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THE P_T -DEPENDENCE OF DILEPTON PRODUCTION IN NUCLEAR COLLISIONS

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Abstract

The P_T distribution of massive lepton pairs produced in hadron-nucleus ($h-A$) collisions becomes broader with increasing A . In a framework based on perturbative QCD, this effect can be interpreted as elastic initial state parton scattering, and it is predicted to saturate for large A . We show that an extrapolation of this behaviour to nucleus-nucleus collisions is in accord with measured continuum (Drell-Yan) dilepton behaviour, but that it cannot account for the P_T -dependence of J/ψ suppression. Consequently, the behaviour of $\langle P_T^2 \rangle_{J/\psi} / \langle P_T^2 \rangle_{D-Y}$ in the large E_T region of nuclear collisions provides a crucial test for the production of a quark-gluon plasma.

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The ultimate aim in the study of high energy nuclear collisions is to observe the transition from hadronic matter to a plasma of deconfined quarks and gluons. Therefore it is crucial to find an unambiguous signature of quark deconfinement. It was proposed that a suppression of the J/ψ peak relative to the Drell-Yan continuum in the lepton pair spectrum constitutes such a signature.¹ The subsequent observation of a strong J/ψ suppression in $O-U$ and $S-U$ collisions at the CERN-SPS^{2,3} naturally led to an extensive search for alternative "conventional" ways to account for the observed effect.

The transverse momentum dependence of J/ψ suppression turns out to be a very important factor in determining the origin of this effect. If the suppression is caused by quark deconfinement, then it must disappear once the J/ψ has a sufficiently high P_T .⁵ Given a plasma bubble of finite size or life-time, a fast $c-\bar{c}$ pair will be out of the deconfining medium either in space or in time before having separated enough to cause deconfinement. In fig. 1, we show the J/ψ suppression measured in collisions from a 200 GeV/A oxygen beam incident on a stationary uranium target^{2,3}. The observed behaviour agrees quite well with the form obtained from a deconfining plasma of about 1.5 fm life-time⁶. The most successful "conventional" alternative is based on absorption in dense hadronic matter⁷⁻⁹. Through interactions of the type

$$J/\psi + h \rightarrow D + D + X, \quad (1)$$

the J/ψ is broken up locally, rather than being dissolved by a global screening effect. For sufficiently high density, such absorption leads to an overall J/ψ suppression in accord with the data. The resulting P_T distribution, however, is even qualitatively wrong. If the hadrons leading to the break-up in reaction (1) are pions, then a J/ψ momentum of ~ 600 MeV is necessary to overcome the $D-D$ threshold, so that the suppression increases with P_T . The presence of resonances as scattering partners reduces this effect, but still the P_T dependence remains very weak, as also shown in fig. 1. Because of the long life-time of the absorbing medium, the suppression disappears only for $P_T \gtrsim 10-15$ GeV.

Not only the final state — whether a deconfining medium or dense hadronic matter — can modify the P_T distribution of the J/ψ . Initial state effects become evident in the (Drell-Yan) production of massive lepton pairs. The electromagnetic process

$$q + \bar{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^- \quad (2)$$

should not be affected by the presence of a hadronic medium. Any A -dependence in the P_T distribution of $\mu^+ \mu^-$ pairs produced in $h-A$ collisions must therefore be due to an initial state interaction of either the q or the $\bar{q}$ in the nuclear target before the annihilation (2). Such a dependence is indeed observed¹⁰, comparing $\pi-D$ and $\pi-W$ interactions; it is found that

$$< P_T^2 >_{DY}^W - < P_T^2 >_{DY}^D = 0.15 \pm 0.06 \text{ GeV}^2. \quad (3)$$

Since the integrated $h-A$ cross-sections remain just A times the $h-h$ cross-section¹¹, the initial state interaction experienced by one of the collision partners of reaction (2) must have been elastic: it has simply shifted events from the low P_T to the high P_T region of phase space. A similar effect is found for J/ψ production,

$$< P_T^2 >_{J/\psi}^W - < P_T^2 >_{J/\psi}^D = 0.29 \pm 0.02 \text{ GeV}^2, \quad (4)$$

in ref.(10) as well as in other experiments.^{12,13} In this case it is one of the gluons which fuse to form the J/ψ that first undergoes elastic scattering in the nuclear target. In addition, however, there will now also be absorption of the J/ψ in the final state.

