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Source Parameters from Particle Correlations and Spectra in S + Pb Reactions at CERN SPS

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Abstract Analytic and numerical approximations to a hydrodynamical model describing longitudinally expanding, cylindrically symmetric, finite systems are fitted to NA44 data measured in 200 AGeV central $S + Pb$ reactions. The model describes the measured spectra and HBT radii of pions, kaons and protons, simultaneously. The source is characterized by a central freeze-out temperature of $T_0 = 154 \pm 8 \pm 11$ MeV, a "surface" temperature of $T_r = 107 \pm 19$ MeV and by a well-developed transverse flow, $\langle u_t \rangle = 0.53 \pm 0.12$. The transverse geometrical radius and the mean freeze-out time are found to be $R_G = 5.4 \pm 0.9 \pm 0.7$ fm and $\tau_0 = 5.1 \pm 0.3 \pm 0.3$ fm/c, respectively. The absolute normalization of the measured particle spectra together with the experimental determination of both the statistical and the systematic errors were needed to obtain a successful fit.

1 Introduction

The reconstruction of the space-time picture of particle emission in high energy heavy ion and particle physics became a focal point of current research interest. In high energy heavy ion physics, the space-time information on particle production is needed to determine the volume of hot hadronic matter at freeze-out [1] while in particle physics Bose-Einstein correlations of pions from different decaying W mesons may result in large contribution to the systematic errors of W-mass measurements at LEP II [2], a major problem in forthcoming precision determination of W mass.

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In this paper, we attempt to reconstruct the space-time picture of high energy heavy ion reactions by checking whether the hydrodynamical model of ref. [3] is able to fit the final NA44 data on two-particle correlations and single-particle spectra at S + Pb 200 AGeV central reactions at CERN SPS. This model of ref. [3] corresponds to a class of longitudinally expanding, cylindrically symmetric, finite systems, where the local rest density distribution, the local inverse temperature distribution and the freeze-out proper-time distribution is characterized by their means and variances, respectively. A scaling longitudinal flow field is assumed together with a linear transverse flow profile. As a consequence of the cylindrical symmetry of the model, a $1/\sqrt{m_t}$ scaling of the HBT radius parameters was predicted in certain limiting regions of the parameter space [3, 4]. Such a scaling is difficult to obtain in other type of models, however, the scaling law is satisfied by not only the NA44 data on S+Pb reactions [5] but also by the NA22 data on hadron-proton interactions at CERN SPS [6] and, to some extent, by preliminary $e^+ + e^-$ annihilation data in two-jet events at LEP-I [7]. The $1/\sqrt{m_t}$ scaling in the model is connected to the appearance of large geometrical source sizes or large inhomogeneities in the transverse temperature and/or flow distributions. In ref. [8, 3] it was observed, that the source parameters can, in general, be determined precisely only if a simultaneous analysis of the particle spectra and the correlation functions is performed.

In ref. [3], the form of the particle spectra and that of the correlation functions were evaluated analytically for the hydrodynamical model. The domain of applicability of the analytical approximations is determined numerically in ref. [9]. In ref. [10], the model was shown to describe the single-particle spectra and the two-particle correlations at $(\pi/K) + p$ reactions at CERN SPS simultaneously, in a statistically acceptable manner. In addition, the model was tested in refs. [4, 14] against the *preliminary* NA44 data on $S + Pb$ reactions at CERN SPS, however, it was difficult to find unique, reliable values of the fit parameters, due to the lack of full error estimate on the single-particle data, lack of absolute normalization of the particle spectra and lack of data on proton spectra.

Note, that the two-particle correlation data for this reaction are published in ref. [5]. The final NA44 single-particle spectra are obtained from the experiment now as a private communication [15]. Should the single-particle spectra in $S + Pb$ reaction be published by NA44, this would become the first data set where both the particle correlations and the single-particle spectra are published in refereed journals in ion-ion reactions at CERN SPS. We know from earlier fitting the model to spectra without absolute normalization [14], that the final results are rather sensitive to errors and normalizations, and we are aware of the fact that preliminary data may (and frequently do) change before final publication.

