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Probing the Space-Time Geometry of Ultra-Relativistic Heavy-Ion Collisions

NA35 Collaboration

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LBL-24646

PROBING THE SPACE-TIME GEOMETRY OF ULTRA-RELATIVISTIC HEAVY-ION COLLISIONS

NA35 COLLABORATION

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ABSTRACT

We report results from a pion interferometry analysis of 200 GeV/nucleon ^{16}O + Au collisions. Both a Gaussian source model and a model based on the inside-outside cascade are used to fit the experimental correlation function, giving transverse and longitudinal shape parameters, a freezeout-time parameter, and a chaoticity parameter for the pion emitting source. We find a transverse source size consistent with the projectile radius except at the c.m. rapidity, where significantly larger transverse and longitudinal sizes and a longer freezeout time are measured suggesting a thermalized source. Calculation of correlation lengths, and comparisons with a simple freezeout model and other pion interferometry experiments are presented.

A study of the evolution in space-time of ultra-relativistic nucleus-nucleus collisions is of interest from several points of view. First of all, it presents an extension of existing studies of e^+e^- annihilations and hadron-hadron collisions to a more macroscopic scale, which might provide an extra opportunity to understand the more point-like systems [1]. Secondly, there have been many predictions that in sufficiently high energy nucleus-nucleus collisions a quark-gluon plasma will be created, with dimensions comparable to the nuclear size and with a correspondingly long life-time [2]. Finally, the extreme relativistic nature of the collisions is of interest in itself. Given a hadronization time of the order of 1fm/c in the rest frame of the produced hadron, the Lorentz transformation leads to a length for the hadron source [3] of about 20 fm in the present instance ($\sqrt{s_{NN}}$ = 19.4 GeV). It also leads to a strong correlation between space, time and rapidity coordinates within the source, which has an important effect on what information can be extracted [4].

The most direct way to investigate the shape and size of a hadron source is to employ pion interferometry [5,6]. The basis of this method is that for production of two identical bosons, there is a correlation in four-momentum space (Bose-Einstein effect) between the two particles, which has a width inversely related to the dimensions of the source in space-time. The method has been applied in numerous studies with a variety of energies, beams and targets [7-11]. We have studied the effective source in ^{16}O + Au central collisions at 200 GeV/nucleon and find that there seems to be a central source at rest in the c.m. system having large radius, freezeout time and chaoticity. Elsewhere the lateral dimensions of the source are consistent with the size of the ^{16}O nucleus, it is more coherent, and it freezes out earlier. Finally, in the longitudinal direction we find that size information is limited to a measurement of the <u>correlation length</u> which is a small fraction of the expected longitudinal source size.

In our experiment (CERN/NA35) we have studied central collisions of ^{16}O+ Au using the 200 GeV/nucleon ^{16}O beam from the CERN SPS. Our experimental setup [12,13] consisted of a 2 x 1.2 x 0.72 m^3 Streamer Chamber in the 1.5 T magnetic field of a superconducting vertex magnet for particle momentum analysis, and a system of downstream calorimeters for triggering and energy flow measurements. Three cameras, each equipped with two-stage magnetically focused image intensifiers of 2000-fold luminous gain, viewed the Streamer Chamber and recorded events on 70 mm film. The picture measurements were carried out with the CERN ERASME facility. To identify and measure tracks at the high track densities encountered, an interactive program was developed to facilitate the matching of streamer patterns in all three views. The average momentum resolution was 1%. For the present study, 105 events were analyzed, taken with a central collision calorimeter trigger for which the energy flow into the projectile fragmentation region was required to be less than 300 GeV (out of 3.2 TeV for the incident ^{16}O) corresponding to a cross section of about 50 mb. Only negative tracks were used in this study and these were all assumed to be negative pions, giving less than 10% possible particle misidentification (e.g. K^-, e^-) according to the Fritiof (Lund model) event simulation program [14].

The rapidity distribution of negative tracks used in the pion interferometry analysis is shown by the solid line in Figure 1. Tracks with insufficient momentum accuracy have been removed. Close pairs of tracks were rescanned to ensure that they did not arise from double measurement of a single track. The dashed line shows the rapidity distribution after corrections for acceptance and for reconstruction and scanning efficiency. We have restricted our analysis to the laboratory rapidity interval $0.6 < y < 4.6$ because the overall measurement efficiency drops below acceptable limits below and above. The average uncorrected (corrected) π^- multiplicity in this rapidity range is 86 ± 4 (133 ± 7). Indicated in Fig. 1 is the "16 + 50" c.m. rapidity at $y_{cm} \cong 2.5$ which is calculated assuming a clean-cut geometry at near-zero impact parameter (i.e., a cylinder of about 50 nucleons in the Au target is struck by the ^{16}O). This value, located roughly near the peak in the rapidity distribution, was taken to be the rest frame for the pion interferometry analysis.

