Testing parton distribution functions with *W* and *Z* bosons in the ATLAS experiment

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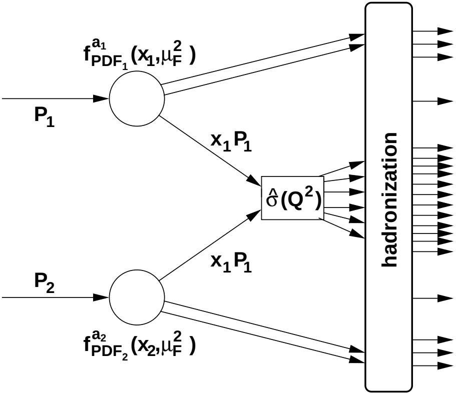
Outline

- Importance of W/Z boson measurements in the context of parton distribution function studies
- ATLAS measurements of W/Z boson production in pp collisions:
  - $\sqrt{s} = 5.02$ TeV
    - Performance studies
    - Background estimation
    - Results/Comparison to theory
  - $\sqrt{s} = 13$ TeV
    - Results/Comparison to theory
  - $\sqrt{s} = 7$ TeV
    - Results/Comparison to theory
    - Impact of results on PDFs
- Summary and outlook

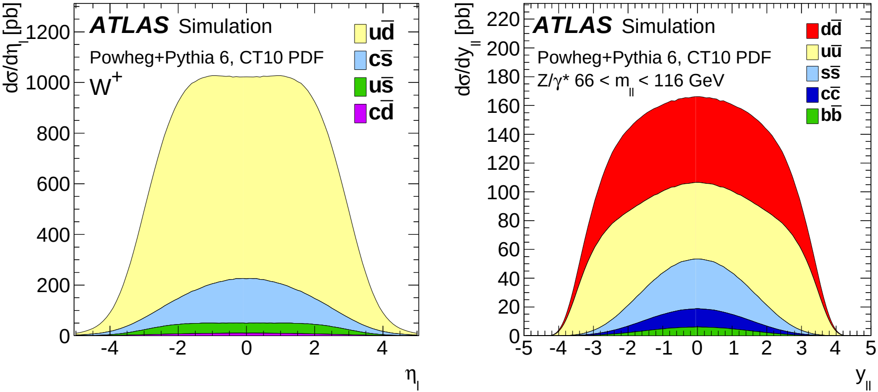
Brief introduction to parton distribution functions



- The **factorization theorem** for QCD calculations states that non-perturbative and perturbative parts can be factorized, e.g. into:
    - non-perturbative **parton distribution functions (PDFs)** which define the initial-state kinematics of the process
    - perturbative **matrix element** which describes the actual hard process
    - non-perturbative **fragmentation functions** which describe hadronization
- PDFs can be extracted from **global fits** to measurements of different processes.
- PDFs are usually parametrized in the Björken variables x and Q^2.

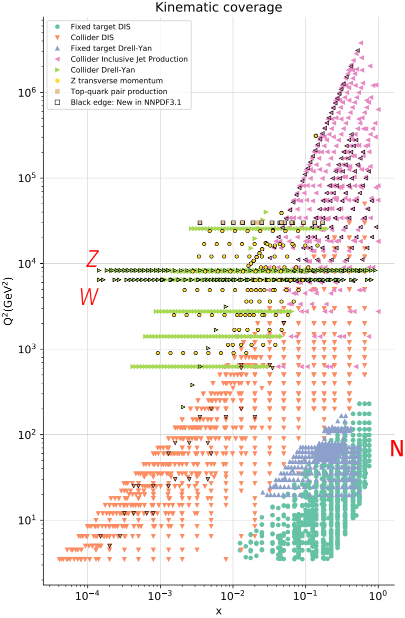
W and Z boson measurements at LHC energies

$\sqrt{s} = 7$ TeV



- Measurements of weak boson production in *pp* collisions provide a powerful tool to **test both the electroweak theory and underlying QCD dynamics**.
- Dominant production mode at the LHC is through **quark-antiquark annihilation**.
- Contributions from different quark flavours vary with $\sqrt{s}$.
- **Rapidity differential cross-sections** are very useful to provide constraints on PDFs.

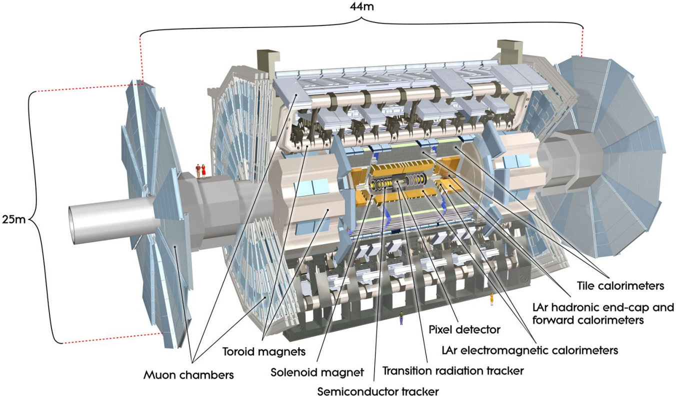
W and Z boson measurements at LHC energies



- Measurements of weak boson production cross-sections are **sensitive to PDFs** over a wide range in x at a fixed Q^2.
- Example: (x, Q^2) coverage of measurements used in fits for the NNPDF3.1 PDF set.
- NNPDF3.1 fit **includes** measurements of **rapidity differential W/Z cross-sections** at:
  - $\sqrt{s} = 7$ TeV (ATLAS, CMS)
  - $\sqrt{s} = 8$ TeV (CMS)
- This talk presents ATLAS results on W/Z boson production at:
  - NEW **$\sqrt{s} = 5.02$ TeV (2015 dataset): arXiv:1810.08424, under review in Eur. Phys. J. C**
  - $\sqrt{s} = 7$ TeV: Eur. Phys. J. C 77 (2017) 367
  - $\sqrt{s} = 13$ TeV (early 2015 dataset): Phys. Lett. B 759 (2016) 601

