Constraining Sea Quark Distributions Through $W^{\pm}$ Cross Section Ratios Measured at STAR

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Over the past several years the STAR experiment at RHIC has been contributing to our understanding of the proton structure. Through its instrumentation, STAR is well equipped to measure $W \rightarrow \nu + e$ in $\sqrt{s} = 500/510$ GeV proton-proton collisions at mid-rapidity ($-1.1 \leq \eta \leq 1.1$). The $W$ cross section ratio ($W^+/W^-$) is sensitive to unpolarized $u$, $d$, $\bar{u}$, and $\bar{d}$ quark distributions. At these kinematics, STAR is able to measure the quark distributions near Bjorken-$x$ values of 0.1. The RHIC runs in 2011, 2012 and 2013 at $\sqrt{s} = 500/510$ GeV saw a significant increase in delivered luminosity from previous years. This resulted in a total data sample being collected of about 352 pb$^{-1}$ of integrated luminosity. The increased statistics will lead to a higher precision measurement of the $W^+/W^-$ cross section ratio than was previously measured by STAR’s 2009 run, as well as allow for a measurement of its $\eta$ dependence at mid-rapidity. Presented here is an update of the $W$ cross section ratio analysis from the STAR 2011, 2012 and 2013 runs.
1. Motivation

Over the past several years parton distribution functions (PDFs) have been becoming more and more precise [1, 2, 3]. However, there are still regions in which more precision data is needed which can be used to help constrain the PDFs. For example the sea quark distributions near the valence region, $x \sim 0.1$-0.3, still have sizable uncertainties [4].

One of the data sets used to determine the anti-quark PDFs is the $\bar{d}/\bar{u}$ measurement from E866 [5], which measured $\bar{d}/\bar{u}$ to good precision at lower $x$ ($x < 0.15$). However, their precision quickly deteriorates as they approach higher $x$ ($x > 0.2$). These data suggest an interesting behavior, as $x$ increases there seems to be a transition from being $\bar{d}$ dominated to $\bar{u}$ dominated around $x \sim 0.25$. Many models are able to describe the general $\bar{d} > \bar{u}$ behavior seen at low $x$, but fail to predict the suggested $\bar{u} > \bar{d}$ transition [6]. To better determine the behavior of $\bar{d}/\bar{u}$ the experiment SeaQuest (E-906) [7] has been designed and is currently running. Through Drell-Yan scattering, SeaQuest will probe the sea quark distribution at lower $Q^2$ than E866, but increase the precision and $x$ reach of the $\bar{d}/\bar{u}$ measurement. Although this will help constrain the PDF fits, ideally one would like more data to fit from different scattering processes and $Q^2$ scales. This will help to add more independent data to global fits, and serve as a cross check of our understanding of the QCD sea.

The $W$ boson production in proton-proton collisions is also sensitive to the sea quarks. The $W^+$ boson is sensitive to the $\bar{d}$ quark, while the $W^-$ boson is sensitive to the $\bar{u}$ quarks which can be seen in equation 1.1, and probes the distribution at $Q^2 \sim M_W^2$. The leptonic decay from $W$ bosons can be detected by looking for leptons with a high transverse momentum, $p_T$, near $M_W/2$. Then a charge separation of the leptons can be used to determine which charged $W$ boson they decayed from.

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu, \quad d + \bar{u} \rightarrow W^- \rightarrow e^- + \bar{\nu}. \quad (1.1)$$

By considering the leading order expression for the charged $W$ cross section ratio [8], $\sigma_{W^+}/\sigma_{W^-}$ ($R_W$), the direct relationship to the sea quarks can be seen

$$R_W \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} \sim \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}. \quad (1.2)$$

It should be noted that although $R_W$ can be measured at the LHC, the region of $x$ that would be probed is below the valence region near $x \sim 0.08$ (assuming a $\sqrt{s} = 1$ TeV and $\eta = 0$).

2. Experiment

The STAR experiment at RHIC [9] serves as an excellent place to measure the charged $W$ cross section ratio, which was first measured in the STAR 2009 run [10]. The STAR experiment measured $R_W$ using proton-proton collisions at center of mass energies of $\sqrt{s} = 500/510$ GeV in the mid-rapidity region ($-1.1 \leq \eta \leq 1.1$). Several sub-detectors were used to select the $W$ events and separate their charge: the time projection chamber (TPC) [11], used for particle tracking, and the barrel electromagnetic calorimeter (BEMC) [12], used to measure particle energy. A third
sub-detector, the endcap electromagnetic calorimeter (EEMC) [13], was used to estimate the background contributions. The mid-rapidity region of STAR corresponds to about $0.1 \leq x \leq 0.3$ and $Q^2 \sim M_W^2$, which could have an impact on constraining PDFs as this is the $x$ region where E866’s precision starts to drop off and is the region where the data suggests that the $\bar{u}$ quark density is greater than the $\bar{d}$ quark density. STAR has taken advantage of the yearly increase in luminosity that RHIC has provided. This luminosity increase has led to roughly 352 pb$^{-1}$ of integrated luminosity being collected during the 2011-2013 runs. With the 2013 data set still under analysis, a preliminary $R_W$ result is presented using only a fraction (102 pb$^{-1}$) of the collected 2011-2013 data.

