Measurements of the W branching fractions in $t\bar{t}$ production with the ATLAS experiment at the LHC

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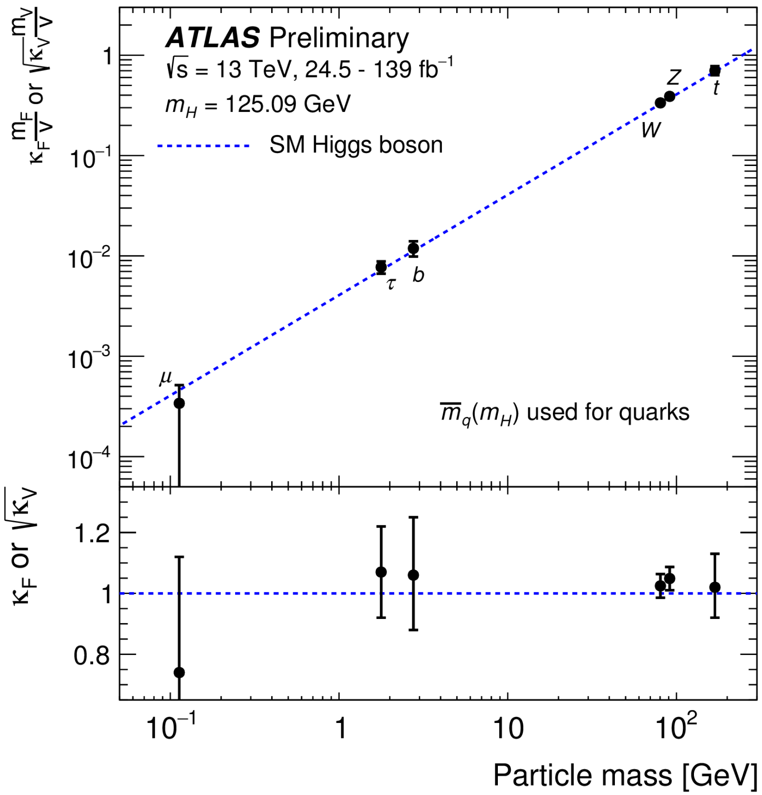
Lepton Flavour Universality

- In the Standard Model (SM) the coupling of all charged leptons (electron, muon, tauon) with *W* boson is the same
- This assumption is known as Lepton Flavour Universality (LFU)
- The only difference between the leptons is due to their mass
  - the coupling of leptons to the Higgs boson is different



LFU tests at low energy

- At low energy, the decays of tauon provide a stringent test of LFU
- It is expressed as the ratio of coupling constants (g_{l1}/g_{l2}) of leptons *l1* and *l2* to *W* boson
  - $g_\mu/g_e = 1.0018 \pm 0.0014$ (from the ratio $\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$)
  - $g_\tau/g_e = 1.0011 \pm 0.0015$ (from the ratio $\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$)
  - $g_\tau/g_\mu = 1.0018 \pm 0.0014$ (from the ratio $\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$)

LFU Tests with *W* decays

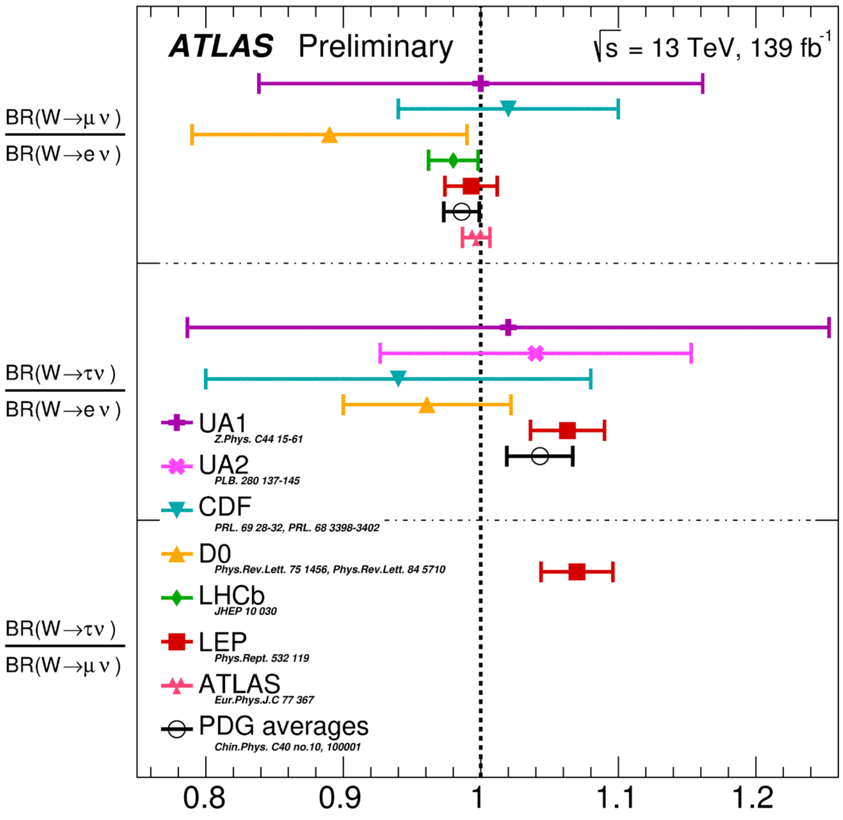
- LFU is also tested in the decays $W \to l\bar{\nu}$
  - The measurements are performed at LEP and at LHC (for g_μ/g_e)
- The uncertainty of the measurements is large, especially for the coupling of τ

$$\frac{g_\mu^2}{g_e^2} = \frac{\Gamma(W\to\mu\bar{\nu})}{\Gamma(W\to e\bar{\nu})} = 0.996 \pm 0.008$$

$$\frac{g_\tau^2}{g_e^2} = \frac{\Gamma(W\to\tau\bar{\nu})}{\Gamma(W\to e\bar{\nu})} = 1.043 \pm 0.024$$

$$\frac{g_\tau^2}{g_\mu^2} = \frac{\Gamma(W\to\tau\bar{\nu})}{\Gamma(W\to\mu\bar{\nu})} = 1.070 \pm 0.026$$

- There is a mild tension with the SM in the τ measurements
  - ~2.7 σ for g_τ/g_μ



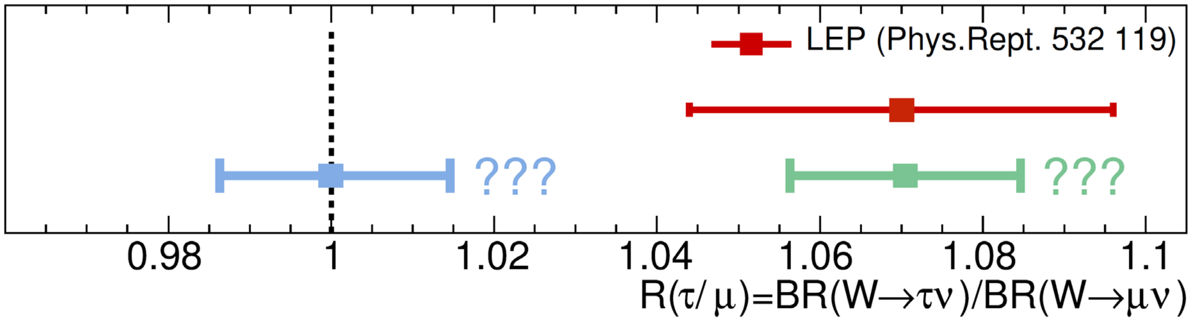
Conclusive test of LFU

- A possible violation of LFU observed at LEP prompts a task of

$$\text{Measuring } R(\tau/\mu) = \Gamma(W \to \tau\bar{\nu})/\Gamma(W \to \mu\bar{\nu})$$

with ~1% precision

  - Measuring the same value of $R(\tau/\mu)$ as at LEP with the precision of ~1% would be a definitive confirmation of LFU violation
  - It would be an unambiguous discovery of physics beyond the SM



