INITIAL STATE SCATTERING IN NUCLEAR DRELL-YAN AND J/ψ PRODUCTION

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INTRODUCTION

Nuclear effects discovered in the transverse momentum spectra of Drell-Yan dimuons by experiment NA10 [1] have been attributed to initial state parton scattering [2-4]. Similar phenomena occur to a progressively greater extent in J/ψ production in hadron-nucleus [5,6] and nucleus-nucleus collisions at 200 AGeV [7]. The realization that the $AB \to J/\psi$ and Drell-Yan effects can have the same cause has taught us that quark gluon plasma detection at the SPS is not easy — the p_T pattern of J/ψ suppression thought to be the signature of quark gluon plasma production can be forged [8-11]. But "can be" is not the same as "is". In this report I examine the degree to which the systematics of Drell-Yan and J/ψ hadroproduction establish initial state scattering. Extending Satz's recent work [12], I study the confidence level of our extrapolation to ion-beam experiments, focusing on the new precision measurements from the 800 GeV $p+A$ experiment E772 at Fermilab [13]. I then speculate about the energy dependence of initial state scattering and discuss experiments that can help to pin down the present theoretical uncertainties.

As at the SPS, J/ψ suppression in LHC ion-ion collisions is likely to prove a very complex phenomenon. To conclude, I briefly discuss various additional nuclear and dense matter contributions and speculate about their relative importance at the LHC.

INITIAL STATE SCATTERING

The strong influence of initial-state parton scattering on the p_T dependence of hard processes such as J/ψ formation in nuclear targets is suggested by recent Drell-Yan dimuon data. NA10 [1] found a broadening of the p_T distribution in $\pi^- + {}^{184}W \to \mu^+\mu^-$ relative to $\pi^- + {}^2H$ corresponding to an increase of the p_T dispersion of $\langle p_T{}^2\rangle_{\pi W\to\mu^+\mu^-} - \langle p_T{}^2\rangle_{\pi H\to\mu^+\mu^-} = 0.15 \pm 0.06\mathrm{GeV}^2$. Such an increase can only arise from initial-state interactions, since the final-state in the Drell-Yan production of high-mass pairs does not interact strongly. In fact, the effect had been predicted [2,3] due to the quasielastic scattering of the sea quark and antiquark before their annihilation. Scattering adds to the $\langle p_T{}^2\rangle$ of the resulting dimuons but does not reduce the p_T-integrated dimuon yield, because it directs the beam momentum transversely without changing the net parton flux. The absence of an absorptive component of initial-state interactions is supported by the $A^{1.00\pm0.02}$ dependence of the p_T-integrated cross section.

As the pion crosses the nucleus, the quark (or antiquark) suffers a number of elastic collisions before its annihilation that is proportional to $(\overline{n}_A - 1)/2$, where $\overline{n}_A$ is the average number of inelastic π-nucleon collisions. This random walk increases the p_T dispersion of the dimuon from the intrinsic Drell-Yan value $\langle p_T\rangle_0 \approx \langle p_T\rangle_{\pi p}$ to

$$\langle p_T{}^2\rangle_{\pi A} \approx \langle p_T{}^2\rangle_0 + \delta_q{}^2\{\overline{n}_A - 1\}. \qquad (1)$$

The mean number of collisions grows with the target length, which is roughly $\propto A^{1/3}$. The NA10 data implies that the effective p_T transfer per quark-nucleon collisions is $\delta_q \approx 0.24$ GeV, since $\overline{n}_A$ is roughly 3.7 in $\pi + W$. The small magnitude of δ_q suggests that initial state scattering occurs at soft scales.

