Testing Lepton Flavour Universality: $B(W \to \tau\nu)/B(W \to \mu\nu)$

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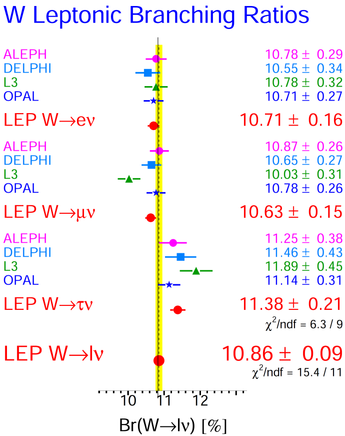
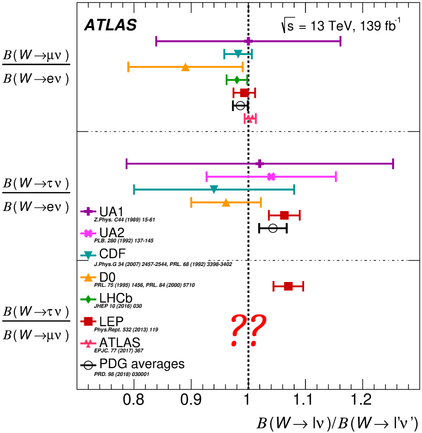
TU Dortmund Seminar





Introduction + Outline

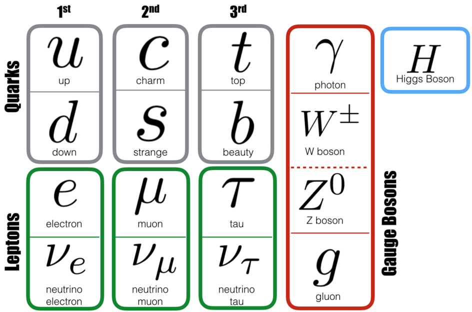
- The universality of the couplings of the leptons to the gauge bosons is one of the fundamental axioms of the Standard Model.
- This means that branching ratios of the W and Z bosons should be equal to each of the different charged leptons; $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$. (Note; mass effects are small)
- Here I present an analysis from the ATLAS collaboration which directly tests this fundamental assumption of the Standard Model by measuring the ratio;

$$R(\tau/\mu) = \frac{B(W \to \tau\nu_{\tau})}{B(W \to \mu\nu_{\mu})}$$

- Outline
  - Previous measurements of the W and Z ratios of BRs
  - Our methodology:
    1. Strategy
    2. Selection
    3. Background estimation
    4. Systematics and fit
  - Our Result + the Broader Picture + Conclusion

The Standard Model

- The Standard Model contains three generations of quarks and leptons.
- The relative couplings of the W boson to the different quark pairs is governed by the CKM matrix.
- For leptons the vector boson couplings should be identical for all generations.
- As the vector bosons as much more massive than the leptons this means that the branching ratios should all be identical – and we can test this experimentally.

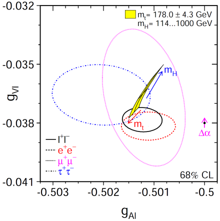


LEP Measurements for Z

- The $e^+ - e^-$ collider at CERN that preceeded the LHC; the Large Electron Positron Collider produced a large number of Z bosons allowing precise measurement of the properties. [1]
- The final analyses used 1.7 million $Z \to \ell^+\ell^-$ events across the 4 experiments recorded at the Z peak between 1990 and 1995.
- Of particular interest in this context are the results;

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{\mathrm{ee}}} = \frac{B(\mathrm{Z} \to \mu^+\mu^-)}{B(\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-)} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{\mathrm{ee}}} = \frac{B(\mathrm{Z} \to \tau^+\tau^-)}{B(\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-)} = 1.0019 \pm 0.0032$$



and the extracted axial and vector couplings (figure). Good agreement with unity is seen and the precision of the results is $\sim 0.3\%$.

LEP Measurements for W

- From 1997-2000 LEP ran at $\sqrt{s} > 2 \times m_W$ so WW production was possible.[2]
- By performing a fit across all decay channels the branching fractions to each lepton species could be extracted, and the ratios then test the universality of the couplings;

$$\begin{aligned}
\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) &= 0.993 \pm 0.019\,,\\
\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) &= 1.063 \pm 0.027\,,\\
\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) &= 1.070 \pm 0.026\,.
\end{aligned}$$

- While the lighter generations are in good agreement, the ratio w.r.t. τ-leptons show significant discrepancies.
- **In particular the ratio that we have measured;** $B(W \to \tau\nu)/B(W \to \mu\nu)$**, is found to be** 2.7σ **from the Standard Model expectation of unity.**
- The uncertainty on their measurement is 2.6% so we aim to significantly improve on this precision to provide an unambiguous solution to this tension with the Standard Model value.

