Direct-Photon Production in Au+Au Collisions at RHIC

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Abstract. Results from the PHENIX experiment on direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for transverse momenta $1 \lesssim p_T \lesssim 13$ GeV/c are presented. Direct-photon yields at high $p_T$ scale as expected for particle production in hard processes. This supports jet-quenching models which attribute the suppression of high-$p_T$ hadrons to the energy loss of fast partons in the quark-gluon plasma. The low-$p_T$ direct-photon spectra, measured via $e^+e^-$ pairs with small invariant masses, are possibly related to the production of thermal direct photons in Au+Au collisions at RHIC.

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INTRODUCTION

Depending on their transverse momenta, $p_T$, direct photons, i.e., photons not coming from hadron decays like $\pi^0 \rightarrow \gamma\gamma$, convey information about different aspects of ultra-relativistic nucleus-nucleus (A+A) collisions.

Direct photons at high $p_T$ are produced in initial parton-parton scatterings with large momentum transfer (hard scatterings) in processes like quark-gluon Compton scattering ($q + g \rightarrow q + \gamma$) and quark-antiquark annihilation ($q + \bar{q} \rightarrow g + \gamma$). Unlike scattered quarks and gluons, photons from initial hard scatterings are not affected by the hot and dense medium subsequently produced in a A+A collision. High-$p_T$ direct photons ($p_T \gtrsim 6$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV) can therefore be used to test the theoretical description of the initial phase of a A+A collision with perturbative Quantum Chromodynamics (pQCD). Moreover, they serve as a measure of the rate of initial hard parton-parton scatterings in A+A collisions.

A significant fraction of low-$p_T$ direct photons (1 $\lesssim p_T \lesssim 3$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [2]) is expected to come from the thermalized medium of deconfined quarks and gluons, the quark-gluon plasma (QGP), possibly created in A+A collisions. These so-called thermal photons carry information about the initial temperature of the QGP. The QGP created in a A+A collision expands and cools until the critical temperature for the transition to a hadron gas is reached. Thermal direct photons are created in the QGP as well as in the hadron gas over the entire lifetime of these phases. The initial temperature $T_i$ of the QGP just after thermalization can be extracted by comparing thermal photon data with predictions from models which convolve thermal photon production rates with the space-time evolution of the QGP and hadron gas phase.

At low and intermediate $p_T$ (up to $p_T \sim 6$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV)
FIGURE 1. Nuclear modification factor $R_{AA}$ for direct photons, neutral pions, and $\eta$ mesons in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The suppression of $\pi^0$ and $\eta$ production can be described by energy loss of partons in the QGP.

200 GeV) the interaction of quarks and gluons from hard scattering processes with the QGP might be a further significant source of direct photons [3]. An example for such a hard+thermal interaction is a jet-photon conversion like $q_{\text{hard}} + g_{\text{QGP}} \rightarrow q + \gamma$ in which the photon usually obtains a large fraction of the momentum of $q_{\text{hard}}$.

HIGH-$p_T$ DIRECT PHOTONS

In the PHENIX experiment at RHIC photons are measured with two types of highly segmented electromagnetic calorimeters: a lead scintillator sampling calorimeter (PbSc) and a lead glass Cherenkov calorimeter (PbGl) [1]. Neutral pions and $\eta$ mesons are reconstructed via their two-photon decay branch. The $p_T$ spectrum of direct photons is obtained by subtracting the spectrum of decay photons calculated based on the measured $\pi^0$ and $\eta$ spectra from the $p_T$ spectrum of all photons.

The yield of direct photons from hard scattering processes in A+A collisions relative to $p+p$ collisions is expected to scale with the increase of the initial parton luminosity per collisions. This increase is quantified with the nuclear overlap function $T_{AA}$. In the absence of nuclear effects the nuclear modification factor

$$R_{AA}(p_T) = \frac{dN/dp_T|_{A+A}}{\langle T_{AA} \rangle \times d\sigma/dp_T|_{p+p}} \quad (1)$$

is unity for particles production in hard scattering processes.

