CORRELATION FEMTOSCOPY FOR STUDYING η MESON PRODUCTION MECHANISM[1]

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The high statistics data from the $pp \to pp\eta$ reaction measurement, delivered by the COSY-11 collaboration, are now being evaluated using the correlation femtoscopy technique. This method is based on the relative momentum correlations of two emitted protons and may permit determination of the size of the reaction volume.
For the very first time, we apply an intensity interferometry technique to study the mechanism of the meson production via the nucleon-nucleon interaction close to the kinematical threshold. We invented a method to determine correlation function for the $pp\eta$ system free from the physical multi-pion production background. We show the comparison of experimental results with theoretical predictions and appraise the accuracy achieved for the determination of the size of the emission source.

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1 Introduction

One of the possible mechanisms of the η meson production via the $pp \to pp\eta$ reaction is a direct emission of the η meson from the interaction region and the other possibility, believed to be dominant, is the creation of this meson via the resonant state $S_{11}(1535)$ [1–3]. Very close to the kinematical threshold the direct influence of the resonant state on the form of differential distribution of the cross section (e.g. Dalitz plot) is very difficult to observe due to the fact that

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the resonance is more than an order of magnitude broader ($\Gamma \approx 150$ MeV [4]) than the available range of the invariant mass distribution, which in the case considered in this article amounts to 15.5 MeV [5]. Therefore it is worth trying to find an observable different from the distributions of the cross sections which can deepen our understanding of the reaction dynamics. We assess that such an additional information about the production mechanism may be derived from the size of the reaction region from which the particles emerge.

In comparison to the direct production, the presence of the resonance in the production process ($pp \to pN^* \to pp\eta$) will increase the effective size of the protons separation at the moment when they appear as free (on-shell) particles. The information about the effective spatial proton's separation at this moment may be derived from the proton-proton correlation function. However, the shape of this function depends also on the interaction between the emitted particles, and in order to draw unbiased conclusions about the spatial size of the emission source, the effect from the final state interaction (FSI) has to be determined precisely. Due to the presence of the Coulomb and strong interaction, and the non-trival problems with the description of the three body (nucleon-nucleon-meson) system, there exists at present no rigorous description of the interaction within the $pp\eta$ system [6]. Yet, in practice we can account for the $pp\eta$ FSI, parametrizing it from the precisely measured $m_{p\eta}$ and m_{pp} invariant mass distributions [7]. Therefore, by the analogy to the successful analysis based on the Dalitz plot and correlation function, performed for the determination of the size of the neutron halo in the ^{14}Be ($^{12}Be + n + n$) and the mechanism of its dissociation on C and Pb targets [8], we would like to conduct similar investigations for the $pp\eta$ system in $pp \to pp\eta$ reaction. In case of the $pp \to pp\eta$ reaction it can be possible that two protons coming from the reaction volume could be emitted with a uncorrelated phases since the reaction proceeds in two steps ($pp \to pN^* \to pp\eta$) via the excitation of the intermediate resonance state N^* (1535) which decays delayed in time into the proton and the η meson.

Due to the short life-time of the resonant state, the average increase of the effective size of the source in respect to the direct production is expected to be small (in the order of the fraction of femtometer), but as we will argue later, the accuracy we can achieve is better than 0.1 fm. Moreover, there is another interesting aspect connected to the study of the reaction volume. Namely, it cannot be a priori excluded that the geometrical dimensions of the source can be much larger due to the reflection of the topological (Borromean) bounding in the $pp\eta$ system. As Borromean we call a bound three-body system in which none of the two-body subsystems is bound. There exists, an encouraging and interesting conjecture of S. Wycech who pointed out that a large enhancement in the excitation function of the $pp \to pp\eta$ reaction observed close to the kinematical threshold may be described assuming, that the proton-proton pair is produced from a large (Borromean like) object of a 4 fm radius [9].

The Borromean bounding in the three body system is a very intriguing issue attracting the researchers from different fields of science. In nuclear physics the ^{11}Li ($^{9}Li + n + n$) and ^{6}He ($\alpha + n + n$) nuclei have been found to have such a property [10]. Another, interesting and worth noticing example, is that very recently nanoscale Borromean rings were constructed in a wholly synthetic molecular form [11, 12].

At present it is, however, still not established whether the low energy $pp\eta$ system can form a Borromean or resonant state.

