Direct photon elliptic flow in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV

Mike Sas,
for the ALICE Collaboration

Utrecht University & NIKHEF

July, 2018
Direct Photon production mechanisms

Three classes of photons:

- **Inclusive photons**: photons from any source
- **Decay photons**: photons from hadronic decays ($\pi^0$, $\eta$, ...)
- **Direct photons**: photons *not* coming from hadronic decays

Direct photons...

In pp, pA, and AA collisions:

- **prompt photons**
  - dominant at $p_T > 5$ GeV/c
  - calculable within NLO pQCD

Additional sources in AA collisions:

- **Thermal photons**
  - dominant at $p_T < 4$ GeV/c
  - scattering of particles in the hot matter
  - susceptible to flow evolution

- **Jet-Medium interactions**
  - Scattering of hard partons with partons of the QGP
  - In-medium (photon) bremsstrahlung emitted by quarks
Why measure the flow of direct photons?

Direct photon measurements give access to the temperature and space-time evolution of the produced medium!

- Early emission of photons: high yield $\leftrightarrow$ low $v_2$
- Late emission of photons: low yield $\leftrightarrow$ high $v_2$

Extracting the direct photon yield:

$$\gamma_{direct} = \gamma_{incl} - \gamma_{decay} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{incl}$$

$$R_\gamma = \frac{\gamma_{incl}}{\gamma_{decay}}$$

Direct photon flow calculation:

$$v_2^{\gamma,\text{dir}} = \frac{R_\gamma \, v_2^{\gamma,\text{inc}} - v_2^{\gamma,\text{dec}}}{R_\gamma - 1}$$
Photons in ALICE

**Photon Conversion Method (PCM)**
- $\gamma_{\text{conversion}} \rightarrow e^+ e^-$
- ITS and TPC
- $|\eta| < 0.9$ and $0^\circ < \varphi < 360^\circ$
- Conversion probability $\sim 8\%$
- Signal selection based on the decay topology

**PHOS calorimeter**
- PbWO$_4$ crystals
- $|\eta| < 0.12$ and $260^\circ < \varphi < 320^\circ$

**Trigger and event plane orientation detectors**
- V0A ($2.8 < \eta < 5.1$)
- V0C ($-3.7 < \eta < -1.7$)
Results

Inclusive photon elliptic flow calculated with the Scalar Product method:

\[ v_2 = \sqrt{\frac{\langle \bar{u}_2 \cdot \bar{Q}_A^* / M_A \rangle \langle \bar{u}_2 \cdot \bar{Q}_C^* / M_C \rangle}{\langle \bar{Q}_A^2 / M_A \cdot \bar{Q}_C^+ / M_C \rangle}}, \]

where

\[ \bar{u}_2 = e^{i2\phi}, \]

are the unit flow vectors build from the inclusive photons. And

\[ \bar{Q}_n = \sum_{i \in \text{RFP}} w_i e^{in\phi_i}, \]

where \( \phi_i \) is the azimuthal angle of the \( i \)-th reference particle (V0A/V0C), \( n \) is the order of the harmonic, and \( w_i \) is the applied weight.
Results

Inclusive photon elliptic flow calculated with the Scalar Product method:

\[ v_2 = \sqrt{\frac{\langle \vec{u}_2 \cdot \vec{Q}_A^* \rangle \langle \vec{u}_2 \cdot \vec{Q}_C^* \rangle}{\langle \vec{Q}_A^2 \rangle \langle \vec{Q}_C^2 \rangle}}, \]

where \( \vec{u}_2 = e^{i2\phi} \),

are the unit flow vectors build from the inclusive photons. And

\[ \vec{Q}_n = \sum_{i \in \text{RFP}} w_i e^{in\phi_i}, \]

where \( \phi_i \) is the azimuthal angle of the \( i \)-th reference particle (V0A/V0C), \( n \) is the order of the harmonic, and \( w_i \) is the applied weight.

