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INITIAL STATE EFFECTS ON DILEPTON PRODUCTION IN NUCLEAR COLLISIONS*

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Abstract

For hadron-nucleus collisions, multiple elastic scattering of the incident parton inside the nucleus leads to a broadening of the P_T distribution of high mass dilepton production. Such a broadening has been used to explain the P_T dependence of the J/ψ suppression observed in high energy $O - U$ and $S - U$ collisions. Precision measurements of the A -dependence of dilepton distributions from $h - A$ collisions can provide a test of this explanation. Furthermore, a comparison of the P_T -dependence of J/ψ and Drell-Yan production in nucleus-nucleus collisions, as function of E_T , can be used to distinguish between quark deconfinement and hadronic absorption as origin of the observed J/ψ suppression.

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The dilepton spectrum from high energy $O-U$ and $S-U$ collisions at CERN shows with increasing centrality a suppression of the J/ψ signal relative to the Drell-Yan continuum.¹ Such a suppression had been predicted as signature for quark deconfinement² and was subsequently shown to account for the observed behaviour³⁻⁵. It therefore became crucial to check if other "conventional" explanations for these observations could be found, and it was shown that a model combining initial state parton scattering with final state absorption in dense hadronic matter can indeed also account for the data⁶⁻⁸. Thus we are now faced by the question: how can one distinguish experimentally whether quark deconfinement or absorption are responsible for the observed J/ψ suppression?

The transverse momentum dependence of J/ψ suppression turns out to be a very important factor in determining the origin of the effect⁹. If the suppression is caused by quark deconfinement, then it must disappear once the J/ψ has a sufficiently high transverse momentum³. In accord with this prediction, the observed J/ψ suppression indeed appears to stop for $P_T \geq 2$ GeV. In the absorption scenario, the J/ψ is broken up locally through interactions of the type $J/\psi + h \rightarrow D + \bar{D} + X$, and for sufficiently high density, this leads to an overall J/ψ suppression of the magnitude observed in the data¹⁰⁻¹². The resulting P_T distribution, however, is qualitatively wrong. If the hadrons leading to the break-up are pions, then a J/ψ momentum of about 600 MeV is necessary to overcome the $D - \bar{D}$ threshold, so that the suppression increases with P_T . The presence of resonances as scattering partners reduces this effect¹¹, but still the P_T dependence remains very weak. It was therefore suggested⁶⁻⁸ 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

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

where the subscript x denotes either J/ψ or Drell-Yan production, c_x is a constant empirically determined from the existing data on $h-A$ collisions¹³⁻¹⁵, and $< P_T^2 >_x^0$ is the corresponding $h-h$ value¹³. This form is based on the assumption that the broadening is proportional to the number $\bar{n} \sim A^{1/3}$ of elastic collisions suffered by the incoming parton within the target before it undergoes the hard reaction leading to Drell-Yan or J/ψ production. For 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 production¹¹, so that instead of eq. (1) we now have

$$(\Delta P_T^2)_x^{AB}(E_T) \equiv < P_T^2 >_x^{AB}(E_T) - < P_T^2 >_x^0 \simeq c_x (E_T/c_T), \quad (2)$$

where the E_T -scale c_T is determined from other heavy ion experiments or from event generator studies. Combining multiple initial state parton scattering of the form (2) with final state absorption in dense hadronic matter leads to a P_T -dependence for J/ψ suppression which is in accord with the CERN NA38 data.

Let us now return to the basis of the A -dependence of multiple initial state parton scattering, form (1). It assumes that the particular parton which later on will undergo

the hard interaction leading to dilepton production first experiences a number of elastic collisions. In ref. 6 and 8, this number is taken to be proportional to the number $\bar{n}$ of inelastic interactions undergone by the parton's "parent" hadron; in turn, $\bar{n}$ is proportional to $A^{1/3}$. In ref. 7, it is assumed that the incoming parton itself suffers multiple gluon exchange with different nucleons along its path through the nucleus; summing these exchange terms¹⁶ also leads to an $A^{1/3}$ dependence of ΔP_T^2 . Both versions assume that the "hard" parton will have a mean free path in nuclear matter which is so short as to allow multiple scattering during its passage through the nucleus. Even if we divide the total hadron-hadron cross section of 40 mb among just the valence quarks, we get in normal nuclear matter a mean free path of about 14 fm; but the hard parton should actually be related only to that fraction of the total cross section which is due to large transverse momentum scattering. It thus appears difficult to understand conceptually how genuine multiple scattering can occur here. Moreover, if we describe dilepton production in lowest order perturbative QCD, we expect one-gluon exchange to give the dominant A -dependent correction to $< P_T^2 >_x^0$. In ref. 17, the A -dependence of this process is calculated; for A not too small ($A \geq 8$), it has the approximate form

$$(\Delta P_T^2)_x \simeq \bar{c}_x (1 - \frac{1}{A^{1/3}}). \quad (3)$$

The crucial point here is that the P_T -broadening now is not proportional to $A^{1/3}$, as assumed in eq. (1), but instead becomes weaker with increasing A . Whether the A -dependence of ΔP_T^2 is determined by the one-gluon exchange form, or whether multiple exchange terms become important - this appears to be a question which can only be settled experimentally.

