PHENIX MEASUREMENTS OF LOW MOMENTUM DIRECT PHOTON RADIATION FROM LARGE AND SMALL SYSTEMS IN (ULTRA)RELATIVISTIC HEAVY-ION COLLISIONS: DIRECT PHOTON SCALING*

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The PHENIX Collaboration has measured low momentum direct photon radiation in Au+Au collisions at 200 GeV, 62.4 GeV and 39 GeV, in Cu+Cu at 200 GeV as well as in p+p, p+Au and d+Au at $\sqrt{s_{NN}}$ = 200 GeV. In these measurements, PHENIX has discovered a large excess over the scaled p+p yield of direct photons in A+A collisions, and a non-zero excess, observed within systematic uncertainties, over the scaled p+p yield in central p+A collisions. Another finding is that at low-p_{T}, the integrated yield of direct photons, $\mathrm{d}N_\gamma/\mathrm{d}y$, from large systems shows a behavior of universal scaling as a function of the charged-particle multiplicity, $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^\alpha$, with $\alpha = 1.25$, which means that the photon production yield increases faster than the charged-particle multiplicity.

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1. Introduction

Direct photons determine the excess yield, which one obtains by subtracting the hadronic decay photon yield (mostly from π^0 and η decays) from the total observed photon yield. By measuring these photons, we can study the strongly interacting medium produced in (ultra)relativistic heavy-ion collisions, and gain information on the properties and dynamics of the

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produced matter integrated over space and time. The direct photons possibly originate from the hot fireball of the Quark–Gluon Plasma (QGP), late hadronic phase as well as from initial hard scattering processes like QCD Compton scattering among the incoming and outgoing partons.

After PHENIX measured large invariant yield and large anisotropy of low momentum direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [1–3], a challenging problem arose, commonly referred to as "thermal photon puzzle", where different theoretical models encounter difficulties when they are used to describe these two quantities simultaneously (though there is also some progress in recent years [4–6] on this matter). For resolving this puzzle, PHENIX continues measuring low momentum direct photons in large and small collision systems. These past and new measurements revealed very interesting findings, which we report in these proceedings.

2. Some results on direct photon elliptic flow from large systems and on direct photon p_{T} spectra from large/small systems

In this section, we represent some of the PHENIX recent results on direct photon measurements. Figure 1 shows two plots on direct photon elliptic flow (v_2) in two centrality bins, from an ongoing analysis in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV obtained based upon an external conversion method. Figure 2 shows p_{T} spectra, obtained with another external conversion method, for minimum bias data samples in Au+Au at $\sqrt{s_{NN}} = 62.4\,\mathrm{GeV}$ and $39\,\mathrm{GeV}$ [7]. Previously published results in Au+Au at 200 GeV can be seen in [2]. In our analyses, two types of external conversion methods are utilized. The photons are measured through their conversions to e^+e^- pairs at the Silicon Vertex Tracker (VTX) and Hadron Blind Detector (HBD) in the PHENIX

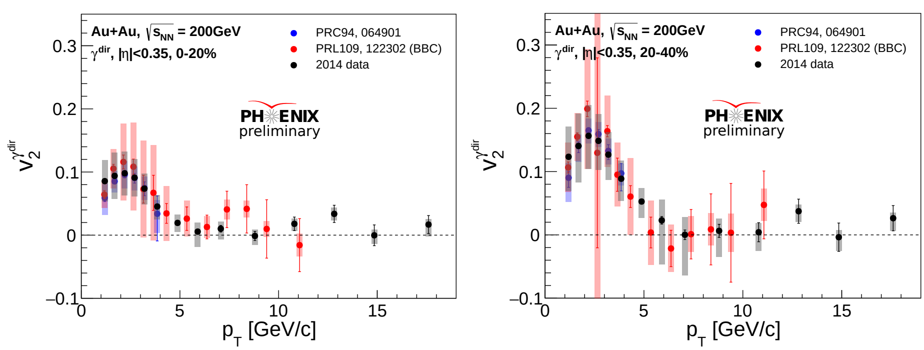

Fig. 1. Left: Direct photon v_2 *vs.* p_{T} in 0–20% central Au+Au collisions compared with the published results from [3]. Right: Direct photon v_2 *vs.* p_{T} in 20–40% centrality Au+Au collisions compared with the published results from [3]. The new results are based upon external conversions with VTX.

detector system, where the fraction of direct photons is determined after tagging photons from π^0 decays. Comparing these data to $N_{\rm coll}$ scaled $p+p$ fit (or pQCD calculations), one finds a significant excess over the scaled $p+p$ yield of low-$p_{\rm T}$ (above 0.4 GeV/c) direct photons in all Au+Au systems.

