DOI: https://doi.org/10.37547/mesmj-V7-I6-26 Pages: 253-261

MENTAL ENLIGHTENMENT SCIENTIFIC –
METHODOLOGICAL JOURNAL

MENTAL ENLIGHTENMENT SCIENTIFIC –
METHODOLOGICAL JOURNAL
http://mentaljournal-jspu.uz/index.php/mesmj/index

CORRELATIONS OF SECONDARY PARTICLES IN MULTIPLE PROCESSES

Nasir Shakirovich Saidkhanov
D.Sc. (Physics and Mathematics), Professor
Scientific Secretary of the S.A. Azimov Physical-Technical Institute of the Academy of Sciences of the Republic of Uzbekistan
said@uzscu.net
Tashkent, Uzbekistan

ABOUT ARTICLE

Key words: interactions, nucleus, proton, model, correlations, π-meson, momentum, energy, mass, event, resonances, correlation function.

Received: 05.07.26
Accepted: 06.07.26
Published: 07.07.26

Abstract: Three methods for analyzing the processes of interaction of particles and nuclei at high energies are described: exclusive, inclusive and eventual. The advantages of each of these methods are listed. The importance of studying the processes of multiple particle production in particle collisions at high energies is substantiated. Theoretical models are presented, with the predictions of which the experimental data are compared. Theoretical models - FRITIOF-1, the additive quark model (AQM) and the dual parton model (DPM) predict significant cross sections of resonance production, which is confirmed by the experiment. The experiment showed that the magnitude and shape of the correlation function are similar at all four energies used in the study. It is concluded that the mechanism responsible for correlations in the final multiparticle state is the same throughout the entire energy range under consideration.

Introduction. When analyzing high-energy collision processes, various research methods are employed: exclusive, inclusive, and event-by-event. [1,2]. The exclusive method is used when complete information about all reaction products is available. This method has limitations because as the energy of colliding particles increases, the number of secondary particles grows, and not all characteristics of secondary particles can be measured. Therefore, at high energies, the inclusive analysis method is applied, which allows determining the properties of the interaction from the characteristics of one of the secondary particles. The inclusive method consists of reducing a multi-particle reaction to a two-particle one, where the characteristics of only one of the secondary particles produced in the interaction are considered, while the characteristics of all other particles are summed up. The total cross-section of a collision process is composed of elastic, inelastic, and quasi-elastic processes:

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} + \sigma_{qel}. \qquad (1)$$

Elastic process

$$a+b \rightarrow a+b \qquad (2)$$

allows for the use of the exclusive method.

Inelastic and quasi-elastic processes are analyzed using both exclusive and inclusive methods. In the reaction:

$$a + b \rightarrow a + b + c_1 + c_2 + \ldots + c_n \qquad (3)$$

the exclusive method is applied if the characteristics of all secondary particles are measured. Limitations in the exclusive method are primarily related to the production of neutral particles among the reaction products. In this case, the characteristics of neutral particles are often unavailable for measurement. Furthermore, as the energy of colliding particles increases, information about the characteristics of charged particles can also be lost. In such situations, the inclusive method is implemented, where the interaction process can be represented as a two-particle reaction:

$$a + b \rightarrow c_i + X \ (i = 1 \div n). \qquad (4)$$

The system X includes all secondary particles, including the primary particles that survived the collision.

Information about an event can be obtained using the event-by-event method, or as it is now called, the event-by-event analysis.

The meaning of this method is that in the reaction

$$a + b \rightarrow a + b + X \qquad (5)$$

the characteristics of the X-system are determined: the value of the inelasticity coefficient for such a reaction, the multiplicity of secondary particles, the features of the angular characteristics of the X-system, etc. In this case, in events with a given multiplicity or with a given inelasticity coefficient, the momentum spectra of secondary particles and their other characteristics are studied. The exclusive method contains more information about the collision process than the inclusive one and has no limitations as the energy of the colliding particles increases.

