PROCEEDINGS OF SCIENCE

nCTEQ PDFs at the LHC:

Vector boson production in heavy ion collisions

The nCTEQ Collaboration:*

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Extraction of the strange quark PDF is a long-standing puzzle. We use the nCTEQ nPDFs with uncertainties to study the impact of the LHC W/Z production data on both the flavor differentiation and nuclear corrections; this complements the information from neutrino-DIS data. As the proton flavor determination is dependent on nuclear corrections (from heavy target DIS, for example), LHC heavy ion measurements can also help improve proton PDFs. We introduce a new implementation of the nCTEQ code (**nCTEQ++**) based on C++ which has a modular strucure and enables us to easily integrate programs such as HOPPET, APPLgrid, and MCFM. Using ApplGrids generated from MCFM, we use **nCTEQ++** to perform a preliminary fit including the pPb LHC $W^{\pm}/Z$ vector boson data.

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1. Introduction

The Parton Distribution Functions (PDFs) are the key elements which allow us to generate concrete predictions for processes with hadronic initial states. The success of this theoretical framework has been extensively demonstrated in fixed-target and collider experiments (*e.g.*, at the TeVatron, SLAC, HERA, RHIC, LHC), and will be essential for making predictions for future facilities (EIC, LHeC, FCC). Despite the above achievements, there is yet much to learn about the hadronic structure and the detailed composition of the PDFs [1, 2, 3].

Although the up and down PDF flavors are generally well-determined across much of the partonic x range, there is significant uncertainty in the strange component, $s(x)$. The strange PDF is especially challenging because, in many processes, it is difficult to separate this from the down component. Fixed-target neutrino–nucleon DIS production of dimuons ($\nu N \to \mu^+\mu^- X$) provided important constraints on $s(x)$; however, as these neutrino experiments were performed on heavy targets, the nuclear corrections must be considered.[1] Proton–proton (pp) production of W and Z bosons at the LHC also provides insight on $s(x)$; however, preliminary results show some tension between the various measurement channels [5].

In the current investigation, we will study the production of W and Z bosons in proton–lead (pPb) collisions at the LHC; this involves similar considerations as the pp case, but also brings in the nuclear corrections. We will be focusing, in particular, on the $s(x)$ distribution and look to compare with the expectations from both fixed-target and pp LHC measurements.

2. The nCTEQ++ Project

The nCTEQ project[2] extends the proton PDF global fitting effort by fully including the nuclear dimension. Previous to the nCTEQ effort, nuclear data was "corrected" to isoscalar data and added to the proton PDF fit *without* any uncertainties. In contrast, the nCTEQ framework allows full communication between the nuclear data and the proton data. This enables us to investigate if observed tensions between data sets could potentially be attributed to the nuclear corrections.

The details of the nCTEQ program are presented in Ref. [1]. The analysis includes Deeply Inelastic Scattering (DIS), lepton pair production (Drell-Yan), and pion production data from a variety of experiments totaling 740 data points (after cuts) and 19 nuclei. The computed PDFs compare favorably to other determinations from the literature [6, 7, 2].

More recently, the code base was converted to a modular C++ platform (**nCTEQ++**) which enabled us to easily integrate programs such as HOPPET [8], APPLgrid [9], and MCFM [10]; the fit output is exported in YAML format and then processed by Python Jupyter notebooks. Additionally, using ApplGrids generated from MCFM we can easily include a wide variety of higher-order processes directly into the PDF fitting loop. An important step in this process was the validation that MCFM grids were sufficiently "PDF independent" so that proton PDF and nuclear PDF grids could be interchanged. This groundwork provided the foundation for a nuclear PDF fit including the NLO $W^{\pm}/Z$ production data from the LHC.

[1] See Ref. [4] and references therein.

[2] For details, see www.ncteq.org which is hosted at HepForge.org.

3. Comparisons: LHC Heavy Ion W Production with nCTEQ15 PDFs

In a previous study we compared our predictions for the production of $W^{\pm}/Z$ bosons with available LHC data for proton-lead collisions [11]. This process is an ideal QCD "laboratory" as it is sensitive to i) the heavy flavor components $\{s,c,...\}$, ii) the nuclear corrections, and iii) the underlying "base" PDF.

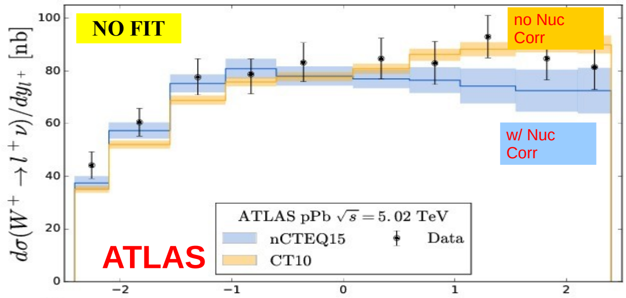

Figure 1: Comparison of LHC W boson production in *p-Pb* processes *vs.* rapidity. The lighter (yellow) band uses CT10 with no nuclear corrections, and the darker (blue) band uses the nCTEQ15 PDFs; this data is *not* included in the nCTEQ15 fit [11].

