Electroweak boson measurements with ALICE

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for the ALICE Collaboration
Electroweak bosons and PDFs

- W and Z boson production in pp collisions is:
  - theoretically well known
  - measured with good precision at LHC

- Can be used to constrain Parton Distribution Functions

LHCb, JHEP 1605 (2016) 131
Nuclear PDFs

• PDFs are modified in nuclei:

• Precise knowledge of the nPDFs needed to better understand the initial conditions of heavy-ion collisions

Experimental data

- nPDFs are poorly constrained by experiments:
  - generally less data available compared to pp
  - need processes/colliding systems that are not affected by the presence of a strongly interacting medium in the final state

- Typical data:
  - pA, eA collisions: DIS, DY, ... => small $Q^2$, large $x$
  - new data from LHC: di-jets, electroweak bosons => large $Q^2$, wide $x$ range
Electroweak bosons and nPDFs

- W/Z bosons are **sensitive probes of the nPDF**:  
  - production theoretically well-understood (as in pp)  
  - produced in the initial hard scattering  
  - unaffected by the strong interaction

- W-boson production depends on flavor charge =>  
  - sensitive to the flavor dependence of the nPDF
W/Z production at the LHC

- The nuclear modification depends on rapidity (different Bjorken-x region explored)
- Complementarity in rapidity coverage between LHC experiments

\[ x = \frac{M}{\sqrt{S}} e^{\pm y} \]

A useful concept: collision centrality

• Centrality related to the impact parameter \( (b) \) of the collision:

Central collision:
• small \( b \)
• large number of participants

Peripheral collision:
• large \( b \)
• small number of participants

• Hard process cross sections scale with the number of binary nucleon-nucleon collisions \( \langle N_{\text{coll}} \rangle \)
  • w/o medium effects
  • w/o cold nuclear matter effects (nPDFs, etc.)
The ALICE experiment

- SPD (primary vertex)
- V0 (trigger, centrality)
- MUON Spectrometer
  \[-4 < \eta < -2.5\]
- ZDC (centrality)
Data sample

- Same magnetic rigidity for the two beam lines
- Different ratio $Z/A$ for proton and Pb ion => larger (per-nucleon) energy for proton
  => CM boosted along proton direction ($\Delta y = 0.465$)

<table>
<thead>
<tr>
<th>System</th>
<th>p-Pb (Pb-going)</th>
<th>p-Pb (p-going)</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidity</td>
<td>$-4.46 &lt; y_{CMS} &lt; -2.96$</td>
<td>$2.03 &lt; y_{CMS} &lt; 3.53$</td>
<td>$2.5 &lt; y_{CMS} &lt; 4$</td>
</tr>
<tr>
<td>$\sqrt{s_{NN}} = 5.02$ TeV</td>
<td>5.8 nb$^{-1}$</td>
<td>5.1 nb$^{-1}$</td>
<td>~225 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>$\sqrt{s_{NN}} = 8.16$ TeV</td>
<td>12.8 nb$^{-1}$</td>
<td>8.4 nb$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>
W-boson measurement

- Signal extracted through MC template fit of the single muon $p_T$ distribution

$$f(p_T) = N_{bkg}^{raw} f_{bkg}(p_T) + N_{\mu-W}^{raw} f_{\mu-W}(p_T) + R f_{\mu-Z}(p_T)$$

- MC inputs: FONLL (HF), POWHEG ($W$, $Z$)
- The raw yield is corrected by the acceptance-times-efficiency of the detector

FONLL: M. Cacciari et al., JHEP 10, 137, (2012)
POWHEG: S. Alioli et al., JHEP 07, 060 (2008)
Z-boson measurement

- Signal extraction: counting the opposite-sign muons with $p_T(\mu) > 20$ GeV/$c$ and $60 < m_{\mu\mu} < 120$ GeV/$c^2$
- Combinatorial background accounted for by looking at same-sign dimuon distribution
- Negligible contribution (<1%) from other background sources ($b\bar{b}, c\bar{c}, t\bar{t}, Z \rightarrow \tau\tau \rightarrow \mu\mu$) estimated with Pythia + POWHEG simulations
- Raw yield corrected by AccxEff obtained with MC simulations (+embedding in Pb-Pb)

POWHEG: S. Alioli et al., JHEP 07, 060 (2008)
W-boson results in p-Pb collisions @ 5.02 TeV

\[ \mu^+ \leftrightarrow W^+ \]

\[ \mu^- \leftrightarrow W^- \]

Asymmetry

- Cross section of muons from W-boson decay with \( p_T(\mu) > 10 \text{ GeV/c} \)
- Lepton charge asymmetry:
  \[ \frac{N_{\mu^+ \leftrightarrow W^+} - N_{\mu^- \leftrightarrow W^-}}{N_{\mu^+ \leftrightarrow W^+} + N_{\mu^- \leftrightarrow W^-}} \]
  - partial cancellation of theoretical and experimental uncertainties
- Compared to pQCD and FEWZ: agreement with and without including nPDFs

