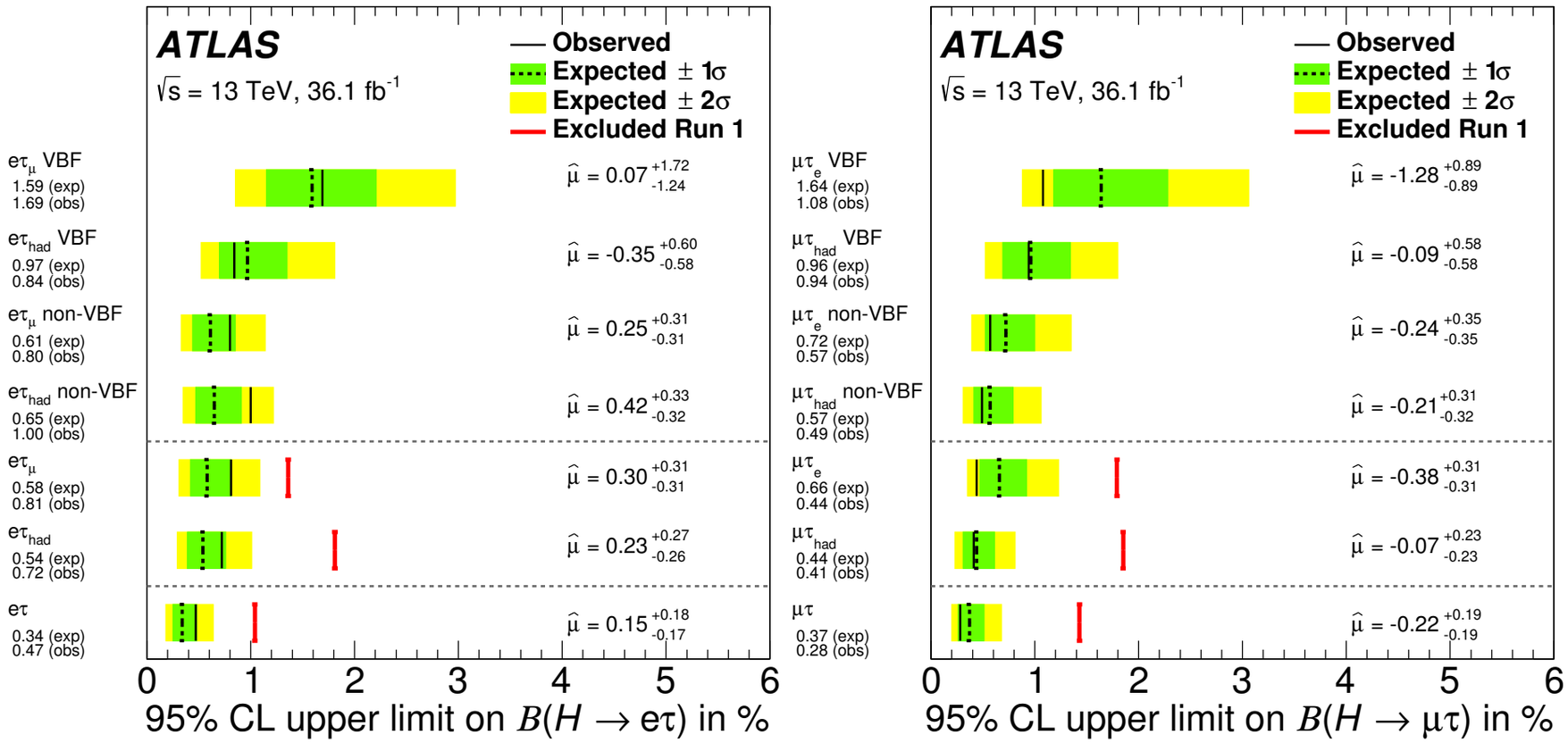
Higgs decaying to τ + (e or μ) (3)

- **Signal regions:** baseline selection and…
  - **VBF:** $n_{jets} \geq 2$, $m_{jj} > 400$ GeV and $|\eta_{jj}|>3$
  - **nonVBF:** fails VBF cuts
- A BDT is trained in each channel to separate signal from bkg using kinematic variables
- A statistical fit is performed using the BDT score



Higgs decaying to τ + (e or μ) (4)

- **RESULTS:** Observed (expected) limits on
  - BR(H→τe)<0.47% ($0.34^{+0.13}_{-0.10}$ %)
  - BR(H→τμ)<0.28% ($0.37^{+0.14}_{-0.10}$ %)



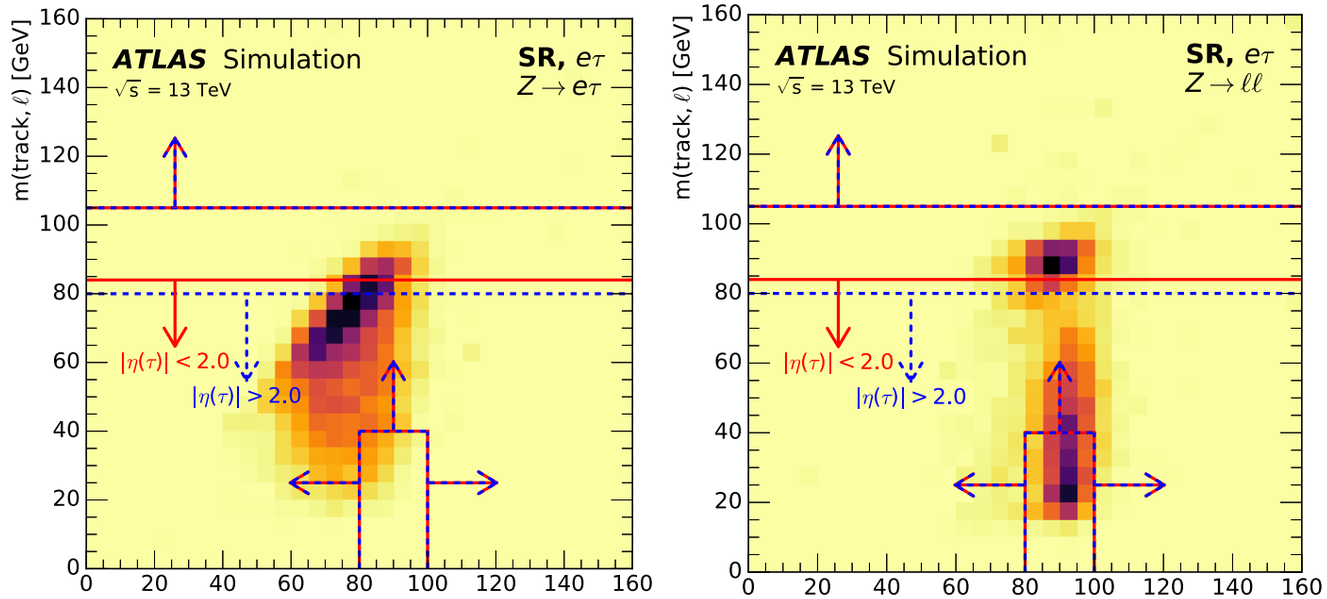
Good improvement from Run1 results, compatible with CMS results