In the subsequent sections we will present a correlation function for the $pp\eta$ system produced in the collisions of nucleons, where the η meson is identified via the missing mass technique. In such measurements it is impossible to identify the production of $pp\eta$ system on the event-by-event basis due to the physical background originating from the $pp \rightarrow pppions$ reactions. We have, however, succeeded to develop a method for constructing a correlation function free from the multi-pion production background. The technique will be described in this article.

2 Correlation femtoscopy

The momentum correlations of particles at small relative velocities are widely used to study space-time characteristics of production processes, so serving as a correlation femtoscopy [13]. Correlation femtoscopy originates from an intensity interferometry known as HBT effect [14]. Implemented into nuclear physics [13, 15, 16], this technique permits to determine the size of the source from which the particles are emitted. It is based on the correlation function, which relates the space-time separation of the particles to their momenta p_1 and p_2 at the emission time. This function can be expressed in terms of pair- and single-particle cross section [17]:

$$R(p_1, p_2) = C \cdot \frac{d^6\sigma/d^3p_1 d^3p_2}{(d^3\sigma/d^3p_1)(d^3\sigma/d^3p_2)} - 1, \qquad (1)$$

where C denotes the overall normalization constant. Generally one can relate a correlation function with a Fourier transform of the spatial distribution of the emission source [18]. The shape of a two-proton correlation function depends on the spatial size of the source, quantum statistics and the interaction between the outgoing particles.

In our case the influence of the $pp\eta$ FSI can be derived from the experiment. More details will be given in the next section. Thus, taking FSI into account when calculating a correlation function will permit to study the dependence of the shape of this function on the spatial dimensions of the reaction region.

As far as the experiment is concerned, in case of impossibility for the single particle cross section measurement, an alternative definition for the correlation function can be applied. Equivalently to Eq. (1), one can calculate such a function by generating an "uncorrelated" yield via event mixing technique, as shown by Kopylov and Podgoretsky [16]. The correlation function is then given by [17]:

$$R(q) + 1 = C^*_{12} \frac{Y_{12}(q)}{Y^*_{12}(q)}, \qquad (2)$$

where $Y_{12}(q)$ denotes the coincidence yield and $Y^*_{12}(q)$ stands for the yield derived from the uncorrelated reference sample. C^*_{12} is an appropriate normalization constant. Here, $R(q)$ denotes a projection of the correlation function onto the relative momentum of emitted particles $q = |\vec{p_1} - \vec{p_2}|$.

3 Interaction within the $pp\eta$ system

The influence of the interaction between ejectiles of the $pp \rightarrow pp\eta$ reaction on the correlation function can be inferred from the invariant mass distributions of the two-particles subsystems.

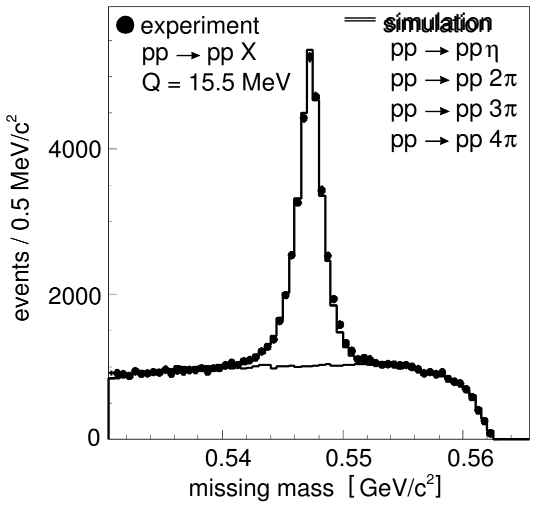

Fig. 1. Missing mass spectrum for $pp \to ppX$ rection determined in the experiment at beam momentum $p_B = 2.0259$ GeV/c [5] (points). The solid line histograms present the simulation of 1.5×10^8 events of $pp \to pp\eta$ reaction, and 10^{10} events for the $pp \to pp2\pi$, $pp \to pp3\pi$ and $pp \to pp4\pi$ reactions. The simulated histograms were fitted to the data varying only the magnitude.

