Nuclear Rescattering Effects in Massive Dihadron Production

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We describe some implications for massive dihadron production experiments of recent observations in Fermilab experiments E609 and E557 of large nuclear rescattering effects in dijet production in hard pA collisions. Substantial upward corrections to α (in the A^α cross section parametrization) are indicated for dihadron experiments which detect symmetric back-to-back hadrons with narrow acceptance in azimuth or p_T. Other consequences of the large nuclear rescattering are also discussed.

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It has been realized for many years that a nucleus can serve as a valuable "laboratory" for experimental study of the scattering and hadronization of high energy quarks and gluons. In this Letter, we shall consider experiments which have used nuclear targets to study hard scattering reactions such as Drell-Yan dilepton production, dijet production, and dihadron production. For these reactions, perturbative QCD now provides a well-understood, experimentally established framework for describing the basic hard scattering process. Nuclear effects can be observed as changes in the properties of hard scattering events compared to scattering from a free-nucleon target.

Experiments [1,2] have shown that nuclear effects are quite small for Drell-Yan dilepton production in hadron-nucleus collisions. The measured k_T (the rms value of the magnitude of the transverse momentum vector) of the dilepton system produced from a free-nucleon target is typically [3] about 1.4 GeV/c. This k_T represents the combined effects of intrinsic transverse momentum (confinement) and initial-state gluon emission. For Drell-Yan dilepton production using heavy nuclear targets rather than a nucleon target, it was found that k_T hardly changed by a detectable amount [1,2], implying that the initial-state parton had experienced very little nuclear scattering. The measured nuclear contribution to k_T was about 0.4 GeV/c.

More recently, in Fermilab experiment E609 [4], a drastically different situation was found for dijet production in pA collisions at 400 GeV/c. The nuclear contribution to k_T, where k_T is now the rms net transverse momentum of the final-state dijet system, was measured to be about 2.5 GeV/c. Similar very large nuclear k_T effects are also evident in the dijet data of Fermilab experiment E557 [5] at 800 GeV/c.

A straightforward interpretation of the above experimental results is that parton hard scatterings within nuclei involve very little nuclear scattering of the *incident* parton, but that there is substantial nuclear rescattering of *outgoing* hard scattered partons. Such an asymmetry between initial-state and final-state nuclear scattering may be related to the so-called Landau-Pomeranchuk effect [6,7]: Initial-state soft gluon radiation within the nucleus will be strongly suppressed because of the smallness of the proper time which is available between an initial-state nuclear scattering and the hard scattering.

These two phenomena, the large value of k_T (nuclear) for dijets and the fact that the nuclear rescattering seems to be primarily of the outgoing partons, have some striking consequences for the interpretation of the large body of published experimental data on the "anomalous nuclear enhancement" of cross sections, particularly for $pA \to$ massive dihadrons. In the remainder of this Letter, we describe some of those consequences and their implications for the analysis of experimental data. The issues are of particular importance for dihadron data, because there is a large body of published data [8–12] of high statistical accuracy whose interpretation may become clearer when nuclear k_T effects are taken into account in the analyses.

Several experiments [8–12] have measured the A dependence of a differential cross section for the process $pA \to$ dihadrons for proton beams of momenta ≥ 400 GeV/c. The A dependence is usually parametrized as A^α, where $\alpha > 1$ is called an anomalous nuclear enhancement; $\alpha < 1$ is called shadowing, and $\alpha = 1$ would be expected for independent hard scattering from each of the nucleons. The dihadron cross section is normally measured in a small region of phase space. The choice of this region is a crucial matter, as we shall explain.

First, it is necessary to recall that anomalous nuclear enhancement effects at large p_T, which were originally discovered in inclusive single pion production [13], have been generally interpreted as being caused mainly by nuclear scattering. Nuclear scattering of fast partons will tend to enhance the differential cross section in regions of low population density in phase space. In particular, because the cross section is falling so rapidly with increasing p_T, nuclear scattering, which has effects similar to broadening the resolution function of the detector, can lead to a substantial increase in the measured cross section at large p_T. In this way, nuclear scattering of either incident or scattered fast partons will naturally yield

$\alpha > 1$ for single particle or single jet production at large p_T. Figure 1 shows the kinematic variables of the scattered parton for a typical case considered in this paper: $p(\text{beam}) = 400$ GeV/c, $\theta(\text{c.m.}) = 90°$, $\theta(\text{lab}) = 3.9°$, and $p_T = 5$ GeV/c.

