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

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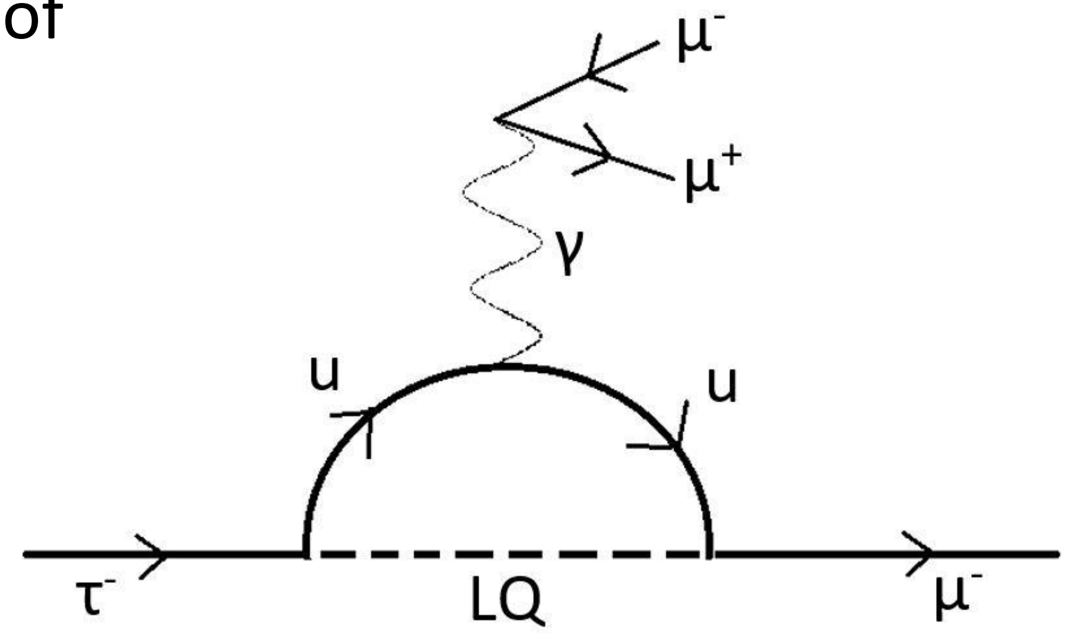
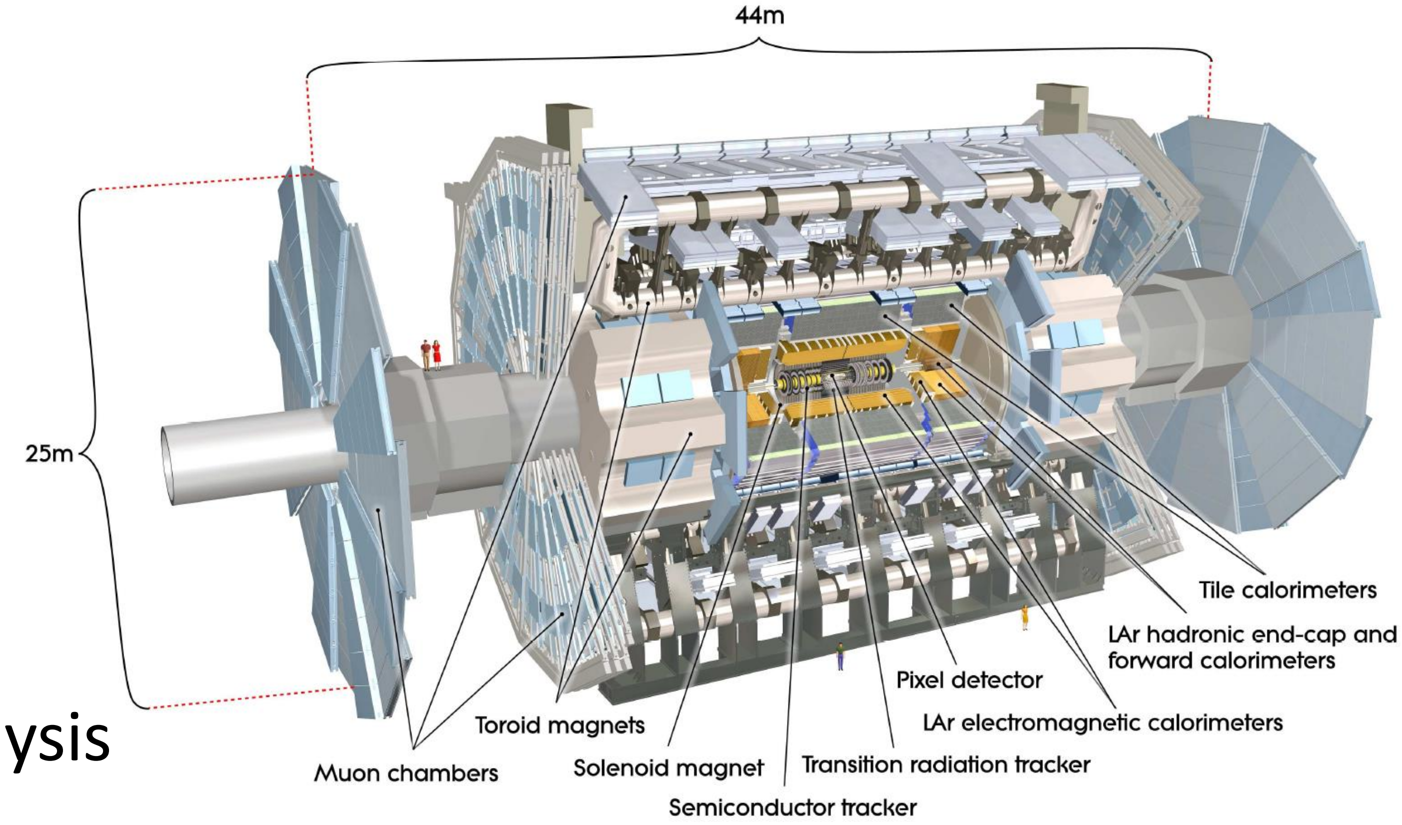
Charged Lepton-Flavour Violation

- Flavour is not a fundamental symmetry of the Standard Model
- Flavour violation observed in neutrinos and quarks
- If found in charged leptons would be evidence of beyond standard model physics- such as leptoquarks or type-II seesaw mechanism
- Limits on tau are much less stringent than that of muons and electrons by approximately $O(10^4)$
- Decay to be analysed $\tau^{\pm} \rightarrow \mu^{\pm}\mu^{\pm}\mu^{\mp}$
  - Standard model BR: $x10^{-55}$-$x10^{-56}$
  - Far below current detection ability



The LHC and ATLAS

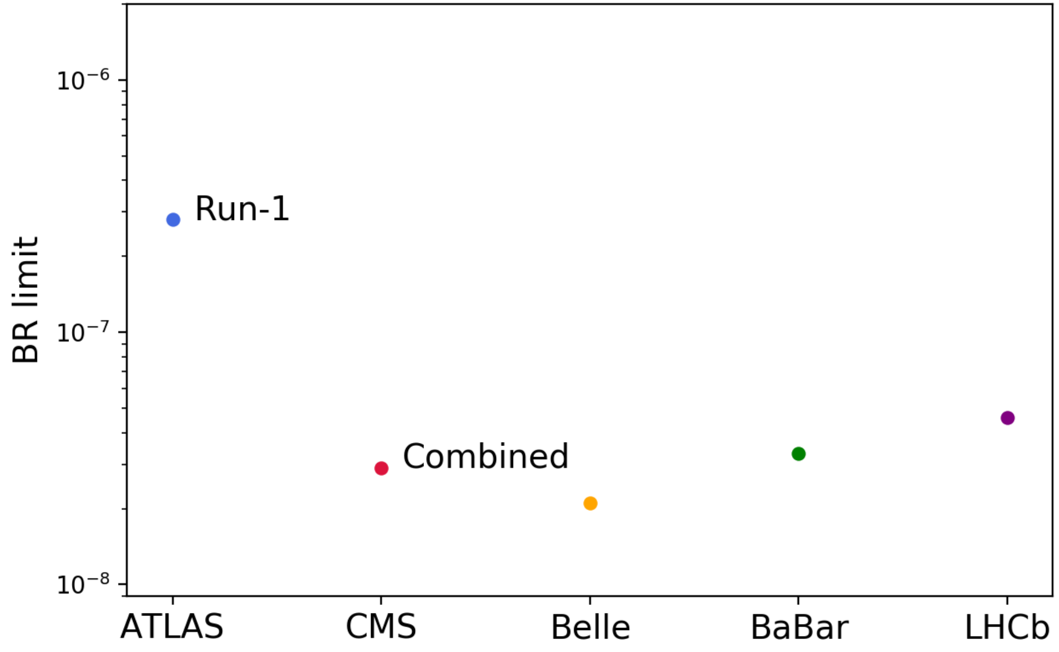
- The LHC at CERN is a high energy proton- proton collider
- The ATLAS experiment is a multipurpose particle detector made up of: the inner detector, electron/ hadron calorimeters and a muon spectrometer
- During run-2 (2015-18):
  - Centre of mass energy of 13 TeV
  - 139 fb^{-1} of luminosity collected
- Two main τ production modes at LHC
  - Heavy Flavour (HF) – e.g. $D_s \rightarrow \tau\nu$
  - Electroweak (EW) – mainly $W \rightarrow \tau\nu$
- Hope to use ATLAS run 2 data to achieve a highly sensitive analysis

