Experimental proton-proton correlation function derived for the $pp \rightarrow pp\eta$ reaction

P. Klaja[a,b], P. Moskal[a,b] and A. Deloff[c] for the COSY–11 collaboration

[a]*Nuclear Physics Department, Jagellonian University, 30-059 Cracow, Poland*
[b]*Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[c]*Institute for Nuclear Studies, Warsaw, Poland*

Abstract. Based on the high statistics data from the $pp \rightarrow ppX$ reaction measured by the COSY-11 collaboration [1] we have derived a two-proton correlation function for the production of the $pp\eta$ and $pp+pions$ systems. The measured correlation function normalized to the value simulated for a point-like source was compared with a theoretical prediction in order to estimate the size of the reaction volume.

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INTRODUCTION

The momentum correlations of particles at small relative velocities are widely used to study the spatio-temporal characteristics of the production processes in the relativistic heavy ion collisions [2]. This technique, called after Lednicky *a correlation femtoscopy* [3], originates from photon intensity interferometry initiated by Hanbury-Brown and Twiss [4]. Implemented into the nuclear physics [3,5,6] it permits to determine the duration of the emission process and the sizes of the source from which the particles are emitted [3]. A central role plays the correlation function which has been defined as a ratio of the measured two-particle distribution divided by the reference spectrum obtained from the former by mixing the particles from different events [3]. The importance of the correlation femtoscopy has been well established for the investigations of the dynamics in heavy ion collisions with high multiplicity. However, as pointed out by Chajecki [7], in the case of low-multiplicity collisions the interpretation of the correlation function measurements is still not fully satisfactory, especially in view of the surprising STAR collaboration observation indicating universality of the resulting femtoscopic radii for both, the hadronic (proton-proton), and heavy ion collisions [8]. One of the challenging issues in this context is the understanding of the contributions from the non-femtoscopic correlations which may be induced by the decays of resonances, global conservations lows [7], or by other unaccounted for interactions.

In particle physics the best place to study two-proton correlations is a kinematically complete measurement of meson production in the collisions of hadrons. Particularly favourable are exclusive experiments conducted close to the kinematical threshold where the fraction of the available phase-space associated with low relative momenta between ejectiles is large [9].

In this note we report on the η meson and multi-pion production experiment in which the mesons were generated in the collisions of protons at the beam momentum close to the kinematical threshold for the $pp \to pp\eta$ reaction. The measurement of the two-proton correlation function for these reactions is important not only in the context of the studies of the dynamics underlying the heavy ion physics. Such investigations are interesting by themselves because they offer a new promissing diagnostic tool, still not exploited, for studying the dynamics of meson production in the collisions of hadrons.

The correlation function carries information about the emitting source and, in particular, about of the size of the interaction volume of the $pp \to pp\eta$ process. The knowledge of this size might be essential to answer the intriguing question whether the three-body $pp\eta$ system is capable of supporting an unstable Borromean bound state. The Borromean systems may be realized in the variety of objects on the macroscopic (e.g. strips of papers), molecular [10, 11] and nuclear scale (e.g. ^{11}Li or ^{6}He nuclei [12–14]). According to Wycech [15], the large enhancement of the excitation function for the $pp \to pp\eta$ reaction observed close to the kinematical threshold may be explained by assuming that the proton-proton pair is emitted from a large (Borromean like) object whose radius is about 4 fm.

TWO-PROTON CORRELATION FUNCTION

The experiment was conducted using the proton beam of the cooler synchrotron COSY [16] and the internal hydrogen cluster target [17]. Momentum vectors of outgoing protons from the $pp \to ppX$ reaction were measured by means of the COSY-11 facility [18]. The two-proton correlation function $R(q)$ was determined for the $pp\eta$ and $pp(m\pi)$ systems, respectively. It was calculated as a ratio of the reaction yield $Y(q)$ to the uncorrelated yield $Y^*(q)$ according to the formula (cf. [19])

$$R(q) + 1 = C^* \, \frac{Y(q)}{Y^*(q)}, \tag{1}$$

where C^* denotes an appropriate normalization constant. $Y^*(q)$ was derived from the uncorrelated reference sample obtained by using the event mixing technique [6]. Here, $R(q)$ denotes a projection of the correlation function onto the relative momentum of emitted particles $q = |\vec{p_1} - \vec{p_2}|$ [1]

Separation of events from the production of $pp\eta$ and $pp + pions$ systems

In the discussed experiment, only four-momenta of two protons were measured and the unobserved meson was identified via the missing mass technique [1, 20]. In such situation an entire accessible information about an event is contained in the momentum vectors of registered protons. Therefore, it is impossible to know

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[1] Note, that some authors instead of q take as the independent variable the proton-proton center-of-mass momentum $k = q/2$ (c.f. the accompanying contribution [24]).

whether in a given event the η meson or a few pions have been created. However, statistically, one can separate these groups of events on the basis of the missing mass spectra, for each chosen region of the phase-space.

