Description of the HERMES Data on Hadronization in Nuclear Medium in Framework of the String Model

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- The TSM and ITSM
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Theoretical Models

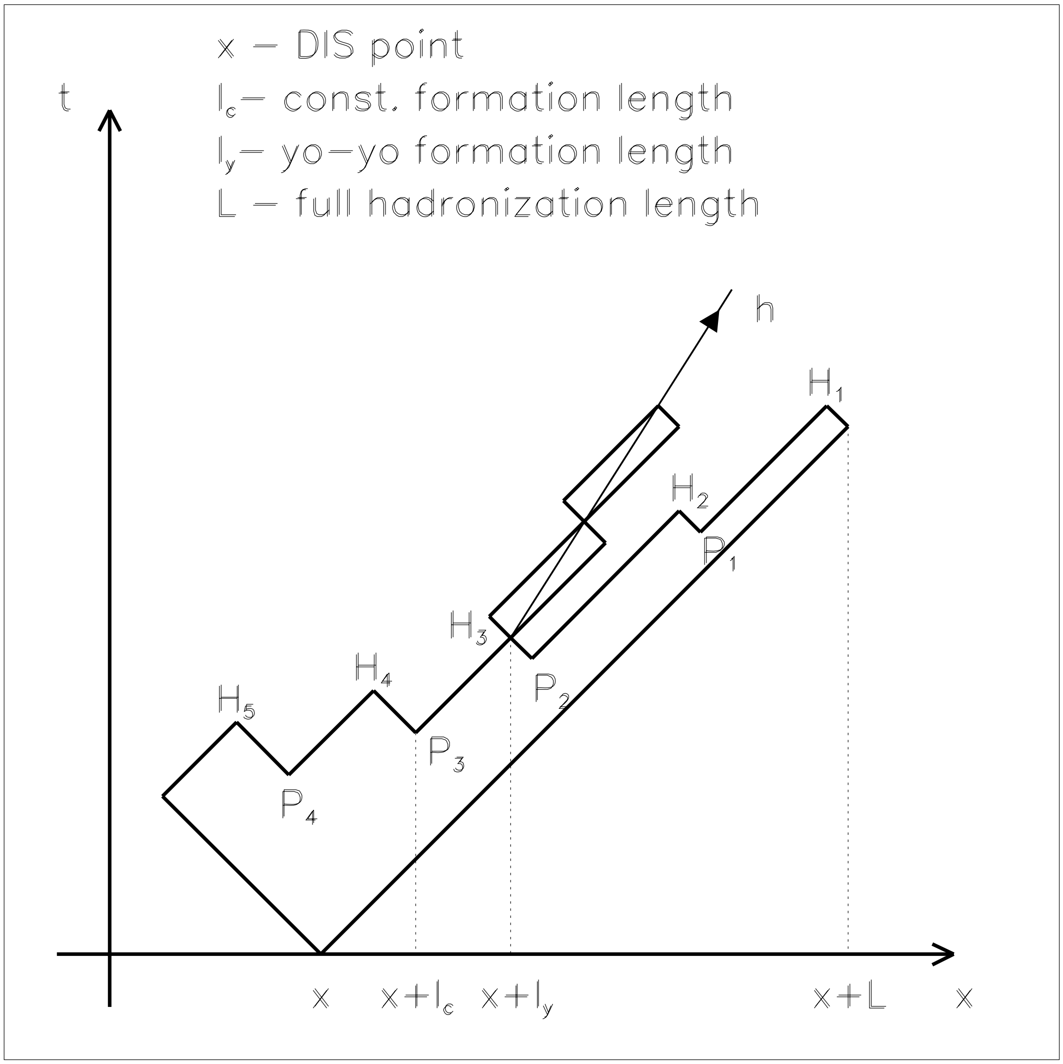
- Rescaling Model
  A.Accardi, V.Muccifora, H.J.Pirner et al.

- Gluon Bremsstrahlung Model
  B.Kopeliovich, J.Nemchik, B.Zakharov et al.

- Energy Loss Model
  X.Guo, M.Gyulassy, X.-N.Wang et al.

- FSI by means of BUU Transport Model
  W.Cassing, T.Falter, K.Gallmeister et al.

- String Model
  B.Andersson et al., Phys.Rep.97(1983)31
  A.Bialas, M.Gyulassy, Nucl.Phys. B291(1987)793
  J.Czyzewski and P.Sawicki, Z.Phys. C56(1992)493
  J.Ashman et al., Z.Phys. C52(1991)1
  N.Akopov, L.Grigoryan, Z.Akopov, hep-ph/0409359 (will be published soon in EPJ C)



Space-time structure of hadronization in the string model. The two constituents of the hadron are produced at different points. The constituents of the hadron h are created at the points P_2 and P_3. They meet at H_3 to form the hadron.

The TSM and ITSM

The Two-Scale Model

J.Ashman et al., Z.Phys. **C52**(1991) 1

The TSM is a purely absorption string model. Basic formula is:

$$R_A = 2\pi \int_0^\infty bdb \int_{-\infty}^\infty dx \rho(b, x) \left[1 - \int_x^\infty dx' \sigma^{str}(\Delta x) \rho(b, x') \right]^{A-1}$$

b, x - coordinates of the DIS point,
$\rho(b, x)$ - nuclear density function,
x'- longitudinal coordinate of the string-nucleon interaction point,
A - atomic mass number,
$\sigma^{str}(\Delta x)$ - the string-nucleon cross section on distance $\Delta x = x' - x$ from DIS point

$$\sigma^{str}(\Delta x) = \theta(\tau_c - \Delta x)\sigma_q + \theta(\tau_h - \Delta x)\theta(\Delta x - \tau_c)\sigma_s + \quad (1)$$

$$+\theta(\Delta x - \tau_h)\sigma_h$$

where σ_q, σ_s and σ_h are the cross sections for interaction with the nucleon of the initial string, open string and final hadron respectively.