The fact that nuclear scattering will tend to preferentially populate regions of low density in phase space also means that there will be a *depopulation* for regions of high density. This depopulation can also be a large effect. This is illustrated by Fig. 2, the measured dijet azimuthal opening angle distribution for hydrogen and Pb targets from Fermilab experiment E609 [4]. This experiment had the unique feature of full azimuthal acceptance for jet triggering. Both data sets are normalized to the same area. A dijet Pb/H cross section ratio measurement which required that the jets be exactly 180° apart in azimuth would yield a ratio which is almost a factor of 2 *lower* than the true dijet cross-section ratio. To obtain the correct ratio from Fig. 2, it is clearly necessary to integrate over all relative azimuths of the two jets.

For dijet or dihadron measurements, if the azimuthal acceptance of the detector were narrow (as, for example, in the Fermilab dihadron experiment of McCarthy *et al.* [8], where the width of the $\Delta\phi$ acceptance at 180° was about 5°), a substantial correction to the measured value of α would be required in order to obtain the dijet or dihadron cross section integrated over the entire azimuthal peak in Fig. 2. Using the E609 data of Fig. 2 to estimate a correction, we find that the observed [8] dipion value of $\alpha = 1.00 \pm 0.05$ should be increased to about 1.12 ± 0.05. Although 0.12 does not seem to be a huge additive correction, it is much larger than the uncertainties in α which have been quoted for all dihadron experiments, and represents almost a factor of 2 in cross section for a heavy nucleus. Furthermore, it is equal in magnitude to the full anomalous nuclear enhancement effect as originally observed [13] in high p_T single pion production, an effect which sets the entire scale under study.

We also note that the limited acceptance of a dijet or dihadron experiment in Δp_T (and to a much lesser extent for $\Delta\theta$) can lead to further upward corrections for α. The essential physics ingredients are those mentioned above: If $k_T = 0$ and there were no experimental resolution effects, the two jets of the dijet would have the exact correlations $p_T(1) = p_T(2)$ and $\phi(1) = \phi(2) + 180°$. [In contrast, $\theta(1)$ and $\theta(2)$ are only broadly correlated, because of their wide distribution in longitudinal momentum of the initial-state partons.] Since dijet production from a nucleus is characterized by a substantially larger value of k_T than for a nucleon target, the ϕ and p_T correlations will be broader for a nuclear target. Unless the experimental acceptances in both $\Delta\phi$ and Δp_T are sufficiently broad to accept the entire dijet correlation function for the nuclear target case, the measured value of α will be smaller than the true value.

Of course, the idealized dijet correlations will be broadened by experimental resolution and by loss from the "jet cone." For a dihadron experiment, the parton hadronization process also leads to a broadening of resolution in $\Delta\phi$ and Δp_T. However, for the kinematic region discussed in this paper, significant corrections to α are likely to be required for dihadron experiments whose acceptance in either $\Delta\phi$ or Δp_T is narrow.

Although some of the papers on dihadron production do not give complete information on their acceptances in $\Delta\phi$ and Δp_T, it does seem likely that discrepancies between values of α reported by different experiments are due at least in part to the acceptance effects which we are

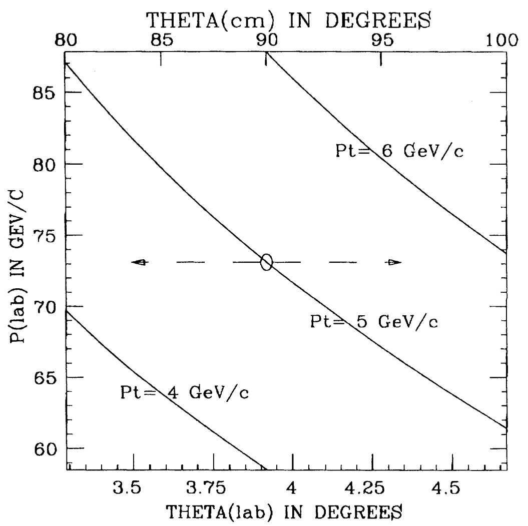

FIG. 1. Kinematics for a typical final-state parton near 90° c.m., for a proton beam momentum of 400 GeV/c. The dashed line shows how (elastic) rescattering in $\theta(\text{lab})$ will affect p_T of the outgoing parton.

