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SPACETIME EFFECTS IN RELATIVISTIC HEAVY ION COLLISIONS

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T. Csörgő, J. Zimányi: Spacetime effects in relativistic heavy ion collisions. KFKI 1990-37/A

ABSTRACT

This booklet containes our contributions to the HIPAGS and CAMP workshops and to the QM '90 conference.

Т. Чёргё, Й. Зимани: Пространство-временные эффекты в столкновениях релятивистских тяжелых ионов. KFKI-1990-37/A

АННОТАЦИЯ

Настоящий сборник включает наши труды в рамках международных рабочих групп HIPAGS и CAMP, а также материалы докладов, прочитанных на конференции QM'90.

Csörgő T., Zimányi J.: Téridő effektusok relativisztikus nehéz ion ütközésekben. KFKI 1990 37/A

KIVONAT

A kiadvány a HIPAGS és a CAMP nemzetközi műhelyek munkájához való hozzájárulásukat és a QM '90 konferencián tartott előadás anyagát tartalmazza.

SCALING IN FRAGMENTATION OF TARGET SPECTATORS*

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* Contribution to the HIPAGS workshop (Brookhaven, N.Y., U.S.A. March 1990, ed. O. Hansen)

Scaling in Fragmentation of Target Spectators

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Abstract: The assumption that target spectators fragment isotropically in a gently moving coordinate system is in agreement with pseudorapidity distributions, measured in central ultrarelativistic heavy ion collisions from 14.5 AGeV to 200 AGeV bombarding energy. Follows an approximate scaling for $dn(baryon)/d\eta$.

1. Introduction

The LUND string picture [1] is a remarkably successful phenomenological description of high energy hadronization processes, occuring in jet events. The FRITIOF model is a combination of the soft collisions occuring in high energy hadron–hadron, hadron–nucleus and nucleus–nucleus collisions, followed by string fragmentation [2]. FRITIOF and also other models for hadronic interaction which try to describe experimental observables as a superposition of nucleon–nucleon collisions describe the pseudorapidity distributions measured in emulsion experiments well [3], where the angular distribution of relativistic shower particles are measured. However they fail to describe the pseudorapidity distribution of charged particles at target fragmentation and midrapidity, see refs. [4],[5]. In these experiments the contribution of particles with lower energy were included in the measurement, too.

2. Motivation and model assumptions

Although the application of FRITIOF at relatively low, 14.5 AGeV, bombarding energy is questionable, it reproduces the measured pseudorapidity distribution [4] in central collisions of 14.5 AGeV $O^{16} + Au^{197}$ within 10 % in the projectile fragmentation region ($2 < \eta$). We note that the pseudorapidity distributions for $\eta < 2$ measured with different experimental cutoffs differ from each other with more than 100 %! (See Fig.1., data from refs. [3,4]). The emulsion data of ref. [3] show the η distribution of relativistic shower particles defined with the inequalities $E^{\pi}_{kin} > 70$ MeV, $E^{p^+}_{kin} > 400$ MeV. After applying these cutoffs to FRITIOF output, we obtain results also shown in Fig. 1. The width and the shape of the calculated and measured pseudorapidity distributions agree, although FRITIOF overestimates the normalisation by a factor of 1.2. On the other hand, data were taken with an $E^{p^+}_{kin} > 30$ MeV cutoff in ref. [4]. Thus protons emerging from the fragmented spectator parts of Au^{197} were probably included here, too. If they are included into the measurement, we have to add their pseudorapidity distribution to that of FRITIOF, which describes the participant matter.

Let's describe the fragmentation of spectator remnants to nucleons as a thermal emission of classical Boltzmann particles from a source moving with non relativistic speed u in the direction of the z axis. Their momentum distribution function will be:

$$f(p) = Ce^{-\frac{(p\cos(\theta) - mu)^2 + p^2\sin(\theta)^2}{2mT}} \tag{1}$$

This momentum distribution leads to the following ideal pseudorapidity distribution of spectator fragments:

$$\frac{dn^{SP}_{ideal}}{d\eta} = \frac{N^{SP}_{TOT}}{\cosh^2(\eta)}\left[(a^2 + \frac{1}{2})\mathrm{erfc}(-a) + \frac{a}{\sqrt{\pi}}e^{-a^2}\right]e^{-\frac{b^2}{\cosh(\eta)^2}}, \tag{2}$$

where

$$a = b\tanh(\eta) \tag{3}$$

and the source temperature and velocity enters eq. (2) only through the combination

$$b = \sqrt{\frac{m_N}{2T}}u. \tag{4}$$

Of course, the number of spectators is to be replaced by the number of charged spectators when only charged particles are measured. In the real experiments the ideal distribution of eq. (5) is distorted by the efficiency of the detector. Thus the measured distributions are to be compared with the detection efficiency corrected distribution.

3. Comparision with E802 data

From the older data of 14.5 AGeV reactions the parameter b cannot be determined directly. The measurement [4] was not performed in the target fragmentation region, thus particles, emerging from the participant region, dominate. However, the contribution of the spectator fragments is not negligible. Adding the thermal model contribution to FRITIOF results we fit b so that we reconstruct the measured pseudorapidity distribution.

In Fig 2.a one can see that the FRITIOF output added to an isotropically decaying spectator target with $N_{TOT}^{SP} = 148$ and $b = 0.7 \pm 0.1$ reproduces the experimental data within statistical errors, calculated for 100 central events of $O^{16} + Au^{197}$ collisions at 14.5 AGeV. At $2 \leq \eta \leq 3$ there is a tendency to overestimate the number of produced charged particles by 10 per pseudorapidity unit. A fit to $O^{16} + Cu^{64}$ data with $N_{TOT}^{SP} = 30$ yields $b = 0.5 \pm 0.2$, see Fig. 2.b. We draw attention to the point that these fits were done in the central and the projectile fragmentation region. The recent $E802$ data [11], measured in the target fragmentation region, point out a scaling behaviour in the backward hemisphere. The pseudorapidity distributions of charged particles are proportional to each other for different targets. The analysis of the measurement suggested the target charges as proportionality constants, 79 : 47 : 29 : 13 in case of Au, Ag, Cu, Al targets. From our spectator toy model, neglecting the contribution of pions, one can guess that the backward pseudorapidity distributions are proportional to the charge number of the spectator part of the target $Z_{SP} \approx Z/A(A^{2/3} - B^{2/3})^{3/2}$, yielding 79 : 47 : 29 : 13 for the above rates. The ratio of the measured points, taken at $\eta = -1$ where the contribution of poins is the less, is given by 79 : 37.5 : 21.7 : 3.9. These values are a little bit more decreasing than the total target charge however they are not decreasing as fast as the charge of the spectator part determined from clean cut geometry. Clearly, a more careful analysis is neccessary, with fit in the whole η interval, taking into account the pionic degrees of freedom, too.