τ_c and τ_h are constituent and yo-yo formation times.

$$\tau_h - \tau_c = z\nu/\kappa,$$

where $z = E_h/\nu$, κ - string tension (string constant). Two expressions for τ_c are using:

for hadrons containing leading quark

$$\tau_c = (1 - z)\nu/\kappa \quad (2)$$

B.Kopeliovich, Phys.Lett. **B243**(1990) 141

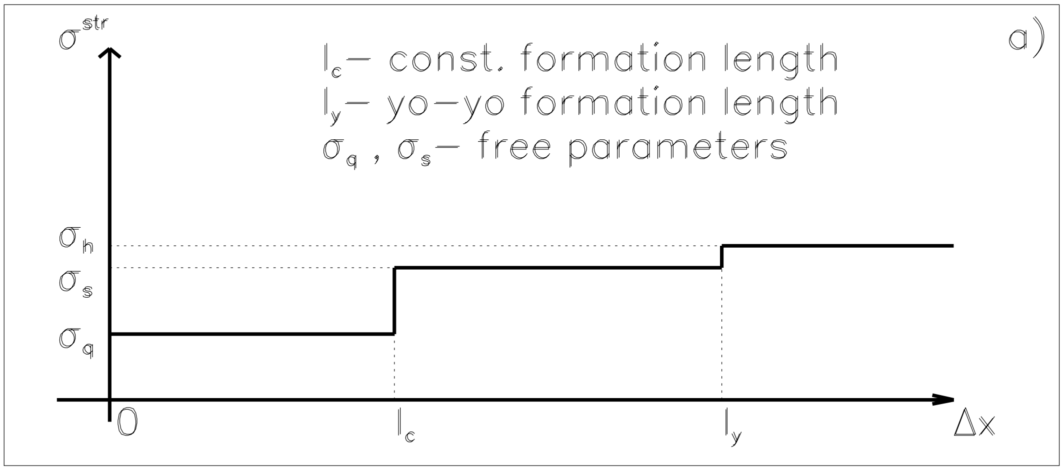
in framework of the standard Lund model

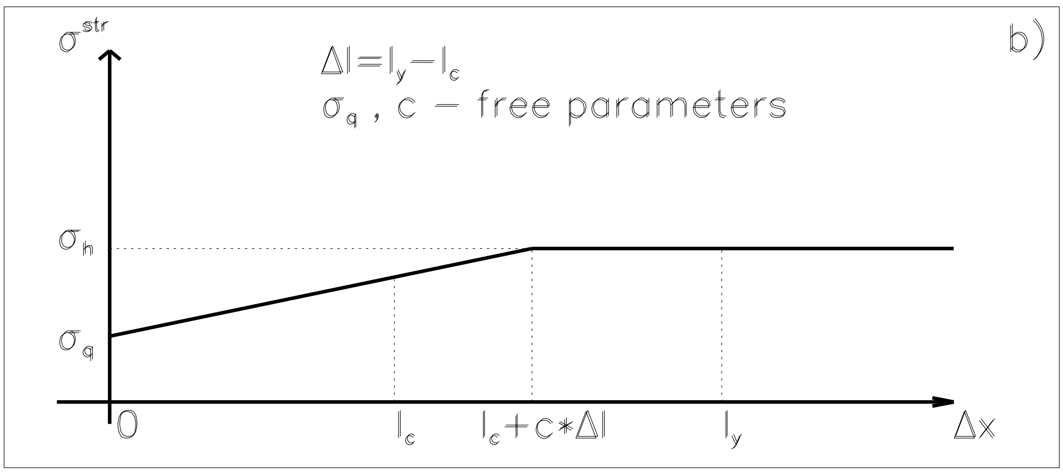
$$\tau_c = \left[\frac{\ln(1/z^2) - 1 + z^2}{1 - z^2}\right]\frac{z\nu}{\kappa} \quad (3)$$

In calculations instead of approximate expression (3) we use the precise expression for τ_c from

A.Bialas, M.Gyulassy, Nucl.Phys. **B291**(1987) 793

In our calculations we also take into account absorption in deuterium, and use the ratio $R_M^h = R_A/R_D$.





a) The behavior of the string-nucleon cross section as a function of distance in the TSM. b) The same as in a) for ITSM taking into account more realistic smoothly increasing string-nucleon cross section.

Improved Two-Scale Model

Some models for the shrinkage-expansion mechanism were applied. We used four versions for the definition of σ^{str}.

G.Farrar et al., Phys.Rev.Lett. **61** (1988) 686

The first version of σ^{str} definition is based on quantum diffusion:

$$\sigma^{str}(\Delta x) = \theta(\tau - \Delta x)[\sigma_q + (\sigma_h - \sigma_q)\Delta x/\tau]+ \quad (4)$$

$$+\theta(\Delta x - \tau)\sigma_h$$

where $\tau = \tau_c + c\Delta\tau$, $\Delta\tau = \tau_h - \tau_c$.