The experimental two-pion correlation function is the ratio between the numbers of correlated and uncorrelated pion pairs:

$$C(p_1, p_2) = A \frac{N_2(p_1, p_2)}{N(p_1)\, N(p_2)} \qquad (1)$$

where p_1, p_2 are the pion four-momenta, N_2 (p_1, p_2) is the two-pion count rate, N(p) is the single-pion count rate, and A is a normalization constant. This quantity was evaluated by taking all pion pair combinations per event and summing over events to get the correlated pairs and by taking all pair combinations of pions from different events to get the uncorrelated (background) pairs. To test the effect of induced correlations in the background [7], another method to form the background was tried: to take pair combinations of pions from different events, but to use each pion only once. The correlation function did not depend significantly on which background was used. In order to correct for final state Coulomb repulsion between the pions which tends to "wash out" the Bose-Einstein correlations, the standard Gamow correction [6] was applied to the experimental correlation function*. Figures 2 a,b,c) show projections of $C(p_1, p_2)$ on the relative transverse momentum Q_T axis (where $Q_T = |\vec{p}_{1T} - \vec{p}_{2T}|$) for various rapidity intervals, for pairs with relative longitudinal momentum $Q_L < 100$ MeV/c (where $Q_L = |p_{1L} - p_{2L}|$). A binning of 10 MeV/c, which is matched to our momentum resolution, is used for the Q_T and Q_L variables.

* The fit to the non-Gamow-corrected correlation function is indicated in Fig. 2(a) by the dashed line.

The enhancement near $Q_T = 0$ and the corresponding enhancements in the other projections provide a measure of the properties of the source. Figure 2 d) shows a correlation function for 105 simulated events calculated using the Fritiof program [14] which does not include any Bose-Einstein effect. No enhancement is visible here (rather a slight anti-correlation for $Q_T <$ 100 MeV/c). Thus, there are no dynamical "background" correlations.

Two models which parameterize the space-time geometry of the collision have been used to fit the experimental correlation function and thus to extract pion source parameters. The first is the simple and widely used static Gaussian distribution model [15] in which the pion source points are assumed to be fixed in space-time and described by Gaussians separable in space and time. In the present application of this model, the dependence on the source lifetime was omitted because the data were found not to be sensitive to it. The correlation function then becomes

$$C(Q_T, Q_L) = A[1+\lambda\exp(-Q_T^2R_T^2/2)\exp(-Q_L^2 R_L^2/2)] \qquad (2)$$

where A is the normalization parameter, $R_T(R_L)$ is the transverse (longitudinal) radius parameter of the source with respect to the beam axis, and $Q_T(Q_L)$ is the momentum difference between the two pions in the transverse (longitudinal) direction. The chaoticity parameter λ is expected to fall between $\lambda = 1$, implying totally chaotic pion emission and $\lambda = 0$, implying totally coherent emission. However, several competing mechanisms might be responsible for any deviation of λ from unity [16,17]. The curves in Figure 2 correspond to the best fits using Eq. 2.

The second model applied is that due to Kolehmainen and Gyulassy [18] which incorporates appropriately the relativistic collision dynamics of a high energy reaction The correlation function is

$$\begin{aligned} &C(Q_T, \Delta y, m_{T1}, m_{T2}) \\ &\qquad = A\,[1 + \lambda\,|\,G(p_1, p_2)|^2 / G(p_1, p_1)\,G(p_2, p_2)] \end{aligned} \qquad (3)$$

where the function G is

$$G(p_1, p_2) = a\,K_o(\sqrt{u})\exp(-Q^2{}_T\,R^2{}_T/4) \qquad (4)$$

where $K_o(\sqrt{u})$ is a modified Bessel function of the complex argument

$$\begin{aligned} u = \quad & 2\,m_{T1}\,m_{T2}\,(1/4T^2 + \tau_o^2)\cosh\Delta y \\ & + (m_{T1}^2 + m_{T2}^2)\,(1/4T^2 - \tau_o^2) \\ & + i\,(\tau_o/T)\,(m_{T1}^2 - m_{T2}^2) \end{aligned} \qquad (5)$$

Here λ, R_T, Q_T have the same meaning as in Eq. 2*), τ_o is the proper time for pion freezeout, T is the temperature of the source, Δy is the rapidity difference between the two pions, and m_{T1} and m_{T2} are their transverse masses.

