Measurement of electro-magnetic radiation at RHIC-PHENIX

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Abstract

Recent results on direct photons and dileptons from the PHENIX experiment opened up a possibility of landscaping electro-magnetic radiation over various kinetic energies in heavy ion collisions. Results on direct photon measurement in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV are discussed from the point of view of structure function and isospin effect. The first measurement of direct photons at $\sqrt{s_{NN}}=62.4$ GeV in the same collisional system suggested that these effects are existing and would manifest at $p_T>16$ GeV/c at $\sqrt{s_{NN}}=200$ GeV.

Key words: direct photons, dileptons, Au+Au, p+p, RHIC, PHENIX, QGP, pQCD
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1. Introduction

Electro-magnetic radiation is an excellent probe for extracting thermodynamical information of a matter produced in nucleus-nucleus collisions [1]. They are emitted from all the stages of collisions, and don’t interact strongly with medium once produced. As stated in several literatures [1,2,3], the electro-magnetic radiations stand for a thermal radiation from the matter or a prompt emission from the initial stage. They are primarily produced through a Compton scattering of quarks and gluons ($qg \rightarrow q\gamma$) or an annihilation of quarks and anti-quarks ($q\bar{q} \rightarrow g\gamma$) as leading order processes, and the next leading order (NLO) process is dominated by bremsstrahlung (fragment) ($qg \rightarrow qg\gamma$). A calculation predicts that the photon contribution from a quark gluon plasma (QGP) state is predominant in the transverse momentum ($p_T$) range of $1<p_T<3$ GeV/c [4].

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For $p_T < 1 \text{ GeV}/c$, the signal from hadron rescattering process is dominant. There is also a prediction of a jet-photon conversion process, which occurs, if QGP is formed, by a secondary interaction of a hard scattered parton with thermal partons in the medium [5]. The predictions are shown in Fig. 1.

One of the big successes by now is the observation of high $p_T$ direct photons produced in the initial hard scattering [3]. The high $p_T$ hadron suppression found at RHIC is interpreted as a consequence of an energy loss of hard-scattered partons in the hot and dense medium. It was strongly supported by the fact that the high $p_T$ direct photons are not suppressed and well described by a NLO pQCD calculation [6].

In this paper, the recent measurement on direct photons is focused, out of various electromagnetic radiation measurements from the PHENIX experiment. The recent dilepton measurement at RHIC has just been published [7]. A discussion on comprehensive understanding of electromagnetic radiations is presented in [8].

2. Direct photon measurement in Au+Au collisions at $\sqrt{s_{NN}}=200 \text{ GeV}$

Direct photon $p_T$ spectra have been measured in Au+Au collisions at $\sqrt{s_{NN}}=200 \text{ GeV}$ in RHIC Year-4 run as shown in Fig. 2 [9]. The ones in p+p collisions at the same energy are also shown. The p+p data is used as a baseline for quantifying the medium effect in Au+Au collisions. Since the $p_T$ binning is different between Au+Au and p+p results, the p+p data is fitted with a power-law function to interpolate to the $p_T$ of the Au+Au data. The fit describes the data very well within $\sim 5\%$ [9]. Figure 3 shows the nuclear modification factor ($R_{AA}$) of direct photons in minimum bias and 0-10% central Au+Au collisions. The $R_{AA}$ is defined as:

$$R_{AA} = \frac{(1/N_{evt})dN/dydp_T}{T_{AB}(b)d\sigma_{pp}/dydp_T},$$

where $\sigma_{pp}$ is the production cross section in p+p collisions, and $T_{AB}$ is the nuclear thickness function calculated from the Glauber model. With Year-2 run statistics, we were able to reach only up to the region where the $R_{AA}$ is consistent with unity, and thus concluded that direct photons are unmodified by the medium [3]. The latest data shows a trend of decreasing at high $p_T$ ($p_T > 14 \text{ GeV}/c$).

The NLO pQCD calculation predicts that the fragment photons contributes $\sim 30\%$ to the total at $p_T \sim 14 \text{ GeV}/c$. An energy loss of quarks may result in a suppression of the
yield of the fragment photons. However, the calculation suggests that the contribution of the fragment photons decreases as $p_T$ increases, which is contradictory to the observation.

Here, we propose simple models to understand the result. The major contribution to the direct photon production in the $p_T$ range of the interest is from the Compton scattering process ($qg \rightarrow q\gamma$), therefore, we can assume that the yield is naively described as:

$$Yield(x_T, Q^2) = F_2p(x_T) \times g_p(x_T) \times \sigma_{dir.\gamma}(x_T, Q^2)$$

where $x_T = 2p_T/\sqrt{s}$, $F_2p(x_T)$ is the quark parton distribution function (PDF), and $g_p(x_T)$ is the gluon PDF. The $R_{AA}$ can be written as:

$$R_{AA} = \frac{d^2\sigma_{\gamma AA}/dp_T^2dy}{AAd^2\sigma_{\gamma pp}/dp_T^2dy} \approx \left( \frac{F_2A(x_T)}{AF_2p(x_T)} \times \frac{g_A(x_T)}{g_p(x_T)} \right)$$

The PDFs are shown in Fig. 4(a)[10]. The decrease of the yield in Au+Au starts at $\sim 12$ GeV/$c$ ($x_T=0.12$) and drops by $\sim 30\%$ at 18 GeV/$c$ ($x_T=0.18$). The PDF does not change by 30% between the two $x_T$ regions.

