Exploring hot QCD matter via direct photons at ALICE

D. Peresunko for the ALICE collaboration
NRC “Kurchatov institute”, Kurchatov sq. 1, Moscow, Russia
E-mail: Dmitri.Peresunko@cern.ch

Abstract. We review ALICE results on direct photon production in pp, pA and AA collisions and compare them to predictions of NLO pQCD calculations, hydrodynamic, and transport models. In pp and pA collisions the measured direct photon yield is consistent with NLO pQCD calculations, scaled with the number of binary collisions. In Pb-Pb collisions an additional direct photon contribution is observed at low $p_T < 4$ GeV/c which can be interpreted as a thermal direct photon contribution. The measured yield is larger than predictions of hydrodynamic models, but still consistent with them within uncertainties. The elliptic collective flow of direct photons was measured in central and mid-central Pb–Pb collisions and compared with hydrodynamic model predictions.

1. Introduction
Direct photons are the photons created in interactions of charged particles in course of pp, pA or AA collision and not in decays of final hadrons. Unlike hadrons, direct photons freely escape from the hot matter and provide information about all stages of the collision. One can classify direct photons according to processes which led to their creation. Thus, *prompt* direct photons are produced in collisions of partons within incoming nucleons. Prompt direct photons have an approximately power-law spectrum [1] and dominate at high transverse momenta. The measurement of direct photon spectra in pp, pA and AA collision provides the possibility to impose restrictions on parton distribution functions (PDF) and fragmentation functions (FF) and their modification in nuclei, and test scaling with the number of binary collisions in pA and AA cases. In AA and possibly in pA collisions in addition to prompt photons one can expect emission of *thermal* direct photons created in collisions of particles in hot matter. Thermal direct photons have approximately an exponential spectrum [2] and contribute mostly to the low-energy part of the spectrum. The spectrum of thermal direct photons provides tools to probe the properties of hot matter in the central hottest part of the collision, such as temperature, space-time volume and radial collective flow. In addition, the measurement of elliptic collective flow of the thermal direct photons gives the possibility to trace the development of the collective expansion of hot matter at the earliest stage of the collision.

2. ALICE experiment
ALICE is one of four large experiments at LHC, dedicated to studying the properties of hot quark-gluon matter. Photons in ALICE can be reconstructed via several complementary methods: using electromagnetic calorimeters PHOS [3] and EMCAL [4] and by the Photon
Conversion Method (PCM) [5] – by identifying photons converted to $e^+e^−$ pairs and reconstructed with the Inner Tracking System (ITS) [6] and the Time Projection Chamber (TPC) [7]. The PHOS has fine granularity (cell size $2.2 \times 2.2 \times 18 \text{ cm}^3$), installed at a distance to the Interaction Point (IP) of 460 cm but limited acceptance $\Delta \phi = 60^\circ$, $|\eta| < 0.13$. The EMCal has coarser granularity ($5.5 \times 5.5 \times 24.6 \text{ cm}^3$), installed at a distance of 428 cm from IP but with larger acceptance $\Delta \phi = 107^\circ$, $|\eta| < 0.7$. The PCM method uses the central tracking system with a large acceptance ($\Delta \phi = 360^\circ$, $|\eta| < 0.9$), however it is efficient only when the photon conversion takes place at radii up to the middle of the TPC ($R < 180 \text{ cm}$). The integrated material budget of the beam pipe, the ITS and the TPC corresponds to $(11.4 \pm 0.5)\%$ of a radiation length $X_0$, resulting in a photon conversion probability that saturates at about 8.5\% for transverse momentum $p_T > 2 \text{ GeV/c}$. Each of these approaches uses the respective advantages of the detectors, that is the excellent momentum resolution of the tracking system in the measurement of conversion photons down to very low transverse momenta, and the high reconstruction efficiency, triggering capability and good energy resolutions of calorimeters at high transverse momentum. As a result, each ALICE measurement includes several independent analyses with very different systematic uncertainties, thus allowing measurement of photon and neutral meson spectra in a wide $p_T$ range with good precision.

3. Direct photon production in pp collisions

The method of statistical subtraction to extract the spectrum of direct photons is used. In this method, the spectrum of all (inclusive) photons is measured, followed by the measurements of hadronic spectra which contribute to the decay photon spectrum. The dominant contribution comes from the $\pi^0 \to 2\gamma$ decay which contributes up to 85-90\% to the total decay photon yield, therefore its precise measurement is necessary. The next-to-dominant contribution is one from $\eta \to 2\gamma$ ($\sim 10\%$), while contributions of other hadron decays are much smaller. Since the $\pi^0$ contribution is the dominant one, it is convenient to construct a photon double ratio $R_\gamma$ [8]:

$$R_\gamma = \left( \frac{N_{\text{incl}}}{N_{\pi^0}} \right)_{\text{meas}} \left/ \left( \frac{N_{\text{dec}}}{N_{\pi^0}} \right)_{\text{MC}} \right. \approx \left( \frac{N_{\text{incl}}}{N_{\gamma}} \right),$$