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QCD@LHC - Buffalo 15-19 July 2019

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W-boson production: centrality dependence

- For the centrality dependence, the contributions of $W^+$ and $W^-$ were added

- Compatible with constant within uncertainties

ALICE, JHEP 1702 (2017) 077
Z-boson cross section in p-Pb collisions @ 5.02 TeV

- Z-boson cross section compared with:
  - pQCD calculations (NLO)
  - FEWZ calculations (NNLO)

- Results in agreement with calculations with and without including nPDF (EPS09)
Z-boson cross section in p-Pb collisions @ 8.16 TeV

- Recent results at 8.16 TeV: ~3 (~14) times larger statistics than at 5.02 TeV in the p-going (Pb-going) direction
- The increase is due to cross section and luminosity

- Limited nPDF effect => results compatible with calculations with and without including nPDF (EPPS16nlo and nCTEQ15nlo)

K.Kovaric et al., PR D 93, 085037 (2016)
Z-boson production in Pb-Pb collisions

- Larger Z-boson data sample compared to p-Pb (due to the much larger $\langle N_{\text{coll}} \rangle$)

<table>
<thead>
<tr>
<th>0-90% Pb-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
</tr>
<tr>
<td>CT14 Pb-isospin, free PDF</td>
</tr>
<tr>
<td>CT14 + EPS09 Pb-isospin, nPDF</td>
</tr>
<tr>
<td>CT14 + EPPS16 Pb-isospin, nPDF</td>
</tr>
<tr>
<td>nCTEQ15 Pb-isospin, nPDF</td>
</tr>
</tbody>
</table>

- Results in agreement with calculations using three different nPDFs
- Calculations without nPDF overestimate data by 2.3σ
Differential studies

- PDF modification depends on rapidity
- Centrality dependence of nPDF included in calculations
- Results are in better agreement with calculations including nPDFs
- Calculations without nPDFs overestimate measurement by $\sim 3\sigma$ in the 0-20% most central collisions
Conclusions

• W and Z boson production measured in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ and 8.16 TeV:
  • Results well reproduced by theoretical calculations
  • Not enough statistics to conclude on nPDF

• Z-boson production measured in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV:
  • calculations without nPDF overestimate data
    • by 2.3σ integrated
    • by 3σ for the 0-20% most central collisions

• Results can be included in nPDF global fit to better constrain calculations
Perspectives

Ongoing:
• Pb-Pb data taking 2018 => ~3 times larger statistics compared to 2015

Near future:
• LHC heavy-ion program extended to Run 3-4 (2021-2029):
  • 50 kHz collisions in Pb-Pb
  • Continuous readout of some detectors

Example:
• Z boson production in p-Pb collisions at $\sqrt{s_{NN}} = 8.8$ TeV for (0.25+0.25) pb$^{-1}$
  • Factor ~50 increase in luminosity w.r.t. published results: more differential studies in rapidity will be possible
Thank you for your attention
Backup
## nPDF sets

<table>
<thead>
<tr>
<th></th>
<th>EPS09</th>
<th>DSSZ12</th>
<th>KA15</th>
<th>nCTEQ15</th>
<th>EPPS16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order in $\alpha_s$</td>
<td>NLO</td>
<td>NLO</td>
<td>NNLO</td>
<td>NLO</td>
<td>NLO</td>
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<tr>
<td>Data points</td>
<td>929</td>
<td>1579</td>
<td>1479</td>
<td>708</td>
<td>1811</td>
</tr>
<tr>
<td>Free params</td>
<td>15</td>
<td>25</td>
<td>16</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Baseline PDF</td>
<td>CTEQ6.1</td>
<td>MSTW2008</td>
<td>JR09</td>
<td>CTEQ6M-like</td>
<td>CT14NLO</td>
</tr>
<tr>
<td>Flavor separation</td>
<td></td>
<td></td>
<td></td>
<td>partial</td>
<td>full</td>
</tr>
</tbody>
</table>

|                      |       |        |      |         |        |
| DIS in $\ell^- + A$  | ✓     | ✓      | ✓    | ✓       | ✓      |
| DY in p+A            | ✓     | ✓      | ✓    | ✓       | ✓      |
| RHIC $\pi$ d+Au      | ✓     | ✓      |      | ✓       | ✓      |
| $\nu$+A DIS          |       |        | ✓    |         | ✓      |
| DY in $\pi$+A        |       |        |      | ✓       |        |
| LHC p+Pb di-jets     |       |        |      | ✓       |        |
| LHC p+Pb W+Z         |       |        |      | ✓       |        |