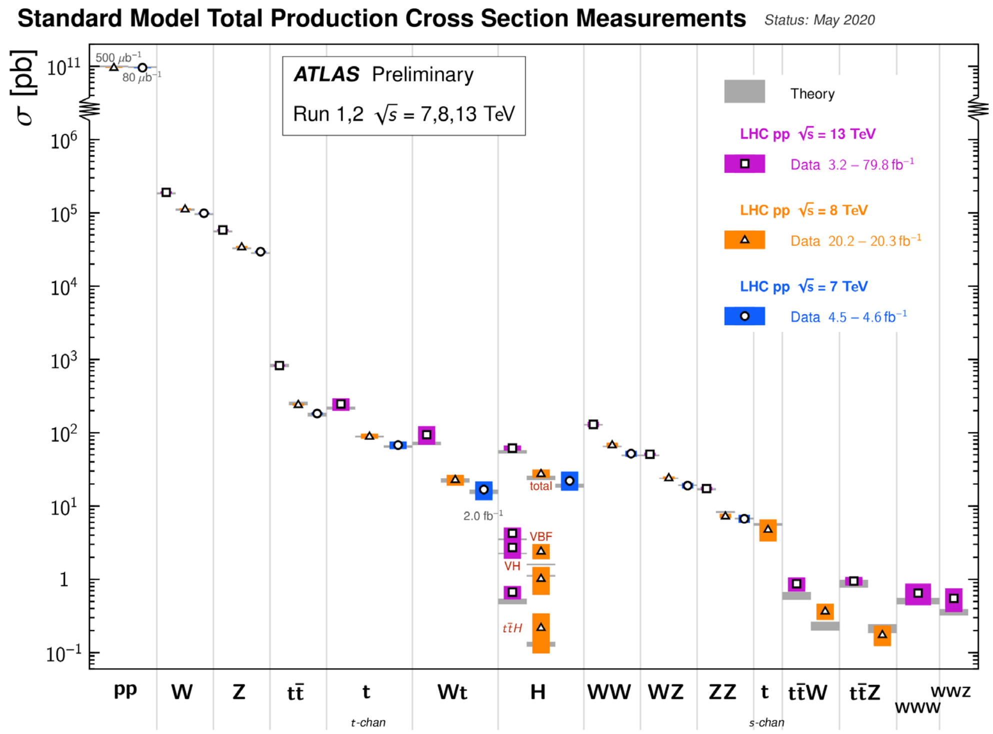
Conclusive test of LFU

- For a long time it was thought that this level of precision is impossible to achieve at hadron colliders
  - large background
  - large uncertainties in the selection efficiency

The new ATLAS result, which will be presented here, disproves this belief

Analysis Strategy

- The test of LFU is performed using the top quark decays
  - Huge production cross section of $t\bar{t}$ pairs
  - More than 100 million $t\bar{t}$ pairs are produced at $\sqrt{s} = 13$ TeV
  - Selection of $t\bar{t}$ is relatively simple and clean
- Each top quark decays mainly as $t \to Wb$
- there are two W bosons in each event



Tag-and-probe method

- One W boson is used to select events
- The second W boson is used to measure $R(\tau/\mu)$
- We use the decay $\tau \to \mu\nu\bar{\nu}$ and measure

$$\frac{\mathrm{Br}(W \to \tau(\to \mu\nu\bar{\nu})\nu)}{\mathrm{Br}(W \to \mu\nu)}$$

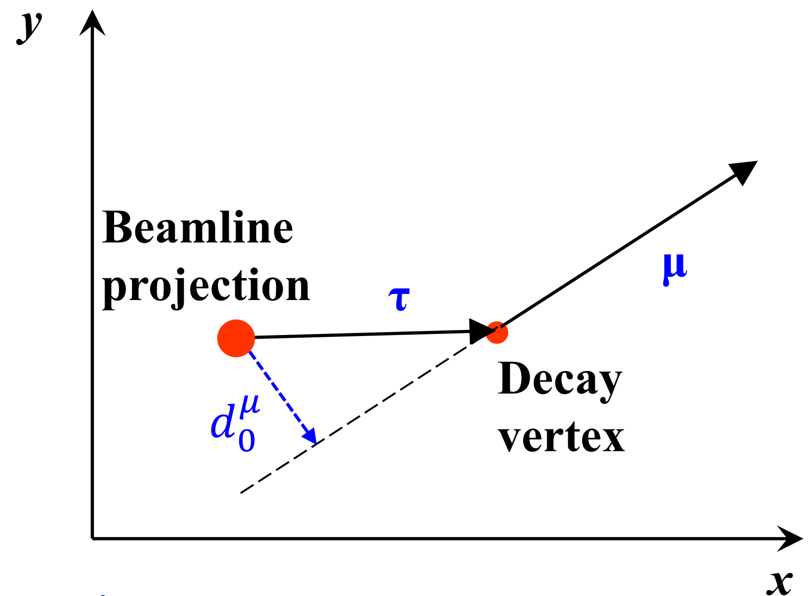
  – $\mathrm{Br}(\tau \to \mu\nu\bar{\nu}) = (17.39\pm0.04)\%$ is known with small uncertainty
  – the same particles (a muon) in the final state
- Many uncertainties cancel in the ratio
  – jet reconstruction, flavour tagging uncertainties
  – uncertainties related to the tag W selection (trigger, efficiency, identification)

Event selection

- Standard selection of $t\bar{t}$ events with both top quarks decaying semileptonically $t \rightarrow l\nu b$
  - require two isolated opposite charge leptons ($e\mu$ or $\mu\mu$ pairs)
  - the tag lepton (electron or muon) is selected with a single lepton trigger
  - the probe lepton must be a muon with $p_T^\mu > 5$ GeV
  - require two b-tagged jets
  - For ($\mu\mu$) events apply the Z^0 veto
    - remove events with $85 < M(\mu\mu) < 95$ GeV
- Fraction of background events is 0.9% in $e\mu$ and 8% in $\mu\mu$ samples
  - Larger fraction of background in $\mu\mu$ events is due to Drell-Yan di-muon production

Muon impact parameter

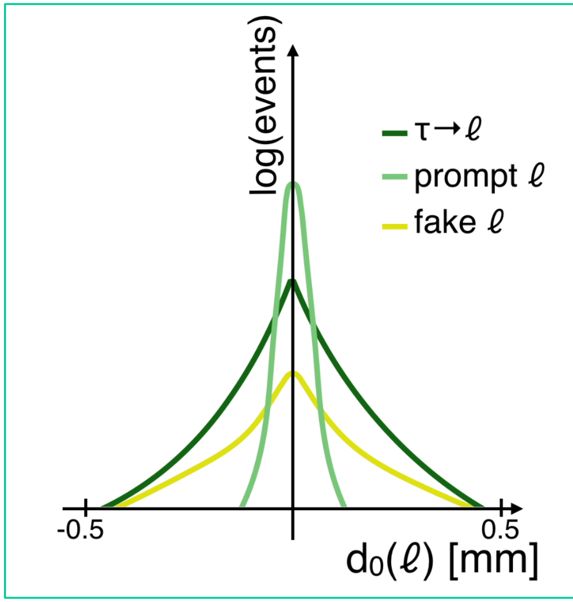
- Muon impact parameter, d_0^μ, is the most essential variable of this analysis
- d_0^μ is defined as a distance of closest approach of a charged track to the beam line in the transverse plane

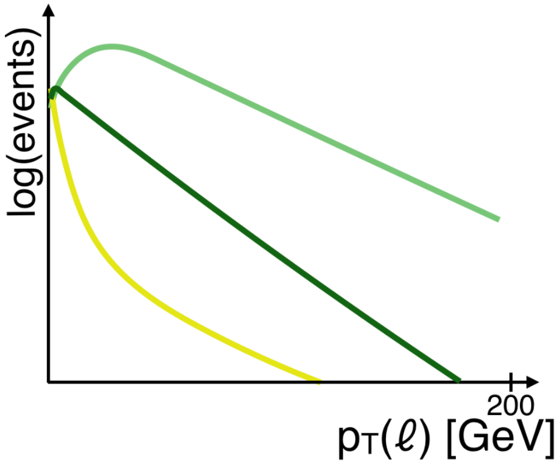


- d_0^μ is zero for particles produced in the primary vertex (approximated by the beamline projection)
- d_0^μ is non-zero for the decay products of long-living particles (like muons from $\tau \to \mu\nu\bar{\nu}$ decay)
- Measuring d_0^μ with respect to the beamline makes its definition process-independent

