Valence Quark and Gluon Distributions of Kaon from $J/\psi$ Production

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(Dated: November 3, 2017)

The only experimental information on the parton distribution of kaons was obtained from the scarce kaon-induced Drell-Yan cross section data. From these data, evidence for a valence $u$ quark distribution of kaon softer than that of pion was found. We study the feasibility to extract kaon’s valence quark distribution via the existing kaon-induced $J/\psi$ production data. We compare the NA3 data on the $K^-/\pi^-$ and $K^+/\pi^+$ ratios for $J/\psi$ production on a platinum target with theoretical calculations based on the color-evaporation model. We show that the NA3 data on $J/\psi$ production provide an independent evidence for a valence $u$ quark distribution softer in kaon than in pion. The data also suggest different gluon distributions for kaon and pion.

PACS numbers: 12.38.Lg,14.20.Dh,14.65.Bt,13.60.Hb

Since the discovery of partonic structures of hadrons in deep inelastic scattering (DIS), extensive theoretical and experimental progress has been made in our knowledge on proton’s partonic distributions. In contrast, the partonic structures of pion and kaon, which have the dual roles of the lightest quark-antiquark bound states and the Goldstone bosons, remain poorly known. Significant theoretical efforts have been devoted to predicting the quark and gluon distributions in pion and kaon, using QCD-based frameworks [1]. These predictions remain to be tested against new experimental information.

As mesons are not available as targets for performing DIS experiments, the existing experimental inputs for the parton structures of mesons almost exclusively come from Drell-Yan process [2–6] and direct photon production [7] with meson beams. These data led to the extraction of pion’s valence quark distribution [8–11], but pion’s sea-quark and gluon distributions are only poorly constrained. Even less is known about the kaon’s partonic structure. The scarce experimental information is from the measurement of the $K^-$-induced Drell-Yan process [4,5]. Based on a total of ~700 Drell-Yan events, the NA3 Collaboration [5] found the valence $\bar{u}$ quark distribution of $K^-$ to be softer than that of $\pi^-$. This softer $\bar{u}$ valence quark distribution in $K^-$ is attributed to the presence of the heavier $s$ valence quark, resulting in a larger fraction of $K^-$’s momentum being carried by the $s$ quark than the lighter $\bar{u}$ quark. This indication of the flavor dependence of the kaon valence quark distributions has been compared with theoretical calculations [12–14]. Further experimental constraints on the flavor dependence of the kaon valence quark and gluon distributions are clearly of interest.

In this paper, we examine the feasibility to extract information on kaon’s valence quark and gluon distributions using $J/\psi$ production data with kaon beams. We show that the existing NA3 data on the $K^-/\pi^-$ ratio for $J/\psi$ production provide an independent experimental evidence that valence $\bar{u}$ quark distribution of $K^-$ is softer than that of $\pi^-$. The $K^+/\pi^+$ data also suggest that the gluon distribution in kaon is different from that in pion.

We first briefly review the experimental evidence for a flavor-dependent valence quark distribution in kaon. The NA3 Collaboration reported a simultaneous measurement of $K^- + Pt \rightarrow \mu^+\mu^- + X$ and $\pi^- + Pt \rightarrow \mu^+\mu^- + X$ using a 150 GeV/c beam on a platinum target [5]. The negatively charged beam contained $\pi^-$, $K^-$ and $p$ particles. The particle type was identified by two Cherenkov counters placed in the beam. To select the Drell-Yan events, the masses of the dimuon events satisfied $4.1 < M < 8.5$ GeV. Approximately 700 dimuon events produced by $K^-$ and 21,200 events produced by $\pi^-$ were selected. Figure 1 shows the ratio $R$ for the dimuon yields measured for $K^-$ and $\pi^-$ beams as a function of $x_1$, which is the fraction of the beam momentum carried by the interacting parton. The ratio $R$ at large $x_1$ ($x_1 > 0.65$) clearly falls below unity. Since the Drell-Yan cross sections with $\pi^-$ and $K^-$ beams at large $x_1$ are dominated by the term containing the product of $\bar{u}_M(x_1)$ in the meson ($M$) and $u_A(x_2)$ in the nucleus ($A$), the fall-off in $R$ at large $x_1$ was interpreted as an evidence that $\bar{u}_K(x)$ is softer than $\bar{u}_\pi(x)$ [5].

