NUCLEAR INTERFEROMETRY FROM LOW ENERGY TO ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

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Abstract : The interferometry, i.e. the correlations of light particles emitted at small relative velocities, is a powerful tool for analysis of space-time development of nuclear collisions. In order to be complete, the description of the interferometry measurement should take into account the effects of quantum statistics, Bose-Einstein or Fermi-Dirac, and final state, strong and Coulomb, interactions.
The same methods can be applied over a very large incident energy domain, from MeV to TeV, involving very different reaction mechanisms. The experimental data from GANIL, MSU, CERN-SPS as well as the simulations performed for future measurements at RHIC and LHC illustrate the possibilities and the universality of the interferometry technique. Various models describing the dynamics of the collisions, like QMD, BUU, RQMD, VENUS, are strongly constraint when used in the frame of the interferometry analysis.

I INTRODUCTION

The nuclear interferometry is a technique based on the properties of light particles. Correlations of the particles at small relative velocities are sensitive to the space-time development of the emission process due to the effects of Bose-Einstein or Fermi-Dirac statistics (an analog of HBT effect in astronomy) [1] and to the strong and Coulomb final state interaction [2].

Due to the final state interaction, correlation methods can be applied also to pairs of non-identical particles. The relative importance of the effects giving rise to correlations is different for different particle species and depend on the space-time distance between particle emission points. The correlated particles can undergo also the interaction with the emitter and with other products of the heavy-ion collision. This interaction cannot be a source of correlations, i.e. cannot correlate two particles emitted independently, but it can modify the interferometry pattern. The contribution of the long range Coulomb interaction can be particularly significant [3].

Using the correlation technique, we can deduce the size and the shape of the emitting zone and, in particular, analyse its dynamical evolution.

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In order to extract information contained in the correlation function we interpret experimental data within the frame of a model including the quantum statistics effects as well as the final state interaction of two particles and the Coulomb interaction between the particles and their emitter (Fig. 1).

For characteristic emission times τ of several hundred fm/c or higher, this complicated three-body problem can be solved in the classical approximation. To extend the theoretical description to lower values of τ, i.e. smaller relative distances between the two particles, we have developed a quantum approach in the adiabatic approximation, assuming the relative motion of the two particles much slower than their motion with respect to the Coulomb center.

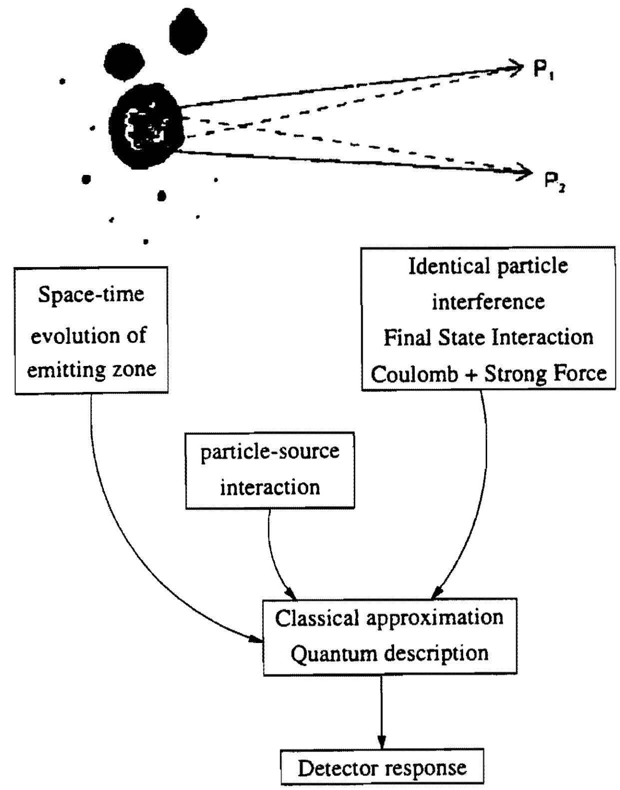


Fig.1 Effects giving rise to light-particle correlations can be described in the frame of classical or quantum approach taking into account the detector resolution.

As far as the emitting nucleus is concerned, the distribution of emission points can be simply parametrized by a static distribution, usually gaussian or exponential. However, to extract information about dynamical evolution of the emitting zone, the space-time coordinates of the emission points and particles momenta should be provided by a model describing the dynamics of the nuclear collisions. Various dynamical models, assuming different reaction mechanisms like QMD, BUU, RQMD, VENUS, can be used for the analysis of interferometry measurements at incident energies ranging from MeV to TeV.

In order to illustrate some possibilities of the interferometry technique, we have selected experimental data from GANIL, MSU, CERN-SPS as well as simulations performed for future measurements at RHIC and LHC.

II LIGHT-PARTICLE CORRELATIONS BELOW 100 MeV/u

a) Two-proton correlation function measured at very low relative momenta.

The experimental correlation function is usually constructed dividing the distribution of pairs of particles measured in coincidence, each pair taken from the same event, by a background distribution of pairs from different events. The region of small relative momenta is particularly sensitive to correlation effects. However, due to a limited resolution of detectors a lack of data is usually observed in this region .

To analyse the correlation function of two protons emitted in the reaction $^{129}Xe+^{48}Ti$ at 45 MeV/u with relative momenta q<10MeV/c we performed an experiment using the magnetic spectrometer SPEG at GANIL [3]. The comparison of the data with the calculation, using the static source parametrization, gives a value of the source lifetime which is very high $\tau = 1500 fm/c$ (Fig. 2).

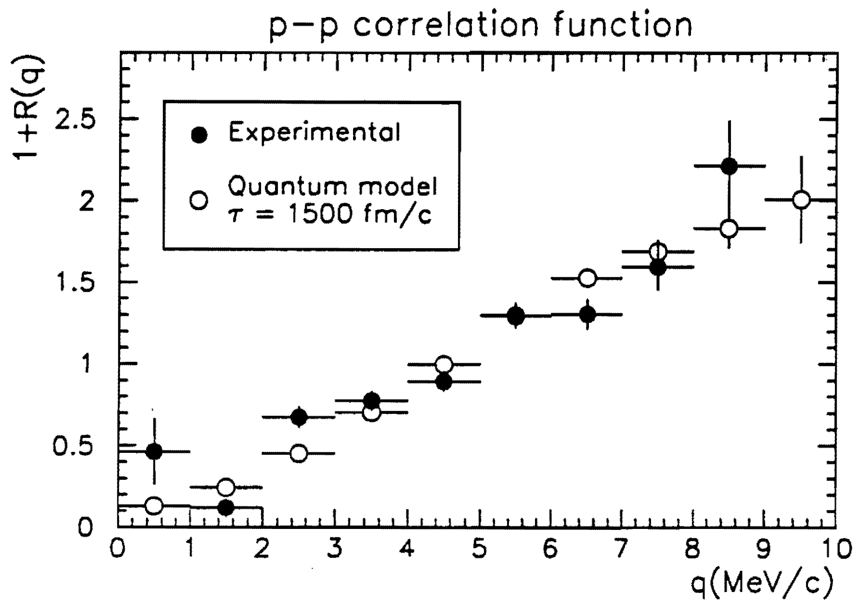


Fig.2 Two-proton correlation function measured in the region of very low relative momenta in the reaction $^{123}Xe + ^{48}Ti$ at 45 MeV/u using the magnetic spectrometer SPEG at GANIL. Data are compared with calculation assuming the static source parametrization. Normalization was performed by setting equal areas of the correlated and uncorrelated spectra.

High lifetimes correspond to large delays in emission times leading to large distances between particles. The short range strong interaction and quantum statistics effects become negligible and the long range Coulomb force remains the main source of correlations. The size of the emitter, estimated to be 3.5 fm, is here very small compared to the distance induced by the difference in emission times.

