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Pion-kaon femtoscopy in Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV measured with ALICE

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Abstract

Femtoscopic correlations between charged pions and kaons for different charge combinations are measured in Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with ALICE at the LHC. The three-dimensional pion-kaon ($\pi - \mathrm{K}$) correlation functions and double ratios in the out-side-long pair rest frame are studied in different centrality bins. The $\pi - \mathrm{K}$ femtoscopic source size parameter (R_{out}) and emission asymmetry (μ_{out}) are extracted. It is observed that the average source size of the system and the emission asymmetry between pions and kaons increase from peripheral to central events.

Keywords: heavy-ion collisions, femtoscopy, emission asymmetry

1. Non-identical particle femtoscopy

Relativistic heavy-ion collisions at the Large Hadron Collider (LHC) provide an excellent environment to study a deconfined state of quarks and gluons. Femtoscopic techniques, i.e. analyzing the momentum correlations of produced particles at small relative momenta, are used to study the space−time characteristics of the system created. Due to this interplay and Final State Interactions (FSI) among the particles, the two-particle correlations for non-identical pairs are sensitive to space−time coordinates of the particle emission points as well as the difference in average emission points (emission asymmetry) of different particle species.

2. Method

The two particle correlation function is defined as

$$C(\mathbf{p}_{\mathrm{a}}, \mathbf{p}_{\mathrm{b}}) = \frac{P_2(\mathbf{p}_{\mathrm{a}}, \mathbf{p}_{\mathrm{b}})}{P_1(\mathbf{p}_{\mathrm{a}})P_1(\mathbf{p}_{\mathrm{b}})}, \tag{1}$$

where P_2 is the conditional probability to observe particles with momenta $\mathbf{p}_{\mathrm{a}}$ and $\mathbf{p}_{\mathrm{b}}$ together, while P_1 is the probability of observing a particle with a given momentum. The experimental correlation function is

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constructed as

$$C(\mathbf{k}^*) = \frac{\int N(\mathbf{p}_a, \mathbf{p}_b)\delta(\mathbf{k}^* - \frac{1}{2}(\mathbf{p}_a^* - \mathbf{p}_b^*))d^3p_a d^3p_b}{\int D(\mathbf{p}_a, \mathbf{p}_b)\delta(\mathbf{k}^* - \frac{1}{2}(\mathbf{p}_a^* - \mathbf{p}_b^*))d^3p_a d^3p_b} = \frac{N(\mathbf{k}^*)}{D(\mathbf{k}^*)}, \quad (2)$$

where $N(\mathbf{p}_a, \mathbf{p}_b)$ is the distribution when both particles originate from same event and contain correlations while $D(\mathbf{p}_a, \mathbf{p}_b)$ is the distribution when particles originate from two different events and hence contain no correlation. The half of the relative momentum of pairs in the Pair Rest Frame (PRF) is represented by k^*.

The Koonin-Pratt's equation [1], which relates the experimental correlation function with the source emission function, is given by

$$C(\mathbf{k}^*) = \int d\mathbf{r}' |\psi(\mathbf{k}^*, \mathbf{r}')|^2 S(\mathbf{r}'). \quad (3)$$

The experimental correlation functions were parametrized by assuming the source function as a three dimensional Gaussian function with three different sizes R_{out}, R_{side} and R_{long} in Out, Side and Long directions [2], respectively, with the mean value μ_{out} corresponding to the emission asymmetry:

$$S(\mathbf{r}) = exp\left(-\frac{(r_{\text{out}} - \mu_{\text{out}})^2}{R_{\text{out}}^2} - \frac{r_{\text{side}}^2}{R_{\text{side}}^2} - \frac{r_{\text{long}}^2}{R_{\text{long}}^2}\right) \quad (4)$$

where r_{out}, r_{side} and r_{long} are the components of the relative separation vector $\mathbf{r}$ of the emission points.

2.1. Double ratios

The strength of the correlation function depends on the sign of $\mathbf{k}^* \cdot \mathbf{v}$ where $\mathbf{v}$ is the pair velocity. In the transverse plane C+ corresponds to the case where pions are faster, i.e. $\mathbf{k}^* \cdot \mathbf{v} > 0$, and C- corresponds to the case where kaons are faster, i.e. $\mathbf{k}^* \cdot \mathbf{v} < 0$

C+ will be different from C- if both particles leave the system at different space−time points. For example, if kaons leave the system earlier than pions, C+ will be stronger since faster pions will be catching up the kaons and will have larger interaction time. In this case, C- will be weaker because both particles will be moving away and will have smaller interaction time. The ratio C+/C- is known as double ratio and is sensitive to the emission asymmetry. If it deviates from unity, an emission asymmetry exists.

