STUDY OF THE MULTIPLICITY OF HADRONS ON NUCLEI

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Abstract–Improved two-scale model with symmetric Lund distribution function is used to perform the fit to semi-inclusive deep-inelastic scattering (SIDIS) data on nuclear targets of HERMES experiment at DESY. The ratio of hadron multiplicity on nuclear target to the deuterium one is chosen as observable, as usually. Some peculiarities of the fit are discussed. The two-parameter's fit gives satisfactory agreement with the data. The results of the present and previous fits are compared.

1. Introduction

Hadronic reactions in a nuclear medium can shed additional light on the hadronization process. In comparison with other reactions electroproduction has the virtue that energy and momentum of the struck parton are well determined, as they are tagged by the scattered lepton. Study of hadron production in SIDIS on nuclear targets offers an opportunity to investigate the quark (string, color dipole) propagation in nuclear matter and the space-time evolution of the hadronization process. For this purpose we investigate the nuclear attenuation (NA), which is a ratio of differential hadron multiplicity on a nucleus to that on deuterium:

$$R_{M}^{h}(\mathbf{v},z) = \frac{\left(N^{h}(\mathbf{v},z)/N^{e}(\mathbf{v})\right)_{A}}{\left(N^{h}(\mathbf{v},z)/N^{e}(\mathbf{v})\right)_{D}},$$

where $z = E_h/v$, E_h and v are energies of the final hadron and virtual photon, $N^h(v, z)$ is the number of semi-inclusive hadrons at given v and z and $N^e(v)$ is the number of inclusive DIS leptons at given v. Subscripts A(D) denote that reaction takes place on nucleus (deuterium). In the above formula more variables like $-Q^2$ (the photon virtuality) and p_t (hadron transverse momentum) over which the NA is averaged, are not written. The simple version of the string model, so-called two-scale model (TSM), was introduced in [1]. In [2] improved version of TSM (ITSM) was proposed. In our previous work [3] ITSM was used for a fitting of the SIDIS data of HERMES experiment on nuclear targets [4]. For the fit we used those versions of the distribution function, which possible to present in the finite form. As a result, two versions were used: (i) the leading hadron distribution function, which corresponds to the term with rank equal one of the distribution function; and (ii) the standard Lund distribution function, which possible to sum analytically over all ranks of hadrons carrying momentum *z*. Unfortunately, more realistic symmetric Lund distribution function it is not possible to sum over all ranks analytically. For this reason it was not included in the fit.

The aim of this work is a fitting similar to that which was done in [3] with using the symmetric Lund distribution function and a comparison of the results of fit with the results of the previous one.

The paper is organized as follows. In section 2 some details of the fitting procedure with symmetric Lund distribution function are discussed. In section 3 we compare results of the present fit with the previous one and discuss them. Conclusions are given in section 4.

2. Some Features of Fit

In the string models, for the construction of fragmentation functions, the scaling functions f(z) are introduced. For calculations we use [5, 6]:

(i) standard Lund scaling, function

$$f(z)=(1+C)(1-z)^{C},$$

where *C* is the parameter which controls the steepness of the standard Lund fragmentation function (C = 0.3);

(ii) symmetric Lund scaling function

$$f(z) = Nz^{-1}(1-z)^{a} \exp(-bm_{\perp}^{2}/z),$$

where *a* and *b* are parameters of the model (a = 0.3, $b = 0.58 \text{ GeV}^{-2}$), $m_{\perp} = \sqrt{m_h^2 + p_{\perp}^2}$ is the transverse mass of final hadron, *N* is normalization factor. We begin by considering the distribution of the constituent formation lengths *l* of hadrons carrying fractional energy *z*. The simplified version without identifying flavor of partons has the form:

$$D_{c}^{h}(L,z,l) = \left(f(z)\delta(l-L+zL) + \sum_{i=2}^{N} D_{ci}^{h}(L,z,l)\right)\theta(l)\theta(L-zL-l),$$

where $L = v/\kappa$ is the full hadronization length, κ is the string tension ($\kappa = 1$ GeV/fm). The functions $D_c^h(L, z, l)$ are distributions of the constituent formation length l of the rank i hadrons carrying fractional energy z. For calculations we use the average value of the formation length $\tau_c = \langle l \rangle$:

$$\tau_{c} = \frac{\int_{0}^{\infty} l dl D_{c}^{h}(L,z,l)}{\int_{0}^{\infty} dl D_{c}^{h}(L,z,l)}$$

The same versions of string-nucleon cross sections, σ^{str} , and the same set of the nuclear density functions (NDF) as in [3] are used for fit. The semi-inclusive data [4] of HERMES experiment on four nuclear targets (helium, neon, krypton, xenon) and deuterium are used. As in previous fit we use one- and two-dimensional data (the one (two) dimensional data means that data are presented as

functions of one (two) variables) for pions, all together 332 experimental points. The fit was performed to tune two parameters: the initial value of string-nucleon cross section σ_q and coefficient *c*.



Fig. 1. $\hat{\chi}^2$ as a function of N_{had} . Left part presents results of .fit with standard Lund distribution function and right part results of fit with symmetric Lund distribution function. Panels (a), (b); (c), (d); (e), (f) correspond NDF 1; NDF 2; NDF 3, respectively. Filled circles, open circles, filled triangles, open triangles are results of fit with σ^{str} corresponding to Eqs. (7), (8), (9), (10) of [3].

