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A new Coulomb correction method for Bose-Einstein correlations, based on the $\pi^+\pi^-$ correlation measurements

The NA35 Collaboration

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Abstract. We present the measured correlation functions for $\pi^+\pi^-$, $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs in central S+Ag collisions at 200 GeV per nucleon. The Gamov function, which has been traditionally used to correct the correlation functions of charged pions for the Coulomb interaction, is found to be inconsistent with all measured correlation functions. Certain problems which have been dominating the systematic uncertainty of the correlation analysis are related to this inconsistency. It is demonstrated that a new Coulomb correction method, based exclusively on the measured correlation function for $\pi^+\pi^-$ pairs, may solve the problem.

1 Introduction

The space-time evolution of a particle system created in a nuclear collision may be strongly influenced by the collision dynamics, particularly by the presence of a phase transition from a quark gluon plasma to hadronic matter. There has been much interest in the study of Bose-Einstein correlations (BEC) of identical pions and kaons recently, because they can yield the information on the space-time evolution of the system.

The correlation functions of charged particles need to be corrected for the Coulomb interaction among the particles. In our previous publications [1–3] on the BEC of negative pions, we have expressed our suspicion that the "traditional" Coulomb correction method, based on the Gamov function [4, 5], could be responsible for the existence of certain problems which dominate the systematic errors of the analysis. In this paper we present a study of the correlation functions for $\pi^+\pi^-$ pairs in S+Ag collisions at 200 GeV per nucleon, measured by the NA35 Collaboration at the CERN-SPS, and we demonstrate that the Gamov function is indeed inconsistent with all the $\pi^+\pi^-$, $\pi^-\pi^-$ and $\pi^+\pi^+$ correlation data. A new Coulomb correction method is introduced, which uses the measured $\pi^+\pi^-$ correlation function instead of the Gamov function. We apply the new correction method and we find an excellent description of the experimental data, in contrast to correlation functions corrected by the standard Gamov function.

The reason for the failure of the Gamov function in the ultrarelativistic nuclear collisions could be related to the absence of the conditions which have been assumed in its the-

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oretical evaluation. The Gamov correction function is evaluated for an isolated pair of non-relativistic pions emerging from a small volume. In contrast to that, in the ultrarelativistic nuclear collisions the final state consists of many charged particles, emitted from an extended, rapidly expanding volume.

The paper is structured as follows: the NA35 experiment is described and the data samples are characterized in Sect. 2. The derivation of the two-particle correlation function, and the influence of the applied corrections is discussed in Sect. 3. In Sect. 4. the evidence for the failure of the Gamov correction, stemming both from the studies of the correlations of like and unlike charged pions is shown in some detail. The results of the new proposed correction method are presented and compared to the old results in Sect. 5 and Sect. 6.

2 Experiment and data sets

The experiment NA35 at the CERN SPS studies collisions of p, ^{16}O and ^{32}S projectiles of 200 GeV per nucleon incident energy with various nuclear targets [6–8]. The experiment used two large-volume tracking chambers and four calorimeters. The Streamer Chamber (SC), which was in a 1.5 Tesla superconducting magnet, measured pions in the lab rapidity range $0.5 < y < 3.5$. The Time Projection Chamber (TPC) was located downstream of the magnet, and measured pions in rapidity range $2.5 < y < 5$. Essentially the entire phase space, excluding the projectile and target fragmentation domains, was covered by tracking. Neither the SC nor the TPC had track-by-track particle identification capabilities. The Streamer Chamber events were recorded by three cameras on film and analyzed either with manual [2] or with fully automated event reconstruction facilities [3, 9, 10]. The events from the TPC were reconstructed by the TRAC analysis chain [11].

