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Physics Letters B

www.elsevier.com/locate/physletbFlavor asymmetry of the nucleon sea and W -boson production

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ARTICLE INFO

Article history:

Received 22 May 2009

Received in revised form 24 July 2009

Accepted 30 August 2009

Available online 8 September 2009

Editor: J.-P. Blaizot

PACS:

13.85.Qk

14.20.Dh

24.85.+p

13.88.+e

Keywords:

 W -boson

Sea quark asymmetry

RHIC

LHC

ABSTRACT

The advantage and feasibility of using W -boson production to extract unique information on the flavor asymmetry of the \bar{u} and \bar{d} sea-quark distributions in the proton are examined. The W^+ and W^- production cross section ratios in $p + p$ collisions are shown to be sensitive to the \bar{d}/\bar{u} ratios, and they are free from charge-symmetry-breaking and nuclear-binding effects. The feasibility for measuring these ratios at the RHIC and LHC proton–proton colliders, as well as the expected sensitivity to the \bar{d}/\bar{u} ratios, are also presented.

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The earliest parton models assumed that the proton sea was flavor symmetric, even though proton's valence quark distributions were known to be flavor asymmetric. Inherent in this assumption is that the content of the sea is independent of the valence quark's composition. The assumption of sea-quark flavor symmetry was not based on any known physics, and it remained to be tested by experiments. Neutrino-induced charm production experiments [1] provided clear evidences that the strange-quark content of the nucleon is only about half of the up or down sea quarks. This flavor asymmetry is attributed to the much heavier mass for strange quark compared to the up and down quarks. The similarity between the masses of up and down quarks suggests that the nucleon sea should be nearly up–down symmetric. However, it was pointed out that the existence of a pion cloud in the proton could lead to an asymmetric up–down sea [2].

A measurement of the Gottfried integral in deep-inelastic scattering (DIS) provides a direct check of the \bar{d}/\bar{u} flavor-symmetry assumption. The Gottfried integral [3] is defined as

$$I_G = \int_0^1 [F_2^p(x) - F_2^n(x)]/x dx = \frac{1}{3} + \frac{2}{3} \int_0^1 [\bar{u}_p(x) - \bar{d}_p(x)] dx, \quad (1)$$

where F_2^p and F_2^n are the proton and neutron structure functions measured in DIS experiments and x is the fraction of the nucleon's momentum carried by the quark. The second step in Eq. (1) follows from the assumption of charge symmetry (CS) at the partonic level, namely, $u_p(x) = d_n(x)$, $d_p(x) = u_n(x)$, $\bar{u}_p(x) = \bar{d}_n(x)$, and $\bar{u}_n(x) = \bar{d}_p(x)$. Under the assumption of a symmetric sea, $\bar{u}_p = \bar{d}_p$, the Gottfried Sum Rule (GSR), $I_G = 1/3$, is obtained. The most accurate test of the GSR was reported by the New Muon Collaboration (NMC) [4], which measured F_2^p and F_2^n over the region $0.004 \leq x \leq 0.8$. They determined the Gottfried integral to be 0.235 ± 0.026 , significantly below $1/3$. This surprising result has generated much interest. Although the violation of the GSR can be explained by assuming unusual behavior of the parton distributions at very small x , a more natural explanation is that the assumption $\bar{u} = \bar{d}$ is invalid.

The proton-induced Drell–Yan (DY) process provides an independent means to probe the flavor asymmetry of the nucleon sea [5]. An important advantage of the DY process is that the x dependence of \bar{d}/\bar{u} asymmetry can be determined. Using a 450 GeV pro-

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ton beam, the NA51 Collaboration [6] at CERN measured dimuons produced in $p + p$ and $p + d$ reaction and obtained $\bar{u}/\bar{d} = 0.51 \pm 0.04(\text{stat}) \pm 0.05(\text{syst})$ at $x = 0.18$ and $\langle M_{\mu\mu} \rangle = 5.22$ GeV. At Fermilab, a DY experiment (E866/NuSea) covering a broad kinematic range with high statistics has been carried out [7–9]. The E866 Collaboration measured the DY cross section ratios for $p + d$ to that of $p + p$ at the forward-rapidity region using intense 800 GeV proton beams. At forward rapidity region and assuming the validity of charge symmetry, one obtains

$$\sigma_{\text{DY}}(p + d)/2\sigma_{\text{DY}}(p + p) \simeq (1 + \bar{d}(x)/\bar{u}(x))/2. \quad (2)$$

This ratio was found to be significantly different from unity for $0.015 < x < 0.35$, indicating an excess of \bar{d} with respect to \bar{u} over an appreciable range in x .

