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

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Abstract. We review recent ALICE results on direct photon production in pp, p–Pb and Pb–Pb collisions at LHC energies. In light systems, pp and p–Pb, no signal of direct photons at low $p_T < 3{-}5$ GeV/c is observed within uncertainties, while at high p_T our measurements are consistent with NLO pQCD calculations. In central and mid-central Pb–Pb collisions a thermal photon contribution is observed at low $p_T < 3 - 4$ GeV/c with slopes $T_{\rm eff} = (304 \pm 11^{\rm stat} \pm 40^{\rm syst})$ MeV and $(407 \pm 61^{\rm stat} \pm 96^{\rm syst})$ MeV respectively. A collective elliptic flow of direct photons is measured and appeared to be close to the decay photon flow.

1 Introduction

Direct photons are the photons created in interactions of charged particles in course of pp, p-A or AA collision and not produced in decays of final-state hadrons which are copiously produced in these collisions. In contrast to hadrons, photons do not interact after their production and deliver information about the state of the system at the moment of their emission. Direct photon production in pp collisions can be described as a convolution of proton structure functions, elementary parton cross-sections and parton-to-photon fragmentation functions [1]. Recent NLO pQCD calculations with re-summations are able to reproduce quite well most of available measurements of direct photons spectra in pp collisions and therefore one can use direct photon measurements in global fits of structure/fragmentation functions.

One can classify direct photons created in collisions of relativistic heavy ions according to their production mechanisms. First, *prompt* direct photons are emitted from scattering of initial-state partons of colliding nuclei. This is the same mechanism as in pp collisions, but in AA case it should be scaled with the number of binary nucleon-nucleon collisions, corrected for the isospin difference and possible modification of structure functions in nuclei. Spectrum of prompt photons has approximately power-law shape so that they dominate the direct photon spectrum at high-pT. Hot QCD matter created in collisions, similar to any hot matter, emits thermal electromagnetic radiation. These *thermal* direct photons have approximately exponential spectrum and therefore can show up in the direct photon spectrum at low p_T. Finally, hot matter decouples into hadrons, which decay among other particles to photons and populate *decay* photon spectrum. There is no possibility to separate photons according to production mechanisms event by event, but one can estimate and subtract decay photons contribution, then thermal and prompt contributions can be separated on the statistical basis using the shapes of their spectra.

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2 Photon registration in ALICE

Photons in ALICE are reconstructed via several complementary methods: using electromagnetic calorimeters PHOS [2] and EMCAL [3] and by the Photon Conversion Method (PCM) [4] which identifies photons converted to e^+e^- pairs and reconstructed with the Inner Tracking System (ITS) [5] and the Time Projection Chamber (TPC) [6]. Combination of these approaches uses respective advantages of the detectors, that are the excellent momentum resolution of the tracking system in 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 p_T thus allowing measurement of photon and neutral meson spectra in a wide range of transverse momenta with very good precision.

The PCM method uses the central tracking system with a large acceptance ($\Delta\phi = 360°$, $|\eta| < 0.9$), however it is efficient only when the photon conversion takes place at radii up to the middle of the TPC ($R < 180$ 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 saturating at about 8.5% for $p_T > 2$ GeV/c. The photon spectrometer PHOS has fine granularity (cell size $2.2{\times}2.2{\times}18$ cm^3, installed at a distance from the Interaction Point (IP) of 460 cm) but limited acceptance ($\Delta\phi = 60°$, $|\eta| < 0.13$). The electromagnetic calorimeter EMCAL has coarser granularity ($6 \times 6 \times 24.6$ cm^3, installed at a distance of 428 cm from IP) but large acceptance ($\Delta\phi = 107°$, $|\eta| < 0.7$). As a result, ALICE uses several approaches with significantly different systematic uncertainties and even opposite energy dependence of energy resolutions in tracking and calorimetric cases so that each ALICE result combines from two up to six independent measurements, providing reliable cross-check and reducing the total systematic uncertainties.

