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Initial-state nuclear effects in proton-nucleus collisions

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Abstract. Two important initial-state nuclear effects in hadron-nucleus collisions are considered. The ratios of inclusive differential cross-sections for Drell-Yan dimuon production are calculated. The calculated results are compared to the E866 data. It is shown that the consideration of multiple soft rescatterings of incident quarks in nuclei and initial-state quark energy loss effects allow to get a good agreement between the calculated results and the experimental data.

PACS. 13.85.Qk Inclusive production with identified leptons, photons, or other nonhadronic particles – 24.10.Lx Monte Carlo simulations (including hadron and parton cascades and string breaking models) – 25.40.Ve Other reactions above meson production threshold (energies > 400 MeV) – 25.75.-q Relativistic heavy-ion collisions

1 Introduction

Nowadays there is a great interest among the widest circles of physicists in non-trivial effects of relativistic nuclear physics such as anomalous nuclear dependence in processes with large transverse momentum p_T. This problem has become especially important in connection with the recent data from RHIC [1–4].

It was first observed in 1975 [5] that high-p_T hadrons in proton-nucleus (pA) collisions are produced copiously in the range of $p_T \gtrsim 2$ GeV/c. This effect ("Cronin effect") was observed in fixed target pA collisions at energies of 200, 300 and 400 GeV. The Cronin effect demonstrates that a hadron-nucleus (hA) collision cannot be presented as a simple superposition of hadron-nucleon (hN) collisions. Analogous behavior was observed in collisons of heavy nuclei (Pb + Pb, Pb + Au) at $\sqrt{s_{NN}} = 17$ GeV (SPS, CERN) [6]. But the recent experimental data from RHIC showed strong suppression of produced hadrons in central Au + Au collisions at $\sqrt{s_{NN}} = 130, 200$ GeV [1–4].

The anomalous A-dependence can be affected by initial- and final-state effects, *i.e.* the effects before and after hard scattering, respectively. The investigation of the final state could give the information on the properties of the produced medium. But this information can be extracted from data only when the initial state can be reliably predicted. A unique tool for studying the initial state is the Drell-Yan (DY) lepton pair production [7], which provides the possibility of probing the propagation of partons through nuclear matter in its ground state, with the produced lepton pair carrying away the desired information about the initial state, without being affected by the produced medium.

In this paper two important initial-state effects which take place in hA collisions are studied: multiple soft rescatterings of quarks of the incident hadron in nuclei and energy loss of fast quarks in nuclear matter. In order to simulate the mentioned effects in DY lepton pair production in proton-nucleus and nucleus-nucleus (AA) collisons we developed a new Monte Carlo (MC) event generator HARDPING (Hard Probe Interaction Generator). It is based on the HIJING generator [8], an extension of PYTHIA [9] for hadron collisions on jet production in nuclear collisions.

Multiple soft rescatterings and energy loss of quarks were taken into account according to refs. [10,11]. The obtained results were compared with the E866 Collaboration (FNAL, USA) data at 800 GeV [12].

2 Studying the initial state

2.1 Nuclear shadowing versus energy loss

Measurements of nuclear structure functions in deeply inelastic lepton-nucleus scattering (DIS) [13–15] indicate clearly that parton distributions of bound nucleons are different from those of free nucleons.

It is very important to disentangle between the effects of shadowing and energy loss, since they are similar in

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many respects. In order to describe the modification of parton distributions in nucleus, a variety of approaches to this question exist in the literature [16,17].

The first DY data suitable for such an analysis were obtained in Fermilab E772/E866 experiments. An analysis of the E772 data [18] was made in ref. [19], ignoring shadowing. A better analysis was performed by the E866 Collaboration using the E866 data [12]. The E866 experiment extends the kinematic coverage of the previous E772 experiment, which significantly increases its sensitivity to parton energy loss and shadowing. Vasiliev *et al.* attempted to improve the analysis of ref. [18] by including shadowing. However the procedure employed by Vasiliev *et al.* used the EKS shadowing parametrization [20], which included the E772 DY data, which are subject to corrections for energy loss. Thus the EKS "shadowing" already includes corrections for energy loss. And this is why the analysis of the E866 data performed by the E866 Collaboration resulted in zero energy loss.

