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Authors
Syulassy, M.
Padula, S.S.

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M. Gyulassy and Sandra S. Padula

Nuclear Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720
USA

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Implications of Pion Interferometry for O+Au at 200 AGeV*

M. Gyulassy and Sandra S. Padula[1]

Nuclear Science Division, Mailstop 70A-3307
Lawrence Berkeley Laboratory, Berkeley, CA 94720 USA

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Abstract:
Recent NA35 data on $O + Au \to \pi^-\pi^- + X$ at 200 AGeV are shown to be consistent with both a hadronic resonance gas model and a quark-gluon plasma model for this reaction. We show, in addition, that much higher statistics data will be required to differentiate between these models even with the outward and sideward transverse projected correlation functions.

Correlations between identical pions provide unique information about the space-time dimensions of pion interaction region in hadronic processes[1]. Recently, the NA35 collaboration[2] measured $\pi^-\pi^-$ correlations in O+Au at 200 AGeV and reported that the freeze-out distribution for pions in this reaction is characterized by a surprisingly large freeze-out proper time and transverse radius, $\tau_f \sim R_{\perp f} \sim 7$ fm. In addition, they reported an unusually high degree of coherence for pions away from the central rapidity region. These results are of interest because they may imply a breakdown of popular hadronic transport models like LUND[3,4] and possibly provide evidence for novel dynamical effects associated with the formation of quark-gluon plasma in nuclear collisions[5,6,7].

In this letter, we show, however, that the above results are not conclusive and that the present data are in fact consistent with a wide range of pion source parameters when additional non-ideal dynamical and geometrical degrees of freedom are incorporated into the analysis. In particular, both a hadronic transport model[3] and a quark-gluon plasma hydrodynamic model[8] are found to be consistent with the present correlation data. We also study the sensitivity of "outward" and "sideward" transverse momentum interferometry[5,6] and show that, in contrast to first expectations[7], much higher precision data will be required to differentiate between such competing dynamical models.

In its simplest form, pion interferometry involves fitting the $\pi\pi$ correlation function with the following ansatz:

$$C(k_1, k_2) \equiv P_2(k_1, k_2)/P_1(k_1)P_1(k_2) = 1 + \lambda|\rho(k_1 - k_2)|^2 \ , \tag{1}$$

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where P_m denotes the m identical pion inclusive distribution, k_1 and k_2 are the four-momenta of the observed pions, $\rho(q) = \int d^4x e^{iqx}\rho(x)$ is the Fourier transform of the freeze-out space-time density, and λ is the incoherence or chaoticity parameter. This simple relation is, however, only valid if the freeze-out space-time and momentum coordinates of the pions are uncorrelated. In high energy hadronic processes there are many potential sources of such correlations which can significantly modify[5,9,10,11] the form of $C(k_1, k_2)$, and thus, the geometrical parameters obtained with (1) could be misleading. In phase-space, strong correlations[12] between the space-time and momentum rapidity variables, defined by $\eta = \frac{1}{2}\log((t+z)/(t-z))$ and $y = \frac{1}{2}\log((E+p_z)/(E-p_z))$, resulting from approximate longitudinal boost invariance, have to be taken into account. In addition, a large fraction of the observed π^- could arise from the decay of long lived resonances such as $\omega, K^*, \eta, \cdots$ [13]. It has been known for a long time[14] that those resonances can produce effects that could be misinterpreted as due to unusually long lived sources and partially coherent fields. For nuclear collisions at moderate energies ~200 AGeV, additional complications due to the non-uniformity of the rapidity density[2] and to the large spread of pion freeze-out proper times must also be considered. Other correlations, e.g., between the transverse coordinate ($\mathbf{x}_\perp$) and the transverse momentum component ($\mathbf{p}_\perp$), may have to be considered if collective hydrodynamic flow occurs[5].

