Vector-boson production in p-Pb collisions with ALICE at the LHC

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for the ALICE collaboration

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science & technology
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NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

ALICE

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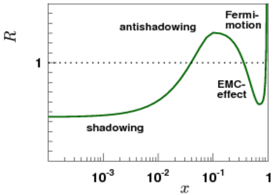
Outline

ALICE

Introduction

- Electroweak gauge bosons W and Z do not interact strongly
- Thus they constitute clean probes of the initial state of nucleus-nucleus and proton-nucleus collisions and a test of the scaling of hard processes with the number of binary collision $\langle N_{\mathrm{coll}} \rangle$



- Their production provides an excellent tool to study:

Cold Nuclear Matter (CNM) effects

- nuclear modifications, generally known as shadowing and anti-shadowing
  $\Rightarrow$ refer to the modification of parton distribution functions in nuclei
- other effects are: isospin, absorption, EMC effect, Fermi motion and neutron skin effects (arXiv:1412.2930,Eur. Phys. J. C (2015) 75:426)

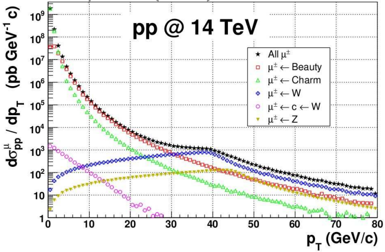
- Their leptonic final states allow their detection, despite low production cross section at LHC energies, especially at forward rapidity

Introduction

W-boson signal: $W^{\pm} \rightarrow \mu^{\pm}$

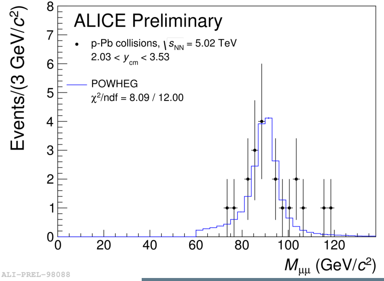
- Measured via its semi-leptonic decay channel
- The signal is a Jacobean peak in an inclusive single muon differential p_{T} spectrum at $p_{\mathrm{T}} = M_{\mathrm{W}}/2$
- Single muon decay from heavy-flavour (B- and D-meson decays) and Z-boson decays are the dominant background contributions

Eur. Phys. J.C(2007)149

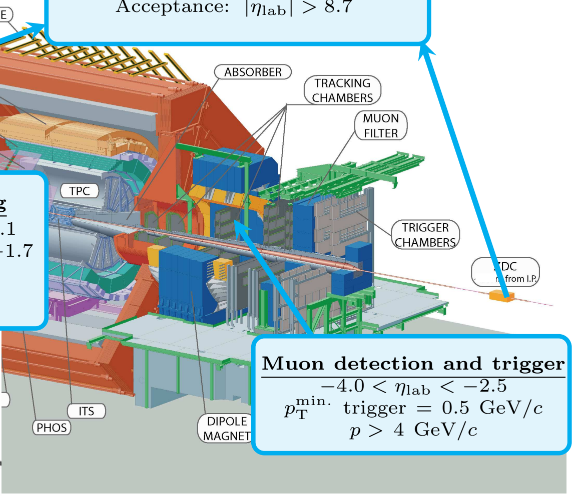


Z-boson signal: $Z^{0} \rightarrow \mu^{+} + \mu^{-}$

- Is observed in the invariant mass distribution of unlike-sign muon pairs as a peak around the Z-boson mass
- Compared with POWHEG Next-to-Leading Order (NLO) event generator JHEP 0807(2008)060



Detectors used for the measurement

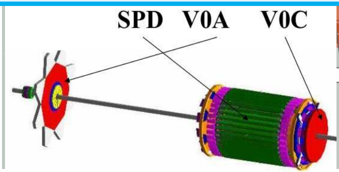


Event activity

Zero Degree Calorimeter(ZDC)
ZNA and ZNC ± 112.5 m from the interaction point
Acceptance: $|\eta_{\rm lab}| > 8.7$