LEP Measurements for W

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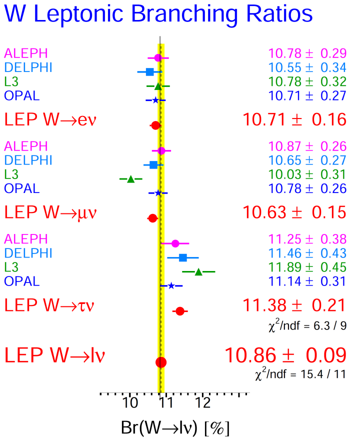
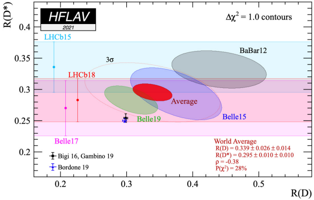


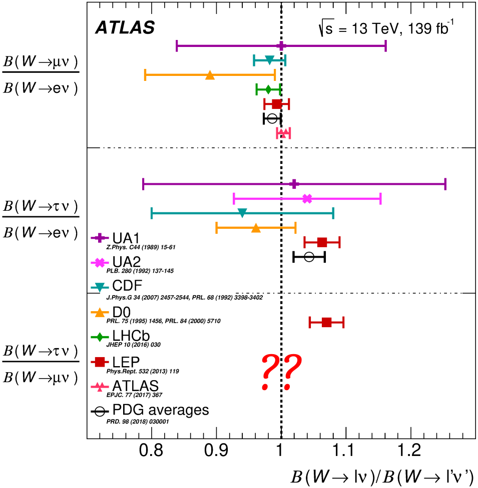
Low energy results and Other Measurements

- There have also been a series of low energy measurements which are sensitive to the couplings of the W boson to different lepton generations.
- Many of these are much more precise than those for on-shell bosons.
- For example; $|g_\tau|/|g_\mu| = 0.9999 \pm 0.0014$ from $\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$, $\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$ and $\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$ and using the lifetime [3]
- There is therefore a tension between these highly precise low energy results which show good agreement with the Standard Model and those for on-shell W bosons.
- Additionally, interestingly, in the measurement of $R(D)$ and $R(D^*)$ which also tests τ/μ universality this is a 3.4σ discrepancy with the Standard Model.

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

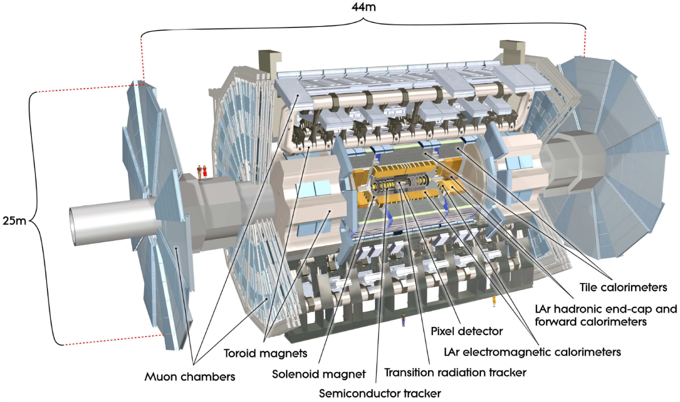


Summary of Previous Experimental Results



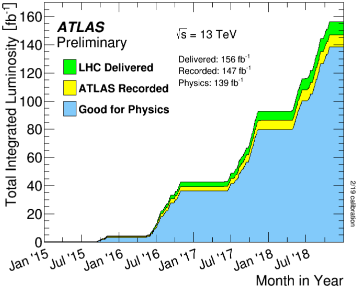
The ATLAS Experiment

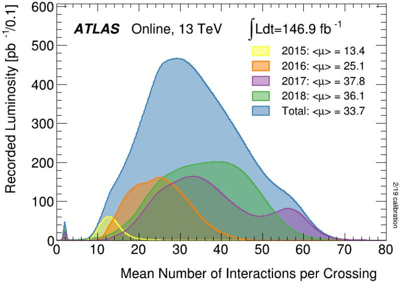
- The ATLAS general purpose experiment surrounds the interaction point and has various sub-detectors to reconstruct the different particles produced in the LHC collisions.



The Run 2 Dataset

- From 2015-2018 the LHC ran with a center of mass energy of $\sqrt{s} = 13$ TeV.
- ATLAS efficiently recorded this data and 139fb^{-1}of data is available for analysis.
- This corresponds to 8.4 billion $W \to \ell\nu$, 813 million $Z \to \ell\ell$, 115 million $t\bar{t}$ and 7.7 million Higgs events!
- A complication in reconstructing the events is the large number of simultaneous collisions - there was an average of 33.7 interactions per crossing.



