Particle correlations in ultra-relativistic heavy-ion experiments STAR at RHIC and ALICE at LHC

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Abstract

Particle interferometry is one of the tools proposed to extract quark-gluon plasma signatures in ultra-relativistic heavy-ion collisions at RHIC and LHC. From an experimental point of view, STAR and ALICE experiments installed at these facilities will provide exceptional conditions to study particle correlation studies. Some of the new possibilities open by these experiments are investigated.

1 Introduction

From low-energy heavy-ion reactions to high-energy particle collisions, particle interferometry has been widely used in order to extract information on particle production. Due to the interplay between the effects of Bose-Einstein or Fermi-Dirac statistics and the strong and Coulomb final state interactions, the

⋆ Talk presented at the IV TAPS Workshop (Mont Sainte Odile, FRANCE, September 14-20, 1997) C97-09-14.1

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correlation functions of identical particles are sensitive to the relative space-time distances between the particle emission points. Similar information can be deduced from non identical-particle correlations induced by the effects of the final state interactions (FSI). Moreover, evolutive sources are produced in heavy-ion reactions leading to dynamical correlations which can be studied with the help of particle interferometry.

In the near future, two main colliders : RHIC at Brookhaven (USA) and LHC at CERN will be available in order to analyze ultra-relativistic heavy-ion reactions. Physicists will study nuclear matter at very high temperature and density and search for a possible quark-gluon plasma formation. In order to distinguish between the creation of such new phase and a pure hadronic gas scenario, several observables will need to be simultaneously measured. Particle correlations will be one of the main sources of information and will fully benefit from the exceptional detection capabilities of these experiments.

The formalism and the methods currently used to analyze experimental correlation functions at high-energy will be detailed. The STAR and the ALICE experiments will be described emphasizing on their detection capabilities with respect to correlation measurements. Finally, some of the new possibilities of particle interferometry open by the future detectors will be investigated.

2 Formalism and methods used to analyze particle correlations

In the most general case, two-particle correlations are the result of the interplay between quantum statistics effects (also called interferometric or HBT effects) and the final state interactions between the two particles (the Coulomb interaction for charged particles and the strong interaction for hadrons). Thus, the features of the emitting sources can be investigated in the frame of an approach which includes both types of effects giving rise to correlations. Such kind of models have been already worked out [1–3] and are successfully used in low-energy heavy-ion reaction domain [4]. The correlation functions are calculated by integration of the two-particle wave function over the source dimensions and the spin variables [2]. In the frame of such models, dynamical correlations can be included based on simple source evolution pictures or extracted from microscopic models describing the collisions. In the same way, systematic effects such as experimental resolution and apparatus acceptance can be easily introduced.

In the high-energy domain, the interferometry has been initiated and developed from a different perspective. Particle correlation studies started with the analysis of two-pion correlation functions for which the quantum effects were dominant. Then, correlation function studies have been extended to other kind of two-particle systems such as kaon pairs but the method of analysis developed in the early times is still currently used in high-energy experiments. The validity of this method is based on two main assumptions :

- The two particles do not interact with them self and the rest of the system. In this case the final state interactions are not taken into account and only the quantum statistics effects are considered via the (anti-)symetrization of the two-particle wave function (in this case the individual wave functions are plane waves).
- The source emitting particles is characterized by a Gaussian shape. The space-point and time of emission of the particles are completely decoupled from their kinematic characteristics.

Under those assumptions, the correlation function can be derived and takes the following form :

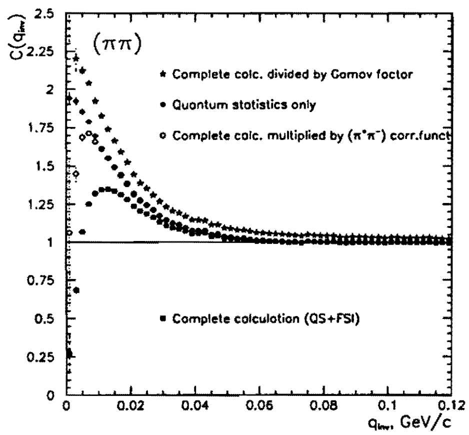
$$C(Q_{inv}) = 1 + \lambda e^{-Q_{inv}^2 R_{inv}^2} \tag{1}$$

where Q_{inv} is the invariant relative momentum ($Q_{inv}^2 = Q^2 - Q_0^2$), R_{inv} is the parameter describing the space-time extend of the emitting source and λ is a parameter usually interpreted as the degree of incoherence of the source. The dimensions and the shape of the source can be further detailed by introducing additional parameters R_L, R_{Tout}, R_{Tside} leading to the following correlation function parameterization :

$$C(Q_L, Q_{Tout}, Q_{Tside}) = 1 + \lambda e^{-Q_L^2 R_L^2 - Q_{Tside}^2 R_{Tside}^2 - Q_{Tout}^2 R_{Tout}^2} \tag{2}$$

where Q_L is the component of the relative momentum parallel the to beam axis,Q_{Tside} is the component perpendicular to the beam axis and parallel to the pair transverse momentum and Q_{Tout} is the component perpendicular to both the beam axis and the transverse momentum of the pair.

