Measurement of direct photons in $\sqrt{s_{NN}} = 200$ GeV $p+p$ and Au+Au collisions with the PHENIX Experiment at RHIC

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Abstract. The measurement of direct photons in $\sqrt{s_{NN}} = 200$ GeV $p+p$ and Au+Au collisions is presented. The signal is compared to NLO pQCD calculations, which, in case of Au+Au, are scaled with the number of underlying nucleon-nucleon collisions. The agreement of the calculation with the data in both cases confirms the scaling of hard processes with the number of nucleon-nucleon collisions and supports the explanation of the earlier-observed pion suppression as a final-state effect.

1. Introduction
Direct photons are a unique probe of the hot and dense matter created at RHIC: they allow access to the initial, thermalized state of the nuclear collision. Their measurement, however, is challenging. One has to cope with a large background from hadronic decays. While several definitions of direct photons are used, we pragmatically attribute this term to all photons that are not decay photons. The main direct photon production processes are quark-antiquark annihilation and quark-gluon Compton scattering [1]. In addition, direct photons are produced through fragmentation of hard partons. These are also called bremsstrahlung photons.

Direct photon measurements in $p+p$ collisions provide a superb test of pQCD. They probe the gluon distribution function. At RHIC they can also probe the spin gluon distribution function [2] in the polarized-proton program. In contrast to hadron measurements, their interpretation does not suffer much from uncertainties on the fragmentation function. Furthermore, they provide a constraint on the hard-scattering contribution to direct photon production in Au+Au collisions.

In heavy ion collisions, thermal direct photons allow, in principle, measurement of the temperature of the collision system in its hottest phase. Also, hard direct photons serve as a crucial baseline for the interpretation of the earlier observed high-$p_T$ hadron suppression [3]. Interactions of hard partons with the medium provide an additional source of direct photons, either through annihilation and Compton scattering [4] or through medium-induced bremsstrahlung [5].

With its high-resolution, highly-segmented electromagnetic calorimeter PHENIX [6] has an excellent capability to measure photons. PHENIX has made precision measurements of neutral pions and $\eta$ mesons up to transverse momenta of 15 GeV/c. With this crucial measurement of the direct photon background, PHENIX has extracted direct photons in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
2. Direct Photon Analysis

The first step in the direct photon analysis in Au+Au is to get a clean inclusive photon sample. To achieve this, non-photon backgrounds, as from charged particles, have to be subtracted. The next step is to measure the $p_T$ spectrum of $\pi^0$'s and $\eta$'s. From these spectra, the number of decay photons is determined in a Monte Carlo calculation, which also considers contributions from other hadronic decays. Finally, the decay photon spectrum is subtracted from the inclusive photon spectrum to obtain the direct photon spectrum. This method makes no attempt to identify direct photons on an event-by-event basis. Therefore it is called the subtraction method or statistical method. Further details can be found in [8].

In $p+p$ collisions, where the multiplicity and the occupancy on the detector are small, it is possible to tag and subtract decay photons event by event. In addition, an isolation cut, i.e., a cut on the maximum energy allowed in a cone around a direct photon, allows further suppression of decay photons on an event-by-event basis. As an additional feature the isolation cut helps to identify fragmentation photons. Further details on the $p+p$ analysis can be found in [7].

For the measurement of direct photon production in $p+p$ collisions, an integrated luminosity of 266 nbarn$^{-1}$ sampled in the 2003 RHIC $p+p$ run was analyzed. The Au+Au result is based on the 2002 run with an integrated luminosity of 24 $\mu$barn$^{-1}$. Photons were detected by the electromagnetic calorimeter (EMCal), which is located in the two central arms of the PHENIX detector, each covering $2 \times 90^\circ$ in azimuth and a pseudorapidity ($\eta$) range of $\pm 0.35$. For the $p+p$ measurement, only one arm was used. The energy calibration was checked by the position and width of the $\pi^0$ invariant-mass peak. The fraction of charged-particle contamination was determined with the central-arm tracking detectors which are located in front of the EMCal.
3. Direct Photon Cross Section in $p+p$ Collisions

Figure 1 shows the PHENIX preliminary direct photon cross section measured in $\sqrt{s} = 200$ GeV $p+p$ collisions as a function of $p_T$ [7]. The left panel shows the result obtained with event-by-event tagging and subtraction of decay photons. The curves represent a NLO pQCD calculation for three different scales [9]. The calculation agrees well with the measurement. The right panel of Fig. 1 compares this result to the result obtained by an isolation cut. No significant reduction of the direct photon yield by the isolation cut is observed. This suggests that either the contribution from fragmentation photons is small or that the efficiency of the isolation cut to discount fragmentation photons is low. These preliminary results substantially increase the statistical significance and the $p_T$ reach of the published result from the 2002 run [10].

4. Direct Photon Yield in Au+Au Collisions

The direct photon spectra measured in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions [8] are shown in Fig. 2 for different centrality selections. They are compared to NLO pQCD calculations [9] scaled by the corresponding number of binary nucleon collisions. It can be seen that the pQCD calculations provide a good description of the measured direct photon spectra.

A common way to study possible medium effects in AA collisions is the nuclear modification factor $R_{AA}$, i.e. the ratio of the AA invariant yields to the NN-collision-scaled $p+p$ invariant yields [3]. The centrality dependence of $R_{AA}$ for the integrated yield in $p_T > 6$ GeV/c for direct photons (closed circles) is now compared to that of $\pi^0$'s (open circles) in Fig. 3. The direct photon $p+p$ yield is taken as the NLO pQCD calculation [9] as in the previous figure, while the $\pi^0$ $p+p$ yield is taken from the measured $\pi^0$ yield [11]. The $R_{AA}$ trend confirms the observation from above in more detail: the direct photon production in Au+Au is consistent with the binary-scaled $p+p$ pQCD calculation. This is in sharp contrast [3] to the centrality dependence of the $\pi^0$ $R_{AA}$, indicating that the observed large suppression of high-$p_T$ hadron production in central Au+Au collisions is dominantly a final-state effect due to parton energy loss in the dense produced medium, rather than an initial-state effect.
Figure 3. $R_{AA}(p_T > 6\text{GeV/c})$ as a function of centrality ($N_{\text{part}}$) for direct photons (closed circles) and $\pi^0$'s (open circles) [8]. The error bars indicate the total error excluding the error on $\langle N_{\text{coll}} \rangle$ shown by the dashed lines and the scale uncertainty of the NLO calculation shown by the shaded region at the right.

5. Summary
Direct photon production has been measured in $p+p$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. In $p+p$, NLO pQCD calculations agree well with the measurement. The equally good agreement between measurement and binary scaled pQCD calculations in $Au+Au$ suggests that nuclear modifications at mid-rapidity are small. The result provides strong confirmation that the observed large suppression of high $p_T$ hadron production in central $Au+Au$ collisions is dominantly a final-state effect.

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