Lepton flavour universality in W→μν vs. W→eν

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on behalf of the ATLAS Collaboration

LHC top WG meeting, 25/4/24

- Outline
  - Introduction
  - Event selection and kinematic distributions
  - Analysis method
  - Lepton isolation corrections
  - Overview of systematics
  - Results and cross-checks
  - Conclusions

- Documentation
  - Paper: arXiv:2403:02133, further information
  - ATLAS physics briefing

Introduction

- Equality of e, μ, τ couplings to W boson is an axiom of the Standard Model
  - Tested in τ, π, K decays to 0.1-0.2%
  - Some tensions in B→D$^{(*)}\tau$ vs B→D$^{(*)}$μ and [no longer?] in b→sμμ vs. b→see
- Tested in real W decays in e^+e^-→WW, pp→W, tt→WWbb to % level
  - LEP discrepency in $R_W^{\tau/\mu}$=B(W→τ)/B(W→μ) 'resolved' by ATLAS , 0.992±0.013
- Now focus on μ vs. e – existing measurements of $R_W^{\mu/e}$:

Experiment	Process	Result
CMS, $\sqrt{s}$ = 13 TeV	$t\bar{t}$	1.009 ± 0.009
ATLAS, $\sqrt{s}$ = 7 TeV	W	1.003 ± 0.010
LHCb, $\sqrt{s}$ = 8 TeV	W	0.980 ± 0.018
LEP2 $\sqrt{s}$ = 130–209 GeV	WW	0.993 ± 0.019
PDG average	-	1.002 ± 0.006

  - Most precise measurements from LHC:
    - σ(W→μ) vs σ(W→e) in 7 TeV ATLAS data
    - Global fit of tt→WbWb events in 13 TeV CMS data (partial sample, 36 fb^{-1})
  - New ATLAS measurement exploits tt→WbWb→lνblνb events in full Run-2 data

Measurement in dileptonic top-pair events

- 116M Run-2 top-pair events provide a big sample of $tt \rightarrow WbWb \rightarrow l\nu bl\nu b$
  - Simultaneous measurements of top-pair cross-section σ_{tt} in ee, eμ and μμ final states gives sensitivity to $R^{\mu/e}_W = B(W\rightarrow\mu)/B(W\rightarrow e)$
- Model: compensating variations Δ_W in $W\rightarrow\mu$ and $W\rightarrow e$, with $W\rightarrow\tau$ fixed

$$R_W^{\mu/e} = \frac{B(W \rightarrow \mu\nu)}{B(W \rightarrow e\nu)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)} \qquad \Delta_W = (R_W^{\mu/e} - 1)/(R_W^{\mu/e} + 1)$$

- Measurement would be limited by electron and muon efficiency uncertainties
  - Instead, normalise using ratio $R_Z = B(Z\rightarrow\mu\mu)/B(Z\rightarrow ee)$ measured from $Z\rightarrow ll$ sel^n

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{B(W \rightarrow \mu\nu)}{B(W \rightarrow e\nu)} \cdot \sqrt{\frac{B(Z \rightarrow ee)}{B(Z \rightarrow \mu\mu)}} \qquad \Delta_Z = (R_Z^{\mu\mu/ee} - 1)/(R_Z^{\mu\mu/ee} + 1)$$

  - Determine $R^{\mu/e}_W$ from ttbar selection
    - Determine auxillary parameter R_Z in parallel $Z\rightarrow ll$ analysis with similar selections
  - Take $R^{\mu/e}_{WZ}$ as output from analysis – reduced lepton efficiency uncertanties
  - Convert to $R^{\mu/e}_W$ using $R^{\mu\mu/ee}_Z = 1.0009 \pm 0.0028$ from LEP/SLD as external input

