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Pion Interferometry as a Probe of Time Varying Sources *

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Abstract

We discuss the way in which Bose-Einstein correlations among identical pions are affected by the presence of an explicit time dependence in the pion-source's space-time distribution. A particular functional form for this distribution has been assumed in order to compute both the longitudinal and transverse radii. In addition, the variations of these radii with the two pions center-of-mass rapidity is studied.

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1 Introduction

Pion interferometry [1]-[6] is an important tool that can be used to study the properties of the multi-hadron production in ultra-relativistic nucleus-nucleus collisions. If the sources are completely chaotic, the Bose-Einstein correlation function (BEC) among identical bosons is larger than 1 for low values of the relative momentum of the particles. The enhancement is related to the modulus squared of the Fourier transform of a function that gives the distribution of a pion source in space and time [5]. This way, we can obtain important information about the structure of the hadronization process.

These collision experiments are important because it is expected that they will allow us to attain the necessary conditions for the formation of Quark-Gluon Plasma (QGP). The reaching of this new state of matter constitutes the ultimate goal of this experimental effort. We are then compelled to investigate all the possible ways we might have to recognize the phase transition from the hadronic state to the plasma state. It is in connection with this point that pion interferometry shows its use: We may be able to detect the presence of a new dynamics through the analysis of the correlations among identical pions.

The theory of BEC is not complicated as it will soon be showed. Yet, the physical interpretation of its results stays obscure, and the meaning of the experimental data [7] unclear. Regge Field Theory shows that the longitudinal size of the sources has to be of 1 fm, while the transverse radius must be approximately equal to the radius of the smallest nucleus, [8]. Instead, experimental data of sources' radii are surprisingly large, and, most especially, they present a strong dependence on the rapidity of the particles.

The aim of this paper is to study this problem focusing in one of its aspects that has commonly been neglected [9]: The effect of the formation time on the measured radius. It turns out that this effect is not as negligible as it was first thought since it introduces significant changes on the values of the sources' apparent longitudinal radii. On the contrary, no significant effect seam to appear on the values of the transverse radii.

2 Bose-Einstein Correlations

The idea of using the Bose-Einstein symmetrization to measure the size of the emitting source has its antecedents in astrophysics. Known as Hanbury Brown-Twiss effect, it was used in that context to measure the radius of the stars. Let us briefly summarize the idea. Assume that an extended source emits bosons at points distributed over the region occupied by it. At another distant position, detectors are placed so the particles created by the source can be identified. We adopt the normalization in which the wave function of a particle of four-momentum k_a created at x_i is given by:

$$< x|k_a >_{x_i}= e^{i\, k_a(x - x_i)} \;=\; e^{i\,[k_a^0(x^0 - x_i^0) - \vec{k}_a \cdot (\vec{x} - \vec{x}_i)]} \qquad . \tag{1}$$

If we are interested in measuring the production of pairs of identical bosons, then we have to consider that the corresponding wave function has to be symmetric under the exchange of the momenta. When the points at which the bosons are emitted are distributed according to a probability density, $\varrho(x)$, the probability for detecting a pion with a momentum k_a, and another one with momentum k_b is given by,

$$P(q)\, d^4q\, d^4K = (1 + |\tilde{\varrho}(q)|^2)\, \mu(q, K)\, d^4q\, d^4K \quad . \tag{2}$$

Here $q = k_a - k_b$, $K = k_a + k_b$, and

$$\mu(q, K) \;=\; \delta[(k_a(q, K))^2 - m^2]\, \delta[(k_b(q, K))^2 - m^2] \quad , \tag{3}$$

m being the mass of each particle. Finally, $\tilde{\varrho}(q)$ is the Fourier transform of $\varrho(x)$,

$$\tilde{\varrho}(q) \;=\; \int d^4x\, e^{i\, qx}\, \varrho(x) \quad , \tag{4}$$

which has two important properties:

- Since $\varrho(x)$ is normalized to 1, $\tilde{\varrho}(0) \;=\; 1$.
- Also, $|\tilde{\varrho}(q)| \;=\; |\int d^4x\, e^{i\, qx}\, \varrho(x)| \;\leq\; \int d^4x\, |\varrho(x)| \;\leq\; 1$.

