Understanding Nuclear Effects with QCD

J. Hüfner[1,3], B.Z. Kopeliovich[2,3], A. Schäfer[2], A.V. Tarasov[1−3]
[1]University of Heidelberg, [2]University of Regensburg, [3]MPI-Kernphysik Heidelberg

Jet quenching and partonic energy loss

High-p_T hadron production is expected to provide a sensitive probe for dense QCD matter created in heavy ion collisions. This probe, usually called jet quenching, exploits the theoretical expectation of an enhanced energy loss of a parton propagating through hot matter. The effect is predicted to be proportional to the density of the medium. In spite of much theoretical work done over the last decade, no experimental evidence for energy loss even in a cold nuclear medium has been found so far. Moreover, the existing analysis of nuclear effects in Drell-Yan reactions which is sensitive to energy loss detected no effect at all. This confusing conclusion contradicting theoretical expectations has raised doubts about the correctness of our understanding of the QCD dynamics of induced gluon radiation.

The main difficulty one faces trying to single out the effect of energy loss from Drell-Yan reactions is a strong overlap with the phenomenon of nuclear shadowing. This problem needs a more profound analysis employing the best of our knowledge of the dynamics of shadowing. A new analysis based on reliable and well tested predictions for the net shadowing effect was undertaken in [1, 2]. The combined analysis of data from the E772 and E866 experiments at Fermilab resulted in a rather large energy loss rate,

$$-\frac{dE}{dz} = 2.73 \pm 0.37 \pm 0.5\,\mathrm{GeV/fm}\ , \tag{1}$$

which is, however, consistent with theoretical expectations [2]. This it the first time that a energy loss was extracted from data.

Cronin effect

Unfortunately, there is no direct access to final state interactions of high-p_T partons with the medium. It always comes in combination with the nuclear effects originating from multiple interactions with bound nucleons in the colliding nuclei. Those effects cannot be measured, but only computed theoretically. They have been known over many years as Cronin effect which is an observed nuclear enhancement of high-p_T hadron production in pA collisions.

Recent data from RHIC for high-p_T hadrons in gold-gold collisions raised again the long standing problem of a quantitative understanding of the Cronin effect for which no parameter-free explanation has been achieved so far.

A phenomenological description based on the light-cone QCD-dipole approach which allows to explain available data and to provide predictions for pA collisions at RHIC and LHC was suggested recently in [3] . The crucial observation is that the underlying mechanism changes with energy being controlled by the coherence length of the process,

$$l_c = \frac{\sqrt{s}}{m_N k_T}\ , \tag{2}$$

where k_T is the transverse momentum of the parton produced at mid-rapidity. It turns out that at the SPS energy l_c is short compared to the nuclear radius, and the high-p_T partons are produced incoherently on different nucleons. The effect of multiple soft initial state interactions was calculated using the color-dipole approach suggested earlier in [4]. The key entry in this formalism is the universal phenomenological color dipole cross section fitted to HERA data for the proton structure function. We calculated the nuclear effects for high-p_T pions produced in pA collisions in fixed target experiments ($200-800$ GeV lab. energy), in good agreement with data as is demonstrated in Fig. 1.

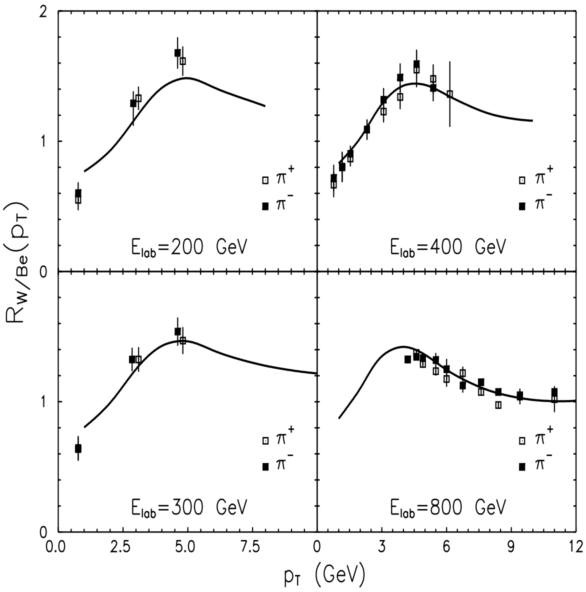

Figure 1: Ratio of the charged pion production cross sections for tungsten and beryllium as function of the transverse momentum of the produced pions. The curves correspond to the parameter free calculation [3], the depicted data are from fixed target experiments.