To incorporate these many effects into the pion interferometric analysis of nuclear collisions, we have developed a Monte Carlo program based on the covariant current ensemble formalism[9]. In that formalism the source of pions is represented by a large ensemble of current elements, $\{j_a(x) = j_0(u_a^\mu(x-x_a)_\mu)\}$, where x_a^μ and u_a^μ denote the space-time origin and four-velocity of current element a, and $j_0(x)$ specifies each current element in its rest frame. The amplitude for the production of a pion with momentum k is given by the Fourier transform of the total source current,

$$j(k) = \sum_a j_0(u_a k) e^{ikx_a} e^{i\phi_a} \quad , \tag{2}$$

where the factors $e^{i\phi_a}$ are random phases in the case of completely chaotic sources. The m-pion inclusive distribution function is then given by

$$P_m(k_1, \cdots, k_m) = \langle | j(k_1) |^2 \cdots | j(k_m) |^2 \rangle \quad , \tag{3}$$

where $\langle \cdots \rangle$ denotes the ensemble average over the space-time coordinates x_a, four-velocities u_a, and random phases ϕ_a. In the absence of dynamical multi-pion correlations, that ensemble average can be expressed in terms of a "freeze-out" phase-space distribution

$$D(x,p) = \langle \delta^4(x - x_a)\delta^4(p - p_a) \rangle \quad , \tag{4}$$

where $p_a^\mu = m u_a^\mu$. The m pion inclusive distribution functions is then given by[9]

$$P_m(k_1, \cdots, k_m) = \sum_\sigma \left\{ \prod_{i=1}^m G(k_i, k_{\sigma_i}) \right\} \quad , \tag{5}$$

where $\sigma = (\sigma_1, \cdots, \sigma_m)$ runs over the $m!$ permutations of indices. The complex amplitude $G(k_i, k_j)$ is given by the convolution of the freeze-out distribution and two current elements that characterize the production dynamics,

$$G(k_i, k_j) = \int d^4p D(k_i - k_j, p) j_0^*(pk_i/m) j_0(pk_j/m) = \langle e^{i(k_i - k_j)x_a} j_0^*(p_a k_i/m) j_0(p_a k_j/m) \rangle \ , \tag{6}$$

The objective of pion interferometry from this point of view is to constrain the form of the freeze-out source distribution. The model dependence enters, however, not only through the parameterization of $D(x,p)$ but also through the model adopted for $j_0(k)$. In this formalism the current elements play the same role as wavepackets do in the Wigner density formalism[5,15]. From (6) it is clear that (1) can apply only in the very special case that $D(q,p) \approx \rho(q) f(p)$, and that $f(p)$ is sharply peaked compared to $j_0(k)$. In other words, the space-time and velocity coordinates of the source elements must be uncorrelated and the Doppler shift of the pion spectra from each source element must be negligible. Neither of these conditions is satisfied in high energy hadronic processes.

In our calculations, we adopt for simplicity a covariant pseudo-thermal model for the current elements[9],

$$j_0(pk/m) = \exp(-pk/(2mT)) \ . \tag{7}$$

where the effective "temperature", T, characterizes the spread of the source elements in momentum space and controls the transverse momentum distribution of pions in our case. With this model the amplitude assumes the particularly simple form

$$G(k_1, k_2) = \langle \exp\{iqx_a - Kp_a/(mT)\} \rangle \ , \tag{8}$$

depending not only on $q^\mu = k_1^\mu - k_2^\mu$ but also on the mean pair momentum $K^\mu = \frac{1}{2}(k_1^\mu + k_2^\mu)$. Note that this dependence is, however, quite different from the K dependence arising in the non-covariant Wigner formalism[5,15].

The effects of long lived resonances can be easily included in the semiclassical approximation. Note that the pion freeze-out coordinates, x_a^μ, are related to its parent resonance production coordinates, x_r^μ, through

$$x_a^\mu = x_r^\mu + u_r^\mu \tau \ , \tag{9}$$

where u_r^μ is the resonance four velocity and τ is the proper time of its decay. Inserting (9) into (8), summing over resonances r of widths Γ_r, and averaging over their decay proper times, we obtain the final expression

$$G(k_1, k_2) \approx \langle \sum_r f_{\pi^-/r} (1 - iqu_r/\Gamma_r)^{-1} \exp(iqx_r - Ku_r/T_r) \rangle \ , \tag{10}$$

where $f_{\pi^-/r}$ is the fraction of the observed π^-'s arising from the decay of a resonance of type r, and T_r characterizes the decay distribution of that resonance. The factor $(1 - iqu_r/\Gamma_r)^{-1}$ insures that pions arising from decay of long lived resonances do not interfere effectively at moderate q. While (10) is only valid in the semiclassical limit and involves an idealized model (7) of the decay dynamics, it is manifestly Lorentz covariant and is of sufficient generality to allow the study of a variety of nontrivial dynamical models of high energy nuclear collisions.

