Jet acoplanarity as a quark-gluon-plasma probe

Manfred Rammerstorfer and Ulrich Heinz
Institut for Physik I, Theoretische Physik, Universitat Regensburg, Universitatsstrasse 31, D-8400 Regensburg, West Germany
(Received 23 March 1989)

We reinvestigate the probability distribution of jet acoplanarity as a tool to search for quark-gluon-plasma formation in nuclear collisions. We find serious hadronic background effects from the surrounding nuclear matter in nuclear collisions, which severely limit the usefulness of jet acoplanarity as a quark-gluon-plasma probe. Only if quark-gluon-plasma creation can be ascertained or excluded independently may a high jet acoplanarity provide qualitative additional information.

Two recent papers[1,2] studied the probability for jet acoplanarity as a probe of a quark-gluon plasma (QGP) created in ultrarelativistic nuclear collisions. In contrast with proton-proton collisions, jets from nuclear collisions have to propagate through the surrounding hot nuclear medium before hadronizing, which may significantly affect the momentum distribution of the outcoming hadrons. While Refs. 1 and 2 analyzed the case where the nuclear collision initially produces QGP, we complement this work by a study of nuclear collisions *without plasma formation.* We pay particular attention to the experimental biases caused by the need to identify the jet particles among a multitude of other, softly produced hadrons and improve on the qualitative, but not very rigorous treatment of this issue given in Ref. 2.

A characteristic feature of jet events in *pp* and $\bar{p}p$ collisions is their acoplanarity, defined[3] as the amount of momentum orthogonal to the scattering plane fixed by the initial hard scattering. Even for *pp* collisions, due to soft-gluon bremsstrahlung in the initial state, the strict confinement of the final particles to the ideal scattering plane (determined experimentally by minimizing the acoplanarity) is lost.[4] The quantity of interest is the resulting probability distribution $dP/d\tilde{k}_{t\eta}$ to acquire a certain transverse momentum $\tilde{k}_n$ with respect to this ideal scattering plane. The additional broadening of this "acoplanarity distribution" in *nuclear* collisions through scattering of the jet partons by the surrounding nuclear matter is the subject of Refs. 1 and 2 and of this note. Our notation is as in Ref. 2 except that we use tildes when referring to the jet axis, while coordinates without tildes are measured relative to the nuclear collision axis.

Experimentally, a quantity is to be determined to which the momentum of each individual particle of the jet contributes; thus a simple jet-searching algorithm based on calorimetry is not sufficient, but individual particles and their momenta have to be identified. Although in nuclear collisions generally the rapidity density of transverse energy will be large, due to the very large multiplicity of soft ($E_T < 2$ GeV) particles, a jet can then be distinguished[5] from this background by the presence of a cluster of particles with very high momentum ($k_T > 2$ GeV). The lower limit on the total transverse energy of a jet ("jet mass") that can in this way be identified is given by a few times the average E_T (about 1–2 GeV) of the soft particles. We will therefore calculate the acoplanarity for jets with $E_T \geq 10$ GeV.

However, in doing so it has to be taken into account[2] that the low-k_t component of the jet cannot be separated from the soft nuclear background and therefore should not be used in calculating the acoplanarity distribution. The calculation thus has to include a low rapidity cutoff $\tilde{y}_0$ for the rapidity $\tilde{y}$ along the jet axis, and the acoplanarity distribution has to be computed with the remaining very high rapidity component. In Ref. 2 a very rough estimate of this cutoff was made; since it influences the acoplanarity distribution in a crucial way, we give in the appendix a more accurate treatment of this problem.

The aim of this note is the following. The authors of Refs. 1 and 2 compared the probability distribution $dP/d\tilde{k}_{t\eta}$ for jets passing through QGP with the plasmaless case of e^+e^- or *pp* collisions. We complement these analyses by a study of the background caused by nuclear collisions in which only hot hadronic matter and no QGP is excited. We find that, after correcting for the effects from the above low-k_t cutoff, a comparison of the QGP scenario to the purely hadronic one leaves only very small and uncharacteristic differences in the acoplanarity distribution. Thus it appears very hard to extract specific information about the surrounding partonic or hadronic matter from a measurement of the jet acoplanarity.

