PROCEEDINGS OF SCIENCE

# Vector Boson production with Heavy Ions at the LHC

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High Energy proton-proton collisions at the LHC are capable of producing many electroweak bosons (W/Z) at high rapidity. Measurements of properties of these particles are essential standard candles used to calibrate detectors such as ATLAS and CMS. The collision of heavy nuclei can show significant modifications to the distribution of these bosons. We will present an analysis of electroweak boson production in lead-lead and proton-lead collisions at the LHC using the nCTEQ nuclear Parton Distribution Functions (nPDFs). The cross-sections are calculated at NLO with FEWZ at 2.76 and 5.02 TeV respectively. Comparison to other popular nPDF distributions will also be presented.

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## 1. nPDFs and Nuclear Modifications

Parton Distribution Functions (PDFs) are an essential component for the calculation of any observable in a hadronic collision. Collisions involving Heavy Nuclei (HI) require input from nuclear PDFs (nPDFs) which show significant modifications to free proton PDFs. These modifications were first seen by the EMC collaboration in 1983[**?**] and later measured and described by SLAC in the 1980s and '90s[**?**]. The nuclear modifications are generally known as shadowing, anti-shadowing, the EMC effect, and Fermi motion. These modifications are easily seen in the SLAC measurement of Fig.1. This measurement shows the ratio of the $F_2$ structure function for iron over deuterium as a function of Bjorken x. Shadowing (the EMC effect) occurs in the region where $x < 0.05-0.1$ ( $0.3 \leq x \leq 0.8$) and corresponds to a suppression of the cross section for HI collision over the cross section for a nucleus of free protons. Anti-shadowing (Fermi Motion) occurs for $0.1 \leq x \leq 0.3$ ($x > 0.8$) and corresponds to an enhancement of the cross section over that of a free proton. These modifications vary with atomic mass and are visible in the PDFs as well as any observable resulting from a collision involving heavy nuclei but may not appear in the same regions of $x$.

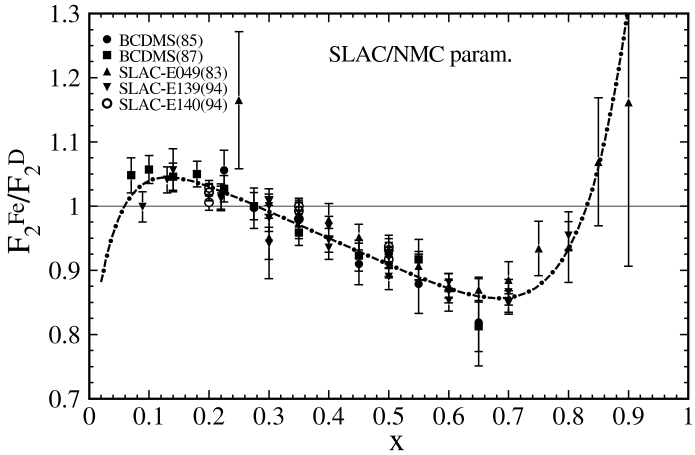


**Figure 1:** The results of the SLAC measurements of the nuclear modifications of the $F_2$ structure function for iron over deuterium is seen on the left. [**?**] The nuclear modifications are clearly visible.

The `nCTEQ` collaboration has produced a set of nPDFs for 19 different values of $A$ according to the prescription in [**?**]. These nPDFs can be used to compute observables for HI collisions at NLO along with Hessian estimations of the PDF errors. The nuclear modifications on the free proton PDF are described by an $A$-dependent parameterization to 740 data points from DIS, D-Y and inclusive pion production data. The $A$-dependence is given to the parameters of the fee proton PDF such that a value of $A, Z = 1$ will reproduce the free proton. This smooth transition from $A = 1$ is unique in the nPDF community [**?**] and helps to limit the number of theoretical assumptions that go into the fit.

Hessian error sets are provided for the errors on the nuclear parameters only. These errors are much larger than the errors on the proton PDF parameterization as can be seen in Fig. 2 All

