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

Course on Physics at the LHC

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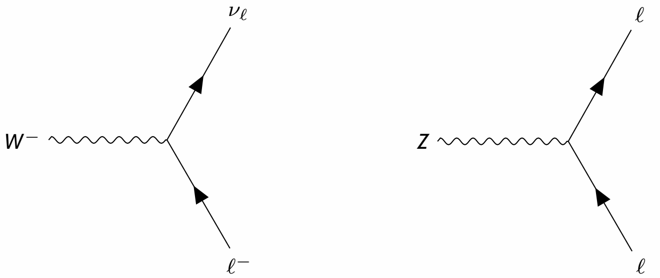
Lepton-Flavour Universality

- The Standard Model (SM) is based on the axiom of the universality of the coupling of the different generation of leptons to the electroweak gause bosons;
- The leptons coupling to gauge boson are flavour-independent;
- The interaction between leptons and a gauge boson measures the same for each lepton.



(1)

$$\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5) \qquad \frac{-ig_Z}{2\sqrt{2}}\gamma^\mu(-\frac{1}{2}+2\sin^2\theta_W+\frac{1}{2}\gamma^5)$$

Introduction

- To test this axiom the ratio of the rate decay of W bosons to τ-leptons and muons is measured:

$$R(\tau/\mu) = \frac{B(W \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)} \to 1(SM)$$

- This paper uses di-leptonic $t\bar{t}$ events.

Previous results from LEP: R(τ/μ) = 1.070 $\pm$ 0.026:

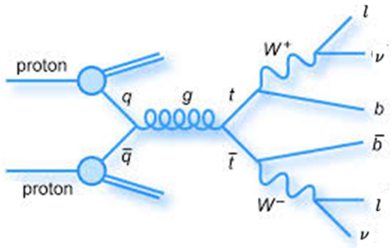
- This deviates from the SM expectation by 2.7σ;
- Motivating a precise measurement at the LHC.

Analysis Strategy

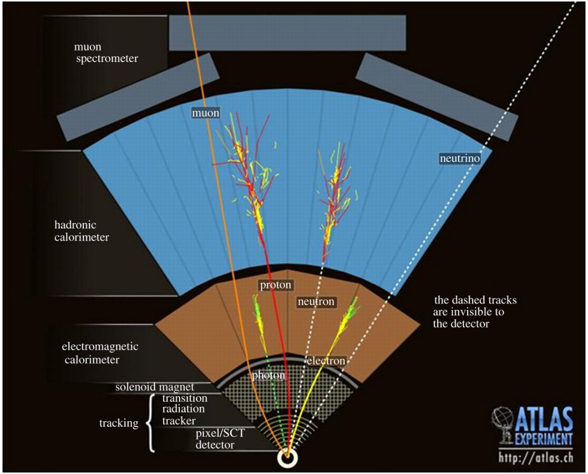
- Since $B(t \to Wb) \approx 100\%$ the $t\bar{t}$ process yields a large sample of W pairs;

- Case study is W boson decay to muons or τ-leptons using a tag and probe approach:
  - One of the W decays is selected through the muon or electron decay (tag lepton);
  - Second W decay is selected through a final state muon (probe muon) where the R(τ/μ) is measured:
    - $W \to \tau\bar{\nu_\tau} \to \mu\bar{\nu_\mu}\nu_\tau\bar{\nu_\tau}$;
    - $W \to \mu\bar{\nu_\mu}$;
    - and charged conjugate;

Muons are distinguished by the displacement of the τ decay vertex and the different muon transverse momentum (p_T).



The ATLAS Experiment



Data and Simulated Samples

- Events analysis: produced on 139 fb^{-1} of data with the ATLAS detector in p-p collisions at 13TeV;
- Monte Carlo (MC) samples of simulated events were produced to model the different SM processes;
- Simulated inelastic $p - p$ collisions were overlaid on events in all samples to model the pile-up;
- The data and MC simulated events were passed through the same reconstruction and analysis procedures.

Muon Reconstruction and Identification

- Reconstructed using combined fits of Inner Detector (ID) and Muon Spectrometer (MS) tracks;
- Muons must be isolated;
- $|\eta| < 2.5$;
- Muons must have:
  - The same momenta measure in the ID and MS;
  - Originated in the primary vertex (where the W was produced and decayed):
    - Distance of closest approach in the r-z plane of less than 0.3mm;
    - Transverse impact parameter relative to the beamline $|d_0^\mu| < 0.5mm$.