Included EW boson measurements in EPPS16

- Data are taken as ratio forward/backward => loss of information at $y = 0$ but reduced dependence on free PDFs

Comparison with other experiments: Z boson

- Results not directly comparable (different kinematic cuts): compare the ratio over the corresponding pQCD predictions with nPDFs

- ALICE measurement in a rapidity region complementary to CMS and ATLAS. Slightly better precision than LHCb

- Calculations can describe data over the full rapidity interval
Comparison with other experiments: W boson

- Comparison with CMS data:
  - results divided by predictions from pQCD calculations with nPDFs
- Calculations can describe data over the full rapidity interval explored
W boson kinematics

• W/Z boson mainly produced by valence quarks (carry more momentum than sea quarks)
• Electroweak interaction couples left-handed fermions with right-handed anti-fermions
• Helicity is conserved at high energies

• This implies:
  • $\mu^-$ mainly emitted in the direction of the incoming quark
  • $\mu^+$ mainly emitted in the opposite direction of the incoming quark
Rapidity dependence of isospin and nuclear effects

- Rapidity dependence of the ratio of normalized cross sections in Pb-Pb and pp collisions
  - w/o accounting for nPDF
  - accounting for nPDF

- Difference is mostly visible at forward rapidities
Centrality determination in A-A

- Centrality defined by the impact parameter
  - central collisions: large number of participants ($N_{\text{part}}$)
  - peripheral collisions: small $N_{\text{part}}$

- Experimentally: centrality determined by Glauber model fit of the V0 amplitude

![Diagram showing centrality and centrality determination in A-A collisions](image)

**Figure**: Experimental data compared to Glauber model fit for V0 amplitude. Centrality bins from 0-5% to 70-80% are shown, with the Glauber fit overlaying the data points. The inset graph highlights the deviation between data and fit for different centrality bins.

Centrality determination in p-Pb

- Small $N_{\text{part}}/N_{\text{coll}}$ in p-Pb => biases in the centrality determination
  - multiplicity fluctuations
  - jet-veto bias
  - geometric bias

- Looser correlations between:
  - $N_{\text{part}}$ vs impact parameter
  - $N_{\text{part}}$ vs multiplicity

- Event selection based on Pb-going neutron energy released in ZDC minimizes the bias

**Systematic uncertainties: p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV**

<table>
<thead>
<tr>
<th>Background contamination</th>
<th>&lt; 1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>4% (p-going)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2%</td>
</tr>
<tr>
<td>Tracker/trigger matching</td>
<td>1%</td>
</tr>
<tr>
<td>Alignment</td>
<td>1% (p-going)</td>
</tr>
<tr>
<td></td>
<td>2% (Pb-going)</td>
</tr>
<tr>
<td>$F_{\mu\text{-trig}/MB}$</td>
<td>1%</td>
</tr>
<tr>
<td>MB cross section</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

| Signal extraction                | 2 – 6%        |
| vs centrality                    | 5 – 15%       |
| Tracking efficiency (c)          | 2% (p-going)  |
| Trigger efficiency (c)           | 3% (Pb-going) |
| Tracker/trigger matching (c)     | 1%            |
| Alignment (c)                    | 0.5%          |
| $F_{\mu\text{-trig}/MB}$ (c)     | 1%            |
| MB cross section (c)             | 3.3%          |
| Pile-up                          | 1 - 3%        |
| $\langle N_{\text{mult}} \rangle$| 2 – 8%        |

(c) = correlated vs centrality
### Systematic uncertainties: $Z$ boson in Pb-Pb

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background contamination</td>
<td>$&lt; 1.0%$</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>$3.0%$ (⋆)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$1.5%$ (⋆)</td>
</tr>
<tr>
<td>Tracker/trigger matching</td>
<td>$1.0%$ (⋆)</td>
</tr>
<tr>
<td>Alignment</td>
<td>$3.5%$ (⋆)</td>
</tr>
<tr>
<td>$F_{\mu\text{-trig/MB}}$</td>
<td>$0.5%$ (⋆◊)</td>
</tr>
<tr>
<td>$\sigma_{pp}$</td>
<td>$4.5%$ (⋆)</td>
</tr>
<tr>
<td>$\langle T_{AA} \rangle$</td>
<td>$3.2 - 3.5%$ (◊)</td>
</tr>
<tr>
<td>Centrality limits</td>
<td>$1.5 - 2.3%$ (◊)</td>
</tr>
</tbody>
</table>

(⋆) = correlated vs centrality
(◊) = correlated vs rapidity
ALICE upgrade: Muon Forward Tracker

- High resolution muon vertexing for the ALICE muon spectrometer
ALICE upgrade: Muon Forward Tracker

- High resolution muon vertexing for the ALICE muon spectrometer