Beauty 2020
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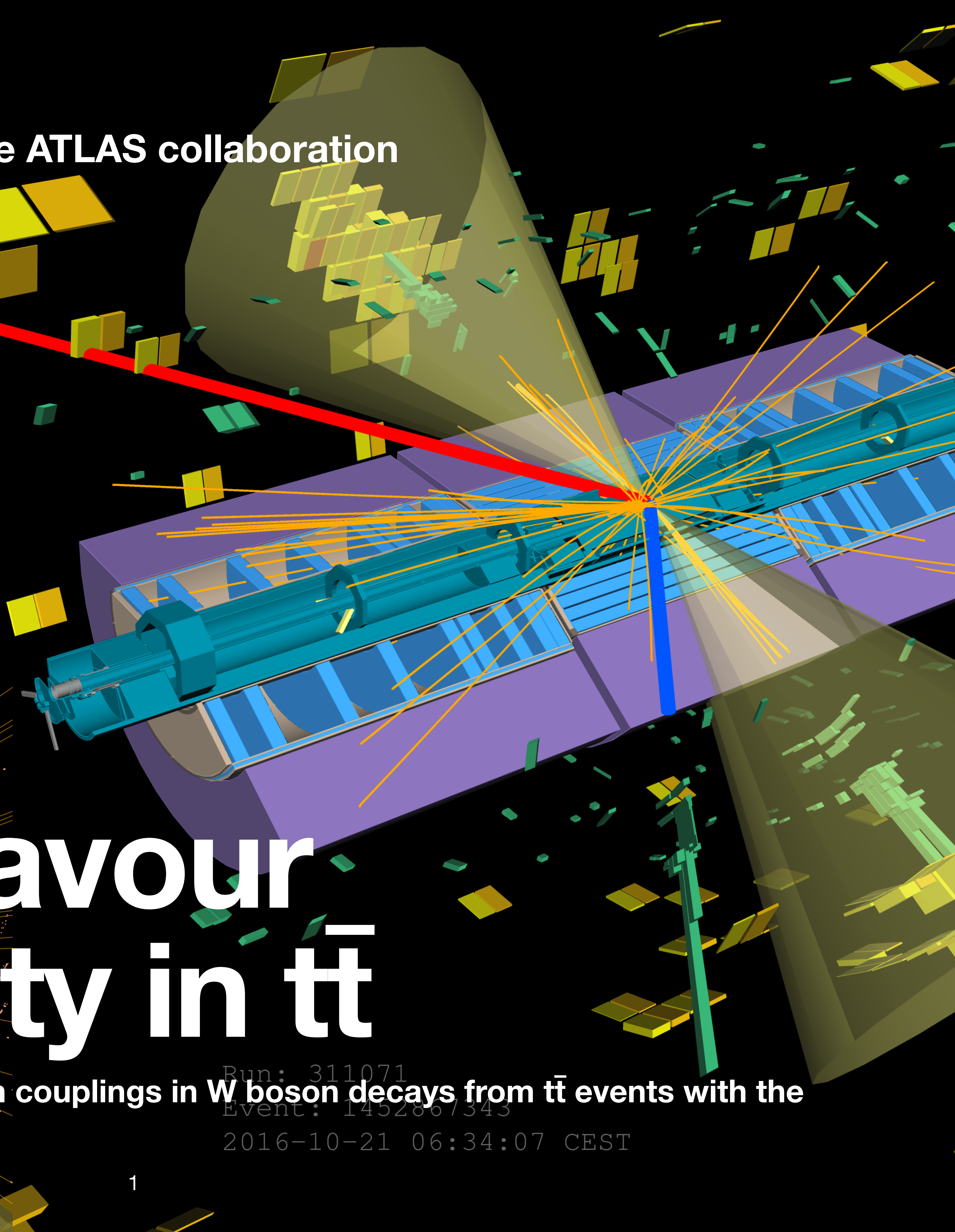
ATLAS EXPERIMENT



Lepton Flavour Universality in $t\bar{t}$

Test of the universality of τ and μ lepton couplings in W boson decays from $t\bar{t}$ events with the ATLAS detector

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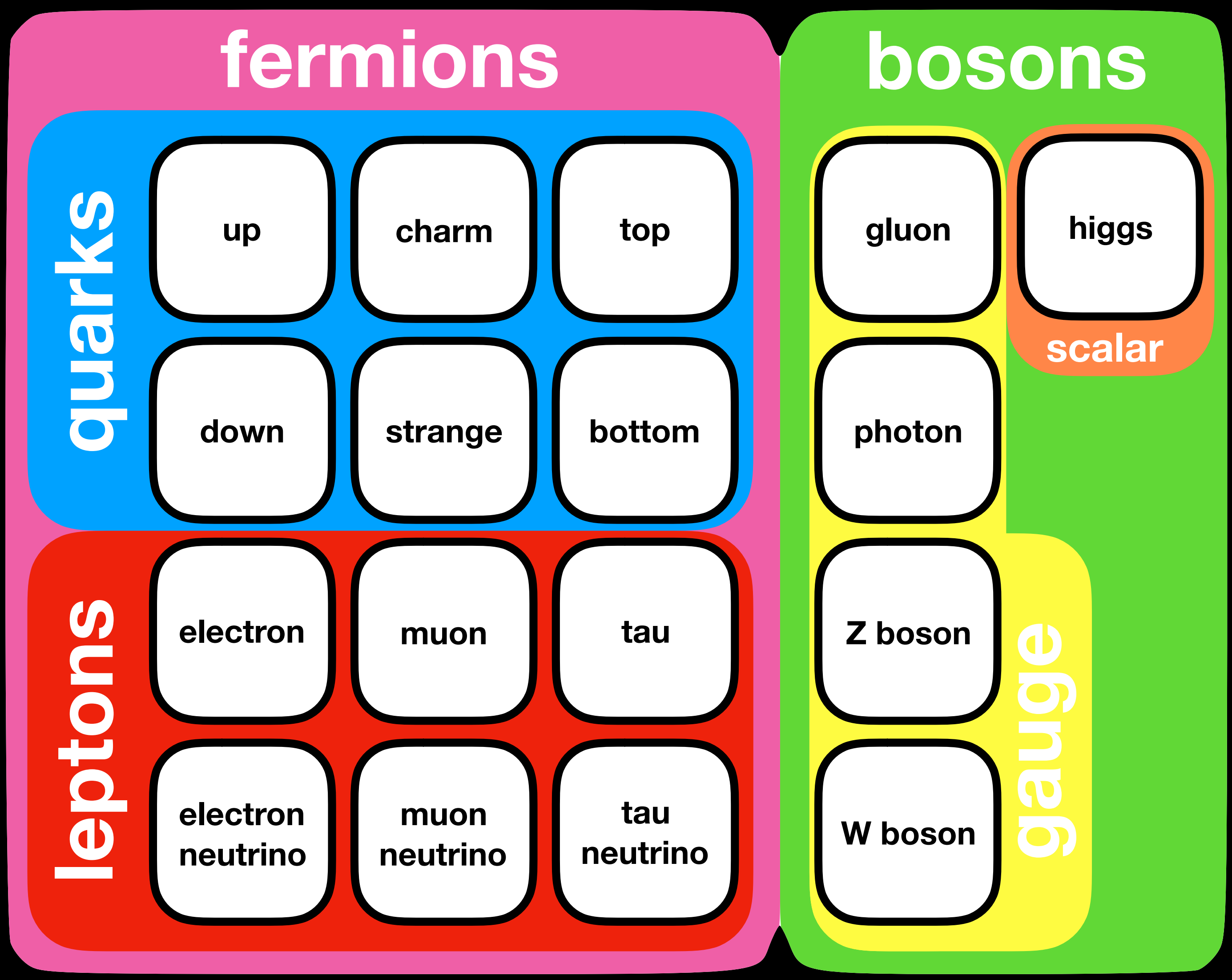
Today's talk

- Introduction
  - Motivation and Background
  - Analysis Strategy
  - Event Selection
- Analysis Procedure
  - MC Calibration
  - Background Normalisation
- The Fit
  - Fit setup
  - Systematics
  - Post fit distributions
- Results
- Summary