DESCRIPTION OF THE MODEL

To simulate the effects of the surrounding hadronic matter on the jet acoplanarity we assume that it can be described as a hot hadronic resonance gas in local thermal equilibrium. We take into account all known particles with rest masses below about 1 GeV. Otherwise, to facilitate comparison, we take over the assumptions made in Ref. 2, i.e., boost-invariant longitudinal expansion and cooling of this resonance gas, and a vanishing chemical potential. In slight variation to Ref. 2, we parametrize the initial conditions of the collision zone by its initial temperature rather than by the final multiplicity density (which are directly related[6]). The technique for calculating $dP/d\tilde{k}_{t\eta}$ is identical to Ref. 2. The acoplanarity distribution is formally given by the impact-

 © 1990 The American Physical Society

parameter integral

$$\frac{dP}{d\tilde{k}_{t\eta}}=\frac{1}{\pi}\int_0^\infty db\,\cos(\tilde{k}_{t\eta}\cdot b)\exp[\bar{B}(b)+\bar{C}(b)+\bar{F}(b)]\ . \tag{1}$$

where $\bar{B}(b)$, $\bar{C}(b)$, and $\bar{F}(b)$ are defined in Ref. 2: In elementary pp collisions only initial-state gluon bremsstrahlung, described by $\bar{B}(b)$, contributes. For nuclear collisions both $\bar{C}(b)$ (as an unavoidable effect from soft background subtraction, see the Appendix) and $\bar{F}(b)$ (which contains the interesting effects from final-state scattering off the surrounding hot matter) also enter. The crucial factor in $\bar{F}(b)$ is[1,2] the product of surrounding particle density and the cross section of the jet partons (here as in Ref. 2 assumed to be gluons) with those particles, averaged over the jet trajectory. We take the same cross-section values as in Ref. 2 (derived from the additive quark model); for baryons the parton-meson cross section is multiplied by a factor of $\frac{3}{2}$. Thus the main difference between the QGP and hadron-gas scenario for, say, a given temperature is the different particle densities of the surrounding hot matter.

RESULTS

The original calculations of Refs. 1 and 2 were taken as a hint that an experimental study of jet acoplanarity could yield useful information about a QGP formed in nuclear collisions. They indicated a characteristic flattening of the acoplanarity distribution $dP/d\tilde{k}_{t\eta}$ (compared to the case of pp collisions) due to scattering by the surrounding plasma. However, our analysis shows (see dotted and dashed-dotted lines in Figs. 1 and 2) that the dominant part of this effect is due to the bias introduced by the (experimentally unavoidable) low-k_t cutoff. (All calculations were done for equal $A=100$ nuclei, for which we derive in the Appendix a lower limit $\tilde{y}_0=2.69$ for the rapidity cutoff.) The observed shift in the distribution towards larger $\tilde{k}_{t\eta}$ arises from the removal of a large fraction of soft particles which are closely confined to the scattering plane and produce the large peak at small $\tilde{k}_{t\eta}$ in the pp case.

