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PHENIX measurements of low momentum direct photon radiation

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Abstract

The versatility of RHIC allowed the PHENIX collaboration to measure low momentum direct photons from small systems, such as p+p, p+A, d+Au at $\sqrt{s_{NN}}$ =200 GeV as well as from large A+A systems, such as Au+Au and Cu+Cu at 200 GeV and Au+Au at 62.4 GeV and 39 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 over the scaled p+p yield in central p+A collisions. Another PHENIX discovery is that at low-p_T the integrated yield of direct photons, dN_γ/dy, from large systems follows a universal scaling as a function of the charged-particle multiplicity, $(dN_{ch}/d\eta)^\alpha$, with $\alpha = 1.25$. The observed scaling properties of direct photons from these systems show that the photon production yield increases faster than the charged-particle multiplicity.

Keywords: Heavy ion collisions, small/large collision systems, direct photons, charged-hadron multiplicities

1. Introduction

Direct photons are an important tool with unique capabilities to study the strongly interacting medium produced in (ultra)relativistic heavy ion collisions. By measuring these photons, one can gain information on the properties and dynamics of the produced matter integrated over space and time. By definition, the direct photons are the "remnants" of subtraction of a large number of hadronic decay photons (mostly from π^0 and η decays) from the total observed yield. They 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.

A quite challenging problem, dubbed as "thermal photon puzzle", emerged when PHENIX measured large invariant yield and large anisotropy (elliptic flow) of low momentum direct photons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [1]. Various theoretical models encounter difficulties when they are used to describe these two quantities simultaneously though there is also some progress [2, 3, 4]. In order to resolve this puzzle, PHENIX has measured low momentum direct photons in large and small collision systems. These measurements revealed very interesting findings reported in this article.

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2. Large and small systems: recent results on low momentum direct photon p_T spectra

Recently PHENIX accomplished low momentum direct photon measurements for large systems: Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV through their internal conversions, and Au+Au at $\sqrt{s_{NN}}$ = 62.4 GeV and 39 GeV with the external conversion method. In Fig. 1 one can see the results for minimum bias data samples. In the external conversion method the photons are measured through their conversions to electron-positron pairs at the HBD (or VTX) in the PHENIX detector system, and the fraction of direct photons is determined after tagging photons from neutral pion decays. Comparing these data to T_{AA} scaled p+p fit or pQCD calculations one finds a significant excess over the scaled p+p yield of low p_T direct photons in all three systems.

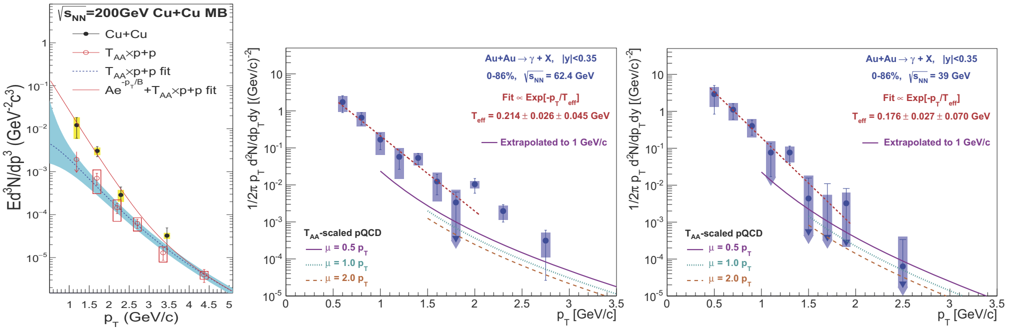

Fig. 1. Direct photon spectra at low-p_T in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV [5] (internal conversions) and in Au+Au at $\sqrt{s_{NN}}$ = 62.4 GeV and 39 GeV (external conversions with HBD) [6]. All data are in minimum bias.

With the external conversion method PHENIX recently also measured low momentum direct photons in p+p and p+A collisions (shown in Fig. 2). Within systematic uncertainties, the observed a non-zero excess yield (~ one sigma) in central p+Au collisions above the scaled p+p fit may come from the possible production of QGP droplets in small central systems.

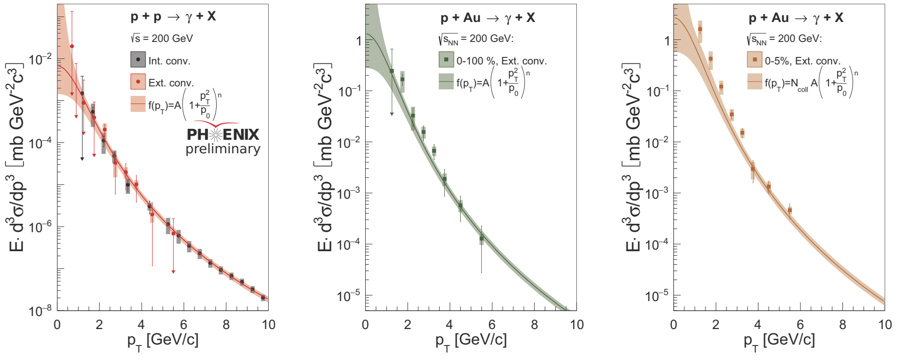

Fig. 2. Direct photon spectra at low-p_T in p+p and in minimum bias and central p+Au collisions at 200 GeV (external conversions with VTX). In the left plot the comparison with the PHENIX p+p results from internal conversions [7] is also shown.