In order to extract the value of the source parameters, the formulation in eq. 1 is used to perform a fit, or a multiple fits using eq. 2, to the experimental correlation functions. Unfortunately, the first assumption of this method is fulfilled in very limited cases. Very often, the contributions of the Coulomb and strong interactions are far from being negligible. The limits of this assumption is illustrated in figure 1 and figure 2 for respectively two-pion and two-kaon correlation functions. Simulations of $Pb + Pb$ collisions at SPS energy ($158 MeV/A$) have been performed with the RQMD model (v.1.08) [5]. The $\pi\pi$ correlation function calculated with the quantum statistic effects only (filled circles) significantly deviate from the correlation function including in addition the final state interaction effects (filled squares). The Coulomb interaction being repulsive between the two pions, it attenuates the correlations



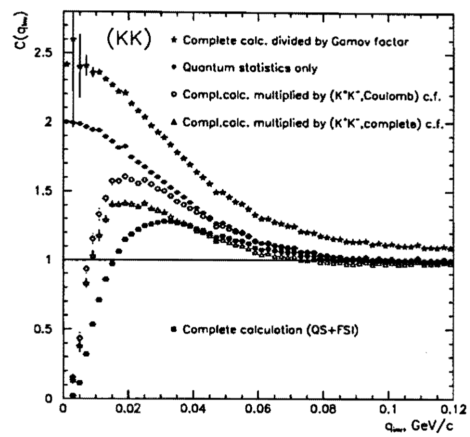


Fig. 1. Two-pion correlation functions simulated with various calculation options and Coulomb corrections (see text for details).

Fig. 2. Same as Fig. 1 for two-kaon correlation functions

and induces a depletion at small relative momentum. The deviation is stronger for two positive kaons and extends over a larger range in relative momentum.

In order to be still able to fit experimental correlation functions with simple formulations such as eq. 1, various corrections have been proposed to unfold Coulomb effects from experimental correlation functions.

The so-called Gamov factor was the first correction introduced. It is based on calculations of non-relativistic Coulomb wave function at zero distance and is founded (or at least can be considered as a good approximation) only if the effective size of the emitting source is much smaller than the two-particle Bohr radius. Effects of this correction on correlation functions are represented by open stars in Fig. 1 and Fig. 2. Obviously this correction overestimates the Coulomb FSI effects at small relative momentum and introduces a non flat behavior at large relative momentum.

Recently, a correction using unlike-charged particle correlation functions has been proposed to overcome the Gamov factor failure [6]. This correction assumes that identical particle systems ($\pi^+\pi^+$ or $\pi^-\pi^-$) and opposite-charge system ($\pi^+\pi^-$) have similar correlations due to Coulomb interaction. Two other assumptions are hidden behind this hypothesis : both type of particles (π^+ and π^-) are produced by the same emitting source and the effects of the strong final state interaction are negligible. Like-charge correlation functions including all the correlation effects divided by the opposite-charge correlation functions are represented by open circles in Fig. 1 and Fig. 2. In the case of two-pion system, the corrected correlation function follows the correlation function simulated with only the quantum effects for most of the range covered in relative momentum. However, underestimating the importance of the Coulomb effects it starts to diverge at small relative momenta. Moreover, this technique is totally failing for two-kaon correlation functions (Fig. 2). As a matter of fact, the contribution of the strong interaction is rather significant for this two-particle system (open circles compared to open triangles).

More recently, an approach [7] has been developed to overcome the Gamov factor difficulties for size-dependent Coulomb corrections which gives reasonable approximations for pions. On the other hand, iterative procedures have been developed using full Coulomb wave function calculations in order to converge to a given source size using consistent Coulomb correction [8,9].

The simple formulation of the correlation function (equation 1) which was the appealing feature of this analysis method is now obscured by the complicated corrective procedures used to unfold the Coulomb interaction contribution. Although it might be still applicable for the analysis of pion pairs, this method is not suited at all for higher-mass system (KK,pp,...) and non identical particle correlation functions. One should note that, at RHIC and LHC, one expects to produce relatively large emitting source. In such case, the Coulomb interaction effect is the dominant effect for the correlation function and consequently cannot be treated as a correction. On the other hand, the effects of Coulomb interaction and for a majority of two-particle system the effects of nuclear interaction are well understood and can be easily introduced in theoretical model aiming to predict correlation functions. Moreover, it is the only way to perform a consistent analysis of several correlation functions (identical and non identical pairs) measured in a given experiment.

