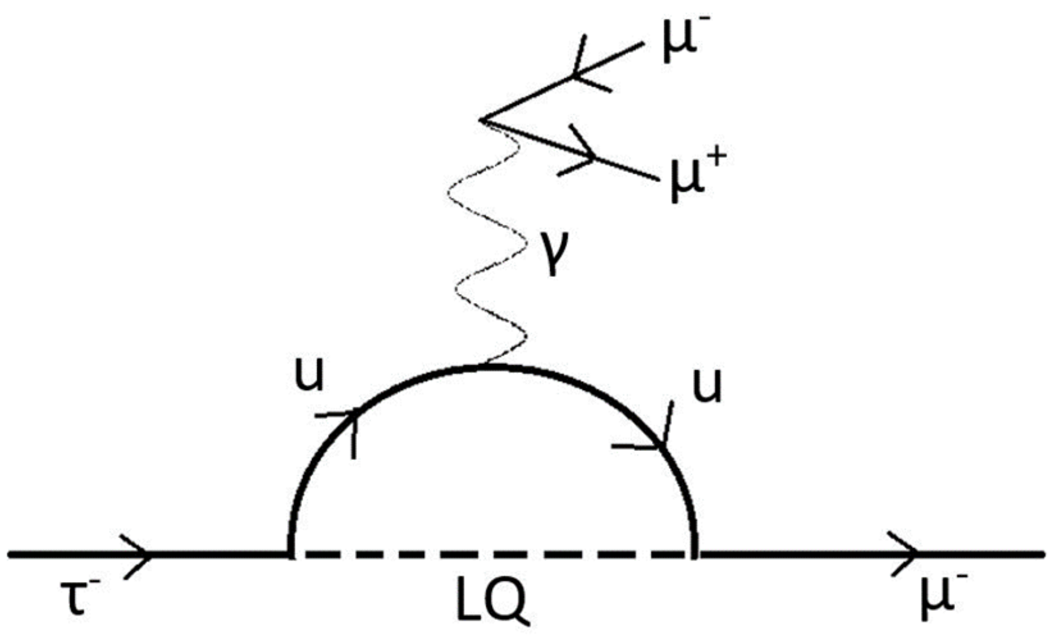
A search for lepton-flavour violating $\tau \rightarrow 3\mu$ decays with the ATLAS experiment

