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

58th Rencontres de Moriond 2024

Andrea Knue, on behalf of the ATLAS Collaboration

Are the boson couplings the same for all charged leptons?

- Higgs boson coupling to leptons: depends on the lepton mass
- W/Z couplings assumed to be independent of mass

  $\hookrightarrow$ lepton flavour universality, fundamental axiom in the Standard Model

How can we test this assumption?

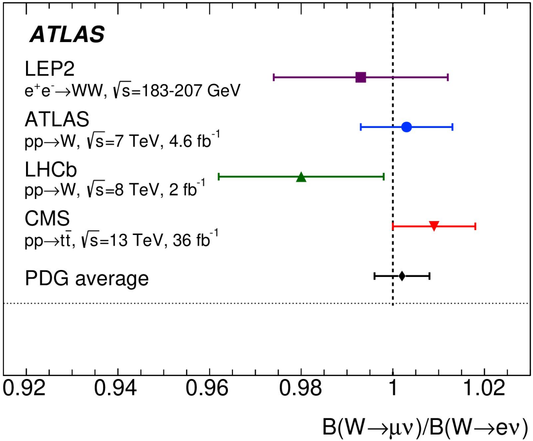
Measure ratio R of boson decay rates:

$$R = \frac{B\left[W \longrightarrow \ell_1 \, \nu_1\right]}{B\left[W \longrightarrow \ell_2 \, \nu_2\right]}$$

How can we use top-quark events for this measurement?

- top-quark pair production: large cross-section at the LHC
  $\hookrightarrow$ 116 million events produced in Run 2 dataset in ATLAS alone !
- top quarks decay to almost 100% into W boson and b quark
- decay with two leptons: very clean source with two W bosons:
  $\hookrightarrow$ still 12 million events before selection
  $\hookrightarrow$ small background contamination
  $\hookrightarrow$ small systematic uncertainties

This measurement: focus on W decays into muons and electrons



- ➢ most precise single measurement so far: also uses $t\bar{t}$ events ▸ Phys. Rev. D 105 (2022)
- ➢ relative precision of that measurement: 0.9%
- ➢ will now present ATLAS analysis with full Run 2 dataset! ▸ arXiv:2403.02133

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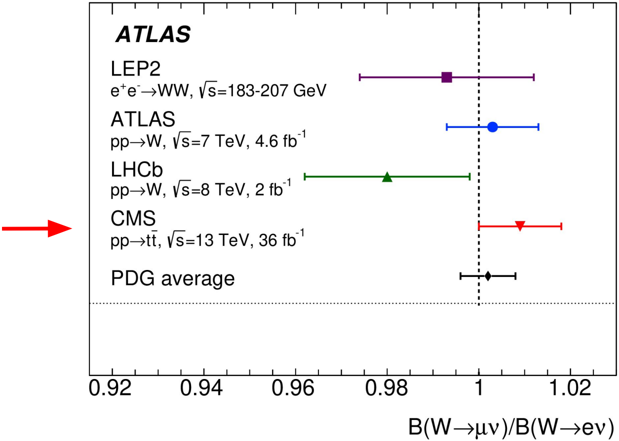

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We are interested in:

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

$\hookrightarrow$ advantage: many uncertainties already cancel in the ratio

$\hookrightarrow$ but: measurement limited by lepton identification uncertainties

Solution: measure ratio of $R_W^{\mu/e}$ and $\sqrt{R_Z^{\mu\mu/ee}}$

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

$\hookrightarrow$ have one power of efficiencies: better cancellation of uncertainties

Get final value by utilising precise LEP/SLD result for $R_Z^{\mu\mu/ee}$:

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

Use well-tested method that allowed for very precise $t\bar{t}$ cross-section (and $t\bar{t}/Z$) measurement at 5, 13 and 13.6 TeV: ▸ JHEP 06 (2023) 138 ▸ JHEP 07 (2023) 141 ▸ PLB 848 (2024) 138376

First step: select events in 3 analysis regions

Opposite flavour tt:

- 1e with 27.3 GeV
- 1μ with 27.3 GeV
- opposite charge
- 1 or 2 b-tagged jets (30 GeV, 70% eff.)