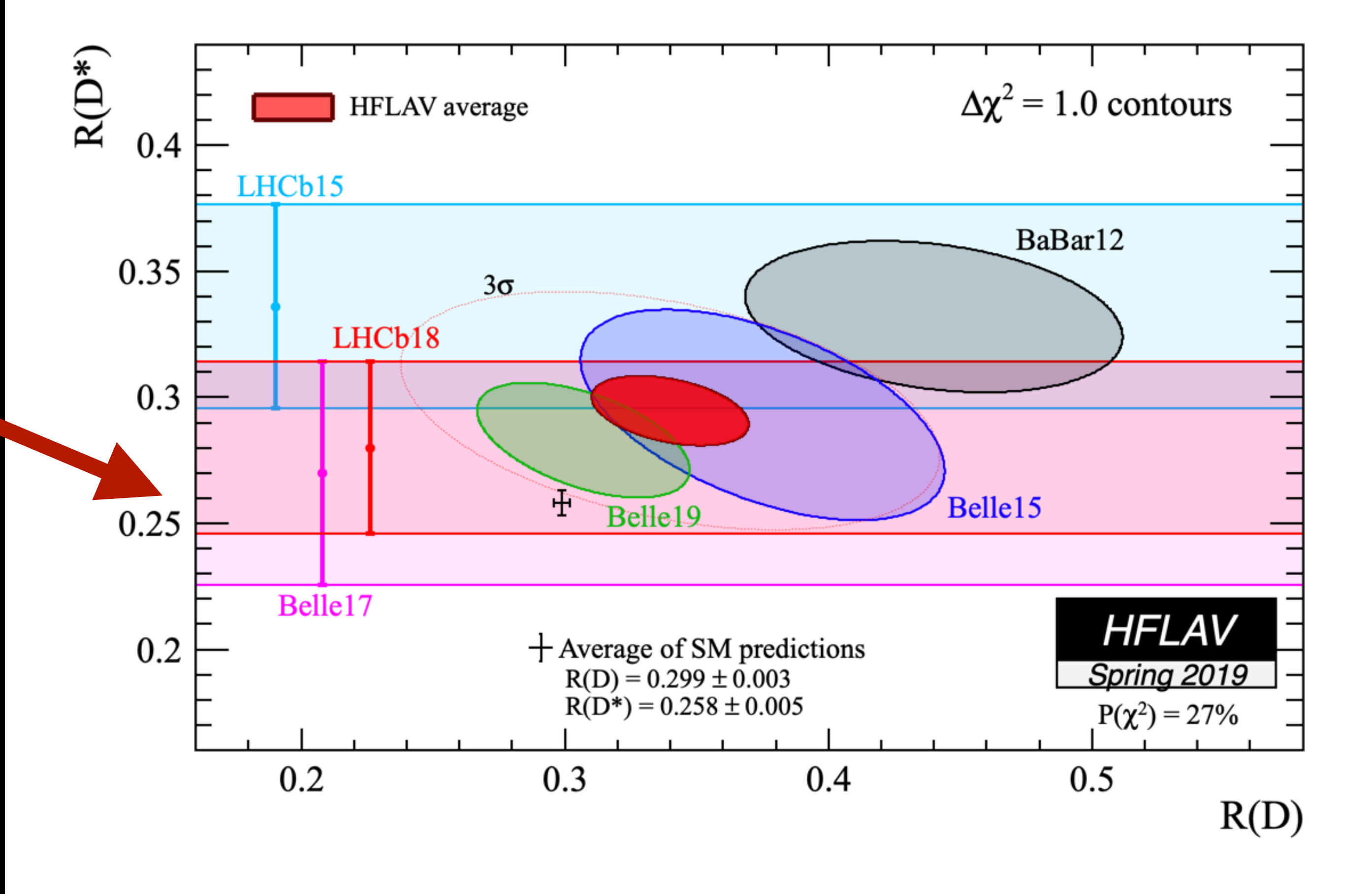
Motivation & Background

- In the Standard Model, Lepton Flavour Universality (LFU) is the assumption that, in the massless limit, there is a universality of the lepton couplings to the vector bosons, i.e. $g_e=g_\mu=g_\tau=g_\ell$
- LFU is tested by comparing the decay rates of (semi-)leptonic processes that differ only by lepton flavour



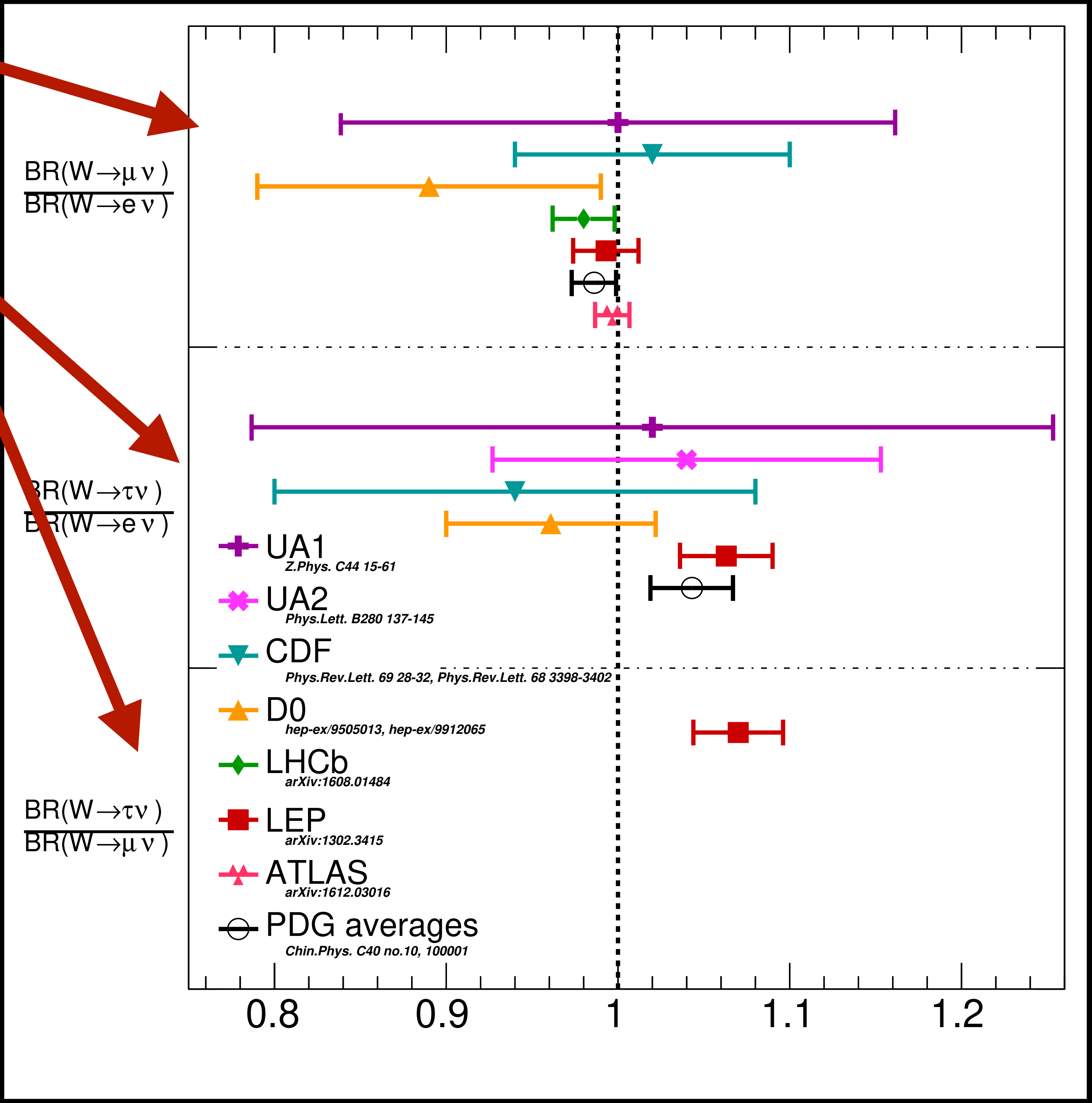
Motivation & Background

- LFU is well constrained in charged current interactions at low momentum transfer by tests in tau decays and light meson decays
- However, some tests in B-meson decays show some tension with the SM
- These tests can be sensitive to many areas of new physics and are complimented by tests using on-shell vector bosons



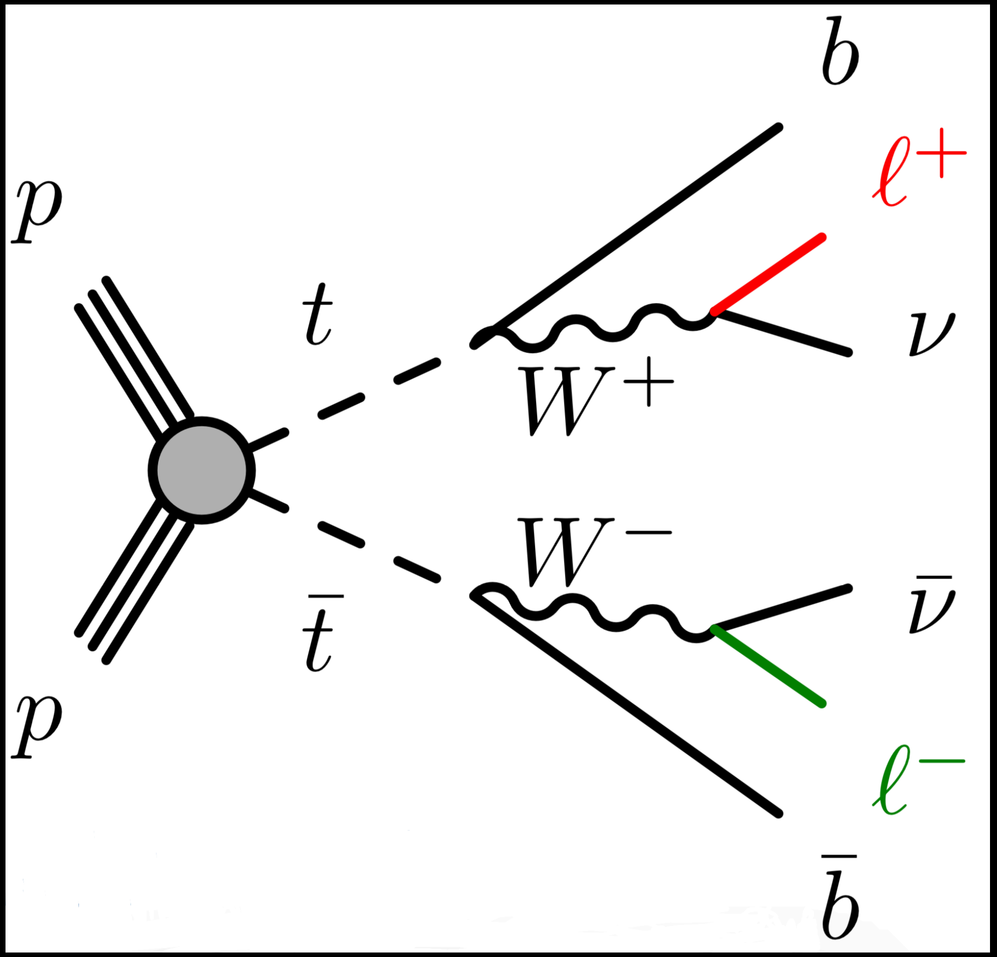
Motivation & Background

- Tests in on-shell W boson decays put tight constraints on LFU between electrons & muons
- The constraints between light leptons and taus are not as clear
  - The combined LEP results are the most precise (~2.5% precision) and 2.6σ high compared to SM
- Can precisely test LFU in **taus** and **muons** in on-shell W bosons using large ATLAS dataset
- If the LEP central value could be replicated, a precision of at least 1-2% would be required to confirm non-universal couplings
  - Such precision not previously thought possible at a hadron collider



