Precise test of lepton flavour universality in W boson decays into muons and electrons in pp collisions at 13 TeV with the ATLAS detector

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A test of lepton flavour universality in W boson decays is presented, using W bosons that originate from top-quark pair production. The cross-section of top-quark pairs is measured in final states with either two electrons, two muons or an electron-muon pair. From these cross-sections, the ratio of the $W \to \mu\nu$ decay rate to the $W \to e\nu$ decay rate can be obtained and confirms the universality of the lepton couplings to the W boson. The precision of the presented measurement is improved using various techniques, leading to the most precise measurement of this quantity to date.

1 Introduction

In the Standard Model (SM) of particle physics, the couplings of charged leptons to the Higgs boson depend on their masses. For the couplings of the leptons to W or Z bosons, the coupling is however predicted to be independent of the mass, after accounting for radiative and phase-space effects. This assumption is called “lepton flavour universality” in the following and is a fundamental axiom of the SM. Tests of this assumption have been performed at various energies and in several signatures, however no clear departure from the universality of the lepton couplings could be observed so far. In the following the focus will be on the measurement of the ratio of decay rates of W bosons into two different lepton flavours, typically denoted with $R_W^{\ell_1/\ell_2}$.

Recent measurements of R_W were performed using either $e^+e^- \to WW$ production [1], $pp \to W$ production [2,3] or $pp \to t\bar{t}$ production [4] as source of the W bosons under study. The latter process is particularly interesting, since it is abundantly produced at the LHC and always provides two W bosons in the decay. For the decay channels that contain one or two leptons it is furthermore possible to reject a large fraction of background events and reduce the overall uncertainty in R.

While a deviation of almost three standard deviations for $R^{\tau/\mu}$ was measured at the LEP accelerator [1], this was not confirmed with a recent ATLAS measurement using $t\bar{t}$ events [6]. The latter reached an uncertainty of 1.3%.

In the following, a new measurement of $R_W^{\mu/e}$ is discussed [7], using the full Run 2 dataset of pp collisions taken with the ATLAS detector at $\sqrt{s} = 13$ TeV. A previous measurement of this quantity in $t\bar{t}$ events using a partial Run 2 pp dataset allowed for a relative precision of 0.9% [4]. $R_W^{\mu/e}$ is defined as:

$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu_\mu)}{\mathcal{B}(W \to e\nu_e)} \quad . \tag{1}$$

By measuring the ratio of the decay rates, some uncertainties already cancel in the ratio. Since the precision would still be limited by the lepton identification uncertainties however, instead the ratio of $R_W^{\mu/e}$ to $\sqrt{R_Z^{\mu\mu/ee}}$ was measured:

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} \quad . \tag{2}$$

In this double-ratio, both the numerator and denominator contain one power of the lepton efficiencies, which allows for a better cancellation of the corresponding uncertainties. The final value is then obtained by utilising a previous precise result from the LEP and SLD experiments for $R_Z^{\mu\mu/ee}$[1]:

$$R_W^{\mu/e}(\text{ATLAS}) = R_{WZ}^{\mu/e}(\text{ATLAS}) \cdot \sqrt{R_Z^{\mu\mu/ee}}(\text{LEP+SLD}) \tag{3}$$

2 Analysis

2.1 Event selection

In the first step of this measurement, three different datasets (signal regions) are selected, which are combined in the final analysis in order to improve the precision of the measurement. Each of the regions uses a different discriminating variable. The three selections are as follows:

- Opposite-flavour $t\bar{t}$ events: Events with exactly one electron and one muons with opposite charge are selected. In addition, exactly one or two b-tagged jets are required. The discriminating variable in this region is the number of b-tagged jets.
- Same-flavour $t\bar{t}$ events: Events with exactly two electrons or exactly two muons with opposite charge are selected. Also here, exactly one or two b-tagged jets are required. The discriminating variable is the invariant mass of the two leptons, split into separate distributions for one and two b-tagged jets.
- Same-flavour Z events: Events with exactly two electrons or exactly two muons with opposite charge are selected. No requirement on the number of jets is made. The invariant dilepton mass is required to be close to the Z-boson mass. The discriminating variable in this region is the number of ee and $\mu\mu$ events.

2.2 Efficiency reweighting

If the lepton efficiencies between electrons and muons are different, the effect of the modelling of the physics processes could lead to larger uncertainties due to less cancellation in the ratio. These differences in efficiencies can occur for example due to different isolation requirements or different detector acceptance effects. In order to reduce these modelling effects, each muon is assigned a weight as a function of p_T and η. The effect of this reweighting procedure is displayed in Fig. 1 (left), while the weights themselves are shown in Fig. 1 (right). These weights are applied everywhere in the remainder of the analysis.