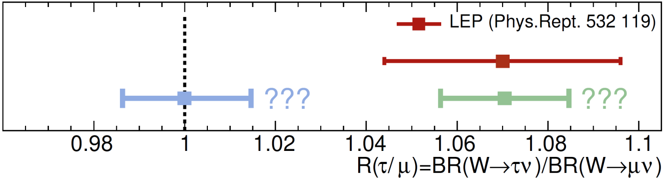


Introduction to the ATLAS Analysis

- The aim of the measurement is to determine

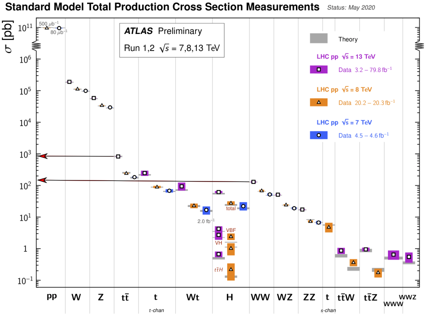
$$R(\tau/\mu) = B(W \rightarrow \tau\nu)/B(W \rightarrow \mu\nu)$$

  with a precision significantly better than the 2.6% accuracy achieved by LEP.
- A precision of 1-2% would either be able to refute the LEP excess or lead to **an unambiguous discovery of beyond the Standard Model physics!**
- This level of precision was not thought possible at a hadron collider; large backgrounds and kinematic biases (eg. due to trigger selection).
- **How can we get a large unbiased sample of W bosons where we can evaluate $B(W \rightarrow \tau\nu)$ and $B(W \rightarrow \mu\nu)$?**



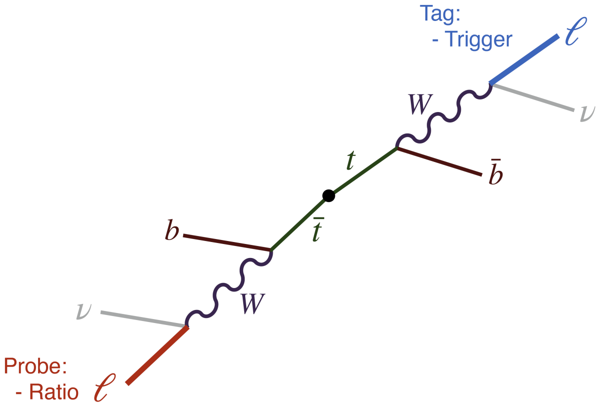
Introduction to the ATLAS Analysis

- **How can we get a large unbiased sample of W bosons where we can evaluate $B(W \to \tau\nu)$ and $B(W \to \mu\nu)$?**
- We use $t\bar{t}$ events to give us this sample.
- The $t\bar{t}$ cross-section is very large at the LHC - over 100 million top pairs were produced in Run 2!
- Note this is almost an order of magnitude higher than WW production.



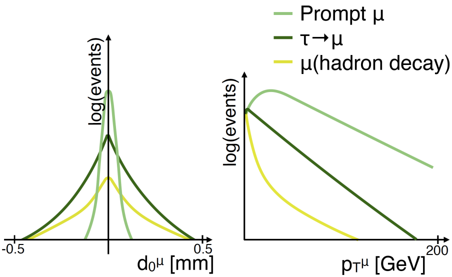
Introduction to the ATLAS Analysis

- **How can we get a large unbiased sample of W bosons where we can evaluate $B(W \to \tau\nu)$ and $B(W \to \mu\nu)$?**
- The two W bosons can then be used in a **tag and probe** approach.



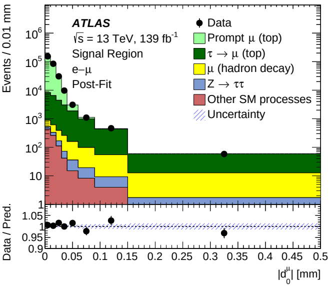
Identifying τ-leptons

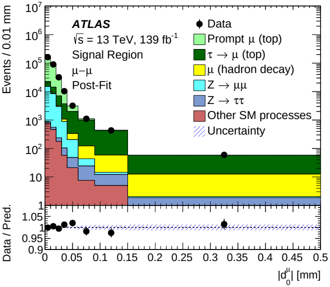
- The analysis focuses on the decay; $\tau^{\pm} \to \mu^{\pm}\nu_{\mu}\nu_{\tau}$.
- Hadronic decays are harder to reconstruct and come with larger associated uncertainties so we only use the decay to muons.
- This branching fraction is very well known ($17.39 \pm 0.04\%$ [4]) so we can extrapolate to the full τ final state.
- Muons from intermediate τ-leptons are distinguished from prompt muons by their different p_{T} and different transverse impact parameter, $|d_0^{\mu}|$.



