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2008 J. Phys. G: Nucl. Part. Phys. 35 104118

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Measurements of thermal photons in heavy ion collisions with PHENIX

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Received 28 April 2008

Published 17 September 2008

Online at stacks.iop.org/JPhysG/35/104118

Abstract

Thermal photons are thought to be the ideal probe to measure the temperature of the quark–gluon plasma created in heavy ion collisions. PHENIX has measured direct photons with $p_T < 5 \text{ GeV}/c$ via their internal conversions into e^+e^- pairs in Au + Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ and has now provided a baseline measurement from $p + p$ data.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Direct photons are produced during all stages of heavy ion collisions at the relativistic heavy ion collider (RHIC). Because they do not interact strongly, they escape the medium unaffected by final state interactions and provide a promising signature of the earliest and hottest stage of the quark–gluon plasma (QGP) [1]. The main sources of direct photons from a QGP are quark–gluon Compton scattering ($qg \rightarrow \gamma q$), quark–antiquark annihilation ($q\bar{q} \rightarrow \gamma g$) and bremsstrahlung involving thermalized and incoming partons [2]. At RHIC energies thermal photons are predicted to be the dominant source of direct photons in $1 < p_T < 3 \text{ GeV}/c$ [1].

The formation of a hot and dense medium has been established by experimental results at RHIC [3]. The measurement with the electromagnetic calorimeter (EMCal), based on a statistical subtraction of the expected background from hadronic sources, remains limited at low p_T due to large systematic uncertainties [4, 5].

The uncertainties in knowledge of the decay background can be reduced by avoiding its explicit measurement. A tagging method has been developed in which a very pure photon sample is selected with strict photon identification cuts [6]. In this sample those photons are tagged, which combined with other clusters in the EMCal (selected with less-stringent photon identification cuts) can be identified via their invariant mass as the result of a π^0 decay. In

¹ A list of members of the PHENIX Collaboration can be found at the end of this issue.

the ratio of pure photons and tagged photons the reconstruction efficiency of the pure photons cancels and with it the associated systematic uncertainty.

Furthermore, to circumvent the limitations due to the energy resolution at low photon energies, the excellent capabilities of the PHENIX detector to measure electrons can be utilized by measuring photons via their external conversion into e^+e^- pairs [7]. These conversion pairs can be used as an alternative clean photon sample in the method described above.

2. Internal conversions

To overcome the statistical and systematic limitations an alternative approach has been pursued [8] and is outlined in the following. Any process that produces a real photon can also create a virtual photon which converts internally into an e^+e^- pair. Therefore, e^+e^- pairs are also produced through internal conversions of virtual direct photons, e.g. via the qg Compton scattering ($qg \rightarrow \gamma^* g \rightarrow e^+e^- g$). The relation between photon production and the associated e^+e^- pair production can be written as:

$$\frac{d^2 n_{ee}}{dm} = \frac{2\alpha}{3\pi} \frac{1}{m} \sqrt{1 - \frac{4m_e^2}{m^2}} \left(1 + \frac{2m_e^2}{m^2}\right) S dn_\gamma \quad (1)$$

with m being the mass of the e^+e^- pair and $m_e = 511 \text{ keV}/c^2$ the mass of the electron. The process-dependent factor S goes to 1 as $m \rightarrow 0$ or $m \ll p_T$. For π^0 and η decays, S is given by $S = |F(m^2)|^2 (1 - m^2/m_h^2)^3$ [9] where m_h is the hadron mass and $F(m^2)$ is the form factor. For e^+e^- pair masses approaching m_h , the factor S goes to zero. While the measurement of real thermal photons suffers from a large background of hadron decays, measuring virtual photons allows us to select a mass range, in which π^0 decays are suppressed due to the cut-off in S .