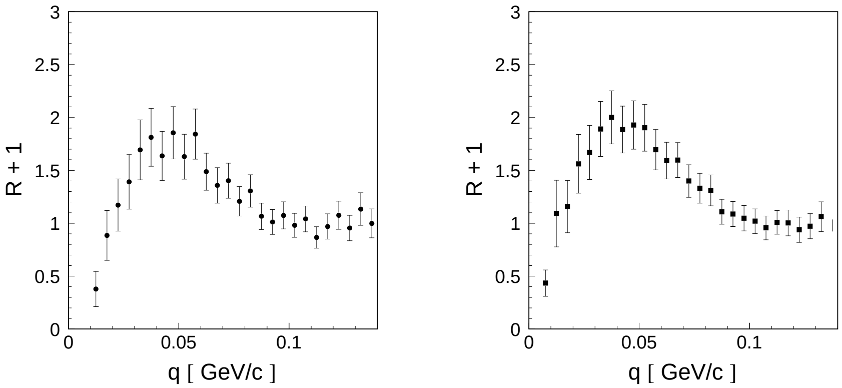

Figure 1: Experimental two-proton correlation function determined for the $pp \rightarrow pp\eta$ reaction (left panel), and for the $pp \rightarrow pp + pions$ reaction (right panel). The result shown in this figure is not corrected for the acceptance of the detection system.

The derivation of the denominator in (1) was much more complicated. In order to extract Y^* we have developed a method based on the assignment of the statistical weigths to the registered events. The weights describe the probability that a given event corresponds to the $pp\eta$ or to the $pp+pions$ production. This technique allowed us for the derivation of the uncorrelated yield separately for the production of the η meson and for pions. For details the interested reader is referred to [21]. Figure 1 presents the determined correlation functions but at this stage of the evaluation the result is biased by the limited detection acceptance and efficiency to be considered in the next section.

Acceptance corrections

As the next necessary step in the data evaluation we have corrected the determined yields to account for the finite geometrical acceptance of the COSY-11 detection setup.

First, we calculated the acceptances and efficiencies of the COSY-11 system for the registration and reconstruction of the $pp \rightarrow pp\eta$ and $pp \rightarrow pp(m\pi)$ reactions as functions of the relative momentum of the outgoing protons. The results of the simulations are presented in the figure 2.

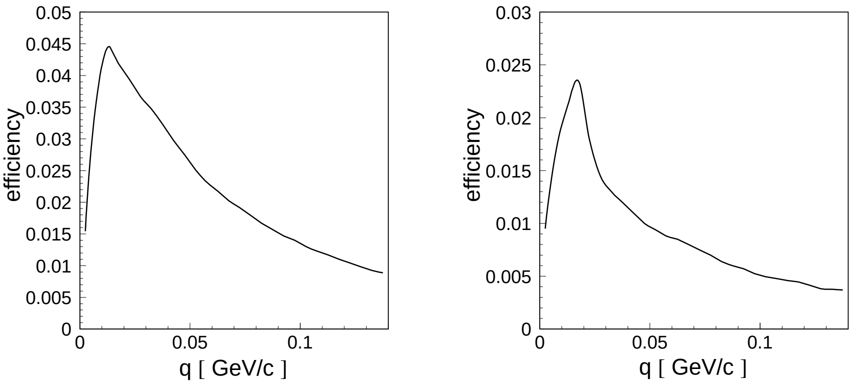

Figure 2: Overall detection efficiency (acceptance and efficiency) of the COSY-11 detection setup for the measurement of the $pp \rightarrow pp\eta$ reaction at the excess energy of Q = 15.5 MeV (left panel) and for the measurement of the $pp \rightarrow pp(m\pi)$ reactions with the invariant mass of mπ system equal to the mass of the η meson (right panel).

Knowing the acceptance it would be straightforward to correct the nominator in (1), however the correction of the uncorrelated yield $Y^*(q)$ is not trivial since the momenta of the protons in the uncorrelated event originate from two independent real events which, in general, could correspond to different values of the detection efficiency.

Therefore, in order to derive a correlation function corrected for the acceptance, we have created a sample of data that would have beeen measured with an ideal detector. For this purpose we multiplied each reconstructed event so many times as it results from the known acceptance. This means that a given reconstructed $pp \rightarrow pp\eta$ ($pp \rightarrow pp(m\pi)$, respectively) event with a proton-proton relative momentum equal q was added to the sample 1/A(q) times.

With the aid of this corrected data sample we calculated the two-proton correlation function according to the formula (1). In order to avoid mixing between the same events, a 'mixing step' in the calculations was set to a value bigger than the inverse of the lowest acceptance value. A random repetition of the identical combinations was also omitted by increasing correspondingly a 'mixing step'. In particular, a kth real event, from the acceptance corrected data sample, was "mixed" with a (k+n)th event, where $n > max(1/A(q))$. If the (k+1)th event was the same as kth, then this was mixed with a (k+1+2n) event, etc.