In 2001, Hirai, Kumano and Miyama (HKM) [21] proposed nuclear parton distributions, which were obtained by quadratic- and cubic-type analysis, and determined by a χ^2 global analysis of existing experimental data on nuclear structure functions without including the proton-nucleus DY process.

In our present analysis we use the HKM nuclear shadowing parametrization. Since the HKM fit did not include Drell-Yan data, we expect to find energy loss and shadowing corrections which are unambiguously separated.

2.2 Multiple soft rescatterings of quarks

First of all, the mechanism of multiple interactions significantly changes with energy. At low energies a high-transverse-momentum parton is produced off different nucleons incoherently, while at high energies it becomes a coherent process. This is controlled by the coherence length [22]

$$l_c = \frac{\sqrt{s}}{m_{\mathrm{N}} k_{\mathrm{T}}}, \tag{1}$$

where k_{T} is the transverse momentum of the parton produced at mid rapidity and then hadronizing into the detected hadron with transverse momentum p_{T}.

For a coherence length which is shorter than the typical internucleon separation, the projectile interacts incoherently with individual nucleons. The energy range of the E866 experiment corresponds to the regime of short coherence lengths. Hence the effects of coherence are not so important here. Thus, we are not going to consider coherence effects in our present analysis.

In hA interactions a quark of the incoming hadron can undergo soft collisions (with small momentum transfers: $|t| < 1\ \mathrm{GeV}^2$) as well as hard ones (with large momentum transfers: $|t| > 1\ \mathrm{GeV}^2$) inside the nucleus. It was first shown by Levin and Ryskin [23] that the observed Cronin effect cannot be explained by only the hard collisions taken into account. One also have to consider soft rescatterings of additive quarks of the incident hadron before the hard process [24].

Such a picture was suggested in ref. [10] in the framework of the additive quark model [25]. In this approach the dynamics of hA interactions could be visualized in the following manner. Each constituent quark of the incident hadron (valon) is scattered independently of the other quarks (as in the additive quark model) several times softly, *i.e.* with small momentum transfer, by the nucleons of the target nucleus. Then a (anti-) quark-parton, which belongs to this quark, undergoes a hard collision with an antiquark (quark) of the nucleus producing an observed DY pair. All these soft rescatterings affect the p_{T} distribution of the quarks of the incident hadron, and therefore, the p_{T} spectrum of the observed DY pairs.

According to ref. [10] the probability for a quark to undergo n soft rescatterings in nuclear matter is

$$P_n = \frac{1}{(n-1)!} \int_{-\infty}^{\infty} \mathrm{d}z \int \mathrm{d}^2 b \left[\sigma T_-(b,z)\right]^{n-1} \times \rho(b,z)\, \mathrm{e}^{-\sigma T_-(b,z)} \,. \tag{2}$$

Here b is the impact parameter of hA collision, σ is the cross-section of the inelastic soft quark-nucleon interaction, $\rho(r)$ is the nuclear density normalized to unity

$$\int \rho(r)\, \mathrm{d}^3 r = 1 \,,$$

$T_-(b,z)$ is the profile function:

$$T_-(b,z) = \int_{-\infty}^{z} \rho(b,z')\mathrm{d}z' \,.$$

The transverse momentum k_{T} distribution for the quark suffered n soft rescatterings can be written in the following form [26]:

$$G_{\mathrm{q}}^n(k_{\mathrm{T}}) = \int \prod_{i=1}^{n} \mathrm{d}^2 p_{\mathrm{T}_i}\, f_{\mathrm{q}}(p_{\mathrm{T}_i})\, \delta^2\left(k_{\mathrm{T}} - \sum_{i=1}^{n} p_{\mathrm{T}_i}\right) \,, \tag{3}$$

where p_{T_i} is the transverse momentum of the quark in the i-th rescattering process. Here $f_{\mathrm{q}}(p_{\mathrm{T}})$ is the probability for the quark q to have the transverse momentum p_{T} after a single quark-nucleon interaction:

$$f_{\mathrm{q}}(p_{\mathrm{T}}) = \frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_{\mathrm{T}}} \,. \tag{4}$$

