SEARCH FOR Z-SCALING VIOLATION
IN $p-p$ AND $p-A$ COLLISIONS AT HIGH ENERGIES

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Abstract

New analysis of experimental data on hadron ($\pi^\pm, K^\pm, \bar{p}$) production at high-$p_T$ in $p-p$ and $p-D$ collisions in z-presentation is performed. Data on inclusive cross sections of cumulative particles produced in backward hemisphere in $p-A$ collisions are analyzed as well. The scaling function for nuclear targets (Li, Be, C, Al, Cu and Ta) are constructed and compared with high-$p_T$ data z-presentation. The hypothesis on z-scaling violation as a signature of new physics phenomena is discussed.

Key-words: high energy, hard proton-proton and proton-nucleus collisions, cumulative particles, scaling

1 Introduction

The numerous results obtained from data analysis for high-$p_T$ particle production in $p-p$ and $p-A$ collisions at high energy show that z-scaling reflect general properties of particle formation. Data z-presentation can be obtained using the experimental observables, the momentum and the inclusive cross section $E d^3\sigma/dq^3$ of produced particle at given energy $\sqrt{s}$ and the multiplicity density of charged particles $dN/d\eta|_{\eta=0} = \rho(s)$.

As argued in [1, 2, 3, 4, 5] the scaling function $\psi(z)$ describes the probability density to form a particle with formation length $z$. The scaling variable $z$ reveals the property of fractal measure. It means that the formation length increases with the scale resolution.

Therefore the violation of z-scaling is of interest to search for new phenomena in particle and nuclear physics.

In the paper experimental data [8] for charged hadrons ($\pi^\pm, K^\pm, \bar{p}$) produced in $p-p$ and $p-D$ at $p_{lab} = 400$ and 800 GeV/c obtained at Fermilab are analyzed and compared with results obtained at $p_{lab} = 70, 200, 300$ and 400 GeV/c before.

Data sets [9] for cumulative particle production in $p-A$ collisions are analyzed in the z-presentation as well. Assuming that the shape of the scaling curve $\psi(z)$ is the same as for high-$p_T$ data [8, 14, 11] the angular dependence of multiplicity particle density for backward hemisphere particles production [9] is found.

The obtained results allowed us to compare different data sets and point out the kinematical regions interested for search for new physics phenomena.

1 See contributions presented by I.Zborovský, G.Škoro and M.Tokarev
2 Hadron production in $p − p$ and $p − D$ at high-$p_T$

Experimental data sets [10, 11] and [8] of inclusive cross sections for $\pi^\pm, K^\pm, \bar{p}$ hadrons produced in $p − p$ and $p − D$ collisions at high transverse momentum $p_T$ are analyzed. The experimental data [11] includes the cross sections for $p − p$ and $p − D$ collisions for $\pi^\pm, K^\pm, \bar{p}$ hadrons produced at 70 GeV/c over the range $1.5 < p_T < 4.0$ GeV/c. The measurements were made at an angle corresponding to approximately 90° in the nucleon-nucleon center-of-mass frame. Data [8] used in our new analysis corresponds to cross sections for $\pi^\pm, K^\pm, \bar{p}$ hadron production in $p − p$ and $p − D$ collisions at $p_{lab} = 400$ and 800 GeV/c. The produced particles were registered over the transverse momentum range of $p_T = 4.0 − 10.0$ GeV/c and at $\theta_{cm} \approx 90^0$.

2.1 $p − p$ collisions

In this section we study the properties of $z$-scaling for hadrons produced in $p − p$ collisions. We verify the hypothesis of energy scaling for data $z$-presentation for hadron production in $p − p$ collisions using the available experimental data [10, 11] and [8]. The energy scaling for data $z$-presentation means that the shape of the scaling curve is independent of the collision energy $\sqrt{s}$.