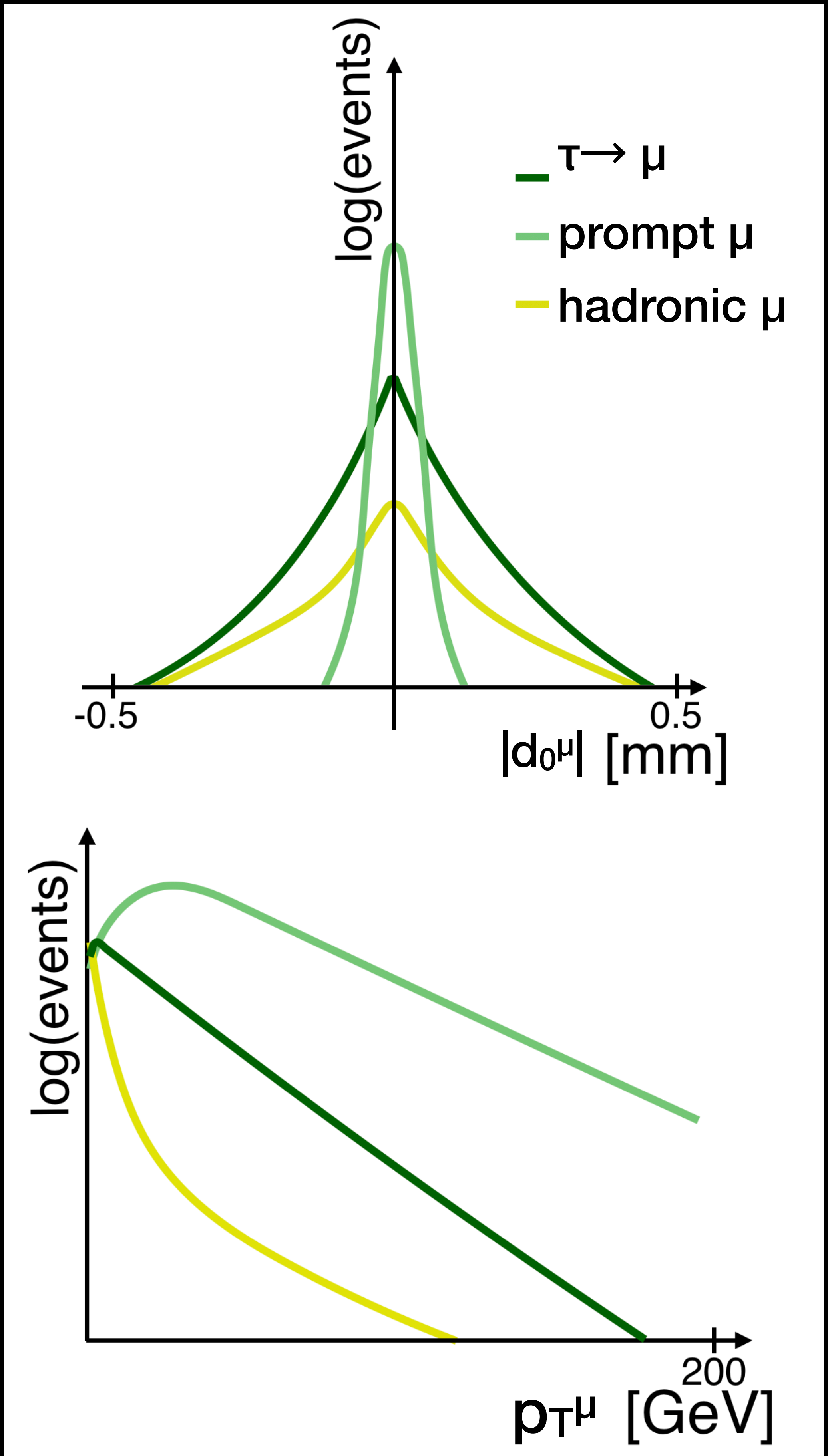
Analysis Strategy

- The LHC is a top quark factory — over 100 million top quark pairs produced in ATLAS in Run-2
- Assuming ~100% decay via charged current means there is a huge on-shell W boson dataset to make use of
- With two W bosons per event, can use a **tag-and-probe** approach to measure **R(τ/μ)**=B(W→τν)/B(W→μν)
    - Use **tag** lepton to trigger the event, **probe** muon to perform measurement
        - The **probe** avoids trigger SF uncertainties and high p_T single lepton trigger requirements
    - This enables us to take advantage of ATLAS's excellent muon reconstruction across wide range of $\mathbf{p_T^\mu}$
        - This analysis goes down to 5 GeV
    - Which in turn allows us to avoid large hadronic tau reconstruction uncertainties by only using leptonic tau decays
        - Lots of correlated uncertainties cancel



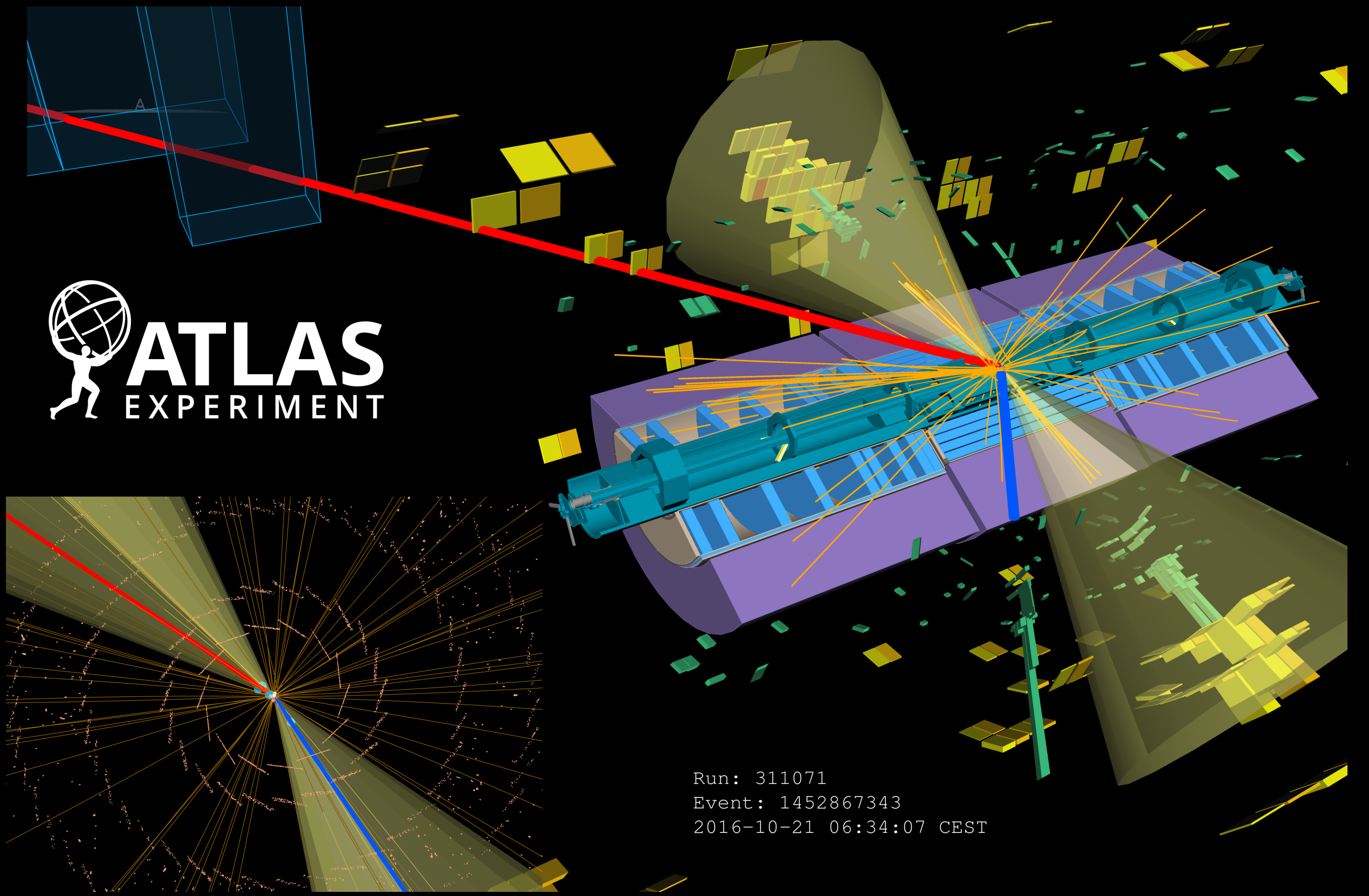
Analysis Strategy

- μ from τ can be distinguished by their larger transverse impact parameter ($|d_0^\mu|$) and different transverse momenta (p_T) spectra (as shown in doodles)⟶
  - $\tau \to \ell\nu$ has been previously very precisely (0.26%) measured, so this should not dominate at our targeted precision
- Perform 2-D fit of the probe lepton in p_T^μ and $|d_0^\mu|$, allow overall rate of top events to float along with $R(\tau/\mu)$. This allows best separation between prompt muons, muons from intermediate tau and muons from hadronic decays



Event selection

- Standard dileptonic $t\bar{t}$ selection:
- ≥2 b-tagged jets, 2 oppositely charged leptons, Z boson veto for dimuon channel
- Tag lepton (e or μ) must pass single lepton trigger requirements
- Probe muon must have $p_T^\mu > 5$ GeV
- Remaining backgrounds are Z(→μμ)+bb and muons from hadronic decays
- This gives two channels: eμ and μμ