Finally, eq. (3) can be presented in the following form [27]:

$$G_{\mathrm{q}}^m(k_{\mathrm{T}}) = \frac{B^2}{2\pi\Gamma\left[(3m+1)/2+1\right]} \left(\frac{B k_{\mathrm{T}}}{2}\right)^{(3m+1)/2} \times K_{(3m+1)/2}(B k_{\mathrm{T}}) \,, \tag{5}$$

where $m = n-1$, $K^m(y)$ is the McDonald function of m order, $\Gamma(\alpha)$ is the gamma function, $B = 2/\langle k_{\mathrm{V}} \rangle$, where

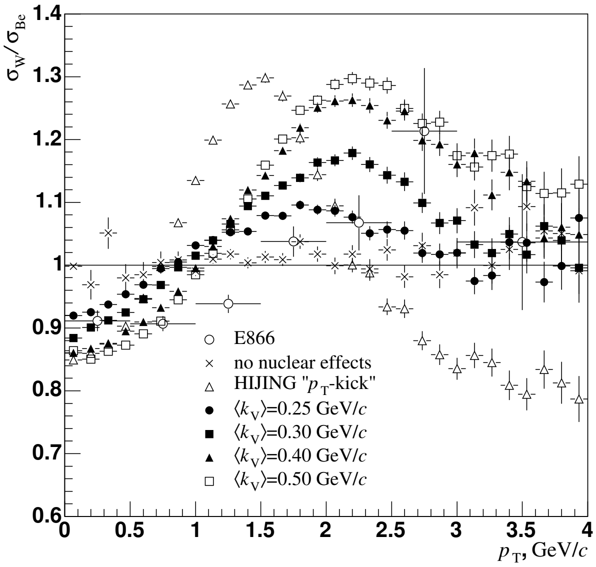

Fig. 1. Ratio of the cross-sections for Drell-Yan events *versus* p_T with quarks multiple rescatterings taken into account. Ratios calculated for $\sigma = 10$ mb and for different $\langle k_V\rangle$ values.

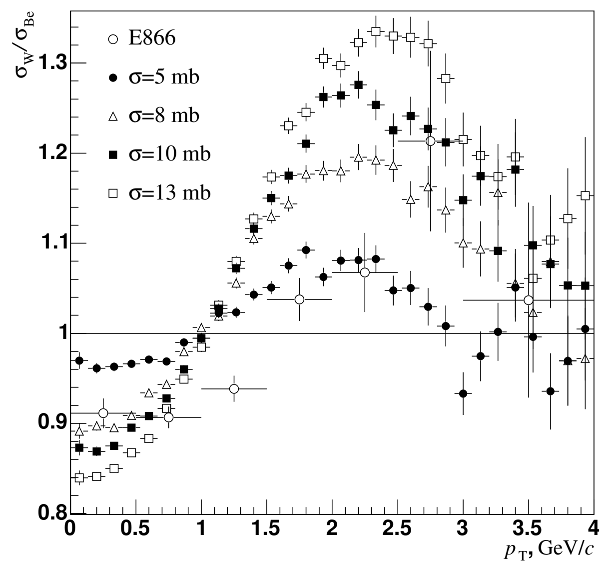

Fig. 2. The same as in fig. 1 but for different σ and $\langle k_V\rangle = 0.4$ GeV/c.