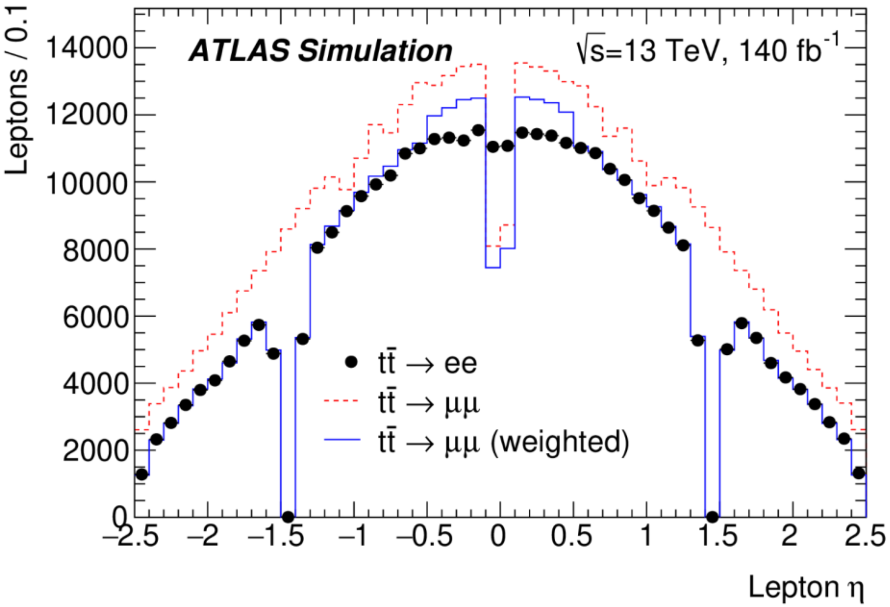
Event selection

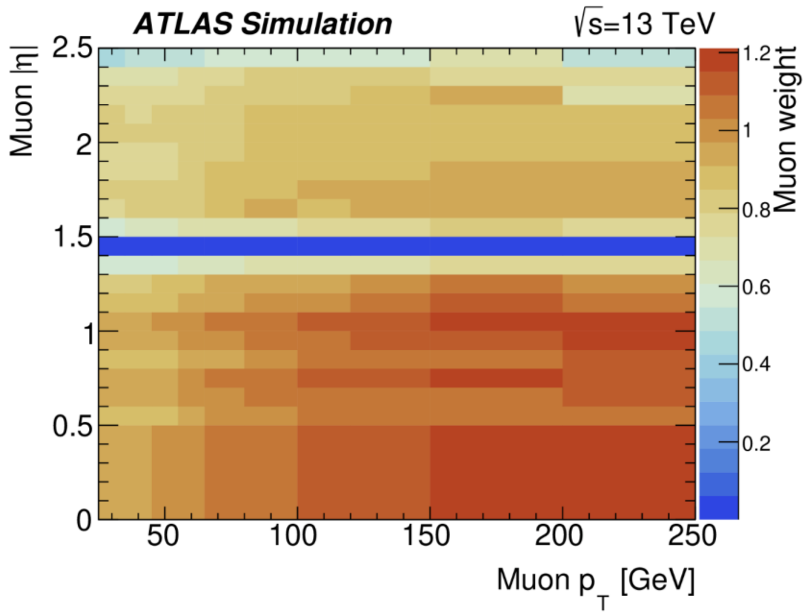
- Two parallel selections with common lepton definition
  - Standard identified electrons and muons, both passing tight isolation requirements
    - At least one lepton must pass single lepton trigger
  - **ttbar**: Opposite-sign ee, eμ, μμ with m_{ll}>30 GeV and 1 or 2 b-tagged jets
  - **Z**: Opposite-sign ee or μμ with $66<m_{ll}<116$ GeV and no requirements on jets

Object selection		
Electrons	$p_T > 27.3$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	
Muons	$p_T > 27.3$ GeV, $\lvert\eta\rvert < 2.5$	
b-tagged jets	$p_T > 30.0$ GeV, $\lvert\eta\rvert < 2.5$, b-tagging DL1r 70%	
Event selection	$t\bar{t} \to \ell\ell b\bar{b}\nu\bar{\nu}$	$Z \to \ell\ell$
Dilepton flavour ($\ell^+\ell^-$)	ee, $e\mu$, $\mu\mu$	ee, $\mu\mu$
Dilepton invariant mass	$m_{\ell\ell} > 30$ GeV	66 GeV $< m_{\ell\ell} <$ 116 GeV
b-tagged jet multiplicity	1 or 2	–

Muon efficiency weighting

- Efficiency differences between electrons and muons vs. p_T, $|\eta|$ would spoil the cancellation of physics modelling systematics between ee and μμ
  - Derive a binned per muon efficiency weight such that the 2D (p_T,$|\eta|$) distributions of selected leptons in ee and μμ events are the same

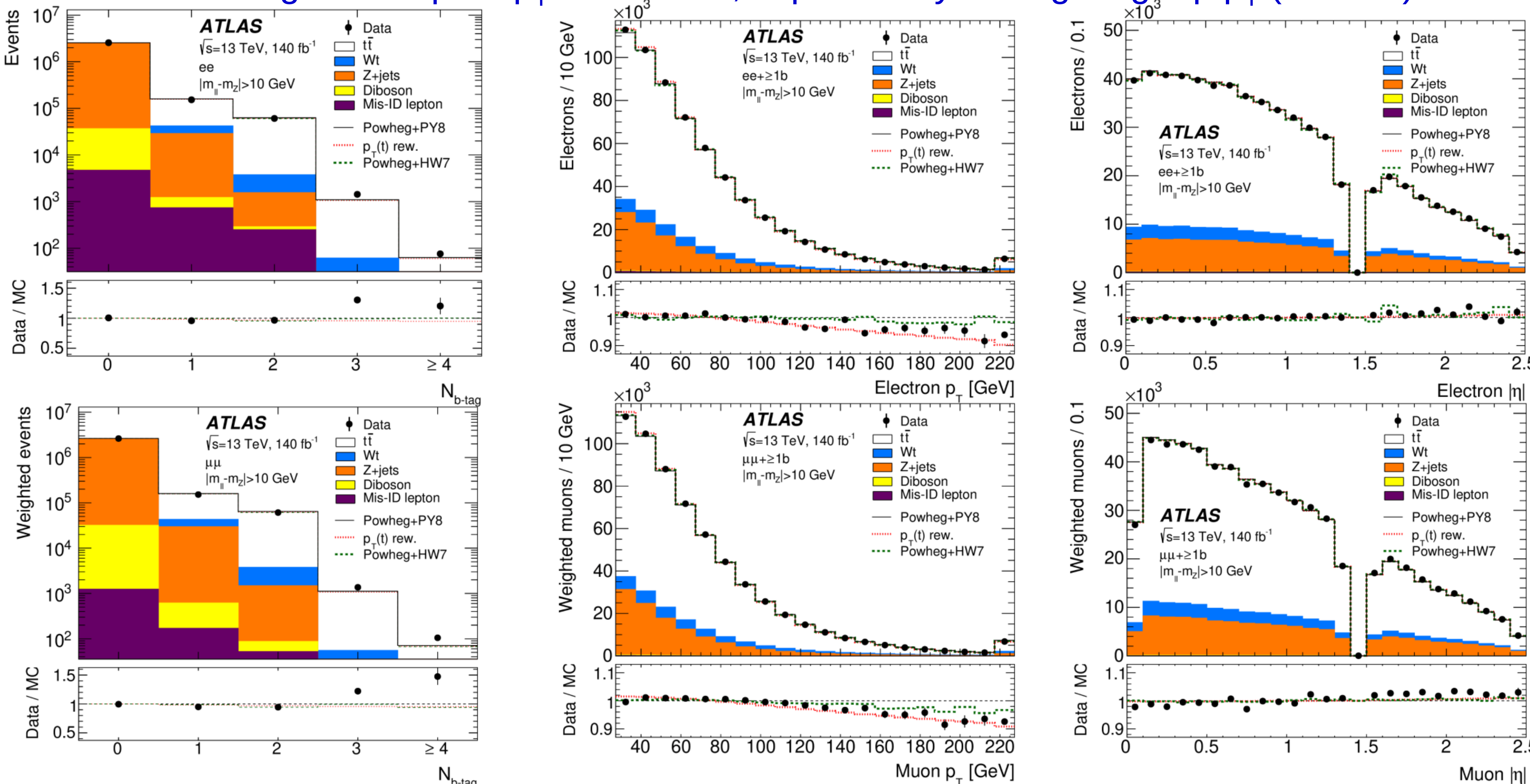




    - First weight bin is $|\eta|<0.5$, so do not model the muon efficiency loss at $\eta\approx 0$, but the physics modelling uncertainties are small in this region
  - Results in **weighted** event counts for μμ and eμ channels – included in all plots
  - Data statistical error is no longer $\sqrt{N}$; taken into account in fit