The quality of a correlation measurement is determined by the resolution of the two-particle momentum difference (“relative momentum”) and the two-track resolution. The error on the two-particle relative momentum depends on the track measurement error and on multiple scattering, whereas it is, for pairs of particles of the same charge at small relative momenta, to a high degree independent of errors arising from distortions, detector alignment uncertainties and other large-scale biases. The error on the two-particle relative momentum for the oppositely charged particle pairs is influenced by those errors as well. In repeated independent measurements of SC events we have found that the error on the invariant two-particle relative momentum used in the analysis (Q_i, defined in (2) in the following section) arising from the event alignement and reading errors, which dominate the track measurement error, is less than 2 MeV/c on average. The combined error for the oppositely charged particle pairs, which also includes the error arising from distortions, detector alignment and other large-scale uncertainties was deduced from the measurement [8] of the K^0_S invariant mass spectra, and equals 7 MeV/c on average. The contribution arising from multiple scattering depends primarily on the target material and thickness and never exceeds 6 MeV/c. These contributions add approximately in quadrature and the combined relative momentum error is less than 7 MeV/c and 9 MeV/c for the like and the oppositely charged particle pairs, respectively. The smallest bin-size used in the analysis of SC data was taken to be 10 MeV/c in all relative momentum components, appropriate to the momentum resolution. In contrast to the Streamer Chamber, the TPC has in the present analysis accepted only tracks of negatively charged particles. The errors resulting from the limited spatial accuracy of the TPC and from multiple scattering were estimated both from the data and from Monte Carlo simulations and were found to be of a similar magnitude. Adding them in quadrature results in an error of 10–15 MeV/c for the three relative momentum components used in the analysis. Accordingly, the smallest bin-size adopted in the analysis of the TPC data is 20 MeV/c.

The two-track resolution for the tracks of like charged particles corresponds to the limiting relative momentum of a particle pair below which the two corresponding tracks are too close to be individually resolved. This limit depends on particle momenta and may have different values in different parts of momentum space. In order to avoid a bias due to insufficient two-track separation for the tracks of like charged particles, pairs with $Q_i < 5$ MeV/c (Q_i is defined in (2) in the next section) have been excluded from the analysis. Note that the region below 5 MeV/c is nearly unpopulated with primary pion pairs because of the low phase space probability density. Since the magnetic field separates tracks of positive and negative particles in the Streamer Chamber, the two-track resolution for the tracks of oppositely charged particles is essentially perfect; the acceptance of a particle pair is independent of the relative momentum. Simulations of the TPC show that the reconstruction efficiency (for track pairs of like charged particles) approaches 100% for tracks with an average two-particle separation larger than 2.5 cm. Therefore, all pairs with less than 2.5 cm separation have been excluded from the analysis. This cut results in the loss of a significant fraction of pairs only for $Q_i < 10$ MeV/c.

The Forward Energy Trigger (FET) was used for online event selection of the data presented in this paper. That trigger selects events with a small energy deposited in the forward Veto Calorimeter, which covered an opening angle of $\theta < 0.3^o$ [8]. The FET trigger selects collisions with small impact parameter for which all projectile nucleons have collided with the target nucleus (“dive-in collisions”).

Table 1 shows important characteristics of the data sets that were analyzed: target thickness, measured charge, cross section (expressed in percentage of the total inelastic cross section), rapidity density of negative hadrons at mid-rapidity (corrected for acceptance and contamination), and the number of analyzed events.

3 Evaluation of the correlation function

The two-pion correlation function $C(\mathbf{p}_1, \mathbf{p}_2)$ is the ratio of the two-pion differential cross section $\sigma(\mathbf{p}_1, \mathbf{p}_2)$ and the product of the two single-pion cross sections $\sigma(\mathbf{p}_1)$ and $\sigma(\mathbf{p}_2)$ (see e.g. [5] and references therein):

$$C(\mathbf{p}_1, \mathbf{p}_2) = N \frac{\sigma(\mathbf{p}_1, \mathbf{p}_2)}{\sigma(\mathbf{p}_1)\sigma(\mathbf{p}_2)} \qquad (1)$$

Table 1. Characteristics of the analyzed data are listed: the target thickness, the measured charge and the cross section (expressed in percentage of the total inelastic cross section), the rapidity density $d\langle n^-\rangle/dy$ of negative hadrons at mid-rapidity, and the number of analyzed events

Reaction	target [g/cm^2]	Measured Charge	σ (%)	Acceptance	$\frac{d\langle n^-\rangle}{dy}$	Number of events
S+Ag	0.75	+,–	3.3	$0.5 < y < 3.5$	46	15000
		–		$2.5 < y < 4.5$		131500
S+Au	0.94	–	6.3	$2.5 < y < 4.5$	58	126850

where $\mathbf{p}_1, \mathbf{p}_2$ are the momenta of the two pions, and N is the normalization factor. In the traditional terminology the numerator is the "signal", and the denominator is the "uncorrelated background" or "reference sample". The signal is influenced by the Bose-Einstein correlations, as well as other correlations (like the correlations due to the Coulomb interaction in the final state, which is the subject of this paper), while the uncorrelated background ideally contains only the information on the momentum-space distribution of pairs of uncorrelated particles. The experimental signal distribution has been formed from all possible particle pairs in each analyzed event. The uncorrelated background distribution is created in a similar way, but particles of a pair are taken from different events. A different background formation technique has also been tested in which each particle is used only once, but no significant difference between the two methods was found. To form the correlation function, the background and the signal distributions have to be normalized first. This has been done by imposing the requirement that the correlation function should equal unity in a chosen interval in Q_i (usually outside the Bose-Einstein correlation peak). The fact that the final results of a correlation measurement have been found, in certain circumstances, to depend on the position of the normalization interval is one of the central topics of this paper.

