Probing flavor-dependent EMC effect with W boson production

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Abstract

A recent theoretical model predicts that the modification of quark distributions in the nuclear medium (EMC effect) depends on the flavor of the quarks. We investigate W-boson production in proton-nucleus collision as a possible tool to test this theoretical prediction. Several experimental observables in W production sensitive to the flavor-dependent EMC effect are identified. Calculations for these experimental observables at the RHIC and LHC energies are presented using the recent flavor-dependent EMC model.

Keywords: EMC effect, flavor dependence, W boson

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The first definitive evidence for the modification of quark distributions in the nuclear medium was observed in muon deep inelastic scattering (DIS) experiment \cite{1}. This surprising finding, called the EMC effect, was later confirmed by other DIS experiments using electron, muon, and neutrinos beams \cite{2,3,4}. Many theoretical models have been proposed to explain the EMC effect \cite{5,6}. Although these models are capable of describing certain features of the EMC effect, they span a wide range of underlying physics. The physics origin of the EMC effect remains to be better understood.

An effective tool to shed additional light on this subject is to study the quark flavor dependences of the EMC effect. This was clearly demonstrated by the measurements of the nuclear dependence of the proton-induced Drell-Yan process \cite{7,8}, which was primarily sensitive to the $\bar{u}$ quark distributions in the nucleus. The lack of the nuclear enhancement of $\bar{u}$ distributions in these experiments has already provided strong constraints on various EMC models \cite{9}.

To further understand the EMC effect, it would be very valuable to examine other flavor dependences of the EMC effect. In this paper, we discuss the possible dependence of the EMC effect on the flavor of valence quarks for an $N \neq Z$ nucleus, where $N$ and $Z$ are the numbers of neutrons and protons in the nucleus. We investigate the feasibility for observing such flavor-dependent EMC effect with W-boson production at the RHIC and LHC colliders.

The possibility for a flavor-dependent modification of quark distributions in $N \neq Z$ nuclei was recently considered by Cloët, Bentz, and Thomas (CBT) \cite{10,11}. In the CBT model, the isoscalar and isovector mean fields in a nucleus will modify the quark distributions in the bound nucleons according to the Nambu-Jona-Lasinio model. These modified nucleon quark distributions will then be convoluted with nucleon’s momentum distribution in the nucleus to obtain the nuclear quark distributions. An interesting consequence of this approach is that the presence of the isovector vector meson ($\rho^0$) mean field in an $N \neq Z$ nucleus will modify the $u$ and $d$ quarks in the bound nucleons differently, leading to flavor dependence of nuclear quark distributions.

The predictions of the CBT model can be compared with existing DIS data. Figure \textbf{1} shows the $F_2^A/F_2^\rho$ ratios, where $F_2^A$ and $F_2^\rho$ are the structure functions (per nucleon) of $N = Z$ nuclear matter and deuteron, extracted by Sick and Day \cite{11}. The CBT model calculation, shown as the solid curve, is in good agreement with the data. For $N > Z$ nuclei, such as $^{197}$Au and $^{208}$Pb, the $\rho^0$ mean field causes stronger binding for the $u$ quarks compared to the $d$ quarks in the protons \cite{12}. Therefore, the nuclear modification of the $u$-quark distribution is greater than that of the $d$-quark distributions. This is illustrated in Fig. \textbf{1} where the dotted and dashed curves show the nuclear modification of $u$ and $d$ quarks, denoted as $u_{Au}/u_D$ and $d_{Au}/d_D$ respectively, in the $^{197}$Au nucleus. Note that for an $N < Z$ nucleus, the $\rho^0$ mean field will lead to an opposite effect, namely, the $d$-quark distribution will be modified more by the nuclear medium than the $u$-quark distribution.

There are other reasons for different nuclear modifications of $u$ and $d$ quarks in an $N \neq Z$ nucleus \cite{12}. In particular, the well-established difference between the $u$ and $d$ quark distributions in the proton would lead to some difference between $u_{Au}/u_D$ and $d_{Au}/d_D$. This ‘trivial’ flavor dependence is usually taken into account in EMC models automatically when the nucleon parton distributions are
weighted by the N and Z of the nucleus. To illustrate the size of this ‘trivial’ flavor dependence, the $\rho^0$ mean-field in the CBT model is turned off and the resulting $u_A/u_D$ and $d_A/d_D$ are shown in Fig. 1. The relatively small difference between $u_A/u_D$ and $d_A/d_D$ confirms that the effect of this ‘trivial’ flavor dependence is much smaller than that caused by the $\rho^0$ mean-field.