→ **Number of b-tagged jets**

Same flavour tt:

- 2e or 2μ
- opposite charge
- 1 or 2 b-tagged jets (30 GeV, 70% eff.)

→ **Invariant dilepton mass, split for 1 and 2 b-tags**

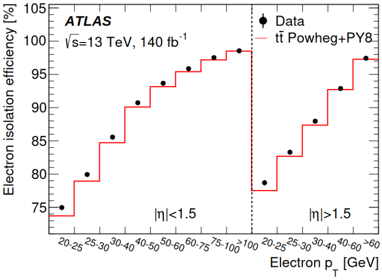
Same flavour Z events:

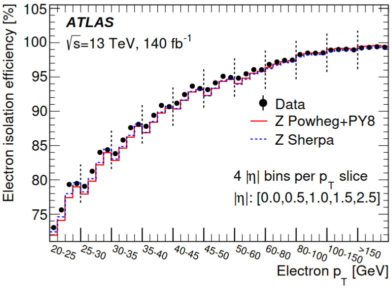
- 2e or 2μ
- opposite charge
- Invariant dilepton mass between 66 and 116 GeV

→ **Number of ee/μμ events**

➢ use data-driven estimates for non-prompt lepton background

Measurement of isolation efficiencies



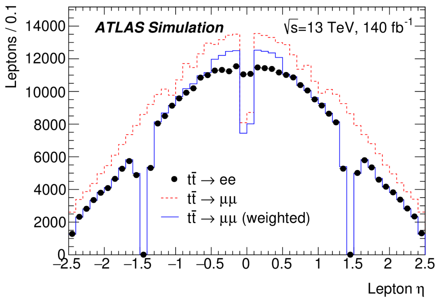


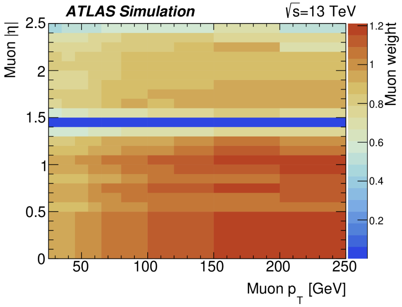
- usually assume scale-factors can be applied universally
- for a precision measurement like this:
  - $\hookrightarrow$ want to reduce uncertainties as much as possible
  - $\hookrightarrow$ difference between the $t\bar{t}$ and inclusive Z environment does matter
  - $\hookrightarrow$ solution: derive dedicated lepton isolation scale-factors

Reduce the impact of physics modelling uncertainties from the start:

- lepton efficiencies are different between electrons and muons
  - $\hookrightarrow$ also have different p_T and η dependence
  - $\hookrightarrow$ signal modelling uncertainties larger if kinematics different
- idea: calculate weight per muon as function of p_T and η:

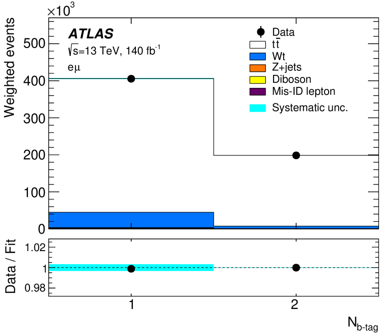
$$w_\mu(p_T, \eta) = w_0 \frac{N_{t\bar{t}}^{ee}(p_T, |\eta|)}{N_{t\bar{t}}^{\mu\mu}(p_T, |\eta|)}$$





➢ all following plots have these weights applied per muon

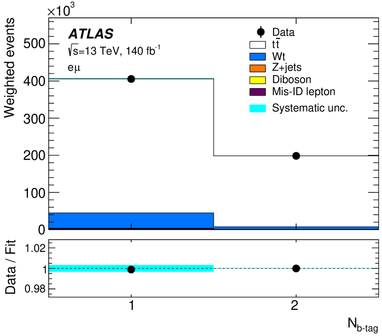
Opposite-flavour $t\bar{t}$ events:



$$N_1^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\,2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k\, N_1^{e\mu,k}$$

$$N_2^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\,C_b^{e\mu}(\epsilon_b^{e\mu})^2 + \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k\, N_2^{e\mu,k}$$

