Large-$p_T$ Inclusive $\pi^0$ Production in Heavy-Ion Collisions at RHIC and LHC

Sangyong Jeon$^{1,2}$, Jamal Jalilian-Marian$^3$ and Ina Sarcevic$^4$

$^1$RIKEN-BNL Research Center, Upton, NY 11973-5000
$^2$Department of Physics, McGill University, Montreal, QC H3A-2T8, Canada
$^3$Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA 11794
$^4$Department of Physics, University of Arizona, Tucson, Arizona 85721, USA

We present results for the large-$p_T$ inclusive $\pi^0$ production in p-p and A-A collisions at RHIC and LHC energies. We include the full next-to-leading order radiative corrections, $O(\alpha^2_s)$, and nuclear effects such as parton energy loss and nuclear shadowing. We find the next-to-leading order corrections and the parton energy loss effect to be large and $p_T$ dependent, while the nuclear shadowing effects are small ($< 10\%$). We calculate the ratio of prompt photons to neutral pions produced in heavy ion collisions and show that at RHIC energies this ratio increases with $p_T$ approaching one at $p_T \sim 8$ GeV, due to the large suppression of $\pi^0$ production. We show that at the LHC, this ratio has a steep $p_T$ dependence and approaches 25% effect at $p_T \sim 40$ GeV. We discuss theoretical uncertainties inherent in our calculation, such as choice of the renormalization, factorization and fragmentation scales and the K-factors which signify the size of higher-order corrections.

I. INTRODUCTION

In high energy heavy ion collisions hard scatterings of partons occur in the early stages of the reaction, well before the possible formation of a quark gluon plasma, resulting in production of large transverse momentum particles. Fast partons produced in these hard collisions propagate through the hot and dense medium created in the heavy ion collision and lose their energy. Therefore, a possible signature for parton energy loss in a hot, dense medium is the suppression of pion production in heavy ion collisions relative to hadron-hadron collisions. The Relativistic Heavy-Ion Collider (RHIC) at BNL with Au-Au collisions at $\sqrt{s} = 130$ GeV and at $\sqrt{s} = 200$ GeV, and the Large Hadron Collider (LHC) at CERN which will collide Pb-Pb at $\sqrt{s} = 5.5$ TeV provide the best opportunity to study the properties of the hot and dense matter and the possible formation of a new phase, the quark-gluon plasma. Recent measurements of inclusive $\pi^0$ production at RHIC energy of $\sqrt{s} = 130$ GeV [1] and at $\sqrt{s} = 200$ GeV [2] show a large suppression in the $p_T$ region ($1 \text{ GeV} < p_T < 10 \text{ GeV}$) which has created much excitement in the field. The question of the origin of this suppression has inspired many interpretations. Clearly, the low $p_T$ region has large nonperturbative contributions and perturbative calculation cannot be trusted. Here we concentrate on production of $\pi^0$ in the large-$p_T$ region where perturbative QCD calculations are expected to be more reliable.

In addition to being of interest for studying nuclear effects, such as parton energy loss and nuclear shadowing, large-$p_T$ $\pi^0$ mesons form a significant background for the prompt photons. In principle, large-$p_T$ pions could form “fake prompt photons” when one photon from pion decay escapes detection. Theoretical predictions for the ratio of prompt protons to pions at RHIC and LHC energies are crucial for studying possible quark-gluon plasma formation via photons. In addition, this ratio may reduce some of the theoretical uncertainties, such as choice of factorization, renormalization and fragmentation scale, or the choice of gluon fragmentation function.

In perturbative QCD, the inclusive cross section for pion production in a hadronic collision is given by:

$$E_p \frac{d^3\sigma}{d^3p_\pi} = \int dx_a \int dx_b \int dz \sum_{i,j} F_i(x_a, Q^2) F_j(x_b, Q^2) D_{c/\pi}(z, Q^2) E_p \frac{d^3\sigma_{i\to cX}}{d^3p_\pi}$$  \hspace{1cm} (1)

where $F_i(x, Q^2)$ is the $i$-th parton distribution in a nucleon, $x_a$ and $x_b$ are the fractional momenta of incoming partons, $D_{c/\pi}(z, Q^2)$ is the pion fragmentation function, $z$ is the fraction of parton energy carried by the pion and $d^3\sigma_{i\to cX}/d^3p_\pi$ are parton-parton cross sections which include leading-order, $O(\alpha_s^2)$, subprocesses such as:

$$q + q \to q + q$$
$$q + \bar{q} \to q + \bar{q}$$
$$q + g \to g + g$$
$$g + g \to g + g$$

and the next-to-leading order, $O(\alpha_s^3)$, subprocesses such as:

$$q + q \to q + q + g$$
$$q + \bar{q} \to q + \bar{q} + g$$
$$q + q' \to q + q' + g$$
$$q + \bar{q} \to q' + \bar{q} + g$$
$$g + g \to g + g + g$$  \hspace{1cm} (2)