Note also that the hydrodynamical model is applicable only to the central finite core of the particle emitting source. A factor of experimentally determined $1/\sqrt{\lambda(y, m_t)}$ is taken into account [5] when fitting the absolutely normalized spectra in case of pions and kaons. We assume that at the center of the fireball, the pions and the kaons both have a vanishing chemical potential. The central chemical potential is not determined for protons, since the protons are present in the incoming beam and at CERN SPS their finite state is characterized by a non-vanishing baryo-chemical potential. This chemical potential together with the unknown long-lived resonance contribution to the proton spectra results in a freedom to fit the normalization constant of these spectra to data.

In section two the basics of the hydrodynamical model are briefly summarized along with the indroduction of some physical parameters. Results of data fitting to analytical and numerical approximations are presented in section three. In the discussion section comparisons are made to other results obtained in a similar manner. We draw conlusions on the achievements in the last section.

2 The model and its re-parameterization

The model of ref. [3] is briefly recapitulated below. In connection with data fitting, analytic approximations are also sketched in this section. For later conclusions, we re-express the fitted dimensionless model parameters with quantities of more direct physical meaning.

2.1 *The model*

According to the ref. [3] the model makes difference between the central (core) and the outskirts (halo) regions of the collided matter. The following emission function $S_c(x,p)$ applies to a hydrodynamically evolving three dimensionally expanding, cylindrically symmetric finite system:

$$S_c(x,p)\, d^4x \quad = \quad \frac{g}{(2\pi)^3} \frac{d^4\Sigma^\mu(x)p_\mu}{\exp\left(\dfrac{u^\mu(x)p_\mu}{T(x)} - \dfrac{\mu(x)}{T(x)}\right) - 1}\ , \tag{1}$$

where the subscript $_c$ refers to the core, the factor $d^4\Sigma^\mu(x)p_\mu$ describes the flux of particles through a finite, narrow layer of freeze-out hypersurfaces. It is assumed that any of the layers can be labelled by a unique value of $\tau = \sqrt{t^2 - z^2}$, and the random variable τ is characterized by a probability distribution, such that

$$d^4\Sigma^\mu(x)p_\mu \quad = \quad m_t \cosh[\eta - y]\, H(\tau)d\tau\, \tau_0 d\eta\, dr_x\, dr_y\ , \tag{2}$$

Here $m_t = \sqrt{m^2 + p_x^2 + p_y^2}$ stands for the transverse mass, the rapidity y and the space-time rapidity η are defined as $y = 0.5\log\left[(E+p_z)/(E-p_z)\right]$ and $\eta = 0.5\log\left[(t+z)/(t-z)\right]$ and the duration of particle emission is characterized by $H(\tau) \propto \exp(-(\tau-\tau_0)^2/(2\Delta\tau^2))$. Here τ_0 is the mean emission time, $\Delta\tau$ is the duration of the emission in (proper) time. The four-velocity and the local temperature and density profile of the expanding matter is given by

$$u^\mu(x) = \left(\cosh[\eta]\cosh[\eta_t],\, \sinh[\eta_t]\frac{r_x}{r_t},\, \sinh[\eta_t]\frac{r_y}{r_t},\, \sinh[\eta]\cosh[\eta_t]\right), \quad (3)$$

$$\sinh[\eta_t] = b\frac{r_t}{\tau_0}, \qquad r_t = \sqrt{r_x^2 + r_y^2}. \quad (4)$$

The inverse temperature profile is characterized by the central value and its variance in transverse and temporal direction, and we assume a Gaussian shape of the local density distribution:

$$\frac{1}{T(x)} = \frac{1}{T_0}\left(1 + a^2\,\frac{r_t^2}{2\tau_0^2}\right)\left(1 + d^2\,\frac{(\tau-\tau_0)^2}{2\tau_0^2}\right), \quad (5)$$

$$\frac{\mu(x)}{T(x)} = \frac{\mu_0}{T_0} - \frac{r_x^2 + r_y^2}{2R_G^2} - \frac{(\eta - y_0)^2}{2\Delta\eta^2}, \quad (6)$$

where $\mu(x)$ is the chemical potential and $T(x)$ is the local temperature characterizing the particle emission. Note that the strength of the transverse changes of the temperature profile, the gradient of the transverse flow and the strength of the temporal changes of the temperature profile are controlled by the dimensionless parameters a, b and d, respectively.

