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# Systematic studies of the centrality dependence of soft photon production in Au+Au collision with PHENIX

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#### Abstract

Since the earliest days of Heavy Ion Physics thermal soft photon radiation emitted during the reaction had been theorized as a smoking gun signal for formation of a quark-gluon plasma and as a tool to characterize its properties. In recent years the existence of excess photon radiation in heavy ion collisions over the expectation from initial hard interactions has been confirmed at both RHIC and LHC energies by PHENIX and ALICE respectively. There the radiation has been found to exhibit elliptic flow  $v_2$  well above what can currently be reconciled with a picture of early emission from a plasma phase. During the 2007 and 2010 Au+Au runs PHENIX has measured a high purity sample of soft photons down to  $p_T > 0.4 \text{ GeV}/c$  using an external conversion method. We present recent systematic studies by PHENIX from that sample on the centrality dependence of the soft photon yield, and elliptic and triangular flow  $v_2$  and  $v_3$  in Au+Au collisions which fill in the experimental picture and enable discrimination of competing soft photon production scenarios.

Keywords:

## 1. Introduction

Collisions of heavy ions create dense and hot states of hadronic medium like the Quark Gluon Plasma (QGP), for which direct photons, i.e. photons not produced in decays of hadrons, provide an excellent probe: they can be produced during all stages of the interaction, and leave the medium virtually undisturbed due their vanishing interaction cross section with the hadronic medium. They can thus probe the full space-time evolution of the system. Here photons with transverse momenta  $p_T = \sqrt{p_x^2 + p_y^2} \gtrsim 2.5 \text{ GeV}/c$  are produced predominately in early, hard interactions and called *hard* photons, while photons with smaller transverse momentum are called *soft* and thought to be produced from the medium. The photon yield gives experimental access to the rates of their different production processes, and their correlation with the event geometry, i.e. their elliptical and triangular flow coefficients  $v_2$  and  $v_3$ , are sensitive to the dynamics of the medium. While direct photon yield and flow integrate over all production channels, both quantities measured together strongly constrain possible production scenarios.

Measurements of soft photons are notoriously difficult in electromagnetic calorimeters due to large contamination from misidentified hadrons and a deteriorating energy resolution. Instead we here reconstruct photons from external conversions to electrons and positrons. For the 2007 and 2010 RHIC runs the HBD detector was installed in the PHENIX detector providing spatially well-defined conversion locations on a cylindrical shell R = 60 cm from the beam pipe with  $X/X_0 = 2$  to 3% [1]. We identify conversion pairs by their characteristic apparent pair masses

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positron at the nominal interaction point  $M_{cgl}$ , and at the HBD shell  $M_{atm}$ . pared to the virtual photon result from PHENIX [2]. Here and later sta-The concentration of photons with  $10 \text{ MeV}/c^2 < M_{cgl} < 15 \text{ MeV}/c^2$  and tistical uncertainties are shown as bars, systematic uncertainties as boxes.  $M_{\rm atm} < 5 \,{\rm MeV}/c^2$  corresponds to conversions in the HBD shell; the op- Both results agree within uncertainties. posite concentration at  $10 \text{ MeV}/c^2 < M_{\text{atm}} < 15 \text{ MeV}/c^2$  and  $M_{\text{cgl}} < 10 \text{ MeV}/c^2$ 5 MeV/ $c^2$  is due to decay photons from  $\pi^0$  Dalitz decays,  $\pi^0 \rightarrow \gamma(ee)$ 

(a) Correlation between pair mass assuming production of electron and (b)  $R_{\gamma}$  for different centrality classes from the 2007 and 2010 runs, com-

Figure 1.

(opening angles) at the nominal interaction vertex and at the HBD detector shell. Momenta of electrons and positrons can be calculated assuming they came from either the vertex or the HBD shell, and their invariant pair mass (opening angle) at the vertex and the HBD shell can be compared, see Fig. 1a. Applying a simultaneous selection on both mass variables allows a clean separation of electron-positron pairs from Dalitz decays and external photon conversions with the level of background < 1% in the conversion sample while maintaining a good photon momentum resolution.