3 Experiments and detection capabilities

In the near future, two main facilities will be available to physicists to study ultra-relativistic heavy-ion collisions and to search for quark-gluon plasma formation. In the year 1999, the RHIC (Brookhaven,USA) collider will deliver $100GeV/A$ Gold beam. In Europe, the LHC will be available in 2005 at CERN (Geneva) to produce Pb-Pb collisions at $\sqrt{s} = 6300GeV/A$. Two major experiments, dedicated to heavy-ion reaction studies will be installed at these facilities, respectively STAR [10] (Fig 3) and ALICE [11] (Fig 4). Despite their different sizes, the design of both experiments is based on two major detectors : a time projection chamber and a silicon vertex tracker will detect charged particles at mid-rapidity. Covering the same acceptance, a third apparatus will allow particle identification by time-of-flight measurement.

In order to build quality correlation functions and perform a meaningful analysis, two main experimental conditions have to be fulfilled. A very good one-

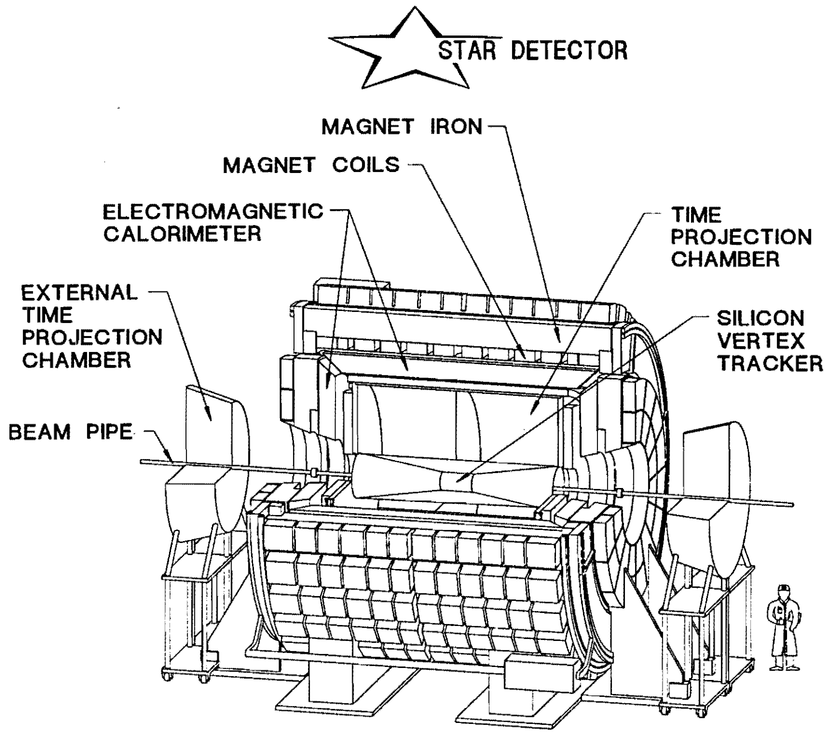


Fig. 3. General View of the STAR experiment

particle momentum resolution has to be achieved to reach satisfactory two-particle relative momentum resolution. In addition, particles should be well identified in order to avoid pollution from other particle species leading to attenuated or wrong correlation signals.

Current AGS and SPS experiments can be roughly sorted in two classes with respect to the correlation measurements :

- Experiments dedicated to particle interferometry are characterized by a good momentum resolution and particle identification but small acceptance. The good momentum resolution usually achieved with the help of a spectrometer forbids the possibility to study non-identical particle interferometry.
- Generic experiments are usually covering a large acceptance but with a limited momentum resolution and particle identification capabilities. Moreover, since interferometry is a quite beam time consuming method, particle pair data are usually collected with limited statistics.

In the future, experimental conditions will be rather good in STAR [10,12] and ALICE [11] to measure correlation functions :

- Both experiments have a large acceptance for charged particles. The central detectors cover more than 2 units of rapidity at mid-rapidity with a full azimuthal coverage.