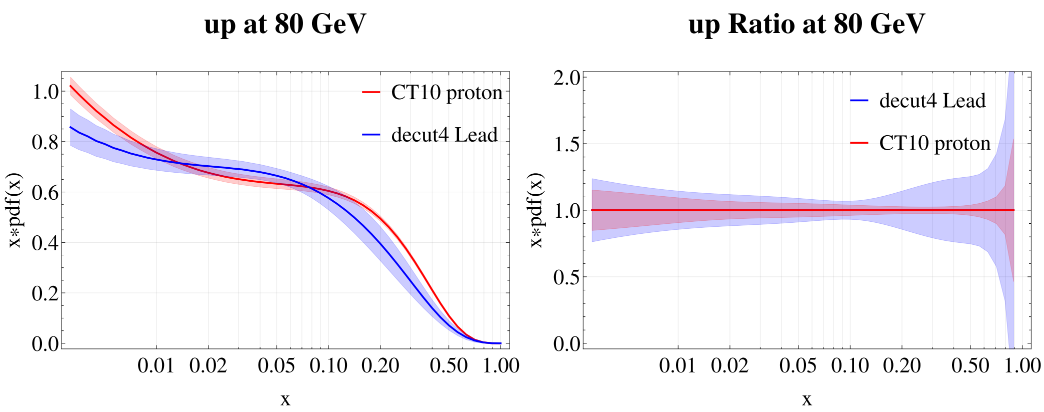


**Figure 2:** ...

errors shown in this note are due to the nuclear parameters only. At this time, no statistically sound method to combine the errors on the proton parameters with the errors on the nuclear parameters exists in the literature.

Each of the nPDFs in the `nCTEQ` release is for the proton bound in a nucleus $f_i^{p/A}(x,Q)$ with atomic mass number $A$. To construct the full nuclear target for a calculation, the PDF for the neutron $f_i^{p/A}(x,Q)$ is found by the approximate iso-spin symmetry present at NLO. That is, the neutron PDF is constructed by the replacements $u \longleftrightarrow d$ and $\bar{u} \longleftrightarrow \bar{d}$. The total averaged PDF per nucleon is the written as the combination

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q) \tag{1.1}$$

where $A-Z$ is the number of neutrons in the nuclear target.

## 2. Vector Boson Production

The LHC produces many electroweak bosons at high rapidity. Properties of these bosons have been well-studied at the major experiments. [**?**] In the CSS factorization formalism [**?**], the cross section for lepton pair production is written as a convolution of the partonic cross section with the PDFs for each of the colliding beams as in Eq.2.1. The PDFs are integrated over the longitudinal momentum fractions $\xi_{1,2}$ of the partons involved in the interaction. In the collinear approximation, the longitudinal momentum fraction becomes the Bjorken scaling variable $x$. So for a fixed partonic energy $Q$, a change in rapidity corresponds to a change in the relative fractions of $x_{1,2}$ for the incoming beams. Thus, measurement of the rapidity distribution of lepton pairs produced in hadronic collisions gives a handle on the PDF distribution in $x$.

$$\frac{d\sigma}{dQ^2\,dy} = \sum_{a,b} \int_0^1 d\xi_1 \int_0^1 d\xi_2 \frac{d\hat{\sigma}}{dQ^2 dy} f_{a/A}(\xi_1) f_{b/B}(\xi_2) \tag{2.1}$$

Comparison of different observables involving electroweak bosons allows for flavor decomposition in the measured PDFs. This is because different quark flavors contribute to the production of different vector bosons. For example, the major contribution to the $W^+$ cross-section is the $u-\bar{d}$ interaction to produce a positively charged boson. The major contribution to the $W^-$ cross section is the $d-\bar{u}$ interaction to produce a negatively charged boson. By comparing these measurements, the validity of the nPDFs can be established.

The contribution of the error on each flavor to the overall error on the measurements can be seen by looking at the cosine of the correlation angle as in Fig. 3. A correlation of $\approx 1$ tells us that the error on the measurement of this observable is being driven by the error on that quark flavor. Alternatively, a high correlation tells us that inclusion on this measurement in the fit will directly effect error on that quark flavor. From this figure we also see that the $u$ and $d$ quark PDFs are anti-correlated over the range of $x$. This gives us the ability to decompose these flavors in the determination of the PDFs.

Do we need a discussion on Bjoken x and light cone coordinates here to explain how to interpret the effect of the PDFs here???

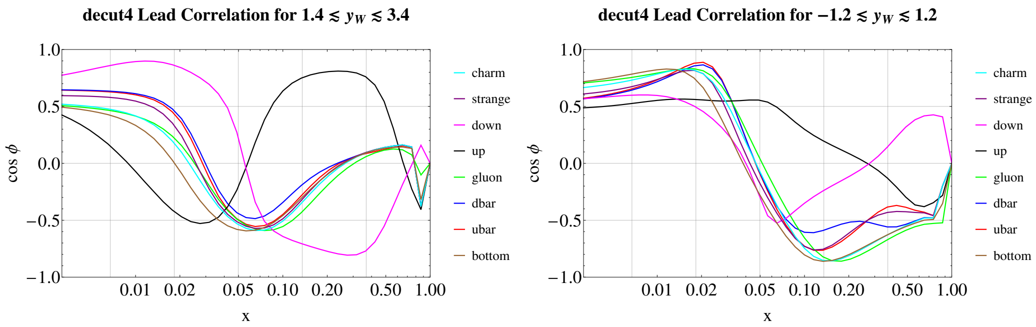


**Figure 3:** Here we see the cosine of the correlation angles for the $W^+$ rapidity distribution for the various quark flavors as a function of Bjorken $x$. The left plot is for the high rapidity bins and the plot on the right is for the central region.