2.2 *Analytic approximations*

In Ref. [3], the Boltzmann approximation to the above emission function was evaluated in an analytical manner, applying approximations around the saddle point of the emission function. The resulting formulas express the Invariant Momentum Distribution (IMD) and the Bose-Einstein correlation function (BECF) in an analytic way. The resulting analytical formulas are given in refs. [3, 4, 9, 10] and shall not be recapitulated herewith. This Boltzmann approximation was also applied to the numerical approximate evaluation of the model, as given in the next section.

2.3 *Core/halo correction*

The effective intercept parameter $\lambda_*(y, m_t)$ of the Bose-Einstein correlation function controls the core ratio in the particle production in the core/halo picture developed in refs. [11, 12, 13]. With this factor the total invariant spectrum in y rapidity and transverse mass m_t follows as

$$\frac{d^2 n}{dy\, dm_t^2} = \frac{1}{\sqrt{\lambda_*}}\frac{d^2 n_c}{dy\, dm_t^2} = \frac{1}{\pi\sqrt{\lambda_*}}\int S_c(x,p)\, d^4x, \quad (7)$$

The momentum dependence of λ_* parameter was mesured by NA44 in ref. [5], although with a very limited momentum resolution.

2.4 *Re-parameterization*

We introduce the surface temperature $T_r = T(r_x = r_y = R_G, \tau = \tau_0)$ and the temperature after most of the particles were emitted as $T_t = T(r_x = r_y = 0; \tau = \tau_0 + \sqrt{2}\Delta\tau)$. Here R_G stands for the the transverse geometrical radius of the source, τ_0 denotes the mean freeze-out time, $\Delta\tau$ is the duration of the particle emission and we denote the temperature field by $T(x)$. The central temperature at mean freeze-out time is denoted by $T_0 = T(r_x = r_y = 0; \tau = \tau_0)$.

Then the relative transverse and temporal temperature decrease can be introduced as

$$\langle \frac{\Delta T}{T} \rangle_r = \frac{T_0 - T_r}{T_r} \tag{8}$$

$$\langle \frac{\Delta T}{T} \rangle_t = \frac{T_0 - T_t}{T_t} \tag{9}$$

and it is worthwhile to introduce the mean transverse flow as the transverse flow at the geometrical radius as

$$\langle u_t \rangle = b \, \frac{R_G}{\tau_0} \tag{10}$$

The original version of the model contains 3 dimensionless parameters, a, b and d, which control the transverse decrease of the temperature field, the strength of the (linear) transverse flow profile and the temporal changes of the temperature field, respectively, keeping only the mean and the variances of the inverse temperature distributions. These are very useful in obtaining simple formulas, however, they make the interpretation of the fit results less transparent. Hence we re-express them with the physical parameters introduced above as

$$a^2 = \frac{\tau_0^2}{R_G^2} \, \langle \frac{\Delta T}{T} \rangle_r \tag{11}$$

$$b = \frac{\tau_0}{R_G} \, \langle u_t \rangle \tag{12}$$

$$d^2 = \frac{\tau_0^2}{\Delta\tau^2} \, \langle \frac{\Delta T}{T} \rangle_t \tag{13}$$

3 Fitting the model to NA44 data

The model has been tested in two different ways using the analytical approximation referenced above and the numerical approximation that is based on a numerical integration of the emission function. The kinematic parameters are fitted simultaneously both to the IMD and the HBT radii measured by the CERN NA44 experiment in central $S + Pb$ collisions at 200 AGeV.

As emphasized previously, absolutely normalized data were utilized in these fits, which were performed with the help of the CERN function minimization package MINUIT. Moreover, core/halo correction $\propto 1/\sqrt{\lambda_*}$ is applied and the corresponding errors are propagated properly. Due to the these conditions a unique minimum is found, and the strongly coupled, normalization sensitive d and $\Delta\tau$ parameters are well determined. In contrast, if the data are fitted without absolute normalization, we reproduce the results in ref. [14] and we obtain big errors on these parameters. If we evaluate the surface temperature, we reproduce the preliminary and unusually low value of the local temperature as was also given in ref. [4] where temperature inhomogeneities were not included in the fitting.