Both models were fitted to the experimental correlation function in multi-dimensional parameter and phase space using the maximum likelihood method [7]. For the Gaussian source the free parameters were λ, R_T, R_L; for the K-G source the free parameters were λ, R_T and τ_o while the temperature T was fixed at 130 MeV to fit our experimental pion p_T distribution. The results are shown in Table I for various rapidity intervals. The chi-squared per degree of freedom for all fits is close to unity and the errors (statistical only) shown in the table are 1 s.d., measured along the longest axis of the error ellipsoid in 3-parameter space, i.e., the most conservative error estimate, allowing for correlations between the parameters. Figure 3 compares maximum likelihood contours for Gaussian fits to the interval $1 < y < 4$ and $2 < y < 3$ for projections on to three planes in (R_T, R_L,λ) parameter space (1σ contours: solid curves, 2σ contours: dashed curves). For the K-G correlation function, binnings of 20 MeV/c, 0.1, 50 MeV, and 50 MeV were used for Q_T, Δy, m_{T1}, and m_{T2}, respectively. No K-G fit was carried out in the interval $3 < y < 4.5$ due to inadequate statistics. Consider first the results for the wide rapidity interval $1 < y < 4$. The value of R_T and λ extracted from both fits agree, and have values of about 4 fm and 0.3 respectively. The Gaussian fit yields $R_L \approx 3$ fm, while the K-G fit yields $\tau_o \approx 3$ fm/c. The value for R_T is only slightly greater than the radius of the ^{16}O projectile (the charge distribution of which roughly resembles a Gaussian). This suggests that very little, if any, transverse expansion has occurred before pion freeze out. The freezeout time τ_o is comparable to the traversal time of the ^{16}O projectile through the Lorentz-contracted Au nucleus (about 2.6 fm/c in the 16 + 50 c.m. frame). It therefore seems as if the pions are emitted during or soon after the "projectile traversal" stage of the collision. The small value for the λ parameter, similar to that observed in e^-e^+ [8] and hadron-hadron [11] studies, may reflect some degree of coherent pion production [6] during the early stage of the collision. Note that other possible mechanisms for producing a small λ-parameter include the misidentification of K^- as π^- and the decay of long-lived resonances (e.g. η', η, ω) far outside the interaction region which, unlike short-lived resonances (e.g., Δ, ρ), can effectively suppress the Bose enhancement [8,9,17,19].

The interpretation of R_L is complicated by two factors. First, R_L is not Lorentz invariant along the beam direction. To give an idea of the frame dependence of the source parameters, the Gaussian model was fitted to the rapidity interval $1 < y < 2$ in the frame $y_{cm} = 1.5$ instead of the usual $y_{cm} = 2.5$ used for Table I. The result is $R_T = 3.8 \pm 0.5$ fm, $R_L = 4.0 \pm 0.8$ fm, and $\lambda = 0.34 \; +0.09/-0.06$. It can be seen from Table I that R_T and λ are not affected, whereas R_L is larger by a factor of 1.54 in the $y_{cm} = 1.5$ frame, which is just the value of γ for $\Delta y = 1$, as expected.

(*) Note that the <u>square</u> of G, Eq. 4, enters in the correlation function.

The second complication is that the collision dynamics in the longitudinal direction restricts the effective size which can be measured in this direction by pion interferometry [4]. This can be demonstrated using the relativistic expression [4] for the longitudinal extent, L, of the source in a given rapidity interval, Δy, and with pion freeze out time, τ_0,

$$L \cong 2\,\tau_0 \sinh(\Delta y/2)\,. \qquad (6)$$

The K-G analysis for $1 < y < 4$ yields $\tau_0 = 2.9$ fm/c, and this value in Eq. 6 yields $L \cong 12$ fm. The measured value of $R_L \cong 3$ fm is much less than L, as expected from the arguments of reference [4]. Thus, R_L is a frame-dependent measure of the correlation length of the pion source in the longitudinal dimension, its value being sensitive to the source dynamics in this direction. If we set $L = R_L = 3.1$ fm (from $1 < y < 4$) and solve for Δy in Eq. 6, we get an estimate for the rapidity correlation length of $\Delta y \cong 1$, in agreement with the Lund model prediction of ref. [4]. Pions with $\Delta y > 1$ thus do not contribute to Bose-Einstein correlations.

