Electroweak-boson measurements from small to large collision systems with ALICE at the LHC

Shingo Sakai for the ALICE collaboration (Univ. of Tsukuba)
**Motivation**

- **W/Z boson**
  - Produced predominantly via a quark–antiquark pair annihilation (Drell-Yan)
  - $u\bar{d} \rightarrow W^+, d\bar{u} \rightarrow W^-$, and $q\bar{q} \rightarrow Z$
  - Sensitive to isospin
  - Decay leptons insensitive to the strongly-interacting medium

- **pp collisions**
  - Good test for pQCD and electroweak theory
  - Give insight into multiparton interactions (MPI) in high-multiplicity events and role of color-reconnection mechanism (CR)

- **p–Pb and Pb–Pb collisions**
  - Provide insights on the nuclear modification of the parton distribution functions (nPDF)
  - Important to understand the initial-state nuclear effects
  - A good test for binary scaling
ALICE detector

- Electron channel ($|\eta|<0.6$)
- $e^\pm \leftrightarrow W^\pm$
- $Z \rightarrow e^+e^-$
  - TPC (dE/dx)
  - EMCal (Energy, trigger)

- Muon channel ($-4 < \eta < -2.5$)
- $\mu^\pm \leftrightarrow W^\pm$
- $Z \rightarrow \mu^+\mu^-$
  - Muon spectrometer
    - trigger
    - tracking

- p–Pb, p-going
  - $2.03 < y_{\text{cms}} < 3.53$

- p–Pb, Pb-going
  - $-4.46 < y_{\text{cms}} < -2.96$

- Pb–Pb
  - $2.5 < y_{\text{cms}} < 4$
## Weak-boson measurements with ALICE

<table>
<thead>
<tr>
<th>Collision system</th>
<th>Energy</th>
<th>Luminosity</th>
<th>Year</th>
<th>Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>13 TeV</td>
<td>≈ 6.6 pb⁻¹</td>
<td>2016 + 2017 + 2018</td>
<td>Z, W (e, midrapidity)</td>
</tr>
<tr>
<td>p–Pb Pb–p</td>
<td>5.02 TeV</td>
<td>5.03 ± 0.18 nb⁻¹</td>
<td>2013</td>
<td>Z, W (μ, forward /backward)</td>
</tr>
<tr>
<td>p–Pb Pb–p</td>
<td>8.16 TeV</td>
<td>6.73 ± 0.16 nb⁻¹ 10.0 ± 0.22 nb⁻¹</td>
<td>2016</td>
<td>Z, W (μ, forward /backward)</td>
</tr>
<tr>
<td>Pb–Pb</td>
<td>5.02 TeV</td>
<td>663 ± 15 μb⁻¹</td>
<td>2015 + 2018</td>
<td>Z, W (μ, forward)</td>
</tr>
</tbody>
</table>

### Recent weak boson measurements in ALICE
- W-boson and Z-boson production at midrapidity in pp collisions at 13 TeV
$W^\pm$ in pp collisions at 13 TeV (1)

- $p_T$ differential cross sections of $e^\pm \to W^\pm$ in $|y| < 0.6$, and ratio for $e^+ \to W^+$ and $e^- \to W^-$ as a function of $p_T$
- Compared to the predictions of pQCD NLO (POWHEG) + CT10NLO PDF
  - Measurements and model are consistent within the uncertainties
  - Larger cross section for $e^+ \to W^+$ due to isospin effects

CT10nlo
H. L. Lai et al., PRD 82 (2010), 074024
$W^\pm$ in pp collisions at 13 TeV (2)

- Cross sections for $e^{\pm} \leftrightarrow W^{\pm}$ in $|y| < 0.6$
- Electrons in $30 < p_T < 60$ GeV/c
- Compared to a model including pQCD NLO (POWHEG) + CT10NLO
  - Consistent with data within uncertainties

Data
Syst. Unc. (data)
POWHEG (CT10nlo) + PYTHIA6

±5.4% lumi. uncertainty not shown

ALICE Preliminary
pp, $\sqrt{s} = 13$ TeV
$e^- \leftrightarrow W^-$

ALICE Preliminary
pp, $\sqrt{s} = 13$ TeV
$e^+ \leftrightarrow W^+$

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A faster-than-linear trend was observed when requiring hadrons on the away side of the W boson:

→ Non-linear dependence due to auto-correlation between hadrons and multiplicity in the absence of “strong” final-state interactions?