In ref. [9] we have determined the domain of validity of this approximations for 10-20 % relative errors. We have checked at each data point whether we are in the domain of this precision for the best fitted values of the parameters. We found that we are within this domain except the very low p_t pion data points below $p_t = 70$ MeV. These data points represent 3 % of the fitted data sample. We thus expect that the systematic errors on the parameters will be of the order of 10 - 20 %.

The resulting source parameter values are summarized in Table 1. In Table 2, the goodnesses of the fits are presented for different sub-samples of the data. The analytic and numeric results are combined in Table 3 to estimate the model parameters and their errors properly (see Discussion section). On Figure 1, the analytic and numeric fits to measured data are shown simultaneously.

3.1 *On the numerical approximation scheme*

Instead of performing the Fourier transformation we evaluate the means and the variances of the core as suggested in ref. [16]. Possible double-Gaussian structures or non-Gaussian features are neglected in this approximation. The analytic approximation yields Gaussian functions in proper time τ and space-time rapidity η, hence includes deviation from Gaussian shape in t and z. The numerical approximation assumes Gaussian forms in t and z that is not so well suited to the kinematics of ultra-relativistic reactions as Gaussians in τ and η.

Since this numerical approximation scheme is not an exact calculation, but an approximation in a different way than the analytic approach, we use it to estimate the systematic errors of the model parameters and to cross-check the uniqueness of the minimum that we find. The poorly determined momentum dependent $\lambda(y, m_t)$ parameter may yield further systematic errors in both the numerical and the analytical approximations.

4 Discussion

A comparision between the numerical and the analytical approximation schemes indicates that the minima found by the two rather different fitting methods coincide within 2 standard deviations for each parameter of the model. To estimate the systematic errors half of the difference between the minima of the two fits is evaluated for each parameter. To estimate the best values of the fit parameters, the mean of the analytic and numerical minima is taken. To estimate the errors on these values, the statistical error equals to the bigger of statistical error of the numerical and the analytical fits, the systematical error is defined as above. The results are shown on Table 3. Note that we obtain similar values for the statistical and for the systematic errors of the parameters.

The parameters a, b and d are transformed to the corresponding relative transverse temperature decrease, the mean transverse flow and the relative temporal temperature decrease on Table 4.

4.1 *The Source of particles in space-time*

On Figures 2 and 3 we indicate the reconstructed space-time distribution of the source of particles in 200 AGeV central $S + Pb$ reactions, as a function of the time variable t and the coordinate along the beam direction, z, both measured in the mid-rapidity frame that moves in the laboratory with $y_0 = 3.0$. The momentum-integrated emission function at $r_x = r_y = 0$ is given by

$$S_c(t, z) \propto \exp\left(-\frac{(\tau - \tau_0)^2}{2\Delta\tau^2}\right) \exp\left(-\frac{(\eta - y_0)^2}{2\Delta\eta^2}\right) \tag{14}$$

where the parameters are taken from Table 3, corresponding to the best fit to NA44 $S + Pb$ data in this picture. Note the relation $(t, z) = (\tau\cosh(\eta), \tau\sinh(\eta))$. The contour-plot of $S_c(t, z)$ on Figure 2 shows that the with of particle emission is found to be narrow in proper-time. The parametric plot of $S_c(t, z)$ on Figure 3 indicates the long tails of particle production in the $|z| \approx t$ regions, the height of the curve is proportional to the production probability.

Note that in our case the hypothesis that pions, kaons and protons are emitted from the same hydrodynamical source is in a good agreement with the fitted data. The hypothesis that pion and kaons are emitted from different sources was investigated in ref. [14], and this hypothesis resulted in a worse description of the data than the hypothesis that the pions and kaons are produced from the same source.