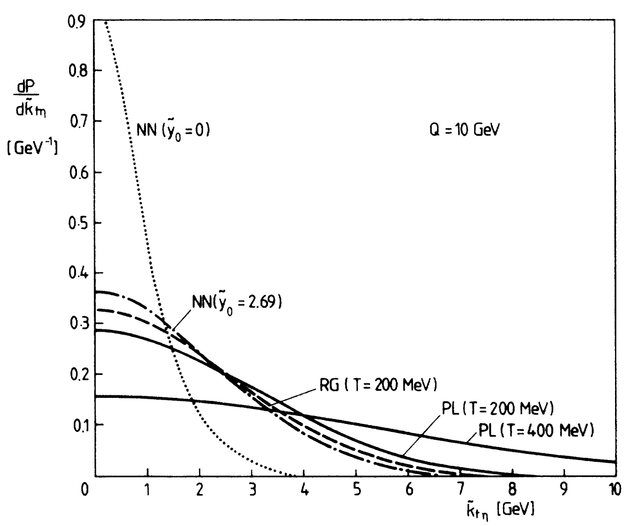

FIG. 1. The acoplanarity distribution expected for QGP (solid lines) compared to the case of a hot hadron resonance gas (dashed line). Dotted line: pp collisions without rapidity cutoff; dashed-dotted line: including the low rapidity cutoff, Eq. (15), but no plasma or hadron gas effects. All curves are calculated for $A=100$. Two plasma temperatures $T=200$ MeV and $T=400$ MeV are shown whereas for the resonant gas we have $T=200$ MeV. $Q=10$ GeV is the jet mass.

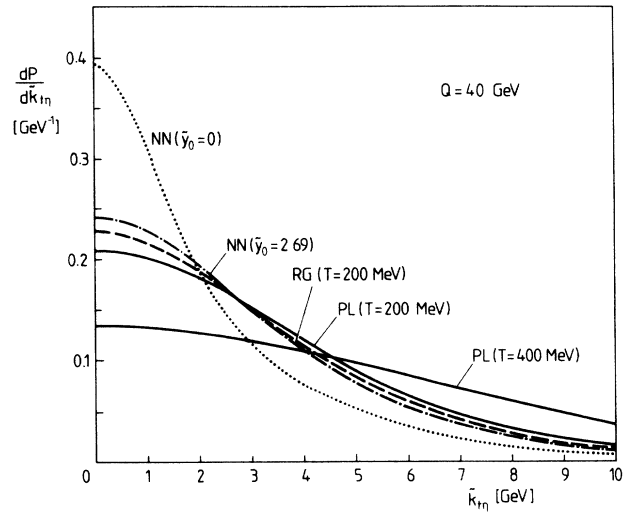

FIG. 2. Same as Fig. 1, but for a jet mass $Q=40$ GeV.

The remaining effect from the actual scattering of the jet partons in the surrounding dense matter is given by the other three curves in Figs. 1 and 2 describing three possible scenarios: an initial resonance gas (RG) of temperature $T=200$ MeV, and initial QGP with subsequent conversion to a mixed phase[2] (PL) for temperatures $T=200$ and 400 MeV. The curves for a massless pion gas with $T=200$ MeV were found to be very close to the ones for the resonance gas, due to compensating effects on the hadron density from neglecting the pion mass here and including additional resonance degrees of freedom there.

SUMMARY

The general features of our results are that the differences between the plasma and hadron-gas scenarios are small compared to the change in the distribution caused by the low-rapidity cutoff which is forced on us by the large background of soft nuclear particles. Even for the extreme value $T=400$ MeV the distribution from the QGP scenario is reduced by less than a factor 2 in the region $\tilde{k}_{t\eta}\leq 5$ GeV/c relative to the hadron resonance gas. The same effect could at constant particle density be generated by a larger rescattering cross section, while for smaller cross sections the differences between QGP and hadron gas are even further diminished. On the other hand, the effect of low-rapidity cutoff remains very strong even for the highest-mass jets as shown in Fig. 2.

If one combines these findings with the further complication of an increased uncertainty in the determination of the ideal jet scattering plane (which is caused by the abundant soft nuclear particles and has so far been neglected), it appears very unlikely that from the shape alone of the acoplanarity distribution for jets from nuclear collisions any detailed information about the properties of the hot nuclear matter formed in these collisions can be gained.

Only in combination with other signals may it be of some value. If it were known for a certain high-acoplanarity event on other grounds that a QGP had been formed, then a large temperature for the plasma may be inferred; if it were known that QGP formation had not taken place, a high acoplanarity might indicate anomalously large rescattering cross sections.

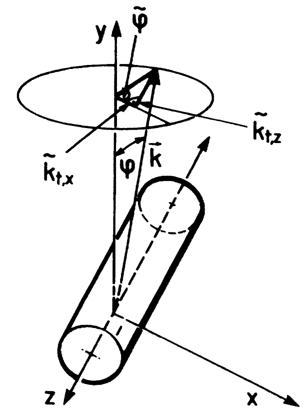

FIG. 3. Geometrical situation of a jet being emitted at 90° relative to the nuclear collision (z) axis. y is the jet axis, ϕ is the angle in the x,y plane between the momentum of the emitted particle and the jet axis. $\tilde{\phi}$ is measured in the x,z plane and is the angle between the x axis and the particle's transverse momentum $\tilde{\mathbf{k}}_t$ with respect to the jet axis.