A pion pair with pion momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ has six degrees of freedom in momentum space. In the most general case, the two-pion correlation function depends on all six components. The studies presented in this paper are carried out mostly in terms of a single variable, the invariant momentum difference Q_i:

$$Q_i^2 = -(p_1^\mu - p_2^\mu)(p_{1\mu} - p_{2\mu}), \tag{2}$$

where p_1 and p_2 are the four-momenta of the two particles. However, in Sect. 5, where the effect of a new Coulomb correction procedure will be demonstrated, the momentum components and the analysis procedure described in detail in [1] will also be used.

To account for the lack of track-by-track particle identification and for the contamination by particles originating from photon conversions, weak decays or secondary interactions, a Monte Carlo correction procedure was developed [1, 2]. According to the Monte Carlo simulation the fraction of pairs containing at least one particle which is not a pion from the primary interaction, varies between 15% and 70%, depending on momentum, and on the target material and thickness, and reaches its maximum for small transverse momenta, at target-fragmentation rapidities. In order to correct binned data for contamination, we have subtracted the estimated contamination contribution, derived in the Monte Carlo simulation, from the original number of pairs in each bin. The estimate for the contamination is based on the Lund Fritiof Monte Carlo program (version 1.6) [12], modified to have momentum distributions and strange particle yields similar to the data [7, 8]. In fact, any other event generator which reproduces the experimental particle spectra will lead to similar corrections. A full detector simulation was performed, based on the Geant simulation package [13].

The final corrected correlation function was obtained by subtracting the estimated signal contamination S_c from the measured signal S_m, and by subtracting the estimated background contamination B_c^G from the measured background B_m^G:

$$C = \frac{S_m - NS_c}{B_m^G - B_c^G}. \tag{3}$$

We have previously reported [1] that for pairs of like-charged particles the correlation intensity is strongly influenced by the contamination, while the width of the correlation function stays unchanged. That is because the contamination contribution for pairs of like-charged particles consists of essentially uncorrelated pairs and when subtracted from the corresponding measured distributions, it only boosts the correlation intensity without changing the shape, i.e. the width of the correlation function. On the other hand, the contamination in the case of the pairs of oppositely charged particles contains a positively correlated component due to the correlation of electrons and positrons from the conversion of photons in the target. In order to reduce the sensitivity of the measurement to this sort of contamination, the correlation functions for unlike-charged particle pairs have been evaluated with a cut on transverse momentum of a particle in a pair $p_T > 200$ MeV/c, which leaves essentially no electron-positron pairs in the data [3]. It has been verified that the resulting correlation functions for $p_T > 200$ MeV/c are consistent with the ones obtained without a cut in p_T [3].

Another contamination to the pure $\pi^+\pi^-$ sample corresponds to particle pairs containing a charged kaon: $K^+\pi^-$, $K^-\pi^+$ and K^+K^-. A positive correlation arising due to the attractive Coulomb interaction may be neglected, because the kaon contamination presents only a small contribution to the pure $\pi^+\pi^-$ sample.

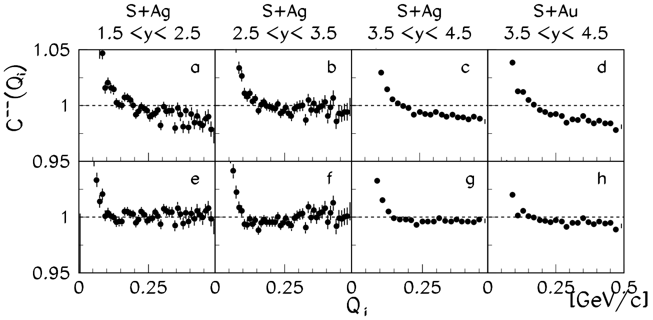

Fig. 1a–h. Examples of correlation functions for negative pions as a function of Q_i. Gamov corrected (**a–d**) and uncorrected (**e–h**). Note the strongly magnified scale

Apart from the Coulomb interaction, correlations of positive and negative particles may be influenced also by particle decays and strong interaction in the final state.