Since the inclusive DIS on nuclear targets probes the combined nuclear medium effects of $u$ and $d$ quarks, they do not provide a sensitive test for the flavor-dependent EMC effect predicted by the CBT model. Several new measurements sensitive to the flavor-dependent EMC effects have been considered. They include the parity-violating DIS asymmetry proposed at the future JLab 12 GeV facility [13], the semi-inclusive DIS on nuclear target first considered by Lu and Ma [14] and recently proposed at JLab [15], and future pion-induced Drell-Yan experiments [16]. In this paper, we discuss another process, the W-boson production in proton-nucleus collision, as an experimental tool sensitive to the flavor-dependent EMC effect.

![Graph 1: Ratios of quark distributions and structure functions in nuclear matter versus the deuteron plotted as a function of Bjorken-x, at $Q^2 = 10$ GeV$^2$. The solid circles are data for $N = Z$ nuclear matter from Ref. [13]. The solid curve is the calculation of $F^A/F^D$ for $N = Z$ nuclear matter from Cloët, Bentz, and Thomas [3] [16]. The dotted curves are the ratios of quark distributions in a gold nucleus to those in a deuteron, for $u$ and $d$ quarks, respectively. The dashed and dot-dashed curves are obtained by setting the $\rho^0$ mean field to zero.](image1)

The differential cross section for $W^+$ production in hadron-hadron collision can be written as [17]

$$\frac{d\sigma}{dx_F}(W^+) = K \frac{2\pi}{3} G_F \left( \frac{x_1 x_2}{x_1 + x_2} \right) \left\{ \cos^2 \theta_c [u(x_1) \bar{d}(x_2) + \bar{d}(x_1) u(x_2)] + \sin^2 \theta_c [u(x_1) \bar{s}(x_2) + \bar{s}(x_1) u(x_2)] \right\},$$

where $u(x), d(x),$ and $s(x)$ signify the up, down, and strange quark distribution functions in the hadrons. $x_1$ and $x_2$ are the fractional momenta carried by the partons in the colliding proton and nucleus, respectively, and $x_F = x_1 - x_2$. The $W$ mass, $M_{W'}$, is related to $x_1, x_2$ and the center-of-mass energy squared $s$ as $M_{W'}^2 = x_1 x_2 s$. $G_F$ is the Fermi coupling constant and $\theta_c$ is the Cabibbo angle. The factor $K$ takes into account the contributions from first-order QCD corrections

$$K \simeq 1 + \frac{8\pi}{9} \alpha_s(Q^2).$$

At the $W$ mass scale, $\alpha_s \simeq 0.1158$ and $K \simeq 1.323$. This indicates that higher-order QCD processes are relatively unimportant for $W$ production. An analogous expression for $W^-$ production cross section is given as

$$\frac{d\sigma}{dx_F}(W^-) = K \frac{2\pi}{3} G_F \left( \frac{x_1 x_2}{x_1 + x_2} \right) \left\{ \cos^2 \theta_c [\bar{u}(x_1) d(x_2) + d(x_1) \bar{u}(x_2)] + \sin^2 \theta_c [\bar{u}(x_1) s(x_2) + s(x_1) \bar{u}(x_2)] \right\},$$

To explore the sensitivity of $W$ production to a flavor-dependent EMC effect, we first consider the ratio of $W$ production cross sections for $p + A$ and $p + D$ collisions. If

![Graph 2: Calculations of the three $W$ production ratios, $R_{A/D}$, $R_{A/D'}$, and $R_{A/D''}$, for negative $x_F$ at $\sqrt{s} = 5.520$ TeV. The solid curves correspond to calculations using the flavor-dependent PDFs from the CBT model with $N/Z$ equal to that of $^{208}$Pb. The dashed curves are obtained by setting the $\rho^0$ mean field to zero in the CBT model.](image2)
one ignores the much smaller contribution from the strange quarks, the ratio can be written as

\[
R_{A/D}^+(x_F) \equiv \frac{d\sigma}{dx_F}(p + A \to W^+ + X) \approx \frac{d\sigma}{dx_F}(p + D \to W^+ + X)
\]

\[
\approx \frac{u_p(x_1) d_A(x_2) + \bar{d}_p(x_1) u_A(x_2)}{u_p(x_1) d_D(x_2) + \bar{d}_p(x_1) u_D(x_2)}. \quad (4)
\]

where the subscripts \(p, D, \) and \(A\) refer to the parton distributions in the proton, deuteron, and nucleus, respectively. At large negative \(x_F, x_1 << x_2, \bar{d}(x_2)\) is negligible compared to \(u(x_2),\) and \(R_{A/D}^+(x_F)\) becomes

\[
R_{A/D}^+(x_F) \approx \frac{u_A(x_2)}{u_D(x_2)}. \quad (5)
\]