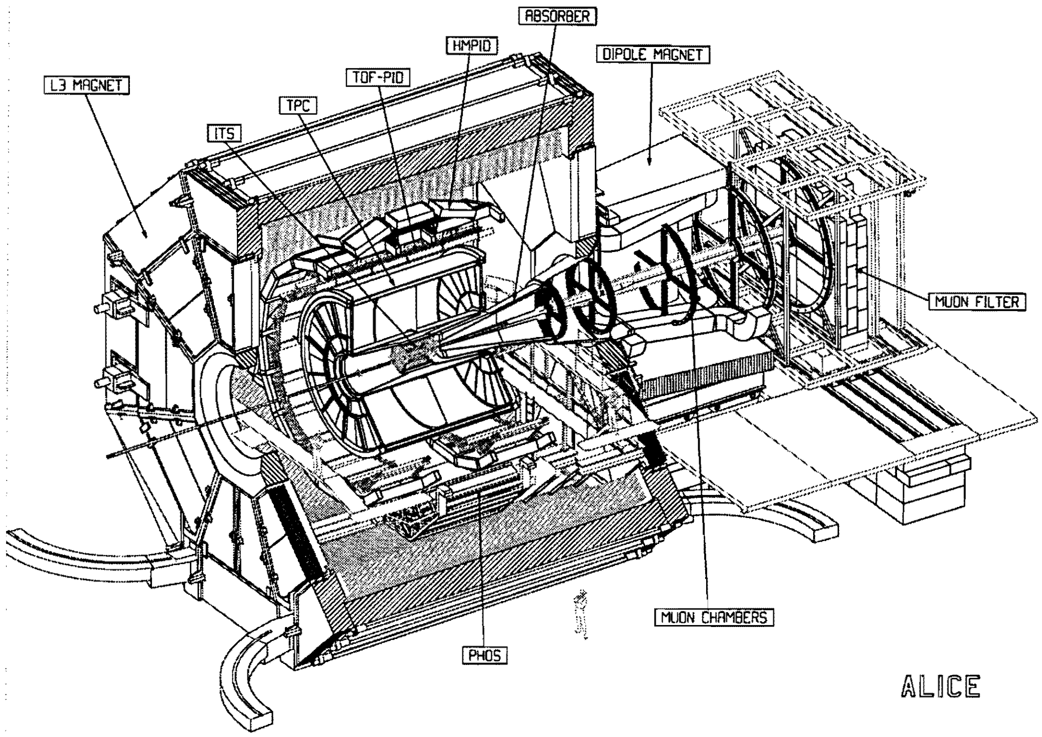


Fig. 4. General view of the ALICE experiment

- Due to use of a time projection chamber, a very good momentum resolution of the order of few percents will be achieved. The angular resolution is estimated to be of the order of few mrad in both the polar and the azimuthal direction. In addition, the fine granularity of the vertex trackers and the particle identification detectors imply a good two-track separation which is essential to measure particle pairs at low relative momenta. [11].
- Very good particle identification performances will be achieved with the help of dedicated detectors (by time-of-flight measurements) and due to the good tracking capabilities of the devices for secondary particles.
- A very large amount of particles will be produced at mid-rapidity in central collisions. Between 5000 and 8000 particles per unit of rapidity are expected to be produced in Pb+Pb collisions in ALICE and of the order of 2000 charged particles will be measured in the central barrel of STAR in each Au+Au event. Consequently, a limited beam time will be necessary in order to collect large statistics of data and construct good quality correlation functions.

4 Particle correlations in STAR and ALICE experiments

As already mentioned in the previous section, the situation from an experimental point of view to do particle correlation analysis will be much better in

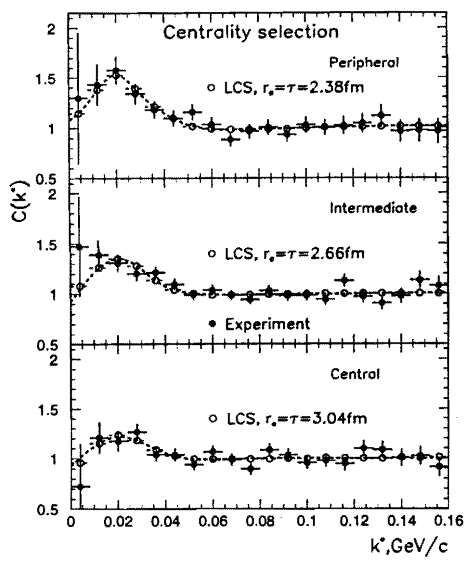


Fig. 5. Experimental two-proton correlation functions measured by the NA44 collaboration in $S+Pb$ in three centrality intervals