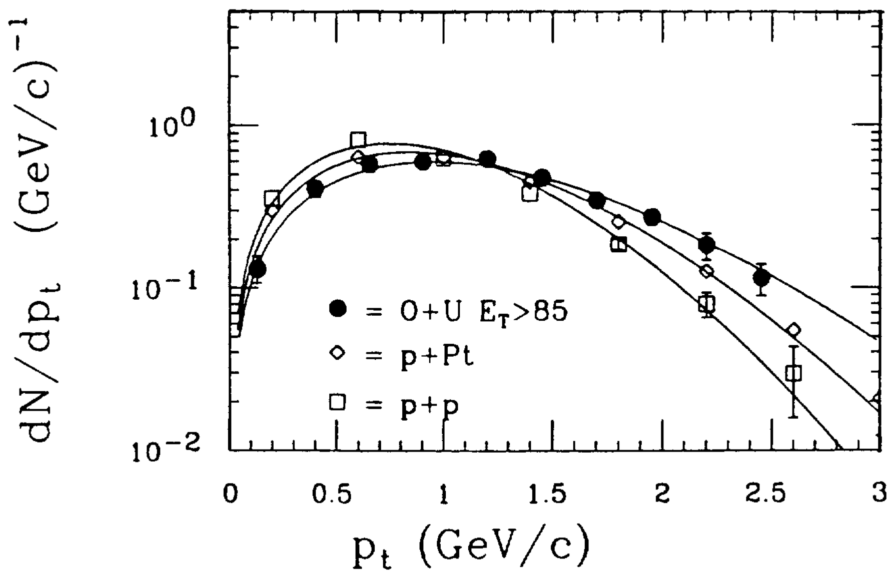

Fig. 1. Measured p_T spectra in $p+p$, $p+Pt$ and $O+Au \to J/\psi$ display a broadening trend at 'low' energies which can be attributed to initial state scattering. Data from NA3 [5] and NA38 [7] are compared to model extrapolations in Ref. 8.

Gyulassy and I, along with many others, observed that a similar initial-state scattering of gluons can occur in J/ψ production prior to the formation of the $c\bar{c}$ pair, and such scattering can in fact account [8-11] for much of the p_T dependence seen by NA38 [7]. NA3 [5] studied $p + A \to J/\psi + X$ at 200 GeV for Pt and ^2H targets, and I show their measured p_T distributions in Fig. 1 together with the distribution for central $O+U$ from NA38. The normalized distribution $N_\psi{}^{-1}dN_\psi/dp_T$ for Pt is broader than that for H, and that the $O+U$ distribution is broader still. NA3 found that $\langle p_T{}^2\rangle_{pPt} = 1.57 \pm 0.03\,\mathrm{GeV}^2$ and $\langle p_T{}^2\rangle_{pp} = 1.23 \pm 0.05\,\mathrm{GeV}^2$, so that $\delta_g{}^2 \approx (0.36\,\mathrm{GeV})^2$ for gluon-nucleon collisions, which is $\approx 9\delta_q{}^2/4$ as expected from perturbative QCD arguments [8,9]. The $p+A$ spectra in Fig. 1 are fit by taking $dN_\psi/d^2p_T \propto \exp\{-\alpha(p_t{}^2 + m_\psi{}^2)^{1/2}\}$, where we use $\langle p_T{}^2\rangle$ to relate the slope parameter α to the measured dispersion [8].

In a nucleus-nucleus collision, the number of initial-state interactions depends on impact parameter. The p_T dispersion is increased by the scattering of both target partons in the projectile and projectile partons in the target, so that $\langle p_T\rangle_{AB} \approx \langle p_T\rangle_{pA} + \langle p_T\rangle_{pB}$, for $\langle p_T\rangle_{pA}$ of the form (1). Glauber theory implies $\bar{n}_O + \bar{n}_U \approx 8$ in a central $O+U$ collision. The p_T dependence of the NA38 data in Fig. 1 is accounted for essentially by (1), together with a 20% contribution from the final-state interactions (details are discussed in [8]).

Despite the circumstantial evidence offered by NA10 and NA3, the case for initial state interactions in hard processes is far from closed. Satz has emphasized that the random-walk increase of $\langle p_T{}^2\rangle$ with the number of collisions $\bar{n}$ is not demonstrated by NA10 and NA3: These groups studied only two targets, so that the linear rise of $\langle p_T{}^2\rangle$ with $A^{1/3}$ implicit in (1) was not checked. Another potential test of (1) is the centrality dependence of the p_T shift for NA38's dimuon continuum. One expects $\langle p_T{}^2\rangle$ to increase with increasing total transverse energy E_T (the larger is E_T, the more central is the event). So far, NA38 has not resolved the expected dependence, perhaps due to their limited statistics compared to NA10 as discussed by Varela [7].