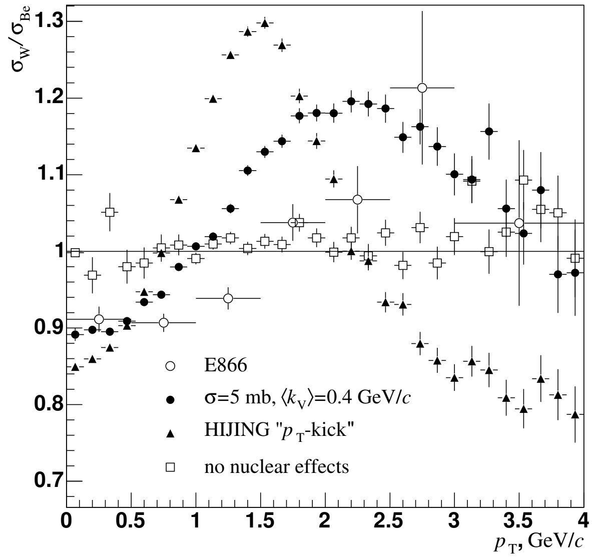

Fig. 3. The same as in fig. 1 but for $\sigma = 5$ mb and $\langle k_V\rangle = 0.4$ GeV/c.

$\langle k_V\rangle$ is the mean momentum of the quark in the projectile proton.

The modification of primordial p_T due to soft rescatterings of the quark undergoing the hard process was implemented in HIJING according to the mentioned distributions (eqs. (2) and (5)). Figure 1 represents HARDPING simulation results for the ratios of the DY pairs production cross-sections in pA collisions *versus* p_T of the produced pairs. The ratios were calculated for different $\langle k_V\rangle$ values and for $\sigma = 10$ mb. Also the simulation results, obtained with the standard HIJING multiple scatterings algorithm (HIJING "p_T-kick") [8] as well as E866 data are presented.

The ratio σ_W/σ_{Be} is a fraction of inclusive differential cross-sections, normalized to the corresponding atomic number:

$$\sigma_W/\sigma_{Be} = \left(\frac{1}{A_W}\,\frac{d\sigma^{pW}}{dp_T}\right)\bigg/\left(\frac{1}{A_{Be}}\,\frac{d\sigma^{pBe}}{dp_T}\right), \qquad (6)$$

where A_W and A_{Be} are atomic numbers of corresponding nuclei, $d\sigma^{pW}/dp_T$ and $d\sigma^{pBe}/dp_T$ are inclusive differential cross-sections for DY pairs production in corresponding reactions.

Figure 2 represents the same ratio for different values of the quark-nucleon cross-section and for $\langle k_V\rangle = 0.4$ GeV/c.

As seen from figs. 1 and 2 considering the multiple soft quark rescatterings effect allows to improve the agreement with the experimental data compared to the results obtained without taking into account this effect as well as to the HIJING "p_T-kick" results. Also, one can see that the results strongly depend on the values of σ and $\langle k_V\rangle$. Unfortunately, in spite of the obvious improvement of the agreement between experimental and simulated data compared to the original HIJING, there is a large quantitative inconsistency. In fig. 3 one can see the best result obtained within this model, where the value of $p_T \approx 2.2$ GeV/c, corresponding to the maximum of the ratio, is about 1.2 times less than the experimental one. Moreover, the value of $\sigma = 5$ mb corresponding to this figure is about 2 times less than the one predicted by the additive quark model ($\sigma \approx \frac{1}{3}\,\sigma_{NN} \approx 10$ mb, where $\sigma_{NN} \approx 30$ mb). So we need a more accurate model.

The above treatment of multiple scatterings of quarks was oversimplified because there was no distinction between constituent quarks (valons) which undergo soft scatterings and point-like partons which undergo the hard process. In fact, to obtain the distribution function of the parton, which undergoes the hard process, of the incident