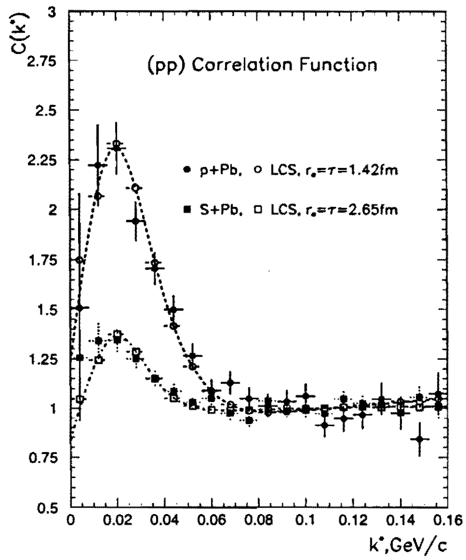


Fig. 6. Experimental two-proton correlation functions measured by the NA44 collaboration in $p+Pb$ and $S+Pb$

ALICE and STAR than in AGS and SPS experiments. Nevertheless, current experiments have already permitted to deduce interesting information from the interferometry measurements [13–15].

As a matter of illustration, the two-proton correlation function measured by the NA44 collaboration in $p+Pb$ and $S+Pb$ at $200MeV/A$ are presented [16]. For the $S+Pb$ colliding system, the experimental correlation functions have been constructed for three different cut in centrality (Fig. 5). For the typical source produced at these beam energies, the two-proton correlations are mainly induced by the short-range strong interaction leading to a peak in the correlation function at relative momenta of 20 MeV/c. The amplitude of the nuclear interaction quickly vanishing with the relative distances between the two protons, the amplitude of the peak rapidly diminishes with the extension of the emitting zone as confirmed by the size parameters extracted from the experimental correlation functions. Experimental correlation functions measured in $p+Pb$ and $S+Pb$ are compared in figure 6 showing a nice dependency on the total size of the colliding system. Preliminary results indicate that the same conclusion can be drawn from experimental data measured in $Pb+Pb$ from which very flat correlation functions have been constructed.

A systematic analysis of SPS data seems to indicate that particle freeze-out appears at constant density. If such a trend survives at higher energies, one should expect larger source dimension at RHIC and LHC. Simulations have been performed with the microscopic model VENUS (v.5.14) [17] in order to

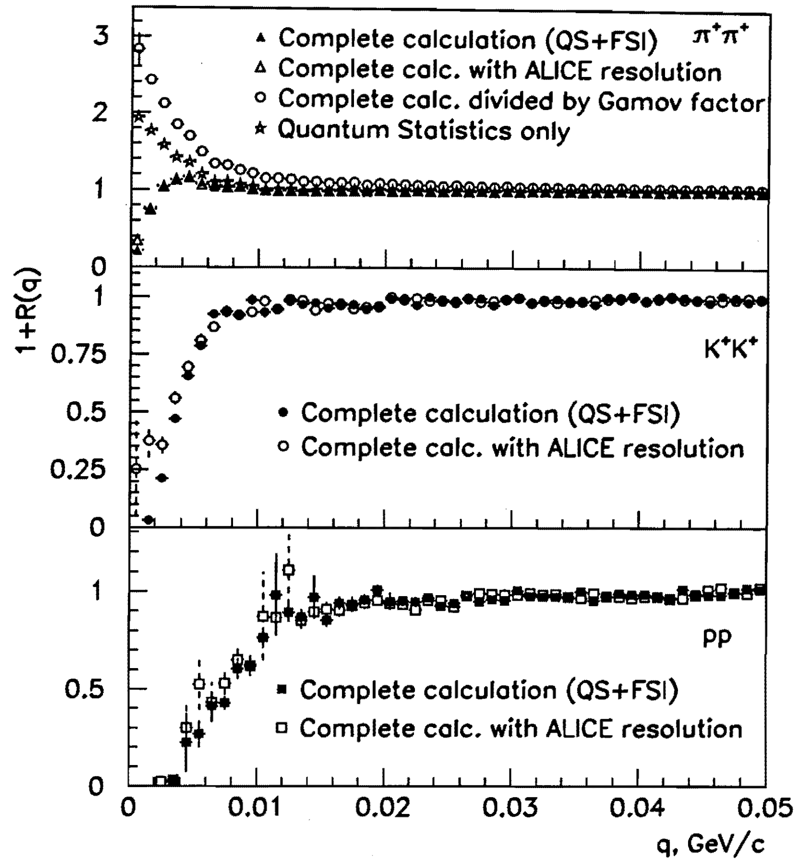


Fig. 7. Simulated correlation functions for two identical charged pions, kaons and protons without and with the effect of the ALICE experimental resolution accounted for.

get qualitative estimates of the sensitivity of the interferometry measurement to the source dimensions at these energies. At the present time this model is certainly not suited for the LHC energy regime. However, it provides space-time and momentum space characteristics of the freeze-out points of different particle species, which can be used as a reasonable approximation accounting for the presently known basic features of the multi-particle production, including the fast longitudinal motion of the particle sources and resonance production. Besides, it allows to expand the space-time extent of the production region in order to quantify the sensitivity of correlation functions to extremely large sources.

