Standard-Model precision measurements with W and Z bosons using the ATLAS detector

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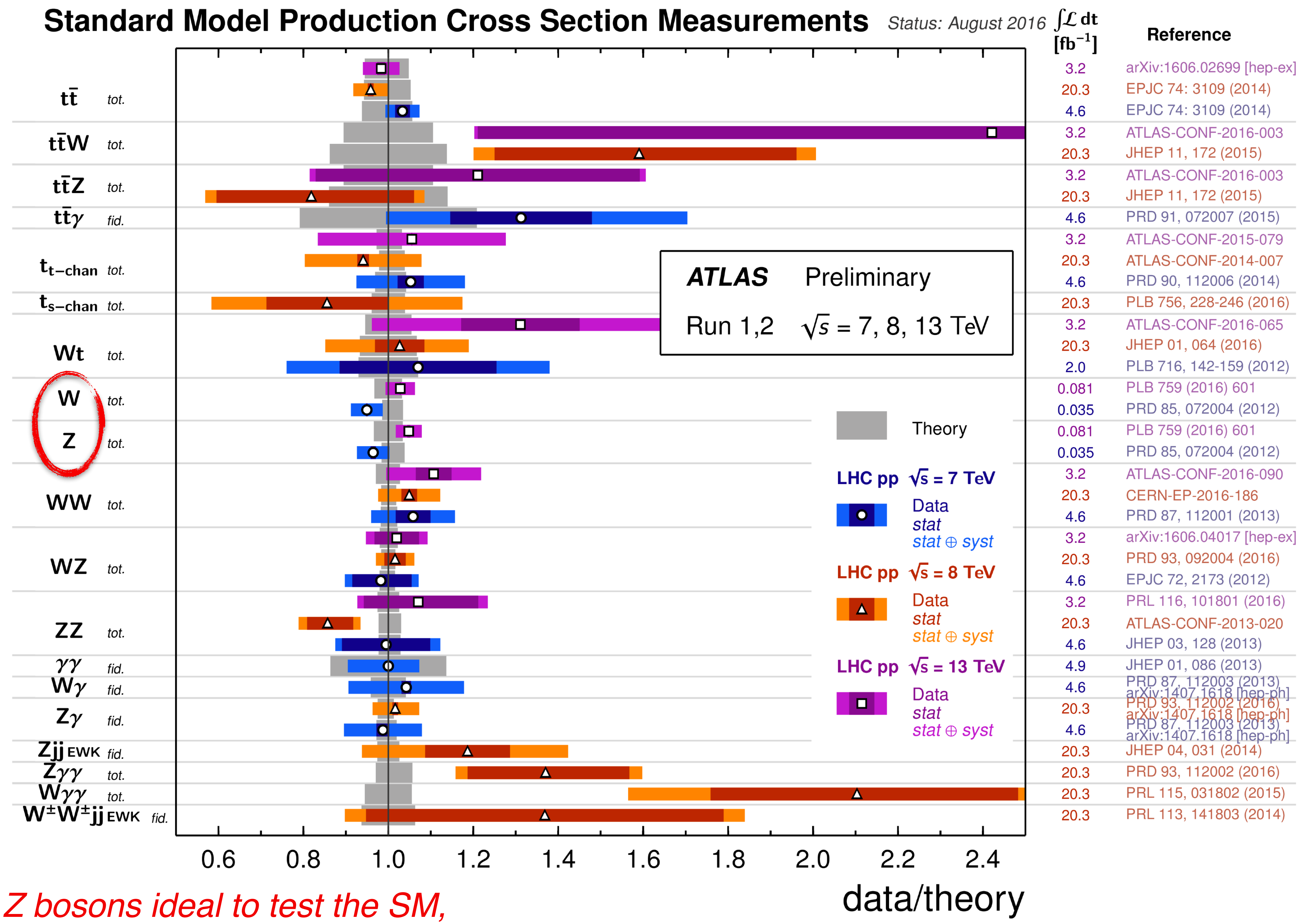
on behalf of the ATLAS Collaboration

BROOKHAVEN
NATIONAL LABORATORY

March 5-11
La Thuile 2017

Standard Model: a successful theory



W and Z bosons ideal to test the SM, study the QCD and EW predictions

List of *latest* ATLAS precision measurements

- Measurements of the production cross section of a Z boson in association with jets in pp collisions at √s=13TeV with the ATLAS detector 1702.05725 ***covered by F. Siegert***
- **Measurement of the W-boson mass in pp collisions at √s=7TeV with the ATLAS detector 1701.07240**
- **Precision measurement and interpretation of inclusive W^+, W^- and Z/γ* production cross sections with the ATLAS detector 1612.03016**
- **Measurements of top-quark pair to Z-boson cross-section ratios at √s=13,8,7TeV with the ATLAS detector 1612.03636**
- Measurement of W boson angular distributions in events with high transverse momentum jets at √s=8TeV using the ATLAS detector 1609.07045 ***covered by F. Siegert***
- Measurement of the double-differential high-mass Drell-Yan cross section in pp collisions at √s=8TeV with the ATLAS detector 1606.01736
- Measurement of the angular coefficients in Z-boson events using electron and muon pairs from data taken at √s=8TeV with the ATLAS detector 1606.00689
- **Measurement of W and Z-boson production cross sections in pp collisions at √s=13TeV with the ATLAS detector 1603.09222**

Overview

- High precision measurements from ATLAS with W and Z bosons
  - W and Z cross section measurements at 7TeV and 13TeV
  - $t\bar{t}$ and Z cross section ratios at 7, 8 and 13 TeV
  - first W mass measurement at 7TeV

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W and Z production cross section 7TeV, 4.6fb^{-1}

- Measurements of differential and integrated cross sections arxiv:1612.03016

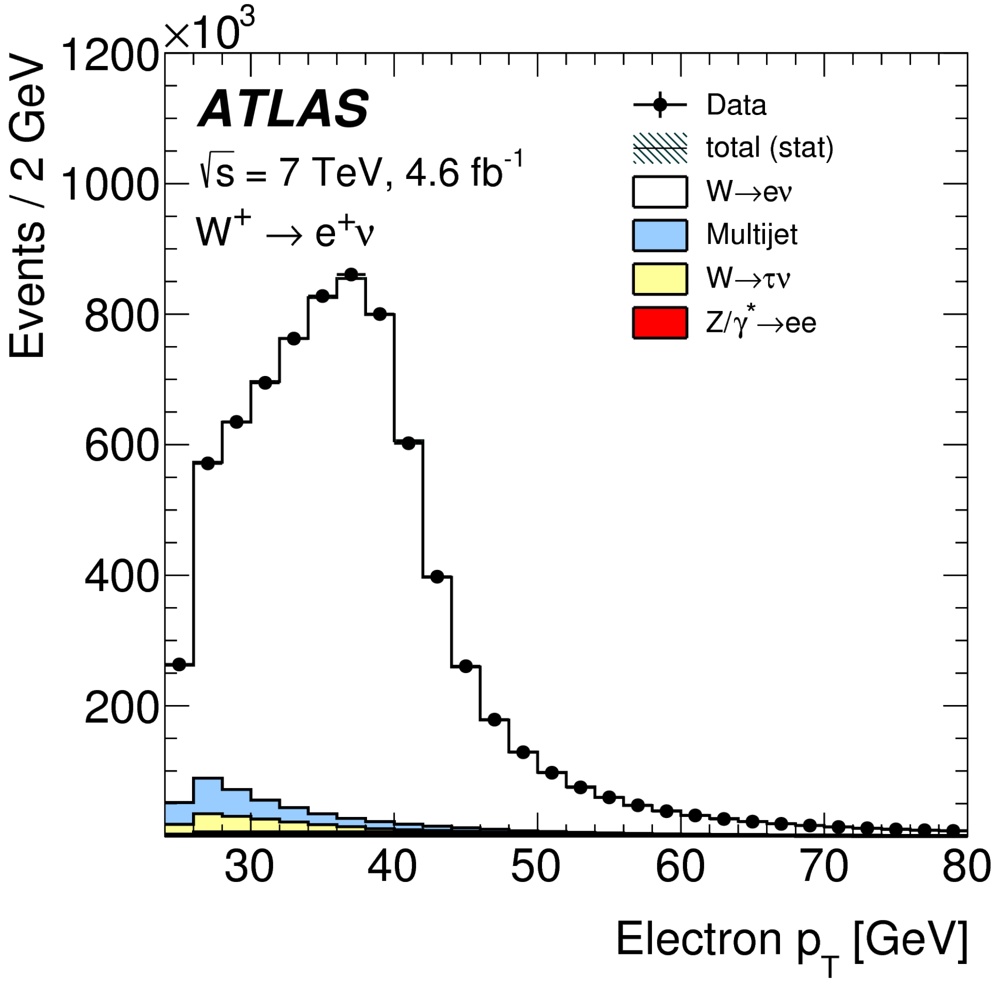
observed events background events

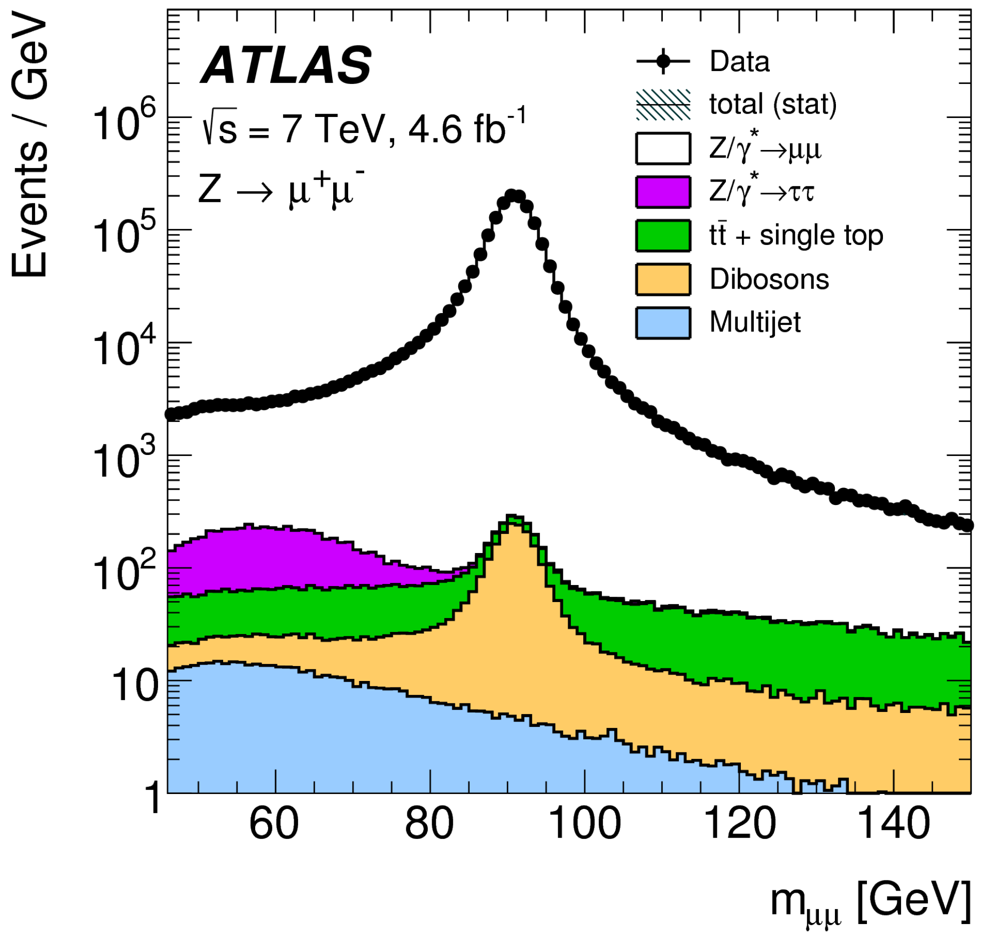
$$\sigma^{\mathrm{fid},e(\mu)}_{W\to e(\mu)\nu[Z\to ee(\mu\mu)]} = \frac{N_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot L_{\mathrm{int}}}$$

MC efficiency correction int. luminosity

W→e(μ)ν	Z→ee(μμ)
$\lvert\eta_{e(\mu)}\rvert$	$\lvert y_{ee(\mu\mu)}\rvert$ in 3 mass bins

- Good understanding of trigger efficiencies and lepton reconstruction
  - reduced systematics

