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Correlations of neutral pions in ultrarelativistic heavy ion collisions

WA80 Collaboration

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Abstract. Correlations of 4 photons representing neutral pions have been studied in ultrarelativistic heavy ion collisions. Data were taken in the WA80 experiment at the CERN-SPS with a 200 A GeV oxygen beam. The π^0 are detected via their decay photons with a high-granularity lead glass array. Special features of interferometry using neutral pions will be discussed. The extracted preliminary parameters for high pt pions emitted near midrapidity in O + Au collisions lead to rather small effective source sizes.

Pion interferometry is a tool to study the properties of the particle-emitting source in high energy collisions. It can provide information about both the geometry and the evolution of the reaction system. The method relies on the fact that the symmetrization of the multi-boson wavefunction favours the emission of pions in the same state or nearly identical states. This results in an enhanced measurement of pion pairs with small momentum differences (also known as the Hanbury-Brown - Twiss effect¹ or the Goldhaber - Goldhaber - Lee - Pais effect²). The range of the correlation is related to the space-time structure of the source.

In this paper we present the first attempt to analyze correlations of neutral pions in oxygen induced interactions at 200 A GeV measured by the WA80 collaboration at the CERN SPS. The experimental setup is described in detail elsewhere³. In this study we will focus on the data measured with the finely granulated lead glass calorimeter SAPHIR, which is able to identify photons and to reconstruct neutral pions. SAPHIR covers roughly 1/6 of the total azimuth in the pseudorapidity range between 1.5 and 2.1. Details about the detector are given in Ref. 4.

Until now pion interferometry has only been performed with charged pions. The use of π^0 , although more difficult experimentally, has several advantages:

- No Coulomb correction has to be applied to the data.

- π^0 are detected via their decay photons. This allows us to measure two pions even in the case that they have exactly the same momentum, because the decay photons are in general clearly separated, when they reach the detector.

In a high multiplicity environment, however, photons may accidentally combine to an invariant mass close to the pion mass. Such combinatorial (background) pairs cannot be distinguished from a true photon pair originating from a π^0 -decay. Thus the pair reconstruction works only on a statistical level, but not event-by-event. Because of the high multiplicities and the small acceptance for pions with low transverse momentum, the analysis must be restricted to pion candidates above a certain cut in p_T . For this study we analyzed $1.5 \cdot 10^6$ events for the system $^{16}\text{O} + ^{39}\text{Au}$ and 500,000 events for $^{16}\text{O} + ^{12}\text{C}$. The requirement of two photon pairs with a pt above the actual cut reduces the statistics considerably. Only those events were accepted, where all involved photons were separated by an opening angle of at least 2.3° . This represents a very conservative limit in order to prevent any distortion of the measurement due to the overlap of showers in the detector.

Fig. 1: Detector resolution in the variable Q (defined in equation (1)), obtained from a Monte Carlo simulation. The dashed and the dash-dotted lines show the contributions of the position resolution and the energy resolution, respectively, and the filled circles represent the overall resolution.

Fig. 2: Invariant mass distribution for photon pairs in the system O + C with $p_{T,min} = 400 \text{ MeV}/c$. The solid vertical lines indicate the mass window used for the selection of pion candidates.

We calculated the two pion correlation function as a function of the single variable Q , defined as

$$Q = \sqrt{-(p_1 - p_2)^2} \quad (1)$$

where p_1 , p_2 are the four-momenta of the two pions. The limited pair statistics restricts the analysis to one dimension. Q is a Lorentz-invariant quantity and is furthermore related to the invariant mass of the pair $M_{2\pi^0}$ by $Q^2 = M_{2\pi^0}^2 - 4m_\pi^2$. Hence the influence of two-body resonances can be easily recognized, because they should show up as peaks in the

Q spectrum. The detector resolution in this variable was investigated by a Monte-Carlo simulation, where both the energy and the position resolution are taken into account. The results of this calculation (shown in Fig. 1) exhibit an overall resolution of the order of $\sigma(Q) = 10$ MeV.

