Production of electroweak bosons in Pb+Pb, p+Pb and pp collisions with the ATLAS detector

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(on behalf of the ATLAS Collaboration)
Electroweak bosons in heavy ion collisions

- Electroweak bosons and their leptonic decay products do not interact strongly. Therefore if formed in a hard parton-parton interaction at a very early stage of the Pb+Pb or p+Pb collision they carry out unmodified by the surrounding medium information about the geometry of the collision and possible nuclear modifications of PDFs in a nucleon.

- Recent ATLAS results to be reviewed in this talk:
  - Measurement of $W^\pm$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. to be submitted to EPJC
  - $Z$ Boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ATLAS detector. ATLAS-CONF-2019-024
  - More details and results from the heavy ion physics program realized by ATLAS are available in https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

M. Przybycień (AGH UST)
Reconstruction of $Z/W$ bosons with the ATLAS detector

- $Z/W$ bosons are measured in their leptonic ($\ell = e, \mu$) decay channels: $W^\pm \rightarrow \ell^\pm \nu$ and $Z \rightarrow \ell^+ \ell^-$

- Events collected with single-lepton triggers:
  
  \[ p_T^\ell > 15 \text{ GeV and } p_T^\mu > 14 \text{ GeV} \]

- High quality reconstruction and isolation (minimize hadronic activity around) requirements on the leptons.

- Final kinematic selection cuts on $Z/W$ bosons:
  \[ |\eta_e| < 1.37, \quad 1.52 < |\eta_e| < 2.47, \quad |\eta_\mu| < 2.4 \]

  Specific cuts for $Z$ boson selection:
  - opposite charge leptons with $p_T^\ell > 20 \text{ GeV}$,
  - invariant mass $66 < m_{\ell\ell} < 116 \text{ GeV}$.

  Specific cuts for $W^{\pm}$ boson selection:
  - $p_T^\ell > 25 \text{ GeV}$, $p_T^{\text{miss}} > 25 \text{ GeV}$,
  - $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta \phi)} > 40 \text{ GeV}$,
  - veto on $Z$ events: $m_{\ell\ell} < 66 \text{ GeV}$, with $p_T^{\ell,2} > 20 \text{ GeV}$.

- Multi-jet bkgr. (semileptonic decays of HF, decays of $K$-s and $\pi$-s in muon channel, photon conversions, misidentified hadrons, ...) - estimated from data using template fits.
Z/W boson production in pp collisions at $\sqrt{s} = 5.02$ TeV

Fiducial integrated and differential cross sections measured in pp collisions serve as a reference for Pb+Pb interactions.

- Separate measurements in $e$ and $\mu$ decay channels.
- Combined integrated fiducial cross sections:
  - $W^+$: $2266 \pm 9$ (stat) $\pm 29$ (sys) $\pm 43$ (lumi) pb
  - $W^-$: $1401 \pm 7$ (stat) $\pm 18$ (sys) $\pm 27$ (lumi) pb
  - $Z$: $374.5 \pm 3.4$ (stat) $\pm 3.6$ (sys) $\pm 7.0$ (lumi) pb
- Overall good agreement with NNLO pQCD calculations.

\[ A_\ell = \frac{dN_{W^+ \to \ell + \nu_\ell}/d\eta_\ell - dN_{W^- \to \ell - \bar{\nu}_\ell}/d\eta_\ell}{dN_{W^+ \to \ell + \nu_\ell}/d\eta_\ell + dN_{W^- \to \ell - \bar{\nu}_\ell}/d\eta_\ell} \]
Normalized $Z$ boson yields as function of rapidity, integrated over centrality, are in better agreement with free proton PDF (+isospin) than with nPDFs.

$$R_{AA} = \frac{N_{AA}Z/N_{evt}}{\langle T_{AA} \rangle \times \sigma_{Zpp}}$$ is consistent with the isospin effect expected only from the different valence quark content of $p$ and $n$ in the Pb nucleus.

No significant difference in rapidity distribution between different centrality classes.
Normalized $W^\pm$ boson yields as function of $|\eta_\ell|$, integrated over centrality, are in better agreement with free proton PDF (+isospin) than with nPDFs.

