

LOW- p_T DIRECT PHOTON PRODUCTION AT RHIC
MEASURED WITH PHENIX*

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PHENIX has used the versatility of RHIC to map out low- p_T direct photon production as a function of collision system size and beam energy. For systems with a size corresponding to a $dN_{\text{ch}}/d\eta$ larger than 20–30, we observe a large yield of direct photons, a large azimuthal anisotropy with respect to the reaction plane, and a characteristic centrality dependence of $dN_\gamma/dy \propto (dN_{\text{ch}}/d\eta)^\alpha$, with $\alpha \sim 1.2$. In these proceedings, we will present new results from Au+Au collisions at $\sqrt{s_{NN}} = 39, 62.4$, and 200 GeV. After subtracting the prompt photon component, the inverse slope for the p_T range from 1–2 GeV/ c is 250 MeV/ c , but increases to about 400 MeV/ c for the range from 2 to 4 GeV/ c . Within the experimental uncertainty, there is no indication of a system-size dependence of the inverse slope. Furthermore, the system-size dependence of the yield, expressed through the power α , remains independent of p_T over the entire observed range from 1 to 6 GeV/ c . Like the large yield and azimuthal anisotropy, these features, while qualitatively consistent with the emission of thermal photons from the quark–gluon plasma, elude a quantitative description through theoretical model calculations.

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1. Introduction

Photons are a unique probe in understanding the properties of the hot and dense medium produced in relativistic heavy-ion collisions as they do not interact with the medium strongly and carry unmodified information about the space-time evolution of the system. Direct photons are defined as those which do not come from hadronic decays. The direct photon spectrum is sensitive to the temperature of the medium and its measurement will help constrain initial conditions, sources of photon production, emission rates, and the space-time evolution of relativistic heavy-ion collisions.

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All the photon sources can be classified into two categories — decay photons, which constitute around 80–90% of all the photons produced in heavy-ion collisions, and direct photons. The direct photons can further be split into two categories — prompt and non-prompt. Prompt photons are the ones that come from sources similar to that in $p + p$ collisions and scale as the number of binary collisions. Beyond the known thermal sources from the Hadron Gas and the QGP phase, other examples of sources contributing to non-prompt direct photons are those from jet–medium interactions and from the pre-equilibrium state. Throughout the evolution of the system, it expands and cools. Hence, earlier phases are characterized by higher temperatures and likely to dominate the emissions at higher p_T .

The wealth of data and an optimized detector configuration has enabled PHENIX to measure direct photons over a large- p_T range, across 7 systems, 3 collision energies using 3 different methods, namely, the calorimeter method, the virtual photon method, and the external conversion method. The availability of multiple data sets and different detector configurations for the same beam energies provides for consistency checks.

These proceedings will focus on the external conversion method used for analyzing the direct photons from the years 2010 [1] and 2014 [2].

2. Direct photons

Photon conversions on the backplane of the Hadron Blind detector (HBD) were analyzed for Au+Au collisions recorded in 2010 at $\sqrt{s_{NN}} = 39$ GeV and $\sqrt{s_{NN}} = 62.4$ GeV, and the corresponding direct photon spectra as a function of p_T are shown in Fig. 1 (left) with the T_{AA} -scaled pQCD curve shown in solid line.

Significantly larger statistics of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were recorded in the year 2014. This allowed for a more differential measurement of direct photons. Instead of the HBD, which was removed, conversions in the layers of a new Silicon Vertex tracker, with a material budget of around 13%, were analyzed. The spectrum for every 20% collision centrality is shown in Fig. 1 (right). Good agreement with all the previous PHENIX measurements is observed. With the direct photon spectra established, the next step would be to understand the centrality dependence and the shape of the spectrum.

Universal scaling: In order to look deeper into centrality dependence, the integrated yields are analyzed in Fig. 2 (left), where the p_T -integrated direct photon yield is shown for various collision systems and energy spanning almost 2 orders of magnitude as a function of charged particle multiplicity at midrapidity. A universal scaling behaviour is seen in all $A + A$ systems with a trend similar to that of scaled $p + p$, but with a 10 times larger yield.