The running coupling constant $\alpha_s(\mu^2)$, calculated to next-to-leading order, is given by

$$\alpha_s(\mu^2) = \frac{12\pi}{(33 - 2N_f) \ln \mu^2/\Lambda^2} \left[ 1 - \frac{6(153 - 19N_f) \ln \mu^2/\Lambda^2}{(33 - 2N_f)^2 \ln \mu^2/\Lambda^2} \right]$$
where $\mu$ is the renormalization scale, $N_F$ is the number of flavors and $A$ is the $\Lambda_{QCD}$ scale.

The parton distribution functions $F_i(x, Q^2)$ are measured in Deep Inelastic Scattering experiments such as those at HERA [3] while fragmentation functions, $D_{i/P}(z, Q^2)$, that describe the transition of the partons into the final-state pions are extracted from $e^+e^-$ annihilation data from PETRA, PEP and LEP [4]. The gluon fragmentation function, which gives the dominant contribution to $\pi^0$ production at the LHC, is not well determined by $e^+e^-$ data, since it appears only at NLO. Nevertheless, it is possible to get some constraint on the gluon fragmentation function from measurements of large $p_T$ pion production in hadronic collisions at high energies. Such a study has been done using UA1 data in the range $5\text{GeV} < p_T < 20\text{GeV}$ [5]. The gluon fragmentation function of Binnewies, Kniehl and Kramer (BKK) [4] is found to be consistent with the UA1 data. The fragmentation scale, $Q_f$, when taken to be too small, i.e. $Q_f = p_T/3$, probes the region currently not tested by the data. In addition, theoretical improvement is needed in resumming large $ln(1-z)$ terms present in the higher-order corrections.

Divergences present in the calculation of parton cross section, $d\sigma_{ij}$, require careful treatment of collinear and “soft” singularities in the matrix elements. Divergences cancel between real and virtual graphs when the physical $\pi^0$ cross section is calculated. Infrared or “soft” divergences ($k \rightarrow 0$) cancel between virtual amplitudes and real amplitudes. Collinear divergences ($\theta \rightarrow 0$ between initial quark and radiated gluon, for example) are reabsorbed in structure function and fragmentation function renormalization (“mass” singularities).

Detailed study of large-$p_T$ inclusive $\pi^0$ production in hadronic collisions show very good agreement between theory and experiments, apart from an overall normalization [6].

II. LARGE-$p_T$ INCLUSIVE $\pi^0$ PRODUCTION IN HEAVY ION COLLISIONS

To calculate the inclusive cross section for pion production in heavy ion collisions, we will use (1) with the distribution and fragmentation functions appropriately modified to include nuclear effects such as shadowing and energy loss.

It is a well known experimental fact that the distribution of quarks and gluons inside nuclei is modified compared to that in a free nucleon. This modification is known as nuclear shadowing (for a review of nuclear shadowing, we refer the reader to [7]). The parton distribution in a nucleus $F_{a/A}(x, Q^2, b_j)$, can be written as

$$F_{a/A}(x, Q^2, b_j) = T_A(b_j) S_{a/A}(x, Q^2) F_{a/N}(x, Q^2)$$

where $T_A(b_j)$ is the nuclear thickness function, $F_{a/N}(x, Q^2)$ is the parton distribution function in a nucleon and $S_{a/A}(x, Q^2)$ is the parton shadowing function, $S_{a/A}(x, Q^2) = F_{a/A}(x, Q^2)/F_{a/N}(x, Q^2)$. It should be emphasized that the $Q^2$ dependence of nuclear shadowing is poorly known, especially in the small $x_{bj}$ region. Also, gluon shadowing is measured only indirectly through scaling violation of $F_2$ structure function which leads to large uncertainties in the gluon distribution function in nuclei. In this work, we use the nuclear shadowing parametrization due to Eskola, Kolhinen and Salgado (EKS98), which is $Q^2$ dependent and distinguishes between quarks and gluons [9] and was shown to be in very good agreement with the NMC data on $Q^2$ dependence of $F_2^n/F_2^C$ [10], while some other parametrizations which have large gluon suppression due to nuclear shadowing are ruled out [11]. It is also shown that modifications to the DGLAP evolution due to gluon fusion are small for the kinematic region of relevance to RHIC.