ATLAS detector / Datasets

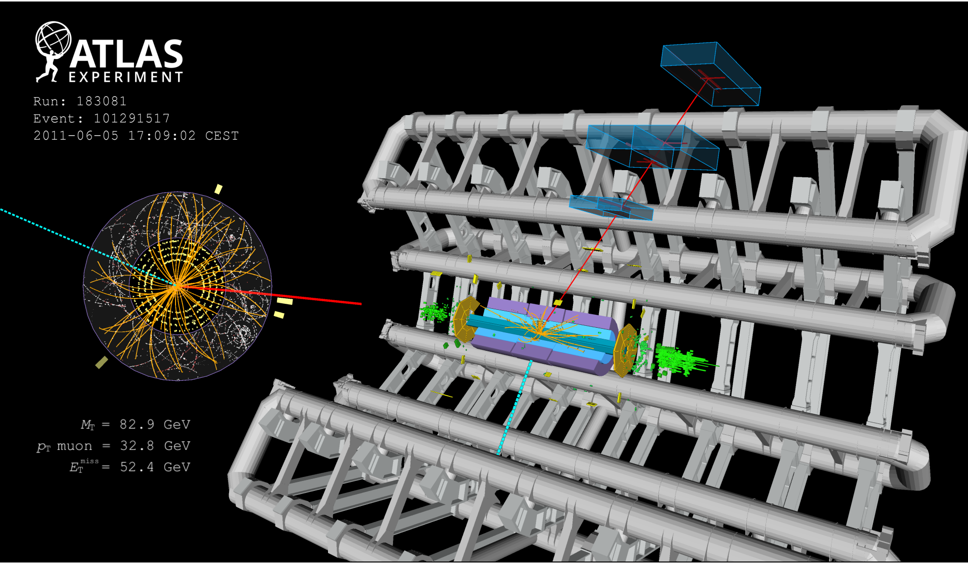
- All presented measurements use **leptonic decay channels** ($W^{\pm} \to \ell^{\pm}\nu$, $Z \to \ell^{+}\ell^{-}$, where $\ell = e, \mu$) to profit from the excellent lepton reconstruction in ATLAS:
  - **Charged particle tracking** in $|\eta| < 2.5 \to$ electrons, muons, MET
  - **Calorimeter system** in $|\eta| < 4.9 \to$ electrons, MET
  - **Muon reconstruction** in $|\eta| < 2.4$ (muon spectrometer + inner detector)



Datasets:

- *pp* collisions at $\sqrt{s} = 5.02$ TeV: 25 pb^{-1} (2015)
- *pp* collisions at $\sqrt{s} = 7$ TeV: 4.6 fb^{-1} (2011)
- *pp* collisions at $\sqrt{s} = 13$ TeV: 81 pb^{-1} (2015)

$W \to \mu\nu$ candidate event



W/Z bosons at $\sqrt{s} = 5.02$ TeV

Event selection

- Events collected with **single-lepton triggers** ($p_{\mathrm{T}}^{e} = 15$ GeV and $p_{\mathrm{T}}^{\mu} = 14$ GeV thresholds).
- Leptons required to pass reconstruction quality and isolation selections.
- Kinematic selections: $p_{\mathrm{T}}^{e(\mu)} > 25$ GeV (W candidates), $p_{\mathrm{T}}^{e(\mu)} > 20$ GeV (Z candidates), $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, $|\eta_\mu| < 2.4$

W boson candidates:

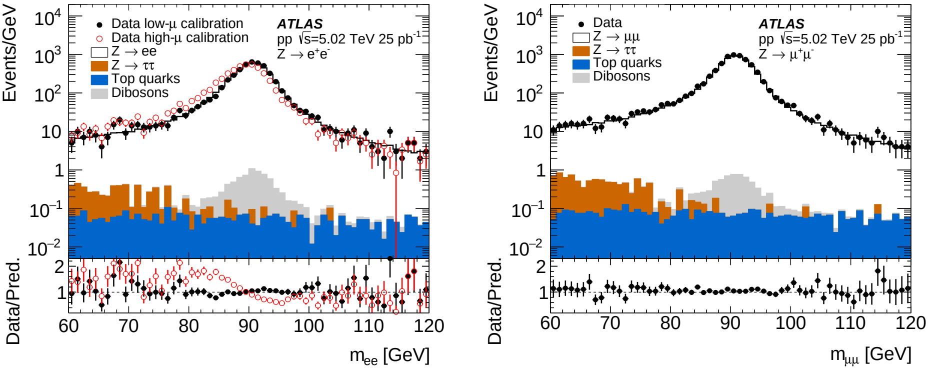
- Additional selection using missing transverse momentum: $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, and transverse mass: $m_{\mathrm{T}} > 40$ GeV.
- Require exactly one good lepton matched to trigger in the event.
- **$\sim$38000 (44000) $W^+ \rightarrow e^+\nu$ ($W^+ \rightarrow \mu^+\nu$) candidates**
- **$\sim$24000 (27000) $W^- \rightarrow e^-\nu$ ($W^- \rightarrow \mu^-\nu$) candidates**

Z boson candidates:

- Oppositely charged lepton pairs in mass range: $66 < m_{\ell\ell} < 116$ GeV
- One of the leptons matched to trigger.
- Roughly **4800 (7400)** events with **$Z \rightarrow ee$ ($Z \rightarrow \mu\mu$) candidates** found.