Event selection results

- Kinematic plots for same-flavour channels – generally good modelling
  - Powheg+PY8 lepton p_T is too hard, improved by reweighting top p_T (red line)



Analysis method - I

- Extension of the double-tag method used to measure σ_{tt} in eμ

eμ:

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

  - Expected numbers of events N_i^{ll} with i=1,2 b-tagged jets expressed in terms of dilepton efficiency $\varepsilon_{e\mu}$, jet+b-tag efficiency ε_b, tagging correlation C_b≈1 and background sources k (k=Wt, Z+jets, diboson, misidentified leptons)
- Same flavour channels have peaking background from Z→ee/μμ + b-jets
  - Split into mass bins m, with fractions $f_{i,m}$ in each bin

ee/μμ:

$$N_{1,m}^{\ell\ell} = L\sigma_{t\bar{t}}\, \epsilon_{\ell\ell}\, g_{\ell\ell}^{t\bar{t}}\, 2\epsilon_b^{\ell\ell}(1 - C_b^{\ell\ell}\epsilon_b^{\ell\ell})\, f_{1,m}^{\ell\ell,t\bar{t}} + \sum_{k=\mathrm{bkg}} s_1^k g_{\ell\ell}^k\, f_{1,m}^{\ell\ell,k} N_1^{\ell\ell,k}$$
$$N_{2,m}^{\ell\ell} = L\sigma_{t\bar{t}}\, \epsilon_{\ell\ell}\, g_{\ell\ell}^{t\bar{t}}\, C_b^{\ell\ell}(\epsilon_b^{\ell\ell})^2\, f_{2,m}^{\ell\ell,t\bar{t}} + \sum_{k=\mathrm{bkg}} s_2^k g_{\ell\ell}^k\, f_{2,m}^{\ell\ell,k} N_2^{\ell\ell,k}.$$

- Factors g_{ll} encode changes in efficiencies wrt. simulation due to BR changes

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

  - Fractions $f_{n\tau}$ account for fixed contributions from W→τ→e/μ in dilepton samples
    - $f_{0\tau}$=0.88, $f_{1\tau}$=0.11, $f_{2\tau}$=0.004, taken from simulation

Analysis method - II

- Analogous equations for numbers of Z→ll events in Z selections:

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

  - Depends on Z cross-section, dilepton effciency $\varepsilon_{Z\to ll}$, branching ratio changes Δ_Z, and background sources k (k=dibosons, Z→$\tau\tau$, ttbar, Wt, misidentified leptons)
- In ttbar selection, Wt and diboson events have two Ws – effectively signal
  - Use same efficiency scalings g_{ll} as for ttbar events
  - g_{ll} for Z+jets background depend on Δ_Z (from Z BR) and Δ_{Z+b}

$$g_{ee}^{Z+\mathrm{jets}} = (1-\Delta_Z)(1-\Delta_{Z+b})$$
$$g_{e\mu}^{Z+\mathrm{jets}} = 1$$
$$g_{\mu\mu}^{Z+\mathrm{jets}} = (1+\Delta_Z)(1+\Delta_{Z+b})$$

  - Δ_{Z+b} corrects for potential mismodelling of the electron vs. muon isolation efficiency in Z+(b) jet events compared to inclusive Z events

Analysis method - III

- Maximum likelihood fit to observed / expected event counts in each bin
  - 6 mass bins for ee / μμ with 1/2 b-tagged jets (24 bins)
  - eμ with 1/2 b-tagged jets (2 bins); Z→ee / μμ (2 bins)
- Fit with 10 free parameters:
  - Cross-sections σ_{tt} and σ_Z, branching fraction ratios R_{WZ} and R_Z
  - Jet/b-tagging efficiency parameters ε_b for ee, eμ and μμ selections
  - Scaling of Sherpa Z+1b, 2b predictions (R_1^Z and R_2^Z), and R_{Z+b} isolation param.

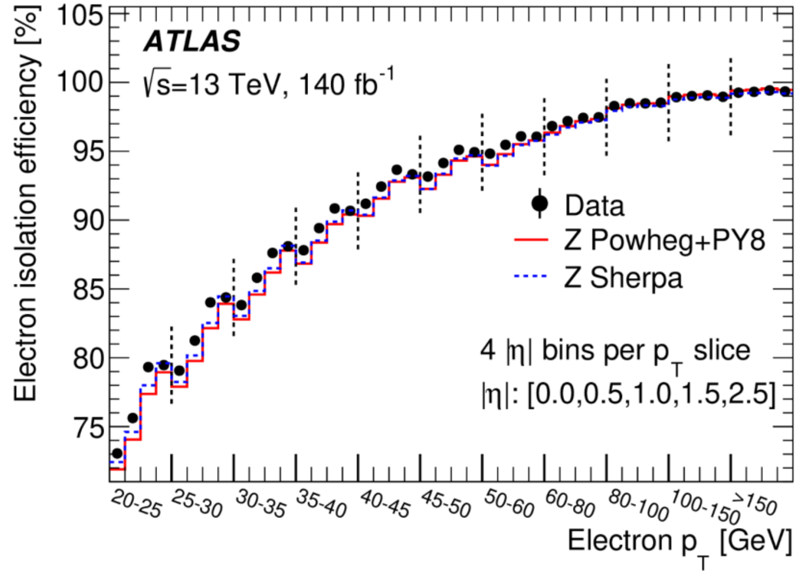
- Misidentified lepton backgrounds determined from data
  - In ttbar selection, using same-sign events with a SS→OS transfer factor R^i_j

