Probing nuclear parton densities (and more) from $\gamma + Q$ production in p–A and A–A collisions

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Abstract. We present a detailed phenomenological study of the associated production of a prompt photon and a heavy-quark jet (charm or bottom) in proton-nucleus (p–A) collisions. The dominant contribution to the cross-section comes from the gluon–heavy-quark (gQ) initiated subprocess, making this process very sensitive to the gluon and the heavy quark nuclear parton densities. We show that the future p–A data to be collected at the LHC in this channel should help to disentangle the various nPDF sets currently available. In heavy-ion collisions, the photon transverse momentum can be used to gauge the initial energy of the massive parton propagating through the dense QCD medium produced in those collisions, making $\gamma + Q$ production a powerful process in order to probe energy loss dynamics in the heavy-quark sector.

1. $\gamma + Q$ as a versatile tool in nuclear collisions

The production of $\gamma + Q$ is a rich and versatile process in various hadronic collisions:

- In p–p and p–$\bar{p}$ collisions, first of all, $\gamma + Q$ production offers sensitive checks of perturbative QCD (pQCD) and might serve as a probe of intrinsic heavy-quark distributions inside the proton [1];
- In p–A collisions (e.g. at RHIC and soon at the LHC), this process can be used to constrain the gluon PDF in nuclei (nuclear PDF, nPDF), [2] which are pretty much unconstrained at small values of $x$. One should underline that knowing precisely nuclear PDF is a prerequisite in order to obtain reliable predictions in heavy-ion collisions;
- In A–A collisions, finally, the study of $\gamma + Q$ provides an ideal tool for investigating the energy lost by heavy quarks in the hot QCD medium produced in those collisions. Being an electromagnetic probe, the photon produced directly in the hard process is expected to traverse the medium unaffected. Its momentum can therefore serve as a proxy for the initial momentum of the heavy-quark propagating through the dense medium and eventually fragmenting into the heavy-quark jet. The imbalance between the prompt photon and the heavy-quark jet momentum from p–p to A–A collisions might thus reflect the amount of energy loss experienced by the heavy-quark. Furthermore, the comparison between $\gamma + c$ and $\gamma + b$ production would provide access to the mass hierarchy of parton energy loss.
In these proceedings we will discuss the constraints given by $\gamma + Q$ production in $p$–$A$ collisions on nuclear parton densities. Energy loss effects on $\gamma + Q$ production in $A$–$A$ collisions will also be briefly discussed.

2. Constraining the gluon nPDF through $\gamma + Q$ production

Unlike the PDF for a gluon inside a free proton, the nuclear gluon PDF is largely unconstrained due to the dearth of available data. Currently, only the NMC structure function data ($F_2^D(x,Q^2)$ and $F_2^Sn/F_2^C(x,Q^2)$) impose weak constraints on the gluon nPDF in the $x$-range $0.02 \lesssim x \lesssim 0.2^1$, so that a precise determination is not possible.

Figure 1. $R_p^Pb(x,Q = x\sqrt{s}/2 \sim p_T)$ for nCTEQ [3], EPS09 [4] and HKN07 [5]. The box exemplifies the $x$-region probed at the LHC.

This large uncertainty in $g^A(x,Q^2)$ is presented by the nuclear modification factor to the gluon nPDF, $R_g^Pb(x,Q) = g^{Pb}(x,Q)/g^p(x,Q)$, in Figure 1 where a comparison between different nuclear PDF sets currently available (nCTEQ [3], HKN07 [5], EPS09 [4]) is shown.

The need for measurements of processes sensitive to the gluon nPDF is evident. Here we point out that $\gamma + Q$ production is an excellent probe of $g^A(x,Q^2)$, and can serve as one such process, as evidenced by Figure 2 and Figure 3. Figure 2 shows the differential cross-section for both $\gamma + c$ and $\gamma + b$ at $\sqrt{s_{NN}} = 8.8$ TeV for $p$–Pb collisions in the ALICE EMCal acceptances. The anticipated event rate (before experimental efficiencies) is sufficiently large for a measurement ($N_{\gamma+c}^{pPb} = 1.2 \times 10^4$, $N_{\gamma+b}^{pPb} = 2.3 \times 10^3$). In Figure 3 the subprocess contributions to $d\sigma_{\gamma+c}/dp_T$, are presented, with $gQ$ and $gg$ fusion being the dominant ones; for more details see Ref. [2]. The sensitivity to the gluon nPDF further shows up in the nuclear modification factor to the cross-section, $R_{pPb}^{Pb} = 1/208 \times d\sigma/dp_T(PPb \rightarrow \gamma + c + X)/d\sigma/dp_T(PP \rightarrow \gamma + c + X)$ in Figure 4a, when compared to $R_{g}^{Pb}(x,Q)$ in Figure 4b. It can clearly be seen by juxtaposing both figures that $R_{pPb}^{Pb}$ follows closely $R_{g}^{Pb}$ in the region of $x$ probed at the LHC for each nPDF set. Therefore we can conclude that this process is an excellent candidate for constraining the gluon nuclear distribution as a measurement of the prompt photon + heavy-quark jet process with appropriately small error bars will be able to distinguish between the various nPDF sets.

3. Summary and outlook

Prompt photon + heavy-quark jet production is a versatile and potentially very useful process which proves highly sensitive to the heavy-quark and gluon content of the incoming hadrons.

1 The EPS09 fit also includes data on $\pi^0$ production at RHIC.
As a consequence, we showed in these proceedings that it can be used in p–A collisions in order to bring important constraints on heavy-quark and gluon nuclear PDF, both of which being presently poorly constrained.

In a recent work [6], we study the role of parton energy loss processes on the production of photon and heavy-quark jets in heavy-ion collisions. As an illustration, the quenching of the charm $p_T$ spectrum in $\gamma + c$ production has been computed as a function of $p_T^c$ in Fig. 5a under various hypothesis regarding the energy loss of charm quarks, i.e. assuming the charm quarks to suffer the same energy loss as that of a light quark (dash-dotted line) or that of a heavy-quark assuming $m_Q = m_c = 1.5$ GeV (dashed) and $m_Q = m_b = 4.5$ GeV (solid) in the continuous part of the quenching weights (for completeness the calculation has also been carried out using the quenching weight of a propagating gluon, dotted line). The calculation is performed at leading order according to the Compton subprocess. The quenching factors computed using these various prescriptions follow closely the hierarchy of parton energy loss in the BDMPS-Z
at large momenta, $p_T$ momenta, charm quark jet should be less suppressed than assuming light quark energy loss while between the predictions assuming light quark and charm quark energy loss. At low transverse charm quark lose energy like a gluon (respectively, bottom quark). Interesting is the comparison a much stronger (respectively, weaker) heavy-quark jet quenching would be expected should the quenching weights [7] used for each flavours in the calculation (shown in Fig. 5b). In particular, a much stronger (respectively, weaker) heavy-quark jet quenching would be expected should the charm quark lose energy like a gluon (respectively, bottom quark). Interesting is the comparison between the predictions assuming light quark and charm quark energy loss. At low transverse momenta, charm quark jet should be less suppressed than assuming light quark energy loss while at large momenta, $p_T c \gg m_c$, the induced energy loss of a charm and a light quark should be identical and so does the quenching factor, as can be seen in Fig. 5a (compare the dotted and dash-dotted lines). This result and others are presented and discussed in [6].

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