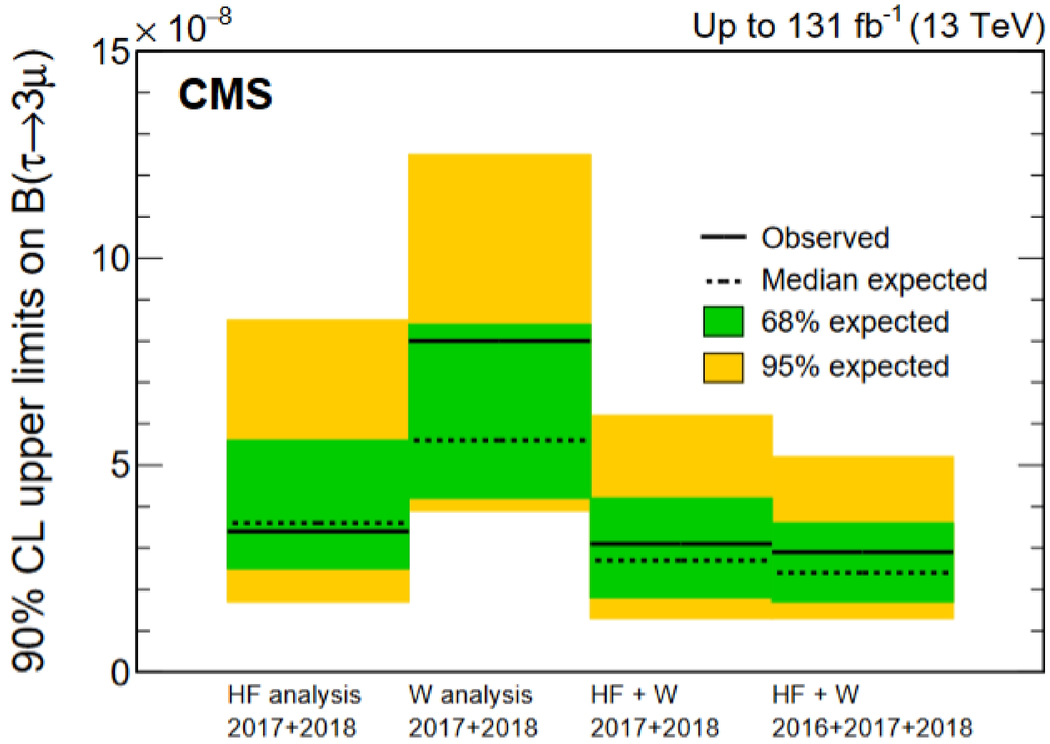


Previous Limits

- Current Branching Ratio Limits 90% confidence interval:
  - CMS run-2 (2023 paper- [arXiv:2312.02371](https://arxiv.org/abs/2312.02371)):
    $2.9\text{x}10^{-8}$
  - Belle:
    $2.1\text{x}10^{-8}$ (current best)

- Belle/ BaBar use high luminosity e^+e^- collisions as opposed to the proton-proton collisions at the LHC experiments





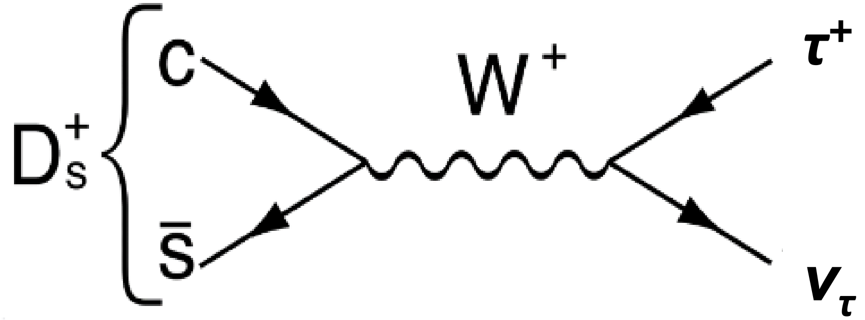
Signal and Background

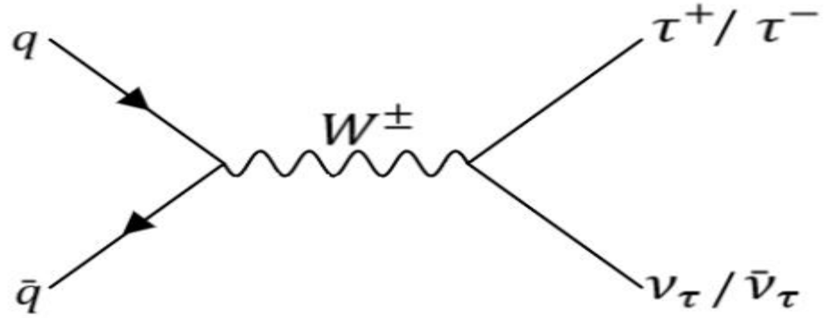
- Three HF signal samples

Sample	Relative rate
pp → D_s → τν	65%
pp →bb → τX	25%
pp → bb→ D_s+X → τν+X	10%

- Three EW channel samples
- Optimise analysis for just W - as it's the main signal