#### 2. Direct photon yield

While by selecting on the two apparent pair masses we have already arrived at a very pure photon sample its relation to the actual photon production rate  $Y_{\nu}^{\text{incl}}$  depends on detector-specific quantities, namely the photon conversion probability  $p_{conv}$ , the geometrical acceptance of the detector for electron-positron pairs  $a_{ee}$ , and the efficiency of the used experimental cuts  $\varepsilon_{ee}$ , with the exact values only known inside relatively large systematic uncertainties. Instead of attempting to accurately determine these correction factors we follow a different approach: in addition to the raw yield of photons  $N_{\gamma}^{\text{incl}}$ , we measure a raw yield of photons from the decay  $\pi^0 \to \gamma\gamma$ ,  $N_{\gamma}^{\pi^0}$  which we extract by pairing one photon reconstructed in a conversion pair with another photon reconstructed in the PHENIX calorimeters with very loose cuts and estimation of the combinatorial background with mixed-event photon-photon pairs. The raw  $\pi^0$ -tagged yield  $N_{\gamma}^{\pi^0}$  is related to the yield  $Y_{\gamma}^{\pi^0}$  by the same detector-dependent factors as the inclusive photon yield, and additionally a conditional acceptance factor  $\langle \varepsilon f \rangle$  quantifying the probability to reconstruct both photons from a  $\pi^0$  decay, given that one photon was already reconstructed in a conversion pair. Since we use only very loose cuts to select calorimeter photons we can trade less dependence on systematic uncertainties for reduced statistical significance via the signal-to-background ratio in the  $\pi^0$ -tagged sample. The shared factors then drop out in the ratio of both quantities so that we can formulate a quantity  $R_{\gamma}$ ,

$$R_{\gamma} = \frac{Y_{\gamma}^{\text{incl}}}{Y_{\gamma}^{\text{decay}}} = \frac{Y_{\gamma}^{\text{incl}}/Y_{\gamma}^{\pi^{0}}}{Y_{\gamma}^{\text{decay}}/Y_{\gamma}^{\pi^{0}}} = \frac{\frac{N_{\gamma}^{\text{incl}}/p_{\text{conv}}a_{ee}\varepsilon_{ee}}{\frac{N_{\gamma}^{\pi^{0}}/p_{\text{conv}}a_{ee}\varepsilon_{ee}\langle\varepsilon_{\gamma}\rangle}{\frac{Y_{\gamma}^{\text{decay}}}{Y_{\gamma}^{\pi^{0}}}} = \frac{\langle\varepsilon_{\gamma}\rangle\frac{N_{\gamma}^{\text{incl}}}{N_{\gamma}^{\pi^{0}}}}{\frac{Y_{\gamma}^{\text{decay}}}{Y_{\gamma}^{\pi^{0}}}}$$
(1)



shape shows little change, also see the text.

(a) Direct photon  $p_T$  spectra for different centrality classes. The shaded (b) The  $p_T$ -integrated direct photon yield for different lower integration bands indicate N<sub>coll</sub>-scaled fits to PHENIX pp data. While the direct pho- limits, note logarithmic axes. The dashed lines indicate independent fits ton yield varies over two orders of magnitude between centralities the to each set up measurements. The centrality-dependence of the integrated direct photon yield shows no dependence on the lower integration limit outside of uncertainties.

Figure 2. Direct photon yield

Here we have used the yield of photons from the decay of any hadron  $Y_{\gamma}^{\text{decay}}$  which can be calculated from the known hadron yields and their branching ratios to photons. The numerator of the RHS of Eq. (1) depends only on measured raw yields and the conditional acceptance  $\langle \varepsilon f \rangle$  which has to be determined in a Monte Carlo simulation of the detector; the denominator depends on known yields and branching ratios and can be calculate in e.g. a simple phase space simulation. With these definition any measurement  $R_{\gamma} > 1$  corresponds to a direct photon signal. Our results for  $R_{\gamma}$  are show in Fig. 1b. We observe a substantial direct photon signal.