(1)

![Figure 1.](ALICE_pp_8TeV)

**Figure 1.** Left: Photon double ratio $R_\gamma$ as a function of $p_T$ measured in pp collisions at $\sqrt{s} = 8 \text{ TeV}$ by three different methods. Right: combined $R_\gamma$ as a function of $p_T$ measured in pp collisions at $\sqrt{s} = 8 \text{ TeV}$ compared to NLO pQCD predictions.
where $N_{\text{incl}}$ and $N_{\pi^0}$ are the measured inclusive photon and $\pi^0$ spectra respectively, $N_{\text{dec}}$ is the total decay photon spectrum calculated in Monte-Carlo simulations and $N_{\pi^0}^{\text{dec}}$ is the parameterization of the $\pi^0$ spectrum used in Monte-Carlo simulations. If both photon and $\pi^0$ spectra are measured in the same detector, some important systematic uncertainties (material budget uncertainty in the case of PCM method or energy scale uncertainty in calorimeters etc.) cancel partially or completely. By construction, $R_\gamma$ should be greater or equal to 1. Values measurably $R_\gamma > 1$ mean the presence of a direct photon contribution.

ALICE measured direct photon spectra in pp collisions at $\sqrt{s} = 2.76$ and 8 TeV [10]. In Fig. 1, left, the $R_\gamma$ measured in pp collisions at $\sqrt{s} = 8$ TeV with 3 different methods, PCM, EMCAL and hybrid PCM+EMCAL are shown. Here hybrid method means that the inclusive photons are measured with the PCM method, while the neutral meson yield is obtained by combining photons reconstructed with PCM and in EMCAL. All three measurements agree with each other within uncertainties. In the right plot the combined result is presented. At low $p_T < 6$ GeV/c the $R_\gamma$ is consistent with unity which means no significant direct photon excess, but at higher $p_T$ a signal consistent with the theoretical predictions is observed. To make a proper comparison with the theoretical calculations the $R_\gamma^{\text{NLO}} = 1 + N_{\gamma}^{\text{NLO}}/N_{\gamma}^{\text{dec}}$ is shown, where $N_{\gamma}^{\text{NLO}}$ is the NLO pQCD calculations of direct photon yield in pp collisions [9] and $N_{\gamma}^{\text{dec}}$ is the decay photon yield which is calculated in our cocktail simulations. One can conclude that theoretical NLO calculations reproduce measurements within theoretical and experimental uncertainties. Simultaneously, at low $p_T < 6$ GeV/c measurements are consistent both with theory and with no direct photon signal. Similar results were found in pp collisions at $\sqrt{s} = 2.76$ TeV [10].

4. Direct photon production in p–Pb collisions

The direct photon measurement in p–Pb collisions is even more interesting: at high transverse momenta one can test the possible modification of the nucleon structure function in nuclei and check the validity of scaling with the number of binary collisions. At low $p_T$ it is interesting to find a thermal photon contribution which would suggest creation of sufficiently long-lived hot matter in these collisions [11]. Previously, ALICE measured direct photon production in the minimum

![Figure 2](image-url)

**Figure 2.** Left: Photon double ratio $R_\gamma$ as a function of $p_T$ measured in the highest 0-20% multiplicity class of p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by four different methods. Right: combined $R_\gamma$ as a function of $p_T$ measured in the highest 0-20% multiplicity class of p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to NLO pQCD predictions scaled with the number of binary collisions.
bias sample of p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. No direct photon excess in the low $p_T$ region was found within uncertainties. Here a more differential analysis, which was performed recently, is presented. The direct photon double ratio $R_\gamma$ and spectra were measured in four multiplicity classes in p–Pb collisions. The direct photon double ratio, measured with four methods in the highest multiplicity class 0-20% is shown in Fig. 2, left. All methods produce results which are consistent within uncertainties. In the right plot of Fig. 2 a combined $R_\gamma$ is compared to NLO pQCD predictions scaled with the number of binary collisions $R_\gamma^{\text{NLO}} = 1 + \langle N_{\text{coll}} \rangle_{NLO}^\gamma/N_{\text{dec}}^\gamma$. Similar to pp collisions, the significant signal of direct photons at high $p_T > 6$ GeV/c is found to be consistent with NLO pQCD calculations while at low $p_T < 6$ GeV/c measurements are consistent with no signal of direct photons. The measurement is also compared to the prediction of hydrodynamic model of Shen et al., [11], assuming creation of hot matter in these collisions. The data are consistent with predictions of this model too, and presently one can not neither confirm or reject creation of hot matter in p–Pb collisions at LHC energies.

