Low $p_T$ direct photon production at RHIC measured with PHENIX

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Double differential analysis of the shape of the momentum spectra of direct and non-prompt direct photons and the rapidity density, $dN_\gamma/dy$, in $p_T$ and $dN_{ch}/d\eta$

Low $p_T$ direct — photon production in Au+Au collisions at $\sqrt{s_{NN}} = 39$ and 62.4 GeV

The measurement of direct photons from Au+Au collisions at $\sqrt{s_{NN}}$ and 62.4 GeV in the transverse momentum range $0.4 < p_T < 3$ GeV/c is presented by the PHENIX collaboration. A significant direct photon yield is observed in both the systems. A universal scaling is observed when the direct photon $p_T$ spectra for the different center of mass energies and for different centrality selection at $\sqrt{s_{NN}} = 62.4$ GeV is scaled with $(dN_\gamma/dy)^{1/2}$ with $\alpha = 1.21 \pm 0.04$. This scaling also holds true for direct photon spectra from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by PHENIX, as well as the spectra from Pb+Pb at $\sqrt{s_{NN}} = 2.760$ GeV published by ALICE. It is also demonstrated that the scaling power $\alpha$ seem to be independent of $p_T$, center of mass energy, and collision centrality. The spectra from different collision energies, have a similar shape up to $p_T$ of 2 GeV/c. They have a local inverse slope $T_s/T$ increasing with $p_T$ that is 0.174 ± 0.018 GeV/c in the range $0.4 < p_T < 1.3$ GeV/c and increases to 0.289 ± 0.024 GeV/c for $0.9 < p_T < 2.1$ GeV/c. The observed similarity of low $p_T$ direct photon production from $\sqrt{s_{NN}} = 39$ GeV to 2760 GeV suggests a common source of direct photons for the different collision energies and event centrality selections, and that the possible differences in the space time evolution do not alter direct photon emission significantly.

Nonprompt direct — photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

The measurement of the direct-photon spectrum from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is presented by the PHENIX collaboration using the external-photon-conversion technique for 0%-93% central collisions in a transverse-momentum ($p_T$) range of 0.8-10 GeV/c. An excess of direct photons, above prompt-photon production from hard-scattering processes, is observed for $p_T < 6$ GeV/c. Nonprompt direct photons are measured by subtracting the prompt component, which is estimated as $N_{cem}$-scaled direct photons from p+p collisions at 200 GeV, from the direct-photon spectrum. Results are obtained for $0.8 < p_T < 6.0$ GeV/c and suggest that the spectrum has an increasing inverse slope from ≈0.2 to 0.4 GeV/c with increasing $p_T$, which indicates a possible sensitivity of the measurement to photons from earlier stages of the evolution of the collision. In addition, like the direct-photon production, the $p_T$-integrated nonprompt direct-photon yields also follow a power-law scaling behavior as a function of collision-system size. The exponent, $\alpha$, for the nonprompt component is found to be consistent with 1.1 with no apparent $p_T$ dependence.
Photons are “color blind” probe of Quark Gluon Plasma

- Sensitive to space-time evolution and temperature of matter produced in relativistic heavy-ion collisions
- Evidence of thermal radiations from QGP and Hadron Gas
- 80-90% photons are decay photons

Measurement of yield constrains initial conditions, sources, emission rates and space-time evolution
Introduction

Photon sources

- Direct
  - Prompt
  - Jet medium interactions
- Nonprompt
  - Pre-equilibrium
  - QGP
  - Thermal
  - Hadron Gas

Jet-medium interaction

Measurement of the nonprompt direct photons possible due to large statistics

$dN/dp_T$

$p_T$ [GeV/c]

Hadron gas

QGP

Pre-equilibrium

Jet-medium interaction

pQCD
# Photon measurements from PHENIX

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<th>200</th>
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Published | Recently submitted | Ongoing
Significant direct photon component relative to those from hadron decays.
Direct $\gamma$ for Au+Au at 200 GeV

**Poster by Wenqing Fan**

Session 2 T13

Conversions in the layers of the Silicon Vertex detectors

Significantly higher statistics for a more differential measurement
Universal scaling of direct $\gamma$ yields

$$dN_\gamma/dy = A \times (dN_{ch}/d\eta)^\alpha$$

Universal scaling behavior in all A+A systems

$1.0 < p_T < 5.0$ GeV/$c$
- PHENIX Au+Au 200 GeV (2014)
  - fit to new data
  - fit p+p 200 GeV scaled by $N_{coll}$

PHENIX
- Au+Au 39 GeV
- Au+Au 62.4 GeV
- Au+Au 200 GeV
- Cu+Cu 200 GeV
  - fit to published data

ALICE
- Pb+Pb 2760 GeV

$\alpha > 1$ and independent of $p_T$

arXiv:2203.17187
arXiv:2203.12354 (vs $p_T$, min)
Similar spectra around 2 GeV/c — common source of photon production independent of $\sqrt{s_{NN}}$
Nonprompt direct photons

**Direct photon**

\[ \frac{1}{2\pi p_T} \frac{d^2N}{dy dp_T} = A \left( \frac{p_T^2}{1 + \frac{p_T^2}{p_0^2}} \right) \]

**Non-prompt direct photon**

\[ \frac{1}{2\pi p_T} \frac{d^2N}{dy dp_T} = N_{\text{coll}} \text{scaled} \]

