Direct Photons in Pb-Pb Collisions with ALICE

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September 30, 2015
Definition: Photons not coming from particle decays

- Photons from all stages of a heavy-ion collision
  - Prompt Photons
    - Initial hard scattering, described by NLO pQCD
    - Fragmentation photons: maybe suppressed by QGP?
    - Dominant at high $p_T$
  - Jet-medium interactions
    - Hard partons scatter with thermalized medium
    - Quarks emit photon bremsstrahlung
  - Thermal Photons
    - Thermalized medium (QGP, hadron gas)
    - Exponential distribution, dominant at low $p_T$

New ALICE paper: arXiv:1509.07324
Analysis Strategy

• Challenge: not all photons are direct
  – Large decay photon background ($\pi^0$, $\eta$, …)
  – Photons cannot be directly discriminated

• Statistical method
  – Measure all photons (inclusive photons)
    • Obtain clean photon sample
  – Measure hadrons, simulate decay photons
  – Subtract decay photons from inclusive photon sample

• Indirect subtraction by “double ratio” $R_\gamma$

\[
\gamma_{\text{direct}} = \gamma_{\text{inc.}} - \gamma_{\text{decay}} = (1 - \frac{1}{R_\gamma}) \cdot \gamma_{\text{inc.}}
\]

– Some uncertainties cancel in the ratio

\[
R_\gamma = \frac{\gamma_{\text{inc.}}}{\pi^0_{\text{param}}} / \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}}
\]

$\pi^0$: ≈ 86-88%
$\eta$: ≈ 10-12%
$\omega$: ≈ 2-3%
Others: very small

0-20% Pb-Pb Monte Carlo simulation

ALICE: arXiv:1509.07324

ALI-PUB-97735
**Photon Conversion Method**

- Excellent energy resolution in pp, p-Pb and Pb-Pb collisions
  - $\sigma(\pi^0) \approx \text{FWHM}/2.36 \approx 3 \text{ MeV}/c^2$ at low $p_T$
- Photons by secondary vertex reconstruction
- High purity with cuts on topology and electron track properties
  - Photon purity $> 90\%$ in central Pb-Pb, $> 98\%$ in peripheral
- Conversion probability $\approx 8.5\%$
- Large acceptance ($0 < \varphi < 2\pi$, $|\eta| < 0.9$)
- Limited by statistics at high $p_T$
PHOS Calorimeter Measurement

- New, complementary method to PCM, different systematics, statistically independent
  - Cross check and improvement of measurement

- Direct measurement of photons

- Good energy resolution
  - $\sigma(\pi^0) \approx 7$ MeV/$c^2$ at low $p_T$

- Photons selected by cuts on energy, cluster size, and cluster dispersion, charged particle veto
  - Cuts tuned to photon efficiency of 96-99%
  - Contamination < 3% at low $p_T$

Poster 716 by D. Peresunko:
Direct photons in p-Pb collisions with PHOS

PHOS Calorimeter

- Direct Photons in Pb-Pb Collisions with ALICE
- QM 2015
- 30/09/2015
• η decay photons second largest contributor to background
  - Use η/π^0 ratio to derive η spectrum
    • Published so far only in pp collisions (\(\sqrt{s} = 0.9\) TeV and 7 TeV)
    - Likely different behaviour in Pb-Pb collisions due to flow
      • Scaling at low \(p_T\): \(m_T\) scaling? Use \(K^0_s\) shape as proxy?

• Average between \(m_T\) scaling and \(K^0_s\) shape used

• New: preliminary η measurement in Pb-Pb collisions: high \(p_T\) scaling confirmed, low \(p_T\) not fully constrained
Comparison between PCM/PHOS

- Comparison of inclusive photon measurements
  - PHOS in general above PCM, same observation as for $\pi^0$

- Rigorous quantification of differences taking into account the correlation of uncertainties
  - Agreement at the level of $1.2\sigma$ between PHOS and PCM inclusive photon spectra