To obtain a more quantitative determination on how $\bar{u}_K(x)$ is modified with respect to $\bar{u}_\pi(x)$, we have calculated $R$ using the leading-order (LO) and next-to-leading-order (NLO) Drell-Yan cross section expression. The solid curve in Fig. 1 is a LO calculation using the SMRS (set 2) [11] parton distribution function (PDF) parametrizations for both $K^-$ and $\pi^-$. The CTEQ5L [16] parametrization for the proton PDFs was used for the platinum target, weighted by the number of protons and neutrons in the platinum nucleus. The dot-dashed curve represents a calculation including the NLO contribution with the DYNNLO code [17]. The nearly identical results from LO and NLO show that the cross section ratio $R$ is insensitive to contributions from high-order processes. Thus the simpler calculation with LO is adequate for $R$. Figure 1 shows that the data at the large $x_1$ region are clearly different from the calculation assuming the same valence-quark distributions for kaon and pion.

In order to account for the drop of $R$ as $x_1 \rightarrow 1$, we as-
providing the same factor. The normalizations of the \(\bar{u}\) and \(s\) valence quark distributions are modified to satisfy the valence-quark number sum rule:

\[
\int_0^1 \bar{u}^V_K(x) dx = 1; \quad \int_0^1 s^K(x) dx = 1.
\]

Using LO calculation, the best-fit value for \(a\) to describe the NA3 data is found to be \(a = 0.203 \pm 0.06\) with the normalization factors \(N_u = 1.061\) and \(N_s = 0.937\). We assume that \(a\) is \(Q^2\)-independent in the range of \(4.1 < M < 8.5\) GeV.

This assumption is reasonable, since the \(Q^2\) dependence in this range is found to be small for the pion PDFs. The dashed curve in Fig. 1 corresponds to calculation with these best-fit values. The fall-off in \(R\) at large values of \(x_1\) is well described by a \(\bar{u}^V_K\) distribution softer than \(\bar{u}^V_x\).

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where $x_1$, $x_2$ are the momentum fraction carried by the beam (B) and target (T) partons, and $x_F = x_1 - x_2$. The mass of the $Q\bar{Q}$ pair is $m$, and $x^2 = m^2/s$ where $s$ is the center-of-mass energy squared. $H_{BT}$ is the convolution of the hard-process cross sections and the parton distributions of the projectile and target hadrons

$$H_{BT}(x_1, x_2; m^2) = G_B(x_1)G_T(x_2)\sigma(gg \rightarrow Q\bar{Q}; m^2)$$

$$+ \sum_{i=u,d,s}[q^i_B(x_1)\bar{q}^i_T(x_2) + \bar{q}^i_B(x_1)q^i_T(x_2)]$$

$$\times \sigma(q\bar{q} \rightarrow Q\bar{Q}; m^2), \quad (5)$$

where $G(x), q(x)$, and $\bar{q}(x)$ refers to the gluon, quark, and antiquark distribution functions, respectively. The expressions for the cross sections of the QCD subprocesses $\sigma(gg \rightarrow Q\bar{Q})$ and $\sigma(q\bar{q} \rightarrow Q\bar{Q})$ can be found in Ref. [18].

To go from the production of $c\bar{c}$ pair to the production of the $c\bar{c}$ bound state $J/\psi$, we use the color-evaporation model [19]. This in model the $c\bar{c}$ bound state is obtained by integrating the free $c\bar{c}$ cross section from the $c\bar{c}$ threshold, $\tau_1 = 2m_c/\sqrt{s}$, to the open-charm threshold, $\tau_2 = 2m_D/\sqrt{s}$. The differential cross section for $J/\psi$ production is then given as

$$\frac{d\sigma}{dx_F} = F \int_{\tau_1}^{\tau_2} 2\tau d\tau H_{BT}(x_1, x_2; m^2)/(x_F^2 + 4\tau^2)^{1/2}, \quad (6)$$

where the factor $F$ accounts for the fraction of the $c\bar{c}$ pairs forming $J/\psi$ either directly or indirectly via the decay of more massive charmonium states. Despite its simplicity, the color-evaporation model is capable of describing many salient features of hadronic $J/\psi$ production [20–24]. For example, the shape of $d\sigma/dx_F$ as well as their beam-energy and beam-type dependencies, which are sensitive to the relative contributions of $q\bar{q}$ annihilation and $gg$ fusion, are very well reproduced. The success of the color-evaporation model suggests that this model gives an adequate prediction for the relative contribution of these two processes.

The solid curve in Fig. 2 represents the calculation of the $K^-/\pi^-$ ratio for $J/\psi$ production on a platinum target utilizing the color-evaporation model. The same valence-quark, sea-quark, and gluon distributions (SMRS PDFs) were assumed for $\pi^-$ and $K^-$, and the nucleon PDFs are taken from CTEQ5L. Identical values of $F$ were assumed for the $\pi^-$ and $K^-$ cross sections in Eq. (6). Hence the result is independent of the value of $F$. Figure 2 shows that the color-evaporation model gives good description of the NA3 data for the region $0 < x_F < 0.65$, indicating the adequacy of this model. However, at the largest values of $x_F$ ($0.65 < x_F < 1.0$), the calculation is significantly above the data.