In this letter, we consider a class of dynamical models that can be characterized by a set of resonance fractions $\{f_{\pi^-/r}\}$, and a freeze-out phase space distribution of the form

$$D(x,p) \propto \tau e^{-\tau^2/\tau_f^2} e^{-(\eta-y)^2/2\Delta\eta^2} e^{-(y-y^*)^2/2Y_c^2} e^{-r_\perp^2/R_\perp^2} \ , \tag{11}$$

where τ_f specifies the width and mean value of the freeze-out proper time, $\tau = (t^2 - z^2)^{1/2}$, distribution, $\Delta\eta$ specifies the rms fluctuations of $\eta = \frac{1}{2}\log((t+z)/(t-z))$ around $y = \frac{1}{2}\log((E+p_z)/(E-p_z))$, Y_c is the width of the rapidity distribution centered at y^*, and $R_\perp$ is the rms transverse radius at freeze-out. In this work, we estimate the parameters of the freeze-out distribution and resonance fractions using the ATTILA version of the LUND Fritiof multi-string model[3] and a string tension, $\kappa = 1$ GeV/fm, to map momentum space into coordinate space. For O+Au at 200 AGeV, we find that $Y_c \approx 1.4$, $y^* = 2.5$, $\Delta\eta \approx 0.7$, $\tau_f \approx 3$ fm/c and $R_\perp \approx 3$ fm. The π^- pedigree is determined to be $f_{\pi^-/direct} \approx 0.19$, $f_{\pi^-/\rho} \approx 0.40$, $f_{\pi^-/\omega} \approx 0.16$, and $f_{\pi^-/K^*} \approx 0.09$, in rough agreement with data on hadron-hadron reactions[13]. The contribution from longer lived resonances is set to zero.

In Ref.[6] a similar form for D was employed to parametrize the results of a quark-gluon plasma hydrodynamic calculation. In that case, the parameters were found to be $\tau_f = 9.0$ fm/c, $R_\perp = 3.3$ fm, $\Delta\eta = 0.76$, assuming that $Y_c = \infty$ and neglecting resonances. The characteristic long lifetime found in such hydrodynamic models results from the slowness of the hadronization transition[16,10,11] when the latent heat of transition is large.

For comparison, the idealized inside-outside cascade model[12] considered in [9] and used in [2] to fit the data corresponds to

$$D(x,p) \propto \delta(\tau - \tau_f)\delta(\eta - y)\exp(-r_\perp^2/R_\perp^2) \ , \tag{12}$$

with resonances neglected.

Given the freeze-out distribution, we calculate the amplitude, $G(k_1,k_2)$, by Monte Carlo sampling with typically 400-800 freeze-out phase-space coordinates selected according to (11) for each (k_1,k_2) pair. The freeze-out distributions for all resonance species is taken to be identical, and all T_r are set to 0.13 GeV to reduce the number of free parameters. To compare with data on the transverse projected correlation function[2], $\langle C(q_\perp)\rangle$, we must compute

$$\langle C(q_\perp)\rangle = 1 + \lambda \frac{\int d^3k_1 d^3k_2 \Theta(q_\perp; k_1, k_2)|G(k_1,k_2)|^2}{\int d^3k_1 d^3k_2 \Theta(q_\perp; k_1, k_2) G(k_1,k_1) G(k_2,k_2)} \ , \tag{13}$$

where the experimental constraints are built into Θ. For the present data Θ is nonvanishing only if $|\mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}|$ is within 5 MeV/c of $q_\perp$, $|k_{1z} - k_{2z}| \leq 0.1$ GeV/c, and if both y_1 and y_2 are in a certain interval $[y_{min}, y_{max}]$. The six dimensional integrals are computed by importance sampling using a model single inclusive distribution to generate typically ~ 200 pairs and repeating 2000-4000 times to insure convergence.

A good test of the numerical method is provided by reproducing the fitted curves in Ref.[2], which follow assuming the ideal inside-outside cascade distribution (12). In Fig 1a and 1d, we show that our calculations employing the reported parameters[2], $\tau_f = 6.4$ fm/c, $R_\perp = 7.3$ fm and $\lambda = 0.84$ for π^- in the rapidity interval $2 < y < 3$ and $\tau_f = 2.5$ fm/c, $R_\perp = 4.0$ fm, and $\lambda = 0.30$ in the interval $1 < y < 2$, do in fact provide a good fit to the data (note that the data have been corrected for Coulomb final state interactions).

