Direct Photon Spectra and Elliptic Flow in 2.76 TeV Pb-Pb Collisions from ALICE

Martin Wilde
on behalf of the ALICE Collaboration

Westfälische Wilhelms-Universität Münster

December 5, 2012
Table of Contents

1 Direct Photon Production and the ALICE Detector

2 Part I: Direct Photon Spectra
   - Analysis Strategy
   - Detection of Converted Photons and $\pi^0$s
   - Inclusive Photon Results in pp and Pb-Pb
   - Decay Photon Background Calculation
   - Direct Photon Results in pp and Pb-Pb

3 Part II: Direct Photon $\nu_2$
   - Analysis Strategy
   - Inclusive Photon $\nu_2$ Analysis
   - Decay Photon $\nu_2$
   - Direct Photon $\nu_2$
Direct Photons in pp and Pb-Pb Collisions

Direct Photons - Definition
Photons that are not produced by particle decays

Prompt Photons: In pp and Pb-Pb
- Calculable within NLO pQCD
- Predominant source in pp
- Signal scales with number of binary collisions in Pb-Pb
- Fragmentation photons may be modified by parton energy loss in the medium

(a) Quark-gluon Compton scattering
(b) Quark-Anti-quark annihilation
(c) Fragmentation photons (bremsstrahlung)

Measurement of direct photons in pp is an ideal test for pQCD
Additional sources of direct photons in Pb-Pb collisions

Jet-Medium Interactions:
- Scattering of hard partons with thermalized partons
- In medium (photon) bremsstrahlung emitted by quarks

Thermal Photons:
- Scattering of thermalized particles
  QGP: $q\bar{q} \rightarrow g\gamma$ and $qg \rightarrow q\gamma$ (+NLO)
  HHG (hot hadronic gas): Hadronic interactions (e.g. $\pi^+\pi^- \rightarrow \gamma\rho_0$)
- Exponentially decreasing but dominant at low $p_T$

Photons leave medium unaffected, an ideal probe to study HI collisions
The ALICE Detector and Data Sample

pp, $\sqrt{s} = 7$ TeV:
- Data sample: $3.54 \times 10^8$ events (min. bias)
- Monte Carlo: Pythia-Perugia0 and Phojet

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV:
- Data sample: $17 \times 10^6$ min. bias events
- Monte Carlo: Hijing (min. bias plus enriched events with high $p_T \pi^0$s)

Photons are measured via their conversion products in ITS and TPC
Part I: Direct Photon Spectra
General Strategy of the Analysis

**Subtraction Method**

\[ \gamma_{\text{direct}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = \left(1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}} \right) \cdot \gamma_{\text{inc}} \]

- Inclusive photons: measure all photons that are produced
- Decay photons: calculated from measured particle spectra with photon decay branches (\(\pi^0\), \(\eta\), ...)

**Double Ratio**

\[ \frac{\gamma_{\text{inc}}}{\pi^0_{\text{param}}} / \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}} \approx \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \quad \text{if} \quad > 1 \quad \text{direct photon signal} \]

→ advantage of ratio method: cancellation of uncertainties

- Photons and \(\pi^0\)s (and \(\eta\)) are measured via conversion method
  \[ \pi^0 \rightarrow \gamma\gamma, \ \gamma \rightarrow e^+e^- \]
Secondary Vertex Algorithm - V0 Particles

- Charged tracks with large impact parameter are paired
- Candidates with a small DCA → V0 candidate
- Most abundant particle species: $K^0_s$, $\Lambda$, $\bar{\Lambda}$ or $\gamma$
- Photon conversion probability in $|\eta| < 0.9$ up to $R = 180 \text{ cm}$ at 8.5%

- Cuts on the decay topology of photons and electron track properties → Purity at 90% at 2 GeV/c for 0-40% Pb-Pb events
- Background is mainly combinatorial - Strange particle contribution negligible
Photon Corrections and Invariant Cross Section for pp

- Raw $\gamma$ spectrum in pp and Pb-Pb corrected for:
  - purity ($P$)
  - efficiency ($E$)
  - conversion probability ($C$)

  and secondary photon candidates subtracted

- Inclusive photon cross section in pp:

$$E \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi} \frac{\sigma_{MBOR}}{N_{events}} \frac{1}{p_T} \frac{P}{C E} N_{\gamma^{prim}}$$