Comparision with WA80 data

Now let's turn towards older data measured by WA80 collaboration [5],[6] with Plastic Ball detector, which has a low energy cutoff of 20 MeV for protons [7]. We note, that the pseudorapidity distribution of relativistic shower particles, measured in emulsion experiments, is very well described by FRITIOF (see e.g. Fig.1.c,d in ref. [9].)

WA80 collaboration has measured the average $p_{\parallel}$ and $p_{\perp}$ for protons in the target fragmentation region. In case of a thermal source moving with velocity u in the LAB system, these average values are given as $:< p_{\parallel} >= mu$, $< p_{\perp} >= \sqrt{\pi m T/2}$. The preliminary $< p_{\perp} >= 500 \pm 40$ MeV/c [5] decreased to about $< p_{\perp} > \approx 310$ MeV [5a] which corresponds to a temperature $T \approx 66 \pm 7$ MeV. The reported [5] $< p_{\parallel} >= 320 \pm 50$ MeV/c corresponds to $u = 0.34 \pm 0.05$. These values are in agreement with the transverse energy spectra of particles around $y \approx 0.14$, which was found to be an exponential with slope of 66 MeV [5a,10]. The reported $< p_{\parallel} >$, $< p_{\perp} >$ are the same for Au^{197}, Ag^{108} and Cu^{64} targets with 200 AGeV bombarding O^{16} projectiles [5]. These values yield the same T, u for Au^{197}, Ag^{108} and Cu^{64} targets with 60 and 200 AGeV bombarding O^{16} projectiles. How can this be explained? We give a qualitative explanation in the next paragraph.

From experiences with our spacetime version of FRITIOF [8] we know, that particles, emerging from participant strings, up to the same maximal velocity could hadronize within the target. The most energetic particles hadronize outside the target, explaining why the excitation of target spectators is independent of the large enough bombarding energy. Part of the particles, born within target, crosses the volume occupied by the spectators and excite the spectator matter. The average length of their path within this volume is about 3 or 4 fm, which is not much larger than the mean free path in nuclear matter ≈ 2 fm. Thus the excitation given to the spectator matter is roughly proportional to the volume of this matter, which is proportional to N_{TOT}^{SP}. In the spectator zone the average excitation per nucleon is independent of the type of the target nucleus. Thus $< p_{\perp} >$ and $< p_{\parallel} >$ should be independent of the bombarding energy and of the target mass number in the above mentioned cases. Follows that $\frac{dn^{SP}}{d\eta}$ must be independent of the bombarding energy if the bombarding energy is sufficiently high (≥ 60 AGeV). The proportionality constant is the only parameter which determines the spectator pseudorapidity distribution if the projectile type is given. Thus from eq. (5) follows that $\frac{1}{N_{TOT}^{SP}}\frac{dn^{SP}}{d\eta}$ is independent of the bombarding energy and of the target. Sufficient conditions for this scaling are $N_{TOT}^{SP} \geq 30$, $E_{LAB} > 60$AGeV for oxygen projectile. The different projectile nucleons transfer different amount of momenta to a randomly chosen "spectator" nucleon, thus the u and T parameters might depend on the projectile type. In case of proton projectile WA80 reported smaller average transverse and longitudinal momentum. A possible interpretation could be that a smaller projectile can transfer only less longitudinal push and less transverse excitation to a given target, than a bigger projectile.

The u, T parameters have significant systematic error due to the mixing of "spectator" and "participant" baryons in the $0 < \eta < 1.5$ interval. They determine b through eq. (3) with a rather large error. A more precise method for determining b is to express b from equation (2) at $\eta = 0$ as follows

$$b = \left[\ln\left(\frac{N_{TOT}^{SP}}{2\frac{dn_{ideal}^{SP}}{d\eta}\Big|_{\eta=0}}\right)\right]^{\frac{1}{2}}. \quad (5)$$

In this equation the contribution of participant baryons to $\frac{dn^{SP}}{d\eta}\Big|_{\eta=0}$ is negligible (see Fig.1 of ref.[5]). From Fig. 3.b. of ref.[5] $\frac{dn_{exp}^{SP}}{d\eta}\Big|_{\eta=0} = 30 \pm 5$ for the Au^{197} target. The detection efficiency of the Plastic Ball $\epsilon(\eta = 0)$ is 0.7 for protons [10]. The ideal pseudorapidity density is the experimental one divided by the detection efficiency: $\frac{dn_{ideal}^{SP}}{d\eta}\Big|_{\eta=0} = 45 \pm 7$. The number of target spectator baryons were determined from clean cut geometry for central collisions to be $N_{TOT}^{SP} \approx (A^{2/3} - B^{2/3})^{3/2}$ where A and B are the mass numbers of target and projectile, respectively. For an $O^{16} + Au^{197}$ collision we find $N_{TOT}^{SP} = 145$ and this yields $b = 0.7 \pm 0.1$. For the Ag^{108} and Cu^{64} targets we obtain $N_{TOT}^{SP} = 66, 30$ and $b = 0.5 \pm 0.2$, 0.6 ± 0.1, respectively. With these parameters we calculated the spectator model prediction and multiplied it by the η dependent detection efficiency, as given in [10]. We have compared our results with data in Fig. 3. We note, that the $\epsilon(\eta)$ detection efficiency of ref. [10] decreases strongly for $\eta > 0.6$, due to multiple hits in the forward segments of the Plastic Ball detector. Thus we have restricted our investigation to the pseudorapidity interval $-1 < \eta < 0.6$. Our model describes the measured pseudorapidity density of baryons in this window within the three standard deviations of the data. In the $0.2 < \eta < 0.6$ interval the spectator baryon contribution calculated from eq. (8) systematically underestimates the data. The contribution of the participant zone was obtained from the FRITIOF code for the case of the 200 AGeV $O^{16} + Au^{197}$ collision. The sum of "spectator" and "participant" contribution is shown in Fig. 4. Now the data are described by the model fairly well. We note, that the 20 MeV low energy cutoff, applied to baryons from FRITIOF, had practically no effect on the pseudorapidity density distribution.

