Electroweak boson measurements in $p+Pb$ and $Pb+Pb$ collisions with ATLAS

Jakub Kremer for the ATLAS Collaboration
23 May 2019

AGH University of Science and Technology, Kraków, Poland
Introduction

• Measurements of electroweak (γ, W, Z) bosons in proton-proton collisions provide precise tests of Standard Model predictions including both the EW theory and QCD.
• They are also important to set a reference for heavy-ion analyses.
• In proton-nucleus collisions, one can probe cold nuclear matter effects such as nuclear modifications of PDFs or energy loss of initial-state partons.
• Nucleus-nucleus collisions at LHC energies create a strongly interacting quark-gluon plasma, which however does not significantly affect EW bosons or their leptonic decay products.
• In addition to cold nuclear matter effects, the collision centrality and geometry can be studied through $T_{AA}$ scaling of EW boson production.
• Presentation of results from:
  • $\gamma$ production in $p+$Pb at $\sqrt{s_{NN}} = 8.16$ TeV: arXiv:1903.02209 NEW!
  • $W$ production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015 dataset): ATLAS-CONF-2017-067
  • $Z$ production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015 dataset): ATLAS-CONF-2017-010
• **Charged particle tracking** in $|\eta| < 2.5 \rightarrow$ electrons, muons, track MET

• **Calorimeter system** in $|\eta| < 4.9 \rightarrow$ electrons, photons, MET, centrality determination (forward calorimeters, $3.1 < |\eta| < 4.9$)

• **Muon reconstruction** in $|\eta| < 2.4$ (muon spectrometer + inner detector)

Datasets:

• Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV: 0.49 nb$^{-1}$ (2015)

• p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV: 165 nb$^{-1}$ (2016)

• **pp collisions** at $\sqrt{s} = 5.02$ TeV: 25 pb$^{-1}$ (2015)
Events collected with single-lepton triggers ($p_T^e = 15$ GeV and $p_T^\mu = 14$ GeV thresholds).

- Leptons required to pass reconstruction quality and isolation selections + match trigger.

- Kinematic selections for $W$ ($Z$) boson selection: $p_T^e/\mu > 25$ ($20$) GeV, $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, $|\eta_\mu| < 2.4$

- $W$ boson selection:
  - missing transverse energy calculated using hadronic recoil from particle flow: $E_T^{\text{miss}} > 25$ GeV, $m_T > 40$ GeV

- $Z$ boson selection:
  - opposite-charge same-flavour lepton pairs in mass range $66 < m_{\ell\ell} < 116$ GeV

- Subtracted backgrounds (EW bosons + dibosons and top quarks from MC, multi-jet from data): $3$-$4\%$ ($W \rightarrow e\nu$), $5$-$6\%$ ($W \rightarrow \mu\nu$), $0.3\%$ ($Z \rightarrow \ell\ell$)
**W bosons in pp: Differential cross-sections**

Lepton pseudorapidity differential cross-sections measured in fiducial phase-space volume.

Combination of decay channels using the BLUE method accounting for uncertainty correlations.

Comparison to several NNLO theory predictions (different PDF sets) calculated with an optimised version of DYNNLO 1.5.

Good agreement of predictions from NNPDF3.1 and HERAPDF 2.0 PDFs with data, while other PDF sets systematically tend to underestimate measured cross-sections.

---

ATLAS

**pp $$\sqrt{s}$$=5.02 TeV 25 pb$$^{-1}$$**

**W$$^+$$ → l$$^+$$ν**

**p$$^+_T$$>25 GeV**

**m$$_T$$>40 GeV**

**|$$\eta$$|<2.5**

---

ATLAS

**pp $$\sqrt{s}$$=5.02 TeV 25 pb$$^{-1}$$**

**W$$^-$$ → l$$^-$$ν**

**p$$^+_T$$>25 GeV**

**m$$_T$$>40 GeV**

**|$$\eta$$|<2.5**
Rapidity differential cross-sections measured in fiducial phase-space volume.

Comparison to the same set of theory predictions as for W bosons.

