Production of W bosons in p-Pb collisions measured with ALICE at the LHC

E. Z. Buthelezi for the ALICE Collaboration
Department of Nuclear Physics, iThemba LABS, Cape Town, South Africa
Outline

- Physics motivation
- $W$-boson measurements in p-Pb collisions with ALICE
- ALICE detector setup
- Data sample
- Analysis method
- Cross-section results
- Yields of $\mu^\pm \leftrightarrow W^\pm$ scaled to $\langle N_{\text{coll}} \rangle$
- Summary
Electroweak W boson: Mass: $80.385 \pm 0.015$ GeV/$c^2$ and life time $\approx 0.1$ fm/$c$

(J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012))

- Discovered at CERN SPS in 1983
  - 1984 Nobel Prize in Physics: Rubbia and van der Meer

- Produced in initial hard processes before formation of QGP
  - Dominant process LO approximation: $q + \bar{q}' \rightarrow W^\pm$
  - Colorless probes $\rightarrow$ not affected by the strong interaction
  - Sensitive to (valence) quark and (sea) antiquark content of the nucleus

- W-boson production in p-Pb collisions
  - Investigate cold nuclear matter effects and constrain nuclear PDFs JHEP 1103 (2011) 071
  - Measurements serve as an important baseline for the understanding and the interpretation of the Pb-Pb data
W-boson measurements in p-Pb collisions

- Measurement in the semi-muonic decay channel → no modification by strongly-interacting matter.

\[
W^+ \rightarrow \mu^+ + \nu_\mu, \quad W^- \rightarrow \mu^- + \bar{\nu}_\mu
\]

- \(p_T\) distribution peaks at \(p_T \approx M_W/2 \approx 40\ \text{GeV}/c\)
- Dominant at \(p_T > 30\ \text{GeV}/c\) in the single muon \(p_T\) distribution

- Previous measurements in p-Pb collisions
  - CMS collaboration: \(W \rightarrow \mu \nu\) and \(W \rightarrow e \nu\),
  \(|\eta_{\text{lab}}| < 2.4, \ p_T > 25\ \text{GeV}/c\) arXiv:1503.05825

- In this study we use the ALICE Forward Muon Spectrometer
  \(2.03 < y^\mu_{\text{cms}} < 3.53\) and \(-4.46 < y^\mu_{\text{cms}} < -2.96, \ p_T^\mu > 10\ \text{GeV}/c\)
  → Rapidity coverage complementary to that of CMS
  → Probe Bjorken-\(x\) region \(\sim 10^{-4} - 10^{-1}\)
Event activity:
Zero Degree Calorimeter (ZDC)
ZNA & ZNC ±112.5 m from the interaction point, $|\eta_{\text{lab}}| > 8.7$

Multiplicity and trigger:
VZERO-A (V0A) $2.8 < |\eta_{\text{lab}}| < 5.1$
VZERO-C (V0C): $-3.7 < |\eta_{\text{lab}}| < -1.7$
Silicon Pixel Detector (SPD): CL1
Clusters in 2nd layer: $|\eta_{\text{lab}}| < 1.4$

Muons from W decays:
Muon Spectrometer
Acceptance: $-4 < |\eta_{\text{lab}}| < -2.5$
Minimum $p_T$ for trigger: $p_T > 0.5$ GeV/c
Minimum muon momentum: $p > 4$ GeV/c
p-Pb and Pb-p collisions at $\sqrt{s_{NN}} = 5.02$ TeV

**Forward rapidity:**
Proton beam direction (proton moving towards the muon arm)

$$\Delta y_{\text{cms}} = 0.465$$ in the p-beam direction

**Backward rapidity:**
Pb-beam direction (Pb nucleus moving towards the muon arm)

**Trigger condition:**
High-$p_T$ muon triggered events: minimum-bias (MB) events (coincidence of V0A $\cap$ V0C) and muon with $p_T \geq 4$ GeV/c

**Integrated luminosity:**
Forward: 4.9 nb$^{-1}$  Backward: 5.8 nb$^{-1}$

**Muon track selection:**
- Geometrical acceptance
  
  $$-4 < \eta_{\text{lab}} \mu < -2.4 \quad , \quad 170^\circ < \theta_{\text{lab}} \mu < 178^\circ$$
- Matching between tracking and trigger tracks
  