3. Direct photons scaling

For a given beam energy one can compare data from different centrality classes (or system size) using number of participants, N_{part}, or the number of binary collisions, N_{coll}. However, this is not useful to compare data at different energies. We therefore use charged-particle multiplicity, $dN_{ch}/d\eta$, which itself has an interesting scaling behavior with N_{coll} shown in Fig. 3. Here N_{coll} scales like $(dN_{ch}/d\eta)^{\alpha}$ for all $\sqrt{s_{NN}}$ with a logarithmically slowly increasing function called specific yield. The exponent α is found to be $\alpha = 1.25$. The other details are given in the caption of Fig. 3.

Thereby, we scale the direct photon yield by $(dN_{ch}/d\eta)^{\alpha}$, which for a given $\sqrt{s_{NN}}$ is equivalent to N_{coll}. For example, taking the photon spectra in minimum bias Au+Au collisions at 62.4 and 39 GeV with pQCD curves from Fig. 1, and normalizing them by $(dN_{ch}/d\eta)^{\alpha}$, one can see that the data fall on top of each other at low-p_T as shown in the panel (a) of Fig. 4. At high-p_T the p+p data coincide with the pQCD calculations within the quoted uncertainties as expected. In the 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, fit and pQCD. In the panel (c) the data are compared for different $\sqrt{s_{NN}}$ from 62.4 GeV to 2760 GeV, scaled in the same way. And again all the data coincide at low-p_T, while at high-p_T we see the expected difference with $\sqrt{s_{NN}}$ and N_{coll} scaling.

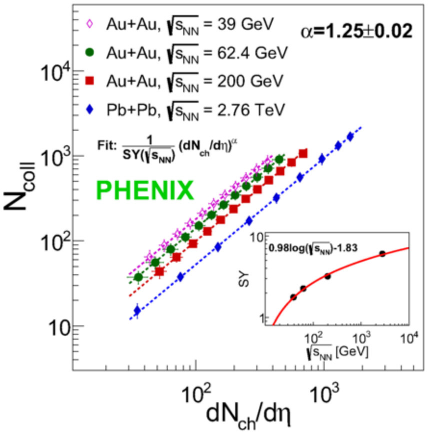

Fig. 3. The number of binary collisions, N_{coll}, vs. charged-particle multiplicity, $dN_{ch}/d\eta|_{\eta=0}$, for four beam energies shown in the plot. All the data describing the large systems are simultaneously fitted by a power-law with $\alpha = 1.25$, with horizontal and vertical error bars showing the uncertainties of $dN_{ch}/d\eta|_{\eta=0}$ [8, 9] and of N_{coll} (from the Glauber Monte-Carlo simulations), respectively.
The small box on the bottom right shows data demonstrating a remarkable scaling between N_{coll} and $dN_{ch}/d\eta$, which takes the form: $N_{coll} = \frac{1}{SY(\sqrt{s_{NN}})}\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$, where the specific yield, SY, is introduced, which logarithmically increases with $\sqrt{s_{NN}}$: SY$(\sqrt{s_{NN}}) = 0.98\log(\sqrt{s_{NN}}) - 1.83$.