Due to a huge combinatorial background, the contribution of pairs of oppositely charged particles in the measured data, originating from decays of K^0_S, Λ and $\bar{\Lambda}$ particles and Δ resonances (which appears as a contamination to the pure $\pi^+\pi^-$ sample) amounts to less than 0.5%, and could be neglected in our analysis.

In order to exclude the contribution of ρ mesons (which peak at Q_i = 716 MeV/c and have a width of Γ = 154 MeV/c), the correlation function C^{+-} has been studied in the range $Q_i < 500$ MeV/c.

To summarise, the correlations of oppositely charged particles studied are in a good approximation representative for the $\pi^+\pi^-$ correlations.

The Gamov function which will be discussed in the following sections is [4, 5]:

$$G(\eta) = \frac{2\pi\eta}{e^{2\pi\eta} - 1}, \quad \eta = \pm\frac{m_\pi \alpha}{Q_i} \tag{4}$$

where the sign of η is positive for pairs of like charged pions, and negative for unlike charged pions (see e.g. [14]), m_π is the pion mass, and α is the fine structure constant. Note that the Gamov function for pairs of like charged particles in a very good approximation is equal to the inverse Gamov function for pairs of unlike charged particles; a slight difference is seen only for $Q_i < 10$ MeV/c. The same is true also for Baym's model [15], independently of the assumed particle source size.

4 Results

Let us first review the original indication for the possible failure of the Gamov correction, which came from the studies of $\pi^-\pi^-$ correlations [1–3]. Examples of the correlation functions for negative pions are shown as a function of Q_i in Fig. 1. Gamov corrected and uncorrected correlation functions are shown in Figs. 1(a–d) and 1(e–h), respectively. It is evident that , for the Gamov corrected correlation functions, a slope is present outside the Bose-Einstein correlation peak ($Q_i > 150$ MeV/c), in the region of increasing Q_i. The presence of this slope has been reported to be the most important source of problems in the correlation data analysis [1–3], because it introduces a systematic uncertainty on the fitted parameters. This effect is illustrated in Fig. 2, where the fitted parameters[1] are plotted as a function of the position of the interval in Q_i, in which the correlation function was normalized (i.e. the interval in which the correlation function was forced to equal unity). Depending on the position of the normalization interval the results vary by about 20%.

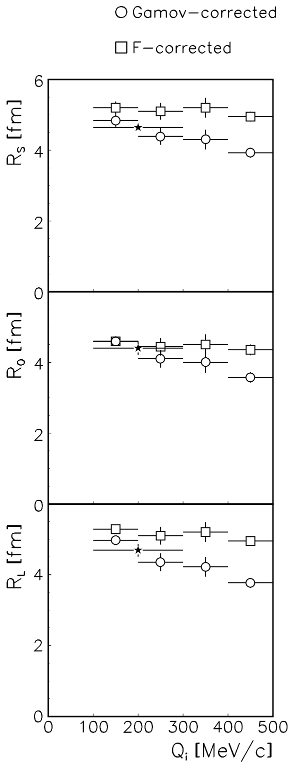

Fig. 2. The fitted results for the negative pion correlation functions in the reaction S+Ag ($1.5 < y < 2.5$) are plotted as a function of the position of the interval in which the correlation function was normalized. The normalization interval used in the published analysis [1] is indicated by star symbols. Standard Gamov correction-open circles, new correction procedure based on the F-function, (5)-rectangles. In the latter case there is no more normalization-dependence

In general, different effects could be responsible for the presence of the slope in the correlation function. However, the fact that the correlation functions before the Coulomb correction do not contain the slope (Fig. 1(e-h)) indicates that the bulk of the slope seen in the Gamov corrected correlation functions (Fig. 1(a-d)) originates essentially from the Gamov correction. Under the hypothesis that an appropriately corrected correlation function should be flat outside the Bose-Einstein correlation peak, it is natural to suspect [1–3] that the Gamov function could be inappropriate for the correction of these data, at least in the region outside the Bose-Einstein correlation peak. The correlation function would be overcorrected by the Gamov correction. The hypothesis that the correlation function should be flat outside the Bose-Einstein correlation peak finds support in the overall consistency of different data, as it will be demonstrated below, and also in the Monte Carlo studies using different event generators.