Event Selection

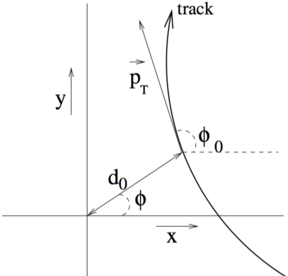
- A simple di-leptonic $t\bar{t}$ selection is applied.
- Two opposite sign leptons (e, μ), two b-tagged jets, Z mass window veto.
- Require "tag" lepton to trigger the event.
- Probe lepton required to be a muon and have $p_\mathrm{T} > 5\,\mathrm{GeV}$ – tag and probe allows us to go below trigger thresholds.
- Main backgrounds are then muons from hadron decays, and $Z \to \mu\mu$ in the $\mu - \mu$ channel.





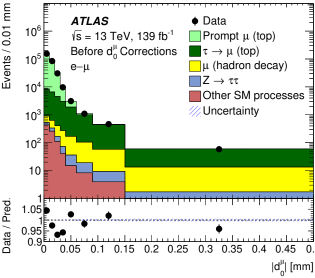
Transverse Impact Parameter; $|d_0^\mu|$

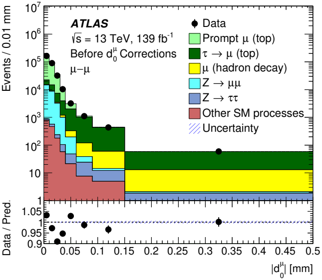
- To extract $R(\tau/\mu)$ a 2-D fit is performed in the probe muon p_T and $|d_0^\mu|$.
- Therefore the accurate modeling of $|d_0^\mu|$ is very important.
- We define this variable as the distance of closest approach of a track to the beam-line.
- Importantly, we define it with respect to the beam-line rather than the primary vertex to make it only dependent on the properties of the muon (p_T, η, etc).
- Therefore we can take the modeling from a different process and apply it to muons in $t\bar{t}$ – **data-driven method!**



Transverse Impact Parameter; $|d_0^\mu|$

- We use $Z \to \mu\mu$ events to derive templates for $|d_0^\mu|$ for prompt muons.
- Selection; two opposite sign muons, $85 < m(\mu\mu) < 100$ GeV, no b-tagged jets.
- Extremely high purity but we subtract from simulation the small $Z \to \tau\tau$ background.
- We produce templates year-by-year in 33 bins in $p_\mathrm{T}, |\eta|$ and then apply them based on the signal yields in the $t\bar{t}$ selection.
- Before corrections discrepancies from beamspot size, alignment and material.





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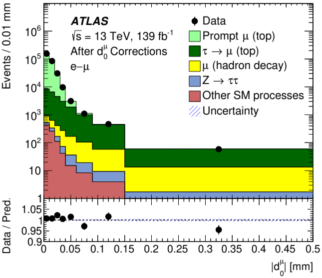
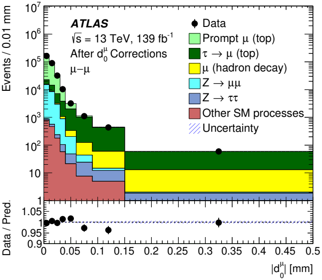
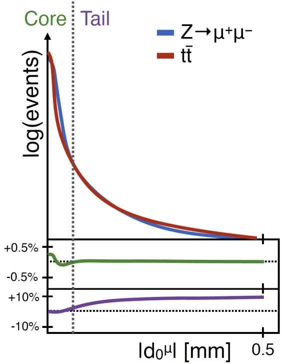
- After corrections agreement is very good.





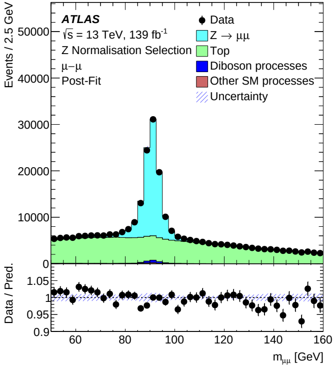
Transverse Impact Parameter; $|d_0^\mu|$

- For systematic uncertainties on these templates we look at the closure in simulation.
- The limited binning in p_T, η is a potential source of non-closure along with the amount of nearby hadronic activity.
- Closure is seen to be very good and the full size of the small differences is taken as an uncertainty.
- Different parts of the spectrum could be affected by different sources such that this uncertainty is split into a core and tail component.
- For processes with real displacement - eg. $\tau \to \mu\nu\nu$ or hadron decays, we smear the simulation to match the resolution determined from a gaussian fit of the core of the distribution in the same $Z \to \mu\mu$ selection.