We remark that the spectator fragments generally do not give a negligible contribution to the pseudorapidity distribution; in case of $b = 0.6$ their distribution peaks at $\eta \approx 0.5$, and its half width is ≈ 1. Thus their distribution descends only for $\eta \geq 2.0$. This means that the η distribution of spectators and participants strongly overlap. However they might be separated by a suitably chosen low energy cutoff, because particles from the zone of the geometrical overlap emerge from a hot zone with a temperature of $T \geq 100 - 120$ MeV [8], which is much higher than the calculated $T \approx 66 MeV$ for the spectators. Note that a more extended writeup, without comments on the recent data, can be found in [12].

Conclusions and a note

1. We have shown that the FRITIOF model for soft hadronic processes combined with a moving thermal source for target spectator fragmentation describes the [4] measured pseudorapidity distribution of produced hadrons at 14.5 AGeV within 10 % error as well as at 60 and 200 AGeV for different targets and O^{16} projectiles.

2. At 14.5 AGeV, only the parameter b (eq.(4)) was determined. To obtain the velocity and the temperature in this case, one has to analyse the recent [11] data. An energy spectrum of particles in the backward hemisphere would be appreciated. Recent E802 data [11] suggests that the pseudorapidity distributions are proportional The proportionality constant is a little bit less than the target charge and higher than the charge of the spectators.

3. Our model explains why the measured baryon pseudorapidity distributions were proportional for central 60 and 200 AGeV $O^{16}+B$ collisions in the target fragmentation region. They are thermal distributions with $T \approx 66$ MeV, moving with $u \approx 0.3c$. In this case N^{SP}_{TOT} is the only parameter which determines the spectator pseudorapidity distribution for a given projectile. From eq. (2) it follows that $\frac{1}{N^{SP}_{TOT}} \frac{dn^{SP}}{d\eta}$ is independent of the bombarding energy and of the target mass number. The scaling function for oxygen projectile is presented in Fig. 5.

4. We emphasize that the pseudorapidity distribution of the spectators given by eq. (5) peaks at $\eta \approx 0.5$ for $b \approx 0.6$ thus the contribution of spectator fragments is not negligible for pseudorapidity $\eta \leq 1.5$.

It is tempting to note that the peculiar peak in the pion p_T spectra, much discussed in this workshop, has also a slope parameter of ≈ 60 MeV. Maybe some participant pions cool down in the spectator matter during their trip from the participant matter to the detector, meanwhile they heat up and disintegrate the spectator baryons?

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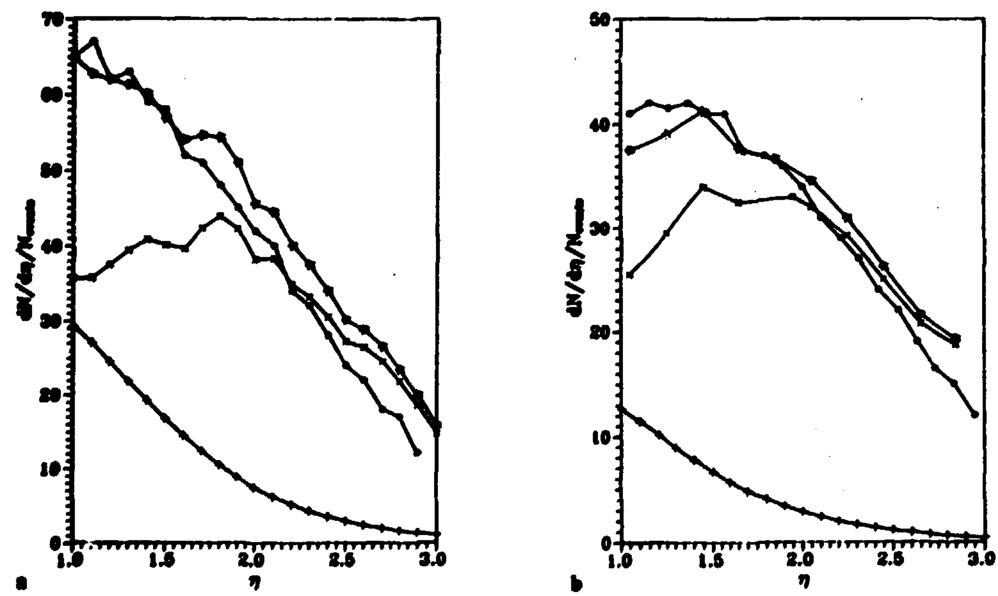

Fig. 2a, b. Pseudorapidity distribution of charged particles for central 14.5 A GeV $O^{16}+Au^{197}$ a and for central $O^{16}+Cu^{64}$ reaction. It can be seen that the data can be decomposed to contributions from FRITIOF and from spectator model. a (•) Data from [4]. (×) FRITIOF prediction for 100 events. (+) (5) with $b=0.7$, $N_{sp}^{tot}=148$. (∗) FRITIOF prediction added to (5), with (+) parametrisation. b (•), (×), (+), (∗) denotes the same as in a but for the case of central 14.5 A GeV $O^{16}+Cu^{64}$ reaction. For the spectator distribution the parameters $b=0.52$, $N_{tot}^{sp}=30$ were used

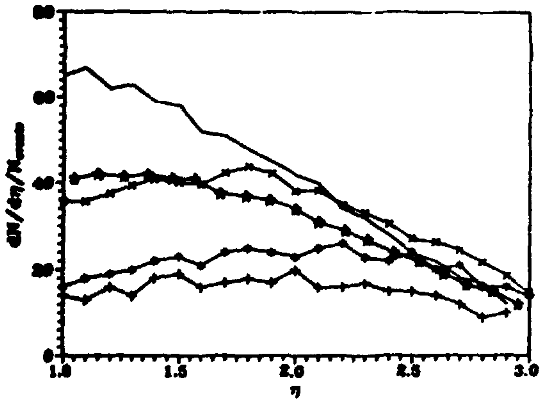

Fig. 1. Pseudorapidity distributions of charged particles for central 14.5 AGeV collisions. The solid lines, connecting the measured and calculated points (which have statistical errors) are drawn only *to guide the eye. Lines, marked with different symbols refer to* the following cases: (−) Central $O^{16}+Au^{197}$ data from [4]. (•) Central $O^{16}+Cu^{64}$ data from [4]. (+) Central $O^{16}+Ag^{108}$ data from [3]. In case of cuts of [4] this curve should be placed between (−) and (•). (×) Central $O^{16}+Au^{197}$ given by FRITIOF with no cut. (•) Central $O^{16}+Ag^{108}$ *given* by FRITIOF with cuts of [3]