The multiplicity of secondary particles is one of the main exclusive characteristics of the interaction process. The process of multiple production, which plays a decisive role in high-energy particle collisions, is a combination of many different interaction mechanisms. Experiments have shown that multiple particle production occurs when any currently known particles collide, provided their energy exceeds a threshold of several gigaelectronvolts. Therefore, while multiple production was initially studied mainly in hadron-hadron collisions, experimental data on multiple production have now been obtained in $e^{\pm}p$, $\mu^{\pm}p$, γp, νp collisions, and in e^+e^- annihilation processes. Thus, multiple particle production is a universal process occurring in all types of interactions: strong, electromagnetic, and weak.

Multiple particle production is a universal process for all types of interactions. In any type of interaction, multiple particle production occurs as a result of the hadronization of quarks in quark and gluon jets.

Methodology. In the study of hadron-nucleon and hadron-nucleus interactions, the investigation of secondary particle correlations is of great importance [3,4]. This is due to the weak sensitivity of the general characteristics of secondary particles and their single-particle spectra to the choice between different theoretical approaches to the problems of multiple particle production.

The main reason for the emergence of dynamic correlations between final-state secondary particles in multi-particle reactions is the formation of intermediate states (particle subsystems) – resonances and clusters [5].

Theoretical approach. Theoretical models – FRITIOF-1, the additive quark model (AQM), and the dual parton model (DPM) – predict significant resonance production cross-sections, which is confirmed by experiment. Regarding the question of the existence of heavy clusters, it remains open to this day – meaning clusters are more correctly considered as abstract objects introduced to explain the existence of multi-particle correlations [6].

Correlations caused by the two-stage nature of particle production (resonance formation and decay) in multiple production should be short-range: particles with small pseudorapidity differences $\Delta\eta = |\eta_1 - \eta_2|$ should be more strongly correlated (particles from the same resonance) than particles with large $\Delta\eta$ (i.e., from different resonances). In the case of a statistical particle production mechanism without intermediate states, correlations between particles should not depend on $\Delta\eta$. The real situation when studying correlations is complicated by several reasons (primarily the law of conservation of energy-momentum; as well as the need to study ensembles of events, which are typically heterogeneous, i.e., consist of events with different particle production mechanisms [7,8]). The latter circumstance strongly depends on the methodological aspect of the issue – the method of searching for and studying correlation phenomena.

Correlation Functions. When studying correlation phenomena in multi-particle final states of reactions, the apparatus of correlation functions from statistical mechanics of many-particle systems is often used [9]. Henceforth, we will work in the center-of-mass system of pp-interactions.

The two-particle correlator is defined as

$$C_2(\eta_1, \eta_2) = \rho_2(\eta^*_1, \eta^*_2) - \rho_1(\eta^*_1)\,\rho_1(\eta^*_2), \quad (6)$$

or

$$R_2(\eta^*_1, \eta^*_2) = C_2(\eta^*_1, \eta^*_2)/\,\rho_1(\eta^*_1)\,\rho_1(\eta^*_2) =$$
$$= [\rho_2(\eta^*_1, \eta^*_2)/\,\rho_1(\eta^*_1)\,\rho_1(\eta^*_2)] - 1, \quad (7)$$

where $\rho_1(\eta^*_1, \eta^*_2)$ is the one-particle and $\rho_2(\eta^*_1, \eta^*_2)$ is the two-particle inclusive density; η^* is the pseudorapidity in the center-of-mass frame of the pN interaction. Both types of two-particle correlation functions are equivalent (C_2 and R_2) and. We will use normalized correlators (η^*_1, η^*_2).

The meaning of correlators (6) and (7) is obvious. In the absence of any correlations (dynamic, due to conservation laws, inhomogeneities of the ensemble under study, particle identity, etc.), as already noted, $C_2(\eta^*_1, \eta^*_2) = R_2(\eta^*_1, \eta^*_2)$,

i.e., two-particle correlation functions are a measure of two-particle correlation links in inclusive reactions.

