Three-pion interferometry in high energy collisions

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(Received 3 April 1997; published 4 December 1997)

The data of the three-pion correlation function are analyzed. It is shown that three-pion interferometry not only can act as an independent tool to extract the source information but also can be used to test if we have assumed the right correlation function. [S0556-2821(98)03701-1]

PACS number(s): 12.38.Mh, 13.85.Hd, 25.75.Dw

I. INTRODUCTION

Two-pion interferometry is now widely used in high energy collisions to provide the information of the space-time structure, degree of coherence, and dynamics of the region where the pions were produced [1–6]. Experimentally, ultrarelativistic hadronic and nuclear collisions provide the environment for creating dozens, and in some cases hundreds, of pions [7–9]. Theoretically, it is easy to extend the two-pion correlation function to the three-pion correlation function [5,10,11,13–16]. Then the question arises, can we get more information from three-pion interferometry to supplement what can we learn from two-pion interferometry? To anwer this question, in Sec. II, we analyze the difference between three-pion interferometry and two-pion interferometry for a totally chaotic source and a partially coherent source [5]. In Sec. III, we collect part of multipion correlation data and see if the results of three-pion correlation are consistent with the results of two-pion correlation. Finally, we give our conclusions in Sec. IV.

II. THREE-PION CORRELATION FUNCTION

Two-pion correlation function $C_2(\vec{p}_1,\vec{p}_2)$ for a chaotic source can be expressed as [12–14]

$$C_2(\vec{p}_1,\vec{p}_2) = 1+\frac{\int S(x,K_{12})S(y,K_{12})\exp[iq_{12}(x-y)]d^4x d^4y}{\int S(x,p_1)S(y,p_2)d^4x d^4y} = 1+\frac{|\rho_{12}|^2}{\rho_{11}\rho_{22}}. \tag{1}$$

Here $K_{ij}=(p_i+p_j)/2$ and $q_{ij}=p_i-p_j$. $S(x,K)$ is a Wigner function which can be explained as the probability of finding a pion at point x with momentum K. The definition of ρ_{ij} is

$$\rho_{ij}=\rho(p_i,p_j)=\int S\left(x,\frac{p_i+p_j}{2}\right)\exp[-i(p_i-p_j)x]d^4x = |\rho_{ij}|\exp(i\phi_{ij}). \tag{2}$$

We define the true two-pion correlation as

$$R_2(1,2)=R_2(p_1,p_2)=C_2(p_2,p_2)-1=\frac{|\rho_{12}|^2}{P(p_1)P(p_2)}. \tag{3}$$

The three-pion correlation function for a totally chaotic source can be expressed as

$$C_3(\vec{p}_1,\vec{p}_2,\vec{p}_3)=1+R_2(1,2)+R_2(2,3)+R_2(3,1)+\frac{2\,\mathrm{Re}(\rho_{12}\rho_{23}\rho_{31})}{P(p_1)P(p_2)P(p_3)}. \tag{4}$$

Then the true triplet-pion correlations that do not contain any lower order correlation can be expressed as [16,17]

$$R_3(\vec{p}_1,\vec{p}_2,\vec{p}_3) = C_3(\vec{p}_1,\vec{p}_2,\vec{p}_3)-R_2(1,2)-R_2(2,3)-R_2(3,1)-1 = \frac{2\,\mathrm{Re}(\rho_{12}\rho_{31}\rho_{23})}{P(\vec{p}_1)P(\vec{p}_2)P(\vec{p}_3)} = \frac{2\,\mathrm{Re}\{|\rho_{12}\rho_{23}\rho_{31}|\exp[i(\phi_{12}+\phi_{23}+\phi_{31})]\}}{P(\vec{p}_1)P(\vec{p}_2)P(\vec{p}_3)}. \tag{5}$$

It is very interesting to notice that 3π interferometry contains more information on the phase which does not appear in two-pion interferometry. As has been shown in Refs. [18,19], this phase is too small to be detected. Then what is the usage of three-pion correlation? First, three-pion correlation for a totally chaotic source can be taken as a independent tool to extract the space-time information of the source. Second, as the two-pion correlation and three-pion correlation should give the same source parameters, any inconsistency between the results of three-pion interferometry and the results of two-pion interferometry means that the ‘‘assumed function form ρ_{ij}’’ is in error. So three-pion correlation can be used to test if we have choosen the right function form of the source.