Main sources of uncertainty:

- Material budget of the detector $\sim 4.5\%$
- Efficiency estimation by cut variations
  - $p_T < 5$ GeV: pp $\sim 3\%$, Pb-Pb $\sim 6\%$
  - $p_T > 5$ GeV: pp $\sim 6\%$, Pb-Pb $\sim 15\%$

  e.g. geometrical cuts, detector PID, sharing of tracks between sec. vertices

- Main sources of uncertainty:
  - Material budget of the detector $\sim 4.5\%$
  - Efficiency estimation by cut variations
  - $p_T < 5$ GeV: pp $\sim 3\%$, Pb-Pb $\sim 6\%$
  - $p_T > 5$ GeV: pp $\sim 6\%$, Pb-Pb $\sim 15\%$

  e.g. geometrical cuts, detector PID, sharing of tracks between sec. vertices
Two centrality selections: 0-40% and 40-80%
(central and peripheral)
\(\pi^0\) and \(\eta\) Reconstruction via Conversion

Neutral pion and \(\eta\) (pp only) based on converted photons

Measurement based on identical set of photons as used for photon results

- Inv. mass calculated for all photon pairs in an event
- Combinatorial background obtained via mixed event technique
- Raw \(\pi^0\) spectrum obtained by peak integration
- Efficiency and acceptance estimated with MC simulations

For more details see:
- Pb-Pb and pp at 2.76TeV: published soon, similar method
Decay photon spectra are obtained via calculation

- Based on a fit to measured $\pi^0$ and $\eta$ (in pp)
- Other meson spectra obtained via $m_T$-scaling
- Incorporated mesons: $\pi^0$, $\eta$, $\eta'$, $\omega$, $\phi$ and $\rho_0$

$m_T$-Scaling:
Same shape of cross sections, $f(m_T)$, of various mesons

$$E \frac{d^3\sigma_m}{dp^3} = C_m \cdot f(m_T)$$

<table>
<thead>
<tr>
<th>Meson ($C_m$)</th>
<th>Mass</th>
<th>Decay Branch</th>
<th>B. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>134.98</td>
<td>$\gamma\gamma$</td>
<td>98.789%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e^+e^-\gamma$</td>
<td>1.198%</td>
</tr>
<tr>
<td>$\eta$</td>
<td>547.3</td>
<td>$\gamma\gamma$</td>
<td>39.21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi^+\pi^-\gamma$</td>
<td>4.77%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e^+e^-\gamma$</td>
<td>$4.9 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>770.0</td>
<td>$\pi^+\pi^-\gamma$</td>
<td>$9.9 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>(1.0)</td>
<td>$\pi^0\gamma$</td>
<td>$7.9 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>781.9</td>
<td>$\pi^0\gamma$</td>
<td>8.5%</td>
</tr>
<tr>
<td></td>
<td>(0.9)</td>
<td>$\eta\gamma$</td>
<td>$6.5 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>957.8</td>
<td>$\rho^0\gamma$</td>
<td>30.2%</td>
</tr>
<tr>
<td></td>
<td>(0.25)</td>
<td>$\omega\gamma$</td>
<td>3.01%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma\gamma$</td>
<td>2.11%</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1019.5</td>
<td>$\eta\gamma$</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>(0.35)</td>
<td>$\pi^0\gamma$</td>
<td>$1.25 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\omega\gamma$</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

Direct photon double ratio

In the ratio uncertainties related to:
- normalization
- $\pi^0$ measurement
- rec. efficiency

partially or exactly canceled

The NLO double ratio prediction is plotted as

$$R_{NLO} = 1 + \frac{\gamma_{direct,NLO}}{\gamma_{decay}}$$

Measurement is consistent with the expected direct photon signal

Direct photon signal in pp at 7 TeV is consistent with zero
Double ratio for peripheral events shows no excess at any value of $p_T$.