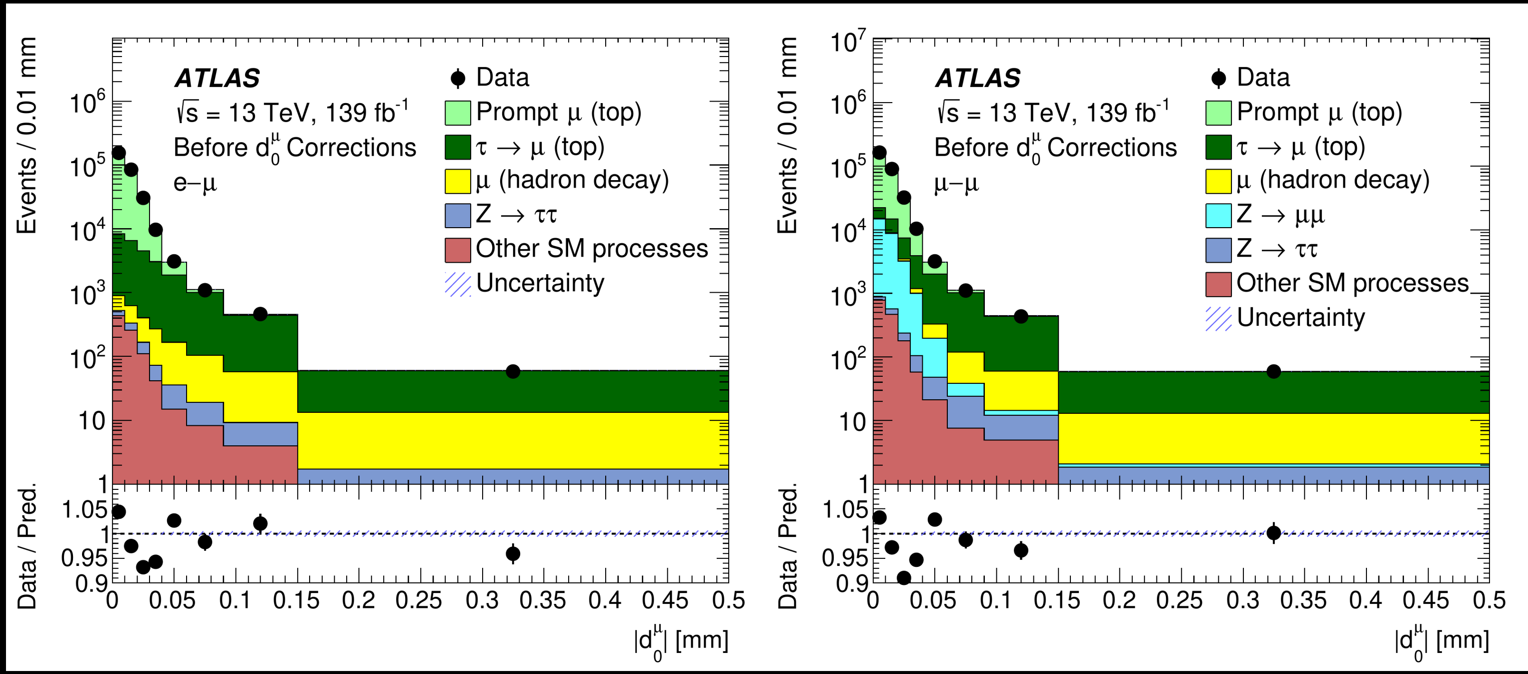


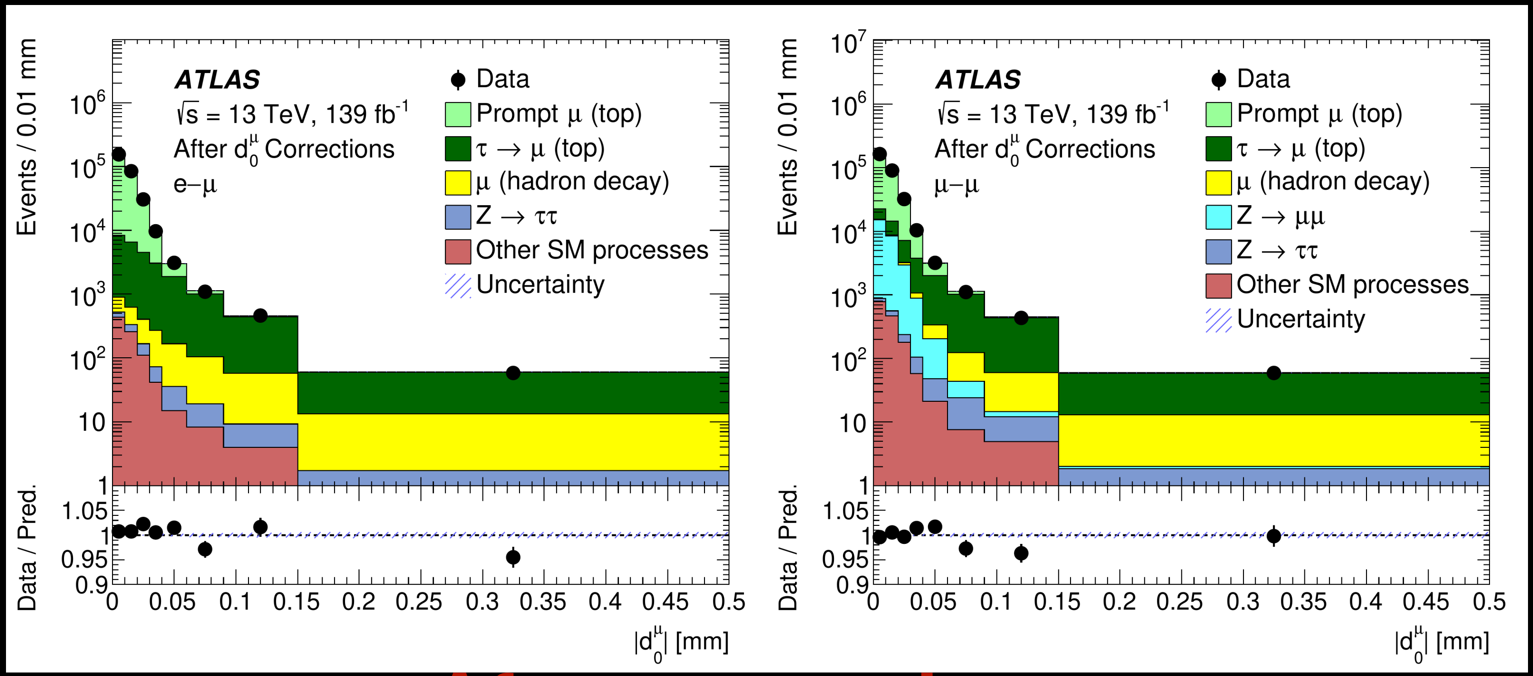
$t\bar{t}$ candidate event reconstructed with one electron, one muon and two b-tag jets, recorded in 2016.

Transverse Impact Parameter ($|d_0^\mu|$)

- Measured as the closest approach of the track to the beamline in the transverse plane
    - Using beamspot decreases dependence on the physical process
- $|d_0^\mu|$ of prompt muons and $|d_0^\mu|$ resolution of non-prompt muons are separately calibrated in 33 kinematic bins of p_T and η using $Z \to \mu\mu$ events in data
- Use shapes as templates in fit to extract $R(\tau/\mu)$
    - See improved data/MC agreement
- Systematic uncertainty due to application of shape from $Z \to \mu\mu$ to $t\bar{t}$ signal region

