Direct photons in 200 GeV $p+p$, d+Au, and Au+Au from PHENIX

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Direct photons were measured with the PHENIX experiment in $p+p$, d+Au, and Au+Au at $\sqrt{s_{NN}} = 200$ GeV. To tackle the p_T region below 5 GeV/c, direct photons were measured through their internal conversion into e^+e^- in Au+Au collisions.

1. Introduction

Direct photons are a unique probe of the hot and dense matter created at RHIC: they allow access to the initial, thermalized state of the collision. Their measurement, however, is challenging. One has to cope with a large background from hadronic decays.

Direct photon measurements in $p+p$ constrain the hard-scattering contribution in Au+Au. A comparison to d+Au allows to quantify contributions from initial-state effects. In heavy ion collisions, thermal direct photons constrain the temperature of the collision system in its hottest phase while hard direct photons serve as a crucial baseline for the interpretation of the high-p_T hadron suppression observed earlier [1].

2. Direct Photon Analysis Via Low-Mass Electron Pairs

The conventional direct photon measurement with the EMCal has been described elsewhere [2,3]. In the following we will focus on the measurement through internal conversion of direct photons into e^+e^-. Compared to the conventional measurement, this technique improves both the signal-to-background ratio and the energy resolution at intermediate p_T where thermal production is expected to contribute substantially [4]. The measurement relies on a combination of excellent mass resolution at low invariant mass, m_{ee}, and a low conversion probability due to little material in the aperture. It has been carried out in heavy ion experiments for the first time [5,6].

The full 2004 data set of about 900 M minimum bias events was analyzed. Events and centrality were selected as described in [7]. Electrons in the central arms were identified by matching charged particle tracks to clusters in the EMCal and to rings in a ring imaging Čerenkov (RICH) detector.

To illustrate the underlying idea we consider the π^0 Dalitz decay where one decay photons is a virtual photon that further decays into an e^+-e^- pair. The invariant-mass distribution of the virtual photon is given by [8]

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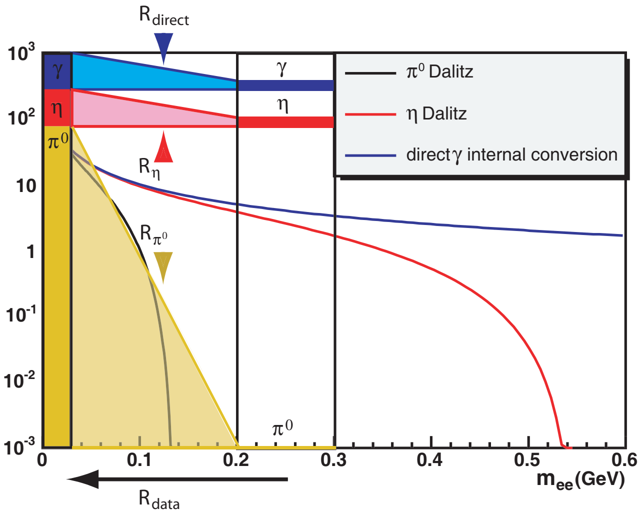

Figure 1. Invariant-mass distribution of virtual photons from the π^0 and η Dalitz decays as well as from direct photons according to Eq. 1. It is illustrated how the various contributions decrease to a fraction R when going to higher invariant mass with the π^0 contribution exhausting.

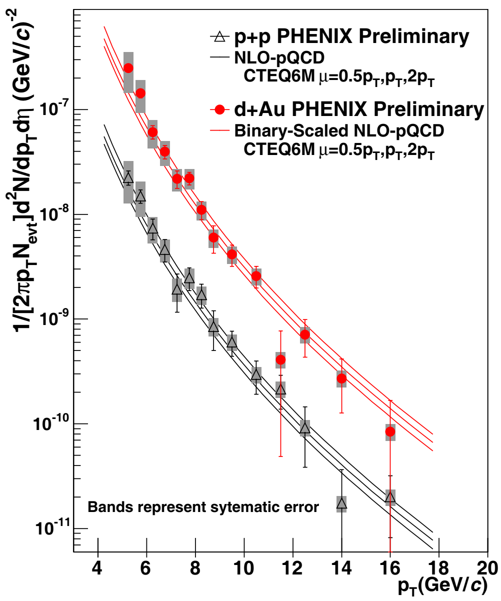

Figure 2. Preliminary direct photon invariant yield as a function of p_T for $p+p$ [3] and minimum-bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The solid curves are pQCD predictions [9] for three different scales that represent the uncertainty on the calculation.