The following analysis is based on 800 M minimum bias events collected during the Au + Au run at $\sqrt{s_{NN}} = 200 \text{ GeV}$ in 2004 and 2.25 pb^{-1} of single electron triggered data recorded during the $p + p$ run at $\sqrt{s} = 200 \text{ GeV}$ in 2005. Electrons have been identified using information of the ring imaging Cherenkov detector (RICH) and a matching of momentum and the energy deposited in the EMCal. Details of the analyses can be found in [10, 11]. The invariant mass spectrum of e^+e^- pairs after background subtraction is shown in figure 1 for $p + p$ (left) and Au + Au (right) for various e^+e^- pair- p_T bins above $1 \text{ GeV}/c$. The data are corrected for the electron identification efficiency based on a full Monte Carlo simulation, but are not corrected for the geometrical acceptance [10, 11]. These data are then compared to a cocktail of hadron decays from a fast Monte Carlo simulation whose input is based on the measured hadron spectra [10, 11]. The cocktail is normalized to the data in the mass range $0\text{--}30 \text{ MeV}/c^2$. While in $p + p$ the agreement of the cocktail to the data is remarkable and a small excess is only observed at very high p_T and large mass, the Au + Au data show a large excess over the full p_T range of $1\text{--}5 \text{ GeV}/c$.

The observed excess above the hadronic cocktail can be analyzed under the assumption that it is solely due to internal conversions of direct virtual photons. While at zero mass e^+e^- pairs from hadron decays have the same shape in mass as internal conversions of direct photons, the suppression due to S when approaching the hadron mass changes the shape of e^+e^- pairs from hadron decays. Therefore, one can fit, after an initial normalization to the mass range $0\text{--}30 \text{ MeV}/c^2$, the two expected shapes for e^+e^- pairs from hadronic decays f_{cocktail} (as shown in figure 1) and from direct photons f_{direct} in the mass range $80\text{--}300 \text{ MeV}/c^2$ in which the π^0 contribution is severely suppressed. The only fit parameter is the relative fraction of direct photons r :