Two-pion correlation function for a partially coherent source can be expressed as [5]

$$C_2^{\mathrm{part}}(\vec{p}_1,\vec{p}_2)=1+\frac{|\rho_{12}^{\mathrm{cha}}|^2}{P(\vec{p}_1)P(\vec{p}_2)}+\frac{2\,\mathrm{Re}[\rho_{21}^{\mathrm{coh}}\rho_{12}^{\mathrm{cha}}]}{P(\vec{p}_1)P(\vec{p}_2)} \tag{6}$$

with

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$$\rho_{ij}^{\rm coh}=|\rho_{ij}^{\rm coh}|\exp(i\phi_{ij}^{\rm coh})$$
$$=\int d^4xS^{\rm coh}(x,p)\exp[-i(p_i-p_j)\cdot x],$$
$$\rho_{ij}^{\rm cha}=|\rho_{ij}^{\rm cha}|\exp(i\phi_{ij}^{\rm cha})$$
$$=\int d^4xS^{\rm cha}(x,p)\exp[-i(p_i-p_j)\cdot x]. \qquad (7)$$

Here $S^{\rm coh}$ and $S^{\rm cha}$ are the source distribution for chaotic source and coherent source, respectively. The ''true'' two-pion correlation function can be written as

$$R_2^{\rm part}(i,j)=R_2^{\rm part}(\vec{p}_i,\vec{p}_j)=\frac{|\rho_{12}^{\rm cha}|^2}{P(\vec{p}_1)P(\vec{p}_2)}+\frac{2\,{\rm Re}[\rho_{21}^{\rm coh}\rho_{12}^{\rm cha}]}{P(\vec{p}_1)P(\vec{p}_2)}. \qquad (8)$$

Similarly, the three-pion correlation function can be expressed as [5]

$$C_3^{\rm part}(\vec{p}_1,\vec{p}_2,\vec{p}_3)=1+R_2^{\rm part}(1,2)+R_2^{\rm part}(2,3)+R_2^{\rm part}(3,1)+R_3^{\rm part}(1,2,3). \qquad (9)$$

We define the ''true triplet-pion'' correlation $R_3^{\rm part}(1,2,3)$ as

$$R_3^{\rm part}(1,2,3)=\frac{2\,{\rm Re}[\rho_{12}^{\rm cha}\rho_{23}^{\rm cha}\rho_{31}^{\rm cha}+\rho_{12}^{\rm coh}\rho_{23}^{\rm cha}\rho_{31}^{\rm cha}+\rho_{12}^{\rm cha}\rho_{23}^{\rm coh}\rho_{31}^{\rm cha}+\rho_{12}^{\rm cha}\rho_{23}^{\rm cha}\rho_{31}^{\rm coh}]}{P(\vec{p}_1)P(\vec{p}_2)P(\vec{p}_3)}. \qquad (10)$$

Here the ''true'' two-pion (three-pion) correlation is not the ''true'' two-pion (three-pion) correlation at all, because they contain a contribution from coherent pions which does not interfere with the chaotic pions. The ''true'' two-pion correlation function can be rewritten in the following form:

$$R_2^{\rm part}(i,j)=\epsilon(\vec{p}_1)\epsilon(\vec{p}_2)|B_{12}^{\rm cha}|^2+2\sqrt{\epsilon(\vec{p}_1)\epsilon(\vec{p}_2)[1-\epsilon(\vec{p}_1)][1-\epsilon(\vec{p}_2)]}\cos(\phi_{ij}^{\rm cha}-\phi_{ij}^{\rm coh})|B_{12}^{\rm cha}| \qquad (11)$$

with

$$\epsilon(\vec{k})=\frac{P^{\rm cha}(\vec{k})}{P(\vec{k})},\qquad B_{ij}^{\rm cha}=\frac{\rho_{ij}^{\rm cha}}{\sqrt{P^{\rm cha}(\vec{p}_1)P^{\rm cha}(\vec{p}_2)}}. \qquad (12)$$

Here $\epsilon(\vec{k})$ is the parameter of chaotic degree. For a totally chaotic source, $\epsilon(\vec{k})=1$, for a totally coherent source $\epsilon(\vec{k})=0$. For three-pion case, we have [5]