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}(1+\frac{2m_e^2}{m_{ee}^2})\frac{1}{m_{ee}} \mid F(m_{ee}^2) \mid^2 (1-\frac{m_{ee}^2}{M^2})^3 \,, \tag{1}$$

and depicted in Fig. 1. In general, any source of real photons produces virtual photons with very low invariant mass. The rate and mass distribution of those virtual photons is given by the same formula[3]. For direct photons the phase space is not limited when $m_{ee} << p_T^{photon}$.

To obtain a clean invariant-mass distribution of e^+-e^- pairs, pairs originating from photon conversions in the beam pipe or detector material are rejected by an analysis cut. The combinatorial background is removed by the mixed-events technique. In this measurement decay photons can mostly be eliminated by measuring the yield of e^+-e^- pairs in an invariant-mass region where pairs from the π^0 Dalitz decay are largely suppressed due to their limited phase space. In order to convert the measured virtual photons into real photons, the obtained yield has to be related to the yield in an region where the phase space is unrestricted, so that $\gamma^\star_{\rm direct}/\gamma^\star_{incl.} = \gamma_{direct}/\gamma_{incl.}$. The term $\gamma^\star_{\rm direct}/\gamma^\star_{incl.}$ can be calculated from the ratio of total yields in the two intervals, $R_{\rm data} = N$(90-300 MeV)/N(0-30 MeV),

[3]Since the virtual photons decay in the medium, this relation might be slightly modified. This would not affect the significance of the observed excess of direct photons, only its translation into an absolute yield of real direct photons.

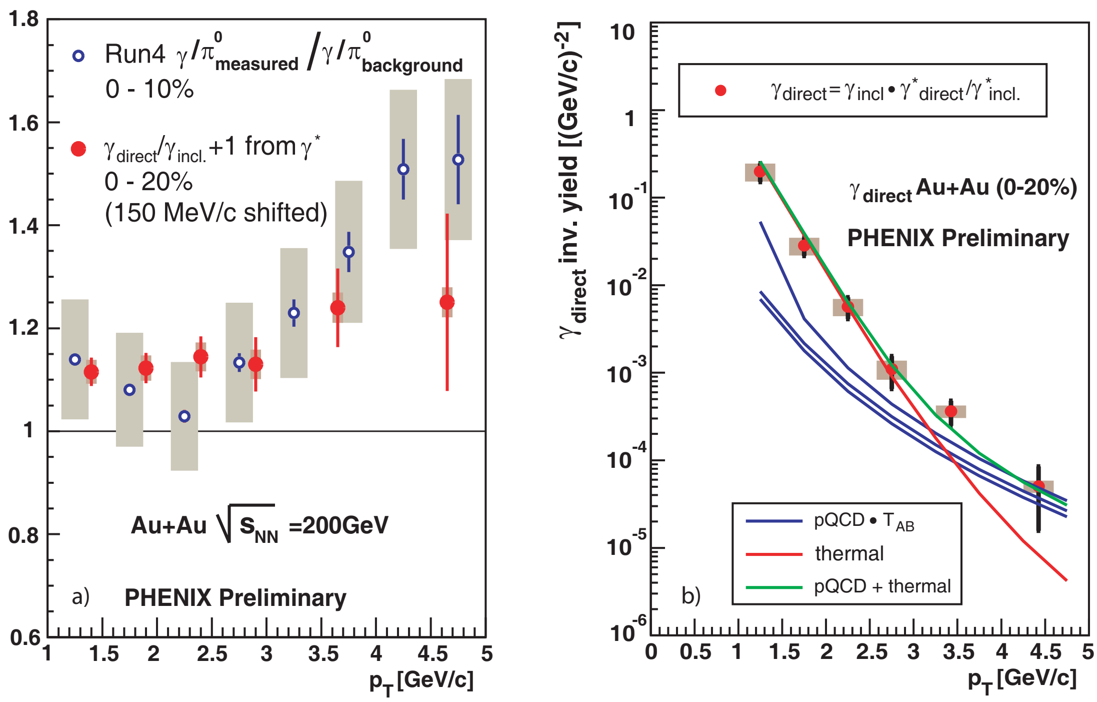

Figure 3. a) Direct photon excess for the conventional and the internal-conversion measurement in central Au+Au. b) Direct photon spectrum from the latter compared to pQCD [9], thermal-photon [11], and the sum of both calculations.