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

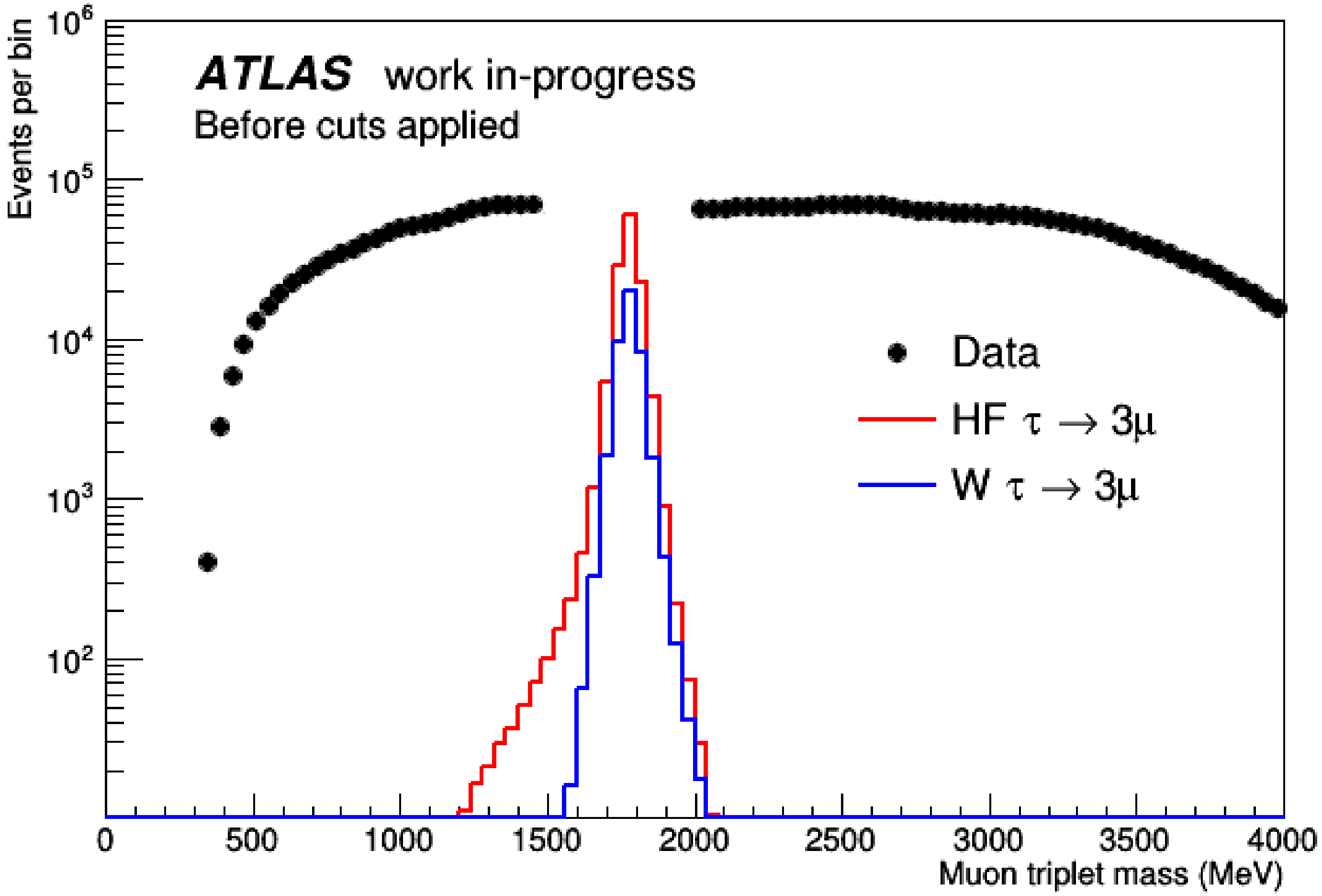




- Two main background sources:
  - Incorrectly identified vertices and misidentified muons
  - Resonant meson background processes e.g. Ds → ϕμν
- Using MC for signal and data sidebands as a proxy for background

Analysis Strategy

- 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 background and small signal
- Background
  - Mass cuts to remove resonant meson background processes e.g. Ds → ϕμν
  - Use fit in data sidebands as a proxy for background
- Same approach for both HF and EW channels

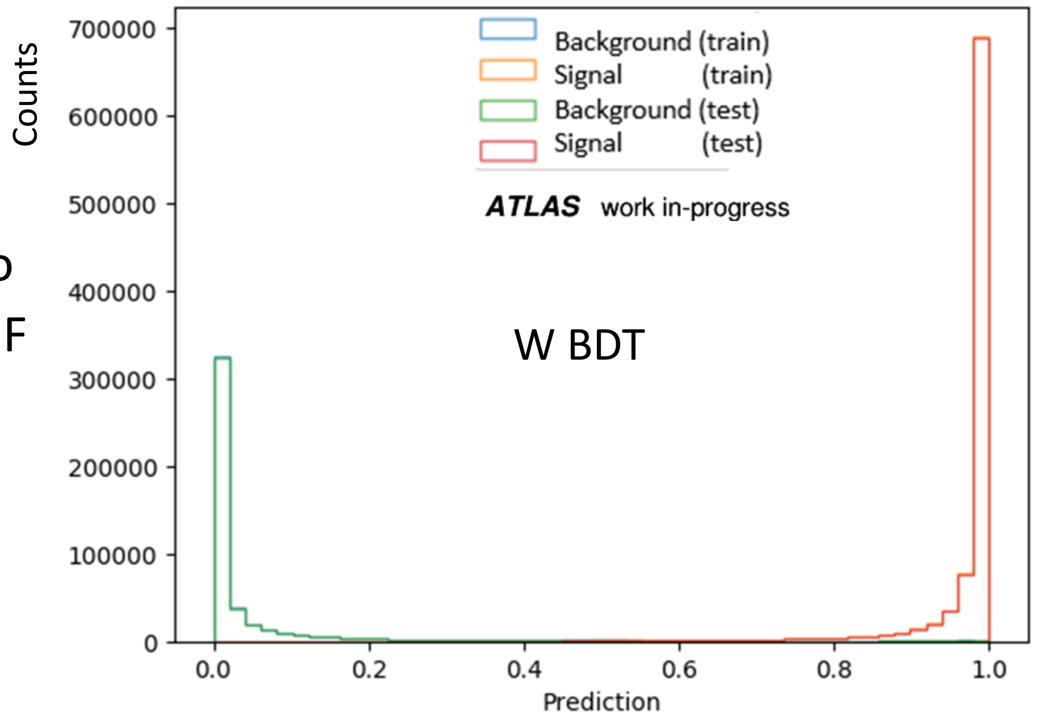


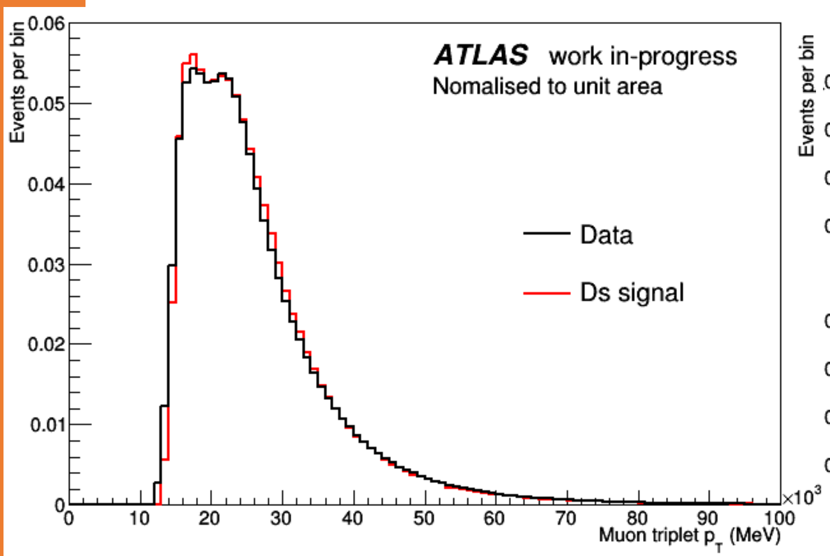
Data blinded around mass peak: 1700-1850 MeV

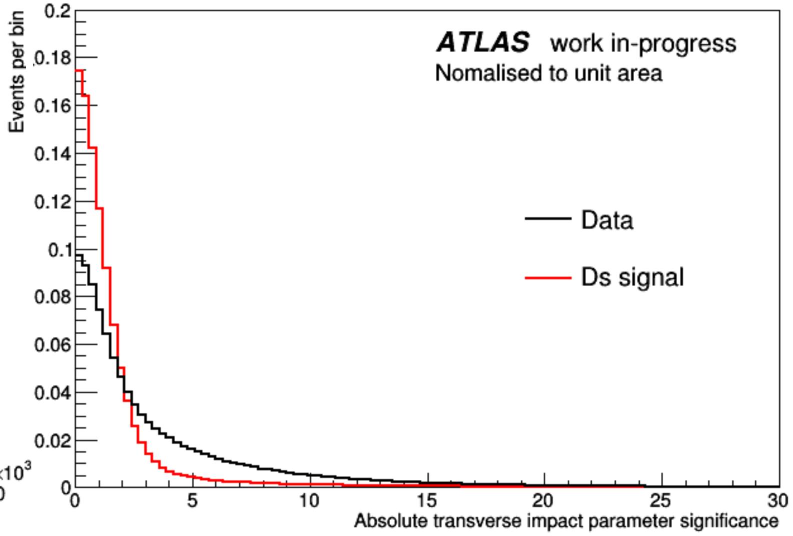
Preselection → MVA → Resonant background cut → Fit to three muon mass