  $\rightarrow$ reject punch-through hadrons
- $p_x$DCA - correlation of momentum ($p$) and the Distance of Closest Approach (DCA) to the interaction vertex
  
  $\rightarrow$ remove tracks from beam-gas interactions as well as particles produced in the absorber.
Analysis Method

- $W^\pm \to \mu^\pm$ main contributor in the single-muon $p_T$ distribution at $p_T > 30$ GeV/c

- Main background sources:
  - Heavy-flavour decay muons: $8 < p_T < 40$ GeV/c
  - $Z^0 / \gamma^*$: $p_T > 50$ GeV/c

- Signal extraction - number of $\mu^\pm \leftarrow W^\pm (N_{\mu^\pm \leftarrow W^\pm})$ estimated through suitable fits of the $p_T$ distribution

\[ f(p_T) = N_{bkg} \cdot f_{bkg}(p_T) + N_{\mu\leftarrow W} \cdot f_{\mu\leftarrow W}(p_T) + N_{\mu\leftarrow z/\gamma^*} \cdot f_{\mu\leftarrow z/\gamma^*}(p_T), \]

- $f_{bkg}(p_T) \to$ Fixed Order Next-to-Leading-Log (FONLL) based template

- $f_{\mu\leftarrow W}(p_T)$ and $f_{\mu\leftarrow z/\gamma^*}(p_T) \to$ Monte Carlo templates (POWHEG)

- $N_{bkg}$ and $N_{\mu\leftarrow W}$ \to free normalization parameters

- $N_{\mu\leftarrow z/\gamma^*}$ \to fixed to $N_{\mu\leftarrow W}$

- Correct signal ($N_{\mu^\pm \leftarrow W^\pm}$) for acceptance x efficiency ($A \times \varepsilon$)

- Normalize the yield of $\mu^\pm \leftarrow W^\pm (Y_{\mu^\pm \leftarrow W^\pm})$ to MB cross section

- Compare cross-section results with pQCD at NLO calculations

- Measure the yield of $\mu^\pm \leftarrow W^\pm (Y_{\mu^\pm \leftarrow W^\pm})$ scaled to $\langle N_{coll} \rangle$
W and Z⁰/γ* templates from realistic Monte Carlo (MC) simulations are used for signal extraction.

- \( N_{\mu\pm\rightarrow W\pm} \) and \( N_{Z^0/\gamma*} \) generated with POWHEG\(^1\) using CTEQ6m\(^2\) PDF set in pp and pn collisions.
- Forced to decay to \( \mu^\pm \)
- Shadowing effects evaluated using PYTHIA 6.4\(^3\)
- Systematics determination

Simulation: pp and pn collisions are considered. Templates obtained by combining results using:

\[
\frac{1}{N_{pPb}} \cdot \frac{dN_{pPb}}{dp_T} = \frac{Z}{A} \cdot \frac{dN_{pp}}{dp_T} + \frac{A-Z}{Z} \cdot \frac{dN_{pn}}{dp_T},
\]

\( A = 208 \) (mass number of Pb nucleus),
\( Z = 82 \) (atomic number of Pb nucleus)

Background consists of muons from heavy-flavour decays.

- Small shadowing effects expected at high \( p_T \) \( \rightarrow \) FONLL based template JHEP 1210 (2012) 137

\( \mu^\pm\rightarrow W\pm \) yields (\( Y_{\mu\pm\rightarrow W\pm} \)) obtained by correcting \( N_{\mu\pm\rightarrow W\pm} \) for acceptance x efficiency (Ax\( \varepsilon \))
Number of $\mu^\pm \leftrightarrow W^\pm$ is a weighted average over a number of fit trials obtained by varying

- $p_T$ range of the fit
- QCD background description
- Fraction of $Z^0/\gamma^*$ to $W$ decay muons obtained from PYTHIA and POWHEG
- Alignment effects – varying the position of detector elements