In this particular case, the protons detected in the spectrometer were emitted with small kinetic energies in the source frame. We suppose that these particles originate mainly from the end of the desexcitation chain. This could explain the large value of the estimated lifetime.

It should be emphasized that we are able to analyse, using the interferometry method, such long living sources provided the experimental resolution is sufficiently high.

b) Dependence of the two-particle correlation function on the centrality of the collision.

The detection of correlated particle pairs together with other observables increases the selectivity of the measurement and leads to higher sensitivity to different reaction mechanisms. An experiment has been performed at GANIL to obtain new information about the influence of the centrality of the events on the correlation functions measured in the reaction $^{208}Pb + ^{93}Nb$ at 29 Mev/u.

A set of 40 CsI detectors of light charged particles was installed inside the reaction chamber of the neutron detector ORION used as a calorimeter [4].

The two-proton correlation function constructed without any selection appears to be flat. A weak anti-correlation is however observed mainly due to the Coulomb repulsion between the two particles (Fig. 3).

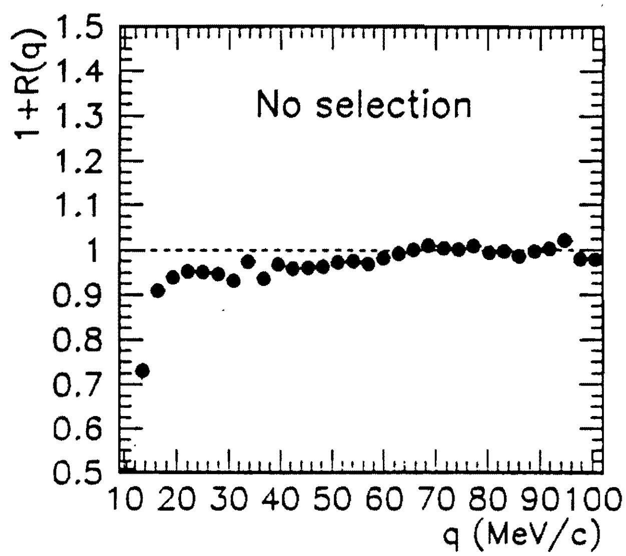
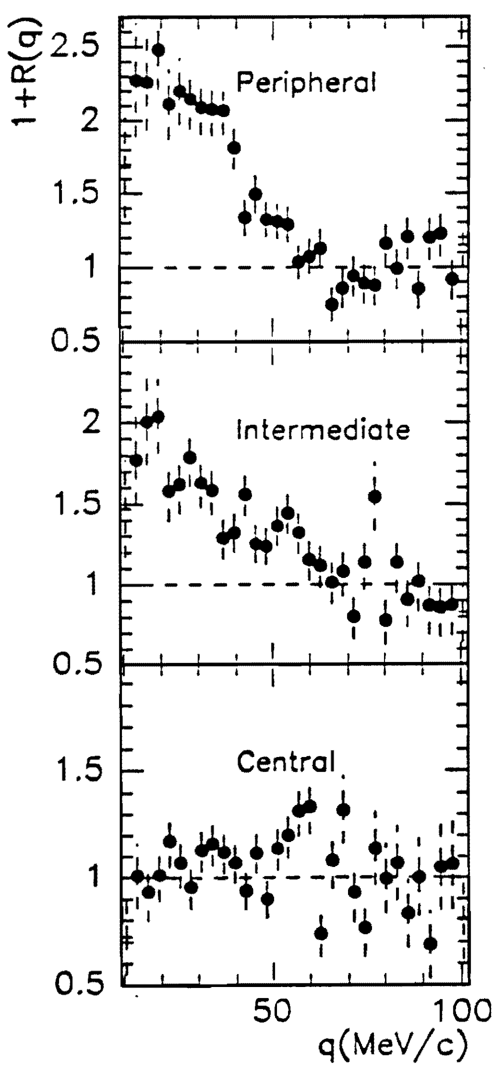


Fig. 3 Correlation function constructed without any selection with protons emitted in the reaction $^{208}Pb+^{93}Nb$ at 29 MeV/u.



The shape of the correlation function changes when we select the type of the collision using the information provided by the neutron calorimeter ORION (Fig. 4). In the case of peripheral collisions we observe a peak due to short range nuclear interaction. This means that we selected here the particles emitted at shorter distances - smaller relative space-time coordinates. The peak decreases for the intermediate centrality collisions and disappears for central ones. Here again we are sensitive to the particles emitted at large relative distances and times.

The impact parameter selection can be achieved also making cuts on transverse energy of the coincident charged particles [5].

Similar trends are observed for other pairs of correlated particles. The dependence of p-d and d-d correlation functions on the centrality of the collision has been studied using both the information provided by the ORION [6] and the data obtained with the INDRA detector at GANIL [7]. In Ref [7] the problem of multi-emission processes is investigated which involve other charged particles, like alphas, and their influance on p-d correlations.

Fig.4 Experimental two-proton correlation functions obtained for different centrality selections.

c) Direct measurement of the delays in the emission of the particles of different types.

The standard interferometry technique gives us information about relative space-time coordinates of the emitter. A new method has been recently proposed to determine the sequence of emission of two kinds of particles [8]. The sensitivity of the correlation function of two non-identical particles (1) and (2) to the sign of the difference of their emission times $\Delta t = t_1 - t_2$ can be used to measure directly the delays in their emission.

The dependance of the correlation function on the sign of the difference of particle emission times has a simple interpretation in terms of the classical trajectory approach. Clearly, the interaction between the particles in the case of a later emission of the faster particle (Fig. 5 a) will be different compared with the case of its earlier emission (Fig. 5 b). The time of the interaction, which is the main source of correlations of non-identical particles, is longer in the first case leading to the correlation stronger $(1+R(q))_+$ than in the second case $(1+R(q))_-$. The sensitivity of the correlation function to the delays in the emission of particles is reflected in the ratio $(1+R(q)_+)/(1+R(q)_-)$. (Fig 5 c).

