PHENIX measurements of low momentum direct photon radiation

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Large yield and large anisotropy have been observed in Au+Au at 200 GeV by PHENIX.

It is challenging to describe the large yield and anisotropy simultaneously.

In order to help resolving this puzzle, PHENIX has measured low momentum $\gamma$ in large systems:
- Au+Au at 200, 62.4, 39 GeV, Cu+Cu at 200 GeV
- direct photon scaling independent of center-of-mass energy, centrality, system
- small systems
  - p+p, d+Au, p+Au at 200 GeV
  - direct photon excess in central p+Au is consistent with QGP droplets’ formation

The plots are from PRC 94, 064901.
Photon measurement techniques include:

- photons that directly deposit energy into electromagnetic calorimeters:
- virtual photons that internally convert into $e^+e^-$ pairs:
- real photons that externally convert into $e^+e^-$ pairs in a selected detector material:

The new results on low momentum direct photons are obtained with conversion methods based on photon conversions in

- HBD backplane
- VTX layers

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Higher $p_T$ reach is accessible as compared to the previous $v_2$ results

For more details on the $v_2$ results, see the poster of Wenqing Fan!

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Large Systems: Direct Photon $p_T$ Spectra

- We have new direct photon data
  - from Au+Au at 62.4 GeV and 39 GeV
  - from Cu+Cu at 200 GeV

**p_T spectra in minbias**
The specific yield, SY, is a function of $\sqrt{s_{NN}}$.

\[ SY\left(\sqrt{s_{NN}}\right) = c_1 \log\left(\sqrt{s_{NN}}\right) - c_2 \]

$N_{\text{coll}}$ scales like $(dN_{\text{ch}}/d\eta)^{1.25}$ for all center-of-mass energies with a logarithmic increasing constant (specific yield).

$N_{\text{coll}}$ scales with $dN_{\text{ch}}/d\eta$ as

\[ N_{\text{coll}} = \frac{1}{SY\left(\sqrt{s_{NN}}\right)} \left(\frac{dN_{\text{ch}}}{d\eta}\right)^\alpha \]
Large Systems: Direct Photon Scaling

- PHENIX low energy 62.4/39 GeV data are above $p_T = 0.4$ GeV/c
- The data at 62.4/39 GeV falls on top of each other
- At high-$p_T$ the 62.4 GeV pQCD is consistent with ISR data

Direct photon $p_T$ spectra normalized by $(dN_{ch}/d\eta)^\alpha$, where $\alpha = 1.25$

The pQCD curves are also normalized
All Au+Au data are on top of each other at low- and high-\(p_T\) at 200 GeV

At low-\(p_T\) they are distinctly above the \(p+p\) data/fit/pQCD

Direct photon \(p_T\) spectra normalized by \((dN_{ch}/d\eta)^\alpha\), where \(\alpha = 1.25\)

The pQCD curves and \(p+p\) fit are also normalized
Now we compare different energies from 39 GeV to 2760 GeV.

Again all data coincides at low-\(p_T\).

We see the expected difference with the energy and \(N_{\text{coll}}\) scaling at high-\(p_T\).

Direct photon \(p_T\) spectra normalized by \((dN_{\text{ch}}/d\eta)^\alpha\), where \(\alpha = 1.25\).

ALICE data from Pb+Pb at 2760 GeV and ISR data from p+p at 62.4 GeV are included.

The pQCD curves and \(p+p\) fit are also normalized.
Large Systems: Direct Photon Scaling

- Direct photon $p_T$ spectra -- quantified by integrating the invariant yield from some $p_T$ value

PHENIX

Integrate from 5.0 GeV/c

Integrate from 1.0 GeV/c
Integrated direct photon yield above $p_T = 1.0 \text{ GeV/c}$

- Another representation of the direct photon scaling
- The integrated yield grows faster than the multiplicity
- The prompt photons described by the purple band and integrated pQCD curves have nearly the same slopes

For more details on the direct photon scaling, see the poster of Axel Drees/Vlad Khachatryan!
Integrated direct photon yield above $p_T = 5.0 \text{ GeV/c}$

Large Systems: Direct Photon Scaling

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Large Systems: Direct Photon Scaling

Integrated direct photon yield above $p_T = 1.0 \text{ GeV/c}$

Small systems

At a given center-of-mass energy the direct photon invariant yield in A+A collisions scales with $N_{\text{coll}}$ down to below 1 GeV/c in $p_T$.

The scaling at low-$p_T$ can be generalized to different center-of-mass energies and centrality/collisions systems if the yield is scaled by $(dN_{\text{ch}}/d\eta)^{1.25}$ instead of $N_{\text{coll}}$.