At very high energies l_c substantially exceeds the nuclear size and production amplitudes interfere. Correspondingly, the mechanism causing Cronin effect drastically changes between the energies of fixed target experiments and RHIC-LHC. In particular, nuclear enhancement of high-p_T hadrons at these energies is predicted to be much smaller than at SPS. This is demonstrated in Fig. 2 where the prediction for $\sqrt{s} = 200\,\mathrm{GeV}$ is depicted by a solid curve. This predictions will be checked in deuteron-gold collisions at RHIC, probably within a year.

Probing the QGP with charmonium production

It is expected that the modification of the charmonium production rate due to final state interactions (FSI) with the matter created in relativistic heavy ion collisions may serve as a probe for its properties. However, it is still a challenge to disentangle the effects of initial state in-

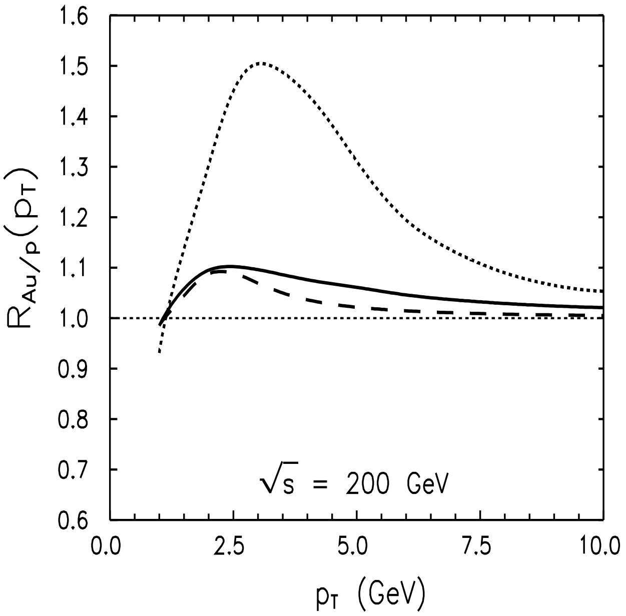

Figure 2: Predictions for RHIC. The dotted and dashed curves are calculated at $\sqrt{s} = 200\,\mathrm{GeV}$ using QCD factorization and asymptotic high energy ($l_c \gg R_A$) prescriptions respectively. The final prediction taking into account the coherence length is shown by the solid curve.

teraction (ISI) at the early stage of a collision, when the nuclei propagate through each other, from the late stage FSI, when charmonium with a low speed travels through the comoving debris of the nuclei. Since ISI seems to be the main source of suppression, uncertainties in our understanding of the early stage nuclear effects are transferred to the interpretation of FSI.

Remarkably, nuclear effects for charmonium production were not properly analyzed quantitatively so far for pA collisions. Apparently, lacking a good understanding of nuclear effects in pA collisions one should not jump to any certain conclusions about the mechanisms of nuclear suppression (or enhancement) in HI collisions.

The mechanism of ISI which is usually called "standard" is simply fitted to data for J/Ψ production at $x_F = 0.15$ in pA collisions. It is oversimplified, since it predicts no x_F dependence, while data demonstrates a dramatic enhancement of nuclear suppression of J/Ψ at large x_F.

First of all, it was realized in [5] that the mechanisms of nuclear effects for J/Ψ production change drastically as function of energy from SPS via Fermilab to RHIC and LHC. This is controlled by the coherence length of charmonium production. The first successful attempt to understand quantitatively the nuclear effects for J/Ψ production and to describe available data at different energies and as function of x_F in a parameter-free way was undertaken in [6]. The dominant source of x_F dependence is energy loss at SPS energies, at Fermilab nuclear effects get a substantial contribution from gluon shadowing, which then becomes the main mechanism of nuclear suppression at RHIC and LHC. Fig. 3 compares the contributions of these different mechanisms for pA collisions with data from the E866 experiment at 800 GeV at Fermilab (see the figure caption).

