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Thermal radiation and direct photon production in Pb–Pb and pp collisions with dielectrons

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Electromagnetic probes such as photons and dielectrons (e^+e^- pairs) are a unique tool to study the space-time evolution of the hot and dense matter created in ultrarelativistic heavy-ion collisions. At low dielectron invariant mass (m_{ee}), thermal radiation from the hot hadronic phase contributes to the dielectron spectrum via decays of ρ mesons, whose spectral function is sensitive to chiral-symmetry restoration. At larger m_{ee}, thermal radiation from the quark–gluon plasma carries information about the early temperature of the medium. At LHC energies, it is nevertheless dominated by a large background from correlated heavy-flavor hadron decays affected by energy loss and flow in the medium. Complementary to the real photon measurements, dielectron data also allow the extraction of the real direct photon fraction, including thermal photons at low pair transverse momentum $p_{T,ee}$. The latest ALICE results on dielectron studies in Pb–Pb, and in inelastic and high-multiplicity pp collisions, at $\sqrt{s_{NN}}$ = 5.02 TeV and at $\sqrt{s}$ = 13 TeV, respectively, are presented and compared to simulations and expectations from theory. The status of the Run 3 analysis is also reported.

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PoS(HardProbes2023)060

1. Introduction

The production of e^+e^- pairs (dielectrons) is a promising tool for the understanding of the chiral symmetry restoration and of the thermodynamical properties of the Quark-Gluon Plasma (QGP) created in ultra-relativistic heavy-ion collisions. Since dielectrons are unaffected by strong final-state interactions and emitted during all stages of the collision, they carry undistorted information about the fireball at the time of their emission, and thus about the whole space-time evolution of the medium. Their invariant mass ($m_{\rm ee}$) allows for an approximate chronological view on this evolution. At $m_{\rm ee} < 1.1$ GeV/c^2, the dielectron spectrum is sensitive to in-medium modification of the spectral function of the ρ meson related to the chiral symmetry restoration. In the intermediate-mass region (IMR, $1.1 < m_{\rm ee} < 2.8$ GeV/c^2), the dominant contribution of correlated pairs from semileptonic decays of charm and beauty hadrons is sensitive to in-medium effects on heavy-flavor (HF) production. Thermal radiation emitted by the system, both during the partonic and hadronic phase, contributes as well to the dielectron yield over a broad mass range. In the IMR, the contribution from thermal radiation from the partonic phase is expected to be negligible compared to the one from the QGP, giving insight into the early temperature of the medium. Finally, at vanishing $m_{\rm ee}$, the real direct-photon fraction can be extracted from the dielectron data. Such measurements in inelastic pp collisions serves as a fundamental test of perturbative QCD calculations, and as a baseline for the studies in heavy-ion collisions, while studies in high charged-particle multiplicity events allow one to search for thermal radiation in small colliding systems. The latter show surprising phenomena similar to those observed in heavy-ion collisions [1–5].

The results reported in this article are based on data collected by ALICE [6] during the LHC Run 2 (2015-2018) and Run 3 (2022-2025). The complete available data set in pp collisions at $\sqrt{s}$ = 13 TeV is analyzed, corresponding to integrated luminosities of $L_{\rm int}^{\rm INEL}$ = 30.3 nb^{-1} in inelastic (INEL) collisions and $L_{\rm int}^{\rm HM}$ = 6.08 pb^{-1} in events with the 0.072% highest charged-particle multiplicity (HM) in the V0 detector at the forward and backward rapidity. This represents a factor 4 times more data compared to the previous publication [7] by ALICE. The Pb–Pb data at $\sqrt{s_{\rm NN}}$ = 5.02 TeV were collected in 2018 with a centrality trigger defined by the V0 detector. The number of analyzed events is about 65×10^6 in the 0–10% centrality class, corresponding to an integrated luminosity of 85 μb^{-1}. The Run 3 data are described in its dedicated section. Electrons are tracked and identified at midrapidity ($|\eta_{\rm e}| < 0.8$) in the ALICE central barrel with the Inner Tracking system (ITS), the Time Projection Chamber (TPC), and the Time-Of-Flight detector (TOF).

