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Looking for the gluonic EMC effect in associated $J/\psi + \gamma$ production

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Abstract

We study the associated production of $J/\psi + \gamma$ in fixed-target experiments with nuclear targets as well as at the relativistic heavy-ion collider (RHIC). We find that this process affords a very clean probe of ρ_g, the ratio of gluon density in a heavy nucleus to that of a proton. The combined x range thus available can be used to discriminate between the predictions of different models of the EMC effect for ρ_g.

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The importance of a good knowledge of the parton densities in hadrons cannot be overemphasized in view of their significance for the physics that can be studied at both the $p\overline{p}$ and the relativistic heavy ion colliders. The parton distributions, which are often obtained by using nuclear targets, have a non-trivial dependence on the environment, viz. the well-known EMC effect [1, 2]. While the nuclear effects on the quark densities can be directly studied in deep inelastic scattering (DIS) experiments, the gluon densities $g(x, Q^2)$ get determined only indirectly, through their effect on the QCD evolution of the structure function. A good determination of the gluon densities in nuclei is possible only through studies of different hard scattering processes, dominated by gluons, in photon/lepton/hadron - nucleus collisions. A direct determination of the nuclear gluon densities will help in pinning down the correct model of the EMC effect. The theoretical basis of this effect still remains unclear as there are a large number of models [2], all of which are in reasonable conformity with the data available from DIS. However, these models give very distinct predictions for ρ_g defined as,

$$\rho_g = g^A(x, Q^2)/g^p(x, Q^2). \tag{1}$$

Thus experimental information on this ratio may help in clarifying the dynamical origin of the EMC effect.

The standard processes that have been used to measure gluon densities in protons are large-p_T jet production, heavy flavour production and direct photon/dimuon production at large p_T in hadron-nucleon collisions, and lepto- and photoproduction of quarkonia with nucleon targets.The same processes can, of course, be used as an effective tool to determine the gluonic EMC ratio, ρ_g [3, 4]. In fact the NMC collaboration [5] has measured the ratio of gluon distributions in Sn and C, by studying inelastic J/ψ production by scattering 200 and 280 GeV muon beams off these targets. With the cuts imposed in this experiment, the values of x probed are in the range 0.05 to 0.15. It will be interesting to complement this information with gluon distributions from other processes mentioned above. With the exception of lepto- and photoproduction of J/ψ, and jet production at lower p_T values, all the other processes receive contributions from quarks as well. So one has to either choose special kinematic regions or find clever combinations of different cross-sections [4] to separate the quark contributions from those of the gluon.

In the context of the colour singlet model [6], it has been shown recently [7] that a study of the associated production of J/ψ and γ in hadronic collisions affords a very clean determination of the gluon density. In this process, one looks for a photon recoiling against the J/ψ produced at large p_T. The authors of Ref. [7] have studied this process for the $p\overline{p}$ and the HERA ep collider and their study has been later extended [8] to polarised pp scattering. In this note, we analyse the effectiveness of this process to probe the gluon densities in nuclei in fixed- target experiments and at the RHIC. We find that, owing to the lower values of $\sqrt{s}$ in fixed target experiments, the range of x values for which g^A can be probed increases considerably. This can be done by studying the triple differential cross-section $d\sigma/dp_T\ dy^\gamma dy^{J/\psi}$ for negative rapidities of the photon and J/ψ. Moreover, when the J/ψ is tagged through its leptonic decay the final state is particularly clean.

This further increases the efficacy of this process in probing g^A at larger values of x, as compared with direct photon production [4]. The study of this process at the RHIC will be shown to probe g^A at the same small values of x as in lepto- and photoproduction of J/ψ. Determination of ρ_g using this process turns out to have two additional advantages: i) it is less sensitive to the theoretical uncertainties of the production mechanism, and ii) it is directly proportional to the ratio of experimentally measured cross-sections.

Since some of the statements regarding the production process depend crucially on the hadronization mechanism in the production of J/ψ, it is worthwhile summarising its main features. J/ψ production is assumed to take place through the mechanism specified in the colour singlet model [6]. In this model, one projects out the state with the correct spin, parity and colour assignments from the full $c\overline{c}$ production amplitude, to match the quantum numbers of the J/ψ. This projection is done at the level of the hard scattering amplitude itself, which yields a multiplicative factor, $R(0)$, the J/ψ wavefunction at the origin in coordinate space.

