Measurement of electroweak boson production in $pp$, $p+Pb$ and $Pb+Pb$ collisions with the ATLAS detector.

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on behalf of the ATLAS Collaboration

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Electroweak bosons:

- high-precision test of pQCD ($pp$),
- the nuclear modifications to PDF can be investigated ($p+Pb$, $Pb+Pb$),
- provides information on centrality and geometry of $p+Pb$ and $Pb+Pb$ systems ($T_{AA}$ scaling) as EW bosons are insensitive to final state interactions,
- with LHC energies, a range of photon spectra can be measured in a broader scope.
Muon, electron and photon triggers are designed to collect high-$p_T$ objects.

Measurements of electroweak bosons are based on:

- $pp$: $\sqrt{s} = 5.02$ TeV (25 pb$^{-1}$)
- $p+Pb$: $\sqrt{s} = 8.16$ TeV (0.16 pb$^{-1}$)
- Pb+Pb: $\sqrt{s} = 5.02$ TeV (0.49 nb$^{-1}$)
Z bosons in $pp$ at 5.02 TeV

- 15 GeV single electron trigger and 14 GeV single muon trigger
- isolated and good quality leptons
- $p_T^{e(\mu)} > 20$ GeV, $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47, |\eta_\mu| < 2.4$
- opposite-charge dilepton pairs in mass range: $66 < m_{\ell\ell} < 116$ GeV
- $\sim 4800$ (7400) $Z \rightarrow e^+ e^- (Z \rightarrow \mu^+ \mu^-)$ candidates
- subtracted backgrounds ($Z \rightarrow \tau^+ \tau^-, t\bar{t}$ and dibosons from MC, multi-jet from data) at the level of 0.3%
- corrections for trigger, reconstruction and isolation efficiencies
**W bosons in *pp* at 5.02 TeV**

- 15 GeV single electron trigger and 14 GeV single muon trigger
- isolated and good quality leptons (exactly one per event - veto on Z boson candidates)
- \( p_T^{e(\mu)} > 25 \text{ GeV}, \ |\eta_e| < 1.37 \text{ or } 1.52 < |\eta_e| < 2.47, \ |\eta_\mu| < 2.4 \)
- \( E_{\text{miss}} > 25 \text{ GeV}, \ m_T > 40 \text{ GeV} \)
- \(~ 38000 \text{ (44000) } W^+ \rightarrow e^+\nu \ (W^+ \rightarrow \mu^+\nu) \) candidates
- \(~ 24000 \text{ (27000) } W^- \rightarrow e^-\nu \ (W^- \rightarrow \mu^-\nu) \) candidates
- subtracted backgrounds: 2-6% EW, top-quark and diboson estimated from MC, 0.1-1.4% multi-jet estimated with data-driven method
- corrections for trigger, reconstruction and isolation efficiencies, as well as missing energy calibration

![Graphs showing W boson production in *pp* collisions at 5.02 TeV](image)
Z bosons in $pp$ - differential cross section

- Rapidity differential cross-sections measured in fiducial phase-space volume.
- Combined results are compared with several theory predictions (different PDF sets) calculated at NNLO using an optimised version of DYNNLO 1.5.
- 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.
- High precision measurement.

![Graph showing differential cross-sections](image)

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

$pp \rightarrow Z < 116 \text{ GeV} \ell \ell$
$66 < m_{\ell\ell} < 116 \text{ GeV}$
$p_T > 20 \text{ GeV}$
$|\eta| < 2.5$

Data NNLO QCD
CT14 NNLO
MMHT2014
NNPDF3.1
HERAPDF2.0

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EW boson production  
22-26.10.2018  
arXiv:1810.08424
W bosons in $pp$ - differential cross section

- 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 1-2$\sigma$.
- Similar observations made in previous ATLAS measurements at 7 and 13 TeV.
- **High precision measurement.**
Z bosons in Pb+Pb at 5.02 TeV

- 8 GeV single muon trigger
- good quality muons
- $p_T > 20$ GeV, $|\eta| < 2.5$
- opposite-charge dilepton pairs in mass range: $66 < m_{\mu^+\mu^-} < 116$ GeV
- $\sim 5500$ $Z \rightarrow \mu^+\mu^-$ candidates
- subtracted backgrounds ($Z \rightarrow \tau^+\tau^-, t\bar{t}$ and dibosons from MC, multi-jet from data) at the level of 0.5%
- corrections for trigger and reconstruction efficiencies
Z bosons in Pb+Pb - rapidity and centrality yields

- 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 ($\sim 1.5\sigma$).
- Caveat: preliminary results on $pp$ cross-sections used to construct $R_{AA}$.