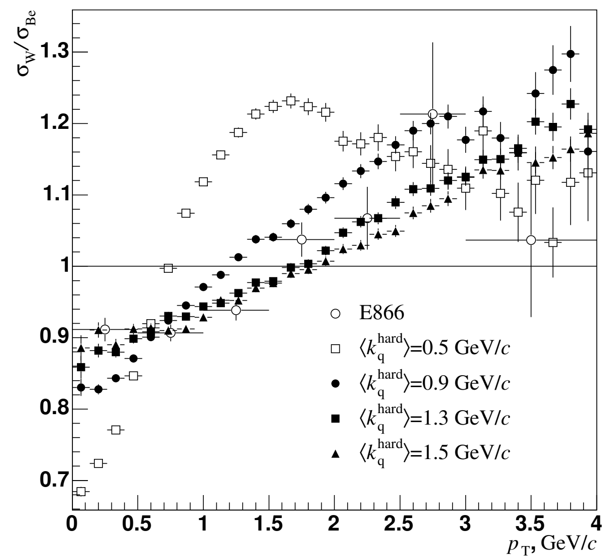

Fig. 4. Ratio of the cross-sections for Drell-Yan events *versus* p_{T} calculated for different $\langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle$ and $\langle k_{\mathrm{V}}\rangle = 0.4$ GeV/c (see the text).

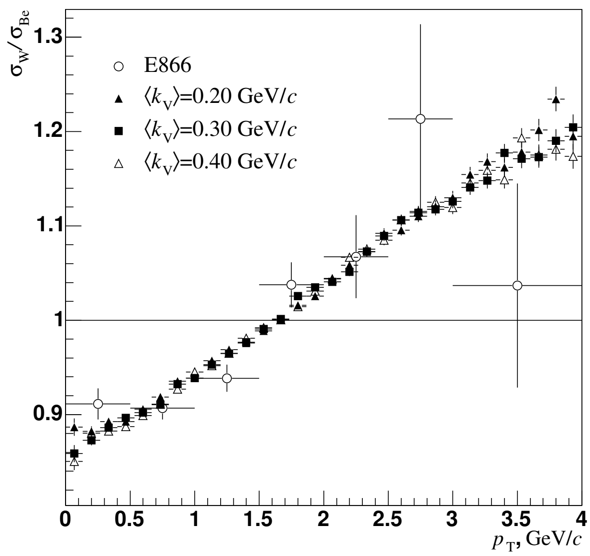

Fig. 5. The same as in fig. 4 but for different $\langle k_{\mathrm{V}}\rangle$ and $\langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle = 1.3$ GeV/c (see the text).

hadron one should calculate the convolution of the distribution function of a valon after n multiple soft collisions $G_{\mathrm{q}}^{n}(k_{\mathrm{T}})$ and the distribution function of the parton inside the valon $F_{\mathrm{V}}(k_{\mathrm{T}})$:

$$\begin{aligned} F_{\mathrm{N}}(k_{\mathrm{T}}) &= G_{\mathrm{q}}^{n} \otimes F_{\mathrm{V}} \\ &= \int \mathrm{d}^2 p_{\mathrm{T}_1} \mathrm{d}^2 p_{\mathrm{T}_2}\, G_{\mathrm{q}}^{n}(p_{\mathrm{T}_1}) F_{\mathrm{V}}(p_{\mathrm{T}_2}) \\ &\quad \times \delta^2(k_{\mathrm{T}} - p_{\mathrm{T}_1} - p_{\mathrm{T}_2})\ . \end{aligned} \tag{7}$$

The distribution function of the parton inside the valon was taken in the following form:

$$F_{\mathrm{V}}(k_{\mathrm{T}}) = \frac{B^2}{2\pi}\, \mathrm{e}^{-Bk_{\mathrm{T}}}\ , \tag{8}$$

where $B = 2/\langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle$, and $\langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle$ is the mean momentum of the parton in the valon.

The HARDPING calculation results with the above treatment of multiple interactions are presented in figs. 4 and 5 for different values of $\langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle$ and $\langle k_{\mathrm{V}}\rangle$. All calculations were performed for $\sigma = 10$ mb, which corresponds to the additive quark model. One can see that the ratio $\sigma_{\mathrm{W}}/\sigma_{\mathrm{Be}}$ is rather sensible to the variations of $\langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle$ and changes weakly with the variations of $\langle k_{\mathrm{V}}\rangle$. The new model gives us much better agreement with the experiment than the previous one. One should estimate the optimal model parameters as

$$\begin{aligned} \sigma &= (8\text{–}10)\ \mathrm{mb}, \\ \langle k_{\mathrm{q}}^{\mathrm{hard}}\rangle &= (0.8\text{–}1.5)\ \mathrm{GeV}/c, \\ \langle k_{\mathrm{V}}\rangle &= (0.2\text{–}0.4)\ \mathrm{GeV}/c. \end{aligned}$$