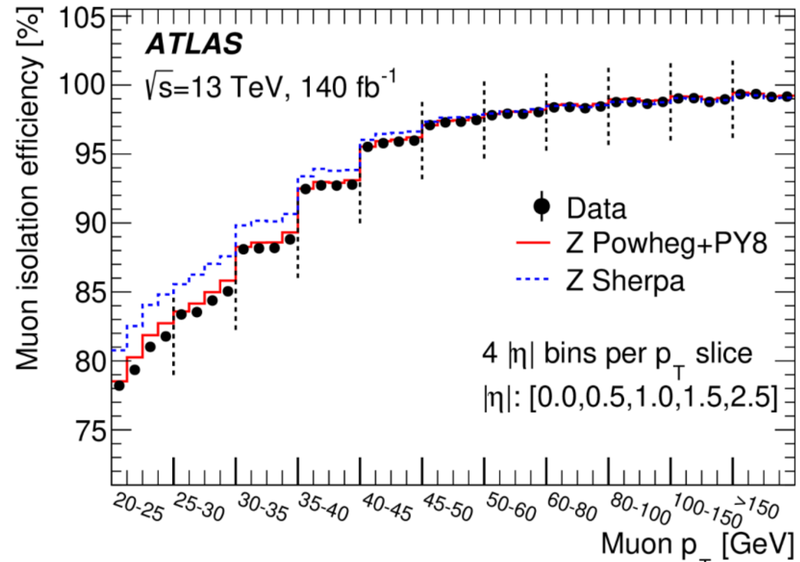
$$N_j^{i,\text{mis-id}} = R_j^i (N_j^{i,\text{d,SS}} - N_j^{i,\text{prompt,SS}}) \qquad R_j^i = \frac{N_j^{i,\text{mis-id,OS}}}{N_j^{i,\text{mis-id,SS}}}$$ from simulation

  - In Z→ll events, using 'ABCD' method with reversed isolation/identification cuts, and same-sign events

Lepton isolation efficiency: Z events

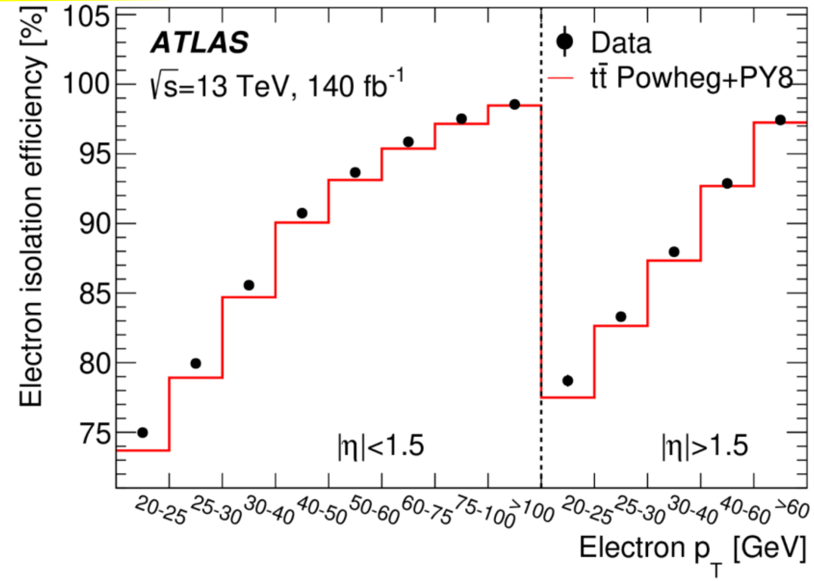
- Dedicated in-situ lepton isolation efficiency measurements for both Z→ll and ttbar
  - Different environments – do not cancel
- Efficiencies for Z→ll measured using tag and probe techniques
  - In bins of p_T and $|\eta|$ (and per year)
  - Uncertainties on $\varepsilon(Z\to ee/\mu\mu) < 0.05\%$
    - Powheg+PY8 (used for inclusive Z modelling) underestimates low p_T electron efficiency by 2%, and overestimates muon efficiency by 1%
  - Sherpa Z(+jets) used for Z+jets background in ttbar selection overestimates low p_T muons by 3%
  - This effect may carry over to Sherpa Z+1b,2b in ttbar selection,
    - Motivates dedicated R_{Z+b} fit parameter

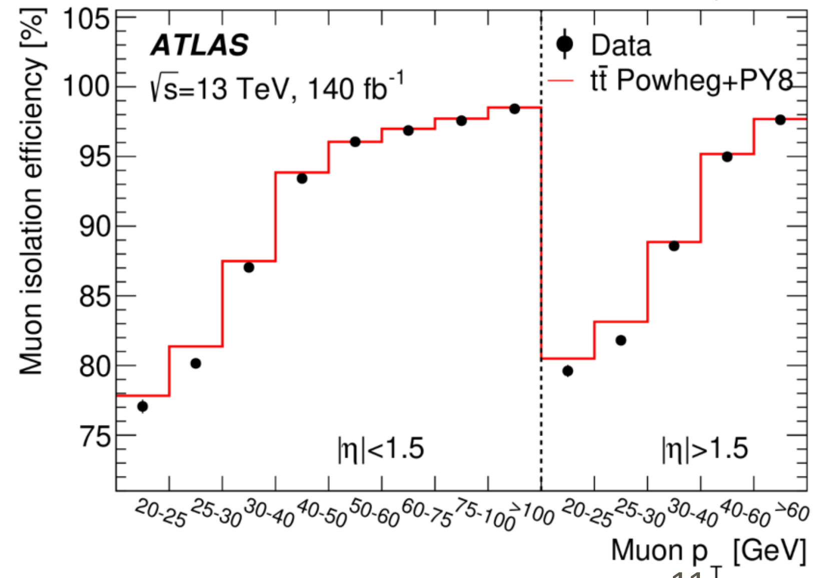




Lepton isolation efficiency: ttbar events

- Isolation efficiency measured in eμ ttbar events with 1 or 2 b-tagged jets
  - As function of p_T in two $|\eta|$ bins
    - Large misidentified lepton background estimated using SS events
  - Uncertainties around 0.1% per lepton
  - Again, Powheg+PY8 underestimates electron and overestimates muon efficiency
- Data/MC ratios used to define scale factors
  - ttbar-measured SFs applied to all MC events passing the ttbar selection
  - Likely inappropriate for Sherpa Z+jets
    - Corrected by R_{Z+b} fit parameter
    - Fit result: $R_{Z+b}=0.990\pm0.003$
    - Compatible with the Powheg+PY8 vs. Sherpa difference in isolation efficiencies in inclusive $Z\rightarrow ll$ events