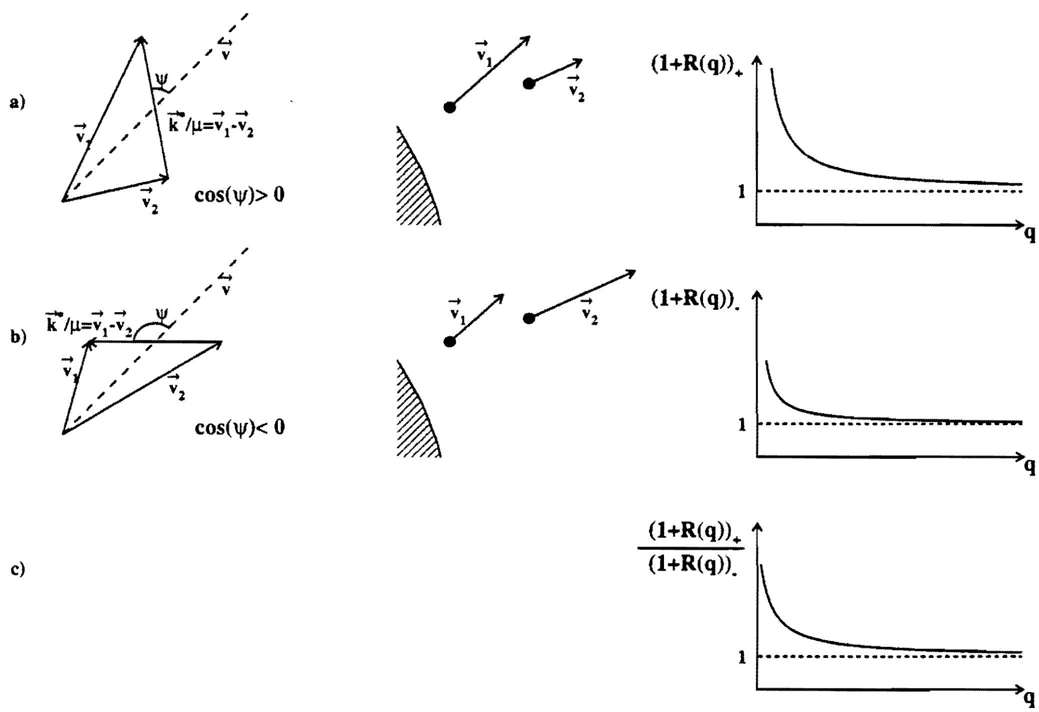
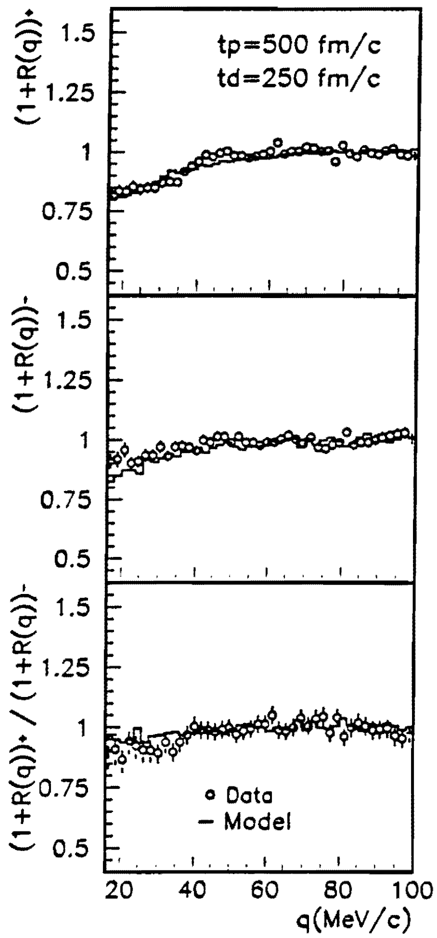


Fig. 5 Sensitivity of the correlation function to the sign of the time difference of particle emission can be simply interpreted in the frame of the classical trajectory approach.

This method has been already applied to the analysis of the p-d correlation functions measured at GANIL, in the experiments described previously (Sections II *a* and *b*). From this analysis we can deduce that the mean time of deuteron emission is smaller than that of protons (Fig 5, 6 and 7). The comparison with the model using a static exponential source parametrization gives an estimation of mean emission times for protons $t_p = 500 fm/c$ and deuterons $t_d = 250 fm/c$ [6]. This result is in agreement with description of deuteron production in the frame of the coalescence model.



d) Correlations in a strong Coulomb field.

Usually, in the description of particle correlations, only the effects of quantum statistics and the mutual interaction of two particles are taken into account. This is however questionable in the case of heavy-ion reactions when the particles are likely to be produced in a strong Coulomb field of residual nuclei. In the case of emission times τ of several hundreds fm/c or greater this three-body problem can be solved in the classical approximation [9]. To extend the theoritical description to lower values of τ , a quantum approach has been developed in the adiabatic approximation, assuming the relative motion of the two particles much slower than their motion with respect to the Coulomb center [10].

The influence of the interaction with the emitter can be particularly important for pairs of particles with different charge-to-mass ratio, which undergo different acceleration in the Coulomb field. This interaction is expected to suppress the correlation. In fact, the analysis in the frame of the three-body calculation shows that the correlation in a strong Coulomb field is weaker but it does not disappear even for p-n pairs. [11].

Fig. 6 Correlation function $(1+R(q))_+$ and $(1+R(q))_-$ and their ratio constructed for p-d pairs produced in the reaction $^{208}Pb+^{93}Nb$ at 29 MeV/u. Comparison with the model using exponential distributions of particles emission times shows that the mean time of deuteron emission is smaller than that of protons.

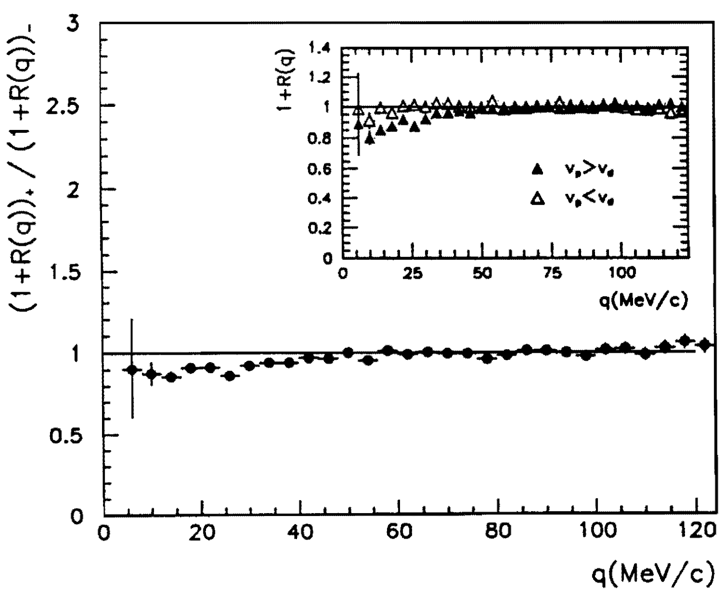


Fig 7 : Measurement of delays in the emission of protons and deuterons emitted in the reaction $^{123}Xe+^{48}Ti$ at 45 MeV/u. Shape of the ratio $(1+R(q))_+/(1+R(q))_-$ indicates that, in average, deuterons are emitted before protons.

On the other side, the effect of emitting nucleus charge can influence even the pairs of identical particles. The two-proton correlation function measured at MSU in the reaction $^{36}Ar+^{45}Sc$ at 80 MeV/u [12, 13] has been analysed in the frame of three-body approach using a static source parametrization [14]. Assuming a realistic charge of the source, the influence of its Coulomb field on the shape of the correlation function appears to be important over a broad range in relative momentum (Fig 8). However, a really good agreement with the experimental data cannot be obtained. The results of the two-body calculation including the space-time evolution of the collision, predicted by the microscopic transport model BUU [13], indicate the importance of the dynamical correlations and, at the same time, the limits of a simple static picture of the source.

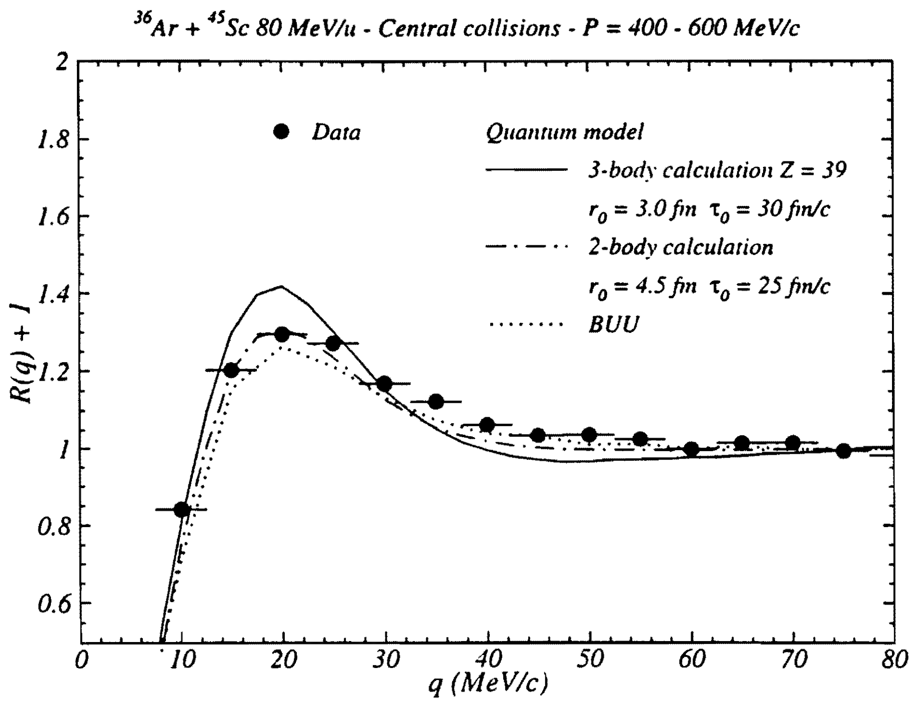


Fig. 8 Two-proton correlation function compared with : predictions of the three-body quantum model, assuming a source of charge Z=39, radius r_0=3 fm and lifetime τ_0 =25 fm/c ; calculation in the two-body approximation with r_0 = 4.5 fm and τ_0 = 25 fm/c and two-body calculation including the space-time evolution of the collision predicted by BUU model.

