Thermal and direct photons in PHENIX

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Abstract. Thermal and direct photons in PHENIX are measured by virtual photons \((\gamma^* \rightarrow e^+e^-)\) for \(p_T\) 1-5 GeV/c, and real photons for \(p_T\) 4-20 GeV/c. In Au+Au, high \(p_T\) direct photons show no strong deviation from the \(T_{AA}\)-scaled p+p spectrum. The low \(p_T\) thermal photon spectra lie above the \(T_{AA}\)-scaled p+p fit. Partonic photon production models describe this enhancement with early formation times and high initial temperatures. The Au+Au direct photon elliptic flow, \(v_2\), is large at \(p_T < 4\) GeV/c and consistent with zero at \(p_T > 4\) GeV/c. Hydrodynamic parton models under-predict the low \(p_T\) photon \(v_2\).

1. Introduction
Thermal radiation emitted by the quark-gluon plasma (QGP) provides information on the QGP initial temperature and thermalization process. Thermal photons dominate the direct photon spectrum at low \(p_T\) and have positive elliptic flow. Hard processes are the dominant photon source at high \(p_T\). In heavy ion collisions, direct photon yields may be altered by isospin and nuclear parton distribution function effects. There may be additional yields due to jet-medium interactions, and fragmentation photon yields may be suppressed by energy loss of the partons.

2. Prompt photon measurement
The PHENIX detector [1] at RHIC has measured \(\sqrt{s}=200\) GeV p+p, d+Au, Cu+Cu and Au+Au collisions. The beam-beam counter (BBC), \(3.1 < |\eta| < 3.9\), and the reaction plane detector, \(1.0 < |\eta| < 2.8\), separately determine the reaction plane. Two central arm spectrometers extend to \(\pm 0.35\) in \(\eta\) and \(\pi/2\) in \(\phi\). Two methods measure photons, real photons in the calorimeters reach high \(p_T\) and virtual photons \((\gamma^* \rightarrow e^+e^-)\) access lower \(p_T\) thermal photons. Real photons shower in the lead-glass Cherenkov and lead-scintillator sampling calorimeters. Electrons are identified by calorimeter showers and rings in the ring imaging Cherenkov detector.

2.1. High \(p_T\) direct photons
High \(p_T\) direct photons are measured by removing large hadronic decay backgrounds from the inclusive real photons. In the 2006 p+p data, the \(\pi^0\) tagging method [2] removes these backgrounds, while in the 2004 Au+Au data the double ratio method [3] is used. The 2006 direct photon \(p_T\) spectrum agrees with a NLO pQCD calculation. Using the 2004 data set, the Au+Au high \(p_T\) photon spectrum shows no apparent deviation from \(T_{AA}\)-scaled p+p fit [3], where \(T_{AA}\) is the average nuclear thickness function and is calculated using the ratio of the average number of binary collisions in a Glauber Monte Carlo over the total inelastic p+p cross-section of 42 mb. The direct photon nuclear modification factor, \(R_{AA}\), at high \(p_T\) is
consistent with one for all centralities [3]. Figure 1 shows the high $p_T$ direct photon $R_{AA}$ for 0-5% Au+Au collisions compared with theoretical models that consider initial and final state effects [4][5][6]. The data are consistent with hard scattering processes with initial state effects including isospin effects and nuclear parton distribution functions. High $p_T$ direct photon yields are either unaffected by the final state or a balancing of parton energy loss and medium-induced bremsstrahlung effects results in no net modification.

2.2. Thermal photons from dielectron pairs

Direct photons at lower $p_T$, where thermal photons dominate, are measured via virtual photons in the dielectron spectrum. These photons have internally converted into electron-positron pairs. When $m \ll p_T$, photon production, which follows the Kroll-Wada formula, is approximately $d^2N_{ee}/dmdp_T \approx 2\alpha/3\pi \times m^{-1}dN_\gamma/dp_T$ [7]. The region $0.1 < m < 0.3$ GeV/$c^2$ and $p_T > 1$ GeV/$c$ contains virtual photons and excludes $\sim 99\%$ of $\pi^0$ backgrounds in minimum bias events.

All electron-positron pairs in an event are made. Combinatorial and correlated backgrounds are generated and statistically subtracted [8]. A cocktail of hadronic backgrounds from $\pi^0$, $\eta$, $\omega$, $\eta'$ and $\phi$ Dalitz decays is simulated with a decay generator assuming $m_T$ scaling of the measured $\pi$ spectrum and known meson-to-$\pi$ ratios to set meson yields. The $m^{-1}$ thermal lineshape is also simulated. These simulations are filtered into the PHENIX acceptance.

