Nuclear medium effects in Drell-Yan process

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We study nuclear medium effects in Drell-Yan processes at small target x using quark parton distribution functions and nucleon structure functions for a bound nucleon calculated in a microscopic nuclear model which takes into account the effect of Fermi motion, nuclear binding and nucleon correlations through a relativistic spectral function. The contributions of π and ρ mesons, target mass corrections and nuclear shadowing are also included. The results are compared with the theoretical and experimental results. The model is able to successfully explain the low target x results of E772 and E866 Drell-Yan experiments and is applicable to the forthcoming experimental analysis of E906 Sea Quest experiment at Fermi Lab.

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INTRODUCTION

Drell-Yan production of lepton pairs from nucleons and nuclear targets is an important tool to study the quark structure of nucleons and its modification in the nuclear medium. In particular, the proton induced Drell-Yan production of muon pairs on nucleons and nuclei provides a direct probe to investigate the quark parton distribution functions (PDF) and nucleon structure functions for bound nucleons in nuclei. The Drell-Yan production takes place through basic process of quark-antiquark annihilation into lepton pairs i.e \( q_b(x_b) + q_{\bar{b}}(x_b) \rightarrow \ell^+ + \ell^- \) where b and \( \bar{b} \) indicate the beam proton and target nucleon. In this basic process a quark(antiquark) in the beam carrying a longitudinal momentum fraction \( x_b \) interacts with an antiquark(quark) in the target carrying longitudinal momentum fraction \( x_t \) of the target momentum per nucleon to produce a virtual photon which decays into lepton pairs. The cross section per target nucleon \( \frac{d^2\sigma}{dx_bdx_t} \) is given by

\[
\frac{d^2\sigma}{dx_bdx_t} = K \frac{4\pi\alpha^2}{9Q^2} \sum_f e_f^2 \left\{ q_f^b(x_b, Q^2)q_{\bar{f}}(x_t, Q^2) + q_{\bar{f}}^b(x_b, Q^2)q_f(x_t, Q^2) \right\}
\]

where \( \alpha \) is the fine structure constant, \( e_f \) is the charge of quark(antiquark) of flavor f, and Q^2 is the photon virtuality. \( q_f^b(x, Q^2) \) and \( q_{\bar{f}}^t(x, Q^2) \) are the beam(target) quark PDF. The sum is over all quark flavors f i.e u, d, s, c, b, t. K describes the higher order effects and is found to be independent of \( x_b, x_t \). By adding and subtracting \( q_f^b(x_b, Q^2)q_{\bar{f}}(x_t, Q^2) \) in first and second term, Eq. (1) is rewritten as

\[
\frac{d^2\sigma}{dx_bdx_t} = K \frac{4\pi\alpha^2}{9Q^2} \left\{ \sum_f e_f^2 v_f^b(x_b, Q^2)\bar{q}_f(x_t, Q^2) + \frac{1}{x_t} q_{\bar{f}}^b(x_b, Q^2)F_2(x_t, Q^2) \right\}
\]

where \( v_f^b(x_b, Q^2) \) is the valence quark PDF in the beam proton given by \( v_f^b(x_b, Q^2) = q_f^b(x_b, Q^2) - \bar{q}_f^b(x_b, Q^2) \) and \( F_2(x_t, Q^2) \) is the nucleon structure function of bound nucleons in the target nucleus. Eq. (2) shows that in the small \( x_b \) region \( (x_b < 0.3) \) which is dominated by beam proton sea quarks, the second term will give the dominant contribution. The term includes the nuclear medium effects through the structure function \( F_2(x_t, Q^2) \) for bound nucleon in the nuclear target. In this region of \( x_b \), any model for \( F_2(x_t, Q^2) \) which gives satisfactory description of DIS of charged leptons and \( \nu(\bar{\nu}) \) should be able to explain the Drell-Yan production of lepton pairs from nuclear targets. On the other hand in the region of large \( x_b \) \( (x_b > 0.3) \) where the first term is expected to give leading contribution, the analysis of Drell-Yan yields will provide useful information about the sea quark PDF in the nuclear medium. It is important to point out that \( (x_b, x_t) \) profile of Drell-Yan yields, thus provides very useful information about the nuclear medium modification of quark PDF and nucleon structure functions. \( F_2(x_t, Q^2) \) is either determined by a phenomenological analysis of nuclear PDF using experimental data on DIS of charged leptons and neutrino and antineutrino on nuclei or alternatively, by a theoretical model to describe the nuclear medium effects in DIS charged leptons and \( \nu(\bar{\nu}) \) in nuclei.
The study covers the region of $x_t < 0.3$ in which the experimental data on Drell-Yan yield ratios are presently available from E772 \cite{28} and E866 \cite{29, 30} on $^{12}$C, $^{40}$Ca, $^{56}$Fe, and $^{184}$W nuclei. The results are also presented up to the extended region of $x_t = 0.45$ which are applicable to the SeaQuest E906 experiment being done at Fermilab \cite{31}.