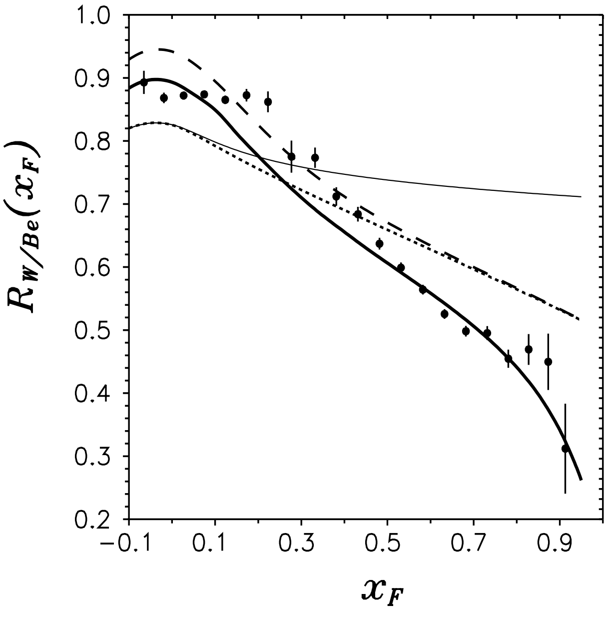

Figure 3: Tungsten to beryllium cross section ratio as function of Feynman x_F for J/Ψ production at proton energy $800\,GeV$. The thin solid curve represents contribution of initial state quark shadowing and finals state $\bar{c}c$ attenuation for χ production. The dotted curve includes also gluon shadowing. The dashed curve is corrected for gluon enhancement at large x_2 (small x_F). Experimental points are from the E866 experiment.

A nontrivial observation made in [6] is that nuclear gluon shadowing at the charm mass scale substantially deviates from universality prescribed by QCD factorization. In the case of charmonium production it is much stronger than in deep-inelastic scattering or the Drell-Yan process (see below). This fact becomes especially important at the higher energies of RHIC and LHC where gluon shadowing is expected to be the main source of nuclear suppression. One can see from the prediction for RHIC depicted by the dotted curve in Fig. 4 that J/Ψ is indeed enormously suppressed by ISI, namely by about an order of magnitude.

On the other hand, the x_F dependence of FSI suppression may serve as a novel probe [5] for the properties of the matter produced in HI collisions. Indeed, the density of the created matter is not homogeneous, but peaks at the mid-rapidity. Therefore, one should expect a strong variation of suppression (or enhancement is some scenarios) with x_F caused by FSI which may serve as its signature. The calculations [7] performed with two popular models for FSI, one with QGP production and another one with comoving hadrons, are depicted in Fig. 4 by solid and dashed curves respectively. Comparison with the dotted curve shows that the deep and minimum in x_F dependence due to FSI nearly compensate the peak at $x_F = 0$ which is expected be formed by ISI.

Nuclear suppression for Drell-Yan lepton pairs

The Drell-Yan cross section has been used at SPS in the NA38/50 experiments as a baseline for nuclear effects in charmonium production. Indeed, at this energy shadowing is absent and only energy loss affects the cross section,

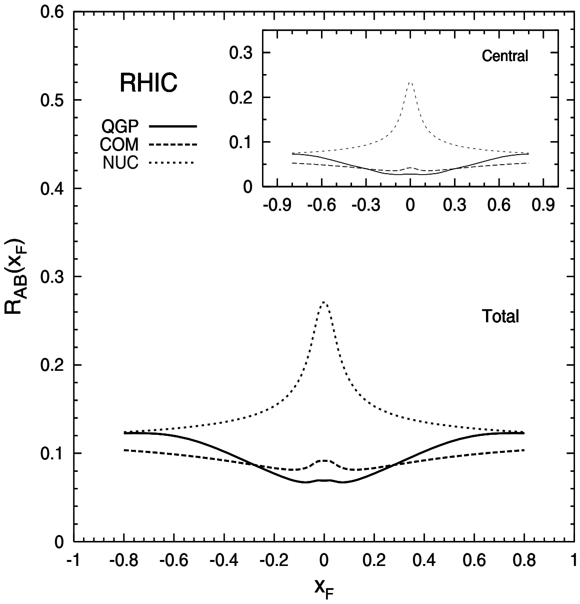

Figure 4: Ratios of cross sections of charmonium production as function of x_F for gold-gold collisions at RHIC at $\sqrt{s} = 200\,\mathrm{GeV}$, with respect to the pp case. The dotted curve presents the effect of nuclear suppression alone. Dashed and full lines refer to the full suppression resulting from nuclear effects and also from the interaction with plasma or comovers, respectively. The large and small panel represent the results for total cross section and central collisions, respectively.

mostly at large x_F. Already at Fermilab energies one faces the onset of nuclear shadowing which is sizeable at large x_F. At the energies of RHIC and LHC shadowing of quarks and gluons in nuclei becomes very strong and spans the whole x_F range. The parton model is unable to predict these effects, especially for heavy ion collisions, starting from currently available experimental information. The effects of shadowing were calculated within the light-cone dipole formalism in [8]. It was found that gluon shadowing for the Drell-Yan process is much weaker that for charmonium production. This deviation from QCD factorization is caused by presence of a semihard scale which emerges due to the strong nonperturbative interaction of light-cone gluons. The parameters of this interaction are well fixed by high statistics data for diffractive dissociation of protons into states of large invariant mass [9].

