Direct photons in pp and Pb-Pb collisions

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Introduction

• Direct photons provide a tool to test
  – Temperature
  – Collective flow development
  – Space-time dimensions of hot matter
  – Calibration of the initial state

• ALICE peculiarities compared to PHENIX, STAR, WA98
  – Higher temperature => Higher thermal photon yield
  – Higher $\sqrt{s}$ => better separation prompt and thermal photons
  – Stronger $\pi^0$ suppression => better S/Bg ratio
ALICE experiment
Photon measurement with ALICE

Photon Conversion Method (PCM)

- Good momentum resolution at low $p_T$
- High momentum reach is limited only by statistics
- Low conversion probability (~8.5%), coverage of full azimuthal angle, $|\eta|<0.9$
- Low contamination of photon spectrum

PHOS

- Good energy resolution at high $p_T$
- High photon registration efficiency, limited azimuthal angle (100°) and $|\eta|<0.135$
Reconstruction of converted photon

V0 algorithm
- Tracks with large impact parameters are paired
- Select pairs with small Distance of Closest Approach (DCA)
- Most abundant particle species $K_s^0$, $\Lambda$, $\bar{\Lambda}$, $\gamma$
- Photon conversion probability in $|\eta|<0.9$ up to $R = 180$ cm saturates at 8.5%

Photon identification
- Apply electron identification cuts
- Pair topology cuts
Measurement of $\pi^0$ spectrum

Both PCM and PHOS have comparable energy resolutions and dependence on multiplicity.

$\pi^0$s are dominant source of decay photons => each detector measures $\pi^0$ spectrum independently to reduce sys. uncertainties
Neutral pion spectra measured in Pb-Pb collisions with PCM and PHOS agree in all centrality bins. Good cross-check of both measurements.
Direct photon calculation

\[ \gamma_{direct} = \gamma_{incl} - \gamma_{decay} \]

\( \gamma_{incl} \) – measured photon spectrum

\( \gamma_{decay} \) – decay photon spectrum, estimated from cocktail simulation

\[ R_\gamma = \frac{\gamma_{incl}/\pi^0_{meas}}{\gamma_{decay}/\pi^0_{cocktail}} \approx \frac{\gamma_{incl}}{\gamma_{decay}} \]

Some uncertainties cancel in double ratio. Facilitates normalizations of decay photon spectrum.

\[ \gamma_{direct} = \gamma_{incl} - \gamma_{decay} = \left(1 - \frac{1}{R_\gamma}\right) \gamma_{incl} \]
Double ratio and spectrum in pp

**Double ratio and spectrum in pp**

\[ R_{NLO} = 1 + \frac{\gamma_{\text{direct, NLO}}}{\gamma_{\text{decay}}} \]

- **pp, \( \sqrt{s} = 7 \text{ TeV} \)**
- Analyzed statistics \( 3.8 \cdot 10^8 \) Min.Bias events
- In the ratio uncertainties related to:
  - normalization,
  - \( \pi^0 \) measurement,
  - reconstruction efficiency partially or exactly canceled
- Measurement is consistent with zero direct photon yield
- Measurement is consistent with NLO predictions
Low mass virtual photons ($e^+e^-$)

\[
\frac{1}{N_\gamma} \frac{dN}{dM_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m_e^2}{M_{ee}^2}} \left(1 + \frac{2m_e^2}{M_{ee}^2}\right) \frac{1}{M_{ee}} \left(1 - \frac{M_{ee}^2}{M^2}\right)^3 |F(M_{ee}^2)|^2
\]


(+ $\pi^0$ contribution decrease with increase of $m_{ee}$)

(-) big combinatorial background, rapidly increasing with multiplicity
Extraction direct photon contribution

\[ f_{\gamma,\text{combined}} = (1-r) f_{\gamma,\text{decay}} + r f_{\gamma,\text{dir}} \]

\[ r = \frac{\gamma_{\text{dir}}}{\gamma_{\text{incl}}} \]

\[ 3 \cdot 10^8 \text{ MinBias pp events (2010 sample)} \]

ALICE preliminary
pp, \( \sqrt{s} = 7 \) TeV
\( p_T^e > 0.2 \) GeV/c
\(|\eta^e| < 0.8 \)

2.4 < \( p_T^{ee} \) < 3.2 GeV/c
Direct photons in pp at $\sqrt{s}=7$ TeV

Virtual and real photon measurements agree within uncertainties.
Virtual photons in Pb-Pb

Full Run1 statistics.

Huge combinatorial background: after subtraction only wide $p_T$ bins can be analyzed.