Figure 1 shows the nuclear modification factor for direct photons, neutral pions, and $\eta$ mesons in central Au+Au collisions at RHIC. $\pi^0$ and $\eta$ production at high $p_T$ is
suppressed by a factor of $\sim 5$ whereas high-$p_T$ direct-photon yields scale as expected for particle production in hard processes. This is in line with jet-quenching models which assume that the rate of hard processes in A+A collisions scales with $T_{AA}$ and which attribute the hadron suppression to the energy loss of quarks and gluons from hard scattering in the quark-gluon plasma.

LOW-$p_T$ DIRECT PHOTONS

At low $p_T$ ($\lesssim 4 \text{ GeV}/c$) the direct-photon signal is small so that the standard method of measuring direct photons with the electromagnetic calorimeters essentially only yields upper limits. Therefore a new method based on the measurement of $e^+e^-$ pairs identified with the aid of the Ring Imaging Cherenkov detector of the PHENIX experiment was employed. The idea is that all sources of real photons also produce virtual photons which decay into $e^+e^-$ pairs with small invariant masses. An example is the $\pi^0$ Dalitz decay $\pi^0 \rightarrow \gamma e^+e^-$. The basic assumption in this analysis is that the ratio of real direct to all real photons is equal to the same ratio for virtual photons with small invariant masses ($m_{\gamma^*} < 30 \text{ MeV}$):

$$\frac{\gamma_{\text{direct}}^{\gamma^*}}{\gamma_{\text{incl}}^{\gamma^*}} = \frac{\gamma_{\text{direct}}^{m<30 \text{ MeV}}}{\gamma_{\text{incl}}^{m<30 \text{ MeV}}}.$$  \hspace{1cm} (2)

Furthermore, it is assumed that the distribution of the $e^+e^-$ invariant masses can be described by the Kroll-Wada formula [4]

$$\frac{1}{N_{\gamma}} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m^2_{ee}}{m^2_{\pi^0}} (1 + \frac{2m^2_{ee}}{m^2_{\eta}})} \frac{1}{m_{ee}} |F(m^2_{ee})|^2 \left(1 - \frac{m^2_{ee}}{M^2}\right)^3$$ \hspace{1cm} (3)

which is shown in Fig. 2 for $e^+e^-$ pairs from $\pi^0$ and $\eta$ Dalitz decays and from the decay of virtual direct photons. For $e^+e^-$ pairs from $\pi^0$ and $\eta$ Dalitz decays the yield is suppressed towards higher $m_{ee}$ due to the mass $M$ of the parent meson in the phase space factor $(1 - m^2_{ee}/M^2)^3$ whereas no such suppression occurs for $e^+e^-$ pairs from virtual direct photons as long as $m_{ee} \ll p_T^e$. For the small $e^+e^-$ invariant masses considered here the form factor $|F(m^2_{ee})|$ is assumed to be unity in all cases.

The key idea is to make use of the increased signal/background ratio for $e^+e^-$ pairs from virtual direct photons at higher $m_{ee}$. The experimentally observed quantity is the ratio $R_{\text{data}}$ of the $e^+e^-$ pair yield at low invariant masses and at higher invariant masses, e.g., $R_{\text{data}} = \frac{N_{ee}^{m<30 \text{ MeV}}}{N_{ee}^{200<m<300 \text{ MeV}}}$. In the absence of a direct photon signal $R_{\text{data}} = R_{\text{Kroll–Wada}}^{\text{hadron}}$, i.e., $R_{\text{data}}$ can be calculated from Eq. 3 based on the known ratio $\eta/\pi^0 = 0.45 \pm 0.1$ and the known branching ratios for the $\pi^0$ and $\eta$ two-photon decay. An excess $R_{\text{data}} > R_{\text{Kroll–Wada}}^{\text{hadron}}$ translates into the fraction of virtual direct photons according to