$$R_3^{\rm part}(1,2,3)=2\epsilon(\vec{p}_1)\epsilon(\vec{p}_2)\epsilon(\vec{p}_3)\cos(\phi_{12}^{\rm cha}+\phi_{23}^{\rm cha}+\phi_{31}^{\rm cha})|B_{12}^{\rm cha}B_{23}^{\rm cha}B_{31}^{\rm cha}|+2\epsilon(\vec{p}_3)\sqrt{\epsilon(\vec{p}_1)\epsilon(\vec{p}_2)[1-\epsilon(\vec{p}_1)][1-\epsilon(\vec{p}_2)]}\cos(\phi_{12}^{\rm coh}+\phi_{23}^{\rm cha}+\phi_{31}^{\rm cha})|B_{23}^{\rm cha}B_{31}^{\rm cha}|+2\epsilon(\vec{p}_1)\sqrt{\epsilon(\vec{p}_3)\epsilon(\vec{p}_2)[1-\epsilon(\vec{p}_3)][1-\epsilon(\vec{p}_2)]}\cos(\phi_{12}^{\rm cha}+\phi_{23}^{\rm coh}+\phi_{31}^{\rm cha})|B_{12}^{\rm cha}B_{31}^{\rm cha}|+2\epsilon(\vec{p}_2)\sqrt{\epsilon(\vec{p}_3)\epsilon(\vec{p}_1)[1-\epsilon(\vec{p}_1)][1-\epsilon(\vec{p}_3)]}\cos(\phi_{12}^{\rm cha}+\phi_{23}^{\rm cha}+\phi_{31}^{\rm coh})|B_{12}^{\rm cha}B_{23}^{\rm cha}|. \qquad (13)$$

Different from the two-pion correlation for a chaotic source, two-pion correlation for a partially coherent source also contains information on the phase $\phi_{ij}^{\rm cha}$ and $\phi_{ij}^{\rm coh}$. $\epsilon(\vec{k})$, $B_{ij}^{\rm cha}$, and $\phi_{ij}^{\rm cha}-\phi_{ij}^{c}$ can be determined by two-pion interferometry. As $\rho_{12}\rho_{23}\rho_{31}$ is real, we have the relationship that $\phi_{12}^{\rm coh}+\phi_{23}^{\rm coh}+\phi_{31}^{\rm coh}=0$. Then all the parameters that appeared in three-pion correlation can be derived from two-pion interferometry. What is the usage of three-pion correlation function for a partially coherent source? Three-pion correlation for a partially coherent source can be taken as an independent tool to extract the source information and to test if we have assumed the right source function in two-pion interferometry.

Experimentalists usually assumed that the imaginary parts of $\rho_{ij}^{\rm cha}$ and $\rho_{ij}^{\rm coh}$ are very small and they take $\rho_{ij}^{\rm cha}$ and $\rho_{ij}^{\rm coh}$ as real. It is clear that without the imaginary part of $\rho_{ij}^{\rm cha}$, the three-pion correlation cannot supply more information than two-pion interferomtry does. But we can check if the results derived from two-pion correlation are consistent with the

TABLE I. The data from UA1 group, r_G and $r_{\rm exp}$ are the fitted value of Eqs. (16), (17) and Eqs. (18), (19), respectively.

$\sqrt{s}$	r_G(fm) 2π	r_G(fm) 3π	$r_{\rm exp}$(fm) 2π	$r_{\rm exp}$(fm) 3π
630 GeV	0.742 ± 0.009	0.821 ± 0.005	1.264 ± 0.017	2.613 ± 0.015
900 GeV	0.814 ± 0.016	0.831 ± 0.007	1.374 ± 0.018	2.643 ± 0.016

TABLE II. The data from UA1 group, ϵ_G and $\epsilon_{\rm exp}$ are the fitted value of Eqs. (16), (17) and Eqs. (18), (19), respectively.

$\sqrt{s}$	ϵ_G 2π	ϵ_G 3π	$\epsilon_{\rm exp}$ 2π	$\epsilon_{\rm exp}$ 3π
630 GeV	0.168 ± 0.004	0.150 ± 0.003	0.410 ± 0.015	0.505 ± 0.019
900 GeV	0.186 ± 0.006	0.152 ± 0.004	0.531 ± 0.038	0.538 ± 0.027

results of three-pion correlation to test if the assumed function $B_{ij}^{\rm cha}$ is right. In the next section we will use experimental data to test the conclusion given in this section.

III. THREE-PION INTERFEROMETRY IN EXPERIMENT

Similar to the UA1-MINIMUM BIAS group [20], we take the approximation that $\phi_{ij}^{\rm cha}$, $\phi_{ij}^{\rm coh}\sim 0$, $\epsilon(\vec{k})=\epsilon$, and assume a symmetric configuration in momentum space, that is

$$q_{12}^2=q_{13}^2=q_{23}^2=\cdots=q_{n-1,n}^2=q^2=Q_{n\pi}^2\,\frac{2}{n(n-1)}. \quad (14)$$