Analysis is ongoing....
Double ratio in Pb-Pb

In **central** collisions
- double ratio agrees with $N_{\text{col}}$ scaled pp NLO predictions;
- at low $p_T < 2\ \text{GeV/c}$ there is a $\sim 20\%$ excess w.r.t. NLO predictions.

In **peripheral** events
- double ratio is consistent with no direct photon excess at any $p_T$;
- double ratio is also consistent with $N_{\text{col}}$ scaled pp NLO predictions.
Direct photon spectrum in Pb-Pb

\[ N_{\gamma}^{dir} = \left(1 - \frac{1}{R}\right) N_{\gamma}^{incl} \]

Both theoretical estimates of thermal photon yield underestimate data by factor 2-10 at low \( p_T < 2 \text{ GeV/c} \).

At high \( p_T > 4 \text{ GeV/c} \), spectrum agrees with \( N_{\text{col}} \) scaled NLO pp predictions.

Intermediate region – interplay between prompt and thermal (jet conversion, …?) contributions.
Direct photon collective flow

Inclusive photon collective flow contains contributions from direct and decay photons:

\[
\nu_n^{incl} = \frac{N_{\gamma}^{dir}}{N_{\gamma}^{incl}} \nu_{n}^{\gamma,dir} + \frac{N_{\gamma}^{decay}}{N_{\gamma}^{incl}} \nu_{n}^{\gamma,decay}
\]

With the double ratio \(R\) and decay photon flow calculated from cocktail, one can estimate the direct photon flow:

\[
\nu_{n}^{\gamma,dir} = \frac{R \nu_{n}^{\gamma,incl} - \nu_{n}^{\gamma,decay}}{R - 1}
\]
Inclusive photon flow extraction

Collective flow is estimated using event plane method. Inclusive photon flow is decomposed as

$$\frac{dN}{d\varphi} = \frac{1}{2\pi} \left( 1 + \sum_n 2v_n \cos(n(\varphi - \Psi_{RP})) \right)$$

where reaction plane is measured with one of 3 detectors

- **VZEROA**: $2.8<\eta<5.1$
- **VZEROC**: $-3.7<\eta<-1.7$
- **TPC**: $-0.9<\eta<0.9$

Event plane resolution was estimated using 3-subevent method.

**Cocktail simulations:**

- Use $\pi^+$ flow for estimate $\pi^0$ one
- Use $KE_T$ scaling for other mesons

Above 3 GeV/c inclusive photons significantly smaller than decay photons

Below 3 GeV/c consistent within uncertainties
Similar to the yield, direct photon flow at low $p_T < 2$ GeV/c is underestimated by theory calculations by a factor 2-10.

Difference between data and theory is ~1-2 sigma: not very significant

Careful error treatment is necessary
Error propagation

\[ v_n^{\gamma, \text{dir}} = \frac{R v_n^{\gamma, \text{incl}} - v_n^{\gamma, \text{decay}}}{R - 1} \]

Assume \( R, v_2^{\text{incl}}, v_2^{\text{decay}} \) to be independent with uncertainties described by Gaussians.

Due to the pole \((R-1)\) resulting (lower) distribution for \( v_n^{\text{dir}} \) will not be Gaussian.
\( \nu^2 \) comparison

Compare inclusive photon flow

\[
\left( \nu^2,^{\gamma, incl} - \nu^2,^{\gamma, model} \right) / \sigma_{total}
\]

where for \( \nu^2,^{\gamma, model} \) one can use cocktail, cocktail+theory etc.

- Cocktail does not reproduce \( \nu^2,^{\gamma, incl} \)
- Cocktail+NLO agree with data
- Cocktail+NLO+thermal (Shen et al.) agree with data
- Cocktail+NLO+thermal (Holopainen et al.) somewhat under predict \( \nu^2 \)
Triangular flow

Similar to elliptic flow, $v_3^{\gamma,\text{incl}}$ is not reproduced by cocktail $v_3^{\gamma,\text{decay}}$. All models failed to reproduce $v_3^{\gamma,\text{incl}}$ at low $p_T < 1$ GeV/c.

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Conclusions

• Direct photon spectrum in pp collisions at √s=7 TeV was measured with real and virtual photons. Double ratios obtained with two methods agree with each other and with NLO predictions.

• Photon double ratios were measured in Pb-Pb collisions at √s_{NN}=2.76 TeV.
  - In peripheral 40-80% collisions R_γ agrees both with no direct photon access and with scaled NLO predictions.
  - In central 0-40% collisions R_γ agrees with N_{col} scaled NLO predictions at high p_T>4 GeV/c.
  - An excess ~20% compared to N_{col} scaled NLO predictions in R_γ has been measured in 0-40% central Pb–Pb collisions at p_T<2 GeV/c.