→ Insights into the observed non-linear dependence of heavy-flavor hadrons (D, J/ψ, ...) vs multiplicity

Z production in pp at 13 TeV

- First ALICE measurement of the Z boson at midrapidity
- Z bosons are reconstructed by electron-positron pairs at midrapidity
  - One of electron (positron) has $p_{T,e} > 30$ GeV/c & $|y_e| < 0.6$
  - Fiducial cross section of Z bosons ($60 < m_Z < 108$ GeV/c²)
  - Consistent with POWHEG + CT14nlo PDF within uncertainties
$W^\pm$ in p–Pb at 8.16 TeV (1)

- $W^-$ production cross section measured as a function of rapidity
- Model calculations
  - Based on pQCD predictions
  - Including isospin effect with/without nPDF
- Calculations underestimate data for bins closest to midrapidity, both at forward and backward (1.4 and 2σ from EPPS16 predictions)

$\mu^- \leftrightarrow W^-$

Data
- MCFM + CT14 + isospin
- MCFM + CT14 + EPPS16
- FEWZ + nCTEQ15
- FEWZ + nCTEQ15WZ
- MCFM + nNNPDF2.0

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W± in p–Pb at 8.16 TeV (2)

- W± production cross section measured as a function of rapidity
- Model calculations:
  - Based on pQCD predictions
  - Including isospin effect with/without nPDF
- 3.5σ deviation from free-PDF calculation (MCFM + CT14) for W± at forward rapidity for the bin at largest rapidity

**Diagrams**

- **μ⁺ ↔ W⁺**
- **Data**
  - MCFM + CT14 + isospin
  - MCFM + CT14 + EPPS16
  - FEWZ + nCTEQ15
  - FEWZ + nCTEQ15WZ
  - MCFM + nNNPDF2.0

**Backward**

- x ≈ 10⁻¹
- Anti-shadowing

**Forward**

- x ≈ 10⁻⁴
- Shadowing

**References**

- CT14 : S. Dular et. al., PRD 93 (2016) 033006
- CT14 + EPPS16 : K. J. Eskola et. al., EPJ C77 (2017) 163
- nCTEQ15 : K. Kovarik et. al., PRD 93 (2016) 085037
- nCTEQ15WZ: A. Kusina et. al., EPJC 80 (2020) 968
- nNNPDF2.0 : JHEP 09 (2020) 183

**arXiv:2204.10640[nucl-ex]**
Ratio to CT14 as a function of rapidity compared with CMS results (PLB 800 (2020) 135048)

- ALICE reaches the largest $|y|$ region (down to $x \sim 10^{-4}$ at forward region)
- ALICE results in agreement with the trend at the edges of the CMS acceptance
- Suppression at large rapidity
$W^\pm$ in Pb–Pb at 5.02 TeV (1)

larger cross section for $\mu^- \leftrightarrow W^-$ than for $\mu^+ \leftrightarrow W^+$
- effect of isospin due to different content of $u$ and $d$ in Pb nucleus

Model with CT14 for free nucleon (MCFU+CT14)
- Overestimates the cross sections
- Suggests a significant modification of the PDFs
- Fair agreement with nPDF models

arXiv:2204.10640[nucl-ex]
$W^\pm$ in Pb–Pb at 5.02 TeV (2)

- Ratio to CT14 as a function of rapidity compared with ATLAS results (EPJC 79 (2019) 935)
- ALICE results well described by EPPS16 calculations (2$\sigma$ lower than CT14 without EPPS16)
- EPPS16 underestimates ATLAS data
- Ratio to CT14 is smaller than unity at large rapidity
  - Suggests a significant modification of the PDFs
Production of hard probes in peripheral collisions

- Significantly affected by event selection and geometry biases
- These biases cause a “suppression” in peripheral collisions

