Direct photon production in pp, p-Pb and Pb-Pb collisions measured with the ALICE experiment

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Direct photons in pp collisions

Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision.

\[
\frac{d\sigma^{\gamma,\text{dir}}}{dp_T \, d\eta} = F_{i/h} \otimes \sigma_{ij} \otimes D_{\gamma/k}
\]

- \(F_{i/h}\) – nucleon structure function
- \(\sigma_{ij}\) – cross-section of the elementary process
- \(D_{\gamma/k}\) – fragmentation function
Direct photons in AA (and p-A?) collisions

- Prompt direct photons
- Thermal direct photons
- Decay photons

Graph showing photon yield vs. $p_T$ (GeV/c):
- Thermal: $e^{-E_\gamma/T}$
- Prompt: $1/p_T^n$
- Decay
ALICE apparatus
Photon measurement in ALICE

**EMCal calorimeter**
- Pb/scintillator sampling calorimeter
- $|\eta| < 0.7$, $80^\circ < \phi < 180^\circ$

**Photon Conversion Method (PCM)**
- ITS and TPC
- $|\eta| < 0.9$, $0^\circ < \phi < 360^\circ$
- Conversion in detector material
- $X / X_0 = (11.4 \pm 0.5)\%$
- Conv. probability $\sim 8\%$

**PHOS calorimeter**
- PbWO$_4$ crystals
- $|\eta| < 0.12$, $260^\circ < \phi < 320^\circ$
Direct photon extraction

Subtraction method:

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

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

Inclusive photons: all photons that are produced

Decay photons: calculated by decay simulation from measured or \( m_T \) scaled hadron spectra

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

Numerator:
Measured inclusive \( \gamma \) spectrum per measured \( \pi^0 \)

Denominator:
Estimated sum of all decay photons per \( \pi^0 \)

Advantage of ratio: cancellation of some large systematic uncertainties
Double ratio in pp collisions

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

Systematic uncertainties of individual meas. are dominated by \( p_T \)-independent ones: material budget unc. of 4.5% PCM, 2.8% EMC

\[ R_{\gamma,NLO} = 1 + \frac{Y_{\text{dir}}^{\text{NLO}}}{Y_{\text{dec}}} \]

Within uncertainties no significant excess at low \( p_T \) observed
About 1 – 2σ deviation from unity for \( p_T > 7 \) GeV/c
Direct photon spectrum in pp collisions

- Upper limits at 90% C.L. (arrows) determined where $R_\gamma$ with total uncertainties consistent with unity

- Theory NLO calculations:
  - W. Vogelsang (CT10, GRV)
  - J.F. Paquet (CTEQ6.1M, BFG)
  - Thermal (Shen et al.) are consistent with measurements
Direct photons in p-Pb

Is hot matter created in collisions of small systems?

Pro
- Observation of collective flow
- Increase of strangeness yield

Contra
- No hard hadron suppression

Can we see thermal radiation in p-Pb collisions?

Theoretical NLO prediction plotted as

$$R_{Y,NLO} = 1 + \frac{N_{coll} Y_{dir}^{NLO}}{Y_{dec}}$$
Direct photons in p-Pb

Systematic uncertainties of individual measurements are mostly $p_T$-independent.

Within uncertainties no significant excess at low $p_T$ observed. Accuracy is not yet sufficient to confirm/close thermal radiation at p-Pb collisions.
Direct photons in p-Pb

Upper limits at 90% C.L. (arrows) determined where $R_γ$ with total uncertainties consistent with unity.

Both NLO calculations scaled with number of binary collisions $N_{\text{coll}}$ (W. Vogelsang) and hydrodynamic model predictions (Shen et al.) are consistent with measurements.
Direct photon spectrum in Pb-Pb

Double ratio was measured in 3 centrality classes with 2010 Pb–Pb data by two methods, PCM and PHOS.

Measurements are consistent (remember that systematic unc. are mostly $p_T$-independent)
Direct photon excess in Pb-Pb

At low $p_T$
~ 15% excess in $0 - 20\%$;
~ 9% in $20 - 40\%$

At high $p_T$ above $\sim 5$ GeV/c
in agreement with NLO pQCD and JETPHOX

Remember, in pp collisions: no low $p_T$
excess seen at same center-of-mass energy
Direct photon spectra are measured in 3 centrality classes. Hydrodynamic models, assuming thermal emission and prompt contribution predict 2-7 times smaller yield, though within uncertainties.
Direct photon spectrum in Pb-Pb

Both absolute yield of direct photons and effective slope increases in increase of the collision energy.
Collective flow – asymmetry in particle production, common for all soft particles in event.

\[
\frac{dN}{d\phi} = 1 + 2v_1 \cos(\phi - \Psi_{RP}) + 2v_2 \cos(2(\phi - \Psi_{RP})) + 2v_3 \cos(3(\phi - \Psi_{RP})) + \ldots
\]

\(v_1\) - directed, \(v_2\) – elliptic, \(v_3\) – triangular flow, ...
Direct photon collective flow

Collective expansion transforms initial spacial asymmetry of fireball to asymmetry in momentum space.