The basic subprocess, at the parton level, which is responsible for the final state with the J/ψ and the photon at large p_T is

$$g + g \to J/\psi + \gamma. \tag{2}$$

The $q\overline{q}$ initial state does not contribute because in that case the produced $c\overline{c}$ pair is not a colour singlet. Thus this final state is accessible only to gluons, and therefore depends directly on the gluon distribution. Moreover, the P-state charmonia do not get produced in this process. This is so because the subprocess

$$g + g \to \chi \to J/\psi + \gamma \tag{3}$$

does not produce the J/ψ and photon at large p_T, whereas the subprocess

$$g + g \to \chi + \gamma \tag{4}$$

is disallowed because of C-invariance and colour neutrality of the final state. Thus, this process is purely gluon-initiated and one does not have to worry about χ production and the subsequent decay of the χ into a J/ψ. It is worth noting that for the P-states it is the derivative of the bound-state wavefunction at the origin, and not the wavefunction itself, that is relevant. From simply this consideration, one expects χ production to be suppressed by a factor of 50, given that the amplitudes for the processes in eqs. (2) and (4) are of the same order of magnitude. Also, outside the framework of the colour singlet model the $q\overline{q}$ initial state can give rise to a final state containing a quarkonium and γ. However, this production mechanism will give rise to additional hadronic activity in the vicinity of the photon. Hence demanding a high-p_T, isolated γ will always ensure that the process is gluon-initiated.

It may be noted that in the framework of the colour singlet model the formation of J/ψ takes place on a perturbative time scale, being $\sim 1/m_{J/\psi}$. This can have extremely interesting implications for the J/ψ suppression signal [9] of quark gluon plasma formation, which may also have a comparable or even larger formation time. Thus the only effect the plasma can have in this case will be on the propagation of the J/ψ. This makes the physics of confinement/deconfinement cease to have any significant effect on the experimentally observed suppression of the J/ψ cross-sections. Instead the physics of its relative propagation through quark gluon plasma and a hadronic gas assumes an important role, bringing out further the model-dependence of the proposed signal.

The colour singlet model detailed above has been used in the past to describe both leptoproduction and hadroproduction of J/ψ, and is known to give a good description of the kinematical distributions [5, 10]. However, it has been found that there is considerable uncertainty in the overall normalisation for J/ψ production. This is probably due to the non-relativistic treatment of the J/ψ in this model, as well as to the small mass of the charm quark. However, we propose to study ratios of the cross-sections for different targets and hence the effect of these K-factors will be reduced. Moreover, the data [5] require a K-factor ≥ 1.0. This would mean that our cross-sections can indeed be considered as a conservative estimate.

The cross-section for the subprocess $g + g \to J/\psi + \gamma$ is given in the colour singlet model as [6, 7]

$$\begin{aligned}\frac{d\hat{\sigma}}{d\hat{t}} =& \frac{16\pi\alpha\alpha_s^2 M_\psi |R(0)|^2}{27\hat{s}^2}\Bigg[\frac{\hat{s}^2}{(\hat{t}-M_\psi^2)^2(\hat{u}-M_\psi^2)^2} \\ &+ \frac{\hat{t}^2}{(\hat{s}-M_\psi^2)^2(\hat{u}-M_\psi^2)^2} + \frac{\hat{u}^2}{(\hat{t}-M_\psi^2)^2(\hat{s}-M_\psi^2)^2}\Bigg],\end{aligned} \tag{5}$$

where $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the Mandelstam variables for the subprocess, and the modulus squared, $|R(0)|^2$, of the wavefunction is related to the leptonic decay width by

$$|R(0)|^2 = \frac{9M_\psi^2}{16\alpha^2}\Gamma(J/\psi \to e^+e^-) = 0.544 \text{ GeV}^3, \tag{6}$$

if the value of the leptonic width of the J/ψ is taken to be 5.36 keV.