The direct photon fraction is determined by fitting the cocktail and thermal lineshapes to the mass spectrum in different $p_T$ bins with the function, $(1 - r_\gamma)f_c(m) + r_\gamma f_{th}(m)$, where $f_c(m)$ is the hadronic cocktail, $f_{th}(m)$ is the thermal photon lineshape and $r_\gamma$ is the only fit parameter, the direct photon fraction [7]. A separate external conversion analysis [9] finds consistent $r_\gamma$ values. The real direct photon yield is the product of $r_\gamma$, the inclusive virtual photon yield, and a real-to-virtual photon production scale factor of $2\alpha/3\pi \times \int m^{-1}dm$ in the 0.1-0.3 GeV/$c^2$ mass range.

2.3. Spectra

The p+p and d+Au direct photon spectra agree within systematic errors with $T_{AA}$-scaled NLO pQCD calculations [7][10]. The d+Au nuclear modification factor in d+Au collisions is consistent with one at all $p_T$, suggesting little to no visible cold nuclear matter effects [10]. In Cu+Cu and Au+Au collisions, a substantial excess in $r_\gamma$ is seen at low $p_T$. The low $p_T$ spectrum of direct photons in p+p and Au+Au collisions is shown on the left in Figure 2. The Au+Au spectra are shown with a fit of the p+p spectrum scaled by the average number of binary collisions, $\langle N_{coll} \rangle$, as determined by Glauber Monte Carlo. The inverse slope of the Au+Au low $p_T$ excess provides an average effective temperature of $233 \pm 14 \pm 19$ MeV in minimum bias (MB) events [7]. A recent ALICE result finds an average effective temperature of $304 \pm 51$ MeV for low $p_T$. 

![Figure 1. The direct photon $R_{AA}$ for 0-5% Au+Au collisions vs. $p_T$ [3]. Theoretical models consider initial and final state effects [4][5][6].](image)
Figure 2. The low $p_T$ direct photon spectrum in p+p and MB, 0-20% and 20-40% Au+Au collisions [7] is on the left. The p+p spectrum is compared to a pQCD calculation [18] and the Au+Au data are shown with a $N_{coll}$-scaled fit of the p+p spectrum. On the right, the 0-20% Au+Au direct photon spectrum [8] is shown with thermal production models [12]-[17] and a pQCD calculation [18]. Virtual (filled) and real (open) photon measurements are shown.

direct photons in 0-40% $\sqrt{s} = 2.76$ TeV Pb+Pb collisions [11]. Thermal photon emission models [12]-[17], on the right in Figure 2, deduce initial temperatures from 300-600 MeV and formation times of 0.15-0.5 fm/c from the 0-20% Au+Au direct photon spectrum [8].

3. Elliptic flow

The direct photon azimuthal anisotropy provides another metric to study photon production. Elliptic flow, $v_2$, is the second Fourier component of the direct photon’s azimuthal distribution with respect to the event’s reaction plane. The thermal photon $v_2$ is expected to be positive and can provide insight into the viscosity of the QGP [19]. The direct photon elliptic flow, $v_2^{\gamma,dir}$, is determined from the real inclusive photon elliptic flow, $v_2^{\gamma,inc}$, according to Equation 1

$$v_2^{\gamma,dir} = v_2^{\gamma,inc} + \frac{v_2^{\gamma,inc} - v_2^{\gamma,bkg}}{r_\gamma(p_T) - 1}$$

where $v_2^{\gamma,bkg}$ is the elliptic flow of photons from hadron decays and $r_\gamma$ is the direct photon fraction [20]. The $v_2^{\gamma,bkg}$ is determined by Monte Carlo simulation using the $\pi^0$ $v_2$ and assuming $m_T$ scaling of the hadron $p_T$ spectra and $KE_T$ scaling of the hadron $v_2$. $r_\gamma$ is from the real photon method [3] for $p_T > 5$ GeV/c and from the virtual photon method [7] at $p_T < 5$ GeV/c.