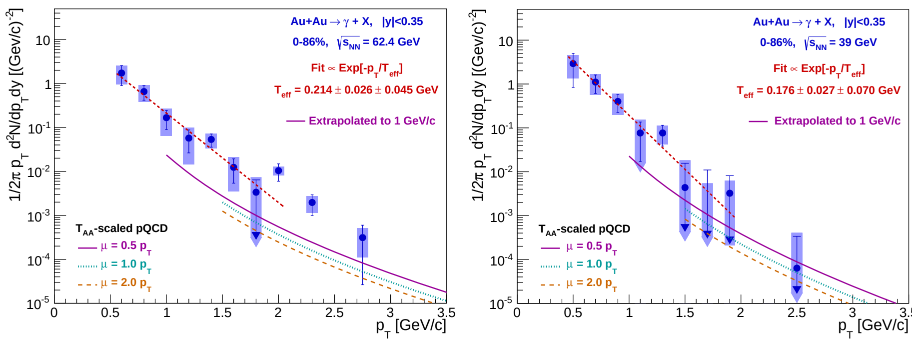

Fig. 2. Direct photon $p_{\rm T}$ spectra in minimum bias Au+Au collisins at $\sqrt{s_{NN}}$ = 62.4 GeV (left panel) and 39 GeV (right panel) [7]. All data are obtained using the external conversion method with HBD.

With the external conversion method, PHENIX recently measured also low momentum direct photons in $p+p$ and $p+A$ collisions (shown in Fig. 3). Within systematic uncertainties, the observed a non-zero excess yield ($\sim$ one sigma) in central $p+$Au collisions above the scaled $p+p$ fit may come from the possible production of QGP droplets in small systems [9].

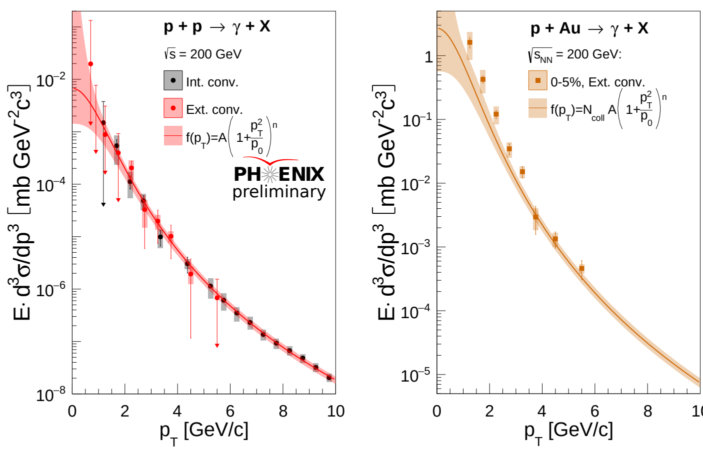

Fig. 3. The left and right panels show direct photon $p_{\rm T}$ spectra in $p+p$ and in the 0–5% central $p+$Au collisions at 200 GeV (external conversions with VTX). The PHENIX previous measurements on $p+p$ cross section from the internal conversion method [8] are also included and shown in the left panel.

3. Scaling properties of direct photons

For a given center-of-mass energy, one can compare data from different centrality classes (or system size) using the number of nucleons participating in $A+A$ collisions, N_{part}, or the number of binary nucleon–nucleon interactions, N_{coll}. Nevertheless, this way is not useful when we compare data at different energies. Instead, we use charged-particle multiplicity, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, which itself has an interesting scaling behavior with N_{coll} shown in Fig. 4. Here, N_{coll} scales like $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^{\alpha}$ for all center-of-mass energies with a logarithmically slowly increasing function called specific yield, SY. Four datasets are simultaneously fitted by a power-law, with vertical and horizontal uncertainties of N_{coll} and $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\eta=0}$, respectively [10, 11].

