Photon production in $\sqrt{s_{NN}}=200$ GeV Au+Au collisions measured by the PHENIX experiment at RHIC.

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Direct photon production in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV has been measured in the $p_T$ range of $1<p_T<5$ GeV/$c$. The yield as a function of centrality is in agreement with published data of the RHIC 2002 run, and with results from a new method that explores very low mass dileptons. The result is compared to several theoretical calculations, and it is found that the measurement is not inconsistent with calculations including thermal photon contributions.

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1 Introduction

Several discoveries from the first five years at the Relativistic Heavy Ion Collider (RHIC) indicate that a new hot and dense partonic matter have most likely been produced in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV [1–4]. The drastically increased hard scattering cross-section at the RHIC energy makes it possible to use hard probes (jets, heavy quarks, etc.) as “measures” of the colliding system. High $p_T$ hadrons, i.e. fragments of jets, have been found to be suppressed as a consequence of a final state interaction (energy loss) of hard scattered partons with the partonic medium. This observation is supported by the high $p_T$ direct photon measurement by the PHENIX experiment [5]; the high $p_T$ photons originating from an initial hard scattering were not suppressed. The energy loss phenomena has also been observed with electrons from semi-leptonic decay of charm and bottom quarks [6]. In addition to new probes, conventional observables also provided important information. For instance, a large collective flow of bulk particles gives a hint of a rapid thermalization of the partonic matter, because a large asymmetry of pressure gradient that results in a large flow can only be realized in the early time. In summary, the results suggest that the matter created in heavy ion collisions at RHIC is strongly interacting and quite opaque like a perfect liquid.

Provided that the hot and dense partonic matter is created, its thermodynamical nature such as temperature, phase transition order parameters and the degree of freedom in the medium are of great interest. The temperature obtained from a statistical model fit to particle yield ratios

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is the chemical freeze-out temperature, and no longer reflecting the one in the partonic matter. Therefore, more direct probes are deserved.

Photons are an excellent probe for extracting such the thermodynamical information, because once produced, they do not interact strongly with a medium. They are produced through Compton scattering of quarks and gluons and annihilation of quarks and anti-quarks (leading order), and bremsstrahlung or fragment (next leading order). There is also a prediction of a jet-photon conversion process, which occurs if the hot and dense matter is formed, by a secondary interaction of a hard scattered parton with thermal partons in the medium [7]. The contributions from various processes are mixed up in any \( p_T \) range, but each can dominantly be seen at certain \( p_T \)'s. The calculation shown in Fig. 1 predicts that photons with \( p_T < 1 \) GeV/c are mostly contributed by hadron gas interaction via processes of: \( \pi\pi(\rho) \rightarrow \gamma\rho(\pi) \), \( \pi K^\ast \rightarrow K\gamma \) and etc.. [7] The thermal radiation from QGP state is predominant in \( 1 < p_T < 2.5 \) GeV/c. For \( p_T > 2.5 \) GeV/c, a contribution from jet-photon conversion process will be seen on top of the one from the initial hard scattering as shown in Fig. 2 [8].

The PHENIX experiment at RHIC has succeeded to scope \( 1 < p_T < 5 \) GeV/c in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV where the thermal radiation and the jet-photon conversion process are likely to manifest. This paper will present a detailed description of the analysis and the results, together with theoretical models.

## 2 Detector and Analysis

Fig. 3 shows the PHENIX detector at RHIC. Both central arms (East and West) of the detector include Drift Chamber (DC), Pad Chamber (PC), Ring Imaging Čerenkov Counter (RICH), lead-scintillator sandwich type (PbSc) and lead-glass type (PbGl) calorimeter. The East arm has a Time Of Flight (TOF) detector and a Time Expansion Chamber (TEC) in addition. Each covers a pseudo-rapidity range of \( |\eta| < 0.35 \) and a quarter azimuth. A detailed description of the detector is given in the literature [9].
In this analysis, PbSc was used for measuring energies of photons and π^0's. The analysis of direct photons requires a precise determination of background photons decaying from known hadronic sources such as π^0 and η. PHENIX has measured the transverse momentum spectra of π^0 up to 20 GeV/c in Au+Au collisions at √s_{NN}=200 GeV with ~900 M minimum bias events from RHIC 2004 run [10]. This work used ~93 M events out of the above in order to control run-by-run systematic fluctuation. The momentum spectra of η and other hadronic sources were estimated by replacing p_T by (p_T^2 − M_{π^0}^2 + M_h^2)^{1/2} in fit functions to π^0 spectra. Normalization factors for the estimated function were determined so that η/π^0_p_T=∞=0.45±0.05 [5], η'/π^0_p_T=∞=1.0 and ω'/π^0_p_T=∞=1.0. The ratio of background photons are shown in Fig. 4(a).

Photon candidates were selected by applying a threshold on a PID likelihood variable computed from several quantities such as cluster shower shape or ratio of energies among towers (Fig. 4(b)). It resulted in a significant reduction of hadronic clusters in the samples. The remaining hadron contamination and PID efficiency were corrected for based on a simulation study. Since the ratio of γ to π^0 cancels their common systematic errors, the excess of the measured photon over the estimated background photon is evaluated in terms of (γ/π^0)_{measured}/(γ/π^0)_{background} (double ratio). The systematic errors are summarized in Tab. 1. The total p_T-correlated error is 7.5 %, and the total point-by-point systematic error is 7.0 %, respectively.