At central rapidities (|y_{ll}| < 1) all predictions tend to underestimate measured cross-sections.

At larger rapidities good agreement with most considered PDF sets.

Similar observations made in high-precision measurement at 7 TeV.
Prompt photons in $p+$Pb: Measurement strategy

- Events collected with single-photon triggers ($p_T^\gamma$ thresholds between 15 GeV and 35 GeV).
- Photons required to pass reconstruction quality and isolation selections.
- Kinematic selections: $p_T^\gamma > 20$ GeV, $|\eta_\gamma| < 1.37$ or $1.56 < |\eta_\gamma| < 2.37$
- Background estimation using sidebands in isolation and identification (purity between 45% and 99%).
- No direct reference measurement in $pp$ collisions, existing results at 8 TeV extrapolated to 8.16 TeV using NLO calculations.
Prompt photons in $p+$Pb: Nuclear modification factor

- Nuclear modification factor $R_{pPb} = \frac{d\sigma_{p^+Pb \rightarrow \gamma + X} / dE_T^\gamma}{A \cdot d\sigma_{pp \rightarrow \gamma + X} / dE_T^\gamma}$ ($A = 208$ is the Pb mass number).

- At forward and central rapidities, nuclear effects are small resulting in $R_{pPb}$ values consistent with unity.

- For backward rapidities, the $R_{pPb}$ seems to decrease at high $E_T^\gamma$ which can be explained by different fractions of $u$ and $d$ quarks in the proton and the Pb nucleus.

- Comparison to model predictions suggests no large initial-state parton energy loss.
Reduction of systematic uncertainties for ratios of forward and backward $R_{pPb}$.

Comparison to NLO calculations from JETPHOX using free-nucleon PDFs (CT14) and nPDFs (EPPS16 and nCTEQ15).

The free-nucleon prediction shows the best agreement with data.

Data also compatible with small nuclear modifications represented by nPDFs in most of the considered $E_T^\gamma$ range.
Events collected with **single-muon trigger** ($p_T = 8$ GeV threshold).

- Muons required to pass reconstruction quality selection.
- Kinematic selections:
  - $p_T > 20$ GeV, $|\eta_{\mu}| < 2.5$
  - Opposite-charge muon pairs in mass range: $66 < m_{\mu\mu} < 116$ GeV
  - One of the muons required to match trigger.

- Roughly **5500** events with **Z boson candidates** found.

- **Subtracted backgrounds** ($Z \rightarrow \tau\tau$ and $t\bar{t}$ estimated from MC, multi-jet from data) at the level of 0.5%.

- Dimuon candidates are corrected for reconstruction efficiency, trigger efficiency and muon $p_T$ selection.
• Rapidity differential yields per minimum-bias event divided by $\langle T_{AA} \rangle$ to compare with $pp$ cross-sections.

• Mostly consistent with $\langle T_{AA} \rangle$ scaling - only peripheral bin is somewhat high ($\sim 1.5\sigma$).

• Nuclear modification factor $R_{AA} = \frac{N_{AA}^Z/N_{evt}}{\langle T_{AA} \rangle \times \sigma_{PP}^Z}$ expected to be $\approx 1.02$ because of isospin effect.

• Caveat: preliminary results on $pp$ cross-sections used to construct $R_{AA}$.
Yields per minimum-bias event divided by $\langle T_{AA} \rangle$ (integrated in $|y_{Z}| < 2.5$).

High-precision measurement: uncertainties related to EW bosons smaller than normalisation uncertainties.

Most peripheral bin shows a hint of excess, otherwise no significant dependence of scaled yields or $R_{AA}$ on centrality observed.