Before corrections



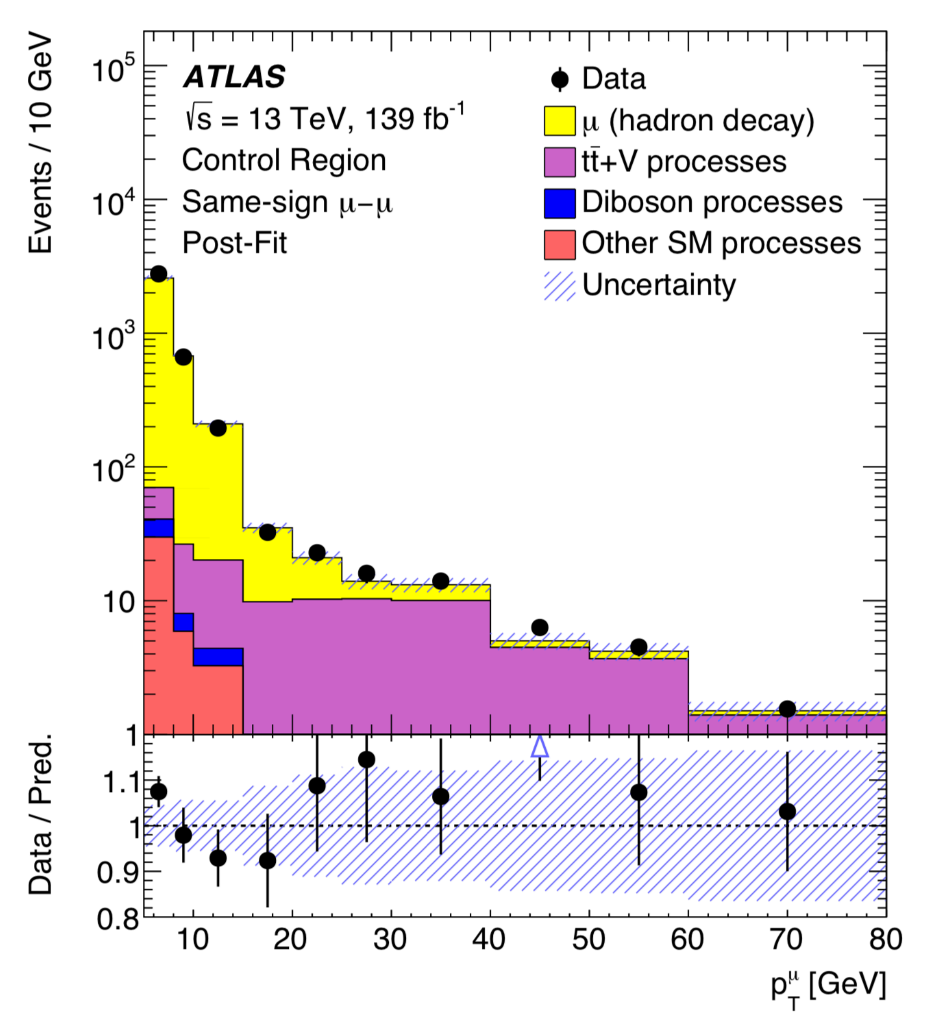


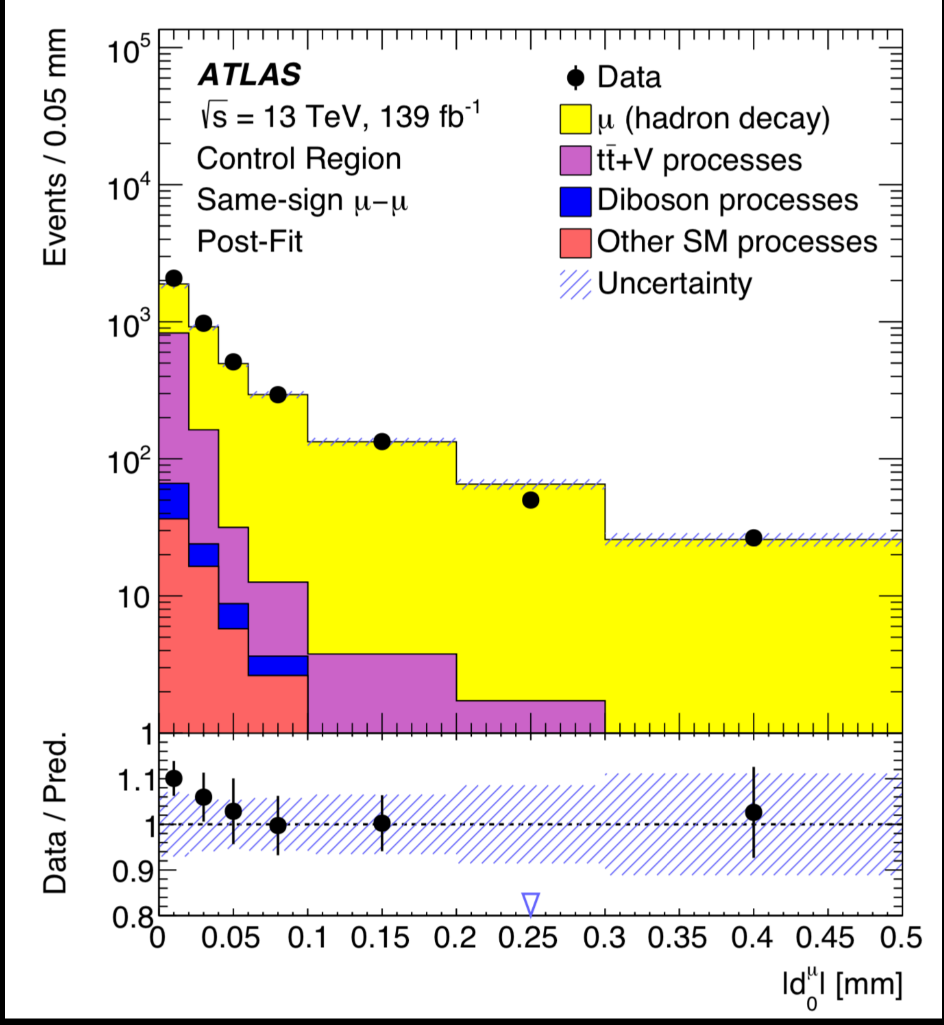
After corrections

Backgrounds

Muons from hadron decays (μ(hadron decay))

- The most significant background at large $|d_0^\mu|$ is muons originating in b- and c- decays
- Estimate the normalisation using a same-sign (SS) control region
    - Correct prompt contributions using high p_T^μ region
    - Obtain normalisation scale factor by taking the SS rate in data (subtracting corrected prompt)
    - Divide by SS rate in MC
- Simulation is used to extrapolate from SS to OS, and for the $|d_0^\mu|$ distribution shape
- Data and simulation agree within uncertainties in control region — gives confidence that $|d_0^\mu|$ and p_T^μ of μ(hadron decay) are well modelled
- Main uncertainties from limited statistics in SS control region and from MC modelling, with small uncertainty due to the correction to prompt contributions

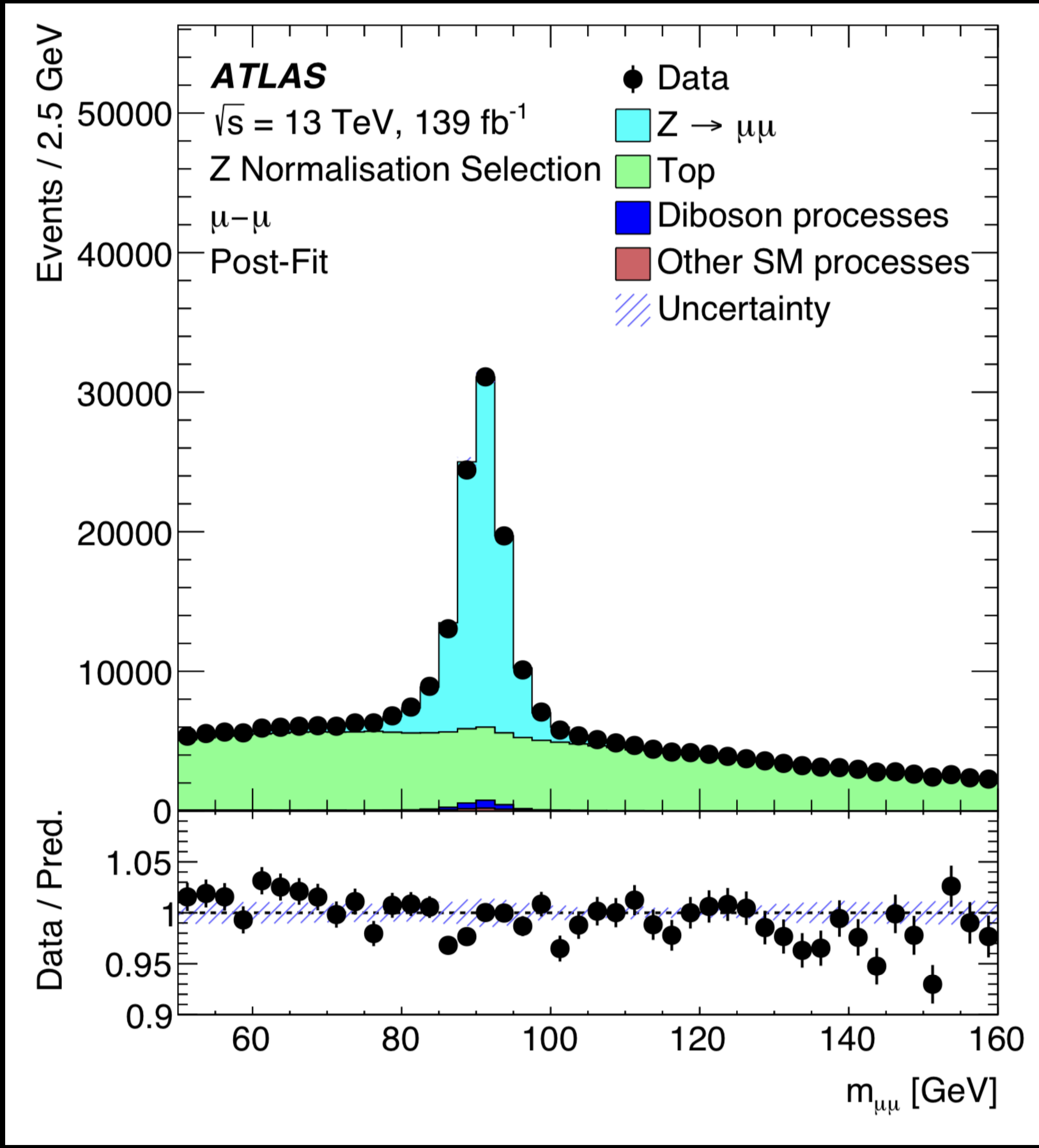




Backgrounds

Z(→μμ)+bb

- The μμ channel also sees significant background contribution at low $|d_0^\mu|$ from Z(→μμ)+bb
- Normalisation obtained from data
    - Use nominal selection without a Z-veto
- Fit dimuon invariant mass between 50 - 140 GeV
    - Use Voigt profile (Breit Wigner ⊕Gaussian) for Z→μμ resonance
    - 3rd-order Chebychev polynomial for everything else
    - Tested other functions to provide a systematic uncertainty



Uncertainties

Reconstruction

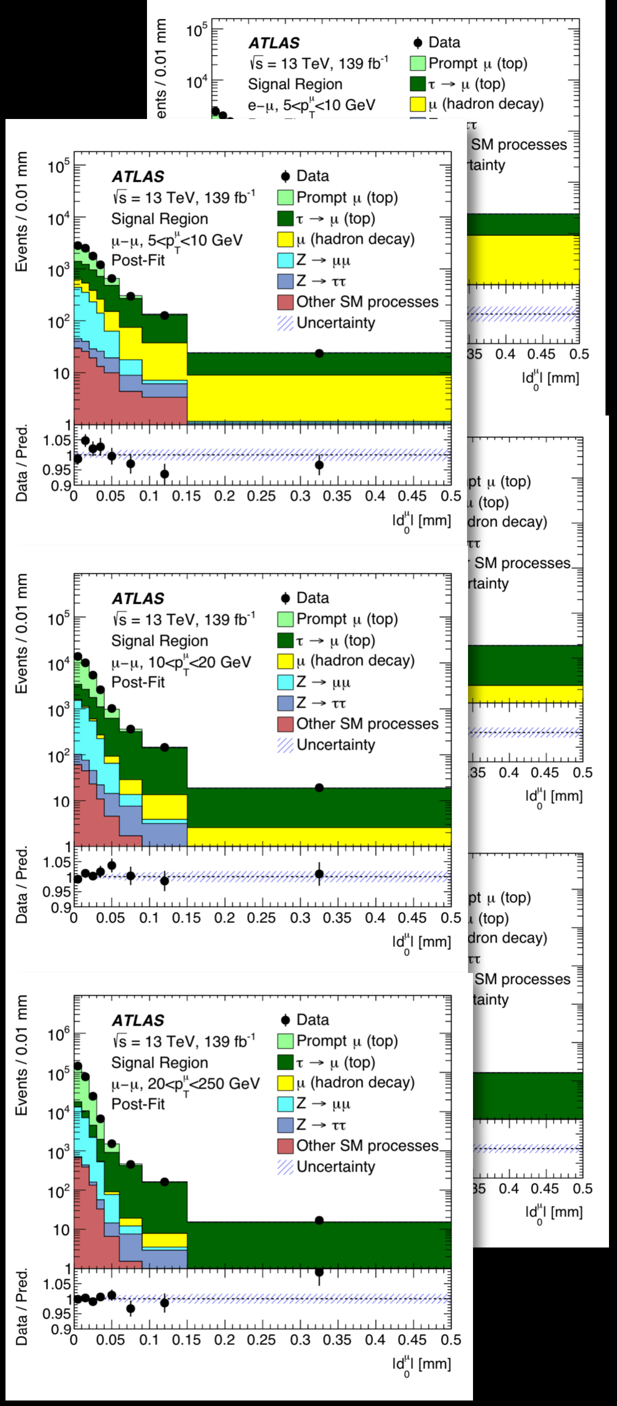
- The measurement relies on precise muon reconstruction
  - Uncertainties on muon efficiency corrections are most important
  - p_T dependent scale factors correct MC to data
    - They affect prompt μ and τ→μ differently which affects R(τ/μ)
    - Muon isolation (~9% of total) and low p_T muon identification scale factors (~7.5% of total) are most important of these
- Pile up modelling is also important (~2% of total)
  - Simulated events are reweighted to different ⟨μ⟩ to provide an uncertainty
  - Impact on R(τ/μ) is mostly due to residual effect on p_T^μ modelling
- Detector & reco uncertainties make up ~40% of total systematic uncertainty

