Femtoscopy at High m_T in Heavy-Ion Collisions with ALICE

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Abstract. Femtoscopic two-particle correlations carry important information about the particle emitting source. Of particular interest is the m_{T} dependence of extracted source radii, which is introduced by the dynamics of the system created in heavy-ion collisions. The reach in m_{T} of the traditional pion-pion correlation measurements is limited by the small rest mass of the examined particles. Thus, it can be extended with the analysis of pairs of heavier particles: kaons and protons, and proton-lambda pairs, being the heaviest system to extract source sizes so far. The excellent particle identification capabilities and high statistics datasets of ALICE allow to extract source radii differentially in transverse mass and provide new constraints on hydrodynamic models.

1. Introduction

Femtoscopy allows to extract radii that describe the regions of homogeneity of the particle emitting source in a heavy-ion collision, i.e., the fireball at kinetic freeze-out. The m_{T} dependence of these radii is sensitive to a variety of properties of the produced matter, e.g., the order of the phase transition from the QGP to hadrons, the existence of pre-flow, the viscosity of the QGP, the time scales of the evolution, and the temperature [1, 2]. The standard way of carrying out a femtoscopic analysis of heavy-ion collisions is to investigate pairs of identically charged pions. Their reach in pair transverse mass m_{T} in ALICE is limited due to their small pair transverse mass for vanishing pair transverse momentum $m_{\mathrm{T}}(k_{\mathrm{T}} \to 0)$ of only 0.14 GeV/c^2. Thus, the reach in m_{T} can easily be extended by investigating pairs of heavier particles: charged kaons, neutral kaons, protons, and pairs of protons and lambdas, with a $m_{\mathrm{T}}(k_{\mathrm{T}} \to 0)$ of $0.49, 0.50, 0.94$, and 1.03 GeV/c^2, respectively. These systems are affected differently by several sources of correlations. Pairs of identical particles are subject to quantum statistical effects; charged particles will be affected by the Coulomb interaction and all particles will interact strongly, although this interaction can be neglected for the charged pions and charged kaons.

The effect of quantum statistics introduces for bosons a tendency to occupy the same state. The way to experimentally access this enhancement of particles with the same quantum numbers is to divide the two-particle distribution by the product of single-particle distributions. This is realized by dividing pairs in real events by pairs in mixed events. The result is the two-particle correlation function $C_2(q_{\mathrm{inv}})$, here measured as a function of the generalized invariant relative momentum of the pair: $q_{\mathrm{inv}} = |q - P(qP)/P^2|$, with $q = p_1 - p_2, P = p_1 + p_2$, and p being the momentum of the particles [3]. The correlation function carries information about the spatial extent of the source. In the case of ideal bosons, the correlation function will be a constant at unity for high relative momenta plus a Gaussian-shaped enhancement with the maximum at $q_{\mathrm{inv}} = 0$ and the width being inversely proportional to the size of the source. Impurities in the boson sample will lower the height of the correlation function, but will not affect the width, leaving the size measurement undisturbed. The impact of quantum statistics goes into the opposite direction for fermions, leading to a depletion for small momentum differences. To extract a source size from particle pairs that interact strongly, a sufficient knowledge of the interaction is neccessary. Precise measurements for all discussed pairs here are existing. A model [4] can be utilized to translate the source size via the known interaction to an observable correlation function and vice versa. The correlation functions with a large contribution from the final state strong interaction, i.e., these of pairs of protons and protons and lambdas, are sensitive in height and shape to the size of the source.

While for low m_{T} pairs the region of homogeneity, i.e. the region from which correlated pairs get emitted, still spans over the full source, the expansion of the medium introduces a reduction of this homogeneity region for high m_{T} pairs. With the strong flow developed in Pb-Pb collisions at the LHC the apparent source size decreases as a function of m_{T}. The flow velocity is competing with the thermal velocity $v_{\mathrm{Therm}} = \sqrt{T/m_{\mathrm{T}}}$, thus the dependence is expected to be most pronounced as a function of m_{T} [5].

2. Data analysis

ALICE is the dedicated heavy-ion experiment at the LHC. The analysis presented here was done with the central barrel; i.e. the Inner Tracking System (ITS), Time Projection Chamber (TPC), and Transition Radiation Detector (TRD) were used for tracking. Particle identification (PID) was provided by the TPC and the Time-Of-Flight (TOF) detector. In the following, as an example, a selection of primary protons will be discussed.

The measurement of the specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC and ITS allows to identify single particles in the region where the $\mathrm{d}E/\mathrm{d}x$ is proportional to $1/\beta^2$, with $\beta = v/c$ being the velocity of the particles. This region extends to roughly a momentum of 1 GeV/c for protons. TOF provides PID by measuring the time it takes for a particle to travel from the primary vertex to the TOF detector and is thus sensitive to the mass of the particle when the momentum measurement of the TPC gets included. It provides PID in the momentum region where the specific energy loss becomes the same for different particle species.

