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

Course on Physics at the LHC

Beatriz Pereira

Professor: Michele Gallinaro
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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 gauge bosons;
- The leptons coupling to gauge boson are flavour-independent;
- The interaction between leptons and a gauge boson measures the same for each lepton.

\[
\begin{align*}
\ell^- & \rightarrow W^- \nu_{\ell} \\
\ell^- & \rightarrow Z \ell
\end{align*}
\]

\[
\begin{align*}
\frac{-ig_W}{2\sqrt{2}} \gamma^\mu (1 - \gamma^5) \\
\frac{-ig_Z}{2\sqrt{2}} \gamma^\mu (-\frac{1}{2} + 2 \sin^2 \theta_W + \frac{1}{2} \gamma^5)
\end{align*}
\]
Introduction

• To test this axiom the ratio of the rate decay of $W$ bosons to $\tau$-leptons and muons is measured:

\[ R(\tau/\mu) = \frac{B(W \rightarrow \tau\nu_\tau)}{B(W \rightarrow \mu\nu_\mu)} \rightarrow 1(SM) \]

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

Previous results from LEP: $R(\tau/\mu) = 1.070 \pm 0.026$:

• This deviates from the SM expectation by $2.7\sigma$;

• Motivating a precise measurement at the LHC.
Analysis Strategy

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

- Case study is $W$ boson decay to muons or $\tau$-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 $R(\tau/\mu)$ is measured:
    - $W \rightarrow \tau \nu_\tau$ and $\mu \nu_\mu$;
    - and charged conjugate;

Muons are distinguished by the displacement of the $\tau$ 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 13$TeV$;
- 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 $|d^\mu_0| < 0.5\text{mm}$.

Tag muons:
- $p_T^\mu > 27.3\text{GeV}$;

Probe muons:
- $p_T^\mu > 5\text{GeV}$.
Electron Reconstruction and Identification

- Reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters;
- Electron be isolated;
- Electrons must have $p_T^e > 27\text{GeV}$;
- $|\eta| < 2.47$ 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;
- $p_T > 25\text{GeV}$;
- $|\eta| < 2.5$.
- Jets from $b$-quarks are distinguished based on the decay properties of $B$-hadrons.
Event Selection

- One electron and one muon (e$\rightarrow$µ channel) of opposite electric charge or two muons (µ$\rightarrow$µ channel) with opposite electrical charge;

- Events are triggered by:
  - The electron in the e$\rightarrow$µ channel;
  - The tag muon in the µ$\rightarrow$µ 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 µ$\rightarrow$µ channel;
  - $m_{ll} < 15$ Gev from both channels.
Background

- \(Z(\rightarrow \mu\mu) + \text{jets}\)
- Probe muons from multi-jets;
Background normalisation — $Z(\rightarrow \mu\mu) + jets$

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 $1.36 \pm 0.01$;
Background normalisation — Multijets

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

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

- 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 $\mu(\tau \to \mu)$, to those which come from $W \to \mu\nu\mu$ (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

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
Signal Region
\( e^{-} \mu^{-}, 5<p_T<10 \text{ GeV} \)
Post-Fit

Data
- Prompt \( \mu \) (top)
- \( \tau \rightarrow \mu \) (top)
- \( \mu \) (hadron decay)
- \( Z \rightarrow \tau \tau \)
- Other SM processes

\( |d_{ij}| \) [mm]

Events / 0.01 mm

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
Signal Region
\( e^{-} \mu^{-}, 10<p_T<20 \text{ GeV} \)
Post-Fit

Data
- Prompt \( \mu \) (top)
- \( \tau \rightarrow \mu \) (top)
- \( \mu \) (hadron decay)
- \( Z \rightarrow \tau \tau \)
- Other SM processes

\( |d_{ij}| \) [mm]

Events / 0.01 mm

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
Signal Region
\( \mu^{-}\mu^{-}, 20<p_T<250 \text{ GeV} \)
Post-Fit

Data
- Prompt \( \mu \) (top)
- \( \tau \rightarrow \mu \) (top)
- \( \mu \) (hadron decay)
- \( Z \rightarrow \tau \tau \)
- Other SM processes

\( |d_{ij}| \) [mm]

Events / 0.01 mm
Results

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

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

• 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 $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ data and MC using a tag and probe method;

- Background ($\mu$ (had)) scale factor uncertainties.