Similarly, for \(W^-\) production at the large negative \(x_F\) region, we have

\[
R_{A/D}^-(x_F) \equiv \frac{d\sigma}{dx_F}(p + A \to W^- + X) \approx \frac{d\sigma}{dx_F}(p + D \to W^- + X)
\]

\[
\approx \frac{\bar{d}_A(x_2)}{d_D(x_2)}. \quad (6)
\]

Finally, for the ratio of \(W^+\) and \(W^−\) production in \(p + A\) collision at negative \(x_F\) region, we obtain

\[
R_{A}^{\pm}(x_F) \equiv \frac{d\sigma}{dx_F}(p + A \to W^+ + X) \approx \frac{\bar{d}_p(x_1) u_A(x_2)}{u_p(x_1) \bar{d}_A(x_2)}. \quad (7)
\]

Eqs. (5)-(7) show that these three \(W\) production ratios are sensitive to the flavor dependence of the EMC effect. With the advent of the \(W\) production physics program at the RHIC and LHC colliders, the measurements of these \(W\) production ratios now become feasible.

To study the sensitivity of the \(W\) production in \(p + A\) collisions to the flavor dependence of the EMC effect, we have calculated the three ratios \((R^+, R^-, \) and \(R^\pm)\) using the nucleon and nuclear PDFs from the CBT model. The PDFs in the CBT model are evolved to the \(W\) mass scale for these calculations. Instead of using the approximate expressions of Eqs. (5)-(7), the full expressions in Eqs. (1) and (3) are used for the \(W\) production cross sections. The solid curves in Fig. 2 show the results for the three \(W\) production ratios for \(p + D\) and \(p + \mathrm{Au}\) collisions at the RHIC energy of \(\sqrt{s} = 5.520\ \text{TeV}\) [22]. Only the results at \(x_F < 0\) are shown, since this is the region sensitive to \(u_A(x_2)\) and \(d_A(x_2)\) distributions for the valence quarks. Also shown in Fig. 2 are the dashed curves obtained by setting the \(\rho^0\) mean field in the CBT model to zero, that is, removing the flavor-dependent EMC effect. The significant difference in the predicted ratios using the flavor-dependent versus the flavor-independent nuclear PDFs suggests the feasibility for such measurements to check the flavor dependence of the EMC effect.

Figure 3 shows calculations for \(W\) production ratios at the RHIC energy of \(\sqrt{s} = 200\ \text{GeV}\) for \(p + D\) and \(p + \mathrm{Au}\). The predictions at the RHIC energy (Fig. 3) are quite similar to those at the LHC energy (Fig. 2). This is expected from Eqs. 5 - 7, which show that these ratios are insensitive to the center-of-mass energies. The larger \(W\) production cross sections at higher energies offer a significant advantage for measurements at LHC, and we will focus on measurements at LHC from now on.

Although Figs. 2 and 3 show that the \(W\) production ratios are sensitive to the flavor dependence of the EMC effect, in practice it is not the \(x_F\) distributions of the \(W\) which are measured but rather the charged leptons from the \(W\) decays. The relevant ratios can be expressed in terms of the charged lepton’s rapidity \(y = (1/2)\ln[(E + p_t)/(E - p_t)],\) where \(E\) and \(p_t\) are the charged lepton’s energy and longitudinal momentum, respectively. We have therefore convoluted the \(d\sigma/dx_F\) with the \(W \to l\nu\) decay.
that of valence quarks. First results on sensitive to the flavor dependence of the nuclear modifications between the solid and dashed curves show that measurements can be obtained with existing detectors at LHC \cite{20, 21} have shown that high-statistics precision measurements can provide valuable new insight on the origin of the EMC effect.

In conclusion, this study shows that \( pA \) collisions can offer a sensitive check of the flavor dependence of the EMC effect predicted by the CBT model.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Calculations of the three \( W \) production ratios, \( R_{A/D}^\pm \), \( R_{A/D}^- \), and \( R_{A/D}^\pm \), for negative rapidity \( y \) of the charged leptons at \( \sqrt{s} = 5.520 \) TeV. The solid curves correspond to calculations using the flavor-dependent PDFs from the CBT model with \( N/Z \) equal to that of \( ^{208}\text{Pb} \). The dashed curves are obtained by setting the \( \rho^0 \) mean field to zero in the CBT model.}
\end{figure}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Yield & ~ Yields & Calculation \hline
\end{tabular}
\end{table}

\section*{Acknowledgments}

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