If we assume

$$B_{ij}^{\rm cha}=\exp(-r^2q_{ij}^2)=e^{-r^2[2Q_{n\pi}^2/n(n-1)]}, \quad (15)$$

then the two-pion and three-pion correlation function for a partially coherent source can be expressed as [22]

$$C_2=1+\epsilon^2e^{-2r^2Q_{2\pi}^2}+2\epsilon(1-\epsilon)e^{-r^2Q_{2\pi}^2} \quad (16)$$

$$C_3=1+6\epsilon(1-\epsilon)e^{-(1/3)\,r^2Q_{3\pi}^2}+3\epsilon^2(3-2\epsilon)e^{-(2/3)r^2Q_{3\pi}^2}+2\epsilon^3e^{-r^2Q_{3\pi}^2}. \quad (17)$$

If we assume $B_{ij}^{\rm cha}=e^{-rq_{ij}}=e^{-r[2/n(n-1)]Q_{n\pi}}$ then we have the following function:

$$C_2=1+\epsilon^2e^{-2rQ_{2\pi}}+2\epsilon(1-\epsilon)e^{-rQ_{2\pi}}, \quad (18)$$

$$C_3=1+6\epsilon(1-\epsilon)e^{-\sqrt{1/3}rQ_{3\pi}}+3\epsilon^2(3-2\epsilon)e^{-2\sqrt{1/3}rQ_{3\pi}}+2\epsilon^3e^{-\sqrt{3}rQ_{3\pi}}. \quad (19)$$

Theoretically, high-order pion correlation function and two-pion correlation function should give the same space time information of the source. The differences between those fitted parameters may be due to the following reasons: (1) $B_{ij}^{\rm cha}$ is not right; (2) we have not correctly treated the data (Coulumb correction, pion misidentification, etc.); (3) $\phi_{ij}^{\rm cha}$, $\phi_{ij}^{\rm coh}$ ~ 0 is not a good approximation.

In the following, we use the data of UA1 [20] and Mark II [21] to test if the results of two-pion interferometry are consistent with the results of three-pion correlation. The data of UA1 were also analyzed in Ref. [22], but there, the authors want to show that the high-order correlations provide evidence for the Gaussian form of the current distribution as well as for the presence of coherence. Here we want to show that the higher-order correlations can be used to test if we have assumed the right correlation function.

The data used in this analysis were collected in 1985 by the UA1 group at the SPS proton-antiproton collider. The center-of-mass energies ($\sqrt{s}$) for $p\overline{p}$ are 630 and 900 GeV, respectively. Equations (16), (17) and Eqs. (18), (19) have been used to fit the data. The fitted values of UA1 group are shown in Tables I and II.

From the above tables, we find that there are some differences between the fitted value ϵ and r. As a Gaussian or exponential function is too simple to describe the source distribution in $p\overline{p}$ collisions, it is not surprising to find the difference between the results of two-pion interferometry and the results of three-pion interferometry. Here we have shown the power of three-pion interferometry, which can act as a tool to test if we have assumed the right function form of $B_{ij}^{\rm cha}$ and if the imaginary part of the $\rho_{ij}^{\rm cha}$ and $\rho_{ij}^{\rm coh}$ are very small.

In Table III, the data from Mark II at the SPEAR and PEP e^+e^- storage rings at SLAC are given. They used

$$C_2=1+\lambda_2e^{-r_2^2Q_2^2} \quad (20)$$

to fit the two-pion correlation function and used

$$C_3=1+\lambda_3e^{-r_3^2Q_3^2} \quad (21)$$

to fit the three-pion correlation function. Here $Q_2^2=(p_1-p_2)^2$, $Q_3^2=q_{12}^2+q_{23}^2+q_{31}^2$. It is impossible for us to compare r_3 with r_2 but we can compare λ_3 with λ_2. In Table III,

TABLE III. The data from Mark II.

Data	λ_2	λ_3	λ_3'
SPEAR J/Ψ	$0.96\pm0.03\pm0.08$	$4.97\pm0.33\pm0.62$	$4.67\pm0.25\pm0.62$
PEP $\gamma\gamma$	$1.20\pm0.08\pm0.10$	$4.56\pm0.45\pm0.57$	
SPEAR $q\overline{q}$	$0.72\pm0.04\pm0.06$	$2.58\pm0.24\pm0.33$	$3.07\pm0.23\pm0.34$
PEP $q\overline{q}$	$0.45\pm0.03\pm0.04$	$1.54\pm0.23\pm0.19$	$1.68\pm0.14\pm0.18$

TABLE IV. The fitted results of 1.8 GeV/nucleon Ar on Pb and 1.5 GeV/nucleon Ar on KCl.