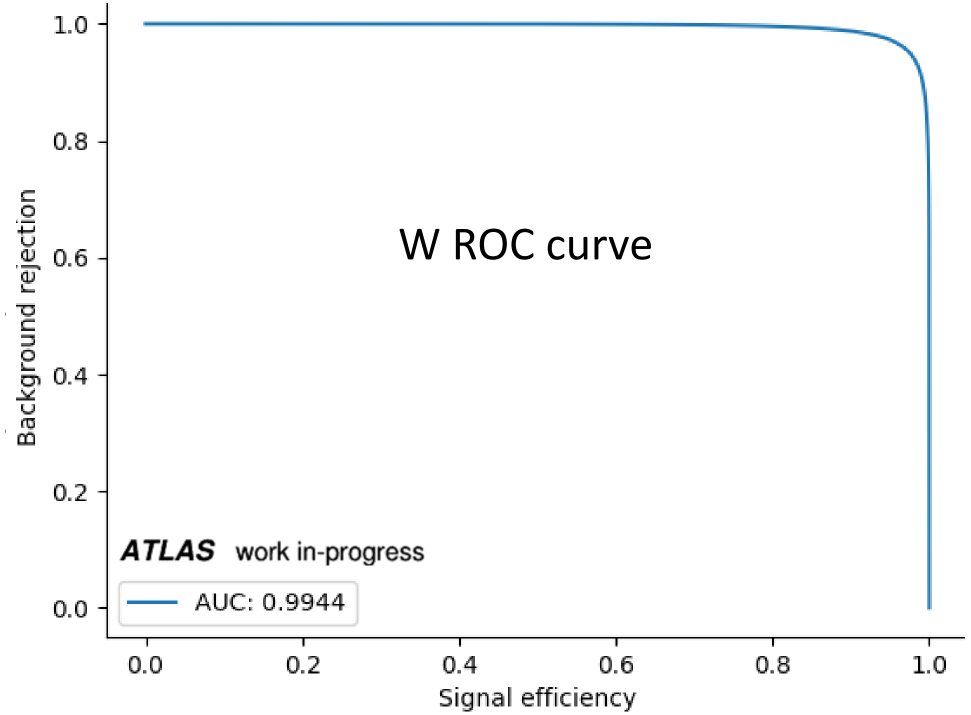
MVA

- 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 related variables
  - Variables are not correlated with muon triplet mass
- Trained with signal vs sideband data
  - Training sample composed of two equal halves