Systematic uncertainties considered are

<table>
<thead>
<tr>
<th>Summary of systematic uncertainties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>~ 6-10%</td>
</tr>
<tr>
<td>Acceptance x efficiency</td>
<td></td>
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<tr>
<td>- Tracking / trigger efficiency</td>
<td></td>
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<tr>
<td>- Alignment</td>
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<tr>
<td></td>
<td>2.5%</td>
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<td></td>
<td>1%</td>
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<tr>
<td>Normalization to MB</td>
<td></td>
</tr>
<tr>
<td>- $F_{\text{norm}}$</td>
<td>1%</td>
</tr>
<tr>
<td>- $\sigma_{\text{MB}}$</td>
<td>3.2% (forward) and 3% (backward)</td>
</tr>
<tr>
<td>- Pile up</td>
<td>0 - 7.5%</td>
</tr>
</tbody>
</table>
Measured cross sections at forward and backward rapidity

- $\sigma_{\mu^\pm \rightarrow W^\pm}$ measured in rapidity intervals: $2.03 < y_{\text{cms}}^\mu < 3.53$ and $-4.46 < y_{\text{cms}}^\mu < -2.96$

- Isospin effects are visible at backward rapidity: more $d$ quarks than $u$ quarks in Pb compared to proton
  $\rightarrow \sigma_{W^-} \sim \sigma_{W^+}$ at forward rapidity and $\sigma_{W^-} > \sigma_{W^+}$ at backward rapidity
- $\sigma_{\mu^\pm \rightarrow W^\pm}$ measured in rapidity intervals: $2.03 < y_{\text{cms}}^\mu < 3.53$ and $-4.46 < y_{\text{cms}}^\mu < -2.96$

- POWHEG predictions do not include nuclear shadowing effects

- Agreement between measurement and POWHEG predictions is within $1.5\sigma$
Measured cross sections vs pQCD NLO predictions

- $\sigma_{\mu \pm} \leftarrow W^\pm$ measured in rapidity intervals: $2.03 < y_{\text{cms}}^\mu < 3.53$ and $-4.46 < y_{\text{cms}}^\mu < -2.96$

- pQCD NLO with CT10 (PDFs) predictions by Paukkunen et al.* are in agreement with the measurements within uncertainties
  
  *Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071

- Consistent with observations by CMS collaboration arXiv:1503.05825
Measured cross sections vs pQCD at NLO predictions with nuclear PDFs

- $\sigma_{\mu\pm \leftarrow W\pm}$ measured in rapidity intervals: $2.03 < y_{\text{cms}}^\mu < 3.53$ and $-4.46 < y_{\text{cms}}^\mu < -2.96$
- pQCD NLO with CT10 (PDFs) and EPS09 (nPDFs) predictions by Paukkunen et al.* are compared with measurements *Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071
- At forward rapidity measured $\sigma_{\mu^+ \leftarrow W^+}$ and $\sigma_{\mu^- \leftarrow W^-}$ are in better agreement with predictions including nPDFs
- Consistent with observations by CMS collaboration arXiv:1503.05825
W$^\pm$ production is a hard process thus it is expected to scale with the number of binary nucleon-nucleon collisions, $N_{\text{coll}}$

$\langle N_{\text{coll}} \rangle$ expected to correlate with the event activity

Use different estimators with different approaches to extract $\langle N_{\text{coll}} \rangle$

- Glauber fit + Negative Binomial Distribution fit to V0A, V0C
- Hybrid Method
  \[ \langle N_{\text{coll}}^{\text{Mult}} \rangle \] is calculated by scaling $\langle N_{\text{coll}} \rangle$ in minimum-bias collisions by the ratio between the average multiplicity density measured at mid-rapidity for a given ZDC energy event class and the one measured in minimum bias collisions

Systematic uncertainty on the normalization to $\langle N_{\text{coll}} \rangle$: 8 - 21% depending on a multiplicity bin
The yield of $\mu^\pm \leftrightarrow W^\pm$ is normalized to $\langle N_{\text{coll}} \rangle$ to test binary scaling.

To increase statistics, results of $\mu^+ \leftrightarrow W^-$ and $\mu^- \leftrightarrow W^-$ are added together.

Within uncertainties, the yield of $\mu^\pm \leftrightarrow W^\pm$ per binary collision is independent of the event activity.

