Direct Photon measurements in pp and Pb-Pb collisions with ALICE

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Physics Motivation: Photon production in hadronic collisions

Direct prompt production in pp & Pb-Pb
- Compton Annihilation scattering
- Bremsstrahlung & Fragmentation

Additional direct production in Pb-Pb
- Jet-medium interaction
- Thermal photons

Production in pp & Pb-Pb
Hadronic decays ($\pi^0, \eta, \ldots \rightarrow \gamma \gamma$)

- Rate and cross sections in pQCD @ NLO: constraint on PDF/nPDF
- Direct processes (Compton & annihilation): access to parton energy loss in medium via $\gamma$-jet.

In Pb-Pb collisions, access to the medium properties via excess measurement.

At high energy mainly from parton fragmentation: jet quenching studies.
**ALICE experiment**

**Photon measurements:**
- Calorimetry: EMCal, PHOS
- Conversions: TPC+ITS

**Event Selection and Trigger:**
- V0, EMCal

**TPC:**
- $|\eta| < 0.9$; $0^\circ < \varphi < 360^\circ$

**EMCal:**
- $|\eta| < 0.7$; $80^\circ < \varphi < 180^\circ$

**V0:**
- $2.8 < \eta < 5.1$
- $-3.7 < \eta < -1.7$

**PHOS:**
- $|\eta| < 0.13$; $260^\circ < \varphi < 320^\circ$

**ITS:**
- $|\eta| < 0.9$
Analysis Strategy

Direct photon at low and intermediate $p_T$ ($\lesssim 10$ GeV/$c$)

Statistical Subtraction:

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

$$R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} = \frac{\gamma_{\text{incl}}^{\pi^0_{\text{param}}}}{\gamma_{\text{decay}}^{\pi^0_{\text{param}}}}$$

- $\gamma_{\text{incl}}$: measured in PHOS, PCM
- $\pi^0_{\text{param}}$: parametrisation of measured $\pi^0$ in PHOS, PCM
- $\gamma_{\text{decay}}$: from MC simulations

Direct photon at high $p_T$ ($\gtrsim 10$ GeV/$c$)

Isolation:

R. Ichou et al.,

Reduction of fragmentation and decay components (pp 14 TeV but valid at 7 TeV)

Measurement in EMCal
Photons at low and high $p_T$ in ALICE

**PCM: Photon Conversion Method**

- $\gamma$ by secondary vertex reconstruction
- Conversion probability: 8.5%
- $\pi^0$ by invariant mass analysis (see D. Muhlheim (id 102), A. Passfeld (id 138), H. Murakami (id 139), M. Danish (id 89))

**PHOS**

- $\gamma$ measured in calorimeter
- $\pi^0$ by invariant mass analysis (see P. Pareek (id 143), D. Sekihata (id 122), S. Yano (id 255))

**EMCAL**

- $\gamma$ measured in calorimeter
- $\pi^0$ by invariant mass analysis (see A. Matyja (id 107))
Direct photon double ratio $R_\gamma$: pp at $\sqrt{s} = 7$ TeV

PCM only

$$R_\gamma = \frac{\gamma^{\text{incl}}}{\gamma^{\text{decay}}} \equiv \frac{\gamma^{\text{incl}}}{\pi^0_{\text{param}}} / \frac{\gamma^{\text{decay}}}{\pi^0_{\text{param}}}$$

$$R_{NLO} = 1 + \frac{\gamma^{\text{direct,NLO}}}{\gamma^{\text{decay}}}$$

$R_\gamma \simeq 1$

- Consistent with NLO pQCD
- No significant direct photon signal
Direct photon Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

$R_{\gamma} > 1$

Intermediate $p_T$: excess beyond known prompt yield
- increases for more central collisions
- consistent with thermal radiation
- higher effective temperature than at RHIC
Direct Photon at high $p_T$: pp at $\sqrt{s}=7$ TeV: Isolation

