

Direct Photons: Flow, Thermal Yield and High p_T R_{AA} from the PHENIX experiment at RHIC

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Abstract. Electromagnetic radiation has been of interest in heavy ion collisions because it sheds light on early stages of the collisions where hadronic probes do not provide direct information since hadronization and hadronic interactions occur later. The latest results on direct photon measurements in Au+Au collisions together with ones in d +Au collisions from the PHENIX experiment at RHIC provide thermodynamic properties of the matter produced in the heavy ion collisions. An unexpectedly large positive elliptic flow measured for direct photons are hard to be explained by many models.

1. Introduction

Many intriguing phenomena have been observed at RHIC since it started running in 2000. The high transverse momentum (p_T) hadron production from the initial hard scattering was observed, and the large suppression of their yields suggested that the matter is sufficiently dense to cause parton energy loss prior to hadronization [1]. The large elliptic flow of particles and its scaling in terms of particle kinetic energy suggests that the system is locally in equilibrium as early as 0.3 fm/c, and the flow occurs already on the partonic level.

Because photons interact with the medium and other particles only electromagnetically and are largely unaffected by final state interactions, they serve as a direct and penetrating probe of the early stages at high temperature and high density [2]. At leading order, the production processes of photons are annihilation ($q\bar{q} \rightarrow \gamma g$) and Compton scattering ($qg \rightarrow \gamma q$) (Figure 1). Their yields are proportional to $\alpha\alpha_s$, where α is the electromagnetic coupling constant and α_s is the strong coupling constant, and are ~ 40 times lower than those of hadrons from strong interactions ($\propto \alpha_s^2$). A calculation predicts that the photon contribution from the QGP state is predominant in the p_T range of $1 < p_T < 3$ GeV/c [3]. For $p_T > 3$ GeV/c, the signal is dominated by a contribution from initial hard scattering, and $p_T < 1$ GeV, the signal is from hadron gas through processes of $\pi\pi(\rho) \rightarrow \gamma\rho(\pi)$, $\pi K^* \rightarrow K\gamma$ and etc. Figure 2 shows a landscape of photon sources as a function of the time they are produced. The vertical axis corresponds to transverse momenta of photons. We have one additional degree of freedom, virtual mass, in photon measurement, which will be explained in detail in a later section. These photons can be measured after a huge amount of background photons coming from hadron decays (π^0 , η , η' and ω , etc.) are subtracted off from inclusive photon distributions. The typical signal to background ratio is $\sim 1\%$ at 2 GeV, and $\sim 10\%$ at 5 GeV in case of p+p collisions. The signal from QGP is predicted to be $\sim 10\%$ of the inclusive photons. For Au+Au collisions, thanks to a large suppression of high p_T hadrons, the ratio is enhanced by the same degree. PHENIX [4]

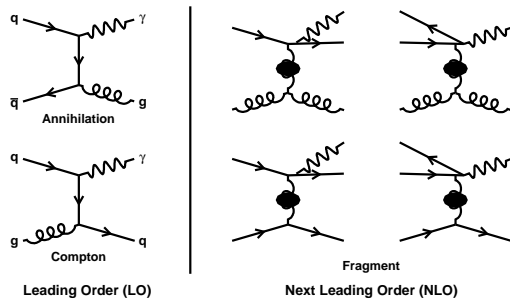


Figure 1. Photon production process.

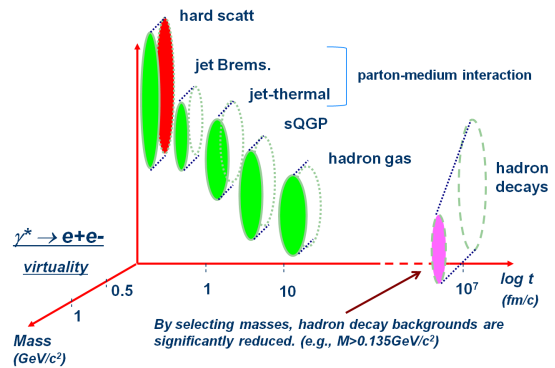


Figure 2. Sources of photons from various stages of collisions.

has measured photons throughout the first decade of RHIC operations. We present here the latest results on direct photons.