For the analysis of three-particle correlations, we will use the following definition of the three-particle normalized correlation function:

$$R_3(\eta^*_1, \eta^*_2, \eta^*_3) = R'_3(\eta^*_1, \eta^*_2, \eta^*_3) - R''_3(\eta^*_1, \eta^*_2, \eta^*_3), \quad (8)$$

where $R'_3(\eta^*_1, \eta^*_2, \eta^*_3) = [\rho_3(\eta^*_1, \eta^*_2, \eta^*_3)/\,\rho_1(\eta^*_1)\,\rho_1(\eta^*_2)\,\rho_1(\eta^*_3)] - 1 \quad (9)$

$\rho_3(\eta^*_1, \eta^*_2, \eta^*_3) = [d^3\sigma/\,\sigma\, d\eta^*_1 d\eta^*_2 d\eta^*_3] - 1$ is the three-particle inclusive density.

$$R''_3(\eta^*_1, \eta^*_2, \eta^*_3) = R_2(\eta^*_1, \eta^*_2) + R_2(\eta^*_1, \eta^*_3) + R_2(\eta^*_2, \eta^*_3). \quad (10)$$

The correlator $R_3(\eta^*_1, \eta^*_2, \eta^*_3)$ is presented as two parts, R'_3 and R''_3. Here, R'_3 characterizes "full" three-particle correlations – the excess of the three-particle density compared to the product of three one-particle densities, while R'_3 reflects the contribution to the three-particle correlator from pairwise correlations between particles constituting the three-particle sub-ensembles.

In most works carried out to date, rapidity correlations in two-particle inclusive reactions have been measured at various collision energies and types of colliding particles. Positive correlations have been observed in the central region, with the magnitudes of the normalized functions (7) for any pair of particles being independent of the type of primary particles or the total collision energy over a wide range of primary energies – from tens to 2000 GeV. The magnitude of the correlator for oppositely charged pairs is approximately twice that for similarly charged pairs [10]. The saturation effect of two-particle correlation links suggests the dominant contribution of ordinary mesonic resonances to multiple particle production.

Correlations in the three-particle system have been studied significantly less. Due to statistical limitations, works [11, 12] did not obtain clear evidence of additional three-particle correlations in pp-collisions. In [9], when analyzing π-p collisions at 200 GeV, positive rapidity correlations were observed in the central region for $\pi^+\pi^+\pi^-$ -states, but no effect was noted for $\pi^-\pi^-\pi^-$ -combinations. This result qualitatively agrees with the picture where correlations arise due to low-multiplicity and limited electric charge clusters. The magnitudes of semi-inclusive correlators are smaller and exhibit different trends.

However, the fact that the details of inclusive correlations are reproduced by Monte Carlo calculations [13] on the one hand, and the small values of semi-inclusive correlators on the other, indicate a small contribution of dynamic correlations to the values of inclusive correlation functions. Thus, the application of the correlation function apparatus requires careful separation of trivial causes of correlation from dynamic ones.

To quantitatively account for pseudo-correlations, we use the independent emission model (IEM), widely used in previous chapters.

Since the number of intranuclear collisions in pA interactions is unknown, the IEM provides the maximum available information about pseudo-effects that can be obtained in a model-independent way, without relying on any specific hadron-nucleus interaction mechanism.

In work [12], correlation functions were compared in inclusive ensembles of random stars obtained by the cylindrical phase space (CPS) model, which accounted for conservation laws and limited transverse momenta, and an ensemble obtained by the IEM for pN interactions. The comparison showed that conservation laws, in the form inherent to statistical theory of multiple production, weakly reduce the values of $R_2(\eta^*_1, \eta^*_2)$ compared to $R^{IEM}_2(\eta^*_1, \eta^*_2)$ for $\Delta\eta = |\eta_1 - \eta2| <2$ ("close" correlations) and increase them for larger $\delta\eta^*$.