Analysis: 2011 Data, EMCal L0 trigger at 5.5 GeV

**Photon selection: EMCal**

- Charge Particle Veto: Cluster-track matching residual: $|\Delta \varphi| > 0.03$, $|\Delta \eta| > 0.025$
- Shower Shape for $\pi^0 \rightarrow \gamma \gamma$ rejection:
  \[
  \sigma_{\text{long}}^2 = 0.5 \left( \sigma_{\varphi \varphi}^2 + \sigma_{\eta \eta}^2 + \sqrt{(\sigma_{\varphi \varphi} - \sigma_{\eta \eta})^2 + 4\sigma_{\eta \varphi}^2} \right)
  \]
  $\sigma_{\text{long}}^2$ larger eigenvalue squared of the cluster’s energy decomposition in EMCal ($\eta - \varphi$) plane:

  \[
  0.1 < \sigma_{\text{long}}^2 < \sigma_{\text{long}}^{2,\text{max}}; \quad \sigma_{\text{long}}^{2,\text{max}} \text{ energy dependent.}
  \]

**Isolation**

cone with radius $R = \sqrt{\Delta \varphi^2 + \Delta \eta^2} = 0.4$ around photon candidate
Isolated if: $\sum_{\text{charged,neutral}}^{\text{in cone}} p_T \leq p_T^{\text{thres}} = 2$ GeV/c
Isolated Photons in pp at $\sqrt{s} = 7$ TeV: Signal extraction

- The amount of particles is expressed as:
  - $S$ : for direct photons
  - $B$ : for background ($\pi^0$, $\eta$, decay photons ($\pi^0$, $\eta$), ...)
  - $N$ : $S + B$ total number of particles
- Dividing Isolation, $\sigma^2_{\text{long}}$ phase space in 4 regions:
  - $A$ : mainly signal region (isolated photons) + background
  - $B$, $C$, $D$: mainly background ($\pi^0$) + signal

Purity = number of clusters coming from isolated photons in the $N^\text{iso}_n$ sample

$$P = \frac{S^\text{iso}_n}{N^\text{iso}_n} = 1 - \frac{B^\text{iso}_n}{N^\text{iso}_n}$$

Assuming bkg isolation fractions are the same at low and high $\sigma^2_{\text{long}}$: $\frac{B^\text{iso}_n}{N^\text{iso}_n} / \frac{B^\text{iso}_w}{N^\text{iso}_w} = 1$

Taking into account signal in background region: $\Rightarrow \left( \frac{B^\text{iso}_n}{N^\text{iso}_n} / \frac{N^\text{iso}_w}{N^\text{iso}_w} \right)_{\text{data}} = \left( \frac{B^\text{iso}_n}{N^\text{iso}_n} / \frac{N^\text{iso}_w}{N^\text{iso}_w} \right)_{\text{MC(GJ+JJ)}}$

$$P = 1 - \left( \frac{N^\text{iso}_n}{N^\text{iso}_w} \right)_{\text{data}} \times \left( \frac{B^\text{iso}_n}{N^\text{iso}_w} / \frac{N^\text{iso}_n}{N^\text{iso}_w} \right)_{\text{MC(GJ+JJ)}}$$

*MC(GJ+JJ): Pythia pp including processes involving 2 jets (JJ) or a gamma and a jet (GJ) in final state;
Isolated Photons in pp at $\sqrt{s} = 7$ TeV: Purity and systematics

$P = 1 - \left( \frac{N_{n}^{\text{iso}} / N_{n}^{\text{iso}}}{N_{w}^{\text{iso}} / N_{w}^{\text{iso}}} \right)_{\text{data}} \times \left( \frac{B_{n}^{\text{iso}} / N_{n}^{\text{iso}}}{N_{w}^{\text{iso}} / N_{w}^{\text{iso}}} \right)_{\text{MC}(GJ+JJ)}$

Purity increases with $E_{T}^{\gamma}$ up to 80%

Main systematic error source from MC modelling of shower shape $\sigma_{\text{long}}^2$
Isolated Photons in pp at $\sqrt{s} = 7$ TeV: Differential cross section

\[ \frac{d^2 \sigma}{dp_T d\eta} = \frac{d^2 N}{dp_T d\eta} \times \frac{P}{\epsilon_{\text{reco}} \times A_{cc} \times \mathcal{L}_{\text{int}}} \]

\[ \mathcal{L}_{\text{int}} = 473 \pm 22^{\text{stat}} \pm 17^{\text{syst}} \text{nb}^{-1} \]

JETPHOX:

Isolated photon cross section measured in $10 \text{ GeV} \lesssim E_T \lesssim 60 \text{ GeV}$
Compatible with NLO predictions
Isolated Photons: Comparison with CMS, ATLAS