2. Measurement of direct photons in p+p collisions

One of the big successes by now in electromagnetic radiation measurements is the observation of high p_T direct photons that are produced in initial hard scattering [5] in relativistic heavy ion collisions. Figure 3 shows the nuclear modification factors (R_{AA}) for direct photons, π^0 and η for 0-10% central Au+Au collisions at the same center-of-mass (cms) energy. R_{AA} is defined as the ratio of the yield in nucleus-nucleus collisions divided by that in p+p collisions scaled by T_{AA} . The high p_T hadron suppression is interpreted as a consequence of an energy loss of

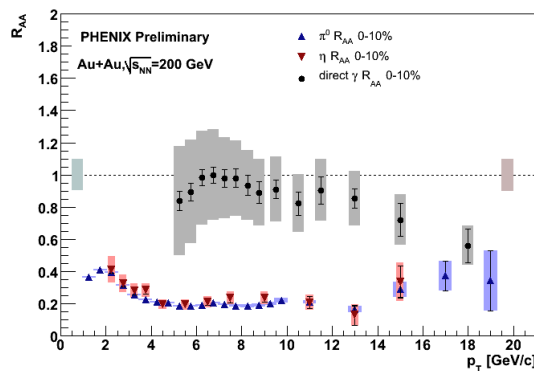


Figure 3. Nuclear modification factors (R_{AA} for photons, π^0 and η in 10% central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV.

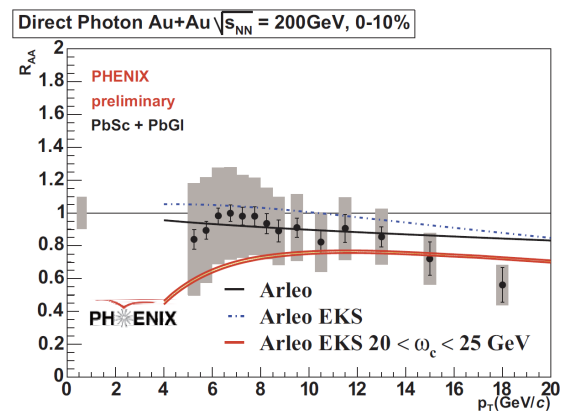


Figure 4. R_{AA} for direct photons in 10% central Au+Au collisions with theory calculations.

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. The small suppression seen in the highest p_T is likely due to the fact that the ratio of the yields in Au+Au to p+p was computed without taking the isospin dependence of direct photon yields into account [6]. Figure 4 shows the same direct photon R_{AA} as Fig. 3, with a theory calculation with isospin effect [6]. The large uncertainty on the measurement at high p_T partly comes from the statistical errors in p+p measurement.

We have measured the direct photons in p+p collisions with RHIC Year-6 data which has larger statistics compared to the one used for calculating R_{AA} in Figs. 3 and 4, as shown in Fig. 5. A

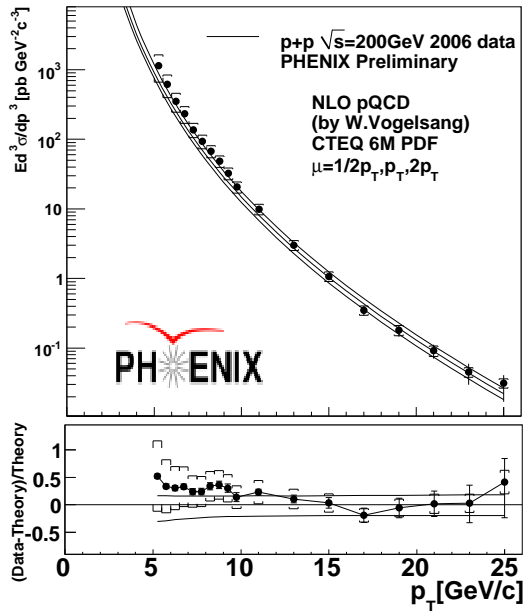


Figure 5. Direct photon spectra in p+p collisions at $\sqrt{s}=200$ GeV from RHIC Year-6 run.