The results of the analysis for three rapidity intervals $\Delta y \cong 1$ compatible with the above discussion are shown in Figure 4. These reveal an interesting feature of the source : the values of all the parameters show a substantial increase in the interval $2 < y < 3$ located at the rapidity of the "16 + 50" c.m. These increases are all compatible with the existence of a large-radius, nearly spherical, thermalized source in this region of rapidity. The increased value of τ_0 follows from the time needed for the pion source to expand to the large radius observed, while the increased value of the chaoticity parameter, λ, supports the idea that some degree of thermalization has taken place.

The radius of such a source can be estimated by a simple model. After formation, expansion and hadronization, it is plausible that the pion distribution should freeze out (i.e., interactions cease) when the scattering mean free path $\lambda_{\pi\pi}$ is of the order of the size of the system. If $\sigma_{\pi\pi}$ is the pion-pion scattering cross section and N_π is the number of pions within radius R, then

$$\lambda_{\pi\pi} = \frac{4/3\,\pi R^3}{N_\pi\,\sigma_{\pi\pi}} \qquad (7)$$

Freezeout will occur at the radius $R_{FO} = \lambda_{\pi\pi}$. Inserting this condition in Eq. (7), assuming $\sigma_{\pi\pi} = 20$ mb [20] and $N_\pi = 3\,N_{\pi^-}$ we find

$$R_{FO} \cong 1.2\,\sqrt{N_{\pi^-}} \qquad (8)$$

For the central rapidity interval the corrected rapidity distribution for negative pions (see Fig. 1) yields $R_{FO} \cong 7.9$ fm, in agreement with the large radius parameter obtained from pion interferometry. For the adjacent rapidity intervals this method predicts too large radii.

The simultaneous changes in both freezeout time and chaoticity suggests that a completely different mechanism occurs there.

A Lorentz invariant form of the simple Gaussian model of Eq. 2 can be constructed by replacing Q_T and Q_L with the invariant momentum difference Q_I, where $Q_I^2 = (p_1 - p_2)^2$, such that Eq. 2 then becomes

$$C(Q_I) = A\,[1 + \lambda \exp(-\,Q_I^2 R^2/2)]\,. \qquad (9)$$

This form is sometimes preferred in e^+- e^- studies [8]. Eq. 6 has been fitted to the present data for the $1 < y < 4$ interval with the result $R = 4.0 \pm 0.2$ fm and $\lambda = 0.29 \pm 0.03$, in agreement with the fit of Eq. 2 to this interval (see Table I).

Finally, although there have been no other pion interferometry measurements with ultra-relativistic heavy-ions, it is useful to compare with p + Xe [10] and $\alpha + \alpha$ [11] measurements which have been done at comparable $\sqrt{s_{NN}}$ (19.4 GeV and 31.5 GeV) as the present experiment, $\sqrt{s_{NN}} = 19.4$ GeV. Having rapidity acceptances of $|\,y\text{-}y_{cm}\,| < 1.5$ and 1.0 for the p + Xe and $\alpha + \alpha$ measurements respectively, and considering central collisions only, both experiments measure values of R_T which are consistent with the size of the projectile, as in the present experiment for all rapidity intervals except $2 < y < 3$. Note that for the $\alpha + \alpha$ experiment, λ is also found to be small. Clearly, it would be interesting to see $|\,y\text{-}y_{cm}\,| < 0.5$ cuts applied to the p + Xe and $\alpha + \alpha$ data.

In summary we have presented a two-π^- Bose-Einstein correlation analysis of central ^{16}O + Au interactions at 200 GeV/nucleon yielding shape and freezeout-time parameters for the pion emitting source, as well as the degree of source chaoticity. Studied in a wide acceptance experiment ($0.6 < y < 4.6$) all parameters exhibit a marked dependence on the rapidity interval considered. At the rapidity of the effective ^{16}O + Au center of mass, a large source of nearly spherical shape, $R_T \approx R_L$ is observed which exhibits a high degree of chaoticity and a relatively long life-time. This suggests that a thermalized "fireball" is formed, which expands towards a low particle density at which the pions decouple. Away from y_{cm}, R_T appears to shrink to the radius of the projectile and R_L diminishes, indicating a rapidity correlation length $\Delta y \approx 1$. In agreement with this picture, the degree of chaoticity decreases at rapidities away from y_{cm}, down to a level $\lambda \approx 0.3$ characteristic of hadron-hadron and e^+ - e^- collisions. With higher statistics it may be possible to analyse precisely the dependence of R_L on y, linked to the string tension in phenomenological QCD hadronization models [4], and to make a comparison of this fundamental parameter in nucleus-nucleus and hadron-hadron collisions.

