Overview of low $p_T$ photon results from PHENIX at RHIC

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Overview of low \( p_T \) photon results from PHENIX at RHIC

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Abstract. Overview of the latest low \( p_T \) direct photon measurements by the PHENIX experiment at RHIC is presented. We found a smooth change of the effective temperature as a function of \( \sqrt{s_{NN}} \). We studied the scaling properties of the direct photon yield with various global observables. When plotting the direct photon yield as a function of \( dN_{ch}/d\eta \), a universal scaling independent of the \( \sqrt{s_{NN}} \) was observed.

1. Introduction

Direct photons are of special interest in the relativistic heavy ion collisions. They are emitted from all the stages of the collisions with wide range of \( Q^2 \) and don’t interact strongly with medium once produced, thus they carry thermodynamical information of the stages they are emitted [1, 2]. The production rate of the photons can be written as:

\[
E dR_\gamma = -\frac{\alpha_{em}}{\pi^2} \text{Im}\Pi_{em}(\omega, k) \frac{1}{e^{E/T} - 1}, \quad \text{Im}\Pi_{em}(\omega, k) \approx \ln \left\{ \frac{\omega T}{m_{th}(\approx gT)^2} \right\},
\]

where \( \Pi_{em} \) is the photon self energy, and is process dependent. When we measure the inverse slope of the distribution at a high energy region (\( E \gg T \)) the inverse slope will tell the temperature of the system. However, the source of photons is not unique as mentioned above, therefore the measured photon spectra are convolution of various sources and so for the inverse slope. Figure 1 shows the photon production sources proposed by now, outlined as a function of their production times and energy ranges that they manifest. We define the direct photons as photons not originating from the hadron decays (\( \pi^0 \), \( \eta \) etc). The general trend is that the earlier the photons are produced, the higher their typical energy ranges will be. The Jet-Bremsstralung and Jet-photon conversion are those produced by the second interaction of hard scattered partons with a hot dense medium [3].

In order to disentangle the various photon sources, we have to perform as many differential measurements as the number of possible photon sources. One of the recently proposed and actually realized measurements is collective flow (\( v_n \)). Practically, this measurement is possible for only first couple orders (2, 3 ...) because of limited statistics. We list the expected behavior of yield, \( v_2 \) and \( v_3 \) for various proposed photon sources in the Table 1.

Comparing to the high \( p_T \) photons (\( p_T > 5 \text{ GeV/c} \)) that have been successfully measured using calorimetric method [4, 5], the measurement of low to mid \( p_T \) photons (\( p_T \lesssim 4 \text{ GeV/c} \)) called for new methods. By now, two methods have been developed; one is called internal
conversion method [6, 7], and the other is external conversion method [8]. The internal conversion method utilizes the fact that the process of producing real photons (zero mass) always has some probability of producing virtual photons with a finite mass that decay into electron-positron pairs. Then, the analysis method similar to dilepton measurement can be applied. The advantage of this method is that one can select the virtual mass region where $\pi^0$ contribution which is the primary background for photon measurement becomes very small. A restriction exists in this method, however, which is that the $p_T$ to measure has to meet $p_T \gg m_{ee}$. The typical lower limit in $p_T$ is 1 GeV/c. The external conversion method measures photons converted to the electron-positron pairs at materials. In this method, there is no lower $p_T$ limit, but one has to deal with a large background from $\pi^0$ decay. Both methods have good energy resolution and small inefficiency of hadron rejection, thanks to the particle tracking system and the Ring Imaging Cherenkov detector (RICH) [9].

**Table 1.** List of photon production sources, and their manifesting $p_T$ regions and the typical behavior of their $v_2$ and $v_3$.

| Production source          | $p_T$         | $v_2$ | $v_3$ | t-dependence of $v_n$ |
|----------------------------|---------------|-------|-------|------------------------|
| Hadron gas                 | low $p_T$     | positive | positive |
| QGP                        | Mid $p_T$     | positive | positive |
| Primordial (hard)          | High $p_T$    | $\sim$zero | $\sim$zero |
| Jet-Bremstrahlung           | Mid $p_T$     | positive | ? |
| Jet-photon conversion      | Mid $p_T$     | negative | ? |
| Initial B-field            | All $p_T$     | positive | $\sim$zero |
2. Direct photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

PHENIX has successfully measured low $p_T$ direct photons with both internal and external conversion methods. A huge excess of photon yield over the primordial hard photon production scaled from the photon spectra in $p+p$ collisions was observed. The inverse slopes (effective temperature, $T_{\text{eff}}$) were measured for the photon spectra for $p_T > 1.0(0.5)$ GeV/c by internal (external) conversions, and were found consistently to be $\sim 220$ MeV which are much higher than the transition temperature (170 MeV) [6]. On the other hand, a sizable $v_2$ for low $p_T$ photons was found [10], which is controversy to the spectra results. A large photon yield implies that the photons are emitted from initial stages of the collisions, while the large $v_2$ implies that the photons are emitted from late stages where the flow is sufficiently built up. The $v_3$ was recently measured and was also found to be sizable [11]. Figure 2 shows the latest measurement of the spectra, $v_2$ and $v_3$ for low $p_T$ direct photons [8, 11] together with representative calculations from several different models [12, 13, 14, 15, 16]. When the $v_2$ result was presented for the first time, none of the model calculations was able to produce spectra and $v_2$. However the considerable theory efforts since then improved the model calculations significantly and the data are reasonably described by now. One of the key ingredients in the model calculations is the blue shift of the spectra [17, 18, 19]: as the collision system expands, the photons are boosted (blue shifted) and give a large inverse slope. This implies that the majority of the photons may have been produced around the hadronization stage.