The quantitative criterium $\hat{\chi}^2$ was used:

$$\hat{\chi}^{2} = \frac{1}{\left(n_{exp} - n_{par} - 1\right)} \sum_{n=1}^{n_{exp}} \left(\frac{R_{M}^{h}\left(theor\right) - R_{M}^{h}\left(exp\right)}{\Delta R_{M}^{h}\left(exp\right)}\right)^{2},$$

where n_{exp} and n_{par} are numbers of experimental points and parameters; $R_M^h(theor)$ is the theoretical value for ratio at given point; $R_M^h(exp)$ and $\Delta R_M^h(exp)$ are experimental value of R_M^h and its uncertainty at given point.

Let us consider the features of fitting with symmetric Lund scaling function. The corresponding distribution function it is impossible to analytically sum over all ranks of hadrons as in case of standard Lund scaling function, therefore we must restrict ourself to finite sum over ranks of hadrons. The recursion equation from [7] is used for calculation of the distribution functions. We performed fits with the sums of ranks until $n = N_{had}$ and convinced that beginning from $N_{had} = 5$

the values of parameters and $\hat{\chi}^2$ do not change essentially. The close result is obtained for the case of standard Lund scaling function. In this case the results for finite sums for $N_{had} > 5$ practically coincide with the result for infinite sum. Results of fits are presented in Fig. 1. In the left part of Fig. 1 (panels (a), (c), (e)) the results of fit with standard Lund distribution function and in the right part of Fig. 1 (panels (b), (d), (f)) the results of fit with symmetric Lund distribution function are presented. Panels (a), (b); (c), (d); (e), (f) correspond NDF 1; NDF 2; NDF 3, respectively. We would like to remind that NDF 1; NDF 2; NDF 3 corresponds to Eqs. (14); (15); (16) of [3]. Filled circles, open circles, filled triangles, open triangles are results of fit with σ^{str} corresponding to Eqs. (7). (8), (9), (10) of [3].

3. Comparison with Data and Discussion

The result of fit with symmetric Lund distribution function and $N_{had} = 10$ are presented in Table 1. Easily to see that they describe data on quantitative level. Minimum $\hat{\chi}^2 = 0.54$ is obtained for $\sigma^{str}(10)$ and NDF 2 from [3] at values of parameters equal to $\sigma_q = 2.34 \pm 0.14$ mb and $c = 0.088 \pm 0.01$. Comparison with Tables 1 and 2 from [3] shows that values of parameters and $\hat{\chi}^2$ in case of symmetric Lund distribution function are close to those for the case of standard Lund distribution function. Figure 1 shows that the good agreement of the leading hadron approximation with the data is accidental, because the agreement worsens with increasing of N_{had} from 1 to the more realistic values for multiplicity of hadrons. Comparison with the one-dimensional data shows that R_M^h calculated with the parameters obtained in result of fit with symmetric Lund distribution function visually does not differ from others. A small difference there is in case of two dimensional data (filled symbols) from [4], and the one-dimensional data (open symbols) from [8]. The theoretical curves are the results of fit with the standard Lund distribution function – solid curves; with leading hadron distribution function – dashed curves; with the symmetric Lund distribution function – dotted curves.

Table 1. Values of fitting parameters and $\hat{\chi}^2$ in case of Symmetric Lund distribution function and total errors. Numbers in parentheses indicate the corresponding equations from [3].

$\sigma^{str}(7)$				
NDF	$\sigma_q mb$	С	$\hat{\chi}^2$	
1	0.00 ± 0.01	0.365 ± 0.013	1.48	
2	0.00 ± 0.01	0.336 ± 0.011	1.32	
3	0.00 ± 0.01	0.307 ± 0.012	1.30	

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$\sigma^{str}(8)$				
NDF	σ_q mb	С	$\hat{\chi}^2$	
1	1.74 ± 0.16	0.172 ± 0.014	0.81	
2	1.88 ± 0.15	0.163 ± 0.011	0.71	
3	1.84 ± 0.15	0.140 ± 0.009	0.74	
$\sigma^{str}(9)$				
NDF	σ_q mb	С	$\hat{\chi}^2$	
1	0.00 ± 0.01	0.112 ± 0.009	0.75	
2	0.00 ± 0.02	0.088 ± 0.009	0.66	
3	0.00 ± 0.02	0.059 ± 0.009	0.66	
$\sigma^{str}(10)$				
NDF	σ_q mb	С	$\hat{\chi}^2$	
1	2.17 ± 0.13	0.098 ± 0.010	0.61	
2	2.34 ± 0.14	0.088 ± 0.010	0.54	
3	2.43 ± 0.15	0.069 ± 0.010	0.59	

Table 1. (Continued)



Fig. 2. The two-dimensional data. The ratio R_M^h for charged pions on ⁴He (panels a, b) and ²⁰Ne (c, d) nuclei as a function of v (left panels) and z (right panels). Experimental points from [4,8].



Fig. 3. The same as described in the caption of the, Fig. 2 done for ⁸⁴Kr (panels a, b) and ¹³¹Xe (c,d) targets.

4. Conclusions

The HERMES data [4] were used to perform the fit for ITSM with symmetric Lund distribution function. It was shown that using in the fit the distribution of the constituent formation lengths of hadrons presented in the form of finite sum gives the stable result beginning with $n \ge 5$. For the final fit we used the value n = 10. Two-parameter's fit gave satisfactory agreement with data (see Table 1 and Figs. 2 and 3). Comparison with other versions of distribution function used in previous fit showed that the results in the cases of the symmetric and standard Lund distribution functions are close enough.

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