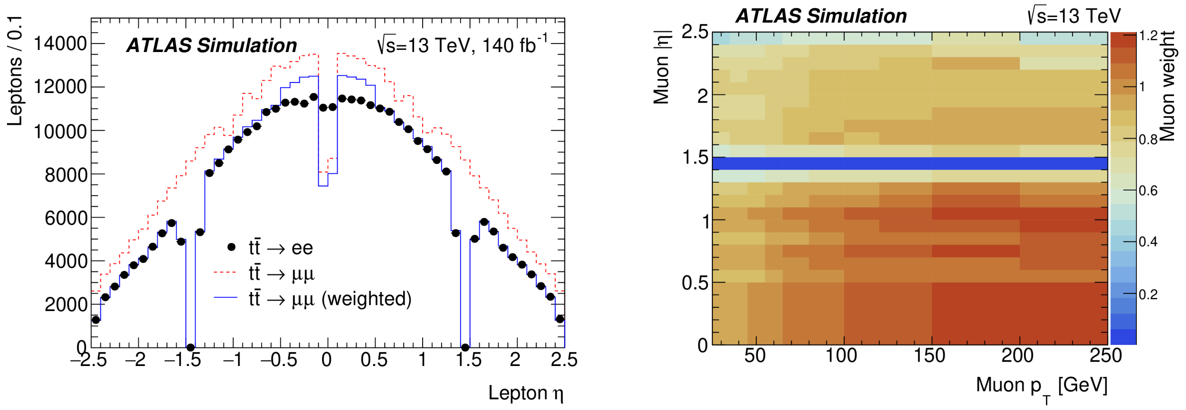

Figure 1 – Left: The muon η distribution (red) is reweighted to match the electron distribution (blue). The reweighted distribution is shown in black. Right: Muon weights as a function of the muon p_T and η [7].

2.3 *Isolation efficiencies*

In the determination of isolation efficiencies for a precision measurement, the difference in the environment in which the efficiencies are being obtained does play a role. Therefore two sets of isolation scale factors are obtained in the following: One set using $Z \rightarrow \ell\ell$ events and a second set using $t\bar{t} \rightarrow \ell\ell$ events, with the latter being surrounded by more additional activity in the event. For both environments, a tag-and-probe method is applied. The measurement was performed for different p_T and η requirements, and the corresponding efficiencies are shown in Fig. 2 for $t\bar{t}$ events (left) and Z events (right). These efficiencies are applied in the following to events passing the $t\bar{t}$ selections and the Z selections, respectively. An additional parameter is introduced in the final analysis setup to take into account the effect from applying the $t\bar{t}$ efficiencies to Z+jets events in the $t\bar{t}$ signal regions.

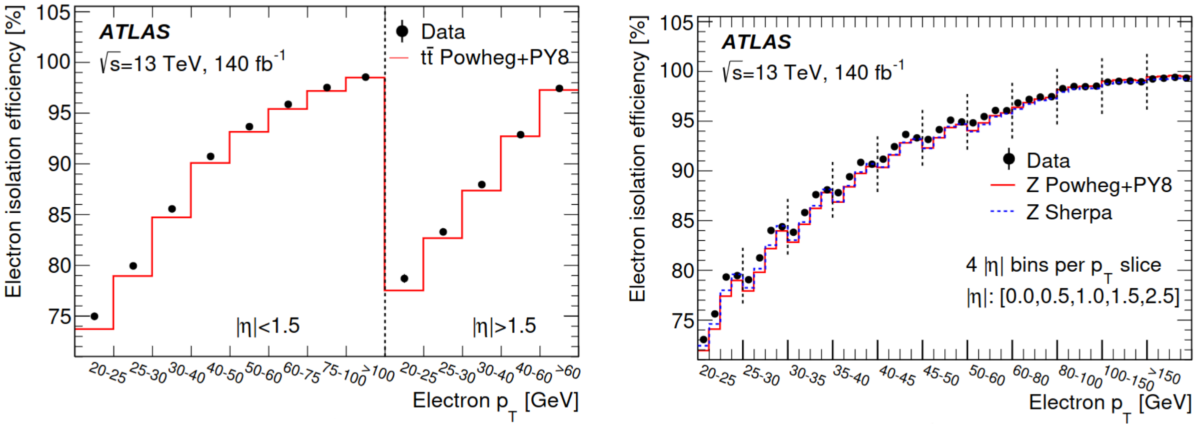

Figure 2 – Electron isolation efficiencies measured in $t\bar{t}$ events (left) and in Z events (right), using the tag-and-probe method [7].