2.2. Spherical harmonics decomposition of the correlation Function

The Spherical Harmonics (**SH**) decomposition of the correlation function is another way to study the emission source. In this method, the 3D correlation function is converted into an infinite set of 1D components defined as

$$C_l^m(\vec{k^*}) = \frac{1}{\sqrt{4\pi}} \int d\varphi d(cos\theta) C(k^*, \theta, \varphi) Y_l^m(\theta, \varphi), \quad (5)$$

where C_l^m are the components of the correlation function and Y_l^m are the spherical harmonics. Most of the real components and all imaginary components of the correlation function vanish due to the azimuthal symmetry [3]. The C_0^0 and $\Re C_1^1$ component signal the source size and the average emission asymmetry, respectively.

3. Analysis details

The present measurements are based on the study of pion-kaon femtoscopic correlations in Pb−Pb collisions measured at $\sqrt{s_{\text{NN}}}$ = 2.76 TeV by the ALICE detector [4] in 2011. The minimum bias events were triggered by the coincidence of a signal in the V0 detector and the Silicon Pixel Detector (SPD) of the ITS detector. The analysis has been performed for 0-5, 5-10, 10-20, 20-30, 30-40 and 40-50 % centrality bins determined by the V0 detector. The reconstructed primary vertex along the beam direction is required to lie

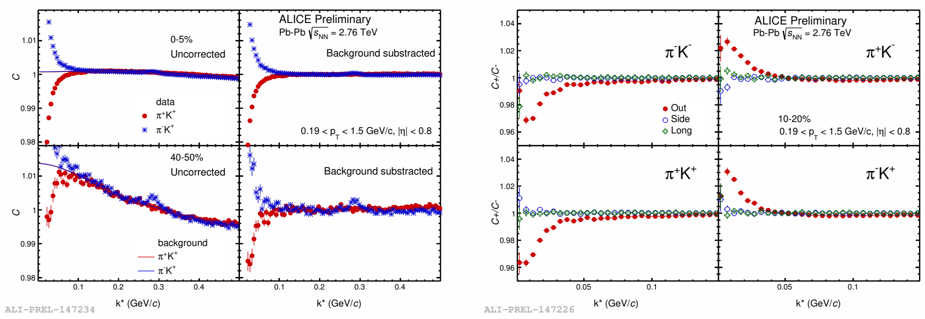

Fig. 1. Left: The pion-kaon correlation function to show the effect of non-femtoscopic background. The background fit corresponds to sixth order polynomial function. Right: The pion-kaon double ratio for Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. (Errors are statisitical only)

within ±10.0 cm with respect to the center of the ALICE detector. The charged tracks were reconstructed using the TPC detector only. The distance of closest approach (DCA) of a track to the primary vertex in the transverse (DCA_{xy}) and longitudinal (DCA_z) directions are required to be less than 2.4 cm and 3.2 cm, respectively, to reduce the contamination from secondary tracks emanating from weak decays and from interactions with the detector material. Tracks with a transverse momentum within 0.19 GeV/c < p_{T} < 1.5 GeV/c measured in the pseudo-rapidity range $|\eta| < 0.8$ are selected. Combined information from TPC and TOF is used to identify charged tracks as pions and kaons. All track pairs, which share more than 5% of their total hits in the TPC, are excluded from the analysis. Another selection on the fraction of merged points was used to find the fraction of two tracks ($|\Delta\eta| < 0.1$), which were closer than the average cluster size (3 cm) in the TPC. The merged fraction is defined as the ratio of the number of points for which the distance between the tracks is less than 3 cm to the total number of steps of 3 cm calculated in the considered TPC radius range. The unlike-sign (like-sign) pairs with a merged fraction above 1% (7%) were removed. To remove contamination of $e^- - e^+$ pairs originating from γ conversions, pairs are removed if the invariant mass of pairs with assumed electron mass and the difference of polar angle $\delta\theta$ between the tracks was less than 0.002 GeV/c and 0.008 radians, respectively. The uncorrelated pair background is constructed by pairing tracks from different events.