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[1] The system of variables used in the evaluation of the results, and the fitting procedure are defined and described in [1]

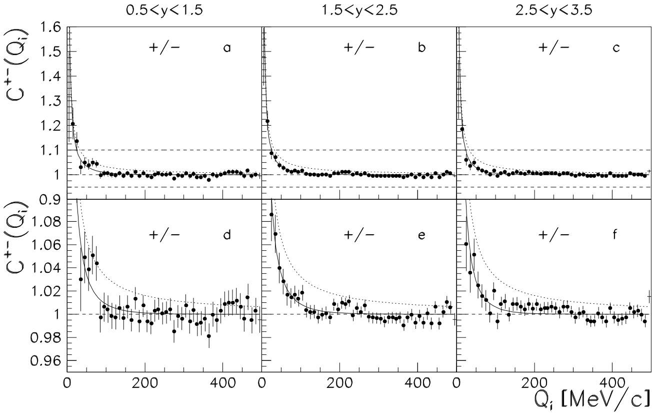

Fig. 3a–f. Correlation functions for $\pi^+\pi^-$ (**a–c**). The region indicated by the horizontal *dashed lines* in (**a–c**) is shown magnified in (**d–f**); the Gamov function (4) is shown by *dotted lines*, the function F (5) as fitted to the data by the *full lines*

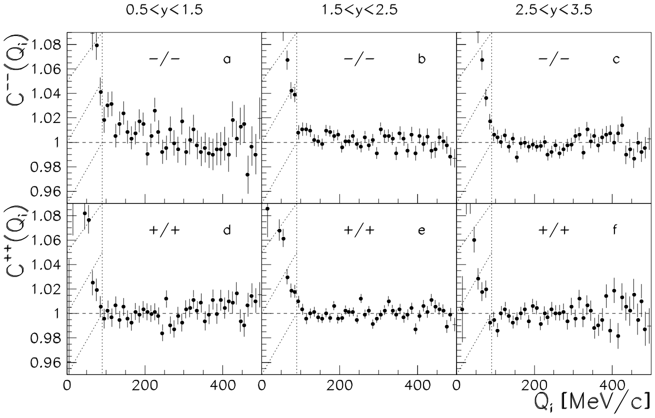

Fig. 4a–f. Correlation functions for $\pi^-\pi^-$ (**a–c**) and $\pi^+\pi^+$ (**d–f**), in the SAg data, corrected by the new Coulomb correction method based on the function F (5). The *shaded area* approximately indicates the region where the Bose-Einstein correlations are dominant

In the following, we will present the correlation functions for unlike-charged pion pairs, which in principle allow a study of the Coulomb attraction effect. In contrast to the correlation functions for like-charged pions, the correlation functions for unlike-charged pions are not subject to the BEC effect, and thus the Coulomb effect may be studied at much lower values of Q_i.

The correlation functions for oppositely charged pions in the S+Ag data are shown in Fig. 3, measured in the rapidity intervals indicated, and for $p_T > 200$ MeV/c. Although a positive correlation effect is evident, like qualitatively expected for pairs of particles which experience the attractive Coulomb force, the shapes of the correlation functions in Fig. 3 differ from the corresponding Gamov function, (4): they reach unity with increasing Q_i much faster than the Gamov function. This effect is consistent with the absence of a slope in the Coulomb-uncorrected correlation functions for negative pions, see Fig. 1(e-h). The idea that the Gamov correction could be inappropriate therefore finds support in the studies of correlations of both the like- and the unlike-charged particles.

There are several possible reasons for the failure of the Gamov function. The standard Gamov correction procedure [5] based on the Gamov function is theoretically evaluated for an isolated pair of non-relativistic charged pions emerging from a relatively small particle source. All three assumptions may be violated in ultrarelativistic nuclear collisions, where many charged particles are emitted from an extended, rapidly expanding source. The presence of numerous charged particles in ultrarelativistic nuclear collisions may influence the Coulomb potential between two particles (dynamic screening of the two-particle Coulomb potential) [2, 16, 17], the net effect being a reduction of the Coulomb force. On the other hand, attempts to include the size of the particle source in the evaluation of the Coulomb correction [14, 15, 18, 19], also indicate that the net Coulomb effect is weaker than the Gamov prediction. Relativistic effects have been studied recently [20], and a sizeable effect has been predicted as well. Let us note finally that, in the case of low multiplicity and a small source size [21] (interaction p+Ta at 70 GeV), a nice agreement of the correlation function for $\pi^+\pi^-$ pairs and the Gamov function was reported.