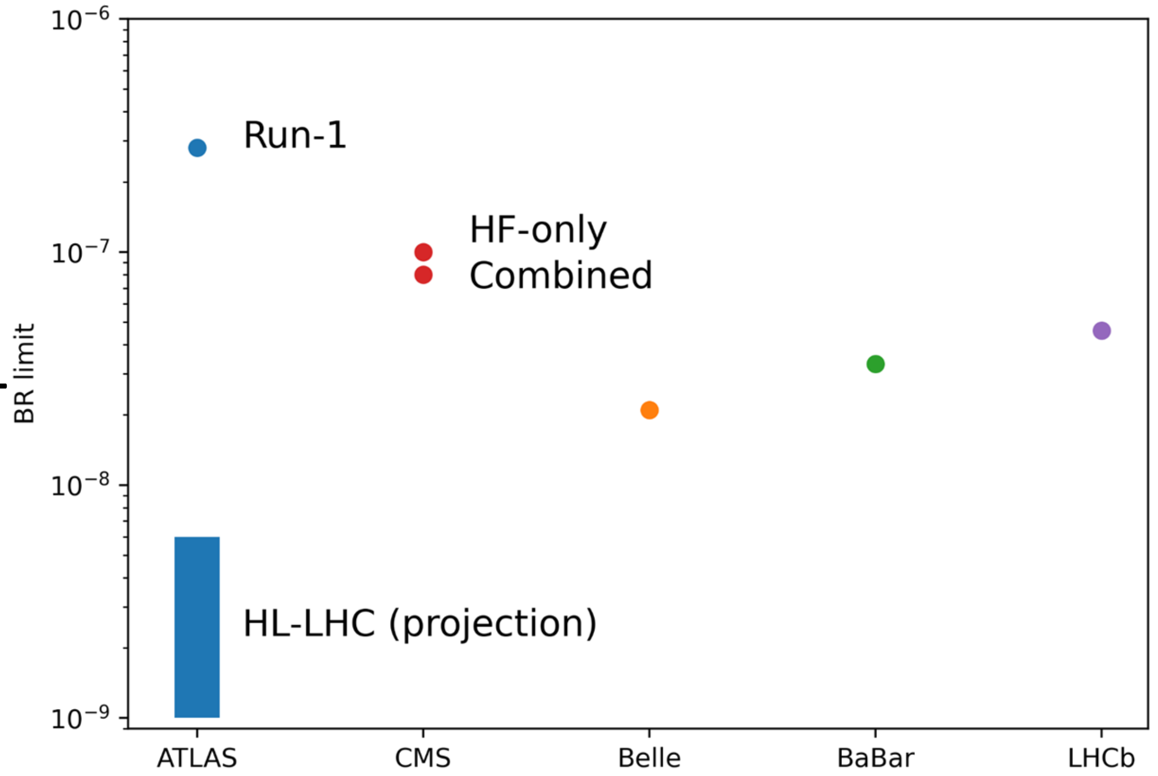
Conor McPartland

Carl Gwilliam, Jan Kretzschmar

Introduction

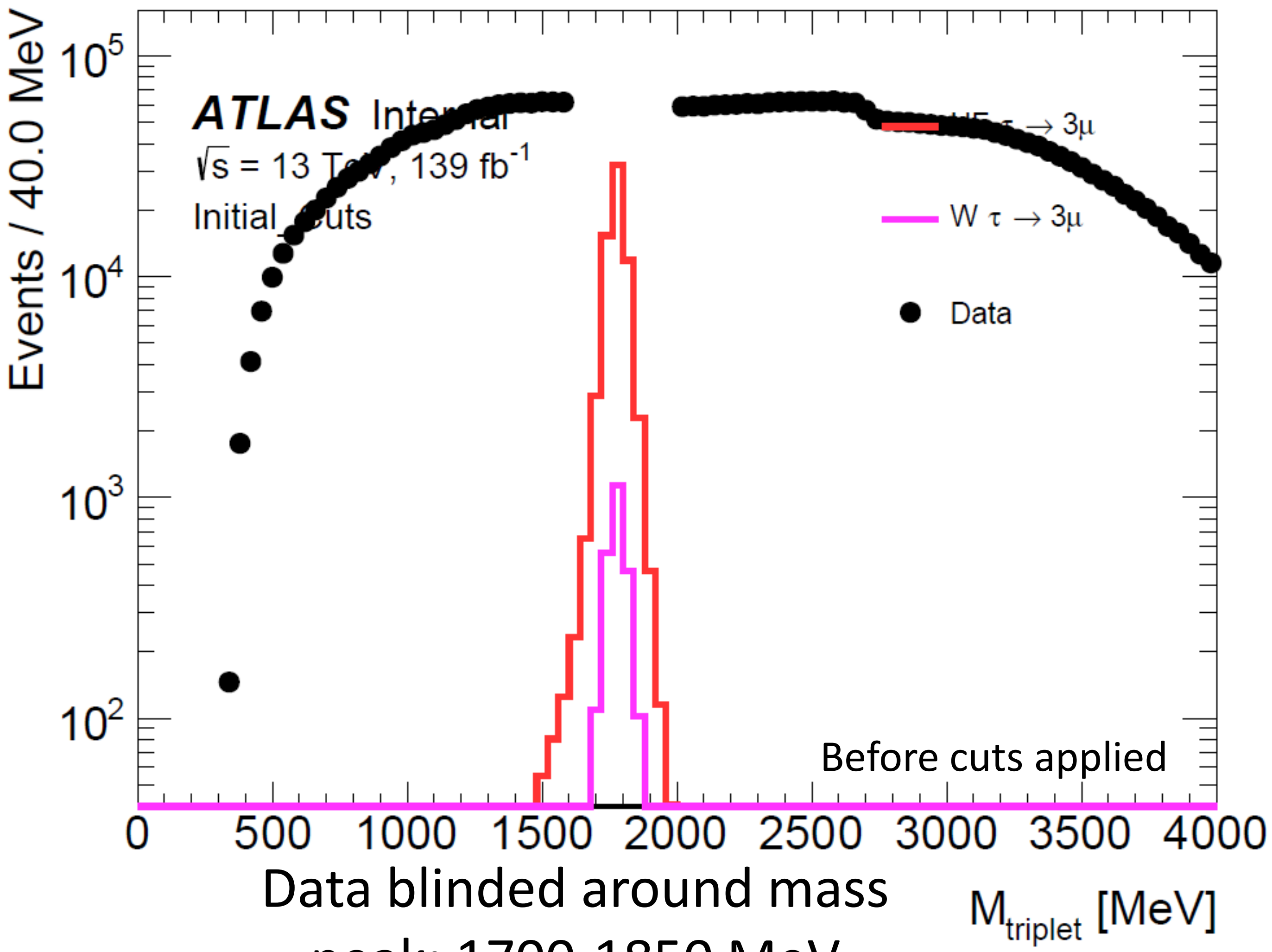
- Flavour is not a fundamental symmetry, violation observed in neutrinos and quarks
  - If violation observed in charged leptons -> evidence of beyond standard model physics
- Decay to be analysed at ATLAS $\tau^{\pm} \rightarrow \mu^{\pm}\mu^{\pm}\mu^{\mp}$
  - Standard model BR: x10^{-55}-x10^{-56}
  - Far below current detection ability
  - Current tau limits much less stringent than that of muons by approximately $O(10^4)$
- Two main τ production modes in proton-protons collisions
  - Heavy Flavour (HF) – e.g. $D_s \rightarrow \tau\nu$
  - Electroweak (EW) – mainly $W \rightarrow \tau\nu$





Analysis Strategy – pt1

- Selection
  - Use a mix of 2 and 3 muon triggers to collect data
  - Apply loose preselection cuts based on di-muon mass, impact parameters and isolation related variables
  - Use MVA technique to discriminate between small signal and background
- Background
  - Mainly incorrectly identified vertices and misidentified muons
  - Mass cuts to remove resonant meson background processes e.g. Ds → ϕμν
  - Use fit in data sidebands as a proxy for background

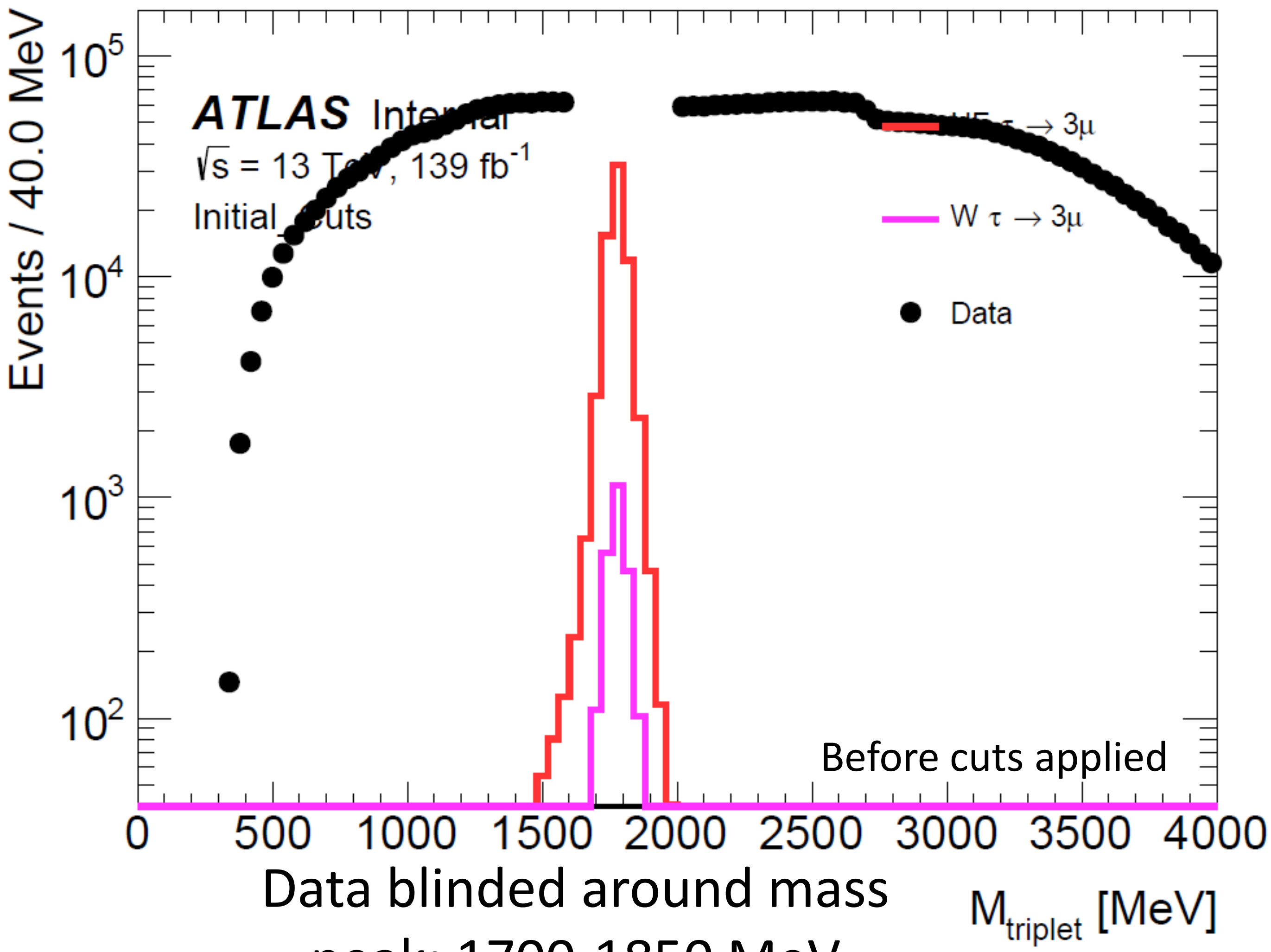


Data blinded around mass peak: 1700-1850 MeV

Preselection → MVA → Resonant background cut → Fit to three muon mass

Analysis Strategy – pt2

- Signal extraction
  - Apply a fit to the three muon mass to extract signal and background yields, to either find evidence of this decay, or to impose a new more stringent limit
- Correct MC trigger efficiency by calculating trigger scale factors (current focus)
- Same approach for both HF and EW channels