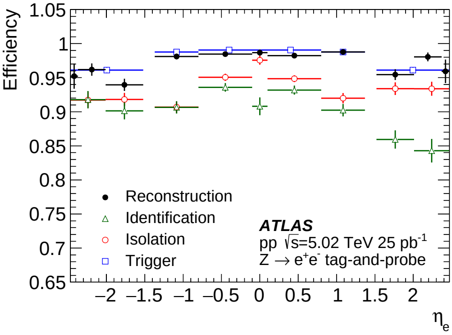
- **Many dedicated performance studies are crucial to achieve high precision of measurements**.
- Data was taken in low-pileup conditions, so the impact on measurements had to be studied.

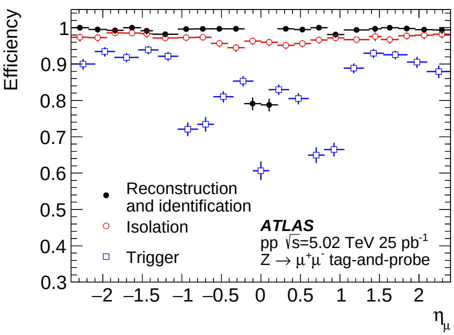
Lepton performance: calibration



- Data was taken in low-pileup conditions, but **standard lepton energy/momentum calibrations are derived for high-pileup datasets**.
- Using the **standard electron energy calibration** in a low-pileup dataset leads to a **shift and widening** of the $Z \to e^+e^-$ **invariant mass peak**.
- **Dedicated corrections** to the calibration were necessary to improve the agreement.
- **Standard muon momentum calibration works well**.
- $Z \to \ell^+\ell^-$ **events** are used to select a **clean sample of leptons** for efficiency measurements.

Lepton performance: efficiencies

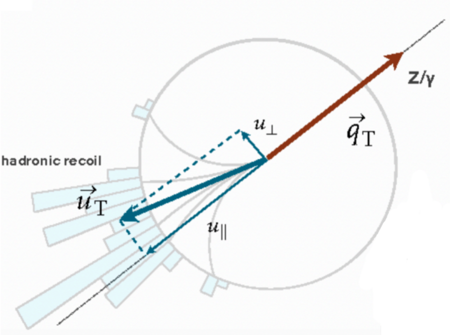




- Any detector inefficiencies need to be corrected for in the measurements.
- Efficiencies are measured with the **tag-and-probe method in $Z \rightarrow \ell^+\ell^-$ events**.
- Precision of efficiency measurements is limited by number of Z boson events in data.
- All **electron efficiences** are in the range **85–100%** and do not vary strongly with η.
- **Muon** reconstruction/identification and isolation **efficiences are above 95%**, but **trigger efficiency is lower** with a significant η dependence.

$E_{\mathrm{T}}^{\mathrm{miss}}$ calculation: hadronic recoil

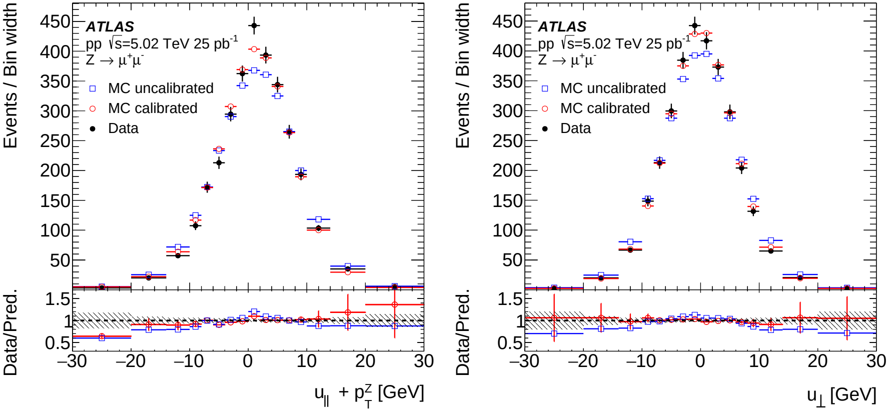
- In W and Z boson events the **hadronic recoil u_{T}** provides an estimate of the **boson transverse momentum**.
- Previous ATLAS measurements used a hadronic recoil reconstruction algorithm based on calorimetric clusters.
- **For this measurement**, the algorithm was improved to **use Particle Flow Objects (PFOs)** which reduces pileup dependence and improves resolution.



- PFOs can be split into two categories: **neutral PFOs** consist of a calorimetric cluster, while **charged PFOs** additionally match a charged-particle track.
- The **recoil is reconstructed as the sum over PFOs** in the event, rejecting the charged ones assigned to pileup vertices, and masking signal leptons.
- **Missing transverse momentum** $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated using the recoil:

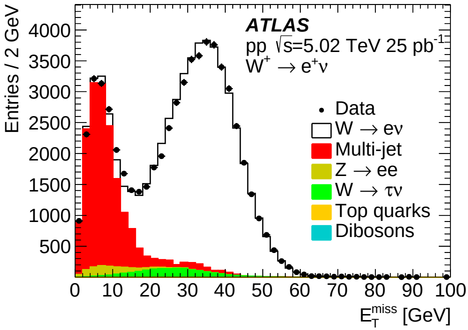
$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -(\vec{u}_{\mathrm{T}}^{\mathrm{PFO}} + \vec{p}_{\mathrm{T}}^{\mathrm{signal\ lepton}})$$

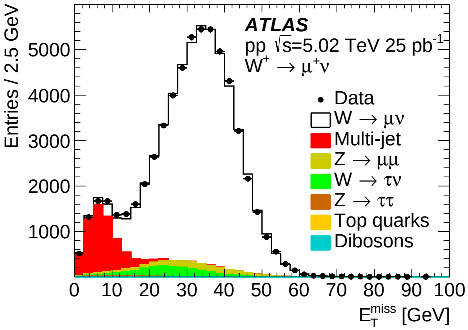
Hadronic recoil: calibration



- The hadronic recoil in simulation needs to be calibrated.
- Corrections to the recoil scale and resolution are derived in $Z \to \ell^+\ell^-$ events as a function of p_T^Z.
- **Calibration improves data/MC agreement** in $Z \to \ell^+\ell^-$ events.
- The derived corrections are then applied to simulated $W^\pm \to \ell^\pm\nu$ events.