3 Results

The value for $R_{WZ}^{\mu/e}$ is finally obtained by a likelihood fit to the distributions mentioned in section 2.1. The event counts in the three different selection regions are parameterised as a function of various parameters, taking into account among others also the cross-sections, dilepton efficiencies and b-jet efficiencies. The ten parameters obtained from the fit are the cross-sections and ratios ($\sigma_{t\bar{t}}$, $\sigma_{Z\to\ell\ell}$, $R_{WZ}^{\mu/e}$, $R_Z^{\mu\mu/ee}$), the three b-jet efficiencies $\epsilon_b^{\ell\ell}$, the Z+jets scale factors as well as the Z isolation efficiency parameter. Other values in the likelhood are taken from simulation. The detailed breakdown on the systematic uncertainties can be found in Figure 3. The leading uncertainties in R_Z, like the muon identification and the lepton trigger uncertainties, are reduced in the R_{WZ} ratio, leading to an overall uncertainty on R_{WZ} of 0.42%. The total uncertainty on the double-ratio is dominated by lepton and parton distribution function uncertainties.

Uncertainty [%]	$\sigma_{t\bar{t}}$	$\sigma_{Z\to\ell\ell}$	$R_{WZ}^{\mu/e}$	$R_Z^{\mu\mu/ee}$
Data statistics	0.13	0.01	0.22	0.02
$t\bar{t}$ modelling	1.68	0.03	0.10	0.00
Top-quark p_{T} modelling	1.42	0.00	0.06	0.00
Parton distribution functions	0.67	0.68	0.15	0.03
Single-top modelling	0.65	0.00	0.05	0.00
Single-top/$t\bar{t}$ interference	0.54	0.00	0.09	0.00
Z(+jets) modelling	0.06	0.73	0.13	0.20
Diboson modelling	0.05	0.04	0.01	0.00
Electron energy scale/resolution	0.05	0.06	0.10	0.11
Electron identification	0.10	0.07	0.04	0.13
Electron charge misidentification	0.06	0.06	0.01	0.13
Electron isolation	0.09	0.02	0.08	0.04
Muon momentum scale/resolution	0.04	0.02	0.06	0.04
Muon identification	0.18	0.12	0.11	0.23
Muon isolation	0.09	0.01	0.07	0.01
Lepton trigger	0.09	0.12	0.01	0.23
Jet energy scale/resolution	0.08	0.00	0.03	0.00
b-tagging efficiency/mistag	0.14	0.00	0.00	0.00
Misidentified leptons	0.17	0.02	0.15	0.05
Simulation statistics	0.04	0.00	0.06	0.00
Integrated luminosity	0.93	0.83	0.00	0.00
Beam energy	0.23	0.09	0.00	0.00
Total uncertainty	2.66	1.32	0.42	0.45

Figure 3 – Systematic and statistical uncertainties for the four main parameters obtained from the likelihood fit[7].

Taking into acount the previous precision measurement for $R_Z^{\mu\mu/ee}$:

$$R_Z^{\mu\mu/ee}(\text{LEP+SLD}) = 1.0009 \pm 0.0028 \text{ (stat.+syst.)} \quad , \tag{4}$$

the final result is:

$$R_W^{\mu/e}(\text{ATLAS}) = 0.9995 \pm 0.0022\,(\text{stat.}) \pm 0.0036\,(\text{syst.}) \pm 0.0014\,(\text{LEP+SLD}) \quad , \tag{5}$$

which agrees with assumption of lepton-flavour universality.

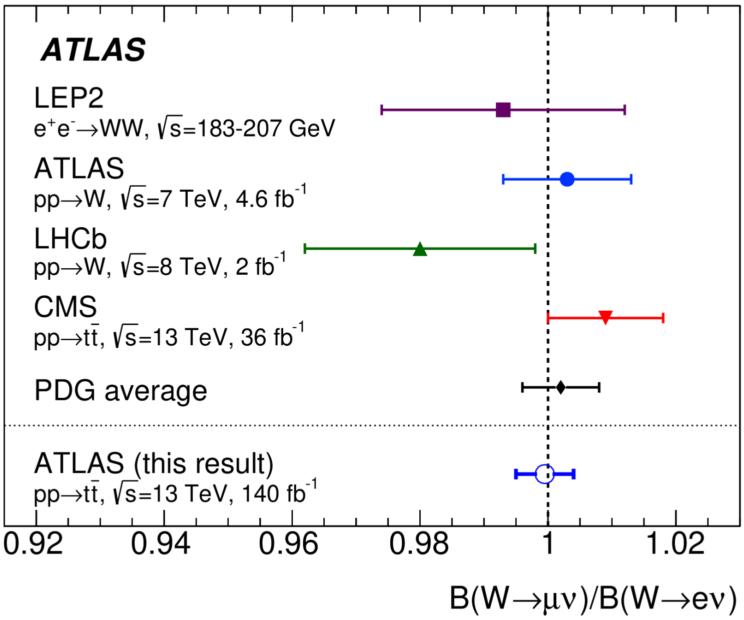

Figure 4 – Comparison of the new result for $R_W^{\mu/e}$ with previous measurements[7].

The relative uncertainty of the new measurement is 0.45 %, and is shown in Figure 4 in comparison with previous measurement of this quantity. This result constitutes the most precise measurement of $R_W^{\mu/e}$ to date, and is even more precise than the current PDG average[5].

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