Separation of τ and μ

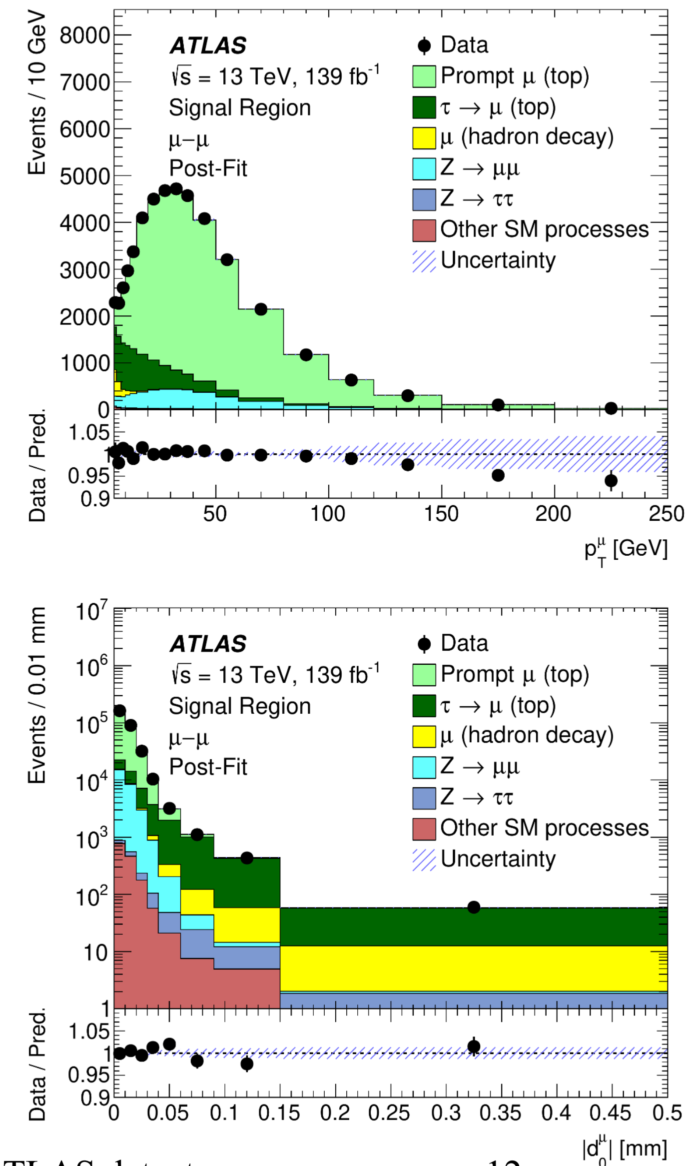
- Compared to prompt muons from W decay, muons from τ decay have on average
  - larger impact parameter d_0^μ
  - smaller transverse momentum p_T^μ
- We exploit these differences to separate τ and μ
  - perform a 2D fit of the probe muon $|d_0^\mu|$ and p_T^μ
  - Extract $R(\tau/\mu)$ and the total number of $t\bar{t}$ events





Sources of muons

- Sources of muons:
  - Prompt muons from $t \to \mu\nu b$ events
  - Muons from $t \to \tau\nu b \to \mu\nu\nu\nu b$
  - Muons from hadron decay
  - Muons from $Z \to \mu\mu$ (tails) and $Z \to \tau\tau$
- The fractions of $t \to \mu\nu b$ and $t \to \tau\nu b \to \mu\nu\nu\nu b$ are floating parameters in the fit
- The fractions of $Z \to \mu\mu$ (tails) and $Z \to \tau\tau$ are measured using data
- The fraction of muons from hadron decay is estimated using data with some input from MC

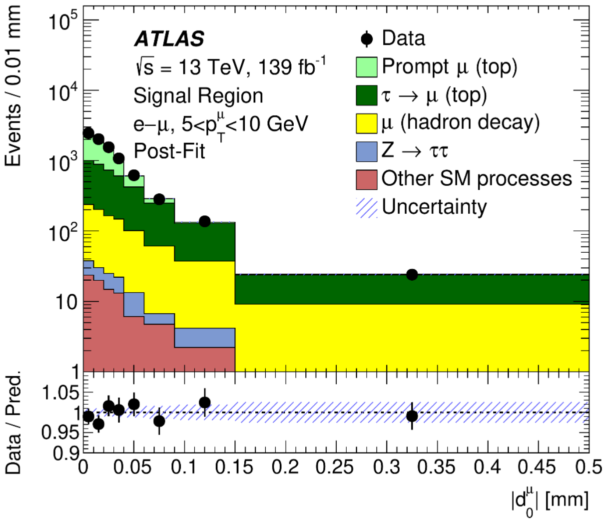


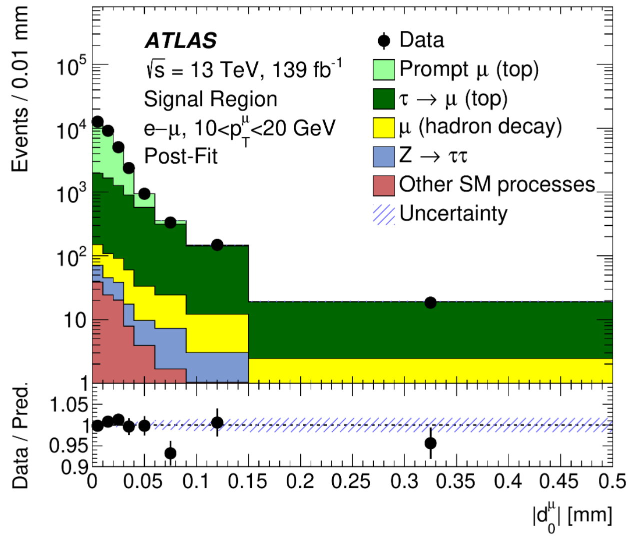
Fit Model

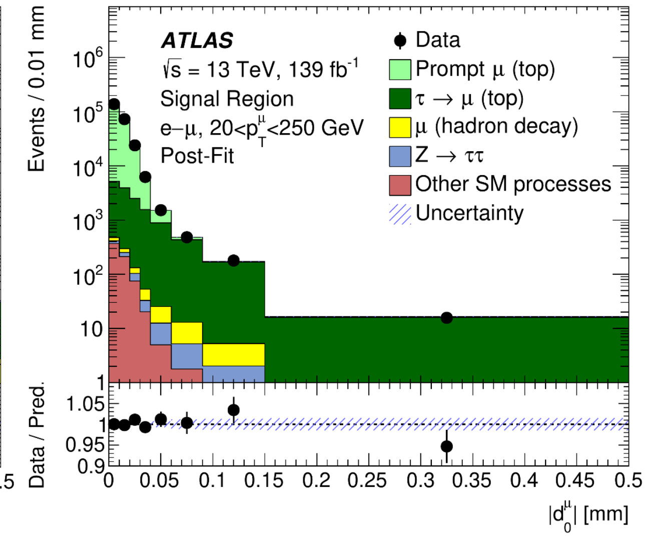
- $R(\tau/\mu)$ is obtained from the profile likelihood fit in 2D
  - Three bins in p_T^μ: [5, 10, 20, 250] GeV
  - Eight bins in $|d_0^\mu|$: [0., 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.50] mm
  - Two channels ($e\mu$ and $\mu\mu$) are fitted simultaneously
  - 48 bins in total
- Two free parameters in the fit
  - a constant scaling factor applied to muons from $t \rightarrow \mu\nu b$ and $t \rightarrow \tau\nu b \rightarrow \mu\nu\nu\nu b$ originating in $t\bar{t}$ and Wt events
  - $R(\tau/\mu)$ applied to $t \rightarrow \tau\nu b \rightarrow \mu\nu\nu\nu b$ component

Results: post-fit $e\mu$

- Excellent agreement between data and MC after the fit
  - Larger background of muons from hadron decay at small p_T^{μ}
  - Higher sensitivity to $R(\tau/\mu)$ at large p_T^{μ}