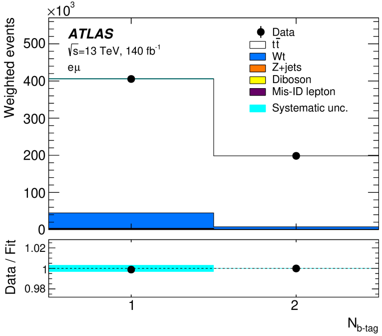
Opposite-flavour $t\bar{t}$ events:



$$\boxed{\begin{aligned} N_1^{e\mu} \\ N_2^{e\mu} \end{aligned}} \begin{aligned} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, 2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k\, N_1^{e\mu,k} \\ &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, C_b^{e\mu}(\epsilon_b^{e\mu})^2 + \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k\, N_2^{e\mu,k} \end{aligned}$$

Number of selected $e\mu$ events
with one/two b-tagged jets

Opposite-flavour $t\bar{t}$ events:



$$N_1^{e\mu} = L\sigma_{t\bar{t}}\, \boxed{\epsilon_{e\mu}}\, g_{e\mu}^{t\bar{t}}\, 2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k N_1^{e\mu,k}$$

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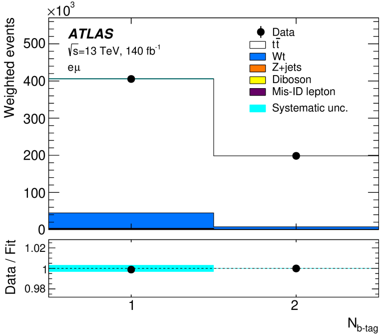
Selection efficiency for $t\bar{t}$ events

Opposite-flavour $t\bar{t}$ events:



$$N_1^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\boxed{g_{e\mu}^{t\bar{t}}}\,2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) + \sum_{k=\text{bkg}} s_1^k g_{e\mu}^k\, N_1^{e\mu,k}$$

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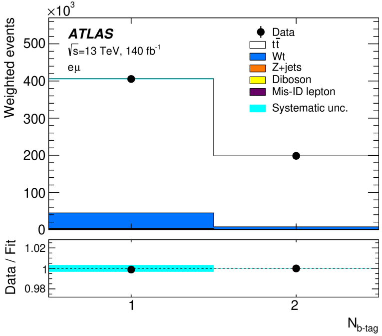
Deviations of W branching ratios from simulated values

Opposite-flavour $t\bar{t}$ events:

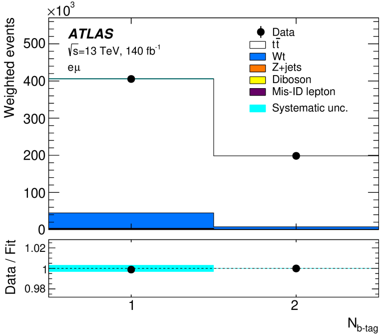


$$N_1^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, 2\boxed{\epsilon_b^{e\mu}}\left(1 - C_b^{e\mu}\boxed{\epsilon_b^{e\mu}}\right) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k\, N_1^{e\mu,k}$$

$$N_2^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, C_b^{e\mu}\boxed{(\epsilon_b^{e\mu})^2} + \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k\, N_2^{e\mu,k}$$

Efficiency to reconstruct and tag b-jet from top decay

Opposite-flavour $t\bar{t}$ events:

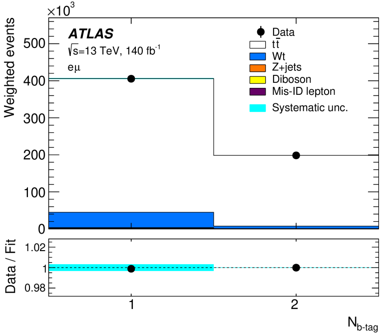


$$N_1^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, 2\epsilon_b^{e\mu}(1 - \boxed{C_b^{e\mu}}\epsilon_b^{e\mu}) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k\, N_1^{e\mu,k}$$

$$N_2^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}} \boxed{C_b^{e\mu}}(\epsilon_b^{e\mu})^2 + \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k\, N_2^{e\mu,k}$$