ArXiv:2203.17187

PRC 91, 064904

PRL 104, 132301

PRL 109, 152302

\[ \frac{1}{2\pi p_T} \frac{d^2N}{dy dp_T} = \text{pQCD} \text{scaled} \]
Nonprompt direct photons

PHENIX Au + Au
s \(= 200 \text{ GeV} \)

- \( N_{\text{coll}} \) scaled
- \( p+p \) fit

Roli Esha

Quark Matter 2022
Scaling of nonprompt direct $\gamma$ with $dN_{ch}/d\eta$ with $s_{NN} = 200$ GeV

PHENIX Au + Au, $s_{NN} = 200$ GeV

Nonprompt $\gamma$
- $0.8 < p_T < 1.2$ GeV/c
- $1.2 < p_T < 1.6$ GeV/c
- $1.6 < p_T < 2.0$ GeV/c

$\alpha$ independent of $p_T$ for direct and nonprompt photons

$\alpha$ for direct
- $2.0 < p_T < 3.0$ GeV/c
- $3.0 < p_T < 4.0$ GeV/c
- $4.0 < p_T < 5.0$ GeV/c

$\alpha$ for nonprompt
- $0.8 < p_T < 1.2$ GeV/c
- $1.2 < p_T < 1.6$ GeV/c
- $1.6 < p_T < 2.0$ GeV/c

$\alpha$ for Au+Au, $s_{NN} = 200$ GeV
- direct
- nonprompt

PHENIX

arXiv:2203.17187
Increasing inverse slope with $p_T$ to above 350 MeV/c suggests contributions from sources beyond those from Hadron Gas.
Multi-messenger heavy-ion physics

- Hybrid model that describes all stages of relativistic heavy-ion collisions
- Effect of the pre-equilibrium phase on both photonic and hadronic observables highlighted

Dominant contribution from pre-equilibrium above 3 GeV/c in the model seems to align well with the data

Overall yield falls short, especially below 2 GeV
Comparison of local inverse slopes

Multi-Layer Perceptron (MLP) — a machine learning based regression algorithm

Contributions from pre-equilibrium may be important at intermediate $p_T$
Cu+Au - coming soon

Spectrum — underway
Azimuthal anisotropy — ongoing

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**Poster by Vassu Doomra**
Session 1
T05

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**Poster by Michael Giles**
Session 1
T06/07

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NEW
Recently published Au+Au measurements for $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV

**Universal scaling**, $N_{\gamma}^{\text{dir}} \propto (dN_{\text{ch}}/d\eta)^\alpha$ — **$\alpha$ independent of $p_T$** for direct and nonprompt direct photons

Direct and nonprompt direct photon spectra exhibit **increasing inverse slope** with $p_T$

Nonprompt direct photon spectra **sensitive to pre-equilibrium emissions** for $p_T > 2$ GeV/$c$

More results coming soon from small system collisions and Cu+Au at $\sqrt{s_{NN}} = 200$ GeV

**Summary and outlook**

arXiv: 2203.17187
Recently published Au+Au measurements for $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV

**Universal scaling**, $N_{\gamma}^{\text{dir}} \propto (dN_{ch}/d\eta)^{\alpha} \quad \alpha$ independent of $p_T$ for direct and nonprompt direct photons

Direct and nonprompt direct photon spectra exhibit **increasing inverse slope** with $p_T$

Nonprompt direct photon spectra **sensitive to** pre-equilibrium emissions for $p_T > 2$ GeV/$c$

More results coming soon from small system collisions and Cu+Au at $\sqrt{s_{NN}} = 200$ GeV
Thank you for your attention!
# Systematic uncertainties

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<th>Systematic uncertainty source (39 GeV)</th>
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<table>
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Closure test with high-multiplicity $\pi^0$ simulation

$$R_\gamma = \frac{N_{\text{inc}}}{N_{\text{tag}}} \langle \varepsilon f \rangle$$

High multiplicity $\pi^0$ simulation

1.0 < $p_T^{\pi^0} < 1.2$ GeV/c

(a) $dN/dm_{ee}$ [GeV/c$^2$]
(b) $dN/dm_{ee}$ [GeV/c$^2$]

Simulating 280 $\pi^0$ per event through the PHENIX reconstruction and analysis framework
Universal ratio for p+p

Accounting for effects of radial flow

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Functional form inspired by pQCD

Fit below 1 GeV/c motivated by Drell Yan measurements [Ito, et al, PRD23, 604 (1981)]

Systematic errors include the fit errors, different functional forms

\[ \frac{dN}{dy} = a \left( 1 + \frac{p_T^2}{b^2} \right)^c \]

\[ a = 6.4 \times 10^3 \quad b = 1.45 \quad c = -3.30 \]
Theoretical comparisons

Au+Au, $\sqrt{s_{NN}} = 200$ GeV

- direct
- nonprompt
- Hadron gas
- QGP

PHENIX


$\alpha$ vs $p_T$ [GeV/c]

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Universal scaling of direct $\gamma$

$p(A,d) + p(A) \rightarrow \gamma_{\text{dir}} + X$

Universal scaling of direct $\gamma$

$\alpha = 1.25$

$dN_{\gamma}/dy (1.5 < p_T < 5.0 \text{ GeV/c})$

$\frac{dN_{\text{ch}}}{d\eta} |_{\eta=0}$