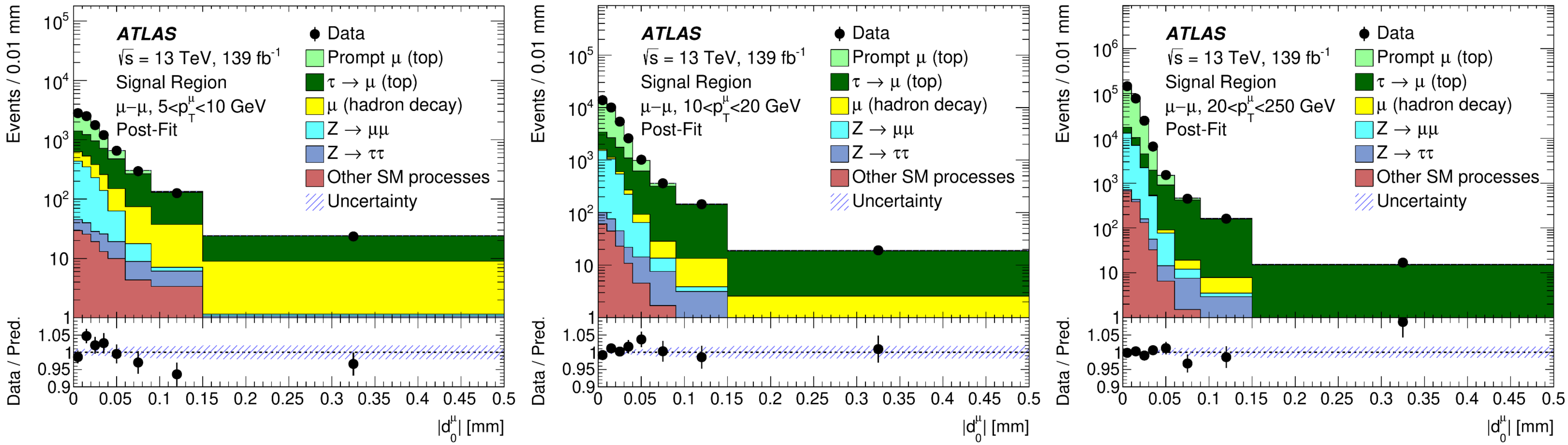






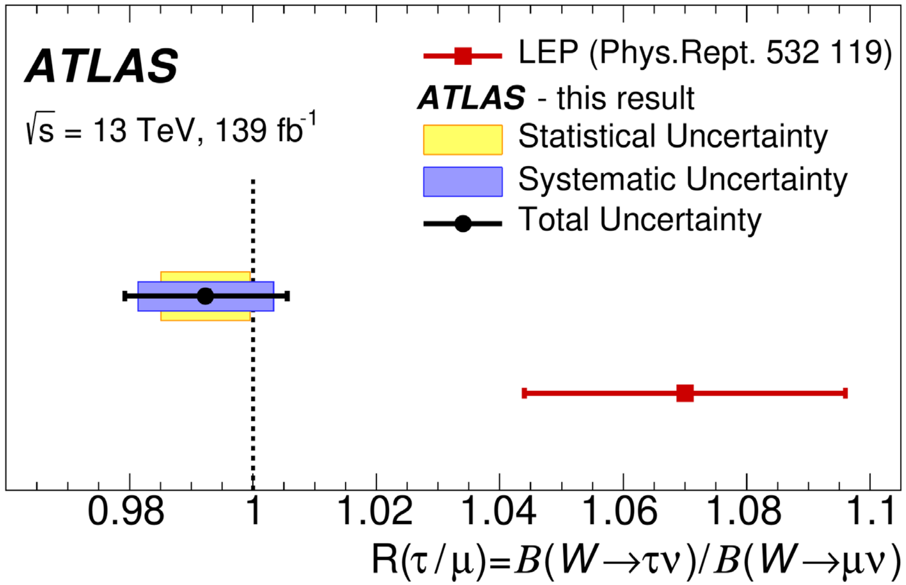
Results: post-fit $\mu\mu$

- Excellent agreement between data and MC after the fit
  - Larger background of muons from hadron decay at small p_T^{μ}
  - Higher sensitivity to $R(\tau/\mu)$ at large p_T^{μ}



Result

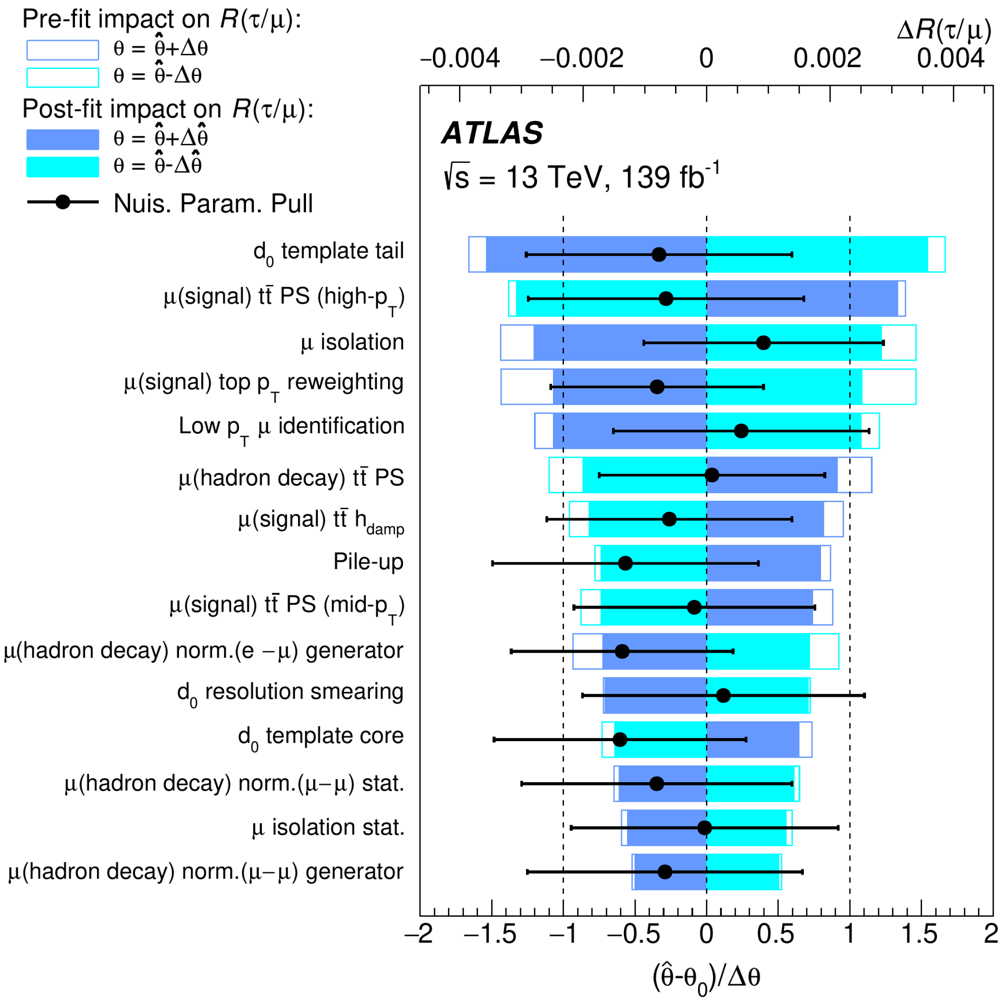
- The measured value is
  $R(\tau/\mu) = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})$
  - good agreement with the SM
  - does not agree to the LEP measurement
- The paper is available in ArXiv: 2007.14040
- Accepted for publication by Physics Nature
- The most precise measurement of this ratio to date



