Probing Cold Nuclear Medium Effects with W/Z Production in Heavy-ion Collisions

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Publications: 1412.2930 [nucl-th], 1505.08106 [nucl-th], 1608.06835 [nucl-th]
CNM effect or NPDFs: baseline of the study on jet quenching

I. **Framework** of the study

II. Vector boson production in HIC at the LHC

III. W/Z production in p+Pb collisions with **KP NPDFs**

IV. W/Z production in **future** heavy-ion collisions

V. Summary
I. Framework of the study

**Vector boson as a probe of Cold Nuclear Medium effect**

<table>
<thead>
<tr>
<th>Features of W/Z production:</th>
<th>In nucleus-nucleus collisions at LHC:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Drell-Yan process</td>
<td></td>
</tr>
<tr>
<td>• High-invariant mass</td>
<td>• Clean signal of initial state of the collision, e.g. parton distributions (PDFs), and cold nuclear medium effects or NPDFs.</td>
</tr>
<tr>
<td>$m_{W/Z} \sim 80-90$ GeV</td>
<td>• The created hot/dense nuclear environment (after $\sim 1$ fm/c) can hardly pollute the signal of initial CNM effect.</td>
</tr>
<tr>
<td>• Produced in early stage</td>
<td></td>
</tr>
<tr>
<td>$\sim 1/m_{W/Z} \sim 10^{-3}$ fm/c</td>
<td></td>
</tr>
<tr>
<td>• Decay later</td>
<td></td>
</tr>
<tr>
<td>$\sim 0.08-0.09$ fm/c</td>
<td></td>
</tr>
<tr>
<td>• Colorless lepton pair in final state</td>
<td></td>
</tr>
</tbody>
</table>

$\lambda_{mfp} > l_{QGP} \sim 10$ fm
I. Framework of the study

Factorization in pQCD

Drell-Yan in hadronic collision

In nuclear collisions:

\[ \sigma_{AB \rightarrow VX \rightarrow llX} = \sum_{a,b} \int dx_a dx_b f^A_a(x_a, Q^2) f^B_b(x_b, Q^2) \hat{\sigma}_{ab \rightarrow VX \rightarrow llX} \]

PDFs

Partonic cross section

- Factorization theorem holds
- Parton distributions is altered in the cold nuclear medium

QCD Factorization theorem

PDFs \(\rightarrow\) NPDFS (EPS09, DSSZ, ...)

Peng Ru  DUT / CCNU  24th Sept.

5.
I. Framework of the study

Partonic sub-process in pQCD

<table>
<thead>
<tr>
<th>Leading order (LO)</th>
<th>Next-to-leading order (NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u\bar{u} \rightarrow Z^0$</td>
<td>$p_T^V = 0$</td>
</tr>
<tr>
<td>$d\bar{d} \rightarrow Z^0$</td>
<td></td>
</tr>
<tr>
<td>$s\bar{s} \rightarrow Z^0$</td>
<td></td>
</tr>
<tr>
<td>$u\bar{d} \rightarrow W^+$</td>
<td>$q\bar{q} \rightarrow Vg$</td>
</tr>
<tr>
<td>$c\bar{s} \rightarrow W^+$</td>
<td></td>
</tr>
<tr>
<td>$u\bar{s} \rightarrow W^+$</td>
<td></td>
</tr>
<tr>
<td>$d\bar{u} \rightarrow W^-$</td>
<td>$qg \rightarrow Vq$</td>
</tr>
<tr>
<td>$s\bar{c} \rightarrow W^-$</td>
<td></td>
</tr>
<tr>
<td>$s\bar{u} \rightarrow W^-$</td>
<td>$\bar{q}g \rightarrow V\bar{q}$</td>
</tr>
</tbody>
</table>

Weak interaction at LO
I. Framework of the study

Numerical simulation in pp collision

**Program :** DYNNLO

**Comparison with the LHC data**


Code : Drell-Yan Next-to-Next-to Leading Order (DYNNLO)

S. Catani, et al, **PRL**(2009), **PRL**(2007)

- High-order QCD correction:
  - NLO\( [O(\alpha_s^0)] \), NNLO\( [O(\alpha_s^2)] \)

- Renormalization and factorization scales
  \( \mu_R = \mu_F = m_{W/Z} \)

- PDFs: MSTW08, CT10, ABMP15

Both NLO and NNLO agree with data.