	Source parameters	1.8*A* GeV Ar+Pb	1.5*A* GeV Ar+KCl
Three-pion	R (fm)	5.65 ± 0.49	5.51 ± 0.86
analysis	λ_3	$0.98^{+0.02}_{-0.26}$	$1.00^{+0.00}_{-0.33}$
	ξ	$0.95^{+0.05}_{-0.49}$	$1.00^{+0.00}_{-0.33}$
Triplet-pion	R (fm)	5.80 ± 0.75	4.06 ± 0.49
analysis	ξ	$1.00^{+0.00}_{-0.25}$	$1.00^{+0.00}_{-0.36}$
Two-pion	R (fm)	5.53 ± 0.45	4.72 ± 0.30
analysis	λ	$0.99^{+0.01}_{-0.24}$	$1.00^{+0.00}_{-0.34}$

we give the value of λ. It is easily seen from Eqs. (16), (17) or Eqs. (18), (19) that $\lambda_2=2\epsilon-\epsilon^2$ and $\lambda_3=3\epsilon^2-4\epsilon^3+6\epsilon$. If we take the λ_2 value from Table III and think that both three-pion and two-pion correlations should give the same value of ϵ, then we can use the fitted value of λ_2 to calculate the value of λ_3, which is also give in Table III (denoted as λ_3'). From the comparion between λ_3 and λ_3', we find that the results of three-pion correlations function are consistent with the results of two-pion interferometry.

In Table IV, the fitted values of Ref. [23] are given. In their fitting, they did not use the configuration momentum approximation. They used

$$C_2=1+\lambda e^{-q_{120}^2\tau^2/2-\vec{q}_{12}^{\,2}R^2/2} \tag{22}$$

and

$$C_3=1+\lambda_3 e^{-(q_{120}^2\tau^2+q_{12}^2R^2)/2}+(2-3)+(3-1)$$
$$+2\xi e^{-[Q_{3\pi0}^2\tau^2+\vec{Q}_{3\pi}^2R^2]/4} \tag{23}$$

to fit their data. Here $(i-j)$ represents the cyclically permuted form of the second term of Eq. (23), $Q_{3\pi0}^2=q_{120}^2+q_{230}^2+q_{310}^2$ and $\vec{Q}_{3\pi}^2=\vec{q}_{12}^{\,2}+\vec{q}_{23}^{\,2}+\vec{q}_{31}^{\,2}$. They also fitted the triplet-pion correlation with the function

$$R_3=2\xi e^{-[Q_{3\pi0}^2\tau^2+\vec{Q}_{3\pi}^2R^2]/4}. \tag{24}$$

From Table IV, we can see that the source is nearly totally chaotic and the results of two-pion correlation are consistent with the results of three-pion correlation. So it seems that Gaussian source is a good model to describe the source in low energy heavy-ion collisions.

For relatively heavy-ion collisions, due to the correlation between coordinate and momentum, a simple Gaussian function is not suitable to describe the data. As multipion correlation functions have the power to test if we have assumed a good function form of $B_{ij}^{\rm cha}$, we strongly suggest that experimentalists use three-pion correlation functions to fit their data.

IV. CONCLUSIONS

In this paper, we analyze the difference between three-pion correlation function and two-pion correlation function for a totally chaotic source and a partially coherent source. For a totally chaotic source, it is shown that three-pion interferometry supplements what can be extracted from two-pion interferometry. For a partially coherent source, three-pion interferometry not only can act as an independent tool to extract the source information but also can act as a independent tool to test if we have assumed the right correlation function.

From the data of the UA1 group, we find that the results of three-pion correlation are not consistent with the results of two-pion interferometry. That means Gaussian or exponential function is too simple to describe the source in $p\bar{p}$ collisions. This result is consistent with the result of previous publications [24,25], where Andreev *et al.* found that in models with a fixed source size the shape of the second order Bose-Einstein correlations in terms of $Q_{2\pi}$ is neither purely Gaussian nor purely exponential. The authors of Refs. [24,25] also found that appropriate projection of the correlator helps one to find out the right source function. From the data of Mark II, it seems that Gaussian source distribution and $\phi_{ij}\sim 0$ is a good approximation in e^-e^+ collisons. But due to the lower statistics at present, no definite conclusion can be given. Three-pion correlation not only can be used as an independent method to extract the source information but also can be used as a tool to test if we have assumed the right correlation function.

ACKNOWLEDGMENTS

The author would like to express his gratitude to Dr. P. Yang and U. Heinz for helpful discussions. This study was partially supported by the Alexander von Humboldt Foundation in Germany.

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