In this letter, we report the results of nuclear medium effects on Drell-Yan production of lepton pairs calculated in a theoretical microscopic nuclear model which has been successfully used to describe the DIS of leptons, $\nu(\bar{\nu})$ from various nuclei \cite{22, 27}. The study covers the region of $x_t < 0.3$ in which the experimental data on Drell-Yan yield ratios are presently available from E772 \cite{28} and E866 \cite{29, 30} on $^{12}$C, $^{40}$Ca, $^{56}$Fe, and $^{184}$W nuclei. The results are also presented up to the extended region of $x_t = 0.45$ which are applicable to the SeaQuest E906 experiment being done at Fermilab Lab \cite{31}.

**NUCLEAR EFFECTS**

The numerical calculation for the Drell-Yan production of lepton pairs from nuclear targets have been done using Eq.\(^2\) where the valence and sea quark PDFs have been taken from the parametrization of the Coordinated Theoretical-Experimental Project on QCD (CTEQ) Collaboration (CTEQ6.6) \cite{32}. The nuclear medium effects are included through $\tilde{q}^i_f(x_t, Q^2)$ and $F^i_f(x_t, Q^2)$ which have been calculated in the nuclear medium using local density approximation. The conventional nuclear medium effects like Fermi motion, nuclear binding and nucleon correlations are taken into account using relativistic hole spectral function of nucleon $S_h(p^0, \rho, \rho(r))$ in the nuclear medium which is defined in terms of nucleon propagator $G(p)$ in the nuclear medium \cite{22, 27, 33}.

The nucleon structure function $F^i_f(x_t, Q^2)$ is obtained by calculating the hadronic tensor in the nuclear medium following Refs. \cite{22, 24} and for nonisoscalar nuclear target($N \neq Z$), separate distributions of the Fermi sea for protons and neutrons are taken \cite{26}. $F^i_f(x_t, Q^2)$ is written as \cite{22}:

$$F^i_f(x_t, Q^2) = 2 \sum_{i=p,n} \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(p)} \times \int_{-\infty}^{t^i} d\rho^0 S^i_h(p^0, \rho, \rho(r))F^i_f(x', Q^2)C(p^0, p)$$

(3)

where $C(p^0, p) = \left(1 - \frac{\gamma}{\gamma^2}ight)\left(\gamma^2 + \frac{6x^2(p^2 - p^2_f)}{Q^2}\right)$, $p^0 = M + \omega$, $\gamma^2 = 1 + 4x^2p^2/Q^2$ and $x' = Q^2/(2p^0 - \omega)$. Factor 2 is a spin factor. $F^i_f$ are the dimensionless structure functions for the free proton and the free neutron respectively. $S^i_h$ are the two different spectral functions, each of them normalized to the number of protons or neutrons in the nuclear target. $\rho_p(\rho_n)$ is the proton(neutron) density inside the nucleus.

Similarly for the antiquark inside the nuclear medium, $\tilde{q}^i_f(x_t, Q^2)$ is written as \cite{26}:

$$\tilde{q}^i_f(x_t, Q^2) = 2 \sum_{i=p,n} \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(p)} \times \int_{-\infty}^{t^i} d\rho^0 S^i_h(p^0, \rho, \rho(r))\tilde{q}^i_f(x', Q^2),$$

(4)

where $\tilde{q}^i_f$ is the antiquark momentum distribution function inside the nucleon.