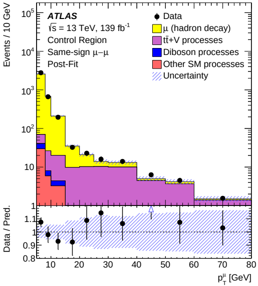
$Z \to \mu\mu$ Background

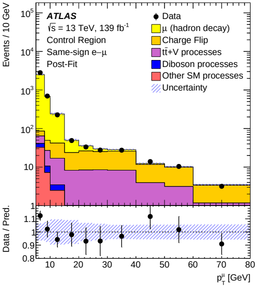
- We extract the normalization of the $Z \to \mu\mu$ background by applying the same selection without the $m(\mu\mu)$ veto.
- The same b-tagged jet requirements are applied – only extrapolating over lineshape.
- A fit is then performed across $m(\mu\mu)$ using a Voigt for the signal and Chebychev polynomial for background.
- Other functions used to derive a systematic uncertainty.
- Find a scaling of 1.36 is required with a 1-2% error.



Hadron Decay Background

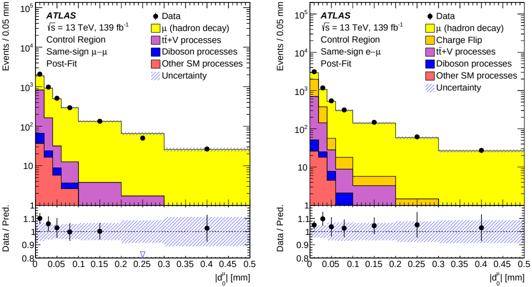
- Modeling of the background from heavy flavour hadron decays is difficult.
- We form a control region to normalize this requiring same-sign leptons.
- In this control region there is significant $t\bar{t}$+V and charge flip (in $e-\mu$) at high p_{T}.
- We normalize these other contributions from the region with $p_{\mathrm{T}} > 30$ GeV, then extract the normalization of the hadron decay background.
- Good agreement is seen in the modeling of the kinematics in the control region giving us confidence in the approach.





Hadron Decay Background

- We are extrapolating from SS to OS regions.
- While hadrons from b-decays are expected to be charge symmetric, the c-hadron component isn't.
- Uncertainties on this normalization come from; limited statistics 4% (4%), varying the generator and generator parameters 8% (3%), and the background subtraction 1% (1%) for the $e-\mu$, and $\mu-\mu$ channels.
- Additional uncertainties on the shape in $p_{\mathrm{T}}, |d_0^{\mu}|$ from generator comparisons.

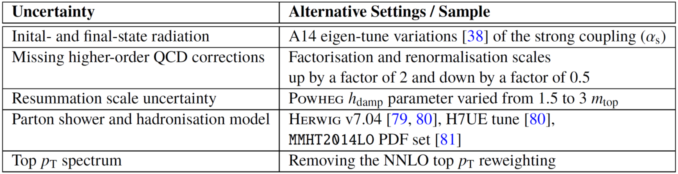


Experimental Uncertainties

- As the analysis is measuring a ratio many systematic uncertainties usually associated with top measurements cancel and become very unimportant.
- For example, all jet energy scale and resolution, as well as b-tagging systematics have little impact on the result.
- The remaining experimental uncertainties come from muon reconstruction and pile-up modeling.
- Pile-up affects the rate of muons passing the isolation cuts, and the reconstruction and identification efficiencies are p_{T} dependent so affect the $W \to \tau(\to \mu\nu\nu)\nu$ and $W \to \mu\nu$ processes differently.
- These effiencies are measured using $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ events using tag and probe methods. These processes have very large statistics so they are now well known at the $< 1\%$ level for almost all of the phase space.

Theoretical Uncertainties

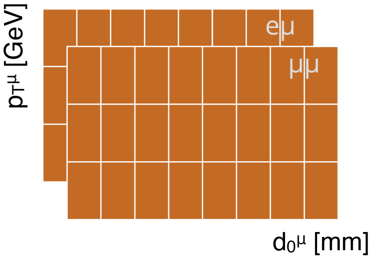
- Theoretical uncertainties affect the p_{T},η distribution of both the $W \to \tau(\to \mu\nu\nu)\nu$ and $W \to \mu\nu$ processes.
- These are evaluated by changing a number of generator settings or using different generators in the case of the parton shower + hadronization uncertainty.
- For the parton shower + hadronization uncertainty as many things are changing this is separated out into separate components for low p_{T}, mid p_{T}, high p_{T} normalization, high p_{T} shape.
- It was checked that different correlation scenarios did not affect the results.
- These variations are also applied to the hadron decay background to give shape uncertainties in the $p_{\mathrm{T}}, |d_0^{\mu}|$ space.



