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# AZIMUTHAL DEPENDENCE OF TWO-PION CORRELATIONS IN RELATIVISTIC HEAVY-ION INTERACTIONS

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We have investigated two-pion normalised pseudorapidity correlation for pions from $^{12}$C-emulsion interactions at 4.5 $A$ GeV at azimuthal angles $\phi \leq 180^\circ$ and $\phi > 180^\circ$. By comparing experimental correlation values with those of Monte-Carlo simulation values, we found that experimental two-pion normalised pseudorapidity correlations depend on azimuthal angle.

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## 1. Introduction

High-energy inelastic nucleus-nucleus interactions are intensively investigated with the advent of high-energy heavy-ion accelerators. For the understanding of the particle-production process, single-particle distributions are not sufficient, although they carry much information [1]. Multiplicity distributions in Regge-pole-dominated intensive reactions did not show a simple Poisson distribution which is, according to Mueller [2], due to higher correlation functions $f_2$, $f_3$ etc., that are direct measures of non-Poisson nature of the multiple particle production. This non-Poisson nature of the multiplicity distribution is a convenient expression of deviation from the independent particle production. Horn and Silver [3] showed by investigating the charged-pion multiparticle production reactions that the data points do not reproduce well the Poisson distributions, indicating that the pions are not emitted independently. Dao et al. [4] showed a correlation by measuring the projected production angle and pseudorapidity in pp interactions at 303 GeV/c.

Stone et al. [5] presented correlation between low values of longitudinal momentum ($p_L$) and transverse momentum ($p_T$), although this may have been due to the peripheral resonance production. They also investigated the correlation between the transverse momenta of pairs of outgoing particles in the two-body inclusive reactions. By studying the inclusive pp interactions between 13 and 28 GeV/c in hydrogen buble chamber, Berger et al. [6] showed that the multiplicity distribution of $\pi^-$ is non-Poisson type because $(\langle n(n-1)\rangle - \langle n\rangle^2) \neq 0$, and it depends on $s^{0.5}$ (c.m. energy). Here $n$ is the number of negative pions per inelastic collision. Shepard et al. [7] presented rapidity distributions for the one- and two-particle inclusive reactions in $\pi^+$p interactions at 18.5 GeV/$c$ and $\pi^-$p interactions at 18.5 GeV/$c$. They observed that the two-particle correlation functions for these reactions depend on the rapidities of the final-state particles and on the momentun of the incident particle. By studying a sample of 67463 $\pi^-$ pairs obtained from a 31-events/$\mu$B K$^+$p interaction experiment at 12 GeV/$c$, Ko [8] showed that the produced negative pions reveal a rapidity-separation-dependent rapidity correlation. At small rapidity separation ($\Delta y$), the $\pi$'s are strongly correlated.

The study of two-particle correlation deals with the modifications induced in the single-particle spectra.

Although investigations on two-pion pseudorapidity correlations at various energies have been done by many researchers, more work should be done in this field.

We have investigated the dependence of two-pion pseudorapidity correlations of relativistic particles from the $^{12}$C-emulsion interactions at 4.5 GeV/$c$ at azimuthal angles $\phi \leq 180°$ and $\phi > 180°$.

## 2. *Experimental data*

The required data on $^{12}$C-emulsion interactions were obtained using the NIKFIBR2 nuclear research emulsion plates (25 cm $\times$ 10 cm $\times$ 600 $\mu$m thick), irradiated horizontally with $^{12}$C beams from the JINR synchrophasotron [7].

Primary inelastic events of $^{12}$C-emulsion interactions at 4.5 $A$ GeV have been investigated. We have classified the charged secondary particles in black (b), gray (g) and shower (s) particles following the usual nuclear-emulsion methodology:

1) s-particles denote relativistic charged particles of relative ionization $g/G <$ 1.4 (corresponding to proton energy $T_{\mathrm{p}} > 400$ MeV), where $g/G$ is the ionisation measured at primary beam track.