The HERMES Collaboration has also reported a semi-inclusive DIS measurement of charged pions from hydrogen and deuterium targets [10]. Based on the differences between charged-pion yields from the two targets, $\bar{d} - \bar{u}$ is determined in the kinematic range $0.02 < x < 0.3$ and $1 \text{ GeV}^2/c^2 < Q^2 < 10 \text{ GeV}^2/c^2$. The HERMES results are consistent with the E866 results obtained at significantly higher Q^2 .

Many theoretical models, including meson-cloud model, chiral-quark model, Pauli-blocking model, instanton model, chiral-quark soliton model, and statistical model, have been proposed to explain the \bar{d}/\bar{u} asymmetry, as reviewed in [11,12]. While these models can describe the general trend of the \bar{d}/\bar{u} asymmetry, they all have difficulties explaining the \bar{d}/\bar{u} data at large x ($x > 0.2$) [14]. Since the perturbative process gives a symmetric \bar{d}/\bar{u} while a non-perturbative process is needed to generate an asymmetric \bar{d}/\bar{u} sea, the relative importance of these two components is directly reflected in the \bar{d}/\bar{u} ratios. Thus, it would be very important to have new measurements sensitive to the \bar{d}/\bar{u} ratios at $x > 0.2$. The upcoming Fermilab E906 Drell–Yan experiment [13] plans to extend the measurement to larger x region.

With the advent of $p + p$ colliders at RHIC and LHC, an independent technique to study the \bar{d}/\bar{u} asymmetry now becomes available. By measuring the ratio of W^+ versus W^- production in unpolarized $p + p$ collision, the \bar{d}/\bar{u} asymmetry can be determined [15–17] with some distinct advantages over the existing methods. First, this method does not require the assumption of the validity of charge symmetry. All existing experimental evidences for \bar{d}/\bar{u} asymmetry depend on the comparison between DIS or DY scattering cross sections off hydrogen versus deuterium targets. The possibility that charge symmetry could be violated at the parton level has been discussed by several authors [18–23]. Ma and collaborators [18,19] pointed out that the violation of the Gottfried Sum Rule can be caused by charge symmetry violation as well as by flavor asymmetry of the nucleon sea. They also showed that DY experiments, such as NA51 and E866, are subject to both flavor asymmetry and charge symmetry violation effects. In fact, an even larger amount of flavor asymmetry is required to compensate for the possible charge symmetry violation effect [24]. A comparison between W production in $p + p$ collision with the NA51 and E866 Drell–Yan experiments would disentangle the flavor asymmetry from the charge symmetry violation effects.

Another advantage of W production in $p + p$ collision is that it is free from any nuclear effects. As pointed out by several authors [25–28], the nuclear modification of parton distributions should be taken into account for DIS and DY process involving deuterium targets. The nuclear shadowing effect for deuteron at small x could lead to a 4% to 10% decrease in the evaluation of the Gottfried integral by the NMC [25,28]. Moreover, the nucleon Fermi motion at large x also affects the extraction of neutron structure function and would cause additional uncertainty in the evaluation of the

Gottfried integral [26]. The nuclear effects and the associated uncertainty are absent in W production in $p + p$ production.

Finally, the W production is sensitive to \bar{d}/\bar{u} flavor asymmetry at a Q^2 scale of $\sim 6500 \text{ GeV}^2/c^2$, significantly larger than all existing measurements. This offers the opportunity to examine the QCD evolution of the sea-quark flavor asymmetry. The large mass of W also implied that the RHIC data are sensitive to the sea-quark flavor asymmetry at the large x region, which remains poorly known both experimentally and theoretically as discussed earlier.