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FIGURE CAPTIONS

Fig. 1 Uncorrected (solid line) and corrected (dashed line) rapidity distributions normalized per event for negative tracks, for 200 GeV/nucleon ^{16}O + Au. The effective CM rapidity is also indicated.

Fig. 2 Correlation function projected on to the Q_T - axis (for pairs with $Q_L < 100$ MeV/c) for different rapidity intervals :
a) $1 < y < 4$, b) $1 < y < 2$, and c) $2 < y < 3$, data; d) $2 < y < 3$, Fritiof calculation.The projected Gaussian fit is shown (solid curve) for each case, and in (a) the dashed curve shows the fit to the non-Gamow-corrected correlation function.

Fig. 3 Comparison of maximum likelihood contours for Gaussian fits to the intervals $1 < y < 4$ and $2 < y < 3$ for projections on to three planes in (R_T, R_L, λ) parameter space (1σ contour: solid curve, 2σ contour: dashed curve).

Fig. 4 Comparison of a) Gaussian and b) Kolehmainen-Gyulassy source parameters fitted to the data for different rapidity intervals.

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Table I Summary of pion source parameters extracted for different rapidity interval and models

		Gaussian			Kolehmainen-Gyulassy		
y-interval	Accepted Pairs	R_T (fm)	R_L (fm)	λ	R_T (fm)	τ_o (fm/c)	λ
1<y<4	203,612	4.1 ± 0.4	3.1 +0.7/-0.4	0.31 +0.07/-0.03	3.6 ± 0.3	2.9 ± 0.7	0.29 ± 0.05
1<y<2	24,633	4.3 ± 0.6	2.6 ± 0.6	0.34 +0.09/-0.06	4.0 ± 0.7	2.5 ± 1.0	0.30 ± 0.12
2<y<3	39,310	8.1 ± 1.6	5.6 +1.2/-0.8	0.77 ± 0.19	7.3 ± 1.6	6.4 ± 1.0	0.84 ± 0.15
3<y<4.5	20,282	4.3 +1.2/-0.8	5.8 ± 2.2	0.55 ± 0.20	-----------	------------	--------------