2) g-particles denote particles with relative ionisation $g/G > 1.4$ and range in the emulsion $R > 3000$ $\mu$m (corresponding to proton energy 26 MeV $< T_p <$ 400 MeV).

3) b-particles denote particles with the range $R < 3000$ $\mu$m.

Only the tracks with emission angles greater than 3° were considered to exclude the contamination of projectile-associated fast fragments.

Here $\theta$ is the emission angle, and $\phi$ is the azimuthal angle of the produced secondary charged particle, where the incident beam direction is taken as the positive

$z$-axis. Target is taken as the origin of the coordinate system. Pseudorapidity is defined by $\eta = -\ln\tan(\theta/2)$.

## 3. Method of analysis

The pseudorapidity space has been divided into eight non-overlapping bins: (-4.0 to -3.0), (-3.0 to -2.0), (-2.0 to -1.0), (-1.0 to 0.0), (0.0 to 1.0), (1.0 to 2.0), (2.0 to 3.0) and (3.0 to 3.6).

Normalised one-particle and two-particle pseudorapidity distributions are given by [11]

$$\rho^{(1)}(\eta) = \frac{1}{\sigma_{\rm in}} \frac{{\rm d}\sigma}{{\rm d}\eta}\,, \tag{1}$$

where $\sigma_{\rm in}$ is the inelastic cross-section

$$\rho^{(2)}(\eta_1,\eta_2) = \frac{1}{\sigma_{\rm in}} \frac{{\rm d}^2\sigma}{{\rm d}\eta_1{\rm d}\eta_2}\,, \tag{2}$$

where $\rho^{(1)}(\eta)$ and $\rho^{(2)}(\eta_1,\eta_2)$ are single-particle and two-particle densities, respectively, while ${\rm d}\sigma/{\rm d}\eta$ and ${\rm d}^2\sigma/{\rm d}\eta_1{\rm d}\eta_2$ are single and double exclusive cross-sections, respectively.

Normalised two-particle correlation function is given by

$$R(\eta_1,\eta_2) = \frac{\langle n_1 n_2\rangle}{\langle n_1\rangle\langle n_2\rangle} - 1, \qquad \text{for} \qquad \eta_1 \neq \eta_2\,, \tag{3}$$

$$R(\eta_1,\eta_2) = \frac{\langle n_1(n_1-1)\rangle}{\langle n_1^2\rangle} - 1, \quad \text{for} \quad \eta_1 = \eta_2\,. \tag{3}$$

The variance of $R$ can be calculated by [11]

$$\begin{aligned}\widetilde{V}[R] = {}& \frac{1}{N\langle n_1\rangle^4\langle n_2\rangle^4}\big\{\langle n_1^2n_2^2\rangle\langle n_1\rangle^2\langle n_2\rangle^2 - 2\langle n_1^2n_2\rangle\langle n_1n_2\rangle\langle n_1\rangle\langle n_2\rangle^2 \\ & -2\langle n_1n_2^2\rangle\langle n_1n_2\rangle\langle n_1\rangle^2\langle n_2\rangle + \langle n_1^2\rangle\langle n_1n_2\rangle^2\langle n_2\rangle^2 + \langle n_2^2\rangle\langle n_1n_2\rangle^2\langle n_1\rangle^2 \\ & +2\langle n_1n_2\rangle^3\langle n_1\rangle\langle n_2\rangle - \langle n_1n_2\rangle\langle n_1\rangle^2\langle n_2\rangle^2\big\} + O(1/N^2)\,, \quad \text{for} \quad \eta_1\neq\eta_2\,,\end{aligned} \tag{5}$$

$$\begin{aligned}\widetilde{V}[R] = {}& \frac{1}{N\langle n_1\rangle^6}\big\{\langle n_1^4\rangle\langle n_1\rangle^2 - 4\langle n_1^3\rangle\langle n_1^2\rangle\langle n_1\rangle + 4\langle n_1^2\rangle^3 - \langle n_1^2\rangle^2\langle n_1\rangle^2 + 2\langle n_1^3\rangle\langle n_1\rangle^2 \\ & -4\langle n_1^2\rangle^2\langle n_1\rangle + 2\langle n_1^2\rangle\langle n_1\rangle^3 + \langle n_1^2\rangle\langle n_1\rangle^2 - \langle n_1\rangle^4\big\} + O(1/N^2)\,, \quad \text{for} \quad \eta_1 = \eta_2\,.\end{aligned} \tag{6}$$