NNLO corrections are small.
I. Framework of the study

Numerical simulation in pp collision: pT spectra

Z Boson

W Boson


- Different process from the rapidity distribution
- NLO calculation agree well with the high-pT data
I. Framework of the study

- Sensitive to the initial-stage cold nuclear medium effect or NPDFs in nuclear collisions
- Well understood process in pQCD (Drell-Yan)
- Numerical results agree well with the LHC proton-proton data
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in Pb+Pb collisions

Results with EPS09 NPDFs show a good agreement with the data.

NNLO correction is small.

PR, B.W.Zhang, et al., JPG 42 (2015) 085104
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in Pb+Pb collisions

Nuclear corrections

Different nuclear corrections from EPS09 and DSSZ

A good probe of the NPDFs


\[ \langle N_{\text{coll}} \rangle \cdot \frac{1}{d\sigma/dy Z} \text{ (fb)} \]

\[ \sqrt{s_{\text{NN}}} = 2.76\text{TeV} \]

\[ R_{\text{AA}}(yZ) \]

\[ \langle N_{\text{coll}} \rangle \cdot \sigma_{\text{dyZ}} \text{ (fb)} \]
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in Pb+Pb collisions: Parton Level

Momentum fraction at LO

\[ x_1 = \frac{m_Z}{\sqrt{s_{NN}}} e^{y^Z}, \quad x_2 = \frac{m_Z}{\sqrt{s_{NN}}} e^{-y^Z} \]

\[ y^Z \sim 0 : \quad x_1 \sim x_2 \sim \frac{m_Z}{\sqrt{s_{NN}}} \sim 0.033 \]

Parton contributions

- Initial partons are mainly quarks and anti-quarks.
- Gluon give small high-order contribution.

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ Q^2 = 10 \text{ GeV}^2 \]

Peng Ru  DUT / CCNU  24\textsuperscript{th} Sept. 12.
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in Pb+Pb collisions: Parton Level

\[ R_f(x, Q^2) = f^{Pb}(x, Q^2) / f^p(x, Q^2) \quad \text{and} \quad x_1 = \frac{m_Z}{\sqrt{S_{NN}}} e^{y^Z}, \quad x_2 = \frac{m_Z}{\sqrt{S_{NN}}} e^{-y^Z} \]

Define: 

\[ R_f f^\bar{f}(y^Z) = \alpha(y^Z) R_f(x_1) R_f^\bar{f}(x_2) + \beta(y^Z) R_f(x_2) R_f^\bar{f}(x_1) \]

A naïve choice: \( \alpha(y^Z) = \beta(y^Z) = 1/2 \)

Probe of the nuclear corrections on quark PDFs

\[ \sqrt{S_{NN}} = 2.76 \text{TeV} \]

\[ O(\alpha_s) \]

References:

II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in p+Pb collisions

Differential cross section at NLO

R\_pA

Nuclear corrections result in an asymmetric distribution

Differences between EPS09 and DSSZ are observed

J. Albacete et al. 1605.09479 [hep-ph]
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in p+Pb collisions: Parton Level

Nuclear correction at parton level

\[ x_{Pb} = x_2 = \frac{m_Z}{\sqrt{s_{NN}}} e^{-y^Z} \]

\[ R_f(x_{Pb}) \rightarrow R_f(y^Z) \]

R_pA provides an image of the nuclear corrections on quark PDFs.

Large-x, valence dominated

small-x, sea quark dominated

Anti-shadowing

\[ \sqrt{s_{NN}} = 5.02 \text{TeV} \]

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II. Vector boson production in heavy-ion collisions at the LHC

Transverse momentum ($p_T$) spectra

NLO results with EPS09 NPdfs show good agreement with the data.

