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Hadron nuclear attenuation in $p-A$ collisions from parton energy loss

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In the framework of perturbative quantum chromodynamics (pQCD), we study the nuclear attenuation of various hadronic processes in $p-A$ collisions (J/ψ, Υ, open charm, light hadron production), due to the parton energy loss ΔE, expected to be large in such processes ($\Delta E \propto E$). The good agreement between the model and the data gives some clue on the parametric dependence of ΔE as a function of the parton energy and of the medium properties. We view the study of nuclear attenuation in cold matter as a prerequisite to understand the attenuation in $A-A$ collisions. This poster presentation is based on a collaboration with the authors of [3].

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1. Motivation: Nuclear Suppression

Relativistic heavy ion collisions make it possible to study nuclear matter at energy densities far above those of normal matter. Information on the properties of quark-gluon plasma (QGP) can be obtained by the nuclear modification factor R_{AA}, which is by definition the ratio between AA and pp collisions of the differential cross section for the production of a given hadron type,

$$R_{AA} = \frac{1}{n_{coll}} \frac{d\sigma_{AA}(p_T)/dp_T}{d\sigma_{pp}(p_T)/dp_T} \tag{1.1}$$

At RHIC and now at LHC one observes a small R_{AA} at high p_T (see Fig.1), which may be interpreted as a consequence of the parton energy loss ΔE suffered by partons through the hot and dense medium. It is common to refer to an observed $R_{AA} << 1$ as "jet-quenching".

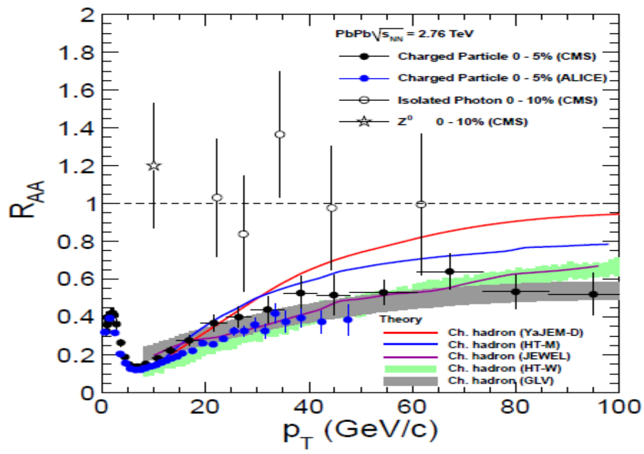


Figure 1: Nuclear modification factor measured in $Pb-Pb$ collisions at $\sqrt{s} = 2.76$ TeV.

Schematically one can illustrate large p_T production as in Fig.2. One sees that, to produce a hadron with energy $\propto p_T$, the parent parton is initially produced with the energy $p_T + \Delta E$.

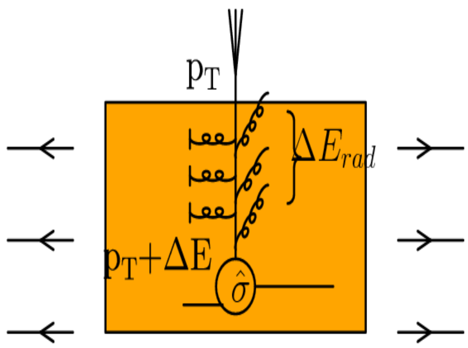


Figure 2: Large p_T hadron production.The parent parton produced in the hard subprocess must have the energy $p_T + \Delta E$.

The expression for R_{AA} can be roughly written by taking into account the shift in p_T (in the presence of the medium) in the $p-p$ cross section:

$$R_{AA} = \frac{1}{n_{coll}} \frac{d\sigma_{AA}(p_T)/dp_T}{d\sigma_{pp}(p_T)/dp_T} \simeq \frac{d\sigma_{pp}(p_T+\Delta E)/dp_T}{d\sigma_{pp}(p_T)/dp_T} \tag{1.2}$$

Typically, the inclusive hadron production at large p_T in $p-p$ collisions can be parametrized as:

$$\frac{d\sigma_{pp}(p_T)}{dp_T} \propto \frac{1}{p_T^n} \quad (n > 1), \tag{1.3}$$

leading to:

$$R_{AA} \simeq \left(\frac{p_T}{p_T+\Delta E}\right)^n << 1. \tag{1.4}$$

The obtained expression for R_{AA} shows qualitatively the suppression of the nuclear modification factor for large ΔE.

Similarly to the data showing the suppression of R_{AA} in $A-A$ collisions at large p_T, there exist some data showing a strong nuclear suppression in $p-A$ collisions at large x_F.