Next, we show in Figs 1b,1e, the calculated curves for the case of non-ideal hadron resonance dynamics. For these calculations we chose $\Delta\eta = 0.8$ and considered $\tau_f = R_\perp = 2, 4, 6$ fm. We have performed an additional Monte Carlo hadronic cascade calculation taking as input the output of the LUND fragmentation model[3] and found that with an effective cross section, $\sigma = 20$ mb, the true freeze-out distribution is roughly characterized by $\tau_f \sim R_\perp \sim 4$ fm for this reaction. In both Fig. 1b and 1e, the chaoticity parameter is fixed to $\lambda = 1$ as appropriate for completely chaotic sources. From this result, we see that the present data are consistent with the freeze-out distribution expected on the basis of this resonance gas model.

On the other hand, in Figs. 1c,1f we find that the data are also consistent with the more provocative quark-gluon plasma model of Ref.[6,8]. Note that our results for the plasma model differ substantially from those reported in Ref.[6]. We attribute this discrepancy to an improved numerical treatment and a more accurate definition of the experimental projected correlation function in the present work. The reason why both models can reproduce the data is that the long lifetime of the mixed phase in the plasma model can lead to the same effect as that produced by long lived hadronic resonances.

While it would be difficult to justify ruling out any of the three models from the present data, the "exotic" parameters obtained with the ideal inside-outside cascade model[9] are the least compelling, since it would be truly remarkable if the degree of coherence in such violent nuclear collisions were not negligible. Note that in Fig 1d, ideal dynamics with $\lambda = 1$ in fact fails to reproduce the data.

Finally, it has been suggested[5,6] that the projected correlation function in terms of "outward" and "sideward" transverse momenta,

$$q_{out} = |\mathbf{q}_\perp \cdot \mathbf{K}_\perp|/K_\perp \;\;,\;\; q_{sid} = |\mathbf{q}_\perp - \mathbf{q}_{out}| \;\;, \tag{14}$$

could differentiate between hadronic and plasma models and provide an "unambiguous"[7] signature of quark-gluon plasma formation. In Fig. 2a and 2b, we compare resonance gas and plasma model predictions for these projected correlation functions for the case $y_1 = y_2 = y^* = 2.5$. Indeed, quantitative differences can be seen. However, when integrated over a broad rapidity interval, $2 < y_\pi < 3$, as in the present data, most of those differences are washed out as can be seen in Figs. 2c,d. This shows that much higher statistics data will be required[17] to differentiate between present models[4] for nuclear collisions. Of course, additional experimental information will be essential to constrain further the dynamical degrees of freedom in both types of models. Especially important will be an independent direct measurement of the abundance of resonances.

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Figure 1:
Analysis of the transverse projected $\pi^-\pi^-$ correlation data of NA35[2]. The histograms in parts (a,d) are calculated assuming an ideal inside-outside cascade (IOC) source with

parameters ($\tau \equiv \tau_f, R_T \equiv R_{\perp f}$) taken from [2]. In parts (b,e) a non-ideal resonance gas source is considered with parameters, $\tau \sim R_T \sim 4$ fm, as suggested by the ATTILA version of the LUND Fritiof model[3]. Parts (c,f) correspond to the quark-gluon plasma model of [6]. Parts (a-c) refer to the central rapidity region, $2 < y_\pi < 3$, and parts (d-f) refer to the region $1 < y_\pi < 2$.

Figure 2:
Comparison of transverse projected "outward" and "sideward" interferometry calculated with a resonance gas model (a,c) and a quark-gluon plasma model (b,d). In (a,b) the two pion rapidities are restricted to $y_\pi = y^* = 2.5$, while in (c,d) a finite range, $2 < y_\pi < 3$, is considered. Q_T, Q_{OUT}, Q_{SID} refer to the argument of the transverse projected correlation function. Q_{OUT} corresponds to the projection of $\mathbf{q}_\perp$ parallel to $\mathbf{K}_\perp$ and Q_{SID} to the projection of $\mathbf{q}_\perp$ perpendicular to $\mathbf{K}_\perp$.

