COHERENT MULTIPLE SCATTERING AND DIHADRON CORRELATIONS IN HEAVY ION COLLISIONS

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We present a systematic calculation of the coherent multiple parton scattering with several nucleons in lepton-nucleus and hadron-nucleus collisions. We show that in $\ell + A$ reactions coherence leads to nuclear shadowing in the structure functions and a modification of the QCD sum rules. In $p + A$ reactions we evaluate the nuclear suppression of single and double inclusive hadron production at moderate transverse momenta. We demonstrate that both spectra and dihadron correlations in $p + A$ collisions at RHIC are sensitive measures of such dynamical nuclear attenuation effects.

1 Introduction

Copious experimental data\textsuperscript{1} from central $Au + Au$ reactions at the Relativistic Heavy Ion Collider (RHIC) has generated tremendous excitement by pointing to the possible creation of a deconfined state of QCD with energy density as high as 100 times normal nuclear matter density\textsuperscript{2}. In order to better understand the jet quenching mechanism in $A + A$ collisions we first need to address the multiple scattering between a partonic probe and the medium in simpler strongly interacting systems, like $\ell + A$ and $p + A$.

In this talk we present a systematic calculation of the coherent multiple parton scattering with several nucleons in lepton-nucleus and hadron-nucleus collisions. Recent theoretical developments\textsuperscript{3,4,5} have been able to provide a consistent picture of the dynamical nuclear shadowing of sea quarks, valence quarks and gluons. Coherence leads to small $x \lesssim 0.1$ suppression\textsuperscript{6} of the structure functions $F_1^A$, $F_2^A$ and $F_3^A$ in $\ell + A$ reactions\textsuperscript{3,4} and suppression\textsuperscript{7} of single and double inclusive hadron production cross sections at small and moderate transverse momenta in $p + A$ reactions\textsuperscript{5}. Coherent multiple scattering and the well-studied elastic multiple scattering\textsuperscript{8} co-exist in nuclear collisions and their relative role depends on the probes (or observables) and the underlying dynamics. The interplay between these two scattering channels is beyond the scope of this talk.

2 Coherence and Shadowing

Hard scattering in nuclear collisions requires one large momentum transfer $Q \sim xP \gg \Lambda_{QCD}$ with parton momentum fraction $x$ and beam momentum $P$. A simple example, shown in Fig. 1(a), is the lepton-nucleus deeply inelastic scattering (DIS). The effective longitudinal interaction length probed by the virtual photon of momentum $q^\mu$ is characterized by $1/xP$. If the momentum fraction...
of an active parton $x \ll x_c = 1/2m_N r_0 \sim 0.1$ with nucleon mass $m_N$ and radius $r_0$, it could cover several Lorentz contracted nucleons of longitudinal size $\sim 2r_0(m_N/P)$ in a large nucleus. In the photon-nucleus frame, Fig. 1(a), the scattered parton of momentum $\ell$ will interact coherently with the partons from different nucleons at the same impact parameter$^3$. In terms of the collinear factorization approach$^3$, we showed$^3$ that the hard partonic interactions for any number of coherent multiple scattering in DIS are infrared safe. The on-shell condition for $\ell$ fixes the incoming parton’s momentum fraction to the Bjorken variable $x = x_B = Q^2/(2P \cdot q)$ but additional final state scattering forces the rescaling$^3$

$$
\frac{1}{A} F_1^A(x_B) = F_1 \left( x_B \left[ 1 + \frac{\xi^2(A^{1/3} - 1)}{Q^2} \right] \right),
$$

(1)

with the scale of power corrections $\xi^2 \approx \frac{3\alpha_s(Q)}{8\pi} \lim_{x \to 0} \frac{1}{x} G(x, Q^2)$. For $\xi^2 = 0.09 - 0.12 \text{ GeV}^2$ the calculated reduction in the DIS structure functions, known as nuclear shadowing, is consistent with the $x_B$, $Q^2$- and $A$-dependence of the data$^6$ as demonstrated in Fig. 2.

Neutrino-nucleus DIS is a particularly instructive example since it provides the possibility to study the interplay between the dynamical power corrections and the heavy quark mass and is a unique handle on valence quark shadowing. For $\nu + s \to \ell^- + c$, the rescaling of the Bjorken-$x$ reads:

$$
x_B \to x_B \left( 1 + \frac{M_c^2}{Q^2} + \frac{\xi^2(A^{1/3} - 1)}{Q^2} \right),
$$

(2)

where $M_c$ is the charm quark mass. From Eq. (2) it is evident that the role of the coherent multiple final state scattering is to generate a dynamical parton mass $m_{\text{dyn}}^2 = \xi^2(A^{1/3} - 1) \text{ in the nuclear chromomagnetic field}^6$. The rescaling of the value of $x_B$ reflects the conversion of the parton’s energy into mass and correspondingly reduces the partonic flux. This attenuation depends on the $x-$slope of the parton distributions and is different for sea quarks and valence quarks$^4$.