- Results can be combined
Inclusive Photons

- Combined result of independent PHOS and PCM measurements
- Inclusive photons measured in three centrality classes
- $0.9 \text{ GeV}/c < p_T < 14 \text{ GeV}/c$
- Main uncertainties (PCM)
  - Material budget of the detector (4.5%)
  - Photon selection criteria (up to 4% at low $p_T \ll 2 \text{ GeV}/c$)
- Main uncertainties (PHOS)
  - Global energy scale (up to 9.6%)
  - Efficiency calculation (3 % in 0-20% central)
Double Ratio $R_\gamma$

- Double ratio $R_\gamma$ calculated independently for PCM and PHOS
  - Using $\pi^0$ measurements from same system

- Partial cancellation of uncertainties
  - Energy scale uncertainties (PHOS)
  - Material budget uncertainty (PCM)

- Both measurements in good agreement
  - $0.4\sigma$ between PCM and PHOS
Combined $R_\gamma$ Result

- Combination of the two individual measurements of the double ratio
  - Independent measurements, error-weighted average
  - Excess at high $p_T$ for all centralities
  - Low $p_T$ excess in central collisions: significance at the level of 2.6$\sigma$ for $0.9 \text{ GeV}/c \leq p_T \leq 2.1 \text{ GeV}/c$
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- Compared with expectation from NLO/JETPHOX pQCD
  - $N_{\text{coll}}$ scaled, measured $\pi^0$ suppression
  - Good agreement with data for $p_T \gtrsim 5 \text{ GeV}/c$
  - Excess in central Pb-Pb at low $p_T$ not explained by pQCD - other photon source
Excess Quantification

- Excess quantified with pseudo experiments
  - Here for \(0.9 \text{ GeV/c} \leq p_T \leq 2.1 \text{ GeV/c}\)
- Assumption of null hypothesis:
  \(R_\gamma\) is unity for all points: \(R_0 = 1\)
- Type B, C systematics shift baseline: \(R_{\text{mod},i}\)
  - \(\varepsilon_{B,C}\): deviation in units of standard deviation
  - Pseudo data points \(R_{\text{pd},i}\) drawn around baseline
  - Gaussian distribution with standard deviation given by type A uncertainties
- Each test statistic \(t\): sum of squared differences of pseudo data points w.r.t. \(R_0\) in units of uncorrected uncertainties
  - \(p\)-value: fraction of pseudo-experiments with \(t\) larger than in real data
  - Significance calculated based on two-tailed test

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
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<tr>
<td>Type A</td>
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Direct Photon Spectra

- Direct photon spectra measured in three centrality classes
  - $0.9 \text{ GeV/c} < p_T < 14 \text{ GeV/c}$
  - Upper limits (90% C.L.) extracted in more peripheral collisions

![Graph showing direct photon spectra with data points for different centrality classes.](image)
Direct Photon Spectra

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  - Upper limits (90% C.L.) extracted in more peripheral collisions

- Comparison with $N_{\text{coll}}$ scaled pQCD and JETPHOX calculations
  - Same calculations as in previous $R_\gamma$ plots
  - Hence: good agreement with data for $p_T \gtrsim 5 \text{ GeV/c}$
  - Excess over calculations in 0-20% and 20-40% central collisions at low $p_T$
Nuclear Modification Factor

- Nuclear modification factor $R_{AA}$ calculated using pQCD reference
- Excess at low $p_T$ visible in 0-20% central events
  - $R_{AA} > 6$ at low $p_T$ in central Pb-Pb collisions
- Excess less significant in 20-40% central events
Comparison with PHENIX

- PHENIX reported direct photon excess in 0.2 TeV Au-Au in 2010 and confirmed in 2015

\[ \text{PRL104 (2010)132301, PRC91/6 (2015) 064904} \]

