Constraining the Sea Quark Distributions Through W Cross-Section Ratios Measured in pp Collisions at STAR

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Abstract. Although the precision to which we know the unpolarized parton distribution functions (PDFs) of the nucleon has improved over the years, there remain kinematic regions where more data are needed to constrain PDFs, such as the ratio of the sea quark distributions $\bar{d}/\bar{u}$ near the valence region. Furthermore, different measurements appear to suggest different high-x behaviors of this ratio. The W cross-section ratio (W^+/W^-) in pp collisions is sensitive to the unpolarized sea quark distributions at large Q^2, set by the W mass, and can be used to help constrain the $\bar{d}/\bar{u}$ ratio. The STAR experiment at RHIC is well equipped to measure the leptonic decays of W bosons produced in pp collisions at center of mass energies of 500 and 510 GeV. These proceedings present recent W cross-section ratio results measured by STAR, including preliminary results from data collected in 2017, which double the statistics when combined with the published results based on data samples recorded in 2011-2013.

1. Introduction

Flavor asymmetry in the proton sea has been measured by several experiments over the years, most notably the NuSea (E866) [1] and SeaQuest (E906) [2] experiments. Both experiments have measured the x dependance of the $\bar{d}/\bar{u}$ distribution in the proton, where x is the fraction of the proton's momentum carried by the struck quark. The measurements from the two experiments agree at low x ($x <\sim 0.25$), but when approaching the valence region ($x >\sim 0.3$) the two measurements seem to suggest different trends. Additional measurements which are sensitive to the $\bar{d}/\bar{u}$ ratio can be included in global analyses, which fit the available world data in order to extract the parton distribution functions (PDFs), to help further constrain the $\bar{d}/\bar{u}$ ratio and provide insights into the large-x behavior.

While NuSea and SeaQuest measure the $\bar{d}/\bar{u}$ ratio through the Drell-Yan process, W production in pp collisions is also sensitive to the sea quarks. The $W^+(W^-)$ boson is sensitive to the $\bar{d}$ ($\bar{u}$) quark, which is illustrated in equation (1).

$$u + \bar{d} \to W^+ \to e^+ + \nu, \;\; d + \bar{u} \to W^- \to e^- + \bar{\nu}. \tag{1}$$

At leading order the W cross-section ratio, σ_{W+}/σ_{W-}, is proportional to the sea quark PDFs as shown in equation (2) and probes the sea quark distribution at a large $Q^2 \sim M_W^2$, which is set by the W boson mass [3].

$$\frac{\sigma_{W+}}{\sigma_{W-}} \sim \frac{\bar{d}(x_2)u(x_1) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_2)d(x_1) + \bar{u}(x_1)d(x_2)}. \quad (2)$$

2. Experiment

The STAR experiment at RHIC [4] is well suited to measure the W and Z cross sections, as well as their cross-section ratios and asymmetries. STAR's W and Z physics program has already provided information to constrain the proton's sea quark structure, including unpolarized [5, 6], helicity dependent [7, 8, 9] and transverse momentum dependent parton distributions [10]. The bosons are created in pp collisions in the center of mass energy range $\sqrt{s} = 500 - 510$ GeV, depending on the specific running year. To date, the STAR W and Z physics program has collected 13 pb^{-1} of data in 2009 [5], 345 pb^{-1} over 2011-2013 [6], 350 pb^{-1} in 2017, and recently another 400 pb^{-1} in 2022, which will ultimately be combined for a high precision W cross-section ratio measurement.

The STAR W measurements are made at a center of mass energy around 500 GeV, and in the pseudorapidity range $-1 < \eta < 2$, which probes the higher x region, near $< x >\approx 0.16$, as compared to measurements performed at the LHC, which probe lower x regions due to the larger center of mass energy. Additionally, due to the W mass, the STAR W cross-section measurements provide sensitivity to $\bar{d}/\bar{u}$ at large Q^2, which provides a complimentary measurement to the Drell-Yan based $\bar{d}/\bar{u}$ measurements of NuSea and SeaQuest.