Recently, the E772 experiment at FNAL has reported measurements of $p+A \to \mu^+\mu^-$

at 800 GeV for *several* nuclear targets with high statistics comparable to NA3 and NA10. This experiment focused on EMC-type nuclear modification of parton structure functions, so that great care was taken to minimize the relative errors in the different targets. Although their p_T acceptance was somewhat limited, ratios of the production rates in C, Ca, Fe, and W relative to deuterium are available. Preliminary results show a clear p_T shift that increases with increasing A for both Drell-Yan and J/ψ production. To exhibit the A dependence of $\langle {p_T}^2\rangle$ indicated by this data, I have fit the measured ratios assuming gaussian distributions $dN/d^2p_T \propto \exp\{-{p_t}^2/\langle {p_T}^2\rangle\}$. Figure 2 shows the extracted $\langle {p_T}^2\rangle$ vs. A. The fitting errors shown were estimated using the standard jackknife procedure. I emphasize that much of the data from which $\langle {p_T}^2\rangle$ was constructed is preliminary, and no attempt was made to compensate for E772's experimental biases. Quantitative results must be interpreted accordingly.

In Fig. 2, I compare the extracted A dependence of $\langle {p_T}^2\rangle$ to the random walk form (1) for $\bar{n} \approx A^{1/3}$,

$$\langle {p_T}^2\rangle_{\rm random} \approx \langle {p_T}^2\rangle_0 + c\{A^{1/3} - 1\}, \tag{2}$$

and also with a saturating form,

$$\langle {p_T}^2\rangle_{\rm sat} \approx \langle {p_T}^2\rangle_0 + c'\{1 - A^{-1/3}\}, \tag{3}$$

proposed in [12]. Both forms are 'correct' with equal probability. This fact is very important because the saturating form (3) does not account for the added broadness of central $O + U \to J/\psi$ compared to $p + Pt$ evident [12].

Saturation – if verified experimentally – would imply that a new mechanism is behind the NA10 and E772 p_T broadening. Initial state scattering *generally* leads to the random-walk increase of $\langle {p_T}^2\rangle$ for increasing A. To stress the generality of this result, I derive (1) in more detail than is perhaps necessary. In typical events at NA10 and E772 energies, the successive interactions of a parton with different nucleons are essentially incoherent, so that Glauber theory implies

$$\langle {p_T}^2\rangle = \frac{\langle {p_T}^2\rangle_0 P_0 + \langle {p_T}^2\rangle_1 P_1 + \cdots}{P_0 + P_1 + \cdots} = \frac{\langle {p_T}^2\rangle_0 + \langle {p_T}^2\rangle_1 L/\lambda + \cdots}{1 + L/\lambda + \cdots}, \tag{4}$$

where $\langle {p_T}^2\rangle_k$ is the dispersion after k initial state interactions, $P_k = (L/\lambda)^k \exp(-L/\lambda)/k!$ is the probability that k such interactions occur, λ is the parton's mean free path and L is the distance traveled through the nuclear medium. Note that (1) is then the average of (4) over the target geometry. If the mean free path is longer than the average path length $\bar{L} \propto A^{1/3}$, then I can take $\langle {p_T}^2\rangle_0 \approx \langle {p_T}^2\rangle_0 + (\langle {p_T}^2\rangle_1 - (\langle {p_T}^2\rangle_0)L/\lambda + \cdots$, which gives the random-walk A-dependence (1). For a general λ, I must allow for any number of collisions. Poisson statistics again implies (1), since the average kick $\langle {p_T}^2\rangle_k - \langle {p_T}^2\rangle_{k-1} \approx \delta^2$ is roughly independent of k (the fitted δ's are much smaller than the beam momenta).

I remark that the mean free path is roughly $\lambda = (\rho\sigma_{qN})^{-1}$, where ρ is the nuclear matter density and σ_{qN} is the effective parton-nucleon cross section. If initial state interactions occur at soft scales in accord with our expectations, then σ_{qN} is likely in the several millibarn hadronic range so that $\lambda \ll R$ [8]. For interactions at hard perturbative scales, I expect the $\lambda \gg R$ regime to be relevant, since both σ_{qN} and δ^2 are then $\propto \alpha_s$ [14].