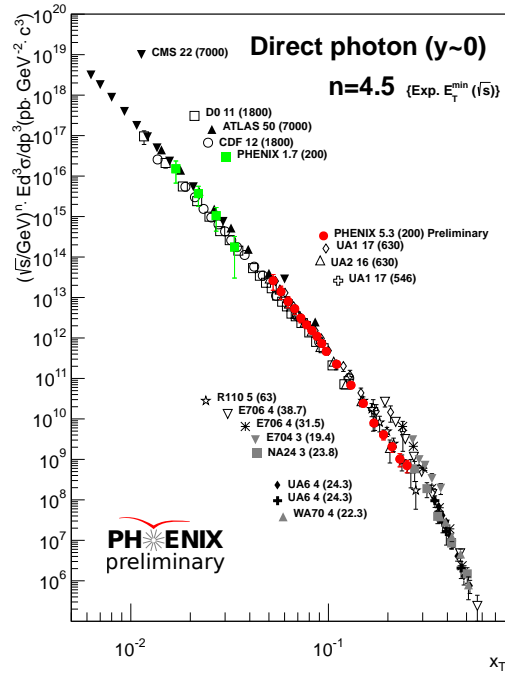


Figure 6. x_T -scaling of direct photons from various experiments. The power used here is $n=4.5$.

NLO pQCD calculation [7] describes the data well given the quoted systematic uncertainties in p+p measurement. In the pQCD picture, the cross-section should scale with x_T ($\equiv 2p_T/\sqrt{s}$), and can be expressed as the following formula:

$$E \frac{d^3 \sigma}{dp^3} = \frac{1}{\sqrt{s}^{n_{eff}(x_T, \sqrt{s})}} G(x_T)$$

where n_{eff} is constant and is 4 for the LO case. We plotted this new data in x_T with the data from other experiments whose center of mass energies vary over two order of magnitudes (from 20 GeV to 7 TeV). We also included the low p_T photons obtained by the virtual photon channel as described in the following section. We found that $n_{eff} = 4.5$ gives an universal scaling of the cross-section for all the data collected. This is consistent with the other study shown in a literature [8]. This fact implies that the direct photon cross-section is explained very well with the pQCD framework over wide center of mass energies. The calculation of R_{AA} of direct photons in Au+Au collisions using this p+p data is now in progress for publication.

3. Measurement of direct photons through its internal conversion

There is a huge background arising from π^0 decaying into two photons, which makes it very difficult to look at the direct photon signal at low p_T , where thermal photons from QGP manifest, with traditional calorimetry of (real) photons. However, if we look at photons with a small mass

(virtual photons) instead, we can select the mass region where π^0 contribution ceases (Fig 7). For the case of $p_T \gg M$, the yield of virtual photons is expected to be dominated by internal conversion of real photons [9, 10]. For obtaining direct photon yield, we fit the measured invariant mass distribution with the function:

$$F = (1 - r)f_c + rf_d,$$

where f_c is the cocktail calculation (photons from various hadron decays), f_d is the mass distribution for direct photons, and r is the free parameter in the fit. Next, using the Kroll-Wada formula [11] to account for the Dalitz decays of π^0 , η and direct photons, r is defined as the ratio of direct photons to inclusive photons:

$$r = \frac{\gamma_{\text{dir}}^*(m_{ee} > 0.15)}{\gamma_{\text{inc}}^*(m_{ee} > 0.15)} \propto \frac{\gamma_{\text{dir}}^*(m_{ee} \approx 0)}{\gamma_{\text{inc}}^*(m_{ee} \approx 0)} = \frac{\gamma_{\text{dir}}}{\gamma_{\text{inc}}} \equiv r_\gamma$$

Then, the invariant yield of direct photons is calculated as $\gamma_{\text{inc}} \times r_\gamma$. As described in [10], the procedure is demonstrated in Fig 7 for $1.0 < p_T < 1.5 \text{ GeV}/c$. The dotted lines show the

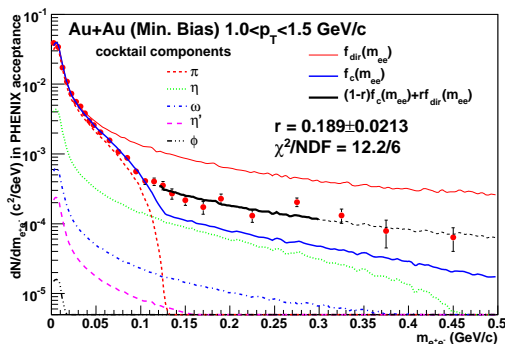


Figure 7. Invariant mass distributions of electron-pairs and comparison with possible hadron sources of electron-pairs.