Correlation coefficient for tagging probabilities of b quark jets

Opposite-flavour $t\bar{t}$ events:

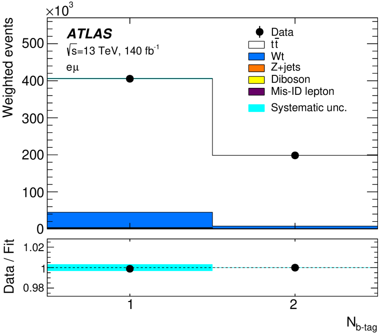


$$N_1^{e\mu} = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, 2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k \boxed{N_1^{e\mu,k}}$$

$$N_2^{e\mu} = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, C_b^{e\mu}(\epsilon_b^{e\mu})^2 + \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k \boxed{N_2^{e\mu,k}}$$

Number of events in background source

Opposite-flavour $t\bar{t}$ events:



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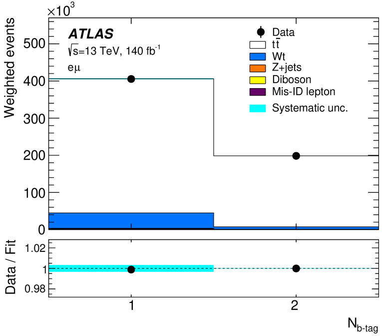
$$N_2^{e\mu} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\,C_b^{e\mu}(\epsilon_b^{e\mu})^2 + \sum_{k=\mathrm{bkg}} \boxed{s_2^k} g_{e\mu}^k\, N_2^{e\mu,k}$$

Scaling factors for each background

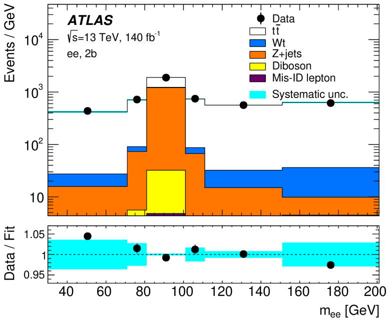
Opposite-flavour $t\bar{t}$ events:

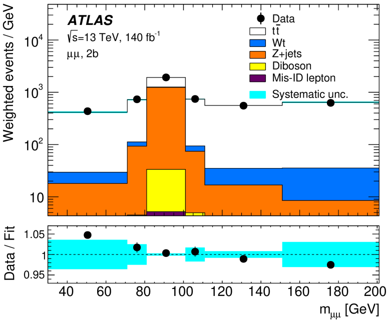


$$
\begin{aligned}
N_1^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, 2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) &+ \sum_{k=\mathrm{bkg}} s_1^k \boxed{g_{e\mu}^k} N_1^{e\mu,k} \\
N_2^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\, C_b^{e\mu}(\epsilon_b^{e\mu})^2 &+ \sum_{k=\mathrm{bkg}} s_2^k \boxed{g_{e\mu}^k} N_2^{e\mu,k}
\end{aligned}
$$

changes in W or Z branching ratios

Same-flavour $t\bar{t}$ events:





$$\boxed{N^{\ell\ell}_{1,m}} = L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\,g^{t\bar{t}}_{\ell\ell}\,2\epsilon^{\ell\ell}_{b}(1-C^{\ell\ell}_{b}\epsilon^{\ell\ell}_{b})\boxed{f^{\ell\ell,t\bar{t}}_{1,m}} + \sum_{k=\mathrm{bkg}} s^{k}_{1}g^{k}_{\ell\ell}\boxed{f^{\ell\ell,k}_{1,m}}N^{\ell\ell,k}_{1}$$

$$\boxed{N^{\ell\ell}_{2,m}} = L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\,g^{t\bar{t}}_{\ell\ell}\,C^{\ell\ell}_{b}(\epsilon^{\ell\ell}_{b})^{2}\boxed{f^{\ell\ell,t\bar{t}}_{2,m}} + \sum_{k=\mathrm{bkg}} s^{k}_{2}g^{k}_{\ell\ell}\boxed{f^{\ell\ell,k}_{2,m}}N^{\ell\ell,k}_{2}$$