Identical-particle correlation functions simulated for $Pb+Pb$ collisions at LHC are presented in figure 7. The two-pion correlation function is rather flat while due to a much bigger Bohr radius, the proton-proton correlation function exhibits a large depletion at small relative momenta. From these calculations, one can conclude that the two-proton correlation function is a much sensitive

Particles	Q_{side}	Q_{out}	Q_{long}	Q_{inv}
$\pi^+\pi^+, \pi^+\pi^-$	0.3	3.8	0.7	1.2
π^+K^+, π^+K^-	0.4	4.0	1.1	1.8
π^+p, π^-p	0.4	3.9	1.3	2.0
K^+K^+, K^+K^-	0.5	6.5	2.6	3.6
K^+p, K^-p	0.6	8.2	3.2	4.8
pp	0.6	11.6	5.0	6.0

Table 1
Expected resolution in relative momentum $\sigma(Q_i - Q_i^{'})$ (in MeV/c) in ALICE for various two-particle systems. A cut $Q_{inv} < 50MeV/c$ has been applied in order to select only low momentum pairs.

probe to large sources. In figure 7 theoretical correlation functions calculated assuming perfect detection (filled symbols) are compared to correlation functions including the experimental resolution expected in ALICE (open symbols). The distortions of correlation functions due to momentum and angular resolution are very small and only limited to the low momentum region. The experimental two-track resolution, presently not included in these calculations, is expected to have marginal effects on correlation functions (it will lead to a fraction of unresolved particle pairs with near-by momenta). Table 1 summarizes the resolution expected for various particle pairs and components of the relative momentum. This very good resolution (of the order of few MeV/c) will allow to do accurate correlation measurements and perform detailed analysis of the correlation function shape.

STAR and ALICE will both provide the opportunity to study non-identical particle correlations which are essential in order to complete the picture of the collision deduced from identical-particle interferometry. In addition, unlike-particle correlation functions are less suffering from experimental two-track resolution since non-identical particles with small relative momenta in the pair rest frame have very different momenta in the laboratory frame. In figure 8, K^+K^- and $\pi^+\pi^-$ correlation functions are compared to K^+K^+ and $\pi^+\pi^+$ correlation functions simulated for two different dimensions of the source. While the shape of identical-particle correlation functions is the result of all the effects producing correlations, unlike-particle correlation functions are often dominated by the contribution of Coulomb interaction. In such a case, the resulting correlation function is more easy to interpret and shows correlation signals in particular conditions where all the effect producing correlations are balanced (like the K^+K^+ correlation function for $\langle r \rangle = 25fm$).

The identical particle interferometry yields an important information on the relative space-time distances between the emission points of the particles of given type. Under certain conditions this relative information can be trans-

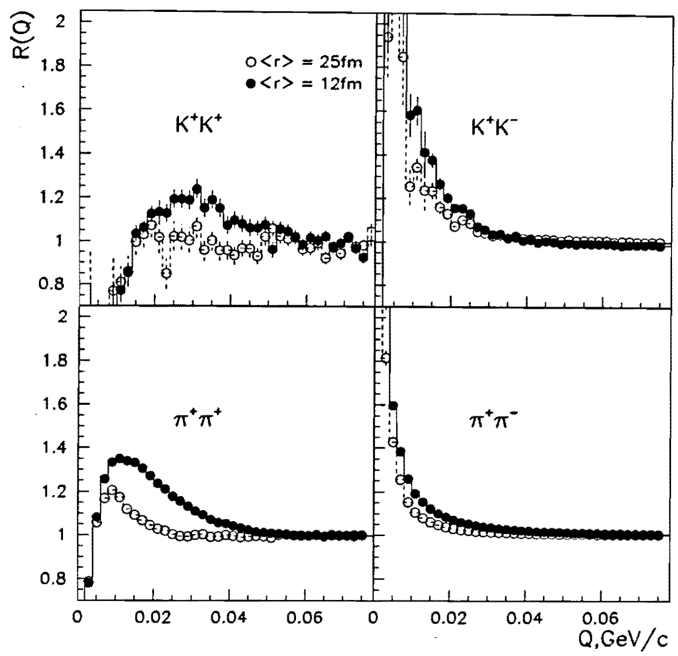


Fig. 8. Correlation functions simulated for identical and non-identical kaon and pion pairs. Identical-particle correlation functions are the result of a mixing of quantum statistics and FSI effects while Coulomb interaction is the dominant source of correlations of non-identical particle pairs

formed to the absolute one, such as the decoupling proper time in the case of an expansion process. On the other hand, the correlations of non-identical particles appear to be directly sensitive to the delays in particle emission and thus can serve as a new source of the important complementary information to the standard interferometry measurements.

