Direct photon measurements in He+Au collisions at 200 GeV

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Abstract. The PHENIX experiment has published direct photon yields from different collisions at RHIC energies and discovered a large excess of low-\(p_T\) direct photons in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV compared to reference p+p collisions, which has been attributed to thermal radiation from the hot and dense medium. PHENIX has also developed a new technique to identify conversion photons without assuming the radius where the conversion happened. This method greatly increases the available statistics and reduces systematic uncertainties. This paper presents the results obtained from real photons in the electromagnetic calorimeter and photons converted at the layers of Silicon Vertex Tracker (VTX).

1. Introduction

The theory of the strong interaction, Quantum Chromodynamics (QCD), predicts a transition from ordinary nuclear matter to a state where quarks and gluons are no longer confined to hadrons [1, 2]. Production and investigation of this deconfined partonic state of matter, so called Quark-Gluon Plasma (QGP), is the major objective in the experimental program of heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) [3].

Direct photons, defined as photons not originating from hadronic decays, are a valuable tool to study details of the evolution of the medium created in heavy-ion collisions. Unlike hadrons, direct photons are produced at all stages of the collision and escape from the hot nuclear matter basically unaffected [4]. Direct photons are being emitted during all stages of the collision and present evolution of the colliding system in different transverse momentum (p\(T\)) regions.

To provide more constraints to the theoretical models, PHENIX experiment has performed systematic direct photon measurement across different collision systems, and different energies, from \(\sqrt{s_{NN}} = 39\) GeV to 200 GeV. Recently a new direct photon reconstruction technique has been developed which consists in conversion photons analysis in the layers of Silicon Vertex Tracker (VTX) in order reach better precision of the final results.

Current analysis is devoted to investigation of transition phase in measurements of direct photon integrated yields in the region of charged particles multiplicity \(dN_{ch}/d\eta\) from 2 to 20 at mid-rapidity. PHENIX experiment has measured low-\(p_T\) direct photon yields in p+p, p+Au, Cu+Cu and Au+Au collisions. Small systems like p+Au and d+Au measurements are consistent with the transition, but He+Au collisions have not been investigated yet. The observed scaling of direct photons yield with charged particle multiplicity \(dN_{ch}/d\eta\) at mid-rapidity obtained from different collisions systems is presented at Figure 1 [5].
Figure 1. Integrated direct photon yield versus charged particle multiplicity \( dN_{ch} / d \eta \) at mid-rapidity measured in various nucleus-nucleus collisions at \( \sqrt{s_{NN}} = 39-2760 \) GeV.

2. Experimental setup

Results presented in the current paper were obtained with central arms of PHENIX spectrometer [6]. Each central arm (east and west) covers \( \pi/2 \) in azimuthal angle and \( |\eta| < 0.35 \) in rapidity (as shown in Figure 2). The central arm mainly consists of three parts: drift chambers (DC) to measure trajectories and momenta of charged particles, electromagnetic calorimeter (EMCal) to determine the energy of photons and electrons, originating from interaction region and Ring Imaging Cerenkov detector (RICH) for the electron identification.

Figure 2. Schematic view of the PHENIX spectrometer central arms, which includes drift chambers (DC), electromagnetic calorimeters (two types of EMCal: PbSc, PbGl) and silicon vertex tracker (VTX).

Measurements of low-\( p_T \) or soft photons in EMCal are notoriously difficult due to the large hadronic background level in heavy-ion collisions. One of the ways to solve this problem is to reconstruct real photons from electron-positron (\( e^+e^- \)) pairs produced in external conversions of photons in the detector material [7]. The external conversion method [8] allows more statistics as compared to the internal...
conversion method and was used to obtain p+Au results [5]. The method is based on selection of the real photons that are converted in the VTX. Conversions are identified by the invariant mass of e+e− pairs:

\[ dN_{\text{dir}}^{pT} = (R_{\gamma} - 1) dN_{\text{hadron}}^{pT} \]

where \( R_{\gamma} \) is defined as the ratio of inclusive photons and hadronic decay photons, and is measured via double ratio tagging method [7]:

\[ R_{\gamma} = \frac{\gamma_{\text{incl}}}{\gamma_{\text{hadron}}} = \frac{\langle \epsilon_{\gamma f} \rangle}{\left( \frac{N_{\text{incl}}}{N_{\pi^0 \text{tag}}} \right)_{\text{Data}}} \]

where \( \langle \epsilon_{\gamma f} \rangle \) is the conditional acceptance for pion tagging, \( \left( \frac{N_{\text{incl}}}{N_{\pi^0 \text{tag}}} \right)_{\text{Data}} \) is measured from data, and the denominator is obtained from Monte-Carlo simulation. Values of \( \gamma_{\text{incl}} \) and \( \gamma_{\text{hadron}}/\pi^0 \) denote yields of photons produced inclusively or in hadron/\( \pi^0 \) decays, \( N_{\text{incl}} \) and \( N_{\pi^0 \text{tag}} \) are the observed inclusive photon yield and the observed yield of photons from \( \pi^0 \) decays. The factor \( \langle \epsilon_{\gamma f} \rangle \) corresponds to the finite value of efficiency to tag photons from \( \pi^0 \) decays. According to the definition above \( R_{\gamma} > 1 \) is considered as an observation of direct photons [9].