Event activity and triggering

VZERO-A (V0A): $2.8 < \eta_{\rm lab} < 5.1$
VZERO-C (V0C): $-3.7 < \eta_{\rm lab} < -1.7$
Silicon Pixel Detector(SPD): $|\eta_{\rm lab}| < 1.4$ (CL1)



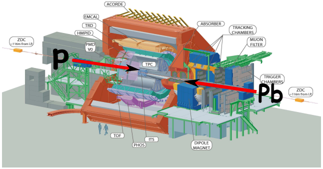
Muon detection and trigger

$-4.0 < \eta_{\rm lab} < -2.5$
$p_{\rm T}^{\rm min.}$ trigger $= 0.5$ GeV/c
$p > 4$ GeV/c

Data Samples

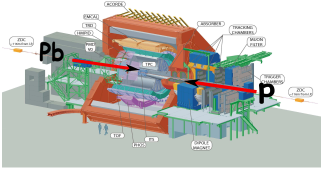
- p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV ($E_{\rm p} = 4$ TeV & $E_{\rm Pb} = 1.58$ TeV)
- Two beam configurations with a rapidity shift ($\triangle y = 0.465$) in the proton direction

p-going (forward rapidity, $y_{\rm cms}$)



$2.03 < y_{\rm cms} < 3.53$

Pb-going (backward rapidity, $-y_{\rm cms}$)



$-4.46 < y_{\rm cms} < -2.96$

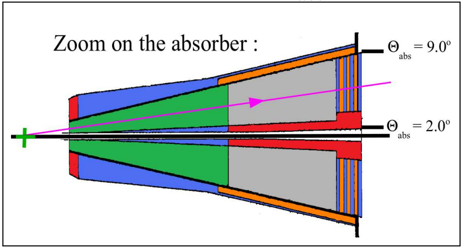
$\Rightarrow y_{\rm cms}$ covered by the muon spectrometer

Triggers:

- high-$p_{\rm T}$ single muon triggered events (for W-boson only)
  - Minimum-Bias (MB,coincidence of V0A and V0C) & a single muon with $p_{\rm T} \gtrsim 1$ GeV/c
- low-$p_{\rm T}$ di-muon triggered events (for Z-boson only)
  - Coincidence of MB and two low-$p_{\rm T}$ ($p_{\rm T} > 0.5$ GeV/c) muons

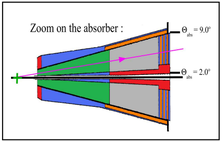
Event and track selection

- Single and di-muon events selection applied for W and Z respectively
- **Muon candidates are reconstructed in the kinematic acceptance of the spectrometer**
  - Pseudorapidity acceptance: $-4.0 < \eta_{\mathrm{lab}} < -2.5$
  - Angle at the end of the absorber: $170° < \theta_{\mathrm{abs}} < 178°$

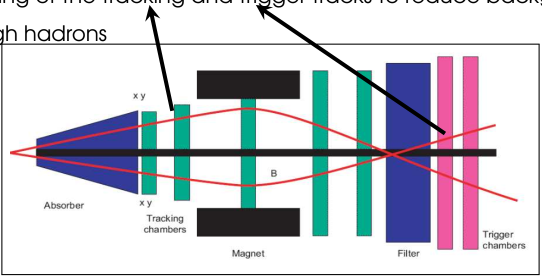


Event and track selection

- Single and di- muon events selections applied for W and Z respectively



- **Muon candidates are reconstructed in the kinematic acceptance of the spectrometer**
  - Pseudorapidity acceptance: $-4.0 < \eta_{\rm lab} < -2.5$
  - at the end of the absorber: 170°$< \theta_{\rm abs} <$178°
- **Muon track selection** in addition to geometrical acceptance cuts:
  - offline matching of the tracking and trigger tracks to reduce background from punch-through hadrons



  - correlation of momentum (p) and **D**istance of **C**losest **A**pproach (DCA) to the interaction point to reduce fake and beam gas tracks

Monte Carlo simulations

ALICE

W and Z/γ^* Monte Carlo (MC) templates

- Based on POWHEG (NLO) generator with CTEQ6m/CT10
- Interfaced with PYTHIA6.4:
  $\Rightarrow$ apply showers to POWHEG hard events
  $\Rightarrow$ parametrize nPDFs using EPS09