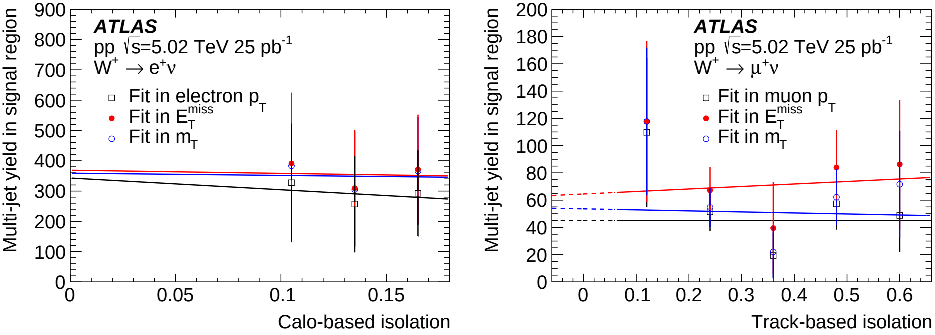
W bosons: multi-jet background estimation





- **Multi-jet background** category includes semileptonic heavy-flavour decays, pion/kaon decays, photon conversions or misidentified hadrons.
- This background contribution is estimated using **template fits to data** in a phase-space region without $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{T} requirements.
- Fits are repeated using several kinematic distributions (p_{T}^{ℓ}, $E_{\mathrm{T}}^{\mathrm{miss}}$ or m_{T}).
- **Multi-jet template** is constructed from **data with anti-isolated leptons**, while templates for signal and other background processes come from MC.

W bosons: multi-jet background estimation



- **Choice of isolation region** used to define **multi-jet template** is arbitrary.
- Therefore, yields of multi-jet background are estimated with templates constructed using **different isolation regions**.
- Final multi-jet background yield in the signal region is defined by:
  - **linear extrapolation** of yields to 0 isolation
  - taking **average of yields obtained using different kinematic distributions**

W/Z bosons: backgrounds

Background	$W^+ \to e^+\nu$ ($W^+ \to \mu^+\nu$) [%]	$W^- \to e^-\nu$ ($W^- \to \mu^-\nu$) [%]	$Z \to e^+e^-$ ($Z \to \mu^+\mu^-$) [%]
$Z \to \ell^+\ell^-$, $\ell = e, \mu$	0.1 (2.8)	0.2 (3.8)	–
$W^\pm \to \ell^\pm\nu$, $\ell = e, \mu$	–	–	<0.01 (<0.01)
$W^\pm \to \tau^\pm\nu$	1.8 (1.8)	1.8 (1.8)	<0.01 (<0.01)
$Z \to \tau^+\tau^-$	0.1 (0.1)	0.1 (0.1)	0.07 (0.07)
Multi-jet	0.9 (0.1)	1.4 (0.2)	<0.01 (<0.01)
Top quark	0.1–0.2 (0.1–0.2)	0.1–0.2 (0.1–0.2)	0.06 (0.08)
Diboson	0.1 (0.1)	0.1 (0.1)	0.14 (0.08)

- All background contributions except for the multi-jet background are estimated from simulation (Powheg+Pythia for W/Z and top quarks, Sherpa for dibosons).
- Sum of background contributions in W boson samples is between 3 and 6%.
- Largest background contributions to $W^\pm \to e^\pm\nu$ samples come from $W^\pm \to \tau^\pm\nu$ production and the multi-jet background.
- $W^\pm \to \mu^\pm\nu$ boson backgrounds are dominated by electroweak processes ($Z \to \mu^+\mu^-$, $W^\pm \to \tau^\pm\nu$).
- Z bosons backgrounds are at the level of 0.3% for both channels.

W/Z bosons: measurement procedure

- W/Z boson **production cross-sections** are measured in **fiducial phase-space volumes**:
  - $p_T^\ell > 25$ GeV, $|\eta_\ell| < 2.5$, $p_T^\nu > 25$ GeV, $m_T > 40$ GeV (W bosons)
  - $p_T^\ell > 20$ GeV, $|\eta_\ell| < 2.5$, $66 < m_{\ell\ell} < 116$ GeV (Z bosons)
- Cross-sections are calculated as follows:

$$\sigma^{\text{fid}}_{W^\pm \to \ell^\pm \nu [Z \to \ell^+ \ell^-]} = \frac{N_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot L_{\text{int}}}$$

  - $N_{W[Z]}$ and $B_{W[Z]}$ are the number of selected events in data and the expected number of background events, respectively.
  - $C_{W[Z]}$ are correction factors evaluated from simulation which account mainly for detector-related inefficiencies.
  - L_{int} is the integrated luminosity of the dataset.
- **Lepton charge asymmetry** defined using differential W boson cross-sections:

$$A_\ell(|\eta_\ell|) = \frac{\mathrm{d}\sigma_{W^+}/\mathrm{d}|\eta_\ell| - \mathrm{d}\sigma_{W^-}/\mathrm{d}|\eta_\ell|}{\mathrm{d}\sigma_{W^+}/\mathrm{d}|\eta_\ell| + \mathrm{d}\sigma_{W^-}/\mathrm{d}|\eta_\ell|}$$