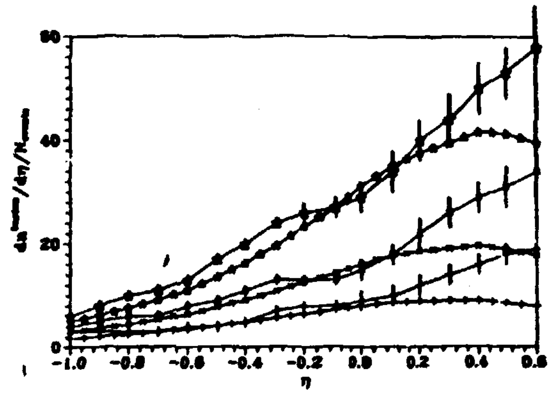

Fig. 3. Pseudorapidity distributions of baryons in central reactions of $O^{16}+A$ at 200 AGeV. Data from [5] are shown with error bars. Spectator model predictions are multiplied by nonideal detection efficiency of [10]. (•) Au^{197} target, $N^{sp}_{tot}=145$, $b=0.70$; (×) Ag^{108} target, $N^{sp}_{tot}=66$, $b=0.60$; (+) Cu^{64} target, $N^{sp}_{tot}=30$, $b=0.52$

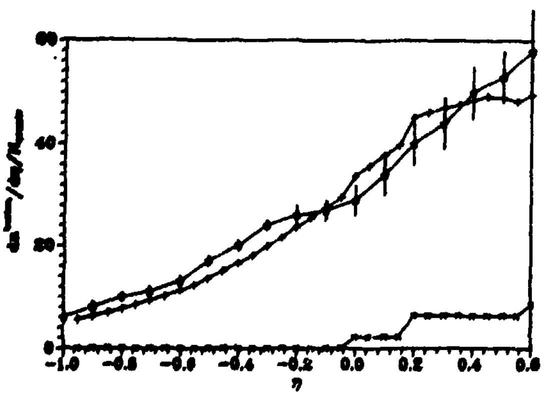

Fig. 4. Same as Fig. 3 (•), but now the correction for the participant contribution is included. This contribution is obtained from *FRITIOF* with 20 MeV low energy cutoff for 300 events. (•) Au^{197} target data. (×) Participant baryon contribution calculated from the FRITIOF model. (+) Spectator model prediction with $N^{sp}_{tot}=145$, $b=0.70$ (function (•) from Fig. 3) added to the participant baryon contribution (×)

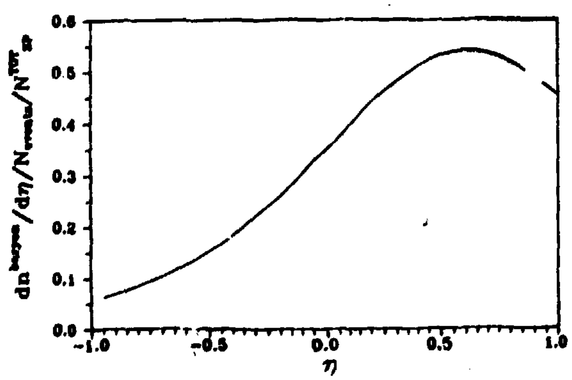

Fig. 5. Approximate scaling function for the target spectators in oxygen induced ultrarelativistic heavy ion collisions. The pseudorapidity distribution of baryons is proportional to this function ((5) with $b=0.6$ and $N^{sp}_{tot}=1$) independently of bombarding energy and target mass number. The proportionality constant is the mass number of the spectator part of the target. Sufficient condition for this type of scaling is $E_{LAB}\geq 60$ AGeV, $N^{sp}_{tot}\geq 30$ for oxygen projectile. We note that a measured pseudorapidity distribution of spectator baryons has to be corrected for detector acceptances by a division with $\varepsilon(\eta)$ detection efficiency before it is compared with the scaling function

ENERGY DENSITIES, TARGET FRAGMENTATION AND PION CORRELATIONS IN ULTRARELATIVISTIC H.I.C. AS PREDICTED BY SPACER*

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ENERGY DENSITIES, TARGET FRAGMENTATION AND PION CORRELATIONS IN ULTRARELATIVISTIC H. I. C., AS PREDICTED BY SPACER

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Abstract

SPACER, a spacetime version of FRITIOF is applied to the calculation of the flow velocity field, local rest densities and energy densities for the case of 14.5 AGeV Si^{28} + Au^{197} collisions as well as 200 AGeV $O^{16}, S^{32} + Au^{197}$ collisions. At CERN energies, the model predicts a 25-30% overall increase in local rest (energy) densities, when using S^{32} instead of the O^{16} projectile. SPACER suggests a strong spectator fragmentation. This effect is taken into account with the help of a simple analytic model, which implies an experimentally observed scaling in the angular distribution of target associated particles. SPACER predicts that the shape of the two-pion correlation function $C(Q_I)$ is exponential with chaocity parameter close to 1.

1 The SPACER model

In ref. [1] a spacetime version of FRITOF [2] was presented, and later was named as SPACER (Simulation of Phasespace distributions of Atomic nuclear Collisions in Energetic Reactions). This model follows the cascade of the leading particles in (ultra)relativistic heavy ion collisions. Particle emission between subsequent collisions of the leading particles is allowed for, based on the LUND jet fragmentation scheme [3]. Although secondaries are not allowed to cascade in this Monte Carlo simulation, some effects of their rescattering on the target spectators can be described with an analytical model,[4].

SPACER, as any other phase-space description of ultrarelativistic heavy ion collisions [5,6], can be considered as a 5-component description. At a given time, the first two components are the incoming uncollided target and projectile nucleons, while the third and fourth components are the excited nucleons formed from the first two components in nucleon–nucleon collisions. The fifth component contains on-shell hadrons formed from the strings of components 3 and 4.