The low-$p_T$ scaling suggests the main photon sources contributing to it, could be similar across beam energies.
R$_\gamma$ from p+p collisions: The new data are in red, the published data are in black.
- $R_\gamma$ from p+p collisions: The new data are in red, the published data are in black
- $R_\gamma$ from p+ Au collisions in minbias
- $R_\gamma$ from $p+p$ collisions: The new data are in red, the published data are in black
- $R_\gamma$ from $p+Au$ collisions in minbias
- $R_\gamma$ from $p+Au$ collisions in 0-5% centrality bin

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After $R_\gamma$ is constructed, we can get the invariant cross section

$$\text{Inv. Yield} = (R_\gamma - 1) \times \gamma^{\text{had}}$$
After \( R_\gamma \) is constructed, we can get the invariant cross section

\[
\text{Inv. Yield} = (R_\gamma - 1) \times \gamma_{\text{had}}
\]

Above \( p_T = 5.0 \text{ GeV/c} \) the published \( p+p \) data are from calorimeter measurements:
PRL 109, 152302
After $R_\gamma$ is constructed, we can get the invariant cross section

$$\text{Inv. Yield} = (R_\gamma - 1) \times \gamma_{\text{had}}$$

The PHENIX new $p+p$ fit made by using three $p+p$ data sets.
After $R_\gamma$ is constructed, we can get the invariant cross section:

$$\text{Inv. Yield} = (R_\gamma - 1) \times \gamma^{\text{had}}$$
After $R_\gamma$ is constructed, we can get the invariant cross section

$$\text{Inv. Yield} = (R_\gamma - 1) \times \gamma_{\text{had}}$$

One can see a clear enhancement of the direct photon yield above the $N_{\text{coll}}$ scaled p+p.
Small Systems: PHENIX Preliminary $R_{pA}$
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$\sqrt{s_{NN}} = 200$ GeV, $|\eta| < 0.35$

- p+Au, 0-100 %
- Thermal, Paquet et al
- pQCD, Paquet et al

$R_{p+Au}$ vs $p_T$ [GeV/c]
Let’s now go back to the plot of the integrated direct photon yield above $p_T = 1.0$ GeV/c.
There seems to be another trend from small systems, different from that of large systems.

Both trends suggest an “intersection region” or “intersection point”.

p+Au 0-5% data point shows a sign of existence of QGP small droplet.
Summary

- New PHENIX direct photon data from Au+ Au 39, 62.4 GeV; Cu+Cu 200 GeV; p+p, p+Au at 200 GeV

- Discovered a new scaling behavior in large systems
  - at a given center-of-mass energy, the low and high-p_T yields scale with N_{coll}
  - across energies, N_{coll} is proportional to \((dN_{ch}/d\eta)^{1.25}\)
  - for all energies, the low-p_T yield scales like \((dN_{ch}/d\eta)^{1.25}\)

- Discovered excess of direct photons in central p+Au
  - above N_{coll} scaled p+p
  - consistent with the formation of QGP droplets
  - data suggests transition from p+p to A+A like scaling

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Back-Ups
Measuring Direct Photon $R_\gamma$ with the Double Ratio

\[ R_\gamma = \frac{\gamma^{incl}(p_T)}{\gamma^{had}(p_T)} = \left\langle \mathcal{E}_\gamma(p_T)f(p_T) \right\rangle \cdot \frac{N_\gamma^{incl}(p_T)}{N_\gamma^{\pi^0,tag}(p_T)} \bigg|_{\text{Data}} \]

\[ \frac{N_\gamma^{had}(p_T)}{N_\gamma^{\pi^0}(p_T)} \bigg|_{\text{Sim}} \]

\[ N_\gamma^{incl}(p_T) = c\mathcal{E}_{ee}a_{ee}\gamma^{incl}(p_T) \]
\[ N_\gamma^{\pi^0,tag}(p_T) = c\mathcal{E}_{ee}a_{ee}\left\langle \mathcal{E}_\gamma f \right\rangle \pi^0(p_T) \]

\[ N^{had}_\gamma(p_T) = a_{ee}\gamma^{had}(p_T) \]
\[ N^{\pi^0,tag}_\gamma(p_T) = f N^{\pi^0}_\gamma = a_{ee} f \gamma^{\pi^0}(p_T) \]

- Pair acceptance, efficiency and conversion probability factors cancel in the ratios

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Three PHENIX independent measurements are in good agreement with each other.

The plots are from PRC 91, 064904.