In Fig. 1 we show selected results of the comparison *without fitting.* While we found generally good agreement in the negative rapidity region, the poor agreement in the positive rapidity region (which corresponds to small x in the lead PDF) suggests this new data set can have a significant impact on the resulting PDFs. At small x, we are in the nuclear "shadowing" region where the lead PDFs are reduced compared to the proton; if the "shadowing" effect were reduced, this would improve the agreement between data and theory.

In fact, a similar behavior was observed for DIS measurements in Refs. [12, 13, 14] when comparing νN charged-current neutrino DIS processes with $\ell^{\pm}N$ neutral-current DIS processes. If we use a nuclear correction with a reduced "shadowing" correction at small x values, this would improve both the νN DIS data and the LHC $W^{\pm}/Z$ comparisons. Both of these data sets are important for distinguishing the various parton flavors—especially the strange PDF.

4. PDF fit to LHC $W^{\pm}/Z$ Data

We now use the **nCTEQ++** framework to include the NLO LHC $W^{\pm}/Z$ pPb data into a PDF fit in addition to the DIS and DY data sets from the nCTEQ15 fit. As we are most interested to

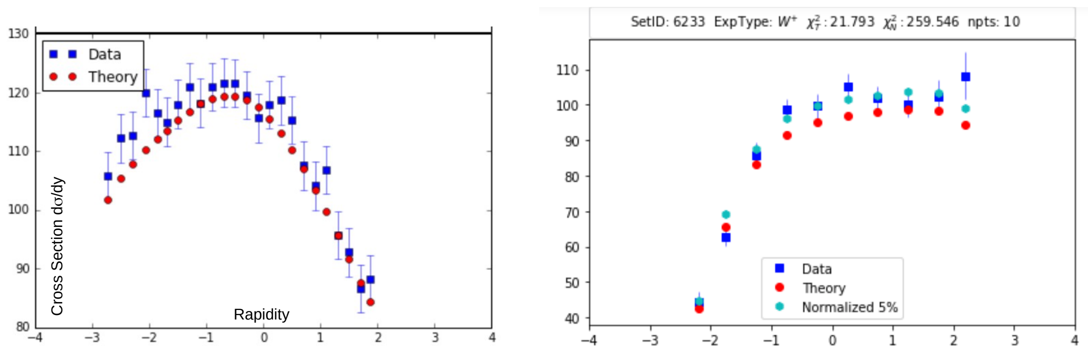

Figure 2: a) Theory predictions for Run II CMS W^- production (ID:6232), and b) for Run I CMS W^+ production (ID:6233) in *pPb*. The data are the blue squares and the theory are the red points. For comparison, we also display the theory predictions in b) with a 5% normalization shift (cyan).

find the impact of the new data on the strange quark PDF, we will free up only a limited set of parameters; hence, this represents only a preliminary fit, and a complete analysis is in progress.[3] A sample comparison is displayed in Figure 2 where the data for CMS $W^+$are shown as blue squares with statistical error bars, and the theory in the red circles. In general, we find the shape of the distributions is well described by our fits; the normalization issues are more complex.

In Fig. 3 we show the computed χ^2/dof results for the individual experiments. The separate processes in the figure are color coded. The DIS data (51xx) is represented by blue bars and the Drell-Yan (52xx) data by red bars; the fits to these data sets are generally quite good ($\chi^2 \sim 1$). The $W^\pm/Z$ data (62xx) is represented by the green bars. If we include the $W^\pm/Z$ data in the fit without allowing for a normalization shift, the overall χ^2/dof improves from 992/816 (no fit) to 828/816; while this is a significant improvement, clearly there are $W^\pm/Z$ data sets with unacceptable χ^2/dof values.

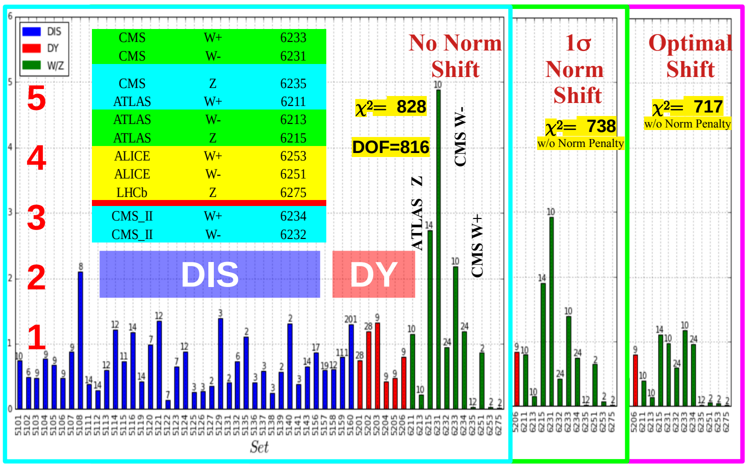

Figure 3: χ^2/dof for individual data sets of the (restricted) nCTEQ+LHC fit; data set ID's are given in Ref. [11]. The LHC $W^\pm/Z$ data is displayed in green. Prelimnary results are shown for i) no normalization shift, ii) a shift of up to 1σ, iii) an unconstrainted (optimal) shift.