4. Results

The left panels of Fig. 1 and 2 show the correlation functions, in the Cartesian coordinate and Spherical Harmonics representation for all possible charge combinations of pion-kaon pairs, respectively. The strength of C+, C- and C_0^0 is above unity for unlike-sign pairs and below unity for like-sign pairs suggesting an attractive and repulsive Coulomb interaction between the pairs, respectively. The non-vanishing signal values of the $\Re C_1^1$ component and the deviation of C+/C- from unity indicates the presence of an emission asymmetry. In other words, on average pions and kaons are not emitted at the same source radius or time.

It can be observed from Fig. 1 that the correlation function is not exactly flat at unity in the non-femtoscopic region. This is essentially due to the presence of other event wide pair correlations like elliptic flow v_2, global event energy and momentum conservation, resonance decay correlations, residual correlation, jets etc. Therefore, one needs to isolate these background correlations before extracting the source parameters. The procedure to estimate the non-femtoscopic background is described in [5], where it is shown that the behavior of the non-femtoscopic baseline can be characterized by a sixth order polynomial function. The same procedure was used to correct the effect of non-femtoscopic background in the present analysis.

A numerical procedure as employed in the STAR experiment was followed to extract source size and emission asymmetry [3, 6] by assuming the source function as in Eq. (4). Using the mentioned source

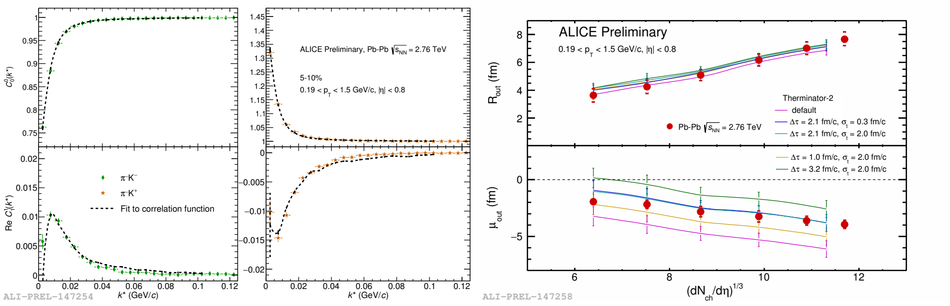

Fig. 2. Left: The pion-kaon correlation function for all charge combinations with their fits computed using CorrFit software (Errors are statisitical only); Right: Source size (upper panel) and pion- kaon emission asymmetry (lower panel) from pion-kaon correlation functions for Pb−Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV as a function of $(dN_{ch}/d\eta)^{1/3}$. The solid lines show predictions from calculation of source-size and emission asymmetry using Therminator-2 model with default and selected values of additional time delays for kaons (Errors are statisitical and systematical).

function, one can numerically integrate the Eq. (3) with the corresponding wave function (indicating the type of interactions) to calculate the correlation function. The input momentum distributions are taken from real pairs to ensure that the momentum acceptance is same. The calculated correlation is compared to the measured via a χ^2 test. The procedure is repeated for different sets of source parameters to arrive at the best agreement with the measured data. In this work, the CorrFit software package [6] was used to perform the numerical fitting described above and extract the experimental $R_{\rm out}$ and $\mu_{\rm out}$.

The right plot in Fig. 2 shows the pion-kaon source size and emission asymmetry as a function of the cube root of charged particle multiplicity density in Pb−Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. One observes that the system size increases from peripheral to central events. The extracted emission asymmetry is also observed to increase with particle multiplicity and is negative. This implies that pions are emitted closer to the centre of the source. The results are compared to the predictions from the Therminator2 model [7] with the default calculations and calculations with selected values of time delay for kaon emission [8]. This was motivated by the recent measurements of identical kaon femtoscopy which showed that kaons are emitted, on average, 2.1 fm/c later than pions. The default Therminator2 calculations overpredict the experimental data while an introduction of a time delay of 2.1 fm/c in kaon emission decreases the asymmetry and is in good agreement with the experimental measurement.

5. Conclusion

The first measurements of pion-kaon femtoscopic correlations in Pb−Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV have been performed. The radius of the source $R_{\rm out}$ shows a decreasing trend from central to peripheral collisions. A finite emission asymmetry is also observed which shows a similar trend as the radius. The results are consistent with the Therminator2 coupled with (3+1)D viscous hydrodynamic model calculations of pion-kaon emission asymmetry when an additional time delay of 2.1 fm/c is introduced for the kaons.

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