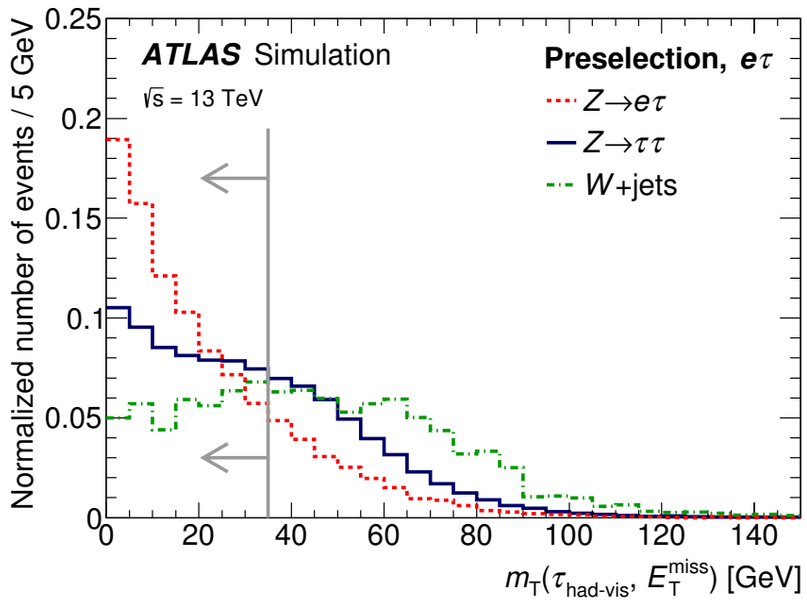
$Z \to \tau e$, $Z \to \tau \mu$

Phys. Rev. D 98 (2018) 092010

Z decaying to τ + (e or μ) (1)

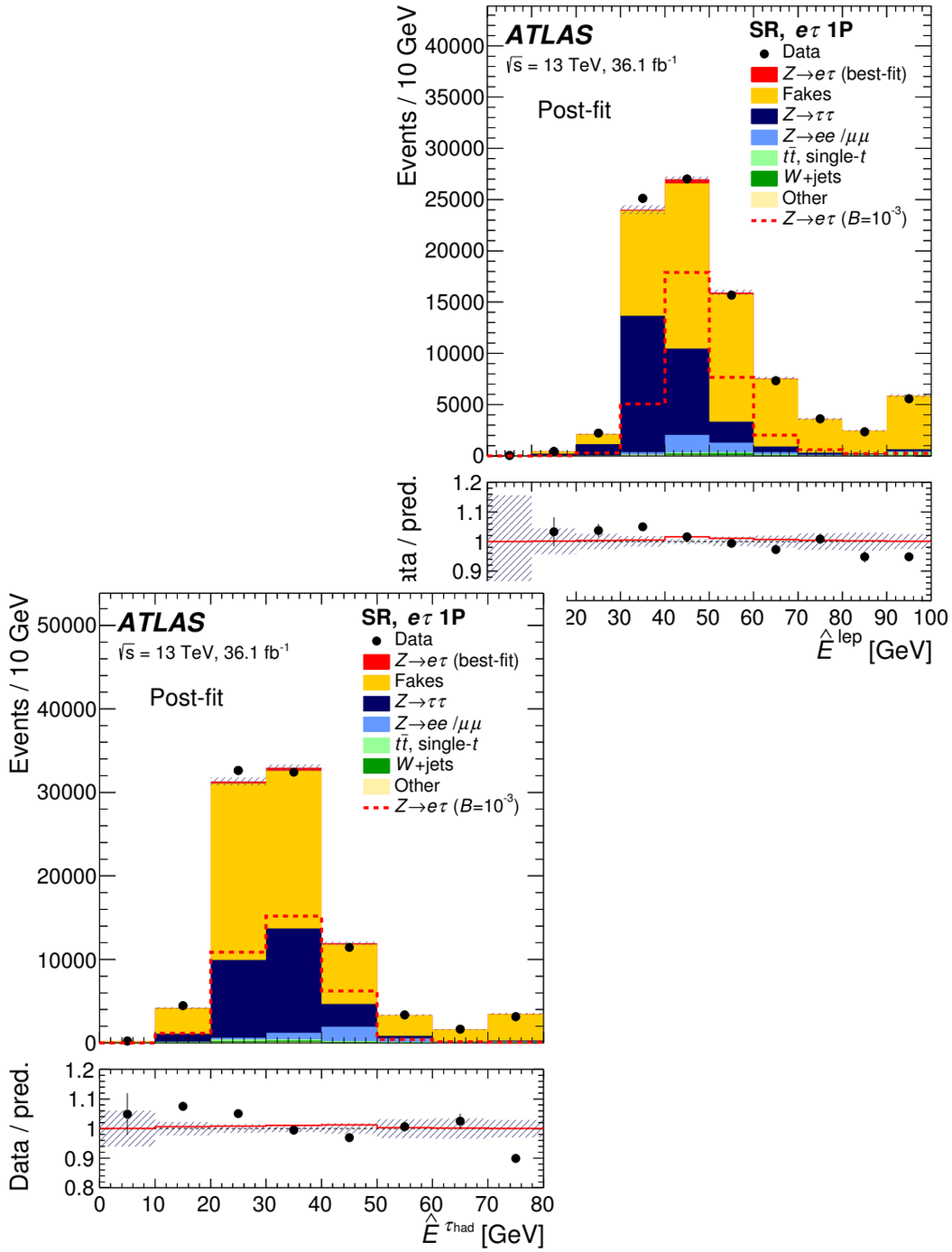
- Using data collected in 2015-2016
  $\Rightarrow \mathscr{L} =$ 36 fb^{-1}
- Two searches: $Z \rightarrow e\tau_{had}$, $Z \rightarrow \mu\tau_{had}$
- **Event selection:**
  - Exactly 1 isolated light-lepton and ≥1 τ_{had}, with opposite charge
  - Reject events with b-jets (suppress Top bkg)
  - Reject events where 1-prong τ_{had} has $|\eta(\tau_{had})|$ >2.2 for eτ channel or $|\eta(\tau_{had})|$<0.1 for μτ channel (suppress $Z\ell\ell$ bkg, high mis-id regions)
- This **baseline** selection is used to train a **NN**
- **Signal region** is defined with extra cuts to separate from main bkgs