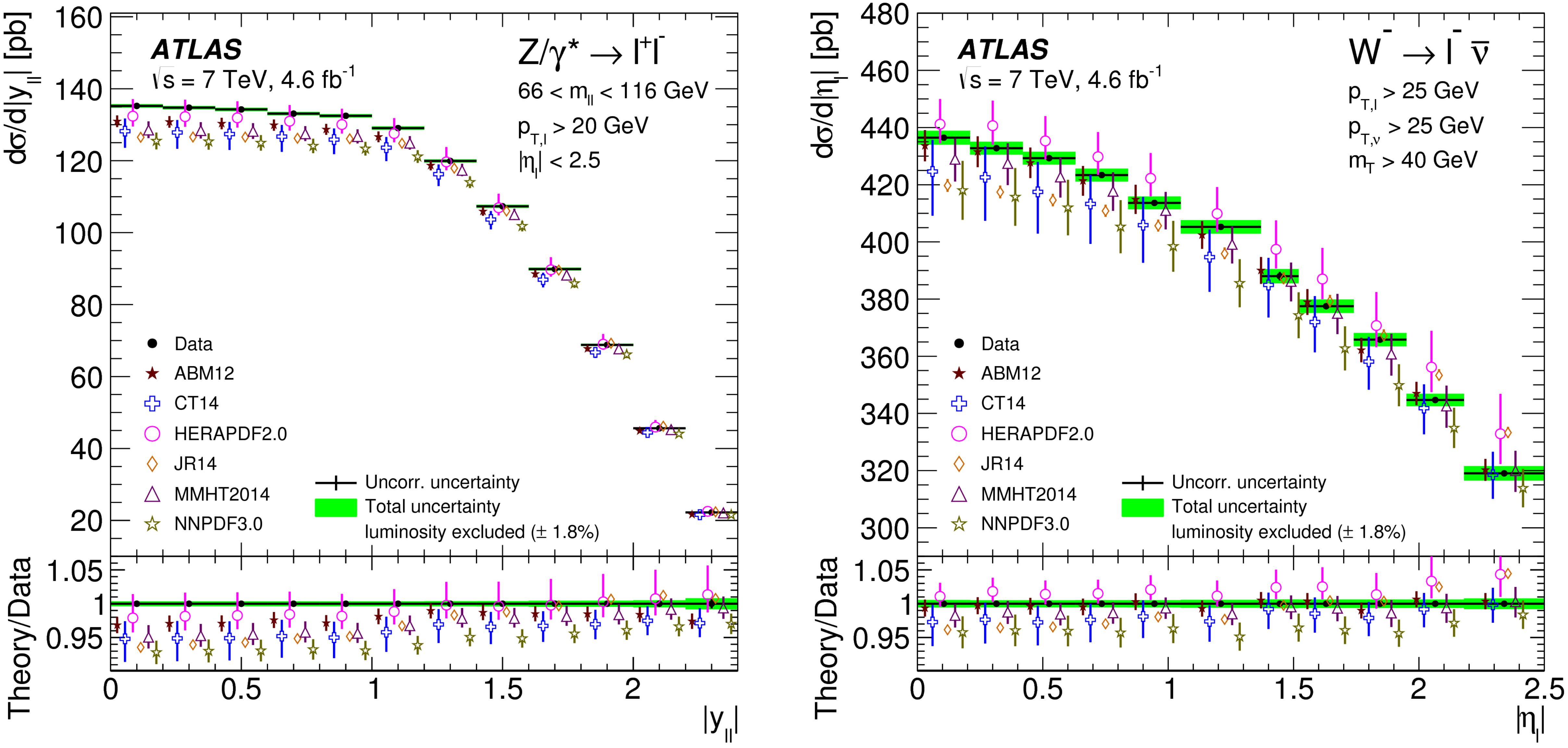




W and Z production cross section

7TeV, $4.6 fb^{-1}$

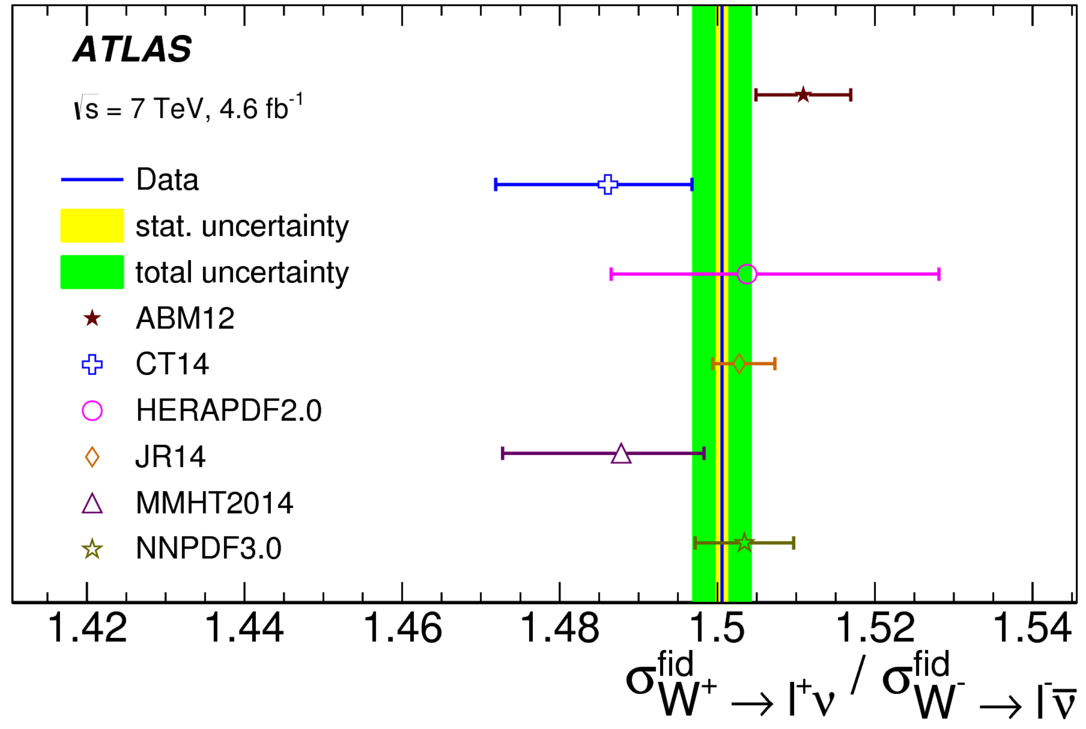
- Differential measurement with a precision of 0.4-0.6 (exp)±1.8(lumi)% for Z and $W^{\pm}$ channels
  - ☑ comparisons with ***state-of-the-art*** predictions at NNLO QCD with NLO EW corrections
  - ☑ significant constraints on PDFs (HERAPDF2.0 describe the Z data and ABM12 the W data)



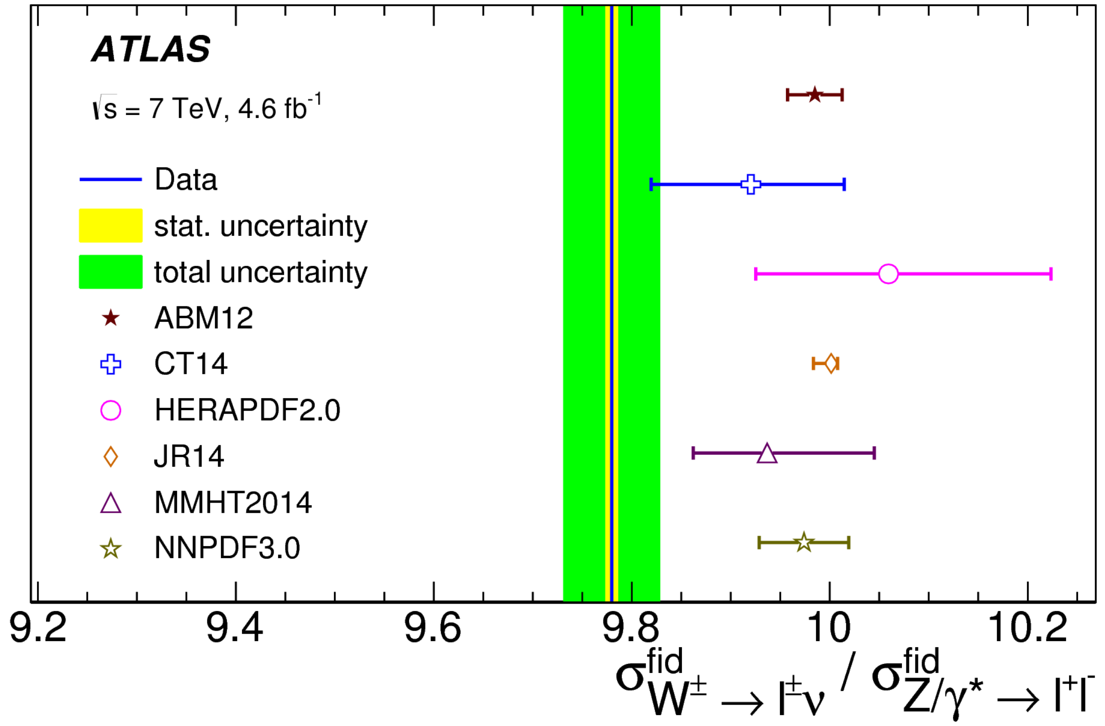
W and Z production cross section

7TeV, 4.6fb^{-1}

measured W+/W- consistent with predictions

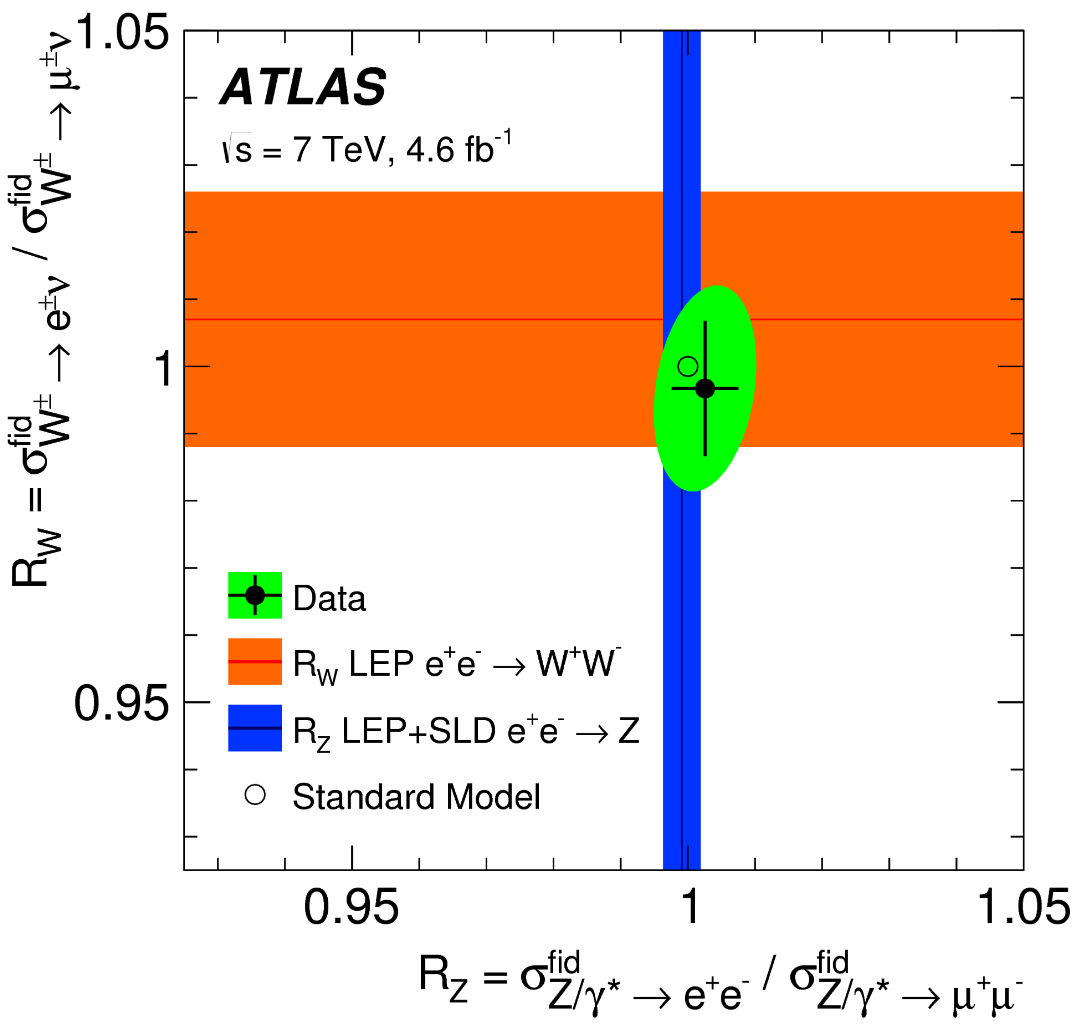


measured W/Z ratio lower than predictions



- Cross section ratios
  - ☑ cancellation of luminosity, lepton-related and theoretical uncertainties
  - ☑ sensitive to proton PDF

Very precise test of e-μ universality in W, Z decays

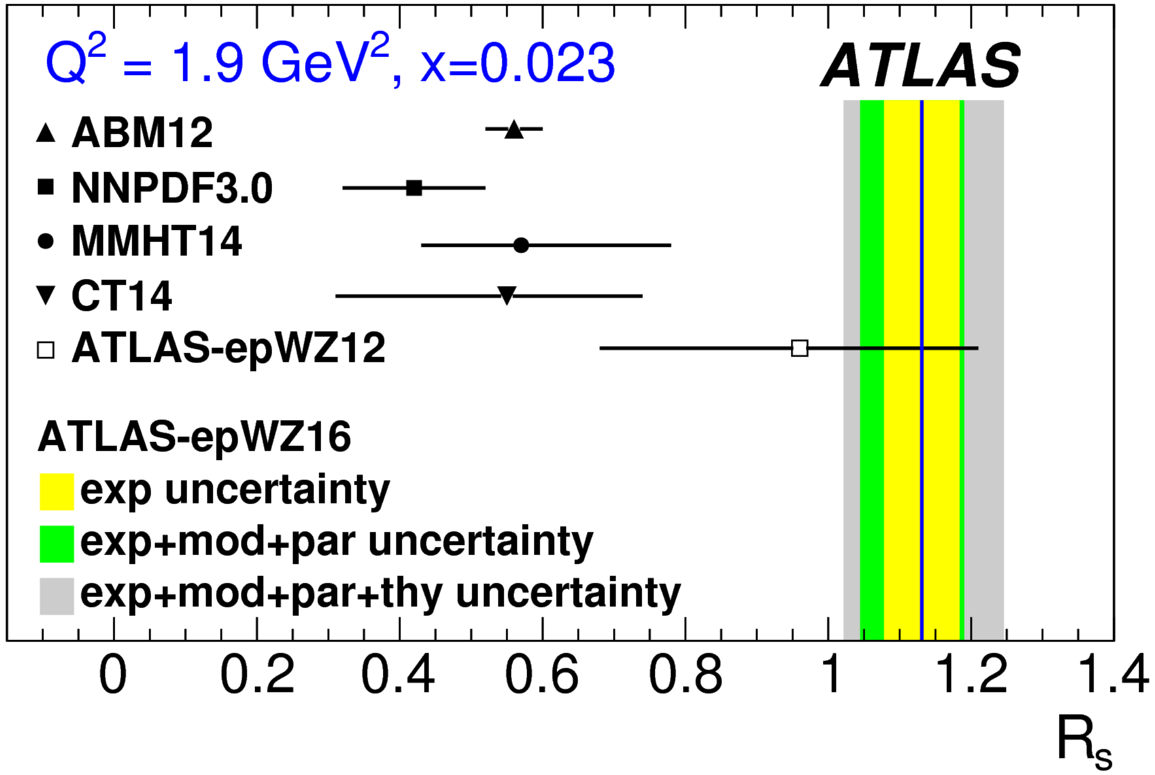


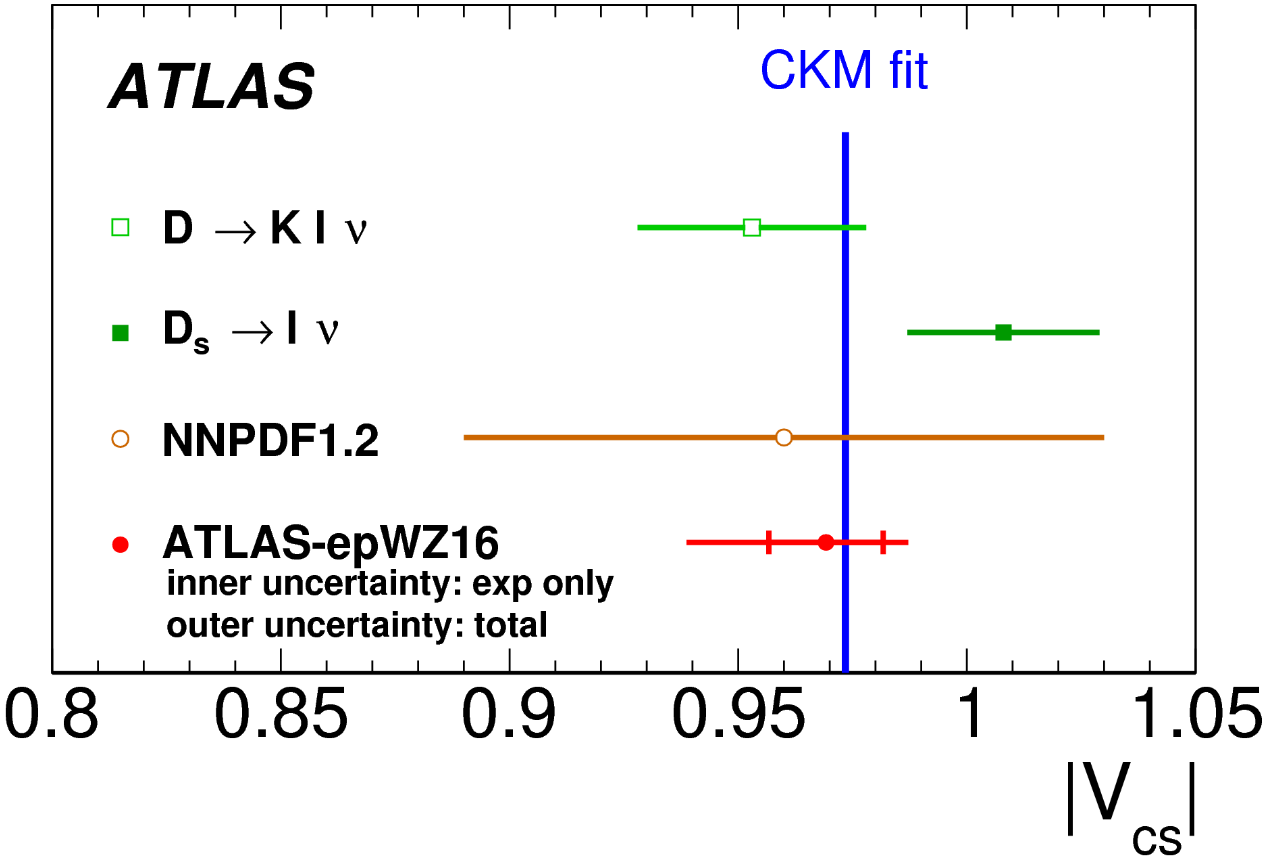
W and Z production cross section

7TeV, 4.6fb^{-1}

- Measurement is used together with HERA DIS data for pQCD fit
  - ☑ new PDF set ATLAS-epWZ16
  - ☑ improved sensitivity of flavor composition w.r.t. DIS-only fits
  - ☑ data confirm large strange-quark density with increased precision and highlights theory limitations

strange-to-light quark ratio $R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$