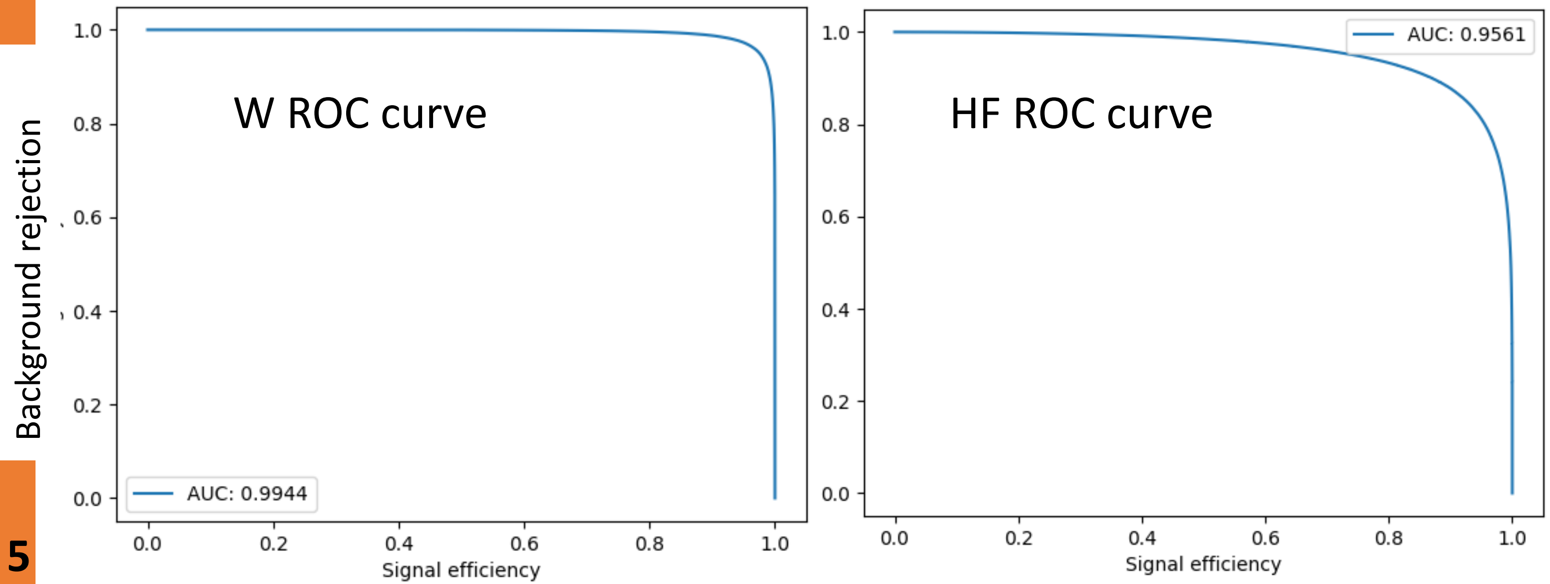


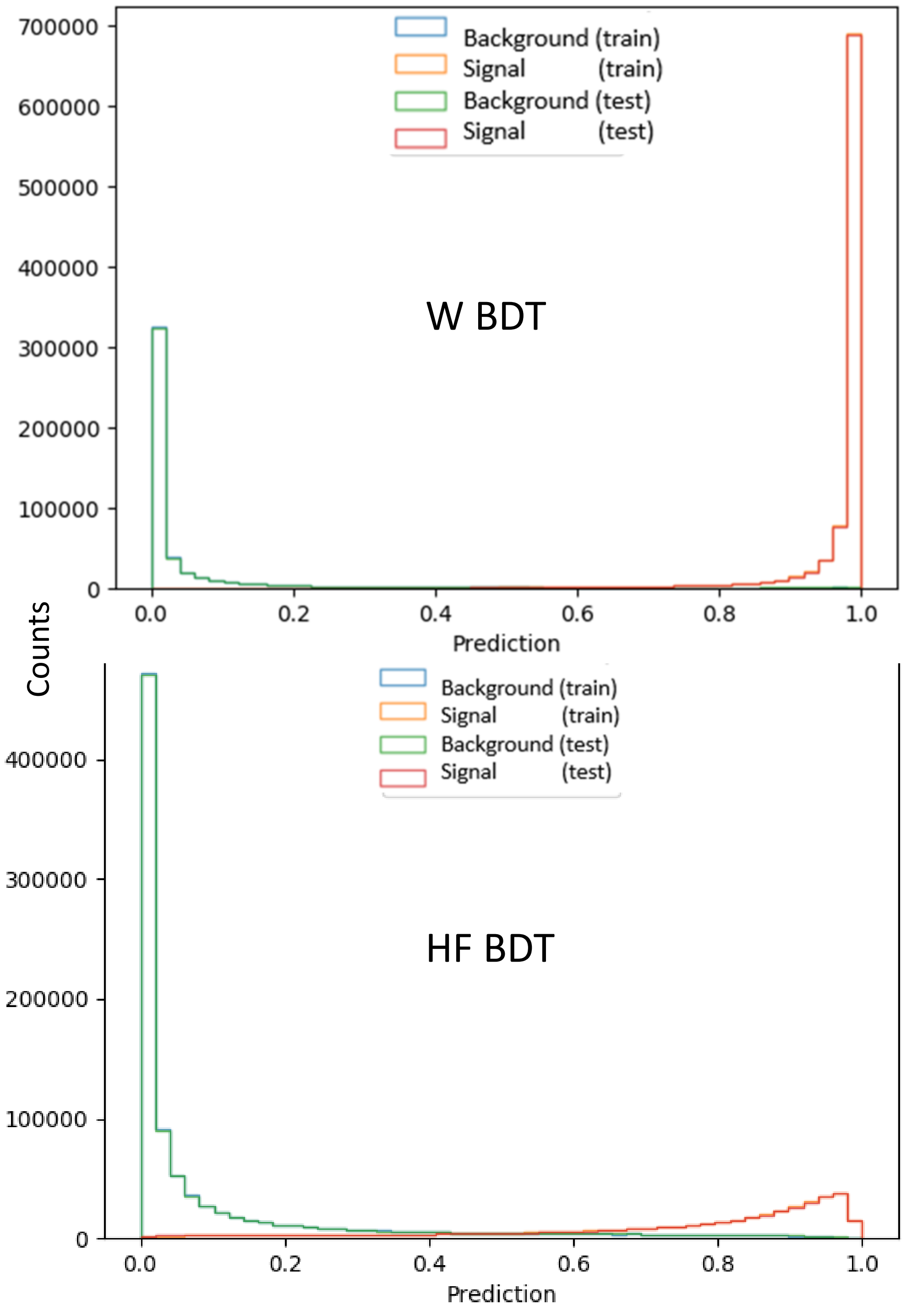
Data blinded around mass peak: 1700-1850 MeV