Systematic uncertainties

- ‘Standard’ systematic uncertainties
  - Explict uncertainty from reweighting top p_T distribution to agree with data
    - Nominal is **unweighted** Powheg+PY8
  - NNPDF3.0 variations evaluated coherently for all processes
  - Lepton identification done with replica SF sets to model correlations across (p_T, η) and between ttbar and Z
    - Significant cancellations in R_{WZ}
  - Lepton isolation and misidentifaction background considered uncorrelated
  - Jet / b-tagging systematics are tiny
- σ_{tt} uncertainty large wrt. eμ result
  - σ_Z dominated by physics modelling
  - Reduces when translated to fiducial cross-section (p_T>25 GeV, $|\eta|$<2.5)

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

Fit to data – weighted event counts

- Number of (weighted) data events compared to 'post fit' predictions
  - ee/μμ counts divided into off-Z ($|m_{ll}-m_Z|$>10 GeV) and on-Z regions

Event counts	$N^{ee}_{1,\mathrm{off-Z}}$	$N^{ee}_{1,\mathrm{on-Z}}$	$N^{e\mu}_{1}$	$N^{\mu\mu}_{1,\mathrm{off-Z}}$	$N^{\mu\mu}_{1,\mathrm{on-Z}}$
Data	222304	442108	405437	223085	448105
$t\bar{t}$	154800 ± 1700	24830 ± 850	361000 ± 4200	152500 ± 1800	24070 ± 860
Wt	17500 ± 1600	2770 ± 240	41500 ± 3800	17800 ± 1700	2730 ± 250
Z+jets	46880 ± 400	410700 ± 2000	859 ± 21	51010 ± 780	418000 ± 2000
Diboson	770 ± 160	3940 ± 840	790 ± 280	770 ± 160	3880 ± 830
Mis-ID leptons	1300 ± 500	360 ± 260	1740 ± 610	390 ± 150	172 ± 87
Total prediction	221280 ± 550	442600 ± 1100	405900 ± 1800	222390 ± 670	448900 ± 1100

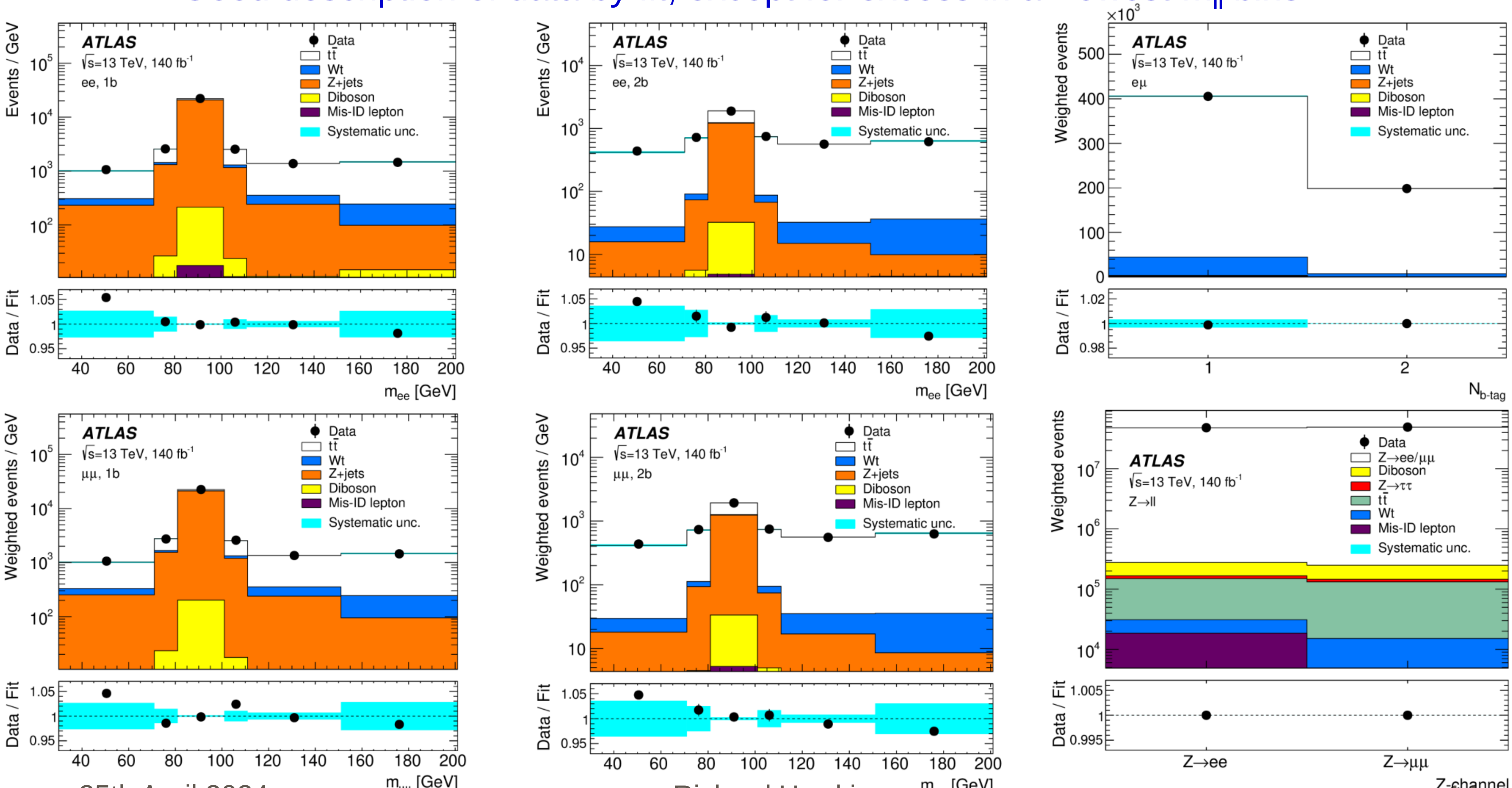
Event counts	$N^{ee}_{2,\mathrm{off-Z}}$	$N^{ee}_{2,\mathrm{on-Z}}$	$N^{e\mu}_{2}$	$N^{\mu\mu}_{2,\mathrm{off-Z}}$	$N^{\mu\mu}_{2,\mathrm{on-Z}}$
Data	85936	37704	198502	86169	38512
$t\bar{t}$	79750 ± 920	13340 ± 480	191000 ± 1800	79770 ± 830	13180 ± 450
Wt	2860 ± 760	400 ± 110	6700 ± 1600	2940 ± 740	423 ± 90
Z+jets	2675 ± 68	23610 ± 590	78 ± 2	3095 ± 87	24110 ± 600
Diboson	67 ± 23	550 ± 110	29 ± 8	71 ± 30	570 ± 110
Mis-ID leptons	400 ± 290	96 ± 59	720 ± 520	350 ± 160	104 ± 56
Total prediction	85760 ± 360	38000 ± 190	198510 ± 440	86230 ± 300	38380 ± 210