$\sqrt{s_{NN}} = 2.76$ TeV

Pb + Pb

$O(\alpha_s^2)$ EPS09

$O(\alpha_s)$ EPS09

$\times 10^{-8}$

CMS Data(11)
CMS Data(14)

II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on pT spectra: Parton Level

\[ y^Z \sim 0 : \quad x \sim \frac{p_T + \sqrt{p_T^2 + m_{Z/W}^2}}{\sqrt{s_{NN}}} \]

\[ R_f(x_{Pb}) \rightarrow R_f(p_T) \]

\[ pT \text{ spectrum provides more knowledge of nuclear correction on gluon PDFs} \]
II. Vector boson production in heavy-ion collisions at the LHC

**W Boson: Charge Asymmetry**

\[ A = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}} \]

\[ \frac{u(x)}{d(x)} \]

\[ \frac{u^{Pb}(x)}{d^{Pb}(x)} = \frac{R_u(x)}{R_d(x)} \cdot \frac{u^p(x)}{d^p(x)} \]

---

**In p+p and Pb+Pb**

- Not sensitive to the order.
- Not sensitive to the choice of NPDPF.
II. Vector boson production in heavy-ion collisions at the LHC

W Boson: Charge Asymmetry

Not sensitive to the choice of NPDF.

Somewhat deviation from the data in negative rapidity.

At the same colliding energy (5.02 TeV)

In p+Pb

\[ \sqrt{s_{NN}} = 5.02 \text{TeV} \]

\[ \eta_{C.M.}=0 \]

\[ p+Pb \rightarrow p+p \text{ in forward region} \]

\[ p+Pb \rightarrow Pb+Pb \text{ in backward region} \]

At small-x (sea-quark dominated), isospin effect is small
III. W/Z production in p+Pb collisions with KP NPDFs

KP nuclear parton distribution

- Predicted from the semi-microscopic model developed by S. A. Kulagin and R. Petti.

  **NPA** 756 (2006) **126**; **PRC** 90 (2014) **045204**

- Not a fit, unlike conventional approaches.

- Offer insights on the underlying nuclear physics mechanisms.

- The KP nuclear PDFs have been validated with data from a wide range of processes including lepton-nucleus DIS, Drell-Yan production in pA collisions, Z,W production in heavy ion collisions at colliders.
III. W/Z production in p+Pb collisions with KP NPDFs

KP nuclear parton distribution

Different nuclear effects on parton distributions (PDF) are taken into account:

\[ q_{a/A} = q_{a}^{p/A} + q_{a}^{n/A} + \delta q_{a}^{MEC} + \delta q_{a}^{coh} \]

- \( q_{a}^{p(n)/A} \): PDF in bound p(n) with Fermi Motion, Binding (FMB), and Off-Shell effect (OS)
- \( \delta q_{a}^{MEC} \): nuclear Meson Exchange Current (MEC) correction
- \( \delta q_{a}^{coh} \): Contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

KP model prediction vs DIS data

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III. W/Z production in p+Pb collisions with KP NPDFs

Results on p+Pb at the LHC

Forward-backward asymmetry of W boson

\[ R_{FB}(y) = \frac{N(+y)}{N(-y)} \]

\[ W^+ \quad \frac{N(+\eta_{lab})}{N(-\eta_{lab})} \]

\[ W^- \quad \frac{\text{data}}{\text{ABMP15}} \]

\[ \sqrt{s_{NN}} = 5.02 \text{TeV} \quad p+Pb \]

PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]
III. W/Z production in p+Pb collisions with KP NPDFs

Results on p+Pb at the LHC

Charge asymmetry of W boson

![Graph showing the charge asymmetry of W boson for p+Pb collisions at the LHC.](image)

- **W/Z production in p+Pb collisions with KP NPDFs**
- **Results on p+Pb at the LHC**
- **Charge asymmetry of W boson**

**Graph:**

- CMS
- ABMP15+KP
- CT10+EPS09
- ABMP15 (Z×p+N×n)

**Data:**

- √s_{NN} = 5.02 TeV
- p+Pb

**Equations:**

- (e) \( u^p(x) / d^p(x) \)
- (f) \( \bar{u}^p(x) / \bar{d}^p(x) \)

**References:**

PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]
III. W/Z production in p+Pb collisions with KP NPdfs

Results on p+Pb at the LHC

Comparison with the ATLAS data

![Graphs showing W^+, W^-, and Z^0 production in p+Pb collisions at the LHC compared to ATLAS data.](image)

PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]
III. W/Z production in p+Pb collisions with KP NPDFs

Nuclear corrections with different effects

W differential cross section

4 nuclear effects (FMB, OS, NS, MEC) play roles at the LHC.

PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]
III. W/Z production in p+Pb collisions with KP NPDFs

Nuclear corrections with different effects

Z boson

![Graph showing Z boson production in p+Pb collisions with nuclear corrections](image)

- a. FMB
- b. FMB+OS
- c. FMB+OS+NS
- d. FMB+OS+NS+MEC

CMS

PR, Kulagin, Petti, B.W.Zhang,
1608.06835 [nucl-th]
III. W/Z production in p+Pb collisions with KP NPDFs

$\chi^2/N_{Data}$ between model and measurement

Good agreement between KP model predictions and the latest LHC data.

Evidence of nuclear modification.
IV. W/Z production in future heavy-ion collisions

Pb+Pb at 39TeV
p+Pb at 63TeV

\[ x \sim \frac{m_{Z,W}}{\sqrt{s_{NN}}} \]

- Vector boson will be produced by smaller-x initial partons.
- The shadowing effect of the sea quark and gluon would be significant.
- Valence quark contribution and isospin effect would be small.
IV. W/Z production in future heavy-ion collisions

Pb+Pb: Z boson rapidity distribution

Nuclear correction at parton level

Parton contributions at LO

\[ R_{f\overline{f}}(y^Z) = \frac{1}{2} \left[ R_f(x_1)R_{\overline{f}}(x_2) + R_f(x_2)R_{\overline{f}}(x_1) \right] \]

\[ R_{u,s+\overline{s}}(y^Z, \mu=m_Z) \]

\[ R_{d,s+\overline{s}}(y^Z) \]

\[ R_{u,v+s} \]

\[ \sqrt{s_{NN}} = 2.76 \text{TeV} \]

\[ \sqrt{s_{NN}} = 39 \text{TeV} \]

Differences between LHC and future

PR, B.W. Zhang, et al.
EPJC 75 (2015) 426
IV. W/Z production in future heavy-ion collisions

LHC + Future

\[ \mathcal{R}(\Delta p_T^W) = \frac{R_{AA}^{LHC}(p_{T0}^W + \Delta p_T^W)}{R_{AA}^{Future}(p_{T0}^W - \Delta p_T^W)} \]

- Valuable constraints on NPDFS

V. Summary

- **Nuclear corrections** on W/Z boson **rapidity** and **transverse momentum** distribution at the LHC are studied at **partonic level**. EPS09 and DSSZ predict different rapidity dependences.

- With the **KP model**, the nuclear corrections on W/Z production with different **underlying physical mechanisms** are shown for the first time.

- The predictions with **KP nuclear effect show a better agreement** with the latest LHC p+Pb data, than those without nuclear correction. The KP NPDFs well describe the W charge asymmetry.

- A further **improvement** of the accuracy of future LHC data may allow to **disentangle the effects** of different underlying mechanisms.

- The W/Z production in **future** heavy-ion collisions may provide more **powerful constraints on the NPDFs**.
V. Summary

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- The W/Z production in **future** heavy-ion collisions may provide more **powerful constraints on the NPDFs**.
Thank you!
I. Framework of the study

Numerical simulation in pp collision

Program: DYNNLO

Comparison with the LHC data

Code: Drell-Yan Next-to-Next-to Leading Order (DYNNLO)


- High-order QCD correction:
  - NLO [$O(\alpha_s)$], NNLO [$O(\alpha_s^2)$]

- Renormalization and factorization scales
  \[ \mu_R = \mu_F = m_{W/Z} \]

- PDFs: MSTW08, CT10, ABMP15

<table>
<thead>
<tr>
<th>Vector boson</th>
<th>Cross-section (nb) at $\mathcal{O}(\alpha_s)$</th>
<th>Cross-section (nb) at $\mathcal{O}(\alpha_s^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z^0$</td>
<td>$0.45 \pm 0.0002$</td>
<td>$0.458 \pm 0.0008$</td>
</tr>
<tr>
<td>$W^+$</td>
<td>$3.000 \pm 0.0016$</td>
<td>$3.062 \pm 0.0092$</td>
</tr>
<tr>
<td>$W^-$</td>
<td>$2.025 \pm 0.001$</td>
<td>$2.045 \pm 0.0048$</td>
</tr>
</tbody>
</table>

NNLO corrections are quite small

~1-2%
II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on PDFs

\[ R_f(x, Q^2) = f^{Pb}_f(x, Q^2) / f^P_f(x, Q^2) \]

\[ R_V^{Pb}, R_S^{Pb}, R_G^{Pb} \]

\[ Q^2 = 100 \text{ GeV}^2 \]

II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on rapidity distribution in p+Pb collisions

Large-x, valence dominated

-3 -2 -1 0 1 2 3

\( R_{pA}(y) \) provides an image of the nuclear corrections on quark PDFs.