Uncertainties

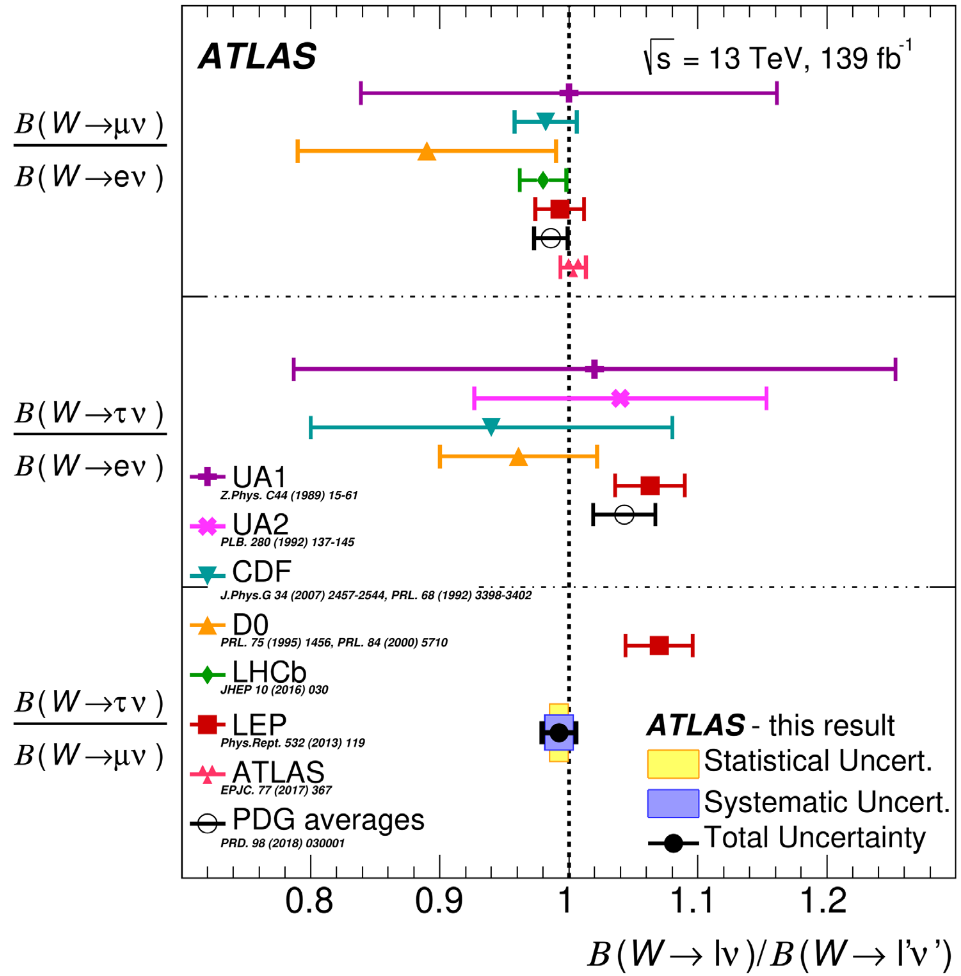
- The systematic uncertainty is dominating
- Main contributions:
  - $|d_0^{\mu}|$ template
  - $t\bar{t}$ modelling
  - modelling of μ from hadron decay
  - Muon reconstruction and identification

Uncertainty group	$\Delta R(\tau/\mu)$
Data statistics	0.007
Systematics total	0.011
- Data-driven backgrounds	0.005
- Theory	0.006
- Instrumental	0.007
- Normalisation factors	<0.001
- Limited MC statistics	0.002
- $BR(W \to \tau\nu \to \mu\nu\nu\nu)$	0.002
Total uncertainty	0.013



Conclusions

- A new technique of measurement, a huge statistics collected in Run 2, and excellent work of ATLAS allowed measuring $R(\tau/\mu)$ with the world best precision
- Resolved the old discrepancy with the SM remained from the LEP era
- (regretfully) beautiful confirmation of the SM



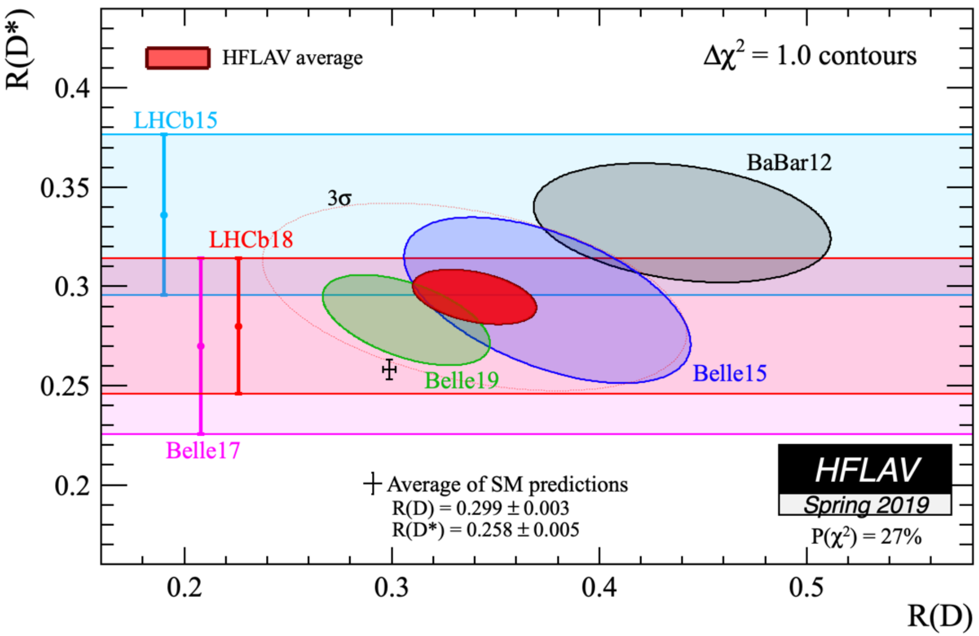
Backup

LFU tests with B hadrons

- Combination of *B*-factories and LHCb results indicate a possible violation of LFU in *B*-hadron decays
- Large discrepancy in the ratio

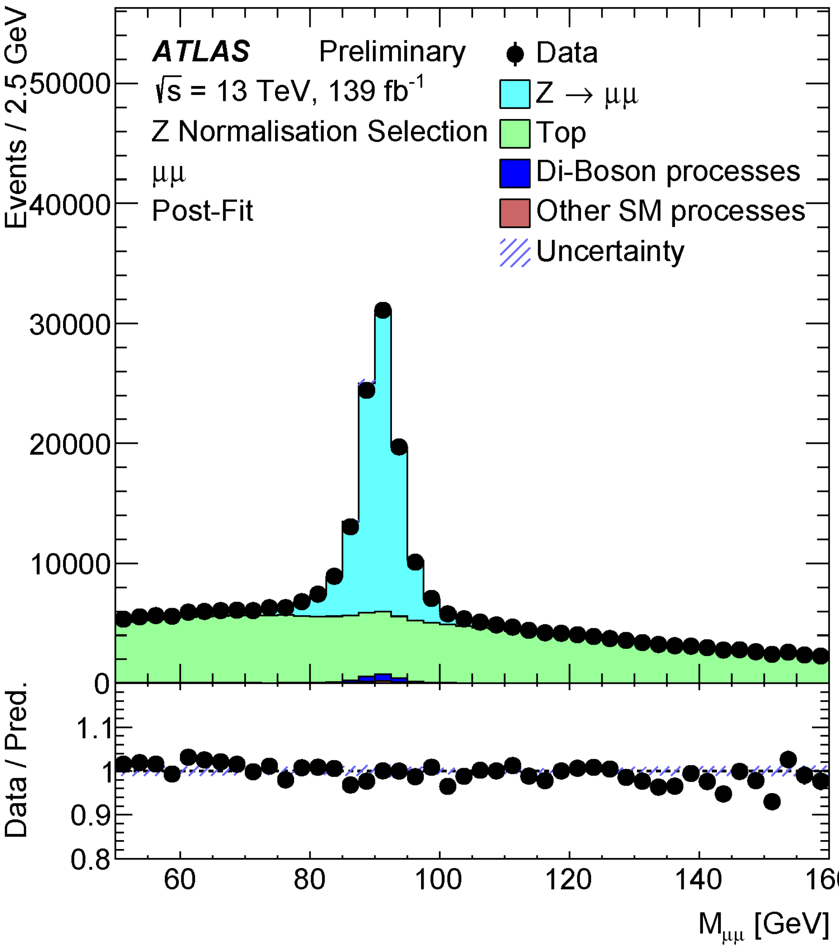
$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\mu\nu)}$$

  - Latest combination by HFLAV shows ~3.1σ deviation from the SM expectation
  - Some inconsistency between the experimental results can also be noticed