Historically [3,12], the saturating result (3) was first obtained from (4) in the $\lambda \ll R$ regime by truncating the multiple-scattering series after one collision. Such a truncation is incorrect from the standpoint of perturbative QCD, but may mimic nonperturbative effects that cut off the possible number of initial state interactions [12]. Alternatively, a saturating A dependence can arise if the source of p_T enhancement is an entirely new mechanism such as the EMC effect [15].

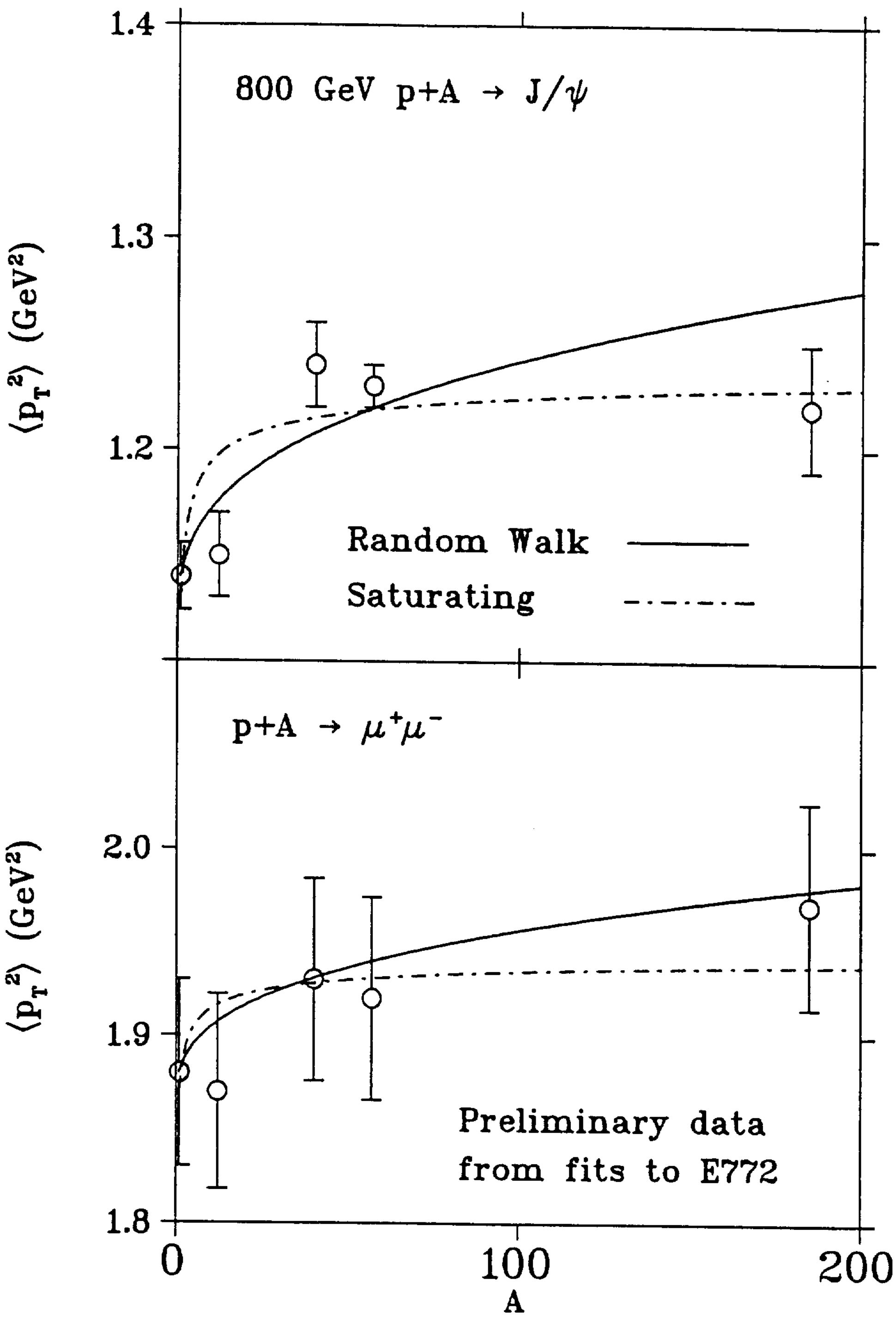

Fig. 2. The target mass dependence of $\langle p_T{}^2 \rangle$ from gaussian fits to preliminary E772 J/psi and Drell-Yan data compared to fits using random-walk and saturating parametrizations, eqs. (2) and (3) respectively.