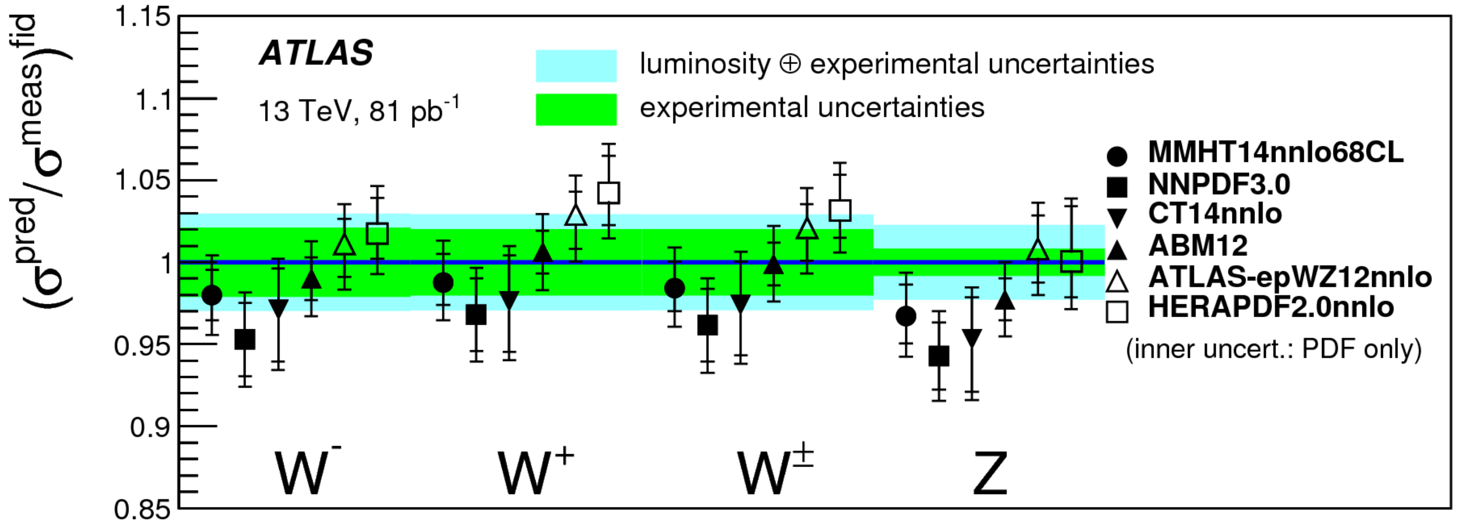
- Independent determination of the CKM matrix element |Vcs| (related to cs→W contribution to the CC DY cross section) with a competitive measurement permitted by enhanced precision

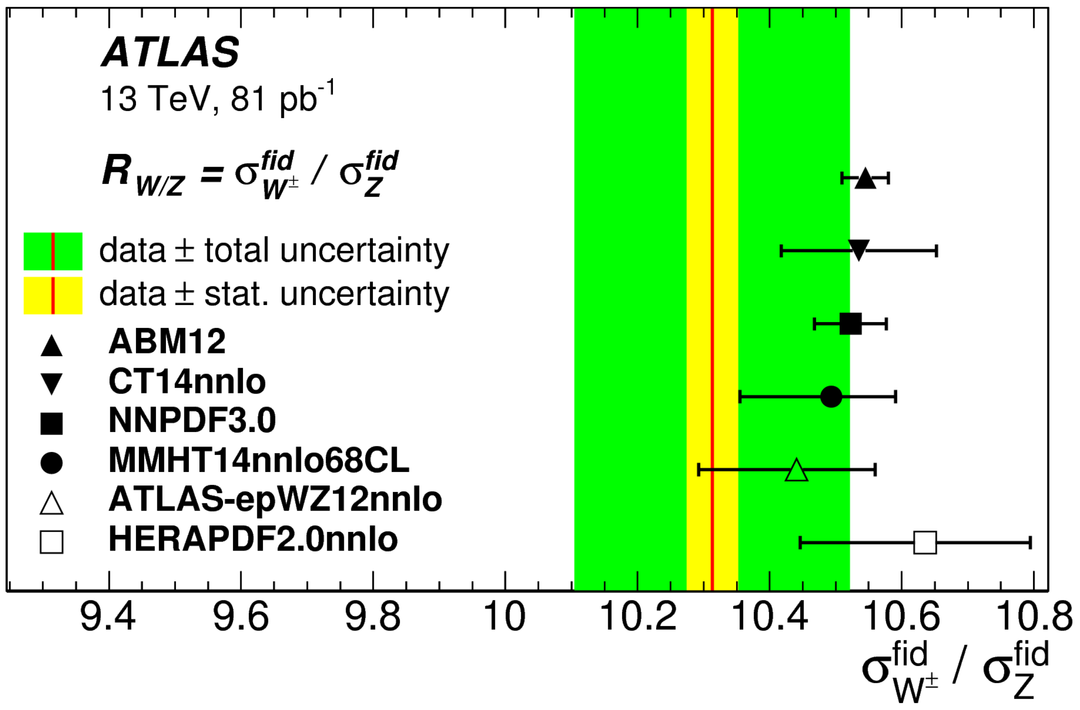
W and Z production cross section

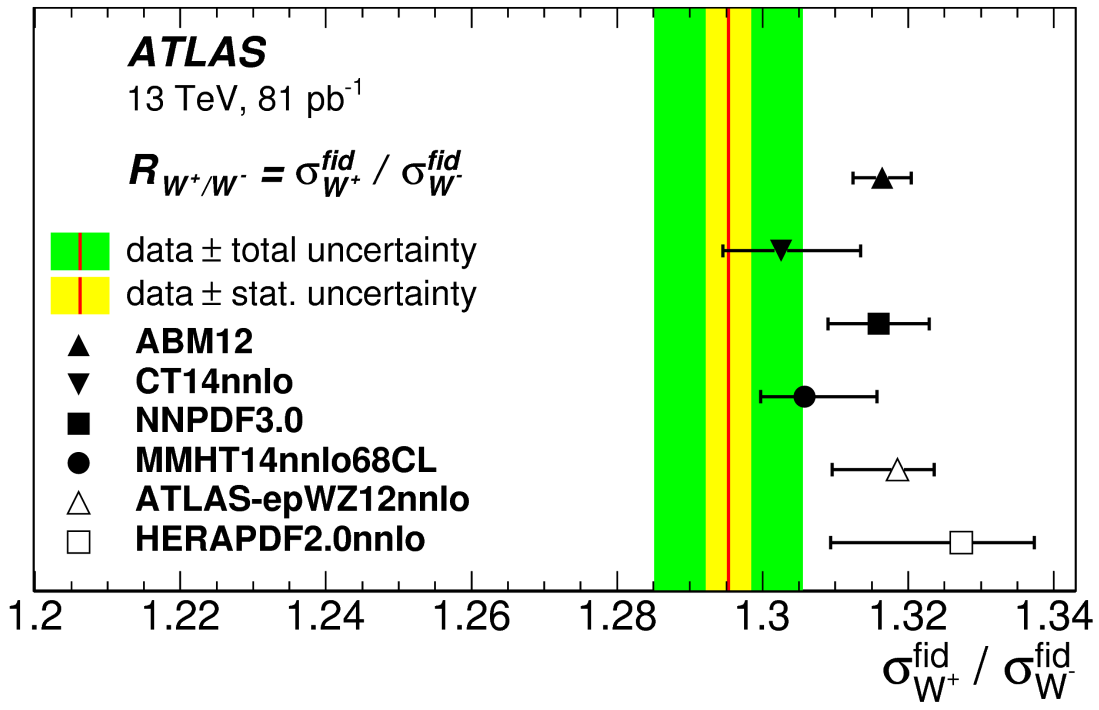
13TeV, $81 pb^{-1}$

[Phys. Lett. B 759 (2016) 601](#)

- Cross section measurements constrain PDFs
- Coherently with the 7TeV result, W/Z ratio at 13TeV is lower than predictions and is inline with the ATLAS data PDF (ATLAS-epWZ12)
- Enhanced strangeness observed in 7TeV ATLAS data seems to be confirmed in 13TeV data







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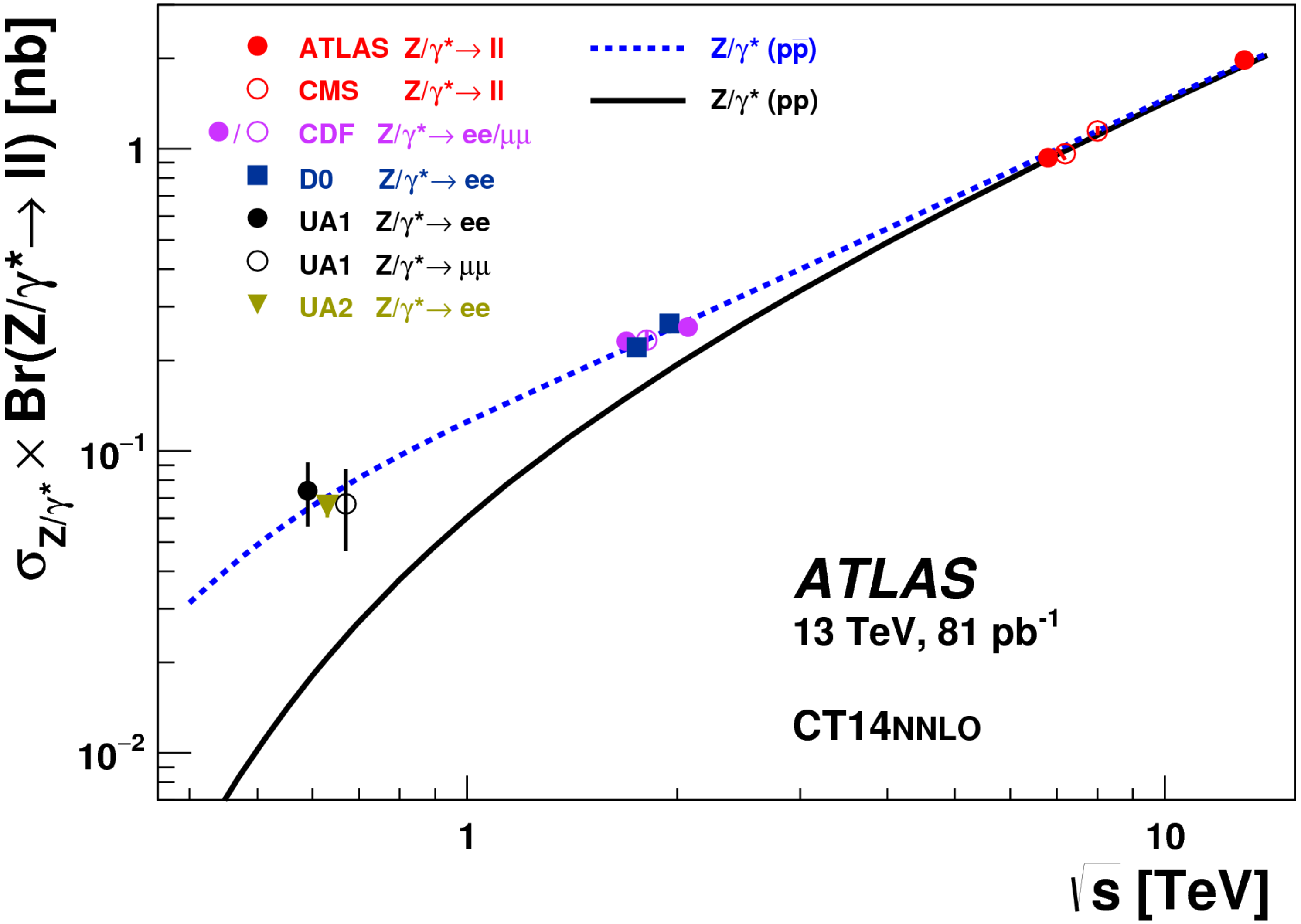


$t\bar{t}$ to Z ratios at 7, 8 and 13TeV

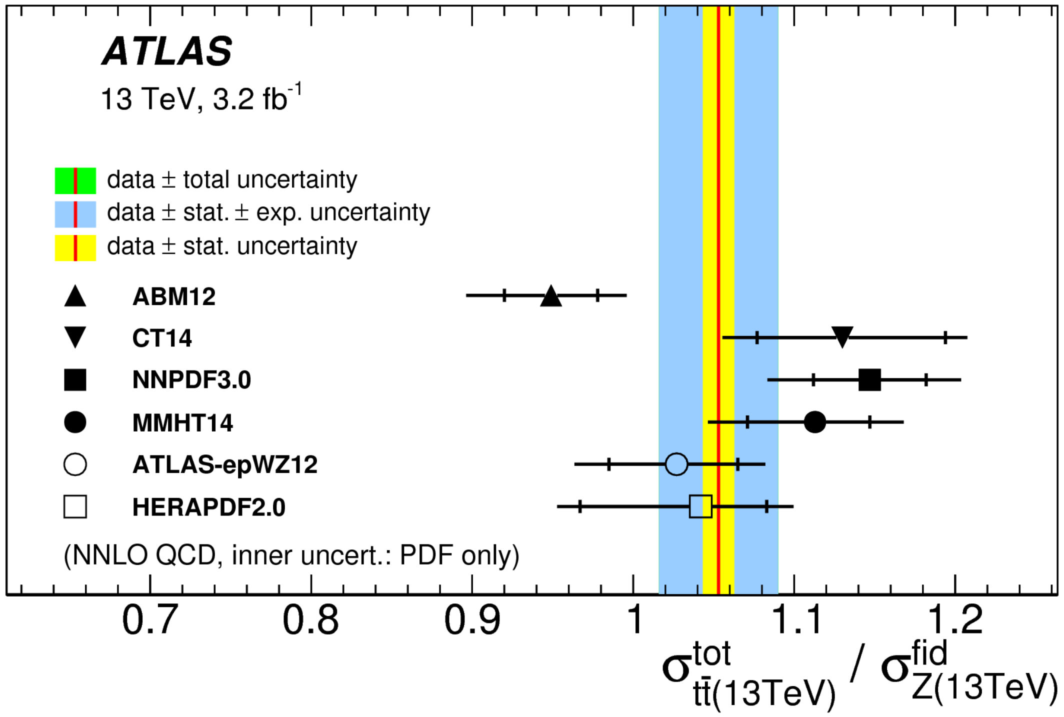
arxiv:1612.03636

- Examine dependence of the cross sections with the collision centre-of-mass energy
- Cancellation of luminosity, lepton-related and theoretical uncertainties
- single ratios:
  - ☑ at a given √s - $R_{t\bar{t}/Z(7TeV)}$, $R_{t\bar{t}/Z(8TeV)}$, $R_{t\bar{t}/Z(13TeV)}$: sensitive to gluon-to-quark PDF ratio
  - ☑ single ratios at different √s - $R_{t\bar{t}/t\bar{t}(13,8,7TeV)}$, $R_{Z/Z(13,8,7TeV)}$: constrain the luminosity uncertainties at different √s