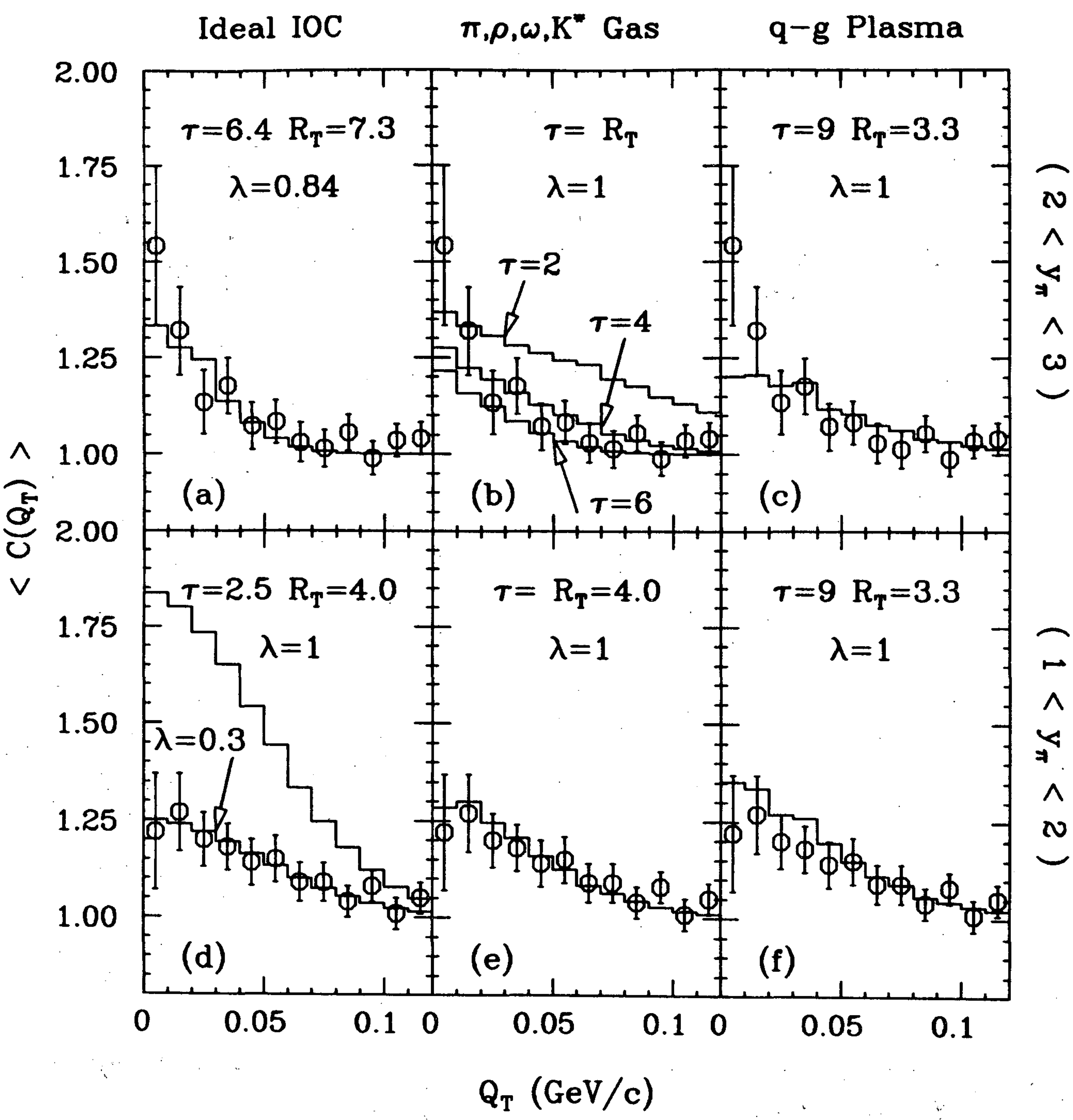
Ideal IOC
π,ρ,ω,K* Gas
q−g Plasma
τ=6.4 R_T=7.3
λ=0.84
τ= R_T
λ=1
τ=9 R_T=3.3
λ=1
τ=2
τ=4
τ=6
(a)
(b)
(c)
τ=2.5 R_T=4.0
λ=1
λ=0.3
τ= R_T=4.0
λ=1
τ=9 R_T=3.3
λ=1
(d)
(e)
(f)
2.00
1.75
1.50
1.25
1.00
< C(Q_T) >
(2 < y_π < 3)
(1 < y_π < 2)
0
0.05
0.1
Q_T (GeV/c)