These results can be explained by the fact that the action of conservation laws leads to the suppression of particle cluster-type fluctuations at the ends of the pseudorapidity scale, which are allowed in the case of independent emission [14,15]. For further discussion of the experimental data, it should be noted that neglecting conservation laws in the IBM only enhances the "dynamic" significance of the excess $R_2(\eta^*_1, \eta^*_2) = R^{IEM}_2(\eta^*_1, \eta^*_2) > 0$ at small $\Delta\eta^*$. It should be noted that due to the practical impossibility of separating secondary particles from pA collisions into those "born" during multiple generation and those emitted by the target nucleus afterwards, as well as identifying the true target mass, an accurate account of pseudo- and kinematic correlations without additional model assumptions is unfeasible [16].

Results and Conclusions. Figure 1a presents [3] the normalized correlation functions at different argument values in pA and pN interactions at an energy of 800 GeV, compared with calculations performed using the IEM model, and Figure 1b compares the same experimental data with calculations using the Lund FRITIOF-1 model. Analysis of these figures leads to the conclusion that:

a) the correlators $R_2(\eta^*_1, \eta^*_2)$ are significantly different in proton-nucleon and proton-nucleus interactions. This difference is particularly large in the target nucleus fragmentation region (see Fig. 1a for diagonal elements of the correlation matrix $R_2(\eta^*_1, \eta^*_1=\eta^*_2)$. It should be noted that the strong asymmetry of the correlation functions in pA collisions is mainly trivial origin, as it is qualitatively reproduced by IEM. This effect is explained by pseudo-correlations caused by large values and fluctuations of multiplicity and single-particle spectra in the target fragmentation region in hadron-nucleus collisions;

b) the FRITIOF-1 model describes the behavior of two-particle correlation functions in pN interactions well, especially in the forward hemisphere (in the pN collision c.m.s.). Some deviation from experimental data in the backward hemisphere can be attributed to the presence of a small contribution from hadron-nucleus interactions in proton-nucleon collisions in emulsion (according to our estimates, it is ~15%. Two-particle correlation functions $R_2(\eta^*_1, \eta^*_2)$ in nuclear collisions are reproduced by the model only in the projectile fragmentation region. In the backward hemisphere, a strong divergence between experimental data and model predictions is observed (this is evident for the diagonal elements $R_2(\eta^*_1=\eta^*_2)$ and $R_2(-2, \eta^*)$. There is nothing unexpected in this divergence due to the expected contribution of cascades;

c) the correlation function R_2^{exp} significantly exceeds R_2^{IEM} at small $\Delta\eta^*$ in pN interactions across the entire pseudorapidity range, i.e., positive "short-range" correlations exist, which are not explained by the simplest pseudo- and kinematic effects.