Because of the mass shell condition, the number of independent momentum variables is reduced to 6. The Bose-Einstein correlation function can be immediately obtained from eq. (2).

$$C(\vec{q}) = 1 + \frac{\displaystyle\int \frac{d^3\vec{K}}{2\,k_a^0\; 2\,k_b^0}\, |\tilde{\varrho}(\vec{q}, q^0(\vec{q}, \vec{K}))|^2}{\displaystyle\int \frac{d^3\vec{K}}{2\,k_a^0\; 2\,k_b^0}} \quad . \tag{5}$$

2.1 The Static Approximation

If we assume that the time dependence of the source is not relevant, every thing simplifies. This would correspond to the case in which pions are only emitted at the time of the collision. This can be represented by a Dirac delta function of the form $\delta(t)$. We then obtain:

$$C_{\mathrm{static}}(\vec{q}) = 1 + \frac{\displaystyle\int \frac{d^3\vec{K}}{2\,k_a^0\; 2\,k_b^0} |\tilde{\varrho}(\vec{q})|^2}{\displaystyle\int \frac{d^3\vec{K}}{2\,k_a^0\; 2\,k_b^0}} \quad . \tag{6}$$

This static approximation has been implicitly assumed throughout most of the literature on this subject. Evidently, in this case, the $\tilde{\varrho}(\vec{q})$ can be taken out of the integral and the two remaining integrals cancel out leaving the expression:

$$C_{\mathrm{static}}(\vec{q}) = 1 + |\tilde{\varrho}(\vec{q})|^2 \quad . \tag{7}$$

In situations in which the time dependence is known to be weak, this last expression provides us with a straight forward way of getting the radios of the emitting source. If a gaussian form is assumed for the distribution $\varrho(\vec{x})$,

$$\varrho(\vec{x}) = \frac{1}{2\pi R_T^2}\, e^{-\dfrac{x^2+y^2}{2\,R_T^2}}\; \frac{1}{\sqrt{2\pi R_L^2}}\, e^{-\dfrac{z^2}{2\,R_L^2}} \quad , \tag{8}$$

we will obtain a gaussian for $\tilde{\varrho}(\vec{q})$ giving a form for the correlation function:

$$C_{\text{static}}(\vec{q}) = 1 + e^{-(q_x^2 + q_y^2)R_T^2}\, e^{-q_z^2 R_L^2} \quad . \tag{9}$$

2.2 The Effect of Time Dependence

Most of the experimental analysis of BEC data have been made applying the static approximation and using expression (9) to extract the source radius. It is, nevertheless, important to explore the effect of the time dependence of the source especially if we want to have a better understanding of the data when different kinematical regions are chosen. Turning our eyes back to eq. (5), we can notice that, if a dependence on time is assumed for $\varrho(t, \vec{x})$, we will no longer be able to simplify that expression the way we did for the static case. This would correspond to the more realistic case in which hadron formation takes a certain amount of time that causes the pions be formed outside the nuclei. Resulting from the integration on $\vec{K}$ and the mass shell condition, $C(\vec{q})$ will pick up an extra dependence on $\vec{q}$. Let us assume, for the sake of simplicity, the following function:

$$\varrho(\vec{x}, t) = \frac{1}{2\pi R_T^2}\, e^{-\dfrac{x^2+y^2}{2\,R_T^2}}\, \frac{1}{\sqrt{2\pi R_L^2}}\, e^{-\dfrac{z^2}{2\,R_L^2}}\, \Gamma\, e^{-\Gamma t} \quad , \tag{10}$$

and let us define the source decay time as $T = \Gamma^{-1}$. It is easy now to obtain an expression for the correlation function:

