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DIRECT PHOTON PRODUCTION AND HBT CORRELATIONS IN Pb–Pb COLLISIONS AT $\sqrt{s_{NN}} = 5.02$ TeV WITH THE ALICE EXPERIMENT[*]

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Measurements of direct photons can provide valuable information on the properties and dynamics of the quark–gluon plasma (QGP) by comparing them to model calculations that describe the whole evolution of the system created in heavy-ion collisions, from the initial hard scattering to the pre-equilibrium, QGP, and hadronic phases. In the ALICE experiment, photons can be reconstructed either by using the calorimeters or via conversions in the detector material. The photon conversion method benefits from an excellent energy resolution and is able to provide direct photon measurements down to transverse momenta of $p_{\mathrm{T}} = 0.4$ GeV$/c$. For Hanbury-Brown and Twiss (HBT) correlation studies, the detector setup can be exploited to combine a conversion photon with a calorimeter photon, such that near-zero opening angles are measured. In this contribution, we present the first measurements of direct photon production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by ALICE, including direct photon spectra from central to peripheral events. The latest results of the first analysis of photon HBT correlations at the LHC are shown as well.

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1. Introduction

One of the main goals of heavy-ion collision experiments is to study Quantum Chromodynamics (QCD) under extreme conditions. The Large Hadron Collider (LHC) and the ALICE experiment provide an environment suited to study QCD matter at very high temperatures and vanishing net-baryon density. Many particle species are created in heavy-ion collisions, but the unique property of direct photons is that they are created during all phases of the collision and leave the reaction region without further interaction [1], so that they store information about earlier times than hadrons do.

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Direct photons originate from the following sources: initial hard scatterings, Bremsstrahlung and the fragmentation process, jet–medium interactions [2], and radiation from the medium (from the pre-equilibrium over the QGP to the hadron gas phase). However, the largest fraction of photons is not direct but originates from hadron decays. These decay photons have to be subtracted in order to measure direct photons.

Prompt photons (from hard scatterings, Bremsstrahlung, and fragmentation) have been measured in pp, pA, and AA collisions. Their production rate is quite well understood; they can be calculated with perturbative QCD (pQCD), which can describe measurements well [3]. Jet–medium photons have not yet been measured.

The work at hand focuses on the goal of measuring photons from the hot and dense medium that is created in heavy-ion collisions. One has to distinguish between the pre-equilibrium phase and the thermal phase (QGP and hadron gas). The radiation from the thermal phase is expected to be emitted with an approximately exponential spectrum [4]. This allows us to partially distinguish between the different contributions; at low photon energies, thermal photons are expected to dominate over prompt photons, considering the power-law spectrum of the latter. Also, the approximately exponential spectral shape gives access experimentally to an effective medium temperature (modified by a blue-shift caused by radial flow and averaged over the medium lifetime). In the pre-equilibrium phase, the medium has not yet been thermalized. There have been several approaches to calculate its direct photon emission, which suggest that this contribution dominates in an intermediate-p_{T} region, between the realm of thermal and prompt photons [5].

2. Method

For the results presented here, inclusive photons are measured either via the Photon Conversion Method (PCM) or in the Photon Spectrometer (PHOS) [6]. The latter is an electromagnetic calorimeter made of $\mathrm{PbWO_4}$ crystals with a cell size of about 2.2×2.2 cm^2, placed at a distance of $R = 4.6$ m from the beams. It covers an acceptance region of $\Delta\varphi = 70^\circ$ in azimuth and $|\eta| < 0.12$ in pseudorapidity.

In the detector material of the inner central barrel, a photon can also convert to an electron–positron pair. Being charged particles, the latter can be tracked in the Inner Tracking System (ITS) and Time Projection Chamber (TPC), and identified with the TPC and the Time Of Flight (TOF) detectors. This is the working principle of PCM. The conversion probability in the detector material up to a radius of 1.8 m from the beams (corresponding to the fiducial volume) amounts to about 8.5%. In the analysis which is presented here, a new data-driven correction of the detector thickness used in Monte Carlo (MC) simulations was applied. It is motivated by local imperfections in the material implementation in the detector geometry. Because the conversion probability is determined by the amount and composition of traversed material, a relatively large systematic uncertainty of 4.5% had to be assigned previously [7]. The new correction is used to weight the reconstruction efficiency obtained from MC, resulting in a more precise estimate of the central value for this efficiency and, therefore, a significantly lower systematic uncertainty of 2.5%.