The A -dependence used in ref. 6-8 was obtained by comparing data from $p-p$ collisions (hydrogen or deuterium targets) with those using heavy targets (W or Pt). Until this year, data for intermediate A values were not available, and so a test of the functional form of the A -dependence of ΔP_T^2 was not possible. At present, however, such data are becoming available from three different experiments at Fermilab (E537¹⁸, E672¹⁹, E772²⁰); if they can achieve sufficient precision, they should be able to settle this issue. So far, results have been shown for the P_T dependence of the ratios of P_T distributions obtained on different targets. What can we say about these ratios?

In the low P_T region of $h-A$ collisions ($P_T \leq 2$ GeV), the transverse momentum distribution for dilepton production can be parametrized in the form

$$(d\sigma_A/dM dP_T^2) / (d\sigma_A/dM dP_T^2)_{P_T=0} \sim \exp - \{ (P_T^2 + M^2)^{1/2} 2M / < P_T^2 >_A \}; \quad (4)$$

here M denotes the mass of the pair, which we take to be 2 GeV or larger. This leads to

$$R_{A/B}(P_T) = N_{A/B} \exp \{ 2M (P_T^2 + M^2)^{1/2} / (< P_T^2 >_B^{-1} - < P_T^2 >_A^{-1}) \} \quad (5)$$

for the ratio of the P_T distributions from $h-A$ and $h-B$ collisions; the normalisation $N_{A/B}$ is not related to initial state parton scattering and hence not of concern here. In ref. 13, collisions of 200 GeV protons on H_2 and Pt targets give for J/ψ production the values of $< P_T^2 >_H$ and $< P_T^2 >_{Pt}$; these values can be used to obtain the coefficients $c_{J/\psi}$ and

$\bar{c}_{J/\psi}$ in eqns.(1) and (3). For $R_{pT/H}$, both forms give by construction the same functional P_T -dependence; in fig. 1 it is seen to agree rather well with the data.

Using the values for the coefficients as determined, we can predict the P_T -dependence of any measured ratio. In fig. 2, this prediction is compared with J/ψ production data²⁰ for π^- at 530-GeV incident on C and Pb. Clearly the errors on the measurements are too large to allow any definite conclusion; however, the data do not show any systematic P_T dependence. Preliminary results of E772²⁰ for J/ψ and Drell-Yan pair production, by 800 GeV protons incident on D, C, C α , Fe and W targets, also show no or very little variation of the ratio of distributions for $P_T \leq 2-3$ GeV. The overall trend of the new data thus does not seem to support the A-dependence of eq.(1). But even the ratio of D to W distributions as obtained by 800 GeV protons²⁰ appears to vary less than the previous results¹³ with a 200 GeV beam; we thus have to understand whether an increase in energy can lead to such an effect.

We now return to nucleus-nucleus collisions. With $c_{J/\psi}$ and c_{DY} determined by existing data from $h-A$ collisions, eq.(2) predicts the E_T dependence of ΔP_T^2 for J/ψ and for Drell-Yan production in nuclear collisions. This dependence was recently determined for both cases in the NA38 experiment at CERN²¹. As seen in fig. 3, the E_T -dependence of $(\Delta P_T^2)_{J/\psi}$ is reproduced well by the prediction, but the Drell-Yan data so far do not indicate any systematic rise with E_T . The errors are too large, however, to rule out an increase, and preliminary results from S-U collisions²¹ show even larger fluctuations. Thus here as well we have to wait for more precise data before we can draw definite conclusions.

In summary, we note that the scenario proposed to account for the P_T -dependence of J/ψ suppression in heavy ion collisions leads to predictions for the A-dependence of both J/ψ and Drell-Yan production in $h-A$ collisions. Precision data on these reactions should therefore do much to clarify the situation; presently available data do not really support the strong dependence on A or E_T proposed in the form obtained from multiple initial state parton scattering. Moreover, a comparison between the P_T -dependence of J/ψ and Drell-Yan production in nuclear collisions could also provide a crucial test.⁹ Multiple initial state parton scattering predicts that $(\Delta P_T^2)_{J/\psi}/(\Delta P_T^2)_{DY}$ should not vary with E_T ; in contrast, from quark deconfinement we expect a continued increase of $< P_T^2 >_{J/\psi}^{AB}$ with E_T , while $< P_T^2 >_{DY}^{AB}$ remains essentially constant. The forthcoming higher statistics S-U run should thus bring us further towards an understanding of J/ψ suppression in nuclear collisions.

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Fig.1: The P_T -dependence of $p - P_t$ vs. $p - p$ collisions, for J/ψ production, from ref. 13; the dashed line gives the form predicted by both multiple parton scattering and lowest order QCD.

Fig.2: The P_T -dependence of $p - Pb$ vs. $p - C$ collisions, for J/ψ production, from ref. 18; curve (a) gives the prediction from multiple parton scattering, curve (b) that of lowest order QCD.

Fig.3: The E_T dependence of $\langle P_T^2 \rangle$ for J/ψ (top) and Drell-Yan (bottom) production in $O - U$ collisions, from ref. 21; the solid lines are the predictions from initial state multiple parton scattering, following ref. 6.