## 3. Calculation

All calculations have been preformed at NLO with a modified version of FEWZ. [**?**] FEWZ has been modified to accept two different PDFs for the two different beams. This allowed for computation of the cross sections for PbPb and pPb collisions at 2760GeV and 5020GeV for the $W^\pm$ and $Z/\gamma$ bosons as well as the reconstructed muon distributions. The results of these calculations were verified against an unmodified version of FEWZ for the pp and PbPb cases.

The error bands are produced for the nuclear errors only. This is achieved by running the error calculation over PDF in the $x_2$ direction. This is the conventional direction for the HI beam in a cpA collision. FEWZ produced asymmetric PDF errors for the PDFs without the error due to $\alpha_S$. I expect that the nuclear error on the measurements presented here is sufficient as these errors are much larger than the errors on the proton PDF as discussed previously and shown in Fig. 2.

## 4. Results

### 4.1 Lead Lead

The rapidity distributions for the $W^+$ boson and the reconstructed $\mu$ distributions are shown in Fig.4. The rapidity for PbPb collisions is compared to the predictions for pp. The PbPb distribution is calculated for the full lead nucleus constructed with the `nCTEQ15` bound Pb PDF. The pp distribution is calculated with the `CTEQ6M` free proton PDF. The shape of the distribution in PbPb is significantly modified from the free proton case. In particular, we see an absence of the characteristic "2-hump" structure of the pp distribution. This is due to the softening of the valance distribution of the up quark as $A$ increases from 1 to 208. The differences in the distributions are well outside of the nuclear error bands and are up to $\approx 20\%$ in some regions of rapidity.

The distributions for $W_-$ and $Z$ bosons for PbPb and pp overlap significantly for most of the $y_\mu$ region and cannot be seperated and are not shown in this note. In these channels, the nuclear modifications are not visible at the energies of Run-I of the LHC. The calculations for Run-II energies are currently underway.

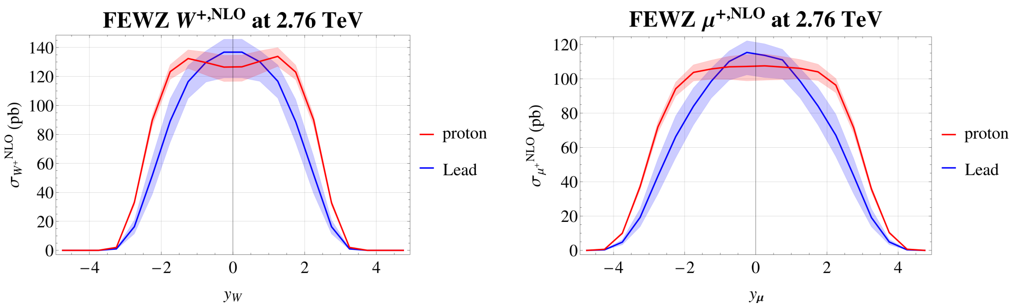


**Figure 4:** Here we see the cross sections for $W^+$ and the produced $\mu$ for PbPb collisions at 2.76 TeV. We see nuclear modifications to the shape of the boson cross section that are still visible in the reconstructed leptons as compared to the results for pp in red.

### 4.2 Proton Lead

The Vector Boson cross section for pPb collisions at 5.02 TeV provide an chance to see the nuclear modifications and compare predictions from different nPDFs. In Fig. 5 we see a comparison of the cross sections calculated with `nCTEQ` and `EPS09` nPDFs. These cross sections allow for the measurement of various asymmetries (??) which posses reduced theoretical uncertainties.

We can understand the shape of the cross sections by considering the LO calculation. In light-cone coordinates, the momentum fraction can be written $x = \tau e^{\pm y}$ where $\pm y$ is the rapidity of the beam with $x_{1,2}$, and $\tau = Q/\sqrt{S}$ at LO. For 2760(5020) GeV we have $\tau \approx 0.029(0.016)$ for on-shell $W^\pm$ production. This is equal to the momentum fraction at central rapidity. For $\pm y$ we scan in the $x_{1,2}$ plane—as $x_{1,2}$ is increasing $x_{2,1}$ is decreasing.

As we move to the negative rapidity $x_2$ increases and from Fig.2 we see that we move into an anti-shadowing region where the Pb PDF is increasing and the proton PDF is decreasing. The opposite occurs for positive rapidity. So we expect an enhanced(suppressed) number density in the region where $y < 0 (y > 0)$. This corresponds to to more(fewer) valance quarks available for the interaction.