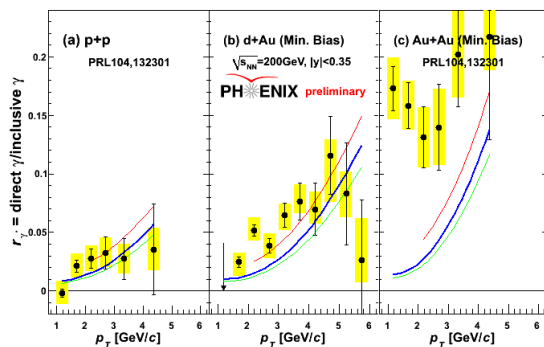


Figure 8. Ratio of direct photons to background photons (r values).

contributions from various hadrons, the solid blue is the sum of these contributions, and the solid red line shows the distribution from direct photons converted internally. The r value is determined by the fit to the data. The error of the fit corresponds to the statistical error. We applied the procedure as a function of p_T for various centrality selections in p+p and Au+Au collisions. Figure 8 shows the r value for p+p, d+Au minimum bias and Au+Au minimum bias collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. The lines are NLO pQCD expectations scaled by corresponding thickness functions. We then obtained the p_T spectra as shown in Fig 9. The distributions are for 0–20 %, 20–40 % centrality and minimum bias events for Au+Au collisions. For $p_T < 2.5 \text{ GeV}/c$ the Au+Au yield is visibly higher than the scaled p+p yield. The distributions were fitted with the p+p fit plus exponential function to obtain slopes and dN/dy for three centralities. The slopes are estimated to be $\sim 220 \text{ MeV}$. The lines show the theoretical expectation from a literature [3]. One may question whether or not the excess arises from a source that exists only in Au+Au collisions. For example, an effect that could increase the yield is cold-nuclear-matter (CNM) effect such as k_T broadening (Cronin effect). To quantify the contribution we analyzed 2008 d+Au data with the same procedure [12]. Figure 10 shows the Au+Au yield compared to the d+Au yield scaled by N_{coll} . It clearly shows that there is an enhancement over CNM effects in Au+Au collisions.

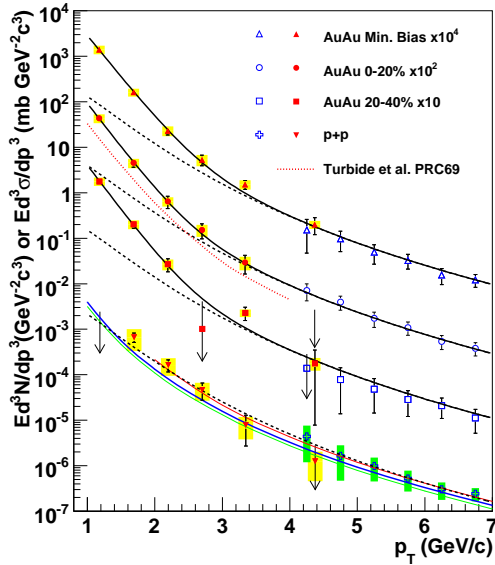


Figure 9. Direct photon spectra obtained from the measurement of internal conversion of photons in Au+Au collisions.

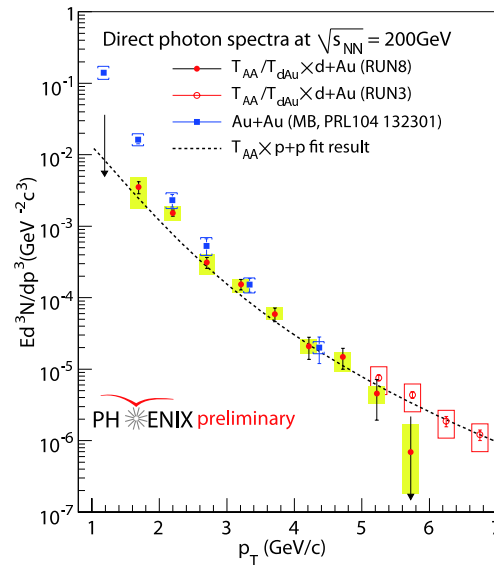


Figure 10. Direct photon yield in Au+Au and $d+Au$ collisions scaled by the difference of N_{coll} .