$$C(\vec{q}) = 1 + e^{-(q_x^2 + q_y^2)R_T^2}\, e^{-q_z^2 R_L^2}\, \mathcal{D}(\vec{q}) \quad , \tag{11}$$

where we have used the following definitions,

$$\mathcal{D}(\vec{q}) = \frac{\Delta(\vec{q})}{\Omega(\vec{q})} \quad ,$$

$$\Delta(\vec{q}) = \int \frac{d^3\vec{K}}{2\,k_a^0\; 2\,k_b^0}\, \frac{\Gamma^2}{\Gamma^2 + (q^0)^2} \quad , \tag{12}$$

$$\Omega(\vec{q}) = \int \frac{d^3\vec{K}}{2\,k_a^0\; 2\,k_b^0} \quad ,$$

and

$$
\begin{aligned}
q^0 &= k_a^0 + k_b^0 \quad , \\
2\,k_a^0 &= \sqrt{\alpha - \beta\mu} \quad , \\
2\,k_b^0 &= \sqrt{\alpha + \beta\mu} \quad , \\
\alpha &= \vec{K}^2 + \vec{q}^{\,2} + 4\,m^2 \quad , \\
\beta &= 2\,|\vec{K}|\,|\vec{q}| \quad , \\
\mu &= \cos\theta = \frac{\vec{K}\vec{q}}{|\vec{K}|\,|\vec{q}|} \quad .
\end{aligned}
\tag{13}
$$

In the above equations m represents the mass of a pion. Now, it is easy to obtain the following expressions, where we will use the convention that $q = |\vec{q}|$ and $K = |\vec{K}|$,

$$
\begin{aligned}
\Delta(\vec{q}) = &\frac{\Gamma}{\sqrt{\Gamma^2 + \alpha}} \frac{2\pi}{q} \int K\, dK \left[\arctan\left(\frac{1}{\Gamma} \frac{\sqrt{\Gamma^2 + \alpha}\,\beta}{\alpha + \sqrt{\alpha^2 - \beta^2}} \right) - \right. \\
&\left. - \arctan\left(\frac{1}{\Gamma} \frac{\sqrt{\Gamma^2 + \alpha}\,\beta\mu_0}{\alpha + \sqrt{\alpha^2 - \beta^2\mu_0^2}} \right) \right] \quad ,
\end{aligned}
\tag{14}
$$

and

$$
\Omega(\vec{q}) = \frac{2\pi}{q} \int K\, dK \frac{1}{2} \left[\arcsin\left(\frac{\beta}{\alpha} \right) - \arcsin\left(\frac{\beta\mu_0}{\alpha} \right) \right] \quad . \tag{15}
$$

We have called μ_0 the smallest value of μ allowed by the kinematics of the collision. It depends on α, β, and the maximum energy available, E, in the following way:

$$
\mu_0 = \begin{cases} 0 & \text{if } \alpha < E^2 \quad , \\ \dfrac{2E}{\beta}\sqrt{\alpha - E^2} & \text{otherwise} \quad . \end{cases} \tag{16}
$$

It will be showed that this effect is weak when no attention is paid to the dependence with the different kinematical regions. This aspect of the time dependence has been studied in ref. [9], but only a quadratic approximation has been used there.

2.3 Comments

Let us discuss here some aspects of the model presented in the former subsections.

The Antsatz. We have picked the gaussian function for the space dependence of the source distribution mainly for simplicity. It is a reasonable approximation that has extensively been used in the literature. So happens with the assumption for the time dependence which has a form similar to those functions representing decay processes, very common in physics. Our point of view is that the important results should not drastically depend on the details of these distributions. This way, these functions are good enough for our purpose since they reproduce the main properties we need, i. e., $\varrho(x)$ is rapidly decreasing with time and it also decreases fast when we go far from the interaction region.