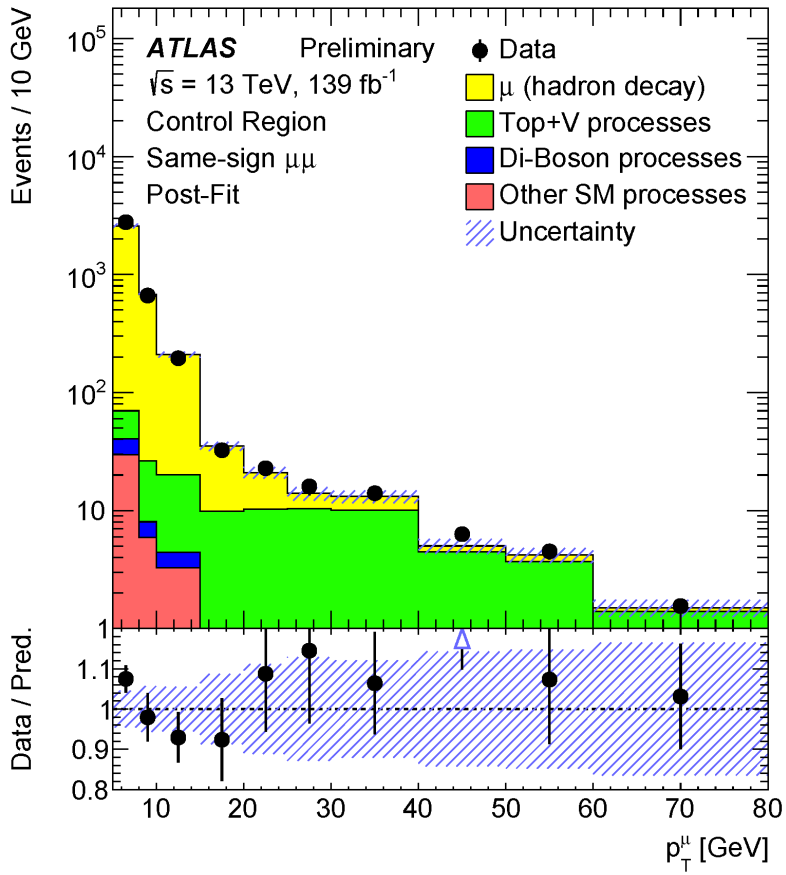
Z^0 background

- $(Z \rightarrow \mu\mu) + b\bar{b}$ events contribute to $\mu\mu$ sample even though we veto events in Z^0 peak
- Normalisation of this background is obtained from data
  - Selection is the same as for the main analysis except we do not apply the Z^0 veto
- Fit $m(\mu\mu)$ with
  - BW ⊕ Gaussian for Z^0 peak
  - Polynomial for background
- Scale factor for this background is obtained as the ratio data/MC of events in the Z^0 peak: 1.36±0.01



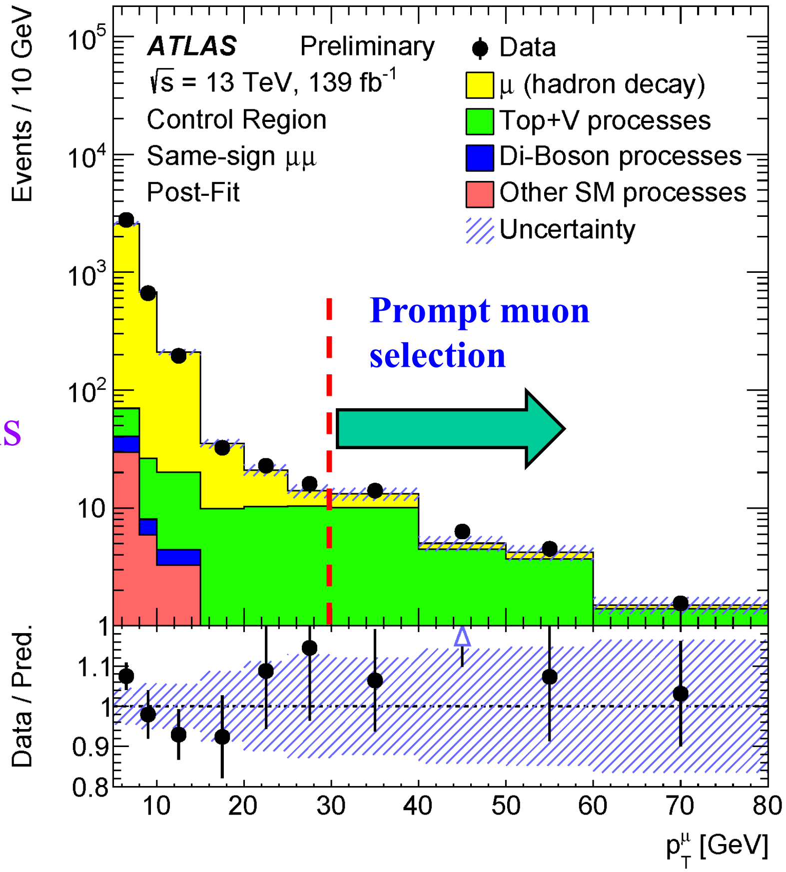
Muons from hadron decay

- The most significant background at large $|d_0^\mu|$
  - Mainly comes from *b*- and *c*-hadron decay
- Normalisation of this contribution is taken from simulation with an additional scale factor applied
- Scale factor is determined using the events with the same-sign (SS) leptons ($e\mu$ or $\mu\mu$)
  - Number of muons from hadron decay is close in SS and opposite sign (OS) sample (contrary to muons from $t\bar{t}$ events)
- Extrapolation from SS to OS is done using simulation



Muons from hadron decay

- Contribution to SS sample comes from
  - muons from hadron decay (small p_T)
  - prompt muons, mainly Top+V (high p_T)
- Procedure to measure the scale factor
  - Determine the scale factor for prompt muons as the ratio of data/MC events with $p_T^{\mu} > 30$ GeV
  - Subtract from the number of SS data events the scaled contribution of prompt muons
    - this gives $N_{h\to\mu}^{data}$ – estimated number of SS muons from hadron decay in data
  - Scale factor of muons from hadron decay is computed as $N_{h\to\mu}^{data} / N_{h\to\mu}^{MC}$
- Scale factors: 1.39 ± 0.13 ($e\mu$ channel) and 1.37 ± 0.07 ($\mu\mu$)

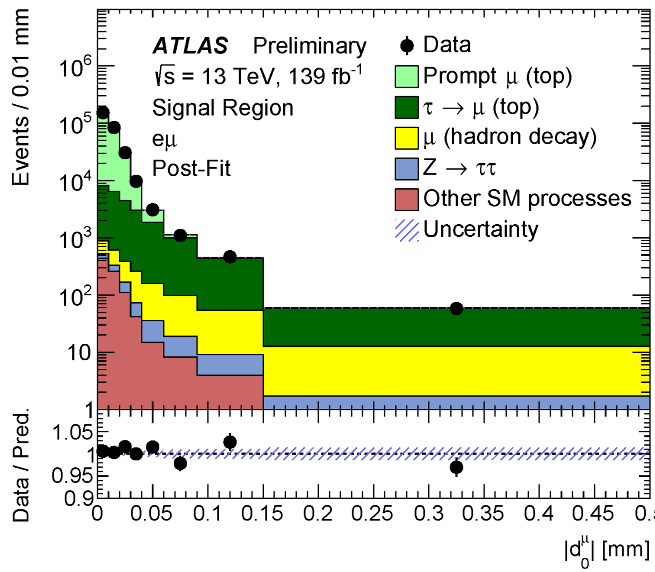


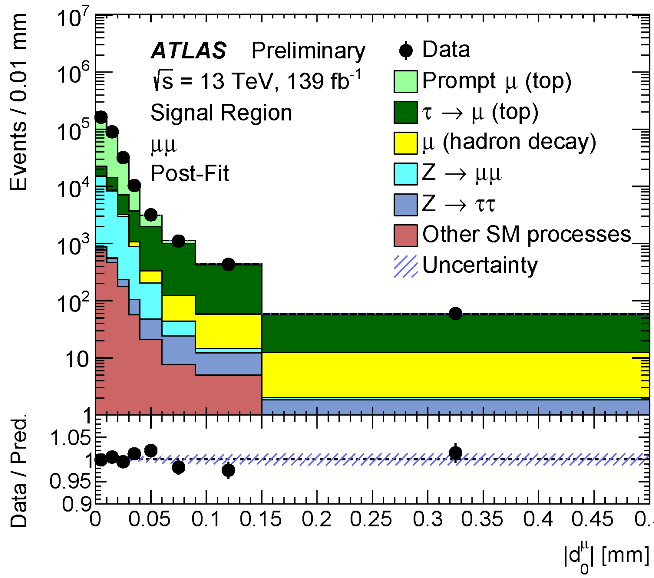
Muons from hadron decay

- Systematic uncertainty on the scale factor comes from
  - Limited size of the SS sample: $e\mu$ – 4%; μμ – 4%
  - MC modelling: $e\mu$ – 8%; μμ – 3%
  - Subtraction of prompt component: $e\mu$ – 1%; μμ – 1%