2 Energy densities

It is clear that the first four components cannot be thermalized so they cannot contribute to thermal QGP production. Particles belonging to component 1 and 3 move approximately with c in the center of mass system of the participant nucleons, while particles of component 2 and 4 move with a velocity approximately $-c$, although they can occupy the same volume cell, during the passage of projectile nucleus through target nucleus. Ref. [1] showed that hadrons of component 5 are emitted from the strings with an approximately linear flow velocity field. Thus a very large part of the hadron as well as energy densities, created in the collision, disappears when transforming to the local comoving systems. An other effect which decreases the maximum available *thermal* energy densities is the transverse flow. Thus in the case of 14.5 AGeV $Si^{28} + Au^{197}$ and 200 AGeV $O^{16}, S^{32} + Au^{197}$ central reactions the pure thermal QGP phase is not expected to appear on the basis of this *conservative model*, perhaps the

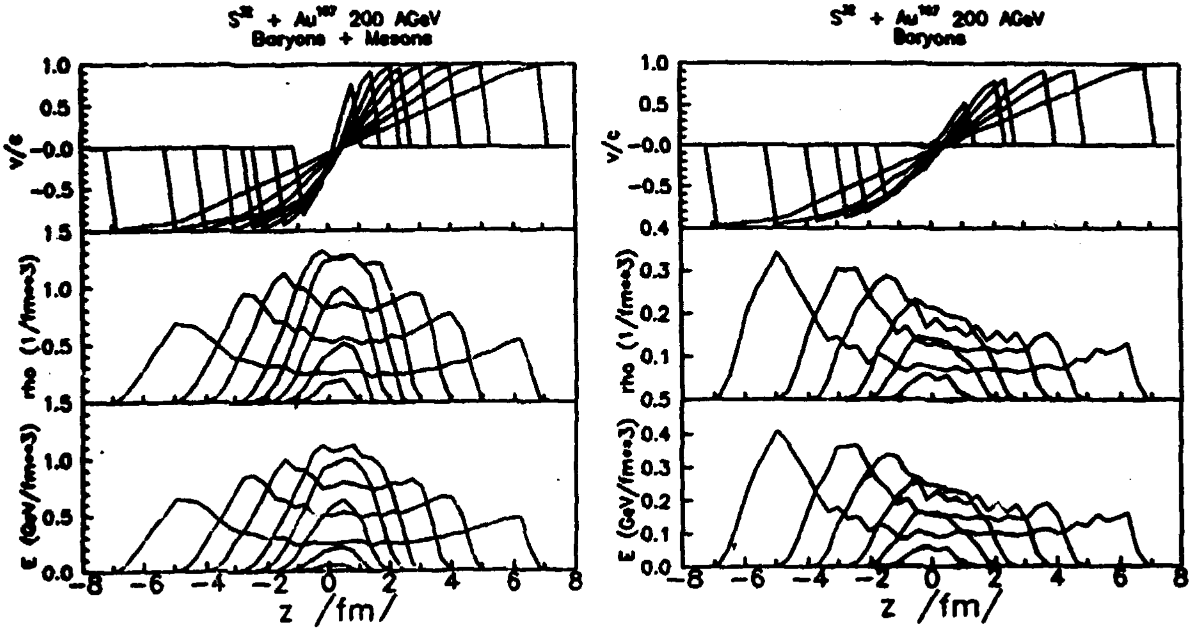

Figure 1: Longitudinal flow field, local rest number and energy densities rho and E of hadrons and baryons of component 5. The *local* rest quantities are shown as function of the participant *center of mass* collision axis at 1.0,1.5,2.0,2.5,3.0,4.0,5.0,7.0 fm/c after the beginning of the collision. For baryons the earliest two curves are unseenly small.

mixed phase can be reached at CERN energies, see Figs 1.a,b and Figs 1-4,Table I. of ref [1]. At 14.5 AGeV bombarding energy, the flow field of the 5th component hadrons deviates from linearity stronger than in the 200 AGeV case. In this lower energy case the local barion densities do not show target and projectile peaks. From the complete stopping assumption of [7] one would expext $\epsilon/\epsilon_0 = \rho/\rho_0 \approx 2\gamma_{cm} \approx 3.8$ in the whole volume, which is a little bit higher than the *maximum* values of our distributions $\epsilon(z)/\epsilon_0$ and $\rho(z)/\rho_0$, where the index 0 refers to ground state nuclear matter. The *volume averages* are smaller by about a factor of 2. At 200 AGeV, the baryon distributions show the asymmetry of the collision, because target and the projectile associated baryons separate. In case of O^{16} projectile the maximum of the local rest energy density of 5th component hadrons is 0.9 GeV/fm^3, while its value is 1.15 GeV/fm^3 in case of the S^{32} projectile. In both the maximum values are reached at about 3 fm/c after the beginning of the collisions, and are close to the predictions of the Bjørken estimate with $\tau_0 = 3$ fm/c. At the beginning, the production of the particles from strings dominates the longitudinal expansion, which proceeds almost with the speed of light. Of course, the expansion dominates later on. The local rest hadron number and energy densities are about 25-30% higher at any spacetime point in the case of sulphur projectile, as compared to the oxigen projectile case.

At both AGS and CERN energies, a lot of particles are born inside the target nucleus and some of them pass through the volume which would be the "spectator" volume in case of clean-cut geometry. This leads to a strong target spectator fragmentation.

3 Target fragmentation

The particles emerging from the zone of geometrical overlap and passing the zone of "spectator" part of target nucleus, transfer some longitudinal push to these nucleons and also heat up the cold spectator matter. If the number of rescatterings of target "spectator" nucleons

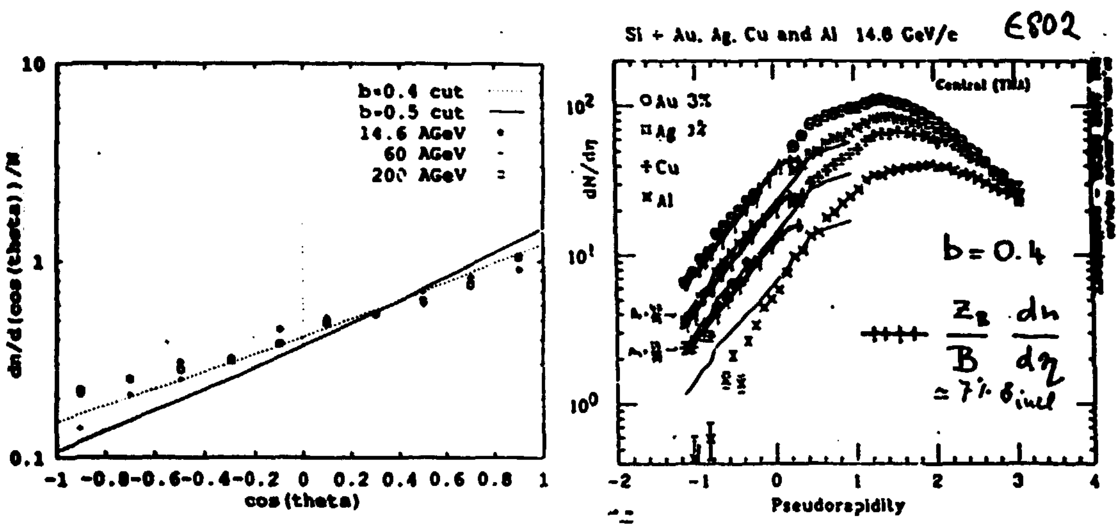

Figure 2: **a,** EMU01 data points and the prediction of the Bolzmann gas model (dotted line) with b=0.4 for "grey prongs", nucleons with $40MeV < E_{kin} < 400MeV$ cut. Solid line shows the $b = 0.5$ case. Data contains periperal and central $O^{16} + Emu$ collisions. **b,** Figure of E802 taken from ref. [9], appended with Bolzmann gas model prediction for $b = 0.4$