Small-x, sea quark dominated

\[ \sqrt{s_{NN}} = 5.02 \text{TeV} \]

\( O(\alpha_s) \)

-3 -2 -1 0 1 2 3

\( y_{c.m.}^{Zc.m.} \)

\( R_{pA}(y) \) provides an image of the nuclear corrections on quark PDFs.

\[ \chi \]

\[ \chi \]

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\[ \chi \]
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in p+Pb collisions: Parton Level

Parton contributions at LO

Nuclear correction at parton level

\[ x_{pb} = x_2 = \frac{m_Z}{\sqrt{s_{NN}}} e^{-y_Z} \]

\[ R_f(x_{pb}) \rightarrow R_f(y^Z) \]
II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on Transverse momentum (pT) spectra: Pb+Pb

R_AA

Parton contributions at LO

Difference between EPS09 and DSSZ are observed.

Gluon gives LO contributions.
II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on Transverse momentum (pT) spectra: p+Pb

\( R_{pA} \) | Parton contributions at LO

Difference between EPS09 and DSSZ are observed.

Gluon gives LO contributions.

\( p_T^Z (\text{GeV}) \)

\( R_{pA} (p_T^Z) \)

\( O(\alpha_s) \)

\( O(\alpha_s^2) \)

\( \sqrt{s_{NN}} = 5.02 \text{TeV} \)
II. Vector boson production in heavy-ion collisions at the LHC

- **Rapidity distribution**: Sensitive to the CNM effect (shadowing and anti-shadowing) on quark distribution (both valence and sea).

- **pT spectrum**: Valuable probe of nuclear gluon distribution.

- **Differences** between predictions with different NPDF are observed.

- **W boson asymmetry**: Sensitive to the isospin effect. A good probe of flavor dependent nuclear corrections on PDFs.
III. W/Z production in p+Pb collisions with KP NPDFs

Results on p+Pb at the LHC

Differential cross section of W boson

PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

Peng Ru  DUT / CCNU  24th Sept.
III. W/Z production in p+Pb collisions with KP NPDFs

Results on p+Pb at the LHC

Z boson

\[ \sqrt{s_{NN}} = 5.02 \text{TeV} \]

- CMS
- ABMP15 + KP
- CT10 + EPS09
- ABMP15 (Z × p + N × n)

PR, Kulagin, Petti, B.W. Zhang, 1608.06835 [nucl-th]
### III. W/Z production in p+Pb collisions with KP NPDCFs

$\chi^2/N_{\text{Data}}$ between model and measurement

<table>
<thead>
<tr>
<th>Observable</th>
<th>$N_{\text{Data}}$</th>
<th>ABMP15 + KP</th>
<th>CT10 + EPS09</th>
<th>ABMP15 (Zp + Nn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma^+ / d\eta^l$</td>
<td>10</td>
<td>1.052</td>
<td>1.532</td>
<td>3.057</td>
</tr>
<tr>
<td>$d\sigma^- / d\eta^l$</td>
<td>10</td>
<td>0.617</td>
<td>1.928</td>
<td>1.393</td>
</tr>
<tr>
<td>$N^+ (+ \eta')/N^+ (- \eta')$</td>
<td>5</td>
<td>0.528</td>
<td>1.243</td>
<td>2.231</td>
</tr>
<tr>
<td>$N^- (+ \eta')/N^- (- \eta')$</td>
<td>5</td>
<td>0.813</td>
<td>0.953</td>
<td>2.595</td>
</tr>
<tr>
<td>$(N^+ - N^-)/(N^+ + N^-)$</td>
<td>10</td>
<td>0.956</td>
<td>1.370</td>
<td>1.064</td>
</tr>
<tr>
<td>$d\sigma / d\gamma^Z$</td>
<td>12</td>
<td>0.596</td>
<td>0.930</td>
<td>1.357</td>
</tr>
<tr>
<td>$N(\gamma^Z)/N(\gamma^Z)$</td>
<td>5</td>
<td>0.936</td>
<td>1.096</td>
<td>1.785</td>
</tr>
<tr>
<td><strong>CMS combined</strong></td>
<td><strong>57</strong></td>
<td><strong>0.786</strong></td>
<td><strong>1.332</strong></td>
<td><strong>1.833</strong></td>
</tr>
</tbody>
</table>