To shed some light on the origin of the discrepancy between the data and the calculation shown in Fig. 2, we show in Fig. 3 the comparison between the $\pi^- + p$ $J/\psi$ production data from NA3 [15, 25] with the color-evaporation model calculation, using the same PDF inputs as in Fig. 2. The factor $F$ for the solid curve is $F = 0.325$, resulting in a very good agreement with the data. This suggests that the discrepancy observed in Fig. 2 originates from the calculation for $K^- + Pt$, rather than $\pi^- + Pt$. Additional information is provided in Fig. 3 where the contributions from the $q\bar{q}$ annihilation and the $gg$ fusion are shown as the dashed and dotted curve, respectively. One notes that the $q\bar{q}$ annihilation process becomes increasingly important at the large $x_F$ region relative to the $gg$ fusion process. This implies that the $K^-/\pi^- J/\psi$ ratio at large $x_F$ should be sensitive to the valence quark distribution in $K^-$, and the drop in $R$ could reflect a softer $\bar{u}$ valence-quark distribution in $K^-$ than in $\pi^-$. We have carried out color-evaporation model calculation, shown as the dashed curve in Fig. 2, using the modified kaon valence-quark PDFs as in Eqs. (1) and (2) with $a = 0.203$. The modified kaon PDFs give a better description of the data. However, the data at the largest $x_F$ region remain slightly below the calculation. It would be very helpful to obtain new high statistics dimuon data at the forward $x_F$ region with kaon beam. A future global analysis of both the Drell-Yan and $J/\psi$ production data would allow an extraction of the quark and gluon distributions in kaon.

The NA3 Collaboration has also measured the $K^+/\pi^+$ ratios for $J/\psi$ production at 200 GeV/c on a platinum target as shown in Fig. 4 [15]. A striking difference between the $K^+/\pi^+$ and the $K^-/\pi^-$ ratios is observed. While there is a pronounced drop of the $K^-/\pi^-$ ratios at forward $x_F$, no such
In the distribution is assumed to be the same in $\pi^u$ valence quark in nucleus, the production to the valence quark distribution in and the target nucleus. Hence, the Pt reaction must involve at least one sea quark from the beam contribution. This leads to the striking difference between the $x$ ratios.

PDFs give a very similar result. The insensitivity of dot-dashed curve corresponds to a calculation where the gluon and sea-quark distributions in kaon maintain the same functional form in $x_F$ region, similar to the data. The dashed curve in Fig. 4 is obtained with a modified $K^+$ PDFs following Eqs. (1) and (2). It is worth noting that the modified $K^+$ PDFs give a very similar result. The insensitivity of $\pi^+/\pi^-$ production with an intense RF-separated kaon beam is under active consideration.

Figure 4 shows that the $K^+/\pi^+$ production data favor a larger gluon content in kaon relative to pion.

In summary, we have investigated the feasibility to extract information of the kaon valence quark distribution via the $J/\psi$ production data. We show that the existing data from NA3 provide an independent evidence that the $\bar{u}$ valence quark distribution of $K^-$ has a softer $x$ distribution than that of $\pi^-$. This is in qualitative agreement with the result obtained from the analysis on the $K^-/\pi^-$ Drell-Yan cross section ratio data. Since $J/\psi$ production proceeds via strong interaction with a cross section much larger than that of the electromagnetic Drell-Yan process, it is a promising independent experiment tool to extract the partonic distributions in the kaon. As the $J/\psi$ production also involves the $gg$ fusion contribution, it is conceivable that one could also extract unique information on the gluon distribution in kaon, which is completely unknown at this moment. The prospect for pursuing Drell-Yan and $J/\psi$ production with an intense RF-separated kaon beam is under active consideration.

This work was supported in part by the U.S. National Science Foundation and the Ministry of Science and Technology of Taiwan.

Note that a recent paper indeed suggests different gluon distributions for pion and kaon. To examine the sensitivity of the $K^+/\pi^+ J/\psi$ cross section ratio to the gluon distributions, the dot-dashed curve in Fig. 4 corresponds to a calculation in which the gluon distribution in kaon at the $J/\psi$ mass scale is increased by 12% so that 45% of kaon’s momentum is carried by gluons, rather than the nominal value of 40% in SMRS (set 2). To ensure the momentum sum rule for kaon, the sea-quark distribution is decreased accordingly so that 10% of kaon’s momentum is carried by the sea-quarks, rather than the nominal value of 15%. The modified gluon and sea-quark distributions in kaon maintain the same functional form in $x_F$, but with different normalizations. Figure 4 shows that the $K^+/\pi^+ J/\psi$ data favor a larger gluon content in kaon relative to pion.

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