There are two sorts of biases in the physics results extracted from the correlation functions for like sign pions, introduced by using the Gamov correction [1]. First, as already discussed, due to uncertainties in the normalization of the correlation function which arise from the presence of the slope in the region outside the Bose-Einstein correlation peak, all fitted parameters have a systematic uncertainty of up to 20%. In the following section we will demonstrate how this bias disappears when the data are corrected using the correlation function measured for $\pi^+\pi^-$ pairs, instead of the Gamov function. Second, since in general the Coulomb interaction depends on the particle density in position and momentum space, as well as on the size of the pion source, the fitted parameters of the Gamov corrected data may suffer from a bias which depends on the source size and the multiplicity. Qualitatively, the fitted parameters (effective source sizes) for reactions with high particle density could be systematically biased to lower values. That is because the correlation function becomes artificially wide after the Gamov correction. It is clear that such biases may introduce severe errors in the interpretation of the correlation data, particularly when results are compared that correspond to events of different multiplicities.

The data presented in this paper, together with the coming high statistics data on Pb+Pb collisions will enable a theoretical derivation of an appropriate correction function that should take into account all relevant parameters. However, in this paper we present a simple pragmatic correction method, based just on the measured C^{+-} correlation functions for $\pi^+\pi^-$ pairs.

5 The new Coulomb correction method

The measured correlation functions for oppositely charged pions were fitted by the function

$$F(Q_i) = 1 + (G^{+-} - 1)e^{-Q_i/Q_0}, \qquad (5)$$

Table 2. Fitted results for Q_0. The function F ((5)) was fitted to the measured correlation functions for oppositely charged pions in the indicated intervals of rapidity, see Fig. 3a–c. The quoted systematic errors correspond to uncertainties in the contamination correction, and the normalization

Reaction	y	Q_0 [MeV/c]	χ^2/NDF
S+Ag	$0.5 < y < 1.5$	$75 \pm 19 \pm ^{20}_{5}$	44/50
	$1.5 < y < 2.5$	$75 \pm 12 \pm ^{15}_{5}$	67/50
	$2.5 < y < 3.5$	$60 \pm 14 \pm ^{15}_{5}$	76/50

where G^{+-} is given by (4). This function approaches the Gamov function in the limit of small Q_i, whereas with increasing Q_i it turns down to unity more rapidly than the Gamov function, see Fig. 3. That decrease is characterised by Q_0, the only fit parameter. The fitted results are shown in Table 2 for the three indicated intervals in rapidity.

The Coulomb correction method introduced in this paper uses simply the function F ((5)) instead of the Gamov function. By doing so, we implicitly assume that the function representing Coulomb repulsion and the inverse of the function representing Coulomb attraction do not differ considerably, like it is indeed the case e.g. for the Gamov function. However, an analysis of much higher statistics data, like the coming Pb+Pb collisions, might offer a chance for a more refined approach.

The resulting corrected correlation functions for $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs are shown in Fig. 4a–c and in Fig. 4d–f, respectively. The slope in the correlation function outside the correlation peak has clearly disappeared in all cases, lending further a posteriori support to the hypothesis, that the Coulomb correction may be determined from the $\pi^+\pi^-$ correlations.

As a direct consequence of the absence of the slope, the fitted parameters became independent of the normalization procedure, as demonstrated by the rectangles in Fig. 2. It is interesting to note that the new fitted parameters are not far from the published values [1] (represented by star symbols in Fig. 2), apparently thanks to the good choice of the normalization region in the published analysis.

The multiplicity-dependence of the effect can not be studied with the present data both because of insufficient statistics, and because the available interval in multiplicity (corresponding to different rapidity intervals in the S+Ag data) is rather narrow. However, that study will become possible soon, when also the new data on Pb+Pb collisions become available.

6 Summary

We have presented experimental evidence that the standard Gamov correction function, traditionally used to correct the Bose-Einstein correlation functions for Coulomb interaction of pions, is inconsistent with the measured correlation functions for $\pi^+\pi^-$, $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs in central S+Ag collisions at 200 GeV per nucleon.

A new correction method is proposed, based on the measured correlation data for $\pi^+\pi^-$ pairs, which cures the problems that have previously dominated the systematic uncertainty of the correlation analysis.

The reason for the failure of the Gamov correction is probably due to the fact that the simple assumptions used in its theoretical derivation do not hold for ultrarelativistic nuclear collisions, where many charged particles are emitted from an extended, rapidly expanding source. The S+Ag data presented in this paper, together with the future high multiplicity Pb+Pb data, should provide solid experimental measurements for a better understanding of the Coulomb interaction in ultrarelativistic nuclear collisions.

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