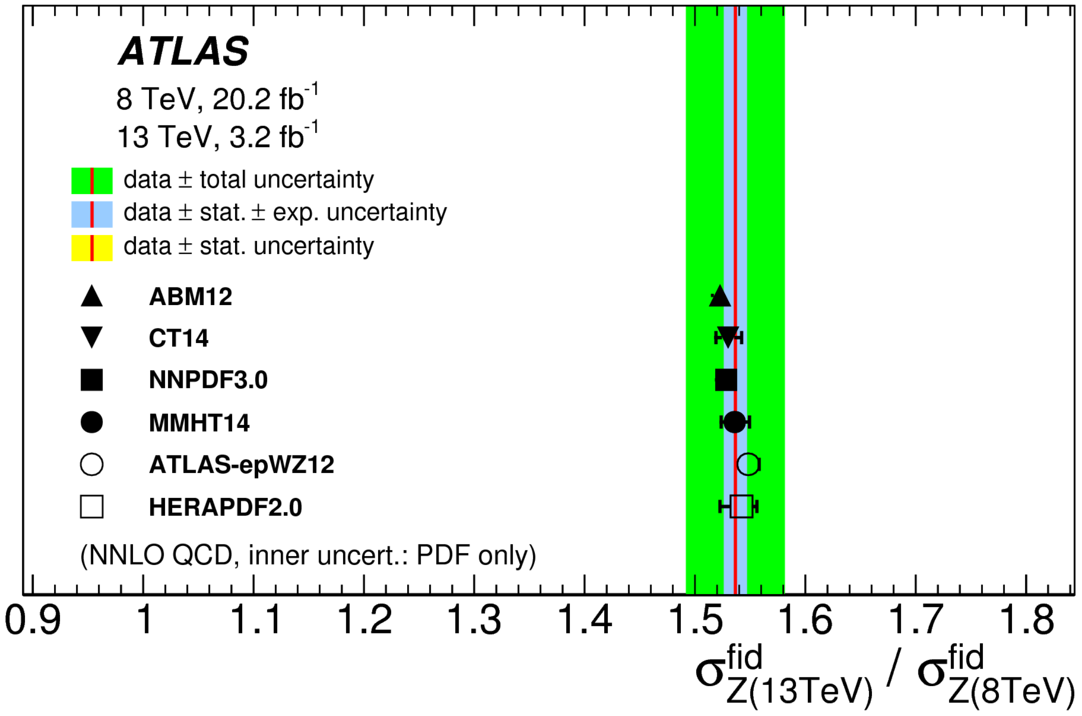
$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu})}$$

only $t\bar{t}\to e\mu$ channel is used

single ratio at given √s



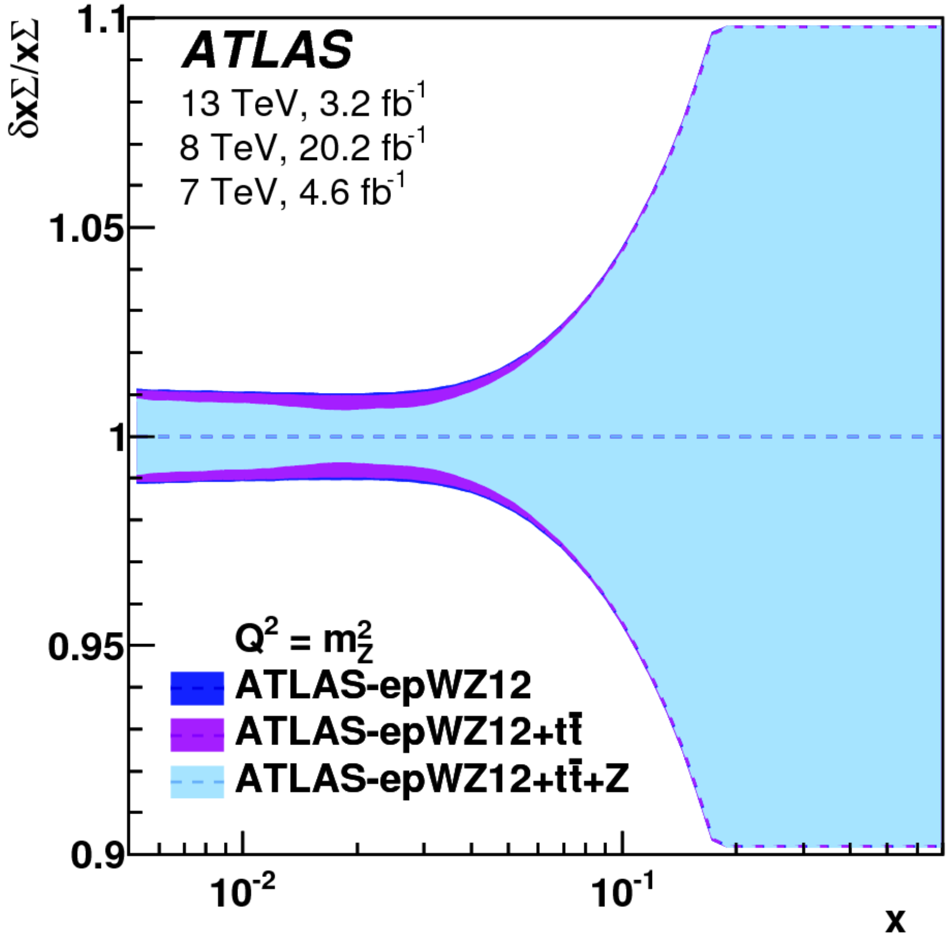
single ratio at different √s



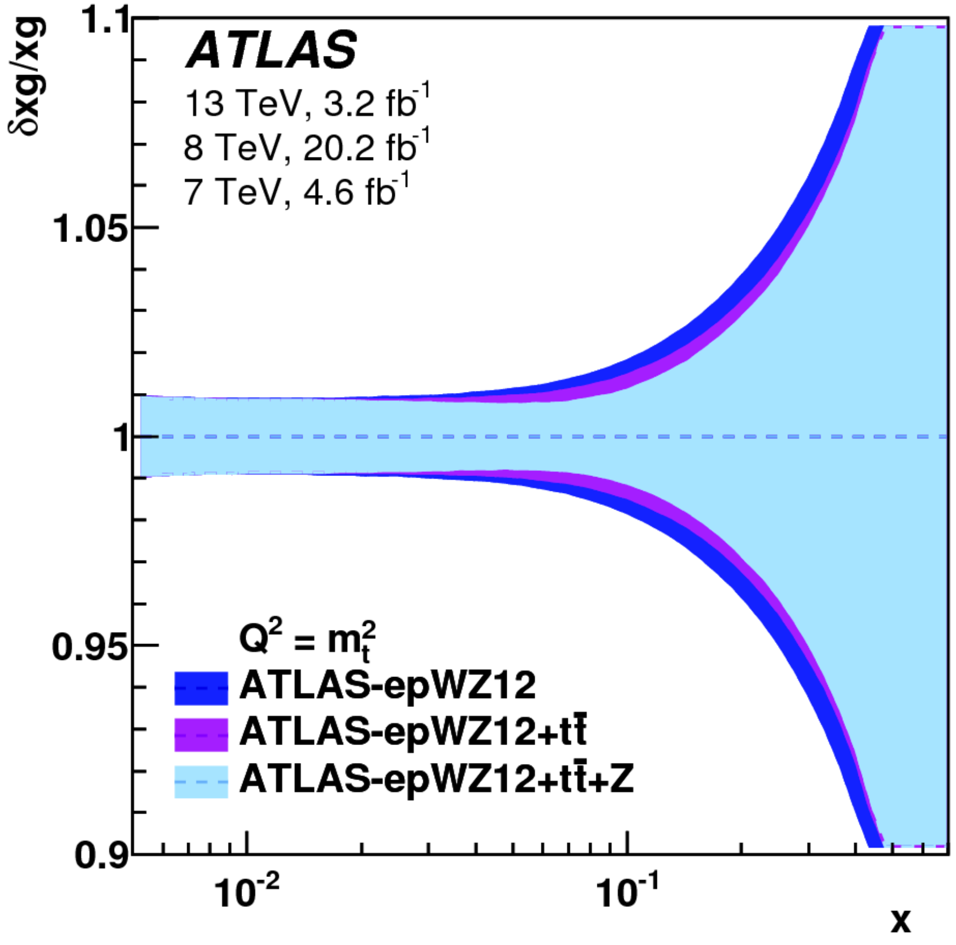
$t\bar{t}$ to Z ratios at 7, 8 and 13TeV

- Impact of ATLAS data on the PDF uncertainties quantified by PDF profiling using ATLAS-epWZ12 PDF set
- Light-quark sea and gluon distributions visibly constrained by the ATLAS $t\bar{t}$ and Z cross section data
  - ☑ Light quark sea distribution at $x < 0.02$
  - ☑ Gluon distribution at $x \sim 0.1$

Light-quark sea distributions



Gluon distributions



Overview

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W mass measurement

7TeV, 4.6fb^{-1}

arxiv:1701.07240

- EW gauge sector of the SM is constrained by 3 parameters
  - ☑ electromagnetic coupling constant
  - ☑ muon decay constant
  - ☑ Z boson mass

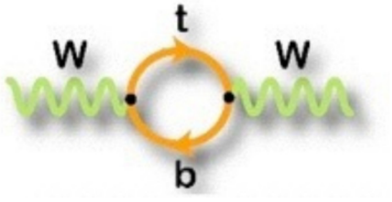
☑ α = 1/137.0359999679

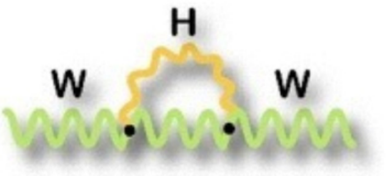
☑ $G_\mu = 1.16637 \times 10^{-5}$ GeV^{-2}

☑ m_Z = 91.1876 GeV

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

Δr incorporates higher-order corrections from the SM and beyond



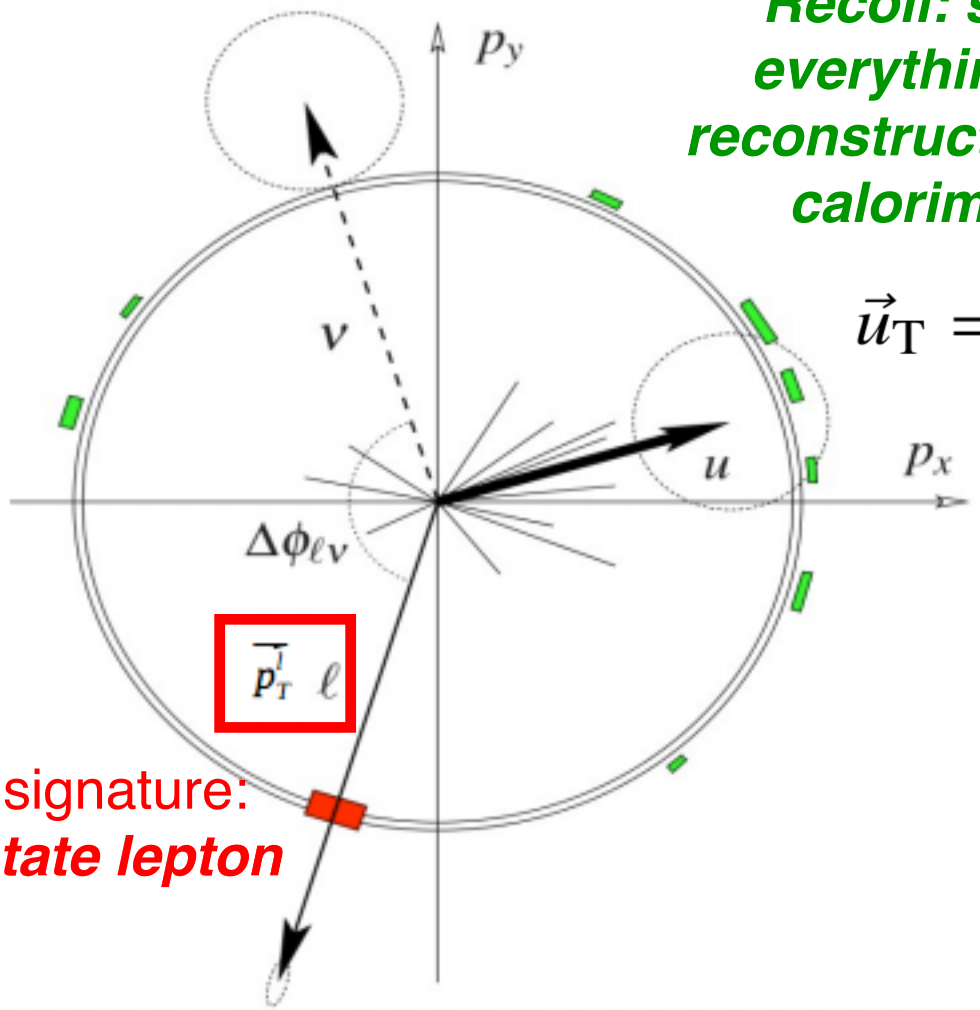


Consistency test of the SM, and a probe for BSM physics

Measurement strategy

7TeV, 4.6fb^{-1}

important components/requirements



Recoil: sum of everything else reconstructed in the calorimeters

$$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

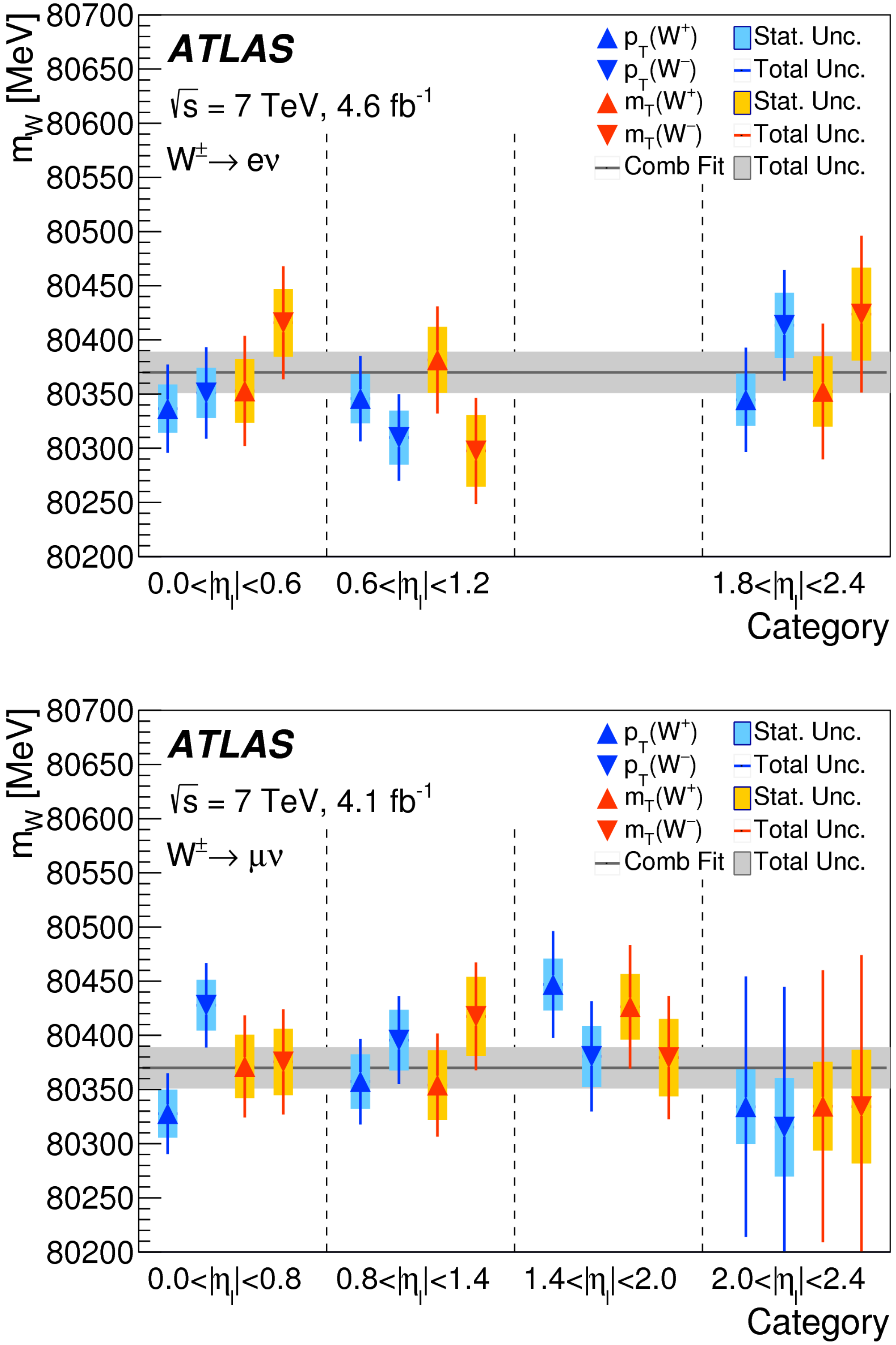
main signature:
final state lepton

derived quantities:

$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right) \quad m_T = \sqrt{2p_T^\ell p_T^{miss}(1-\cos\Delta\phi)}$$

$$p_T^\ell > 30\mathrm{GeV} \ , \ \mathrm{p}_T^{miss} > 30\mathrm{GeV}$$
$$m_T > 60\mathrm{GeV} \ , \ \mathrm{u}_T < 30\mathrm{GeV}$$

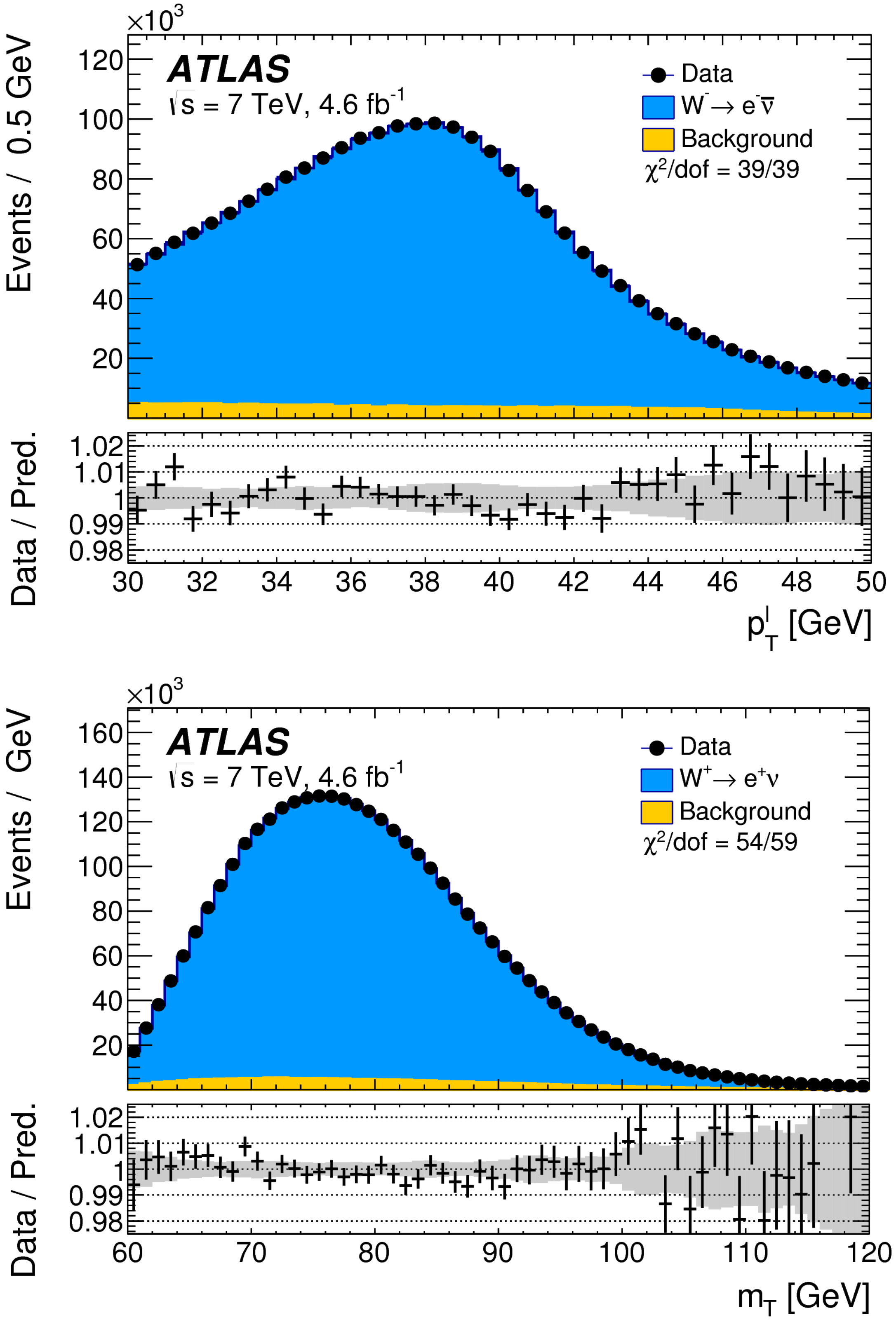
measurement categories



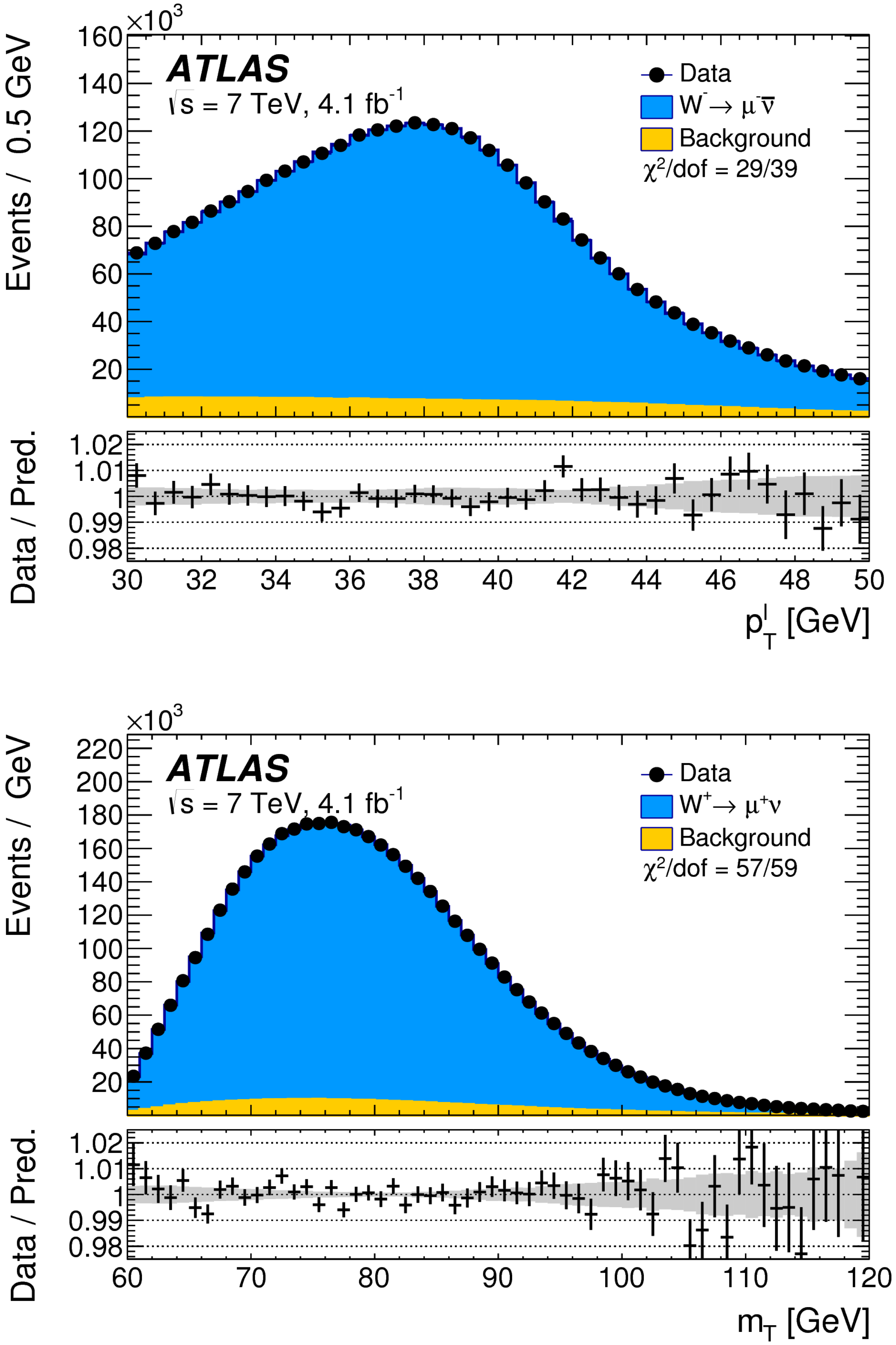
Data/Simulation comparisons

7TeV, 4.6fb^{-1}

electron channel



muon channel



Physics modeling

7TeV, $4.6\mathrm{fb}^{-1}$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_{T}-p_{T}^{ℓ}, $W^{\pm}$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

- dominant uncertainty due to physics modeling
  - measurement based on a mixed-physics model
    - based on the NNLO fixed-order prediction for the rapidity and spin correlations*
    - Parton shower (PYTHIA with AZ tune to describe p_T^Z) used for the modeling of the p_T of the W boson
- Why the W mass measurement is complex in LHC
  - more complex QCD environment at LHC (proton-proton collider) compared to Tevatron (proton-anti-proton collider)
  - sea-quark PDFs play a large role at the LHC
  - 25% of W production is induced by at least one second generation quark (s or c)