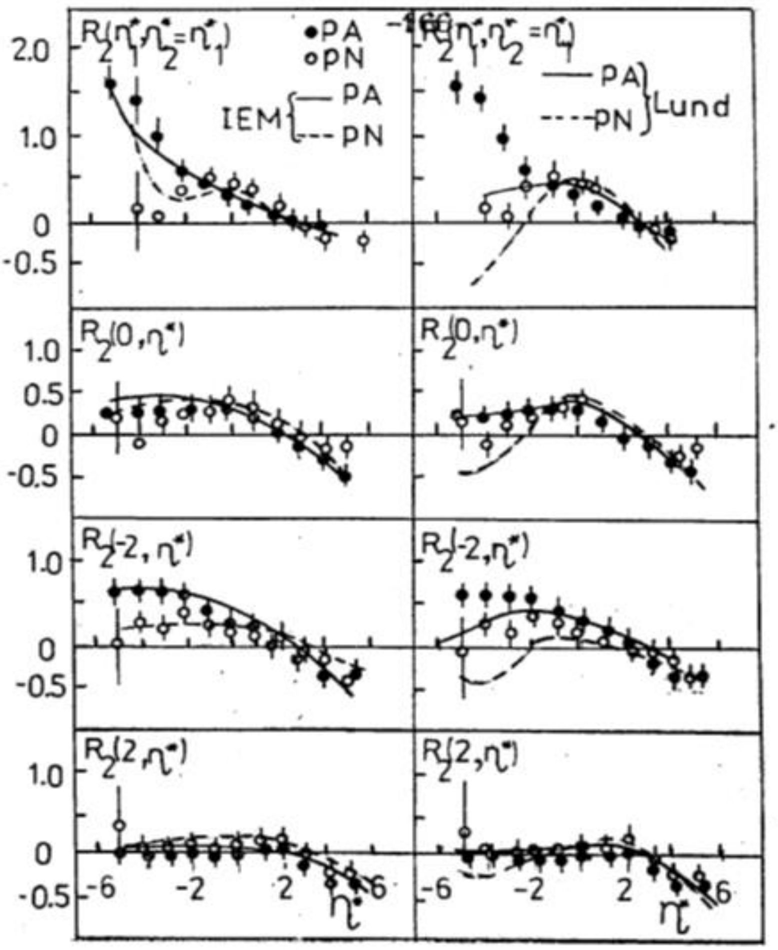

Fig. 1. a) normalized correlation functions $R_2(\eta^*_1, \eta^*_2)$ at different argument va-lues for pA and pN interactions compared to calculations using the IEM model; b) The same experimental data compared to predictions of the FRITIOF-1 model.

At the same time, for pA interactions, R_2^{exp} does not differ from R_2^{IEM} within experimental errors. For small $\Delta\ \eta^*$, both for pA and pN interactions, the Lund model underestimates the values of two-particle correlation functions in the target fragmentation region, as noted above.

Experimental values of two-particle correlations R_2^{exp} at large $\Delta\eta^*$ ($|\Delta\ \eta^*| > 2$) in the backward hemisphere are smaller than in the IEM model, which we use to account for pseudo-correlation effects. The FRITIOF-1 model also overestimates long-range correlations for pA interactions. For a correct interpretation of these results, it is necessary to compare the experimental data with the results of calculations using models that account for the contributions of intranuclear cascades. Monte Carlo implementations of such models are currently unavailable.

Fig. 2 shows [4] the dependence of $R2(\eta_1, \eta_2)$ on η_1 for proton-nucleus

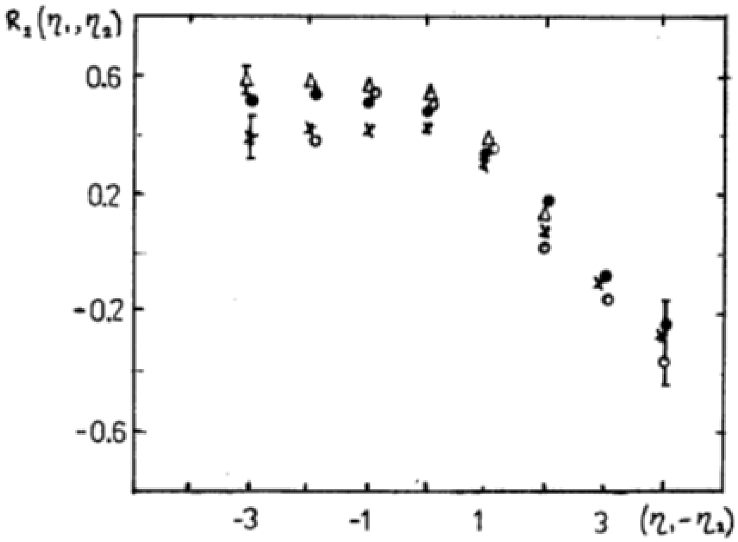

Fig. 2. Values of correlation functions $R_2(\eta^*_1, \eta^*_2)$ for four different energies: (°) 67, (Δ) 200, (●) 400, and (ˣ) 800 GeV.

interactions at energies of 67, 200, 400, and 800 GeV. At each energy, η_2 was chosen to be equal to the rapidity of a particle emitted at 90° (in the center-of-mass frame of an equivalent pp interaction). As can be seen from the figure, the magnitude and shape of the correlation function are similar at all four energies. This implies that the mechanism responsible for the correlations in the final multi-particle state is the same across the entire energy range considered.