Number of same-flavour events per mass bin

fraction of events per mass bin

Now lets look at the finer details:

W branching ratios to e/μ are allowed to differ using parameter Δ_W:

$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu_\mu)}{\mathcal{B}(W \to e\nu_e)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)}$$

$\hookrightarrow$ $\overline{W}$ is the value used in the simulation

We can re-arrange this as:

$$\Delta_W = \frac{R_W^{\mu/e} - 1}{R_W^{\mu/e} + 1}$$

$$\begin{aligned}
g_{ee}^{t\bar{t}} &= f_{0\tau}^{ee}(1-\Delta_W)^2 && +f_{1\tau}^{ee}(1-\Delta_W) && +f_{2\tau}^{ee} \\
g_{e\mu}^{t\bar{t}} &= f_{0\tau}^{e\mu}(1-\Delta_W)(1+\Delta_W) && +f_{1\tau}^{e\mu} && +f_{2\tau}^{e\mu} \\
g_{\mu\mu}^{t\bar{t}} &= f_{0\tau}^{\mu\mu}(1+\Delta_W)^2 && +f_{1\tau}^{\mu\mu}(1+\Delta_W) && +f_{2\tau}^{\mu\mu}
\end{aligned}$$

Fraction of events with n leptons with W → tau → lepton decays

- For tW and WW: $g_{\ell\ell}$ values are set to $g_{\ell\ell}^{t\bar{t}}$: considered as signal

Z branching ratios to $ee/\mu\mu$ are allowed to differ using parameter Δ_Z:

$$R_Z^{\mu\mu/ee} = \frac{\mathcal{B}(Z \to \mu\mu)}{\mathcal{B}(Z \to ee)} = \frac{\overline{Z}(1+\Delta_Z)}{\overline{Z}(1-\Delta_Z)}$$

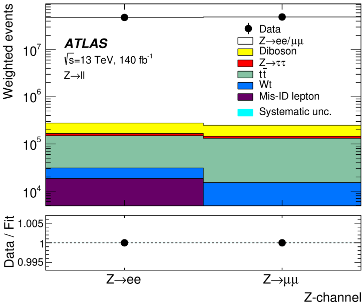
$\hookrightarrow$ $\overline{Z}$ is the average $Z \to \ell\ell$ branching ratio

Same-flavour Z events:

$\hookrightarrow$ no jet multiplicity cut

$\hookrightarrow$ use Powheg to simulate Z production

$\hookrightarrow$ reweighting of $p_{\ell\ell}$ spectrum to data



$$\begin{aligned} N_Z^{ee} &= L\,\sigma_{Z\to\ell\ell}\,\epsilon_{Z\to ee}(1-\Delta_Z) + \sum_{k=\mathrm{bkg}} s_Z^k\, N_Z^{ee,k} \\ N_Z^{\mu\mu} &= L\,\sigma_{Z\to\ell\ell}\,\epsilon_{Z\to \mu\mu}(1+\Delta_Z) + \sum_{k=\mathrm{bkg}} s_Z^k\, N_Z^{\mu\mu,k} \end{aligned}$$

Perform simultaneous likelihood fit to data

Include all three analysis regions:

Opposite flavour tt:

Number of b-tagged jets

Same flavour tt:

Invariant dilepton mass, separately for 1b and 2b

Same flavour Z+jets:

Number of ee/μμ events

Consider 10 free parameters in the fit:

- cross-sections and ratios: $\sigma_{t\bar{t}}$, $\sigma_{Z\to\ell\ell}$, $R_{WZ}^{\mu/e}$, $R_{Z}^{\mu\mu/ee}$
- 3 b-jet efficiencies $\epsilon_b^{\ell\ell}$
- scale factors s_1^{Z+jets}, s_2^{Z+jets}
- Z isolation efficiency parameter

