

Low p_T direct photon results with PHENIX and their bearing on the direct photon puzzle

Gabor David^{1,*} for the PHENIX Collaboration

¹Stony Brook University

Abstract. Despite decades of theoretical and experimental achievements, a coherent picture of the evolution in colliding heavy ion systems is still missing, particularly in the non-perturbative regime. Since photons are penetrating probes, the combined information of direct photon yields at low transverse momenta (p_T) and their azimuthally asymmetric emission (flow) provides important constraints on theories. Simultaneous observation of high yields and significant (almost hadron-like) flow of low p_T direct photons in Au+Au collisions by PHENIX, dubbed the "direct photon puzzle" still eludes a coherent explanation. A closely related issue is the apparent universality of photon production, that depends only on charged particle multiplicity, but not on the size of the colliding ions. We will present new results on direct photon yields and flow in Au+Au and discuss their impact on the "direct photon puzzle".

1 Introduction

Direct photons, particularly those at low transverse momentum (p_T), were always considered excellent probes of the space-time evolution of the hot, dense matter formed in relativistic heavy ion collisions. For a long time, interpretation of the measured spectra was dominated by the "thermal paradigm", i.e. by the assumption that most photons originate from initial hard scattering, radiation from the thermalized quark-gluon plasma (QGP) and the ensuing hadronic gas (HG) phase [1], with minor contributions from other sources. The spatio-temporal evolution of the QGP and HG, as described by relativistic hydrodynamics, should then explain both the observed spectra and azimuthal asymmetries of direct photons.

This paradigm could be upheld as long as only invariant yields have been measured, but failed the PHENIX experiment at RHIC published first results on azimuthal asymmetries of photons in Au+Au collisions [2, 3], showing that the second Fourier-component v_2 at low p_T (1-4 GeV/c) was comparable to final state meson v_2 within uncertainties. A confounding situation emerged, dubbed the "direct photon puzzle" [1]. In the thermal paradigm, large yields are mainly produced at early times, when the system is hottest, but if photons also have large v_2 , most of them must be produced late, when the system is colder – a clear paradox. Moreover, observation of the universal scaling of direct photon yields with system size and collision energy with an unexpectedly small value of the scaling power adds a third prong to the "puzzle".

To alleviate the problem, in the past decade many theoretical calculations included non-thermal photon sources at various stages of the system evolution, resulting in an improved

*e-mail: david@bnl.gov

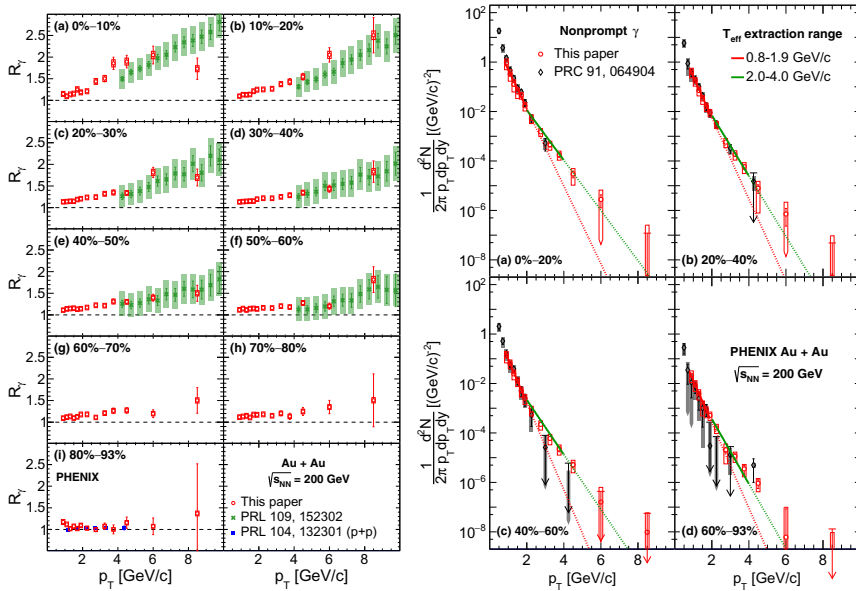


Figure 1. (Left) $R_\gamma = \gamma^{incl}/\gamma^{hadr}$ as a function of conversion photon p_T in 10% centrality bins. The 2014 Au+Au data at $\sqrt{s_{NN}} = 200$ GeV are compared to results from previous PHENIX publications [4, 5]. (Right) Nonprompt direct-photon yield as a function of conversion photon p_T in 20% centrality bins, compared to previously published PHENIX results [6]. Also shown the exponential fits in two disjoint p_T regions. Both figures are from [7].