Replace $R_{AA}$ for other hard probes with $Z_{AA} = \frac{N_{AA}^{X} \cdot \sigma_{pp}^{Z}}{\sigma_{pp}^{X} \cdot N_{AA}^{Z}}$.
$W$ bosons in Pb+Pb: Measurement strategy

ATLAS-CONF-2017-067

- Events collected with single-muon trigger ($p_T = 15$ GeV threshold).
- Muons required to pass reconstruction quality and isolation selections + match trigger.
- Kinematic selection: $p_T^\mu > 25$ GeV, $0 < |\eta_\mu| < 2.4$
- Selection on missing transverse momentum reconstructed from charged-particle tracks: $p_T^{\text{miss}} > 25$ GeV, $m_T > 40$ GeV
- Additional veto on $Z$ boson candidate events.
- Roughly 25000 (23000) events with $W^+$ ($W^-$) boson candidates found.
- Subtracted backgrounds: 2-3% EW and $t\bar{t}$ estimated from MC, 6-12% multi-jet estimated with data-driven method
- Corrections applied for trigger, reconstruction and isolation efficiencies, as well as effects related to $p_T^{\text{miss}}$ reconstruction.
Lepton pseudorapidity differential yields per minimum-bias event divided by $\langle T_{AA} \rangle$ for fiducial phase-space volume: $p_T > 25$ GeV, $p_T^{miss} > 25$ GeV, $m_T > 40$ GeV.

Comparisons with several theory predictions:

- CT10 free-nucleon PDFs (Powheg+Pythia8, NLO scaled to NNLO)
- EPPS16 and nCTEQ15 nPDFs (both MCFM, NLO)

Best agreement with NLO calculation obtained with free-nucleon PDFs scaled to NNLO results, while NLO calculations with nPDFs are somewhat below data.
W bosons in Pb+Pb: Yields vs. centrality

| Fiducial yields per minimum-bias event divided by \( \langle T_{AA} \rangle \) (integrated in \( 0.1 < |\eta_\mu| < 2.4 \)). |
| --- |
| Similarly to Z bosons, most peripheral bin shows a hint of excess. |
| Otherwise no significant dependence of scaled yields on centrality observed. |
| Predictions from Powheg+Pythia8 including isospin effect and scaled to NNLO agree with data. |

ATLAS Preliminary

Pb+Pb, \( \sqrt{s_{NN}}=5.02 \) TeV, 0.49 nb\(^{-1}\)

\( W \rightarrow \mu \nu \)

\( \frac{N_{W \rightarrow \mu \nu}}{\langle T_{AA} \rangle} \) vs. \( \langle N_{\text{part}} \rangle \)
Lepton charge asymmetry defined using differential cross-sections (or yields for Pb+Pb):

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

- Systematic uncertainties are reduced to a large extent.
- Different shapes of asymmetry distributions in pp and Pb+Pb collisions due to isospin effect.
- pp: good agreement of predictions from all considered PDF sets with measured asymmetry.
- Pb+Pb: no preference observed for nPDF sets (little sensitivity with present uncertainties).
• Presented recent ATLAS measurements of electroweak boson production in $pp$ and Pb+Pb collisions at 5.02 TeV, and in $p+$Pb collisions at 8.16 TeV.

• $pp$ collisions:
  • $W/Z$ boson measurements provide high-precision baseline for Pb+Pb results.
  • Good agreement of NNLO theory predictions calculated using NNPDF3.1 and HERAPDF2.0 PDFs with data.

• $p+$Pb collisions:
  • Measured nuclear modifications consistent with nPDF predictions, but disfavour large initial-state parton energy loss.

• Pb+Pb collisions:
  • Measurements consistent with expectations from $T_{AA}$ scaling, no significant dependence of yields on centrality (except most peripheral collisions).
  • With current uncertainties there is little experimental sensitivity to nPDFs.

• Updated Pb+Pb results (electron channels, new $pp$ reference) in preparation.