It was suggested¹⁴⁻¹⁶ that multiple elastic parton interactions in the initial state are responsible for the P_T dependence of J/ψ suppression found in nuclear collisions. To arrive at the observed behaviour, the A dependence of dilepton production in $h-A$ interactions is parametrised in the form

$$(\Delta P_T^2)_x \equiv < P_T^2 >_x^A - < P_T^2 >_x^0 \simeq c_x (A^{1/3} - 1), \quad (5)$$

where the subscript x denotes either J/ψ or Drell-Yan production, c_x is a constant empirically determined from eqs.(3) and (4), and $< P_T^2 >_x^0$ is the corresponding $h-h$ value. This form is based on the assumption that the P_T^2 broadening is proportional to the number $\bar{n} \sim A^{1/3}$ of inelastic collisions suffered by the incoming hadron within the target before one of its partons undergoes the hard reaction leading to Drell-Yan or J/ψ production. In a nucleus-nucleus collision, the number $\bar{n}$ can be expressed in terms of the transverse hadronic energy E_T associated to the observed J/ψ production, and hence one finds

$$(\Delta P_T^2)_{J/\psi} \simeq c_{J/\psi} E_T / E_0, \quad (6)$$

with the proportionality constant $c_{J/\psi}$ determined from eqs.(4) and (5), and a scale factor E_0 obtained either from other heavy ion experiments or from event generator studies. Combining multiple initial state parton scattering of this form with final state absorption in dense hadronic matter leads to a P_T -dependence for J/ψ suppression which is now also in accord with the data, as shown by the third curve in fig. 1.

We should now remember, however, that eq.(6), with $c_{J/\psi}$ replaced by c_{DY} as determined from eqs.(3) and (5), also predicts the shift in the P_T -dependence of Drell-Yan production. The E_T -dependence of both $(\Delta P_T^2)_{J/\psi}$ and $(\Delta P_T^2)_{DY}$ is measured in the NA38 experiment³ at the CERN-SPS, and in fig. 2 we show the result together with the predictions of eq.(6). The E_T -dependence of $(\Delta P_T^2)_{J/\psi}$ is indeed reproduced well; the Drell-Yan data, however, appear to remain independent of E_T and do not show the predicted rise. It is possible, of course, that data with higher statistics and

for larger dilepton masses than available today will show such a growth with E_T ; at present, the two cases do not show the same behaviour.

It therefore seems reasonable to ask to what extent the form (5), on which the entire scheme is based, can be justified theoretically. It assumes that one of the partons, which later on will undergo a hard interaction leading to dilepton production, first experiences a number of soft elastic collisions. This number is taken to be proportional to the number n of inelastic interactions undergone by the parton's "parent" hadron; in turn, n is proportional to $A^{1/3}$. Such a picture implies that with growing A , our parton will scatter more often before it finally comes to its hard interaction. On the other hand, in the framework of perturbative QCD and massive dilepton production is at least in some kinematic regions a process to be treated in this framework such a succession of elastic parton scatterings on a succession of different nucleons in the target is difficult to accommodate. Perturbative QCD instead leads in lowest order^{17,18} to a one gluon exchange term (fig.3) as A -dependent correction to $< P_T^2 >^0$. In ref.17, the A -dependence of this process is calculated; for A not too small ($A \geq 8$), it has the form

$$(\Delta P_T^2)_T \simeq \bar{v}_T \left(1 - \frac{1}{A^{1/3}}\right). \quad (7)$$

The crucial point here is that the P_T -broadening obtained from QCD is not proportional to $A^{1/3}$, as assumed in eq.(5), but instead saturates with A . The reason for this difference is intuitively quite clear. The multiple parton scattering approach leading to eq.(5) assumes that a hard parton interaction can still occur after many soft interactions, a long distance ($\sim A^{1/3}$) away from, and an equally long time after, the first collision point. In perturbative QCD, the interaction modifying the P_T distribution of the parton in question occurs a short time before and a short distance away from the annihilation process leading to dilepton production. Multiple scattering is suppressed by higher powers of the strong coupling constant α_s , and an increase of A in "far-away" regions does not affect the local hard interactions. Such a picture is strictly valid only for large P_T , and its extrapolation to low P_T must certainly be verified. But it is evident that the Ansatz made in eq.(5) disagrees not only with the present data on Drell-Yan production from nuclear collisions, but also with the form (7) expected from an extrapolation of perturbative QCD.