Uncertainties

Modelling

- Monte Carlo generator uncertainties are important for p_T^μ and $|d_0^\mu|$ modelling
  - To improve the modelling of p_T, the simulated $t\bar{t}$ events are reweighted to NNLO in QCD and EW in $p_T(t)$
- Different generator components are varied:
  - Amount of initial state radiation (ISR) and final state radiation (FSR)
    - A14 eigen-tune variations of the strong coupling α_s
  - Factorisation and renormalisation scales
  - Powheg h_{damp} parameter
  - NNLO $p_T(t)$ reweighting
  - Parton shower and hadronisation
    - For prompt μ and $\tau \to \mu$ uncertainty separated into 4 components
      - Low p_T^μ, middle p_T^μ, high p_T^μ (norm), high p_T^μ shape
  - Theory makes up ~30% of systematic uncertainty, which is dominated by PS variations

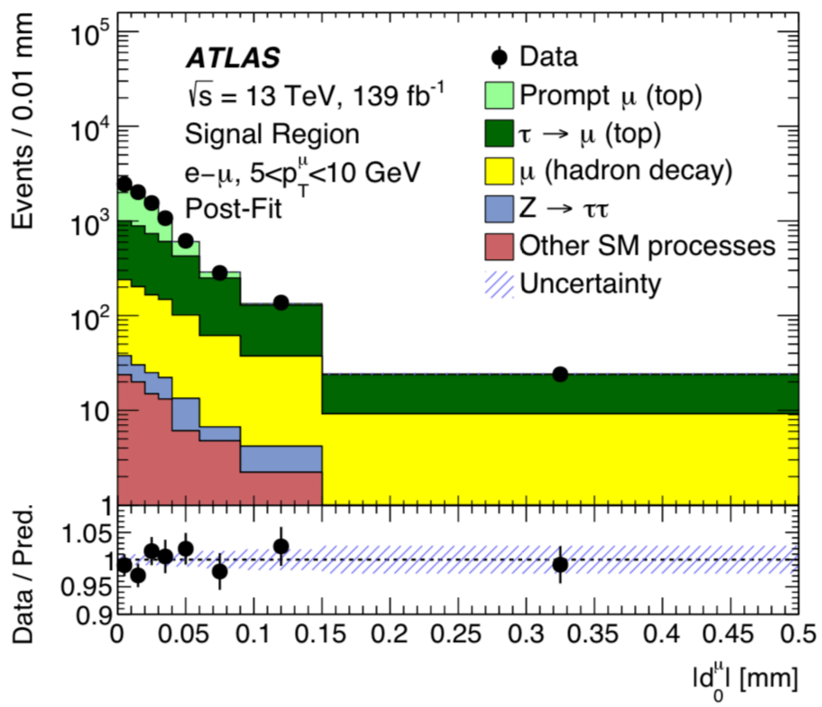
Fit model

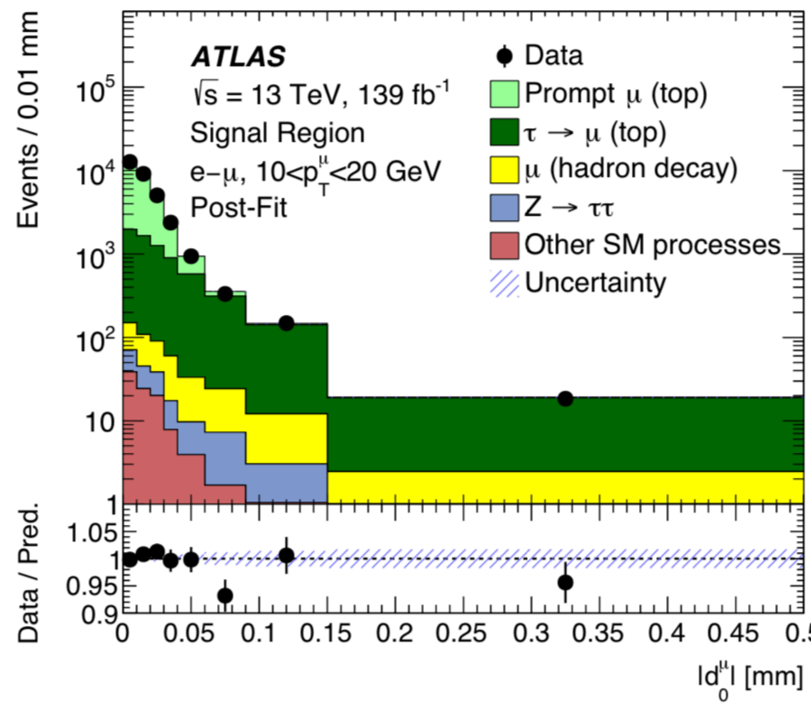


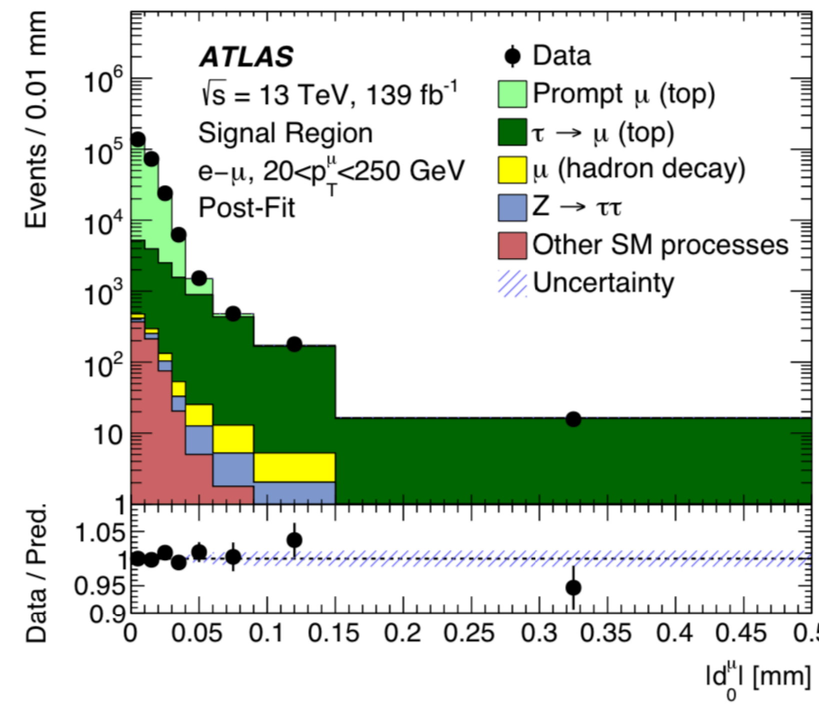
- $R(\tau/\mu)$ is extracted from profile likelihood fit performed in 2-D with
  - Three bins in p_T^μ = [5,10,20,250] GeV,
    - (best separation between τ→μ, prompt μ and μ(hadron decay))
  - Eight bins in $|d_0^\mu|$ = [0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5] mm,
    - (Optimised to maximise sensitivity without making it hard to get good convergence)
  - In two channels eμ and μμ
  - 48 bins total
- Two free floating parameters: $R(\tau/\mu)$ and $k(t\bar{t})$
  - $k(t\bar{t})$ is a constant scaling factor applied to prompt μ, τ→μ, $t\bar{t}$ and Wt components
  - $R(\tau/\mu)$ affects only the τ-muon components
- Many uncertainties are correlated between prompt muons and leptonic tau decays
  - They mostly cancel for the probe muons used to measure **R(τ/μ)**=B(W→τν)/B(W→μν)