Thermal photons, emitted early from hotter fireball carry smaller collective flow than those, emitted at later stages.

=> one can test development of collective flow with direct photons.
Inclusive photon flow

Elliptic flow of inclusive photons was measured with PCM and PHOS and found to be consistent.

\[ p_T < 3 \text{ GeV/c}: \quad v_2^{\gamma,\text{inc}} = v_2^{\gamma,\text{dec}} \]

\[ \Rightarrow \text{Either no contribution of } \gamma,\text{dir} \]

\[ \text{or } v_2^{\gamma,\text{dir}} = v_2^{\gamma,\text{dec}} \]

\[ \rightarrow \text{Theory } \sim 30 - 40\% \text{ too high} \]

\[ p_T > 3 \text{ GeV/c}: \quad v_2^{\gamma,\text{inc}} < v_2^{\gamma,\text{dec}} \]

\[ \rightarrow \text{prompt photon contribution} \]
Direct photon flow

- Large direct photon $v_2$ for $p_T < 3$ GeV/c
- Measured magnitude of $v_2^{\gamma,\text{dir}}$ comparable to hadrons
- Result points to late production times of direct photons after flow is established

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

$v_2^{\gamma,\text{dir}}$ compatible with $v_2^{\gamma,\text{dir}} = 0$ within 1.4(1.0)$\sigma$ in $p_T$ range $(0.9 < p_T < 2.1$ GeV/c$)$

No deviation beyond 2$\sigma$ from theory observed for $v_2^{\gamma,\text{dir}}$
Comparison with direct photon flow at RHIC

\[ \left( v_{2}^{\gamma, \text{dir}} \right)_{\text{LHC}} \approx \left( v_{2}^{\gamma, \text{dir}} \right)_{\text{RHIC}} \]

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Conclusions

- $\gamma_{\text{dir}}$ production in pp & p-Pb collisions:
  - No significant direct photon excess observed in thermal photon region
  - Consistent with $N_{\text{col}}$ scaled NLO pQCD calculations at higher $p_T$

- $\gamma_{\text{dir}}$ production and flow in Pb-Pb Collisions:
  - Direct photon excess for $p_T < 3$ GeV/c observed with 2.6σ for 0-20% and 1.5σ in 20-40% centrality classes
  - Spectrum consistent with $N_{\text{col}}$ scaled NLO pQCD calculations at high $p_T$
  - All low $p_T$ spectrum consistent with hydrodynamic model predictions
  - Direct photon flow measurement with 2 independent reconstruction techniques in Pb–Pb collisions
  - Direct photon flow $v_2$ in centrality classes 0-20% & 20-40% of similar size as the charged hadron flow and inclusive photon flow, but compatible with 0 within 1.4(1.0)σ in $p_T$ range (0.9 < $p_T$ < 2.1 GeV/c)

- Direct photons confirm creation in Pb-Pb collisions of hot matter with significant collective expansion

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Backup
Decay photon flow
Direct photon flow uncertainties

\[ V_{2\gamma,\text{dir}} = \frac{R_\gamma \cdot V_{2\gamma,\text{inc}} - V_{2\gamma,\text{dec}}}{R_\gamma - 1} \]
Hadron spectra used for decay photon calculation
Direct photon excess in Pb-Pb
Direct and isolated photons

\[ R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

\[ E_{\text{hadronic sum}}^{\gamma} (R < 0.5 \text{ rad}) < 0.1 \times E_{\gamma} \]
Isolated photons

$E_T^\gamma$ (GeV)

$\sigma_{\gamma \gamma}$ (nb GeV$^{-1}$)

ALICE Preliminary

Data + stat. Uncertainty
Syst. Uncertainty
NLO pQCD JETPHOX
CT10 PDFs / BFG-II
$\mu_R = \mu_F = E_T$
Theory Scale Uncertainty
$E_T / 2 < \mu < 2 E_T$
PDF Uncertainty

$pp \sqrt{s} = 7$ TeV
$|\eta| < 0.27$

$R^{\text{iso}} = 0.4, E_T^{\text{iso}} < 2$ GeV

ALICE Preliminary

Data / JETPHOX + Stat. Uncertainty
Syst. Uncertainty
JETPHOX 1.3.1 CT10 PDFs / BFG-II
Theory scale uncertainty
$E_T / 2 < \mu < 2 E_T$
PDF uncertainty

$E_T^\gamma$ (GeV)

$\sqrt{\sigma_{\gamma \gamma}}$ (nb GeV$^{-1}$)

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