The experimental correlation function was obtained as follows: Photon pairs with an invariant mass satisfying $|m_{2\gamma} - m_{\pi^0}|/m_{\pi^0} \leq 10\%$ (see Fig. 2) and $p_T \geq p_{T,min}$ were selected (called *pion candidates*). We then calculated the ratio of the actual distribution of pairs of pion candidates to a background distribution. This background distribution, which should represent the uncorrelated pair distribution, was formed by taking pion candidates from different events. This is known as the event-mixing method. For this procedure each pion could be used several times or only once - a difference that does not alter the shape of the background distribution in our case. The same cut in the opening angle of photons $\psi_{\gamma\gamma} \geq 2.3^\circ$ was applied in the event mixing procedure. To parameterize the correlation function we employed a simple Gaussian:

$$C_2(Q) = N \cdot [1 + \lambda \cdot e^{(-Q^2 R_c^2/2)}] \quad (2)$$

where the correlation length R_c , the correlation strength λ (often quoted as the degree of chaoticity⁵) and the normalization N were used as free parameters. The data were fitted with the use of a maximum likelihood method.

Fig. 3: Experimental correlation functions for a) O + Au $p_{T,min} = 400$ MeV/c, b) O + Au $p_{T,min} = 600$ MeV/c, c) O + Au $p_{T,min} = 800$ MeV/c, d) O + C $p_{T,min} = 400$ MeV/c, e) O + C $p_{T,min} = 600$ MeV/c, f) O + C $p_{T,min} = 800$ MeV/c. The solid lines are maximum likelihood fits with equation (2).

Experimental correlation functions were determined for $^{16}\text{O} + ^{12}\text{C}$ 200 A GeV with a lower cutoff in transverse momentum of 400 MeV/c and 600 MeV/c and for $^{16}\text{O} + ^{197}\text{Au}$ 200 A GeV with $p_{T,min} = 400, 600, 800, 1000$ MeV/c. These correlation functions are shown together with the fits in Fig. 3. For sufficiently high p_T a clear enhancement at low values of Q is observed in both data sets. The effect is strongest for the very high p_T particles,

decreases with lower cutoff and vanishes for a $p_{T,min}$ of 400 MeV/c in the O + Au system. While in the last case there is hardly any pion signal (peak in the 2γ mass spectrum) visible at all, the contribution of the combinatorial background pairs (*false pions*) to the pion candidates is not at all negligible even in the other cases, as can be seen in the invariant mass spectrum in Fig. 2. The ratio of true to false pions - calculated as the peak to background ratio in the mass spectra - is below 40% in all considered situations. Hence the role of the combinatorial photon pairs has to be discussed in some detail. That in spite of this high contamination with false pions a correlation can be observed is a consequence of the "global" character of Bose-Einstein correlation. All π^0 carry the information simultaneously, and so do their decay photons. This leads to the supposition that even the false pions, which are nevertheless constructed out of π^0 -decay photons, carry the correlation arising from the BE-symmetrization of the π^0 .

Fig. 4: Schematic representation of pions and their decay photons in momentum space, where Q measures the distance. The range of the correlations is indicated as a white circle with radius Q_{BE} . The decay photons are connected to their parent pions by solid lines. The shaded areas show examples of *false pions* (combinatorial photon pairs).

Fig. 5: The ratio of the parameter λ_f measured in the false pions to the "real" λ as a function of the "real" correlation length R obtained from a Monte-Carlo simulation. A rise in the correlation strength is observed for R approaching 1 fm.

This is no longer surprising, if one looks at the distribution of particles in momentum space. With the variable Q we introduced an invariant distance measure in this space. The situation may be illustrated in a simplified two-dimensional representation (Fig. 4). If you consider one particular pion, all possible pair partners that contribute to the correlation lie within a certain distance Q_{BE} , which defines the range of the correlation. This range is of the order of $Q_{BE} = \hbar c / R$ (with $\hbar c \simeq 200$ MeV · fm) - it is large for a small source and vice versa. Now the pion decay introduces an uncertainty $Q_{decay} \simeq m_{\pi^0}/2$ for the momentum of the photons. If $Q_{BE} \gg Q_{decay}$, the enhanced photons stay inside a certain region of phase space. Thus the possible false pions (denoted by X in Fig. 4) constructed out of these photons lie within the same momentum distance as the true pions. So as the memory

of Q is conserved, the enhancement shows up when analyzed in this variable. If however $Q_{BE} \ll Q_{decay}$, the photon distribution in phase space is random compared to the scale of the correlation and so is the distribution of the false pions. The enhancement is no longer visible.