The Lorentz Transformations. Since only the static approximation has been considered most of the times, the source's radii have been assumed to behave as a common length under Lorentz transformations [7]. However, once we take into account the time dependence of the particle production this has to change. For instance, if our function $\varrho(x)$ depends only on the the space-time interval $\Delta s^2 = (t-t_0)^2 - (x-x_0)^2 - (y-y_0)^2 - (z-z_0)^2$, the parameters appearing in our model should be Lorentz scalars. This would be the case if we have assumed a time dependence of the form $e^{t^2/\sqrt{2}R_T}$ and $R_T = R_L$, which is quite an unrealistic ansatz. We can think of other simple guesses that would turn out to be physically inconsistent as, for example,

$$\varrho(x) \propto e^{\pm(\frac{t}{R_t} - \frac{x}{R_x} - \frac{y}{R_y} - \frac{z}{R_z})} \tag{17}$$

in which case $(1/R_t, 1/R_x, 1/R_y, 1/R_z)$ would behave as the components of a four-vector. But, clearly this assumption is not valid because the behavior of the function either with time or with the spatial components is the opposite of the one we would expect. Summarizing the idea of this paragraph, it cannot generally be assumed that the radii measured with the help of BEC has a definite and simple way of transforming under a Lorentz boost. Only if, for some reason, we can make the assumption that time dependence is negligible before and after the boost, the radii will vary as a length.

3 Rapidity Dependence

This section is devoted to study the dependence of the sources' radii with the rapidity of the produced particles. At this point we have to make a choice and define the way in which we are going to characterize the different kinematical regions. We will pick as our independent variable the rapidity of the center of mass of the system formed by the two pions, y. We then have the following relation:

$$K_L = K_0 \tanh y = K_0 h \quad . \tag{18}$$

Once we fix the value of y, we have one free momentum variable less. So, for a given value of $\vec{K}_T$ the value of K_L is given by the condition

$$4K_L^4 + h^2 \frac{h^2c^2 - 4a}{1-h^2} K_L^2 + 2\frac{h^4 cb}{1-h^2} K_L + \frac{h^4 b^2}{1-h^2} = 0 \quad , \tag{19}$$

where we have used the following definitions,

$$a = q^2 + K_L^2 + 4m^2 \quad ,$$

$$b = 2\vec{K}_T \cdot \vec{q}_T \quad , \tag{20}$$

$$c = 2q_L = 2|\vec{q}_L| \quad .$$

Analytic solution for eq. 19 can be found, however, they are so complicated that it is much easier to solve it numerically.

We can now proceed as we did in the former section and calculate an expression for the BEC for a given value of y. Let us define the functions:

$$d(\vec{q}, y) = \frac{\delta(\vec{q}, y)}{\omega(\vec{q}, y)} \quad ,$$

$$\delta(\vec{q}, y) = \int \frac{d^2\vec{K}_T}{2\,k_a^0\,2\,k_b^0} \frac{\Gamma^2}{\Gamma^2 + (q^0)^2} \quad , \tag{21}$$

$$\omega(\vec{q}, y) = \int \frac{d^2\vec{K}_T}{2\,k_a^0\,2\,k_b^0} \quad ,$$

where the definitions (13) have been used. So, the correlation function now is:

$$c(\vec{q}, y) = 1 + e^{-(q_x^2 + q_y^2)R_T^2}\, e^{-q_z^2 R_L^2}\, d(\vec{q}, y) \quad , \tag{22}$$

As it must seem clear, the computation of these functions is more complicated than in the case of no rapidity dependence since we cannot perform any analytic integration. Therefore, all the calculation has to be performed numerically.

4 Results

To discuss our results, we need to pick a definition of sources' effective radius. This is going to be the parameter that will measure the spatial extension of the region where the hadrons are originated. Our definition of radius has to be such that it will coincide with the radius of the gaussian functions in the static limit. This way, we can compare our results with what it is expected if the static approximation is applied. Besides, we want to keep the definition simple and easy to relate to the physics of the problem.