The target mass correction(TMC) to $F^i_f(x_t, Q^2)$ has been made using prescription of Schienbein et al. \cite{34} and shadowing effect has been taken into account using Glauber-Gribov multiple scattering model following the prescription of Kulagin and Petti \cite{33}.

The pion and rho meson cloud contributions are calculated from a microscopic model of meson self-energies following Refs. \cite{22, 30}. The pion contribution $F^{\pi}_{2x}(x_t, Q^2)$...
and antiquark contribution \( \bar{q}^T_x(x_t, Q^2) \) inside the nuclear target are written as [22]:

\[
F^T_{2\pi}(x_t, Q^2) = -6 \int d^3r \int \frac{d^4p}{(2\pi)^4} \theta(p^0) \delta i M D_\pi(p) \times \frac{x}{x_\pi} 2 M F_{2\pi}(x_\pi) \theta(x_\pi - x) \theta(1 - x_\pi), \tag{5}
\]

and

\[
\bar{q}^T_x(x_t, Q^2) = -6 \int d^3r \int \frac{d^4p}{(2\pi)^4} \theta(p^0) \delta i M D_\pi(p) \times \frac{x}{x_\pi} 2 M \bar{q}(x_\pi) \theta(x_\pi - x) \theta(1 - x_\pi), \tag{6}
\]

where \( D_\pi(p) \) is the pion propagator in the medium defined in terms of the self energy of the pion in the nuclear medium. The pionic PDF has been taken from Ref. [37].

Similarly, the rho contribution \( F^\rho_{2\pi}(x_t, Q^2) \) and \( \bar{q}^\rho_x(x_t, Q^2) \) are obtained from Eq. 5 and Eq. 6 respectively by changing \( D_\pi(p) \rightarrow D_\rho(p) \), \( x_\pi \rightarrow x_\rho \) and the factor (-6) by (-12). The expression for \( \bar{q}^T_x(x_t, Q^2) \) is taken from Ref. [20].

The deuteron structure functions have been calculated using the same formula as for nuclear structure function but performing the convolution with the deuteron wave function squared instead of using the spectral function with the Paris N-N potential. In terms of the deuteron wave function, \( F^D_2 \) may be written as

\[
F^D_2(x, Q^2) = \int \frac{d^3p}{(2\pi)^3} |\Psi_D(p)|^2 C(p^0, p, p_\rho(r)) F^N_2(x', Q^2)(7)
\]

RESULTS AND DISCUSSION

In Fig. 1 we show the results for the ratio in iron to deuteron for \( \frac{d^2\sigma}{dx_t dx_b} \) as a function of \( x_t \) for \( x_b = 0.1 \) and \( x_b = 0.7 \), where we compare our results with the theoretical results of Bickerstaff et al. [4] calculated in various models [3-14]. Our results are presented for the full model i.e. using nuclear spectral function with meson cloud contributions and nuclear shadowing, nuclear spectral function with mesons and only with the nuclear spectral function. We find that in our model the effect of meson cloud contribution is to increase the cross section, and this results an increase of 2 - 3% in the cross section at \( x_t = 0.1 \), which decreases with the increase in \( x_t \). At \( x_b = 0.7 \), the effect of meson cloud is 3 - 4% which decreases with the increase in \( x_t \). The effect of shadowing is to decrease in the cross section considerably at \( x_b = 0.7 \). In Fig. 2 we present our results for \( \frac{d^2\sigma}{dx_t dx_b} \), in the range 0 < \( x_t < 0.45 \), and compared

FIG. 2: \( \frac{d^2\sigma}{dx_t dx_b} \) vs \( x_t \) at \( \sqrt{s}=38.8 \)GeV. Theoretical results of Korpa et al. [19] using different parameter values and Alde et al. [28] in the different models are shown through hands. Dashed line with triangle up: Berger and Coester [13] results, dotted line with triangle up: Berger and Coester [13] results, double dotted dashed line: results of Close et al. [12] and Double dotted with stars: results of Brown et al. [10]. Solid line is our result with full model.