References:

[1]. Saidkhanov N.Sh. Inelastic interactions of protons and nuclei with nucleons and nuclei at high and ultrahigh energies. Fan Publishing House of the Academy of Sciences of the Republic of Uzbekistan. Tashkent, 2021, 214 p.

[2]. Saidkhanov N.Sh., Application of least squares method for particle identification and sampling events in photoemulsion. Mental enlightenment scientific methodological journal. V5 No.03, 2024. 178-187.

[3]. Abduzhamilov A.,.., Saidkhanov N.Sh., et al. Two-particle and three-particle correlation functions in proton-nucleon and proton-nucleus interactions in emulsion at an energy of 800 GeV. // Preprint of the Physical-Technical Institute of Scientific and Production Association "Physics-Sun". - Tashkent, 1991. - No. 1 51-90-FVE.

[4]. Barbier L., Saidkhanov N.Sh.ea Correlations among particles produced in proton interactions with emulsion nuclei at 800 GeV. // Physical Review. - 1988. - v.D37. - P.1113-1119.

[5]. Abdukhamilov A., ..., Saidkhanov N.Sh. et al. Study of multiparticle rapidity correlations in proton-nucleon and proton-nucleus interactions at 800 GeV. // Preprint of the Physical-Technical Institute of Scientific and Production Association “Physics-Sun”. - Tashkent, 1991. - №1. 53-91-FVE,

[6]. Mieller A.N. Multiplicity distributions in Regge-pole dominated inclusive reaction. // Phys. Rev.-1971.-v.D1. - P.150-155.

[7]. Bromberg Cea Structure of events in 200 GeV interactions on hydrogen and aluminum targets in both soft and hard collisions. // Nucl. Phys. -1980. – v.B171. –P.38-53.

[8]. Eggert Kea Angular correlations between the charged par tides in pp-collisions at ISR energies. // Nucl. Phys. -1975. – v.B86. -P.201-214.

[9] . Kafka Tea One-, two- and three particle distributions in pp-collisions at 205 GeV/c. // Phys. Rev.-1977.-v.D16 -P.1261.

[10]. Kenney V. ea Observation of three particle correlations in inclusive xp-reactions at 200 GeV/c. // Nucl.Phys. -1978. -v. B144. - P. 312-319.

[11]. Ammosov V. V. et al. Experimental study of long-range two-particle correlations in the central region in pp-interactions at 69 GeV/c. // Preprint of the Institute of High Energy Physics. - Serpukhov, 1975. - M-16.

[12]. Azimov S. A. et al. Multiparticle correlations in multiple particle production in hadron-nucleon and hadron-nucleus interactions. - Tashkent: FAN. - 1985. - P. 124-167.

[13]. Foa L. Inclusive study of high-energy multiparticle production and two-body correlations.//Phys. Rep.-1975.-v.22. -R1-56.

[14]. Bell Wea Two-particle rapidity correlations in αα, αp, and pp-correlations at the CERN intersecting storage rings. // Zeitschrift fur Physik. -1984. – v.C22. -P.109-118. [15]. Michael L. Link-correlated models for multiparticle production. // Nucl. Phys. -1976. – v.B103. -P.296-332.

[16]. Bell Wea Many-particle rapidity correlations in light ion interactions at the CERN intersecting storage rings. // Zeitschrift fur Physik. -1986. -v.C32. -P.335-342.