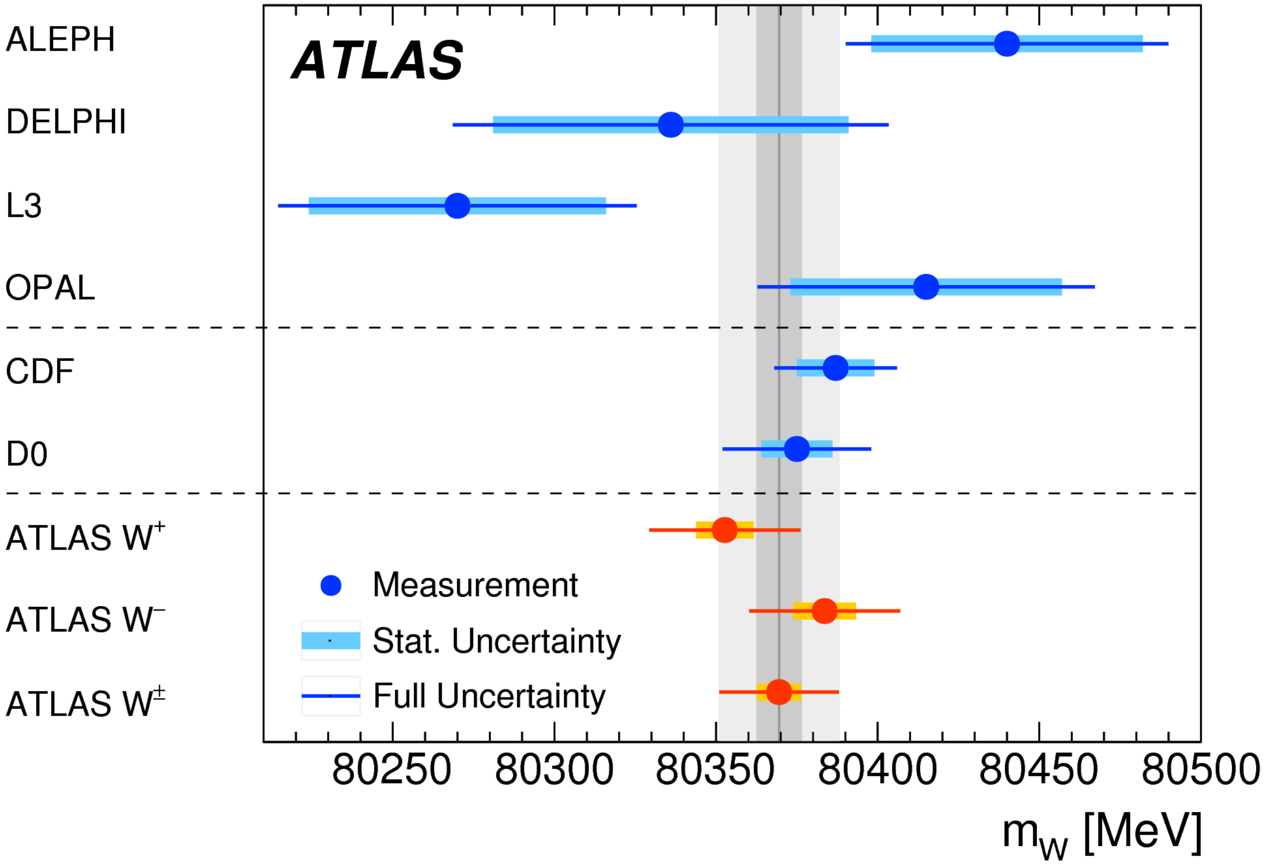
*spin correlations in: JHEP08(2016)159

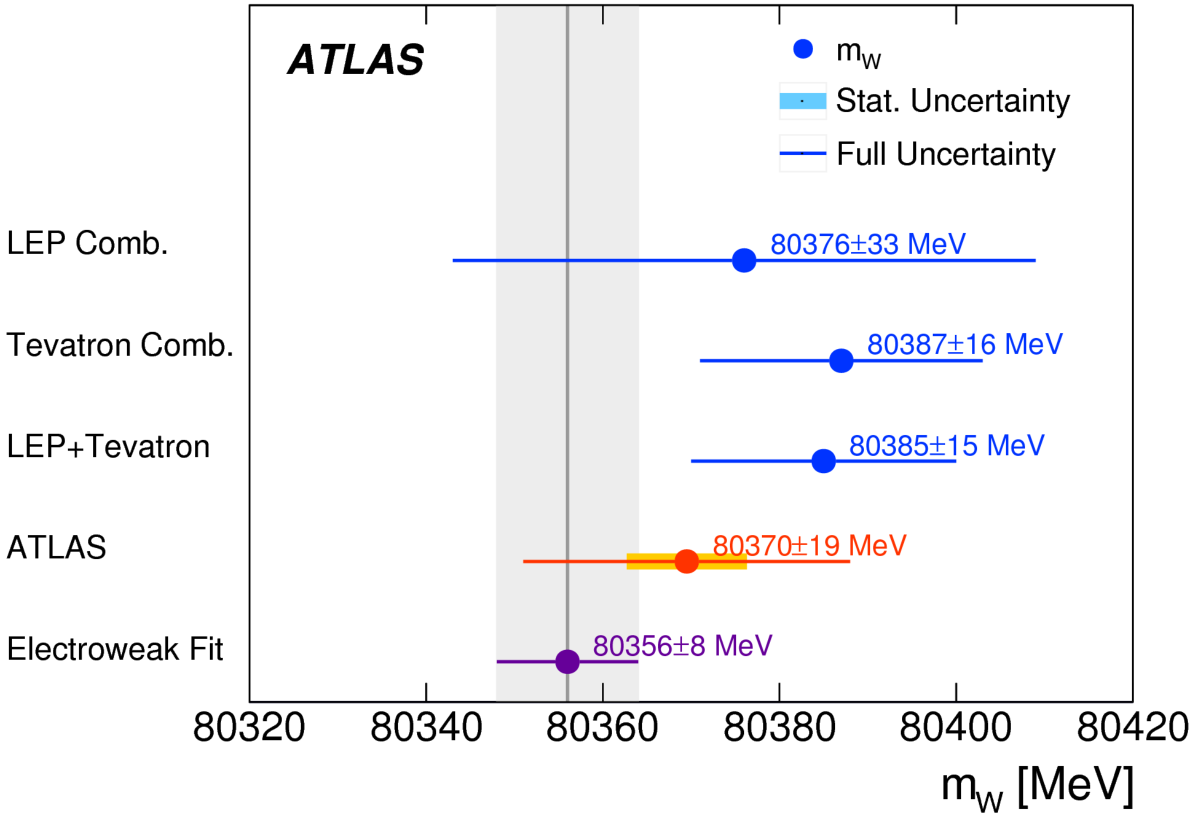
Result

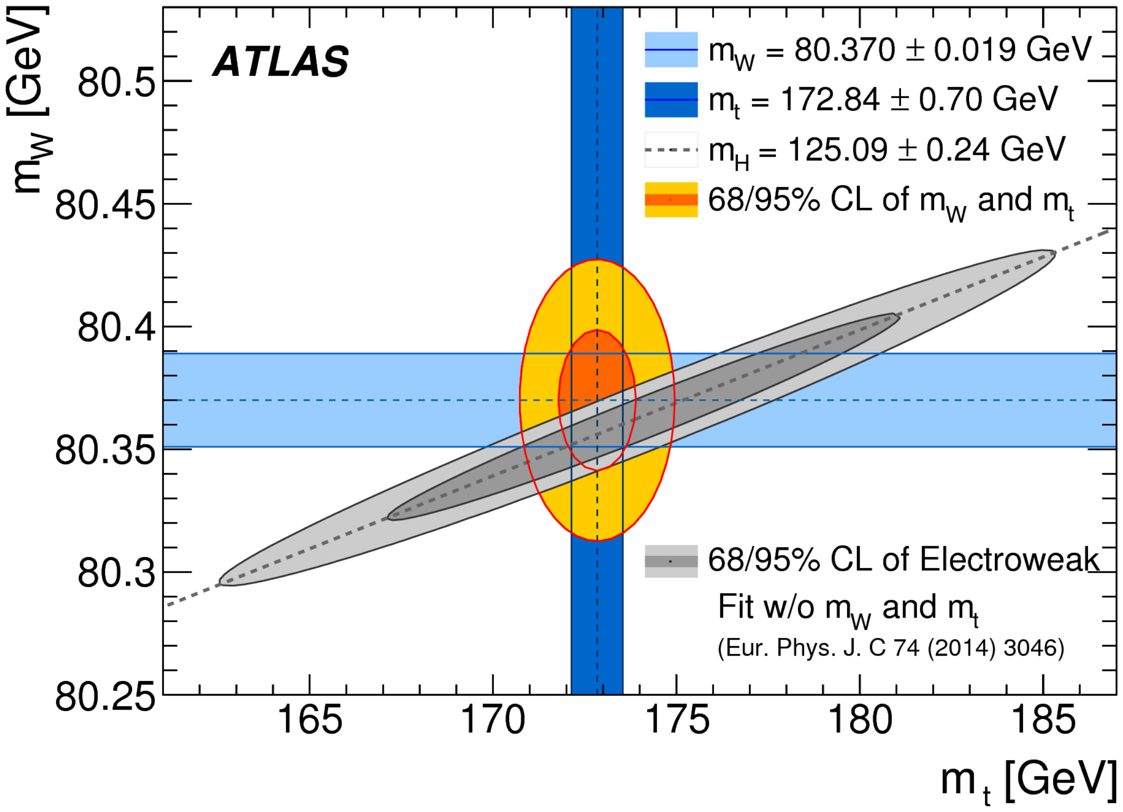
7TeV, 4.6fb^{-1}

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp.syst.}) \pm 14(\text{mod.syst.})\ \text{MeV}$$
$$= 80370 \pm 19\,\text{MeV}$$

Results consistent with the SM expectation, compatible with the world average and competitive in precision w.r.t. the single measurements by CDF and D0







Summary

- High precision W and Z boson measurements with the ATLAS detector
- Rich LHC datasets from Run1 and Run 2 allow for results at 7TeV, 8TeV and 13TeV
- Single W and Z boson physics is a unique playground to study QCD and EW predictions with excellent statistics and clean samples
- We can reach total uncertainties at per mille level
- Test QCD and EW corrections at sub-percent level and constrain PDFs
- It’s time to explore new phase space regions in Run 2 and beyond!

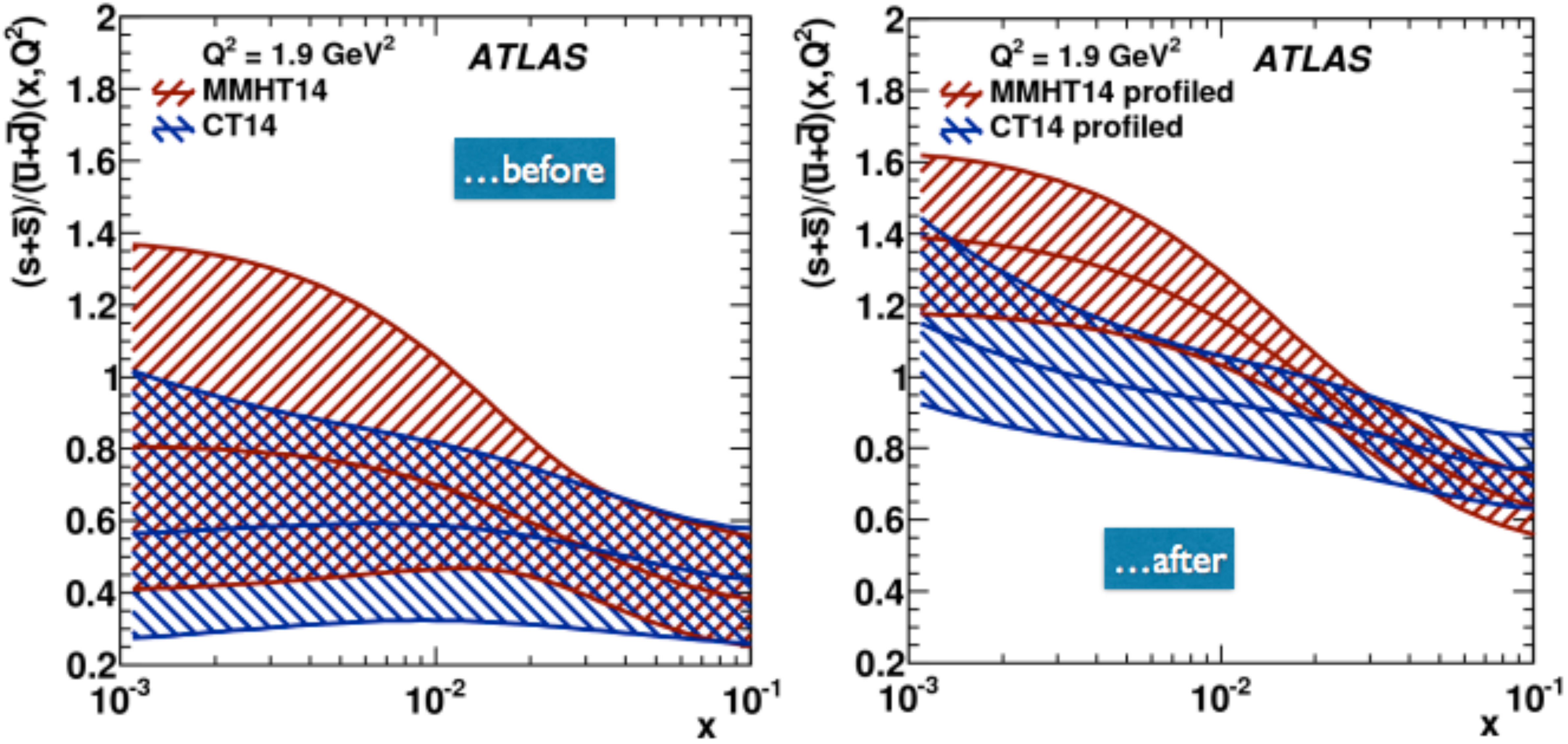
Thank you!

back up

W and Z production cross section

7TeV, 4.6fb^{-1}

Demonstration of impact of measurement when applied to existing PDF.
Showing ratio of strange to up- and down- sea quarks before and after profiling



Uncertainties significantly reduced; strange quarks not suppressed w.r.t. up and down-type sea quarks

W and Z production cross section

7TeV, 4.6fb^{-1}

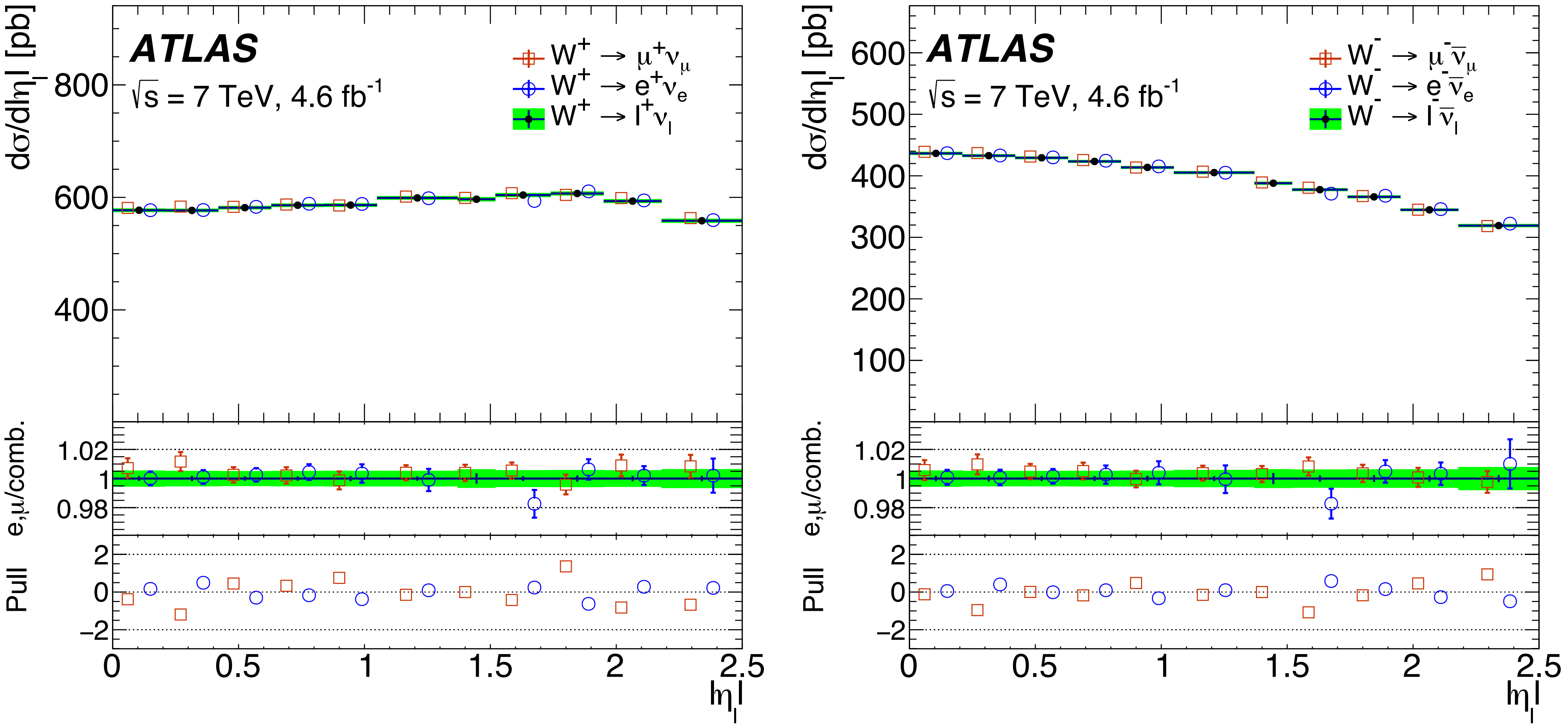


Figure 17: Differential $d\sigma/d|\eta_\ell|$ cross-section measurements for W^+ (left) and W^- (right), for the electron channel (open circles), the muon channel (open squares) and their combination with uncorrelated uncertainties (crosses) and the total uncertainty, apart from the luminosity error (green band). Also shown are the ratios of the e and μ measurements to the combination and the pulls of the individual measurements in terms of their uncorrelated uncertainties, see text.