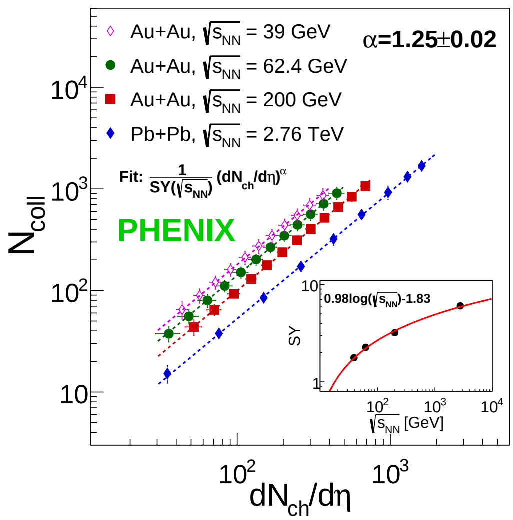

Fig. 4. N_{coll} *vs.* $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\eta=0}$ for given four beam energies. The inset shows data demonstrating a scaling between N_{coll} and $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ of the form of $N_{\mathrm{coll}} = \frac{1}{\mathrm{SY}(\sqrt{s_{NN}})}\left(\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}\right)^{\alpha}$, where the specific yield is a function logarithmically increasing with $\sqrt{s_{NN}}$: $\mathrm{SY}(\sqrt{s_{NN}}) = 0.98\log(\sqrt{s_{NN}}) - 1.83$.

Then we get $\alpha = 1.25 \pm 0.02$. For other details, see the caption of Fig. 4. Thereby, one can scale the direct photon yield by $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^{\alpha}$, which for a specific $\sqrt{s_{NN}}$ is equivalent to N_{coll}. Let us take, *e.g.*, the photon spectra in minimum bias Au+Au collisions at 62.4 and 39 GeV with pQCD curves from Fig. 2, and normalize them by $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^{\alpha}$. It results in the data falling on top of each other at low-p_{T} as shown in panel (a) of Fig. 5. As expected, at high-p_{T}, the $p+p$ data coincide with the pQCD calculations within the quoted uncertainties. In panel (b), all Au+Au data at 200 GeV are on top of each other at high- and low-p_{T}, and at low-p_{T}, they are distinctly above the $p{+}p$ data, the $p{+}p$ fit and pQCD. In (c), the data are compared for different $\sqrt{s_{NN}}$ from 62.4 GeV to 2760 GeV. Again, all the data coincide at low-$p_{\rm T}$, while at high-$p_{\rm T}$, we see the expected difference with $\sqrt{s_{NN}}$ and $N_{\rm coll}$ scaling.

In Fig. 5, all error bars are the quadratic sum of the systematic and statistical uncertainties. Uncertainties on $({\rm d}N_{\rm ch}/{\rm d}\eta)$ are not included. All normalized data, $p{+}p$ fit, pQCD curves are from [7], and they are obtained with Au+Au data [1, 2, 12], Pb+Pb data [13], $p{+}p$ data at 200 GeV [8], $p{+}p$ data at 62.4/63 GeV [14]/[15], the empirical fit to the $p{+}p$ data at 200 GeV [7], the pQCD calculations at different beam energies [5, 16], and the data on $({\rm d}N_{\rm ch}/{\rm d}\eta)$ [10, 11].