In deriving (4), initial state interactions were taken to be incoherent and independent of the hard Drell-Yan or gluon fusion processes. Coherence is expected only in the extreme kinematic regime where the target parton in the hard process has a momentum fraction x_2 smaller than $\sim 0.05 - 0.1$. There the wavelength of a parton exceeds the nucleon size of ~ 1 fm, so that successive initial state interactions can interfere both with the hard process and possibly with each other. Brodsky and Lu [16] have recently proposed that *destructive* interference can explain the shadowing phenomena discussed phenomenologically by Castorina in these proceedings. If the interference is indeed destructive, then I expect the p_T shift (4) to be reduced in the deeply shadowing regime. The E772, NA3, and NA10 signals originate mostly from 'unshadowed' target and projectile partons of roughly equal x's satisfying $x > M/\sqrt{s} \gtrsim 0.1 - 0.15$, since Drell-Yan and J/ψ production is peaked at mid-rapidity (the EMC effect can be important at these energies, see Ref. 15). One can extract information on the shadowing regime, however, by triggering on rare events at high Feynman x_F corresponding to low x_2. In principle, E772 has p_T information for high x_F events, although it is not clear that statistically meaningful spectra can be constructed from present data [17]. In contrast with present experiments, typical LHC events will come from shadowing regime, as emphasized in Eskola's and Castorina's talks. High x_F data from E772 will not only help to distinguish models of the controversial shadowing effect, but will be essential in making convincing LHC predictions.

Experiments at different beam energies suggest that the nuclear broadening of p_T spectra is reduced at higher beam energies for a given dimuon mass. Specifically, the comparison of NA10 140 GeV $\pi + A$ and E772 800 GeV $p + A$ data in fig. 3 for $4 < M_{\mu\mu} < 9$ GeV imply that the relative p_T shift becomes less pronounced as the beam energy is increased. The first hint of this 'flattening' trend is seen by comparing 286 and 140 GeV NA10 data, although the demonstration of the trend is marginal within the errors. The onset of flattening at the moderate NA10 energies implies that this trend is not associated with the shadowing regime, but has a more commonplace origin.

I argue that this flattening is a consequence of the well known rise of the intrinsic $\langle p_T{}^2\rangle_0$ for dimuon production for increasing energy; Karsch has proposed a similar interpretation at this workshop. To illustrate how the flattening arises, I assume Gaussian p_T spectra and write the ratio

$$\frac{(d\sigma/dp_\perp)_W}{(d\sigma/dp_\perp)_{^2H}} \propto \exp\{p_T{}^2(\langle p_T{}^2\rangle_D^{-1} - \langle p_T{}^2\rangle_W^{-1})\}. \tag{5}$$

Equation (1) implies that the scale over which the ratio rises is $\approx \langle p_T{}^2\rangle_D\langle p_T{}^2\rangle_W/(\langle p_T{}^2\rangle_W - \langle p_T{}^2\rangle_D) \propto (\langle p_T{}^2\rangle_0/\delta)^2$. The intrinsic dispersion $\langle p_T{}^2\rangle_0$ grows with energy due to the increase in phase space for Compton and other high-order contributions to dimuon production at finite p_T, as discussed by Gupta in these proceedings. The ratio becomes flatter in a fixed p_T range as in Fig. 3, as long as the p_T kick δ_q grows more slowly with energy than $\langle p_T{}^2\rangle_0$. My fit to E772 and NA10 data gives $\delta_q = 0.24$ GeV independent of energy, in agreement with prediction [2] (see above).

J/ψ production exhibits a similar flattening at high energy. NA3 studied $\pi + A \to J/\psi$ at the beam energies 140, 200 and 280 GeV and reported the p_T dispersion explicitly. Figure 4 shows the measured increase of $\langle p_T{}^2\rangle$ as a function of energy $\sqrt{s}$. Observe that the difference between the Pt and ^2H data is roughly independent of energy, while the dispersions separately rise as log s. These observations support our Drell-Yan picture, although it must be emphasized that the transverse momentum distribution in J/ψ can be influenced by final as well as initial state effects.