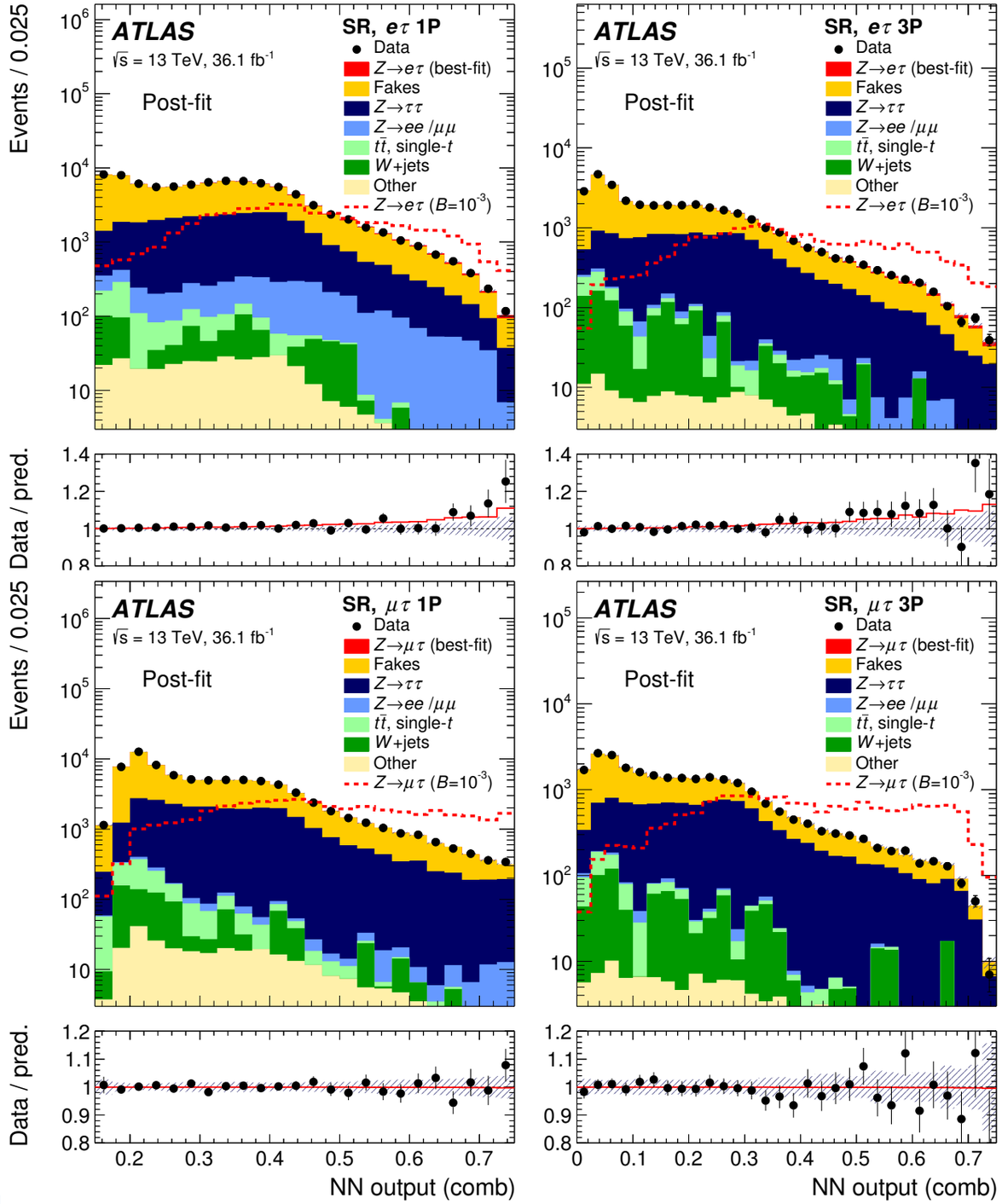
Z decaying to τ + (e or μ) (2)

- **Main bkgs:**
  - Fake bkg (jets mis-id as τ_{had}), estimated from data (fake factor method)
  - $Z\ell\ell$ modelled by MC
    - $Z\tau\tau$, modelled by MC and normalisation set by the fit
- There's a NN classifier for W+jets, $Z\ell\ell$ and $Z\tau\tau$
- A statistical fit is performed using the NN output, in the 1p and 3p signal regions separately



Z decaying to τ + (e or μ) (3)

- **RESULTS:** Observed (expected) limits on
  - BR(Z→eτ)<5.8(2.8)x10^{-5} ⇒ 2.3σ excess
  - BR(Z→μτ)<2.4(2.4)x10^{-5}
- First limit on BR(Z→eτ) from ATLAS, competitive with LEP's <0.98x10^{-5}
- BR(Z→μτ)<1.3x10^{-5} when combined with ATLAS Run1 result, competitive with LEP's <1.2x10^{-5}



Heavy particle→$\ell\ell$’