- Measurement is consistent with the expected direct photon signal.
- pp NLO predictions scaled with $N_{coll}$.
Double Ratio - Pb-Pb 2.76 TeV - central

Direct photon double ratio

NLO prediction: \(1 + \left(\frac{N_{\text{coll}}^{\gamma_{\text{direct,pp,NLO}}}}{N_{\gamma_{\text{decay}}}^{\gamma}}\right)\)

for \(\mu = 0.5\) to \(2.0\ p_T\)

Clear extra yield of 20\% for \(p_T < 2\ \text{GeV/c}\)

\(N_{\text{coll}}\) scaled pp NLO in agreement with high \(p_T\) direct photons
Double Ratio - Pb-Pb 2.76 TeV - central

0-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

**ALICE PRELIMINARY**

- Direct photon double ratio
- NLO prediction: $1 + (N_{coll} \gamma_{direct, pp, NLO}/\gamma_{decay})$
  for $\mu = 0.5$ to 2.0 $p_T$

Clear extra yield of 20% for $p_T < 2$ GeV/c

$N_{coll}$ scaled pp NLO in agreement with high $p_T$ direct photons

- Similar to low $p_T$ direct photon observation by PHENIX
Results of Pb-Pb Direct Photons at 2.76 TeV

Direct Photon Spectrum for central Pb-Pb events

Spectrum derived from double ratio by:

\[ \gamma_{direct} = (1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}}) \cdot \gamma_{\text{inc}} \]
Results of Pb-Pb Direct Photons at 2.76 TeV

- **NLO predictions in agreement with spectrum** ($p_T > 4$ GeV/c)
- **At low** $p_T$ ($< 2.2$ GeV/c) spectrum fitted with an exponential
  $\rightarrow$ slope parameter $T = 304 \pm 51^{\text{stat+syst}}$ MeV
- **Intermediate region**: superposition of low and high $p_T$ direct photons

Spectrum derived from double ratio by:

$$\gamma_{direct} = \left(1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}} \right) \cdot \gamma_{\text{inc}}$$
Conclusions I: Direct Photon Spectra

- Statistical analysis of direct photons based on converted photons via double ratio
- With current uncertainties no significant direct photon signal in pp and peripheral Pb-Pb
- Direct photon signal is consistent with expectation from NLO pQCD

- In central Pb-Pb:
  Low $p_T$ direct photon signal, exponential in shape
- Similar excess measured at RHIC interpreted as thermal signal

Slope parameter:

- $T_{\text{ALICE}} = 304 \pm 51^{\text{stat+syst}}$ MeV (0-40%)
- $T_{\text{PHENIX}} = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}}$ MeV (0-20%)

arxiv:0804.4168 PRL 104 (132301) 2010
Part II: Direct Photon $v_2$
What can we learn from direct photon $v_2$?

Initial azimuthal asymmetry in coordinate space in non-central A+A
$\Rightarrow$ asymmetry in momentum space

$$\frac{dN}{d\phi} = \frac{1}{2\pi} \left( 1 + 2 \sum_{n \geq 1} v_n \cos(n(\phi - \Psi_{RP}^n)) \right)$$

- $v_2$: elliptic flow, collective expansion at low $p_T$
- $v_2$ at high $p_T$: path length dependence of in-medium parton energy loss

Thermal Photon $v_2$
- Constrains onset of direct photon production
- Early production $\rightarrow$ small flow
- Late production $\rightarrow$ hadron-like flow

Thermal Photons
Au+Au@200 AGeV
b = 6 fm

 Ideal hydro th. photon $v_2$ for different QGP formation times $\tau_0$
General Strategy of the $\nu_2$ Analysis

Direct photon $\nu_2$ obtained via comparison between measured and calculated decay photon $\nu_2$

$$\nu_2^{\text{direct}} \gamma = \frac{R \cdot \nu_2^{\text{inc}} \gamma - \nu_2^{\text{decay}} \gamma}{R - 1}$$

Factor $R$ represents the direct photon double ratio

- $R \cdot \nu_2^{\text{inc}} \gamma$: weighted inclusive photon $\nu_2$ due to extra photons compared to background
- $\nu_2^{\text{decay}} \gamma$: calculated decay photon $\nu_2$ from cocktail calculation