The triple differential cross-section $d\sigma/dp_T\, dy^\gamma dy^{J/\psi}$ for the reaction $B + A \to J/\psi + \gamma + X$ is then given by

$$\frac{d^3\sigma}{dy^{J/\psi}dy^\gamma dp_T} = 2p_T x_1 x_2 g^B(x_1) g^A(x_2)\frac{d\hat{\sigma}}{d\hat{t}}, \tag{7}$$

where $g^B(x_1)$ and $g^A(x_2)$ are the gluon distributions in the beam B and the nuclear target A respectively, $d\hat{\sigma}/d\hat{t}$ is the subprocess cross-section given by eq. (5) and $y^{J/\psi}$ and y^γ are the rapidities, in the pA centre-of-mass frame, of the J/ψ and the photon respectively. The momentum fractions x_1 and x_2 of the beam and the target carried by the gluons are given by the following kinematic relations:

$$\begin{aligned} x_1 =& \frac{1}{2}[\bar{x}_T e^{y^{J/\psi}} + x_T e^{y^\gamma}], \\ x_2 =& \frac{1}{2}[\bar{x}_T e^{-y^{J/\psi}} + x_T e^{-y^\gamma}]. \end{aligned} \tag{8}$$

In the above equation $x_T = 2p_T/\sqrt{s}$ and $\bar{x}_T = \sqrt{x_T^2 + 4\tau}$ with $\tau = M_\psi^2/s$. Note that since in this process, the J/ψ and the photon are both detected, the values of p_T, $y^{J/\psi}$ and y^γ are all known and therefore the kinematics is determined completely. The measured cross-section is, therefore, fully differential in the kinematic variables.

We will also discuss the partially integrated cross-section $d\sigma/dp_T$, which is obtained by integrating the differential cross-section given in eq. (7) over restricted regions of phase space. For a given value of x_T the allowed range of phase space is given by

$$\begin{aligned} |y^{J/\psi}| \leq & \ \cosh^{-1}\left[\frac{(1+\tau)}{\bar{x}_T}\right], \\ -\ln\Big(\frac{2 - \bar{x}_T\ e^{-y^{J/\psi}}}{x_T}\Big) \leq & \ y^\gamma \leq \ln\Big(\frac{2 - \bar{x}_T\ e^{y^{J/\psi}}}{\bar{x}_T}\Big). \end{aligned} \tag{9}$$

In order to illustrate the effectiveness of this process in differentiating between different models of the EMC effect, we have chosen three representative cases. These are a) the gas model [11], b) the rescaling model [12], and c) the six-quark cluster model [13]. As was already mentioned, in all these models the construction of nuclear parton densities starts from a choice of nucleon parton densities. The model parameters are then fixed, using the DIS data with nuclear targets. We refer the reader to the original papers for the details of the models and their fits to the DIS data. The model (b) has no cumulative effects whereas the others are two-component models where the nuclear structure function has two contributions – one from the normal nucleons and the other from nucleons that share their partons with the other nucleons. In Fig. 1 we plot the ratio ρ_g defined in eq.(1) as a function of x_2 for the three models for $A = 56^*$. It may be noted here, however, that ρ_g does not depend very strongly on the mass number A of the nuclear target. All the models give somewhat similar predictions, in the vicinity of 1.0, for ρ_g in the range $0.1 \leq x_2 \leq 0.2$. The deviation of the ratio from unity is significant for all the models at larger values of x_2 and also at the smaller values for the rescaling model. It should be noted here that the choice of nucleon parton densities in each model is different. As a result, the relative behaviour of g^A in different models can be different from that for ρ_g shown here. The axis on the top of the figure shows, as an illustration, p_T values for the symmetric configuration $y^\gamma = 0, y^{J/\psi} = 0$ for the FNAL beam energy of 800 GeV in the fixed-target mode, i.e., $\sqrt{s} = 38.75$ GeV. As is clear from eq. (7) the ratio of the triple

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[*] A similar figure appears in the paper by Godbole and Sridhar (Fig. 1 of that paper) quoted in Ref. [3]. The curves for the gas model and the rescaling model shown there are incorrect and should be replaced with those shown here.

differential cross-sections for pA and pp, is directly proportional to ρ_g. Hence this figure also shows the expected ratio of the cross-sections as a function of p_T (for the fixed-target case) for the symmetric point that we have chosen. Moving away from the symmetric configuration in the rapidity space to negative values, it is possible to map large x_2 values to lower p_T values than shown in Fig. 1, where the cross-section is still appreciable. Conversely, it is possible to probe the smaller values of x_2 by going to positive rapidities. In this way one can obtain information on gluon densities over a fairly large range of x values.