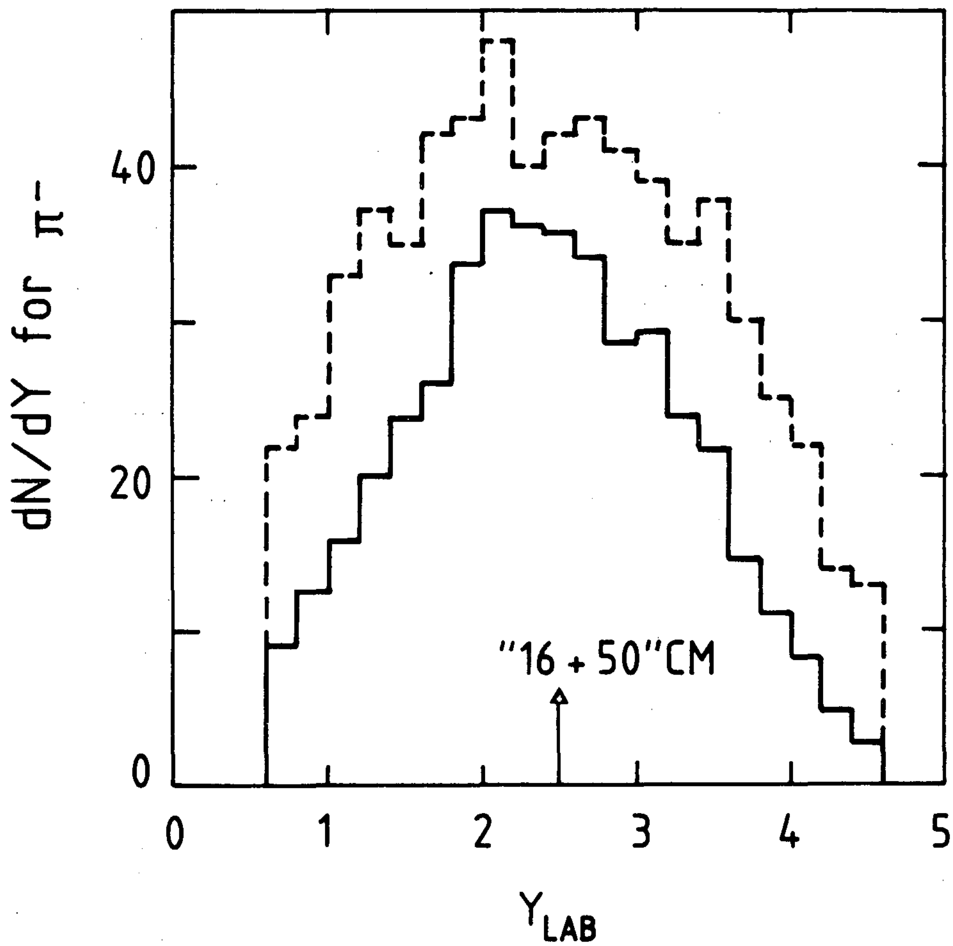

Fig. 1

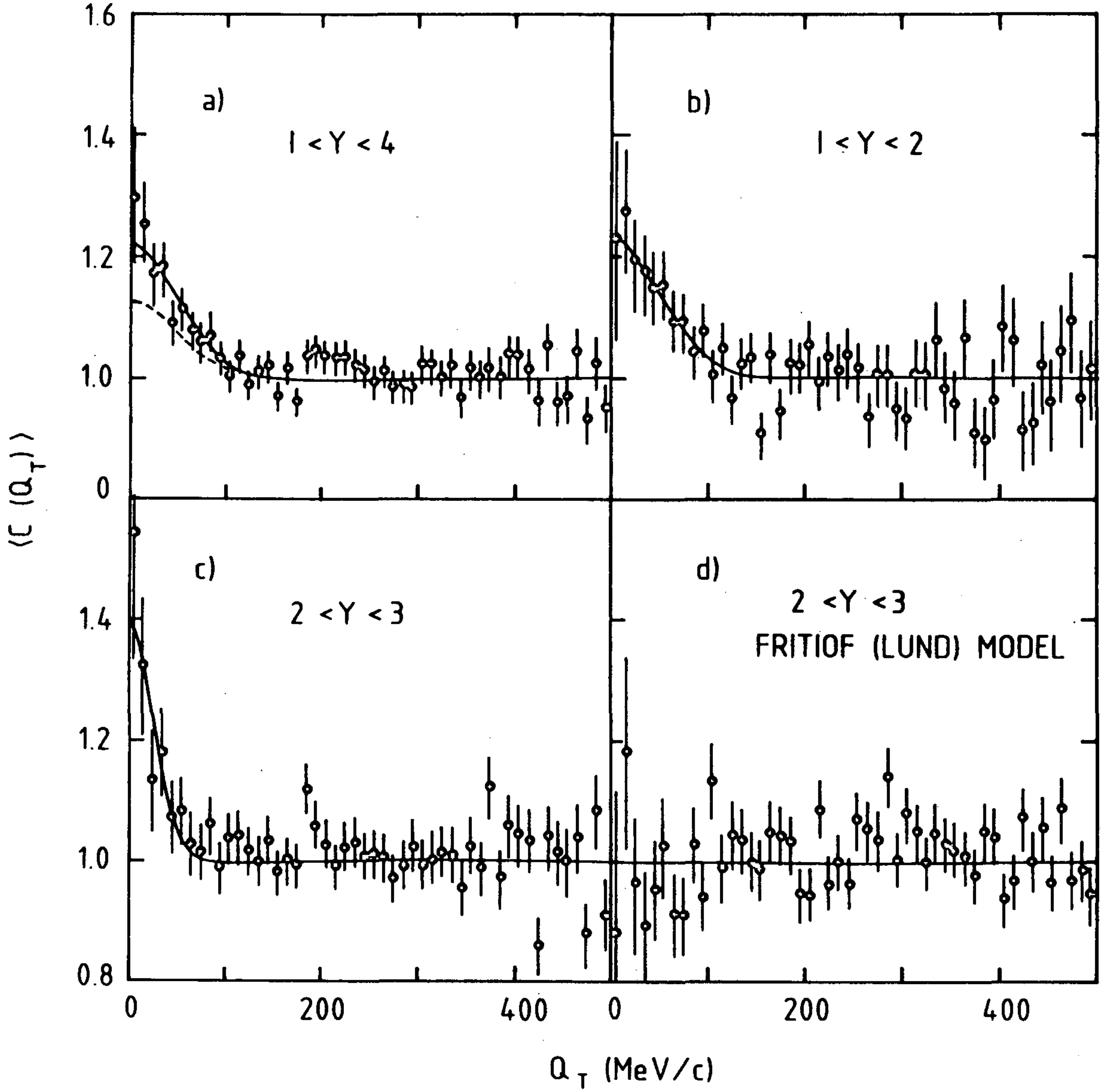
a)
1 < Y < 4
b)
1 < Y < 2
c)
2 < Y < 3
d)
2 < Y < 3
FRITIOF (LUND) MODEL
1.6
1.4
1.2
1.0
0
0.8
⟨C (Q_T)⟩
0
200
400
Q_T (MeV/c)