### 3. Quality assurance

Data from DC and EMCal detectors needs to pass quality assurance before the actual direct photon measurement. DC performance in He+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV was controlled by using two-dimensional occupancy histograms (alpha versus board, where alpha is angle measured by DC and board is a hardware related variable). Unstable regions with large amount of dead boards were removed from the analysis. As a representative example DC occupancy histogram for the east arm before and after quality assurance is presented at Figure 3.

![Figure 3. Two-dimensional occupancy histograms (alpha versus board) for east part of DC before (left) and after (right) removal of unstable and dead areas. West part of DC was handled in the same way.](image)

Quality assurance for EMCal was performed using two-dimensional occupancy histograms obtained from track coordinates (y and z). Unstable regions with high or low occupancy were removed from the analysis. Occupancy histogram as well as unstable regions for two of EMCal sectors are presented at Figure 4.
Figure 4. Two-dimensional EMCal occupancy histograms (y versus z cluster coordinate) for two PbSc sectors (left) and unstable or dead regions (right) removed from the further analysis.

DC and EMCal quality assurance procedures performed for He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV reduced statistics available for further direct photon analysis approximately by 10% (from $2.77 \times 10^9$ to $2.5 \times 10^9$ events).

4. Data analysis

Current paper describes the $R_\gamma$ measurement in He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Representative examples from p+Au analysis at $\sqrt{s_{NN}} = 200$ GeV are presented.

4.1. Inclusive and tagged photon samples

First, $\left( \frac{N^{incl}}{N^0_{\pi^0 \gamma \gamma}} \right)_{Data}$ value was obtained from He+Au data and compared to the one from p+Au analysis. The $N^{incl}$ measurement was performed by counting inclusive photon yield from $\pi^0$ decays. Yield of tagged photons was measured by combining photons from EMCal and photons reconstructed from the conversion pair. Combinatorial background for photon-photon pairs was estimated with mixed event technique [10]. Photon yield from $\pi^0$ decays is determined from integrals of mass peaks in the photon-photon invariant mass distribution near the $\pi^0$ mass. Since $\pi^0$-tagged yield is measured as a function of converted photon $p_T$, the converted photon introduces the identical detector- and reconstruct-ion-specific factors for the inclusive sample and additionally depends on the conditional acceptance efficiency $\langle \epsilon_\gamma f \rangle$ (probability to reconstruct the second photon from a $\pi^0$ decay in the calorimeter if one of the photons from conversion pair has been already reconstructed). Results for He+Au and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV comparison are presented at Figure 5.

4.2. The hadron/$\pi^0$ ratio

Ratio of hadron yields to the $\pi^0$ yields $\left( \frac{\gamma_{\pi^0}}{\gamma_{\pi^0}} \right)_{Sim}$ was calculated by Monte Carlo simulation. The following photon sources were included in the calculation: $\pi^0 \rightarrow \gamma \gamma$, $\eta \rightarrow \gamma \gamma$, $\eta \rightarrow \pi^+ \pi^- \gamma$, $\eta' \rightarrow \gamma \gamma$, $\eta' \rightarrow \pi^+ \pi^- \gamma$, $\omega \rightarrow \pi^0 \gamma$. The shape of $\pi^0$ $p_T$ spectrum is derived from available $\pi^0$ data [11] and the shape for other sources is derived with the help of $m_T$ scaling. Comparison of results for He+Au and p+Au collisions is presented at Figure 6.
Figure 5. Ratios of inclusive and tagged photons yields versus transverse momentum $p_T$ in $p+Au$ (left) and $He+Au$ (right) collisions at $\sqrt{s_{NN}} = 200$ GeV.

Figure 6. Ratio of hadron yields to $\pi^0$ yields versus transverse momentum $p_T$ obtained in $p+Au$ (left) and $He+Au$ (right) collisions at $\sqrt{s_{NN}} = 200$ GeV.

4.3. Tagging efficiency corrections
The tagging efficiency $\langle \epsilon_f \rangle$ depends on the geometrical acceptance $f$ for photons measured in EMCal and its reconstruction efficiency $\epsilon_\gamma$. Centrality-dependent $\langle \epsilon_f \rangle$ values can be calculated in a Monte-Carlo simulation as a function of converted photon $p_T$ if kinematic distribution of parent $\pi^0$ and decay kinematics is known. Current $\langle \epsilon_f \rangle$ calculation results have low statistics. In order to increase statistics Monte-Carlo simulation project is a work in progress and will be used to calculate value of $R_\gamma$ in low-$p_T$ region.

5. Summary
PHENIX DC and EMCal quality analysis was performed in order to remove unstable and dead regions of the detectors from further direct photon analysis. The needed components of $R_\gamma$ were obtained to calculate the excess of low-$p_T$ direct photons yield above the decay photon spectrum in $He+Au$ collisions $\sqrt{s_{NN}} = 200$ GeV. Ratio of the inclusive to tagged photon yields is consistent with one from
p+Au collisions as well as $\gamma^{\text{hadron}}/\gamma^{\pi^0}$ ratio. This might indicate the presence of the transition phase in measurements of direct photon integrated yields in He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

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