Figure 3 shows the direct photon $v_2$ in MB, 0-20% and 20-40% Au+Au collisions using 2007 data with the BBC reaction plane. At $p_T > 4$ GeV/c, the $v_2$ is consistent with zero; this agrees with the initial hard scattering picture. Currently, the measured $v_2$ is unable to resolve the concentration of jet-conversion ($v_2 \approx -0.02$) or fragmentation photons (0 < $v_2$ ≤ 0.01) at high $p_T$. In the thermal photon region, $p_T < 4$ GeV/c, the $v_2$ is large, comparable to the $v_2$ of charged hadrons, and decreases with as collisions become more peripheral [20]. The 0-20% Au+Au direct photon $v_2$ is compared with a hydrodynamic parton model assuming thermalization times of 0.4 (dashed) and 0.6 (dot) fm/c [21]. While the model’s shape is similar to the data’s, the $v_2$ magnitude is under-predicted.
Figure 3. The Au+Au direct photon $v_2$ vs $p_T$ using the BBC reaction plane [20]. Panel (b) shows a hydrodynamic model with thermalization times of 0.4 (dashed) and 0.6 (dot) fm/c [21].

4. Conclusions
Direct photons at high $p_T$ are from initial hard scattering interactions. In p+p and d+Au, direct photons are well described by NLO pQCD. In Au+Au, the high $p_T$ direct photon spectra undergo no net final state effects and shows zero elliptic flow within systematic errors. The low $p_T$ Au+Au thermal photon spectra show an excess above the $T_{AA}$-scaled fit to the p+p data. Partonic production models describe the data with a hot initial temperature, 300-600 MeV, and early formation time, 0.15-0.5 fm/c. The thermal photon $v_2$ is large, comparable to that of charged hadrons. Hydrodynamic parton models are currently unable to reproduce the thermal photon $v_2$. Later emission may be required for the necessary pressure gradients to build up [22].

Recent PHENIX preliminary 2009 p+p and 2010 Au+Au dielectron spectra [11] using the Hadron Blind Detector may provide improved systematics to measure thermal photons. The lower direct photon-to-$\pi^0$ ratio available at RHIC compared to the LHC provides current and future RHIC experiments, such as sPHENIX [23], an advantage in direct photon measurements.

References
[1] K. Adcox, et al. 2003 Nucl. Instrum. Meth. A449 469
[2] A. Adare, et al. 2012 Phys. Rev. D 86 072008
[3] S. Afanasiev, et al. 2012 Phys. Rev. Lett. 109 152302
[4] S. Turbide, C. Gale, E. Frodermann and U. Heinz 2008 Phys. Rev. C 77 024909
[5] I. Vitev and B.-W. Zhang 2008 Phys. Lett. B 669 337
[6] F. Arleo, K. J. Eskola, H. Paukkunen and C. A. Salgado 2011 JHEP 1104 055
[7] A. Adare, et al. 2010 Phys. Rev. Lett. 104 132301
[8] A. Adare, et al. 2010 Phys. Rev. C 81 034911
[9] R. Petti 2011 J. Phys.: Conf. Series 316 012027
[10] A. Adare, et al. 2012 Direct photon production in d+Au collisions at $\sqrt{s}=200$ GeV arXiv:1208.1234
[11] M. Wilde for the ALICE Collaboration. 2012 Measurement of direct photons in p+p and Pb+Pb collisions with ALICE. submitted for publication in Nuclear Phys. A arXiv:1210.5958
[12] D. d’Enterria and D. Peressounko 2006 Eur. Phys. J 46 451
[13] S. Turbide, R. Rapp and C. Gale 2004 Phys. Rev. C 69 014903
[14] P. Houvinnen, P. V. Ruuskanen and S. S. Rasanen 2002 Phys. Lett. B 535 109
[15] D. K. Srivastava and B. Sinha 2001 Phys. Rev. C 64 034902
[16] J.-e Alam, S. Sarkar, T. Hasuda, T. K. Nayak and B. Sinha 2001 Phys. Rev. C 63 021901(R)
[17] F. M. Liu, T. Hirano, K. Werner and Y. Zhu 2009 Phys. Rev. C 79 014905
[18] L. E. Gordon and W. Vogelsang 1993 Phys. Rev. D 48 3136
[19] K. Dusling 2010 Nucl. Phys. A 839 70
[20] A. Adare, et al. 2012 Phys. Rev. Lett. 109 122302
[21] T. Chatterjee and D. K. Srivastava 2007 Phys. Rev. C 79 021901(R)
[22] A. Drees 2012 Hard Probes to be published Nucl. Phys. A
[23] A Adare, et al. 2012 sPHENIX: An Upgrade Concept from the PHENIX Collaboration arXiv:1207.6378