The W bosons used in the cross-section ratio measurements are identified via their electron/position decay channel. To detect a W decay candidate, STAR uses a time projection chamber (TPC) [11] along with a 0.5 T solenoidal magnet for track reconstruction and to provide charge separation. Two calorimeters, the barrel electromagnetic calorimeter (BEMC) [12] and endcap electromagnetic calorimeter (EEMC) [13], are used to measure particle energy and for triggering.

3. Results

The W cross-section ratio can be measured experimentally as

$$\frac{W^+}{W^-} = \frac{N_O^+ - N_B^+}{N_O^- - N_B^-} \cdot \frac{\epsilon^-}{\epsilon^+}, \quad (3)$$

where N_O is the number of recorded W boson candidates, N_B is the number of background events estimated from data and Monte Carlo, ϵ is the detection efficiency, and $+/-$ refers to the respective boson candidate's charge.

The 2017 W cross-section ratio analysis measures N_O by selecting electrons/positrons from W decay candidates using the selection criteria detailed in Ref. [6]. The background contributions, N_B, are assumed to consist of other electro-weak decays and QCD events. The electro-weak decays considered are the $W \to \tau + \nu$ and $Z \to ee$ processes, whose contributions to the $W \to e + \nu$ signal were estimated using Monte Carlo simulations based on Pythia 6.4.22 [15] and GEANT [16]. The QCD background was estimated via a data-driven approach which took advantage of the fact that leptonic W decays have a large imbalance in the transverse momentum vector, due to the undetected ν carrying a significant portion of the momentum. The transverse energy, E_T, distribution of events that pass all W candidate selection criteria, except for the momentum-imbalance requirement were used to estimate the QCD background contribution. Due to STAR only having an EEMC in the positive pseudorapidity region ($1 < \eta < 2$), non-W decay events, such as dijets, could pass the selection cuts, including the momentum-imbalance requirement, by having one of the jets leave STAR through the non-instrumented endcap region ($\eta <$ -1). This contribution, referred to as "second EEMC" background, is estimated using the background information recorded in the EEMC and assuming an endcap calorimeter in the negative pseudorapidity region (-2 < η < -1) would see a similar background. Figures 1 and 2 compare the 2017 BEMC E_T distributions of the measured e^+ (e^-) decay leptons from W^+ (W^-) candidates to the various background contributions. When adding the background contributions to the simulated $W \to e + \nu$ E_T distribution (red-dashed line), good agreement is seen between data and simulation. The background contribution relative to the W signal is greatly reduced after applying the final analysis cut requiring $E_T > 25$ GeV. The remaining background contributions are subtracted from the data.

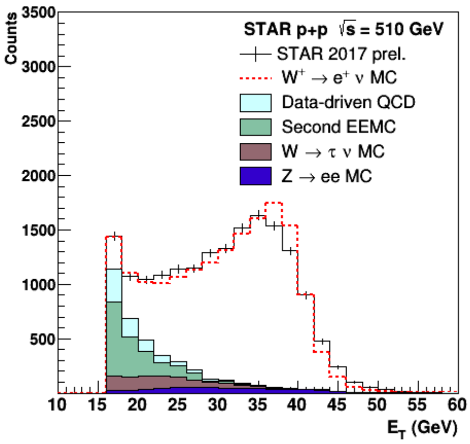

Figure 1. E_T distributions for W^+ (positrons) candidates and estimated background contributions.

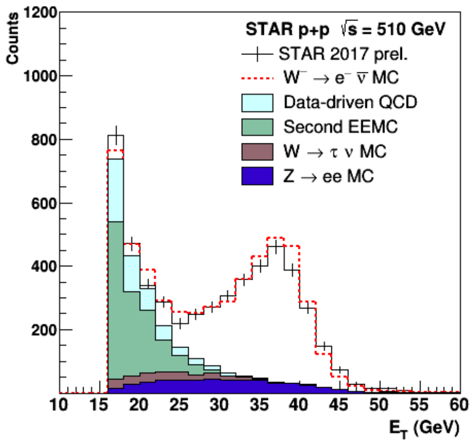

Figure 2. E_T distributions for W^- (electrons) candidates and estimated background contributions.

