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

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Motivation

- **W/Z boson**
  - Weakly interacting particles, and have large masses
  - Produced predominantly via a quark–antiquark pair annihilation (Drell-Yan)
    - $u\bar{d} \rightarrow W^+, d\bar{u} \rightarrow W^-, q\bar{q} \rightarrow Z$
    - Sensitive to isospin

- **pp collision**
  - 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)
  - Leptonic decay insensitive to the strongly-interacting medium

The Universe 4 (2016) 3, 34-44
J. C. Peng and J. W. Qiu

EPJC (2017)77:163
K. Eskola, P. Paakkinen, H. Paukkuuen, C. Salgado
ALICE detector

Electron identification

TPC (dE/dx)
- TPC (dE/dx)
- EMCal (Energy)
- |y| < 0.6

Muon spectrometer

V0
- Centrality estimator

SPD
- primary vertex reconstruction
- Charge particle multiplicity estimator

ZDC
- centrality estimator

EMCal
- Electron identification

\( e^\pm \rightleftharpoons W^\pm \ (pp) \)

\( \mu^\pm \rightleftharpoons W^\pm \ (p-Pb, Pb-Pb) \)

\( Z \rightarrow \mu^\pm \ (p-Pb, Pb-Pb) \)

\( Z \rightarrow \mu^\pm \ (p-Pb, Pb-Pb) \)

p-Pb, p-going

\( p \rightarrow Pb \)

2.03 < y_{cms} < 3.53

p-Pb, Pb-going

\( Pb \rightarrow p \)

-4.46 < y_{cms} < -2.96

Pb-Pb

2.5 < y_{cms} < 4

Quark Matter 2022, 4-10 Apr
W/Z yields extraction in ALICE

- $e^\pm \rightarrow W^\pm (|y| < 0.6)$; Based on isolation cuts on energy; $E_{iso} = \frac{\sum E_R < 0.3}{E_e} < 0.05$
- $e^\pm \rightarrow c, b$ are obtained by data driven subtraction (large isolation energy)
- $\mu^\pm \rightarrow W^\pm (|y|_{lab} < -2.5)$; 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
- $Z \rightarrow \mu^\pm (|y|_{lab} < -2.5)$; Invariant mass of opposite-sign muon pair

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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
New results for QM

- **pp collisions**
  - Multiplicity dependence of $W$ boson production in pp collisions

- **pPb collisions**
  - Cross section for $\mu^\pm \to W^\pm$ vs. rapidity in pPb
  - Charge asymmetry for $\mu^\pm \to W^\pm$ vs. rapidity in pPb

- **Pb-Pb collisions**
  - Cross section for $\mu^\pm \to W^\pm$ in Pb-Pb
  - Centrality dependence for $\mu^\pm \to W^\pm$ production
$W^\pm$ in pp collisions at 13 TeV (1)

- $p_T$ differential cross sections for $e^\pm \rightarrow W^\pm$ in $|y| < 0.6$, and ratio for $e^+ \rightarrow W^+$ and $e^- \rightarrow W^-$ as a function of $p_T$
- Compared to a model including pQCD NLO (POWHEG) + CT10nlo
  - Measurements and model are consistent within the uncertainties
  - Larger cross section for $e^+ \rightarrow W^+$ in data as expected from isospin effects

$\pm$4% lumi. uncertainty not shown

H. L. Lai et al., PRD 82 (2010), 074024

Quark Matter 2022, 4-10 Apr
Cross sections for $e^\pm \rightarrow W^\pm$ 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
Multiplicity 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

Luigi Dello Stritto, talk on 7 Apr at 4 pm Parallel Session T14: Hadron prod. and col. dyn. I
Multiplicity dependence of W production (2)

- **W-boson production is linear w.r.t. multiplicity**
- No strong autocorrelation* between W production and charged-particle multiplicity
- Associated hadron production (W+ q -> h) is faster than linear w.r.t. multiplicity
- W boson is less correlated with multiplicity than associate hadron
- Both multiplicity dependence is consistent with PYTHIA 8 with MPI + CR

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* S. G. Weber, A. Dubla, A. Andronic, and A. Morsch
EPJC (2019) 79:36
$W^\pm$ 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