4. Probing nuclear effect using direct photons and π^0

As mentioned above, the direct photons in $d+Au$ collisions give an insight to the initial state of the collisions, since they are emitted from the initial stage directly, penetrate the medium and provide the kinematic information. Figure 11 shows the R_{dA} of the direct photons obtained from the spectra in Fig. 10 and direct real photons measured using RHIC Year-3 $d+Au$ data. The R_{dA}

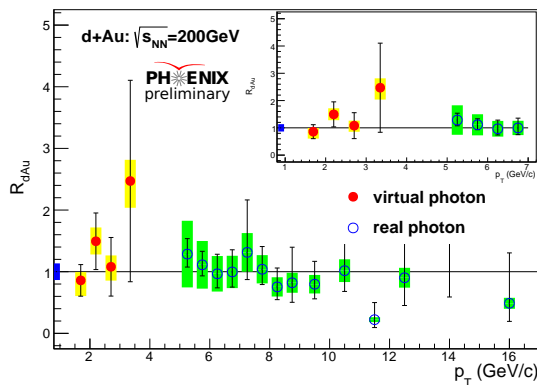


Figure 11. R_{dA} of direct photons in $d+Au$ collisions.

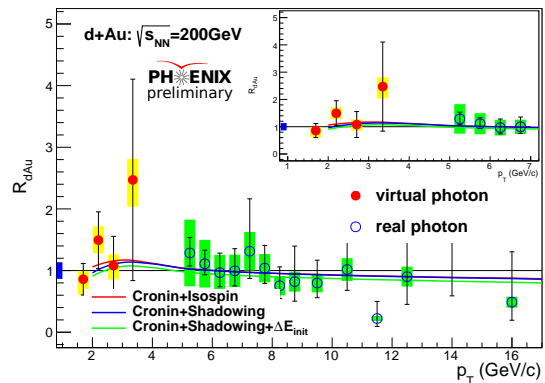


Figure 12. R_{dA} of direct photons in $d+Au$ collisions with theory calculations from Vitev [13].

is consistent with 1 within quoted errors. In Fig. 12, we compared the data with calculations including Cronin enhancement (k_T broadening), isospin effect, anti-shadowing and energy loss of partons in the cold nuclear matter [13]. All the calculations are consistent with the data given the quoted errors. The R_{dA} of direct photons provide a test of the recombination model by

comparing with the R_{dA} of π^0 's [14]. The recombination model predicts that the R_{dA} for direct photons is smaller than that of π^0 's, since the k_T broadening is doubly effective in creating π^0 's. Figure 13 shows the π^0 R_{dA} in a previous publication [15]. Within the current statistical and

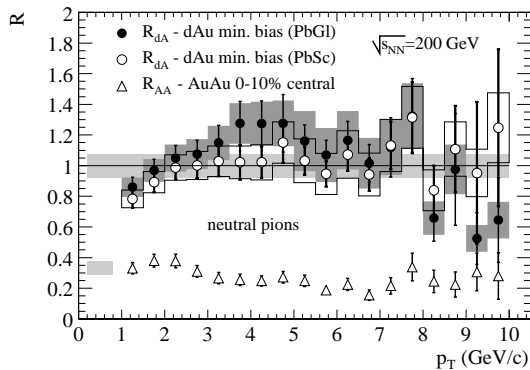


Figure 13. R_{dA} of π^0 's published in a previous publication [15].