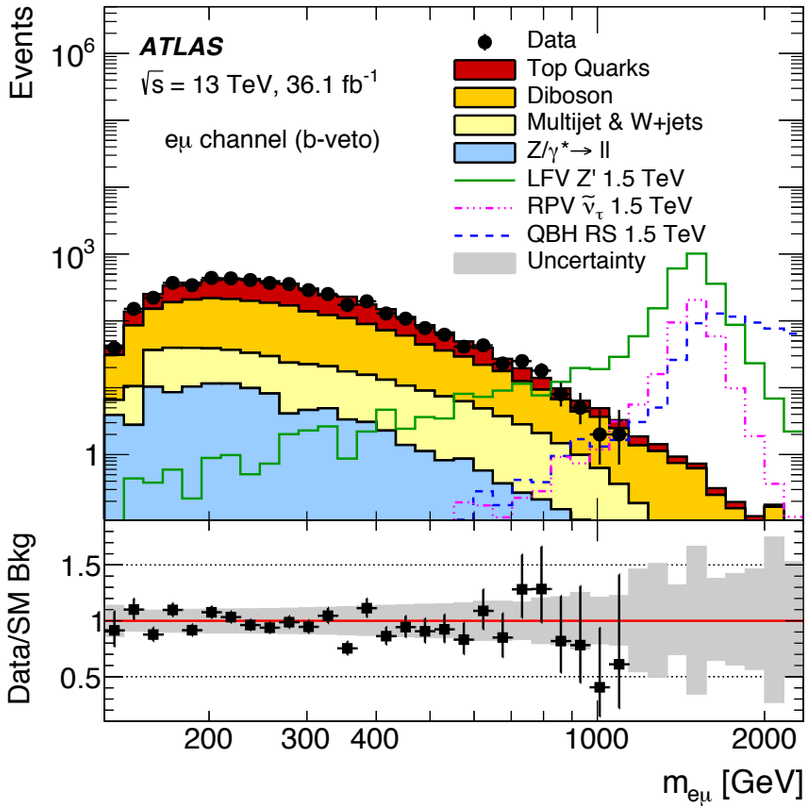
Phys. Rev. D 98 (2018) 092008

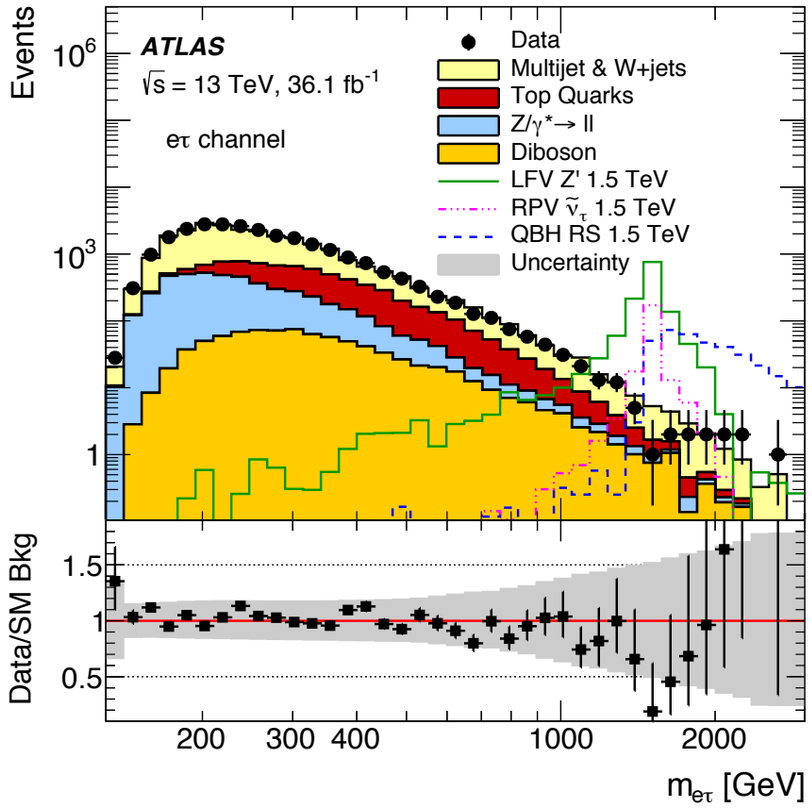
LFV decay of high mass resonance (1)

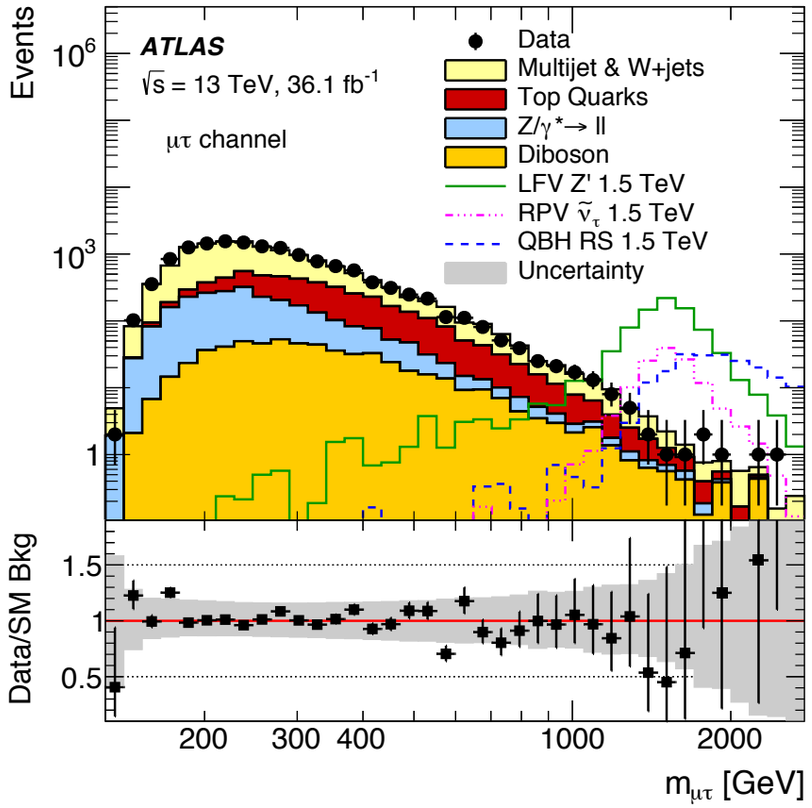
- Using data collected in 2015-2016 $\Rightarrow \mathscr{L} =$ 36 fb^{-1}
- Testing three main models:
  - Z' (same quark couplings, only one LFV coupling)
  - RPV SUSY (τ sneutrino, coupling to 1st gen quarks)
  - Quantum Black Holes (QBH)
- Search channels: eτ, μτ, eμ
- **Event selection:**
  - Exactly two different-flavour leptons
  - Leptons are back-to-back ($\Delta\phi(\ell\ell')>2.7$)