In addition to the above conventional approach, a new method that utilizes very low mass dileptons has been applied [11]. It is well known that the e^+e^- invariant mass distributions from...
Tab. 1. Systematic Errors on direct photon and very low mass dilepton measurement

| Direct photon measurement | Total $p_T$-correlated error | Total point-by-point error |
|---------------------------|-------------------------------|---------------------------|
| $\pi^0$ peak extraction   | 6%                            |                           |
| Energy scale in terms of $\gamma/\pi^0$ | 3%                            |                           |
| $\gamma/\pi^0$ background | 3%                            |                           |
| $\gamma$ unfolding       | 3%                            |                           |
| Acceptance in terms of $\gamma/\pi^0$ | 2%                            |                           |
| PID error in terms of $\gamma/\pi^0$ | 1.5%                          |                           |
| Off-vertex contribution to $\gamma/\pi^0$ | 2.1%                          |                           |
| Hadron contamination estimate | 5%                            |                           |
| $\gamma/\pi^0$ conversion correction | 1.5%                          |                           |
| $\eta/\pi^0$ estimate error | 2%                            |                           |
|                           | Total                         | 7.5%                      |
|                           | point-by-point error          | 7.0%                      |

| Very low mass dilepton measurement | $\gamma^{*}_{\text{direct}}/\gamma^{*}_{\text{all}}$ estimate error |
|------------------------------------|---------------------------|
| $h/\pi^0$ estimate                | 20%                       |
| Acceptance                        | 5%                        |
| Total error                       | 21%                       |
| (point-by-point only)             |                           |

$\pi^0$ or $\eta$ Dalitz decay follow the Kroll-Wada formula as shown below [12].

\[
\frac{1}{N_{\gamma}} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) \frac{1}{m_{ee}} |F(m_{ee}^2)|^2(1 - \frac{m_{ee}^2}{M^2})^3}
\]

where $m_e$ is the mass of electrons, $m_{ee}$ is the invariant mass of a produced dilepton, $M$ and $|F(m_{ee}^2)|$ are the mass and the form factor of a parent particle, respectively. The formula is also valid for internal conversion of direct photons by substituting $|F(m_{ee}^2)|$ with 1. The $e^+e^-$ invariant mass distribution of $\pi^0$ and $\eta$ Dalitz decays as well as direct photon internal conversion are demonstrated in Fig. 5. Using the formula, the amount of dileptons can be estimated at a given invariant mass region where a ratio of the measured to the background is taken as a function of $p_T$ (in this analysis, $90 < M_{ee} < 300$ MeV/c$^2$). Since the yield at the lowest mass region is approximately proportional to the total number of produced $e^+e^-$, the ratio at the measured mass region is then converted into the one at the very low mass region ($0 < M_{ee} < 30$ MeV/c$^2$)
Photon production at RHIC-PHENIX using the Kroll-Wada formula. This work used \( \sim 900 \) M minimum bias events. The systematic errors for this method are also summarized in Tab. 1.

### 3 Results and discussion

Fig. 6 shows the \( \gamma/\pi^0 \) double ratio for 0-10 % central collisions as a function of \( p_T \). The results from very low mass dilepton analysis are also plotted on the figures in blue, in the form of \( \gamma_{\text{direct}}/\gamma_{\text{all}} + 1 \), which is not equivalent to \( \gamma/\pi^0 \) double ratio. Both direct photons and very low mass dileptons are consistent given the large error of the direct photon measurement. They are also consistent with the published results from RHIC 2002 run [5]. In \( 1 < p_T < 2.5 \) GeV/c, there is no significant excess in the direct photon measurement in all the centralities, while the very low mass dilepton has a significant excess except for peripheral events. Overlaid on the plots are expectations from a NLO pQCD calculation scaled by the number of binary nucleon-nucleon collisions [13]. The direct photon results can be well described by the expectations except the 0-10 % centrality data, where the onset of an additional contribution is seen in \( 4 < p_T < 5 \) GeV/c.

The result for most central events is also compared with a model including the thermal radiation, and shown in Fig. 7. The model assumes an initial temperature of \( T_0 = 360 \) MeV (\( T_0^{\text{max}} = 570 \) MeV) and a formation time of \( \tau_0 = 0.15 \) fm/c [14]. The result is not inconsistent with the model, suggesting that there is a possibility of the existence of a thermal source. However, further works on reducing systematic errors on direct photon measurement, and confirmation of no excess in very low mass dilepton in p+p measurement are desired to make a concrete statement.
4 Conclusion

Direct photon production in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV has been measured in the $p_T$ range of $1<p_T<5$ GeV/c. The yield as a function of centrality is in agreement with published data of the RHIC 2002 run, and with results from a new method that explores very low mass dileptons. The result is compared to several theoretical calculations, and it is found that the measurement is not inconsistent with calculations including thermal photon contributions. Further works on reducing systematic errors on direct photon measurement, and confirmation of no excess in very low mass dilepton in p+p measurement are desired to make a concrete statement.

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