2. Direct photon production in pp collisions at $\sqrt{s}$ = 13 TeV

The production of e^+e^- pairs was measured as a function of the invariant mass in INEL and HM pp collisions at $\sqrt{s}$ = 13 TeV for $p_{\rm T,ee} > 1$ GeV/c. The results are described by a cocktail of known hadronic decays (hadronic cocktail) based on measured neutral meson measurements at the same energy and in the same multiplicity class. The direct-photon fraction r can be extracted from the $m_{\rm ee}$ spectrum at low $m_{\rm ee}$ in the quasi-real photon region ($p_{\rm T,ee} \gg m_{\rm ee}$). The $m_{\rm ee}$ distribution in a given $p_{\rm T,ee}(= p_{{\rm T},\gamma})$ interval is fitted with a three component function ($f_{\rm fit}$) including templates for dielectrons from light-flavor hadron decays ($f_{\rm LF}$), heavy-flavor hadron decays ($f_{\rm HF}$), and virtual

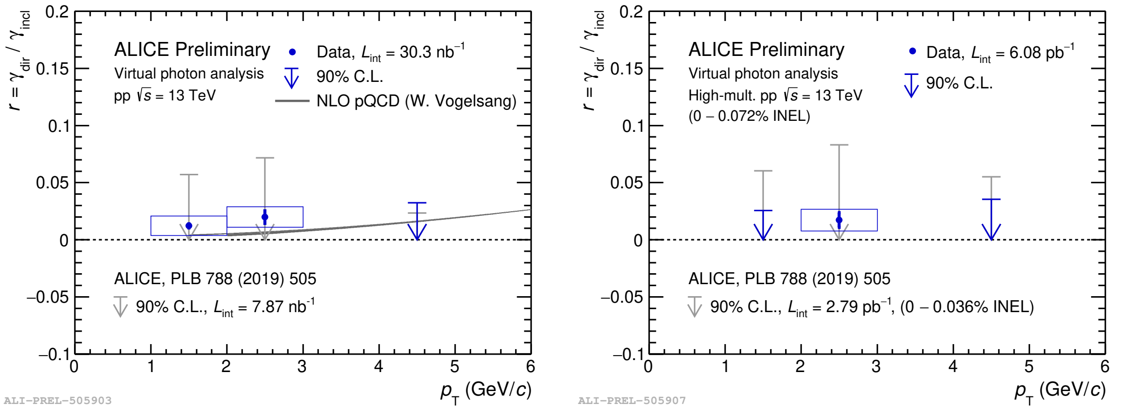

Figure 1: Direct-photon fraction vs p_T in pp collisions at $\sqrt{s}$ = 13 TeV for inelastic collisions (left) and high charged-particle multiplicity events (right).

direct photons (f_{dir}):

$$f_{fit} = r \times f_{dir} + (1 - r) \times f_{LF} + f_{HF}. \quad (1)$$

The shape of the virtual direct photon distribution is given by the Kroll-Wada formula [8]. The only free parameter r is interpreted as the direct-photon fraction. Fitting the m_{ee} spectrum above the π^0 mass ($0.14 < m_{ee} < 0.35$ GeV/c^2) allows a reduction of the systematic uncertainties compared to the real direct photon measurement. The extracted direct-photon fraction is shown as a function of p_T in INEL and HM pp collisions at $\sqrt{s}$ = 13 TeV in Fig .1. Both statistical and systematic uncertainties on r are significantly reduced compared to the previous publication [7]. The direct-photon fraction in INEL pp collisions is found to be consistent with pQCD calculations. In HM pp collisions, the result shows values of r similar to those in INEL pp collisions. Such measurements provide input to theory calculations aiming to understand the direct-photon yield from small to large systems.

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

The measured m_{ee} spectrum in the most 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is compared with two different hadronic cocktails in Fig .2 (left). The first one (blue cocktail) is based on the measured dielectron m_{ee} spectrum from heavy-flavor (HF) hadron decays in pp collisions at $\sqrt{s}$ = 5.02 TeV [9] scaled by the number of binary nucleon-nucleon collisions N_{coll}. It is at the upper edges of the data uncertainties in the IMR, where HF supppression is expected to affect the spectrum. In the second approach (gray cocktail), cold and hot nuclear medium effects on the HF contributions were estimated using a weighting procedure, taking as input the measured nuclear modification factor of single electrons from HF hadron decays [10] and the nPDF EPS09 [11]. This improves the description of the data points in the IMR, where the measured spectrum is consistent with the HF suppression and additional thermal radiation from the QGP as predicted by two different models [12, 13] (see orange and magenta lines in the middle and bottom left panels of Fig. 2). At the same time, it also introduces additional sources of uncertainties to the hadronic cocktail.