LFV decay of high mass resonance (2)

- **Main bkgs:**
  - Zττ, Top quark and diboson. Modelled by MC.
  - Fake bkg (mis-id jets), estimated from data (5% in eμ, 50-60% in eτ, μτ (fake τ_{had}))

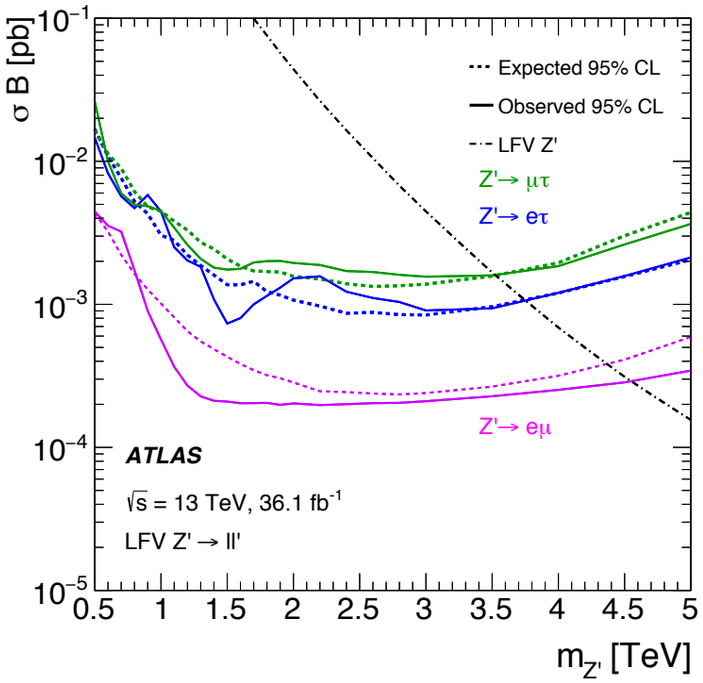


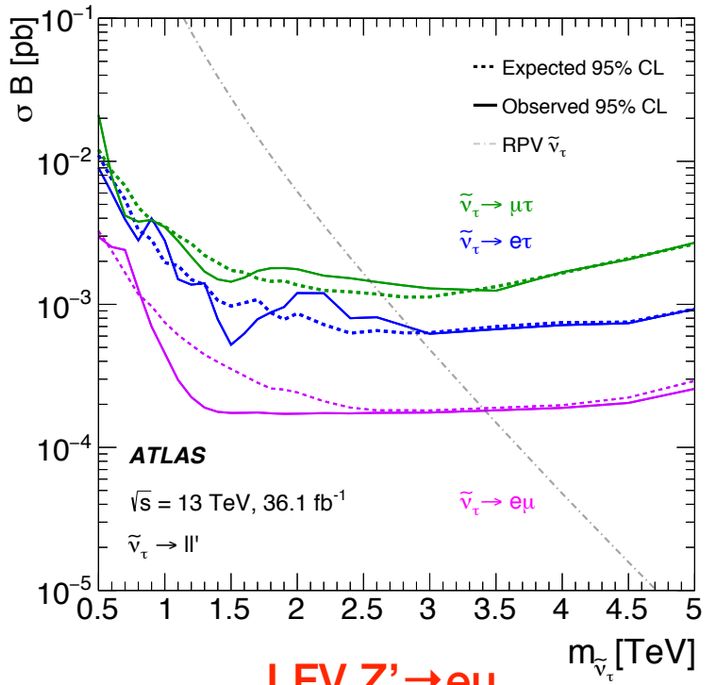


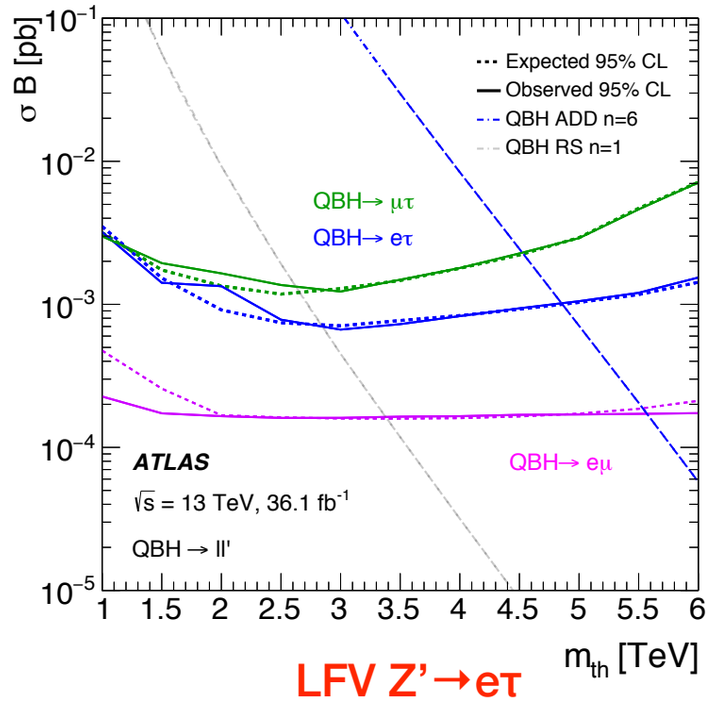


LFV decay of high mass resonance (3)