$\hookrightarrow$ all other values: taken from simulation

Looking at largest uncertainties on $R_{WZ}^{\mu/e}$

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

- R_{WZ}: PDF, fake leptons, lepton uncertainties and Z modelling
- leading uncertainties on R_Z reduced in ratio

Now: can calculate the final value via:

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

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Value obtained from likelihood fit:

$$R_{WZ}^{\mu/e}(\mathrm{ATLAS}) = 0.9990 \pm 0.0022\,(\mathrm{stat.}) \pm 0.0036\,(\mathrm{syst.})$$

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Value from LEP+SLD Phys.Rept.427:257-454,2006:

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

Now: can calculate the final value via:

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Value from LEP+SLD ▸ Phys.Rept.427:257-454,2006:

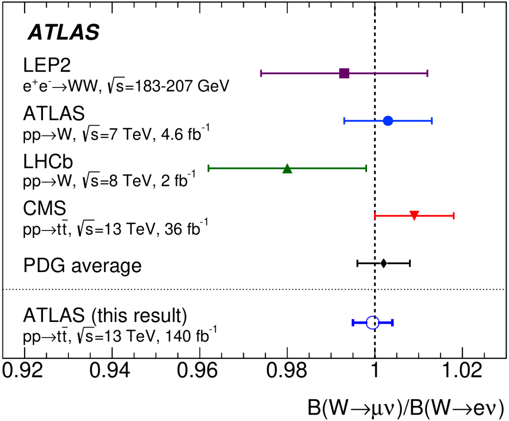
$$R_Z^{\mu\mu/ee}(\text{LEP+SLD}) = 1.0009 \pm 0.0028(\text{stat.+syst.})$$

Final result ▸ arXiv:2403.02133:

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

$\hookrightarrow$ agrees with assumption of lepton-flavour universality!

How does this compare to the previous results?



arXiv:2403.02133

- relative uncertainty of 0.45 %
- most precise single measurement to date!
- also more precise than previous PDG average

Physics Briefing

Tags:
physics results,
lepton flavour universality,
Moriond 2024

Measuring the delicate balance of lepton flavours

24 March 2024 | By ATLAS Collaboration

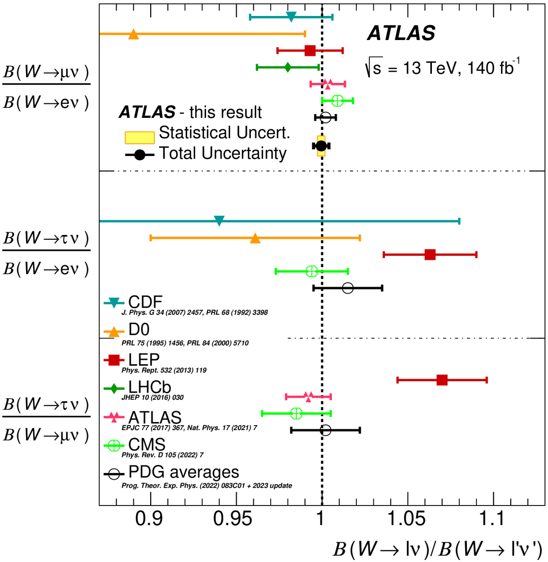
In a new result presented at the Moriond EW conference, physicists at the ATLAS Collaboration tested lepton flavour universality between muons and electrons. The precision of the result stands as the best yet-achieved in W-boson decays by a single experiment and surpasses the world average.