3 Suppression in Hadron-Nucleus Collisions

Unlike in DIS, all diagrams with either final-state and/or initial-state multiple interactions in hadron-nucleus collisions, shown in Fig. 1(b), could in principle lead to medium size enhanced power corrections. However, once we fix the momentum fractions $x_a$ and $z_1$, the effective interaction region is determined by the momentum exchange $q^2 = (x_a P_a - P_c/z_1)^4$. In the head-on frame of $q - P_b$, the scattered parton of momentum $\ell$ interacts coherently with partons from different nucleons at the same impact parameter. Interactions that have taken place between the partons from the nucleus and the

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Particle production can be studied through forward rapidity region. It indicates that the attenuation increases in the sections, and the Eq. (3) leads to a net suppression of the cross section, twice as strongly to the medium via their gluon, respectively, since the gluons couple with the hard scale $t$ and the color factor $C_d$.

Similarly to the DIS case, we find that resumming the coherent scattering with multiple nucleons is equivalent to a shift of the momentum fraction of the active parton from the nucleus in Fig. 1(b),

$$x_b \rightarrow x_b \left(1 + \frac{C_d E^2 (A^{1/3} - 1)}{(-t)}\right),$$

with the hard scale $t = q^2 = (x_d P_A - P_c/z_1)^2$ and the color factor $C_d$ depending on the flavor of parton $d$. $C_q(\bar{q}) = 1$ and $C_g = C_A/C_F = 9/4$ for quark (antiquark) and gluon, respectively, since the gluons couple twice as strongly to the medium via their average squared color charge. The shift in Eq. (3) leads to a net suppression of the cross sections, and the $t$-dependence of this shift indicates that the attenuation increases in the forward rapidity region.

Dynamical nuclear effects in multiparticle production can be studied through the ratio

$$R_{AB}^{(n)} = \frac{\frac{dn_{\text{dAu}}}{dy_{\text{dAu}}}}{\frac{dn_{\text{N+N}}}{dy_{\text{N+N}}}} \cdot \langle N_{\text{coll}} \rangle,$$

Centrality dependence is implicit in Eq. (4) and the modified cross section per average collision $\frac{dn_{\text{dAu}}}{N_{\text{dAu}}}$ can be calculated from the nucleon-nucleon cross section with the shift in Eq. (3). We consider $d + Au$ reactions at RHIC at $\sqrt{s} = 200$ GeV in the following discussions.

The top panels of Fig. 3 show the rapidity and transverse momentum dependence of $R_{\text{dAu}}^{(1)}(b)$ and $R_{\text{dAu}}^{(2)}(b)$ for minimum bias collisions. The amplification of the suppression effect at forward $y_1$ comes from the steepening of the parton distribution functions at small $x_b$ and the decrease of the Mandelstam variable $(-t)$. At high $p_{T1}, p_{T2}$ the attenuation is found to disappear in accord with the QCD factorization theorems.

The bottom panels of Fig. 3 show the growth of the nuclear attenuation effect with centrality. Dihadron correlations $C_2(\Delta \varphi) = \frac{1}{A_{\text{coll}}} \frac{dN_{\text{dAu}}}{d\Delta \varphi}$ associated with $2 \rightarrow 2$ partonic hard scattering processes, after subtracting the bulk many-body collision background, can be approximated by near-side and away-side Gaussians. The acoplanarity, $\Delta \varphi \neq \pi$, arises from high order QCD corrections and in the presence of nuclear matter - transverse momentum diffusion. If the strength of the away-side correlation function in elementary $N+N$ collisions is normalized to unity, dynamical quark and gluon shadowing in $p + A$ reactions will be manifest in the attenuation of the area $A_{\text{Far}} = R_{pA}^{(1)}(b)^5$.

The left panels of Fig. 4 show that for $p_{T1} = 4$ GeV, $p_{T2} = 2$ GeV the dominant effect in $C_2(\Delta \varphi)$ is a small increase of the broadening with centrality, compatible with the PHENIX and STAR measurements. Even at forward rapidity, such as $y_1 = 2$, the effect of power corrections in this transverse momentum range is not very significant. At
small $p_T = 1.5$ GeV, $p_T = 1$ GeV, shown in the right hand side of Fig. 4, the apparent width of the away-side $C_2(\Delta \varphi)$ is larger. In going from midrapidity, $y_1 = y_2 = 0$, to forward rapidity, $y_1 = 4, y_2 = 0$, we find a significant reduction by a factor of 3 - 4 in the strength of dihadron correlations. Preliminary STAR results$^{13}$ are consistent with our predictions.

4 Conclusions

In conclusion, we presented a systematic approach$^{3,4,5}$ to the calculation of coherent QCD multiple scattering and resummed the nuclear enhanced power corrections to the structure functions $F_1^A$, $F_2^A$ and $F_3^A$ and to the single and double inclusive hadron production cross sections in $p + A$ reactions. At low $Q^2$ or $-t \propto p_T^2$, we find a sizable suppression, which grows with centrality and via $-t$ and $x_b$ with rapidity. At high $Q^2$ or $-t$ the nuclear modification disappears in accord with the QCD factorization theorems$^9$. We demonstrated that both particle spectra and dihadron correlations are sensitive measures of such dynamical attenuation of the parton interaction rates in $p + A$ reactions.

Our approach, with its intuitive and transparent results, can be easily applied to study the nuclear modification of other physical observables in $p + A$ reactions. The systematic incorporation of coherent power corrections provides a novel tool to address the most interesting transition region between “hard” and “soft” physics in hadron-nucleus collisions.

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