QCD analysis and effective temperature of direct photons in lead-lead collisions at the LHC

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Abstract

We present a systematic theoretical analysis of the ALICE measurement of low-$p_T$ direct-photon production in central lead-lead collisions at the LHC with a centre-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. Using next-to-leading order of perturbative QCD, we compute the relative contributions to prompt-photon production from different initial and final states and the theoretical uncertainties coming from independent variations of the renormalisation and factorisation scales, the nuclear parton densities and the fragmentation functions. Based on different fits to the unsubtracted and prompt-photon subtracted ALICE data, we consistently find an exponential, possibly thermal, photon spectrum from the quark-gluon plasma (or hot medium) with slope $T = 304 \pm 58$ MeV and $309 \pm 64$ MeV at $p_T \in [0.8; 2.2]$ GeV and $p_T \in [1.5; 3.5]$ GeV as well as a power-law ($p_T^{-4}$) behavior for $p_T > 4$ GeV as predicted by QCD hard scattering.

Keywords: Quark-Gluon-Plasma, Photons, NLO QCD

1. Introduction

Direct photons, i.e. photons not originating from meson decay, represent an important probe of the quark-gluon plasma (QGP) that is assumed to have existed in the early Universe and that is currently under experimental investigation in heavy-ion collisions at the CERN LHC. An extraction of the effective QGP temperature from the transverse momentum ($p_T$) spectrum of the thermal photons requires a precise knowledge and the subtraction of the prompt photons produced in the primary hard collisions of quarks and gluons.

These photons originate not only from the hard scattering processes $qg \rightarrow q\gamma$ (QCD Compton scattering) and $q\bar{q} \rightarrow g\gamma$ (quark-antiquark annihilation) as shown in an exemplary way in Fig.\textsuperscript{1}(left), but also from purely partonic scattering processes followed by the fragmentation of a quark or gluon into a photon as shown in Fig.\textsuperscript{1}(right). At leading order (LO) of perturbative QCD, these processes are formally of the same order $O(\alpha_s \alpha)$ due to the asymptotic $O(\alpha_s)$ dependence of the photon fragmentation function (FF). At next-to-leading order (NLO), they are related through the factorisation of

\begin{center}
\begin{tabular}{c c c}
\text{Ph} & $\times$ & Rem. \text{Ph} \\
\text{Rem.} & $\gamma$ & Rem. \\
\text{Ph} & $\times$ & Rem. \text{Ph} \\
\text{Rem.} & $\times$ & Rem. \\
\end{tabular}
\end{center}

Figure 1: Feynman diagrams for prompt photon production through direct parton scattering (left) and fragmentation processes (right).
logarithmic mass divergences [1].

2. Theoretical uncertainties

This procedure introduces a factorisation scale ($\mu_f$) dependence in the real emission ($R$) squared scattering matrix elements through

$$|M^{\mu_f^2}_{ab \to cde}| = \ln \left( \frac{\mu_f^2}{\mu_T^2} \right) |M^{\mu_T^2}_{ab \to cde} P_{d \to c}(x) + \ldots , \quad (1)$$

where $P_d \to c$ represents an Altarelli-Parisi splitting function. Together with the renormalisation scale ($\mu_R$) dependence inherent in the strong coupling constant $\alpha_s(\mu_R)$ through the QCD $\beta$ function and the virtual loop ($V$) corrections,

$$|M^{\mu_R^2}_{ab \to cde}| = \ln \left( \frac{\mu_R^2}{\mu_T^2} \right) |M^{\mu_T^2}_{ab \to cde} \beta_0 + \ldots , \quad (2)$$

it leads to a theoretical scale uncertainty that is typically estimated by independent variations of $\mu$ and $\mu_f$ by factors of two around the central scale $\mu_T$.

Phenomenologically, fragmentation processes are usually important at low $p_T$, i.e. in the same region where the thermal photon signal is expected, whereas direct photons dominate at high $p_T$. This is also the case in the ALICE experiment [2] performed with lead-lead collisions of $\sqrt{s_{NN}} = 2.76$ TeV at central rapidity (cf. Fig. 2). Below $p_T = 4$ GeV, direct photons contribute less than 25%, fragmentation photons more than 75%. Since the FFs (in particular the one of the gluon) are not known very precisely (i.e. with an uncertainty of up to an order of magnitude) [3], similarly to the photon structure function [5], they represent a second important source of theoretical uncertainty. The reduction of this uncertainty, e.g. through dedicated measurements of low-$p_T$ inclusive photons in $p\bar{p}$ collisions at RHIC, is therefore quite important [6]. Alternatively, one may resort to slightly off-shell photons which do not have important fragmentation contributions [7].

Fig. 2 demonstrates that gluon-initiated scatterings dominate over those initiated by quarks in the whole $p_T$ range. The parton density functions (PDFs) of lead nuclei, in particular the one of the gluon, are also not precisely known, as they are affected by so-called cold nuclear effects such as shadowing [8]. This introduces a third source of theoretical uncertainty that must be estimated, like the one for the FFs, by variations of different parametrisations that describe the fitted experimental data equally well within one standard deviation.