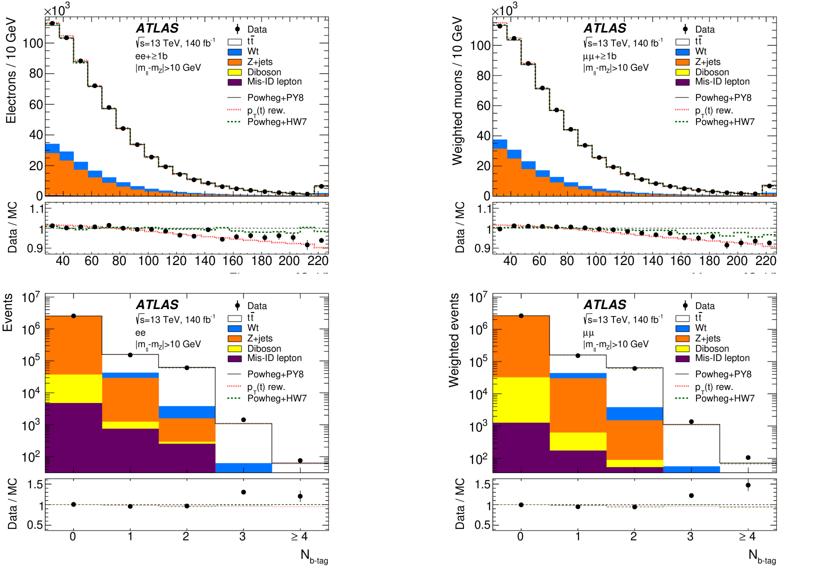
Most elementary particles can be categorised into groups or families with similar properties. For example, the lepton family includes the electron (e), which forms the negatively charged cloud of particles surrounding the nucleus in every atom; the muon (μ), a heavier particle found in cosmic rays; and the tau (τ), an even heavier short-lived particle only seen in high-energy particle interactions. As far as physicists know, the only difference between these particles is their mass. In particular, a remarkable feature of the Standard Model is that each flavour is equally likely to interact with a W boson, a carrier particle of the weak force. This is known as *lepton flavour universality*.

Do you want to know more? We have also prepared a new briefing! Link

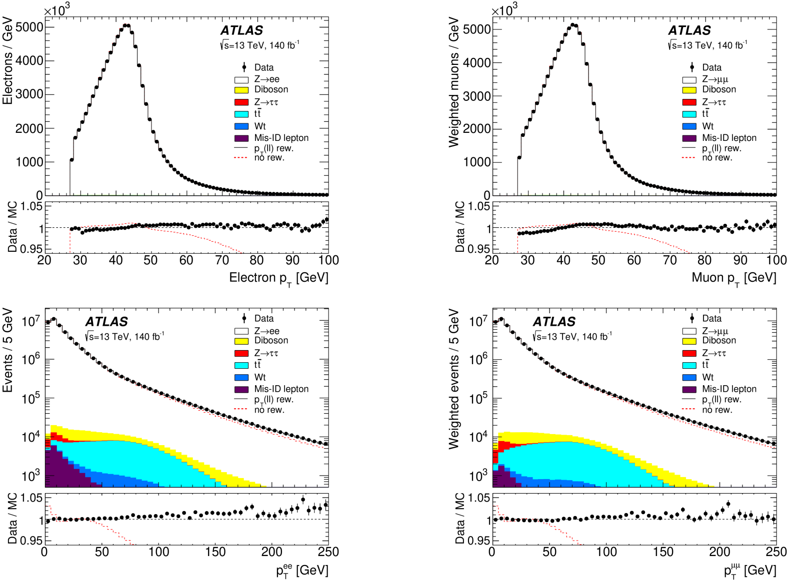
– Backup –

Overview of recent results in different channels



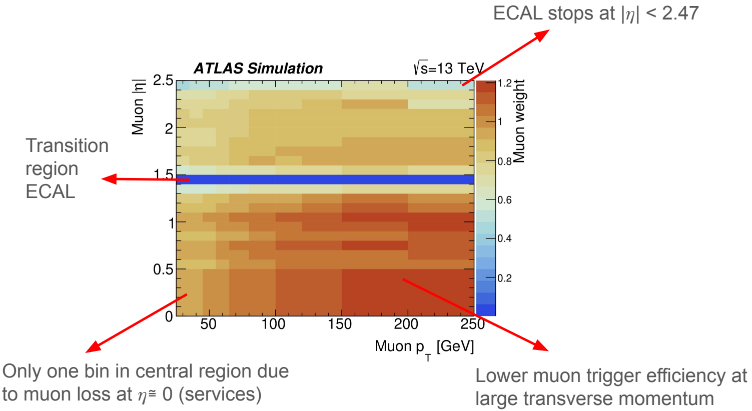


- ➢ in $t\bar{t}$: transverse momenta softer in data than simulation: uncertainty
- ➢ vary events with 3 b at generator level by an additional 50%



➢ $p_T^{\ell\ell}$ reweighted to data to correct for mismodelling

Why are the lepton efficiencies different?