What P_T dependence does the form (7) give for $< P_T^2 >^0$? With the same relation between A and E_T as used in eq.(6), we obtain the behaviour shown in fig. 2. It agrees well with the observed constancy of Drell-Yan production, but it fails to reproduce the P_T^2 broadening of J/ψ production once $E_T \geq 50$ GeV. In other words, the P_T -dependence of J/ψ suppression in the crucial region, for high E_T , cannot be described by initial state parton scattering as obtained from perturbative QCD.

So far, we have made essentially three points.

- (i) The form (5), obtained from multiple parton scattering in the initial state, predicts the P_T dependence of both J/ψ and Drell-Yan production, and the predic-

tion for Drell-Yan production is not in accord with present data from nucleus-nucleus collisions.

- (ii) The A -dependence of multiple parton scattering as proposed in eq.(5) is not in accord with the form (7) obtained from an extrapolation of perturbative QCD.
- (iii) The P_T -broadening obtained from initial state parton scattering according to perturbative QCD agrees well with the present results for Drell-Yan production in nuclear collisions, but it cannot reproduce the P_T -dependence of J/ψ suppression in the high E_T regime.

From this we conclude that if the present data are indeed correct, then there remains now only one viable scenario to account for all observed features of J/ψ suppression: quark-gluon plasma production.* The basis for this conclusion can, moreover, be tested by two well-defined and experimentally clear-cut predictions.

For Drell-Yan production in $k-A$ collisions, we have at present only data at very low (D) and very high (W) values of A .¹⁰ Experiments at intermediate A should certainly be able to determine if the A -dependence saturates, as expected from the perturbative QCD form (7), or if the P_T broadening increases with $A^{1/3}$, as proposed in eq.(5). The possible range of high mass dileptons and the absence of final state absorption makes Drell-Yan production a particularly good tool to study initial state parton interactions. However, a corresponding test can also be carried out for J/ψ production, and a recent study²⁰ comparing $\pi^- - C$ with $\pi^- - Pb$ interactions finds that the functional form of the P_T -distribution shows little or no A -dependence.

A description of J/ψ suppression in terms of multiple parton scattering plus subsequent absorption implies that the ratio $< P_T^2 >_{J/\psi} / < P_T^2 >_{DY} > 1$ in nuclear collisions does not depend on E_T . Quark deconfinement, on the other hand, predicts that the ratio should increase in going from low to high E_T . A reliable study of the E_T -dependence of this ratio in nuclear collisions is certainly within reach.

In closing, we should add that the picture of quark-gluon plasma formation considered here is somewhat oversimplified. In actual nuclear collisions, even if there is plasma production, there will in addition be absorption effects, both from the non-plasma "edges" of the interaction region and from the system present after hadronisation. A more realistic description of J/ψ suppression through quark deconfinement must therefore include such effects^{21,22}. This will, however, not change the conclusions reached here.

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* We note here that nuclear structure functions of an EMC type also lead to a much weaker P_T broadening for Drell-Yan pairs than for J/ψ production.¹⁹ However, such a description has so far not been able to account for the E_T dependence of the suppression.

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Figure Captions

Fig.1 The ratio of J/ψ production at high (>50 GeV) vs. low (<28 GeV) P_T , as function of P_T , in $O-U$ collisions (ref.2). Compared to the data are the theoretical results from quark deconfinement (solid curve, ref. 6), absorption in dense hadronic matter (dashed curve, ref. 7), and absorption plus initial state parton scattering (dash-dotted curve, ref. 15).

Fig.2 The average P_T^2 for J/ψ (closed symbols) and Drell-Yan (open symbols) production, in $O-U$ collisions (from ref.3). Compared to the data are the theoretical results from a perturbative QCD form (solid line) and from the form proposed in refs. 14-16 (dashed line).

Fig.3 Lowest order perturbative QCD contribution to A -dependent P_T broadening of dilepton production (refs. 17 and 18).

Fig. 1

Fig. 2

Fig. 3