3. Direct photon production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Decay photon spectra are obtained using a simulation of hadron decays based on measured particle spectra. The neutral pion and the η meson generate the largest contributions. They are measured via their decay channel into two photons. Afterwards, the parametrized π^0 spectrum is taken as input for the simulation directly. For the η meson, the η/π ratio is measured first, then a parametrization of it (where it is taken into account that it approaches an universal constant towards high p_{T} [8]) is multiplied with the π^0 parametrization in order to get the η input for the simulation.

The direct photon signal is measured using the direct photon excess ratio, where the measured inclusive photon spectrum is divided by the estimated decay photon spectrum. In order to cancel systematic uncertainties, it is measured in form of a double ratio of spectra

$$R_\gamma = \frac{\gamma_{\mathrm{inc}}}{\gamma_{\mathrm{decay}}} = \frac{\gamma_{\mathrm{inc}}/\pi^0_{\mathrm{meas}}}{\gamma_{\mathrm{decay}}/\pi^0_{\mathrm{sim}}}\,, \tag{1}$$

where the measured and simulated π^0 spectra enter. For the results presented in this section, PCM was used to measure inclusive photons and neutral mesons for the decay photon simulation. Systematic uncertainties were estimated by varying the analysis procedure. The dominant uncertainties arise from the estimation of decay photons from η mesons, the material budget and from the electron and positron identification.

The analyzed dataset consists of 76 million Pb–Pb collisions at a centre-of-mass energy per nucleon–nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 1 shows the direct photon excess ratio R_γ in the transverse momentum range of $0.4 < p_{\mathrm{T}} < 14$ GeV/c for four classes of collision centrality. The direct photon signal ($R_\gamma > 1$) for $p_{\mathrm{T}} > 3$ GeV/c can be attributed to prompt photons from hard scatterings. At lower p_{T}, where the medium radiation should dominate, we observe no significant direct photon signal, so that the relative contributions from thermal and pre-equilibrium photons must be relatively small (order of 5%). This is in agreement with predictions by theoretical calculations, which are shown in Fig. 1 as well.

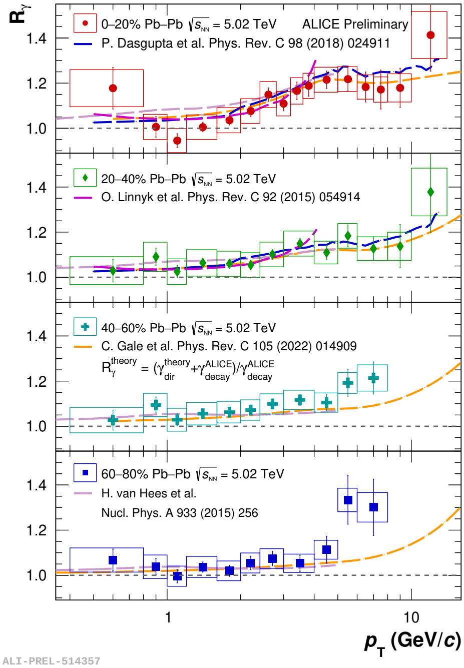

Fig. 1. Double ratio R_γ in four different centrality classes, measured with PCM, compared to model calculations. Statistical and systematic uncertainties are drawn as error bars and boxes.

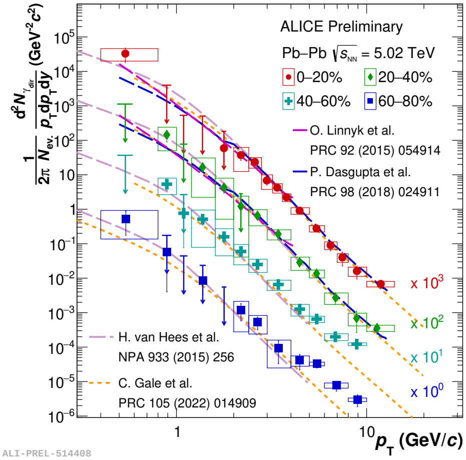

Fig. 2. Direct photon spectra compared to predictions from theoretical calculations.