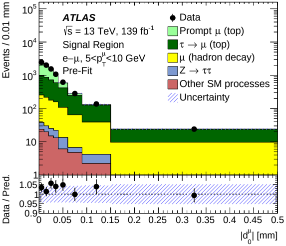
Uncertainty	**Alternative Settings / Sample**
Inital- and final-state radiation	A14 eigen-tune variations [38] of the strong coupling (α_{s})
Missing higher-order QCD corrections	Factorisation and renormalisation scales up by a factor of 2 and down by a factor of 0.5
Resummation scale uncertainty	POWHEG h_{damp} parameter varied from 1.5 to 3 m_{top}
Parton shower and hadronisation model	HERWIG v7.04 [79, 80], H7UE tune [80], `MMHT2014LO` PDF set [81]
Top p_{T} spectrum	Removing the NNLO top p_{T} reweighting

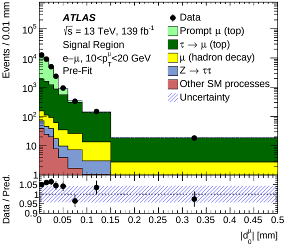
Fit Setup

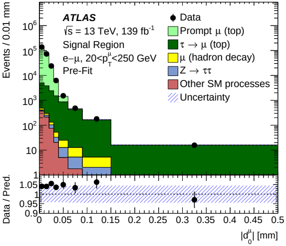
- A profile likelihood fit is performed to extract $R(\tau/\mu)$ in 2-D;
  - 3 bins in p_{T}: [5, 10, 20, 250] GeV
  - 8 bins in $|d_0^{\mu}|$: [0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5] mm
  - 2 channels; $e-\mu$, $\mu-\mu$ – 48 bins in total
- Two parameters are freely floating; the parameter of interest, $R(\tau/\mu)$, and $k(t\bar{t})$ which determines the normalization of the sum of the $W \to \tau(\to \mu\nu\nu)\nu$ and $W \to \mu\nu$ processes in $t\bar{t}$ and Wt.
- Nuicance parameters are then used for all the uncertainties with the appropriate bin-by-bin and process-by-process correlations.
- The normalizations from the control regions are performed in advance of the fit being performed.

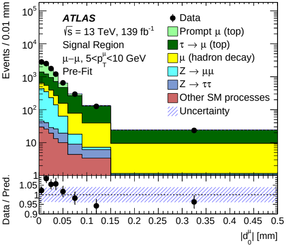


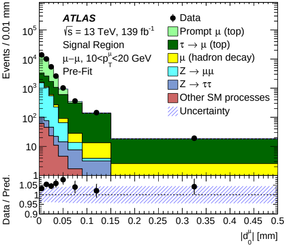
Pre-fit distributions

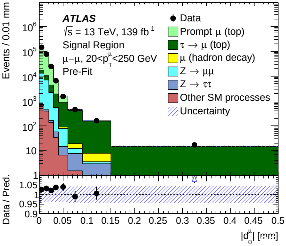




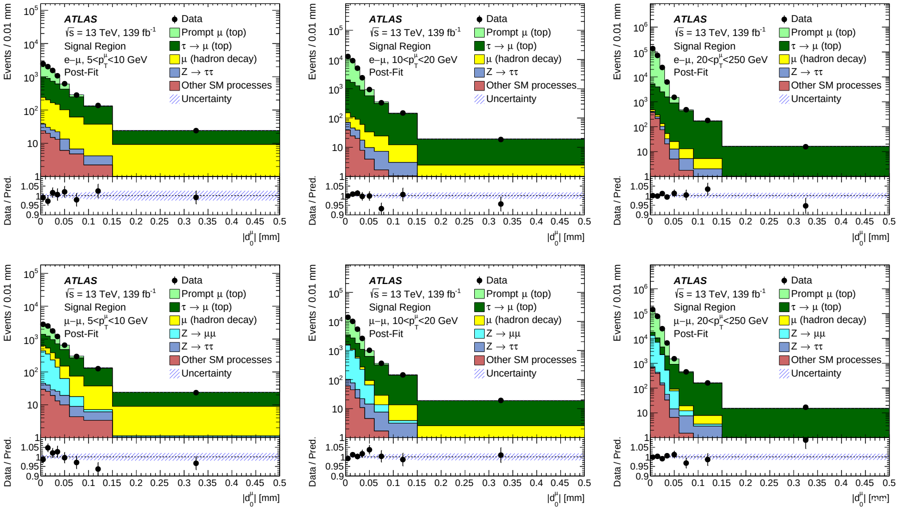






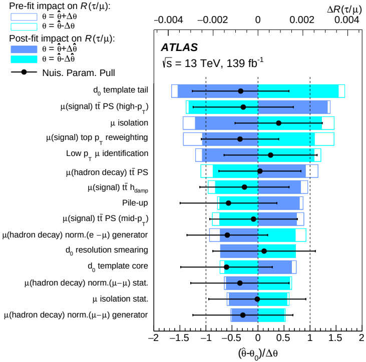


Post-fit distributions



Fit Pull and Constraints

- Good agreement is seen after the fit has been performed – the global goodness of fit when fitting the expectation from simulation: p-value of 0.29.
- The ranked plot of pulls and constraints shows some minor constraints in eg. top p_{T} modeling, and no significant pulls.
- Recall we have a large number of high statistics bins in this analysis!