- **RESULTS:** Limits are set for different models

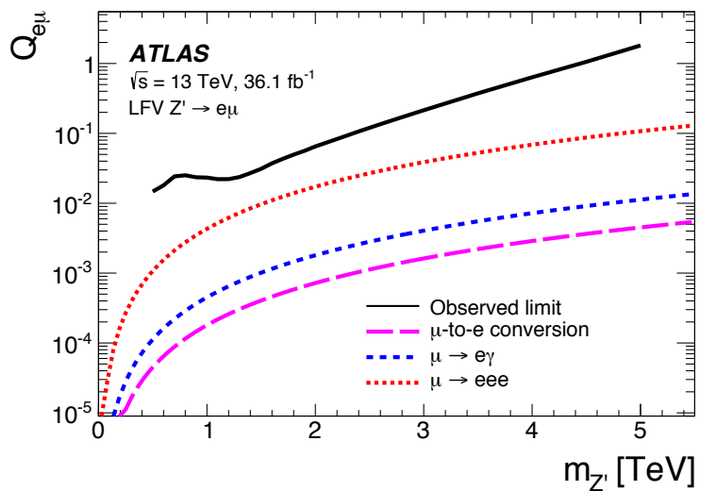




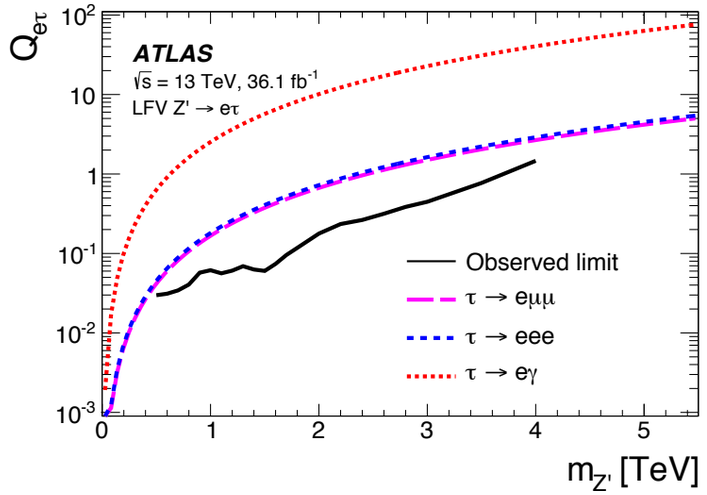


ATLAS is competitive with low-energy results for channels including τ

LFV Z'→eμ



LFV Z'→eτ

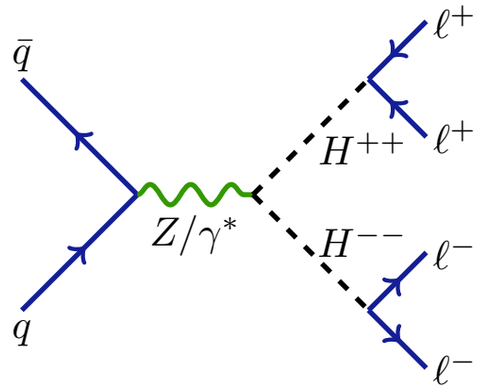


$H^{\pm\pm} \to e\mu$

Eur. Phys. J. C 78 (2018) 199

$H^{\pm\pm} \rightarrow e^{\pm}\mu^{\pm}$ (1)

- Using data collected in 2015-2016 $\Rightarrow \mathscr{L} = 36$ fb^{-1}
- Many BSM theories predict doubly-charged Higgs (LSR, Higgs triplet, little Higgs, …)
- Search limited to leptonic decays (electrons or muons) and pair production via Drell-Yan



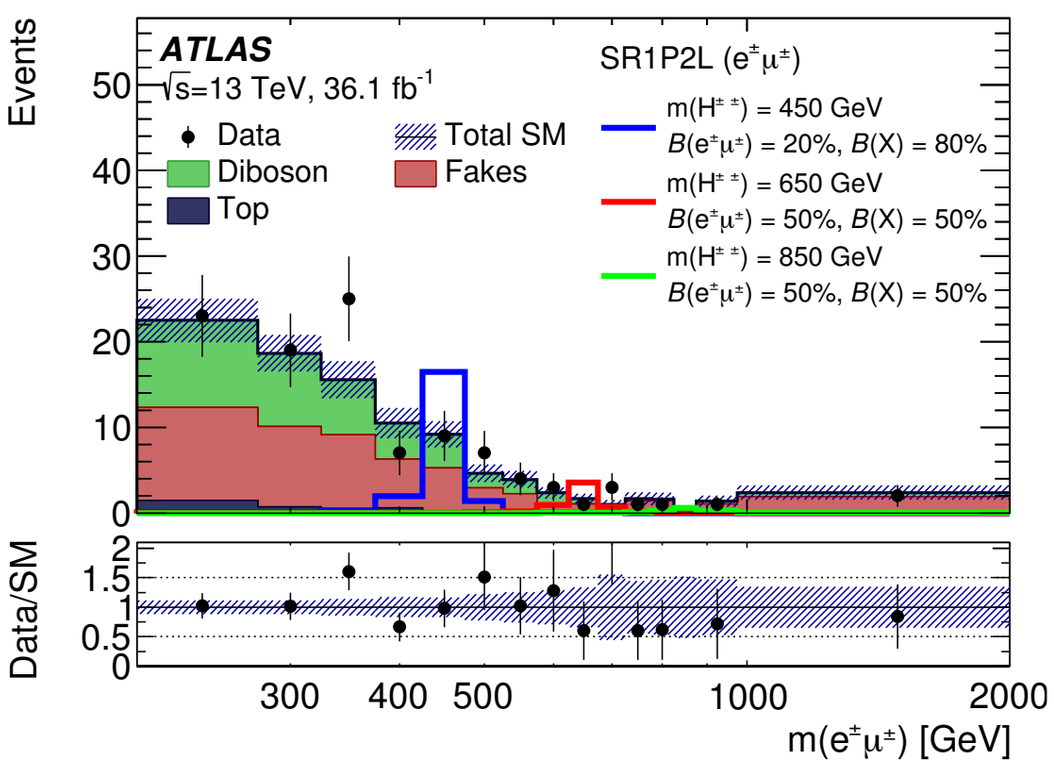
- **Event selection:**
  - Veto events with b-jets
  - Events with 2, 3 leptons (one same-sign pair) or 4 leptons (2 same-sign pairs, sum of charges = 0)
  - $m_{\ell\ell} > 200$ GeV (from same-sign pair, $<m_{\ell\ell}>$ for 4ℓ)