Event counts	$Z \to ee$	$Z \to \mu\mu$
Data	47898836	49016812
$Z \to \ell\ell$	47621000 ± 33000	48767000 ± 29000
Diboson	111000 ± 22000	104000 ± 21000
$Z \to \tau\tau$	16850 ± 140	13780 ± 110
$t\bar{t}$	119000 ± 14000	117000 ± 14000
Wt	12380 ± 890	12390 ± 880
Mis-ID leptons	19000 ± 18000	3000 ± 13000
Total prediction	47898800 ± 6900	49016800 ± 6200

  - ee/μμ + 1b-tagged jet ~70% pure in ttbar, background dominated by Z+jets
  - ee/μμ + 2 b-tagged jet ~93% pure ttbar, equal background from Z+jets and Wt
    - eμ is 89%/96% pure in ttbar, background almost all Wt
  - Inclusive Z are 99.5% pure in Z events, background mainly ttbar and diboson

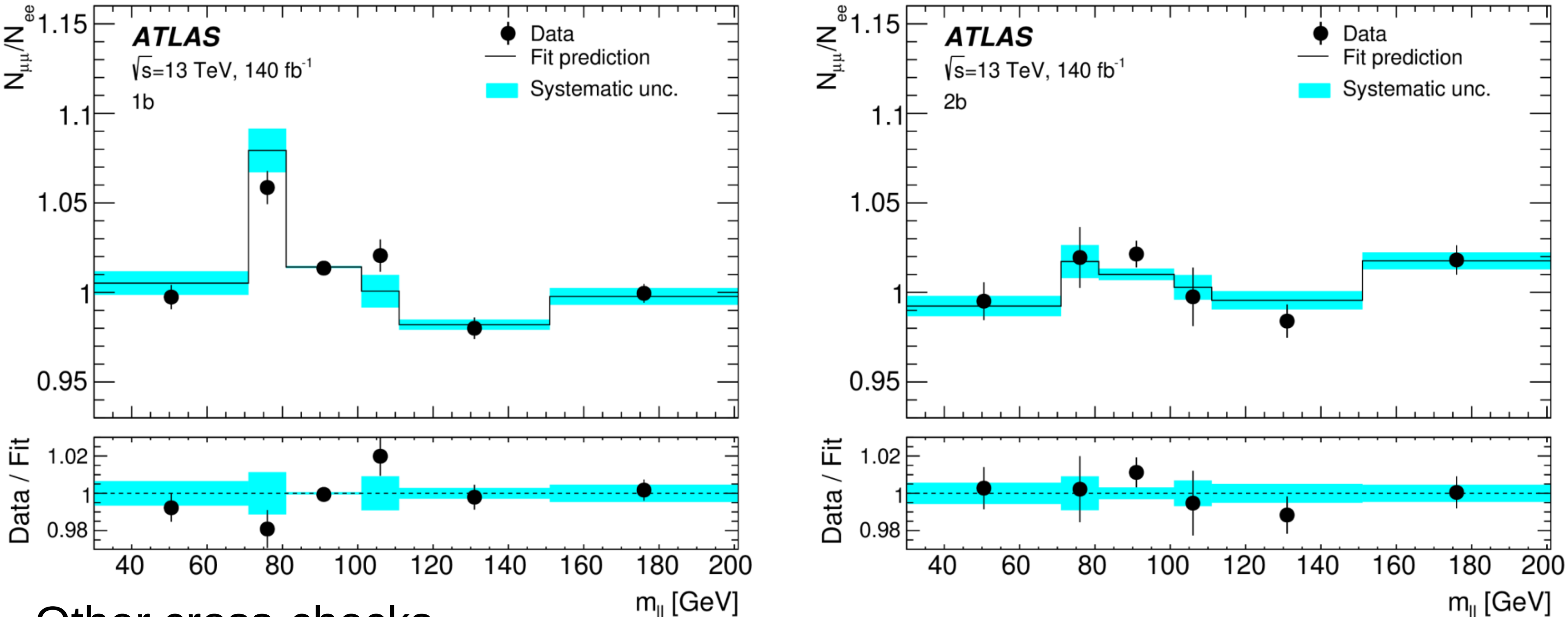
Fit to data – in figures

- Numbers of dilepton events with 1 and 2 b-tags, vs m_{ll} in ee/μμ events
  - Good description of data by fit, except for excess in all lowest m_{ll} bins