The $pp \to pp\eta$ reaction was measured with high statistics by the COSY-11 collaboration at beam momentum $p_B = 2.0259$ GeV/c [5]. The determined missing mass spectrum for the $pp \to ppX$ process is presented in figure 1. One can easly recognize the sharp peak from the η meson production over a flat multi-pion production background. The estimated number of η production events is around 25 thousands. High statistics in an such experiment allows to derive the distributions of differential cross sections free of the multi-meson production background [5, 7]. An example of such a distribution is presented in the left panel of Fig. 2. This figure presents the projection of the phase-space distribution onto the two-proton invariant mass axis. One can easily recognize the growth of the population density at the range where protons have small relative momenta. The shown distribution is free of the multi-pion background since the number of $pp \to pp\eta$ events has been extracted for each point separately, first selecting data according to the square of the proton-proton invariant mass (s_{pp}) value and then for each s_{pp} interval constructing a missing mass distributions. Generally, the full experimentally accessible information of the interaction within the $pp\eta$ system is contained in the Dalitz plot distribution (shown in the right panel of Fig. 2) which we can use when taking into account an influence of the $pp\eta$ FSI on the correlation function.

4 Proton-proton correlation function for the $pp \to pp\eta$ reaction

In this section we would like to present a method of evaluation of proton-proton correlation function for the investigated $pp \to pp\eta$ reaction. Subtraction of the physical background and corrections for the limited acceptance of the detection system constitute the two main challanges

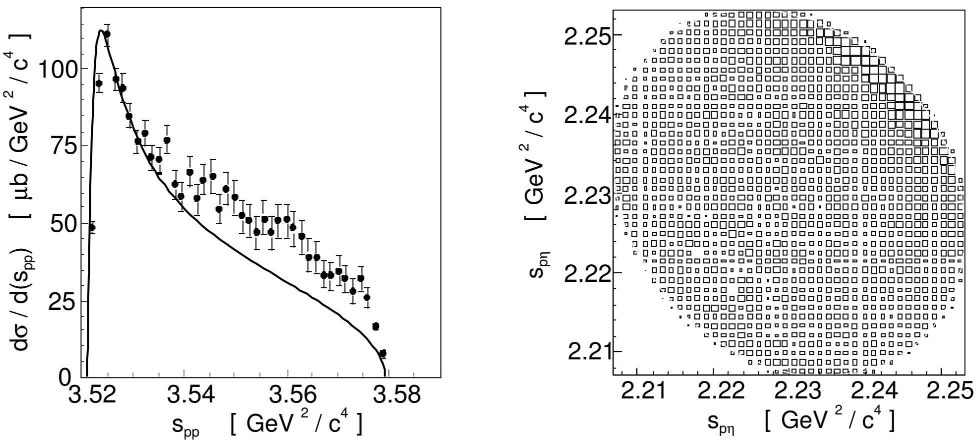

Fig. 2. (Left panel): Distribution of the square of the proton-proton (s_{pp}) invariant mass for the $pp \to pp\eta$ rection at $Q = 15.5$ MeV [5, 7]. The solid line corresponds to the calculations under the assumption of only proton-proton interaction [19]. (Right panel): Dalitz plot distribution. Experimental results determined for the $pp \to pp\eta$ rection at the excess energy of $Q = 15.5$ MeV. Data were corrected for the detection acceptance and efficiency.

we have to face when deriving the correlation function from the experimental data. Here we will concentrate on the former one.

According to Eq. (2) the two-proton correlation function $R(q)$ can be defined [17] as a ratio of the reaction yield $Y_{pp\eta}(q)$ to the uncorrelated yield $Y^*(q)$. In the discussed $pp \to pp\eta$ experiment, only four-momenta of two protons were measured and the unobserved meson was identified via the missing mass technique [5,7]. In such measurement the entire accessible information about an event is contained in the momentum vectors of registered protons. Therefore, it is in principle impossible to decide whether a given event corresponds to the η meson production or whether it is due to the multi-pion creaction. However, statistically, on the basis of the missing mass spectra, one can derive a number of events originated from the production of $pp\eta$ system, for a chosen region of the phase-space. Therefore, $Y_{pp\eta}(q)$ can be easily extracted for each studied interval of q by dividing the sample of measured events according to the value of q, next calculating the missing mass spectra of the $pp \to ppX$ reaction for each sub-sample separately, and counting the number of $pp\eta$ events from these spectra. An example of such histogram for one value of q is presented in the right panel of Fig. 3. To demonstrate the full set of the data in the left panel of Fig. 3 we show also a spectrum of the population density over the plane spanned by q and the missing mass.

The statistics obtained in the considered measurement allowed to divide the kinematically available range of q into bins whose width ($\Delta q = 5$ MeV/c) corresponds approximately to the accuracy of the determination of the relative proton momentum ($\sigma(q) \approx 6$ MeV/c).