In Fig. (1) we show EKS98 nuclear shadowing function at $Q^2 = 2.25\text{GeV}^2$ and, for comparison, we also show nuclear shadowing parametrization due to Benesh, Qiu and Vary (BQV) [8] which is $Q^2$ independent and treats shadowing of quarks and gluons on the same footing.

![Fig. 1. The nuclear shadowing ratio as parametrized by BQV and EKS98.](image)

In Fig. (2) we show the $Q^2$ dependence of the shadowing function for gluons in EKS parametrization [12]. Clearly, there is a strong $Q^2$ dependence in the EKS parametrization of nuclear shadowing, especially for gluons, as well as large anti-shadowing effect in the large $x_{bj}$ region.
Another nuclear effect which we include is the medium induced energy loss. It is expected that fast partons propagating through the hot and dense medium created after a high energy heavy ion collision will scatter from the partons in the medium, lose part of their energy and then fragment into hadrons with a reduced energy. As a result, the spectrum of the final state hadrons observed then fragment into hadrons with a reduced energy. As a second term comes from the emitted gluons each having energy \(\epsilon_a\) on the average. The average number of scatterings within a distance \(\Delta L\) is \(\langle n_a \rangle = \Delta L/\lambda_a\). We take \(\lambda_q = 1/Fm\) and \(\Delta L = R_A\).

In this work, we use the NLO code due to Aurenche et al. for calculating \(\pi^0\) and prompt photon production in p-p collisions [6] with MRS99 parametrization of nucleon structure functions [15] and BKK pion fragmentation functions [4]. We use EKS98 shadowing functions to include nuclear shadowing and we modify the BKK fragmentation functions according to the model of Huang-Sarcevic-Wang [14] in order to take into account medium induced parton [6] energy loss effects. We calculate the invariant cross section for \(\pi^0\) and prompt photon production in heavy-ion collision normalized to the number of binary nucleon-nucleon collisions, \(N_{coll}\), where \(N_{coll}\) can theoretically be determined from nuclear overlapping function, i.e., \(N_{coll} = T_{AA}(|b|\sigma_{NN}^{inel})\) and \(T_{AA}(b) = \int d^2 b_1 T_A(|b_1|) T_A(|b - b_1|)\). The number of N-N collisions depends on the centrality that experiment triggers on. Here we take \(N_{coll} = 975\), which is obtained by PHENIX for their central collisions [2]. In order to investigate the sensitivity of our results to the choice of energy loss parameters in the model of [14], we consider various forms of the average parton energy loss parameter, \(\epsilon\); constant energy loss as well as two different energy dependent forms of energy loss. We find that fractional energy loss, \(\Delta E/E = 6.1\%\) gives the best description of the \(\pi^0\) data at RHIC for \(\sqrt{s} = 200 GeV\) (see Fig. 8). With this energy loss, we make predictions for prompt photon invariant cross sections. We set all the scales, factorization, renormalization and fragmentation scale to be equal, \(Q = Q_F = \mu = \kappa p_T\) where we take \(\kappa = 1\) and \(\kappa = 2\). We discuss sensitivity of our results to the choice of scale. We assume that nucleus consists of \(A\) protons, i.e., we do not take into account isospin effects, which are expected to be small for large \(A\).

In Fig. (3) we show the invariant cross section \(E d^3\sigma/\pi p^2\) for inclusive \(\pi^0\) production in proton-proton and nucleus-nucleus (\(A = 200\)) collisions at \(\sqrt{s} = 130\) GeV. There

\[
z D_{c/\pi}(z, \Delta L, Q^2) = \sum_{n=0}^{N} P_a(n) z_n^{a} D_{c/\pi}^0(z_n^a, Q^2)
+ \langle n_a \rangle z_a^a D_{g/\pi}^0(z_a^a, Q_0^2),
\]

where \(z_n^a = z/(1 - n \epsilon_a/E_T)\), \(z_a^a = z E_T/\epsilon_a\), \(N\) is the maximum number of collisions for which \(z_n^a \leq 1\) and \(D_{c/\pi}^0\) is the hadronic fragmentation function which gives the probability that quark or a gluon would fragment into a pion.