Bold extrapolation to the LHC range using these estimated energy dependencies implies that the p_T shift due to initial state interactions will be negligible for $p_T < 3$ GeV. For

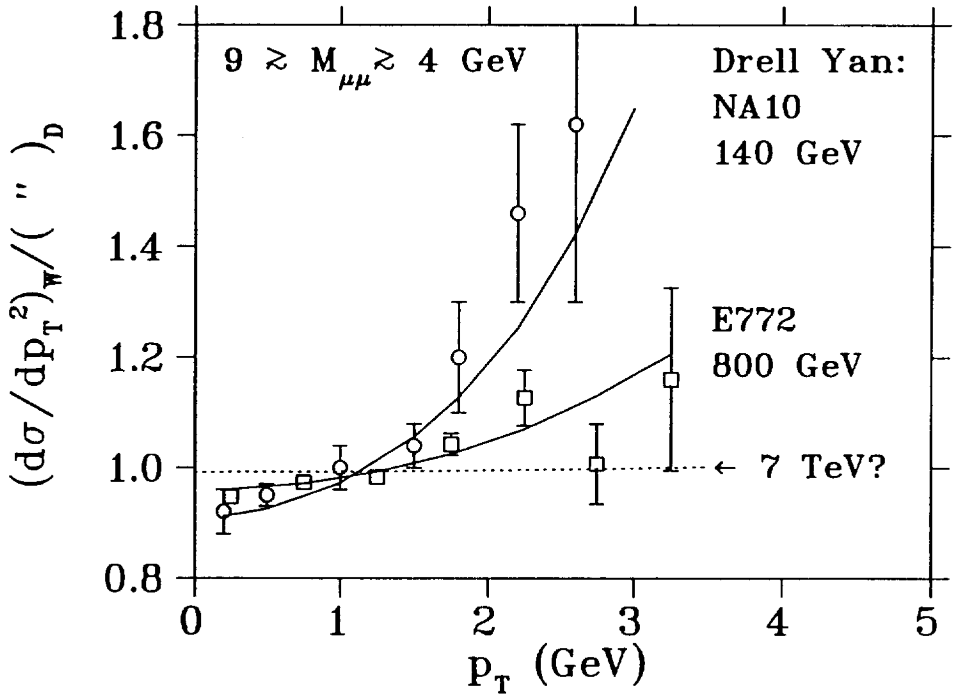

Fig. 3. W-to-^2H ratio for Drell-Yan production from 140 GeV $\pi + A$ [1] and 800 GeV $p + A$ [13] may suggest that the effects initial state scattering are less important as the beam energy is increased. Expectations at LHC energy are indicated by the dashed curve.

example, if I assume a value $\langle p_T{}^2\rangle_0 \approx 10$ GeV^2 as suggested by Gupta, then the calculated p_T ratio is as shown in Fig. 3. Only the bravest among us would believe such an estimate, since experimental information is very limited, and the present models are quite primitive.

Additional experimental information is needed to establish the systematics of initial state interactions in energy and target mass. In terms of planned experiments, we can follow the continuation of E772, E789, and look forward to pA or $^2H + A$ experiments at RHIC. Ideally, one would like to see measurements of $\pi + A \rightarrow$ Drell-Yan and J/ψ using an E772–like multiple target setup down to the lower NA3 energies where the p_T shift is strongest. A goal of these experiments should be to determine the p_T broadening as a function of A to fix the mechanism behind the p_T shift. Measurement of the x_F dependence of $\langle p_T{}^2\rangle$ into the shadowing region for several nuclei would have important implications for LHC energies, as I have argued above. Of course, to calibrate quark-matter studies at the LHC, it is best to have pA input from LHC experiments! While it is perhaps not feasible to study asymmetric systems like pA at the LHC, Drell-Yan studies in AA collisions will provide some information. However, it is preferable to have a direct handle on gluon initial state interactions in isolation from other effects in order to calibrate the nuclear J/ψ p_T shift. Gupta and I realised that these interactions can also be studied in $AA \rightarrow$ direct photons; this possibility merits further study.