Depending on the momentum of the particle, different PID techniques were chosen. Namely the TPC for momenta $p < 0.75$ GeV/c, TPC and TOF for $0.75 \leq p < 1.0$ GeV/c and TOF alone for $1.0 \leq p < 3.25$ GeV/c. The proton selection for $p \leq 0.75$ GeV/c was done by applying an upper and lower cut on the measured $\mathrm{d}E/\mathrm{d}x$, which is based on a parametrization of the Bethe-Bloch curve. A clear separation of the protons is achieved for these momenta with the TPC alone. The purity of the proton sample was determined by fitting the $\mathrm{d}E/\mathrm{d}x$ distributions in slices of total momentum. The data are very well described by a combination of Gaussians for the different particle species. Even at momenta of 0.75 GeV/c the excellent TPC performance allows to select a proton sample of a purity higher than 99% with essentially no loss of protons by applying the selection criteria. A momentum of $0.75 \leq p < 1.0$ GeV/c, where the hybrid approach of using the TPC and TOF was chosen, is quite low for identifying protons with TOF alone. By applying a selection criterion based solely on the TOF information, a purity higher than 90% only is achieved. Looking at the time-of-flight spectrum, one sees that the main background in this momentum region comes from mismatched particles. This mismatch mainly originates from pions, the most abundant particles, which get assigned a wrong TOF cluster. Thus, one can easily apply a mild $\mathrm{d}E/\mathrm{d}x$ pre-selection which rejects pions and safely keeps all protons. Applying the $\mathrm{d}E/\mathrm{d}x$ pre-selection lifts the purity above 99%. For higher momenta the matching improves and no TPC pre-selection is neccessary. Out to $p < 3.25$ GeV/c, where the proton selection currently stops, purities over 99% are achieved.

As we are interested in studying the correlations of primary protons, another selection criterion on the transverse distance of closest approach of the track to the primary vertex (DCA_{xy}) was imposed. Templates for the shapes of the different distributions in DCA_{xy} for primary protons, protons from weak decays and protons produced in the detector material were obtained from Monte-Carlo simulations. It is important that these templates have a different shape in order to reliably discriminate between the contributions. This is the case: primary protons are peaked at $\mathrm{DCA}_{xy} = 0$, protons from weak decays show broad shoulders and protons from material are flat in DCA_{xy}. Fitting the data with the templates, it was found that selecting only tracks with $\mathrm{DCA}_{xy} \leq 0.1$ cm maximizes the significance of the primary protons. Furthermore, one can determine the residual contamination in the sample. In order to take into account the evolution of the amount of the different contributions and the slightly varying shapes in phase space, the fits were performed in bins of rapidity and transverse momentum.

2.1. Kaon analysis

We also report on femtoscopic radii obtained from correlations of charged and neutral kaons. K^0_s were reconstructed via their charged decay $\mathrm{K}^0_s \rightarrow \pi^+\pi^-$. Oppositely charged tracks are paired and potential decay vertices are calculated by a V0 finder. Several analysis cuts were applied, e.g., PID and a maximum distance of closest approach of the daughters was required. K^0_s were finally selected by a window in the invariant mass around the value of the particle data group. A purity of $\approx 95\%$ could be achieved for the 10% most central events with higher purities for more peripheral events. $\mathrm{K}^\pm$ could be identified with only the $\mathrm{d}E/\mathrm{d}x$ measurement of the TPC up to transverse momenta of 0.6 GeV/c with a maximum contamination from $\mathrm{e}^\pm$ in the region $p_\mathrm{T} \approx 0.4$ GeV/c, where the specific energy loss of electrons and $\mathrm{K}^\pm$ are equal, and an amount of $\pi^\pm$ in the region $0.5 \leq p_\mathrm{T} < 0.6$ GeV/c rising with p_T. The growing contamination from $\pi^\pm$ could be reduced with the information from TOF and lead to the requirement of a TOF measurement for $p_\mathrm{T} \geq 0.6$ GeV/c. Using the information from TOF, $\mathrm{K}^\pm$ could be identified up to $p_\mathrm{T} = 1.5$ GeV/c. The contamination in the final $\mathrm{K}^\pm$ sample is significant only in the region $0.4 \lesssim p_\mathrm{T} < 0.6$ GeV/c and is $\lesssim 20\%$.