Preselection → MVA → Resonant background cut → Fit to three muon mass

MVA

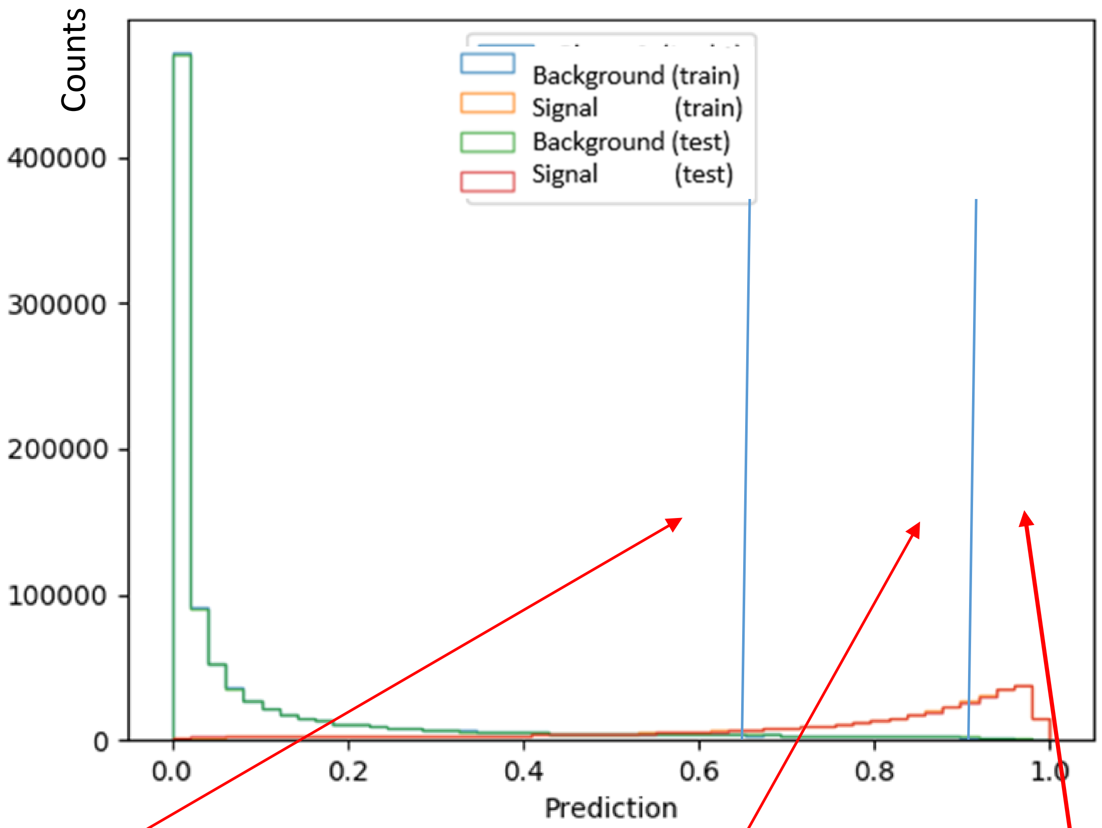
- Several MVA types tried and optimised
  - Using XGBoost BDT to improve signal to background ratio
  - Recently re-opimised preselection cuts for both W and HF
- 17 inputs features
  - Vertex quality, tau displacement, tau kinematics and isolation variables
  - Variables are not correlated with muon triplet mass
- Trained with signal vs sideband data
  - Training sample composed of two equal halves



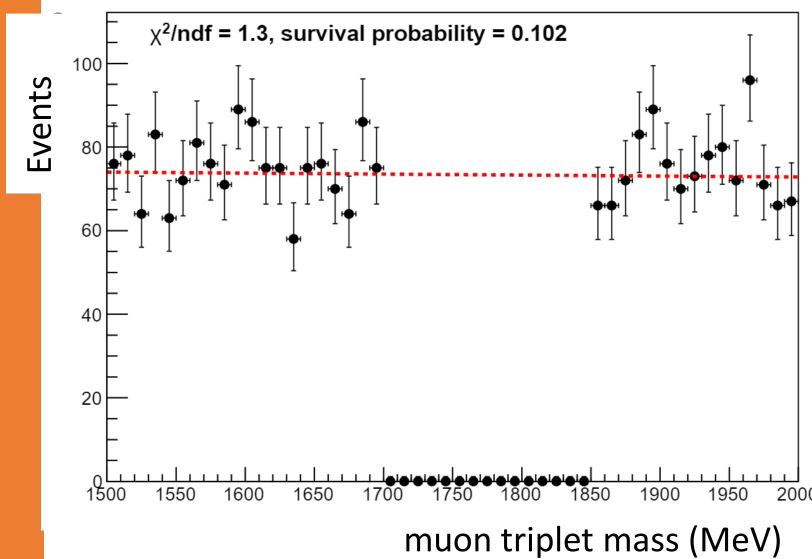


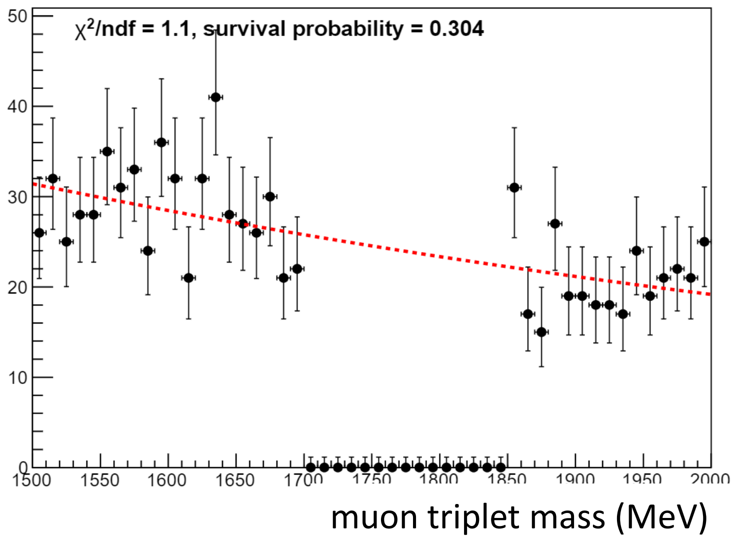
Fitting

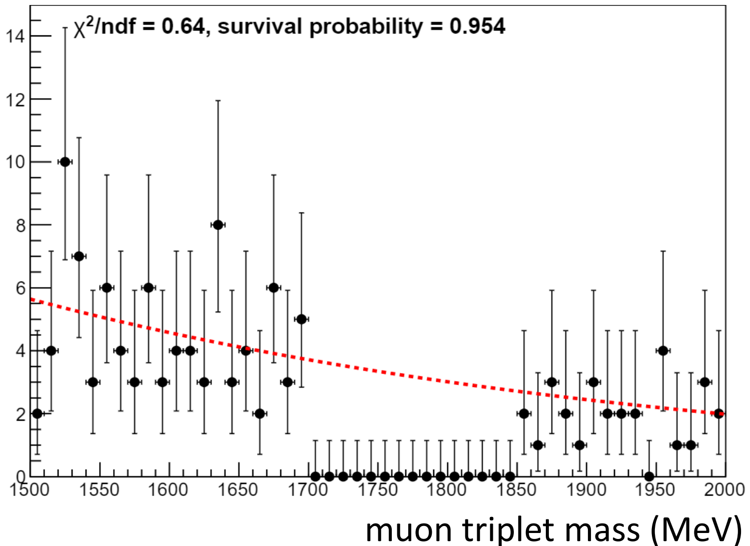
- Simultaneous fit performed in 6 regions
  - 3 BDT bins
  - Barrel and endcap split - different sensitivities
- Same overall approach for HF and W



- Parameterise signal MC with double sided crystal ball
- Parameterise background with polynomial
- Extract signal and background yields to find limit