e) Dynamical correlations

To be more realistic the three-body quantum model describing the particle correlations in a strong Coulomb field should include the description of the dynamical evolution of the collision.

For this purpose, the quantum molecular dynamics model (QMD) is well suited [15]. Smooth phase space distributions are obtained without loosing two-body correlations. The particles interact via two and three-body interactions of local Skyrme, Yukawa and Coulomb type and by momentum dependent interactions. The collisions are treated stochastically, in a similar way as in the cascade models. Additionally, the Pauli blocking is taken into account by regarding the phase space densities in the final state.

As a result of the dynamical evolution, the coordinates of the emission points are correlated with the emission times and with the asymptotic momenta of particles (Fig. 9). These dynamical correlations, reflecting the space-time evolution of the nuclear collisions, influence strongly the shape of the correlation function. The two-proton correlation function, for example, is enhanced if the space-time coordinates and the momenta of particles are dynamically correlated (Fig. 10). The effects of quantum statistics and final state, (Coulomb and nuclear), interactions are taken into account.

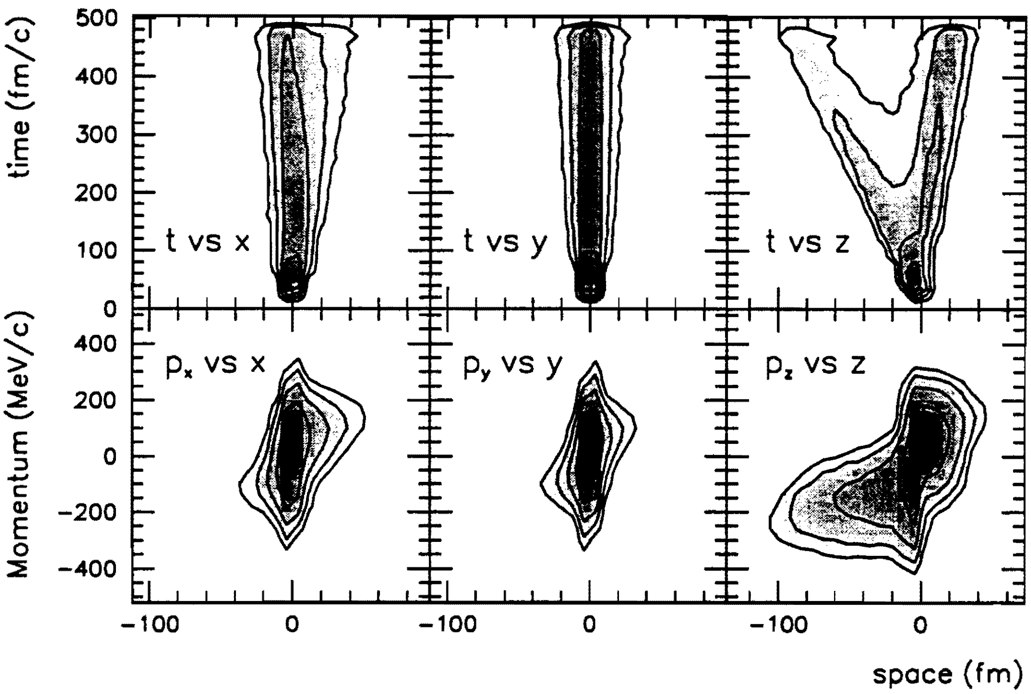


Fig. 9 Correlation between coordinates of emission points, emission times and asymptotic momenta of protons predicted by the quantum molecular dynamics model (QMD).

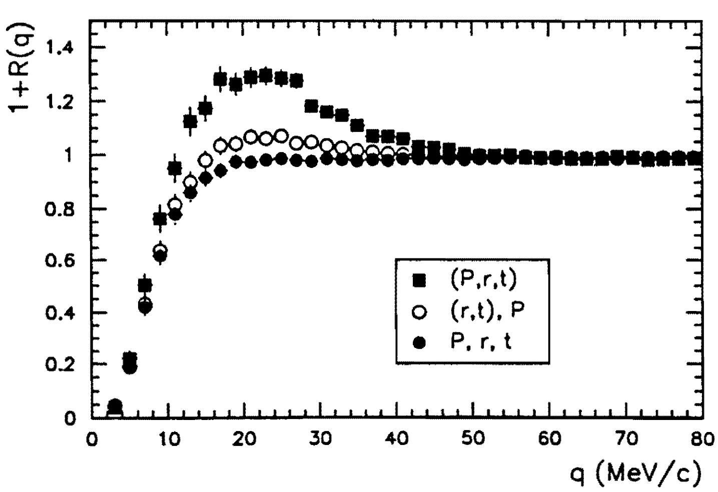


Fig. 10 Correlation function of two protons emitted in the reaction $^{123}Xe + ^{48}Ti$ at 45 MeV/u predicted by QMD : with space-time coordinates and momenta of particles dynamically correlated (see Fig. 9) (squares) ; only space-time coordinates are correlated (open circles) ; space-time coordinates and momenta are decorrelated, i.e. taken from different events (solid circles).

III PARTICLE CORRELATIONS AT ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

At ultra-relativistic energies the dynamical evolution of the collision is likely to be very different from that expected at lower energy (Fig. 11) . In particular, the quark-gluon plasma (QGP) can be created, due to a very high temperature and density. The nuclear interferometry pattern of particles emitted at the hadronization stage or during the mixed phase would be probably sensitive to the space-time development of the collision and may provide important information on the history of heavy-ion reaction.