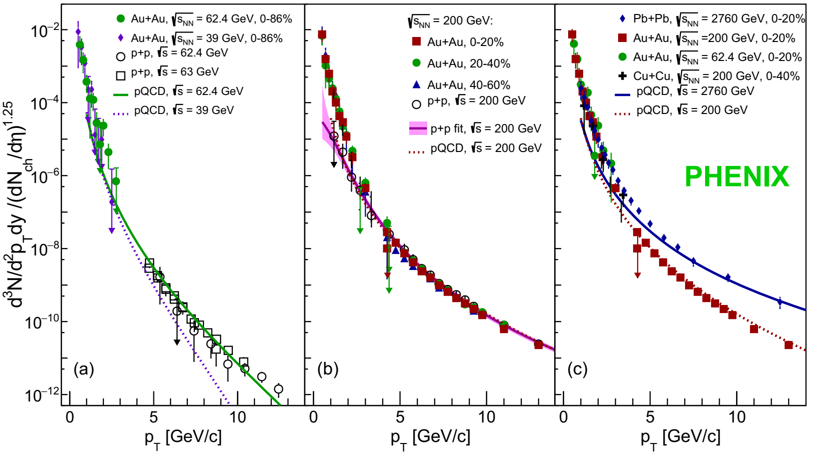

Fig. 4. This three-panel plot is from [6] showing the direct photon spectra normalized by $(dN_{ch}/d\eta)^{1.25}$. One can see the comparison for Au+Au data in minimum bias collisions at 62.4 GeV and 39 GeV (a); for Au+Au data in three centrality bins at 200 GeV (b); and for different A+A systems at four beam energies (c). Panels (a) and (b) also show p+p data, and all panels show perturbative QCD calculations at respective energies. All error bars are the quadratic sum of the systematic and statistical uncertainties. Uncertainties on $dN_{ch}/d\eta$ are not included. All normalized data, p+p fit, pQCD curves are from [6], and they are obtained with Au+Au data from [10, 11, 12], Pb+Pb data from [13], p+p data at 200 GeV from [7], at 62.4 GeV from [14], at 63 GeV [15, 16], the empirical fit to the p+p data at 200 GeV from [6], the pQCD calculations at different beam energies from [3, 17], and the data on $dN_{ch}/d\eta$ from [8, 9].

In order to quantify the direct photon spectra, one can integrate the invariant yield over some p_T threshold value. Then if we integrate above $p_T = 1$ GeV/c, we obtain the left plot of Fig. 5. This plot is another representation of the direct photon scaling, where the integrated yield of the large systems scales with $dN_{ch}/d\eta$ by the same power $\alpha = 1.25$, meaning that dN_{γ}/dy grows faster than $dN_{ch}/d\eta$. It is interesting that the prompt photons described by the purple band and integrated pQCD curves have nearly the same slopes as that of the large systems. In the low multiplicity region one can see the gradually increasing trend of the integrated yield of the small systems, which seems to intersect with the trend from the large systems.

With the integration above high $p_T = 5$ GeV/c, we get the right plot of Fig. 5. Here the observed scaling behavior is expected [12] (since $R_{AA} = 1$), though we see that the slopes are the same as those in the left plot.

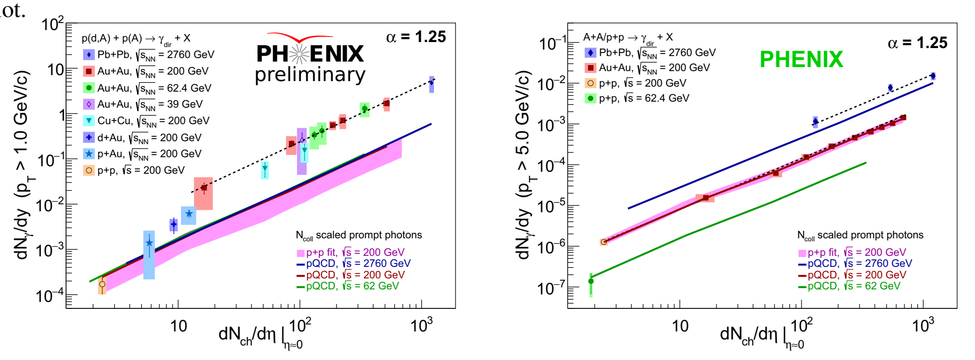

Fig. 5. The left plot shows the data on the direct photon yield, integrated above 1.0 GeV/c in p_T, vs. $dN_{ch}/d\eta$, for five A+A data sets at different collision energies and for one p+Au, one d+Au and one p+p data sets at 200 GeV. Also, shown are the integrated yields of extrapolations (down to $p_T = 1$ GeV/c) of the fit to p+p data and of the three different pQCD calculations scaled by N_{coll}. The right plot shows the yield integrated above 5.0 GeV/c in p_T, for two A+A data sets and two p+p data sets. The integrated yields from different pQCD calculations scaled by N_{coll} are also shown. The black dashed lines are the power-law fits over the A+A data with a fixed $\alpha = 1.25$ slope. In both plots the integration is carried out for the data, p+p fit and pQCD curves from Fig. 4.

4. Summary

The PHENIX collaboration has measured low momentum direct photons in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV, Au+ Au at $\sqrt{s_{NN}} = 62.4$ and $\sqrt{s_{NN}} = 39$ GeV as well as in p+p and p+Au at $\sqrt{s_{NN}} = 200$ GeV. By compiling all the available results on small and large systems at various energies, PHENIX has found 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 from A+A collisions scale with N_{coll}; across different energies N_{coll} is proportional to $dN_{ch}/d\eta$; meanwhile, for all energies the low-p_T yield seems to scale like $(dN_{ch}/d\eta)^{\alpha}$. PHENIX has also discovered direct photon excess yield 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 central systems. Both trends described by the data seen in the left plot of Fig. 5, suggest the existence of a "transition point" between small and large systems.

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