The second version follows from naive parton case:

$$\sigma^{str}(\Delta x) = \theta(\tau - \Delta x)[\sigma_q + (\sigma_h - \sigma_q)(\Delta x/\tau)^2]+ \quad (5)$$

$$+\theta(\Delta x - \tau)\sigma_h$$

Two other expressions for σ^{str} were also used:

$$\sigma^{str}(\Delta x) = \sigma_h - (\sigma_h - \sigma_q)exp(-\frac{\Delta x}{\tau}) \quad (6)$$

and:

$$\sigma^{str}(\Delta x) = \sigma_h - (\sigma_h - \sigma_q)exp(-(\frac{\Delta x}{\tau})^2) \quad (7)$$

Q^2-dependence

QCD predicts the Q^2-dependence of string-nucleon cross section in the form:

$$\sigma_q(Q^2) \sim 1/Q^2; \quad \sigma_s(Q^2_{\tau c}) \sim 1/Q^2_{\tau c}.$$

Using this prediction we can express the cross section for the initial string as

$$\sigma_q(Q^2) = (\hat{Q}^2/Q^2)\sigma_q(\hat{Q}^2).$$

In the same way the expression for the open string cross section can be written as:

$$\sigma_s(Q^2_{\tau c}) = (\hat{Q}^2_{\tau c}/Q^2_{\tau c})\sigma_s(\hat{Q}^2_{\tau c}),$$

where $Q^2_{\tau c} = Q^2(\tau_c)$ is the virtuality of the string in the time interval τ_c after DIS. In order to estimate the ratio of $\hat{Q}^2_{\tau c}/Q^2_{\tau c}$ we adopt the scheme supposing that during time t the quark decreases its virtuality from the initial Q^2 to the value $Q^2(t)$ as follows

$$Q^2(t) = \nu(t)\frac{Q^2}{\nu(t) + tQ^2},$$

where $\nu(t)$ = ν -κt.

Results for Fragmentation

For κ value determined by the Regge trajectory slope was used:

$$\kappa = 1/(2\pi\alpha'_R) = 1GeV/fm$$

The Nuclear Density Functions (NDF) were used as follows:
for deuterium the Hard Core Deuteron Wave Functions were used

R.V.Reid, Annals of Physics **50** (1968) 411

For ^{4}He and ^{14}N, the Shell Model was used

L.Elton, ”Nuclear Sizes” Oxford University Press, 1961, p.34

$$\rho(r) = \rho_0\left(\frac{4}{A} + \frac{2}{3}\frac{(A-4)}{A}\frac{r^2}{r_A^2}\right)exp\left(-\frac{r^2}{r_A^2}\right),$$

where r_A=1.31 fm for ^{4}He and r_A=1.67 fm for ^{14}N.

For ^{20}Ne, ^{84}Kr and ^{131}Xe the Woods-Saxon distribution was used

$$\rho(r) = \rho_0/(1 + exp((r - r_A)/a)).$$

These three sets of NDF's were used for the fitting with the following corresponding parameters:

First set (A.Bialas et al., Phys.Lett. **B133** (1983) 241)

$$a = 0.54\ fm \quad r_A = (0.978 + 0.0206A^{1/3})A^{1/3}\ fm \tag{8}$$

Second set (A.Bialas et al., Nucl.Phys. **B291** (1987) 793)

$$a = 0.54\ fm \quad r_A = \left(1.19A^{1/3} - \frac{1.61}{A^{1/3}}\right)\ fm \tag{9}$$

Third set (A.Capella et al., Phys.Rev. **D18** (1977) 3357)

$$a = 0.545\ fm \quad r_A = 1.14A^{1/3}\ fm. \tag{10}$$

where the values of ρ_0 are determined from the normalization condition:

$$\int d^3r\rho(r) = 1$$

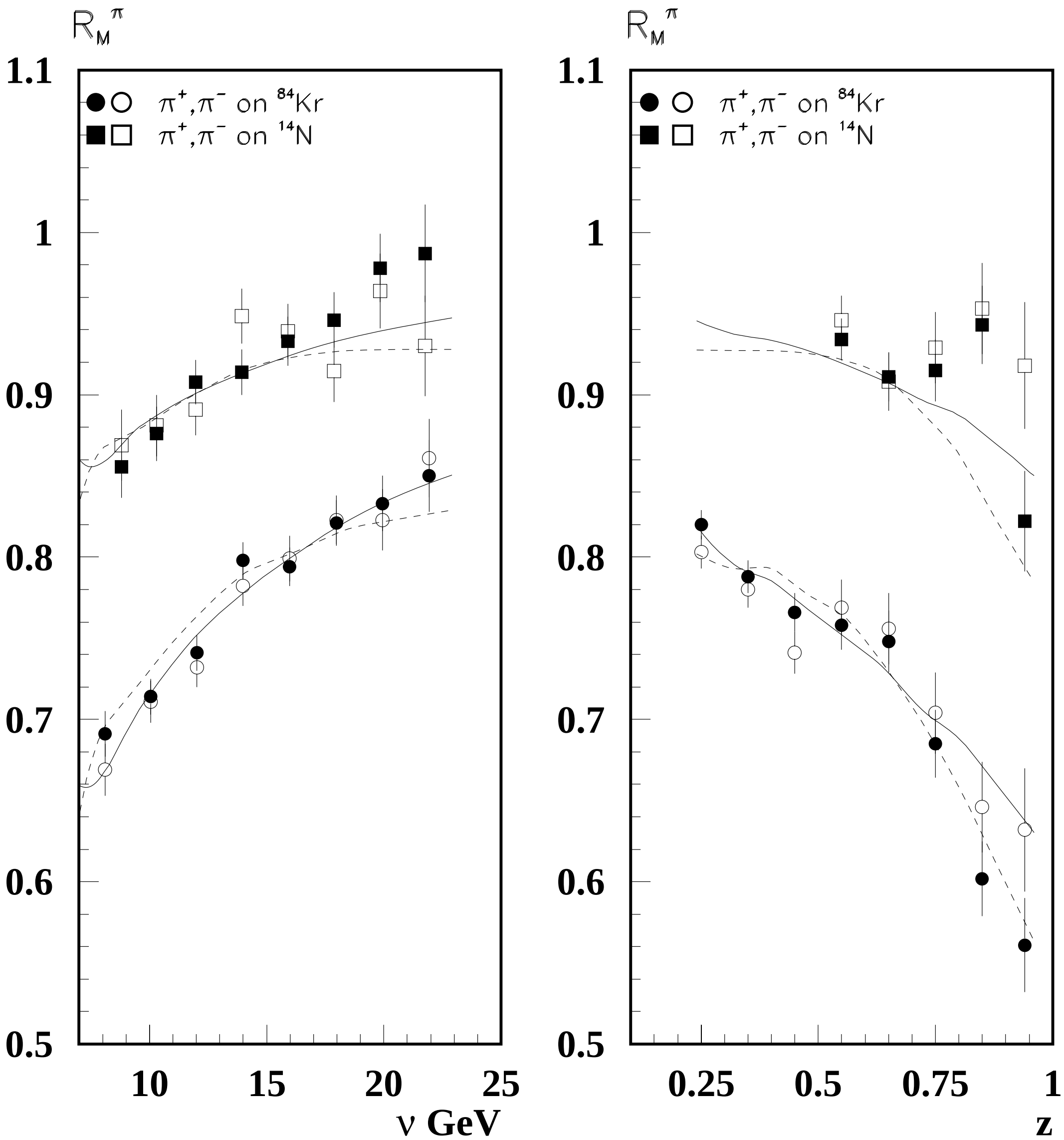
The Fit

The fit was performed based on published HERMES data for nuclear attenuation of π^+ and π^- mesons on nitrogen and krypton nuclei:

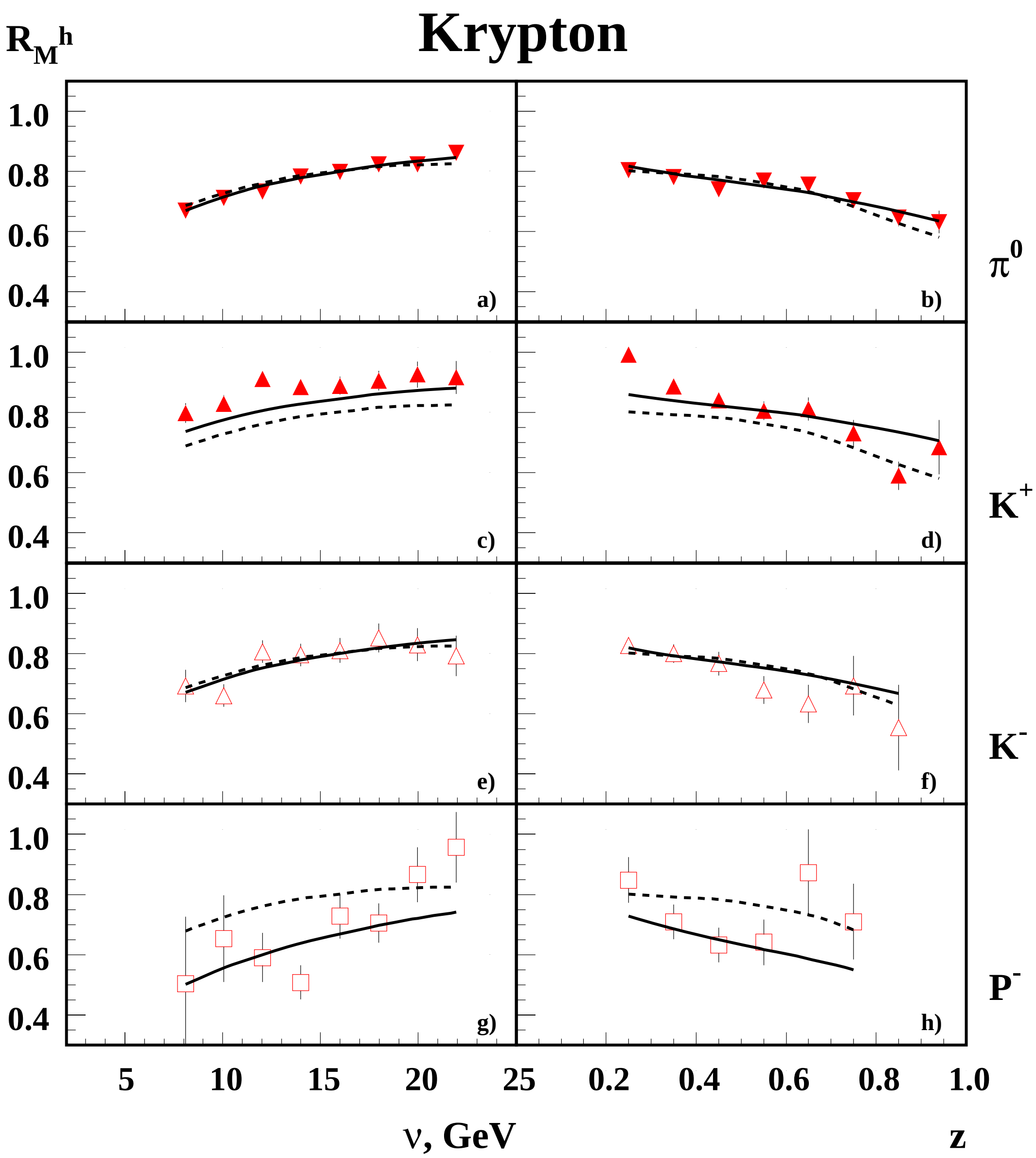
A.Airapetian et al., Eur.Phys.J. **C20** (2001) 479