is large enough their momentum distribution can be described as a gently moving Boltzmann gas. According to ref. [4], this momentum distribution describes the pseudorapidity distribution of baryons if one corrects for detection efficiency (if comparing with preliminary data) and also for the contribution of "participant" baryons, as was done with the help of the FRITIOF model. In the present work we review recent EMU01 and E802 angular distributions and relate the parameter of the model to the scaling exponent β extracted experimentally from $p + A$, $A + B$ collisions. The nonrelativistic Bolzmann gas model yields the angular distribution:

$$\frac{1}{N}\frac{dn_B}{d(cos(\theta))} = \left[(a^2(\theta) + \frac{1}{2})\mathrm{erfc}(-a(\theta)) + \frac{a(\theta)}{\sqrt{\pi}}\exp(-a^2(\theta))\right]\exp(a^2(\theta) - b^2) \qquad (1)$$

where $a(\theta) = b\cos(\theta)$. The quantity $b = \sqrt{\frac{m_N}{2T}}u$ is the only combination of the temperature T and the source velocity u which enters the angular distribution. The value of $b = 0.6 \pm 0.1$ is consistent with pseudorapidity distributions measured in O^{16} induced reactions at bombarding energies 14.5 through 200 AGeV, [4], where we have fixed the total number of the spectator baryons from clean-cut geometry as $N = (A^{\frac{2}{3}} - B^{\frac{2}{3}})^{\frac{3}{2}}$. It is interestig to expand eq. (1) into powers of b. After exponentializing the linear term we gain

$$\frac{dn_B}{d(cos(\theta))} \propto \exp(\frac{4b}{\sqrt{\pi}}\cos(\theta)) \qquad (2)$$

Recent EMU01 data [8] also verify this type of scaling, and demonstrate it's validity in peripheral or central collisions, independently of target and projectile mass numbers and also of bombarding enegy : $\frac{dn}{d(cos(\theta))} \propto \exp(\beta\cos(\theta))$. Fitting this expression to the $p + A$ data, the value of $\beta = 0.96$ was determined, which fitted also the $A + B$ data. Using eq. (2) we obtain the relation $b = \frac{\sqrt{\pi}}{4}\beta \approx 0.4$. Fig. 2.a shows that the Boltzmann gas model describes the $cos(\theta)$ distributions of target associated particles measured in emulsion.

It is tempting to comment on the recent E802 pseudorapidity distribution, measured in the backward hemisphere,[9]. The $\eta < 0.$ part of the charged particle pseudorapidity distribution of 14.6 AGeV $Si^{28} + Au^{197}, Ag^{108}, Cu^{64}$ reactions is described with the help of the Boltzmann gas model, using the $b = 0.4$ value as extracted from the EMU01 data, and multiplying the single particle probabitiy with Z_B the charge number of the target, see Fig. 2.b. Further corrections are necessary to describe the forward angle part, e.g. with FRITIOF, [3]. In ref. 4, where we had access only to forward angle data, we assumed a priori that the proportionality constant is the mass /or Z_{SP} charge/ number of the *spectator* part of the target, and we corrected for the participants with help of the FRITIOF model. Thus we obtained larger values of $b = 0.7 \pm 0.1, 0.5 \pm 0.2$, for gold and sulphur target, respectively. The fact that this distribution scales with Z_B, as observed in ref. [9], suggests that the "participant" target baryons belong to the same momentum distribution as the "spectator" target baryons. In case of complete stopping the scaling factor would be $Z_A + Z_B$, which contradicts to data. To clear up the ambiguities we suggest either to measure the $\frac{dn_E}{d\eta}$ baryon pseudorapidity distribution in the full η interval, or measure the *charged* particle $\frac{dn_{CH}}{d\eta}$ in the backward hemisphere with different projectiles in order to check if the scaling factor is really independent of the projectile charge number or not. Note that some deviation from a scaling with Z_B is already seen experimentally in case of aluminium target. For a discussion of this effect see ref. [10].

4 Pion correlations

In the previous section we have seen that the target "spectator" baryons detect the evolution in the "participant" zone, yielding an indirect tool to study the spacetime characteristics of relativistic heavy ion collisions. Boson interferometry is also a tool to study the geometry of the interaction region. With the help of the SPACER model we can study the pion production directly, as well as indirectly, switching on the interference between pion pairs and calculating the two-pion correlation function. Our first results, obtained in plain wave approximation for central 200 AGeV $O^{16} + Au^{197}$ collisions were published in ref. [11]. Here we review these results very briefly and append them with preliminary results for the case of S^{32} projectile. SPACER [1] yields the (x_i, p_i) phasespace production points for pions. They emerge either from resonance decays or directly from the fragmenting strings. The single and two-pion distributions, simulating the finite binning effects, are calculated in plane wave approximation as given by the Yano - Koonin formula [12]

$$N(\mathbf{p}_1) = \sum_i \delta(\mathbf{p}_1 - \mathbf{p}_i(x_i)), \tag{3}$$

$$N(\mathbf{p}_1, \mathbf{p}_2) = \sum_{i,j} \delta(\mathbf{p}_1 - \mathbf{p}_i(x_i))\delta(\mathbf{p}_2 - \mathbf{p}_j(x_j))[1 + \cos([p_i(x_i) - p_j(x_j)] \cdot (x_i - x_j))]. \tag{4}$$