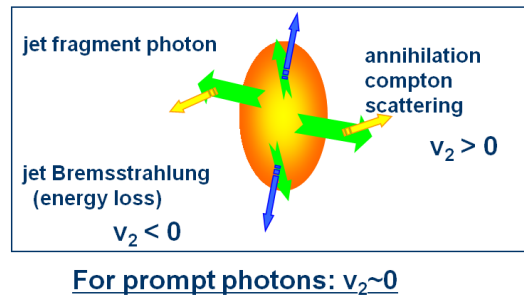


Figure 14. Source dependence of elliptic flow (v_2) of direct photons.

systematic uncertainties, it is difficult to conclude whether or not the recombination mechanism plays a significant role in π^0 production.

5. Elliptic flow of direct photons –A photon source detector–

On exploring the matter produced, one wants to explore a new degree of freedom of the observables. The angular dependence of the photon yield with respect to the plane defined by impact parameter (event plane) is one of the degrees that can be investigated. It is predicted that the second order of the Fourier transfer coefficient (v_2 , elliptic flow) of angular distributions of photons show the different sign and/or magnitude, depending on the production processes [16] (Fig. 14). The observable is powerful to disentangle the contributions from various photon sources in the p_T region where they intermix. The photons from hadron-gas interaction and thermal radiation may follow the collective expansion of a system, and 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 fragmentation photons will give positive v_2 since larger energy loss of jets is expected orthogonal to the event 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:

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

The centrality dependence of elliptic flows of π^0 and inclusive photons are shown in Fig. 15(a), (c) and (e), and the ones for direct photons are shown in Fig. 15(b), (d) and (f) [17]. The v_2 of direct photons is large and positive, and comparable to the flow of hadrons for $p_T < 3$ GeV/c. It is also seen that the magnitude increases as going from central to mid-central collisions. This large positive flow is hard to be explained by many models. Several models qualitatively predicted the positive flow of the photons assuming the photons are boosted with hydrodynamic expansion of the system, but the amount is significantly lower than the measurement [18]. There is one model that gives relatively large flow by including hadron-gas interaction shown as Fig. 16 [19]. The model changed the relative ratio of the various sources of photons since the previous publication [20]. As a result, the photons from hadron gas interaction dominate for

