Direct photons \sim basis for characterizing heavy ion collisions~

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Abstract. After years of experimental and theoretical efforts, direct photons become a strong and reliable tool to establish the basic characteristics of a hot and dense matter produced in heavy ion collisions. The recent direct photon measurements are reviewed and a future prospect is given.

1. Introduction

Direct photons are an excellent probe for extracting thermodynamical information of a matter produced in nucleus-nucleus collisions, as they are emitted from all the stages of collisions, and don’t interact strongly with medium once produced. They are 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) \((qg \rightarrow qg\gamma)\) as depicted in Fig. 1(a). Theoretical studies show that a part of fragment processes arises as leading order [1]. The source of radiations are from various processes and manifest as a function of transverse momentum \((p_T)\) [2](Fig. 1(b)). Photons with high \(p_T\) are primarily produced in the initial hard scattering, and often called as "hard photons". Under the formation of hot and dense medium, in addition to the hard photons, a calculation predicts that the photon contribution from a quark gluon plasma (QGP) state dominates

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Production processes of direct photons (left), and (b) their manifestation as a function \(p_T\) (right).}
\end{figure}
lower transverse momentum ($p_T$) region in heavy ion collisions ($1 < p_T < 3 \text{ GeV}/c$ in Au+Au collisions at $\sqrt{s_{NN}}=200 \text{ GeV}$ [3]). The signal from a hadron rescattering process dominates even lower $p_T$. Compton scattering of hard-scattered partons and partons in the medium (jet-photon conversion), or bremsstrahlung of the hard scattered partons in the medium will also arise [4]. Photons from the processes would become another measure of the parton density of the medium since they are produced through an interaction of hard-scattered partons and the medium. All the contributions are overwhelmed by huge photonic background from known hadron sources such as $\pi^0$'s or $\eta$'s, except for high $p_T$.

2. High $p_T$ direct photons ~how well are they calibrated?~

2.1. $p+p$ collisions: precision test

Hard direct photon production in $p+p$ collisions is extensively studied both experimentally and theoretically. Figure 2 shows the ratios of direct photon cross-sections to NLO pQCD calculation measured by various experiments [5]. The data are explained by NLO pQCD calculations within $\sim 20\%$.

As depicted in Fig. 1(a), photons are produced in the fragment process as well. Several experiments have measured the prompt to all hard photons by applying an isolation cut. The same cut is applied to a NLO pQCD calculation to compare with the measurement. The PHENIX experiment at RHIC has used a similar technique and confirmed that the calculation is consistent with the result [6]. There is a new attempt of measuring fragment contribution more directly. The PHENIX experiment has recently measured photons associated with the same side of trigger high $p_T$ hadrons [7]. These photons are considered to be from fragment processes. Fig. 2(b) shows the associated photon yield $\Delta\phi$ distributions from the analysis. The ratio of near-side-associated fragment to inclusive photons is also measured, and show a consistency with the previous PHENIX measurement [6]. A detailed study of PID efficiency important in the analysis because possible mis-identification of photons/hadrons would produce a trigger bias.

Figure 2. (a) Data over NLO pQCD from various experiments in $p+p$ collisions, and (b) fragment photons measured through $h - \gamma_{\text{dir}} \Delta\phi$ correlation by PHENIX.
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2.2. Hard photons suppressed in Au+Au?

The yield of high $p_T$ direct photons are well-scaled by a nuclear overlap function ($T_{AB}$) in heavy ion collisions. The first measurement of such photons at RHIC confirmed that the high $p_T$ hadron suppression is a consequence of an energy loss of hard-scattered partons in the hot and dense medium. The latest high statistics data from PHENIX showed a trend of decreasing at high $p_T$ ($p_T > 14 \text{ GeV}/c$) (Fig. 3(a)). The decrease of the yield in Au+Au starts at $\sim 12 \text{ GeV}/c$ ($x_T=0.12$) and drops by $\sim 30\%$ at $18 \text{ GeV}/c$ ($x_T=0.18$) [8]. Parton distribution functions (PDFs) do not change by 30\% between the two $x_T$ regions [9].

![Figure 3.](image)

**Figure 3.** (a) $R_{AA}$ for direct photons, $\pi^0$ and $\eta$ in Au+Au collisions at $\sqrt{s_{NN}}=200\text{GeV}$ (left), (b) expected $R_{AA}$ from NLO pQCD calculation at 200 and 62 GeV (middle), and (c) $R_{AA}$ for direct photons in Au+Au collisions at 62 GeV (right) by PHENIX.