3. Results

Using the NLO program JETPHOX [9], we have computed all relevant direct and fragmentation processes and compared them to the ALICE data [2] in Fig. 3 [10]. While we find very good agreement in the perturbatively dominated large-$p_T$ bins, the ALICE data show a clear excess below 4 GeV. Even though the FF uncertainty is indeed very large, it can still not account for the data. The scale (yellow) and PDF (red) uncertainties are also quite substantial. With an exponential
The relative size of the prompt-photon contribution, which falls off like $e^{-p_T/T}$ to the region $0.8 \text{ GeV} < p_T < 2.2 \text{ GeV}$, we extract an inverse slope parameter $T$ of $304 \pm 58 \text{ MeV}$, that is very similar to the value $304 \pm 51 \text{ MeV}$ obtained by the ALICE collaboration. However, the error is now larger as it includes also the various theoretical sources of uncertainty described above.

Since the $p_T$ region selected in this fit is somewhat arbitrary, we perform in Fig. 4 two additional fits to the regions $1.5 \text{ GeV} < p_T < 2.2 \text{ GeV}$ and $1.5 \text{ GeV} < p_T < 3.5 \text{ GeV}$. This can, however, only be done after properly subtracting the perturbative contribution, which starts to be substantial at intermediate $p_T$. The latter fit is of course more reliable, as it includes more data points, and leads to values of $T = 309 \pm 64 \text{ MeV}$ and $329\pm60 \text{ MeV}$ using BFG I and II FFs, respectively. These values are again similar to those above.

This result may at first sight seem surprising and coincidental. One must, however, take into account the relative size of the prompt-photon contribution, which falls off like $p_T^{-2}$ as predicted by our calculations, to the measured direct-photon rate in the different $p_T$ regions, shown in Fig. 5. Indeed, we find that prompt photons contribute less than 20% for $p_T < 2.4 \text{ GeV}$ (less than 10% for BFG II FFs), i.e. their subtraction and the theoretical error do not strongly modify the exponential fall-off of the experimental data in this region. Above 4 GeV, we find instead an almost constant ratio of prompt over direct photons that is consistent with one within the uncertainties, i.e. these observed photons are produced in hard scatterings. In the intermediate region, it was already clear from Fig. 3 that the prompt-photon contribution is substantial, larger than 20% (10% for BFG I FFs), and must indeed first be subtracted from the experimental data. Only then can the excess be described again by an exponential fit, which we found to be in good agreement with the fit to the unsubtracted data at low $p_T$.

4. Summary

In conclusion, we have performed in this work a first systematic theoretical analysis of the ALICE measurement of direct-photon production in central lead-lead collisions with a centre-of-mass energy of $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ at low values of $p_T$ of 0.8 to 14 GeV. Based on a next-to-leading order QCD calculation, we found that prompt photon production in this region was largely induced by initial gluons and dominated by fragmentation contributions. This resulted in large theoretical uncertainties from independent variations of the renormalisation and factorisation scales, nuclear parton densities and fragmentation functions.

Nevertheless, we were able to confirm that the experimental data are well fitted in the region $p_T \in [0.8; 2.2] \text{ GeV}$ by an exponential form $A \exp(-p_T/T)$ with an effective temperature of $T = 304 \pm 58 \text{ MeV}$, with an only slightly larger uncertainty than the 51 MeV quoted by the ALICE collaboration. The reason is that in this region prompt photons contribute less than 10 to 20% to the total direct photon rate, so that their subtraction and theoretical error do not influence the fit result very much. We also verified that already for values of $p_T > 4 \text{ GeV}$ the experimental data fall off with approximately
as predicted by perturbative QCD. In the intermediate $p_T$-region from 1.5 to 3.5 GeV, the prompt-photon contribution had to be subtracted from the experimental data before a sensible exponential fit could be performed. We were able to verify an exponential fall-off with a very similar effective temperature of 309 ± 64 MeV. The inverse slope parameter of this measurement is significantly higher than the one obtained previously by the PHENIX collaboration in 0-20% central gold-gold collisions with $\sqrt{s_{NN}} = 200$ GeV at RHIC, which resulted in $T_{RHIC} = 221 ± 19 ± 19$ MeV [11]. The latter was higher than the transition temperature to the QGP of about $T_{crit} = 170$ MeV, but 1.5 to 3 times smaller than the initial temperature $T_0$ of the dense matter due to the space-time evolution following its initial formation; in hydrodynamical models, which describe the data at $\sqrt{s_{NN}} = 200$ GeV, $T_0$ ranges from 600 to 300 MeV depending on the formation time, assumed to lie between $\tau_0 = 0.15$ and $0.6$ fm/$c$ [12].

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