The preliminary W cross-section ratio from the 2017 data set is plotted in Fig. 3 as a function of the lepton pseudorapidity and compared to results from the STAR 2011-2013 data sets [6] and theoretical calculations using different PDF inputs [17, 18, 19, 20, 21, 22] and frameworks [23, 24]. The statistical uncertainties are represented by the vertical error bars, whereas the systematic uncertainties are given by the open rectangles. Figure 4 shows as a function of lepton pseudorapidity the impact that adding additional data sets (preliminary 2017 and projected 2022 statistics) to the measured 2011-2013 W cross-section ratio has on the statistical precision. The red band illustrates the total statistical uncertainty estimated for the W cross-section ratio when all STAR W data is included.

Several studies [6, 25, 26] assessing the impact that the STAR 2011-2013 W cross-section ratio has on the sea quark distributions found a modest improvement on the uncertainty associated with the $\bar{d}/\bar{u}$ PDF, as well as other light quark PDFs [6, 26], predominately over the range $0.1 < x < 0.3$. While these data do not carry as much weight as the more direct NuSea and SeaQuest measurements in constraining the $\bar{d}/\bar{u}$ distribution, STAR is able to provide new and complimentary data which does give additional constraint.

4. Summary

STAR has measured the W cross-section ratios in pp collisions at $\sqrt{s} = 500$ GeV and 510 GeV. These measurements provide sensitivity to the sea quark PDFs at large Q^2 ($\sim M_W^2$) and large x ($0.06 < x < 0.4$), providing complementarity to the W measurements performed at the LHC, which probe lower x, and the lower Q^2 measurements of the Drell-Yan based $\bar{d}/\bar{u}$ measurements of NuSea and SeaQuest. The published STAR W cross-section ratios have been used in global

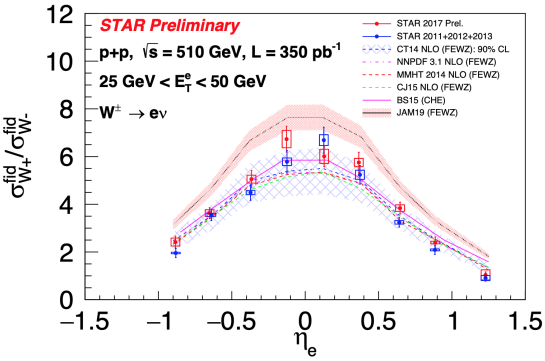

Figure 3. STAR 2017 preliminary W cross-section ratio plotted as a function of lepton pseudorapidity and compared to STAR 2011-2013 results [6] and various PDF sets [17, 18, 19, 20, 21, 22].

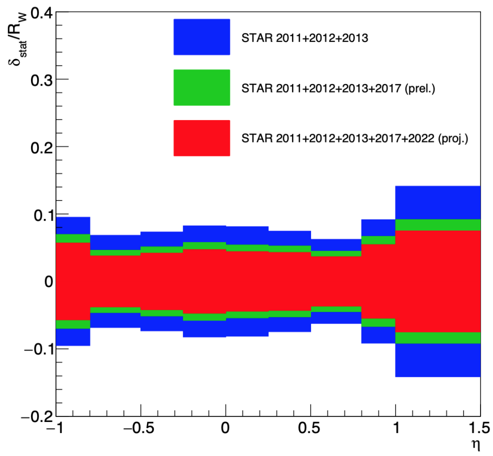

Figure 4. Improvement in statistical precision of the W cross-section ratio when adding the statistics from the 2017 and 2022 data sets.

PDF analyses to help constrain sea quark distributions. Adding additional statistics from the preliminary 2017 W cross-section ratio and the to be analyzed 2022 data set will increase the statistical precision of the cross-section ratio measurement and should improve its constraining power of the sea quark PDFs.

5. Acknowledgments

We thank the RHIC Operations Group and RCF at BNL. This work is supported by U.S. DOE Office of Science and DOE-310385.

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