- Exponential fit to low \( p_T \) excess of direct photon spectrum

- Inverse slope parameter somewhat larger at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) than at \( \sqrt{s_{NN}} = 0.2 \text{ TeV} \):
  \[ T_{\text{eff}} = 304 \pm 11^{\text{stat}} \pm 40^{\text{sys}} \text{ MeV (ALICE)} \]
  \[ T_{\text{eff}} = 239 \pm 25^{\text{stat}} \pm 7^{\text{sys}} \text{ MeV (PHENIX)} \]
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    - $T_{\text{eff}} = 304 \pm 11^{\text{stat}} \pm 40^{\text{sys}}$ MeV (ALICE)
    - $T_{\text{eff}} = 239 \pm 25^{\text{stat}} \pm 7^{\text{sys}}$ MeV (PHENIX)
- 20-40% compatible with 0-20%:
  - $T_{\text{eff}} = 407 \pm 61^{\text{stat}} \pm 96^{\text{sys}}$ MeV (ALICE)
- Relation to medium temperature complicated


ALICE data: arXiv:1509.07324

PHENIX data: PRC91/6 (2015) 064904

ALICE: $\sqrt{s_{NN}} = 2.76$ TeV

PHENIX: $\sqrt{s_{NN}} = 0.2$ TeV
Model Comparisons

- Various models available
  - All models assume QGP formation, include pQCD photons at high $p_T$

- Treatment of space-time evolution
  - $v.$ Hees et al.: ideal hydro with initial flow, $\tau_0 = 0.2$ fm/$c$, $T_{init}^{0-20\%} = 682$ MeV
  - Chatterjee et al.: 2+1 hydro, fluctuating initial conditions, $\tau_0 = 0.14$ fm/$c$, $T_{init}^{0-20\%} \approx 740$ MeV
  - Paquet et al.: 2+1 viscous hydro with IP-GLASMA initial conditions, $\tau_0 = 0.4$ fm/$c$, $<T_{init}^{0-20\%}> = 385$ MeV
  - Linnyk et al.: off-shell transport, microscopic description of evolution

- Comparison shows different levels of agreement
Summary

- Direct photon measurement in Pb-Pb collisions using statistical method

- Low $p_T$, $0.9 \text{ GeV/c} \leq p_T \leq 2.1 \text{ GeV/c}$, direct photon excess has been measured by ALICE in 0-20% central Pb-Pb collisions
  - Two independent measurements (PCM, PHOS) in good agreement
  - $R_\gamma$ excess has significance of $2.6\sigma$

- Direct photon yield measured in three centrality classes
  - pQCD calculations in agreement with measurement for $p_T \gtrsim 5 \text{ GeV/c}$

- Exponential slope of yield in 0-20%: $T_{\text{eff}} = 304\pm11^{\text{stat}}\pm40^{\text{sys}} \text{ MeV}$
  - Appears larger than at RHIC energies

- Various models on the market, show different levels of agreement
  - Not possible to distinguish between models within significance of data
Backup
Systematic Uncertainties

- Three categories
  - Point-by-point uncorrelated (Type A)
  - Correlated in $p_T$ with magnitude varying point-by-point (Type B)
  - Constant (normalization) (Type C)

### PCM

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<tr>
<th>Centrality</th>
<th>0–20%</th>
<th>20–40%</th>
<th>40–80%</th>
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<tbody>
<tr>
<td>$p_T$ (GeV/c)</td>
<td>1.2</td>
<td>5.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

#### $\gamma_{\text{incl}}$ yield
- Track quality (A) 0.6 0.6 0.2 0.2 0.2 0.7
- Electron PID (A,B) 1.5 6.9 0.9 4.8 0.7 4.0
- Photon selection (A,B) 4.0 1.8 2.4 2.1 1.5 1.3
- Material (C) 4.5 4.5 4.5 4.5 4.5 4.5

#### $\gamma/\pi^0$ ratio
- Track quality (A) 0.7 1.7 0.8 0.4 0.6 1.3
- Electron PID (A,B) 1.2 4.8 0.9 3.8 0.9 4.0
- Photon selection (A,B) 3.2 3.2 3.0 1.5 2.5 2.4
- $\pi^0$ yield (A) 1.6 2.9 1.7 2.7 0.5 3.0
- Material (C) 4.5 4.5 4.5 4.5 4.5 4.5