A.Airapetian et al., Phys.Lett. **B577** (2003) 37

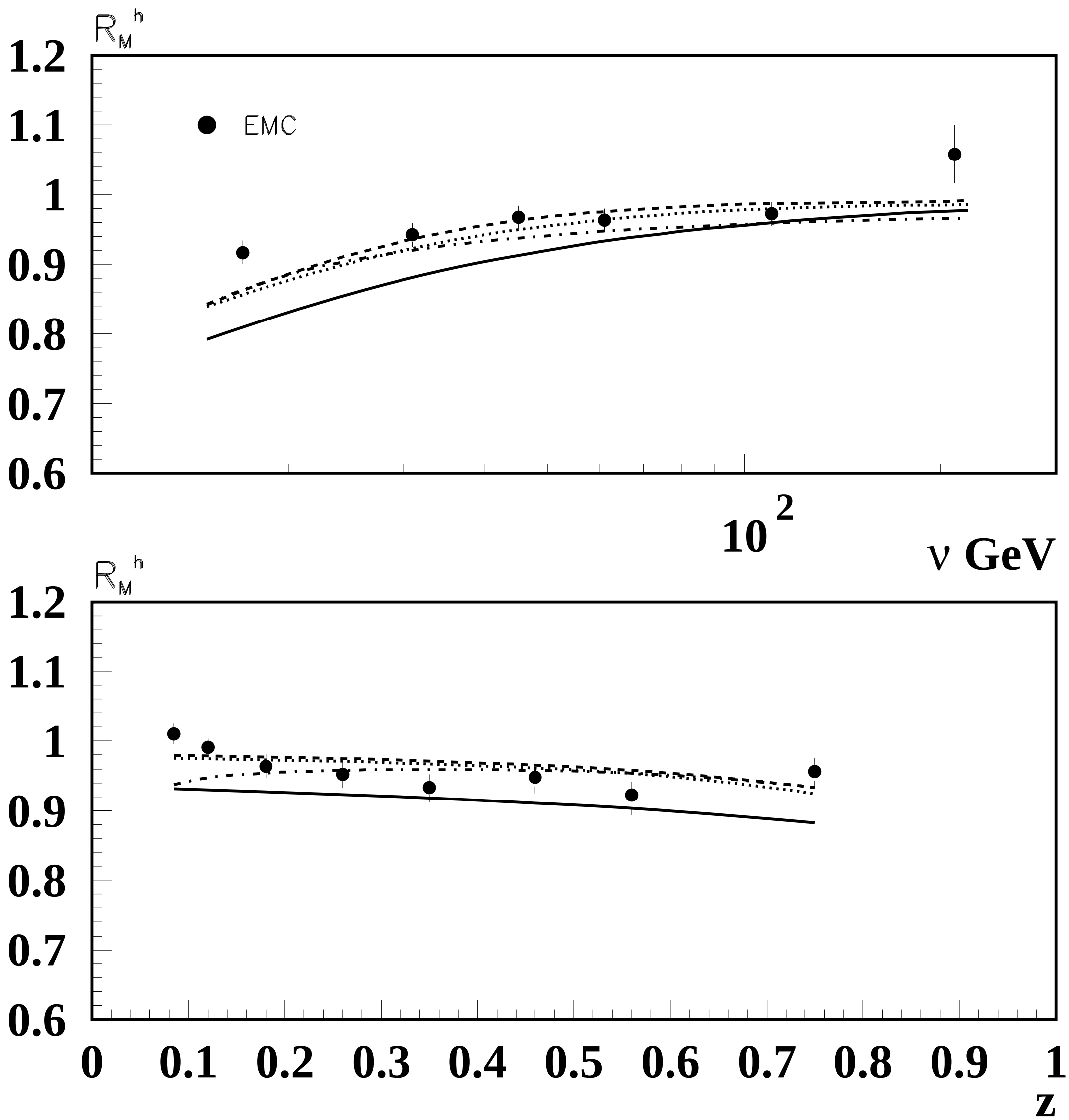
For τ_c two expressions (2)-(3) were used. For $\sigma^{str}(\Delta x)$ one expression (1) in TSM and four different expressions (4)-(7) in ITSM were used. For NDF of krypton three different sets of parameters (8)-(10) were used. The values of σ_h (hadron-nucleon inelastic cross section) used in the fit were set equal to: $\sigma_{\pi+} = \sigma_{\pi-}$ = 20 mb. Two parameters were determined from the fit. In case of TSM and ITSM they are σ_q, σ_s and σ_q, c, respectively. The values of σ_h that were used in calculations are as follows: $\sigma_{\pi^0} = \sigma_{K-}$ = 20 mb, σ_{K+} = 14 mb and $\sigma_{\bar{p}}$ = 42 mb. Results of fit are presented in Table 1 for TSM version, and in Tables 2-3 for ITSM version. The curves correspond to the TSM and ITSM model calculations with the best set of parameters are presented on subsequent three figures.



Hadron multiplicity ratio R_M^π of charged pions for ^{14}N and ^{84}Kr nuclei as a function of ν (left panel) and z (right panel). The solid curves correspond to the ITSM. Minimum value of χ^2 (best fit) is obtained for σ^{str} in form (4) and τ_c in form (2), at the values of parameters: σ_q=0.46 mb, c=0.32. The dashed curves correspond to the TSM. Now best fit correspond τ_c in form (3), at the values of parameters: σ_q=4.2 mb, σ_s=16.6 mb. In both versions best fit is obtained for NDF (8) for ^{84}Kr. These data were included in fit and curves were obtained in a result of fit.



Hadron multiplicity ratio R_M^h of different species of hadrons produced on ^{84}Kr target as a function of ν (left panel) and z (right panel). These data did not included in fit. The curves are calculated with the values of parameters corresponding to the best fit.