- Yields per minimum-bias event divided by $\langle T_{AA} \rangle$ as a function of $N_{\text{part}}$ integrated in $|y_Z| < 2.5$.
- High-precision measurement: uncertainties related to $Z$ 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.
W bosons in Pb+Pb at 5.02 TeV

- 15 GeV single muon trigger
- isolated and good quality muons
- $p_T > 25$ GeV, $0.1 < |\eta| < 2.4$
- $p_T^{\text{miss}} > 25$ GeV
- $m_T > 40$ GeV, where
  $m_T = \sqrt{2p_T^{\mu}p_T^{\text{miss}}(1 - \cos(\Delta \phi))}$
- $\sim 25000$ (23000) $W^+ \rightarrow \mu^+ \nu$ ($W^- \rightarrow \mu^- \nu$) candidates
- subtracted backgrounds: 2-3% EW and $t \bar{t}$
  estimated from MC, 6-12% multi-jet
  estimated with data-driven method
- corrections for trigger, reconstruction and
  isolation efficiencies, as well as MET
  resolution effects
W bosons in Pb+Pb - rapidity yields

- Lepton pseudorapidity differential yields per minimum-bias event divided by $\langle T_{AA} \rangle$ for fiducial phase-space volume: $p_T > 25$ GeV, $p_T^{\text{miss}} > 25$ 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.

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ATLAS Preliminary

$\sqrt{s_{NN}}=5.02$ TeV, 0.49 nb$^{-1}$

ATLAS Preliminary

$\sqrt{s_{NN}}=5.02$ TeV, 0.49 nb$^{-1}$

ATLAS-CONF-2017-067
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.
Prompt photons in \( p+\text{Pb} \) at 8.16 TeV

- single photon triggers with 4 thresholds from 20 to 35 GeV
- good quality photons and passing isolation criterion:
  \[ E_{\text{iso}}^\gamma < 4.8 \text{ GeV} + 4.2 \times 10^{-3} E_T^\gamma / \text{GeV} \]
- \( E_T^\gamma > 25 \text{ GeV} \)
- \( |\eta^\gamma| < 1.37, \ 1.56 < |\eta^\gamma| < 2.37 \)
- rapidity boost by \( \Delta y = \pm 0.465 \)
- corrections for trigger, reconstruction and isolation efficiencies, as well as bin migration in \( E_T^\gamma \)
\( R_{pPb} \) (I)

- \( R_{pPb} \) as a function of \( E_T^\gamma \) and \( \eta^* \)
- At mid-rapidity, the \( R_{pPb} \) is consistent with unity (isospin or other nuclear effects are small).

\[
R_{pPb} = \frac{d\sigma^{p+Pb \to \gamma+X}/dE_T^\gamma}{A \cdot d\sigma^{pp \to \gamma+X}/dE_T^\gamma}
\]

- At high \( E_T^\gamma \) at backward pseudorapidity, the \( R_{pPb} \) is significantly lower than unity.
- This effect is driven by the different isospin composition of \( pp \) and \( p+Pb \) systems.
- Comparison to initial state energy loss model. Data disfavour a large suppression due to energy loss effects.
Comparison to CT14, nCTEQ15 and EPPS16.

Data are consistent with the free proton PDFs and with the small effects expected from a nuclear modification of the parton densities.
Summary

- Presented ATLAS measurements of electroweak boson production in $pp$, $p+$Pb and Pb+Pb collisions.

  - $pp$ collisions:
    - New measurement will serve as high-precision baseline for Pb+Pb results.
    - Expect improved $R_{AA}$ measurements.
    - Theory predictions calculated with different PDF sets at NNLO tend to systematically underestimate measured cross-sections - similar behaviour observed in ATLAS measurements at 7 and 13 TeV.

  - $p+$Pb collisions:
    - $R_{pPb}$ consistent with unity at mid-rapidity range.
    - It is in agreement with JETPHOX with the EPPS16/nCTEQ15 nPDFs while data disfavour large suppression due to energy loss effects.

  - 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.
Backup slides
Fiducial and total cross-section predictions for $W^+$, $W^-$ and $Z$

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<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>
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Additional uncertainties

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Charge asymmetry for $W$ bosons

**Data**

- ATLAS
- $p_{T}$ > 25 GeV
- $m_{T}$ > 40 GeV
- $|\eta| < 2.5$

**Theoretical Predictions**

- NNLO QCD
- CT14 NNLO
- MMHT2014
- NNPDF3.1
- HERAPDF2.0

**ATLAS**

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

$W \rightarrow \nu$

**Experimental Observations**

- $A_{T}$
- $|\eta|$

**ArXiv:** 1810.08424

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