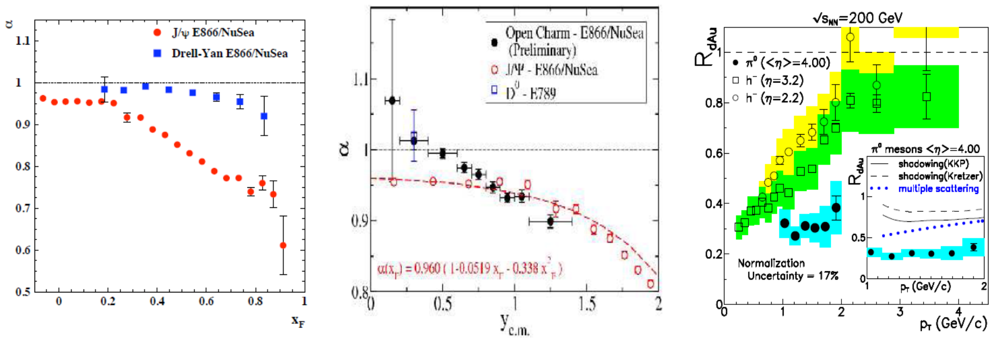


Figure 3: Large x_F/rapidity suppression.

In the early 90s, it has been suggested by Gavin and Milana [1] that parton energy loss in cold nuclear matter might be responsible for the suppression observed in $p-A$ collisions. Indeed, by following the above sketch for jet-quenching at large p_T, one can express the cross section in $p-A$ collisions as the one in $p-p$ with the shift in x_F taking into account the parton energy loss:

$$R_{pA} = \frac{1}{A} \frac{d\sigma_{pA}(x_F)/dx_F}{d\sigma_{pp}(x_F)/dx_F} \simeq \frac{d\sigma_{pp}(x_F+\delta x_F)/dx_F}{d\sigma_{pp}(x_F)/dx_F} \tag{1.5}$$

The $p-p$ differential cross section taken from the experimental data can be parametrized as

$$\frac{d\sigma_{pp}}{dx_F} \propto (1-x_F)^n \tag{1.6}$$

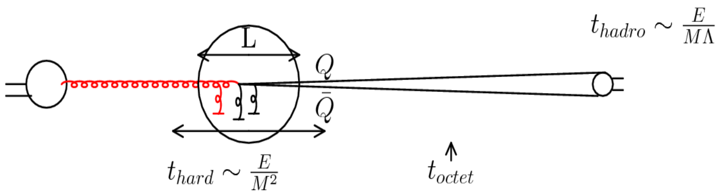
Hence:

$$R_{pA} \simeq \left(1 - \frac{\delta x_F}{1-x_F}\right)^n \tag{1.7}$$

For large energy loss (i.e., large δx_F), one observes a strong suppression of the nuclear modification factor, explaining qualitatively the data using parton energy loss. Cold nuclear matter provides a clean environment to study basic properties of parton energy loss (as compared to a QGP).

2. Energy Loss in $p-A$ collisions

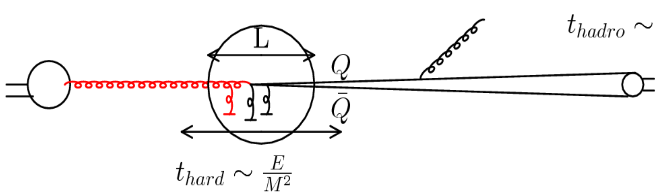
The parton energy loss is a crucial quantity in our studies, therefore it needs to be well defined before we proceed to the model and predictions. In this section we describe the calculation of energy loss associated to J/ψ production in p-A collisions. Studying energy loss through the nucleus is more convenient in the nucleus rest frame. We denote the J/ψ energy in this frame by E and consider for simplicity the generic process $gg \to c\bar{c}$. Let us denote by t_{octet} the time during which the $c\bar{c}$ is in a color octet state and by t_{hadro} the hadronization time of the J/ψ .



We consider the limit where the hard production time t_{hard} of the $c\bar{c}$ pair is large compared to the size of the nucleus, $t_{hard} \sim \frac{E}{M^2} >> L$ and much smaller than the time when the $c\bar{c}$ pair turns into color singlet:

$$L << t_{hard} << t_{octet}$$

With this assumption, the partonic subprocess effectively looks like small angle scattering of a color charge, living up to a time $\sim t_{hadro}$.

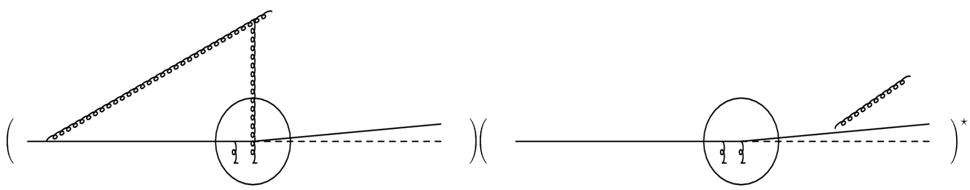


The relevant quantity to calculate is the medium-induced radiation spectrum,

$$\omega \frac{dI}{d\omega}\bigg|_{ind} = \omega \frac{dI}{d\omega}\bigg|_{pA} - \omega \frac{dI}{d\omega}\bigg|_{pp} \tag{2.1}$$

In the limit where the radiated gluon formation time $t_f >> L$, the radiation does not resolve the nuclear target, which thus acts as an effective pointlike scatterer.