W/Z bosons: uncertainties

electron channels

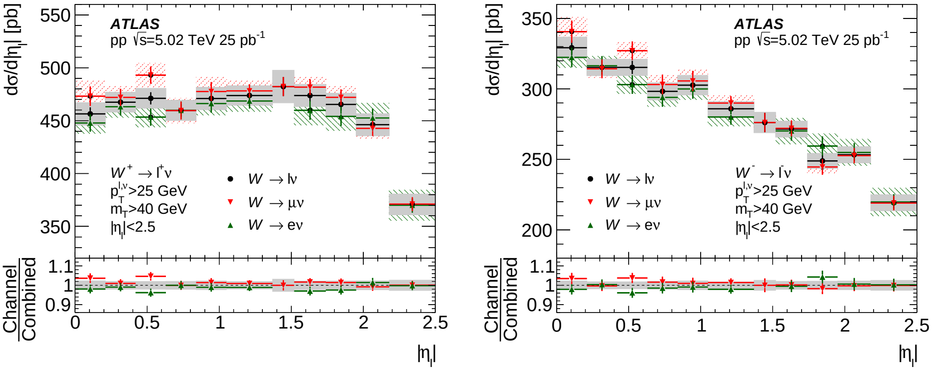
	$\delta\sigma_{W^+}$ [%]	$\delta\sigma_{W^-}$ [%]	$\delta\sigma_Z$ [%]
Trigger efficiency	0.2	0.2	<0.1
Reconstruction efficiency	0.2	0.2	0.4
Identification efficiency	0.6	0.5	1.0
Isolation efficiency	0.4	0.4	0.6
Electron p_T resolution	<0.1	<0.1	0.1
Electron p_T scale	0.3	0.2	0.1
Hadronic recoil calibration	0.5	0.4	–
Multi-jet background	0.7	0.8	<0.1
Electroweak+top background	0.1	0.1	<0.1
Data statistical uncertainty	0.6	0.7	1.4

muon channels

	$\delta\sigma_{W^+}$ [%]	$\delta\sigma_{W^-}$ [%]	$\delta\sigma_Z$ [%]
Trigger efficiency	1.4	1.4	0.4
Reconstruction efficiency	0.2	0.2	0.4
Isolation efficiency	0.4	0.4	0.7
Muon p_T resolution	0.1	<0.1	<0.1
Muon p_T scale	0.1	0.1	<0.1
Hadronic recoil calibration	0.5	0.5	–
Multi-jet background	0.1	0.2	<0.1
Electroweak+top background	0.1	0.2	<0.1
Data statistical uncertainty	0.5	0.6	1.2

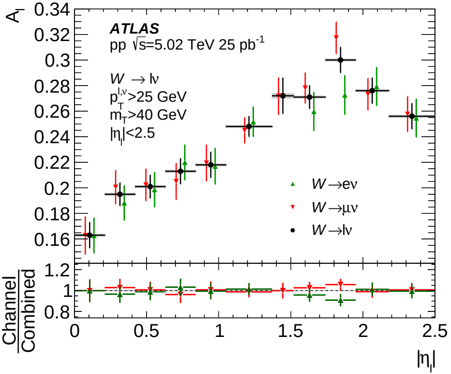
- Lepton- and recoil-related uncertainties are propagated through their impact on correction factors $C_{W[Z]}$.
- **Largest systematic uncertainties**:
  - $W^\pm \to e^\pm\nu$: multi-jet background, identification efficiency
  - $W^\pm \to \mu^\pm\nu$: trigger efficiency
- For Z boson cross-sections, statistical uncertainties are comparable with systematic ones.
- The **most significant source of uncertainty** in all channels (not shown in the tables) is **luminosity calibration** (1.9%).

W bosons: channel comparison



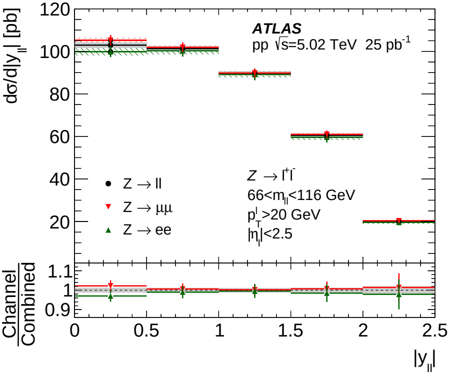
- Cross-sections measured in the muon channels are systematically slightly larger than in the electron channels.
- Results from electron and muon channels are **combined, accounting for uncertainty correlations** across channels and measurement bins.
- Combination yields: $\chi^2/\mathrm{DOF} = 19.3/10$ (W^+), $\chi^2/\mathrm{DOF} = 15.1/10$ (W^-)

W bosons: channel comparison



- **Lepton charge asymmetry** is calculated from cross-sections presented on the previous slide, separately for the electron/muon channels and for the combined results.
- Uncertainties are dominated by the statistical components.
- In general, a relatively **good agreement between the channels** is observed.

Z bosons: channel comparison



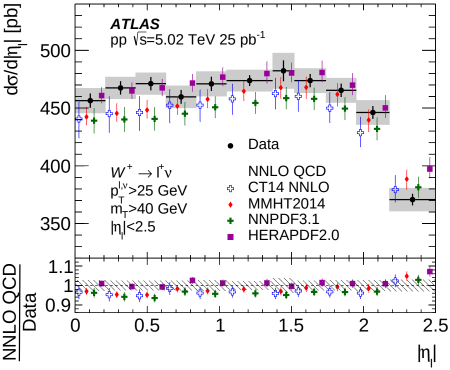
- **Similarly to W bosons**, the cross-sections measured in the muon channel are systematically slightly larger than in the electron channel.
- Combination yields: $\chi^2/\mathrm{DOF} = 3.0/5$ (Z), $\chi^2/\mathrm{DOF} = 37.5/25$ (global)
- In view of the slight but systematic discrepancy between channels, the **uncertainties on the combined results are scaled** such that the global $\chi^2/\mathrm{DOF} = 1$.