– albeit not yet perfect – description of the data. New measurements of the yields and v_2 with smaller uncertainties and smaller centrality bins helped to constrain model calculations better. In this paper we report on the latest results on direct photon yields [7] and v_2 [8] in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions by the PHENIX experiment.

2 Direct photon yield and azimuthal asymmetry

Recently published direct photon results from the $4\mu b^{-1}$ 2014 Au+Au dataset using external conversion and extended p_T range are presented in Fig. 1 [7]. In the left panel the ratio of inclusive over decay photons, $R_\gamma = \gamma^{incl}/\gamma^{hadr}$ is shown. Measuring R_γ with both high accuracy and precision is crucial for the v_2 measurement [3]. The new results are consistent with earlier publications [4, 5] and imply significant excess over hadron decay photons, *i.e.* large direct photon yields in all but the most peripheral centrality bin. By subtracting the prompt photon yield, defined as the yield in $p+p$ collisions scaled by the number of binary nucleon-nucleon collisions, one obtains the nonprompt photon yields in Au+Au collisions, as shown in the right panel in Fig. 1. Also shown are exponential fits in limited p_T ranges; the inverse slopes can be interpreted as effective temperatures T_{eff} , that clearly depend on the p_T range, as expected if those p_T ranges are populated at different stages of the collisions. Remarkably, at a fixed p_T range the slopes are independent of collision centrality [7] indicating that the differences between central and peripheral collisions are quantitative only, not qualitative. They are quantified with the integrated direct photon yield which scales with charged multiplicity (a proxy for centrality) as $dN_\gamma/dy = A \times (dN_{ch}/d\eta)^\alpha$ with $\alpha = 1.11 \pm 0.02(\text{stat})_{-0.08}^{+0.09}(\text{sys})$ [7].

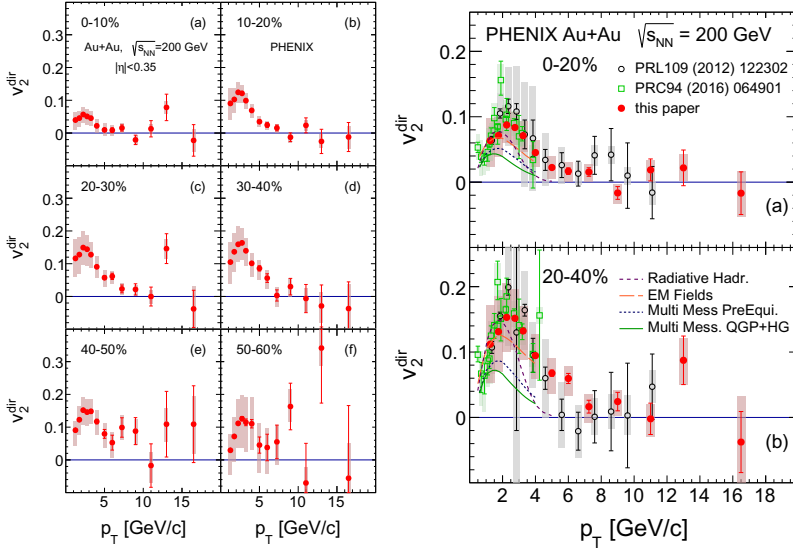


Figure 2. (Left) Anisotropy of direct-photon production v_2^{dir} from central to semiperipheral collisions in 10% bins of centrality. (Right) Azimuthal anisotropy for 0-20% and 20-40% centralities compared to previous measurements [2, 3] and to the multimessenger [10], radiative hadronization [9] and magnetic photons [11] models. The photon sources included in the models are shown in Table 1.

Table 1. Photon sources considered in the multimessenger [10], radiative hadronization [9] and magnetic photons [11] models.

| Source | Multimessenger | Rad. hadronization | Magnetic |
|--------------------|----------------|--------------------|----------|
| prompt | X | X | X |
| magnetic | | | X |
| pre-eq | X | | X |
| QGP thermal | X | X | X |
| HG thermal | X | X | X |
| rad. hadronization | | X | |

From thermal production in the QGP $\alpha \approx 1.85$ and from the hadron gas $\alpha \approx 1.25$ would be expected, so the small α may indicate that non-thermal sources play a major role in photon production. One such subprocess could be radiative hadronization [9], for which α would be unity.