ACKNOWLEDGMENTS

Of of us (M.R.) wishes to thank Dr. Kang S. Lee for fruitful discussions, and Professor H. Baier for initiating this research. This work was supported in part by the Deutsche Forschungsgemeinschaft, Grant. No. He1283/3-1.

APPENDIX

Here we present the correct[6] derivation of the function $\bar{C}(b)$ in Eq. (1), which implements the low-k_t cutoff for the jet particles counting towards the acoplanarity. For simplicity, we consider only the case where the jet is emitted at 90° to the beam axis (which is the most favorable in terms of suppressing soft particles from the nuclear collision). Then k_t, the transverse momentum relative to the beam axis, is directly related to the rapidity $\tilde{y}$ along the jet axis, for which we thus have to determine a cutoff value $\tilde{y}_0$.

We start with the physical condition that, in a given volume element in momentum space, the particle multiplicity originating from soft processes in the A-A collision must be lower than the multiplicity of particles belonging to the jet:

$$\frac{dN^{AA}}{\tilde{k}_t d\tilde{k}_t d\tilde{y}\, d\tilde{\phi}} < \frac{d\tilde{N}}{\tilde{k}_t d\tilde{k}_t d\tilde{y}\, d\tilde{\phi}} . \tag{2}$$

Only if this is satisfied can the particles coming from the volume element be reasonably associated with the jet. The geometrical situation is explained in Fig. 3.

The transformation between jet and beam coordinates is done via

$$\tilde{k}_t = \sqrt{k_t^2 \sin^2\phi + m_t^2 \sinh^2 y} , \tag{3}$$

$$\tilde{y} = \operatorname{arcsinh}\left[\frac{k_t}{\tilde{m}_t}\cos\phi\right] , \tag{4}$$

$$\tilde{\phi} = \arccos\left[\frac{k_t}{\tilde{k}_t}\sin\phi\right] . \tag{5}$$

The two different multiplicities are given by

$$\frac{dN^{AA}}{d\phi\, dy\, k_t dk_t} = f(A)\frac{1}{2\pi M_T^2} e^{-k_t/M_T} \tag{6}$$

for the nuclear background and

$$\frac{d\tilde{N}}{d\tilde{\phi}\, d\tilde{y}\, \tilde{k}_t d\tilde{k}_t} = f(1)\frac{1}{2\pi M_T^2} e^{-\tilde{k}_t/M_T} \tag{7}$$

for the distribution of the jet particles. M_T is a slope parameter for the momentum distributions transverse to the beam or jet axis, respectively, and is taken as 0.4 GeV. $f(A)$ and $f(1)$ are the values for the rapidity distributions dN/dy and $dN/d\tilde{y}$, respectively (assumed[7] to be constant). Using $d\tilde{\phi}\, \tilde{k}_t d\tilde{k}_t d\tilde{y} = d\phi\, k_t dk_t dy$, the transformed version of the nuclear multiplicity reads

$$\frac{dN^{AA}}{\tilde{k}_t d\tilde{k}_t d\tilde{y}\, d\tilde{\phi}} = \frac{f(A)}{2\pi M_T^2}\exp\left[-\frac{1}{M_T}\left[\tilde{k}_t^2\cos^2\tilde{\phi} + \frac{\tilde{m}_t^2}{\tilde{k}_t^2}\sinh^2\tilde{y}\right]^{1/2}\right] . \tag{8}$$