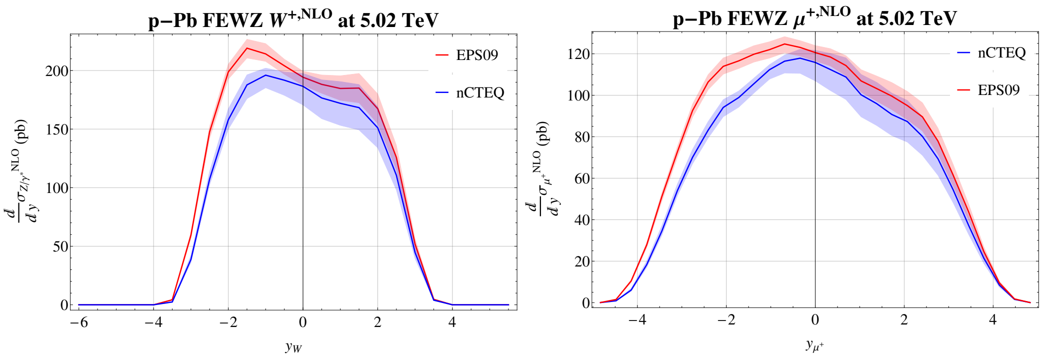


**Figure 5:** Here we see the cross sections for $W^+$ and the produced $\mu$ for PbPb collisions at 2.76 TeV. We see nuclear modifications to the shape of the boson cross section that are still visible in the reconstructed leptons. The `nCTEQ` predictions are compared to the calculation preformed with the `EPS09` nPDFs.

The shapes of the predictions from `nCTEQ` and `EPS09` are significantly different. This provides a chance to compare the methodology of the two nuclear PDF fits. The differences are pronounced in the high absolute rapidity region where the ratios of $u(x,Q)/d(x,Q)$ and $\bar{u}(x,Q)/\bar{d}(x,Q)$ are important to the calculation. These ratios are enforced in the different nPDF fits in different ways and measurements of observables in pPb interaction......

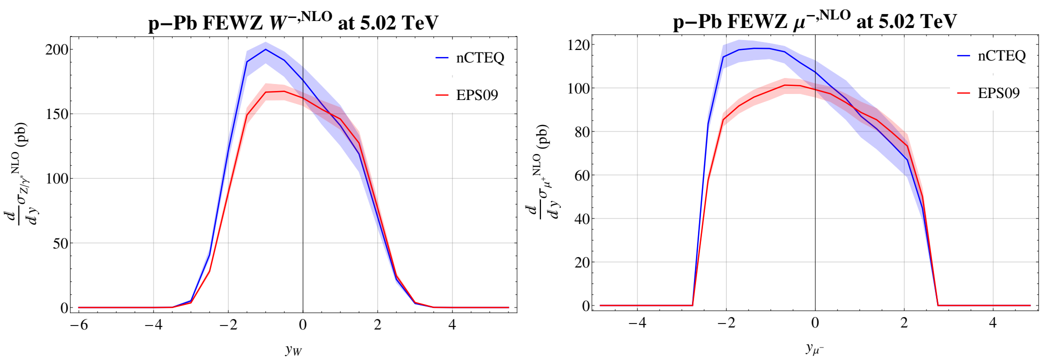


**Figure 6:** Here we see the cross sections for $W^-$ and the produced $\mu$ for PbPb collisions at 2.76 TeV. We see nuclear modifications to the shape of the boson cross section that are still visible in the reconstructed leptons. The `nCTEQ` predictions are compared to the calculation preformed with the `EPS09` nPDFs.

## 5. Conclusions

The nuclear modifications to various electroweak observables should be visible in the measurements. ATLAS, CMS, and LHCb have already taken data for electroweak boson production for PbPb at 2760 GeV and pPb at 5020 GeV. [**?**, **?**, **?**, **?**, **?**] A comparison of these data to my predictions is currently underway. The data has been compared to predictions made with free proton PDFs and with `EPS09` nuclear corrections. These LHC data will then be worked into a future `nCTEQ` fit to help constrain the nuclear errors.

Work is also underway to produce predictions for DY lepton pair production at 8160 GeV and 8800 GeV for Run II at the LHC. This low-$x$ data will move into the shadowing region of the PDFs and provide new insight in a region of x where there is currently very little data to fit the nPDFs.

In particular, the pPb observables give nPDF fitting groups a unique handle to test the validity of theoretical assumptions of the behavior of the ratio of $u(x,Q)/d(x,Q)$. This ratio becomes significant in the high absolute rapidity region of the cross sections for $W^{\pm}$ production and produces large shape changes for the different nPDF fits.

## References

[1] ....