Individual inclusive photon flow measurements:

Observations:

- Agreement: \( p \)-values of 0.93 and 0.43 for centrality classes 0–20% and 20–40%, respectively
- Statistical uncertainty starts to be dominant at \( p_T > 2 \text{GeV/c} \)
Relative contributions to the decay photons

\[ \gamma \rightarrow \gamma (\pi^+ \pi^-) \]
\[ \gamma \rightarrow \gamma (\pi^0 \gamma, \eta \gamma) \]
\[ \gamma \rightarrow \gamma (\pi^+ \pi^- \gamma, \eta \gamma) \]
\[ \gamma \rightarrow \gamma (\pi^0 \gamma, \eta \gamma) \]

\[ \rho^0 \rightarrow \pi^+ \pi^- (\pi^0, \eta) \]

\[ \phi \rightarrow \eta \gamma (\pi^0, \eta) \]

\[ \omega \rightarrow \pi^+ \pi^- (\pi^0, \eta) \]

\[ 0-20\% \text{ Pb-Pb Monte Carlo simulation} \]

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

Simulated the decay of most dominant hadronic decays to photons

- Parametrized the yield and elliptic flow of $\pi^\pm, K^{\pm,0}$
- Apply $m_T$ and $KE_T$ scaling for $\eta$ and $\omega$
Observations:

- Significant elliptic flow develops for inclusive and decay photons; dominated by the elliptic flow of $\pi^0 \rightarrow \gamma \gamma$.
- $v_{2,\text{inc}} \sim v_{2,\text{dec}}$.
- Prediction from theory overshoots the data by $\sim 40\%$.

Using covariance matrices to combine the measurements:

$$\tilde{v}^{\gamma,\text{inc}}_2 = (V^{-1}_{2,\text{PCM}} + V^{-1}_{2,\text{PHOS}})^{-1}(V^{-1}_{2,\text{PCM}} \tilde{v}^{\gamma,\text{inc,PCM}}_2 + V^{-1}_{2,\text{PHOS}} \tilde{v}^{\gamma,\text{inc,PHOS}}_2)$$
Results

Direct photon excess $R_\gamma$

Combined Inclusive photon flow & decay photon cocktail:

Direct photon flow calculation:

$$v_2^{\gamma,\text{dir}} = \frac{R_\gamma v_2^{\gamma,\text{inc}} - v_2^{\gamma,\text{dec}}}{R_\gamma - 1}$$

arXiv:1805.04403
Results

Direct photon excess $R_{\gamma}$

![Graph](image)

**Difficulty of the direct photon $v_{2}$ extraction:**

![Graph](image)

**Direct photon flow calculation:**

$$v_{2,\text{dir}} = \frac{R_{\gamma} v_{2,\text{inc}} - v_{2,\text{dec}}}{R_{\gamma} - 1}$$

arXiv:1805.04403
Results – Direct photon elliptic flow

Final results obtained by employing a Bayesian approach ($R_{\gamma,true} > 1$).

Conclusions:

- Non-zero direct photon flow
- Significance of $1.4\sigma$ (central) and $1.0\sigma$ (semi-central)
- $v_2^{\gamma, dir} \sim v_2^{\gamma, dec}$
- Theory underpredicts the data, but no strong tension due to large uncertainties
- $v_2^{\gamma, dir}$ (ALICE) $\sim v_2^{\gamma, dir}$ (PHENIX)
Final results obtained by employing a Bayesian approach ($R_{\gamma,\text{true}} > 1$).

Conclusions:
- Non-zero direct photon flow
- Significance of 1.4\(\sigma\) (central) and 1.0\(\sigma\) (semi-central)
- \(v_2^{\gamma,\text{dir}} \sim v_2^{\gamma,\text{dec}}\)
- Theory underpredicts the data, but no strong tension due to large uncertainties
- \(v_2^{\gamma,\text{dir}}\) (ALICE) \(~\) \(v_2^{\gamma,\text{dir}}\) (PHENIX)

Outlook:
- Increase precision with new datasets.. \(v_3^{\gamma,\text{dir}}\)
- Study \(R_{\gamma}\) and \(v_2^{\gamma,\text{dir}}\) in small systems at high multiplicity.
Final results obtained by employing a Bayesian approach ($R_{\gamma,\text{true}} > 1$).

Conclusions:

- Non-zero direct photon flow
- Significance of $1.4\sigma$ (central) and $1.0\sigma$ (semi-central)
- $v_2^{\gamma,\text{dir}} \sim v_2^{\gamma,\text{dec}}$
- Theory underpredicts the data, but no strong tension due to large uncertainties
- $v_2^{\gamma,\text{dir}}$ (ALICE) $\sim v_2^{\gamma,\text{dir}}$ (PHENIX)

Thanks for your attention!
BACKUP
Flow method

Collective flow:
Spatial anisotropy of the produced system leads to an anisotropy in momentum space.

Particle distributions as function of azimuthal angle are described by:

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_z dp_z dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_R)) \right),
\]

where

\[v_n = \langle \cos(n(\varphi - \Psi_R)) \rangle.\]
ALI-PUB-158400

ALI-PUB-158404

ALI-PUB-158424