**ATLAS experiment:**

<table>
<thead>
<tr>
<th>$N_{\text{Data}}$</th>
<th>ABMP15 + KP</th>
<th>CT10 + EPS09</th>
<th>ABMP15 (Zp + Nn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma^+ / d\eta^l$</td>
<td>10</td>
<td>0.586</td>
<td>0.348</td>
</tr>
<tr>
<td>$d\sigma^- / d\eta^l$</td>
<td>10</td>
<td>0.151</td>
<td>0.394</td>
</tr>
<tr>
<td>$d\sigma / d\gamma^Z$</td>
<td>14</td>
<td>1.449</td>
<td>1.933</td>
</tr>
<tr>
<td><strong>CMS+ATLAS combined</strong></td>
<td><strong>91</strong></td>
<td><strong>0.796</strong></td>
<td><strong>1.213</strong></td>
</tr>
</tbody>
</table>

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PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]
IV. W/Z production in future heavy-ion collisions

Pb+Pb: Z boson pT spectra

Nuclear correction at parton level

Parton contributions at LO

\[ R_f(x_{Pb}) \rightarrow R_f(p_T) \]

Differences between LHC and future

\[ \sqrt{s_{NN}} = 2.76\text{TeV} \]
\[ \sqrt{s_{NN}} = 39\text{TeV} \]

\[ q_v + q_s, \quad q_v + g \]
\[ u_v + \bar{u}_v, \quad d_s + \bar{d}_s \]
\[ (u_s, \bar{u}_s, d_s, \bar{d}_s) + g \]

\( \sqrt{s} = 7 \text{ TeV} \)

\[ \frac{1}{\sigma} \frac{d\sigma}{d|y^Z|} \]
\begin{align*}
R_{\text{val}}(x) & \quad Q^2 = m_Z^2 \\
R_{\text{sea}}(x) & \\
R_u(x) / R_d(x) & \\
R_{\bar{u}}(x) / R_{\bar{d}}(x) &
\end{align*}
Backup

$W^+$

$\frac{d\sigma}{d\eta'}$ [nb]

Rel. correction

NNLO: ABMP15+KP
NLO: ABMP15+KP
NLO: ABMP15 ($Zp+Nn$)
$\sqrt{s_{\text{NN}}} = 5.02\text{TeV}$

$p+Pb$

NLO

data-ABM

$W$ charge asymmetry

CMS
ABM+KP
CT10+EPS09
ABM ($Z\times p+N\times n$)
CT10($Z\times p+N\times n$)
Backup

$W^+$

$W^-$

$\sqrt{s_{NN}}=5.02\text{TeV}$

$p+\text{Pb}$

$NLO$

CMS

$\text{ABMP+KP}$

$\text{CT10+EPS09}$

$\text{ABMP (Z×p+N×n)}$

$\text{CT10 (Z×p+N×n)}$

Data / ABMP

$\frac{d\sigma}{d\eta_{lab}} [\text{nb}]$
Backup
In future heavy-ion collisions

\[ C_v^f(x) = \frac{f_v(x)}{f_v(x) + f_s(x)} \]

\[ C_s^f(x) = \frac{f_s(x)}{f_v(x) + f_s(x)} \]

\[ r_{ud}(x) = \frac{u(x) - d(x)}{u(x) + d(x)} \]

\[ r_{\bar{u}\bar{d}}(x) = -\frac{\bar{u}(x) - \bar{d}(x)}{\bar{u}(x) + \bar{d}(x)} \]
Backup

S. Alekhin et al., 1508.07923[hep-ph]