• Large Pb+Pb dataset collected in 2018 (3.5 times larger luminosity than in 2015) to be explored.
Additional slides
$W/Z$ bosons in $pp$: Electron calibration

ATLAS $pp \sqrt{s}=5.02$ TeV 25 pb$^{-1}$

Efficiencies measured with the tag-and-probe method in $Z \rightarrow \ell\ell$ events in data.
\( W/Z \) bosons in \( pp \): Channel combination

\[
\begin{align*}
\text{ATLAS} & \quad pp \ \sqrt{s}=5.02 \ \text{TeV} \ 25 \ \text{pb}^{-1} \\
& \quad W^+ \rightarrow \ell^+ \nu \\
& \quad p_T^{\ell^+}>25 \ \text{GeV} \\
& \quad m_{\ell^+\nu}>116 \ \text{GeV} \\
& \quad |\eta|<2.5 \\
& \quad W \rightarrow \nu \\
& \quad W \rightarrow \mu \nu \\
& \quad W \rightarrow e \nu \\
& \quad m_{\nu}>40 \ \text{GeV} \\
& \quad \text{Combined Channel} \\
\end{align*}
\]

\[
\begin{align*}
\text{ATLAS} & \quad pp \ \sqrt{s}=5.02 \ \text{TeV} \ 25 \ \text{pb}^{-1} \\
& \quad W^+ \rightarrow \ell^+ \nu \\
& \quad p_T^{\ell^+}>25 \ \text{GeV} \\
& \quad m_{\ell^+\nu}>116 \ \text{GeV} \\
& \quad |\eta|<2.5 \\
& \quad W \rightarrow \nu \\
& \quad W \rightarrow \mu \nu \\
& \quad W \rightarrow e \nu \\
& \quad m_{\nu}>40 \ \text{GeV} \\
& \quad \text{Combined Channel} \\
\end{align*}
\]
### W/Z bosons in pp: Integrated cross-sections


<table>
<thead>
<tr>
<th>PDF set</th>
<th>$\sigma_{W^+}^{\text{fid}}$ [pb]</th>
<th>$\sigma_{W^-}^{\text{fid}}$ [pb]</th>
<th>$\sigma_{Z}^{\text{fid}}$ [pb]</th>
<th>$\sigma_{W^+}^{\text{tot}}$ [pb]</th>
<th>$\sigma_{W^-}^{\text{tot}}$ [pb]</th>
<th>$\sigma_{Z}^{\text{tot}}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT14 NNLO</td>
<td>$2203^{+62}_{-64}$</td>
<td>$1379^{+34}_{-42}$</td>
<td>$356^{+8}_{-10}$</td>
<td>$4299^{+112}_{-113}$</td>
<td>$2862^{+63}_{-77}$</td>
<td>$648^{+14}_{-16}$</td>
</tr>
<tr>
<td>NNPDF3.1</td>
<td>$2280 \pm 27$</td>
<td>$1403 \pm 17$</td>
<td>$371 \pm 4$</td>
<td>$4393 \pm 48$</td>
<td>$2926 \pm 31$</td>
<td>$682 \pm 7$</td>
</tr>
<tr>
<td>MMHT2014</td>
<td>$2244^{+40}_{-39}$</td>
<td>$1393^{+24}_{-28}$</td>
<td>$363^{+6}_{-5}$</td>
<td>$4357^{+75}_{-73}$</td>
<td>$2902^{+49}_{-57}$</td>
<td>$660^{+11}_{-10}$</td>
</tr>
<tr>
<td>HERAPDF2.0</td>
<td>$2291^{+92}_{-61}$</td>
<td>$1440^{+42}_{-27}$</td>
<td>$369^{+14}_{-7}$</td>
<td>$4459^{+180}_{-108}$</td>
<td>$3042^{+94}_{-56}$</td>
<td>$675^{+24}_{-13}$</td>
</tr>
<tr>
<td>ABMP16</td>
<td>$2205 \pm 19$</td>
<td>$1363 \pm 14$</td>
<td>$362 \pm 3$</td>
<td>$4298 \pm 37$</td>
<td>$2819 \pm 32$</td>
<td>$654 \pm 6$</td>
</tr>
</tbody>
</table>