3 Direct photon spectra

Spectrum of direct photons can be calculated in several ways, but the most straightforward is the statistical subtraction. In this method, the spectrum of all inclusive photons is measured, followed by the measurements of hadronic spectra which contribute to decay photon spectrum. The summary of relative contributions of hadron decays into the total decay photon spectrum in pp collisions at $\sqrt{s} = 2.76$ TeV [7] is shown in Fig. 1. The dominant contribution comes from the π^0 which contributes 85-90% to the total decay photon spectrum, therefore a precise measurement of the π^0 spectrum is necessary. The next-to-dominant contribution

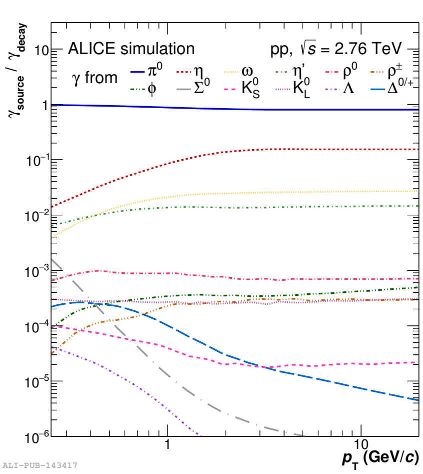

Figure 1. Relative contribution of different hadrons into the decay photon spectrum in pp collisions at $\sqrt{s} = 2.76$ TeV. Hadron spectra are measured with ALICE experiment and then used to estimate decay photon spectrum [7].

comes from η-meson ($\sim 15\%$), while contributions of other hadron decays are much smaller. Since π^0 contribution is dominant, it is convenient to construct a double ratio R_γ [8]:

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

where N_γ^{incl} and N_{π^0} are the measured inclusive photon and π^0 spectra respectively, N_γ^{dec} is the total decay photon spectrum and $N_{\pi^0}^{\text{dec}}$ is the parameterization of π^0 spectrum used in Monte-Carlo decay photon calculation. If both photon and π^0 spectra are measured in the same detector, some important systematic uncertainties (material budget in PCM method or energy scale in calorimeter etc.) cancel partially or completely. By construction, R_γ should be greater or equal to 1. Values larger than unity imply the presence of a direct photon contribution.

ALICE measured direct photon spectrum in pp collisions at $\sqrt{s} = 2.76$ and 8 TeV [7]. In Fig. 2, left, we present the R_γ measured in pp collisions at $\sqrt{s} = 8$ TeV. It was extracted with 3 different methods, PCM, EMCAL and hybrid PCM+EMCAL, which are in good agreement within uncertainties and here we present the combined result. At low $p_T < 4$ GeV/c R_γ is consistent with unity what means no direct photon excess, but at higher p_T an excess consistent with theoretical predictions is observed. To make proper comparison with theoretical calculations we show $R_\gamma^{\text{NLO}} = 1 + \langle N_{\text{coll}}\rangle N_\gamma^{\text{NLO}}/N_\gamma^{\text{dec}}$. We can conclude that theoretical NLO calculations reproduce measurements within theoretical and experimental uncertainties. Simultaneously, at low $p_T < 4$ GeV/c measurements are consistent both with theory and with no direct photon signal.

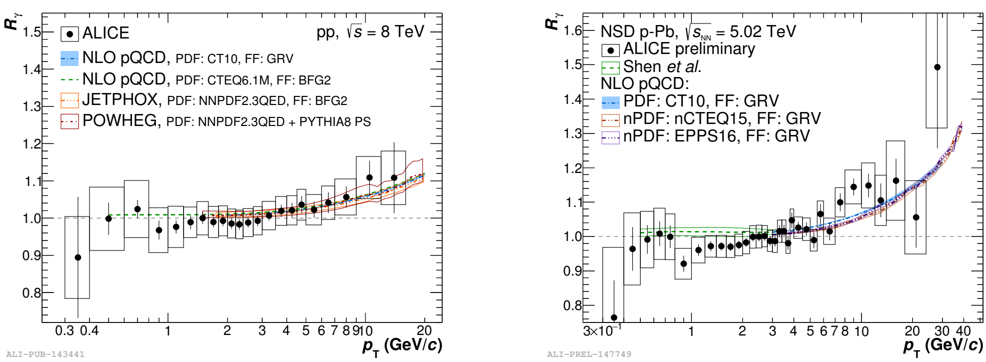

Figure 2. Left: photon double ratios R_γ measured in pp collisions at $\sqrt{s} = 8$ TeV [7]. Right: preliminary results on R_γ measured in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

Measurement of direct photon spectrum in pA collisions is of special interest. On one hand, pA collisions exhibit some features, characteristic to large systems: collective flow development [9] or strangeness enhancement [10]; on the other hand, no sign of parton energy loss in hard hadron or jet production in these systems was observed [11]. Measurement of thermal direct photons in pA collisions would be a strong argument for the creation of hot matter in these collisions. Photon double ratio R_γ was measured with four different methods: PCM, PHOS, EMCAL and hybrid PCM+EMCAL. The measurements are in agreement and the results were combined accounting possible correlations of uncertainties, see Fig. 2, right plot. Similar to pp case, at $p_T < 5$ GeV/c only an upper limit can be set, while at higher p_T the direct photon excess was observed. It is consistent with NLO calculations scaled with the number of binary nucleon-nucleon collisions in p–Pb. We use several NLO pQCD calculations: one using proton structure functions [12] and set of models accounting for nuclear