In fact, it can be shown [18] that the directional analysis of the correlations of two non-identical particles, in contrast to the identical ones, allows to measure not only the anisotropy of the distribution of the relative space-time coordinates of the emission points, but also - its asymmetry. In particular, the differences in the mean emission times of various particle species can be directly determined, including their signs. Figure 9 illustrates in a classical picture this new analysis technique for a scenario where negative kaons are emitted before positive kaons. For some of the emitted pairs the K^- velocity is smaller than the K^+ velocity (top-left part). In this case due to small relative distances the corresponding correlation function $R_+(q)$ will exhibit a given amplitude reflecting the strength of the correlations between the particles (top-right part). On the other hand, kaon pairs with $v_{K^+} < v_{K^-}$ (middle-left part) will be characterized by larger relative distances leading to weaker two-particle correlations $R_-(q)$ (middle-right part). The ratio $R_+(q)/R_-(q)$ (bottom-right part) permits to quantify the difference in amplitude of these correlation functions.

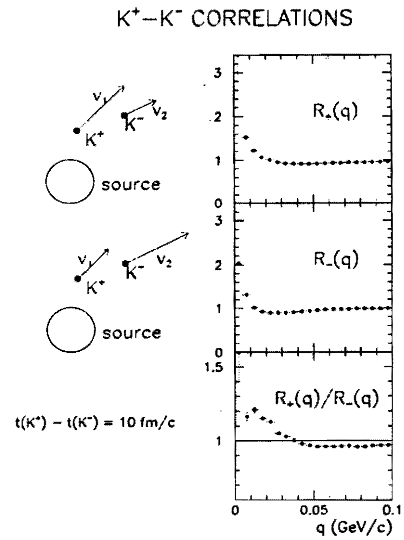


Fig. 9. Illustration of the emission time sequence analysis technique

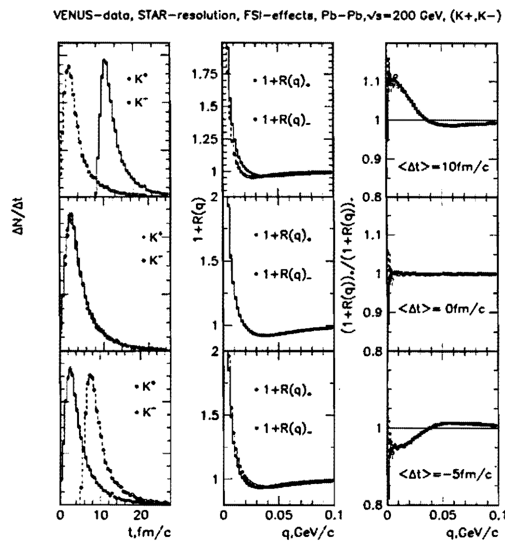


Fig. 10. K^+K^- time distributions (left), correlation functions $R_+(q)$ and $R_-(q)$ (middle) and ratio $R_+(q)/R_-(q)$ (right) calculated for $\langle \Delta t \rangle = 10 fm/c$

The time delay between K^- and K^+ emission lead to a ratio $R_+(q)/R_-(q)$ greater than unity at small relative momenta. The selection of these two classes of particle pairs is done by studying the scalar product $k^* v$ where k^* is the relative momentum and v the two-particle rest frame velocity (k^* respectively parallel and anti-parallel to v).

Figure 10 illustrates this effect for the system pair K^+K^- where different time delays ($\langle \Delta t \rangle = 10, 0, -5 fm/c$) have been introduced in the emission time distributions predicted by VENUS. As expected, the change in the sign of the time delay (from 10 to $-5 fm/c$) induces a different structure in the correlation function ratio (from a peak to a deep). One should note that any spatial asymmetry can attenuate this emission time effect. However, Fig. 10 shows that good sensitivity is preserved for time delays as short as few fm/c. Ratios $R_+(q)/R_-(q)$ calculated for $\langle \Delta t \rangle = 10 fm/c$ and various particle pairs are represented in figure 11.

This opens a new possibility to determine, in a model independent way, which sort of particles ($K^+, K^-, \pi^+, \pi^-, p ...$) was emitted earlier and which later at very short time scales of several fm/c or higher. In particular, this effect could be useful to indicate the formation of QGP. Note that usually kaons are expected to be emitted earlier than pions due to their larger mean free path. In the case of strangeness distillation from the mixed hadronic and QGP phase a delay is expected between the emission of strange (K^-) and anti-strange particles (K^+).