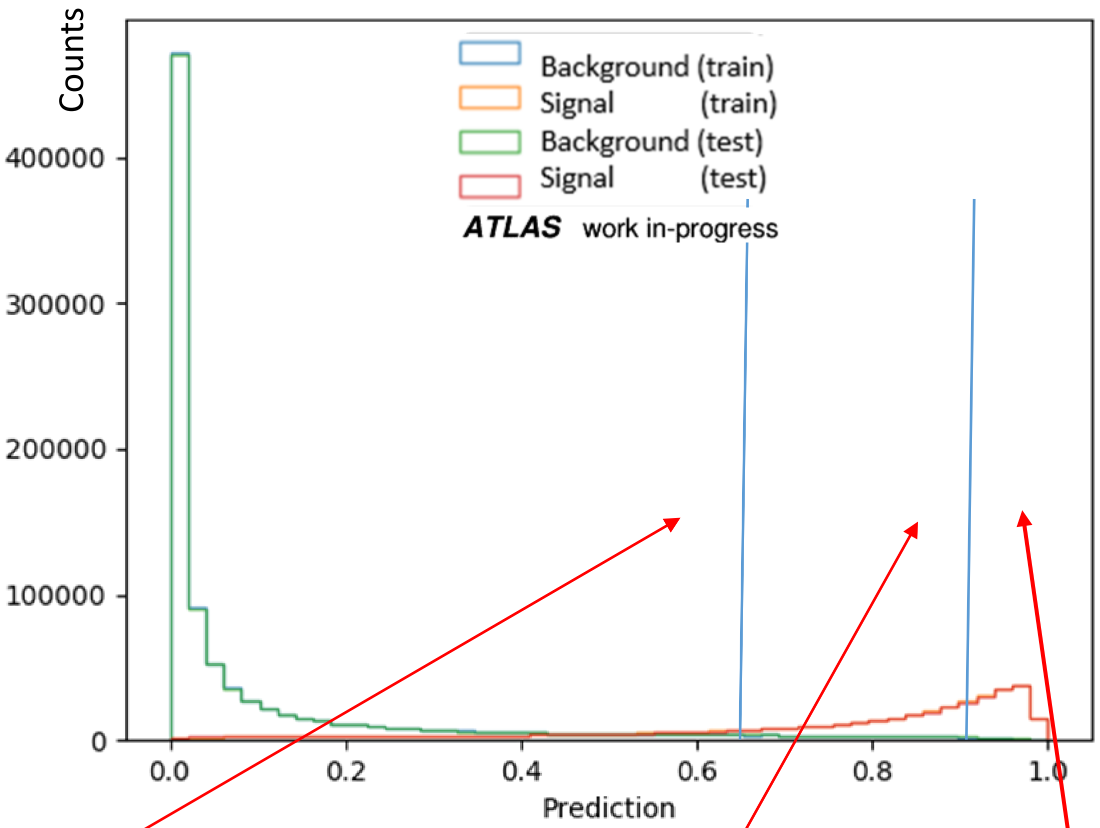




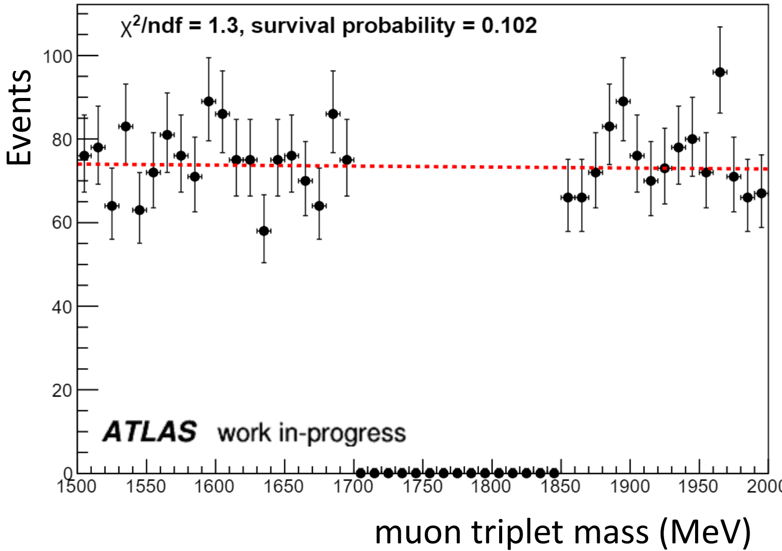


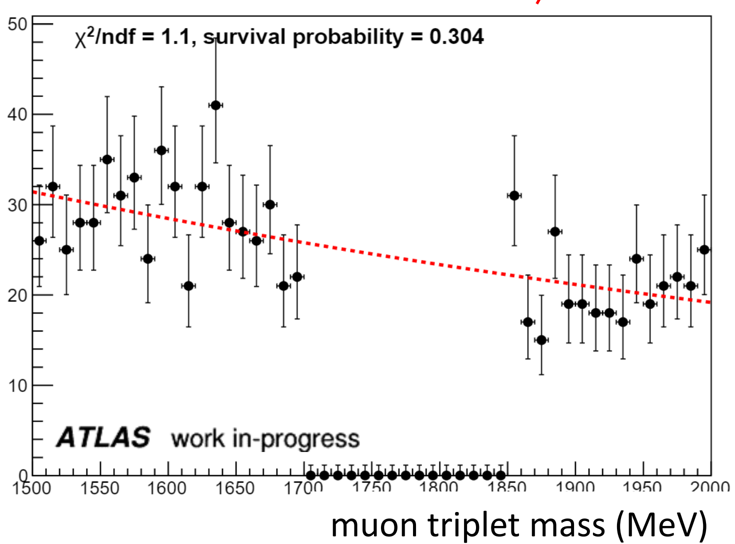
Fitting

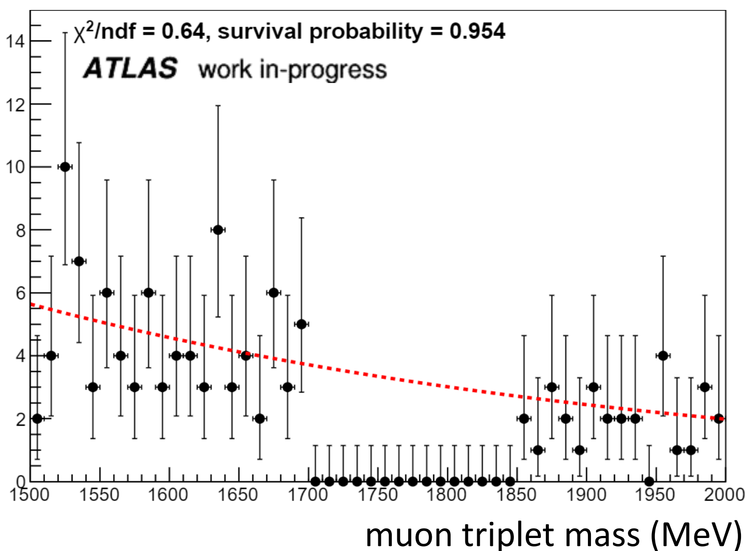
- Simultaneous fit performed in 6 regions
  - 3 BDT bins
  - Barrel and endcap split - different sensitivities
- Same overall approach for HF and EW



