Vector Boson production with Heavy Ions at the LHC

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nPDFs and Nuclear Corrections
Nuclear Modifications to PDFs

- Nuclear PDFs (nPDFs) can show significant modifications to free proton PDFs.

- DIS data suggest several types of corrections:
  - Shadowing \( x < 0.05 - 0.1 \)
  - Anti-shadowing \( 0.1 \leq x \leq 0.3 \)
  - EMC effect \( 0.3 \leq x \leq 0.8 \)
  - Fermi motion \( x > 0.8 \)

(Schienbein et. al. arXiv:0907.2357v2)
Nuclear Modifications

- The nuclear modifications are present in the PDFs, but appear in different regions of $x$ than for the observables.
- We expect modifications to any hadronic observable involving heavy nuclei.
The nCTEQ proton PDFs are parameterized according to the following prescription:

\[ x f_k(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5} \]

\[ k = u_v, d_v, g, \bar{u}, \bar{d}, s, \bar{s}, \]

\[ \bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} + (1 + c_3 x)(1 - x)^{c_4} \]

The nuclear A-dependence is then applied to the coefficients in the parameterization.

\[ c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1} (1 - A^{-c_{k,2}}) , \quad k = \{1, \ldots, 5\} \]

(Schienbein et. al. arXiv:0907.2357v2)
Another popular nPDF set is EPS09.

In this analysis, an $x$-dependent nuclear correction is factorized from a fixed proton PDF.

$$f^A_i(x, Q) \equiv R^A_i(x, Q)f^p_i(x, Q),$$
The nCTEQ group has produced a several sets of nuclear nPDFs at NLO for public distribution.

(Schienbein et. al. arXiv:0907.2357v2)

(Stavreva et. al. arXiv:1012.1178)

The PDF for a general nucleus can be constructed as a linear combination of the PDFs using (approximate) isospin symmetry

\[ f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{(A-Z)}{A} f_i^{n/A}(x, Q) \]

(Hessian error sets for the nPDFs are provided for the parameters of the nuclear correction.)

(Schienbein et. al. arXiv:0907.2357v2)
nCTEQ Errors vs CT10 Errors

- Error sets have been created for the nCTEQ PDFs by A. Kusina, K. Kovařík, and T. Ježo.
- The error sets are over 16 eigenvectors. Each family contains 34 PDF sets.
In January of 2013, ATLAS released the results of their Z boson rapidity distribution for PbPb collisions at 2.76 TeV.

ATLAS observed 1995 candidate events corresponding to 0.15 nb$^{-1}$ of integrated Luminosity.

(ATLAS Collaboration, PRL 110,022301 92013)
In November of 2013, ATLAS released the result of their $\mu^+$ and $\mu^-$ rapidity measurements in PbPb.

All of the heavy ion runs have been compared to predictions made with NLO PDFs.
In March of 2015, CMS released the result of their $\mu^+$ and $\mu^-$ rapidity measurements in pPb collisions at 5.02 TeV.

LHC experiments have yet to detect any nuclear modifications to Vector Boson cross sections.
Heavy Ion Collisions
Vector Boson Production

High Energy collisions at the LHC are capable of producing many electroweak bosons (\(W/Z\)) at high absolute rapidity.

Properties of these bosons are well constrained making them ideal "standard candle" measurements for detector calibration.

The hadronic cross section for Drell-Yan pair production is written

\[
\frac{d\sigma}{dQ^2 dy} = \sum_{a,b} \int_0^1 d\xi_1 \int_0^1 d\xi_2 \frac{d\hat{\sigma}}{dQ^2 dy} f_a/A(\xi_1)f_b/B(\xi_2)
\]

At LO we can make the approximation,

\[
\xi_1 \approx x_1 \equiv \tau e^y, \\
\xi_2 \approx x_2 \equiv \tau e^{-y},
\]

where

\[
\tau \equiv \frac{Q}{\sqrt{S}}.
\]
Vector Boson Production

- This means that rapidity measurements for on-shell vector boson production provide a method for probing the $x$ dependence of the PDFs.

\[ \tau \equiv \frac{Q}{\sqrt{S}}. \]

(Guzey, V. et al, arXiv:1212.5344v1)
For $W^\pm (Z)$ production at 2.76 TeV, $\tau \approx 0.029 (0.033)$

For $W^\pm (Z)$ production at 5.02 TeV, $\tau \approx 0.016 (0.018)$
Results
PbPb vs. p-p Rapidity

- There is an observable shape change for on-shell $W^+$ production. The difference is up to 20% in some regions of parameter space.

- These differences should be seen with a higher integrated luminosity for PbPb collisions.
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PDF Correlations

In the high absolute rapidity region, the error is dominated by the uncertainty on the down PDF.

The up and down distributions are anti-correlated in $x$ allowing for flavor decomposition.

In the central region, the $\bar{u}$ and $\bar{d}$ uncertainty provides the largest contribution.
The shape of the pPb cross sections can be predicted by looking at the nuclear corrections to the PDFs. These predictions are presented in the Center of Momentum frame of the two nuclei. The experimental results include a 0.465 rapidity shift.
Here we look at the $u - \bar{d}$ and $c - \bar{s}$ interactions for $W^+$ production.

\[ \sigma_{DY} \sim f_{a/A}(\tau e^y, Q) \ast f_{b/B}(\tau e^{-y}, Q) \]
The resulting $W^+$ predictions with nCTEQ15 show significant differences to the predictions using EPS09 nuclear corrections.

Current CMS measurements show tension with the EPS09 predictions. A direct comparison to CMS data is underway to see if better agreement is possible with nCTEQ PDFs.
The resulting $W^-$ predictions with nCTEQ15 also show differences to the predictions using EPS09 nuclear corrections.

Differences with EPS09 are visible for all Vector Bosons and for the resulting muon distributions.
Conclusions and Future Work

- Nuclear modifications to PbPb cross sections are up to 20% and should be visible with a higher integrated luminosity.

- Work is underway to produce predictions at $8.16\text{TeV}$ and $8.80\text{TeV}$ for pPb cross sections.

- A comparison to AMC@NLO is in progress. AMC will be used in the next nCTEQ fit containing LHC data.

- Current results from CMS show tension with EPS09 predictions. A comparison of nCTEQ predictions to recent CMS results is underway.

- The nCTEQ predictions show significant differences to the EPS predictions at high negative rapidity where the ratio $d(x, Q_0)/u(x, Q_0)$ is important.
Parton Distribution Functions

- Parton Distribution Functions (PDFs) describe the distribution of quarks and gluons within the Proton.
- Parton Distributions are given as functions of the Bjorken variable $x$ and the hard momentum scale $Q$.

CTEQ 10
A LO calculation of rapidity shows shape changes due to the softening of the $u(x, Q)$ and $\bar{d}(x, Q)$ PDFs.
PDF Comparison

- The nCTEQ proton PDF set gives similar predictions to other commonly used sets.

**FEWZ $W^{+,\text{NLO}}$ at 2.76 TeV**

- **GJR08**
- **HERA**
- **CTEQ 6.1**
- **decut4**
- **CTEQ 6M**
- **NNPDF 2.3**
- **MSTW 2008**
- **CT 10**
- **ABM 11**
- **CJ12mid**
Pb-Pb vs. p-p rapidity

- No shape change for on-shell $Z$ and $W^-$ rapidity is found as we move from the proton PDFs to Lead.

- The shapes of the lepton distributions for these bosons are also indistinguishable.
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