This qualitative understanding can be checked with a Monte-Carlo simulation. In an multi-pion state all particles carry the correlation simultaneously. In principle one would need to simulate a totally symmetrized state. In the case of the false pions considered here there may be decay photons from four different pions involved. So we used a simple procedure to generate four-pion-events, which contain a Bose-Einstein-like correlation. The events were generated so that they fitted the observed single particle distributions. A weight was applied to the events, which was calculated as

$$\mathcal{P} = \sum_{\sigma} \prod_{i=1}^n e^{-Q_{i,\sigma}^2} R^2/4 \quad (3)$$

where $Q_{ij} = \sqrt{-(p_i - p_j)^2}$, the four-momentum distance of pions i and j , and the sum runs over all permutations σ , i.e. all possible pion pairs. (This weight was used as a probability function by Zajc in a simulation method using the Metropolis algorithm⁶.) The π^0 then decayed isotropically in their rest frame. The detection of the photons was simulated by smearing the energy and the position according to the detector resolution. With the same procedure as used for the experimental data, a correlation function was extracted from these events only with pion candidates, where all photons originated from different pions, to check for the correlation in these false pions. This calculation serves as an estimate for the critical point in correlation length, where the correlation starts to show up, not to extract exact values for the parameters R and λ .

The most interesting result is shown in Fig. 5, where the behavior of the ratio λ_f/λ as a function of the input correlation length R is displayed. λ_f is the correlation strength in the false pions and λ is the input value of the correlation strength (or chaoticity). No correlation in the false pions is seen for large radii ($R \gg 1$ fm), but there is a sharp rise in the strength as R approaches 1 fm. So a correlation with $R \simeq 1$ fm will be manifest in the analysis of false pions. The measured λ_f -parameters provide a lower limit for the actual λ - the measured R_f may be distorted but should be reliable in cases where λ is not too small. We can now turn back to the data. The extracted parameters are summarized in the following table:

pT_{min} (MeV/c)	π^0 -peak/bkg	R_s (fm)	λ_s
$^{16}\text{O} + ^{12}\text{C}$			
400	0.23	1.41 ± 0.23	0.33 ± 0.06
600	0.39	1.47 ± 0.29	0.79 ± 0.23
$^{16}\text{O} + ^{197}\text{Au}$			
400	0.05	---	0.
600	0.11	1.16 ± 0.22	0.28 ± 0.07
800	0.13	1.50 ± 0.07	0.57 ± 0.05
1000	0.15	1.32 ± 0.12	1.0 ± 0.3

The errors given are only statistical fit errors. A source of systematic errors can be seen in the case of $\text{O} + \text{Au}$ with $pT_{min} = 600$ MeV/c, when one looks at the correlation spectrum

(Fig. 3.b). There the assumed function does not describe the data, so one cannot expect the fit to be reasonable. If we keep this in mind, we can conclude that there is no significant variation in the measured R -parameters. However, since the measured values of R_s still contain the contribution of the combinatorial background, their interpretation in terms of real radii R has to be investigated. A correction could change R to larger values especially at low pT . In addition, the effect of final state interaction is not yet included.

An interferometry analysis for the system $\text{O} + \text{Au}$ has been carried out by the NA35 collaboration using negative tracks ($\simeq$ negative pions) measured with the streamer chamber⁷. They report radii of $R \simeq 4$ fm for the pseudorapidity range $1 \leq \eta \leq 2$, while the major contribution to their measurement stems from low momentum particles. If we assume the same behavior for both charged and neutral pions this result is compatible with our analysis, as a larger radius would cause the effect to disappear, a fact that is observed for lower pT -values in our analysis. This result emphasizes again that the simple picture of a static source, where space-time and momentum may be considered as independent degrees of freedom, is not adequate^{8,9,10}. As soon as a correlation between these dimensions is introduced, this model breaks down. The complicated dynamics of the source (e.g. transverse expansion) will in general introduce a momentum dependence of the effective source size.

Conclusion. Correlations of neutral pions at small momentum differences were observed in $200 \text{ A GeV O} + \text{C}$ and $\text{O} + \text{Au}$ collisions. The analysis needs no correction for the Coulomb interaction, but has to cope with a high combinatorial background, which leads to a disappearance of the effect for large correlation lengths. The influence of this background still needs to be studied in more detail to understand the relation between the measured and the true R parameters. The preliminary results show a component of small correlation length $R_s \simeq 1. - 1.5$ fm for high $pT(\pi^0)$ even in the bigger system $\text{O} + \text{Au}$. While it is clear that a static model for the source is not sufficient, a full interpretation of the observations can not yet be given.

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