Systematic Uncertainties

- A list of the grouped systematic uncertainties and their impact on $R(\tau/\mu)$.

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**

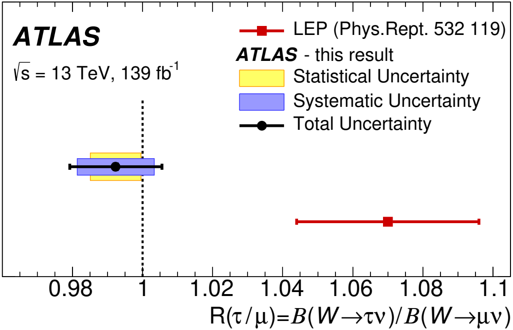
We achieve a precision of 1.3% – half the uncertainty of LEP!

Final Result

- We acheive a precision two times better than LEP and find;

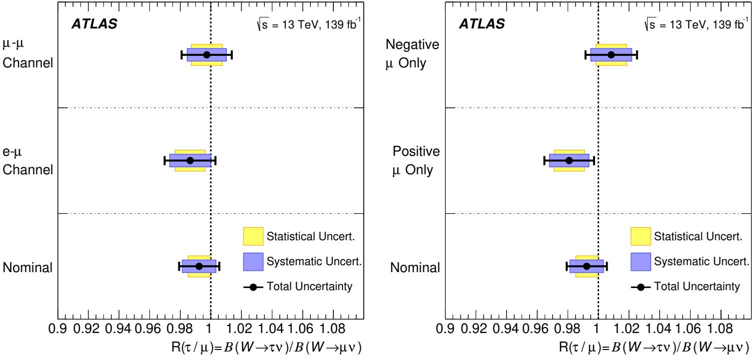
$$R(\tau/\mu) = 0.992 \pm 0.013 \; [\pm 0.007 \; (\text{stat}) \; \pm \; 0.011 \; (\text{syst})].$$

- This agrees well with the Standard Model expectation of unity.
- **The postulate of Lepton Flavour Universality survives this stringent test!**



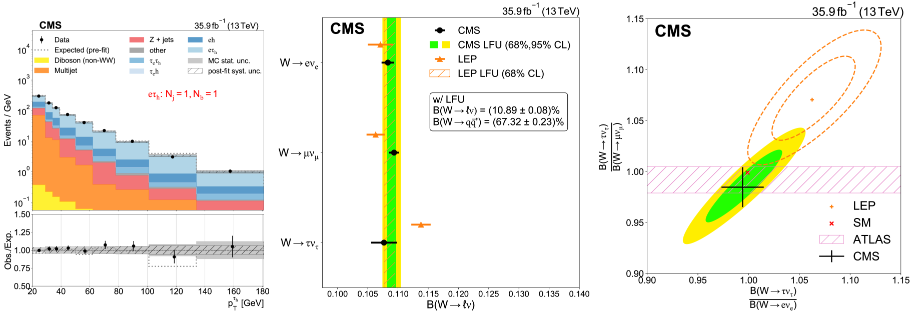
Cross-Checks of Stability

- It was also checked that the result is consistent with respect to different channels, kinematic bins, data-taking periods and the charge of the *probe* lepton.
- Here examples of different channels (left) and different charges (right).

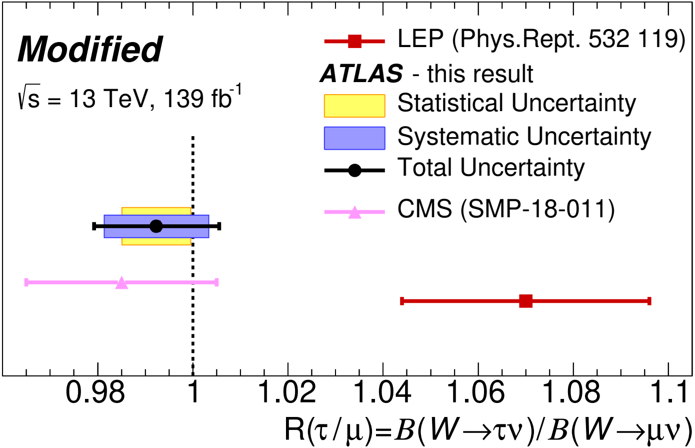


CMS Result

- Following the release of our preliminary result summer 2020 (published 7/21), in March 2021 CMS released a similar preliminary analysis which was published 01/22 .
- They also use di-leptonic $t\bar{t}$ events and the p_{T} spectrum but do not use $|d_0|$.
- They do use hadronic τ-leptons and 1-lepton+jets channels, and extract all branching ratios rather than just a single ratio; $R(\tau/\mu)$.
- The value of the ratio for comparison they get is $R(\tau/\mu) = 0.985 \pm 0.020$.