- Reasonable agreement with CMS, ATLAS in overlapping region
Isolated Photons: Comparison with CMS, ATLAS

- Reasonable agreement with CMS, ATLAS in overlapping region
- Lower $E_T$ reach
- Constraint error on thermal photons
Summary

Direct photon measurements in ALICE:

- **With statistical subtraction:**
  - Measurement in pp and Pb-Pb collisions from $p_T \simeq 0.5 \text{ GeV/c}$ to $12 \text{ GeV/c}$
  - Results compatible with NLO pQCD predictions for $p_T \gtrsim 5 \text{ GeV/c}$.
  - In Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ low/intermediate $p_T$ excess: consistent with thermal radiation.

- **With Isolation in EMCal:**
  - Extension of lower $p_T$ reach in ALICE for isolated photons with respect to other LHC experiments;
  - Agreement with NLO pQCD predictions

Outlook:

- Isolated photons in Pb-Pb
- Isolated photons with PHOS
- Isolated photon-hadron correlations to access fragmentation functions
  - see E. Epple poster (ID 181), A. Vauthier oral presentation (This morning)
- Direct photon flow measurements in Pb-Pb via statistical subtraction
BACKUP
Photon Reconstruction in PCM analysis

Track selection:
- min track $p_T : 50 \text{ MeV/c}$
- dist to primary vertex: $R \in [5-180] \text{ cm}$

Electron identification:
- TPC $dE/dx + \text{TOF} \ n\sigma$ if available

Photon Candidates
- Photon $\chi^2/ndf$ based on Kalman-Filter
- remaining $V^0(\Lambda, K^0_S \ldots)$ removed with further selections: $q_T = p \times \sin(\theta_{\text{mother} - \text{daughter}})$

- purity of photon sample for $p_T \lesssim 3 \text{ GeV/c}$:
  - $\gtrsim 98\%$ in periph Pb-Pb
  - $\gtrsim 90\%$ in central Pb-Pb

- Energy resolution
  - $\sigma_E/E \approx 1.6\%$ for $1 \lesssim E \lesssim 2 \text{ GeV/c}$

- D. Muhlheim (id 102), A. Passfeld (id 138)
- H. Murakami (id 139), M. Danish (id 89)
Photons in EMCal

EMCal: Pb-scintillator layers
- 4.28 m from IP
- $|\eta| < 0.7$, $\varphi \in [80^\circ, 180^\circ]$
- $\Delta \eta, \Delta \varphi = 0.014$
- $\frac{\sigma_E}{E} = \frac{4.8}{E} \oplus \frac{11.3}{\sqrt{E}} \oplus 1.7$

Photon Identification via Shower shape: $\sigma_{\text{long}}^2$ larger eigenvalue squared of the cluster’s energy decomposition in EMCal ($\eta - \varphi$) plane:

\[
\sigma_{\text{long}}^2 = 0.5 \left( \sigma_{\varphi\varphi}^2 + \sigma_{\eta\eta}^2 + \sqrt{ \left( \sigma_{\varphi\varphi} - \sigma_{\eta\eta} \right)^2 + 4 \sigma_{\varphi\eta}^2 } \right)
\]

\[
\sigma_{\varphi\varphi} = \frac{\sum_i w_i \varphi_i^2}{\sum_i w_i^2} - \left( \frac{\sum_i w_i \varphi_i}{\sum_i w_i} \right)^2
\]

\[
\sigma_{\eta\eta} = \frac{\sum_i w_i \eta_i^2}{\sum_i w_i^2} - \left( \frac{\sum_i w_i \eta_i}{\sum_i w_i} \right)^2
\]

\[
\sigma_{\varphi\eta} = \frac{\sum_i w_i \varphi_i \eta_i}{\sum_i w_i^2} - \left( \frac{\sum_i w_i \eta_i x \sum_i w_i \varphi_i}{\sum_i w_i^2} \right)^2
\]

\[
w_i = \max(0, 4.5 + \log \frac{E_i}{E})
\]

$\gamma$ from $\pi^0$ discrimination

$0.1 < \sigma_{\text{long}}^2 < \sigma_{\text{long}}^{\text{max}}$, $\sigma_{\text{long}}^{\text{max}}$ energy dependent.
Direct Photon Spectra: Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

All Models with QGP formation

- **Paquet et al:** 2+1 hydro + IP-Glasma conditions
  \((\tau = 0.4 \text{ fm/c}; < T_{0-20\%} > \approx 385 \text{ MeV})\).