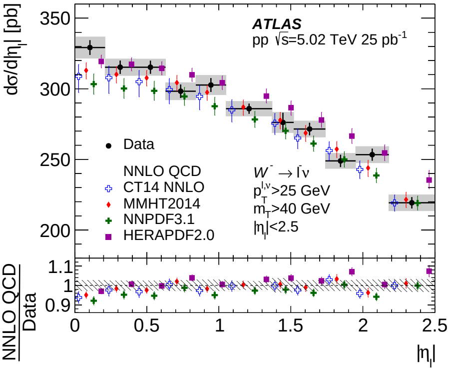
W/Z bosons: comparison to theory

- Theoretical predictions calculated at NNLO accuracy in QCD using an optimised version of DYNNLO 1.5.
- **Various PDF sets** used to calculate predictions:
  - NNPDF3.1 (includes precise ATLAS $\sqrt{s} = 7$ TeV W/Z boson measurements)
  - CT14nnlo, MMHT2014, HERAPDF2.0
- **Predictions of integrated fiducial cross-sections agree with data** within uncertainties, but are systematically lower by a few percent (except for HERAPDF2.0).

PDF set	$\sigma^{\text{fid}}_{W^+}$ [pb]	$\sigma^{\text{fid}}_{W^-}$ [pb]	σ^{fid}_{Z} [pb]	$\sigma^{\text{tot}}_{W^+}$ [pb]	$\sigma^{\text{tot}}_{W^-}$ [pb]	σ^{tot}_{Z} [pb]
CT14 NNLO	2203^{+62}_{-64}	1379^{+34}_{-42}	356^{+8}_{-10}	4299^{+112}_{-113}	2862^{+63}_{-77}	648^{+14}_{-16}
MMHT2014	2244^{+40}_{-39}	1393^{+24}_{-28}	363^{+6}_{-5}	4357^{+75}_{-73}	2902^{+49}_{-57}	660^{+11}_{-10}
NNPDF3.1	2186 ± 45	1344 ± 29	355 ± 7	4301 ± 87	2828 ± 62	645 ± 13
HERAPDF2.0	2291^{+92}_{-61}	1440^{+42}_{-27}	369^{+14}_{-7}	4459^{+180}_{-108}	3042^{+94}_{-56}	675^{+24}_{-13}
Additional uncertainties						
α_S	± 17	${}^{+13}_{-11}$	${}^{+3}_{-2}$	${}^{+31}_{-29}$	${}^{+27}_{-22}$	± 5
μ_R, μ_F scales	${}^{+18}_{-11}$	${}^{+11}_{-8}$	± 1	${}^{+25}_{-36}$	${}^{+13}_{-15}$	${}^{+3}_{-4}$
Data	2266 ± 53	1401 ± 33	374.5 ± 8.6	–	–	–

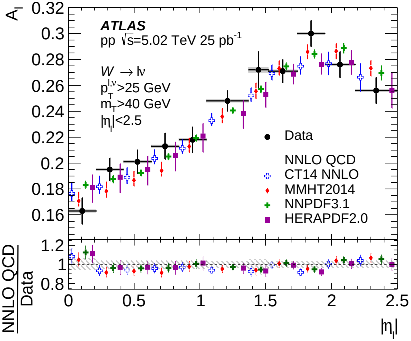
W bosons: differential cross-sections





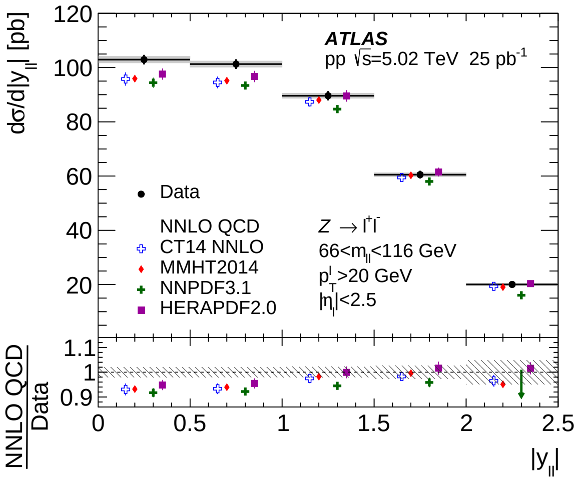
- **Lepton pseudorapidity differential cross-sections** measured in **fiducial** phase-space volume.
- **Predictions (except using HERAPDF 2.0)** systematically tend to **underestimate measured cross-sections**, but deviations are at the level of 1-2σ.

W bosons: lepton charge asymmetry



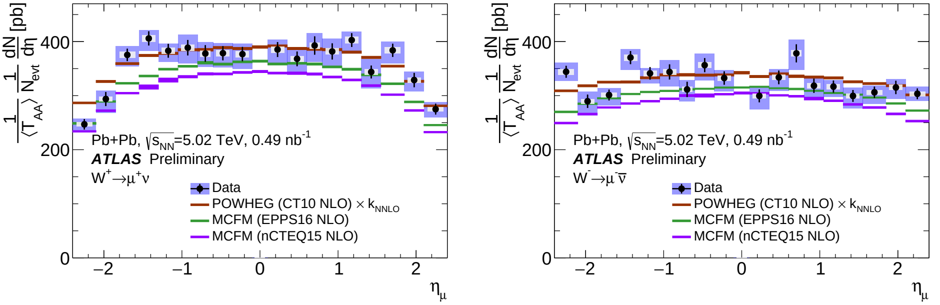
- **Systematic uncertainties**, which are partially correlated between W^+ and W^- boson measurements, are **reduced** to a large extent.
- **Good agreement of predictions** from all considered **PDF** sets with measured asymmetry.