There is a theoretical calculation that tried to explain the suppression at high $p_T$ by combining a structure function and an isospin effect [11]. The isospin effect is an
effect caused by the difference of the quark charge contents in neutrons and protons. The photon production cross-section is proportional to $\alpha_s \Sigma e_q^2$. Therefore, the yield of photons will be different between p+p, p+n and n+n collisions [6]. A gold ion consists of 79 protons and 118 neutrons. We can calculate the hard scattering cross-section for minimum bias Au+Au collisions by weighting those for p+p ($\sigma_{pp}$), p+n ($\sigma_{pn}$) and n+n ($\sigma_{nn}$) as follows:

$$\frac{\sigma_{AA}}{<N_{coll}>} = \frac{1}{A^2} \times (Z^2 \sigma_{pp} + 2Z(A-Z)\sigma_{pn} + (A-Z)^2 \sigma_{nn})$$

where $<N_{coll}>$ is the mean number of binary nucleon-nucleon collisions. The $R_{AA}$ expected from the isospin effect can be computed as:

$$R_{AA} = \frac{\sigma_{AA}}{<N_{coll}> \sigma_{pp}}$$

The $R_{AA}$ expected from this effect at $\sqrt{s_{NN}}=200$ GeV is shown in red in Fig. 4(b) and (c). There is $\sim 15\%$ drop at 18 GeV/$c$ caused by the effect. If we combine the structure function effect with the isospin effect, the data could be explained.

On the other hand, we could also say that there is almost no suppression at high $p_T$ within the uncertainty. The opening angle of two $\gamma$'s decaying from $\pi^0$ becomes very small, and the $\gamma$'s become indistinguishable at high $p_T$ (starting at $p_T \sim 12$ GeV/$c$) due to a limited position resolution (merging effect).

3. Direct photon measurement in Au+Au collisions at $\sqrt{s_{NN}}=62.4$ GeV

The $R_{AA}$ expected from the isospin effect at $\sqrt{s_{NN}}=62.4$ GeV is calculated in the same way as 200 GeV, and shown in blue in Fig. 4(b) and (c). The suppression is larger
at the same \( p_T \) because the effect scales with \( x_T \). The calculation suggests that we can verify the structure function and isospin effect in Au+Au collisions at \( \sqrt{s_{NN}}=62.4 \) GeV without being affected by the merging effect. Following this argument, direct photons in Au+Au collisions at \( \sqrt{s_{NN}}=62.4 \) GeV have been measured for the first time. The \( p_T \) spectra of the direct photons are shown in Fig. 5. The NLO pQCD calculation scaled by \( T_{AB} \) are overlaid on the data. The data is qualitatively well described by the calculation. The ratios of the direct photon yields to the calculation are then computed and shown

![Fig. 5. Direct photon \( p_T \) spectra in Au+Au collisions at \( \sqrt{s_{NN}}=62.4 \) GeV.](image)

in Fig. 6 Unfortunately, the yield in p+p collisions at the same energy has not been measured at any of RHIC experiments. There is a parameterization of the p+p yield using the measurements at ISR [12], but the error is large and systematics is very different. Therefore, we decided not to use p+p yield for now.

The ratios are essentially consistent with the NLO pQCD expectation within the experimental and theoretical uncertainty for \( p_T >5 \) GeV/c. The lower \( p_T \) region may be due to initial multiple scattering of incoming partons or the jet-photon conversion effect.

It is found that the p+p yield is underestimated by the NLO pQCD calculation at \( \sqrt{s}=200 \) GeV [9], and it may well happen at 62.4 GeV. As an attempt, we took the ratio of the p+p yield to the NLO pQCD calculation at 200 GeV, and shifted the horizontal scale by 0.312 (=62.4/200), which is inspired by an idea of:

\[
\frac{\sigma_{pp}}{\sigma_{NLO \ pQCD}} \equiv R, \quad R_{200 GeV}(x_T) = R_{62.4 GeV}(x_T)
\]

The result is shown in the bottom right of Fig. 6. If the assumption is correct and the dot-dashed line is considered as the baseline, we may say that the direct photon yield is suppressed at high \( p_T \) (\( p_T >5 \) GeV/c, corresponding to 16 GeV/c at \( \sqrt{s_{NN}}=200 \) GeV), also at \( \sqrt{s_{NN}}=62.4 \) GeV. The \( p_T \) region of the interest is immune from the merging effect, and thus it is considered to be the hint of physics process such as structure function or

\[1\] We presented 30-60% centrality in the conference as well, but not shown here because of limited pages.
isospin effect. The result is also predicted by a calculation [13]. Combining the current data with the ones from future d+A and p+A runs would disentangle these two effects.

4. Conclusions

Results on direct photon measurement in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV are discussed from the point of view of structure function and isospin effect. The first measurement of direct photons at $\sqrt{s_{NN}}=62.4$ GeV in the same collisional system suggested that these effects are existing and would manifest at $p_T>16$ GeV/c at $\sqrt{s_{NN}}=200$ GeV.

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