An extraction of $Y^*(q)$, unbiased by the multi-pion production is however not trivial. Applying a mixing technique one can construct an uncorrelated reference sample taking momentum vectors of protons corresponding to different real events. A real event is determined by the momentum vectors of two protons registered in coincidence, and an uncorrelated event will thus

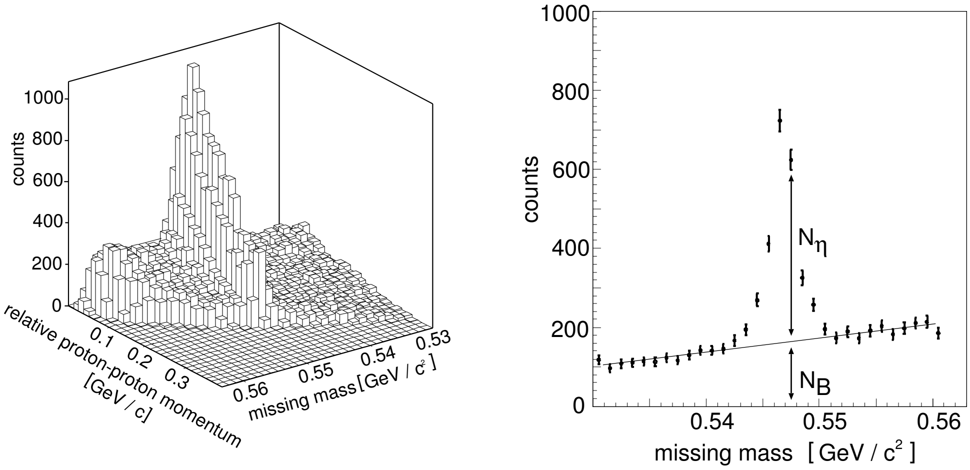

Fig. 3. (Left panel): The example of the high statistics distribution of the measured $pp \to ppX$ reaction close to the η meson production threshold [5]. (Right panel): The example of missing mass spectrum measured [5] for the $pp \to pp\eta$ reaction at $q \in (0.06;\ 0.07)$ GeV/c.

comprise momentum vectors of protons ejected from different reactions. Unfortunately, in such a sample of uncorrelated momentum vectors, due to the loss of the kinematical bounds, the production of the η meson will be not reflected on the missing mass spectrum and hence it can not be used to extract a number of mixed-events corresponding to the production of the η meson. Therefore, in order to determine a background-free correlation function for the $pp \to pp\eta$ reaction we performed an analysis in the following manner: First, for each event, we have determined a probability ω that this event corresponds to the $pp \to pp\eta$ reaction. The probability ω_i, that i^{th} $pp \to ppX$ event with a missing mass m_i, and relative momentum of q_i corresponds to $pp \to pp\eta$ reaction was estimated according to the below formula:

$$\omega_i = \frac{N_\eta}{N_\eta + N_B}(m_i, q_i), \tag{3}$$

where N_η stands for the number of the $pp \to pp\eta$ reactions and N_B is the number of events corresponding to the multi-pion production. The values of N_η and N_B were extracted from the missing mass distributions produced separately for each of the studied intervals of relative momentum q. An example of a missing mass spectrum with the pictorial definitions of N_B and N_η is presented in the right panel of Fig. 3. Next, in order to obtain a value of $Y_{pp\eta}(q)$ for a certain q we have added probabilities of all events for which a relative momentum of two protons belongs to the bin centered at q. Thus, $Y_{pp\eta}(q) = \sum_i \omega_i$ where i enumerates all events with relative protons momentum corresponding to the considered q bin. The result is of course per definition the same as obtained earlier by counting the number of events ($Y_{pp\eta}(q) = \sum_j N_\eta(j)$) where j enumerates bins in the histogram.

However, now having introduced the weights we can calculate also the value of $Y^*(q)$ without a bias of the multi-pion background. We can achieve this by sorting an uncorrelated sample according to the q values similarly as in the case of the correlated events and next for each sub-

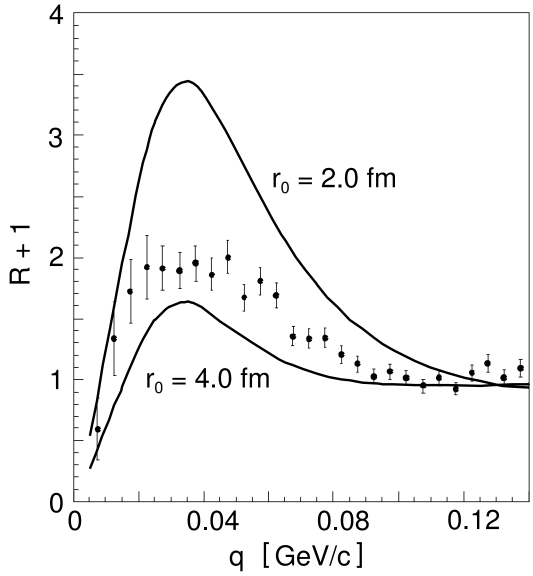

Fig. 4. Comparison of the experimental correlation function for the $pp \to ppX$ reaction, without acceptance correction represented by full dots and theoretical calculations indicated as two solid lines for emission sources parametrized by Gaussian distribution with $r_0 = 2.0$ and 4.0 fm.