The ratio R_M^h for charged hadrons for ^{63}Cu as a function of ν (upper panel) and z (lower panel). The solid, dashed and dotted curves correspond to three sets of parameters with the minimal values of $\chi^2/d.o.f.$ in case of ITSM (see Tables 2 and 3): solid - NDF (8), σ^{str} (4), τ_c (2), σ_q=0.46 mb, c=0.32, $\chi^2/d.o.f.$=1.4; dashed - NDF (9), σ^{str} (5), τ_c (3), σ_q=1.0 mb, c=0.17, $\chi^2/d.o.f.$=1.5; dotted - NDF (8), σ^{str} (7), τ_c (3), σ_q=1.5 mb, c=0.103, $\chi^2/d.o.f.$=1.5. The dashed-dotted curves correspond to the best set of parameters in case of TSM (see Table 1): NDF (8), τ_c (3), σ_q=4.2 mb, σ_s=16.6 mb, $\chi^2/d.o.f.$=2.3.

	$\tau_C(2)$			$\tau_C(3)$		
NDF	σ_q (mb)	σ_s (mb)	χ^2 /d.o.f.	σ_q (mb)	σ_s (mb)	χ^2 /d.o.f.
(8)	5.3±0.01	17.1±0.08	4.3	4.2±0.01	16.6±0.07	2.3
(9)	5.5±0.01	17.7±0.08	4.5	4.3±0.01	17.3±0.07	2.4
(10)	5.8±0.01	18.3±0.08	4.8	4.4±0.01	18.1±0.07	2.6

Table 1: The **TSM**: the best values for the fitted parameters and $\chi^2/d.o.f.$ (N_{exp} = 58, N_{par} = 2).

	$\sigma^{str}(4)$			$\sigma^{str}(5)$		
NDF	σ_q (mb)	c	χ^2 /d.o.f.	σ_q (mb)	c	χ^2 /d.o.f.
(8)	0.46±0.02	0.32±0.03	1.4	3.5±0.01	0.23±0.002	1.9
(9)	0.62±0.01	0.31±0.01	1.7	3.7±0.01	0.22±0.02	2.1
(10)	0.78±0.02	0.30±0.03	1.8	3.9±0.01	0.21±0.003	2.3

	$\sigma^{str}(6)$			$\sigma^{str}(7)$		
NDF	σ_q (mb)	c	χ^2 /d.o.f.	σ_q (mb)	c	χ^2 /d.o.f.
(8)	1.1±0.01	0.15±0.03	2.1	3.7±0.01	0.15±0.02	2.3
(9)	1.3±0.02	0.15±0.03	2.4	3.9±0.01	0.14±0.02	2.6
(10)	1.5±0.02	0.14±0.03	2.8	4.1±0.01	0.14±0.02	2.9

Table 2: The **ITSM**: $\tau_c(2)$. The best values for the fitted parameters and $\chi^2/d.o.f.$ (N_{exp} = 58, N_{par} = 2).

	$\sigma^{str}(4)$			$\sigma^{str}(5)$		
NDF	σ_q (mb)	c	χ^2 /d.o.f.	σ_q (mb)	c	χ^2 /d.o.f.
(8)	0.0±0.001	0.56±0.02	4.6	0.97±0.01	0.17±0.002	1.6
(9)	0.0±0.002	0.53±0.02	4.3	1.0±0.02	0.17±0.02	1.5
(10)	0.0±0.002	0.49±0.006	4.0	1.1±0.02	0.16±0.02	1.6

	$\sigma^{str}(6)$			$\sigma^{str}(7)$		
NDF	σ_q (mb)	c	χ^2 /d.o.f.	σ_q (mb)	c	χ^2 /d.o.f.
(8)	0.0±0.001	0.24±0.02	3.0	1.5±0.02	0.103±0.02	1.5
(9)	0.0±0.002	0.21±0.02	2.9	1.7±0.02	0.096±0.02	1.6
(10)	0.0±0.002	0.18±0.02	2.8	1.8±0.02	0.089±0.02	1.8

Table 3: The **ITSM**: $\tau_c(3)$. The best values for the fitted parameters and χ^2/d.o.f. (N_{exp} = 58, N_{par} = 2).

Conclusions 1

- The HERMES data for ν- and z - dependencies of NA of π^+ and π^- mesons on two nuclear targets (^{14}N and ^{84}Kr) were used to perform the fit of the TSM and ITSM.
- The χ^2 criterion was used for the first time for such kind of analysis, to perform comparion with the NA data.
- Two-parameter fit demonstrates satisfactory agreement with the HERMES data. Minimum χ^2 (best fit) was obtained for the ITSM, including expressions (4) for σ^{str} and (2) for τ_c. The published HERMES data do not give the possibility to make a choice between expressions (4)-(7), as well as to make a distinct preference of definitions (2) or (3) for τ_c, because they give close values of χ^2.
  Preferable NDF's are set (8) and (9).
- More precise data that is expected from HERMES will provide essentially better conditions for the choice of preferable version of the model and preferable expressions for σ^{str} and τ_c.
- In all versions we have obtained that $\sigma_q \ll \sigma_h$. This indicates that at early stage of hadronization process the Color Transparency takes place.