POWHEG:JHEP 0807(2008)060, CTEQ: JHEP 0207(2002)012, PYTHIA6.4: JHEP 05(2006)026, EPS09: JHEP 0904(2009)065, CT10:arXiv:1101.0561

Generation done for pp and pn collisions separately and combined with:

$$\frac{1}{N_{\mathrm{pPb}}}\frac{\mathrm{d}N_{\mathrm{pPb}}}{\mathrm{d}p_{\mathrm{T}}} = \frac{Z}{A}\frac{1}{N_{\mathrm{pp}}}\frac{\mathrm{d}N_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}} + \frac{A-Z}{A}\frac{1}{N_{\mathrm{pn}}}\frac{\mathrm{d}N_{\mathrm{pn}}}{\mathrm{d}p_{\mathrm{T}}}$$

A = 208 and Z = 82

Heavy-flavour Monte Carlo (MC) templates

- Based on Fixed Order Next-to-leading-Log (FONLL) with CTEQ6.6
- Phenomenological function previously used by ATLAS

FONLL: JHEP 1210(2012)137, ATLAS: ATLAS-COM-CONF-2011-088

Signal extraction: W boson

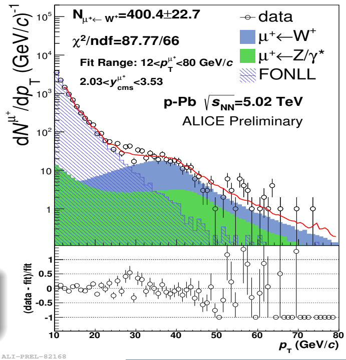
Signal extraction based on a combined fit $f(p_T)$:

$$f(p_T) = N_{\mu\leftarrow HF} \cdot f_{\mu\leftarrow HF} + N_{\mu\leftarrow W} \cdot f_{\mu\leftarrow W} + N_{\mu\leftarrow Z/\gamma^*} f_{\mu\leftarrow Z/\gamma^*}$$

$f_{\mu\leftarrow HF}$ – heavy-flavour and $f_{\mu\leftarrow W}$,$f_{\mu\leftarrow Z/\gamma^*}$ – W and Z templates

$N_{\mu\leftarrow HF}$,$N_{\mu\leftarrow W}$ free normalization parameters and $N_{\mu\leftarrow Z/\gamma^*}$ fixed to $\frac{\sigma_{\mu\leftarrow Z/\gamma^*}}{\sigma_{\mu\leftarrow W}}$ from MC

- $N_{\mu\leftarrow W}$ is extracted between 10 and 80 GeV/c
- $N_{\mu\leftarrow W}$ is an average over p_T range variation, detector configuration parametrization and $\sigma_{\mu\leftarrow Z/\gamma^*}/\sigma_{\mu\leftarrow W}$
- $N_{\mu\leftarrow W}$ is then corrected for acceptance×efficiency ($A\times\varepsilon_{pPb}$ and $A\times\varepsilon_{Pbp}$)



Average acceptance×efficiency ($A\times\varepsilon$)

$A\times\varepsilon_{pPb}$ = 0.88 ± 0.05% and $A\times\varepsilon_{Pbp}$ = 0.77 ± 0.06%

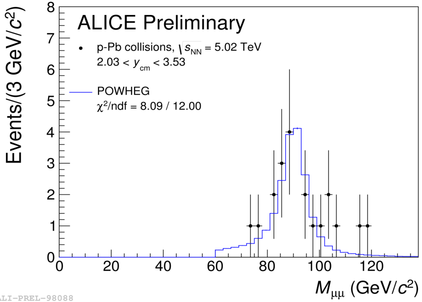
Signal extraction: Z boson

- The signal of the Z-boson is an invariant mass peak of opposite sign muons around its mass
  - Muons with $p_{\mathrm{T}}^{\mu} > 20$ GeV/c are selected
  - $\mathrm{N}_{\mu\mu\leftarrow Z}$ is extracted between 60 and 120 GeV/c^2

Average acceptance×efficiency (A×ε)