$$f(m) = (1 - r)f_{\text{cocktail}}(m) + rf_{\text{direct}}(m). \quad (2)$$

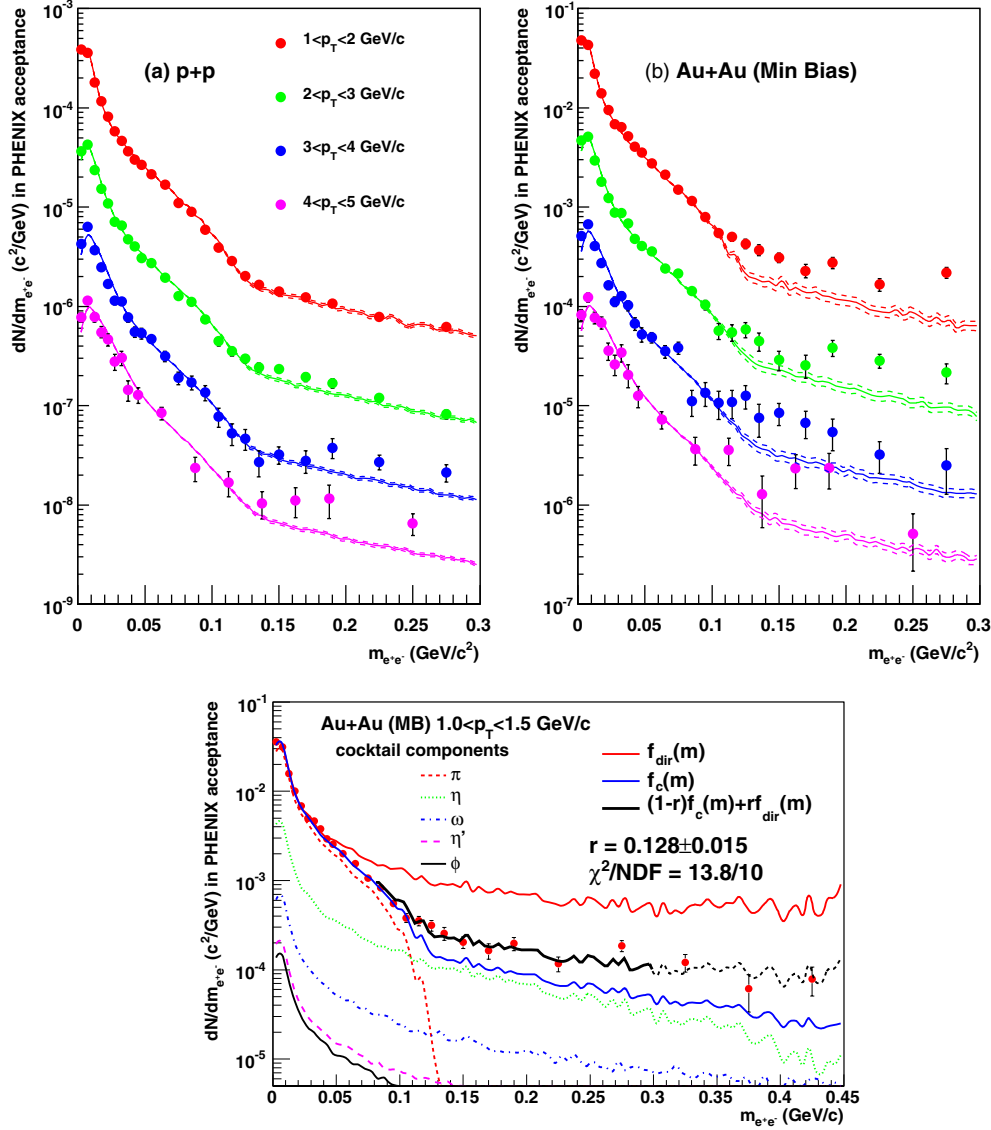


Figure 1. Top: the e^+e^- pair invariant mass distributions in (a) $p+p$ and (b) minimum bias Au + Au collisions compared to a cocktail of hadronic sources. Bottom: mass distribution of e^+e^- pairs for Au + Au minimum bias events for $1.0 < p_T < 1.5$ GeV/c with a fit as described in the text.

As an example, the fit result is shown in figure 1 for e^+e^- pairs with $1.0 < p_T < 1.5$ GeV/c in minimum bias Au + Au collisions. The quality of the fit result (e.g., $\chi^2/NDF = 13.8/10$ for the lowest p_T bin) indeed justifies the assumption that the observed excess is due to internal conversions of virtual photons. A fit with the mass shape of e^+e^- pairs from η Dalitz decays would lead to a two times larger η cross section than measured [12] and a significantly worse $\chi^2/NDF = 21.1/10$. Little contribution from other sources is expected to this kinematic region, as it is limited to $m < 2m_\pi$. PHENIX has reported a large dielectron enhancement for

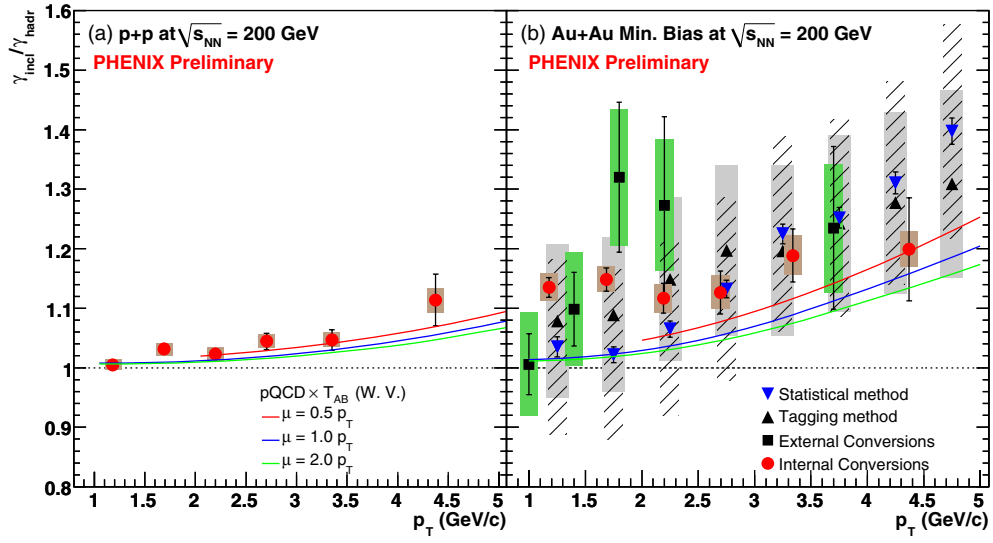


Figure 2. Direct photon excess. (a) The fraction of the direct photon component as a function of p_T in $p + p$. (b) Au + Au (minimum bias) compared to other measurements of direct photons as described in the legend. The curves are from a NLO pQCD calculation [14].