Here $n_1$ is the number of pion tracks in the pseudorapidity interval $(\eta_1 - \Delta\eta_1/2)$ to $(\eta_1 + \Delta\eta_1/2)$, and $n_2$ is the number of pion tracks in the pseudorapidity interval $(\eta_2 - \Delta\eta_2/2)$ to $(\eta_2 + \Delta\eta_2/2)$. $N$ is the total number of events. The term $O(N^{-2})$ has been neglected.

To search for two-pion pseudorapidity correlations for $\phi \leq 180°$ and $\phi > 180°$, we have compared the experimental data of $^{12}$C-emulsion interaction events with the Monte-Carlo simulated events which were calculated assuming the independent emission. We have done the Monte-Carlo simulation assuming the following:

(i) Particles of all types are independent of each other.

(ii) The multiplicity distribution in each ensemble of Monte-Carlo events reproduces the empirical multiplicity spectrum of the real ensemble.

(iii) The pseudorapidity distribution of all types of particles coincides with the corresponding empirical semi-inclusive (i.e. at fixed $n_b$, $n_g$ and $n_s$) distribution.

For a fixed value of $\eta$, we define that $\Delta R|_\eta$ is equal to the difference between the normalised two-pion pseudorapidity correlation calculated from experimental data at some value of $\eta$ and normalised two-pion pseudorapidity correlation calculated from Monte-Carlo simulation values at the same value of $\eta$,

$$\Delta R|_\eta = (R_{ii})_{\rm ex} - (R_{ii})_{\rm M-C} \, , \tag{7}$$

where $(R_{ii})_{\rm ex}$ is the value of the two-pion pseudorapidity correlation derived from the experimental data, and $(R_{ii})_{\rm M-C}$ is the value of the two-pion pseudorapidity correlation calculated from the Monte-Carlo simulation values.

In the following we will write $\Delta R$ in place of $\Delta R|_\eta$ (in the text and in the graphs).

The variance of $\Delta R$ is given by the formula

$$\widetilde{V}[R] = \widetilde{V}[(R_{ii})_{\rm ex}] + \widetilde{V}[(R_{ii})_{\rm M-C}] \, . \tag{8}$$

## 4. *Results and conclusion*

We have calculated the normalised two-pion correlation function $R_{ii}$ (i.e., $R(\eta_1, \eta_2)$ for $\eta_1 = \eta_2$) with the help of Eq. (4), and $\Delta R$ using Eq. (7). The statistical errors of experimental correlation values were obtained with the help of formula (6).

The statistical error of $\Delta R$ was calculated with the help of Eq. (8).

Figure 1 presents the normalised one-particle pseudorapidity distribution of pions, $\rho(\eta)$, in two regions of $\phi$, for azimuthal angles $\phi \leq 180°$ (solid line) and for $\phi > 180°$ (dashed line). From the figure, we find that for $\phi > 180°$, $\rho(\eta)$ is negligible for $\eta = -2.5$. We also find that for $\phi \leq 180°$, $\rho(\eta)$ is negligible for $\eta = -1.5$. So. we have neglected those points of respective $\phi$-regions for the derivation of results from experimental data.