- lowest p lepton trigger: stronger isolation for electrons than muons
- electron efficiency has stronger drop in forward region
- if signal simulation predicts more/less events in certain η or p_T region
  $\hookrightarrow$ different acceptance effects, less cancellation
- could have weighted electrons, but then would have weighted more events up

Summary of extracted values

$$\sigma_{t\bar{t}} = 809.5 \pm 1.1 \pm 20.1 \pm 7.5 \pm 1.9 \text{ pb}$$
$$\sigma_{Z\to\ell\ell} = 2019.4 \pm 0.2 \pm 20.7 \pm 16.8 \pm 1.8 \text{ pb}$$

Scaling parameters for Z+jets:

$$s_1^{Z+jets} = 0.89 \pm 0.09$$
$$s_2^{Z+jets} = 1.12 \pm 0.32$$

Z+jets lepton isolation efficiency difference:

$$R_{Z+b}^{\mu\mu/ee} = 0.990 \pm 0.003$$

Ratios:

$$R_{WZ}^{\mu/e} = 0.9990 \pm 0.0022 \pm 0.0036$$
$$R_{Z}^{\mu\mu/ee} = 0.9913 \pm 0.0002 \pm 0.0045$$

$\hookrightarrow$ potential bias in lepton efficiency, but R_{WZ} protected by ratio

How is the non-prompt lepton background estimated?

In $t\bar{t}$ events:

- fake lepton background rate varies with b-tag multiplicity and $m_{\ell\ell}$ bin
  $\hookrightarrow$ low $m_{\ell\ell}$: originate more from heavy-flavour decays
  $\hookrightarrow$ at high values: more photon conversions
- select events where leptons have the same charge (same-sign, SS)
  $\hookrightarrow$ use this to normalise the fake rate:

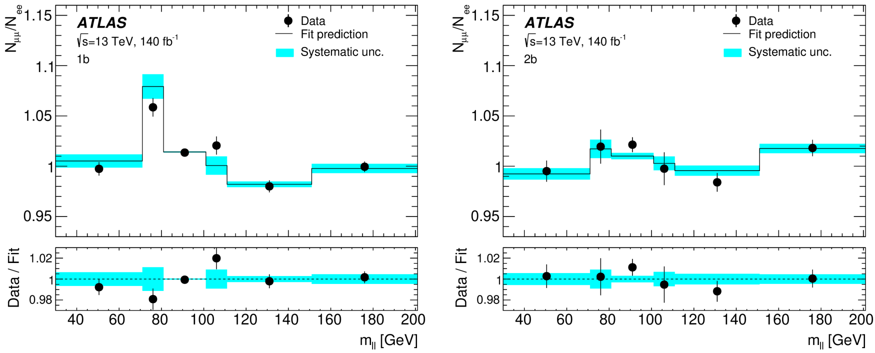
$$N_j^{\text{fake}} = \frac{N_j^{\text{fake, OS}}}{N_j^{\text{fake, SS}}} \cdot (N_j^{\text{data, SS}} - N_j^{\text{prompt, SS}})$$

In Z events:

- simulation is missing multijet production: use data-driven ABCD method
- define A, B, C, D regions enriched in fake leptons based on:
  $\hookrightarrow$ same/opposite charge, isolation and ID...

$$N_{A,\text{Signal}} = \frac{N_B^{\text{fake}} N_C^{\text{fake}}}{N_D^{\text{fake}}}$$

$\hookrightarrow$ less than 0.1% contribution



- removing of first $m_{\ell\ell}$ bin changed R_{WZ} by less than 0.01%
- mismodelling in ee and $\mu\mu$ cancels in the ratio
- found consistent results between three data-taking periods
- R_{WZ} stable against p_T cut (increased up to 40 GeV)
- R_{WZ} stable against cut on $|\eta| < 1.5$