Tag muons:

- $p_T^\mu > 27.3GeV$;

Probe muons:

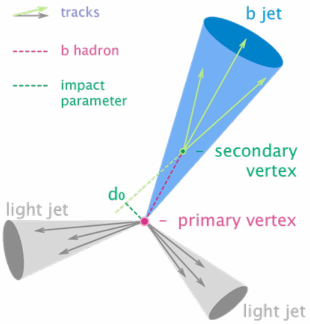
- $p_T^\mu > 5GeV$.

Electron Reconstruction and Identification

- Reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters;
- Electron be isolated;
- Electrons must have $p_T^e > 27GeV$;
- $|\eta| < 2.47$ except $1.37 < |\eta| < 1.52$;
- They have to be originated in the primary vertex (where the W was produced and decayed):
  - Distance of closest approach in the r-z plane of less than 0.3mm.

Hadronic Jets Reconstruction and Identification

- Built from energy clusters of calorimeter-cell using anti-k_t algorithm with a radius parameter of 0.4;
- $p_T > 25 GeV$;
- $|\eta| < 2.5$.
- Jets from b-quarks are distinguished based on the decay properties of B-hadrons.

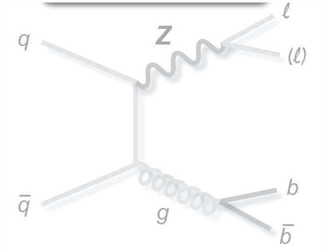


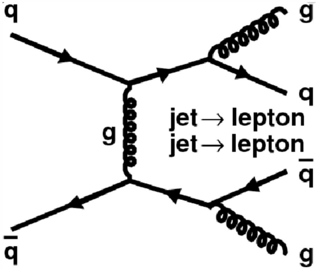
Event Seletion

- One electron and one muon ($e - \mu$ channel) of opposite electric charge or two muons ($\mu - \mu$ channel) with opposite electrical charge;
- Events are triggered by:
  - The electron in the $e - \mu$ channel;
  - The tag muon in the $\mu - \mu$ channel — such that the probe muons have no trigger bias.
- At least two reconstructed hadronic jets identified as b-jets;
- To reduce Z boson and hadron decay background events are excluded:
  - $85 < m_{\mu\mu} < 95$ GeV from $\mu - \mu$ channel;
  - $m_{ll} < 15$ Gev from both channels.

Background

- $Z(\to \mu\mu) + jets$
- Probe muons from multi-jets;





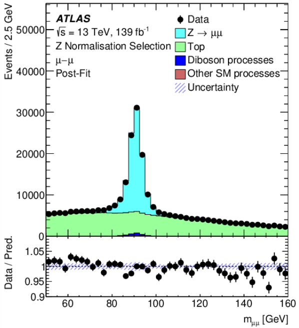
Background normalisation — $Z(\to \mu\mu) + jets$

Important at small values of $|d_0^\mu|$;

The normalization of background in the $\mu - \mu$ channel:

- The same event selection is applied, including the hadronic jet requirements, but without the $m_{\mu\mu}$ criterion;
- The peak of the invariant mass distribution of the dimuon system is fitted over the range 50 < $m_{\mu\mu}$ < 140 GeV.

The normalisation factor required to scale the simulated sample to data is found to be 1.36 ± 0.01;

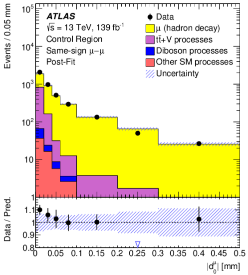


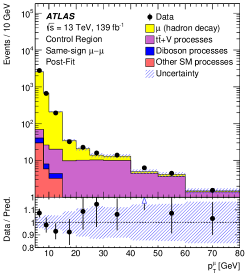
Background normalisation — Multijets

Probe muon originate from hadron decays — $\mu_{(had)}$;

Important background at large values of $|d_0^\mu|$ and low values of p_T^μ;

- Scale factors for this background are calculated using a same-sign control region in each channel;
- Normalisation factors to scale the simulation to data for the $\mu_{(had)}$ background: 1.39 (1.37) in the $e - \mu$ ($\mu - \mu$) channels;