OTHER COMPETING EFFECTS

Initial state scattering is one of several suspected contributions to J/ψ suppression in nucleus-nucleus collisions. The complex scenario discussed in [18] (see also [23]) has emerged from a consideration of the NA38 data together with the data on nuclear effects in J/ψ photo and hadroproduction, Drell-Yan production, and deep inelastic scattering. The formation of a particular $c\bar{c}$ bound state such as the J/ψ can be influenced by a variety of final state

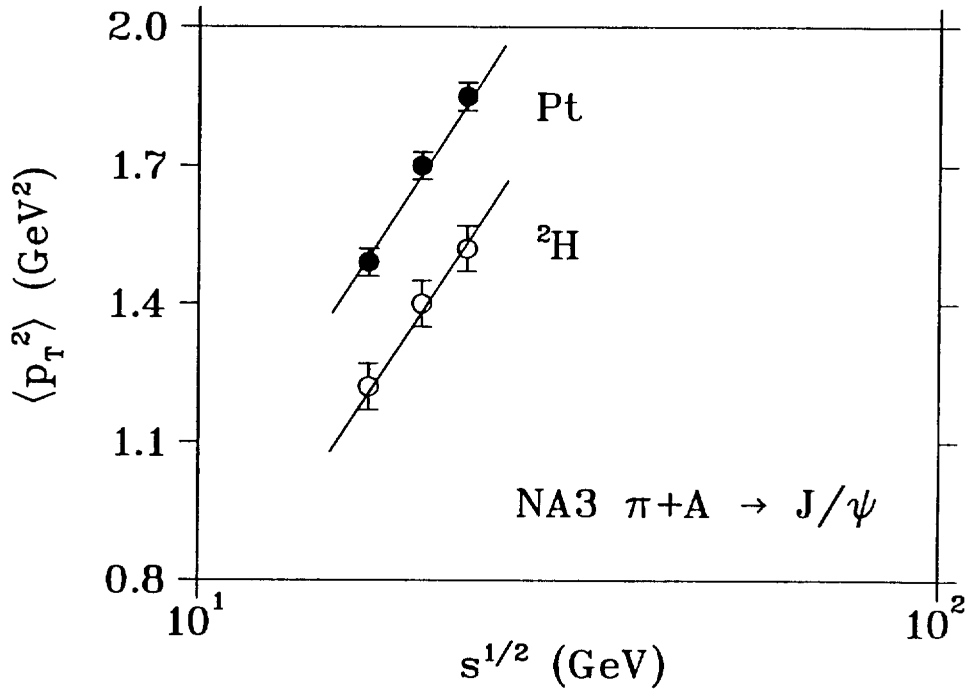

Fig. 4. Energy dependence of $\langle p_T{}^2 \rangle$ for $p + Pt$ and $p + {}^2H \rightarrow J/\psi$ [3].

interactions at both the quark and the hadronic level. In addition, the production of the $c\bar{c}$ pairs in the mid-rapidity dense matter region can be influenced by various nuclear effects, of which initial state scattering is only one. A few of these effects are described in Fig. 5. I must stress that our present knowledge is far from complete, and some contributions may be ruled out as experimental and theoretical work continues.

The following contributions to J/ψ production and suppression can be important at the LHC:

1. Medium Effects: color screening and self energy effects in the quark gluon plasma alters J/ψ abundance by inhibiting bound state formation. Hadron liquid effects are also possible [19].

2. Co-mover Scattering: scattering with co-moving secondaries (produced quarks and antiquarks) can alter the final J/ψ abundance through dissociation, e.g. $\rho\psi \rightarrow D\bar{D}$, and chemical reactions, e.g. $\rho\chi \rightarrow \pi\psi$. Analogous quark-level processes exist in the plasma [20].

3. Shadowing: Nuclear modification of the structure function in the relevant small x regime alters $c\bar{c}$ production, see Castorina's talk.

4. Minijets: new production processes appear as discussed in Gupta's talk.

Scattering and medium effects are important both at SPS and LHC energy, while shadowing is a new effect that is likely to become very important at LHC.