In general, we find that the theory predictions lie below the experimental data; hence, if we allow for a normalization uncertainty, this additional freedom can significantly improve the fit. The experiments have an associated luminosity uncertainty, and we will use this as a gauge as we shift the normalizations. In the second panel of Fig. 3 we show the results allowing for a normalization shift of up to 1 σ. The DIS and DY data (not shown) are essentially unchanged, but this greatly improves the $W^\pm/Z$ fits; however, there are still a few $W^\pm/Z$ data sets with large χ^2/dof values. If we allow larger normalization shifts (up to $\sim 3\sigma$) for these few data sets, the results are shown in the third panel of Fig. 3 and we find it is possible to obtain $\chi^2/dof \sim 1$ for all data sets.

While this preliminary exercise demonstrates it is possible to obtain a good fit, we must ask i) how the uncertainties and the normalization issues affect the resulting PDFs, and ii) whether the results truly reflect the underlying physics or are simply an artifact of our fitting procedure.

We will focus on the the strange and gluon components; these PDFs show the largest variation, in part, because they are less constrained than the up and down flavors. Fig. 4 displays the strange and gluon nPDFs for i) the original nCTEQ15 set, ii) the above fit with no normalization shift [NO NORM], ii) the above fit with a 1σ normalization shift [1σ NORM]. A vertical line (magenta)

[3]Specifically, we fit 12 parameters: 3 for $s+\bar{s}$, and the remaining 9 for $\{g, u_V, d_V, \bar{u}+\bar{d}\}$. This is in contrast to nCTEQ15 which fits 16 parameters for $\{g, u_V, d_V, \bar{u}+\bar{d}\}$ and keeps the strange PDF fixed.

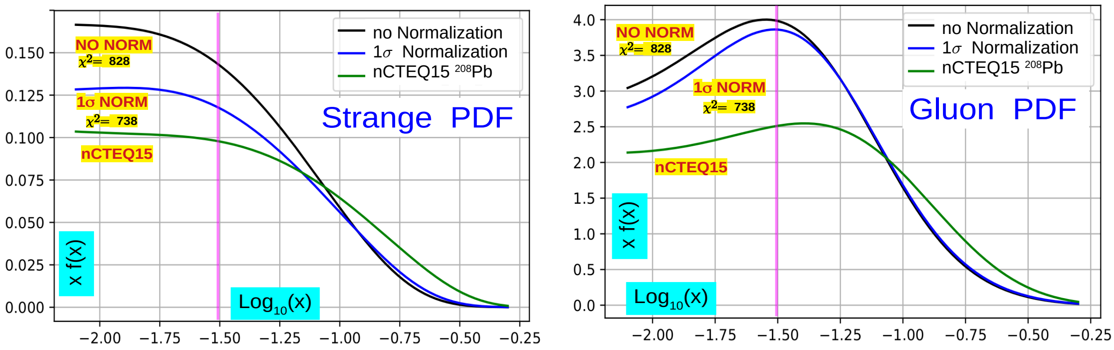

Figure 4: Resulting nPDFs for lead (*Pb*) at $Q = 2$ GeV for the a) strange and b) gluon. The vertical line (magenta) represents the central x value for pPb $W^{\pm}/Z$ production.

indicates the central x value for pPb $W^{\pm}/Z$ production. Compared to the nCTEQ15 result, we see the [NO NORM] fit pulls the strange PDF up by 40% in the x region relevant for $W^{\pm}/Z$ production. In contrast, when we allow for a normalization shift [1σ NORM], the shift of $s(x)$ is reduced by roughly half. The above pattern is also reflected in the gluon distribution to a lesser extent. Thus, the obvious question to ask is the following.

> *Are these new data increasing the strange PDF because that is dictated by nature, or is the fit simply exploiting $s(x)$ because that is one of the least constrained flavors?*

The answer to this important question will require additional study, and this is currently under investigation with our new nCTEQ++ set of tools.

5. Conclusion

Our ability to fully characterize fundamental observables, like the Higgs boson couplings and the W boson mass, and to constrain both SM and BSM signatures is strongly limited by how accurately we determine the underlying PDFs [15]. A precise determination of the strange PDF is an essential step in advancing these measurements.

The new nCTEQ++ framework extends the range of processes we are able to include in our global nPDF analyses. Specifically, we were able to include the LHC W/Z data directly in the fit. While this significantly reduced the overall χ^2 for the W/Z LHC data, we still observe tensions in particular data sets which require further investigation. Our initial analysis has identified factors which might further reduce the apparent discrepancies observed in the strange quark distribution including: increasing the strange PDF, modifying the nuclear correction, and adjusting the data normalization.

The next step is to extend the above preliminary fit with a complete set of free parameters and additional data sets to help separately disentangle issues of flavor differentiation and nuclear corrections. The ultimate goal of the nCTEQ project is to obtain the most precise PDFs using the full collection of both proton and nuclear data.

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