Let's define them as follows:

$$R_{\mathrm{L(eff.)}} = \sqrt{\frac{I_0}{2I_{2L}}} \quad ,$$

$$R_{\mathrm{T(eff.)}} = \sqrt{\frac{I_0}{2I_{2T}}} \quad . \tag{23}$$

Here, we have used the following notation,

$$I_0 = \int_0^\infty dq_L \int_0^\infty dq_T \, [C(\vec{q}) - 1] \quad ,$$

$$I_{2L(T)} = \int_0^\infty dq_L \int_0^\infty dq_T \, q_{L(T)}^2 \, [C(\vec{q}) - 1] \quad . \tag{24}$$

Clearly, these definitions have the feature we wanted: The radii so defined are equal to R_L and R_T respectively, which have been introduced earlier, when $\mathcal{D}(\vec{q}) = 1$, what corresponds to the static limit. Also, this represents well the extension of the source, since it can be interpreted as the incertitude in the relative location of the position of the hadron emitting points. In a wide sense, the inverse of the radius can be taken as to measure of the dispersion of the relative momentum in either the longitudinal or the transverse directions respectively.

We'll divide the results into two parts.

4.1 Total Phase-Space

Figure 1 shows the increment ($R_{\mathrm{L(eff.)}} - R_L$ and $R_{\mathrm{T(eff.)}} - R_T$) of the source radius as a function of the formation time T for two different initial values of $R_{L(T)}$. In this case in which no kinematical cut is made, the correlation function only depends on $|\vec{q}|$;

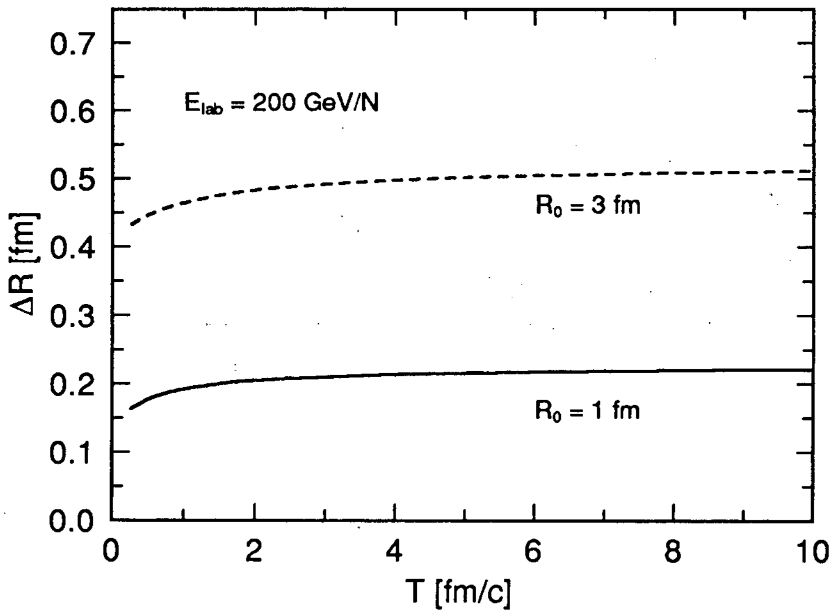

Figure 1: Increase of the value of the source's radius as a function of the decay time T for two values of the initial radius R_0.

then, the only difference among longitudinal and transverse are due to the original value assigned to R_L and R_T. This is the reason we have dropped the subindices L and T in the figure. We have picked the values of 1 and 3 fm based on the results presented in [8]. According to them, the longitudinal radius must be around 1 fm independently of the size of colliding nuclei; the transverse radius, on the other hand, has to be given by the radius of the smallest nuclei. The current experiments are focusing on the study of BEC in ^{16}O + Au collisions [7] at laboratory energies of 200 GeV per nucleon. It then seems convenient to use the transverse radius of the oxygen (aprox. 3 fm) as our initial transverse radius; we'll comment more on this latter in this section. As can be seen, the increase of the radius is of the order of 16 to 20 per cent for physically sensible values of T, i. e. $T \approx$ 1fm. We can see that this effect is not very important once we take into account that the initial values for the radii are not fixed with great accuracy. An incertitude in the value of the initial radii of the order of the computed increase can be expected. Finally, a more pronounced increase of ΔR with T is found when other definitions of the radius are used, but there is no significant difference in the values obtained for the physical region of $T \approx$ 1fm.