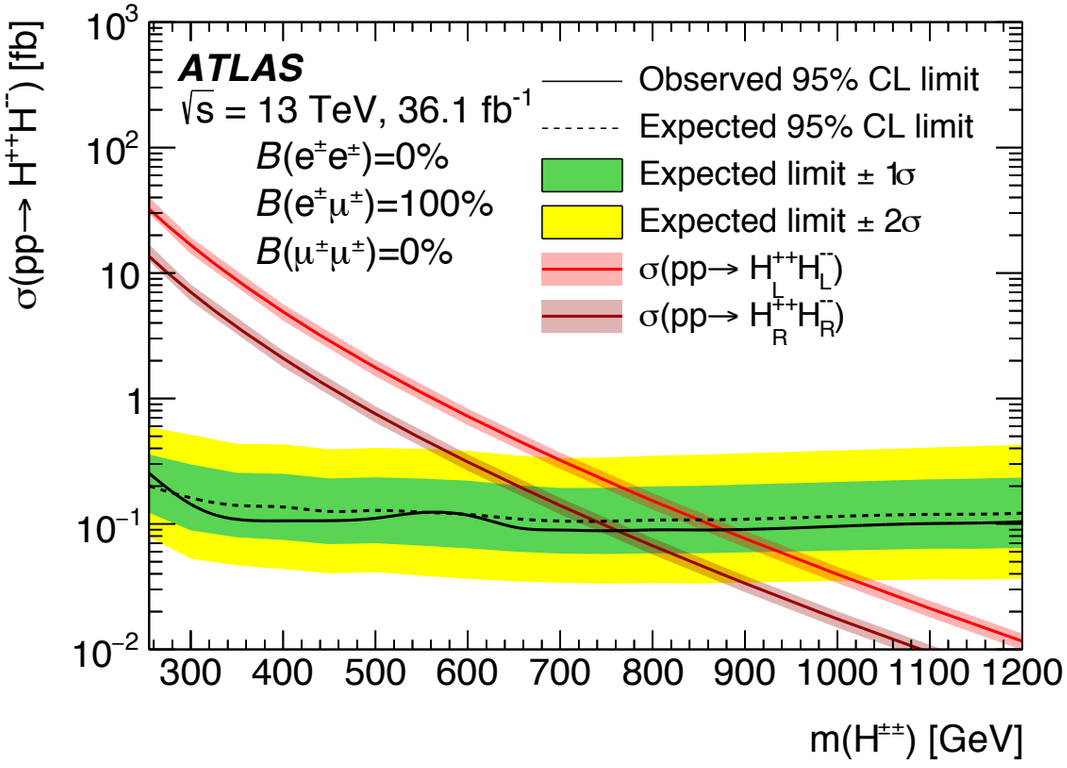
$H^{\pm\pm} \rightarrow e^{\pm}\mu^{\pm}$ (2)

- **Signal:** LRS model, excluding $H^{\pm\pm} \rightarrow WW$ decays, with different $H^{\pm\pm}$ masses (200 - 1300 GeV)
- **Backgrounds:**
  - **Irreducible:** SM processes (diboson, ttbar X, from MC)
  - **Reducible:**
    - SM processes with charge mis-id electrons ($Z/\gamma^* \rightarrow \ell^+\ell^-$ and ttbar, from MC with SFs for charge reco from data)
    - Fake bkg (jets mis-id as e or μ). “Fake factor” method used (data-driven)

$H^{\pm\pm} \rightarrow e^{\pm}\mu^{\pm}$ (3)

- A statistical fit to $m_{\ell\ell}$ (same-sign leptons) is performed
- **RESULT:** Lower limits set on the mass of $H^{\pm\pm}$ (300 GeV higher than previous ATLAS search)





$t \to \ell^{\pm} \ell'^{\mp} q$

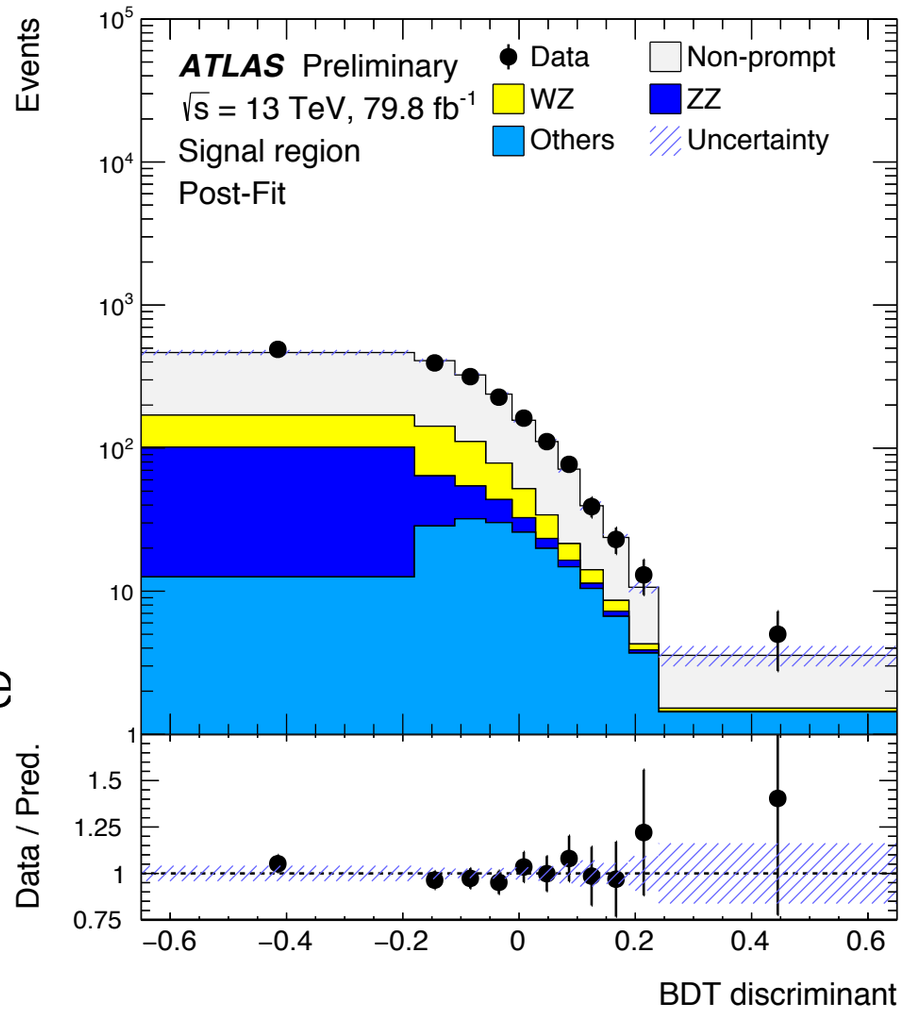
ATLAS-CONF-2018-044

$t \to \ell^{\pm}\ell'^{\mp}q$ (1)