Further effects thought to be important at SPS and FNAL energies are expected to be effectively absent at the LHC. Firstly, scattering with nucleons (valence quarks), which dissociate $c\bar{c}$ at low energies as demonstrated in photoproduction experiments [21], can be inhibited at higher energies due to color transparency [22]. Support for this hypothesis comes from the successful account of E772 800 GeV J/ψ, ψ', and υ data [13] by color-transparency-based model calculations [23] using parameters fit from lower energy data [6,7]. Secondly,

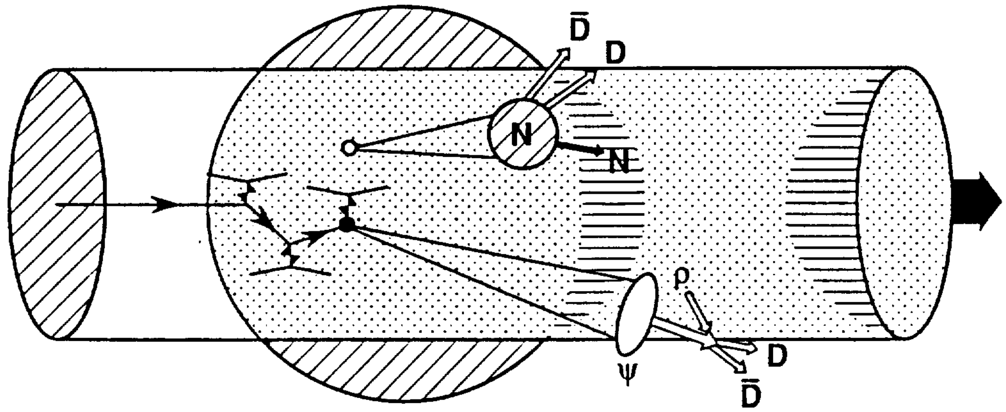

Fig. 5. A schematic representation of J/ψ suppression in an ultrarelativistic collision viewed in the target frame. A parton in the projectile (hadron or nucleus) scatters quasielastically until the hard collision occurs that produces the $c\bar{c}$ pair. The pair then separates to form a J/ψ in the central region provided that it does not scatter with the target nucleons or with co-moving secondaries. It can be dissociated through interactions within the nucleus (the upper event) or by scattering with co-movers (the lower event).

J/ψ formation from a conjectured pre-existing intrinsic charm component in the nucleon can suffer an enhanced nuclear absorption [24]. This mechanism can describe the curiously strong J/ψ absorption found at moderate and high x_F's [24]. However, one expects the domain where this mechanism is important to move to inaccessibly high rapidities at a $\sqrt{s} = 7$ TeV collider, since the measured effect scales with $x_F \approx M_\psi e^{2y}/\sqrt{s}$.

The very difficult problem of distinguishing medium and scattering effects is explored by Karsch in these proceedings. For simplicity he assumes that quark-matter screening and hadron-gas scattering are *exclusive*, alternative mechanisms, and asks how systematics such as the p_T dependence can be exploited to identify the correct one. It is crucial to remember that this formulation is an idealization — one cannot say *ab initio* whether or not these mechanisms are exclusive. The experimental problem is not to decide between distinct alternatives but, rather, to use experimental systematics to distinguish an emerging plasma component from the hadronic background. As in initial state scattering, one can use photo and hadroproduction data in nuclear targets to study final state scattering in the absence of plasma, and then extrapolate to heavy ion collisions. Vogt and I begin to apply this approach at SPS and E772 energies in Refs. [23]. No attempt was made to include plasma formation, however, so there is much work remaining. Blascke *et al.* are working in that direction [25].

Sorting through the various contributions to J/ψ suppression is a theoretical and experimental imperative. The analysis of other heavy-ion probes such as pion interferometry are similarly – if not more greatly – complicated. J/ψ production offers the theoretical advantage that it is directly sensitive to the deconfining nature of quark gluon plasma. The SPS light ion experiments have already yielded convincing evidence of strong nuclear effects in J/ψ production, while the other clues of interesting physics remain at the one or two sigma level. Moreover, one has identified the crucial uncertainties, and can now plan a workable experimental program to establish the *modus operandi* of the alleged plasma forgery.

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