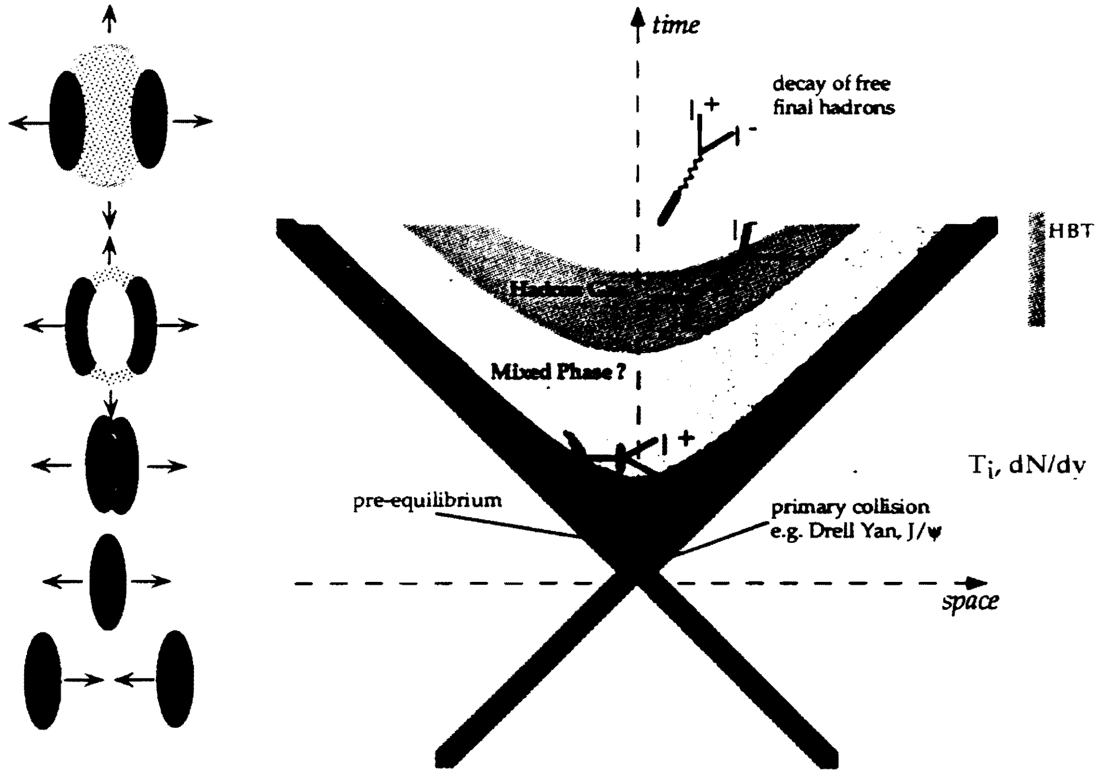


Fig. 11 Space-time evolution of the nuclear collision expected at ultra-relativistic energies.

Usually, source sizes and lifetimes are extracted from the fits of measured correlation functions. [16]. However, the interpretation of the parameters from fitting the data is complicated by resonance decays as well as by the collision dynamics.

Sometimes, the complete description of the quantum statistics effects and final state interaction is replaced by a simple correction for two-particle Coulomb interaction using the so called Gamow factor. Such an oversimplified correction can lead to the extraction of wrong parameters of the fit. (Fig. 12).

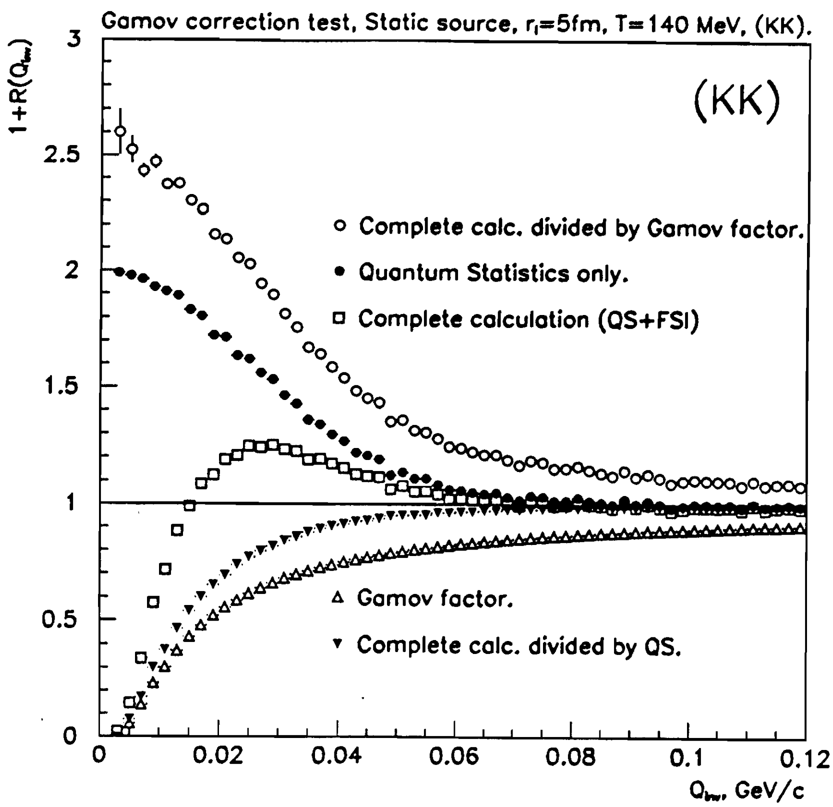


Fig. 12 Simple correction using Gamow factor cannot account for two-particle Coulomb interaction and leads to extraction of wrong parameters of fits of correlation functions (here for two kaons).

Even if the complete description of correlations is used, including a generator describing the dynamics of the reaction, a valuable comparison with the data requires that all experimental acceptance and resolution effects are taken into account.

At relativistic and ultra-relativistic energies, correlated pairs of bosons, mainly pions and kaons, are commonly used for purposes of the interferometry analysis. However, particles like protons or deuterons can also be considered as sensitive probes of space-time development of the collision. The two-proton correlation function has been measured by NA44 collaboration [17] at CERN in the reaction S+Pb at 200 GeV/u in the midrapidity region. The analysis, which is still in progress, has been performed in the frame of two different dynamical models : RQMD and VENUS. The effects of antisymetrization of the two-proton wave function as well as the final state, Coulomb and nuclear, interactions are taken into account.

RQMD is based on the propagation of all hadrons on classical trajectories in the framework of Hamiltonian constraint dynamics [18]. The model includes string and resonance excitation, a finite formation time for produced particles, rescattering of secondaries and modified dispersion relation for baryons.

VENUS (Version 5 - preliminary) introduces a completely different approach, more realistic than the string model and thermal approaches, providing a link between the two [19]. Based on the string model, one first determines connected regions of high energy density. These region are referred to as quark matter droplets which undergo a longitudinal expansion. Once the energy density falls beyond some critical energy density, the droplet decays instantenously into an n-hadron configuration.

The influence of the droplet formation mechanism on two-proton correlation function is illustrated in a schmematic way on (Fig. 13). The distribution of proton emission times is broader in the case of droplet decay. The corresponding correlation is weaker due to larger relative distances between emitted particles.