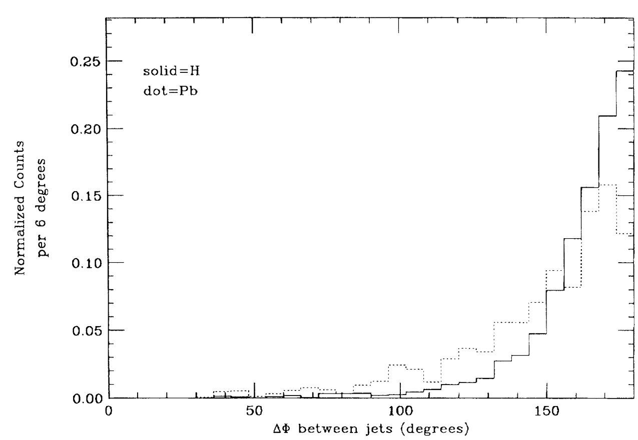

FIG. 2. Experimental data from Ref. [4] on the distribution of azimuthal opening angle for dijet events from H and Pb targets, with $p(\text{beam}) = 400$ GeV/c, $\theta(\text{c.m.}) = 90°$, and $\langle p_T \rangle = 5$ GeV/c. Both distributions are normalized to the same number of events.

describing. For example, consider the results of Finley *et al.* [9] and McCarthy *et al.* [8]. These experiments were at the same beam energy (400 GeV) and covered similar kinematic ranges. Finley *et al.* reported α in the range of 1.1 to 1.2 with large acceptance in $\Delta\phi$ and Δp_T, while McCarthy *et al.* reported α near 1.0 with smaller acceptance in both variables. We find that the corrections for acceptance differences between the two experiments could well bring the two experimental results into agreement. To make such corrections accurately is a substantial task which will require knowledge of experimental acceptances and resolutions for each experiment as well as of k_T (nucleon target) and k_T (nuclear target).

As a final subject, we shall summarize some simple related considerations which lead to a prediction of α for dijet and dihadron experiments. We first recall that the original motivation for the measurement of back-to-back dihadron production in hadron-hadron collisions was the expectation that k_T effects would tend to "cancel out" in the average p_T of the two hadrons. It is indeed true that initial-state scattering and/or gluon emission will indeed have little effect on the average p_T of the two final-state hard scattered partons [14]. By contrast, final-state nuclear scattering, if each of the two outgoing partons scatter independently, will cause a significant dispersion in the average p_T. In this way, final-state (but not initial-state) nuclear scattering can lead to a substantial anomalous nuclear enhancement of dijet or dihadron production at a given average p_T.

In fact, final-state scattering should lead to about one-half as much enhancement for dihadron as for single hadron experiments. This can be seen in the following way. An exponentially decreasing function of p_T, proportional to $\exp(-bp_T)$, when convolved with a Gaussian resolution function (in p_T) of standard deviation σ, is enhanced by a factor

$$C=\exp(b^2\sigma^2/2)\,. \tag{1}$$

If σ_1 corresponds to the k_T effect for a single outgoing parton, then for two independently scattered outgoing partons, their average p_T will be dispersed with standard deviation $\sigma_2=\sigma_1/\sqrt{2}$. Hence the cross-section enhancements will satisfy the relation $C_2=(C_1)^{1/2}$. In terms of the A^α parametrization, this means

$$\alpha_2-1=\tfrac{1}{2}(\alpha_1-1)\,. \tag{2}$$

If data from existing dihadron experiments were corrected for k_T effects as described above, it might become possible to test Eq. (2). Of course, a more precise prediction for α would require consideration of the European Muon Collaboration effect and parton energy loss issues.

In summary, we have interpreted recent dijet data as indicating that nuclear scattering in hard parton-parton scattering events is substantial and is experienced mainly by the final-state outgoing partons. This scattering has large effects upon the dijet and dihadron correlations, and can require significant acceptance corrections for some of the existing dihadron measurements of α. Final-state nuclear scattering is expected to yield $\alpha > 1$ for dijet and dihadron production.

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