Figures 1(a) and 2(a) show the dependence of the cross section $E d^3\sigma/dq^3$ of $\pi^+$ and $K^-$ produced in $p − p$ on transverse momentum $p_T$ at $p_{lab} = 70, 200, 300, 400$ and 800 GeV/c and the angle $\theta_{cm} \approx 90^0$. Note that the data cover the wide transverse momentum range, $p_T = 1 − 10$ GeV/c.

The hadron spectra have a power behavior and demonstrate the strong energy dependence increasing with the transverse momentum.

Figures 1(b) and 2(b) show $z$-presentation of the same data sets. Taking into account the experimental errors we can conclude that the scaling function $\psi(z)$ demonstrates an energy independence over a wide energy and transverse momentum range at $\theta_{cm} \approx 90^0$.

We found that new data [8] included in the analysis give no indications on $z$-scaling violation. The result is the new confirmation of energy independence of data $z$-presentation.

2.2 $p − D$ collisions

The study of the energy independence of data $z$-presentation for $p − D$ collisions is especially interest. It is connected with the possibility to investigate the influence of nuclear matter on particle formation. We assume that in the high-$p_T$ range the effects can give direct information on the state of nuclear medium which determines the properties of particle formation. Moreover as shown in [8] due to A-dependence of data $z$-presentation the scaling functions for different nuclei from $D$ to $Pb$ are coincide each other if the scaling transformation $z \rightarrow \alpha(A) \cdot z$, $\psi \rightarrow \alpha^{-1}(A) \cdot \psi$ depending on the single parameter, the atomic weight $A$ is used. It means that the lightest nucleus, deuterium, can be a good target to search for a signature of nuclear phase transition at high-$p_T$. Let us remind that the quantitative measure of $z$-scaling violation and consequently one of the possible signatures of new physics phenomena is the change of the anomalous fractal dimension $\delta$.

Figures 3(a) and 4(a) show $p_T$-presentation of inclusive cross section $E d^3\sigma/dq^3$ of $\pi^+$ and $K^-$ produced in $p − D$ at $p_{lab} = 70$ and 400 GeV/c and the angle $\theta_{cm}^{NN} \approx 90^0$. Note that the data [8] are in a good agreement with the data obtained by Cronin group [11] at
$p_{lab} = 400$ GeV/c.

As seen from Figures 3(b) and 4(b) $z$-presentation for all data sets [10, 11] and [8] demonstrate the energy independence. It means that $A$-dependence of $z$-presentation is correctly described by the function $\alpha(A) = 0.9A^{0.15}$ established in [5].

Thus we can conclude that data [8] for $p - D$ collisions included in the new analysis do not give any indications on $z$-scaling violation up $z \simeq 20$.

2.3 $z - p_T$ plot

To determine the kinematical region preferable for searching for the scaling violation $z - p_T$ plot is suggested to use.

Figure 5 shows the dependence of $z$ as a function of transverse momentum $p_T$ for $p - p$ (a) and $p - D$ (b) collisions at $p_{lab} = 70, 200, 400$ and $800$ GeV/c and $\theta_{cm} \simeq 90^0$. The results of present analysis allow us to conclude that the systematic experimental study of high-$p_T$ particle spectra for $p - p$ and $p - D$ collisions at $z > 10$ is necessary to determine the asymptotic behavior of the scaling function $\psi(z)$. The kinematical region $z > 10$ is more preferable to search for $z$-scaling violation.

3 Cumulative particle production in $p - A$

Cumulative particles are called particles produced in the kinematical region forbidden for free nucleon-nucleon interaction [12, 15]-[20]. Such particles can be only produced in the processes with participation of nuclei (in hadron-nucleus, nucleus-nucleus and lepton-nucleus collisions).

Inclusive cross sections $Ed^3\sigma/dq^3$ for $\pi^\pm, K^\pm, p^\pm$ hadron production in backward hemisphere in $p - A$ collisions at $p_{lab} = 400$ GeV/c and at the angle $\theta_{lab}$ of $70^0, 90^0, 118^0$ and $160^0$ are presented in [9]. The measurements were performed over the momentum range $0.2 < p < 1.25$ GeV/c. Nuclear targets, Li, Be, C, Al, Cu and Ta were used. The data cover in particular the kinematical range forbidden for particle production in nucleon-nucleon collisions.