**Additional uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha_S$</th>
<th>$\mu_r, \mu_f$ scales</th>
<th>$\alpha_S$</th>
<th>$\mu_r, \mu_f$ scales</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pm 17$</td>
<td>$\pm 13$</td>
<td>$\pm 2$</td>
<td>$\pm 2$</td>
</tr>
<tr>
<td></td>
<td>$\pm 11$</td>
<td>$\pm 11$</td>
<td>$\pm 29$</td>
<td>$\pm 27$</td>
</tr>
<tr>
<td></td>
<td>$\pm 8$</td>
<td>$\pm 1$</td>
<td>$\pm 25$</td>
<td>$\pm 13$</td>
</tr>
</tbody>
</table>

**Data**

- $W^+$: $2266 \pm 9$ (stat.) $\pm 29$ (syst.) $\pm 43$ (lumi) pb
- $W^-$: $1401 \pm 7$ (stat.) $\pm 18$ (syst.) $\pm 27$ (lumi) pb
- $Z$: $374.5 \pm 3.4$ (stat.) $\pm 3.6$ (syst.) $\pm 7.0$ (lumi) pb

| $R_{W^+}^{\text{fid}}$ | 1.617 $\pm$ 0.012 (stat) $\pm$ 0.003 (syst) |
| $R_{W^-}^{\text{fid}}$ | 9.81 $\pm$ 0.13 (stat) $\pm$ 0.01 (syst)   |
| $R_{W/Z}^{\text{fid}}$ | 6.06 $\pm$ 0.08 (stat) $\pm$ 0.01 (syst)   |
| $R_{W^+}^{\text{fid}}$ | 3.75 $\pm$ 0.05 (stat) $\pm$ 0.01 (syst)   |
## W/Z bosons in $pp$: Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\delta\sigma_{W^+}$ [%]</th>
<th>$\delta\sigma_{W^-}$ [%]</th>
<th>$\delta\sigma_{Z}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>0.2</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Identification efficiency</td>
<td>0.6</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron $p_T$ resolution</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Electron $p_T$ scale</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Hadronic recoil calibration</td>
<td>0.5</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>Multi-jet background</td>
<td>0.7</td>
<td>0.8</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Electroweak+top background</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Data statistical uncertainty</td>
<td>0.6</td>
<td>0.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\delta\sigma_{W^+}$ [%]</th>
<th>$\delta\sigma_{W^-}$ [%]</th>
<th>$\delta\sigma_{Z}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>1.4</td>
<td>1.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Muon $p_T$ resolution</td>
<td>0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Muon $p_T$ scale</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Hadronic recoil calibration</td>
<td>0.5</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Multi-jet background</td>
<td>0.1</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Electroweak+top background</td>
<td>0.1</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Data statistical uncertainty</td>
<td>0.5</td>
<td>0.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Prompt photons in $p+Pb$: Efficiencies

ARXIV:1903.02209
Prompt photons in $p+$Pb: Cross-sections, $R_{pPb}$

arXiv:1903.02209
Prompt photons in $p+$Pb: Systematic uncertainties

**ATLAS**

Relative uncertainty in $d\sigma/dE_T^\gamma$

- Combined
- Purity
- Detector performance
- Other

- $1.09 < \eta^* < 1.90$
- $-1.84 < \eta^* < 0.91$
- $-2.83 < \eta^* < -2.02$

Relative Uncertainty

- $1.09 < \eta^* < 1.90$
- $-1.84 < \eta^* < 0.91$
- $-2.83 < \eta^* < -2.02$

Relative Uncertainty in $R_{pPb}$

- Combined
- $p+$Pb cross section
- $p+p$ cross section
- Extrapolation

- $p+$Pb Luminosity uncertainty
$W$ bosons in Pb+Pb: Correction factors

$C_W$ factors account mainly for detector effects, such as lepton calibration and efficiencies, and $p_T^{\text{miss}}$ reconstruction.