Lepton charge asymmetry $A_\ell$ is equally well described by both free proton PDF (+isospin) and the nPDFs. Disagreement on the level of 1-2$\sigma$ is observed in in highest $\eta_\ell$ bin.
Normalized $W^{\pm}$ boson yields as function of $\langle N_{\text{part}} \rangle$ are in good agreement with theory predictions for $\langle N_{\text{part}} \rangle > 200$, but a slight excess of the data over predictions in more peripheral collisions is observed.

- Normalized $Z$ boson yields consistent with the $pp$ cross-section at all centralities and show only weak dependence on $\langle N_{\text{part}} \rangle$.
- These are also reflected in $R_{AA}$ behaviour.
- Comparison of Glauber MC v2.4 and v3.2 (includes different radial distributions of $p$ and $n$ in nuclei, which results in an evolution of the effective $p/n$ ratio with centrality).
- No significant change of the measured yields.
- Theory curves obtained using the CT14 NLO PDF set include the neutron skin effect included in Glauber MC v3.2.
- Slopes of $Z$ boson $R_{AA}$ vs. $\langle N_{\text{part}} \rangle$:
  - Glauber v2.4: $(10 \pm 7)\%$;
  - v3.2: $(5 \pm 6)\%$
Comparison with HG-Pythia predictions

- Peripheral decrease in production yield predicted by HG-PYTHIA (PLB773 (2017) 408)
- In qualitative agreement with charged hadrons $R_{AA}$ suppression observed by ALICE.
- Opposite trends observed by ATLAS in $Z$ and $W$ boson yields.
- Theoretical predictions are calculated with the CT14 NLO PDF set multiplied by the $R_{AA}$ obtained from HG-PYTHIA.
Prompt photons in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

- Sources of prompt photons: quark-gluon Compton scattering $qg \rightarrow q\gamma$ and production of hard photons during parton fragmentation $\bar{q}q \rightarrow g\gamma$ (distinguishable only at LO).
- Prompt photons being colourless are unaffected by the subsequent evolution of the QGP and probe the very initial stages of the collision i.e. nuclear modifications to PDF.
- Kinematical range covered by this measurement gives access also to nuclear gluons.
- Differential cross section for the production of isolated ($E_{T}^{\text{iso}} < 4.8 + 4.2 \cdot 10^{-3} E_{T}^{\gamma}$ [GeV]) prompt photons as a function of $E_{T}^{\gamma}$ in three intervals of $\eta^{*} (= \eta - 0.465)$ in data is underestimated by JETPHOX (NNLO pQCD including nPDF effects).

![Graph showing differential cross section for prompt photons as a function of $E_{T}^{\gamma}$ in three intervals of $\eta^{*}$]
Prompt photons in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

- Using $pp$ data at 8 TeV extrapolated to 8.16 TeV to obtain nuclear modification factor

$$R_{p\text{Pb}} = \frac{d\sigma^{p+\text{Pb}} \to \gamma+X/dE_T^\gamma}{A_{\text{Pb}} \cdot d\sigma^{p+p} \to \gamma+X/dE_T^\gamma}$$

- At forward ($p$-going) and central rapidities $R_{p\text{Pb}}$ is consistent with unity - indicating that nuclear effects are small (probing mainly gluons at $x_A \approx 10^{-2}$).

- At backward rapidities, the $R_{p\text{Pb}}$ decreases with increasing $E_T^\gamma$ - larger relative $d$-quark density in Pb nucleus at $x_A \approx 0.2$ decreases the photon yield.

- Data disfavour a large suppression of the cross section from initial-state energy-loss effects due to possible multiple scattering of energetic partons in the cold nuclear medium before the hard collision.
Prompt photons in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

- Nuclear modification factor $R_{p\text{Pb}}$ for isolated, prompt photons as a function of $E_T^\gamma$.
- Data are compared to two different nuclear PDF sets: EPPS16 and nCTEQ15.
- Behaviour of nPDFs reflects the different relative $d/u$ quark composition in the Pb nuclei than in the proton.
Photon-jet $p_T$ correlations in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Comparison of per-photon yields of photon-jet events in Pb+Pb and $pp$ collisions as a function of transverse momentum ratio, $x_{J\gamma} = p_{T\gamma}/p_T^j$, for different centrality intervals and different photon transverse momenta, $p_T^\gamma$, ranges.
- The $x_{J\gamma}$ distributions in Pb+Pb evolve smoothly with centrality.
- In peripheral collisions ($50 - 80\%$) they are similar to those measured in $pp$ collisions.
- In central collisions ($0 - 10\%$) for lower $p_T^\gamma$ the distributions decrease monotonically, however, for $p_T^\gamma > 100$ GeV they retain a peak even in the most central collisions.