New results on direct photon azimuthal asymmetries v_2 are shown in Fig. 2 [8]. The new analysis took advantage of the improved R_γ [7] and higher statistics of 2014 data, presenting v_2 in 10% bins of centrality (left panel). At low p_T v_2 is comparable to those of hadrons, while at high p_T it is consistent with zero, as expected when the dominant source of photons is initial hard scattering. To compare with previous publications [2, 3] and model calculations [9–11] the results are also shown in 20% wide centrality bins (right panel). Table 1 summarizes what photon sources are considered in the models. All three include the "thermal paradigm" sources, *i.e.* prompt photons from initial hard scattering and thermal radiation from the QGP and HG, but add new ones. The multimessenger model [10] adds pre-equilibrium photons, the "magnetic" model [11] also considers large emission anisotropy due to the large magnetic

fields early in the collision. The radiative hadronization model [9] omits those two sources, but adds the possibility of quark-antiquark coalescence off mass shell, where the final state hadron comes on mass shell by radiating a photon. This mechanism obviously pushes the photon v_2 toward values observed for hadrons. Also, the number of photons created this way would be proportional to those of hadrons, resulting in itself in a scaling power $\alpha = 1$, and could be responsible for the observed low value of α . As seen in Fig. 2, as more unconventional sources are included in the models, the description of the data improves.

3 Summary

New measurements by the PHENIX experiment on direct and nonprompt photon production and azimuthal asymmetry have been presented using $\sqrt{s_{NN}}=200$ GeV Au+Au data collected 2014. The v_2 results were compared to models considering new photon sources in addition to the prompt photons and thermal radiation from the QGP and HG, which results in a significantly improved description of the data and eases the "direct photon puzzle".

References

- [1] G. David, Direct real photons in relativistic heavy ion collisions, Rep. Prog. Phys. **83** 046301 (2020) <https://doi.org/10.1088/1361-6633/ab6f57>
- [2] A. Adare *et al.*, Observation of Direct-Photon Collective Flow in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV, Phys. Rev. Lett. **109** 122302 (2012), <https://doi.org/10.1103/PhysRevLett.109.122302>
- [3] A. Adare *et al.*, Azimuthally anisotropic emission of low-momentum direct photons in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, Phys. Rev. C **94**, 064901 (2016) <https://doi.org/10.1103/PhysRevC.94.064901>
- [4] A. Adare *et al.*, Enhanced Production of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV and Implications for the Initial Temperature, Phys. Rev. Lett. **104**, 132301 (2010), <https://doi.org/10.1103/PhysRevLett.104.132301>
- [5] S. Afanasiev *et al.*, Measurement of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. Lett. **109**, 152302 (2012) <https://doi.org/10.1103/PhysRevLett.109.152302>
- [6] A. Adare *et al.*, Centrality dependence of low-momentum direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C **91**, 064904 (2015) <https://doi.org/10.1103/PhysRevC.91.064904>
- [7] N. J. Abdulameer *et al.*, Nonprompt direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C **109**, 044912 (2024), <https://doi.org/10.1103/PhysRevC.109.044912>
- [8] N. J. Abdulameer *et al.*, Azimuthal anisotropy of direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, arXiv:2504.02955, submitted to Phys. Rev. C
- [9] H. Fujii, K. Itakura, K. Miyachi, and C. Nonaka, Radiative hadronization: Photon emission at hadronization from quark-gluon plasma, PRC **106**, 034906 (2022) <https://doi.org/10.1103/PhysRevC.106.034906>
- [10] C. Gale, J.-F. Paquet, B. Schenke and C. Shen, Multimessenger heavy-ion collision physics, Phys. Rev. C **105**, 014909 (2022), <https://doi.org/10.1103/PhysRevC.105.014909>
- [11] J.-A. Sun and L. Yan, Estimating the magnetic field strength in heavy-ion collisions via direct photon elliptic flow, Phys. Rev. C **109**, 034917 (2024), <https://doi.org/10.1103/PhysRevC.109.034917>