#### $\gamma_{\text{decay}}/\pi^0$
- $\pi^0$ spectrum (B) 0.5 1.2 0.8 1.8 0.5 3.2
- $\eta$ yield (C) 1.4 1.4 1.4 1.4 1.4 1.4
- $\eta$ shape (B) 1.6 0.5 1.2 0.2 1.0 0.2

Total $R_\gamma$ 6.2 8.1 5.7 7.0 5.7 8.3

Total $\gamma_{\text{incl}}$ 6.2 8.5 5.2 6.9 4.8 6.2

### PHOS

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<td>$p_T$ (GeV/c)</td>
<td>2 10 2 10 2 10</td>
<td></td>
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#### $\gamma_{\text{incl}}$ yield
- Efficiency (B) 3.0 3.0 0.7 0.7 2.5 2.5
- Contamination (B) 2.0 2.0 1.3 1.3 2.9 0.5
- Conversion (C) 1.7 1.7 1.7 1.7 1.7 1.7
- Acceptance (C) 1.0 1.0 1.0 1.0 1.0 1.0
- *Global E scale (B) 9.6 9.0 6.1 5.9 5.8 6.3
- *Non-linearity (B) 2.2 0.1 2.1 0.1 2.0 0.1

#### $\pi^0$ yield
- Yield extraction (A) 2.7 4.0 3.1 5.2 1.8 2.9
- Efficiency (B) 1.8 1.8 2.7 2.2 2.5 2.5
- Acceptance (C) 1.0 1.0 1.0 1.0 1.0 1.0
- Pileup (C) 1.0 1.0 1.0 1.0 1.0 1.0
- Feed-down (B) 2.0 2.0 2.0 2.0 2.0 2.0

#### $\gamma_{\text{decay}}/\pi^0$
- $\pi^0$ spectrum (B) 1.3 4.3 1.8 1.8 1.8 1.8
- $\eta$ contribution (B) 2.2 1.7 2.2 1.6 2.1 1.6

Total $R_\gamma$ 6.8 7.9 5.9 6.5 6.1 6.0

Total $\gamma_{\text{incl}}$ 12.4 12.7 9.7 10.0 9.8 9.6
• Pair charged tracks with large impact parameter

• V0 candidates: pairs with a small DCA
  – Mostly $K^0_s$, $\Lambda$, $\bar{\Lambda}$, $\gamma$

• Photon conversion probability for $R < 180$ cm: 8.5%
Neutral pions in $\sqrt{s} = 2.76$ TeV Pb-Pb collisions measured by ALICE

- Input for direct photon measurement
- Measured by PCM and PHOS
Nuclear Modification Factor (all centralities)

- Nuclear modification factor $R_{AA}$ calculated using pQCD reference
- Excess at low $p_T$ visible in 0-20% central events
  - $R_{AA} > 6$ at low $p_T$ in central Pb-Pb
- Excess also possible in 20-40% central events
- Peripheral events show too large uncertainties to conclude
Model Comparisons extended

- Models compared up to high $p_T$

\[ \frac{1}{2\pi N_{ev}} \frac{d^2N_{\gamma, \text{dir}}}{dp_T dy} (\text{GeV}^{-2} \text{c}^{-2}) \]

Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

- 0-20% ALICE
- 20-40% ALICE
- 40-80% ALICE

Paquet et al. 
Linnyk et al.
v. Hees et al.
Chatterjee et al.

ALICE: arXiv:1509.07324

ALI−PUB−97905
Particle Ratios

• Production ratios of various mesons to $\pi^0$
  – Important for cocktail calculations
A word on $v_N$

- Direct photon $v_2, v_3$ rely on $R_\gamma$:  
  \[ v_2^{\text{direct}} = \frac{R_\gamma \cdot v_2^{\text{incl}} - v_2^{\text{dec}}}{R_\gamma - 1} \]

\[ \begin{align*}
  v_2^\gamma, \text{decay} & \quad v_2^\gamma, \text{incl} \\
  v_3^\gamma, \text{decay} & \quad v_3^\gamma, \text{incl}
\end{align*} \]