Figure 1

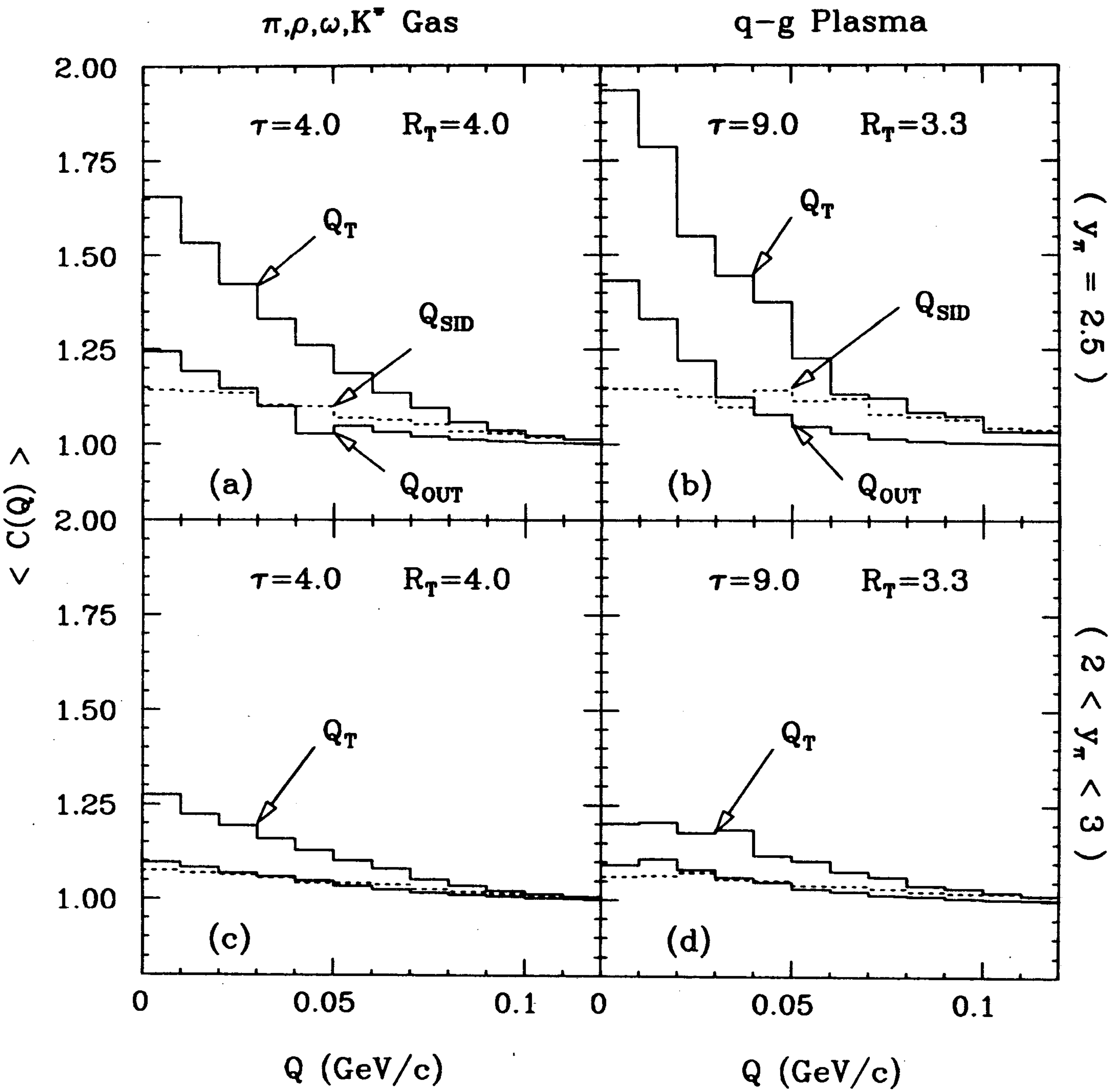
π,ρ,ω,K* Gas
q−g Plasma
τ=4.0 R_T=4.0
τ=9.0 R_T=3.3
Q_T
Q_SID
Q_OUT
(a)
(b)
(c)
(d)
< C(Q) >
(y_π = 2.5)
(2 < y_π < 3)
2.00
1.75
1.50
1.25
1.00
0
0.05
0.1
Q (GeV/c)

Figure 2

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