In the paper we restrict ourselves of the analysis of data [9] obtained at Batavia. More complete analysis of cumulative data sets will be presented elsewhere.

Figures 6(a) and 7(a) present the inclusive cross sections for $\pi^+$ mesons produced in backward hemisphere in $p - Be$ and $p - Ta$ collisions at $p_{lab} = 400$ GeV/c and the angle $\theta_{lab}$ of $70^0, 90^0, 118^0$ and $160^0$. As seen from Figures 6(a) and 7(a) the strong dependence of cross sections as $\theta_{lab}$ changes from $70^0$ to $160^0$ is observed for all nuclear targets, Li, Be, C, Al, Cu, Ta.

We assume that the shape of the scaling curve will be the same as for data points corresponding to the high-$p_T$ region. At present there are not experimental data on the angular dependence of $\rho(s, \eta, A)$ for particles produced in backward hemisphere in order to construct directly the scaling function. Therefore we study the possibility to describe the shape of the $\psi(z)$ found from the analysis of high-$p_T$ data sets [11, 10, 8] using data points [9]. The function $\rho(s, \eta, A)$ is parameterized in the form $\rho(s, \eta, A) = \rho(s, A)|_{\eta=0} \cdot \chi(\theta, A)$, where the angular dependence is described by $\chi(\theta, A)$. The latter is shown in Figure 8(a).

As seen from Figure the ratio $\chi_{Ta}/\chi_{Li}$ decreases from 3.5 to 1.5 as the angle $\theta_{lab}$ increases from $70^0$ to $160^0$. The $A$-dependence of the ratio demonstrates the saturation reached for backward particle production.
Figures 6(b) and 7(b) show the $z$-presentation of data [9]. One can see that the curve found for nuclei $Be$ and $Ta$ is in a good agreement with high-$p_T$ data $z$-presentation for D. Note that the angular dependence of $\chi(\theta, A)$ shown in Figure 8 (a) describes both non- and cumulative data points [9]. Thus we found that there is possibility to combine the scaling functions corresponding to the cumulative and high-$p_T$ data. As seen from Figures 6(b) and 7(b) all points [9] are out of the asymptotic region. Therefore it is of interest to determine the kinematical region for backward pion production where $z_{\text{cum}} > z_{\text{hard}} \simeq 20$.

3.1 $z - p$ plot

The dependence of $z$ on momentum $p$ ($z - p$ plot) as a function of an atomic weight ($A$), an angle of produced particle ($\theta$) and a collision energy $\sqrt{s}$ can be used to select the domain where the scaling can be violated and new physical phenomena can be found.

Figure 8(b) shows a $z - p$ plot for $p - Ta$ collisions at $p_{\text{lab}} = 70, 200, 400$ and $800 \text{ GeV/c}$ and $\theta_{\text{lab}} = 160^\circ$. The value $z = 20$ for $p - Ta$ collisions corresponds to the values of the momentum $p$ of 1.9, 2.1, 2.2 and 2.25 $\text{GeV/c}$, at $p_{\text{lab}} = 70, 200, 400$ and $800 \text{ GeV/c}$, respectively.

4 Conclusions

To search for $z$-scaling violation the analysis of the scaling features of hadrons produced in $p - p$ and $p - A$ collisions at high energies in terms of $z$-presentation are performed. The experimental high-$p_T$ [8, 10, 11] and cumulative [9] data sets on the inclusive cross sections are used in the analysis.

Data $z$-presentation for high-$p_T$ and cumulative data is constructed. It is expressed via the experimental observables, momenta and masses of colliding and produced particles, the invariant inclusive cross section $Ed^3\sigma/dq^3$ and the multiplicity density of charged particles.

A new confirmation of $z$-scaling for particle production in high-$p_T$ range is obtained. It is shown that available experimental high-$p_T$ data [10, 11, 8] on hadron production in $p - p$ and $p - D$ collisions give no indications on $z$-scaling violation. The shape of the scaling curve does not change with the collision energy $\sqrt{s}$.