2.3 Energy loss of fast quarks in nuclear matter

There is another important process which affects the proceeding of hadron-nucleus collisions —the enery loss of fast quarks while travelling through nuclear matter. This process raised also a great interest in the last years; there are a lot of models which are trying to describe such an effect, see, *e.g.*, ref. [28], but unfortunately there is no general agreement on the value of the partonic energy loss rate $\mathrm{d}E/\mathrm{d}z$ neither in cold nor in hot nuclear matter.

Much of the problem originates from the impossibility of direct measurements of this energy loss. And the lack of a common agreement of the processes and mechanisms to be included in specifying the energy loss leads to large differences between the results of each separate experiment. The energy loss in the initial state are usually measured from the data on the A-dependence of the Drell-Yan pair production in proton-nucleus collisions, see, *e.g.*, ref. [12]. In this paper we adopted the model for initial-state quark energy loss described in ref. [11].

It is usually assumed that a quark propagates from the surface of the nucleus to the point where the DY pair is produced, which would mean that the mean quark path in the nucleus would be $\langle L\rangle \approx 3R_{\mathrm{A}}/4$. But, as shown in ref. [29], this value should be shortened by at least the mean free path of a proton in a nucleus, ≈ 2 fm. This would substantially reduce $\langle L\rangle$ by a factor of two or more, so that the mean path between the point of the DY pair production and the first inelastic interaction is actually shorter than the maximum possible distance to the edge of the nucleus. Additionally, there is some probability (dominant for light and medium-heavy nuclei) that the incident hadron has no interactions prior to the point of the DY pair production. In accordance with the above considerations, the mean quark path in the nucleus can be written as [11]

$$\langle L\rangle = (1-W_0)\,\frac{\sigma_{\rm in}^{\rm hN}}{\rm A}\int {\rm d}^2b \int\limits_{-\infty}^{\infty} {\rm d}z_2\,\rho_{\rm A}(b,z_2) \times \int\limits_{-\infty}^{z_2} {\rm d}z_1\,\rho_{\rm A}(b,z_1)\,(z_2-z_1) \times \exp\left[-\sigma_{\rm in}^{\rm hN}\int\limits_{-\infty}^{z_1}{\rm d}z\,\rho_{\rm A}(b,z)\right]. \qquad (9)$$

The exponential factor requires that there is no inelastic interaction of the beam hadron prior to the point z_1. W_0 is the probability of no inelastic interaction of the beam hadron in the nucleus prior to the DY reaction, which can be written as

$$W_0 = \frac{1}{{\rm A}\,\sigma_{\rm in}^{\rm hN}}\int {\rm d}^2b\left[1-{\rm e}^{-\sigma_{\rm in}^{\rm hN}T(b)}\right] = \frac{\sigma_{\rm in}^{\rm hA}}{{\rm A}\,\sigma_{\rm in}^{\rm hN}}\,. \qquad (10)$$

The corresponding probability distribution in L is given by the expression [11]

$$W(L) = W_0\,\delta(L) + W_1(L)\,, \qquad (11)$$

where

$$W_1(L) = \frac{\sigma_{\rm in}^{\rm hN}}{\rm A}\int {\rm d}^2b \int\limits_{-\infty}^{\infty}{\rm d}z_2\,\rho_{\rm A}(b,z_2)\int\limits_{-\infty}^{z_2}{\rm d}z_1\,\rho_{\rm A}(b,z_1) \times\delta(z_2-z_1-L)\exp\left[-\sigma_{\rm in}^{\rm hN}\int\limits_{-\infty}^{z_1}{\rm d}z\,\rho_{\rm A}(b,z)\right]. \qquad (12)$$