The differential cross section for W^+ production in hadron-hadron collision can be written as [29]

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

where $u(x)$, $d(x)$, and $s(x)$ signify the up, down, and strange quark distribution functions in the hadrons. x_1 , x_2 are the fractional momenta carried by the partons in the colliding hadron pair and $x_F = x_1 - x_2$. G_F is Fermi coupling constant and θ_c is the Cabibbo angle. The factor K takes into account the contributions from first-order QCD corrections [29]

$$K \simeq 1 + \frac{8\pi}{9} \alpha_s(Q^2). \quad (4)$$

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

$$\begin{aligned} \frac{d\sigma}{dx_F}(W^-) &= K \frac{\sqrt{2}\pi}{3} G_F \left(\frac{x_1 x_2}{x_1 + x_2} \right) \{ \cos^2 \theta_c [\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)] \\ &\quad + \sin^2 \theta_c [\bar{u}(x_1)s(x_2) + s(x_1)\bar{u}(x_2)] \}. \end{aligned} \quad (5)$$

An interesting quantity to be considered is the ratio of the differential cross sections for W^+ and W^- production. If one ignores the much smaller contribution from the strange quarks, this ratio can be written as

$$R(x_F) \equiv \frac{\frac{d\sigma}{dx_F}(W^+)}{\frac{d\sigma}{dx_F}(W^-)} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}. \quad (6)$$

For $p + p$ collision, it is evident that $R(x_F)$ is symmetric with respect to $x_F = 0$, namely, $R(x_F) = R(-x_F)$. It is clear that $R(x_F)$ in $p + p$ collision is sensitive to the sea-quark distributions in the proton. At large x_F , we have

$$R(x_F \gg 0) = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)} \approx \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)}. \quad (7)$$

At $x_F = 0$, where $x_1 = x_2 = x$, one obtains

$$R(x_F = 0) = \frac{u(x)\bar{d}(x) + \bar{d}(x)u(x)}{\bar{u}(x)d(x) + d(x)\bar{u}(x)} = \frac{u(x)\bar{d}(x)}{d(x)\bar{u}(x)}. \quad (8)$$

As the $u(x)/d(x)$ ratios are already well known, a measurement of $R(x_F)$ in $p + p$ collision gives an accurate determination of the ratio $\bar{d}(x)/\bar{u}(x)$.

Fig. 1 shows the predictions of $R(x_F)$ for $p + p$ collision at $\sqrt{s} = 500$ GeV. Four different structure function sets together with the full expressions for W^+ , W^- production cross sections given

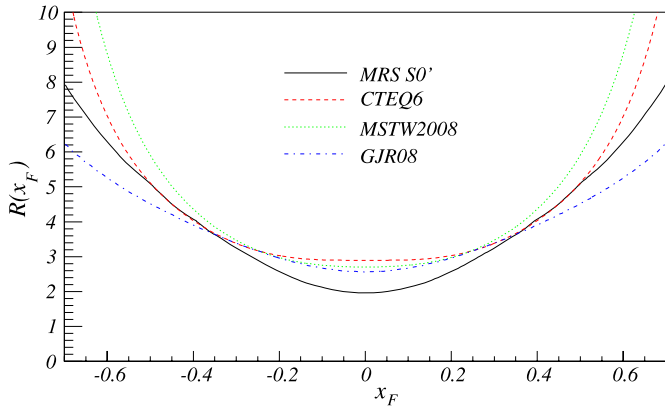


Fig. 1. Prediction of the ratio $R(x_F)$ as a function of x_F for $p + p$ collision at \sqrt{s} of 500 GeV using various parton distribution functions.