Event count ratio and cross-checks

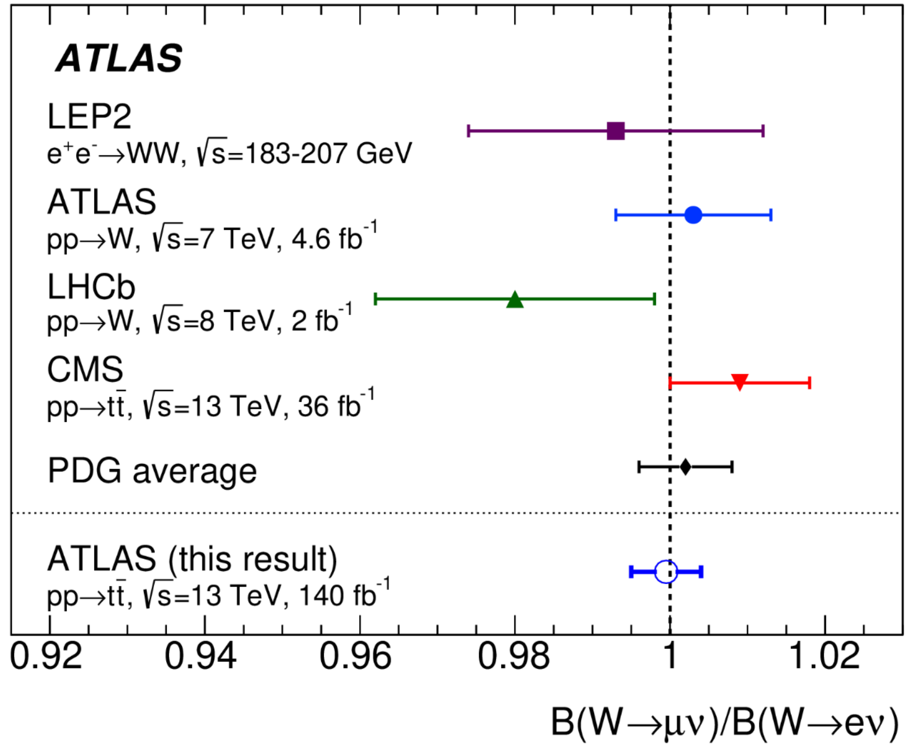
- Ratio μμ/ee cancels common physics modelling systematics (tt, Z+jets)
  - Compare data to fit prediction – good agreement



- Other cross-checks
  - Removing lowest m_{ll} bin has negligable effect on R_{WZ} central value
  - Consistent results from analysing 2015+16, 2017 and 2018 data separately
  - Result for R_{WZ} stable against changing lepton p_T and $|\eta|$ cuts

Results

- Results for cross-sections:
  - σ_{tt} = 809.5 ±1.1 ±20.1 ±7.5±1.9 pb
  - $\sigma_{z\text{-}fid}$ = 774.7 ±0.1 ±1.8 ± 6.4 ±0.7 pb
  - Both agree with previous results
- Results for ratios of branching ratios:
  - R_{WZ} = 0.9990 ± 0.0022 ± 0.0036
  - R_Z = 0.9913 ± 0.0002 ± 0.0045
    - R_Z 1.9σ below unity, similar to trend seen in other 13 TeV ATLAS Z measurements
    - Normalisation to R_Z ‘protects’ R_W against potential biases in lepton efficiencies
- Using external value of R_Z from e^+e^- :
  - R_Z(ext)=1.0009 ± 0.0028
  - Convert R_{WZ} to R_W: $R_W = R_{WZ} * \sqrt{R_Z}$
- R_W=0.9995±0.0022±0.0036±0.0014
  - Uncertainties: stat, syst, external
  - Total uncertainty 0.0045



- Most precise result to date
  - Previous PDG average 1.002±0.006
- No sign of lepton flavour violation ☺ / ☹