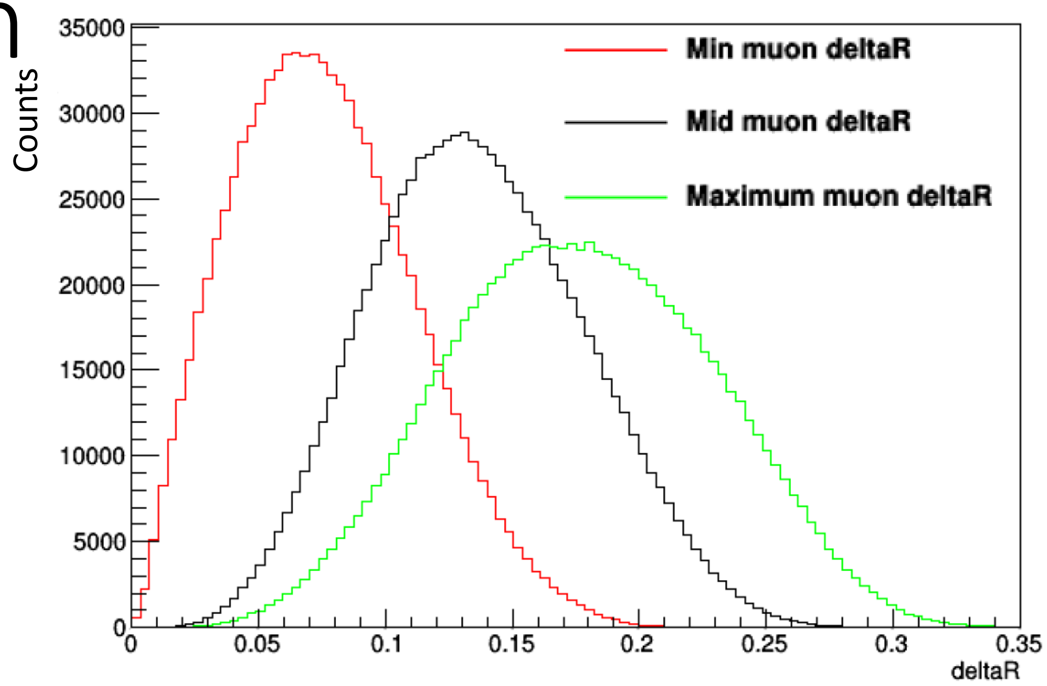


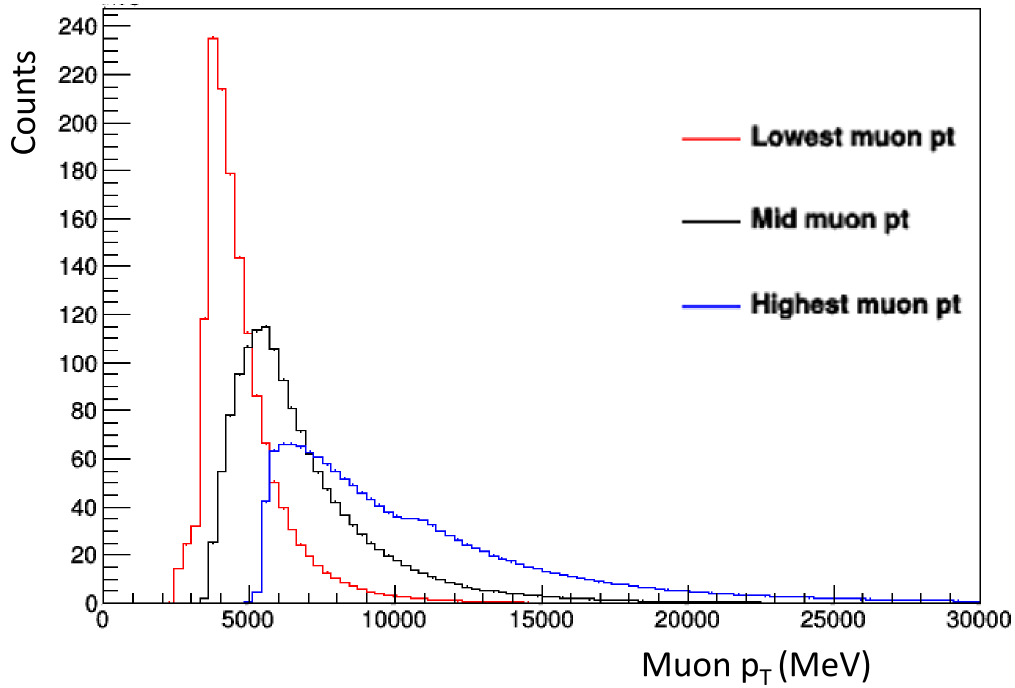


HF Barrel fits shown

Trigger Scale factor correction

- After reducing the background to signal ratio we want to extract the signal
  - Need the number of expected signal and background events -> need the trigger efficiencies
- Complex multi muon triggers with close together muons means MC not able to model well
  - Muons can have a small ΔR (relates to distance between muons). Minimum peaks at 0.06, see top plot
  - Wide spectrum of p_T (see bottom plot)
- Background is from sideband data so trigger efficiency is correct by definition
- Signals come from MC, trigger efficiency not reliable, so we need to calculate a scale factor correction
  - Main challenge for analysis



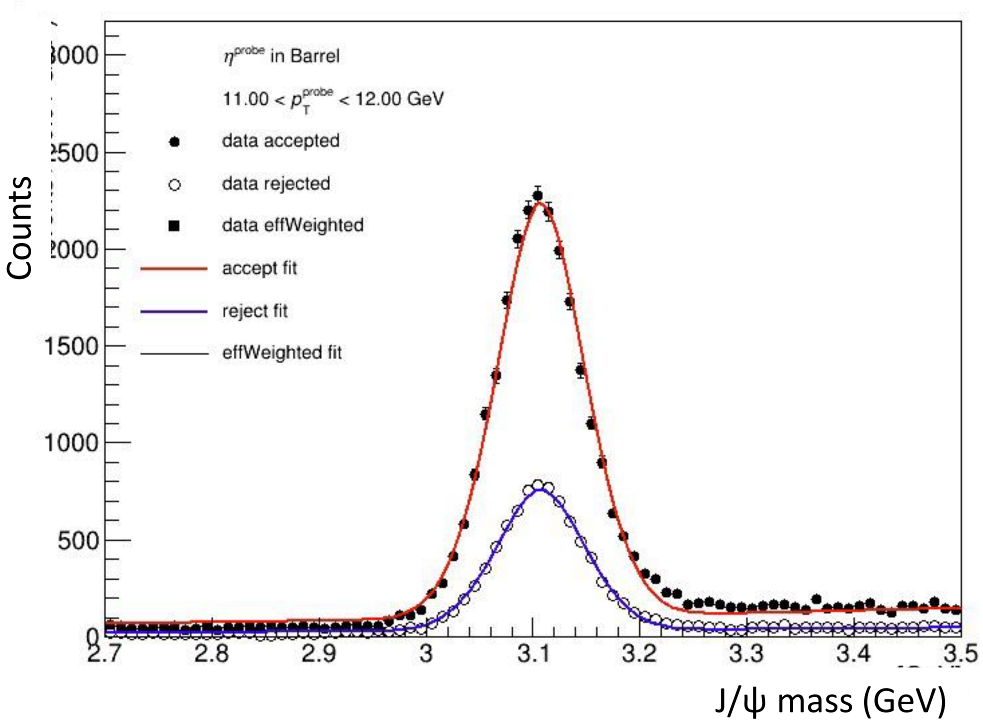


Trigger Scale factor correction

mu6_mu4 trigger
Leg 1 (mu6): > 6 GeV muon
Leg 2 (mu4): > 4 GeV muon

- Following other multi-muon analyses, take a factorised approach
  - Split trigger into individual trigger leg components
  - Multi-muon efficiency -> product of the single muon efficiencies for each leg and correction factors
- For di-muon case: $\epsilon_{di-muon} = \epsilon 1(p_T) \cdot \epsilon 2(p_T) \cdot C12(\Delta R)$
  - Measure p_T efficiency for each muon ($\epsilon 1(p_T)$, $\epsilon 2(p_T)$)
  - This alone does not account properly for muons that overlap with each other (close in dR) so we need a dR correction ($C12(\Delta R)$)
- To find the efficiency for each correction factor use a tag and probe method with muons from J/ψ
  - $\varepsilon = \frac{N(single\ \mu\ trigger\ -matched\ probe)}{N(probe)}$
  - Find yields (N) via unbinned ML fit to J/ψ mass in case where probe is either triggered or not
  - Plot is for p_T correction with bins of p_T- similar approach for dR