![Graphs showing photon-jet $p_T$ correlations in Pb+Pb at 5.02 TeV](image-url)

**ATLAS**

$pp$ 5.02 TeV, 25 pb$^{-1}$

$Pb+Pb$ 5.02 TeV, 0.49 nb$^{-1}$

$p_T^\gamma = 63.1 - 79.6$ GeV

- $pp$ (same each panel)
- Pb+Pb
Comparison of per-photon yields of photon-jet events in Pb+Pb and pp collisions as a function of transverse momentum ratio, $x_{J\gamma} = \frac{p^\text{jet}_T}{p^\gamma_T}$, for different centrality intervals and different photon transverse momenta, $p^\gamma_T$, ranges.

The $x_{J\gamma}$ distributions in Pb+Pb evolve smoothly with centrality. In peripheral collisions ($50 - 80\%$) they are similar to those measured in pp collisions. In central collisions ($0 - 10\%$) for lower $p^\gamma_T$ the distributions decrease monotonically, however, for $p^\gamma_T > 100$ GeV they retain a peak even in the most central collisions.
Summary

ATLAS has provided recently several new results on electroweak bosons production in $pp$, $p+Pb$ and $Pb+Pb$ collisions:

- Precise measurements of $Z/W$ boson yields in $pp$ collisions at $\sqrt{s} = 5.02$ TeV serve as a reference for the measurements in $Pb+Pb$ and $p+Pb$. Good agreement with NNLO theory predictions using NNPDF3.1 and HERAPDF2.0 PDFs.
- $Z/W$ boson yields in $Pb+Pb$ are in best agreement with the free proton PDF including the isospin effect. Predictions from nPDFs underestimate the measured yields by 1-3$\sigma$.
- $R_{AA}$ for $Z/W$ production do not depend significantly on centrality, however, there is an indication of an excess at the level of 1-2$\sigma$ in peripheral collisions in case of $W$ yields.
- No suppression of $Z/W$ yields predicted by HG-Pythia is observed in peripheral collisions.
- Prompt photon production yields in $p+Pb$ collisions are in agreement with free proton PDF, however small nuclear modifications are not excluded.
- No large initial parton energy losses are observed in $p+Pb$ collisions in events with prompt photons.
- New measurement of photon-jet transverse momentum correlations in $Pb+Pb$ and $pp$ collisions provide information on how energy loss in the strongly coupled medium varies with the initial parton $p_T$.

Thank you for your attention!
Backup slides
Heavy-ion data sets

- **A+A collisions:**
  - $\text{Pb+Pb @ 2.76 TeV (2011), } L_{\text{int}} = 0.14 \text{ nb}^{-1}$
  - $\text{Pb+Pb @ 5.02 TeV (2015), } L_{\text{int}} = 0.49 \text{ nb}^{-1}$
  - $\text{Xe+Xe @ 5.44 TeV (2017), } L_{\text{int}} = 3 \mu\text{b}^{-1}$

- **$p + A$ collisions:**
  - $p+\text{Pb @ 5.02 TeV (2013), } L_{\text{int}} = 29 \text{ nb}^{-1}$
  - $p+\text{Pb @ 5.02 TeV (2016), } L_{\text{int}} = 0.5 \text{ nb}^{-1}$
  - $p+\text{Pb @ 8.16 TeV (2016), } L_{\text{int}} = 0.16 \text{ pb}^{-1}$

- **Reference $pp$ samples:**
  - $pp @ 8\text{ TeV (2012), } L_{\text{int}} = 19.4 \text{ fb}^{-1}$
  - $pp @ 2.76\text{ TeV (2013), } L_{\text{int}} = 4 \text{ pb}^{-1}$
  - $pp @ 5.02\text{ TeV (2015), } L_{\text{int}} = 28 \text{ pb}^{-1}$
  - $pp @ 5.02\text{ TeV (2017), } L_{\text{int}} = 270 \text{ pb}^{-1}$
The ATLAS detector

Detector coverage:

- Inner Detector (ID):
  \[ |\eta| < 2.5 \]

- Calorimeter (CAL):
  \[ |\eta| < 3.2 \text{ (EM)} \]
  \[ |\eta| < 4.9 \text{ (HAD)} \]
  \[ 3.2 < |\eta| < 4.9 \text{ (FCal)} \]