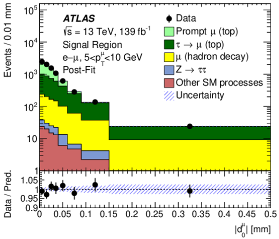
Statistical analysis and $R(\tau/\mu)$ measurement

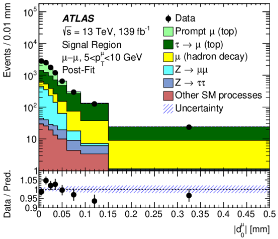
A profile likelihood fit is performed of the probe muon for each channel ($e-\mu$ and $\mu-\mu$);

To extract the ratio of the number of events in which the probe muon orginates from the process $\mu(\tau \rightarrow \mu)$, to those which come from $W \rightarrow \mu\nu_\mu$ ($Prompt\mu$):

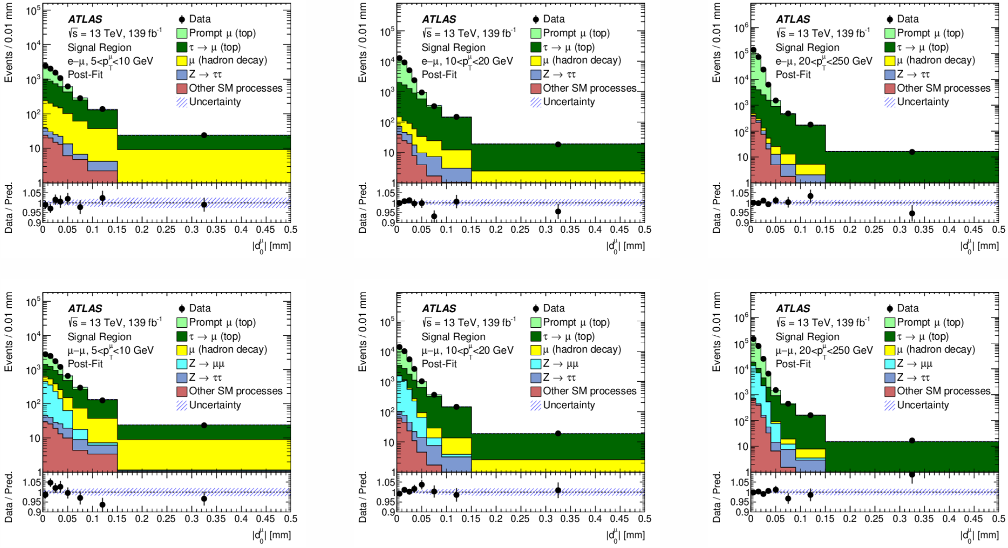
- The negative-log-likelihood minimisation is performed;
- Both the $t\bar{t}$ and Wt processes contain two W bosons both are treated as signal;
- The fit is setup with two floating parameters: $k(t\bar{t})$ and $R(\tau/\mu)$.

The fit is performed after applying the background normalisation scaling factors derived in the control regions;

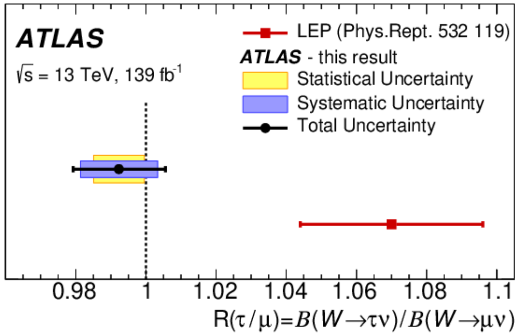




Post-fit distribution



Results



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

Conclusion

- Measurement of $R(\tau/\mu)$ with a novel method with $t\bar{t}$ events in the dilepton decay;
- The analysis provides a precise test of the fundamental assumption of the universality of the lepton coupling to the vector bosons in the SM;
- The best fit observed value is:

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

- It is in agreement with the SM prediction.

Thank you

Systematic Measures

- Uncertainties on the predicted templates for the $\mu(prompt)$ components: These are estimated from the full difference between the templates from Z and $t\bar{t}$ in simulation;
- Top quark modelling uncertainties: These are estimated by comparing various Monte Carlo generator configurations;
- Muon identification and reconstruction uncertainties: These are estimated in dimuon $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ data and MC using a tag and probe method;
- Background ($\mu(had)$) scale factor uncertainties.