A×$\varepsilon_{\mathrm{pPb}}$=83.54±0.72(stat.)±0.44(sys) % and A×$\varepsilon_{\mathrm{Pbp}}$=63.67± 1.40(stat.)±0.27(sys) %

- Z candidates are number of entries (consistent with the integral of a Gaussian fit)
- Validation with the MC simulations



Systematic uncertainties

W boson

- Alignment $\Longrightarrow$ variation of positions of detector elements (efficiency)
  - Same alignment files used for reconstruction and obtaining $A\times\varepsilon$
- Systematic uncertainties on tracking, triggering, tracking-trigger matching efficiency (ε)
- Detector resolution influence on the signal extraction determined considering the track residuals effect (cluster resolution) on the templates

	Signal extraction	$A\times\varepsilon$	Tracking	Triggering	Matching ε	Normalization	σ_{MB}
p–Pb	6∼10%	1%	2%	1%	0.5%	1%	3.2%
Pb–p	6∼10%	1%	3%	1%	0.5%	1%	3%

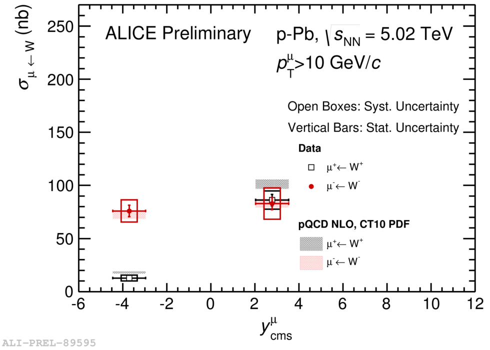
Z boson

- Same alignment files used for reconstruction and obtaining $A\times\varepsilon$
- Detector resolution influence determined considering the track residuals effect (cluster resolution) on the input shape (Gaussian and Breit-Wigner to the track residuals)

	$A\times\varepsilon$	Tracking ε	Triggering ε	Matching ε	Cluster resolution	σ_{MB}
p-Pb	1%	4%	2%	1%	1.3%	3.2%
Pb-p	2%	6%	2%	1%	0.2%	3%

Results: W-boson cross sections

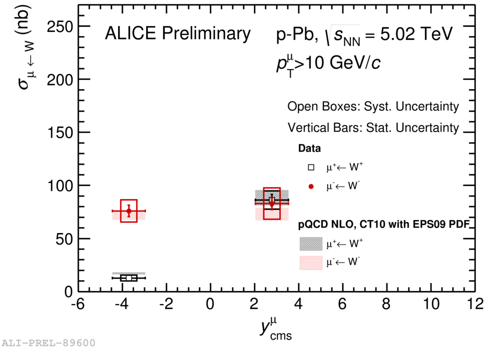
Theory: Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071



- Cross sections of muons from $W^{\pm}$ measured in the forward and backward rapidity
- They are compared with pertubative Quantum Chromodynamics (pQCD) predictions at Next-to-Leading Order (NLO) with CT10 PDFs
- Measured and theoretical cross section of W^{-} are in agreement in both rapidity regions, whereas W^{+} cross sections agrees within uncertainties

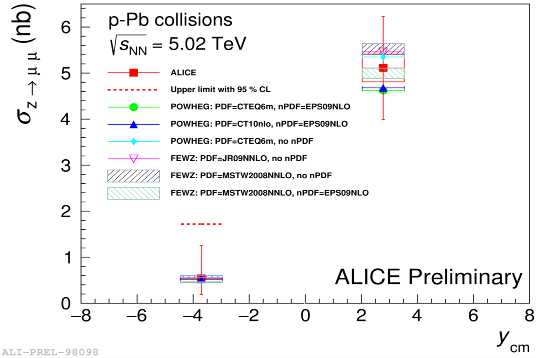
Results: W-boson cross sections

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



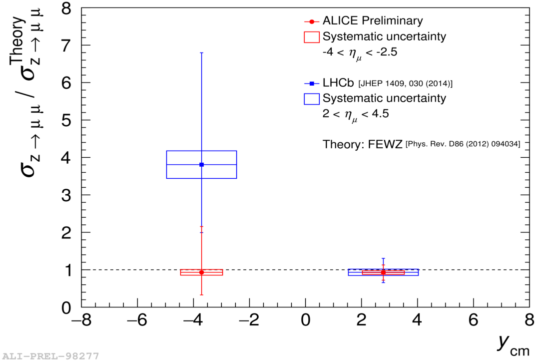
- Cross sections of muons from $W^{\pm}$ measured in the forward and backward rapidity
- They are compared with pertubative Quantum Chromodynamics (pQCD) predictions at NLO and CT10 PDFs with EPS09 nPDFs parametrization
- Theoretical cross sections with shadowing are in agreement with the measured cross sections within uncertainties