Nuclear effects and color transparency

One of the main manifestations of QCD in terms of nuclear effects is the phenomenon of color transparency (CT). As is easy to understand intuitively, a point-like colorless object cannot interact with external color fields, therefore the strength of interaction correlates with the size of the hadronic system. Consequently, if a colorless partonic configuration (pre-hadron) is produced in a hard exclusive reaction, it is expected to have a small size and propagate through nuclear matter without attenuation. A confirmation for this simple prediction has been desperately searched for in many experiments, however, only very few were successful.

High-statistics measurement for electroproduction of ρ-mesons, a process sensitive to CT, has been performed recently in the HERMES experiment at HERA. Although CT has a strong impact on the cross section of this reaction, it may be easily mixed up with the coherence length effect which varies with Q^2. A novel technique to take both effects into account based on the light-cone Green function formalism was suggested in [10]. These calculations made it possible to discriminate between the CT and coherence length effects, and the preliminary results of a new analysis of the HERMES data demonstrate a rather strong signal for CT. In addition, possible effects of higher order $\alpha_{em}Z$ corrections which might be essential for heavy nuclear targets, were investigated in [11]. Indeed, it was found that these corrections may be large and the problem needs further investigation. In particular, it can be important for coherent Coulomb production in peripheral heavy ion collisions.

References

[1] M.B. Johnson, B.Z. Kopeliovich, I.K. Potashnikova, + the E772 Collaboration, *Energy loss of fast quarks in nuclei*, Phys. Rev. Lett. **86** (2001) 4483.

[2] M.B. Johnson, B.Z. Kopeliovich, I.K. Potashnikova, P.L. McGaughey, J.M. Moss, J.-C. Peng, G.T. Garvey, M. Leitch, C.N. Brown, D.M. Kaplan, *Energy Loss versus Shadowing in the Drell-Yan Reaction on Nuclei*, hep-ph/0105195, to appear in Phys. Rev. C.

[3] B.Z. Kopeliovich, J. Nemchik, A. Schäfer, A.V. Tarasov, *Cronin Effect in Hadron Production off Nuclei*, hep-ph/0201010, submitted to Phys. Rev. Lett.

[4] M.B. Johnson, B.Z. Kopeliovich, and A.V. Tarasov, Phys. Rev. **C63** (2001) 035203.

[5] B.Z. Kopeliovich, *Charmonium Production off Nuclei: from SPS to RHIC*, Nucl. Phys. **A698** (2002) 547c

[6] B.Z. Kopeliovich, A.V. Tarasov, J. Hüfner, *Coherence Phenomena in Charmonium Production off Nuclei at the Energies of RHIC and LHC*, Nucl. Phys. **A696** (2001) 669.

[7] B.Z. Kopeliovich, A. Polleri, J. Hüfner, *Scanning the Quark-Gluon Plasma with Charmonium*, Phys. Rev. Lett. **87** (2001) 112302.

[8] B.Z. Kopeliovich, J. Raufeisen, A.V. Tarasov, M.B. Johnson, *Nuclear effects in the Drell-Yan process at RHIC and LHC*, hep-ph/0110221, to appear in Phys. Rev. C.

[9] B.Z. Kopeliovich, *From Hard to Soft Diffraction and Return*, Nucl. Phys. Proc. Suppl. **99A** (2001) 29.

[10] B.Z. Kopeliovich, J. Nemchik, A. Schäfer, A.V. Tarasov, *Color Transparency versus Quantum Coherence in Electroproduction of Vector Mesons off Nuclei*, hep-ph/0107227, to appear in Phys. Rev. C.

[11] B.Z. Kopeliovich, A.V. Tarasov, O.O. Voskresenskaya, *Long-Range Coulomb Forces in DIS: Missed Radiative Corrections?*, Eur. Phys. J. **A11** (2001) 345.