4.2 *Comparision to hadron - proton reactions at CERN SPS*

The NA22 collaboration fitted the same model to 250 GeV meson + p data [6]. Their best fit parameter values were $\Delta\eta = 1.36 \pm 0.02$, $T_0 = 140 \pm 3$ MeV, $\langle u_t \rangle = 0.20 \pm 0.07$ and $\langle \frac{\Delta T}{T} \rangle_r = 0.71 \pm 0.14$. From a combined HBT and spectrum analysis the NA22 experiment finds a mean freeze-out time of $\tau_0 = 1.4 \pm 0.1$ fm/c, and a comparable duration parameter $\Delta\tau \geq \Delta\tau_* = 1.3 \pm 0.3$ fm/c. The transverse geometrical radius was found to be $R_G = 0.88 \pm 0.13 fm$, which is slightly larger than the corresponding Gaussian radius parameter of the proton.

When comparing the source parameters of $S + Pb$ reactions to $h + p$ we find that the freeze-out temperature at the mean emission time at the center is similar in both cases. The surface temperatures are also equal within errors (82 ± 7 MeV vs. 107 ± 19 MeV). The width of the particle emission in spacetime-rapidity η is also similar, 1.36 ± 0.02 vs. $1.6 \pm 0.3 \pm 0.3$. However, we find a significantly larger mean freeze-out time in $S + Pb$ reactions as compared to $h + p$ reactions ($5.1 \pm 0.3 \pm 0.3$ fm/c vs. 1.4 ± 0.1 fm/c). It seems that we observe a sharper freeze-out hypersurface in heavy ion collisions than in hadron-proton reactions, cf. $\Delta\tau = 0.3 \pm 0.3 \pm 0.3$ vs. $\Delta\tau \geq 1.3 \pm 0.3$ fm/c. The transversal radius of the matter is also larger in $S + Pb$ reactions, $5.4 \pm 0.9 \pm 0.7$ vs. 0.88 ± 0.13 fm. We also find a much stronger transverse flow in $S + Pb$ than $h + p$ reactions.

The NA22 analysis has some advantages as well as drawbacks compared to the one, present herewith: a pro is that NA22 has much bigger rapidity coverage, than NA44, the drawback is that the NA22 spectra is not absolutely normalized and they measure only negative particles. The size of the final errors is similar in the NA22 and the present analysis.

4.3 *Comparision to other NA44 data*

A comparision of this analysis of NA44 data for $S + Pb$ reactions to recent NA44 results [17] on $p+p$, $S+S$ and $Pb+Pb$ reactions shows that the freeze-out temperature in the center at the mean freeze-out time, T_0, in our case of $S + Pb$ reactions is within errors similar to the values obtained from an analysis of the particle spectra of $p + p$, $S + S$ and $Pb + Pb$ reactions [17]. In the $S + Pb$ case, we have a complete description, including the low pt part of the pion spectra with an acceptible χ^2/ndf due to our inclusion of the temperature inhomogeneities. Note also that we do not simply reproduce the slopes of particle spectra but we reproduce the absolute normalized particle spectra for pions, kaons, as well as the full shape of the proton spectra and the HBT radii. We find a mean transverse flow of $\langle u_t \rangle = 0.53 \pm 0.12$ in $S + Pb$ reactions, which is within errors similar to $\langle u_t \rangle = 0.41 \pm 0.11$, a a value found in ref. [17] for h^- particles in $Pb+Pb$ reactions in a more qualitative analysis.

5 Conclusions

The first combined HBT and spectrum fitting is presented within the same hydrodynamical parameterization scheme for CERN SPS heavy ion reactions.

It was necessary to use different particles and absolutely normalized particle spectra to obtain a well-defined minimum of each parameters for data from the small NA44 acceptance. The model is shown to describe the data in a statistically acceptable manner. and parameters can be determined with an accuracy of 10 - 20 % relative errors including systematic uncertainties. The transverse flow and the radial temperature inhomogeneity is necessary to achieve this result.

The same model describes meson - p spectra and correlations at CERN SPS with a similar central temperature, similar surface temperature and similar space-time rapidity width. The main difference between $S + Pb$ and $(\pi/K) + p$ reactions is that the geometrical radii, the freeze-out time and the transverse flow are much larger in the first case. The particle emission seems to happen more suddenly in S + Pb as compared to hadron induced reactions at the same energy range.