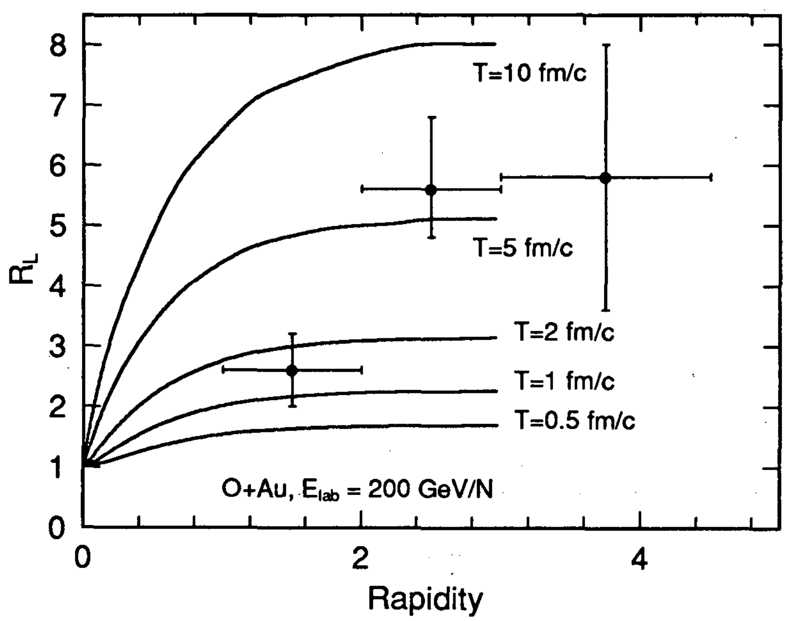

Figure 2: Longitudinal radius versus pion-pion center of mass rapidity for different values of the decay time.

4.2 Rapidity Dependence

When we discuss the dependence on the rapidity, the definition of the effective radii can be made simpler. This is so because we now have a clear distinction between the longitudinal and transverse direction. Let's write the definition for the longitudinal radius being the corresponding one for the transverse radius trivially similar.

$$R_{\mathrm{L(eff.)}}(y) = \sqrt{\frac{i_0(y)}{2 i_{2L}(y)}} \quad , \tag{25}$$

with

$$\begin{aligned} i_0(y) &= \int [c(q_L, q_T = 0, y) - 1] \, dq_L \quad , \\ i_{2L}(y) &= \int q_L^2 [c(q_L, q_T = 0, y) - 1] \, dq_L \quad . \end{aligned} \tag{26}$$

Fig. 2 shows the results obtained for $T = 0.5$, 1, 2, 5 and 10 fm/c, and $R_{L0} = 1\,\mathrm{fm}$. The experimental points are from ref. [7]. These points are not meant to be compare with the results since they don't refer to the same physical quantity. They represent the longitudinal radius of hadron sources defined as the values of R_L (R_T in the case of