Results

The two-proton background-free correlation functions for the $pp \rightarrow pp\eta$ and $pp \rightarrow pp + pions$ reactions corrected for the acceptances are presented in figure 3(left). As mentioned in the introduction the shape of the obtained correlation function reflects not only the space-time characteristics of the interaction volume but it may also be strongly modified by the conservation of the energy and momentum and by the final state interaction among the ejectiles.

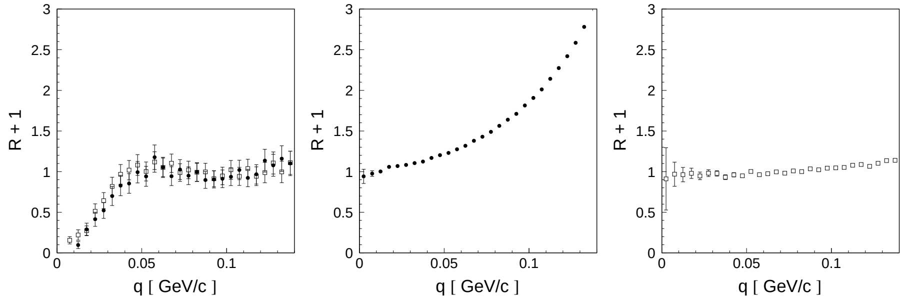

Figure 3: [left panel] Acceptance corrected experimental proton-proton correlation functions for the production of the η meson (full dots) and multi-pions (open squares). [middle panel] The simulated two-proton correlation function for the η meson production. [right panel] The simulated two-proton correlation function for the $pp \rightarrow pp\, pions$ reactions.

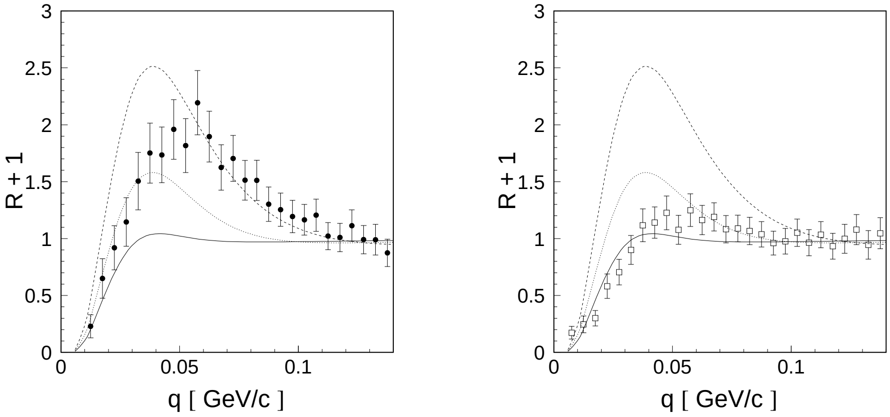

Figure 4: The two-proton correlation functions corrected for acceptance and normalized to the corresponding correlation function simulated for the point-like source. Full dots and open squares represent experimental points for the $pp \rightarrow pp\eta$ and $pp \rightarrow pp + pions$ reaction, respectively. The superimposed lines shows the result of calculations [24] for the reaction volume parametrized by a Gaussian with radius $r_0 = 2.0$ fm (dashed line), $r_0 = 3.0$ fm (solid line) and $r_0 = 5.0$ fm (dotted line), respectively.

In order to estimate the influence of the shape induced by the kinematical bounds we have reconstructed the correlation functions from the data for both, the $pp \rightarrow pp\eta$ and $pp \rightarrow pp + pions$ reaction assuming a point-like source and using a Monte-Carlo simulation. The results of the simulations are presented in figure 3 and it is apparent that they differ significantly from the experimental correlation function. In order to extract from the experimental data the shape of the correlation function free from the influence of the energy and momentum conservation we had constructed a double ratio:

$$R(q) + 1 = C_{exp/MC} \left(\frac{Y_{exp}(q)}{Y^{*}_{exp}(q)} / \frac{Y_{MC}(q)}{Y^{*}_{MC}(q)} \right), \tag{2}$$

where $C_{exp/MC}$ denotes the normalization constant, the indices 'exp' and 'MC' refer to the experimental and simulated samples, respectively. The determined double ratios are presented in figure 4. Such procedure is used e.g. by the ALEPH collaboration for studying the correlation of the Λ pairs from the Z decays [22] or for the studies of correlations in W-pairs decays [23].

In order to estimate the size of the emission source the results are compared with theoretical predictions, obtained by assuming a simultaneous emission of the two protons and derived under the assumption that the final-state interaction between the two detected particles dominates, while other interactions are negligible. This is certainly fairly well satisfied in the case of the studied ppX systems. The source density was taken to be a Gaussian specified by a radius parameter r_0 and further particulars of the calculations are presented in reference [24]. A rough comparison between the theoretical correlation function and the experimental points indicates that the effective size of the emission source amounts to about 2.4 fm for the $pp\eta$ system and about 4 fm for the $pp + pions$ system. A detailed comparison and the interpretation of results is in progress.

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