An important finding of ref. [11] was that the shape of the two-pion correlation function is decidedly not Gaussian, if analysed as a function of the invariant momentum difference $Q_I = \sqrt{-(p_1 - p_2)^2}$. The correlation function, calculated from SPACER without any experimental cuts, has an exponential shape: $C(Q_I) = 1 + \lambda \exp(-r Q_I)$ with parameters $\lambda = 0.90 \pm 0.06$, $r = 3.86 \pm 0.18$ in case of O^{16} projectile. In the case of S^{32} projectile, the shape and the parameter values are unchanged, see Table I. The observation of exponential shape with chaocity parameter close to 1 was confirmed by the NA35 collaboration for the case of $S^{32} + Ag^{108}, Au^{197}$ collisions,[13]. Although SPACER predicts the chaocity parameter λ within the errors of the measurement, the source size is underpredicted by a factor of ≈ 0.5. The source sizes of NA35 are underpredicted by SPACER in case of O^{16} projectile, too, using a Gaussian fitting form: $C(Q_L, Q_T) = 1 + \lambda \exp(-Q_T^2 R_T^2/2 - Q_L^2 R_L^2/2)$, [11]. This is probably due to the neglection of rescattering of hadrons of component 5. Improvements are under progress. The SPACER simulation suggested that shape of the correlation function $C(Q_L, Q_T)$ is more peaked than a Gaussian, although we have to increase the statistics of

Parameter	SPACER	NA35
λ	0.9 ±0.1	0.7 ±0.2
τ	3.8±0.2 fm	6.9±1.1 fm

Table 1: Results for the parametrization $C(Q_I) = 1 + \lambda \exp(-Q_I \tau)$ in 200 AGeV central $S^{32} + Au^{197}$ reaction. The NA35 data are measured in the $1 < y < 4$ interval. No momentum cuts were applied to the SPACER calculation.

the calculation to reach really conclusive results on *this* shape. Analysing the source and the correlation simultaniously, we have found that the transverse sizes of the source are only slightly different from the R_T parameter of the correlation function. One takes into account a factor of $\sqrt{2}$ which relates the "nuclear physicist's R_T", measured by the above expression for $C(Q_L, Q_T)$, to the "mathematician's R_T" in the standard Gaussian form $\exp(-\frac{r_T^2}{2R_T^2})$, [14]. Although the source distribution was well fittable with a Gaussian in the transverse direction, the distribution of the pion production points along the collision axis was definitely more peaked than a Gaussian, it's parametrisation is under progress. Still, the two-pion correlation function was fittable with a Gaussian in Q_L because the statistical errors of the calculation were still too large, after averaging over 1000 central $O^{16} + Au^{197}$ collisions.

WA80 collaboration reports [18] that the low p_T pions ($p_T < 100MeV/c$) stem from a larger volume than pions with higher p_T, measured in oxigen induced central reactions in the target fragmentation region. This result might be explained with the picture used at the target fragmentation model: Pions with low p_T partly originate from the pions which are "cooled down" by the target "spectator " nucleons (T= 66 MeV, see refs. [4,10] and refs. therein). Their source size should be about as large as the target radius. The high p_T pions suffered much less rescatterings on these nucleons so they probe the clean-cut reaction volume, characterised by the radius of the projectile. Further improvements are necessary to make these arguments more quantitative.

Note, that the dynamical correlations between spacetime and momentum space, present in the reactions investigated [14,11], make the relation between the two-pion correlation function and the source distribution nontrivial and the interpretation of the source parameters rather model dependent. A possible new interpretation is discussed in ref. [16]. The effects originating from possible presence of partially coherent pion sources are reinvestigated in refs.[17]. Note that the deviation from the static Gaussian shape was also discussed in refs [15].

A drastic increase in the statistics of the experiments and a strong experimental selection among the possible fitting forms of the two-pion correlation function would be neccessary to a breakthrough in our understanding of Bose-Einstein correlations at ultrarelaticistic heavy ion collisions.

5 Conclusions

For the recent CERN heavy ion runs with O^{16} and S^{32} projectile the pure thermal QGP phase is not expected to appear, based on the SPACER estimate, neglecting rescattering effects of secondaries. Still, a 25-30% overall increase of the available (energy) densities is expected when changing to the S^{32} projectile.

The analytical Boltzmann gas model, describing the momentum distribution of disintegrated target nucleons, agrees with recent EMU01 and E802 data.

The exponential shape of the two-pion correlation function $C(Q_I)$, with intercept close to 1., as predicted by SPACER, was observed by NA35 collaboration, although the NA35 source sizes cannot be understood in the framework of the present version of SPACER, neglecting rescattering of secondaries and assuming hadronic scenario.

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ON AN INTERPRETATION OF THE GGLP FORMULA*

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17/18

On an interpretation of the GGLP formula

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Abstract

The GGLP effect is caused by the Bose–Einstein statistics of identical particles. The authors point out that the "radius" parameter R of the $C(Q_I)$ form of the correlation function can be related to the width of the proper time distribution in case of very strongly correlated spacetime and momentum space.

1 The puzzle of variables of the correlation function

In elementary particle reactions the functional form of the two pion correlation function,

$$C(\vec{p}_1, \vec{p}_2) = \frac{< n_\pi >^2}{< n_\pi(n_\pi - 1) >} \frac{< N(\vec{p}_1, \vec{p}_2) >}{< N(\vec{p}_1) >< N(\vec{p}_2) >}, \tag{1}$$

was studied with high statistics experiments. No significant dependence of C was found on any other combinations of the two pion momenta except a dependence on the Lorentz invariant difference $Q_I = M^2 - 4m^2$, where M^2 is the invariant mass of the pair. The two pion correlation function depends on Q_I only. This observation holds in $e^+ + e^-$ annihilation performed in various circumstances, as well as for lepton–hadron and hadron–hadron reactions, for reviews on data and models see refs.[2,3]. The puzzle is that the measured correlation functions are consistent with the exclusive Q_I dependence, because even the Kolehmainen-Gyulassy form [4] suggests a factorizable Q_T dependence. So do the other forms, which are based on more static models. The Andersson–Hofmann model [5], which takes into account the Bose–Einstein symmetrization for the pion pairs emitted from a string and fits the $e^+ + e^-$ data surprisingly [6] successfully, doesn't suggests an explicit fitting form.