*We do not consider \(\kappa = 0.5\) because for low \(p_T\) the scales would be in the region where currently there is no data and where perturbative QCD is not reliable.
is a clear suppression of the nuclear cross section compared to the hadronic one. While constant energy loss of $\epsilon = 0.3 GeV$ and LPM type energy loss $\epsilon \sim \sqrt{E}$ show similar shape of $p_T$ spectrum, fractional energy loss (BH) leads to a much steeper spectrum. We choose values of $\epsilon$ and $E_{LPM}$ such that the suppression at $p_T = 4 GeV$ is in agreement with the data. However, the data at $\sqrt{s} = 130 GeV$ is not precise enough to distinguish between the different forms of energy loss. Nuclear shadowing effect, which was incorporated using EKS98 shadowing, is found to be very small (few percent) at RHIC energies.

In Fig. (5) we show the ratio of inclusive $\pi^0$ cross section in nucleus-nucleus collisions to the one in p-p collisions. Since the nuclear shadowing effects are small, most of the observed suppression is due to energy loss effects. The difference between different forms of energy loss is striking, specially in the low to intermediate $p_T$ region where they have different slopes. This difference is even more pronounced for the case of fractional energy loss where this ratio actually decreases. However, we point out that we do not expect our rather crude model of energy loss through modified fragmentation functions to be correct at very high $p_T$. This is due to the fact that with a constant fractional energy loss as in the BH case, the ratio of $AA$ and $pp$ cross sections will never become one as one goes to higher momenta unlike the LPM case where fractional energy loss goes away as $1/\sqrt{E}$. Although we cannot determine exact value of $p_T$ at which our model will break down from first principles, it is clear that it will happen at higher values of $p_T$ for higher energies.
We calculate prompt photon production in heavy ion collisions using Aurenche et al. program for prompt photon production in p-p collisions that includes all next-to-leading order contributions [6]. In prompt photon production there are two types of subprocesses that contribute, direct processes and bremsstrahlung processes, the later one being convoluted with the fragmentation functions, $D_{c/\gamma}(z, Q^2_f)$, that describe the transition of the partons into the final-state $\gamma$. The fragmentation functions without medium effects are extracted from $e^+e^-$ data [4]. We use MRS99 parametrization of nucleon structure functions [15], EKS98 nuclear shadowing functions and we modify fragmentation functions in the same way as for pions.

In Fig. (6) we show the inclusive cross section for prompt photon production in heavy ion collisions at $\sqrt{s} = 130$ GeV, normalized to proton-proton collisions, together with the same ratio for inclusive $\pi^0$ production. We note that for the same energy loss parameter $\epsilon = 6.1\% E$, $\pi^0$ production is suppressed more than prompt photons. This is due to the fact that at $p_T = 3$ GeV, about 75% of the photon contributions come from “direct” processes which are not affected by parton energy loss, while in case of pions, all subprocesses are convoluted with the modified fragmentation function. At higher values of $p_T$, direct photons become even more dominant at RHIC and their energy loss becomes negligible (<10% at $p_T = 10$ GeV). Nuclear shadowing effect is small both in photon and in pion production.

In Fig. (8), we show the ratio of invariant cross sections for $AA$ and $pp$ collisions at $\sqrt{s} = 200$ GeV for different forms of energy loss. The $p_T$ spectrum behaves very differently in the case of fractional energy loss as compared to the constant and LPM type energy losses. Comparison to the preliminary PHENIX data [2] seems to favor the fractional energy loss scenario. Furthermore, varying the scales from $p_T$ to $2p_T$, in case of LPM energy loss, gives large uncertainty, about 30%, while in case of BH, this uncertainty is much smaller. This can be seen in Fig (8). It is also interesting to note that change of scales does not affect the shape of the ratio.

Prompt photon and pion invariant cross sections normalized to $pp$ collisions are shown together in Fig. (9). Clearly, prompt photons are affected much less than pions due to direct photons dominating over bremsstrahlung photons at high $p_T$. This is contrary to expectations from approaches where the suppression of high $p_T$ spectra is due to high gluon density in the initial state (color glass condensate). Therefore, measuring prompt photons would enable one to tell whether the observed suppression is due to initial state or final state effects.
FIG. 8. Ratio of inclusive $\pi^0$ cross sections in heavy ion and p-p collisions at $\sqrt{s} = 200$ GeV, data is from PHENIX [2].