d_0^μ templates

- In the fit we use the d_0^μ templates for each source
  - Templates for prompt muons ($t \to \mu\nu b$ and $Z \to \mu\mu$ tails) are taken from data
  - Templates for muons from τ decay and from hadron decays are taken from simulation
  - The associated systematic uncertainties are among the most important for the analysis





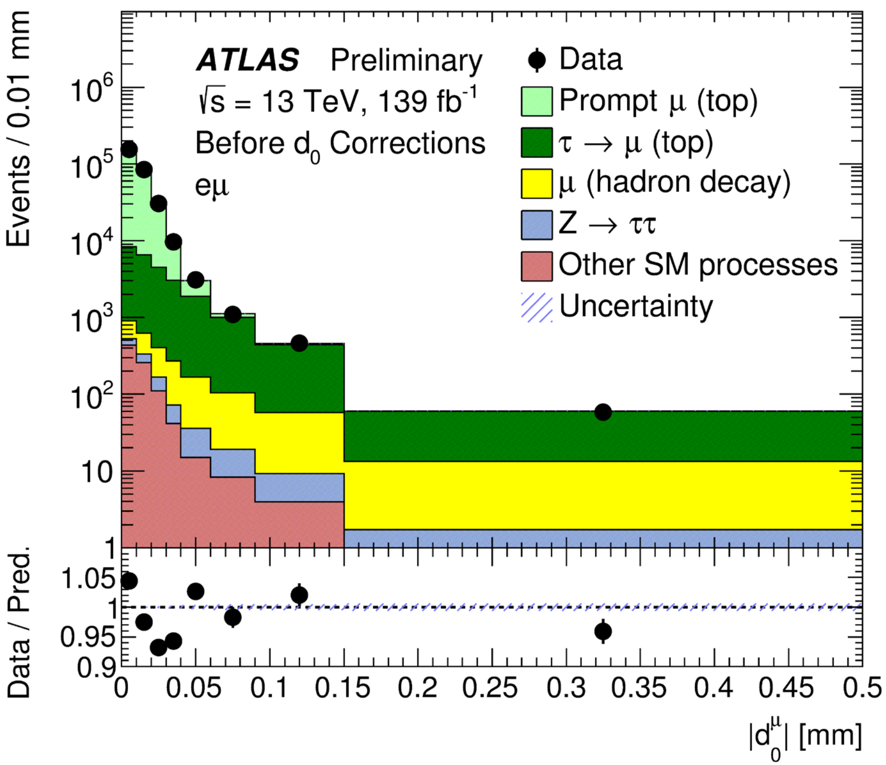
d_0^{μ} templates of prompt muons

- Build d_0^{μ} templates of prompt muons using $Z \to \mu\mu$ events
  - These muons originate from primary vertex like muons in $t \to \mu\nu b$ decay
- $Z \to \mu\mu$ selection
  - Opposite-charge muons
  - No b-tagged jets
  - $85 < M(\mu\mu) < 100$ GeV
  - Very high purity of prompt muons ~99.9%
- Procedure
  - Determine d_0^{μ} distribution in data separately in 33 kinematic bins in p_T^{μ} and $|\eta^{\mu}|$
  - Subtract a small contribution of non-prompt muons (mainly $Z \to \tau\tau$) using MC

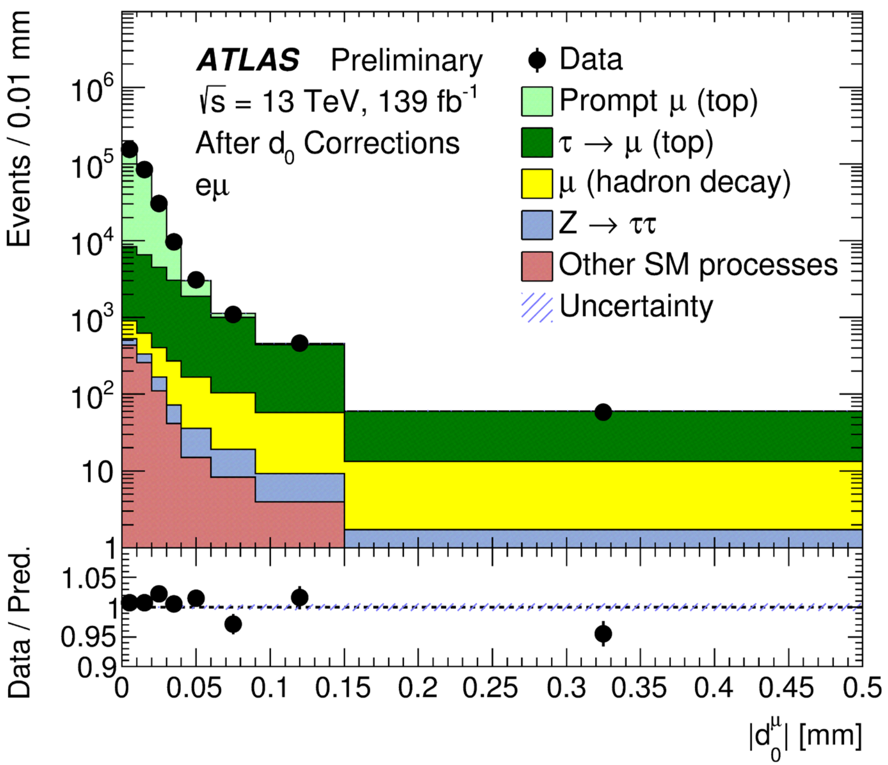
d_0^μ templates of prompt muons

- Considerable improvement in the agreement between data and MC after using d_0^μ templates of prompt muons from $Z \to \mu\mu$ events