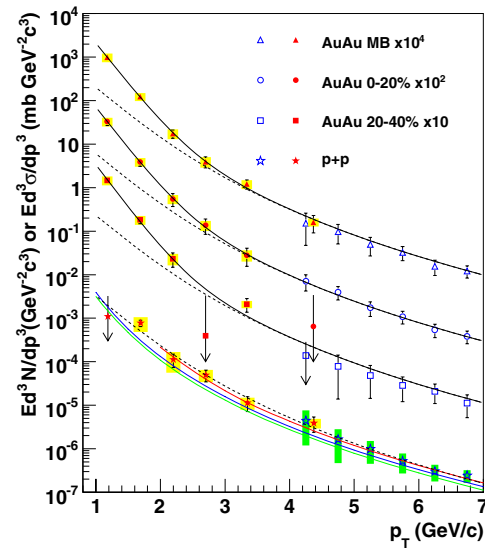


Figure 3. Invariant cross section ($p + p$) and invariant yield (Au + Au) of direct photons. The $p + p$ result is compared to a NLO pQCD calculation. Solid points are from this analysis, open points from [4, 5]. The dashed lines show a T_{AA} scaled, modified power-law fit of $p + p$. The black curves show an exponential plus the T_{AA} scaled $p + p$ fit.

$150 < m < 750$ MeV/ c^2 in [11], but the dominant fraction of the enhancement is concentrated at low p_T [13].

3. Results

The result is shown as $1 + r \approx \gamma_{\text{incl}}/\gamma_{\text{hadr}}$ in the left of figure 2 for $p + p$ collisions. It is compared to a NLO pQCD calculation of direct photons [14]. While the fraction of direct photons measured in $p + p$ agrees well with the pQCD calculation, a clear excess is observed in minimum bias Au + Au collisions shown in the right of figure 2. The Au + Au result is also compared to the other measurements of direct photons at low p_T ; the conventional statistical subtraction of hadronic decay photons [15], the tagging method [6] and the external conversion analysis [7]. While they all agree within their uncertainties, the improvement in statistical and systematic uncertainties is quite significant.

The fraction of direct photons r can be converted into a direct photon spectrum by multiplying with the inclusive photon spectrum. The inclusive photon yield is determined for each p_T bin by $dN_{\gamma}^{\text{incl}} = dN_{ee}^{\text{data}} \times dN_{\gamma}^{\text{cocktail}} / dN_{ee}^{\text{cocktail}}$, where dN_{ee}^{data} and $dN_{ee}^{\text{cocktail}}$ are the yields of e^+e^- pairs in $m < 30 \text{ MeV}/c^2$ for data and cocktail, respectively, and $dN_{\gamma}^{\text{cocktail}}$ is the yield of photons from the cocktail. The resulting direct photon spectra for $p + p$ and Au+Au collisions are shown in figure 3. The $p + p$ data can be well described with a modified power-law function: $A_{pp}(1 + p_T^2/b)^{-n}$. The direct photons measured in Au+Au are above the binary scaled fit to the $p + p$ result. An exponential fit plus the binary scaled modified power law $(A e^{-p_T/T} + T_{AA} \times A_{pp}(1 + p_T^2/b)^{-n})$ reveals an inverse slope of $T = 220 \pm 23 \pm 18 \text{ MeV}$ for central collisions, suggesting an excess possibly of thermal origin. The inverse slope of the direct photon spectrum can be related to the initial temperature of the QGP [16].

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