The found angular dependence of particle multiplicity density for backward pion production in $p - A$ reproduces the shape of the scaling curve obtained from high-$p_T$ data.

New data [8] included in the present analysis point out the asymptotic regime of the scaling function, $\psi(z) \sim z^{-\beta}$, at $z > 4$.

The kinematical ranges for high-$p_T$ and backward hemisphere particle production preferable for search for $z$-scaling violation in $p - p$ and $p - A$ collisions are found using the $z - p_T$ and $z - p$ plots.

Analysis of data on cumulative particle production has shown a possibility to use the class of events to search for $z$-scaling violation. It is assumed that the properties of nuclear matter in the cumulative range should drastically change the mechanism of particle formation due to multiple interactions of elementary constituents. Therefore the systematic study of particle spectra at high-$z$ and multiplicity particle density in the backward hemisphere is of interest.
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Figure 1. (a) Dependence of the inclusive cross section of $\pi^+$-meson production in $p - p$ collisions on transverse momentum $p_T$ at $p_{lab} = 70, 200, 300, 400$ and $800\, GeV/c$ and $\theta_{cm} \approx 90^\circ$. Experimental data are taken from [8, 10, 11]. (b) The corresponding scaling function $\psi(z)$.

Figure 2. (a) Dependence of the inclusive cross section of $K^-$-meson production in $p - p$ collisions on transverse momentum $p_T$ at $p_{lab} = 70, 200, 300, 400$ and $800\, GeV/c$ and $\theta_{cm} \approx 90^\circ$. Experimental data are taken from [8, 10, 11]. (b) The corresponding scaling function $\psi(z)$. 
Figure 3. (a) Dependence of the inclusive cross section of $\pi^+$-meson production in $p - D$ collisions on transverse momentum $p_T$ at $p_{lab} = 70$ and 400 GeV/$c$ and $\theta_{cm} \simeq 90^0$. Experimental data are taken from [8, 10, 11]. (b) The corresponding scaling function $\psi(z)$.

Figure 4. (a) Dependence of the inclusive cross section of $K^-$-meson production in $p - D$ collisions on transverse momentum $p_T$ at $p_{lab} = 70$ and 400 GeV/$c$ and $\theta_{cm} \simeq 90^0$. Experimental data are taken from [8, 10, 11]. (b) The corresponding scaling function $\psi(z)$. 
Figure 5. \( z - p_T \) plot for \( \pi^+ \)-meson production in \( p - p \) (a) and \( p - D \) (b) collisions at \( p_{lab} = 70, 200, 400 \) and \( 800 \ GeV/c \) and \( \theta_{cm} \approx 90^0 \).

Figure 6. (a) Dependence of the inclusive cross section of \( \pi^+ \)-meson production in \( p - Be \) collisions on momentum \( p \) at \( p_{lab} = 400 \ GeV/c \) and \( \theta_{lab} = 70^0, 90^0, 118^0, 160^0 \). Experimental data are taken from [9]. (b) The corresponding \( z \)-presentation of data sets [9] and [8, 10, 11].
Figure 7. (a) Dependence of the inclusive cross section of $\pi^+$-meson production in $p$ $- $ $Ta$ collisions on momentum $p$ at $p_{lab}$ = 400 GeV/c and $\theta_{lab}$ = 70°, 90°, 118°, 160°. Experimental data are taken from [9]. (b) The corresponding $z$-presentation of data sets [8, 10, 11].

Figure 8. (a) Angular dependence $\chi(s, \theta, A)$ of particle multiplicity density for particle production in $p$ $- $ $A$ collisions at $p_{lab}$ = 400 GeV/c and $\theta_{lab}$ = 70°, 90°, 118°, 160°. (b) $z$ $- $ $p$ plot for $\pi^+$-meson production in $p$ $- $ $Ta$ collisions at $p_{lab}$ = 70, 200, 400 and 800 GeV/c and $\theta_{lab}$ = 160°.