FIG. 9. Prompt photon and inclusive $\pi^0$ cross sections in heavy ion collision normalized to p-p at $\sqrt{s} = 200$ GeV.

Measurements of inclusive pion production at RHIC energies for $p_T > 4$ GeV could therefore provide valuable information about the medium induced parton energy loss since nuclear shadowing effects are very small (few %) and most of the observed suppression of hadronic spectra in heavy ion collisions is due to energy loss.

In Fig. (10) we show theoretical uncertainty in predicting inclusive $\pi^0$ cross section by varying scales from $Q = p_T$ to $Q = 2p_T$, with the assumption that $Q = Q_F = \mu$.

We note that uncertainty is about 40% and that, most importantly, the shape of the $p_T$ spectrum is not very sensitive to the choice of scale (the uncertainty due to scale choices of $Q = 2p_T$ and $Q = p_T/2$ are about 100% even though ratio of cross sections is still very insensitive to the scale choice). Similar conclusion was reached in case of $\pi^0$ production in hadronic collisions [6]. Comparison of PHENIX data for inclusive $\pi^0$ production in hadronic collisions shows very good agreement with our NLO predictions obtained with all scales set to be equal to $p_T$ [2]. The ratio of $\pi^0$ production in heavy-ion collisions to the one in proton-proton collision is less sensitive to the change of scales, and in case of BH energy loss, the uncertainty is only a few percent.

In Fig. (11) we show the inclusive $\pi^0$ cross sections in p-p and heavy ion collisions at LHC energy of $\sqrt{s} = 5.5$ TeV. In case of heavy ion collisions, we show results again for three different forms of energy loss parameter $\epsilon$ and include nuclear shadowing using the EKS98 parametrization. In Fig. (12), we present the ratio of $\pi^0$ inclusive cross section in heavy ion collisions to p-p. Again, BH energy loss leads to a very different behavior of this ratio as compared to constant and LPM energy loss. While this ratio has steeply increasing $p_T$ dependence in the case of constant and LPM energy loss, it is almost flat in a large $p_T$ region in the case of BH energy loss. Again, nuclear shadowing effects are small due to the large $p_T$'s involved.
In Fig. (13) we show cross sections for prompt photon and inclusive \(\pi^0\) production normalized to p-p using the BH form of energy loss. Here we note that suppression of prompt photons is comparable to the \(\pi^0\) case because at LHC energies, prompt photon production is dominated by bremsstrahlung processes (about 60% contribution at \(p_T \sim 4\) GeV) which are modified due to the energy loss in a similar way to the \(\pi^0\) case.
shadowing has a strong p dependence which affects the production cross sections through dependence of the factorization scale on $p_T$. If one could measure the $\pi^0$ spectra at very large $p_T$ at RHIC to high accuracy (this would require an accuracy of better than 5% at $p_t \sim 20$ GeV which is quite unlikely), one could in principle rule out some models of nuclear shadowing which are $Q^2$ independent.

We have investigated dependence of our results on three different forms of energy loss. We considered constant energy loss as well as LPM and BH type of energy loss. The medium induced energy loss effects in pion production are large even at $\sqrt{s} = 130$ GeV. However, since our perturbative calculation is not applicable at low $p_T$, and the RHIC data at $\sqrt{s} = 130$ GeV is available for $p_T < 4$ GeV, we can not distinguish between different functional forms of energy loss from RHIC data at $\sqrt{s} = 130$ GeV. Therefore, we use the existing data at RHIC at $\sqrt{s} = 200$ GeV to determine the functional form and magnitude of the average energy loss per collision, $\epsilon$. We find that BH energy loss describes the data the best. We then predict the prompt photon production cross section in Au-Au collisions normalized to the p-p case at high $p_T$ ($4 \text{ GeV} < p_T < 20$ GeV). We also predict the inclusive $\pi^0$ production cross section in heavy ion collisions normalized to p-p at the LHC energy, $\sqrt{s} = 5.5$, assuming BH energy loss. We demonstrate theoretical uncertainties due to scale dependence of perturbative calculations of this ratio are small ($< 15\%$ between $Q = p_T/2$ and $Q = 2p_T$).