- Muon Spectrometer (MS):
  \[ |\eta| < 2.7 \]

- Zero Degree Cal. (ZDC):
  \[ |\eta| > 8.3 \text{ @ } z = \pm 140 \text{ m} \]

- MB Trig. Scint. (MBTS):
  \[ 2.1 < |\eta| < 3.9 \]

Magnetic fields:

- 2T solenoid field in ID
- Toroidal field in MS

Identification of minimum-bias $p$+Pb and Pb+Pb collision measurement of spectator neutrons in ZDC and charged particle tracks (pulse height and arrival times) in MBTS.
Centrality determination in Pb+Pb and p+Pb

- Centrality is measured using forward calorimeters (3.2 < |η| < 4.9):

  - in Pb+Pb use sum of $E_T$ on both sides,
  - in p+Pb use sum of $E_T$ on Pb-going side only,
  - for Pb+Pb use Glauber MC for geometry,
  - for p+Pb use both Glauber and Glauber-Gribov color fluctuation model (PLB 633: 245 (2006)).

- Average number of participants ($N_{part}$) for each centrality bin resulting from fits to the measured $E_T$ distribution for p+Pb.
Fiducial integrated and differential cross sections measured in $pp$ collisions serve as reference for Pb+Pb interactions.

- Separate and combined measurements for electron and muon decay channels.

Normalized production yields for $Z$ boson as a function of rapidity and $\langle N_{\text{part}} \rangle$ in the electron and muon decay channels and their combination.

$\sqrt{s} = 5.02$ TeV

$N_{\text{ev}}^{-1} \langle T_{AA} \rangle^{-1} dN_Z/dy$ [pb]

$66 < m_{ll} < 116$ GeV
$p_T \geq 20$ GeV
$|\eta| < 2.5$

Channel Combined

$\langle N_{\text{part}} \rangle$

ATLAS-CONF-2019-024
W boson production in Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV

- Differential normalized production yields and lepton charge asymmetry for $W^\pm$ as a function of pseudorapidity of the charged lepton separately for their electron and muon decay channels and their combination.

- Normalized production yields for $W^\pm$ as a function of $\langle N_{\text{part}} \rangle$ in the electron and muon decay channels and their combination.
Promt photons in $p+\text{Pb}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

- Cancellation of many systematic uncertainties in the ratio of forward to backward $R_{p\text{Pb}}$
- Data are consistent with the pQCD calculations before incorporating nuclear effects, except at $35 < E_{T}^{\gamma} < 45$ GeV, where the data fall below the free-proton calculation.
- Data are also compatible with small nuclear modifications represented by nPDFs in most of the considered $E_{T}^{\gamma}$ range.

Nuclear models: below $E_{T}^{\gamma} \approx 100$ GeV, the ratio corresponds to photons from gluon nuclear parton configurations in the shadowing $x_{A}$ region to that from quark partons in the anti-shadowing region. This is reversed at higher $E_{T}^{\gamma}$ where the numerator probes the shadowing/anti-shadowing crossover region and the denominator moves deeper into the EMC suppression region ($x_{A} \sim 0.2$).
Comparison of jet energy-loss with models

- Hybrid model gives a good description of $pp$ events over broad range of $x_{J\gamma}$ and $p_T^{\gamma}$.

- Perturbative calculation within framework of soft-collinear effective field theory with Glauber gluons (SCET$_G$) (PRC 96 (2017) 014912).
- JEWEL MC - QCD evolution in HI collisions including energy-loss effects from radiative and elastic scattering processes (EPJC 76 (2016) 695).
- Hybrid Strong/Weak Coupling model which combines initial production using Pythia with a parametrisation of energy loss derived from holographic methods (JHEP 03 (2016) 053).
Comparison of jet energy-loss with models

- Hybrid model gives a good description of $pp$ events over broad range of $x_{J\gamma}$ and $p_T^{\gamma}$.
- In Pb+Pb events at low $p_T^{\gamma}$ all models but BDMPS-Z capture the main features of the $x_{J\gamma}$ distribution. At higher $p_T^{\gamma}$ none of the models describe the increase of the jet yield at $x_{J\gamma} < 0.5$, however, Hybrid and JEWEL predict the reappearance of a localised peak.

- Perturbative calculation within framework of soft-collinear effective field theory with Glauber gluons (SCET$_G$) (PRC 96 (2017) 014912).
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