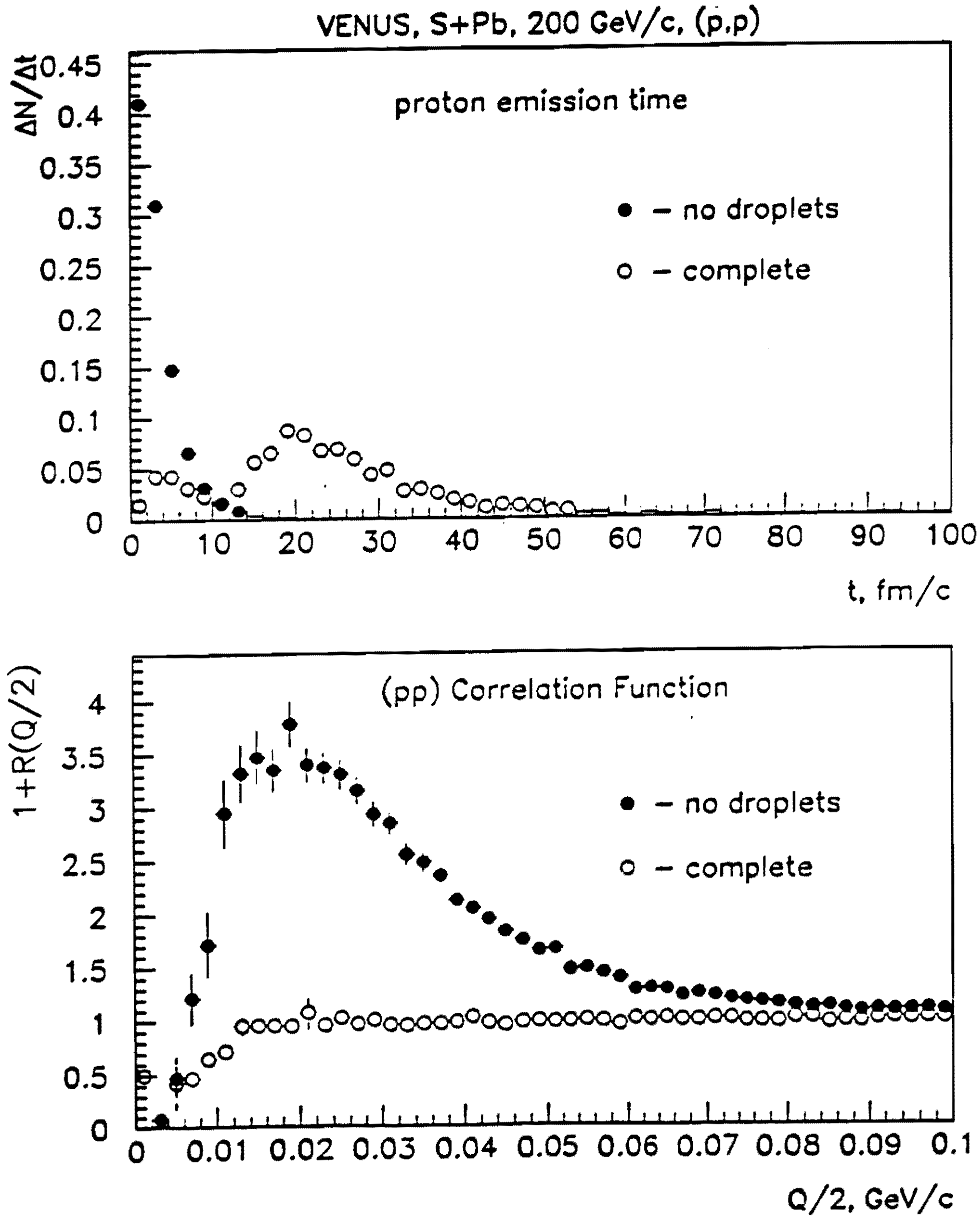


Fig. 13 Schematically illustrated influence of the droplet formation mechanism, predicted by VENUS model, on two-proton correlation function.

Both models, RQMD and VENUS predict strong momentum-position correlations of emitted particles. Even though the distributions of space-time coordinates of the freeze-out points extracted from RQMD and VENUS are different (Fig. 14) , they lead to similar dispersion of the relative distances and both models prédict the same shape for two-proton correlation function (Fig. 15). Both calculations slightly overstimate the experimate data.

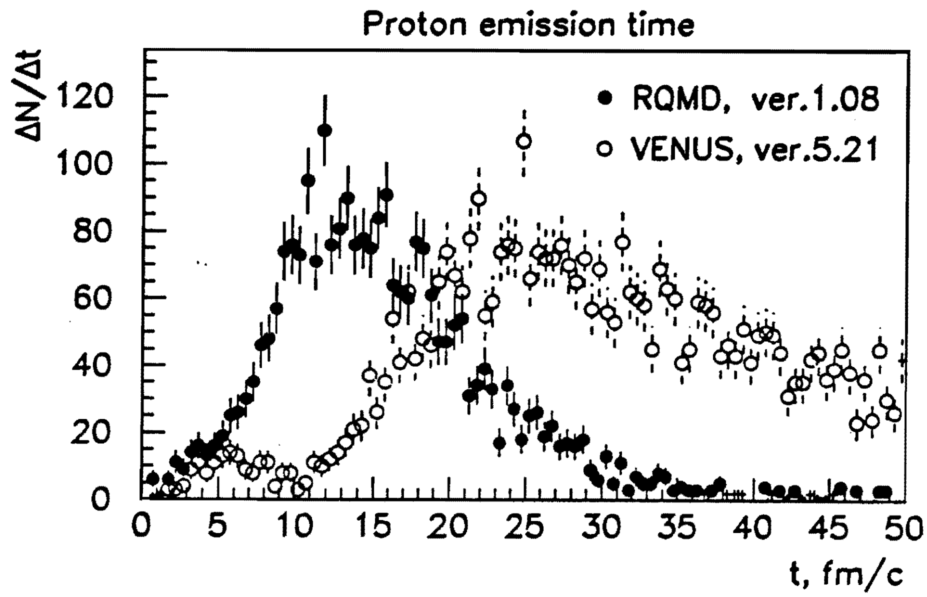


Fig. 14 Distributions of space-time coordinates of freeze-out points extracted from RQMD and VENUS.

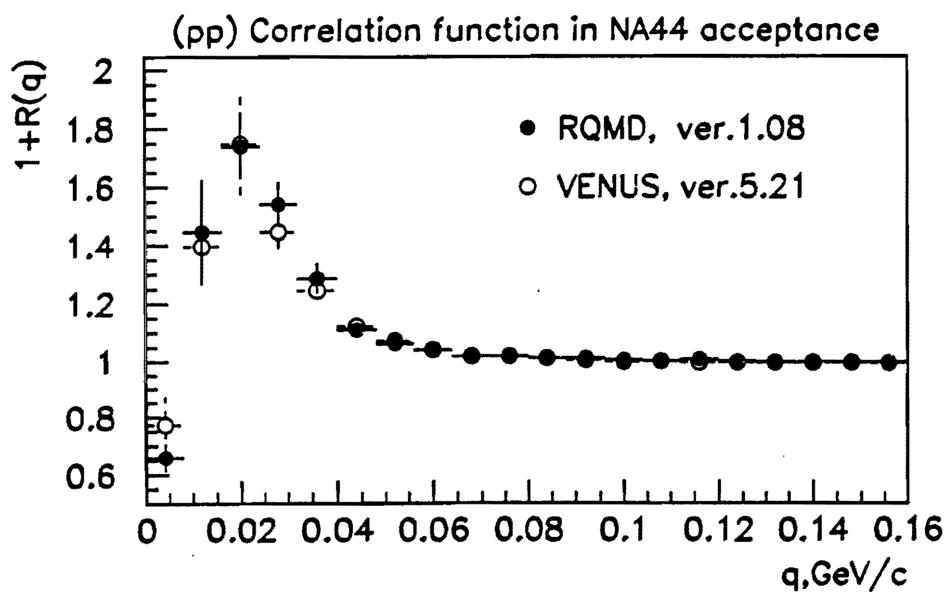


Fig. 15 Theoretical predictions, including dynamical description of collision provided by RQMD and VENUS, for two-proton correlation function measured by NA44 collaboration at CERN in the reaction S+Pb at 200 GeV/u

This preliminary result confims the characteristic feature of the identical-particle interferometry, which is sensitive only to the relative difference of space-time coordinates.

IV INTERFEROMETRY AT THE FUTURE COLLIDERS RHIC AND LHC

A new regime of very high energy density matter will be accessible in nucleus-nucleus collisions at the future colliders RHIC (Relativistic Heavy-Ion Collider) at BNL and LHC (Large Hadron Collider) at CERN. The primary aim for studying nucleus-nucleus collisions at very high energies is to understand the phase diagram of strongly interacting matter and to search for the quark-gluon plasma (Fig. 16).