The HARDPING procedure to simulate quark energy loss uses two parameters: energy loss rate $-{\rm d}E/{\rm d}z$ (free parameter), and length of a quark path L in a nucleus, which is calculated according to the distribution eq. (11). The results of HARDPING calculations with energy loss rate $-{\rm d}E/{\rm d}z = 3$ GeV/fm are presented in fig. 6, which is the DY cross-section ratios for W to Be as functions of x_1 (the light-cone momentum fraction of the incident proton carried by the produced DY pair) for various intervals of the invariant mass M of the produced DY pairs. We calculated the shadowing for the mean value of mass calculated for each interval as $\sqrt{\langle M^2\rangle}$. One may expect a substantial scale dependence of the nuclear structure functions. However, at the considered ranges of $x_1 \geq 0.3$ and $4 \leq M \leq 8$ GeV/c^2 and within our statistical accuracy this dependence is not seen. From comparison with the experimental data, it is found that our calculated results are in good agreement with the Fermilab E866 data.

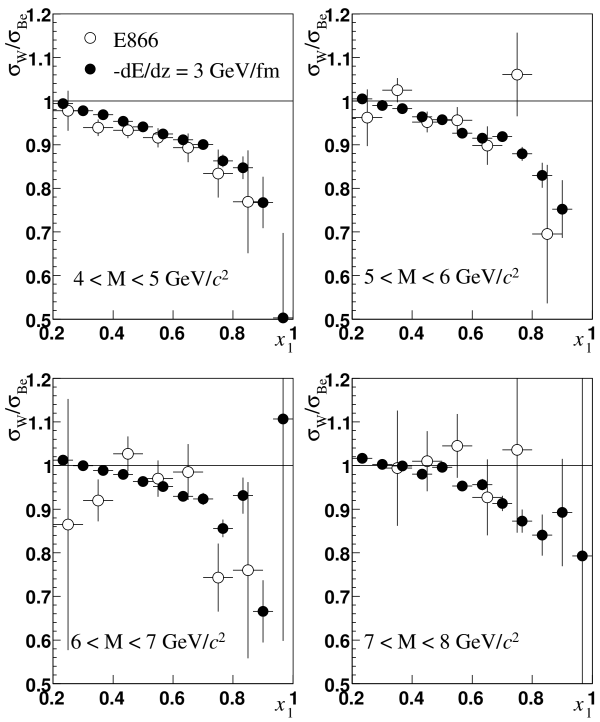

Fig. 6. Ratio of the cross-sections for Drell-Yan events *versus* x_1 calculated for the optimal value of the parton energy loss ratio $-{\rm d}E/{\rm d}z = 3$ GeV/fm. M is the invariant mass of the produced DY pairs.

3 Conclusion

In this work the analysis of the influence of the multiple soft rescatterings and the energy loss of fast-quarks effects on the DY pairs production in proton-nucleus collisions were presented. In order to perform such an analysis we developed a Monte Carlo event generator HARDPING, which extends the HIJING program to the mentioned effects.

The analysis has shown that the proper treatment of multiple soft rescatterings of a quark of the incoming hadron allows to significantly improve the agreement between the simulated and experimental data compared to the original HIJING. The shape of the ratio $\sigma_{\rm W}/\sigma_{\rm Be}$ is very sensitive to variations of the mean momentum of the parton inside the valon $\langle k_{\rm q}^{\rm hard}\rangle$ and the cross-section of the inelastic quark-nucleon interactions σ.

The simulation of the x_1-dependence of the ratio $\sigma_{\rm W}/\sigma_{\rm Be}$ showed that the consideration of the quark energy loss effect improves the agreement with the experimental data. The original HIJING does not take into account this effect, which leads to the contradiction with the data.

However one should be cautious about applying the results of this analysis to higher energies of RHIC and LHC, because at RHIC and LHC energies coherence effects are important. The reason is that coherence length l_c becomes large at high energies compared to the typical internucleon separation, hence the projectile interacts coherently with individual nucleons. Moreover, the initial-state energy loss effect is not really important at the energies of RHIC and LHC. Thus, one can disregard energy loss and test models of shadowing by direct comparison to data.

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