Comparison with HG-PYTHIA
- Including biases from event selection and geometry

**W± in Pb–Pb at 5.02 TeV (3)**

*arXiv:2204.10640[nucl-ex]*

- **µ**− ← **W**−
- **µ**+ ← **W**+

**ALICE, Pb–Pb, s_{NN} = 5.02 TeV**

- 2.5 < y^μ < 4.0
- p_T^μ > 10 GeV/c

**HG-PYTHIA**

C. Loizides and A. Morsch, PLB 773 (2017) 408-411
Summary

- Presented recent electroweak-boson production in ALICE from small to large collision systems with ALICE
  - pp collisions at 13 TeV
    - (New) Z boson production is consistent with NLO pQCD (POWHEG) + PDF (CT14NLO)
    - Linear dependence of W production on charged multiplicity
  - p-Pb collisions at 8.16 TeV and Pb-Pb collisions at 5.02 TeV
    - ALICE reaches the largest rapidity for W boson measurements
    - Suggests a significant modification of the nuclear PDFs
- Outlook at Run3
  - Significant increase of the luminosity (pp : 200/pb, Pb–Pb : 7/nb)
    - Detailed study of nPDFs
    - Differential study for electroweak-boson production (ex. W/Z + jet)
Back up
W/Z yields extraction in ALICE

- $e^\pm \rightarrow W^\pm (|y| < 0.6)$; Based on isolation cuts on energy; $E_{\text{iso}} = \frac{\sum E_R}{E_e} < 0.05$
- $e^\pm \rightarrow c, b$ are obtained by data driven subtraction (large isolation energy)
- $\mu^\pm \rightarrow W^\pm (-4 < y_{\text{lab}} < -2.5)$; Fit of the single muons $p_T$ distribution via MC templates
- $\mu^\pm \rightarrow c, b$ by FONLL, $\mu^\pm \rightarrow W^\pm, Z$ by POWHEG
- $Z \rightarrow \mu^\pm (-4 < y_{\text{lab}} < -2.5)$; Invariant mass of opposite-sign muon pair

ALICE Preliminary
pp, $\sqrt{s} = 13$ TeV
$e^-, |y| < 0.6$
$e^\pm_{c, b}$ with $E_{\text{iso}} = \frac{\sum E_R}{E_e} > 0.1$

ALICE, p-Pb, $|\vec{S}_{NN}| = 8.16$ TeV
$-4.46 < y_{\text{cms}} < -2.96$
Negative muons
- Data
- $\mu \rightarrow W$
- $\mu \rightarrow Z/\gamma^*$
- $\mu \rightarrow c, b$
- Global fit

ALICE, 0-80% Pb-Pb, $|\vec{S}_{NN}| = 5.02$ TeV
$p_T^\mu > 20$ GeV/c
$2.5 < y_{\text{cms}}^\mu < 4$
- Data, opposite charge
- Data, same charge
- POWHEG

FONLL
M. Cacciari, M. Greco and P. Nason
JHEP 9805 (1998) 007

POWHEG
S. Aioli, P. Nason, C. Oleari and E. Re
HEP 07 (2008) 060

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$W^\pm$ in Pb-Pb at 5.02 TeV (2)

- Normalized yields as a function of centrality

$$\frac{1}{\langle T_{AA} \rangle} \times \frac{N_{\mu^+\rightarrow W^+}}{N_{\mu^-\rightarrow W^-}}$$

- Scaled by average nuclear overlap function $<T_{AA}>$
  - $\sigma_{\text{inel}}^{\text{NN}} = 67.6 \pm 0.6$ mb
  - Expected from a hard process

- Model calculation
  - CT14 PDFs with EPPS16
    - A good agreement with data

- Centrality-dependence through shadowed $\sigma_{\text{NN}}^{\text{inel}}$, obtained by forcing the agreement between EPPS16 and the W/Z ATLAS data (Eskola et al. (PRL 125(2020)212301))
  - $\sigma_{\text{NN}}^{\text{inel}} = 41.5^{+16.2}_{-12.0}$ mb

- $<T_{AA}>$ re-evaluated, yields worse agreement between ALICE data and EPPS16
W/Z $R_{AA}$ in CMS and ATLAS

PRL 127, 102002 (2021)

PLB 202 (2020) 135262
FIG. 3. The centrality-dependent nuclear modification ratios for $W^\pm$ and $Z$-boson production in Pb + Pb collisions from ATLAS [39,40] compared to NNLO pQCD calculation with EPPS16 nuclear modification with the nominal value of $\sigma_{	ext{NN}} = 70.0$ mb (left) and with the nuclear-suppressed value $\sigma_{	ext{NN}} = 41.5$ mb (right).
Multiplicty dependence of W production (1)

- Heavy flavour production in pp collisions at 13 TeV
  - Observed productions is faster than linear w.r.t. charge particle multiplicity

- Not fully understood the trend
  - Q2 effect
  - Jet-bias effect
  - Color reconnection in multiparton interactions

- W boson
  - Very large Q2
  - One track in the final state
  - Colorless