Isospin effect has been proposed to explain the suppression [10]. 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. It results in the deviation of $R_{AA}$ from unity at high $p_T$ in Au+Au collisions, where the contribution of valence quarks become prominent. There is a $\sim 15\%$ drop at 18 GeV/c at $\sqrt{s_{NN}}=200\text{GeV}$ expected from the effect (Fig. 3(b)). Combining PDF effect with the isospin effect would explain the data. As shown in Fig. 3(b), the effect will manifest in lower $p_T$ region at $\sqrt{s_{NN}}=62.4\text{GeV}$ because the effect scales with $x_T$. The PHENIX experiment has measured photons in Au+Au collisions at $\sqrt{s_{NN}}=62.4\text{GeV}$ [11] and divided them by NLO pQCD instead of p+p yield (Fig. 3(c)), since there is no p+p data from the experiment. The difference between p+p yield and NLO pQCD calculation measured at 200 GeV is scaled to 62.4 GeV and shown as a dot-dashed line in 62.4 GeV. Assuming this is the baseline, we may have confirmed the isospin effect (i.e., suppressed at $p_T > 5 \text{ GeV}/c$, corresponding to $16 \text{ GeV}/c$ at 200 GeV), also at 62.4 GeV. Combining the Au+Au data with the ones from future high statistics d+Au data would disentangle the PDF and isospin effect.

3. Application of well-calibrated probe \sim $\gamma$-jet analysis~

Well calibrated high $p_T$ photons are ideal as measure of the initial momenta of back-scattered partons. The idea was first proposed a decade ago [12], but the measurement
has not become realized until recent. The PHENIX has measured an associated away-side hadron yield when triggered by a hard photon, both p+p and Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV as shown in Fig. 4(a). The result shows that the away-side per-

trigger hadron yield is reduced in Au+Au collisions compared to that expected from p+p collisions [7]. This is qualitatively consistent with single particle measurement [8]. In this analysis, all the hadron contribution associated with photons from hadron decay are subtracted on statistical basis to obtain $\gamma_{\text{dir}} - h$ correlation as:

$$ (\gamma_{\text{dir}} - h) = (\gamma_{\text{incl.}} - h) - (\gamma_{\text{dec}} - h) $$

There is a new result from the STAR experiment showing $I_{AA}$ in $\gamma_{\text{dir}} - h$ correlation [13]. In this analysis, the correlation is obtained by:

$$ (\gamma_{\text{dir}} - h) = (\text{Clus}_{\gamma - \text{en}} - h) - \alpha \times (\pi^0 - h) $$

where $\text{Clus}_{\gamma - \text{en}}$ stands for $\gamma$-enriched clusters by a shower shape cut. $\alpha$ is determined such that the near side associated hadron yield be zero. This procedure will be justified under the assumption that the $\eta$-triggered hadron yield and fragment-photon-triggered hadron yield are as same as the $\pi^0$-triggered hadron yield. The cross-section measurement of direct photons would help justifying the procedure.

4. Thermal photons from CERN to RHIC

The measurement of thermal photons delivers the temperature of the system. Combining the temperature with an entropy derived from a particle multiplicity measurement will deduce the degree of the freedom of the system [14, 15]. There is a direct photon measurement in thermal region in Pb+Pb collisions, made by WA98 experiments at CERN [16]. However, the lack of p+p measurement at the same energy made it difficult to understand whether or not there is a thermal emission [8]. WA98 has recently analyzed p+Pb and p+C collision data to measure hard photons with a nuclear effect ($k_T$ smearing). Taking the ratio of the yield in Pb+Pb to p+Pb should be able to quantify the pure non-hard photon component. However, the error is too large to make
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Figure 5. (a) Direct photon measurement in thermal region by WA98 at CERN and theoretical interpretation (left), and (b) comparison of direct photon yield in p+Pb and Pb+Pb (right).

a conclusion. The experiment is now making an effort to minimize the systematic errors [17].

The thermal photon contribution is believed to be \( \sim 10\% \) at RHIC energy, and might need a measurement with an error of <5\%. Measurement of the internal conversion of direct photons (\( \gamma \rightarrow \gamma^* \rightarrow e^+e^- \)) opened up a possibility to significantly reduce the systematic errors. The PHENIX experiment has applied the technique of measuring low \( p_T \) and low mass di-electrons to high \( p_T \) and low mass di-electrons. The measured yield is converted into a direct photon yield using Kroll-Wada formula [18, 19]. If \( M_{ee} \ll p_T \), and \( M_{ee} < 2M_{\pi} \), there is little contribution from \( q\bar{q} \rightarrow \gamma^* \), and thus the conversion is straightforward. The yield of direct photons are found to be higher than the ones expected from p+p collisions scaled by the number of binary collisions, suggesting there are additional sources of photons in Au+Au system (Fig. 6(a)). The average of

Figure 6. (a) Low \( p_T \) direct photon spectra (left) and (b) direct photon elliptic flow (right) in Au+Au collisions measured by the PHENIX experiment at RHIC

simple exponential fits to the low \( p_T \) regions gives a temperature of \( 220\pm23\pm8 \) MeV. However, the possible contribution from a nuclear effect (\( k_T \) smearing) to the \( p_T \) region still remains [20]. The internal conversion technique would help precisely determining the contributions in d+Au collisions. It should be noted that there are a number of
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5. Decomposition of photon sources – photon elliptic flow –

It is predicted that the elliptic flow \(v_2\) of photons show the different sign and/or magnitude, depending on the production processes of photons [22]. The observable is powerful to disentangle the contributions from various photon sources in the \(p_T\) region where they intermixes. The photons from hadron-gas interaction and thermal radiation follow the collective expansion of a system, and would give a positive \(v_2\). The amount of photons produced by jet-photon conversion or in-medium bremsstrahlung increases as the medium to traverse increases. Therefore these photons show a negative \(v_2\). The intrinsic fragment or bremsstrahlung photons will give positive \(v_2\) since larger energy loss of jets is expected in out-plane.