• A direct photon v_2 which is of similar size as the charged hadron flow has been measured in 0-40% Pb–Pb collisions.

• The magnitude of the systematic errors and the propagation of the errors from the R_γ to both measurements was discussed.

• A different method to compare data and theory for inclusive photon v_2 & v_3 measurements avoiding pole 1/(R_γ-1) was presented.
Cocktail

<table>
<thead>
<tr>
<th>Meson ((C_m))</th>
<th>meas.</th>
<th>Mass</th>
<th>Decay Branch</th>
<th>B. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^0)</td>
<td>pp, Pb–Pb</td>
<td>134.98</td>
<td>(\gamma\gamma) (e^+e^-\gamma)</td>
<td>98.789% 1.198%</td>
</tr>
<tr>
<td>(\eta) (0.48)</td>
<td>pp</td>
<td>547.3</td>
<td>(\gamma\gamma) (\pi^+\pi^-\gamma) (e^+e^-\gamma)</td>
<td>39.21% 4.77% (4.9 \cdot 10^{-3})</td>
</tr>
<tr>
<td>(\rho^0) (1.0)</td>
<td>pp</td>
<td>770.0</td>
<td>(\pi^+\pi^-\gamma) (\pi^0\gamma)</td>
<td>9.9 (\cdot 10^{-3}) 7.9 (\cdot 10^{-4})</td>
</tr>
<tr>
<td>(\omega) (0.9)</td>
<td>pp</td>
<td>781.9</td>
<td>(\pi^0\gamma) (\eta\gamma)</td>
<td>8.5% 6.5 (\cdot 10^{-4})</td>
</tr>
<tr>
<td>(\eta') (0.25)</td>
<td>pp</td>
<td>957.8</td>
<td>(\rho^0\gamma) (\omega\gamma) (\gamma\gamma)</td>
<td>30.2% 3.01% 2.11%</td>
</tr>
<tr>
<td>(\phi) (0.35)</td>
<td>pp, Pb–Pb</td>
<td>1019.5</td>
<td>(\eta\gamma) (\pi^0\gamma) (\omega\gamma)</td>
<td>1.3% (1.25 \cdot 10^{-3}) &lt; 5%</td>
</tr>
<tr>
<td>(\Sigma^0) (1.0)</td>
<td></td>
<td>1192.6</td>
<td>(\Lambda\gamma)</td>
<td>100%</td>
</tr>
</tbody>
</table>

Use fit to measured \(\pi^0\) (Pb–Pb, pp) and \(\eta\) (pp)

Other particle spectra obtained via \(m_T\)-scaling of measured \(\pi^0\)

\(m_T\)-Scaling:

Same shape of cross sections, \(f(m_T)\), of various mesons

\[
E \frac{d^3 \sigma}{dp^3} = C_m \cdot f(m_T)
\]
Check of $m_T$ scaling

$\approx 10\%$ of decay photons

ALICE, pp $\sqrt{s} = 7$ TeV

$\approx 1-3\%$ of decay photons
Cocktail: decay photon flow

Use charged pion $v_n$ to estimate $\pi^0 v_n$
(flows agree within uncertainties)

$K_E_T$ scaling: $v_n$ of mesons scales with $K_E_T$
$K_E_T = m_T - m$
Electron selection criteria

Global Electron Selection Criteria
- Both tracks originate from the same V0 candidate
- No kinks
- Opposite charge
- Small R cut (R < 5 cm)
- TPC refit condition
- Minimum momentum of 50 MeV/c
- Minimum fraction of the TPC clusters with respect to findable clusters due to conversion radius

PID Based Selection Criteria
nσ around electron energy loss hypothesis in the TPC dE/dx
TOF electron nσ selection (if information available)

After PID ~ 80% pure photon sample
Pair selection criteria

**Photon $\chi^2$/ndf:**
- Based on a Kalman-Filter (AliKFParticle package)
- Measure for conversion likelihood: includes: zero V0 mass, pointing to primary vertex, correct electron mass, mutual secondary vertex

**Further Photon Selection Criteria:**
- Crosschecks for std. photon criteria
- Psi-Pair angle
  opening angle perpendicular to B field
- Cosine of pointing angle
  pointing to the primary vertex

**Photon $q_T$:**
- Transv. mom. component of daughter relative to the V0
  $q_T = p \times \sin(\Theta_{\text{mother-daughter}})$
- Clear separation of $\gamma$, $\Lambda$ and $K^0_s$
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Material Budget

Performance of the ALICE Experiment at the CERN LHC
arXiv:1402.4476 [nucl-ex]