When calculating the medium-induced radiation with physical gluon polarizations, the important contribution comes from the interference term:



The final expression for the medium-induced radiation spectrum and energy loss are [2] :

$$\omega \frac{dI}{d\omega}\bigg|_{ind} = \frac{N_c \alpha_s}{\pi} \{\ln(1 + \frac{E^2 \Delta q_\perp^2}{\omega^2 M_\perp^2}) - \ln(1 + \frac{E^2 \Lambda^2}{\omega^2 M_\perp^2})\}, \tag{2.2}$$

$$\Delta E \propto N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2} - \Lambda}{M_\perp} E, \tag{2.3}$$

Where $M_\perp = \sqrt{M^2 + p_\perp^2}$, $\Delta q_\perp^2$ is the transverse momentum broadening and $\Lambda = \Lambda_{QCD}$.

One must emphasize that the $\Delta E \propto E$ dependence is quantitavely similar to that of Bethe-Heitler radiation.

3. Comparison to quarkonium data

The model consists in expressing the J/ψ differential production cross section in x_F in $p-A$ collisions simply as that in $p-p$ collisions, with a shift in x_F accounting for the energy loss ε of the J/ψ partonic parent through the nucleus :

$$\frac{1}{A}\frac{d\sigma_{pA}^{\psi}}{dx_F}(x_F) = \int_0^{\varepsilon_{max}} P(\varepsilon)\frac{d\sigma_{pp}^{\psi}(x_F + \delta x_F(\varepsilon))}{dx_F}\,d\varepsilon \tag{3.1}$$

According to energy conservation, $\varepsilon \leq \varepsilon_{max} \simeq (1 - x_F)E_p$. The average over ε is performed using the quenching weight $P(\varepsilon)$, which is defined by :

$$P(\varepsilon) \simeq \frac{dI}{d\varepsilon}\exp\{-\int_{\varepsilon}^{\infty}\frac{dI}{d\omega}d\omega\} \tag{3.2}$$

As was mentioned in the previous section, the J/ψ cross section in $p-p$ collisions is extracted from the experiment.

The comparisons were made with data from various experiments. Fig4. shows the predictions for J/ψ suppression from energy loss [3] compared E866 data. As one can see, the agreement with data is quite good.

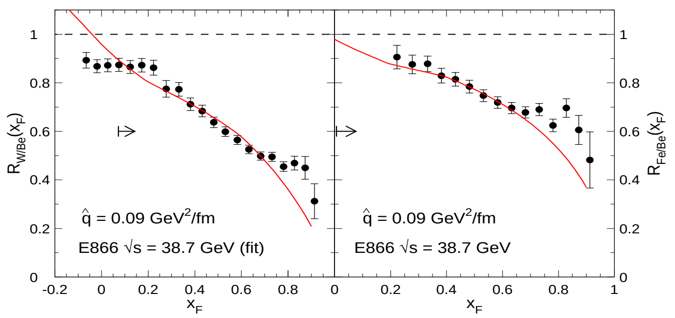


Figure 4: J/ψ suppression predicted at $\sqrt{s} = 38.7$ GeV.

4. Outlook: Open charm suppression

There exist large x_F data for open charm production in $p-p$ collisions (Fig.5).

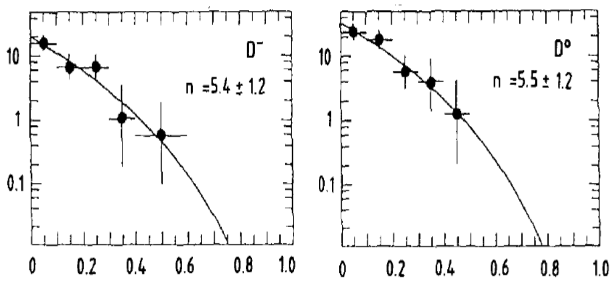


Figure 5: Open charm production in $p-p$ collisions, at $E_p = 360$ GeV [4].

Our model can be used to make predictions for the suppression of open charm in $p-A$ collisions at various energies. As an illustration, in Fig.6 we show the obtained suppression for different values of the energy, $E_p = 360$ GeV ($n = 5.5$) and $E_p = 1$ TeV ($n = 20$).

The model based on the shift in x_F accounting for the energy loss works for J/ψ production up to RHIC energies. However, this model should be tested:

- for J/ψ at LHC energies
- for open charm, light hadron production (with $p_T > 1 GeV$) from fixed target to LHC energies.

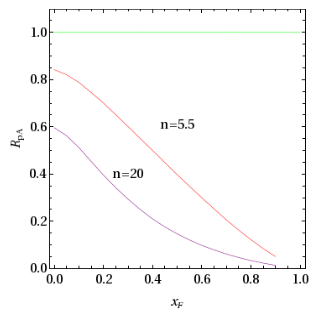


Figure 6: Predictions of the energy loss model for open charm suppression in $p-Au$ collisions. The calculation made with $M = 1.5$ GeV, $\hat{q} = 0.09 GeV^2/fm$, gives an idea of the expected order of magnitude of the suppression.

References

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[4] *LEBC-EHS Collab., M.Aguilar-Benitez et al., Phys.Lett.B 201(1988) 176.*