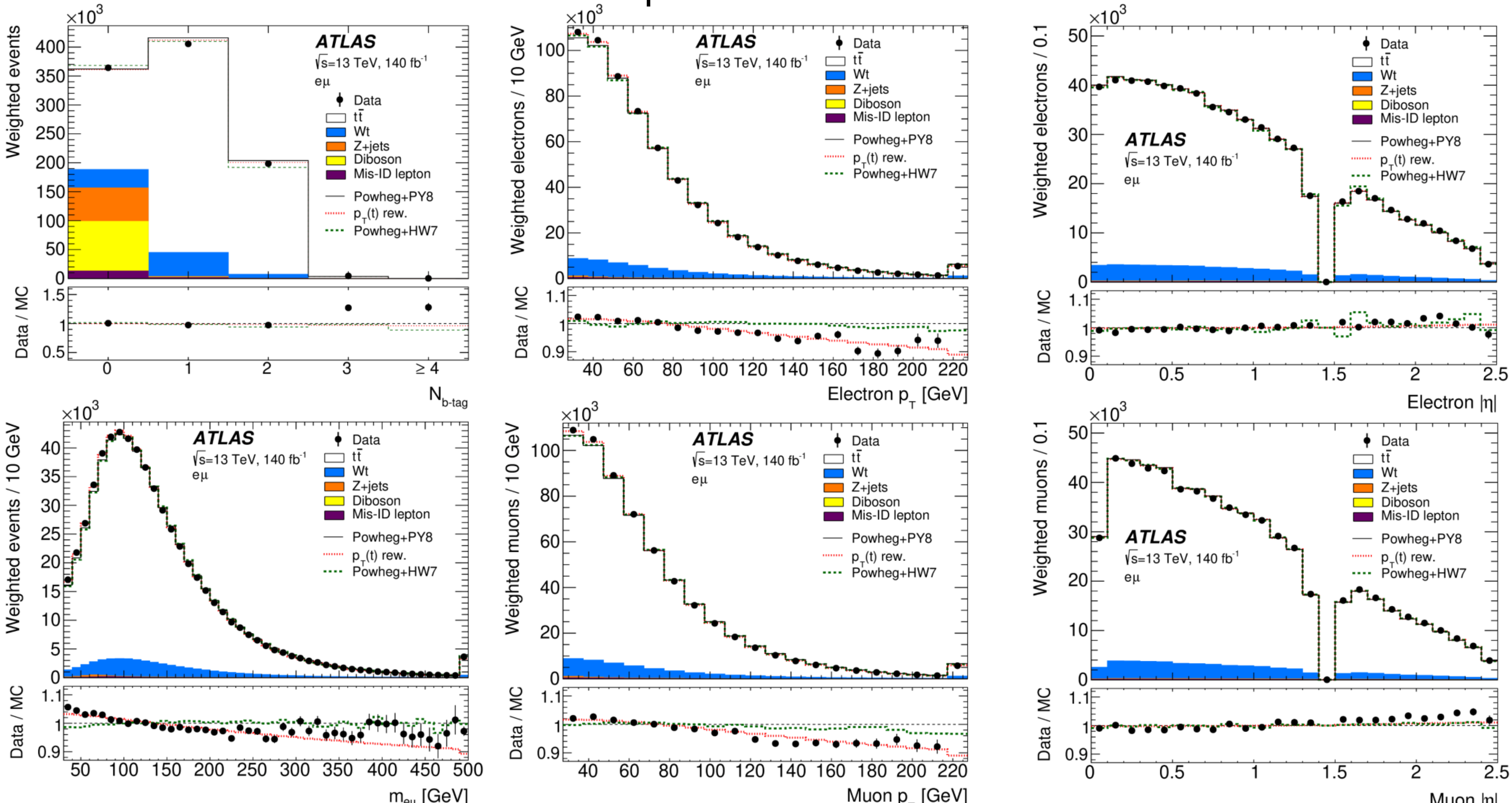
Conclusions

- Determination of R_W=Br(W→μν)/Br(W→eν) exploiting the two W bosons per ttbar event in the complete ATLAS Run 2 13 TeV pp sample
  - Effectively a measurement of the ttbar cross-section in ee, eμ and μμ channels
    - Benefitting from cancellation of some uncertainties between channels
  - Measurement is normalised to R_Z=Br(Z→μμ)/Br(Z→ee) to reduce systematics
    - Using the precise R_Z (±0.0028) measurement from e^+e^- colliders as external input
- Result of $R_W = 0.9995 \pm 0.0022$ (stat) $\pm$ 0.0036 (syst) $\pm$ 0.0014 (ext)
  - Compatible with lepton flavour universality
  - Total uncertainty ±0.0045 more precise than current world average (±0.006)

Backup slides

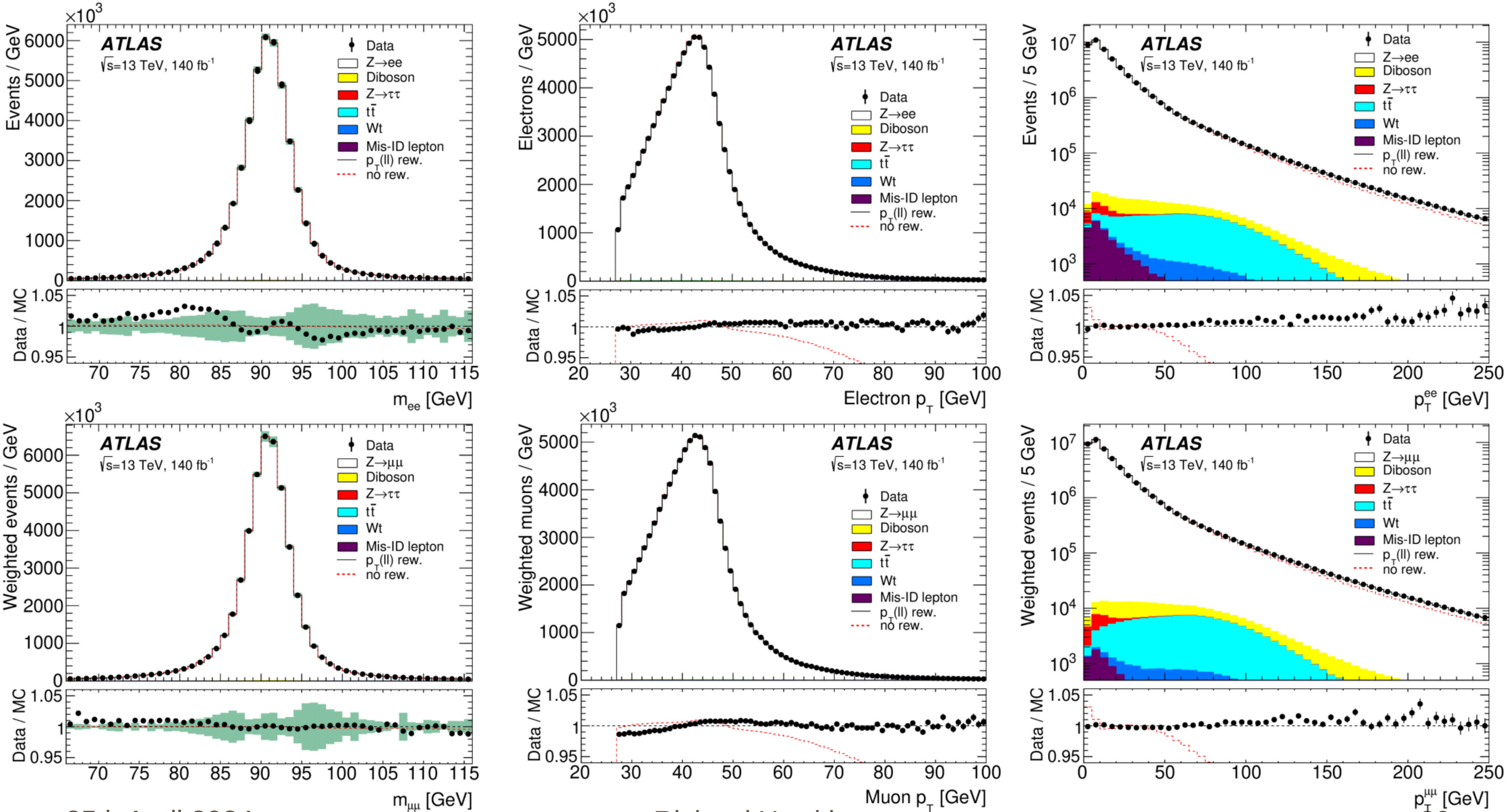
eμ channel kinematics

- Kinematic distributions in the eμ channel



Z selection kinematics

- Kinematic distributions in the Z selection



Grand summary with W→τ

- Measurements of R(μ/e), R(τ/e), R(τ/μ)