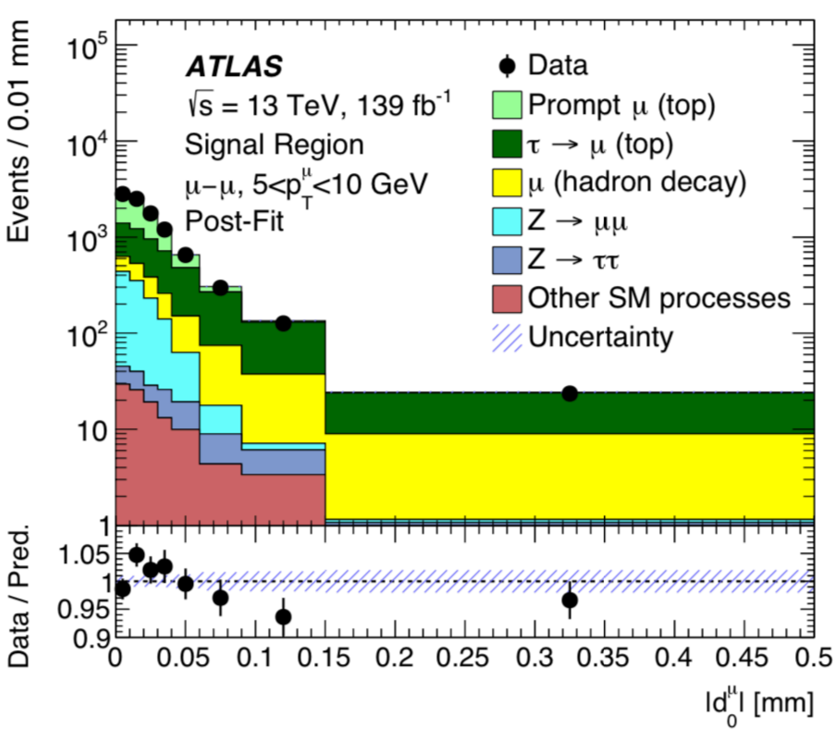
Results

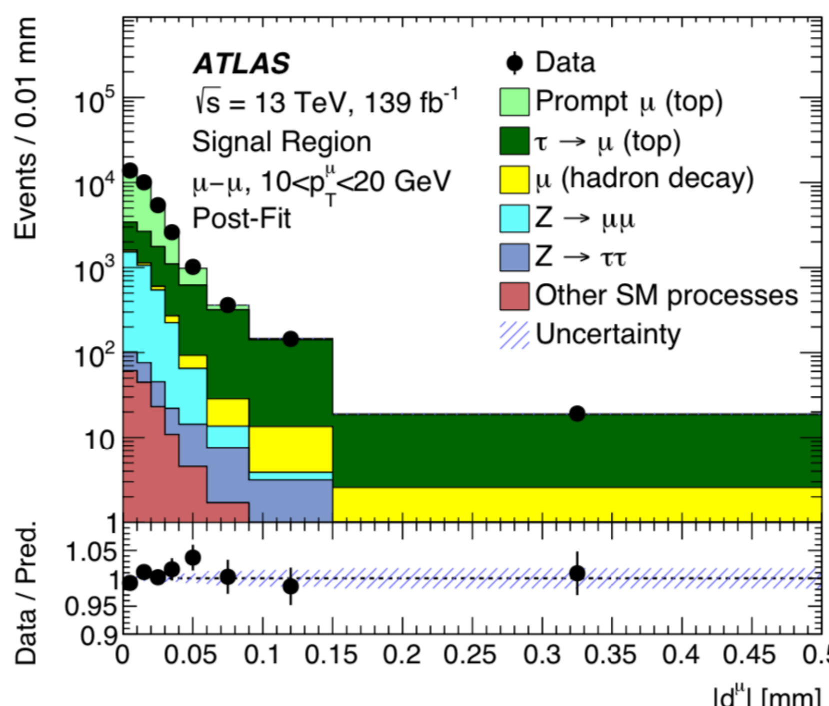
Post-fit data/MC agreement

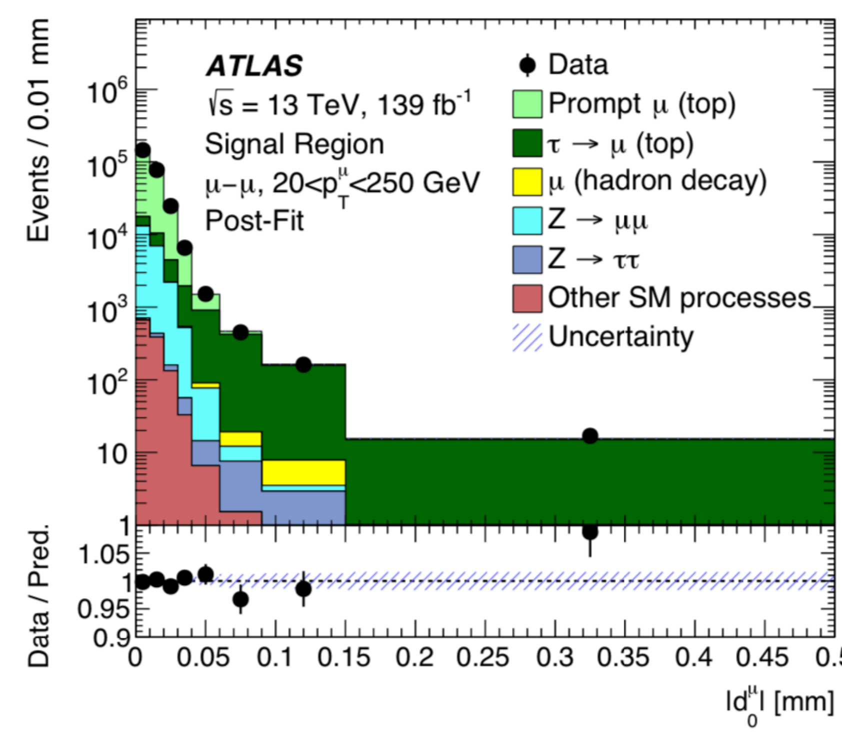








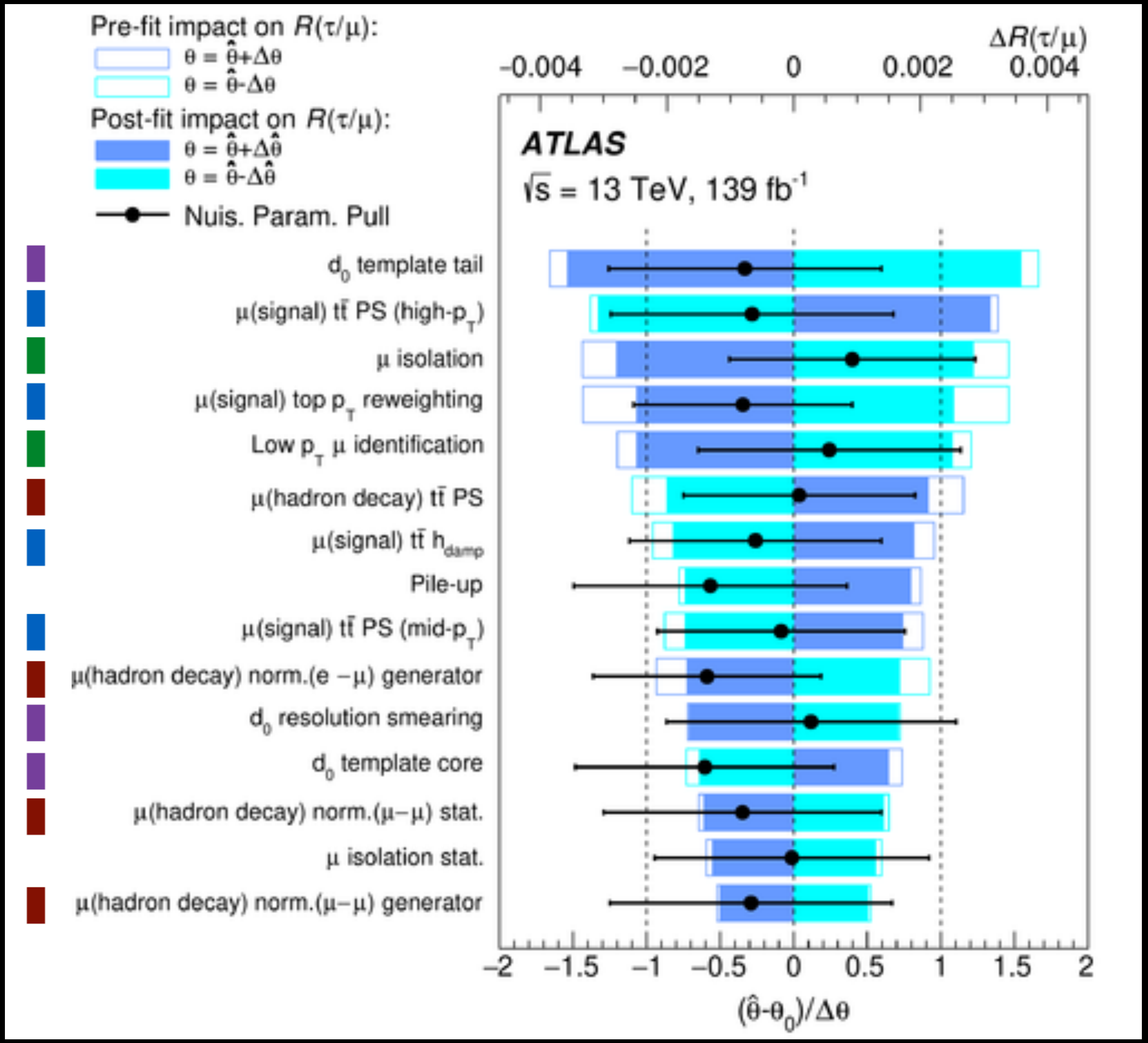


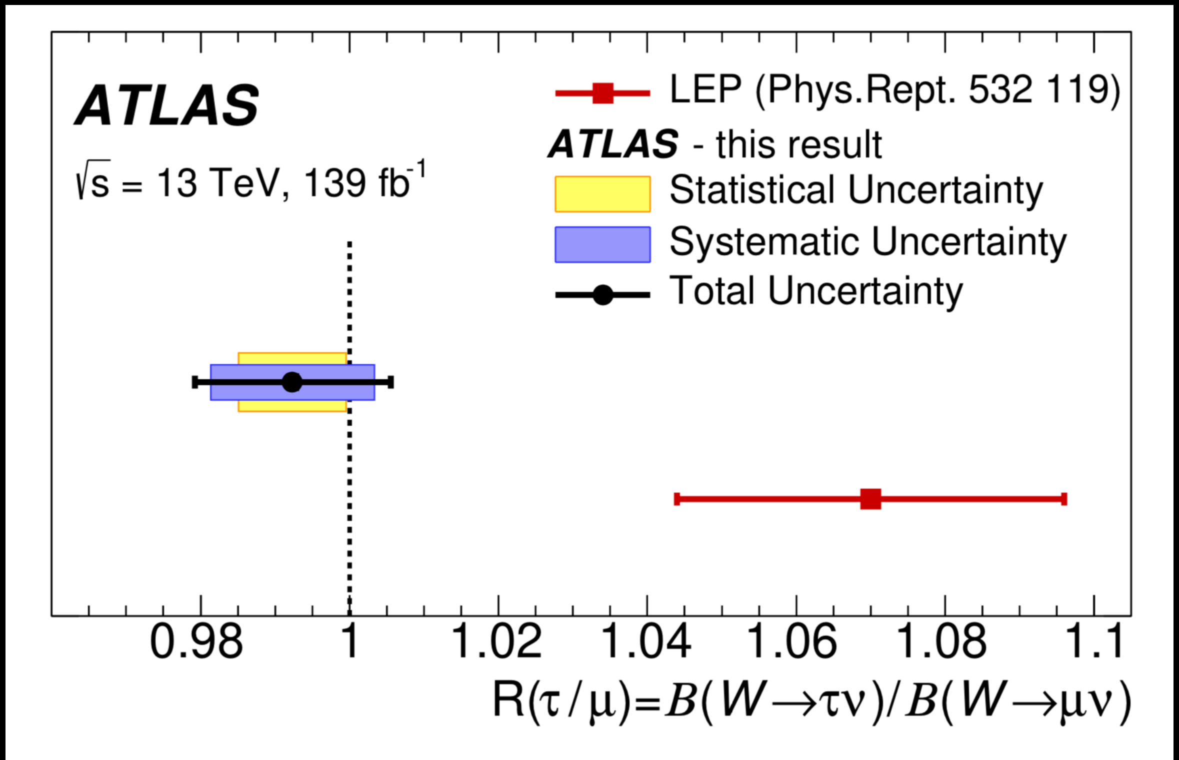


Results

Impact of Uncertainties

- Total uncertainty dominated by systematics with non-negligible statistical component
  - Uncertainty on B(τ→μνν) is ~negligible
- Dominant uncertainties come from
  - Modelling of $|d_0^\mu|$ distributions from data
  - $t\bar{t}$ Modelling of signal
  - $t\bar{t}$ modelling of μ(had)
  - Muon reconstruction efficiencies





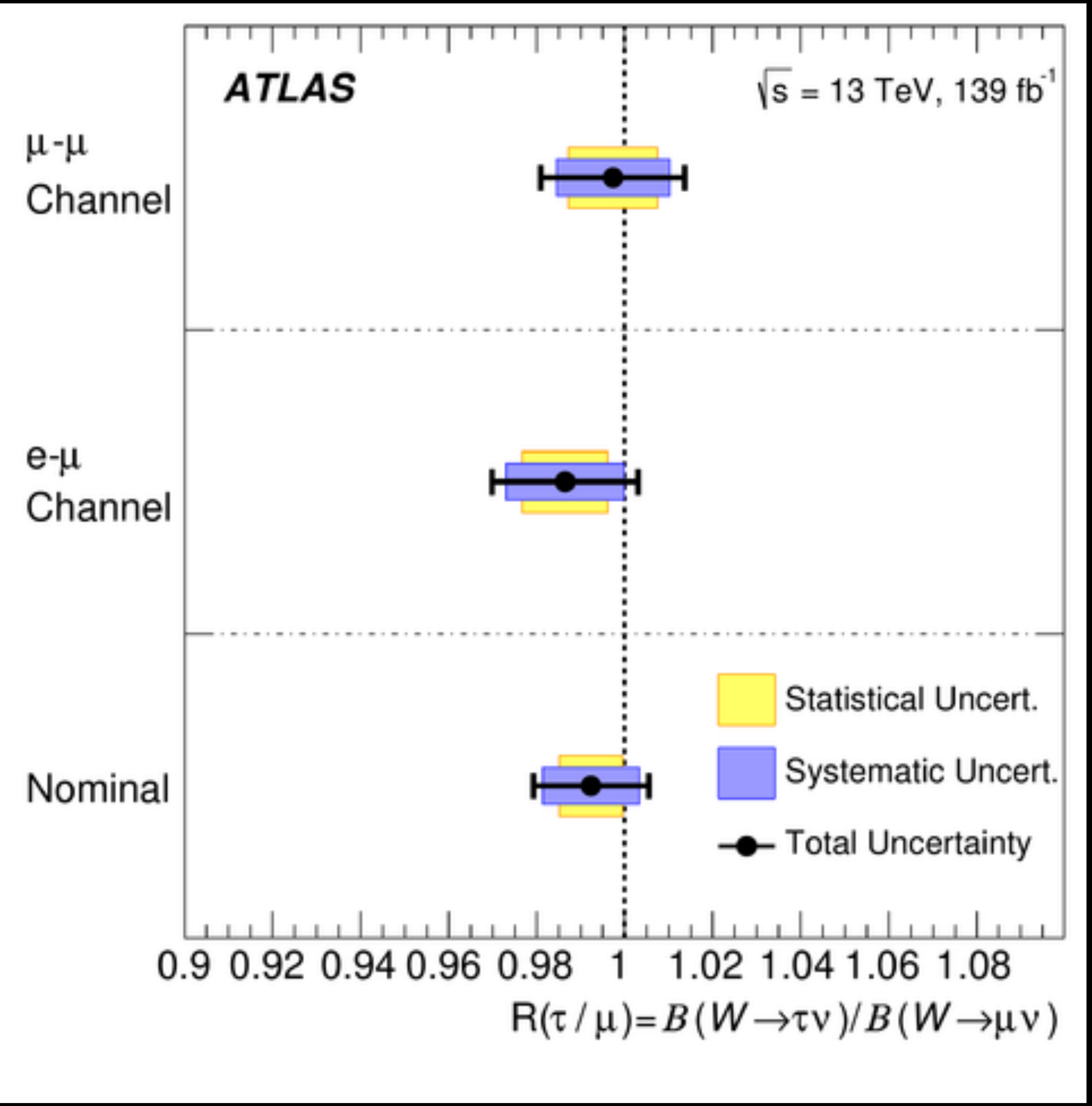
$R(\tau/\mu)=0.992 \pm 0.013$
[± 0.007 (stat) ± 0.011 (syst)]

Measured Value

Shows very good agreement with Standard Model
Most precise measurement of this ratio to date