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Parameter	Analytical	Numerical
T_0 [MeV]	164 ± 8	143 ± 4
τ_0 [fm/c]	4.8 ± 0.3	5.3 ± 0.2
R_G [fm]	6.0 ± 0.9	4.7 ± 0.3
$\Delta\eta$	1.3 ± 0.2	1.8 ± 0.3
$\Delta\tau$ [fm/c]	0.6 ± 0.1	0.0 ± 0.6
a	0.62 ± 0.09	0.63 ± 0.08
b	0.56 ± 0.06	0.44 ± 0.04
d	5.9 ± 0.6	3.8 ± 1.8
χ^2/ndf, full fit	50.8/190	57.2/190

Table 1: Parameters from simultaneous fitting of particle spectra and HBT radius parameters with analytical and numerical approximations to the hydrodynamical core model.

Sub-sample	Analytical $\Delta\chi^2/bins$	Numerical $\Delta\chi^2/bins$
π^+ ($p_t < 350$ MeV)	8.8/32	5.3/32
π^+ ($p_t > 350$ MeV)	14.4/34	12.8/34
K^+	14.5/74	14.6/74
p ($p_t < 350$ MeV)	2.4/16	2.4/16
p ($p_t > 350$ MeV)	5.7/24	4.6/24
HBT radii	5.0/10	17.5/10

Table 2: Contributions of various sub-samples of data to the overall χ^2 of the fitting. The first five sub-samples correspond to the spectra of particles measured with different setups of the spectrometer.

parameter	value	± stat. ± syst.
T_0 [MeV]	154	± 8 ± 11
τ_0 [fm/c]	5.1	± 0.3 ± 0.3
R_G [fm]	5.4	± 0.9 ± 0.7
$\Delta\eta$	1.6	± 0.3 ± 0.3
$\Delta\tau$ [fm/c]	0.3	± 0.3 ± 0.3
a	0.63	± 0.09 ± 0.01
b	0.50	± 0.06 ± 0.06
d	4.9	± 1.8 ± 1.1

Table 3: Combination of the results of the analytical and the numerical fits.

Calculated parameters	
$\langle \frac{\Delta T}{T} \rangle_r$	0.44 ± 0.08
$\langle \frac{\Delta T}{T} \rangle_t$	0.08 + 0.13 - 0.08
T_r [MeV]	107 ± 19
T_t [MeV]	141 ± 30
$\langle u_t \rangle_t$	0.53 ± 0.12

Table 4: Parameters calculated from the table of the combined fit results.