Fig. 2

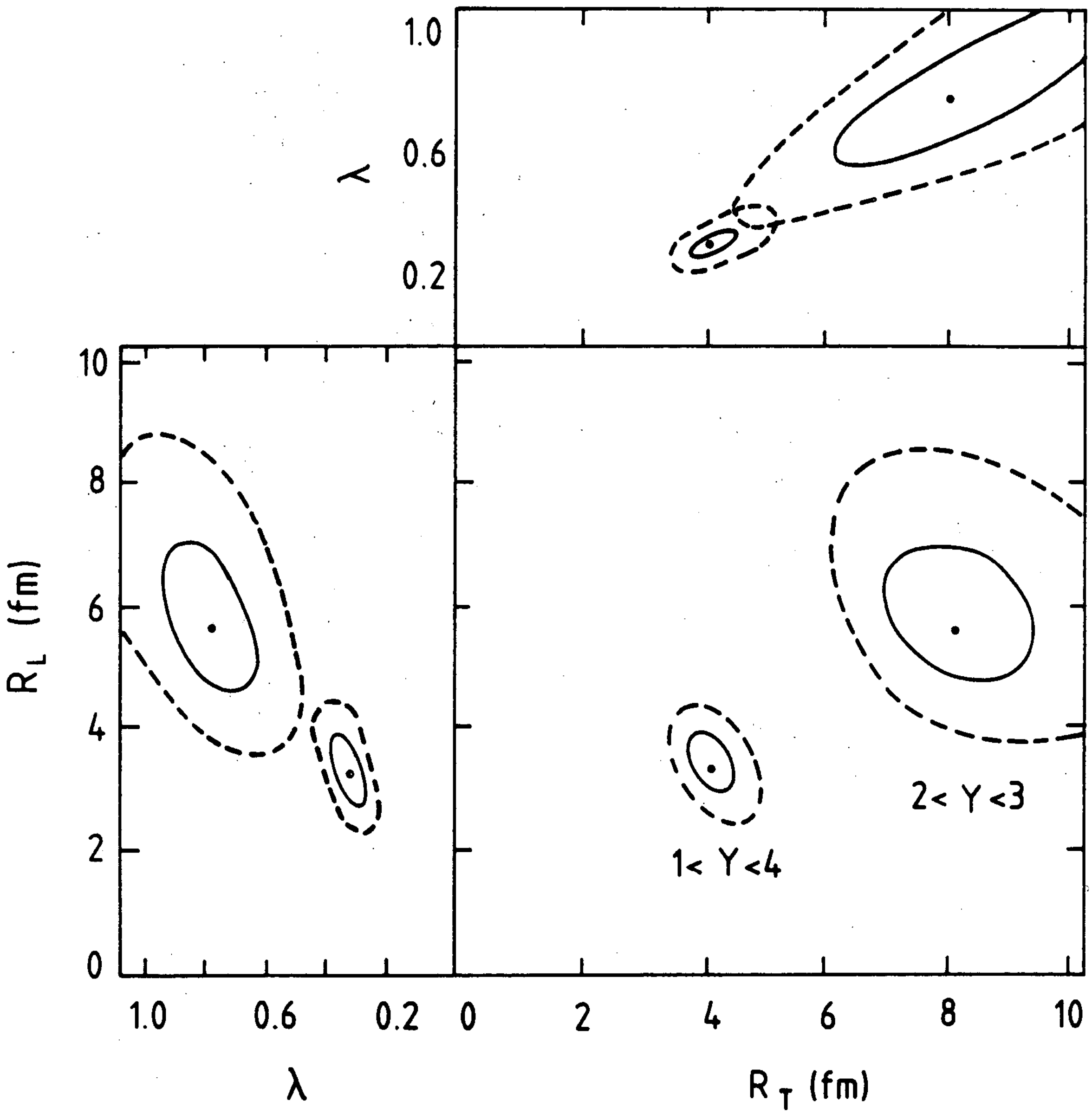

Fig. 3

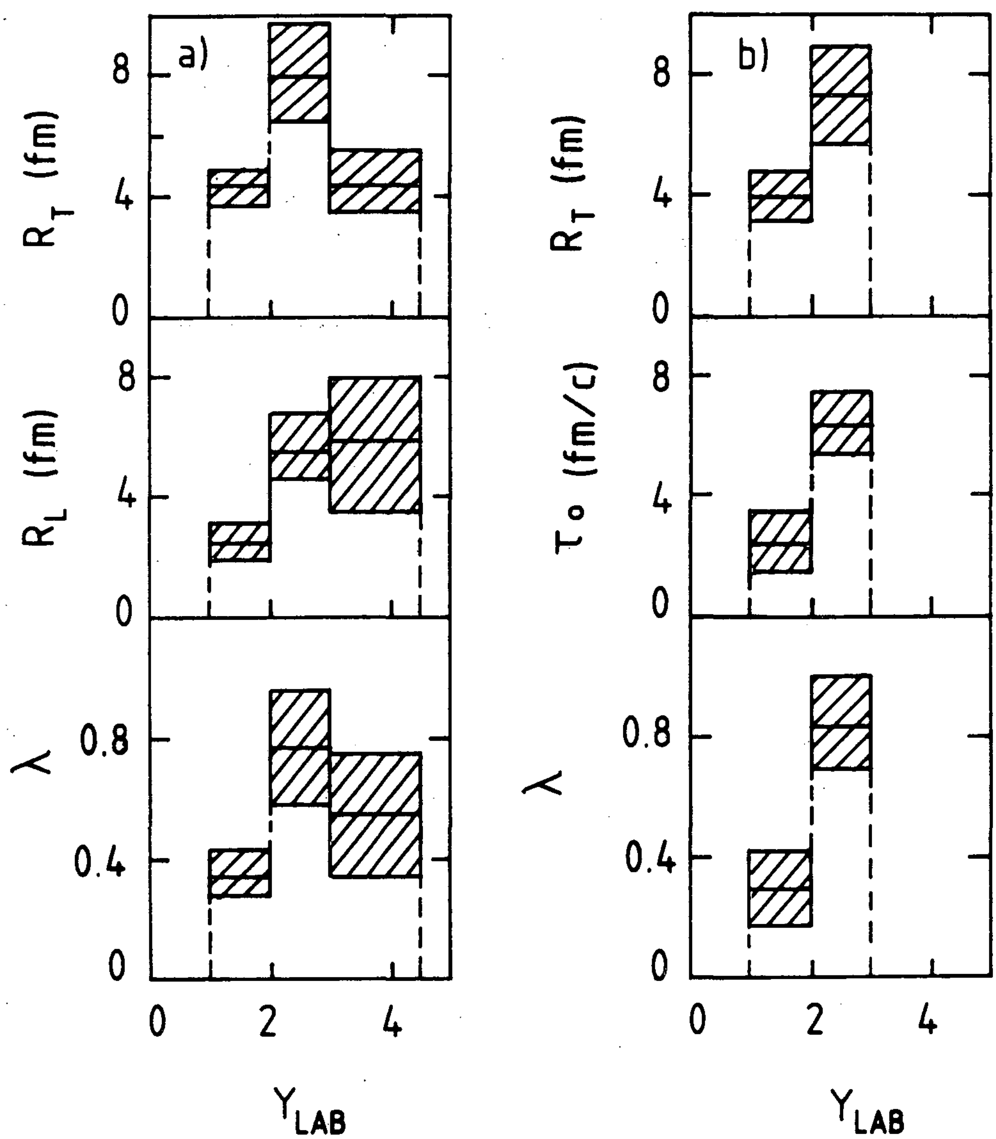

Fig. 4

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