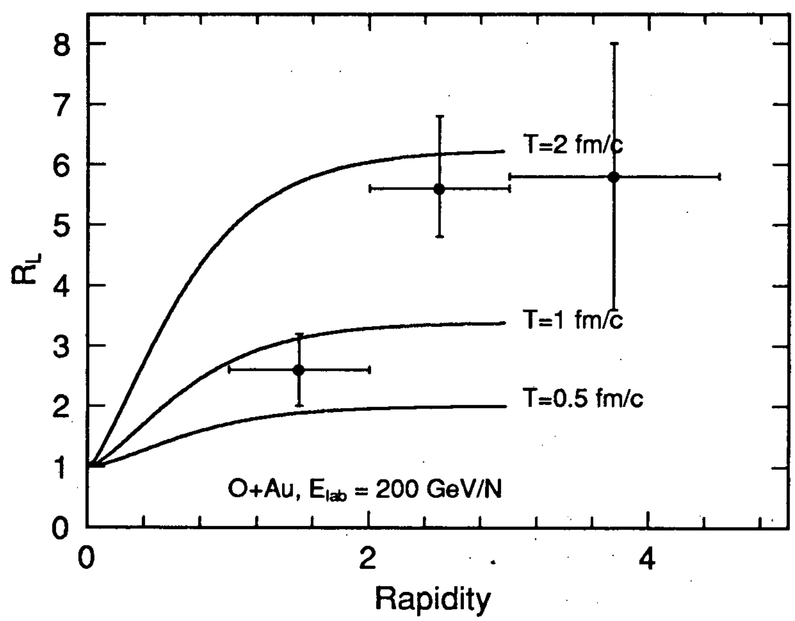

Figure 3: Longitudinal gaussian radius versus pion-pion center of mass rapidity for three different values of the decay time.

the transverse radius) that best fit the data with a function of the form (8) for different rapidity bins. These experimental points can serve to give us a feeling of the order of magnitude and the overall behavior of these quantities. Our results show a 100% increase of the longitudinal radius for $T = 1\,\mathrm{fm}$. The effect is large enough to be observed in the experiments and must be present in the data. Curves for larger values of T show a much important increase. It may look as if we need to assume very large values of T to obtain a result in the range of the experimental points for rapidities higher than

2. Nevertheless, there is a some thing tricky here. If we compute the values for the radii that we would obtain as the parameters of the gaussian functions that best fit the data (gaussian radius) in the sense commented above, for fixed values of T, we obtain the results showed in fig. 3. As we can see, in this latest case, the increase of the radius with the rapidity is much more important, and a result closer to the range of the experimental points is seen for $T = 1\,\text{fm}$. This brings up the fact that numerical results depend strongly upon the definition being used, though the qualitative behavior seems to remain independent.

The effect on the effective transverse radii is quite different. Fig. 4 shows the transverse radius as a function of the rapidity for $R_{T0} = 3\text{fm}$ and different values of T. An increase of the value of R_T is only observed in the low rapidity range. Also plotted are experimental points from ref. [7]; the same comments made for the longitudinal radius data are in order here. We can see that not even for very unrealistic values of T we can obtain any thing close to the observed increase in the mid rapidity bin. Nonetheless, the point at $2 < y < 3$ corresponds to a very large value of the radius that doesn't fit into any theoretical framework. This puzzle has been extensively debated, see for instance the discussion in reference [8]. Also in this reference, arguments are given to justify an initial transverse radius of 4 fm instead of 3 fm, the 1 fm extra being a consequence of the nucleons spatial extension. In this case, we would trivially obtain for $T = 1\text{fm/c}$ a result more consistent with the data if the point mentioned above is ignored. To summarize this paragraph we can say that no exciting effect on the transverse radius is found.