5. Direct photon production and collective flow in Pb–Pb collisions

Direct photon production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was measured with two methods, PCM and PHOS [8]. The combined double ratio $R_\gamma$ and direct photon spectra measured in three centrality classes are shown in Fig. 3. Similar to the direct photons measurements in pp and p–Pb case, at high $p_T > 4$ GeV/c direct photon yield agrees with binary scaled NLO pQCD calculations. But at low $p_T < 3$ GeV/c, in contrast to pp and p–Pb collisions, a clear direct photon excess in central and semi-central collisions is seen while in peripheral collisions the measured $R_\gamma$ is consistent with unity. The significance of the direct photon excess for $p_T < 3$ GeV/c is $2.6\sigma$ in centrality class 0-20% and $1.5\sigma$ in centrality 20-40%.

![Figure 3](image-url)
The direct photon spectrum can be constructed from the double ratio $R_\gamma$ as $N_{\text{dir}}^\gamma = (1 - 1/R_\gamma)N_{\text{incl}}^\gamma$. Direct photon spectra, extracted in the three centrality classes of Pb–Pb collisions are presented in Fig. 3, right plot. For comparison, predictions of several state-of-the-art hydrodynamic models [12, 13, 14] and transport PHSD model [15] are shown in the same plot. At high $p_T$ models reproduce the measured yield, but at low $p_T$ all available calculations predict direct photon yield smaller by factors 2-7 than the measured mean values; however all predictions agree with the data within uncertainties.

![Figure 3. Direct photon spectra, extracted in the three centrality classes of Pb–Pb collisions are presented in Fig. 3, right plot. For comparison, predictions of several state-of-the-art hydrodynamic models [12, 13, 14] and transport PHSD model [15] are shown in the same plot. At high $p_T$ models reproduce the measured yield, but at low $p_T$ all available calculations predict direct photon yield smaller by factors 2-7 than the measured mean values; however all predictions agree with the data within uncertainties.](image)

**Figure 3.** Direct photon spectra, extracted in the three centrality classes of Pb–Pb collisions are presented in Fig. 3, right plot. For comparison, predictions of several state-of-the-art hydrodynamic models [12, 13, 14] and transport PHSD model [15] are shown in the same plot. At high $p_T$ models reproduce the measured yield, but at low $p_T$ all available calculations predict direct photon yield smaller by factors 2-7 than the measured mean values; however all predictions agree with the data within uncertainties.

The elliptic collective flow of direct photons was also extracted in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [16]. The procedure includes the measurement of collective flow of inclusive photons and calculation of the decay photons flow using measured spectra and flow of neutral mesons. Then, using formula

$$v_2^\gamma,\text{dir} = v_2^\gamma,\text{inc} R_\gamma - v_2^\gamma,\text{dec} R_\gamma - 1,$$

the flow of direct photons is calculated. Elliptic collective flow of direct photons measured in central 0-20% and semi-central 20-40% Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV is show in Fig. 4. For comparison the calculated elliptic flow of decay photons and theoretical predictions of hydrodynamic [17, 18] and the PHSD transport model [15] are also shown. At low $p_T$ elliptic flow of direct photons is close to the one of decay photons and considerably larger than all available theoretical predictions. With increase of $p_T$ direct photon elliptic flow decreases, which could correspond to increasing contribution of prompt direct photons which do not carry collective flow. However, because of the large systematic uncertainties the measured values are statistically consistent both with theoretical predictions and with hypothesis $v_2^\gamma,\text{dir} = 0$ in the range $0.9 < p_T < 2.1$ GeV/c [16].

![Figure 4. Elliptic collective flow of direct photons measured in central 0-20% (left plot) and semi-central 20-40% (right plot) Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV compared to the elliptic flow of decay photons and theoretical predictions of hydrodynamic [17, 18] and transport [15] models.](image)
6. Conclusions
ALICE measured direct photon spectra in pp, p–Pb and Pb–Pb collisions at LHC energies. Perturbative QCD NLO calculations scaled with the number of binary nucleon-nucleon collisions reproduce direct photons spectra at high $p_T \gtrsim 5$ GeV/c in all colliding systems. In pp and in minimum bias and most central p–Pb collisions no significant direct photon excess was observed in thermal photon region $p_T < 5$ GeV/c. However, within present uncertainties data are also consistent with predictions of hydrodynamics models which predict some thermal photon emission in this region. In Pb–Pb collisions the direct photon excess for $p_T < 3$ GeV/c was observed with 2.6σ significance in 0-20% and 1.5σ in 20-40% centrality classes. Hydrodynamic models predict 2-7 times smaller yield of direct photons at low transverse momenta, which, however, are statistically consistent with measured spectra. Elliptic collective flow of direct photons was measured in two centrality classes 0-20% and 20-40% in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Direct photon flow appear to be similar to the flow of final hadrons and decay photons and larger than predictions of hydrodynamic models, but systematic uncertainties are still too large to make a firm conclusion.

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