Results: Z-boson cross sections



- The measured $Z \rightarrow \mu^{+} + \mu^{-}$ cross section at forward and backward rapidity compared with NLO and Next-to-NLO pQCD MC calculations (POWHEG and FEWZ, respectively) with different PDFs and/or nuclear PDFs (EPS09)
- The measured and theoretical cross sections are in agreement
- Uncertainties are too high to constrain nPDFs, which is also the case for the W boson

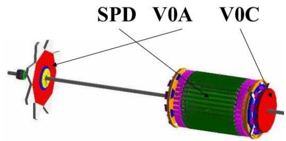
Results: Z-boson cross sections



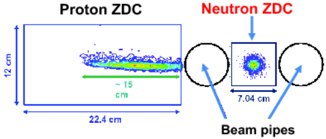
- The ratio of the measured cross section by ALICE and LHCb to the FEWZ theoretical predictions are shown
- The ratios are compatible with unity at forward rapidity for both ALICE and LHCb
- The ALICE point at backward rapidity is also compatible with unity

Test of binary scaling

- Production of W bosons is a hard process, thus is expected to scale with the number of colliding nucleons
- $\langle N_{coll} \rangle$ is expected to be correlated with event activity (centrality of the collision)
- Different estimators with different approaces were used to classify event activity:
  - Glauber Model + Negative Binomial Distribution fit to the signal in the VZEROs and the clusters in the first layer of the SPD



  - Hybrid method: scaling N_{coll} in minimum-bias collisions by the ratio between the average multiplicity density measured at mid-rapidity in a given ZDC energy event class and the one measured in minimum bias collisions

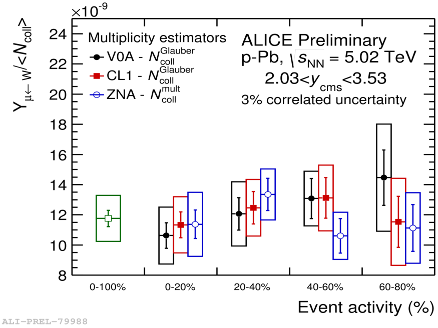


- $\langle N_{coll} \rangle$ systematic uncertainty is multiplicity bin dependent, varies between 8 - 24%

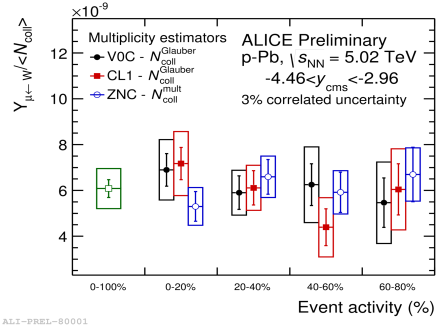
Yield over $\langle N_{coll} \rangle$

- Yield is normalized to $\langle N_{coll} \rangle$ to test binary scaling

Forward



Backward



- The yield per binary collisions is independent of event activity within uncertainties
- Event activity estimators compatible within uncertainties

Summary

W- and Z-boson cross sections

- ALICE has measured massive vector bosons at forward and backward rapidity in p-Pb collisions
- The measured cross sections are consistent with pQCD theoretical predictions with and without shadowing
- Current uncertainties do not allow disentanglement of the shadowing effects, small effect of nPDFs in the models

W-boson yield normalized to $\langle N_{\rm coll} \rangle$

- The $\langle N_{\rm coll} \rangle$-normalized yield is compatible with the notion of hard-processes being independent of event activity, within uncertainties
- This measurement is consistent among different estimators within uncertainties