3. Results

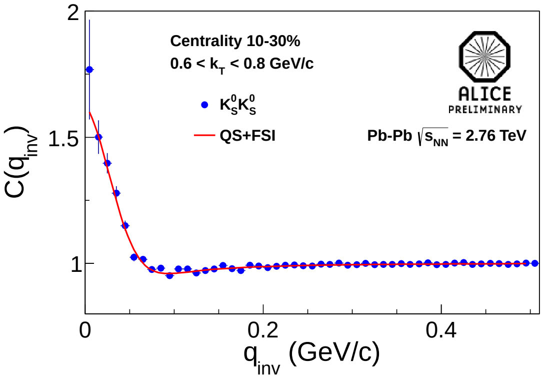

Figure 1: Examplary $\mathrm{K}^0_s\mathrm{K}^0_s$ correlation function

All correlation functions were obtained in common centrality bins: $0-10\%$, $10-30\%$, and $30-50\%$. The negatively and positively charged kaon pair distributions were combined after validating that the correlations functions coincide within errors. The $\mathrm{K}^\pm$ correlation functions were obtained for seven bins in k_T ranging from 0.2 to 1.0 GeV/c and fitted with the Bowler-Sinyukov function:

$$C(q_\mathrm{inv}) = 1 - \lambda + \lambda K(q_\mathrm{inv})(1 + \exp(-R^2_\mathrm{inv} q^2_\mathrm{inv})).$$

$K(q_\mathrm{inv})$ takes into account the Coulomb repulsion of the particles assuming factorization and is determined by the overlap of the square of the Coulomb wave function with the finite source [6, 7]. The data show the expected enhancement at low q_inv and are nicely described by the fit function. A clear k_T dependence is visible. The neutral kaons were fitted in four k_T bins from 0.2 to 1.5 GeV/c taking into account the attractive final state strong interaction and the quantum statistics. The extracted radii are in agreement with the charged kaon

analysis. Also the proton-proton correlation functions were obtained differentially in k_T. As for the other particles, a strong centrality dependence is observed. (See also [8].)
The extracted radii from the measurements discussed are shown together with the ones from pions in Fig. 2. The radii for all species and all m_T decrease for more peripheral events. The reach in m_T is doubled by the kaons and protons with respect to the pions, exhibiting the decrease of the radii with m_T out to $m_T = 1.6$ GeV/c^2. Comparing the radii for the different species, one observes only an approximate m_T scaling. To further study this slight tension, three-dimensional radii in the longitudinally co-moving system are under investigation in ALICE. The excellent PID and the high statistics datasets of ALICE allows for precise measurements over a wide range of m_T with overlapping regions of measurement in m_T for different particle species.

4. Outlook

At the SPS and RHIC, proton-Λ correlations provided femtoscopic radii at highest m_T [9, 10]. Fig. 3 shows the purity of $\bar{\Lambda}$ maximized for significance obtained with ALICE for the 10% most central collisions. Within $|\eta| < 0.9$ typical purities are on the order of 95%, increasing for more peripheral events. A radius parameter obtained from pairs of protons and Λ should be available soon.

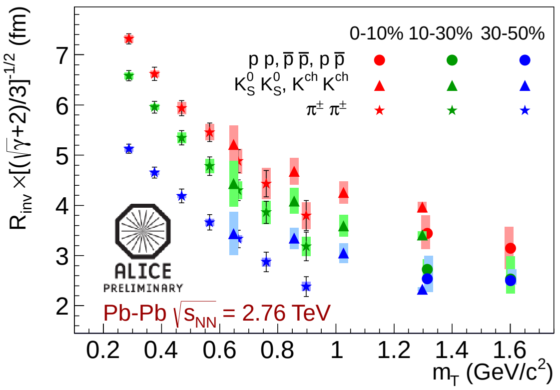

Figure 2: m_T dependence of radii from pions, kaons, and protons

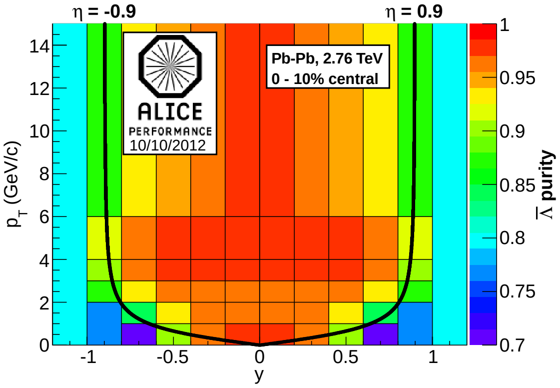

Figure 3: Purity of $\bar{\Lambda}$ as a function of their transverse momentum and rapidity for the 10% most central Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV.

5. Summary

ALICE provides an excellent environment for high purity and high statistics femtoscopy. The doubly differential centrality and m_T dependence of femtoscopic radii for kaons and protons was presented and compared to radii for pions obtained by ALICE. The obtained radii decrease with m_T, exhibiting features of strong collectivity in Pb-Pb collisions at the LHC.

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