- Using data collected in 2015-2017 $\Rightarrow \mathscr{L} = 80\ fb^{-1}$
- Searching for decay $t \to \ell^{\pm}\ell'^{\mp}q$ where q = {u,c} and ℓ={e,μ,τ} in ttbar events with the other top decays semileptonically (SM)
- Many ttbar events at LHC - well suited for this search
- **Event selection:**
  - Exactly three light leptons (e,μ)
  - $n_{jets} \geq 2$, $n_{bjets} \leq 1$
  - Veto events with OS DF lepton pair with $|m_{\ell\ell} - m_Z| < 10$ GeV (suppress $Z\ell\ell$ bkg)
- **Signal region:**
  - ≥1 e and ≥1 μ
  - cLFV reco from OS OF lepton pair + jet with inv. mass closest to top-quark mass

$t \to \ell^{\pm}\ell'^{\mp}q$ (2)

- **Main bkgs:** ttbar with extra non-prompt lepton and $Z\ell\ell$ (60%), WZ and ZZ (25%)
- Fakes estimated with data-driven approach (matrix method)
  - A BDT is trained in the signal region to discriminate S/B
- A statistical fit is performed using the BDT score
- **RESULTS:** Observed (expected) limits on
  - BR($t \to \ell\ell'q$)<1.86(1.36)x10^{-5}
  - BR($t \to e\mu q$)<6.6(4.8)x10^{-6} (no τ in cLFV vertex)



First direct measurement, improvement on previous indirect estimation (BR($t \to e\mu q$)≲10^{-3})

Conclusion

- Various searches for charged LFV decays in ATLAS were presented
  - For Higgs, Z and top quark
  - Heavy particles and doubly-charged Higgs
- No significant excess above the SM was found
- Limits were set for these searches, which are more stringent or are firsts (in some cases) and which complement low-energy results

Thank you!

Back up

Higgs decaying to τ + (e or μ)

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly $1e$ and 1μ, OS	exactly 1ℓ and $1\tau_{\text{had-vis}}$, OS
	$p_{\text{T}}^{\ell_1} > 45\,\text{GeV}$	$p_{\text{T}}^{\ell} > 27.3\,\text{GeV}$
	$p_{\text{T}}^{\ell_2} > 15\,\text{GeV}$	$p_{\text{T}}^{\tau_{\text{had-vis}}} > 25\,\text{GeV}$, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$
	$30\,\text{GeV} < m_{\text{vis}} < 150\,\text{GeV}$	$\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}}) > -0.35$
	$p_{\text{T}}^{e}(\text{track})/p_{\text{T}}^{e}(\text{cluster}) < 1.2$ ($\mu\tau_e$ only)	$\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
	b-veto (for jets with $p_{\text{T}} > 25\,\text{GeV}$ and $\lvert\eta\rvert < 2.4$)	
	Baseline	
VBF	≥ 2 jets, $p_{\text{T}}^{\text{j}_1} > 40\,\text{GeV}$, $p_{\text{T}}^{\text{j}_2} > 30\,\text{GeV}$	
	$\lvert\Delta\eta(\text{j}_1, \text{j}_2)\rvert > 3$, $m(\text{j}_1, \text{j}_2) > 400\,\text{GeV}$	
	–	$p_{\text{T}}^{\tau_{\text{had-vis}}} > 45\,\text{GeV}$
	Baseline plus fail VBF categorization	
Non-VBF	$m_{\text{T}}(\ell_1, E_{\text{T}}^{\text{miss}}) > 50\,\text{GeV}$	–
	$m_{\text{T}}(\ell_2, E_{\text{T}}^{\text{miss}}) < 40\,\text{GeV}$	–
	$\lvert\Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}})\rvert < 1.0$	–
	$p_{\text{T}}^{\tau}/p_{\text{T}}^{\ell_1} > 0.5$	–
Top-quark CR	inverted b-veto:	
VBF and non-VBF	≥ 1 b-tagged jet ($p_{\text{T}} > 25\,\text{GeV}$ and $\lvert\eta\rvert < 2.4$)	
$Z \to \tau\tau$ CR	inverted $p_{\text{T}}^{\ell_1}$ requirement:	
VBF and non-VBF	$35\,\text{GeV} < p_{\text{T}}^{\ell_1} < 45\,\text{GeV}$	

Fake factor method

- The number of events from fakes in SR is:
  - $N^{Id}_{SR,fakes} = (N^{anti-Id}_{SR,data} - N^{anti-Id}_{SR,MC,notjet\to\tau}) \times FF$, where Id (anti-Id) = τ_{had} passes (fails) Id cut (anti-Id is fake dominated and o
  - $FF = \frac{N^{Id}_{CR,data}}{N^{anti-Id}_{CR,data}}$, CR is similar to SR except for the inversion of one (or more) cut to make them orthogonal and is designed to be bkg dominated
  - Since there are a few sources of fake background, $FF = \sum_i R_i FF_i$, where i = W+jets, QCD, Top, Zll, … and R_i is the fractional contribution from a particular source
  - FF are usually measured as a function of the τ_{had} p_T and prongness

Matrix method

- Define two lepton selection: *tight* (nominal selection) and *loose* (looser id and iso requirements)
- Define an inclusive data sample *S* with one loose lepton and n_{jets}
- S = T(tight)+L(loose) = R(real)+F(fake)
- Bkg events in signal region are intersection of T and F
- Matrix method equation:

$$\begin{pmatrix} \langle n_T \rangle \\ \langle n_L \rangle \end{pmatrix} = \begin{pmatrix} \varepsilon_r & \varepsilon_f \\ \overline{\varepsilon_r} & \overline{\varepsilon_f} \end{pmatrix} \begin{pmatrix} n_R \\ n_F \end{pmatrix}$$

- Where ε_r (ε_f) probability of a real (fake) lepton pass the tight criteria, measured in data CRs
- Number of fake leptons in tight selection estimated as:

$$\hat{n}_{TF} = \varepsilon_f \hat{n}_F = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} (\varepsilon_r (n_T + n_L) - n_T)$$