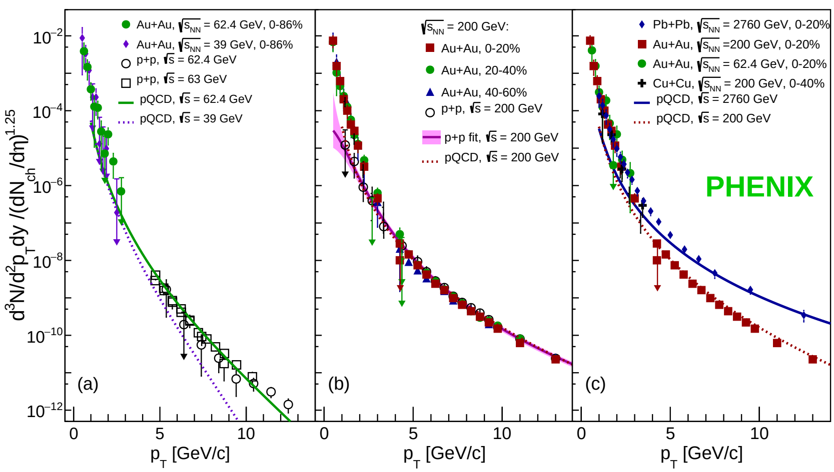

Fig. 5. This three-panel plot is from [7] showing the direct photon spectra normalized by $({\rm d}N_{\rm ch}/{\rm d}\eta)^{1.25}$. The comparison is shown for minimum bias Au+Au collisions at 62.4 GeV and 39 GeV in the panel (a); for Au+Au data in three centrality bins at 200 GeV in the panel (b); and for different $A{+}A$ systems at four beam energies in the panel (c). The panels (a) and (b) also show $p{+}p$ data, and all the panels show perturbative QCD calculations at respective energies.

Now, in order to quantify the direct photon spectra, we first integrate the $p_{\rm T}$ spectra above $p_{\rm T} = 1\,{\rm GeV}/c$ and obtain Fig. 6. This plot is another representation of the direct photon scaling, where the integrated yield from the large systems scales with ${\rm d}N_{\rm ch}/{\rm d}\eta$ by the same power $\alpha = 1.25$, *i.e.*, ${\rm d}N_\gamma/{\rm d}y$ grows faster than ${\rm d}N_{\rm ch}/{\rm d}\eta$. In addition, we show the integrated yield of extrapolations (extrapolated down to $p_{\rm T} = 1\,{\rm GeV}/c$) of the fit to $p{+}p$ data and of the three different pQCD calculations scaled by $N_{\rm coll}$. It is quite interesting that the prompt photons (the gray/purple band) and integrated pQCD curves have nearly the same slopes as that of the large systems.

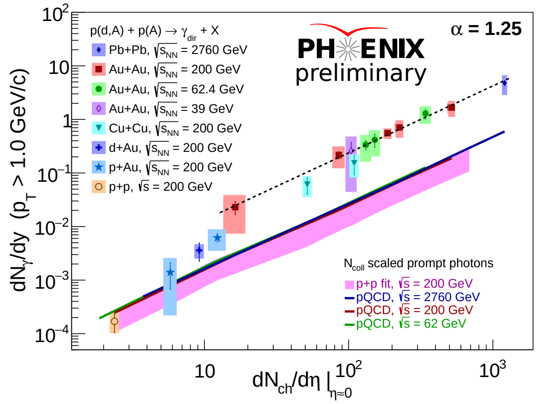

Fig. 6. (Color online) The plot shows the direct photon yield, integrated above 1.0 GeV$/c$ in p_{T}, *vs.* $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, for five A+A datasets at different collision energies and for p+Au, d+Au and p+p datasets at 200 GeV (some of the unintegrated data are shown in Figs. 2 and 3).

4. Concluding remarks and summary

The PHENIX Collaboration has measured low momentum direct photons in Cu+Cu ([17]) and Au+Au at 200 GeV, in Au+ Au at 62.4 and 39 GeV as well as in p+p, p+Au and d+Au at 200 GeV. Considering all the available data on small and large systems at various energies, we observe a surprising scaling behavior of direct photons in large systems, namely: at a given center-of-mass energy, the low- and high-p_{T} direct photon invariant yields in A+A collisions scale with N_{coll}; then N_{coll} is proportional to $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ across different energies; meanwhile, for all energies, the low-p_{T} yield scales like $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^{\alpha}$. PHENIX has also discovered direct photon excess yield (within systematic uncertainties) at low-p_{T} in central p+Au collisions above N_{coll} scaled p+p fit, which may originate from possibly existing QGP droplets in small systems. In the low $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ region of Fig. 6, we see an increasing trend of the integrated yield in small systems, which seems to intersect with a trend from large systems, suggesting the existence of a "thermal transition region or point" between small and large systems.

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