Before



After

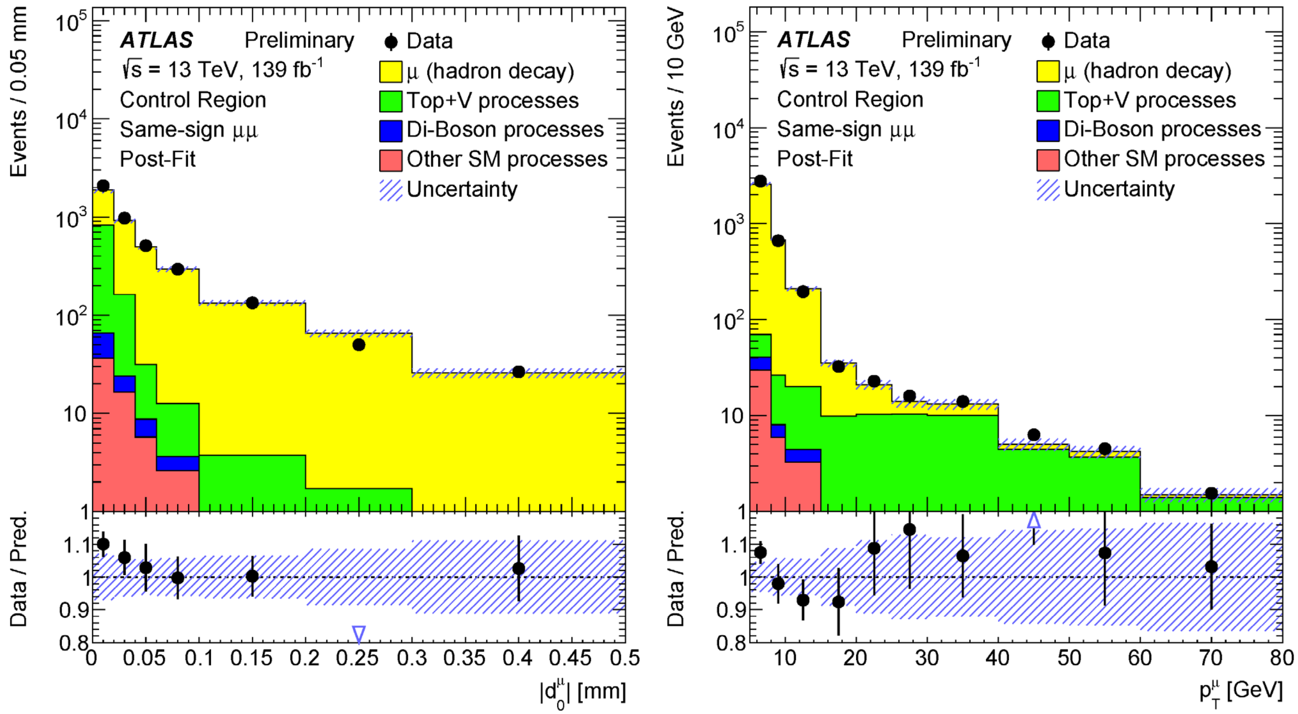


Corrections to the templates

- In MC the d_0^μ distribution in each kinematic bin differs between $Z \to \mu\mu$ and $t \to \mu\nu b$ events
  - different hadronic environment
  - small differences in kinematics within each kinematic bin
- This difference is taken as the systematic uncertainty
  - separate uncertainty for the core and the tail of d_0^μ distribution

Templates for muons from hadron decay

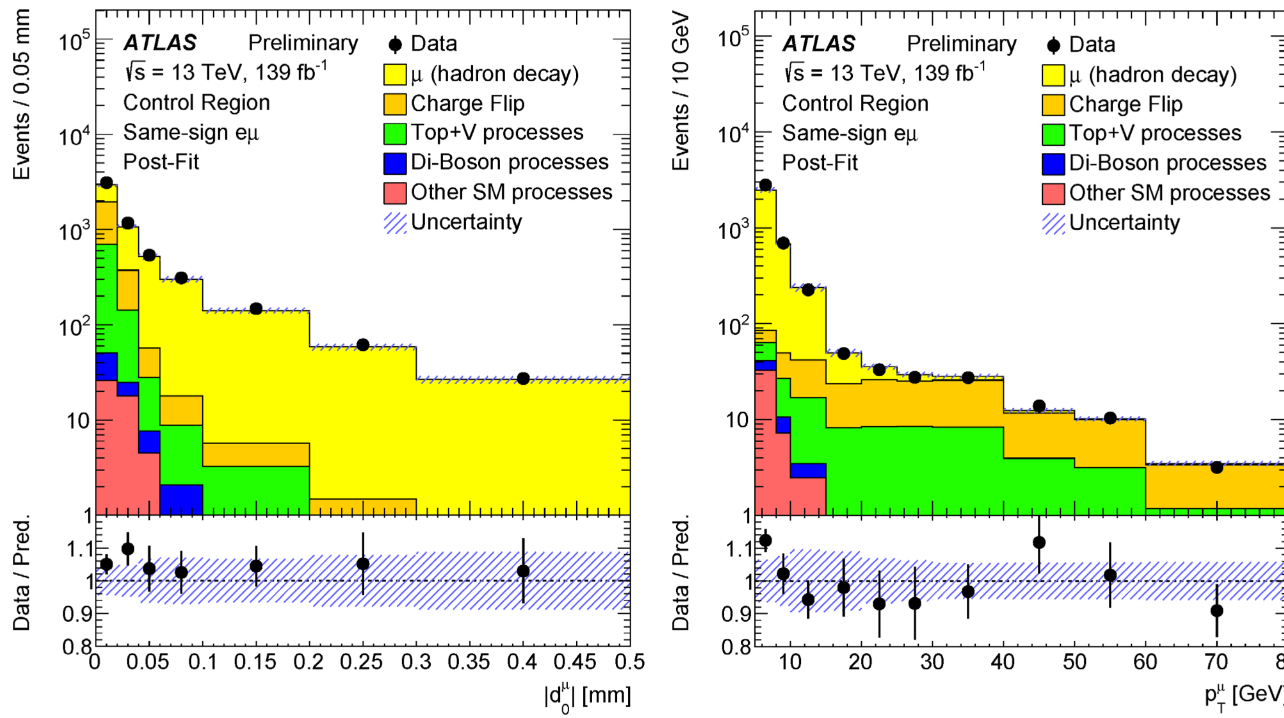
Comparison of distributions for SS muons in μμ sample



- Data and MC agree well both for $|d_0^\mu|$ and p_T^μ distributions
- In the analysis, $|d_0^\mu|$ and p_T^μ distributions of muons from hadron decay are taken from simulation
- The study with SS events gives confidence that these distributions are well modelled
- The modelling is additionally verified in OS events by selecting a subset of the signal events in a background-dominated region

Templates for muons from hadron decay

Comparison of distributions for SS muons in $e\mu$ sample



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Systematic uncertainties

- Efficiency of muon reconstruction and identification is measured in data using tag-and-probe method
  - together with the corresponding systematic uncertainties
- Obtained scale factors are p_T-dependent and affect differently prompt muons and $\tau \to \mu$
- MC generator uncertainties are obtained by varying different generator components
  - Amount of initial state radiation
  - Factorisation and renormalisation scales
  - Powheg h_{damp} parameter
  - NNLO reweighting
  - Parton shower and hadronisation

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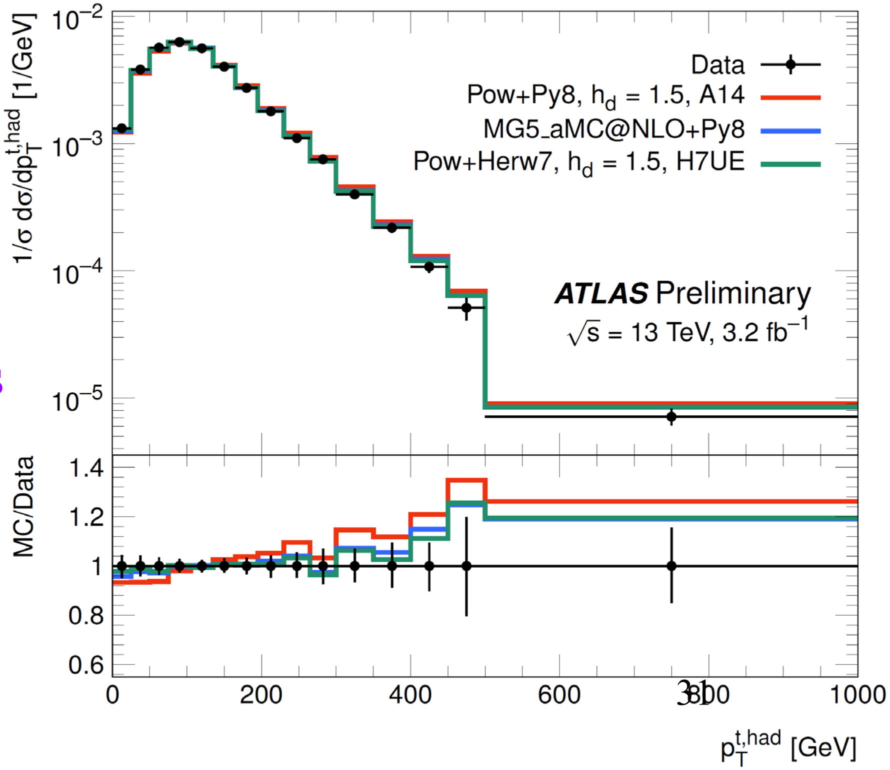

Consistency checks

- Several consistency checks were performed by repeating the analysis in different sub-samples
  - different years (2015-16, 2017, 2018)
  - $e\mu$ or $\mu\mu$ channels
  - individual p_T^μ bins
  - Separately for each muon charge
- In all cases, good consistency is observed