Finally, we show results for the ratio of prompt photon to $\pi^0$ cross sections at RHIC and LHC, of relevance to separating different sources of photon production. We show that contribution of direct photons is large at RHIC (about 75% at $p_T = 4$ GeV) but decreases as the energy is increasing, becoming 40% at $p_T = 4$ GeV (with 60% coming from bremsstrahlung processes) at LHC energies.

### Acknowledgments

We would like to thank P. Aurenche and J. P. Guillet for providing us with the fortran routines for calculating differential distributions for $\pi^0$ and photon production in hadronic collisions and for many useful discussions. We would like to thank D. d’Enterria and M. Tannenbaum for many helpful discussions and suggestions. We would also like to thank ITP, Santa Barbara where part of this work was done. J. J-M. would like to thank the nuclear theory group at SUNY Stony Brook for their hospitality where part of this work was done and is grateful to LBNL nuclear theory group for the use of their computing resources. This work was supported in part through U.S. Department of Energy Grants Nos. DE-FG03-93ER40792 and DE-FG02-95ER40906. S.J. is supported in part by the Natural Sciences and Engineering Research Council of Canada and by le Fonds pour la Formation de Chercheurs et l’Aide à la Recherche du Québec. J. J-M. is supported in part by a PDF from BSA and by U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

### References
[1] K. Adcox, et al., [PHENIX Collaboration], nucl-ex/0109003; W. Zajc [PHENIX Collaboration], nucl-ex/0106001; G. David et al. [PHENIX Collaboration], Nucl. Phys. A698, 227 (2002); K.H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. 86, 402 (2001); C. Adler, et al., Phys. Rev. Lett. 87, 182301 (2001); R. Snellings [STAR Collaboration], nucl-ex/0104006.

[2] David G. D’Enterria for the PHENIX collaboration, hep-ex/0209051; S. Mioduszewski for the PHENIX collaboration, nucl-ex/0210021, invited talks presented at Quark Matter 2002, Nucl. Phys. A715c (2003).

[3] C. Adloff et al. [H1 Collaboration,] Nucl. Phys. B497, 3 (1997); J. Breitweg et al., [ZEUS Collaboration], Eur. Phys. J. C7, 609 (1999).

[4] J. Binnewies, B. A. Kniehl, G. Kramer, Z. Phys. C65 (1995); Phys. Rev. D52 (1995); L. Bourhis, M. Fontanaz, J.-Ph. Guillet, M. Werlen, Eur. Phys. J. C19, 89 (2001)

[5] G. Bocquet et al. [UA1 Collaboration,] Phys. Lett. B366, 434 (1996).

[6] P. Aurenche, M. Fontanaz, J. Ph. Guilhet, B. Kniehl, E. Pilon, and M. Werlen, Eur. Phys. J. C13, 347 (2001); F. Aversa, P. Chiappetta, M. Greco, and J. Ph. Guillet, Nucl. Phys. B327, 105 (1989); R.K. Ellis, J.C. Sexton, Nucl. Phys., B282, 642 (1987).

[7] M. Arneodo, Phys. Rep. 240, 301 (1994).

[8] C.J. Benesh, J. Qiu and J.P. Vary, Phys. Rev. C123, 1015 (1994).

[9] K. Eskola, V. Kolhinen and P. Ruuskanen, Nucl. Phys. B535, 351 (1998); K. Eskola, V. Kolhinen and C. Salgado, Eur. Phys. J. C9, 61 (1999).

[10] M. Arneodo, et al., [New Muon Collaboration,] Nucl. Phys. B481 (1996) 23.

[11] K.J. Eskola, H. Honkanen, V. J. Kolhinen and C. Salgado, Phys. Lett. B532 (2002) 222.

[12] K. J. Eskola, V. J. Kolhinen, P. V. Ruuskanen and C. A. Salgado, Nucl. Phys. A 661, 645 (1999).

[13] R. Baier, Y. Dokshitzer, A. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B483, 291 (1997); ibid. B484, 265 (1997); R. Baier, D. Schiff and B.G. Zakharov, Ann. Rev. Nucl. Part. Sci. 50, 37 (2000).

[14] X-N. Wang, Z. Huang and I. Sarcevic, Phys. Rev. Lett. 77, 231 (1996); X-N. Wang and Z. Huang, Phys. Rev. C55 3047 (1997).

[15] A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C14, 133 (2000).