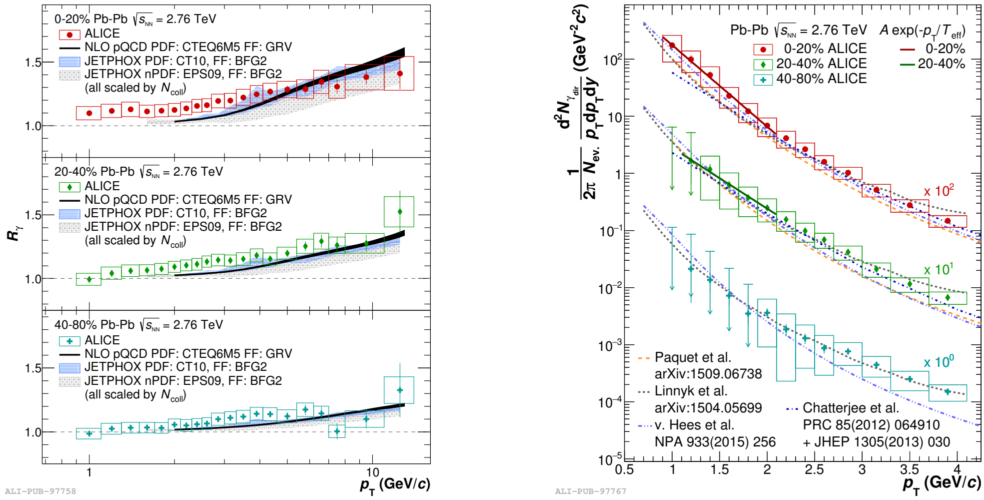

Figure 3. Left: photon double ratio R_γ in three centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Right: direct photon spectra measured in three centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV compared to predictions of several models.

PDF modifications [13]. As one can see, accounting nuclear modifications of structure functions makes modest effect on the total direct photon yield. As for the low p_T part, even after combination and reduction of systematic uncertainties they are too large to observe the direct photon excess at $p_T < 4$ GeV/c region, where calculations within hydrodynamic model by Shen et al. [14] predict appearance of thermal photon contribution on a few percent level.

In collisions of large systems, like Pb–Pb, one expects significant contribution of thermal direct photons at relatively small p_T. ALICE collaboration measured spectra of direct photons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in three centrality classes [8], see Fig. 3. In the left plot the R_γ is shown compared to several NLO calculations (see references in [8] for more details). Similar to pp and p–Pb cases our measurements at $p_T > 3-4$ GeV/c agree with NLO pQCD predictions of prompt direct photon yield scaled with the number of binary nucleon-nucleon collisions corresponding to the selected centrality class. This agreement means that there is no considerable modification of the structure functions in nuclei and scaling with number of binary collisions holds. In contrast to small systems, at $p_T < 2 - 3$ GeV/c a clear excess of direct photons compared to prompt photon predictions is observed. This excess can be interpreted as signal of thermal emission of hot quark-gluon matter.

Direct photon spectra measured in three centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV are shown in Fig. 3, right plot. For $p_T > 4$ GeV/c the measured spectra agree with NLO calculations of prompt direct photons scaled with $\langle N_{coll} \rangle$. In addition, we present predictions of several hydrodynamic models: Paquet et al. [15], van Hees et al. [16], Chatterjee et al. [17] and transport model Linnyk et al. [18]. All models predict considerably smaller direct photon yield compared to the measured one. Finally, we fit the spectra in the range $0.9 < p_T < 2.1$ ($1.1 < p_T < 2.1$) GeV/c with exponential function and extract effective slopes $T_{eff} = (304 \pm 11^{stat} \pm 40^{syst})$ MeV and $(407 \pm 61^{stat} \pm 96^{syst})$ MeV for central and mid-central collisions respectively. Note that slopes are not directly related to the temperature of the system since they are strongly affected by the collective expansion of hot matter.