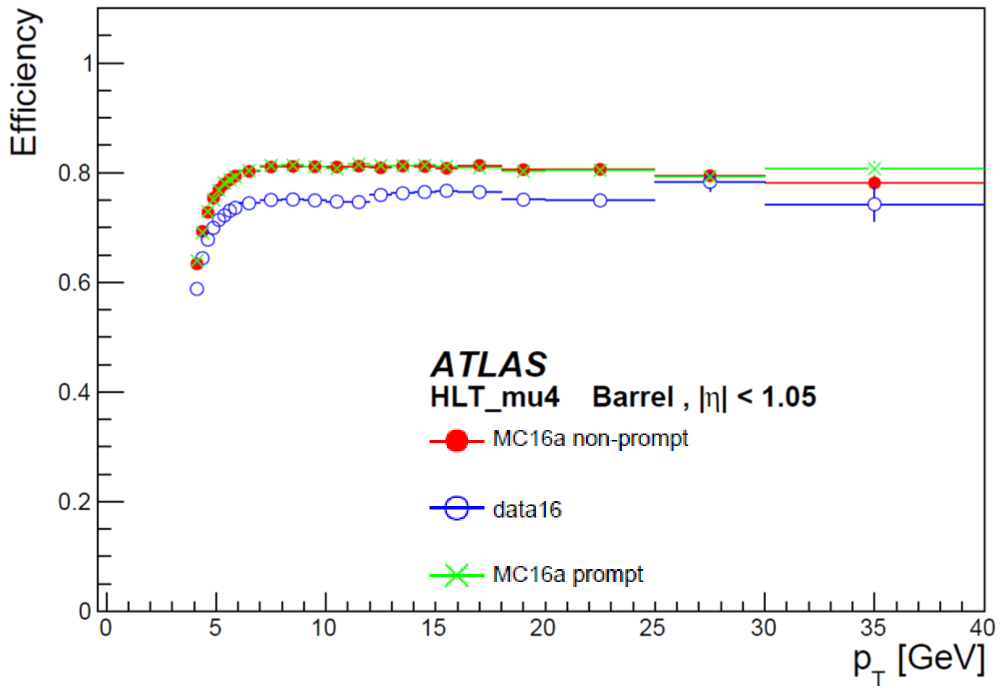
Fit for mu4 in 2016 data

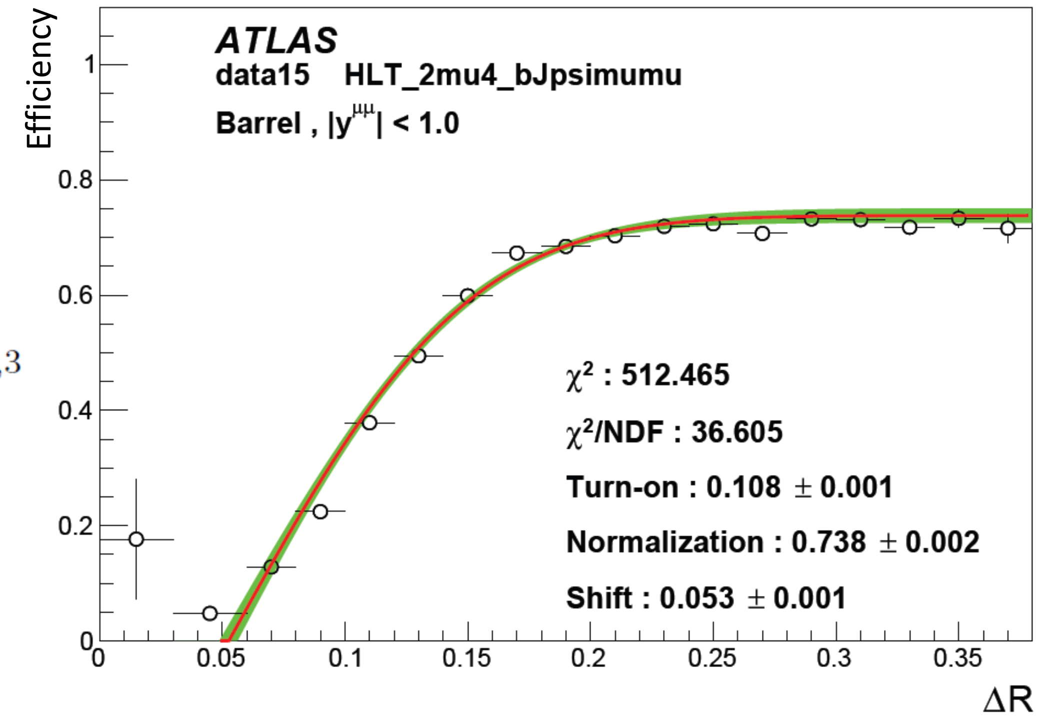


Trigger Scale factor correction

- After finding the p_T efficiency in bins of p_T and dR correction these can be used to find the trigger efficiency
- The p_T efficiency is shown in the top plot – for the barrel in 2016
- The dR correction is shown in the bottom plot- for the barrel with 2015 data
- Combine these, taking into account combinatorics – the correction for a symmetric di-muon trigger with our 3 signal is shown below

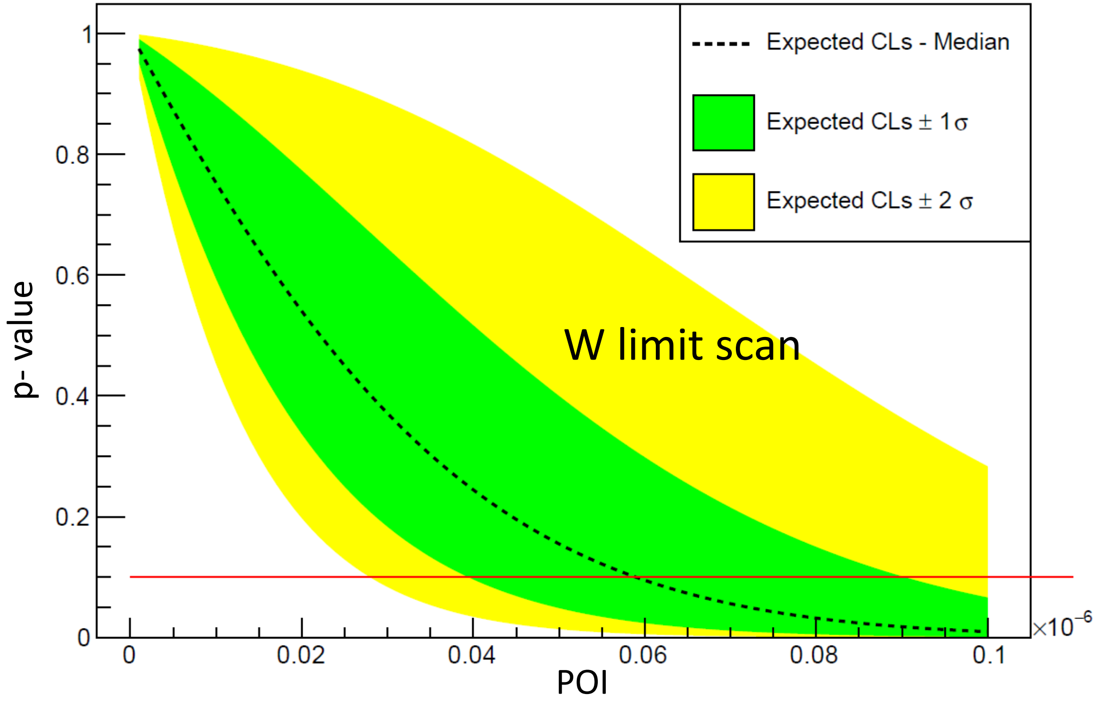
$$
\begin{aligned}
\epsilon_{2muX} =& (1-(1-CF_{12})(1-CF_{13})(1-CF_{23})) \times \epsilon_{muX,1}\epsilon_{muX,2}\epsilon_{muX,3} \\
&+ CF_{12}CF_{12}CF_{13}CF_{23} \times \epsilon_{muX,1}\epsilon_{muX,2}(1-\epsilon_{muX,3}) \\
&+ CF_{13}CF_{12}CF_{13}CF_{23} \times \epsilon_{muX,1}\epsilon_{muX,3}(1-\epsilon_{muX,2}) \\
&+ CF_{23}CF_{12}CF_{13}CF_{23} \times \epsilon_{muX,2}\epsilon_{muX,3}(1-\epsilon_{muX,1})
\end{aligned}
$$