Figure 2. Low $p_T$ direct photon spectra, $v_2$ and $v_3$ in 20-40% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [8]. The lines show representative calculations from several different models.
3. Direct photon production in new collision systems

In order to investigate the origin of photons observed, PHENIX has extended the photon measurement to different systems and different collision energies. In the RHIC Year-2005 run, PHENIX has collected Cu+Cu collision data at $\sqrt{s_{NN}} = 200$ GeV. Figure 3 shows the photon spectra in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV together with the ones in Au+Au collisions previously published [8]. The inverse slope parameters were obtained as $288 \pm 49(stat) \pm 50(syst)$ MeV for minimum bias Cu+Cu collisions, and $242 \pm 28(stat) \pm 7(syst)$ MeV for minimum bias Au+Au collisions, respectively. The parameters for both systems are agreeing each other within quoted uncertainties.

PHENIX has recently measured the direct photons in Au+Au collisions at lower energies as well. Figure 4 shows the low $p_T$ direct photon spectra in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV and 39 GeV. Unfortunately, the photons from initial hard scattering cannot be quantified due to the lack of statistics at high $p_T$. However, from a pQCD calculation that is validated by results from past experiments shows that the hard photon contribution at $\sqrt{s_{NN}} = 62.4$ GeV is small. It is reasonable to also assume that the hard photon contribution at $\sqrt{s_{NN}} = 39$ GeV is even smaller and negligible, since the hard scattering probability decreases much rapidly compared to the bulk particle production.

We summarized the inverse slope parameters, $T_{eff}$ in the Figure 5, for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV and Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ and 39 GeV, together with the measurement in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV performed by the ALICE experiment at the LHC [20]. It is seen that the $T_{eff}$ increases systematically as $\sqrt{s_{NN}}$ increases, but not linearly. This observation is reasonable since the temperature of the system increases by the energy density to the power of $\sim 1/4$.

![Figure 3](image_url)

**Figure 3.** Direct photon spectra in minimum bias Cu+Cu collisions (left) and in minimum bias Au+Au collisions (right) at $\sqrt{s_{NN}} = 200$ GeV.
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4. Scaling property of direct photon yield

With variety of datasets we collected, we studied the scaling properties of the direct photon yields. In the previous publication, we plotted the integrated direct photon yield \(dN/dy\) as a function of \(N_{\text{part}}\) for various integration range \([8]\). This is reproduced in the left plot of the Figure 6. Surprisingly, \(N_{\text{part}}\) dependence of the photon \(dN/dy\) is independent of the lower \(p_T\) limit of the integration, suggesting that the source of these photons are similar. The data points are fitted with a power-law function, \(dN/dy = \beta N_{\text{part}}^\alpha\), and obtained the \(\alpha\) as \(\alpha = 1.48 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})\). This number can be compared with a model calculation
where $\alpha$ is predicted to change as a function of the lower $p_T$ limit [18]. We have extended this scaling study to all the available data as shown in the right plot of the Figure 6 [21]. It is interesting to see that all the available data are on the same power-law function. We performed simultaneous fit over the data and obtained as $\alpha = 1.35 \pm 0.09$, which is consistent with the previous publication.

Lastly, we studied the scaling properties with another global observables, that is charged particle multiplicity ($dN_{ch}/d\eta$). Figure 7 shows the photon $dN/dy$ plotted against $dN_{ch}/d\eta$ for various collisions systems and energies [22, 21, 23]. Interesting enough, all the data points except for those from $p+p$ and $d+Au$ are found to be nicely fitted with a power-law function of $dN/dy = \beta(dN_{ch}/d\eta)^\alpha$ with $\alpha \sim 1.2$. This shows that the photons are emitted similarly over the wide range of the energies in terms of temperature and space time evolution. This may be natural, if most of the photons are emitted near the transition from QGP to hadronic gas. In the same plot, we showed the $dN/dy$ for the pQCD calculations scaled by the number of collisions corresponding to that of A+A collisions. It is interesting to see that the pQCD lines are parallel to the A+A points except for an order of magnitude difference. There looks to be a similar production mechanism playing in $p+p$ collisions as well.

We performed a separate power-law fit only for the $p+p$, $d+Au$ and peripheral $Au+Au$ collision data and showed in Figure 8. It is found that the $\alpha$ is $\sim 2.2$ for this fit and is quite different from the one for the A+A points. It is possible that there is a turn-on of the hot medium production somewhere in this range of $dN_{ch}/d\eta$.

We here note that some of the plots shown here became final and submitted to journals after the conference [24, 25].

5. Summary

We have shown and reviewed the low $p_T$ direct photon measurements performed by the PHENIX experiment at RHIC. PHENIX has measured low $p_T$ direct photons in $Au+Au$ and $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV and in $Au+Au$ collisions at $\sqrt{s_{NN}} = 62.4$ and 39 GeV, either using internal conversion or external conversion methods that reduced the background significantly. The inverse slope was found to change smoothly as a function of $\sqrt{s_{NN}}$ from 39 GeV to 2.76 TeV. It was found that the direct photon yields scale very well with $dN_{ch}/d\eta$ with a power of $\alpha \sim 1.2$. This implies that the photons are emitted similarly over the wide range of the energies in terms
of temperature and space time evolution. This may be natural, if most of the photons are emitted near the transition from QGP to hadronic gas.
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