Inserting this and Eq. (7) into Eq. (2) and integrating over $\tilde{k}_t$, we obtain the condition

$$\frac{dN^{AA}}{d\tilde{y}\,d\tilde{\phi}}=\frac{f(A)}{2\pi M_T^2}\int_0^\infty d\tilde{k}_t\tilde{k}_t\exp\left[-\frac{1}{M_T}\sqrt{\tilde{k}_t^2(\cos^2\tilde{\phi}+\sinh^2\tilde{y})+m^2\sinh^2\tilde{y}}\right]$$
$$=\frac{f(A)}{4\pi M_T^2}\frac{2M_T^2}{\cos^2\tilde{\phi}+\sinh^2\tilde{y}}\left[\frac{m\sinh\tilde{y}}{M_T}+1\right]e^{-m\sinh\tilde{y}/M_T}$$
$$<\frac{f(1)}{2\pi}=\frac{d\tilde{N}}{d\tilde{y}\,d\tilde{\phi}}\,. \quad (9)$$

Finally performing the ϕ integration we end up with the condition

$$\frac{dN^{AA}}{d\tilde{y}}=\frac{2f(A)(m\sinh\tilde{y}/M_T+1)}{\sinh 2\tilde{y}}\times\exp\left[-\frac{m}{M_T}\sinh\tilde{y}\right]<f(1)=\frac{d\tilde{N}}{d\tilde{y}}\,. \quad (10)$$

Taking as in Ref. 2 $f(A)=2Af(1)$, we obtan a numerical value for the cutoff rapidity $\tilde{y}_0$, which for colliding nuclei with mass $A=100$ is $\tilde{y}_0=2.69$, while for $A=1$ we find $\tilde{y}_0=1.01$ and for $A=200$ it is $\tilde{y}_0=2.86$.

The transverse momentum $C(\tilde{k}_t)$ lost from the jet if only the high-rapidity component ($\tilde{y}>\tilde{y}_0$) is considered is given by

$$C(\tilde{k}_t)=\int_0^{\tilde{y}_0}d\tilde{y}\frac{d\tilde{N}}{d\tilde{y}\,d^2\tilde{k}_t}=\frac{f(1)}{2\pi M_T^2}\int_0^{\tilde{y}_0}d\tilde{y}\,e^{-\tilde{k}_t/M_T}\approx\frac{2}{\pi}\frac{\tilde{y}_0}{M_T^2}e^{-\tilde{k}_t/M_T}\,. \quad (11)$$

with[2] $f(1)\approx 4$. Fourier transformation with respect to the impact parameter yields [the -1 serves[1] to correctly normalize $\bar{C}(b)$]

$$\bar{C}(b)=\int d^2\tilde{k}_t(e^{i\mathbf{k}_t\cdot\mathbf{b}}-1)C(\tilde{k}_t)$$
$$=\frac{2\tilde{y}_0}{\pi}\int_0^\infty d\left[\frac{\tilde{k}_t}{M_T}\right]\frac{\tilde{k}_t}{M_T}e^{-\tilde{k}_t/M_T}\times\int_0^{2\pi}d\theta(e^{i\tilde{k}_t b\cos\theta}-1)$$
$$=4\tilde{y}_0\left[\frac{1}{(1+M_T^2b^2)^{3/2}}-1\right]. \quad (12)$$

This form of the "cutoff function" $\bar{C}(b)$ with the above value $\tilde{y}_0=2.69$ for $A=100$ was used in the numerical evaluation.

[1]D. A. Appel, Phys. Rev. D **33**, 717 (1986).
[2]J. P. Blaizot and L. D. McLerran, Phys. Rev. D **34**, 2739 (1986).
[3]A. De Rújula, J. Ellis, E. G. Floratos, and M. K. Gaillard, Nucl. Phys. **B138**, 387 (1978).
[4]P. Bagnaia *et al.*, Phys. Lett. **144B**, 283 (1984); M. Greco, Z. Phys. C **26**, 567 (1985); Nucl. Phys. **B250**, 450 (1985).
[5]We thank K. Kajantie for a useful discussion of this point.
[6]The derivation given in Ref. 2 is not rigrous; however, although their result, Eq. (37), is erroneous [it is not even dimensionally correct—see our Eq. (11) for the correct result], in practice it seems to yield qualitatively similar (though somewhat smaller) effects on the acoplanarity distribution.
[7]J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).