- **Linnyck et al:** Off-shell transport, microscopic description of evolution

- **Chatterjee et al:** 2+1 hydro fluctuating initial conditions
  \((\tau = 0.14 \text{ fm/c}; T_{0-20\%} \approx 740 \text{ MeV})\).

- **v. Hees et al:** ideal hydro with initial flow,
  \((\tau = 0.2 \text{ fm/c}; T_{0-20\%} \approx 682 \text{ MeV})\).

Direct Photon Spectra: Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>$T_{\text{eff}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>ALICE$^1$ 304 $^{+11}<em>{-11}^{\text{stat}}$ $^{+40}</em>{-11}^{\text{syst}}$</td>
</tr>
<tr>
<td>20-40%</td>
<td>407 $^{+61}<em>{-61}^{\text{stat}}$ $^{+96}</em>{-61}^{\text{syst}}$</td>
</tr>
</tbody>
</table>

Direct Photon $R_{AA}$: Pb-Pb at $\sqrt{s_{NN}}=2.76$ TeV

Reference: pQCD calculation by the Mc Gill group ArXiv: 1509.06738

- Excess at low $p_T$ visible in all centrality classes
- confirms $N_{\text{coll}}$ scaling of pQCD photons for $p_T \gtrsim 5$ GeV/c
Direct Photon Flow: Pb-Pb at $\sqrt{s_{NN}}=2.76$ TeV (1)

$$\frac{dN}{d\varphi} = \frac{1}{2\pi} (1 + \sum_{n \geq 1} 2v_n \cos(n(\varphi - \Psi^{RP}))) ;$$

$$v_n^{incl} = \frac{N_n^{dir}}{N_n^{incl}} v_n^{\gamma, dir} + \frac{N_n^{decay}}{N_n^{incl}} v_n^{\gamma, decay}$$

$$\rightarrow v_n^{\gamma, dir} = \frac{R v_n^{\gamma, incl} - v_n^{\gamma, decay}}{1-R}$$

- Inclusive photons measured via PCM;
- Decay photon $v_2$ calculated based on measured charged $\pi^{\mp} v_2$
- Inclusive photon $v_2$ significantly lower than decay photon $v_2$ for $p_T \geq 3$ GeV/c
- below 3 GeV/c: both consistent within uncertainties
  - similar $v_2$ or
  - no direct photons

Direct Photon Flow: Pb-Pb at $\sqrt{s_{NN}}=2.76$ TeV (2)

- hadron-like $v_2$
- Different sources in models but no possible discrimination
## Isolated photons Systematic Error

<table>
<thead>
<tr>
<th>systematic error sources</th>
<th>error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong> $\sigma_{\text{long}}^2$ selection</td>
<td>4-6.5%</td>
</tr>
<tr>
<td>Isolation probability</td>
<td>8%-3%</td>
</tr>
<tr>
<td>Track-matching</td>
<td>1.%-9%</td>
</tr>
<tr>
<td>Monte Carlo (JJ+GJ sample)</td>
<td>1%</td>
</tr>
<tr>
<td>Purity: extrapolation of isolation probabilities</td>
<td>5-17%</td>
</tr>
<tr>
<td>Efficiency and normalisation</td>
<td>10%</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>13-20%</td>
</tr>
</tbody>
</table>

![Graph showing systematic uncertainty](ALI-PREL-112754)

*ALICE Preliminary*

*pp $\sqrt{s} = 7$ TeV*
JETPHOX \textsuperscript{a, b} Version 1.3.1

- FF: BFG II (large gluon)
- PDF: CTEQ6M, CT10
- scales: \( \mu = 0.5 E_T^\gamma, E_T^\gamma, 2 E_T^\gamma \)
- Isolation criteria: \( R = 0.4 \ E_T^{iso} < 2 \) GeV \& \( R = 0.4 \ E_T^{iso} < 5 \) GeV

\[ \sum p_T < 2 \text{ GeV/c} \]

\[ \sum p_T < 5 \text{ GeV/c} \]