CMS Preliminary Result



Measurements of $R(\mu/e)$

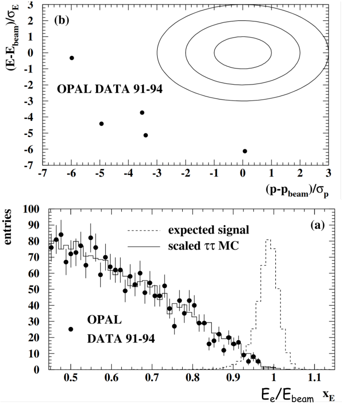
- Closely related to this measurement are the measurements of;

$$R(\mu/e) = \frac{B(W \rightarrow \mu\nu_\mu)}{B(W \rightarrow e\nu_e)}$$

- Earlier we saw the precise LEP result of 0.993 ± 0.019.
- ATLAS and LHCb have also made precise measurements; 1.003 ± 0.010 and 0.980 ± 0.018, using the 2011 and 2012 datasets respectively.
- Due to the similar kinematics of $\mu\nu$ and $e\nu$ decays these measurements are done in specific phase space selections.
- These have been combined with the LEP results to yield 0.996 ± 0.008.
- CMS extracted $R(\mu/e) = 1.009 \pm 0.009$ using Run 2 data with $t\bar{t}$ (previous slide).
- All of the above results are dominated by systematic (rather than stat.) uncertainties – precise knowledge of the reconstruction, identification and isolation is essential for these measurements.
- Better than 1% precision is achieved by the LHC! – half that achieved by LEP!

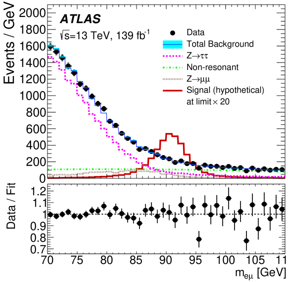
Lepton Flavour Violating Z boson decays at LEP

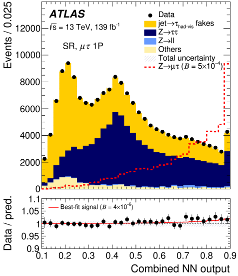
- In the SM we also have the principle of lepton number conservation (although this is violated in neutrino oscillations).
- Therefore decays $Z \to e\mu$, $Z \to e\tau$, $Z \to \mu\tau$ are not expected.
- LEP searched for these using the dataset of $\sim$ 4 million Z bosons produced in each detector.
- Background of $Z \to \tau\tau$ – rejected using that in signal $E_\ell = E_{\rm beam}$, resulting in almost background free search!
- The strictest results in each of the channels were;
- $B(Z \to e\mu) < 1.7 \times 10^{-6}$ (OPAL)
- $B(Z \to e\tau) < 9.8 \times 10^{-6}$ (OPAL)
- $B(Z \to \mu\tau) < 1.2 \times 10^{-5}$ (DELPHI)

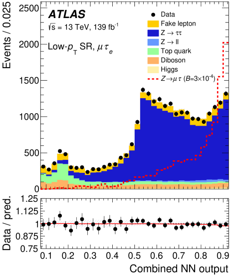


Lepton Flavour Violating Z boson decays at ATLAS

- ATLAS has looked for $Z \to e\mu$ [2204.10783] and $Z \to \ell\tau$ [Nat.Ph.17(2021)][PRL 127 (2021)]
- The ATLAS Run 2 dataset has 8 billion Z bosons – 2000× the LEP dataset, but at a hadron collider the backgrounds are much more significant.
- For $e\mu$ a BDT suppresses background before the mass is fit, for $\ell\tau$ neural networks using m^{coll} are used to distinguish signal and background.
- $B(Z \to e\mu) < 2.62 \times 10^{-7}$ – 6× better than LEP
- $B(Z \to e\tau) < 5.0 \times 10^{-6}$, $B(Z \to \mu\tau) < 6.5 \times 10^{-6}$ – almost 2× better than LEP







Conclusions

- We developed a new method for measuring the ratio

$$R(\tau/\mu) = \frac{B(W \to \tau\nu)}{B(W \to \mu\nu)}$$

  to test the axiom of Lepton Flavour Universality.
- $t\bar{t}$ events were used in a tag and probe approach, and muons from taus were distinguished from prompt muons using their p_{T} and $|d_0^{\mu}|$.
- We acheive **a precision two times better than LEP** and find;

$$R(\tau/\mu) = 0.992 \pm 0.013 \ [\pm 0.007 \ (\mathrm{stat}) \ \pm \ 0.011 \ (\mathrm{syst})].$$

  so **the SM survives this stringent test of Lepton Flavour Universality!**
- Paper published in Nature Physics.
- More information; arXiv, CERN Courier, ATLAS Briefing, YouTube, Press release.
- LHC has more precise $R(\mu/e)$ and more stringent limits on Z boson LFV than LEP!
- We are entering the precision era of the LHC with large statistics data samples and precise detector understanding...

Conclusions