Direct photon spectra are calculated from the inclusive photon spectra γ_{inc} and the double ratio using the following equation:

$$\gamma_{\rm dir} = \gamma_{\rm inc}\left(1 - \frac{1}{R_\gamma}\right) \tag{2}$$

which follows from the definition of direct photons as inclusive minus decay photons. In $p_{\rm T}$ bins, where $\gamma_{\rm dir}$ is consistent with zero within total uncertainties, 90% C.L upper limits are given.

Figures 1 and 2 show that within the current experimental uncertainties, the measurement is not yet sensitive to the small differences between the models.

4. Bose–Einstein photon–photon correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Bose–Einstein correlations can be used to study the space-time evolution of the medium created in heavy-ion collisions. Using a similar technique to that used to measure the HBT radius (named after the Hanbury-Brown and Twiss effect) at kinetic freeze-out with hadrons [9], we can investigate the space-time extent of the emitting source at earlier times with photon correlations. In addition, the correlation strength is sensitive to the direct photon fraction [10].

With the ALICE detector setup, we can correlate photons from PCM with those from PHOS, which allows us to measure pairs with very small opening angles. For this analysis, a dataset consisting of 156 million central and 101 million semi-central Pb–Pb collisions at a centre-of-mass energy per nucleon–nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV was used.

The distributions of photon pair invariant relative momenta $Q_{\rm inv}$, which correspond to invariant masses $M_{\gamma\gamma}$ of photon pairs, are calculated for photons from the same event (A) and from mixed events (B), and the correlation function is computed as the ratio of the two

$$C(Q_{\rm inv}) = \frac{{\rm A}(Q_{\rm inv})}{{\rm B}(Q_{\rm inv})}\,. \tag{3}$$

After correction for detector effects, the blue dots in the left panel in Fig. 3 show a small hint of an enhancement at low $Q_{\rm inv}$, in addition to a peak from neutral pion decays and a slope from correlations in particle showers. A fit with

$$C(Q_{\rm inv}) = 1 + \lambda_{\rm inv}\exp\left(-R^2_{\rm inv}Q^2_{\rm inv}\right) \tag{4}$$

yields the values for the correlation strength $\lambda_{\rm inv}$ in two different centrality classes and bins of photon average transverse momentum $k_{\rm T} = p_{\rm T,pair}/2$, as shown in the right panel of Fig. 3.

It is left for future work to extract values or limits on the radius parameter $R_{\rm inv}$ and on the direct photon fraction from $\lambda_{\rm inv}$. However, this method is a promising approach for measurements of the latter down to very low $p_{\rm T}$.

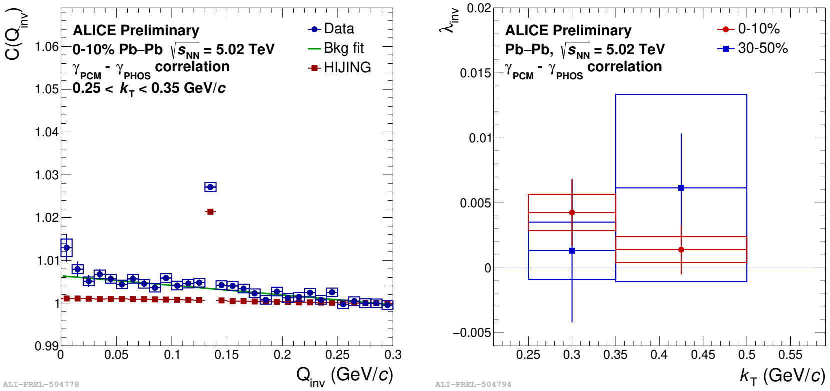

Fig. 3. (Color online) Left: Correlation function $C(Q_{\rm inv})$ in central Pb–Pb collisions for a given $k_{\rm T}$ bin. Right: Correlation strength $\lambda_{\rm inv}$ in two $k_{\rm T}$ bins and two centrality classes.

5. Summary and outlook

The first measurement of direct photons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented. Direct photon spectra are in agreement with state-of-the-art hydrodynamic model-based calculations, while the latter show some tension with the large direct photon yields measured at lower collision energy [11]. The use of PCM, where a new correction of detector thickness was applied, allows for a measurement down to a transverse momentum of 0.4 GeV/c with reduced systematic uncertainties. First results from a photon HBT analysis were presented, a promising method for future measurements with larger statistics down to even lower $p_{\rm T}$.

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