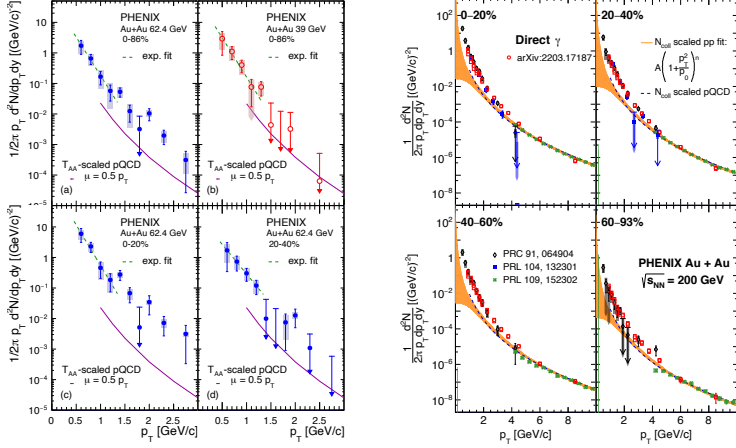


Fig. 1. Invariant yield of direct photons as a function of p_T for Au+Au at $\sqrt{s_{NN}} = 39$ GeV and $\sqrt{s_{NN}} = 64$ GeV (left) and for $\sqrt{s_{NN}} = 200$ GeV (right) for different collision centralities.

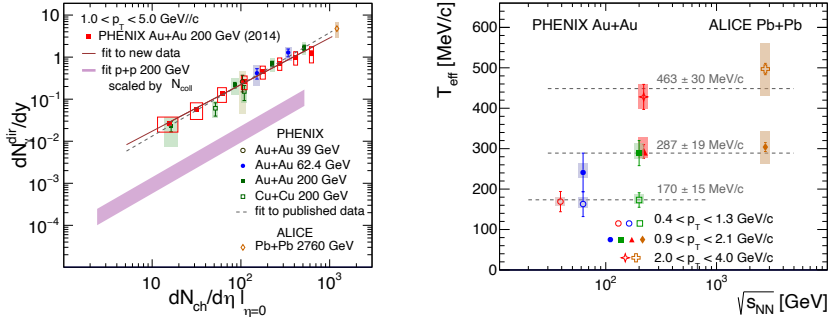


Fig. 2. Integrated yield of direct photons as a function of system size (left) and the inverse slope of the spectrum as a function of collision energy for different p_T ranges (right).

Effective temperature: The effective temperature is estimated as the local inverse slope of the spectrum. In order to better understand the similarity of the low- p_T direct photon spectrum across collision energies, the spectrum is fitted in different p_T ranges. The extracted values of T_{eff} , shown in Fig. 2 (right), seem to be consistent within collision energies for different fit ranges, which suggests common sources for direct photon production independent of the collision energy.

3. Non-prompt direct photons

Non-prompt direct photons are defined as the excess photons above the prompt photon contributions. These are radiations that are emitted during

the collision from the hot and expanding fireball and are estimated by subtracting the N_{coll} scaled $p + p$ fit from the direct photon spectrum. In Fig. 3, the non-prompt direct photon spectra are shown for every 20% collision centrality. There has been a significant increase in the reach of the conversion photon measurement both in p_T and in centrality as compared to previous publications.

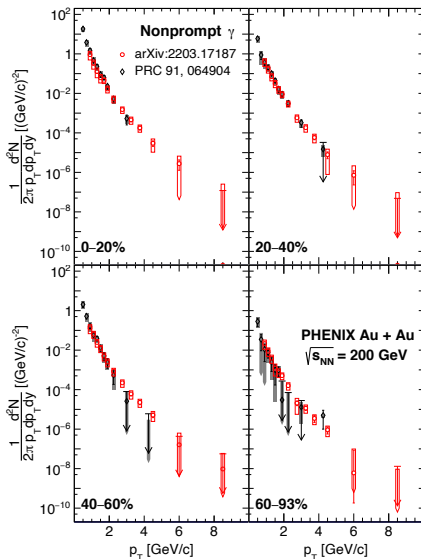


Fig. 3. Invariant yield of non-prompt direct photons as a function of p_T for Au+Au at $\sqrt{s_{NN}} = 200$ GeV for different collision centralities.

Universal scaling: To study the centrality dependence, the scaling power, α , is extracted by fitting the p_T -integrated yield of non-prompt direct photon spectrum as a function of charged particle multiplicity at midrapidity for six non-overlapping p_T ranges. In Fig. 4 (left), α as a function of p_T is shown. It is compared with the α extracted from the p_T -integrated direct photon spectra in the same p_T ranges. Below 3 GeV/c, the direct photon spectra are dominated by the non-prompt direct photon sources and hence the α powers for both direct photons and non-prompt direct photons are similar. However, with increasing p_T , they start to differ, although it should be noted that the non-prompt direct photon spectra run out of statistics. Theoretical calculations suggest that α increases as we go from the Hadron Gas to the QGP phase [3], however, in experiments, we find α to be relatively independent of p_T .