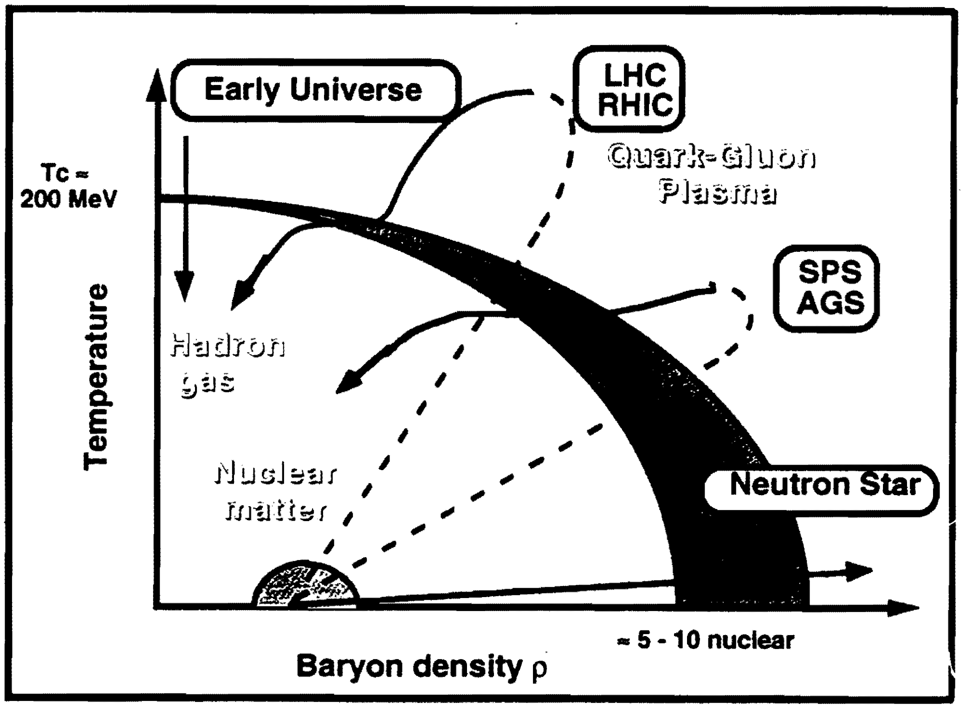


Fig. 16 Phase diagram of matter.

<u>*a) Particle correlations at RHIC.*</u>

The expected multiplicity of emitted particles will be very high : ~ $\frac{dN}{dy} \approx 1000$. At these conditions the parameters of the future detectors like acceptance, particle identification, momentum resolution and two-track resolution will determine the feasibility and quality of interferometry measurements.

The aboundance of particles produced will offert new previously unavailable possibilities. A large-solid angle detector STAR at RHIC provides the ability to investigate single-event pion interferometry. Such a measurement would allow one to get an insight to possible fluctuations and exotic phenomena.

The question whether the high particle yields will require to extent the interferometry technique to multi-particle correlations remains still open.

A review of possibilities of correlation measurements at RHIC with STAR, PHENIX, BRAHMS and PHOBOS detectors is given in Ref. [20].

b) Particle correlations at ALICE (LHC).

An extensive presentation of ALICE (A Large Ion Collider Experiment) can be found in Ref. [21]. Among many signals accessible to this detector, the correlations between identical and non-identical particles should give access to the space-time history of the heavy-ion collision. It should be emphasized that particle correlations contain information on the dynamical evolution of the emission process, such as proper time of decoupling (freeze-out), duration of particle emission and the presence of collective flows. In particular, the decoupling time and intensity of transversal flows should be closely related to QGP formation.

It should be stressed that, depending on the space-time distance between particle emission points, both Coulomb and nuclear final state interactions can significantly influence the shape of the correlation function of identical particles (e.g., they dominate in the case of two-proton correlations) and they are the main source of correlations of non-identical particles. In particular, the shape of the correlation function of two charge particles (identical or non-identical) emitted at large relative distances is mainly determined by the Coulomb interaction and is increasingly sensitive to this distance with increasing particle masses and charges, i.e. with decreasing Bohr radius of the pair.

Simulations were performed using the VENUS model (version 5.14) [19]. Although this approach is certainly not yet suited for the LHC energy region, 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 multiparticle production, including the fast longitudinal motion of the particle sources and resonance production.

- *Correlations of identical particles*

The relative importance of different effects giving rise to correlations : the quantum statistics, the strong and Coulomb interactions will be different for different particle pairs. For instance, for small source sizes, correlations of protons are dominated by the effects of final state interaction while correlations of charged identical pions are dominated by the effect of quantum statistics. It should be emphasized that for large effective source sizes, expected at LHC energies, correlations of two-protons are, due to their relatively small Bohr radius of 58 fm, stronger that those of pions and kaons. The correlation functions are only weakly affected by the expected experimental resolution effects (Fig. 17).

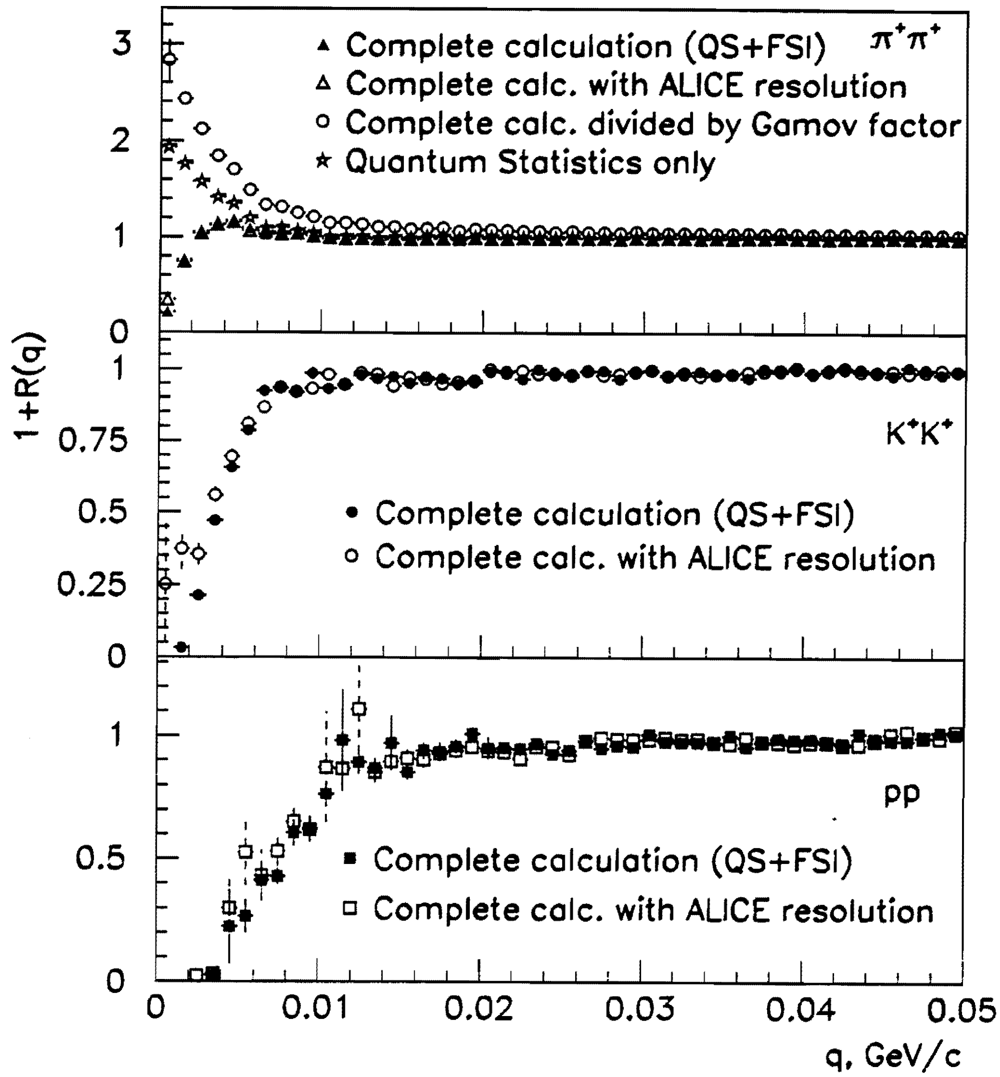


Fig. 17 Simulated correlation functions for two identical charged pions, kaons and protons without and with the effect of experimental resolution accounted for. The simulations were done using VENUS model with extended space-time freeze-out coordinates to set $\langle r \rangle = 30\,fm$ and $\langle t \rangle = 20\,fm/c$. For two pions the Gamow corrected correlation function is compared with that including the effect of quantum statistic only.