2 Strongly correlated spacetime and momentum space – a possible solution to the puzzle

Let's suppose that particles are emitted after a point-like interaction of the target and projectile in case of an ultrarelativistic collision. The rapidity of a particle is $\eta = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$. The momentum distribution of the emitted pions is given by $g(\vec{p})$, normalized to unity. Because of the approximate boost invariance along the collision axis the particle world lines can be continued back to the collision point, at least on the average. The only parameter determining the spacetime evolution is the proper time $\tau = \sqrt{t^2 - x^2 - y^2 - z^2}$. If the overwhelming majority of the collisions are soft, the particles have much less momenta in the transverse direction than along the z axis on the average. If the radius of the primary interaction region is reasonably smaller than the average radius of pion production in the transverse direction, one ends up with an approximately radial expansion in the transverse direction, because of axial symmetry. This type of correlations between x^μ and p^μ are reflected in the limit of infinite bombarding energy by the expressions $\tau = \sqrt{t^2 - z^2}$, $\frac{\vec{r}}{t} = \frac{\vec{p}}{E} = \vec{v}$, $\gamma = \cosh(\eta)$, $E = m_T\gamma$. Let's denote the probability distribution of pion production in proper time by $\frac{1}{N}\frac{dn}{d\tau} = H(\tau)$, normalized to unity. Then the very strongly correlated phasespace distribution of pion production points is given as:

$$f(t,\vec{r};\vec{p}) = g(\vec{p}) \int_0^\infty d\tau H(\tau)\delta^{(4)}(x^\mu - \tau\frac{p^\mu}{m_T}) \quad (2)$$

We call attention to the fact that this formula containes the same correlations between (t,z) and (E,p_z) as the ideal inside-outside distribution of [4]. However we take the correlations to the extremes supposing them valid in transverse direction too. (At this point we do not restrict ourselves to any specific production mechanism. Still we point out that eq. (2) seems to be reasonable for cases when some of the pions are produced from resonance decays. If a pion comes from an energetic resonance emitted from the center, the x^μ of pion production will be proportional to the momenta of the resonance p^μ, and this momentum will be about the pion momentum (corrections are due to the width of the resonance)). Also, we do *not* specify the momentum dependence and the proper time distribution of the pion production points.

In plane wave approximation the Yano-Koonin formula gives the following two pion multiplicity distribution:

$$P(\vec{p}_1;\vec{p}_2) = \int d^4x \int d^4x' f(x;\vec{p}_1)f(x;\vec{p}_2)\{1 + \cos[(x-x')\cdot(p_1 - p_2)]\} \quad (3)$$

Substituting the eq. (2) distribution for extremely correlated phasespace production points we gain:

$$C(Q_I; m_{T,1}, m_{T,2}) = 1 + Re[\tilde{H}(\frac{Q_I^2}{2m_{T,1}})\tilde{H}(\frac{Q_I^2}{2m_{T,2}})]. \quad (4)$$

where

$$\tilde{H}(x) = \int_0^{+\infty} d\tau H(\tau)e^{ix\tau} = \int_{-\infty}^{+\infty} d\tau\Theta(\tau)H(\tau)e^{ix\tau} \quad (5)$$

denotes the Fourier transformed distribution of pion production points in proper time. One has to observe the following features of (4) two pion correlation function: i, The correlation function measures the proper time distribution of the pion production. ii, The correlation function depends dominantly on the invariant momentum difference of the pions, because the transverse mass of the pions has an exponential distribution. After averageing over the m_T -s, they can be replaced by their minimum value $m_{T,0}$:

$$< C(Q_I) >_{m_T} \approx C(Q_I; m_{T,0}, m_{T,0}). \quad (6)$$

The model predicts: the larger the $m_{T,0}$ transverse mass cut the wider the correlation function and the smaller the *effective* source size. As an example, let's consider the Lorentzian proper time distribution: $H(\tau) \propto \frac{1}{(\tau-\tau_0)^2+\sigma_\tau^2}$ In this case we get a correlation function which oscillates within a Gaussian shape with shortening periods, as given by

$$< C(Q_I) >_{m_T} = 1 + \cos(\frac{\tau_0 Q_I^2}{m_{T,0}})\exp(-\frac{\sigma_\tau Q_I^2}{m_{T,0}}). \quad (7)$$

This form starts as a Gaussian but falls a bit more rapidly than that, because of the cosine factor, and goes slightly below 1, before the Gaussian factor damps the oscillations under detection errors, if τ_0 and σ_τ are about the same. However this form is undistinquishable from the standard Gaussian shape if $\tau_0 << \sigma_\tau$. In this case the the Gaussian size, R can be related with the width of the Lorentzian as $R^2 = \sigma_\tau/m_{t,0}$. For elementary particle interactions the typical source size is $R \approx 0.8$ fm, the transverse mass cut can be estimated by 300 MeV, thus the width of the Lorentzian $\sigma_\tau \approx 1.$ fm will not be very much different from R.

In ref.[7] the pion production was described as a convolution of resonance production and decay,

$$H(\tau) = \int_0^\infty dx R(x) D(\tau - x) \tag{8}$$

where $R(x)dx$ is the probability of producing a resonance in the interval dx around the proper time x and $D(\tau - x)d\tau$ gives the probability that the resonance emits a pion in $d\tau$ interval around τ, under the condition the resonance was produced at x. For this type of proper time distributions the correlation function factorizes because of the faltung theorem:

$$C_d(Q_I) = 1 + Re[\tilde{R}^2(\frac{Q_I^2}{2m_{T,0}})\tilde{D}^2(\frac{Q_I^2}{2m_{T,0}})] \tag{9}$$

Now we leave the infinite number of possible examples and comment on the meaning of the intercept or "chaocity" parameter λ of the GGLP formula $C(Q_I) = 1+\lambda\exp(-Q_I^2R^2)$, ref. [1]. In the literature and at this workshop the effects of partially coherent fields on the two pion correlation function were reinvestigated, refs. [8]. This formalism can be extended to our case, too. Note, that the intercept parameters are very sensitive to an *a priori* assumption on the shape of the correlation function. Representative examples are the recent NA35, E802 data [9] and the results of SPACER calculations [7]. The different possible fitting forms (e.g. Gaussian or exponential) result in a 100% uncertainity in the value of the intercept. That's why the authors think that the presently reported $\lambda < 1$ values are not conclusive whether the source had a coherent component or not. Clearly, further increase in the statistics and a settling of the problem of the different possible functional forms would be a very welcomed and a very hard job for our experimental collegaues.

As a summary, the authors pointed out that the R^2 parameter of the GGLP formula can be interpreted as a rate of the width of a Lorentzian proper time distribution over the transverse mass cutoff $\sigma_\tau/m_{T,0}$, if the spacetime and momentum space variables of pion production are extremely strongly correlated. This latter assumption gives an explanation of the experimantal puzzle that the two pion correlation depends on Q_I only.

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