Z bosons: differential cross-sections



- **Rapidity differential cross-sections** measured in **fiducial** phase-space volume.
- At **central rapidities** ($|y_{\ell\ell}| < 1$) all predictions tend to **underestimate measured cross-sections**.
- At **larger rapidities good agreement** with most considered PDF sets.

W bosons: comparison to Pb+Pb collisions

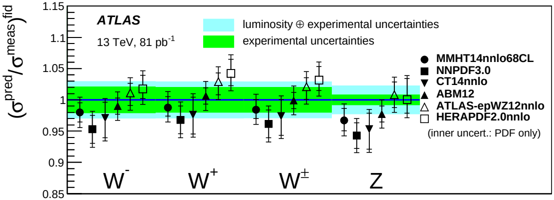


- Our group at AGH is also working on a **measurement of *W* boson production in Pb+Pb collisions** at the same centre-of-mass energy.
- Preliminary results exist already for the muon channel.
- The **measurement in *pp* collisions** will serve as an **important reference** to verify if any nuclear modifications are observed in Pb+Pb collisions.

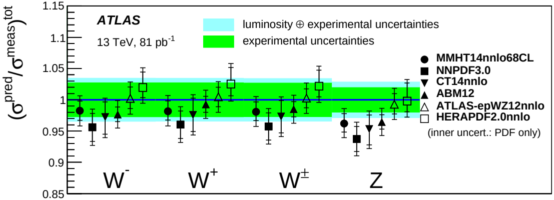
W/Z bosons at $\sqrt{s} = 13$ TeV

W/Z bosons: fiducial and total cross-sections

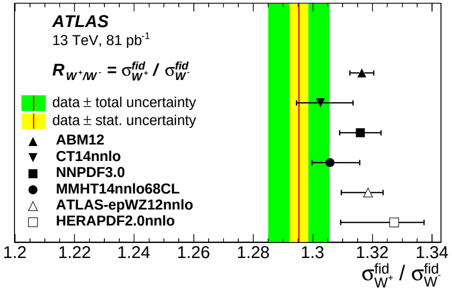
- Similar measurement strategy as for $\sqrt{s} = 5.02$ TeV analysis.
- **Fiducial cross-sections** (W bosons: $m_T > 50$ GeV, Z bosons: $p_T^{\ell} > 25$ GeV) **tend to be slightly underestimated** by some PDF sets, but no large deviations observed.

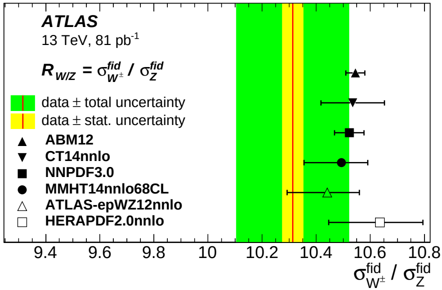


- Predictions for **total cross-sections** follow a **similar pattern**.



W/Z bosons: fiducial cross-section ratios

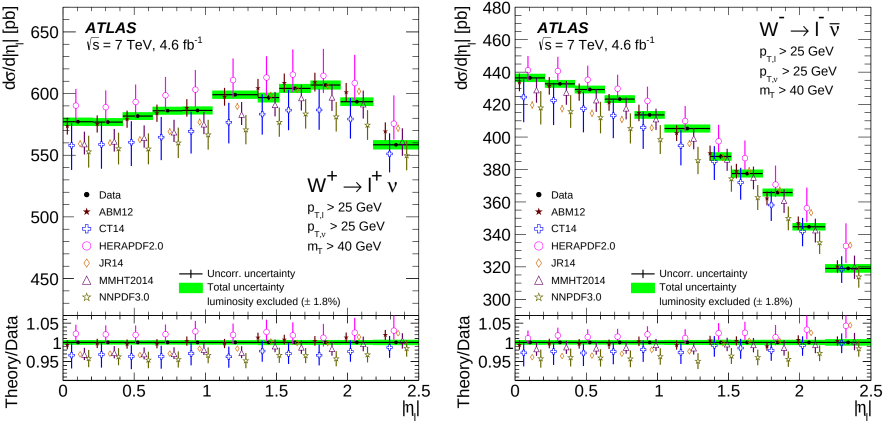




- **Ratio** of W^+/W^- fiducial cross-sections is **overestimated** by most PDF sets.
- Predicted **ratios** of $W^\pm/Z$ fiducial cross-sections show a **better agreement** with data.
- Differential cross-sections not measured in this analysis.