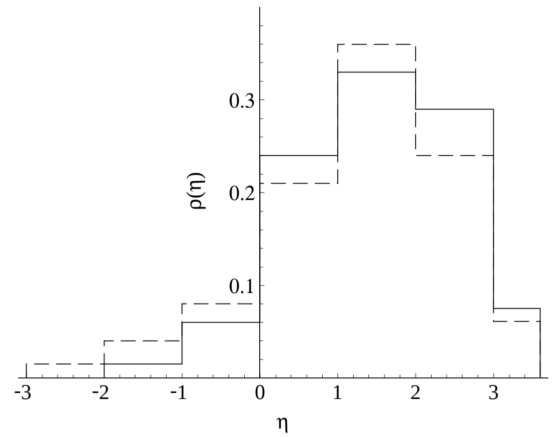


*Fig. 1. Plot of normalised one-particle pseudorapidity distribution of pions, $\rho(\eta)$, vs. pseudorapidity $\eta$ for the regions $\phi \leq 180°$ and $\phi > 180°$. The solid-line histogram represents the values for $\phi \leq 180°$ and the dashed-line histogram for $\phi > 180°$.*

It is found from Fig. 1 that the normalised one-particle pseudorapidity distribution $\rho(\eta)$ depends on azimuthal angle. It is to be mentioned that the Monte-Carlo simulated distribution is identical with the experimental distribution for the two $\phi$-regions. So, $R_{ii}$s are also $\phi$-dependent.

Figures 2 and 3 show the normalised two-pion correlation function calculated from experimental data along with the Monte-Carlo simulated values for the two $\phi$-regions. In these figures, the solid circles and the solid curves represent $R_{ii}$ calculated from experimental data and Monte-Carlo simulated values, respectively.

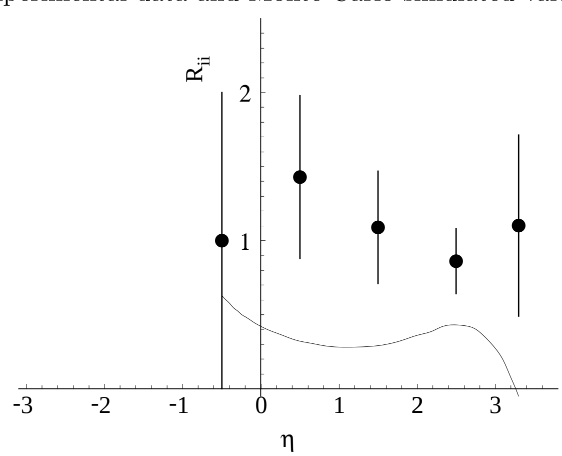


*Fig. 2. Normalised two-particle pseudorapidity correlation function $R_{ii}$ derived from the experimental data vs. pseudorapidity $\eta$ (solid circles) and $R_{ii}$ obtained by Monte-Carlo simulation (solid curve) for shower tracks from $^{12}$C-emulsion interactions at 4.5 GeV/n for $\phi \leq 180°$.*

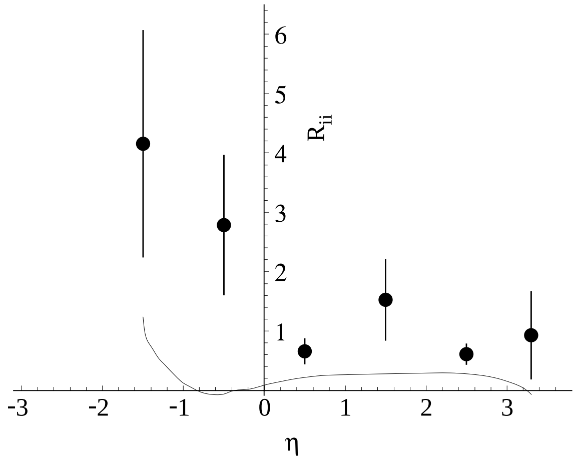


*Fig. 3. Normalised two-particle pseudorapidity correlation function $R_{ii}$ derived from experimental data vs. pseudorapidity $\eta$ (solid circles) and the plot of $R_{ii}$ calculated from Monte-Carlo simulated values (solid curve) for shower tracks from* $^{12}$C*-emulsion interactions at* 4.5 GeV/n *for* $\phi > 180°$.