sample we construct background free $Y^*(q)$ as a sum of the probabilities that both protons in an uncorrelated event originate from the reaction where the η meson was created. Specifically, if in a given uncorrelated event denoted by k, one momentum is taken from a real event say $k1$ and the second momentum from an real event $k2$, then the probability that both correspond to the reactions where the η was created equals to $\omega_{k1} \cdot \omega_{k2}$, and hence the uncorrelated yield $Y^*(q)$ may be constructed as a $\sum_k \omega_{k1} \cdot \omega_{k2}$, where k enumerates events in the uncorrelated sub-sample with a relative protons momentum q.

In the limit of absence of background all values of ω would be equal to 1 and so deriving both $Y_{pp\eta}(q)$ and $Y^*(q)$ we would just count the events. In the presence of the background if a missing mass of real event is from the outside of the η signal than it is certain that this event corresponds to the multi-pion production process and it indeed will not be taken into account in the calculation of $Y_{pp\eta}(q)$ and $Y^*(q)$ since its weight will be equal to zero. If the missing mass of the given event is from the region where N_η is larger than zero than we don't know whether the event is from the η or multi-pion creation. However, for the calculation of the yields we need only the overall number of η events from a given range of the q value. This could be determined either by taking only η events into account and counting them with a weight equal to one (which is in principle impossible since this events are kinematically indistinguishable from the multi-pion production) or as we did by counting all events fulfilling a required kinematical conditions (in our case we look only at q) and assigning them probabilities that they belong to the η production.

The correlation function derived from the data is presented in Fig. 4. It is compared to the calculations, performed assuming a simultaneous emission of the two protons and the η meson and approximating tentatively the effective spatial shape of the emission zone by the Gaussian distribution. In such a case the standard deviation of such distribution - hereafter referred to as r_0 - constitutes the measure of the dimension of the source. For the simulations we presently adapted a computing procedure written by R. Lednicky [20,21], which already has been successfully applied in other studies (example in ref. [8]). At present we take into account proton-proton FSI only, but in further analysis, we would like to make simulations with compliance of the $pp\eta$ FSI as can be extracted from the Dalitz plot distributions.

The determined experimental correlation function shows a maximum at a value of q as predicted by simulations. The height of the peak at q $\approx$ 40 MeV/c depends significantly on the value of r_0 and therefore the magnitude of this maximum may serve as a measure of the volume of the reaction zone. A rough comparison between theoretical correlation functions simulated with $r_0 =$ 2 fm and 4 fm, respectively, and the experimental one shown in Fig. 4 indicates that the size of the reaction volume can be approximated by the Gaussian distribution with $r_0 \approx 3$ fm. Of course, generally the size of the reaction zone can be extracted by the comparison of the experimental and simulated correlation functions treating r_0 as a fitting parameter.

The results presented in Fig. 4 have not been corrected for the acceptance of the COSY-11 detection setup yet, and the theoretical calculations have been performed without taking into account the experimental spread of the momenta. These corrections could significantly influence the final results. Therefore in a present article we do not perform a quantitative analysis. We only put out the emphasis on exploring the method which can be further adapted to examine the dynamics of η and η' meson production mechanism in nucleon-nucleon collisions. Although after the mentioned corrections the result may be different, it is worth noticing that the extracted value of r_0 is compatible with the effective range (2.8 fm [22]) of the proton-proton interaction.

From the comparison of the theoretical lines and the data in Fig. 4 one can appraise a statistical accuracy of the r_0 determination which can be achieved when performing fit with r_0 as a free parameter. Examining in Fig. 4 the range of 0.02 GeV/c $< q <$ 0.10 GeV/c one observes there 15 points with a statistical errors corresponding to the accuracy varying between 0.2 fm and 0.5 fm. Thus as far as the statistical precision is concerned we will be able to determine the effective size of the source with the precision much better than the errors quoted above for the single points.

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