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



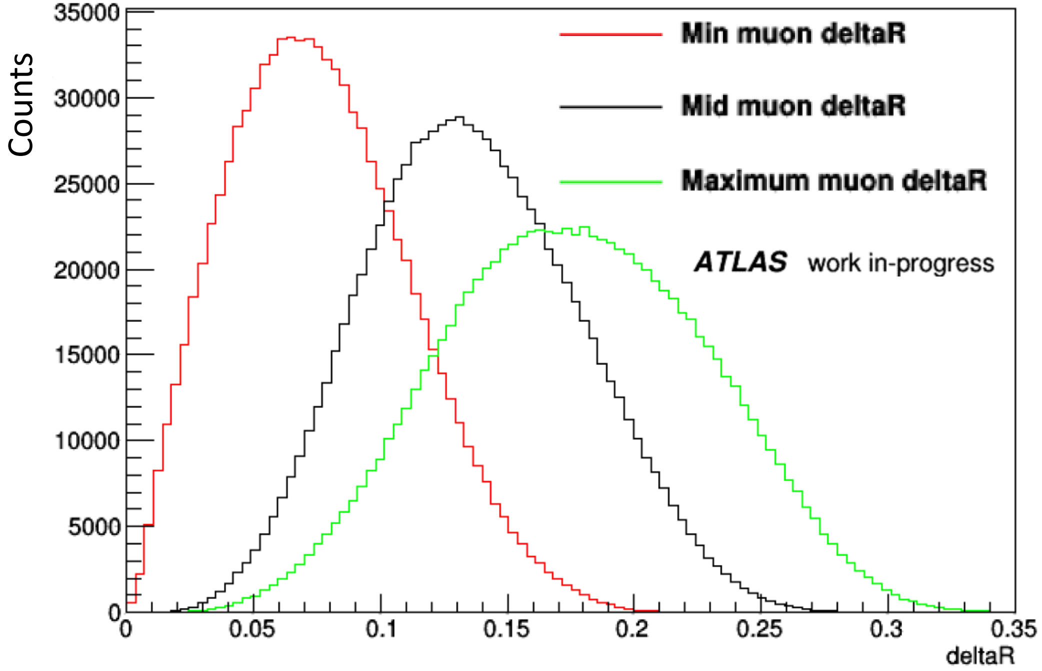


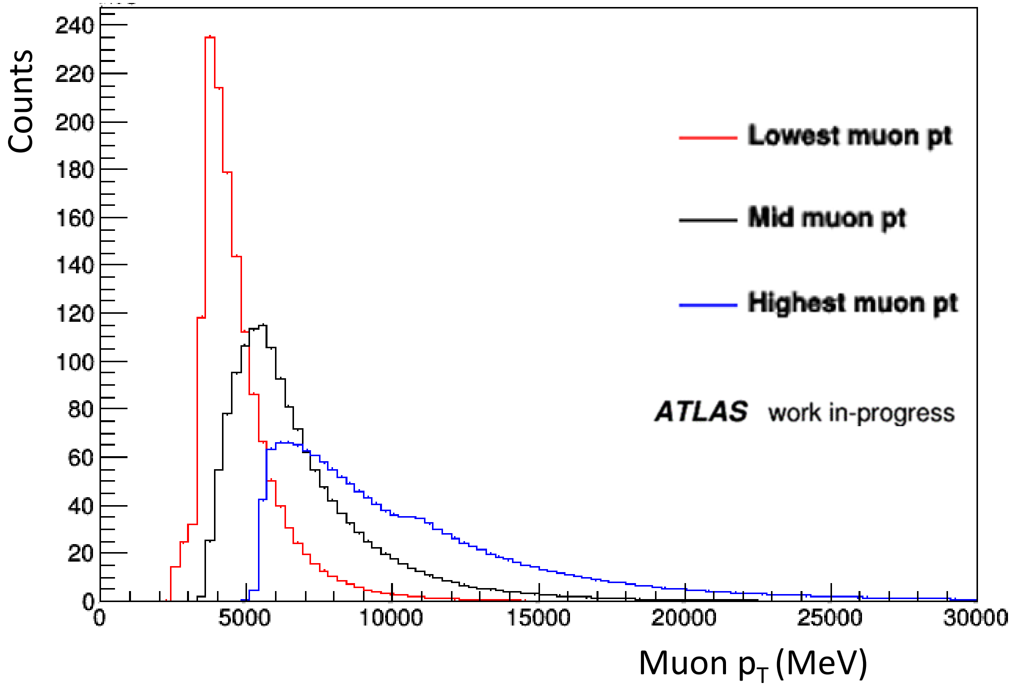


HF Barrel fits shown

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



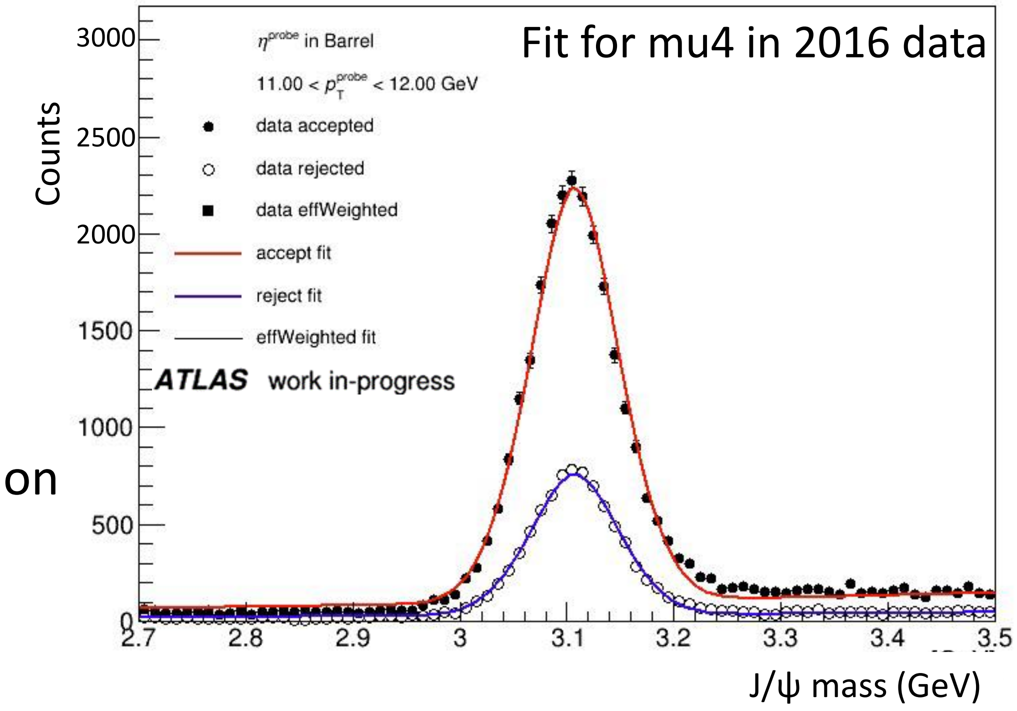


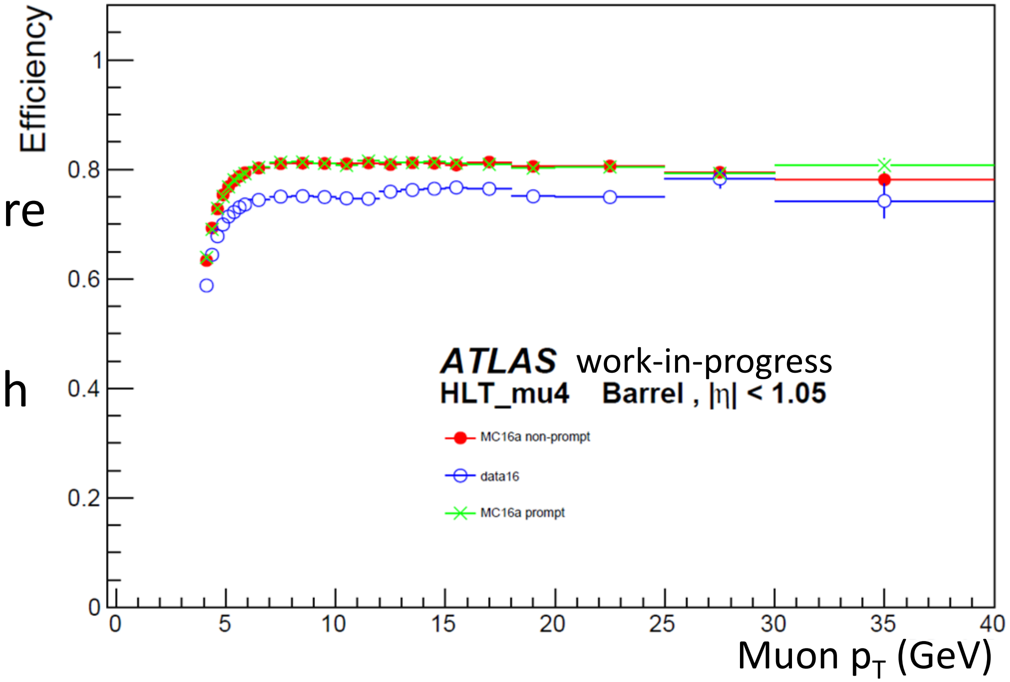
Trigger Scale factor correction

- Complex multi-muon triggers used to collect data, for example:
  - 3 muons each with p_T > 4 GeV (3mu4)
  - Muon with p_T > 11 GeV and another with p_T > 6 GeV, with combined mass of object < 2.9 GeV (mu11_mu6)
- Find the trigger efficiency with a factorised approach
  - Split trigger into individual trigger leg components
    - Leg 1 (mu11): > 11 GeV muon
    - Leg 2 (mu6): > 6 GeV muon
  - Multi-muon efficiency -> product of the single muon efficiencies for each leg and correction factors
- For di-muon case
  - 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 also need a dR correction ($C12(\Delta R)$)
  - Combine to calculate efficiency $\epsilon_{di-muon} = \epsilon 1(p_T) \cdot \epsilon 2(p_T) \cdot C12(\Delta R)$

Trigger Scale factor correction

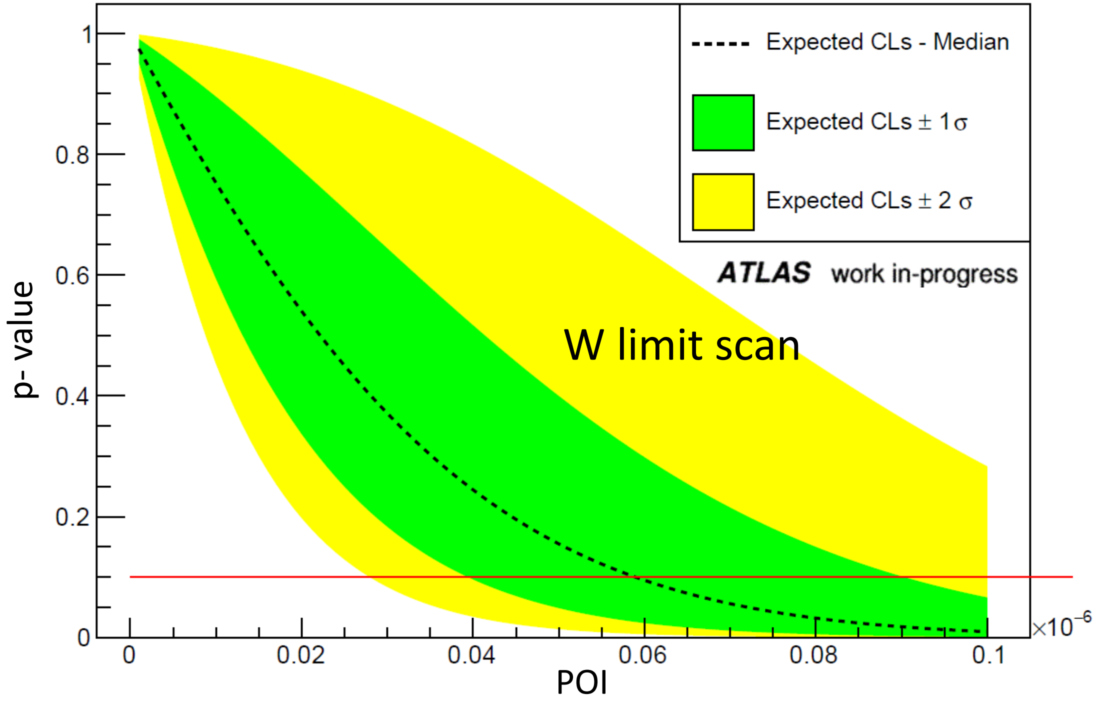
- To find the efficiency for each correction factor use a tag and probe method with muons from $J/\psi \rightarrow \mu^+\mu^-$ signal
- Use a di-muon trigger to find event
  - Treat one muon as a ‘tag’ – check if this passes a single muon trigger
  - If it does check if the other muon passes a single muon trigger – the ‘probe’
  - Efficiency is the number of probes that pass divided by the total number of probes e.g.
    - $\varepsilon = \frac{N(single\ \mu\ trigger - matched\ probe)}{N(probe)}$
  - Find yields (N) via unbinned ML fit to J/ψ mass in case where probe is either triggered or not
  - Ratio of yields gives efficiency vs probe p_T
  - Top plot is for p_T correction with bins of p_T- similar approach for dR
  - Find the p_T efficiency (bottom plot) and dR correction then combine to calculate the total trigger efficiency