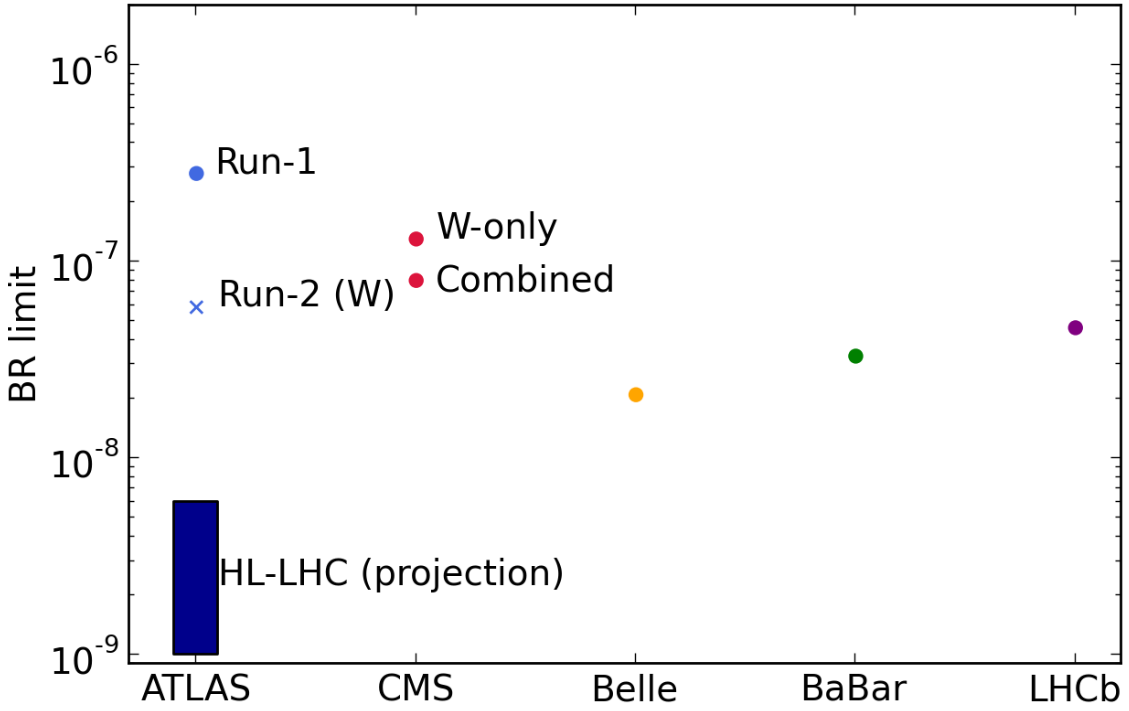




Expected Sensitivity

- Overall normalisation of signal template is treated as parameter of interest in fit
  - POI is interpreted as branching ratio
  - Use CL_S method
- Currently statistics only result without trigger scale factors
- W expected limit (stat only): 5.85×10^{-8}
  - CMS (W) 13.0×10^{-8}
- HF expected limit (stat only): 8.99×10^{-8}
  - CMS (HF) 10.0×10^{-8}
- HF result comparable to CMS but W is better
- Result will be statistics limited





Summary

- All main analysis tools in place to find limit
- Obtained an expected limit for both W and HF channels
- Before systematics expected limits look to be competitive with CMS
- Current focus:
  - Trigger scale factor calculations
- Next steps:
  - Systematics
- Aim to complete analysis at the end of the year and then start writing up thesis

- As part of LIV.DAT Started 3 day a week work placement at AIMES – also continuing with analysis on other days

Backup

Signal and Background

- Signal
  - Three HF production modes

Sample	Relative rate
$pp \to D_s \to \tau\nu$	65%
$pp \to bb \to \tau X$	25%
$pp \to bb \to D_s + X \to \tau\nu + X$	10%

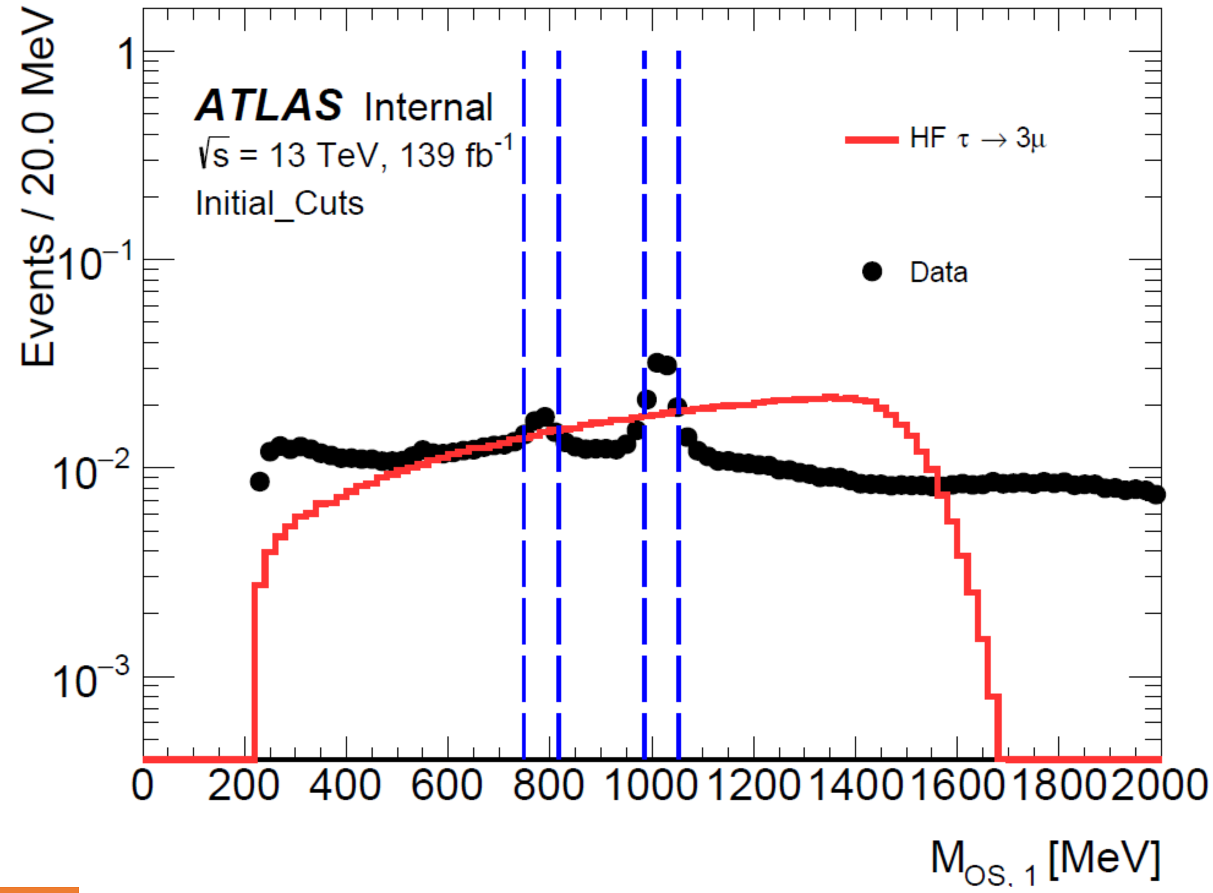
- Three EW production modes
- Optimise analysis for just W as it's the main signal