Table 1

Values for x_1 and x_2 at different x_F for W production at $\sqrt{s} = 500$ GeV.

x_F	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
x_1	0.16	0.22	0.29	0.37	0.46	0.55	0.64	0.73	0.83
x_2	0.16	0.12	0.09	0.07	0.06	0.05	0.04	0.03	0.03

by Eqs. (3) and (5) have been used in the calculations. The first PDF used here is MRS S0' [30]. It assumes symmetric \bar{u} and \bar{d} distributions, therefore, according to Eq. (8), $R(x_F) \simeq 2$ at $x_F = 0$ as shown in Fig. 1. The other three PDFs used here allowed certain flavor asymmetry in nucleon sea. New experimental data from Drell–Yan measurement by E866 Collaboration is included in the global fit performed by CTEQ6 [31], GJR08 [32] and MSTW2008 [33] to determine x -dependence of \bar{u} , \bar{d} asymmetry in the nucleon sea. Thus $R(x_F)$ for those three PDF are similar at $x_F = 0$ and are significantly higher than 2 obtained in the MRS S0' case. Table 1 shows the x_1 and x_2 values for W production at RHIC with center of mass energy 500 GeV.

Although Fig. 1 shows that the differences between the predictions of $R(x_F)$ for various PDFs are quite conspicuous, in practice it is not the x_F distributions of the W which are measured but rather the charged leptons from the decay of the W -bosons. The measured lepton ratio is defined as:

$$R(y_l) = \frac{d\sigma/dy_l(W^+ \rightarrow l^+)}{d\sigma/dy_l(W^- \rightarrow l^-)}, \quad (9)$$

where the lepton rapidity $y_l = 1/2 \ln[(E_l + p_l)/(E_l - p_l)]$ is defined in terms of the decay lepton's energy E_l and longitudinal momentum p_l in the laboratory frame. The differential cross section $d\sigma/dy_l$ is obtained by convoluting the $q\bar{q} \rightarrow W$ cross section for each x_F with the relevant $W \rightarrow l\nu$ decay distribution, $d\sigma/d\cos\theta \propto (1 \pm \cos\theta)^2$, where θ is the angle between the lepton l^\pm direction and the W^\pm polarization in the W rest frame.

In Fig. 2 we show the predicted lepton ratios $R(y_l)$ calculated for various PDFs. The statistical uncertainties for the lepton ratios are estimated for recorded luminosity of 300 pb^{-1} at RHIC [34]. The acceptance is for PHENIX experiment [35], which covers $|y| < 0.35$ in central rapidities and $-2.2 < y < -1.1$, $1.1 < y < 2.4$ in forward rapidities. Fig. 2 has clearly demonstrated that a measurement of $R(y_l)$ at RHIC is able to distinguish flavor symmetric and flavor asymmetric nucleon sea.

The calculation for $R(x_F)$ and $R(y_l)$ has also been carried out for CMS experiment at LHC [36]. Fig. 3 shows results for $R(x_F)$ at LHC. At $x_F = 0$, all PDFs used here obtain similar results for $R(x_F)$. This is due to the fact that at much higher c.m.s. energy, this measurement probes sea quark flavor asymmetry at even lower x

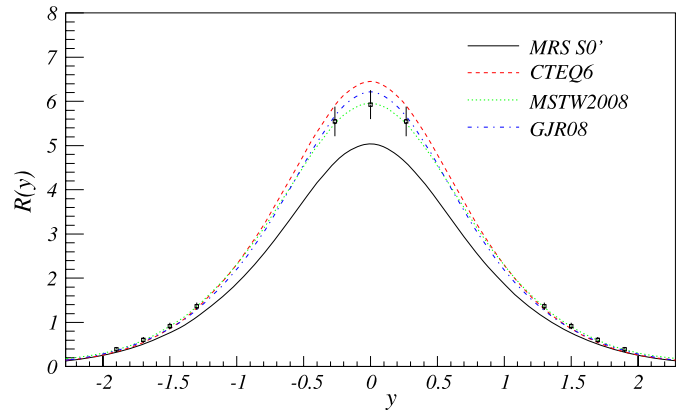


Fig. 2. Prediction of the ratio $R(y_l)$ as a function of y for $p + p$ collision at \sqrt{s} of 500 GeV using various parton distribution functions. The projected sensitivities for a run with recorded luminosity of 300 pb^{-1} for the PHENIX detector are also shown.