In Fig. 2 we first show the cross-section $d\sigma/dp_T$, for the process $p + A \to J/\psi + \gamma \to l^+l^-\gamma$, obtained by integrating eq. (7) over the region $|y^{J/\psi,\gamma}| \leq y_{max}$, for the three models for the fixed-target mode of FNAL, i.e. $\sqrt{s} = 38.75$ GeV, and also for AA collisions for RHIC for $\sqrt{s} = 100$ GeV. We have chosen $y_{max} = 2.0$ for FNAL and $y_{max} = 4.0$ for RHIC. Including both electrons and muons will enhance the cross-section by a factor of 2. We see that, since the x_2-dependence of g^A is different in different models, the p_T-dependence of the cross-sections in these models is also quite different. Recall that the assumed nucleon gluon density in different models is different. Therefore the gas model predicts a harder p_T distribution than the quark-cluster model, contrary to what one would expect from Fig. 1. Interestingly, even the lowest prediction for the FNAL energy, (that of the rescaling model) corresponds to about 30-40 pb at $p_T = 3$ GeV. With the total integrated luminosity of 100 pb^{-1} that is foreseen in this case, this cross-section corresponds to large enough statistics to facilitate a good study of the process. Even for pp collisions we should have ~ 100 events at $p_T = 3$ GeV.

The increased value of $\sqrt{s}$ at RHIC causes the cross-section to be dominated by the low x region. The p_T distribution is much broader, of course. The much higher cross-sections in this case compensate for the decrease in luminosity by about a factor of 100 in going from pp to AA collisions. Since the g^A distribution is much broader for the gas model, the increase in going from FNAL energies to RHIC is only a modest factor of 5 (after taking into account the additional factor of A for the RHIC case). For the other two models the cross-section increases by more than an order of magnitude. As a matter of fact the relative size of the cross-sections predicted in the models changes completely as one goes from FNAL to RHIC. At RHIC largest (smallest) cross-sections are foreseen for the rescaling (gas) model, which is exactly opposite to the situation at FNAL. Thus combining the information on $J/\psi + \gamma$ production in the fixed target experiments and at RHIC, one can probe g^A over a wide range of x_2 and can indeed discriminate between different models. Of course, owing to the completely differential nature of the measured cross-section information can be obtained on $\rho_g(x_2)$ over a wide range of x_2 even at a fixed value of $\sqrt{s}$, by studying the triple differential cross-sections of eq. (7). We choose $p_T = 3$ GeV for doing this: at these large values of p_T, the prompt photon detection is free of background and the rates are still appreciable. The decay leptons in this case will also have on the average $p_T \simeq 2$ GeV.

In Fig. 3 we show the triple differential cross-section for the process for $A = 56$, for the gas model as a function of $y^{J/\psi}$ and y^γ, for $p_T = 3$ GeV at FNAL energy. We have restricted ourselves to values of $y^{J/\psi}$ and y^{γ} in experimentally feasible ranges, $|y^{J/\psi}, y^{\gamma}| \leq 2.0$, even though the kinematic limit is somewhat higher. As is clear from the figure, most of the cross-section is contained in this region. Indeed, the figure also shows that fairly large values of cross-sections are possible at large negative and positive rapidities. These curves show a certain asymmetry between $y^{J/\psi}$ and y^{γ}. This is a result of the fact that the nuclear gluon density is much harder than the nucleon gluon density in this model. For the quark-cluster model, a very similar configuration results. Only the absolute values of the cross-section are somewhat lower. The rescaling model predicts the least cross-section of the three models. This is a reflection of the softer nuclear gluon density in the rescaling model and the somewhat large value of p_T chosen here. The softer gluon also results in narrower rapidity distributions in this case. Thus one sees that the differences in the g^A are indeed reflected in these distributions.