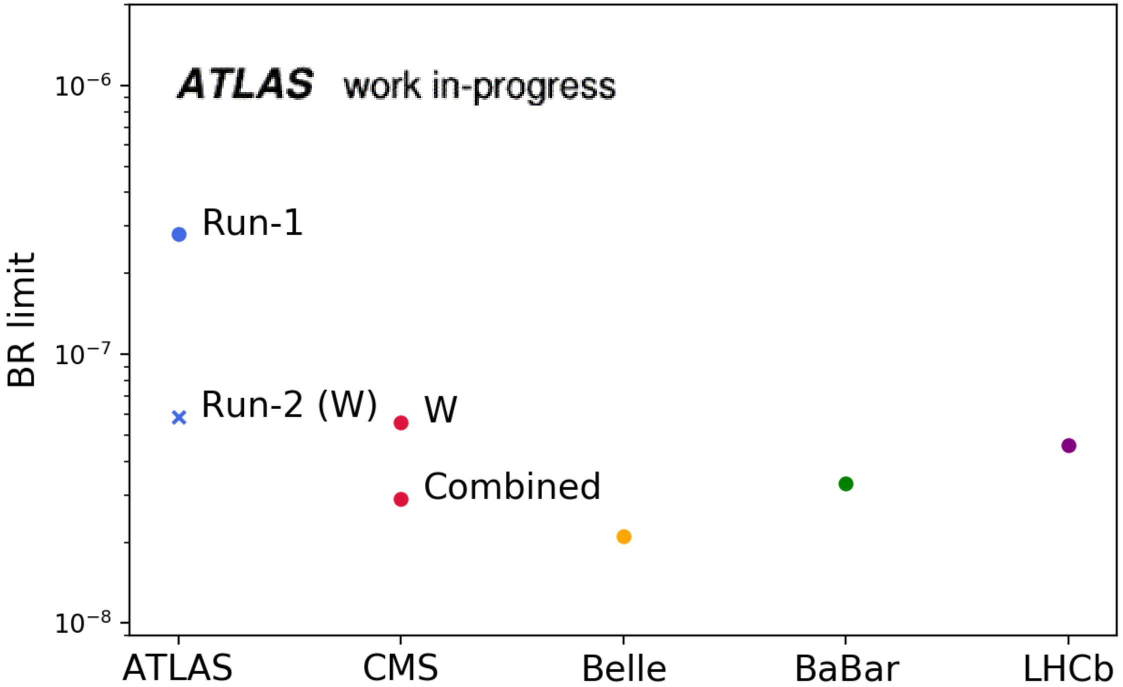




Expected Sensitivity

- Overall normalisation of signal template is treated as parameter of interest in fit
  - POI is interpreted as branching ratio
- Currently statistics only result without trigger scale factors
- W expected limit (stat only): 5.85×10^{-8}
  - CMS (W) 5.6×10^{-8}
- HF expected limit (stat only): 8.99×10^{-8}
  - CMS (HF) 3.6×10^{-8}
- W result comparable to CMS
- Result will be statistics limited

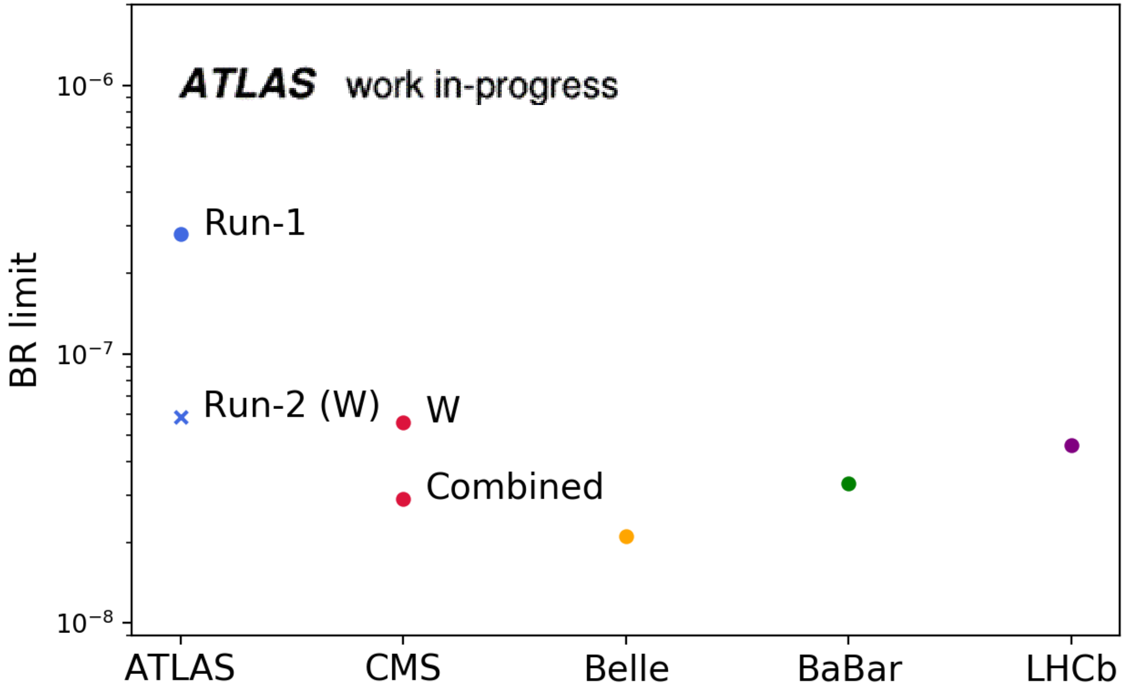




Summary

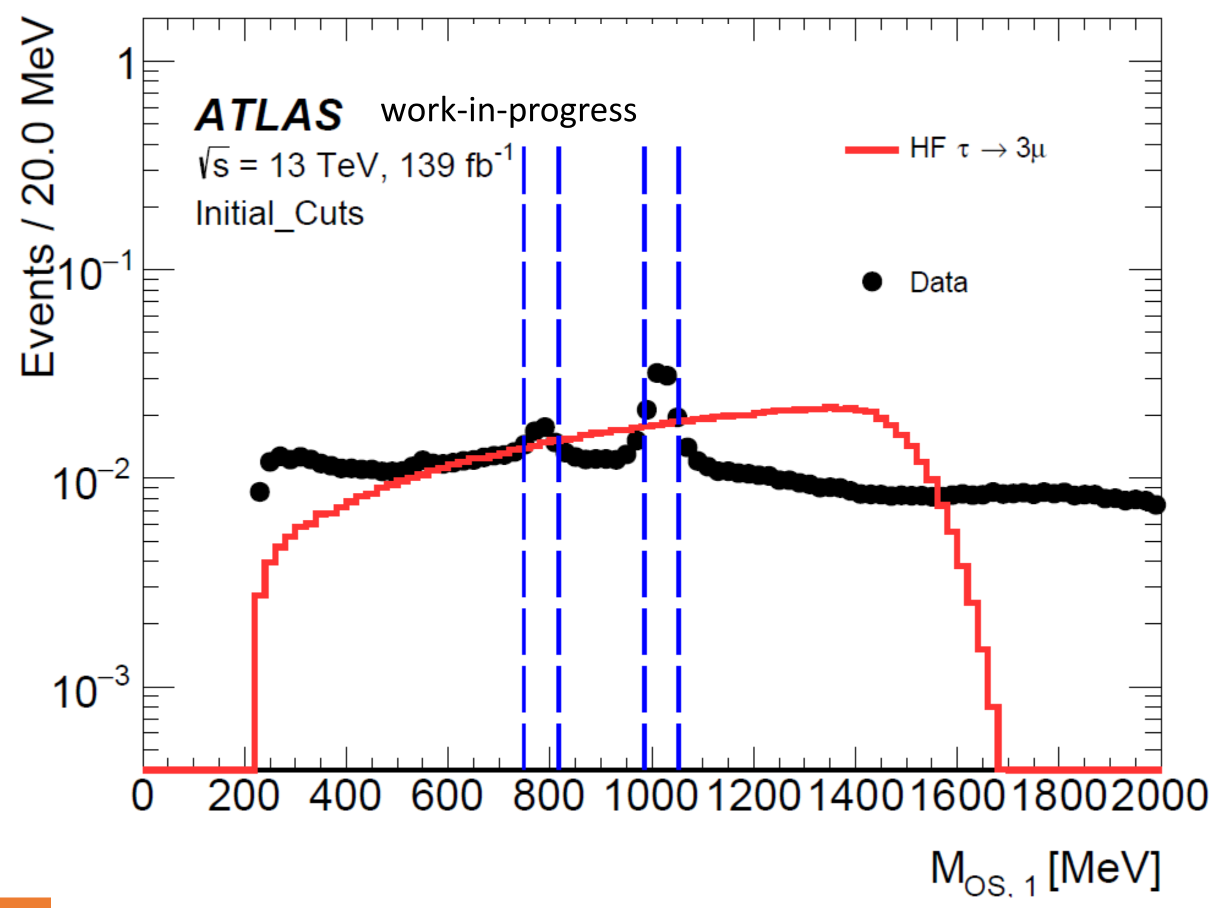
- All main analysis tools in place to find limit
- Obtained an expected limit for both EW and HF channels
- Before systematics expected limits look to be competitive with CMS