W and Z production cross section

7TeV, 4.6fb^{-1}

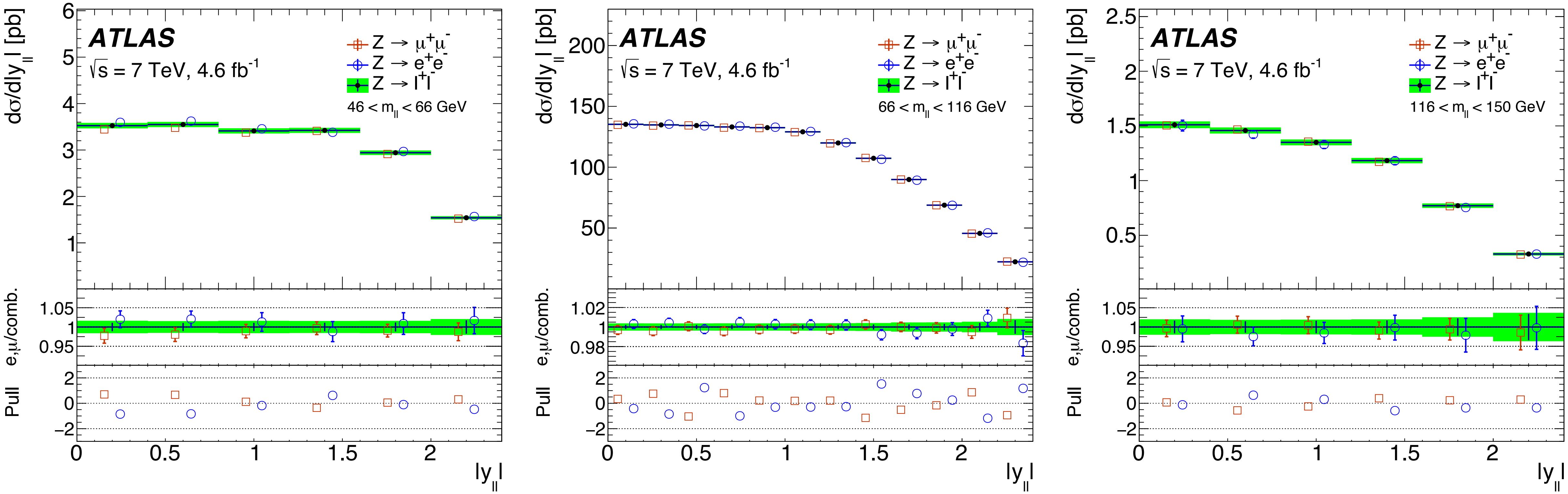
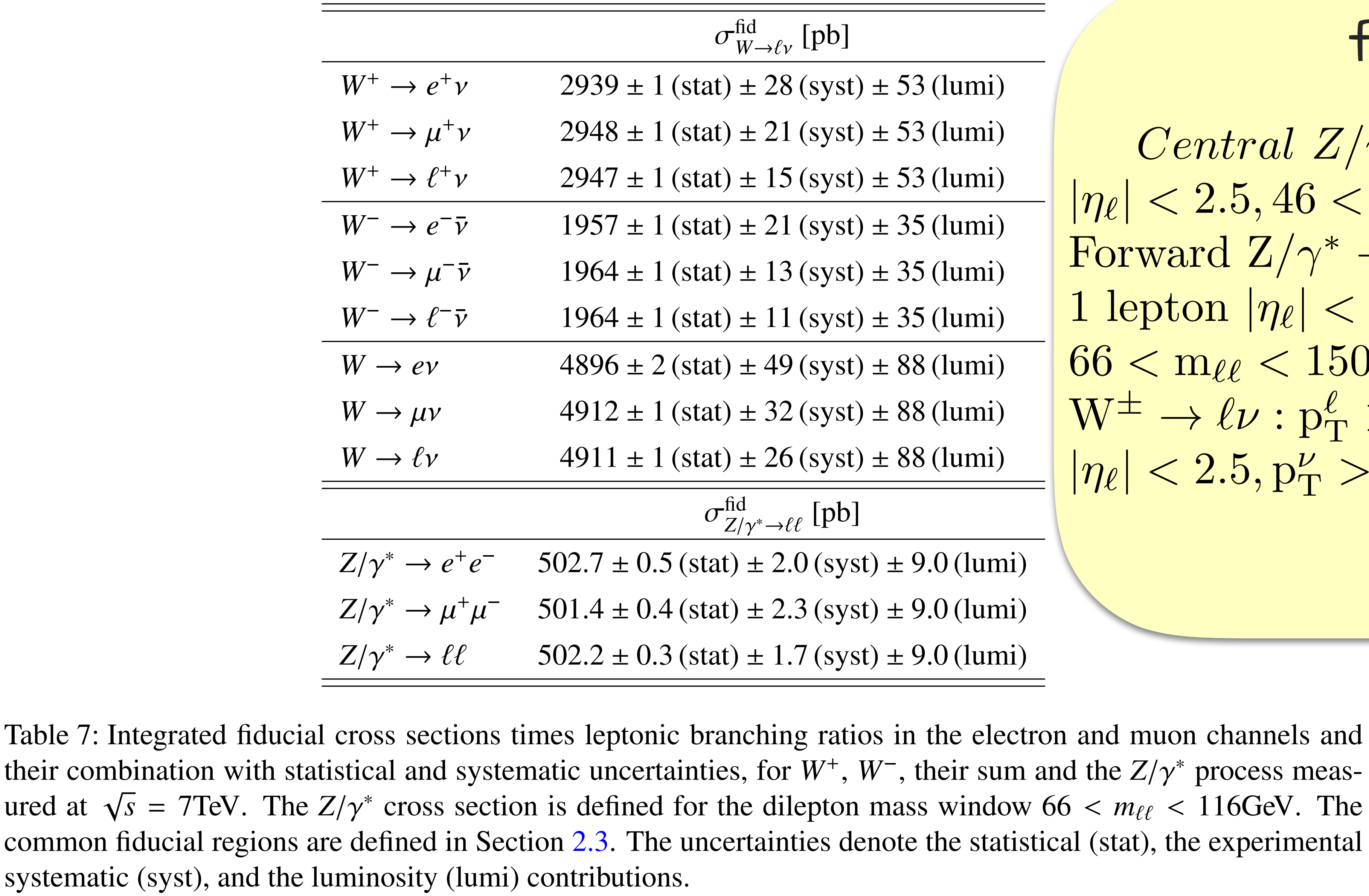


Figure 18: Differential $d\sigma/d|y_{\ell\ell}|$ cross-section measurements for $Z/\gamma^* \rightarrow \ell\ell$ in the three $m_{\ell\ell}$ regions, for the electron channel (open circles), the muon channel (open squares) and their combination with uncorrelated uncertainties (crosses) and the total uncertainty, apart from the luminosity error (green band). Also shown are the ratios of the e and μ measurements to the combination and the pulls of the individual measurements in terms of their uncorrelated uncertainties, see text.

W and Z production cross section

7TeV, 4.6fb^{-1}



	$\sigma^{\text{fid}}_{W\to\ell\nu}$ [pb]
$W^+ \to e^+\nu$	2939 ± 1 (stat) ± 28 (syst) ± 53 (lumi)
$W^+ \to \mu^+\nu$	2948 ± 1 (stat) ± 21 (syst) ± 53 (lumi)
$W^+ \to \ell^+\nu$	2947 ± 1 (stat) ± 15 (syst) ± 53 (lumi)
$W^- \to e^-\bar{\nu}$	1957 ± 1 (stat) ± 21 (syst) ± 35 (lumi)
$W^- \to \mu^-\bar{\nu}$	1964 ± 1 (stat) ± 13 (syst) ± 35 (lumi)
$W^- \to \ell^-\bar{\nu}$	1964 ± 1 (stat) ± 11 (syst) ± 35 (lumi)
$W \to e\nu$	4896 ± 2 (stat) ± 49 (syst) ± 88 (lumi)
$W \to \mu\nu$	4912 ± 1 (stat) ± 32 (syst) ± 88 (lumi)
$W \to \ell\nu$	4911 ± 1 (stat) ± 26 (syst) ± 88 (lumi)

	$\sigma^{\text{fid}}_{Z/\gamma^*\to\ell\ell}$ [pb]
$Z/\gamma^* \to e^+e^-$	502.7 ± 0.5 (stat) ± 2.0 (syst) ± 9.0 (lumi)
$Z/\gamma^* \to \mu^+\mu^-$	501.4 ± 0.4 (stat) ± 2.3 (syst) ± 9.0 (lumi)
$Z/\gamma^* \to \ell\ell$	502.2 ± 0.3 (stat) ± 1.7 (syst) ± 9.0 (lumi)

Table 7: Integrated fiducial cross sections times leptonic branching ratios in the electron and muon channels and their combination with statistical and systematic uncertainties, for W^+, W^-, their sum and the Z/γ^* process measured at $\sqrt{s}$ = 7TeV. The Z/γ^* cross section is defined for the dilepton mass window $66 < m_{\ell\ell} < 116$GeV. The common fiducial regions are defined in Section 2.3. The uncertainties denote the statistical (stat), the experimental systematic (syst), and the luminosity (lumi) contributions.

fiducial volume

$Central\ Z/\gamma^* \to \ell\ell : p_T^\ell > 20\text{GeV}$

$|\eta_\ell| < 2.5, 46 < \mathrm{m}_{\ell\ell} < 150\text{GeV}$

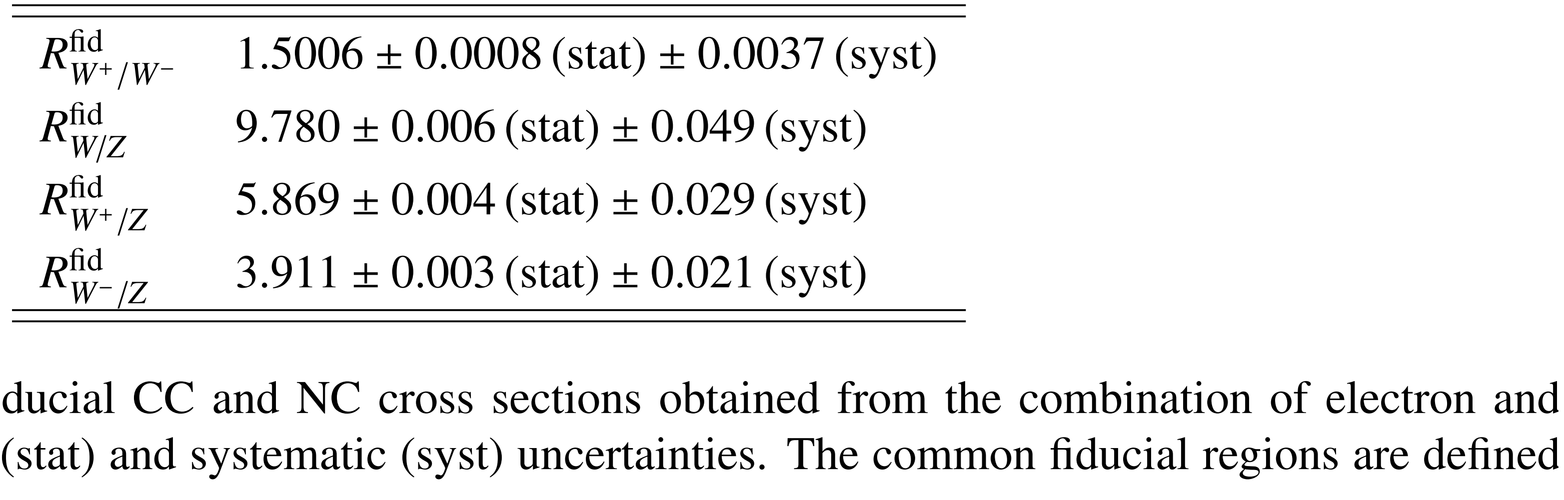
$\text{Forward } Z/\gamma^* \to \ell\ell : \mathrm{p}_\mathrm{T}^\ell > 20\text{GeV}$

$1 \text{ lepton } |\eta_\ell| < 2.5, \text{other lepton } 2.5 < |\eta_\ell| < 4.9,$

$66 < \mathrm{m}_{\ell\ell} < 150\text{GeV}$

$\mathrm{W}^\pm \to \ell\nu : \mathrm{p}_\mathrm{T}^\ell > 25\text{GeV}$

$|\eta_\ell| < 2.5, \mathrm{p}_\mathrm{T}^\nu > 25\text{GeV}, \mathrm{m}_\mathrm{T} > 40\text{GeV}$

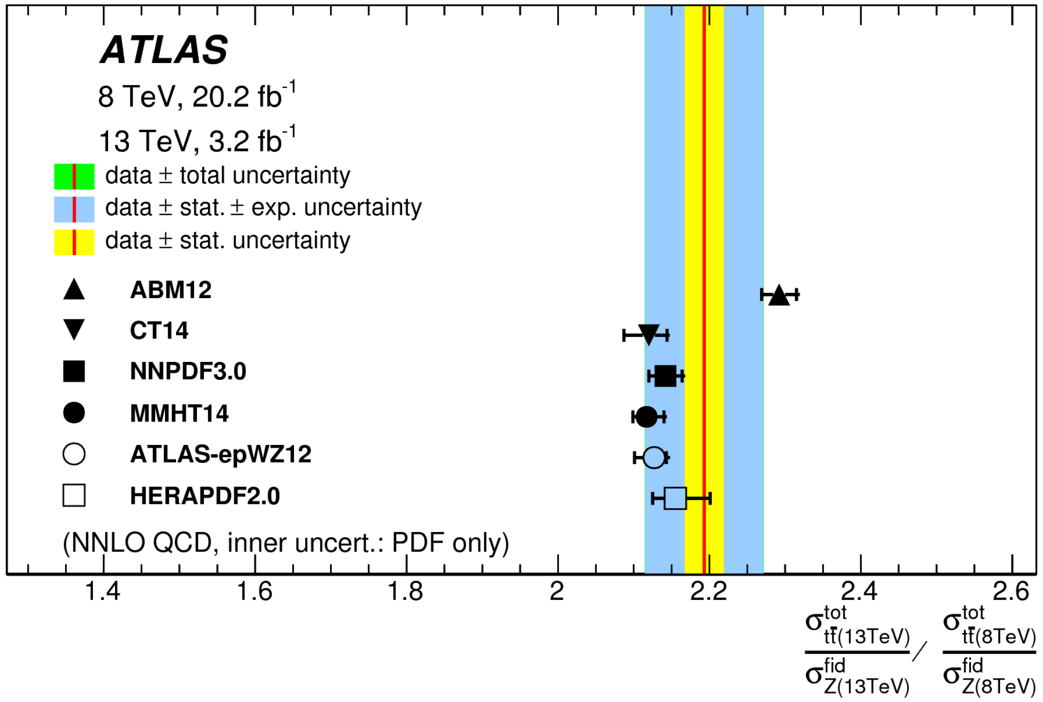


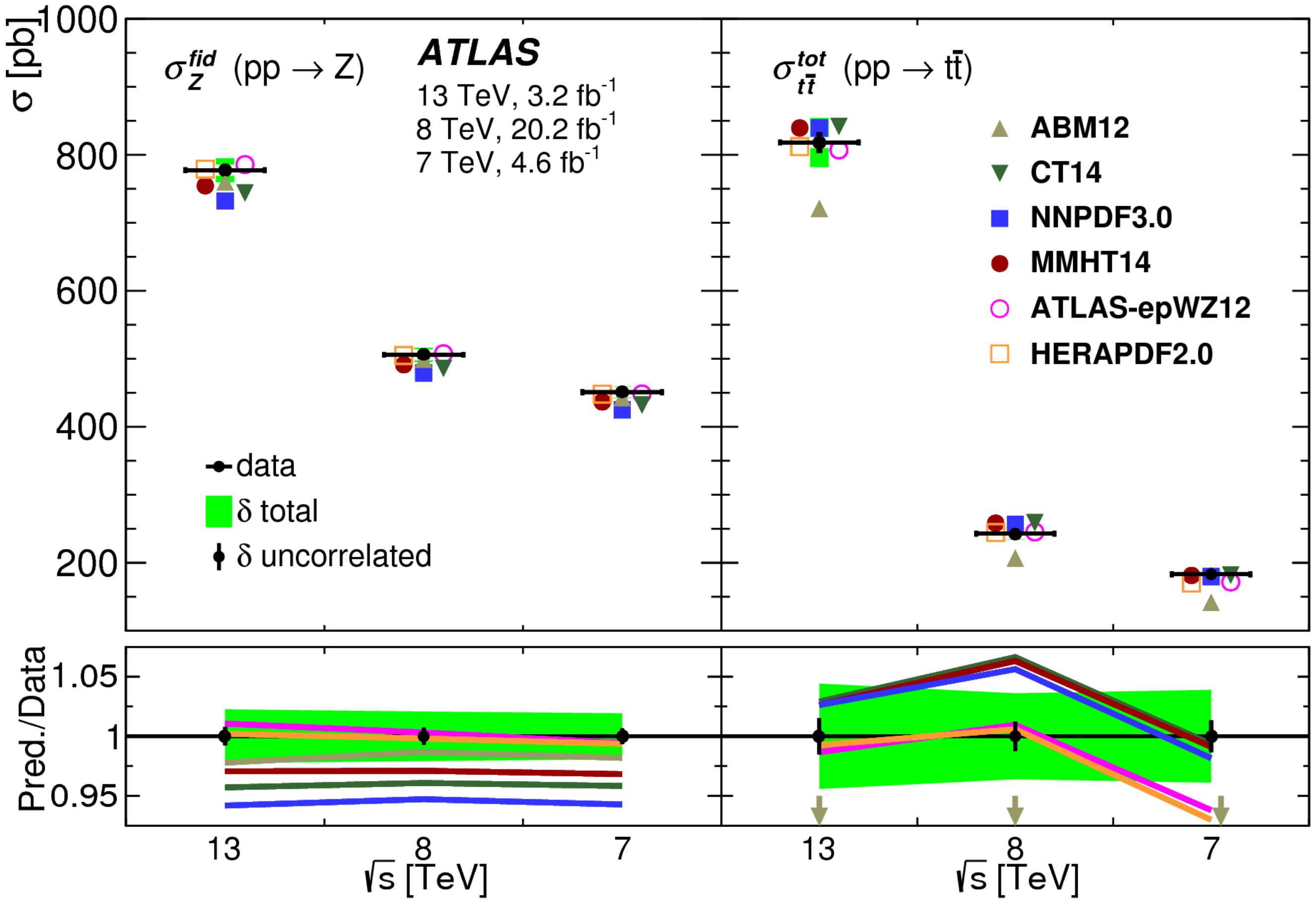
$R^{\text{fid}}_{W^+/W^-}$	1.5006 ± 0.0008 (stat) ± 0.0037 (syst)
$R^{\text{fid}}_{W/Z}$	9.780 ± 0.006 (stat) ± 0.049 (syst)
$R^{\text{fid}}_{W^+/Z}$	5.869 ± 0.004 (stat) ± 0.029 (syst)
$R^{\text{fid}}_{W^-/Z}$	3.911 ± 0.003 (stat) ± 0.021 (syst)

Table 8: Ratios of integrated fiducial CC and NC cross sections obtained from the combination of electron and muon channels with statistical (stat) and systematic (syst) uncertainties. The common fiducial regions are defined in Section 2.3.