FIG. 3: Left panel: \( \frac{d^2\sigma}{dx_t dx_b} \) vs \( x_t \) at \( \sqrt{s}=38.8 \)GeV. Full model: solid line, Full model without pion, rho and shadowing: dotted line, Full model with pion and rho contributions: dashed line. Experimental points are of E772 experiment.
FIG. 4: Left panel: \( \frac{d^2 \sigma}{dx_b dx_t}(F_e,W) \) vs \( x_t \) at \( \sqrt{s}=38.8\text{GeV} \). Full model: solid line, Experimental points are of E772 experiment [28]. Right Panel: \( \frac{d^2 \sigma}{dx_b dx_t}(F_e,W) \) vs \( x_t \), line have same meaning as in left panel. Experimental points are of E866 experiment [29, 30].

the results with the results of various calculations available in literature [13–16, 19, 28]. Our results are presented for the full model. We see from Fig. 4 that in the region \( x_t > 0.2 \), our results agree with the results of Close et al. [11], Brown et al. [16], and lie within the band of Korpa and Dieperink [21]. In region \( x_t < 0.2 \), our results in this model are smaller than all the other calculations and are in the right direction of better agreement in this region with the experimental results shown below in Fig. 3 and Fig. 4. In Fig. 4, we compare our results for this ratio with the experimental results of E772 [28] experiment in the case of \( ^{12}\text{C}, ^{40}\text{Ca}, ^{56}\text{Fe}, \) and \( ^{184}\text{W} \). The three cases of theoretical results with nuclear spectral function, nuclear spectral function with mesons and nuclear spectral function with mesons and nuclear shadowing are shown separately. In Fig. 4, we present the results for the Drell-Yan ratio for \( \frac{d^2 \sigma}{dx_b dx_t} \), integrated over \( x_b \) for fixed \( x_t \) in the range \( 0.2 < x_b < 1 \). i.e. \( \frac{d^2 \sigma}{dx_b dx_t}(A) \) where \( A = F_e \) or \( W \) nucleus and \( A' = B_e \) or \( C \) nucleus, where we have also shown the experimental results from E772 [28] and E866 [29, 30] experiments. We find a good agreement with the experimental results for the various Drell-Yan ratios available from E772 [28] and E866 [29, 30] experiments in the low target \( x_t \) region for \( 0 < x_t < 0.3 \) and \( 0 < x_t < 0.15 \) corresponding to the above experiments. In case of both the experimental results our model slightly overestimates the Drell-Yan yield ratios in very small region of \( x_t < 0.1 \) specially in the case of heavier nuclei where parton energy loss may play a role. A comparison of the Drell-Yan ratios in Figs. 3 and 4 show that the present model explains the nuclear ratios in heavier nuclei better than the ratios when Deuteron is involved implying that in medium nuclear effects for heavier nuclei are well described in this model.

SUMMARY AND CONCLUSION

In this letter, we have studied nuclear medium effects in Drell-Yan processes at small target \( x \) using quark parton distribution functions and nucleon structure functions for a bound nucleon. We have used a microscopic nuclear model which takes into account the effect of Fermi motion, nuclear binding and nucleon correlations through a relativistic spectral function of bound nucleon. The contributions of \( \pi \) and \( \rho \) mesons, target mass corrections and nuclear shadowing are also included. Our results are compared with the various theoretical results available in the literature and with the E772 [28] and E866 [29, 30] experiments. We find a reasonable good agreement with the experimental results for a wide range of nuclei. We have also presented in this paper, results for \( \frac{d^2 \sigma}{dx_b dx_t} \) in the extended region of \( x_t \leq 0.45 \) for various values of \( x_b \) and the results for \( \frac{d^2 \sigma}{dx_b dx_t} \) in this region relevant to the forthcoming E906 SeaQuest [31] experiment at Fermi Lab. Our results show that this model for describing the nuclear medium effects is able to describe the DIS charged leptons and neutrino and antineutrino and Drell-Yan yield ratios on nuclei except in the region of very low \( x_t < 0.1 \) where the nuclear effects other than Fermi motion, binding, nucleon correlations, pion and rho meson cloud contributions and nuclear shadowing may come into play. High statistics, high precision data from E906 SeaQuest [31] experiment on \( \frac{d^2 \sigma}{dx_b dx_t} \) in various regions of \( x_b \) and \( x_t \) will provide important information about the modification of quark PDF and nucleon structure function in the nuclear medium.

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