3. Results

The leptons from $W$ decay are selected by following the methodology previously established by STAR [10]. Several cuts which include matching high $p_T$ tracks to BEMC clusters, a series of isolation cuts used to isolate the leptons, a $p_T$-balance cut which looks for the large missing neutrino momentum, and a charge separation cut are applied to select leptons that are likely produced from $W$ decay. Figure 1 shows the application of several isolation cuts and charge separation cuts to the data. In panel a), one can see that as more isolation cuts are applied there is a decrease in background events, which populate the kinematic region $E_T < 25$ GeV, and an enhancement of the lepton signal near $E_T \sim M_W/2$. Panels b) and c) show cuts applied to the data in order to select events which have likely originated from $W^+$ or $W^-$ decays. Panel b) shows the charge separation as a function of $E_T$, while panel c) projects the charge separation as a function of $E_T$ on to the charge separation axis. The charge separation cuts are indicated by the red lines and were chosen to avoid contamination from the opposite charge.

The charged $W$ cross section ratio can be measured experimentally as

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{(N_D^0 - N_D^+) \epsilon\text{e}}{(N_o^0 - N_o^+) \epsilon\text{e}^+},$$

(3.1)

where $\pm$ corresponds to positively or negatively charged lepton, $N_o$ are the number of events that pass the lepton selection cuts, $N_B$ are the number of background events estimated to be contaminating the data set, and $\epsilon$ is the efficiency at which $W$ events are detected.

Figure 2 shows the various background contributions, Monte Carlo simulation of the $W$ decay (based on Pythia 6.4.22 [14] and GEANT [15]), and a comparison of the data to Monte Carlo $W$ signal with background contributions included for the 2011 and 2012 data sets. The background contribution labeled Second End Cap is an estimate of the background caused by an escaping jet’s $p_T$ being misidentified as the neutrino’s missing $p_T$. This is predominately a QCD like background. When the final cut of $E_T > 25$ GeV is applied, there is very little background contributions from $W \rightarrow \tau + \nu$ and $Z \rightarrow ee$ decays. The background was found to be dominated by QCD background.

A Monte Carlo based on Pythia 6.4.22 [14] and GEANT [15] is used to determine the $W^\pm$ detection efficiencies, shown in Fig. 3. These efficiencies account for all cut and detector efficiencies. The 2011 data was found to have a higher efficiency than the 2012 data due to running at a higher luminosity rate in 2012. Running at a higher instantaneous luminosity lead to more pile-up in the TPC, which resulted in less efficient track reconstruction and hence less efficient $W$ detection.
Figure 1: Some cuts applied to data used to select leptons which likely originated from $W$ decay. a) Application of several isolation cuts including a minimum $E_T$ cut, electron energy ratio cuts, and a signed $p_T$ cut. b) Charge separation cut vs. $E_T$. c) Projection of the charge separation vs. $E_T$ projected onto the charge separation axis.

Figure 2: Background and Monte Carlo contributions compared to data. a) Run-11 $W^+$, b) Run-11 $W^-$, c) Run-12 $W^+$, and d) Run-12 $W^-$. 
However in both data sets there was only a small (∼ 1-2%) charge dependence measured between the $W^+$ and $W^-$ efficiencies, which means the $\varepsilon^+\varepsilon^-$ factor will have a negligible contribution to the charged $W$ cross section ratio.

Figure 3: $W^+$ and $W^-$ efficiencies as a function of electron pseudo-rapidity for a) Run-11 and b) Run-12.

Figure 4: $W^+/W^-$ cross section ratio as a function of electron pseudo-rapidity.

Figure 5: $W^+/W^-$ cross section ratio as a function of the $W$ boson rapidity.

Figure 4(5) shows the charged $W$ cross section ratio for the combined 2011 and 2012 runs, computed using equation 3.1, as a function of the electron pseudo-rapidity, $\eta_e$ ($W$ boson rapidity,
More information on how the $W$ boson kinematics were reconstructed can be found in [16, 17]. The error bar on the data points represents the statistical uncertainty, while the shaded boxes correspond to the systematic uncertainty. The yellow band and colored curves serve as a comparison to different PDF sets [18, 19] and theory frame works [20, 21]. Note that the systematic uncertainties for the charged $W$ cross section ratios as a function of $\eta e$ are well under control and we are dominated by our statistical precision. Further studies into the newly established $W$ boson reconstruction process [16, 17] should reduce the systematic uncertainties on the $W^\pm$ cross-section ratio dependence on the boson kinematics.

4. Summary

We have measured and presented charged $W$ cross section ratios from combined 2011 and 2012 proton-proton STAR data at $\sqrt{s} = 500/510$ GeV. The inclusion of this data into global PDF analysis should help constrain the sea quark distributions and provide additional insight into the $\bar{d}/\bar{u}$ ratio near the valance region. Furthermore, with the inclusion of the STAR 2013 data ($\sim 250$ pb$^{-1}$), we will be able to further improve on the precision of our charged $W$ cross section ratios.

References