Almost twice the precision of the combination of LEP results
Submitted to Nature Physics (arXiv:2007.14040)

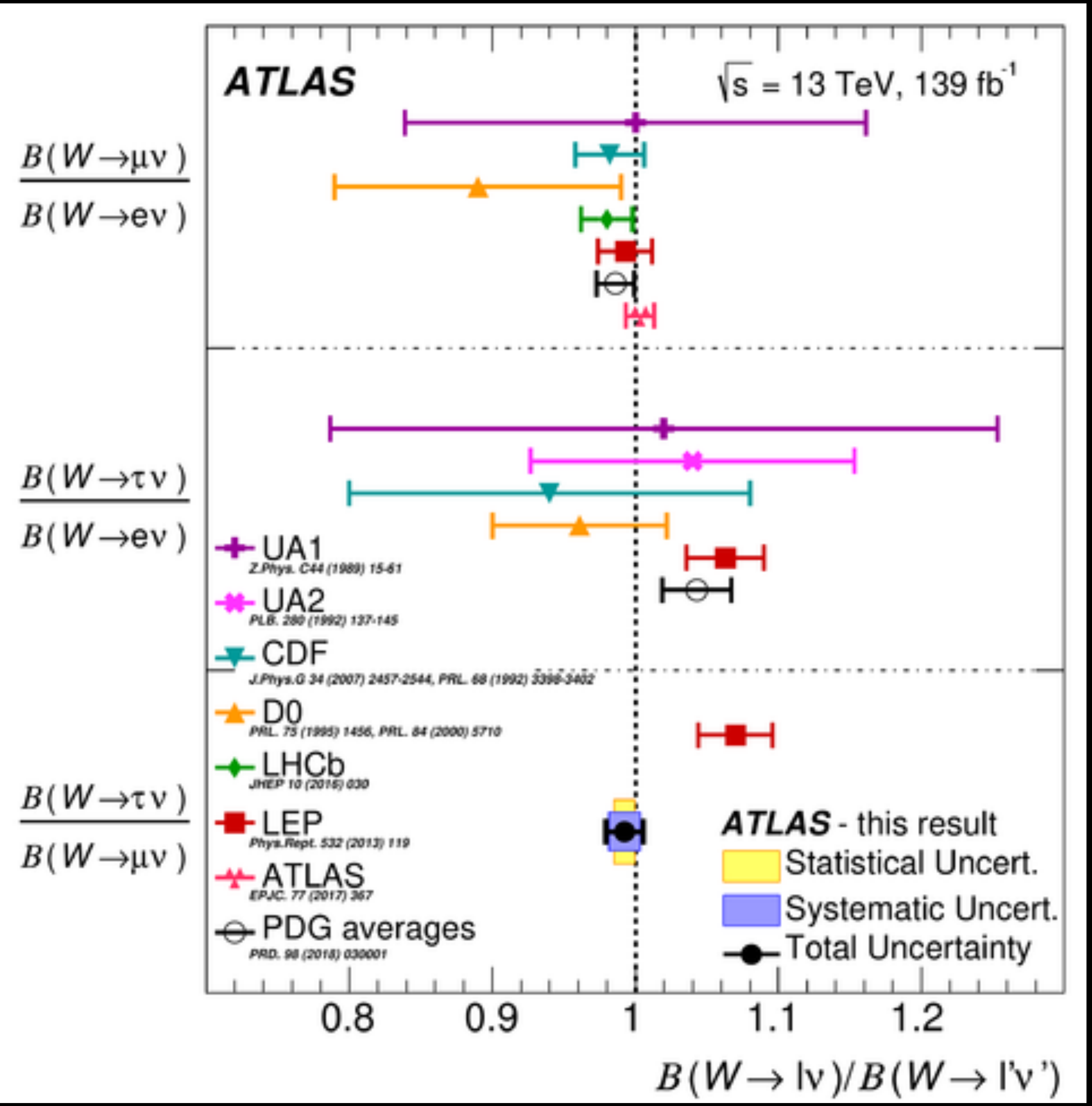
Consistency checks

- Consistency checks performed in separate subsets of the data:
    - Each of 2015-16, 2017, 2018
    - eμ and μμ channels
    - Individual p_T bins
    - Separately for probe muon charge
- This gives confidence that the result is robust



Summary

- A new technique making use of ATLAS's huge Run-2 dataset and excellent muon reconstruction shines new light on an old LEP discrepancy
    - Another example of the impressive high precision measurements possible in the LHC
- A(nother) beautiful confirmation of the Standard Model!



Backup

Sources of uncertainties

Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**