At $m_{ee} < 0.5$ GeV/c^2, a hint for an excess above the hadronic cocktail is observed compatible with predictions for thermal radiation from the hot medium [12, 13]. In this mass region, the

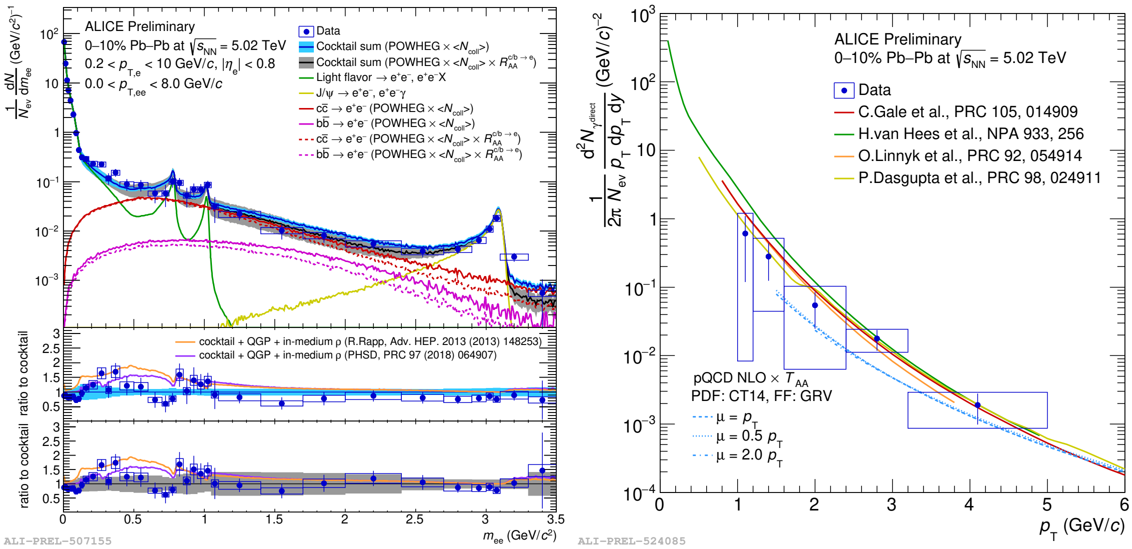

Figure 2: Dielectron invariant mass spectrum (left) and direct-photon p_T spectrum (right) in the most 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

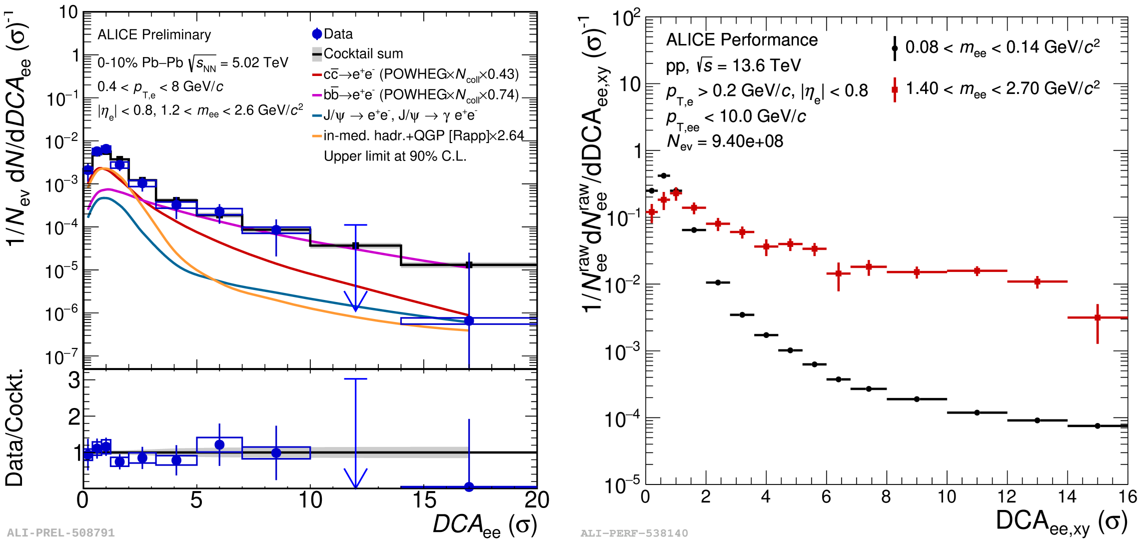

Figure 3: Dielectron DCA$_{ee}$ spectra in the invariant mass region 1.2 < m_{ee} < 2.6 GeV/c^2 for the most 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (left) and in two different invariant mass ranges in pp collisions at $\sqrt{s}$ = 13.6 TeV (right).

direct-photon fraction can be extracted with the same technique as presented in the pp analysis. The p_T spectrum of the direct photons obtained from the extracted r and the measured real inclusive photon spectrum is shown in Fig. 2 (right). The data are consistent with pQCD calculations for prompt photons, although systematically above at low p_T. Theory calculations including other sources (pre-equilibrium and thermal photons) can reproduce the data within uncertainties but tend to overestimate the direct-photon yield at low p_T.