which is known from the measurement, and the ratios, $R_i, i = \{\gamma_{\rm direct}, \pi^0, \eta, {\rm other}\}$, for the various contributions, which can precisely be calculated from Eq. 1 (cf. Fig.1). Decay photons from a cocktail of hadrons are considered here. Finally, the yield of real inclusive photons known from the EMCal measurement [2] is needed to obtain the yield of real direct photons.

Since only the ratio of decay photon yields in the two invariant-mass intervals is needed, the uncertainty on the η-to-π^0 ratio of about 20 % [10] is the main source of uncertainty, translating into an uncertainty of 20 % on the measured direct photon yield. Other sources are the EMCal-measured inclusive photon yield (10 %) and the e^+-e^--pair acceptance (5 %). The total systematic uncertainty is 25 %.

3. Results

The preliminary direct photon spectra from the conventional measurement for $p+p$ [3] and minimum-bias d+Au at $\sqrt{s_{NN}} = 200$ GeV is shown in Fig. 2. For the whole p_T range of 5 to 16 GeV/c the observed yield is consistent with a next-to-leading-order perturbative-QCD (NLO pQCD) calculation [9] for both $p+p$ and d+Au. This supports the validity of the pQCD calculation as a reference for hard direct photon production in Au+Au. As shown by PHENIX in the 2002 run [2], at high p_T direct photon production is consistent with the pQCD expectation also in Au+Au. In the following we will focus on the region at intermediate p_T.

In a preliminary analysis with the conventional method, a small but stable subset of the 2004 data was selected to revisit the intermediate-p_T region, where no significant result had been previously obtained for $p_T \lesssim 3$ GeV/c. The new result is shown in Fig. 3 a) in terms of the double ratio $(\gamma/\pi^0|_{\mathrm{meas.}})/(\gamma/\pi^0|_{\mathrm{b}ckgrd.})$. This ratio indicates a direct photon excess as an enhancement above 1. There is still no significant excess below 3 GeV/c. Further work is ongoing to increase the significance.

The preliminary result from the measurement of virtual photons is presented in the same figure in terms of $\gamma_{\mathrm{d}irect}/\gamma_{incl.} + 1$, which also indicates a direct photon excess as an enhancement above 1. (Note that the two quantities aren't exactly equivalent.). The result shows a significant direct photon excess of about 10 % for $1 < p_T < 5$ GeV/c and the 20 % most central Au+Au collisions. It is consistent with the EMCal measurement. In Fig. 3 b) the direct photon invariant yield from the virtual photon measurement is shown and compared to various theoretical calculations. With large significance, a direct photon spectrum was obtained for $1 < p_T < 5$ GeV/c. The spectrum lies significantly above a T_{AB}-scaled pQCD calculation [9] for $p_T \lesssim 3$ GeV/c. A 2+1 hydrodynamical model [11] for thermal-photon emission with an average initial temperature of $T_0^{\mathrm{ave}} = 360$ MeV ($T_0^{\mathrm{m}ax} = 570$ MeV) and a formation time of $\tau_0 = 0.15$ fm/c underpredicts the data for $p_T \gtrsim 3$ GeV/c. The data can be described when both sources are combined. The obtained temperature is only meaningful if the observed excess is of thermal origin. To confirm the result, an analysis of $p + p$ and d+Au using the same technique is needed. If the excess in Au+Au is mainly from thermal photons the reference data will show a much smaller effect.

4. Summary

Direct photons were measured with the PHENIX experiment in $p + p$, d+Au, and Au+Au at $\sqrt{s_{NN}} = 200$ GeV. At high p_T ($\gtrsim 5$ GeV/c), the measured yield in all systems is consistent with a NLO pQCD calculation. To tackle the p_T region below 5 GeV/c, direct photons were measured through their internal conversion into e^+e^- in Au+Au collisions. With this powerful technique a significant measurement for $1 < p_T < 5$GeV/c was achieved, lying significantly above the NLO pQCD expectation, but consistent with calculations when thermal photon emission is taken into account.

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