Effective temperature: The shape of the non-prompt direct photon spectrum is not described by a single exponential but rather has a continuously increasing inverse slope with p_T . To quantify this changing slope, the

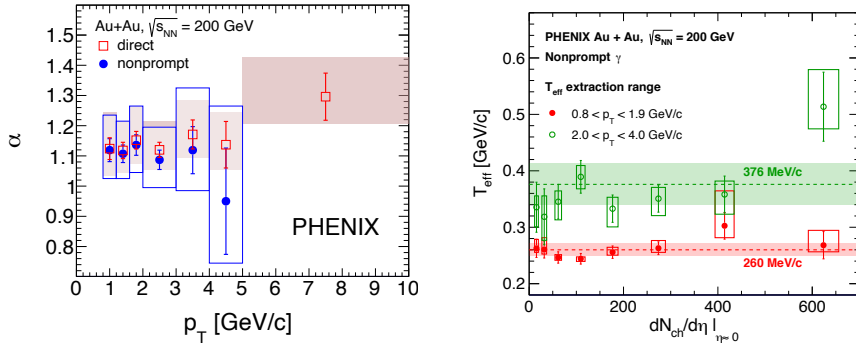


Fig. 4. Scaling power α , as a function of p_T (left) and the inverse slope of non-prompt direct photon spectrum as a function of system size for different p_T ranges (right).

non-prompt direct photon spectra are fitted with exponential in two different p_T ranges, as shown in Fig. 4 (right), and the slopes are found to be consistent with a constant value and independent of the collision centrality. The average value of the slope increases from 200 MeV to about 400 MeV in the p_T range of 0.8 to 4 GeV/c. A T_{eff} greater than 350 MeV suggests that we may be sensitive to sources beyond the Hadron Gas phase. The change, T_{eff} , is not surprising as the underlying spectra are time-integrated over the full evolution of the expanding fireball, from its earliest pre-equilibrium state through the QGP phase, crossing over to the Hadron Gas phase and further expanding and cooling till the hadrons eventually stop interacting among themselves. In turn, contributions from the earliest phase are likely to dominate the spectra at higher p_T , which is consistent with the observation of an increasing T_{eff} with p_T .

4. Theoretical comparisons

The measured non-prompt direct photon spectra are compared to recent theoretical calculations which employ a hybrid model and the contributions from the pre-equilibrium state are highlighted on both photonic and hadronic observables in Fig. 5 (left) [4]. The bottom panel shows the ratio of the measurements with the combined thermal and pre-equilibrium contributions from the theory. The calculations predict that the pre-equilibrium radiations become the dominant source above a p_T of 3 GeV/c. While the shape is reproduced well, the overall yield predicted by the model falls short especially below 2 GeV/c, where the measured yields seem to be a factor 2–3 larger.

In order to further explore the shape of the non-prompt direct photon spectra, they are smoothened using a machine-learning-based regression

algorithm called Multi-Layer Perceptron on the PHENIX data [2, 5]. The inverse slope is extracted by numerical differentiation and is shown in Fig. 5 (right). It can be argued that with the increasing p_T , the contribution from the pre-equilibrium phase may be important.

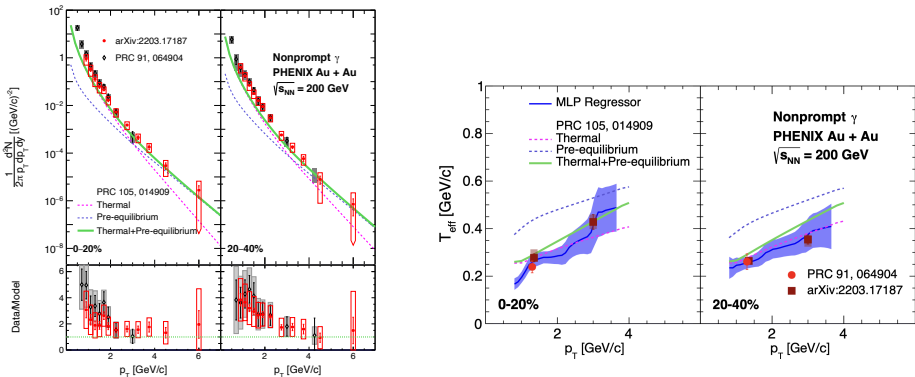


Fig. 5. Comparison of the non-prompt direct photon spectrum for Au+Au at $\sqrt{s_{NN}} = 200$ GeV with theoretical calculations.

5. Summary

To summarize, we discussed the results of the measurement of direct photons for Au+Au collisions at 39, 62.4, and 200 GeV. In addition, a more differential measurement with non-prompt direct photons is shown for the high statistics Au+Au collisions at 200 GeV. Universal scaling, independent of centrality, collision energy, and collision system is observed with charged particle multiplicity at midrapidity. The scaling power, α , is independent of p_T for both direct and non-prompt photons. Both direct photons and non-prompt direct photon spectra exhibit an increasing inverse slope with p_T . Recent theoretical calculations including pre-equilibrium contributions seem to reduce the discrepancy between theory and observation.

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