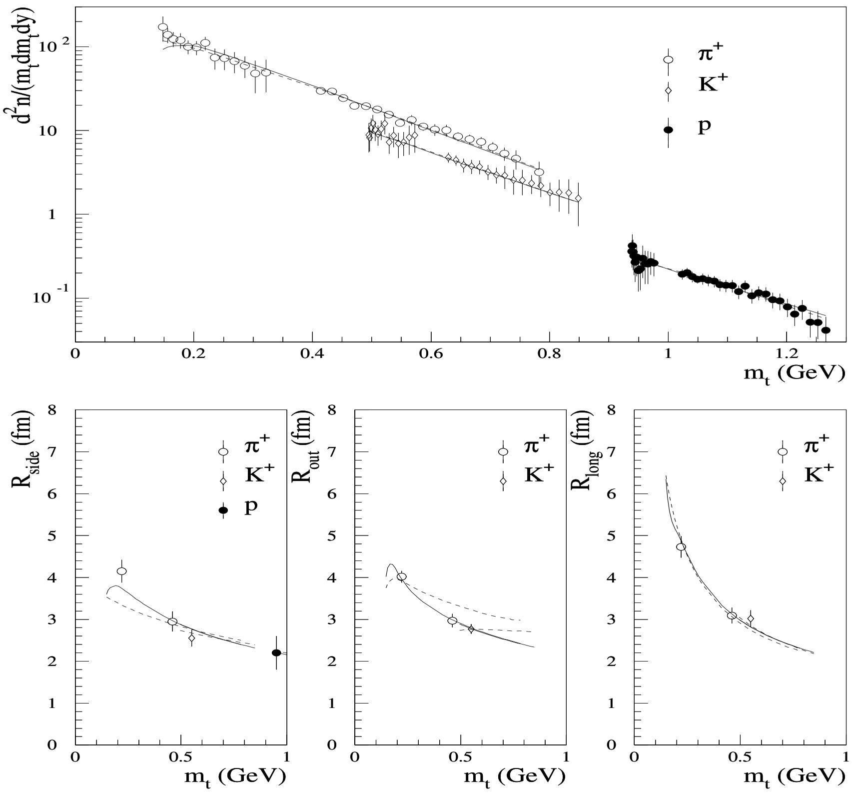

Fig. 1. Simultaneous fitting of particle spectra and HBT radius parameters. Full line shows the fit using the analytical approximation, dashed line shows the result of the numerical approximation. Data points on the spectra represent the y-averaged NA44 2 dimensional $\dfrac{d^2n}{m_t\, dm_t\, dy}$ distribution. HBT data are found in ref. [5].

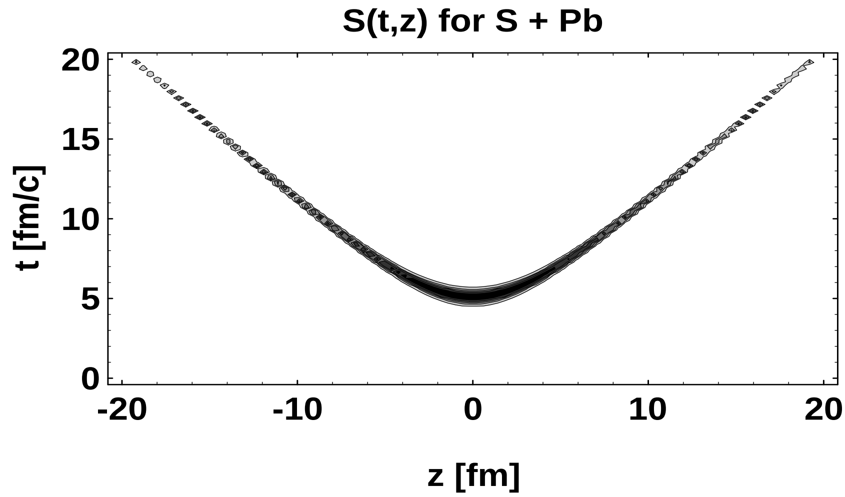

Fig. 2. Contour plot of the reconstructed source function for $S+Pb$ reactions as measured by the NA44 collaboration. Note the large value of the mean freeze-out time and the narrow width of the emission zone in proper-time.

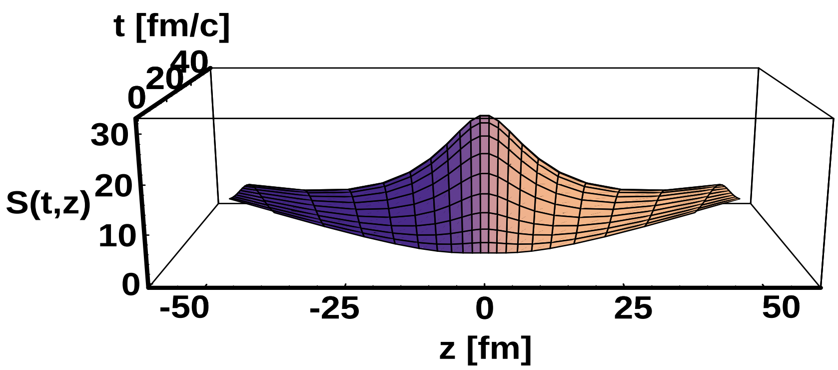

Fig. 3. Parametric plot of the reconstructed source function for $S+Pb$ reactions as measured by the NA44 collaboration. The source is the same as that of Fig. 2., but a different view-point is chosen to show the shape of emission probabilities for large values of $|z|$ in the mid-rapidity frame.