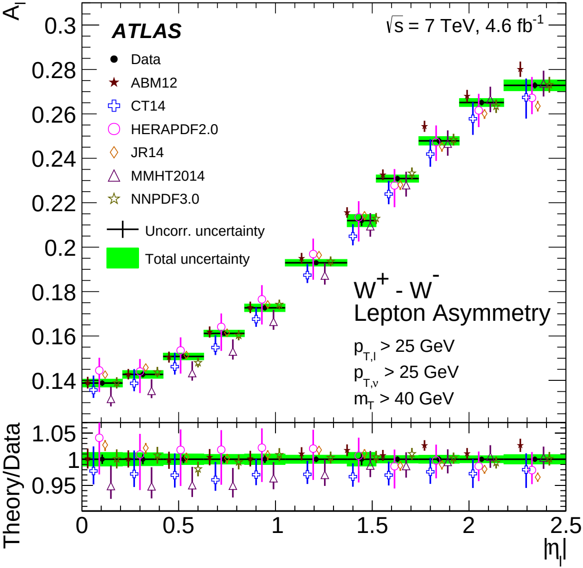
W/Z bosons at $\sqrt{s} = 7$ TeV

W bosons: differential cross-sections



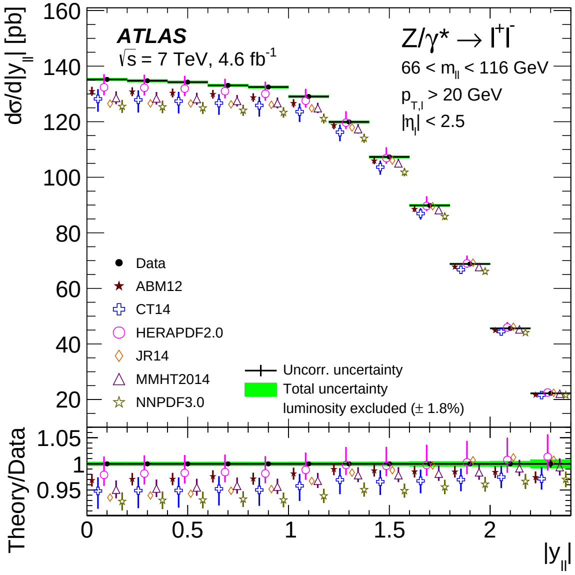
- Similar measurement strategy as for $\sqrt{s} = 5.02$ TeV analysis (same fiducial phase-space).
- By far the **most precise of the presented measurements** (sub-percent uncertainties).
- Most PDF sets lead to **predictions** which **deviate systematically** from the measured cross-sections by a few percent.
- ABM12 predictions describe the data best.

W bosons: lepton charge asymmetry

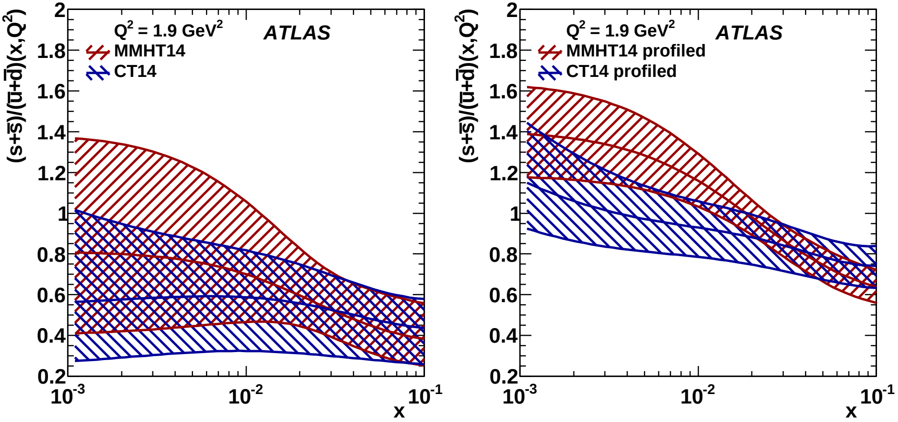


- **Good agreement of predictions** from most considered **PDF sets** with measured asymmetry.
- Only MMHT2014 tends to underestimate the data for central rapidities ($|\eta_\ell| < 1$).

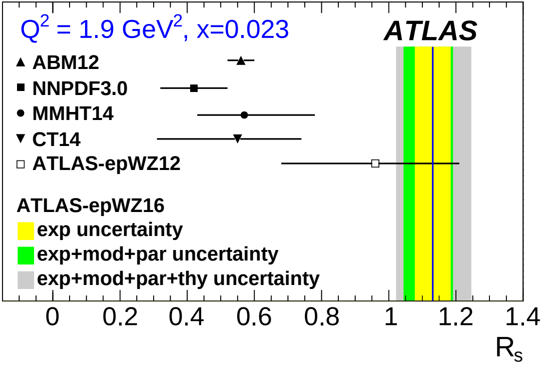
Z bosons: differential cross-sections



- For **central rapidities** ($|y_{\ell\ell}| < 1$), **measured cross-sections are larger** than all predictions (best agreement for HERAPDF 2.0).
- For **larger rapidities**, the **agreement** with most considered PDF sets **improves**.



- The profiling method allows to **estimate the impact of the measured** W/Z boson differential **cross-sections on existing PDF sets**.
- When including these results, the **ratio $R_s(x)$** $= (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$ **increases significantly**.
- This effect comes from an increase of the s quark PDF and a simultaneous slight decrease of $\bar{u}$ and $\bar{d}$ PDFs.



- A **global fit of PDFs is also perfomed**, taking into account HERA DIS data and the measured W/Z boson differential cross-sections.
- For the resulting **ATLAS-epWZ16 PDF set**, R_s is evaluated to be **close to unity** at $Q^2 = 1.9$ GeV^2 and $x = 0.023$.
- Other PDF sets exhibit significantly lower values, which suggest that the s quark density is suppressed in this kinematic region.

Summary and outlook

Summary

- ATLAS has performed **high-precision measurements of W/Z boson production** using LHC Run 1 ($\sqrt{s} = 7$ TeV) and Run 2 ($\sqrt{s} = 5.02,\ 13$ TeV) data.
  arXiv:1810.08424
- Many **dedicated perfomance studies** were **necessary** to achieve a sub-percent or few-percent level precision.
- Similar observations made at all collision energies: **fiducial cross-sections predicted using various PDF sets tend to deviate slightly from data**.
- The effect is most prominent for differential Z boson cross-sections in $|y_{\ell\ell}| < 1$.
- The measurement at $\sqrt{s} = 7$ TeV includes a **re-analysis of PDFs** showing that the ***s*** **quark contribution is underestimated** by most popular PDF sets.

Outlook

- A much larger dataset at $\sqrt{s} = 5.02$ TeV (~ 260 pb^{-1}) and additional low-pileup datasets at $\sqrt{s} = 13$ TeV (~ 340 pb^{-1}) are currently being analysed.
- Full high-pileup $\sqrt{s} = 13$ TeV dataset (~ 140 fb^{-1}) is also planned to be analysed.
- **Very precise** W/Z **boson measurements from ATLAS to come!**

Additional slides

CMS W boson measurement at $\sqrt{s} = 8$ TeV