In the IMR, the extraction of a thermal signal is limited by the current understanding of the hadronic cocktail. Therefore, a cocktail-independent approach is required to extract thermal signal from the QGP. Prompt and non-prompt dielectron sources can be separated based on their decay topology using the distance-of-closest approach ($\mathrm{DCA_{ee}}$) to the primary vertex of the e^+e^- pair, defined as

$$\mathrm{DCA_{ee}} = \sqrt{\frac{(\mathrm{DCA}_1/\sigma_1)^2 + (\mathrm{DCA}_2/\sigma_2)^2}{2}} \tag{2}$$

where 1(2) denotes e^- (e^+) and σ is the single track DCA resolution. The dielectron spectrum as a function of $\mathrm{DCA_{ee}}$ can be fitted with templates extracted from Monte Carlo simulations for each expected dielectron source, as shown in Fig. 3 (left). The beauty contribution (magenta line) dominates the spectrum at high $\mathrm{DCA_{ee}}$, while the charm contribution (red line), together with an additional prompt contribution (orange line) included in the fit to account for thermal radiation from the QGP, define the spectrum at lower $\mathrm{DCA_{ee}}$ values. The extracted HF scaling factors amount to $0.74 \pm 0.24\mathrm{(stat.)} \pm 0.12\mathrm{(syst.)}$ for beauty and $0.43 \pm 0.40\mathrm{(stat.)} \pm 0.22\mathrm{(syst.)}$ for charm with respect to N_{coll} scaling. For the thermal prompt component, a scaling factor of $2.64 \pm 3.18\mathrm{(stat.)} \pm 0.29\mathrm{(syst.)}$ with respect to the calculation of R.Rapp [12] was obtained. Compared to the cocktail based approach this method shows much smaller systematic uncertainties, allowing an extraction of the thermal dielectron yield in the IMR with a larger data sample.

4. Status of Run 3 analysis

The recent upgrade of the ALICE detectors, in particular of the TPC [14] and the ITS [15], allows a larger data acquisition rate by a factor up to 1000 in pp and 100 in Pb–Pb collisions, as well as a better pointing resolution by a factor 3 in the transverse plane and 6 in the beam direction. The raw normalized $\mathrm{DCA_{ee}}$ spectra in two different invariant mass ranges are shown in Fig. 3 (right) for pp collisions at $\sqrt{s} = 13.6$ TeV. The data shown here were collected in two days and correspond to a similar number of events as for the full Run 2 data set. At low m_{ee} ($0.08 < m_{\mathrm{ee}} < 0.14$ GeV/c^2) the dielectron yield is dominated by prompt π^0-Dalitz decays, whereas in the IMR the main contribution to the e^- e^+ spectrum is from open-charm hadron decays. The $\mathrm{DCA_{ee}}$ distribution in the IMR is clearly broader than the one at low m_{ee}, demonstrating the improved separation power of the different dielectron sources in Run 3 compared to Run 2.

5. Summary and outlook

The analysis of the full Run 2 data set in pp collisions at $\sqrt{s} = 13$ TeV allows a significant reduction of both statistical and systematic uncertainties of the dielectron results compared to the previous publication [7]. A significant direct-photon fraction is extracted as a function of p_{T} in INEL and HM events for the first time and found to be similar in both event types. Furthermore, the direct-photon production in 0–10% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV was estimated from the dielectron spectrum. The predicted prompt-photon contribution with pQCD calculations is at the lower edge of the data uncertainties, whereas theoretical models including other sources (thermal and pre-equilibrium photons) tend to overpredict the measured direct photon yields. First results in central Pb–Pb collisions on a topological separation between thermal radiation and the correlated

PoS(HardProbes2023)060

e^+e^- pairs from HF hadron decays using the DCA_{ee} is presented. The data are consistent with a suppression of the beauty and charm contributions compared to the measurements in pp collisions at the same $\sqrt{s_{NN}}$ scaled with N_{coll}, together with an additional prompt contribution. The result is currently limited by large statistical uncertainties. Such analysis will benefit from the recent upgrade of the ALICE detectors and the larger integrated luminosity of 13 nb^{-1} Pb–Pb collisions to be collected during the LHC Run 3 and 4 [14, 15]. Especially, the improved vertex resolution will improve the topological separation between prompt and non-prompt sources, as can be already seen in the raw DCA_{ee} spectrum of the first Run 3 pp collision data at $\sqrt{s}$ = 13.6 TeV.

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PoS(HardProbes2023)060