$$\frac{\gamma_{\text{direct}}^{\gamma^*}}{\gamma_{\text{incl}}^{\gamma^*}} = \frac{R_{\text{data}} - R_{\text{Kroll–Wada}}^{\text{hadron}}}{R_{\text{Kroll–Wada}}^{\text{direct \gamma}} - R_{\text{Kroll–Wada}}^{\text{hadron}}}.$$  \hspace{1cm} (4)
FIGURE 2. Distribution of the invariant masses $m_{ee}$ of $e^+e^-$ pairs from $\pi^0$ and $\eta$ Dalitz decays and from the decay of virtual direct photons with $m_{ee} \ll p_{T}^{ee}$ as given by Eq. 3. The ratio $R_{Kroll-Wada}^{\text{hadron}}$ of the $e^+e^-$ yields in the $m_{ee}$ intervals B and A expected from $\pi^0$ and $\eta$ decays is calculated as the weighted average of $R_{Kroll-Wada}^{\pi^0}$ and $R_{Kroll-Wada}^{\eta}$.

The direct-photon $p_T$ spectrum is then obtained by multiplying the inclusive photon spectrum measured with the PHENIX electromagnetic calorimeters by the ratio $\gamma^{\text{direct}}_{\gamma}/\gamma^{\text{incl}}_{\gamma}$.

Results from this method are depicted in Fig. 3. The left panel shows $\gamma^{\text{direct}}_{\gamma}/\gamma^{\text{incl}}_{\gamma}$ for four different centrality classes. A significant direct-photon excess in central Au+Au collisions is observed for $1 \lesssim p_T \lesssim 4.5$ GeV/$c$. The direct-photon excess appears to decrease towards more peripheral collisions. The systematic uncertainty of $\gamma^{\text{direct}}_{\gamma}/\gamma^{\text{incl}}_{\gamma}$ on the order of 25% is dominated by the uncertainty of the $\eta/\pi^0$ ratio. The right panel of Fig. 3 shows the low-$p_T$ direct-photon spectrum in central Au+Au collisions compared to a next-to-leading-order (NLO) p+p pQCD calculation scaled by the nuclear overlap function $T_{AA}$. The pQCD calculation provides an estimate of the contribution of hard processes to the direct-photon spectrum at low $p_T$. It is planned to replace the pQCD calculation by direct-photon measurements in p+p and d+Au collisions in the future.

The excess of the measured direct-photon spectrum in Fig. 3 over the photons from hard processes as estimated by the QCD calculation hints at a significant contribution of thermal photons in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In order to describe thermal photon production in A+A collisions the entire space-time evolution of the fireball needs to be modeled. This is often done with hydrodynamic calculations which assume local thermal equilibrium. An important free parameter in such models is the initial temperature of the fireball. It has been shown in different calculation that the low-$p_T$ direct-photon spectrum in central Au+Au collisions can be described as the sum of hard pQCD photons and thermal photons from the QGP and the hadron gas [5, 6, 7, 8]. The initial temperatures derived from these calculation are in the range $370 \lesssim T_i \lesssim 570$ MeV. These temperatures are significantly above the critical temperature for the QGP phase transition of $T_c \approx 170$ MeV.
FIGURE 3. Left panel: Ratio of direct to all virtual photons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for four different centrality classes (0 – 20%, e.g., corresponds to the most central class comprising the 20% most central collisions). Right panel: Low-$p_T$ direct-photon spectrum in central Au+Au collisions compared to a NLO pQCD calculation. The three solid curves correspond to different scales used in the pQCD calculation and indicate the theoretical uncertainties.

CONCLUSIONS

Direct-photon data from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have been presented for $1 \lesssim p_T \lesssim 13$ GeV/c. Unlike pions and other hadrons direct photons at high $p_T$ are not suppressed, i.e., they follow $T_{AA}$ scaling. Thus, the control measurement possible with high-$p_T$ direct photons shows that hadron suppression is a final state effect, consistent with parton energy loss in the QGP. The low-$p_T$ direct-photon spectrum in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV might contain a significant contribution of thermal photons. Model descriptions of the data yield initial temperatures above $T_c$. This would provide further evidence for a QGP formation in central Au+Au collisions at RHIC if the NLO pQCD estimate of the contribution of direct photons from hard processes at low $p_T$ is confirmed by p+p and d+Au measurements.

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