To get a clearer picture of the differences in the predictions between different models, as well as to gauge the measurability of the process, we show in Figs. 4(a), (b) and (c) the contours of constant triple differential cross-sections (in pb/GeV) in the $y^{J/\psi} - y^{\gamma}$ plane, again for $p_T = 3$ GeV and for the fixed-target case, for the gas model, the rescaling model and the quark-cluster model respectively. The asymmetry between $y^{J/\psi}$ and y^{γ} is significantly different in all three cases. The gas model predicts measurable cross-sections (~ 1 pb) all the way up to $|y^{J/\psi}, y^{\gamma}| \sim 1.6$, whereas in the rescaling model these are obtained only up to rather small rapidities of 0.8 or so. As was said before, this reflects the much softer g^A in this case.

Superimposed on these contours are the contours of constant x_2. Since different pairs of $y^{J/\psi}$, y^{γ} correspond to the same x_2 at a given p_T, the ratios of triple differential cross-sections integrated along this contour will yield ρ_g at a fixed value of x_2. Note that while taking the ratios, factors of x_1 and p_T in eq. (7) cancel; we can thus integrate the ratio along the x_2 contour. This will clearly help increase the statistics and reduce the errors without losing the differential nature of the information. This enhancement of the statistics is particularly relevant for proton targets, since it is necessary to take the ratios of triple differential cross-sections for the pA and pp case to obtain ρ_g. From Fig. 4(a), for instance, we see that with the assumed luminosity of 100 pb^{-1} at FNAL, for the gas model we expect ~ 600 events corresponding to $x_2 = 0.3$. With the proton (deuterium) target we expect $\sim 15(30)$ events. A further such integration is possible along the p_T axis as well, although the cross-section falls rather rapidly in p_T, as shown in Fig. 2. Note that for an effective study of ρ_g it is necessary that we choose the lighter target to be proton or deuterium, as the EMC effect saturates very fast with increasing A.

In conclusion we see that the associated production of J/ψ and photon at large p_T is a very sensitive probe of the gluon densities. In pA fixed-target experiments, this process can be used to study the gluonic analogue of the EMC effect. As we have shown in this letter, a study of the ratio of the triple differential cross-sections, integrated along a fixed x_2 contour, for pA and pp collisions will directly yield the ratio of gluon distributions in the nucleus and the nucleon over a wide range of x. This information by itself can be used to discriminate between the different models of the EMC effect. The power of discrimination can be increased further by combining this with the measurement of this process at RHIC, which is sensitive to g^A at smaller values of $x \sim 0.1$. In this case it will not even be necessary to measure the triple differential cross-section and a measurement of $d\sigma/dp_T$ will suffice to distinguish between the different models.

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Figure captions

Fig. 1 The predictions of the gas [11], rescaling [12], and quark-cluster model [13], for the ratio of the nuclear gluon density g^A to that of the nucleon ρ_g, for $A = 56$, as a function of x, the momentum fraction. The corresponding values of p_T for the FNAL fixed-target energy, $\sqrt{s} = 38.75$ GeV, are shown on the top axis.

Fig. 2 The expected transverse momentum spectrum of the J/ψ and γ produced in the pA (AA) collisions for the FNAL (RHIC), at $\sqrt{s} = 38.75$ (100) GeV, for $A = 56$, for the gas, rescaling and quark-cluster model. The spectrum is obtained by integrating over $|y^{J/\psi}, y^{\gamma}| \leq 2.0$ (4.0) for FNAL(RHIC) and the leptonic branching ratio of the J/ψ into one lepton species has been folded in.

Fig. 3 The triple differential cross-section $d\sigma/dp_T\, dy^{\gamma} dy^{J/\psi}$ (in pb/GeV), expected in the gas model, for $p + A \rightarrow J/\psi + \gamma \rightarrow l^+ l^- \gamma$, at the fixed-target FNAL energy ($\sqrt{s} = 38.75$ GeV), as a function of the rapidities $y^{J/\psi}$ and y^{γ} of the J/ψ and the γ respectively, at $p_T = 3$ GeV and $A = 56$.

Fig. 4 Contours of constant triple differential cross-section, $d\sigma/dp_T\, dy^{\gamma} dy^{J/\psi}$, for $p + A \rightarrow J/\psi + \gamma \rightarrow l^+ l^- \gamma$, at $\sqrt{s} = 38.75$ GeV, for $A = 56, p_T = 3$ GeV, for the gas (a), rescaling (b) and quark-cluster model (c) of the nuclear parton densities. The values shown are in pb/GeV. Also superimposed are the contours of constant x_2, the momentum fraction carried by the nuclear partons.