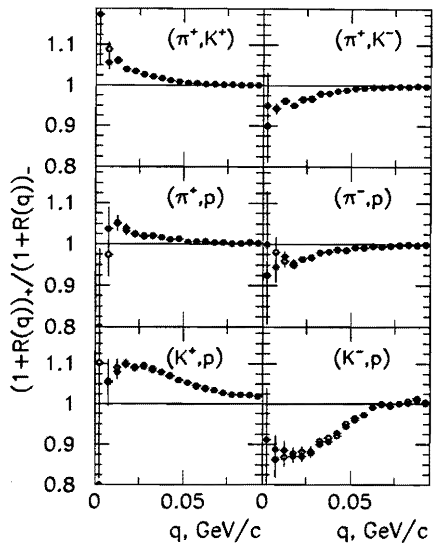


Fig. 11. Ratios $R_+(q)/R_-(q)$ of correlation functions calculated for a time delay $\langle \Delta t \rangle = 10 fm/c$ and various two-particle systems (filled circles) and compared to similar calculations including the ALICE experimental resolution (open circles).

In both experiments, the very good relative momentum resolution reached is provided by the time projection chamber. Unfortunately, this detector is characterized by a transverse momentum threshold due to material and air in front of it and magnetic field. Below this threshold (of the order of 100 MeV/c for pions) the particle detection and the momentum resolution is driven by the vertex detector capabilities. The STAR vertex detector is only made of three concentric layers of silicon drift detectors (compared to six cylindrical layers in ALICE) which implies a loss of detection efficiency and limited momentum resolution for low transverse momentum particles. Three French laboratories (SUBATECH at Nantes, IRES and LEPSI at Strasbourg) have proposed to insert an additional layer of silicon micro-strip detectors (SSD) in order to improve the STAR vertex detector performances (SVT) [19]. Figure 12 illustrates the impact of the SSD on the ability of STAR to measure two-pion correlation functions at very low transverse momenta. The simulated correlation function (open squares) including the additional layer (SVT+SSD) is compared to the correlation function (open triangles) calculated with the current detection geometry (SVT) and to the calculation assuming a perfect momentum resolution (filled circles). Although the effects of a limited resolution is clearly seen, the addition of the SSD strongly improves the quality of the measured correlation function.

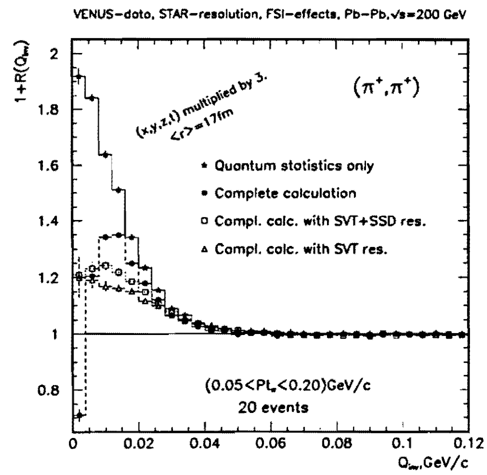


Fig. 12. Impact of the SSD in STAR on two-pion correlation function constructed with low transverse momentum pions

5 Conclusions

The method currently applied in high-energy physics to analyze particle correlations has been described. The correction techniques developped in order to unfold the contribution of the Coulomb interaction from experimental correlation functions appear to be valid in very limited cases and can not be applied to most of the two-particle systems. Only a theoretical approach including the effects of buth the quantum statistics and the final stat interactions coupled to microscopic model predicting the dynamical evolution of the collisions will allow a consistent and complete analysis of experimental correlation functions.

The possibilities to perform correlation measurements in future experiments STAR and ALICE have been reviewed. Very good experimental conditions (large acceptance, good momentum resolution and particle identification) will be achieved. Very high particle multiplicities will be measured in central collisions by STAR and ALICE opening the possibility to construct correlation functions on a event by event basis. In ALICE, the pion multiplicity per event will be high enough to build correlation functions for each two-particle system involving a pion ($\pi^+\pi^-$, $\pi^\pm K$, $\pi^\pm p$,...). Due to a lower beam energy and consequently a lower multiplicity of produced particle, event by event analysis will be only possible for pion pairs in STAR. In both experiments, interferometry analysis will be possible for well defined classes of events for other identical and non-indentical particle systems ($K^\pm K^\pm$, $K^\pm p$, pp). Due to good capabilities of the vertex detectors to detect secondary particles, short-live particle correlations ($K^0_S K^0_S$ and $\Lambda\Lambda$) will be also studied. With these new generation experiments, particle interferometry will allow to draw a complete picture of particle production mecanisms and study dynamical features of heavy-ion collisions.

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