Results from different estimators are compatible within uncertainties.
Summary

- $\mu^\pm \leftrightarrow W^\pm$ are measured in two rapidity intervals in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- Cross-section results
  - Isospin effects are visible at backward rapidity: more d quarks than u quarks in Pb compared to proton
    \[ \sigma_{W^-} \sim \sigma_{W^+} \text{ at forward rapidity and } \sigma_{W^-} > \sigma_{W^+} \text{ at backward rapidity} \]
  - Measured cross sections agree with POWHEG predictions within 1.5$\sigma$
  - Agreement between measured cross sections with predictions by pQCD NLO without shadowing (CT10 PDFs) is within uncertainties
  - A pQCD calculation including nuclear shadowing (nPDFs) agrees better with the measured cross sections
  - Results are consistent with observations by CMS collaboration arXiv:1503.05825

- Yields scaled to $\langle N_{\text{coll}} \rangle$ is estimated using different estimators
  - Results from different estimators are compatible within uncertainties
  - $Y_{\mu^\pm} \leftrightarrow W^\pm / \langle N_{\text{coll}} \rangle$ is independent of the event activity within systematic uncertainties
THANK YOU
Back up slides implement
Fit examples: Signal extraction for W-boson in p-Pb collisions

proton-going direction

2.03 < y_{cms} < 3.53
Fit examples: Signal extraction for W-boson in p-Pb collisions

Pb-going direction

-4.46 < y_{cms} < -2.96
Glauber fit + NBD

Same procedure as for Pb-Pb

- Glauber MC to obtain \( P(N_{\text{part}}) \) assuming \( N_{\text{part}} \) = number of particle sources (ancestors)
- multiplicity distribution per ancestor from Negative Binomial Distribution (NBD)
- minimization procedure to find NBD parameter values
- centrality classes defined slicing measured multiplicity distributions in percentiles of cross section
- \(<N_{\text{part}}>, <N_{\text{coll}}>, <T_{pA}>\) for each centrality class from Glauber
Glauber fit + SNM

Similar procedure but coupled with a model for slow nucleon emission (SNM)
No model is currently available for LHC energies!

Features of emitted nucleons weakly dependent on projectile energy from 1 GeV to 1 TeV
→ “Phenomenological” model based on experimental results at lower energies
• number of protons and neutrons as a function of $N_{\text{coll}}$
• kinematical properties of emitted slow nucleons
→ able to reproduce essential features of the spectrum, still ongoing work!

F. Sikler, arXiv: 0304.065
**W-bosons in Heavy-Ion: Nuclear PDFs**

*Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071*

**Nuclear effects:**

- Difference between cross sections in collisions involving heavy-ion and those in free nucleons (EPS09)

\[ x_a = \frac{M_W}{\sqrt{s}} \exp(y_W), \quad x_b = \frac{M_W}{\sqrt{s}} \exp(-y_W) \]

- W-boson are sensitive to nuclear effects: Fermi motion
  - EMC effects
  - anti-shadowing
  - shadowing

- Isospin effects remain sizable
Signal extraction: example of global fit

- Fit range: $12 < p_T < 80$ GeV/c
- Raw $N_{\mu^+ \leftarrow W^+}$ and $N_{\mu^- \leftarrow W^-}$ extracted by integrating $\mu^\pm \leftarrow W^\pm$ at $10 < p_T^\mu < 80$ GeV/c

proton-going direction
Normalizing yields to MB cross section

- To obtain the cross section $\sigma_{\mu \leftarrow W}$, the yield of $\mu^\pm \leftarrow W^\pm$ is normalized to the MB cross section by considering

$$\sigma_{\mu \leftarrow W} = \frac{N_{\mu \leftarrow W}}{A \times \varepsilon} \times \frac{\sigma_{MB}}{N_{MSH} \times F_{norm}},$$

where:

- $A \times \varepsilon$ - factor for the acceptance and efficiency
- $N_{MSH}$ - number of high-$p_T$ muon triggered (MSH) events
- $\sigma_{MB}$ - the MB cross section is $2.09\pm0.07$ barn for p-Pb collisions and $2.12\pm0.06$ barn for Pb-p [JINST 9 (2014) 11, P11003]
- $F_{norm}$ - fraction of MSH events in MB-triggered data computed using 2 methods:
  - Method 1: uses offline information from trigger inputs
  - Method 2: uses online information from trigger counters
  - Systematic difference between methods is $\sim 1\%$
Number of $\mu^\pm \leftrightarrow W^\pm$ is a weighted average over a number of fit trials obtained by varying
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