4 Direct photon flow

Observation of the collective flow of final hadrons was one of the most important findings in the area of heavy ion collisions (see e.g. review [19]). Collective flow is the azimuthal asymmetry in particle production, common for all soft particles in the collision. It is interpreted as a collective expansion of initially spatially asymmetric hot matter. This initial deformation is the result of a partial overlap of colliding nuclei in non-central collisions. Transforming the initial geometric asymmetry into the asymmetry of momentum distribution of final particles requires strong interaction between particles of the matter, therefore hydrodynamic-like models provide very good description of this effect. Direct photons do not interact with hot matter and deliver information about the collective flow at the moment of their emission. As hydrodynamic models predict, photons emitted at the initial stage by hot quark-gluon matter carry very small collective flow since it is not yet developed at this stage. In contrast, direct photons emitted at the latest stage of hadron gas expansion carry much larger collective flow, similar to that of the final state hadrons. Averaging over the whole history of the collision leads to the prediction of direct photon flow considerably smaller than one of final hadrons. However, the first measurements of direct photon elliptic flow v_2 performed by PHENIX experiment [20], demonstrated that the direct photon flow is comparable with that of final hadrons and much larger than one predicted by hydrodynamic models.

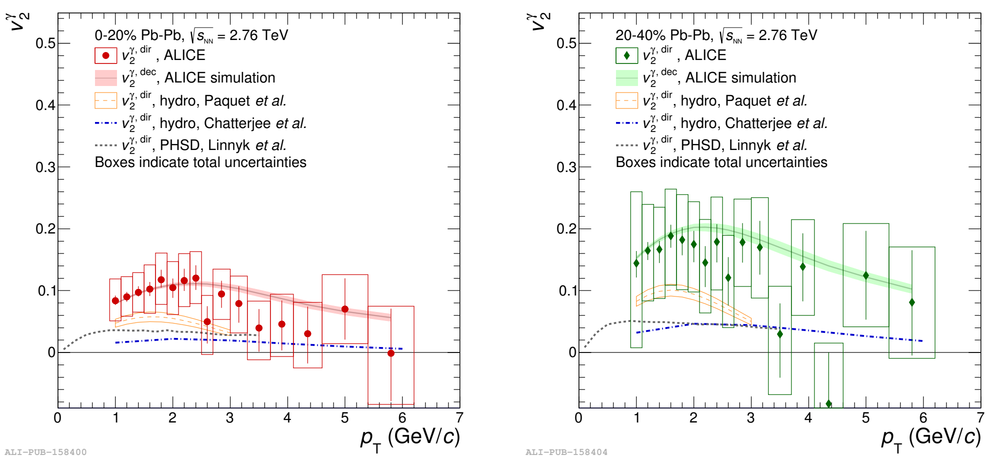

Figure 4. Direct photon elliptic flow measured in two centrality classes, 0-20% (left plot) and 20-40% (right plot) in Pb–Pb collision at $\sqrt{s_{NN}}$ = 2.76 TeV. For comparison the decay photon elliptic flow and predictions of hydrodynamic and transport models are show.

ALICE performed measurements of the direct photon elliptic flow in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV for the two centrality classes, 0–20% and 20–40%, reported in Fig. 4. We compare the measured direct photon elliptic flow $v_2^{\gamma,\mathrm{dir}}$ to the estimated decay photon elliptic flow $v_2^{\gamma,\mathrm{dec}}$ and to the predictions of several theoretical models. We find that, similar to RHIC measurements, the direct and decay photon elliptic flow are very similar. We compare our measurements to the state-of-the-art hydrodynamic model calculations [21, 22] and the transport model [18]. The measured direct photon elliptic flow is systematically higher than theoretical predictions, however given the large uncertainties they are statistically consistent. The direct photon elliptic flow in Au–Au collisions at RHIC measured by PHENIX [20] and in Pb–Pb collisions at the LHC are found to be compatible within uncertainties.

5 Conclusions

ALICE collaboration performed measurement of direct photon spectra in pp, p–Pb and Pb-Pb collisions at LHC energies. In all these systems, at high $p_T > 4$ GeV/c an agreement with NLO pQCD predictions scaled with number of binary nucleon-nucleon collisions is observed. In small systems, pp and p–Pb no signal of direct photons at low p_T is observed within uncertainties. In Pb–Pb collisions a clear signal of thermal direct photons is extracted. The yield appeared to be somewhat higher than predictions of available hydrodynamic and transport models. Elliptic collective flow of direct photons was extracted. It is close to the value measured for the collective flow of decay photons and higher than hydrodynamic or transport models predictions however, due to the large uncertainties, they are statistically consistent.

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