0-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

ALICE PRELIMINARY

NLO prediction: $1 + \langle N_{\text{coll}} \gamma_{\text{direct,pp,NLO}}/\gamma_{\text{decay}} \rangle$

for $\mu = 0.5$ to 2.0 $p_T$
\( \nu_2 \) given by the reaction plane

\[
\nu_2 = \langle \cos(2(\phi - \psi_{2^{RP}})) \rangle
\]

Extracted via this formula or by a fit

Event Plane angle determined by using the VZERO detector

- VZEROA: 2.8 < \( \eta \) < 5.1
- VZEROC: -3.7 < \( \eta \) < -1.7

Reaction plane resolution obtained by the three sub-event method

Relation of RP to EP:

\[
\nu_2 = \frac{\nu_{2}^{EP}}{\langle \cos(2\psi_{2^{EP}} - \psi_{2^{RP}}) \rangle} = \frac{\nu_{2}^{raw}}{\text{resolution}}
\]
Magnitude of $v_2$ increases with decreasing centrality

Similar $v_2$ to hadrons

Expected behavior, main contributions are decay photons
Spectra of other mesons with photon decay branches obtained by $m_T$ scaling

Assumption: $\nu_2^{\pi^0} = \nu_2^{\pi^\pm}$

$\nu_2$ of various mesons ($X$) calculated via $KE_T$ (quark number) scaling from $\nu_2^{\pi^\pm}$

Decay photon $\nu_2^X$ obtained by cocktail calculation

$$\nu_2^X(p_T^X) = \nu_2^{\pi^\pm} \left( \sqrt{(KE_T^X + m_{\pi^\pm})^2 - (m_{\pi^\pm})^2} \right)$$

with:

$$KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$
Comparison of Inclusive and Decay $\nu_2$

- Above 3 GeV/c inclusive photons significantly smaller than decay photons
  - Direct photon $\nu_2$ contribution with $\nu_2^\text{direct} < \nu_2^\text{inc}$

- Below 3 GeV/c consistent within uncertainties
  - Either contribution of direct photons with similar $\nu_2$ or no direct photons

![Graph showing $\nu_2$ vs. $p_T$ for 0-40% Pb-Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV. The graph compares inclusive and decay photon contributions.](ALI-PREL-43608)
Direct Photon $v_2$ 0-40% and Conclusions II

- Significant direct photon $v_2$ for $p_T < 3$ GeV/c measured
- Magnitude of $v_2$ comparable to hadrons
- Result points to late production times of direct photons after flow is established
- Large inverse slope parameter of low $p_T$ direct photon spectrum favours earlier production times
- Similar direct photon $v_2$ results seen by PHENIX
Backup Slides
Denominator Ratio: Cocktail Generator Pb-Pb Results

0-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

40-80% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
Combined Fit for Direct Photons

Combined fit (Hagedorn + Exponential) gives similar result for the inverse slope parameter $T$ as for the exponential only fit.
Systematic Cut Studies pp

Cut Variations for $\gamma$ and $\pi^0$:

<table>
<thead>
<tr>
<th>Cut Name</th>
<th>Std. value</th>
<th>Variation 1</th>
<th>Variation 2</th>
<th>Variation 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Electron dEdx}$</td>
<td>-4.5$\sigma$</td>
<td>-4.4$\sigma$</td>
<td>-3.4$\sigma$</td>
<td>-</td>
</tr>
<tr>
<td>$\text{Pion dEdx}$</td>
<td>1.10$\sigma$</td>
<td>2.1$\sigma$</td>
<td>2.0.5$\sigma$</td>
<td>2.0.5$\sigma$</td>
</tr>
<tr>
<td>$\text{Min. p } e^+ / e^-$</td>
<td>0.4 GeV/c</td>
<td>0.4 GeV/c</td>
<td>0.4 GeV/c</td>
<td>0.3 GeV/c</td>
</tr>
<tr>
<td>$\text{Find. Cls. TPC}$</td>
<td>0.35</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\text{Photon } \chi^2$</td>
<td>20</td>
<td>30</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>$q_t$</td>
<td>0.05</td>
<td>0.07</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>$\text{min. p}_t$ $e^+ / e^-$</td>
<td>50 MeV/c</td>
<td>75 MeV/c</td>
<td>100 MeV/c</td>
<td>-</td>
</tr>
<tr>
<td>$\text{photon } \eta, \pi^0 y$</td>
<td>0.9, 0.8</td>
<td>0.8, 0.7</td>
<td>1.2, 0.9</td>
<td>-</td>
</tr>
<tr>
<td>$\text{min. R}$</td>
<td>5 cm - 180 cm</td>
<td>2.8 cm - 180 cm</td>
<td>10 cm - 180 cm</td>
<td>-</td>
</tr>
</tbody>
</table>