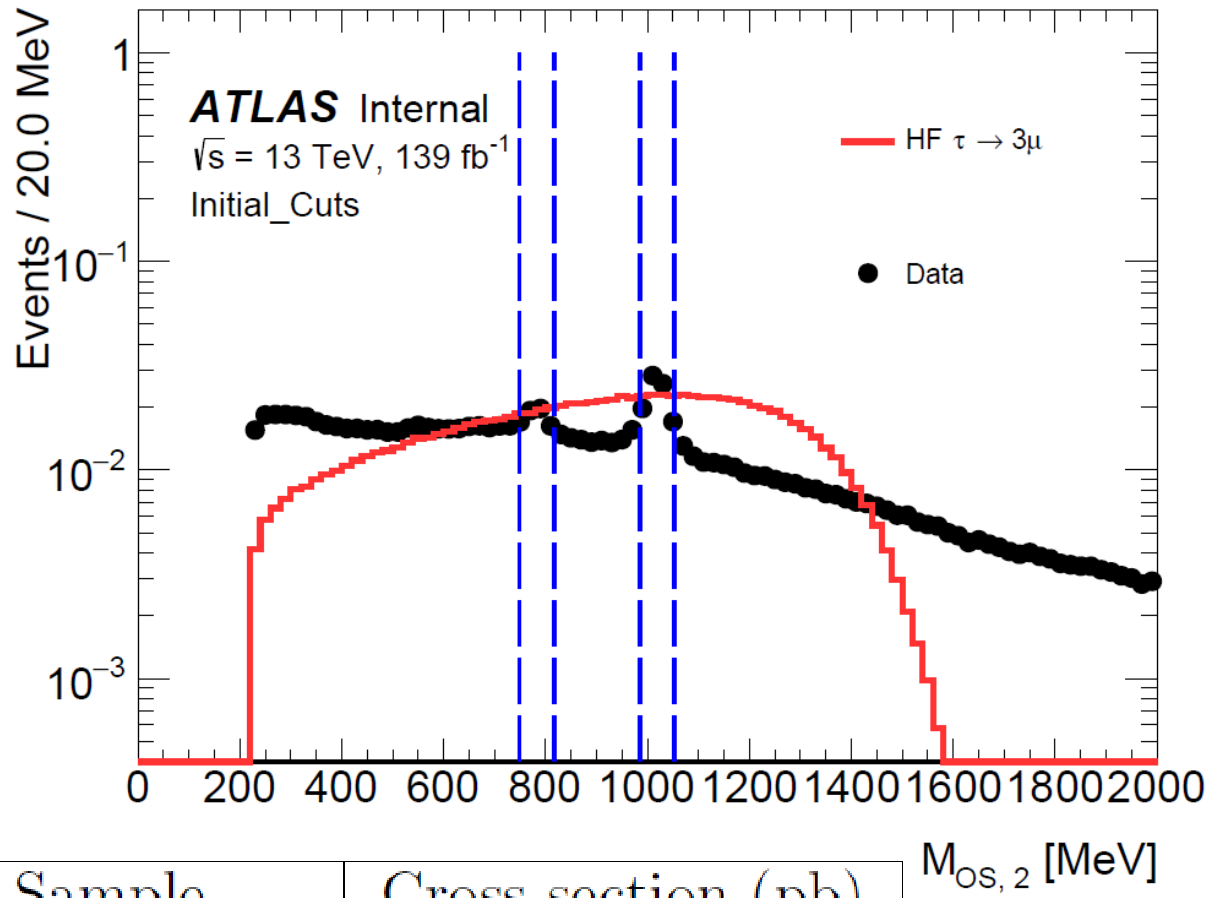
Sample	Relative rate
$W \to \tau\nu$	83%
$Z \to \tau\tau$	16%
$t\bar{t} \to \tau\,\tau\,X$	1%

- Background- use data sidebands as a proxy for background
  - Incorrectly identified vertices and misidentified muons
  - Resonant meson background processes e.g. $Ds \to \phi\mu\nu$

- Use a mix of 2 and 3 muon triggers to collect data
  - Require events with three muons and momentum > 5.5 GeV, 3.5 GeV and 2.5 GeV
  - Loose preselection cuts – di muon mass, p_T, eta and impact parameters etc

Pre-selection cuts





Sample	Cross section (pb)
$D_s \rightarrow \eta' \mu \nu$	3.7847×10^{-4}
$D_s \rightarrow \phi \mu \nu$	7.4425×10^{-4}
$D_0 \rightarrow \eta \mu \nu$	8.8266×10^{-4}
$D_0 \rightarrow \eta' \mu \nu$	9.5559×10^{-4}
$D_0 \rightarrow \rho \mu \nu$	1.6434×10^{-3}
$D_0 \rightarrow \omega \mu \nu$	1.1147×10^{-3}

Triggers

- Using a combination of di- and tri-muon triggers, that vary by year:
  - 2015

Trigger	Unique efficiency (%)
HLT_mu20_msonly_mu6noL1_msonly_nscan05	8.15
HLT_mu11_2mu4noL1_nscan03_L1MU11_2MU6	10.18
HLT_mu6_l2msonly_2mu4_l2msonly_L1MU6_3MU4	24.92
HLT_3mu4_bTau	1.77
HLT_2mu10	0.89

  - 2016

HLT_mu20_nomucomb_mu6noL1_nscan03	4.78
HLT_mu6_nomucomb_2mu4_nomucomb_bTau_L1MU6_3MU4	17.00
HLT_mu11_nomucomb_2mu4noL1_nscan03_L1MU11_2MU6	7.12
HLT_3mu4	6.22
HLT_2mu10	1.33
HLT_mu11_nomucomb_mu6noL1_nscan03_L1MU11_2MU6_bTau	0.99

  - 2017

HLT_mu11_mu6_bTau	18.39
HLT_mu6_2mu4_bTau_L1MU6_3MU4	18.53
HLT_mu11_2mu4noL1_bNocut_L1MU11_2MU6	2.29
HLT_3mu4_bTau	1.83
HLT_mu20_mu6noL1_bTau	1.10

  - 2018

HLT_mu11_mu6_bTau	18.40
HLT_mu6_2mu4_bTau_L1MU6_3MU4	18.37
HLT_mu11_2mu2btrk_bTauTight_L1MU11_2MU6	2.25
HLT_mu20_mu6noL1_bTau	1.17
HLT_3mu4_bTau	1.82