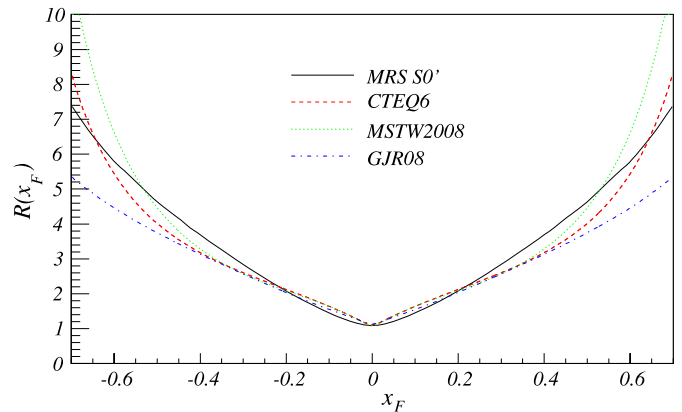


Fig. 3. Prediction of the ratio $R(x_F)$ as a function of x_F for $p + p$ collision at \sqrt{s} of 14 TeV using various parton distribution functions.

Table 2

Values for x_1 and x_2 at different x_F for W production at $\sqrt{s} = 7$ TeV.

x_F	0.0	0.1	0.2	0.3	0.4	0.5	0.6
x_1	0.01	0.10	0.20	0.30	0.40	0.50	0.60
x_2	0.0114	0.0013	0.0007	0.0004	0.0003	0.0003	0.0002

compared to previous measurements from Drell–Yan process and semi-inclusive DIS, and all four PDFs used here have predicted that flavor asymmetry will diminish as $x \rightarrow 0$. Table 2 shows the x_1 and x_2 values for W production at LHC with center of mass energy 14 TeV.

Fig. 4 shows results of the lepton ratio $R(y_l)$ where integrated luminosity is assumed to be 10 fb^{-1} corresponding to one year low luminosity running of $p + p$ collisions at $\sqrt{s} = 14$ TeV and the pseudorapidity coverage is taken as $|\eta| < 5$ [36]. The sensitivity of $R(y_l)$ in Fig. 4 is more than sufficient to differentiate flavor symmetry and asymmetry used in different parameterizations.

In conclusion, W production at RHIC and LHC would offer an independent means to examine the \bar{d}/\bar{u} flavor asymmetry in the proton. Measurements of the cross section ratios of $W^+ \rightarrow l^+$ and $W^- \rightarrow l^-$ production in $p + p$ collisions would provide a sensitive test of current PDFs. The W production experiments at RHIC and LHC will offer the unique opportunity of extracting the \bar{d}/\bar{u} flavor asymmetry at large x and very high Q^2 without the complications associated with the charge symmetry breaking effect and nuclear binding effect. The proposed measurements are within the capabil-

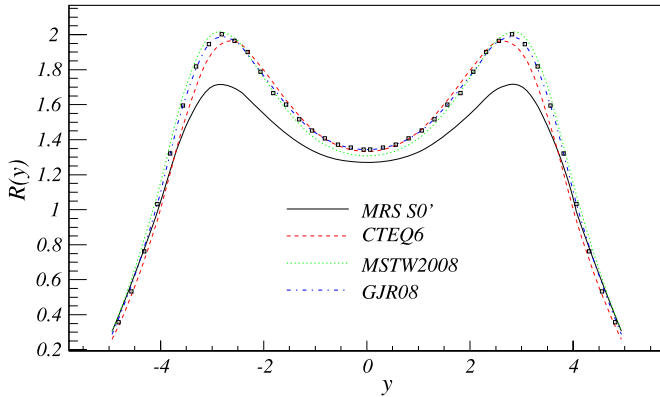


Fig. 4. Prediction of the ratio $R(y)$ as a function of y for $p + p$ collision at \sqrt{s} of 14 TeV using various parton distribution functions. The projected sensitivities for a run with integrated luminosity of 10 fb^{-1} for the CMS detector are also shown.

ities of the existing detectors at RHIC and LHC and can be carried out in the near future.

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