- V0s with shared electrons rejected
- Purity for different centralities used
- TOF and $\alpha$ cut not used for pp
- R cut already considered for material budget

$\pi^0$ yield extraction:
- Three different integration windows
- Different Numbers of mixed events for bg, different mixed event bins (n V0s, n tracks)

Cocktail simulation:
- Two different fits
- Variation of the $m_t$ scaling factors ($\eta$ measured)
Systematic Cut Studies Pb-Pb

Cut Variations for $\gamma$ and $\pi^0$:

<table>
<thead>
<tr>
<th>Cut Name</th>
<th>Std. value</th>
<th>Variation 1</th>
<th>Variation 2</th>
<th>Variation 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron dEdx</td>
<td>-3,5$\sigma$</td>
<td>-4,5$\sigma$</td>
<td>-2.5,4$\sigma$</td>
<td>-</td>
</tr>
<tr>
<td>Pion dEdx</td>
<td>3,-10$\sigma$</td>
<td>2.5,-10$\sigma$</td>
<td>3.5,-10$\sigma$</td>
<td>3,-10$\sigma$</td>
</tr>
<tr>
<td>Min. p e^+/e^-</td>
<td>0.4 GeV/c</td>
<td>0.4 GeV/c</td>
<td>0.4 GeV/c</td>
<td>0.3 GeV/c</td>
</tr>
<tr>
<td>Find. Cls. TPC</td>
<td>0.6</td>
<td>0.7</td>
<td>0.35</td>
<td>-</td>
</tr>
<tr>
<td>Photon $\chi^2$</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>$q_t$</td>
<td>0.05</td>
<td>0.03</td>
<td>0.07</td>
<td>-</td>
</tr>
<tr>
<td>min. $p_t$ e^+/e^-</td>
<td>50 MeV/c</td>
<td>75 MeV/c</td>
<td>100 MeV/c</td>
<td>-</td>
</tr>
<tr>
<td>photon $\eta$, $\pi^0$, $y$</td>
<td>0.75, 0.7</td>
<td>0.9, 0.8</td>
<td>0.8, 0.7</td>
<td>-</td>
</tr>
<tr>
<td>min. R</td>
<td>5 cm - 180 cm</td>
<td>2.8 cm - 180 cm</td>
<td>10 cm - 180 cm</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha$ meson central</td>
<td>0.65</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha$ meson peripheral</td>
<td>0.8</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TOF</td>
<td>-5,-5$\sigma$</td>
<td>-3,-5$\sigma$</td>
<td>-2,-5$\sigma$</td>
<td>-</td>
</tr>
</tbody>
</table>

- V0s with shared electrons rejected
- Purity for different centralities used

$\pi^0$ yield extraction:
- Three different integration windows
- Different Numbers of mixed events for bg, different mixed event bins
  (n V0s, n tracks)

Cocktail simulation:
- Two different fits, with and without blast wave
- Variation of the $m_t$ scaling factors
PHENIX Direct Photon $v_2$ Results

(a) $\pi^0 v_2$ vs $p_T$ [GeV/c]
(b) $\gamma^{inc.} v_2$ vs $p_T$ [GeV/c]
(c) $\gamma^{dir.} v_2$ vs $p_T$ [GeV/c]

- $\pi^0 v_2$
- $\gamma^{inc.} v_2$ (E.P. $^{RXN}$ ($|\eta|$=1.0~2.8)
- $\gamma^{dir.} v_2$ (E.P. $^{BBC}$ ($|\eta|$=3.1~3.9))