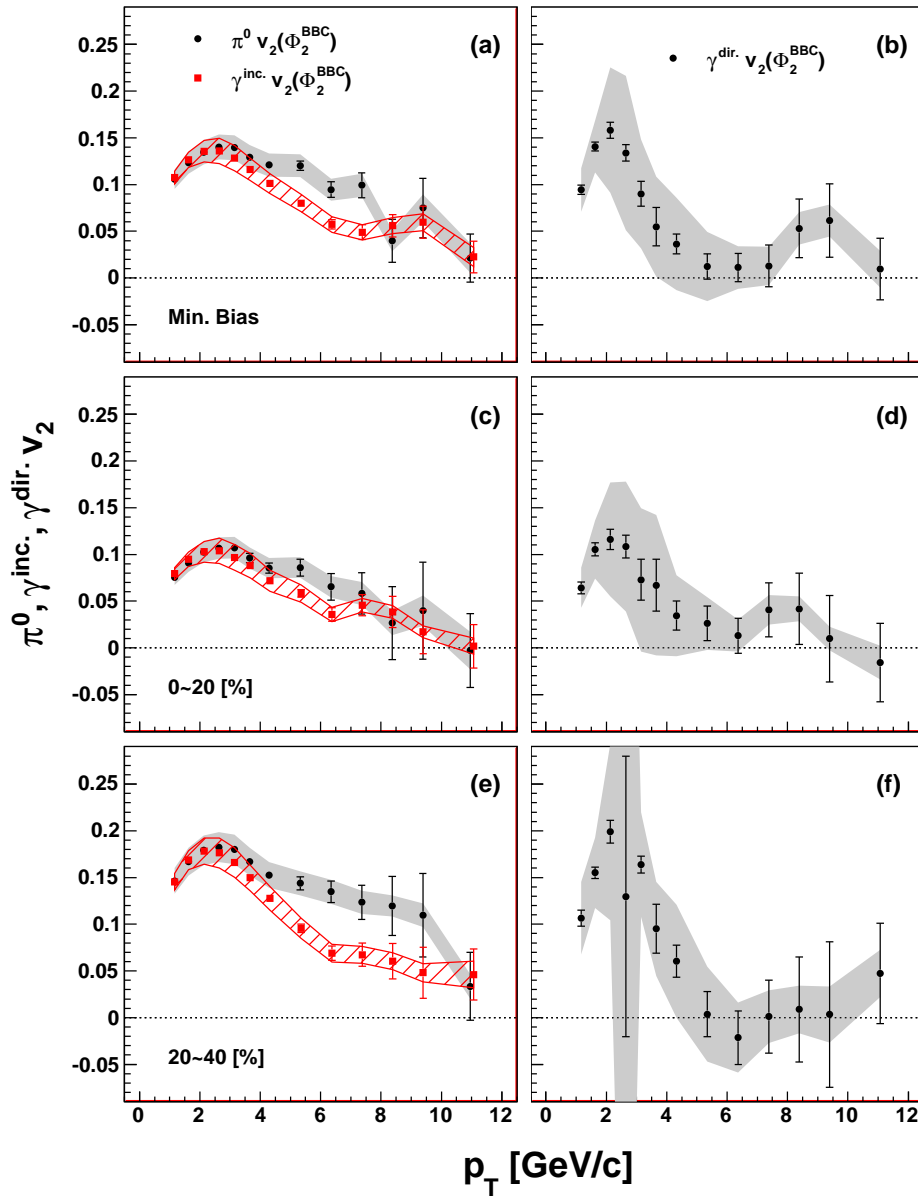


Figure 15. Elliptic flow of (a, c and e, left) π^0 and inclusive photons and (b, d, and f, right) direct photons in Au+Au collisions.

$p_T < 2.5$ GeV/c, as shown in Fig. 17. The model describes both v_2 and the yield for the 0-20% centrality data rather well, but less in 20-40% centrality.

6. Summary

Direct photons are a powerful tool to investigate the collision dynamics. PHENIX has measured direct photons over wide p_T ranges, including hard scattering and thermal photons, and extracted quantities, such as slope parameters, that reflect thermodynamic properties of the matter. The measurement in d +Au proved that the enhancement of the yield in low p_T in Au+Au collisions is not from the cold nuclear matter effect. The d +Au direct photon yields

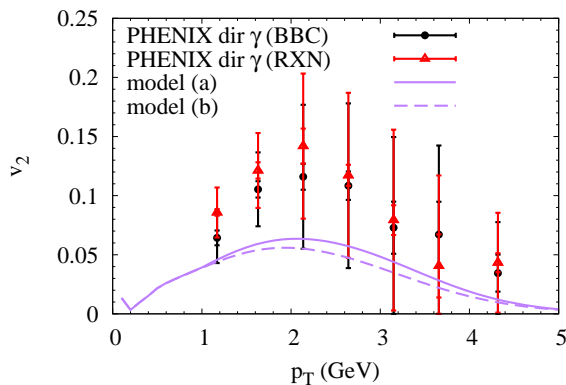


Figure 16. A model calculation for v_2 for direct photons in 0-20 % central Au+Au collisions [19].

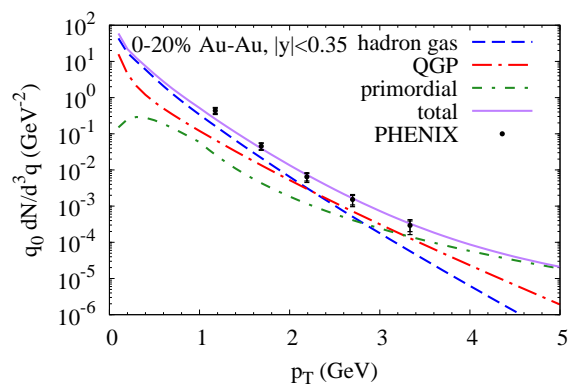


Figure 17. Direct photon invariant yield from the same model that explained the v_2 in Fig. 16.

are compared with a model including k_T broadening, isospin, anti-shadowing and parton energy loss in the cold nuclear matter. Within quoted errors, the model calculations are consistent with data. A comparison of the R_{dA} of π^0 's and direct photons is a test of the recombination model, but with the current errors, it is hard to make a statement on the validity of the model. An unexpectedly large positive elliptic measured for direct photons are hard to be explained by many models except for the one assuming photons from hadron-gas interaction is dominant for $p_T < 2.5$ GeV/c.

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