From  $R_{\gamma}$  we can calculate the direct photon yield shown in Fig. 2a,

$$Y_{\gamma}^{\text{direct}} = (R_{\gamma} - 1)Y_{\gamma}^{\text{decay}} \tag{2}$$

and analyze its centrality-dependence. We find that the direct photon excess over the N<sub>coll</sub>-scaled pp yield has inverse slopes roughly independent of centrality,  $(239 \pm 25 \pm 7) \text{ MeV}/c$  (0-20%),  $(260 \pm 33 \pm 8) \text{ MeV}/c$  (20-40%),  $(225 \pm 25 \pm 7) \text{ MeV}/c$  (20-40%),  $(225 \pm 25 \pm 25 \pm 25 \pm 25) \text{ MeV}/c$  (20-40%),  $(225 \pm 25 \pm 25) \text{ MeV}/c$  (20-40\%),  $(225 \pm 25) \text{ Me$  $28 \pm 6$  MeV/c (40-60%), and ( $238 \pm 50 \pm 6$ ) MeV/c (60-92%), and the  $p_T$ -integrated yield of the excess over the  $N_{\text{coll}}$ -scaled pp yield has a power-law dependence on the number of participants  $N_{\text{part}}$ ,  $N_{\gamma} \propto N_{\text{part}}^{\alpha}$  with a power larger than that of hadrons,  $\alpha = 1.48 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$ , see Fig. 2b.

#### 3. Direct photon $v_2$ and $v_3$

The elliptical and triangular flow coefficients  $v_2$  and  $v_3$  of direct photons can be calculated from the raw inclusive photon flow coefficients  $v_n^{\text{incl}}$ , the expectation for photons from hadron decays  $v_n^{\text{decay}}$ , and the known composition of



Figure 3. The direct photon  $v_2$  (*top*) and  $v_3$  (*bottom*) as a function of the photon  $p_T$  in different centrality classes. The results from this analysis are shown with circle markers, from a preliminary calorimeter analysis as squares. Both results are consistent within systematic uncertainties.

the inclusive photon sample quantified by  $R_{\gamma}$ ,

$$v_n^{\text{direct}} = \frac{R_\gamma v_n^{\text{incl}} - v_n^{\text{decay}}}{R_\gamma - 1}$$
(3)

Here the  $v_n$  can be calculated from the angles between the *n*-th order event plane measured at forward rapidities  $1.0 < |\eta| < 2.8$ ,  $\psi_n$ , and the photon direction  $\phi_n$  with a Fourier decomposition,  $v'_n = \langle \cos 2(\phi_n - \psi_n) \rangle$ . To obtain the actual  $v_n$  we perform resolution corrections of the raw  $v'_n$  with the 3-subevent method [3], taking the difference to results from a 2-subevent resolution correction into account the systematic uncertainties. The  $v_n^{\text{decay}}$  can be calculated in a phase space simulation from the known  $v_n$  and yields of the parent hadrons and their branching ratios to photons by measuring the decay photon  $\phi_n$  against the known event planes, i.e. with perfect resolution. Our result for the direct photon  $v_2$  and  $v_3$  are shown in Fig. 3. We observe markedly positive, non-zero coefficients which remain large down to low  $p_T$  across all centralities.

#### 4. Conclusions

We have extracted a high-purity sample of soft photons and simultaneously measured the direct photon yield and the direct photon elliptical and triangular flow coefficients  $v_2$  and  $v_3$ , and extended the measurements in the soft regime. We find a substantial direct photon signal consistent with an earlier measurement using virtual photons [2], and with  $p_T$ -integrated yields growing with the number of participants  $N_{part}$  faster than the yield of soft hadrons. The shape of the direct photon spectra shows no changes outside of uncertainties across centralities. The coefficients of the elliptical flow measured in the same direct photon sample show markedly positive values, consistent with results from a virtual photon analysis [4] and preliminary results from an analysis of photons measured in the PHENIX calorimeters. While as one might expected from the more eccentric collision geometry we find increasing  $v_2$  values when going to more peripheral collision, the  $v_2$  of direct photons appears to show less  $p_T$  dependence than that of soft hadrons, even with an indication of flattening towards the smallest  $p_T$  as already indicated by earlier measurements [5].

### References

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