- Within experimental and theoretical uncertainties, pQCD + isospin with/without nPDF are consistent with the measured cross section
  - 3.5σ deviation from free-PDF calculation (MCFM + CT14) for $W^+$ at forward rapidity for the bin at largest rapidity

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
Charge asymmetry
- A sensitive probe of the $u$ and $d$ nPDF
- $ -4.46 < y_{\text{cms}} < -2.96$ ; $d\bar{u} \to W^- \text{ dominant}$
- $ 2.03 < y_{\text{cms}} < 3.53$ ; $u\bar{d} \to W^+ \text{ dominant}$

Significant deviation between data and models at large forward rapidity region

Charge asymmetry
- $A_{\text{ch}} < 0$ ; $W^-$ dominant
- $A_{\text{ch}} > 0$ ; $W^+$ dominant
$W^\pm$ in Pb-Pb at 5.02 TeV (1)

- Larger cross section for $\mu^- \leftarrow W^-$ than for $\mu^+ \leftarrow W^+$
  - Effect of isospin due to different content of $u$ and $d$ in Pb

- Model with CT14 for free nucleon (MCFU+CT14)
  - Overestimate the cross sections
  - Suggest a significant effect of modification of the PDFs
**W± in Pb-Pb at 5.02 TeV (2)**

- Normalized yields as a function of centrality

\[
\frac{1}{\langle T_{AA} \rangle} \times \frac{N_{\mu^+\rightarrow W^+}}{N_{MB}^{MB}}
\]

- Scaled by average nuclear overlap function \(\langle T_{AA} \rangle\)
  - \(\sigma_{NN}^{inel} = 67.6 \pm 0.6\) mb
  - Expected from a hard process

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

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

- \(\langle T_{AA} \rangle\) re-evaluated, yields worse agreement between ALICE data and EPPS16
Production of hard probes in peripheral collisions
- Significantly affected by event selection and geometry biases
- These bias cause a suppression in peripheral collisions

Comparison with HG-PYTHIA
- Including biases from event selection and geometry
- Good agreement with data, but not allow to conclude the suppression due to limited statistics

\( W^\pm \) in Pb-Pb at 5.02 TeV (3)
Z in Pb-Pb at 5.02 TeV

- Z Model with free PDF --- 3.4 σ deviation w.r.t. measured Z cross section
- Models with nPDF --- well reproduced measured Z cross section
- Strong evidence of modification of Z production in Pb-Pb collisions
Summary

- **W production in pp collisions**
  - Consistent with POWHEG (NLO) + CT10nlo
  - Multiplicity dependence is linear, suggesting no autocorrelation and jet bias effect
    - PYTHIA included MPI + CR reproduced the dependence

- **W production in p-Pb**
  - Models + isospin with nPDF agree with the data
  - $3.5\sigma$ deviation from free-PDF calculation for $W^+$ at forward rapidity for the bin at largest rapidity

- **W/Z production in Pb-Pb**
  - Model with CT14 PDF for free nucleons overestimate the production for $W$
    - Suggest nuclear modification of the PDF
  - Scaled by average nuclear overlap function $\langle T_{AA} \rangle$
    - Trend with centrality disfavour explanations with reduced $\sigma_{NN}$
**Z production in p-Pb @ 8.16 TeV**

JHEP09(2020)076

- Different Z production cross section measured at forward and backward rapidity
- Model calculations:
  - Based on pQCD
  - including isospin effects
  - With/without nPDF

- Within experimental and theoretical uncertainties, pQCD+isospin with/without nPDF are consistent with the measured cross section
EPPS16 vs. EPPS21

Kari J. Eskola, Petja Paakkinen, Hannu Paukkunen, Carlos A. Salgado
ArXiv: 2112.12462
Modified cross section

FIG. 3. The centrality-dependent nuclear modification ratios for $W^\pm$ and $Z$-boson production in $\text{Pb} + \text{Pb}$ collisions from ATLAS [39,40] compared to NNLO pQCD calculation with EPPS16 nuclear modification with the nominal value of $\sigma_{\text{in}} = 70.0$ mb (left) and with the nuclear-suppressed value $\sigma_{\text{in}} = 41.5$ mb (right).
W/Z $R_{AA}$ in CMS and ATLAS

PRL 127, 102002 (2021)  
PLB 202 (2020) 135262