$t\bar{t}$ to Z ratios at 7, 8 and 13TeV

- double ratios: tests of SM independent from luminosity uncertainties
  - ☑ $R_{tt/Z}^{13TeV}/R_{tt/Z}^{8TeV}$, $R_{tt/Z}^{13TeV}/R_{tt/Z}^{7TeV}$, $R_{tt/Z}^{8TeV}/R_{tt/Z}^{7TeV}$





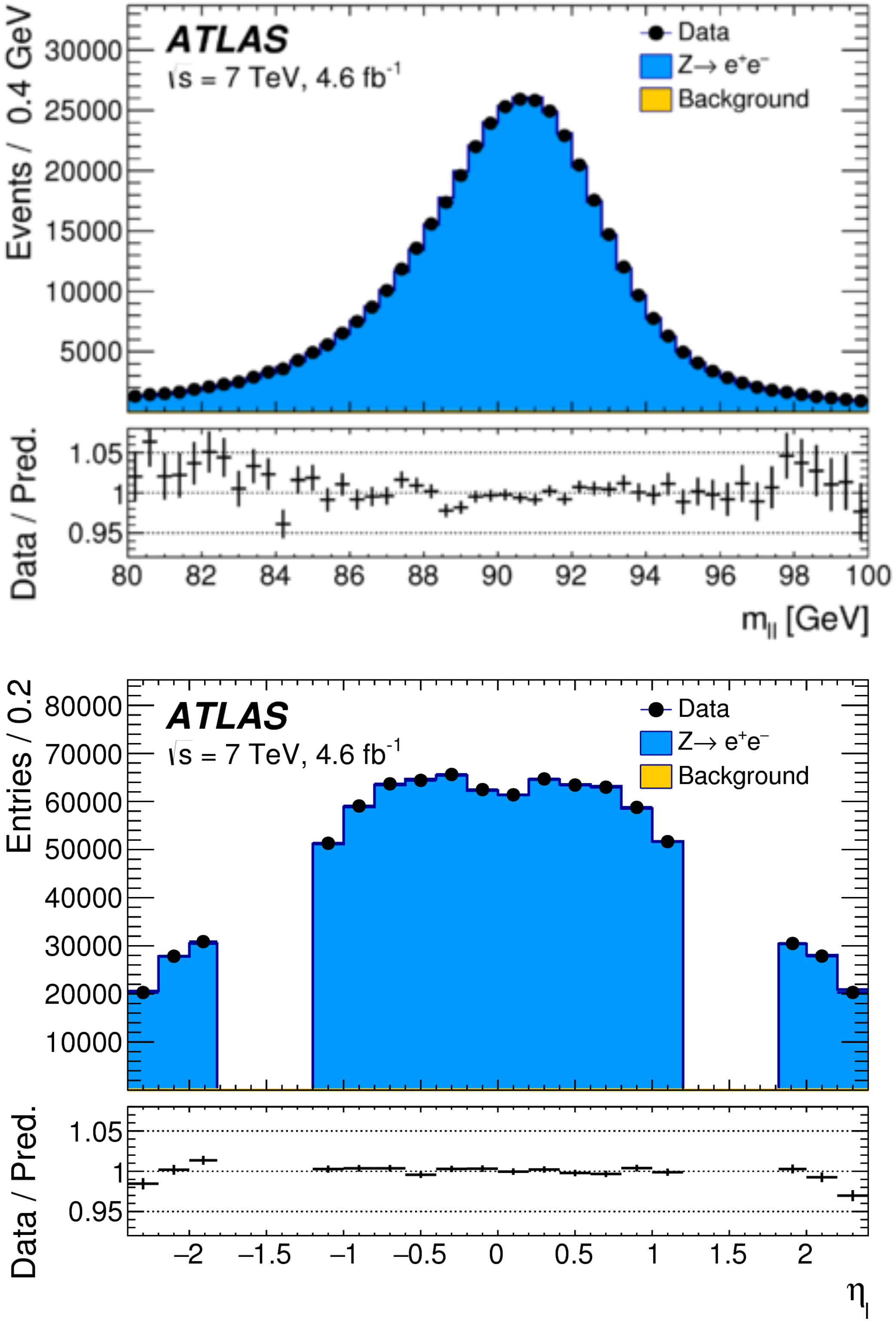
- Simultaneous analysis of all measurements taking into account all correlations in the systematics compared with the latest prediction
- Z: NNLO QCD calculation with DYNNLO 1.5 & NLO EW corrections with FEWZ3.1
- Top: Top++v2.0 for NNLO+NNLL cross-sections calculation
- CT14 PDF set used as baseline

Lepton calibration via Z decays

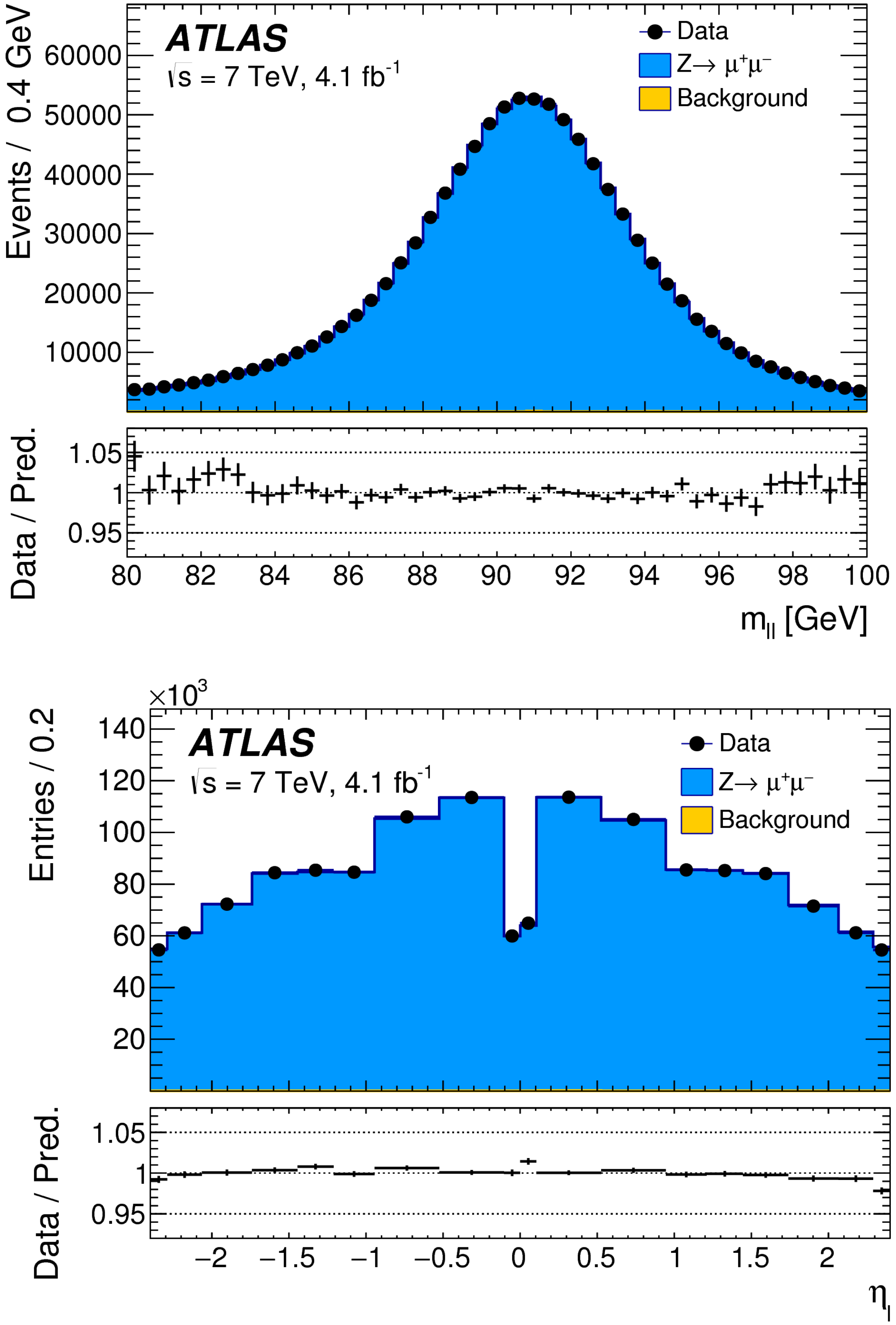
7TeV, 4.6fb^{-1}

- Benefit from the fully reconstructed mass in Z boson decays

electron channel

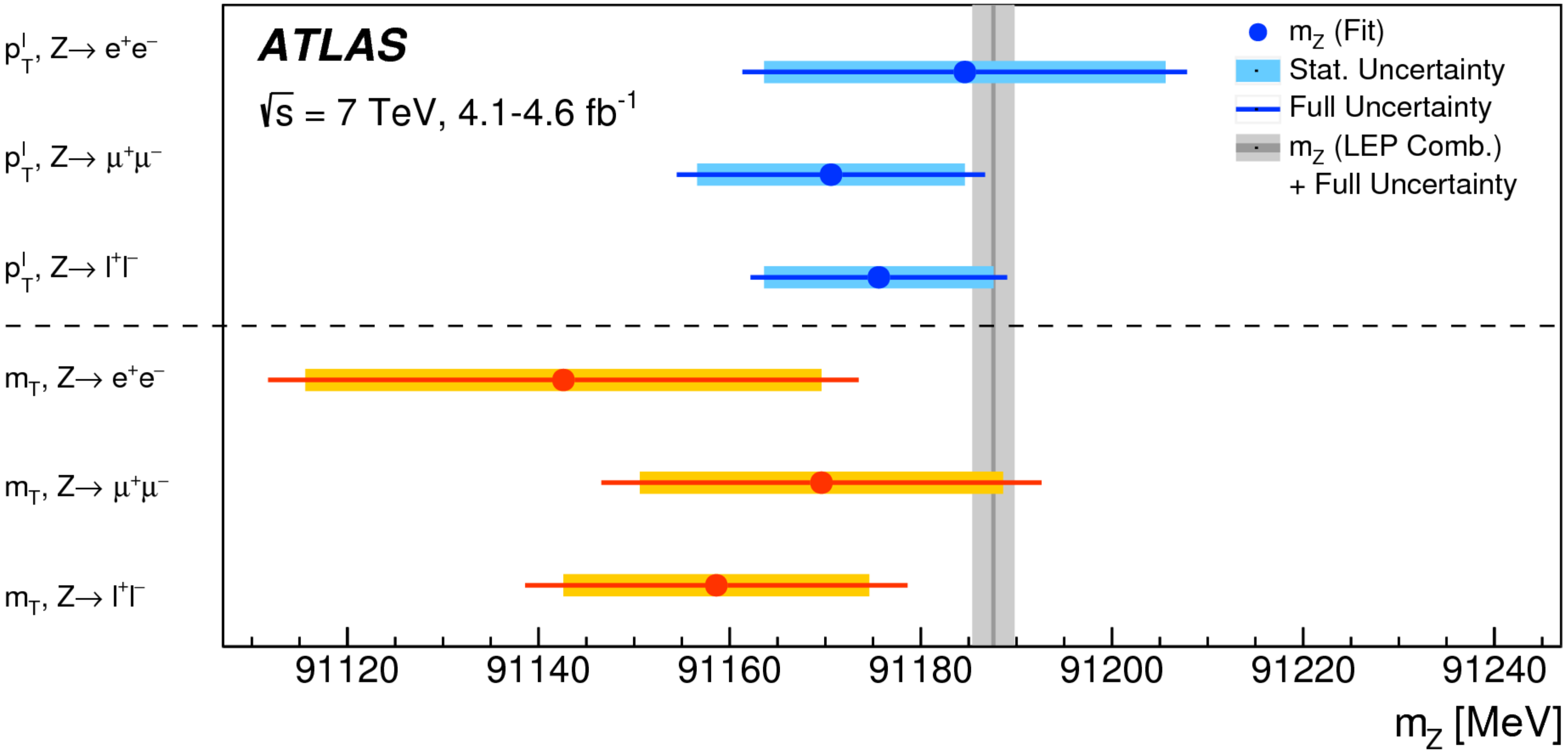


muon channel



W mass measurement: Z control measurements

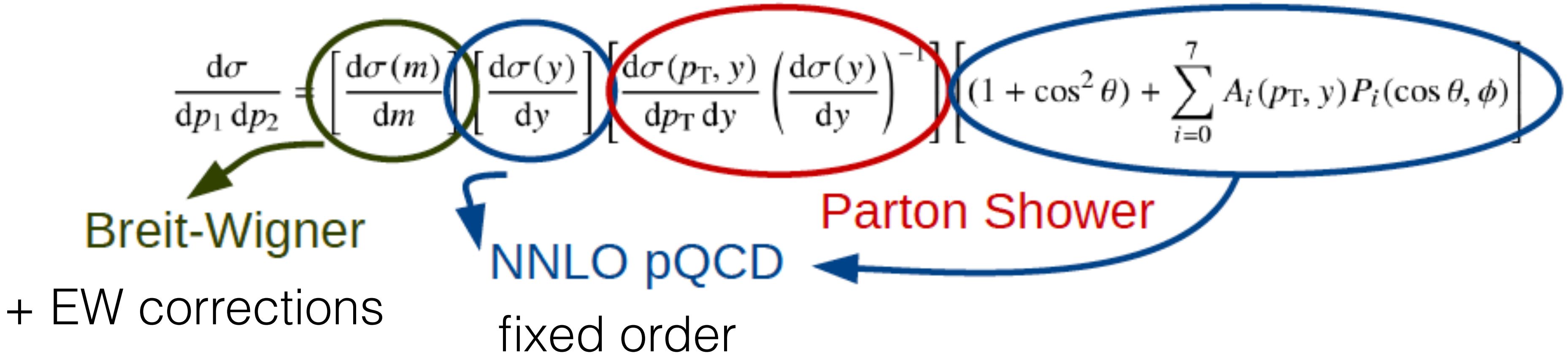
- Cross check with Z events
- Results are consistent with the combined LEP value of m_Z within experimental uncertainties



W mass measurement: physics modelling

- No available single generator to describe all the physics modeling
- Start from Powheg+Pythia8 and apply corrections using DY measurements
- Physics modeling corrections:
  - ☑ EW corrections
    - QED FSR and ISR
    - missing higher order effects and FSR pair production
  - ☑ QCD corrections
    - pT distribution
    - polarisation
    - rapidity

Drell-Yan cross sections



$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

+ EW corrections

NNLO pQCD

fixed order

Parton Shower