Figures 2 and 3 show that $(R_{ii})_{\rm ex}$ and $(R_{ii})_{\rm M-C}$ are $\eta$ as well as $\phi$ dependent. This is due to the fact that pseudorapidity distribution depends on $\eta$ and $\phi$. It is also found from those two figures that the values of $(R_{ii})_{\rm ex}$ and $(R_{ii})_{\rm M-C}$ are not the same for a fixed value of $\eta$ in either of the two $\phi$-regions. Nevertheless, Monte-Carlo simulated data yield the same pseudorapidity distribution as the experimental data, in each of the two $\phi$-regions.

In Figs. 4 and 5, we present the variation of $\Delta R$ with $\eta$ for $\phi \leq 180°$ and for $\phi > 180°$, respectively. Figures 4 and 5 reveal the existence of the two-pion correlation function for the two respective $\phi$-spaces.

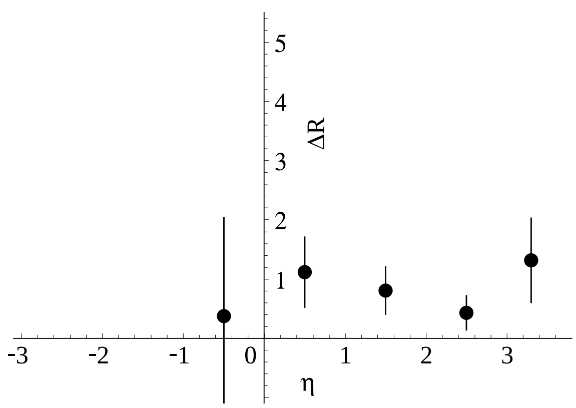


*Fig. 4. Plot of $\Delta R$ vs. $\eta$ for $\phi \leq 180°$.*

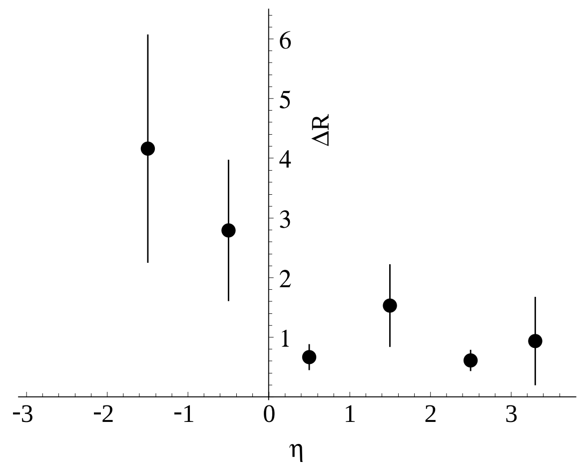


*Fig. 5. Plot of $\Delta R$ vs. $\eta$ for for $\phi > 180°$.*

Comparing graphs of $\Delta R$ vs. $\eta$ for the two $\phi$-regions, we can conclude that the value of $\Delta R$ depends on $\phi$-space. So, we can conclude that $(R_{ii})_{\text{ex}}$ depends not only on $\eta$, but also on $\phi$-space.


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## AZIMUTALNA OVISNOST DVOPIONSKIH KORELACIJA U RELATIVISTIČKIM SUDARIMA TEŠKIH IONA

Istraživali smo dvopionsku normaliziranu korelaciju pseudorapiditeta za pione nastale u sudarima $^{12}$C u emulzijama pri 4.5 $A$ GeV i za azimutalne kutove $\phi \leq 180^\circ$ i $\phi > 180^\circ$. Usporedbom eksperimentalnih korelacija s vrijednostima izračunatim Monte-Carlo simulacijom utvrdili smo ovisnost eksperimentalne dvopionske korelacije pseudorapiditeta o azimutu.