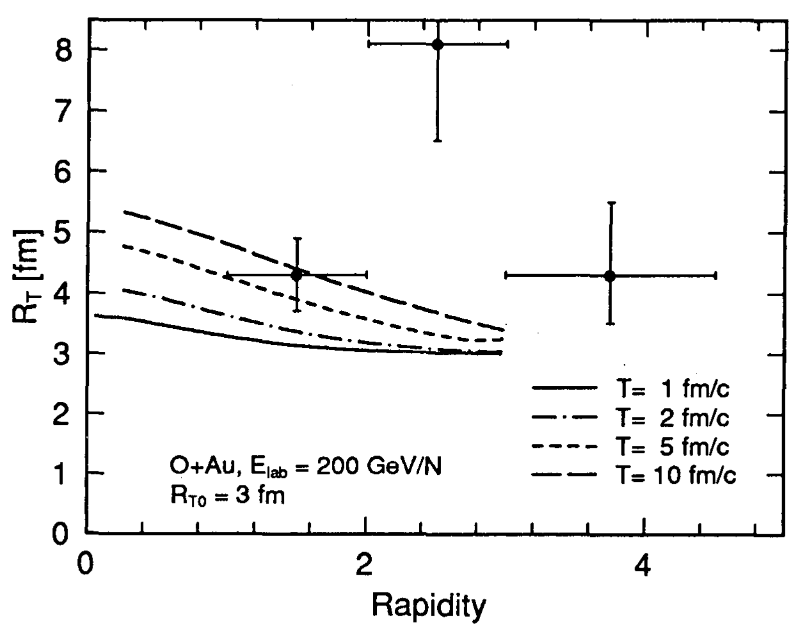

Figure 4: Traverse radius versus pion-pion center of mass rapidity for different values of the decay time.

5 Summary and Conclusions

We have discussed the effect that the time dependence of the one pion-source distribution has on the apparent extension of the hadronization region. A simple model has been used in order to obtain numerical results shown here. The parameter that fixes the rime scale in this model is the decay time T. We have also focus our attention onto the way in which the shape of that distribution depends on the two pions center of mass rapidity.

To present the results, we have chosen a definition of source's radius. This point turned out to be very important because great discrepancies are observed when different definitions are used.

The variation of the source radius caused by a value of $T \neq 0$ is not very important if we don't make any cut in the phase space. Although there is a nearly 20 % effect for $T = 1$ fm/c, this fall into the incertitude of the parameters of the model.

When we look into the dependence of the effect on the CM rapidity, two important results have been obtained:

- The variation of the effective longitudinal radius with the rapidity is important at low y. For larger y's it is nearly constant and about the double of its original value. This increase is more pronounced for larger T. Finally, if the radii are obtained by approximating the correlation function to a form like eq. (8), the results give a significantly greater growth of the radius. This stresses the importance of taking good care of the way in which the extension of the source is measured.

- The transverse radius appears to be sensible to the effect of the time dependence only for low values of y. The increase of the radius is not very important for physical values of T and reaches zero for larger y's.

The physics behind this effect is not complicated. The computed variations of the radii are caused by relativistic effects on both times and lengths plus kinematical constraints on the system: The locations of the source refers to the point at which pions reach their asymptotic state. The existence of a decay time implies that the distance between the positions of hose points will be larger. This is due to the fact that before reaching the asymptotic state the one pion centers of mass are moving. Any dilatation of T will make that distance grow. This mechanism seems to dominate all others and is bounded by the kinematical limits of the experiment. This explains the behaviour of the longitudinal radius as a function of y. It also counts for what happens to the transverse radius since it is at low y where larger values of p_T are allowed by the kinematics of the problem, and then more effect is seen in the transverse plane. However, since the model used in this paper does not include any dynamics in does not mean that those large p_T values allowed by the kinematics are really present in the experiments. This leads us to the conclusion that the small effect seen on the the transverse radius might well be physically meaningless.

We can then say that the increase of the longitudinal radius with the rapidity is a consequence of the fact that hadrons are particles with an structure and can not be created instantaneously. Therefore, it would be worth testing these ideas looking at what happens in the case of bosons without structure, photons for instance, produced in similar experiments.

Finally, we want to point to the fact that no mention has been made to the problem of the chaoticity parameter, λ (see ref. [10]). This problem seems to be independent of the one treated here. Our formalism is insensitive to the introduction of a value of $\lambda < 1$, the definition of radius involves a kind of normalization of the function $C(\vec{q}) - 1$ that would cancel λ.

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