- Correlations of non-identical particles

As previously stressed, the identical particle interferometry provides important information on the *relative* space-time distances between the emission points of the particles of a given type. Under certain conditions, this relative information can be transformed to the *absolute* one, such as the decoupling proper time in the case of expansion process. Measuring the decoupling times for various particle species and assuming the unique onset time for all emission processes, we can even estimate the possible delays in the emission of different particles. 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 important complementary information to the standard interferometry measurements (see section II *c*). This opens a new possibility to determine, in a model independent way, which sort of particles $(K^+, K^-, \pi^+, \pi^-, p, \ldots)$ was emitted earlier and which later at very short time scales. This effect could be particularly 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, a delay is expected between the emission of strange and antistrange particles.

The calculations of the ratio of the correlation functions $(1+R(q))_+$ and $(1+R(q))_-$, show its sensitivity to the sign of the difference of particle emission times even if $\langle \Delta t \rangle$ is of the order of few fm/c (Figs. 18 and 19).

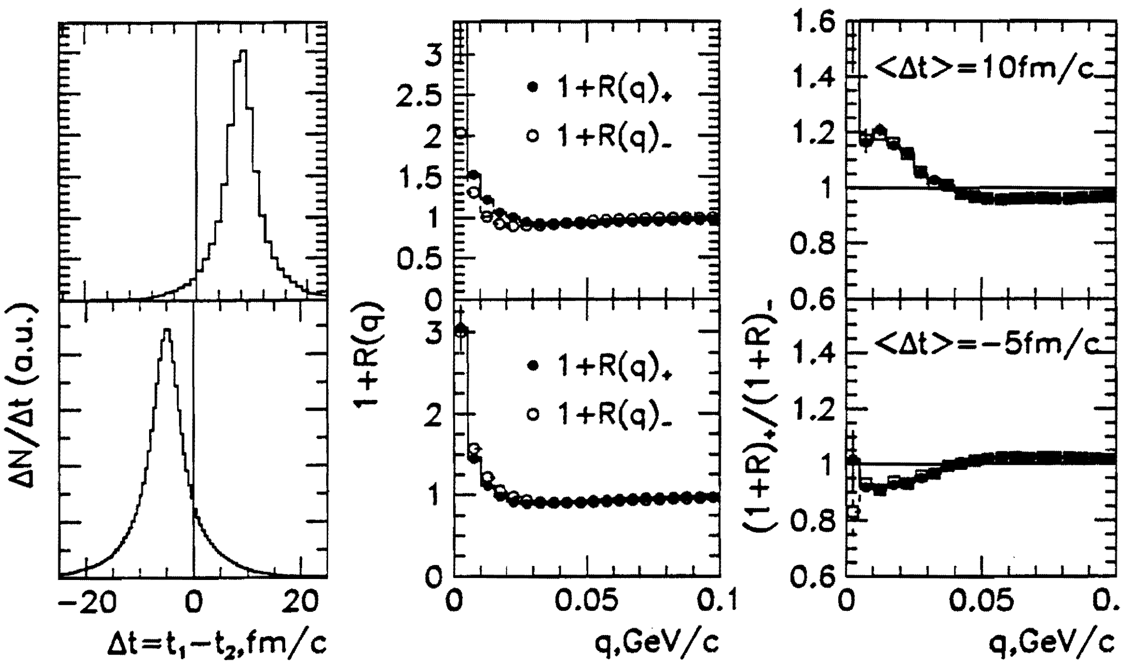
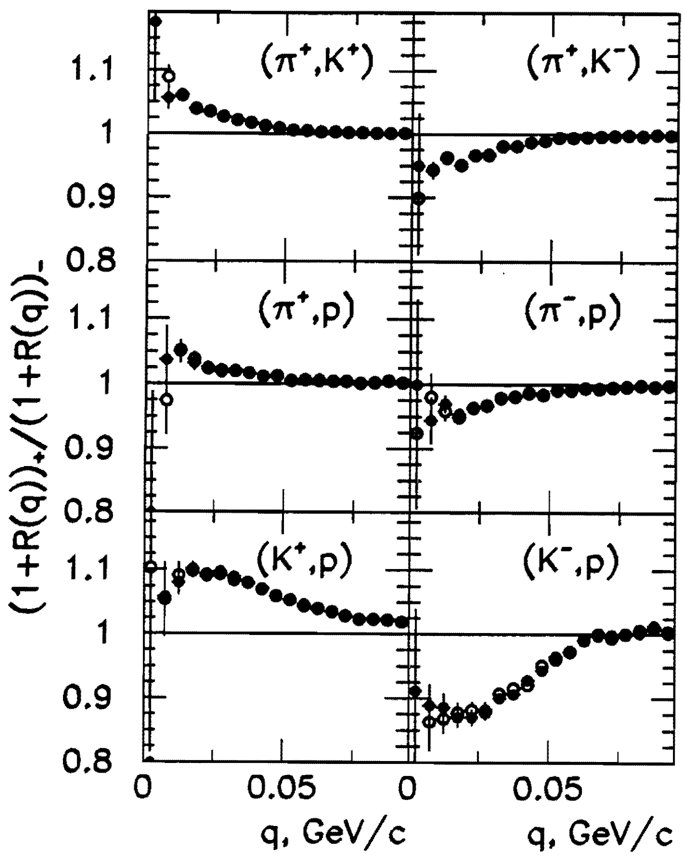


Fig. 18 The distributions of the difference of the K^+ and K^- emission times $\Delta t = t_1 - t_2$ simulated by VENUS with the shifts $\langle \Delta t \rangle = +10, -5 fm/c$ introduced ad hoc and the corresponding correlation functions $(1+R(q))_+$ (for $\vec{v}\vec{k}^* \geq 0$) and $(1+R(q))_-$ (for $\vec{v}\vec{k}^* < 0$) and their ratios calculated for K^+K^- pairs. Positive value of $\langle \Delta t \rangle$ means that K^+ are, on average, emitted after K^-. The ratios corrected for the effect of experimental resolution are represented by open symbols.



One should note that the correlation functions of the pairs $\pi^+K^+, \pi^+K^-, \pi^+p, \pi^-p$ were calculated for one simulated event only. This one-event correlations of non-identical particle will an exclusive possibility offered by the ALICE detector provided the multiplicity of emitted particles is in agreement with predictions, I.E. $\frac{dN}{dy} \approx 8000$.

Concerning the methodical problems, the correlation function of non-identical particles, contrary to the case of identical pairs, is practically not influenced by the two-track resolution.

Fig. 19 The same ratios $(1+R(q))_+/(1+R(q))_-$ as in Fig 18 calculated with $\langle \Delta t \rangle$ = -10fm/c, for different pairs of non-identical particles, taking into account (open symbols) and neglecting (full symbols) the effects of experimental resolution.

V CONCLUSIONS

The nuclear interferometry technique has reached a high level of sophistication dealing with various effects giving rise to correlations of light particles emitted at small relative velocities :

- identical particle interference
- final state interaction
- particle-emitter interaction
- interaction with other reaction products
- multi-particle correlations
- absorption
- resonance decay...

The complexity of the method reflects the complexity of nucleus-nucleus collisions. On the other hand, the strong sensitivity of the interferometry on the space-time development of nuclear reactions provides us with an universal and powerful tool suitable for the analysis of various processes in a very large energy domain.

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