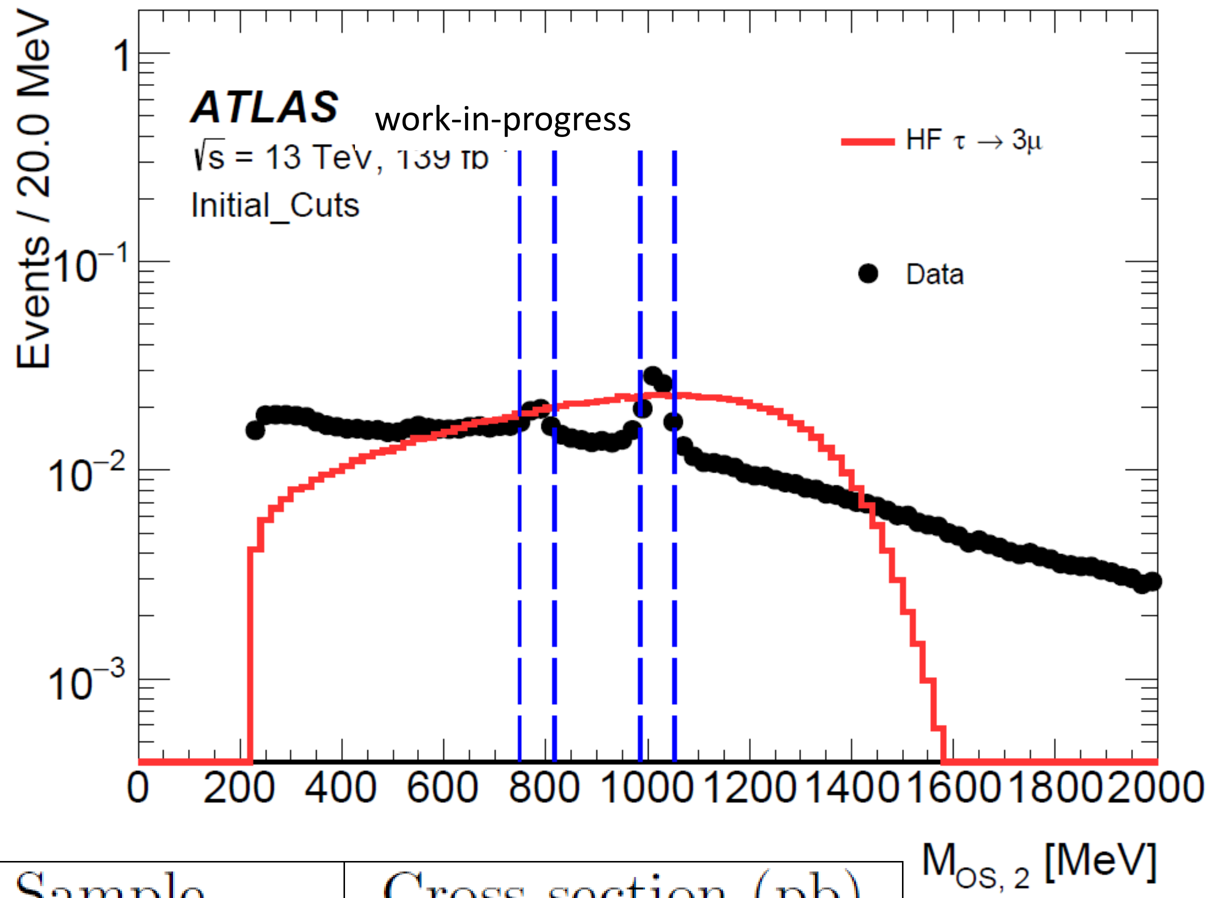
- Still to do:
  - Trigger scale factor calculations (current focus)
  - Systematics
    - Normalisation systematics (pileup weight and reconstruction scale factor) appear small ~3%
    - Others in process of being analysed – e.g. jet and muon related variables
    - Trigger efficiencies will be largest systematic



Backup

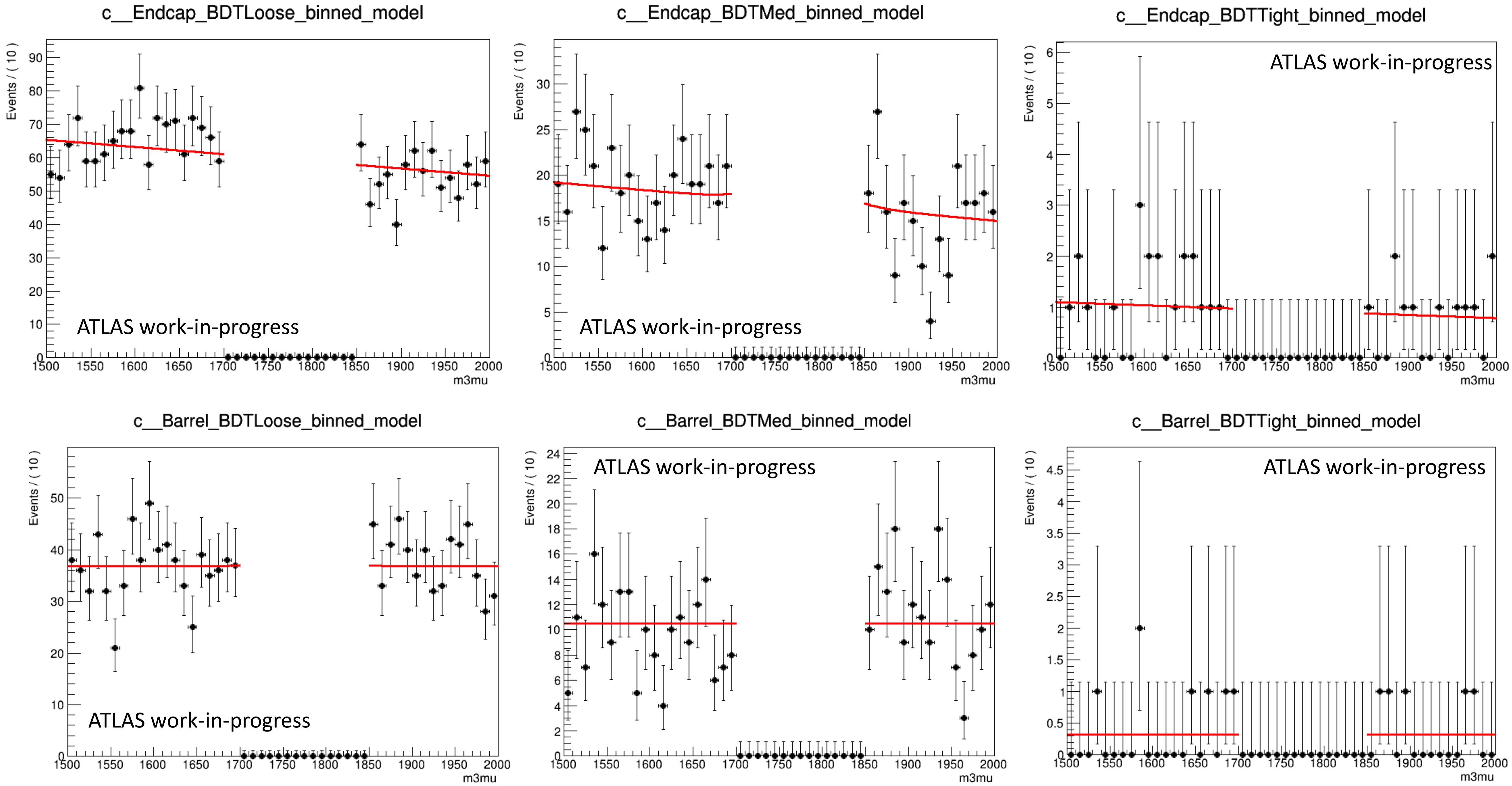
Pre-selection cuts





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

τ→3μ analysis - Background fit



τ→3μ analysis - Signal fit