PHENIX has measured the \(v_2\) of direct photons by subtracting the \(v_2\) of hadron decay photons off from that of the inclusive photons, following the formula below:

\[
v_2^{\text{dir.}} = \frac{(R \times v_2^{\text{incl.}} - v_2^{\text{bkgd.}})}{(R - 1)}, \quad R = \frac{(\gamma/\pi^0)_{\text{meas}}}{(\gamma/\pi^0)_{\text{bkgd}}}
\]

The result is shown in Fig. 6(b). Although the systematic error is very large, the \(v_2\) of direct photons tends to be positive in 3-6 GeV/c independent of centrality [23]. It naively implies that the contribution from intrinsic fragment or bremsstrahlung photons are dominant over that from jet-photon conversion process. It could happen if the energy loss is very large and most of the hadrons observed are produced near surface of the system; hard scattered partons are absorbed before making enough Compton scattering to produce additional photons. In any case, minimizing the systematic error is desired before making a conclusion.

6. What would be the next measurement?

6.1. LHC

At LHC energies, the cross-section of hard photons increases drastically, and therefore the primary target will be to measure the energy loss of hard scattered partons with a trigger of prompt photons; the measurement of \(\gamma\)-jet correlation [24]. The experiments planning the measurement at LHC have already started feasibility studies on the measurement using realistic simulations. Figure 7(a) shows the tagging efficiency of prompt photons and rejection power to hadrons with an optimized cut in the ALICE detector [25]. At high \(p_T\), the tagged samples are shown to be mostly photons. Figure 7(b) shows the reconstructed fragmentation function in CMS detector [26]. The function is in good agreement with the input fragmentation function within systematic errors in hand. These studies show that measurement of energy loss of partons in the medium is promising at LHC.

Turing eyes into the low to mid \(p_T\) region, thermal photon emission would be of great interest as are at CERN and RHIC. Here, we can estimate how well such photons
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\[ \gamma_T \sim 7 \text{ (GeV/c)} \]

\[ n_T = \text{counts/(5GeV/c)} \]

\[ \frac{dN}{dp} \]

\[ \gamma_T = 10^{20} \]

\[ 10^{3} \]

\[ 10^{4} \]

\[ 10^{5} \]

\[ 14 \text{TeV} + X \]

\[ p+p \rightarrow \text{jet - jet photons} \]

\[ \sigma \sim N_{\text{part}} \times (\tau_{\text{freeze}} - \tau_0) \times (s^{1/2})^{1/4} \]

\[ \text{At LHC, the c.m.s. energy will increase by a factor of 70 and the } N_{\text{part}} \text{ by a little, therefore the yield may increase by a factor of } \sim 9. \]

\[ \text{On the other hand, photons related to hard-scattered partons would increase drastically in LHC, because the jet cross-section becomes exponentially larger as a function of c.m.s. energy. The jet-photon conversion yield would be proportional to the multiple of jet cross-section and QGP volume, resulting in:} \]

\[ \sigma \sim N_{\text{part}} \times N_{\text{coll}} \times (s^{1/2})^n \times g(x_T) \]

\[ \text{where the last term represents hard-scattering cross-section, } n \text{ is the } x_T \text{-scaling power, and } \sim 5 - 8. \]

\[ \text{Therefore, the jet-photon conversion would overwhelm thermal photon production. A rough schematics is shown in Fig. 7(c). From these consideration, it would be hard to observe thermal photons, instead, the medium can be investigated by observing photons from the jet-photon conversion process, together with } v_2 \text{ measurement.} \]

6.2. Forward measurement

Comparison of the hadron production at mid and forward rapidities has deduced particle production mechanisms, such as CGC. There is an interesting prediction on photon production at mid and forward rapidity, which can discriminate system expansion scenarios as shown in Fig. [27]. Landau and Björken expansion of the system would differ the ratio of the yield in mid and forward rapidity. At RHIC, STAR has photon detector [28] and has already measured photons at a forward rapidity. PHENIX also has a photon detector at the rapidity [29]. The detectors would provide interesting results on the system expansion.
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![Figure 8. Direct photon cross-section at (a)\(y=0\) (left) and (b)\(y=2\) (right), under different system expansion scenario.](image)

7. Summary

The recent direct photon measurements were reviewed and a future prospect was given. Direct photons would establish a status as one of the most fundamental measurement in heavy ion collisions in the future.

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