Double Hadron Attenuation

J.Czyzewski, Phys.Rev. **C43** (1991) 2426

The semi-inclusive leptoproduction process of two hadrons on nucleus of atomic mass number A is:

$$l_i + A \rightarrow l_f + h_1 + h_2 + X$$

The nuclear attenuation ratio for that process is defined as:

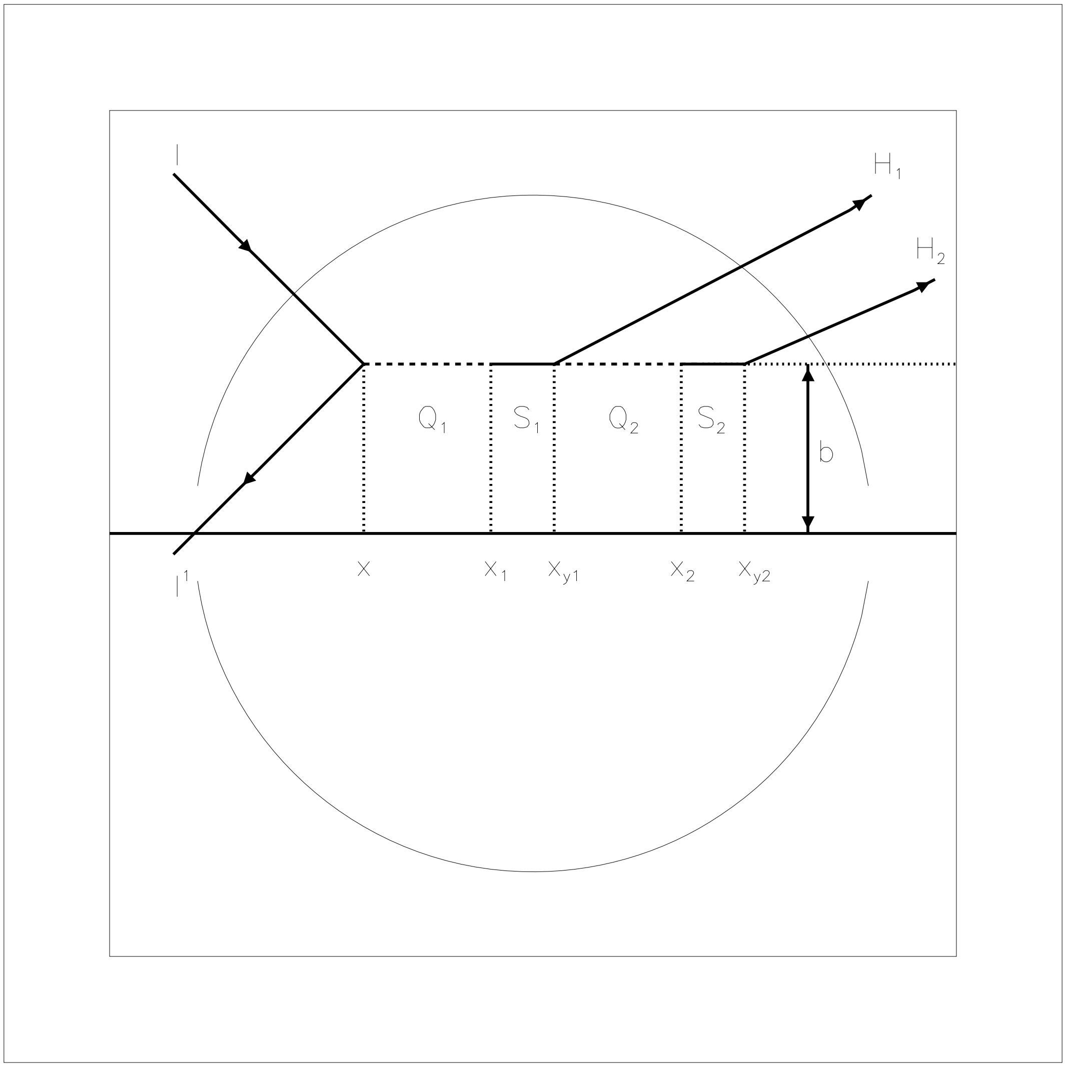
$$R_M^{2h} = 2d\sigma_A(\nu, Q^2, z_1, z_2)/Ad\sigma_D(\nu, Q^2, z_1, z_2),$$

DIS take place at the point (b, x). First constituents arises at the points (b, x_1) and (b, x_2). Second constituents at points(b, x_{y1}) and (b, x_{y2}).

There are simple connections between these points:

x_{y1}-x_1=$z_1 L$ and x_{y2}-x_2=$z_2 L$

L is the full hadronization length, L = ν/κ, κ is string tension (string constant).



Leptoproduction of two-hadron system from a nuclear target

Double attenuation ratio can be expressed as

$$R_M^{2h} \approx \frac{1}{2}\int d^2b \int_{-\infty}^{\infty} dx \int_x^{\infty} dx_1 \int_{x_1}^{\infty} dx_2 \rho(b,x)$$

$$[D(z_1, z_2, x_1 - x, x_2 - x) W_0(h_1, h_2; b, x, x_1, x_2) +$$

$$+ D(z_2, z_1, x_1 - x, x_2 - x) W_0(h_2, h_1; b, x, x_1, x_2)]$$

W_0 is the probability that neither the hadrons h_1, h_2 nor intermediate state leading to their production (initial and open strings) interact inelastically in nuclear matter:

$$W_0(h_1, h_2; b, x, x_1, x_2) = (1 - Q_1 - S_1 - (H_1 + Q_2 + S_2 + H_2 -$$

$$- H_1(Q_2 + S_2 + H_2)))^{(A-1)},$$

The probabilities Q_1, Q_2, S_1, S_2, H_1, H_2 can be calculated using the general formulae:

$$P(x_{min}, x_{max}) = \int_{x_{min}}^{x_{max}} \sigma_P \rho(b,x) dx,$$

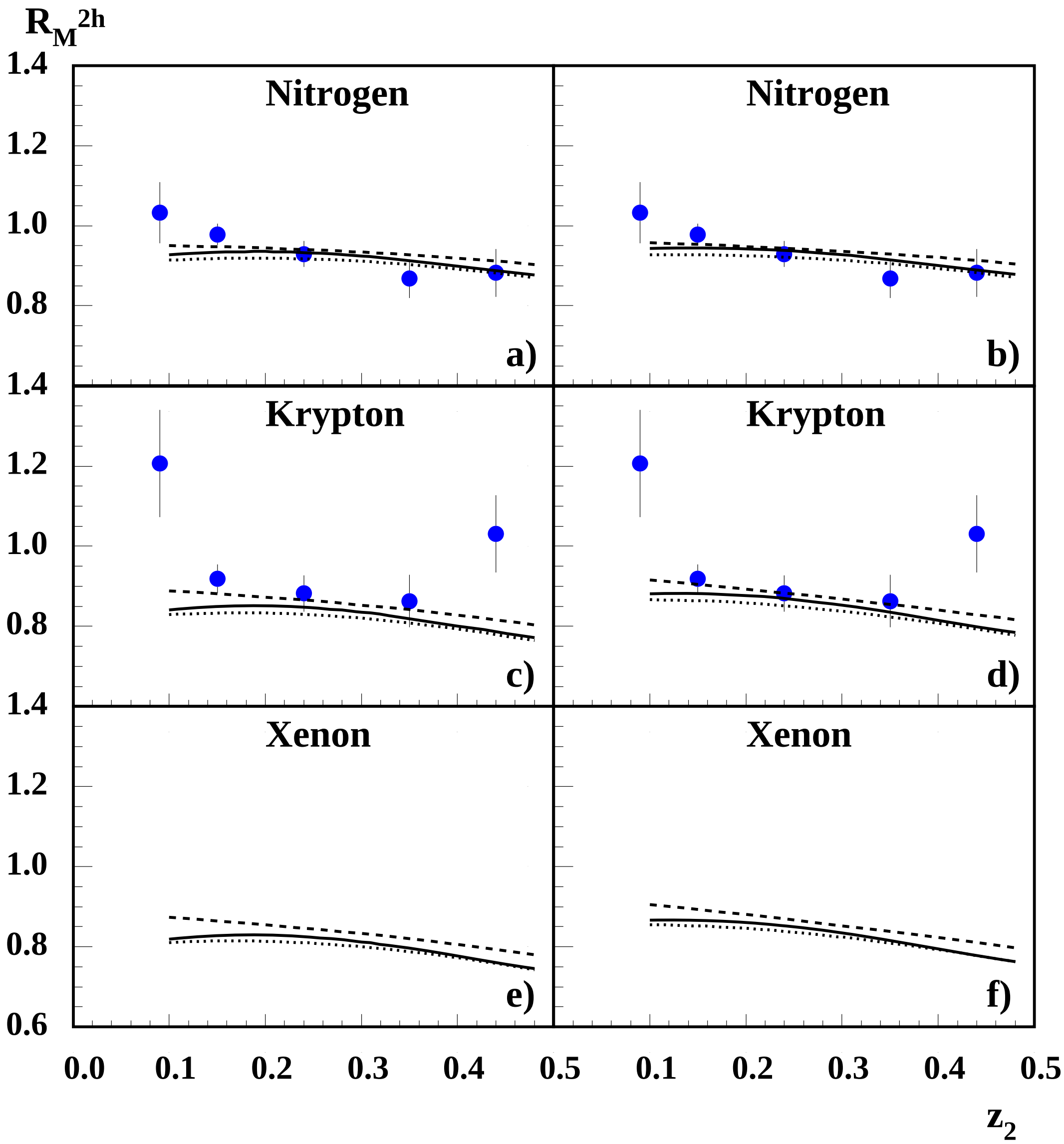
Experimental situation

Recently HERMES obtained for the first time the data on double hadron attenuation.

P.Di Nezza [HERMES Collaboration], J.Phys. **G30** (2004) S783

The following double ratio for leading and subleading hadrons has been considered:

$$R_M^{2h}(z_2) = (d^2N(z_1, z_2)/dN(z_1))_A/(d^2N(z_1, z_2)/dN(z_1))_D$$



Double ratio R_M^{2h} as a function of z_2 with $z_1 > 0.5$. Curves are results of calculations, points are premilinary experimental data of HERMES Collaboration. Only the charge combinations of leading and subleading hadrons: ++, - -, +0, 0+, -0, 0-, 00 were included in experimental data. Curves on panels a), c), e) correspond the case of full attenuation of two-hadron system; while curves on panels b), d), f) obeys additional condition that only first produced hadron attenuates (maximal screening).

Conclusions 2

- String model gives natural and simple mechanism for description of two-hadron attenuation, which allows using the set of parameters obtained for single hadron attenuation, without additional fit satisfactory describe the available experimental data.
- In calculations we used pions only, supposing that contribution of other hadrons in multiplicity is considerably smaller. It will be very useful for us to have data for identified pions.
- Comparison with experimental data for z_2-dependence show that difference between versions is smaller than experimental errors, consequently, different versions of model can not be distinguished by means of comparison with these data.
- As follows from the results, double ratio has a weak sensitiveness to the mutual screening of hadrons for z_2-dependence.
- Theoretical curves satisfactory describes data for nitrogen. For krypton situation is more ambiguous. While three middle points describes satisfactory, two extreme points corresponding lower and higher values of z_2 describes worse. Possible cause is that model do not contain ingredients, necessary for description of these points. From our point of view, experimental point at z_2=0.09 is higher than unity, because in nucleus part of subleading hadrons are protons, which copiously produced at small z, and in this region have value of NA ratio larger than unity. Concerning point at z_2=0.44. We suppose considerable contribution from pairs of pions appeared in result of breaking of coherently produced diffractive ω-mesons, which are proportional to A^2. In result, NA ratio for heavy nuclei raises.
- It is interesting to study also other aspects of two-hadron production in nuclear medium. For instance we propose to analyse the ν - dependence integrated over z_1 and z_2.