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

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Dielectrons are unique tools to study the space-time evolution of the hot and dense QCD matter created in ultra-relativistic heavy-ion collisions. They are produced by a variety of processes during all stages of the collision with negligible final-state interactions. Thermal radiation from the hadronic phase contributes to the spectrum at low invariant mass (m_{ee}), while thermal radiation from the quark-gluon plasma (QGP) at larger m_{ee} carries information about the early temperature of the medium. The latter is dominated by a large background from semileptonic decays of correlated heavy-flavor hadrons affected by parton energy loss and flow in the medium. In the quasi-real virtual photon region where $m_{\mathrm{ee}} \ll p_{\mathrm{T,ee}}$, the direct photon fraction can be extracted from the m_{ee} spectrum as a function of transverse momentum ($p_{\mathrm{T,ee}}$). In pp collisions, such measurement serves as a fundamental test for perturbative QCD calculations and as a baseline for the studies in heavy-ion collisions. We discuss the latest ALICE results on dielectron production in Pb–Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV, respectively. The results are compared with the expected dielectron yield from known hadronic sources and predictions for thermal radiation from the medium. The production of direct photons in the different colliding systems including high-multiplicity pp collisions is also reported.

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1. Introduction

Dielectrons are emitted from several sources that can be separated by the $e^{+}e^{-}$ invariant mass. In the low mass region (LMR) below $m_{ee} < 1.1$ GeV/c^2, the m_{ee} spectrum is sensitive to chiral symmetry restoration via $\rho \to e^{+}e^{-}$ whose spectral function is modified in the hot and dense QCD medium. At the massless limit ($m_{ee} \to 0$ GeV/c^2 or $m_{ee} \ll p_{T,ee}$), the ratio of direct to inclusive photons is the same for real and virtual photons. Thus, thermal photons emitted from the partonic phase (e.g. $qg \to q\gamma^{(*)}$, $q\bar{q} \to g\gamma^{(*)}$) and hadronic phase (e.g. $\pi^{+}\pi^{-} \to \rho\gamma^{(*)}$, $\pi^{\pm}\rho \to \pi^{\pm}\gamma^{(*)}$) are extracted from the LMR using the Kroll-Wada formula [1]. In the intermediate mass region (IMR) between $1.1 < m_{ee} < 2.7$ GeV/c^2, correlated $e^{+}e^{-}$ pairs from semileptonic decays of open heavy-flavor (HF) hadrons and thermal radiation from the partonic phase contribute to the m_{ee} spectrum. The correlated $e^{+}e^{-}$ pairs from open HF hadrons are sensitive to parton energy-loss in the QGP and flow in the medium. In addition, cold nuclear matter (CNM) effects such as shadowing also modify the m_{ee} spectrum in heavy-ion collisions compared to the vacuum expectation [2]. Hence, topological separation between thermal radiation (prompt) and dielectrons from HF hadron decays (non-prompt) is necessary to access the early stage of the collision. In the high mass region (HMR) above $m_{ee} > 2.7$ GeV/c^2, J/ψ meson, HF hadron decays and the Drell-Yan process are the dominant sources.
Recently, it is found that high-multiplicity pp collisions interestingly exhibit similar phenomena to those in heavy-ion collisions. Low mass dielectrons could provide interesting insights to underlying physics in such collisions.

2. Analyses

The results reported in this article are based on data collected by ALICE [3, 4] in LHC Run 2 (2015-2018). The full statistics in pp collisions at $\sqrt{s}$ = 13 TeV which corresponds to integrated luminosities of $L_{\rm int}^{\rm MB}$ = 30.3 nb^{-1} and $L_{\rm int}^{\rm HM}$ = 6.08 pb^{-1} is analyzed. This leads to a large improvment in terms of statistics by a factor of 3.8 in minimum-bias (MB) and 4.4 in high-multiplicity (HM) events, respectively, compared to the previous publication [5] by ALICE. In addition to the increase in statistics, the description of $e^{+}e^{-}$ pairs from known hadronic sources, so called hadronic cocktail simulation, was improved by newly independent measurements of π^0 and η mesons at the same collision energy and in the same charged-particle multiplicity class using the photon conversion method (PCM) in data taken with nominal (B = 0.5 T) and low (B = 0.2 T) magnetic field in the ALICE central barrel, and electromagnetic calorimeters (PHOS and EMCal/DCal). The Pb–Pb data at $\sqrt{s_{\rm NN}}$ = 5.02 TeV was collected in 2018 with a centrality trigger defined by the V0 detector at the forward and backward rapidity. The integrated luminosity $L_{\rm int}^{0-10\%}$ is 83 μb^{-1} in the 0–10 % centrality class.
Tracks from the primary vertex reconstructed with both the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are used in these analyses. Electrons are identified with the specific energy-loss per unit length dE/dx in ITS, TPC and the time-of-flight with the TOF detector at midrapidity in the ALICE apparatus. The kinetic acceptance for single electrons is in $p_{T,e} > 0.2$ GeV/c and $|\eta_e| < 0.8$ in these analyses.

3. Results

In MB pp collisions at $\sqrt{s}$ = 13 TeV, the dielectron invariant mass spectrum at $p_{\mathrm{T,ee}} > 1$ GeV/c was measured. It is described by the hadronic cocktail and established the vacuum baseline. In HM pp collisions, the cocktail uncertainty of the multiplicity-dependent HF production is still large (20 ~ 30 %). There is no hint for thermal radiation in the IMR. The direct photon fraction r as a function of p_{T} is extracted from the m_{ee} spectrum based on a fit of the distribution with a three component function including templates for dielectrons from light-flavor hadron decays (f_{LF}), HF hadron decays (f_{HF}) and virtual direct photons (f_{dir}) with the Kroll-Wada formula [1]. The total fitting function f_{fit} is

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

The only free parameter $r = \gamma^*_{\mathrm{dir}}/\gamma^*_{\mathrm{incl}} \xrightarrow[m_{\mathrm{ee}} \to 0]{} \gamma_{\mathrm{dir}}/\gamma_{\mathrm{incl}}$ is interpreted as the direct photon fraction. Fitting the m_{ee} spectrum above π^0 mass allows us to reduce the systematic uncertainties compared to the real direct photon measurement. Figure 1 shows the extracted r as a function of p_{T} in pp collisions at $\sqrt{s}$ = 13 TeV. These new results significantly reduce both statistical and systematic uncertainties compared to the previous publication. The direct photon fraction r in MB pp collisions is consistent with pQCD calculations. In HM pp collisions, the result shows similar values of r to those in MB pp collisions.

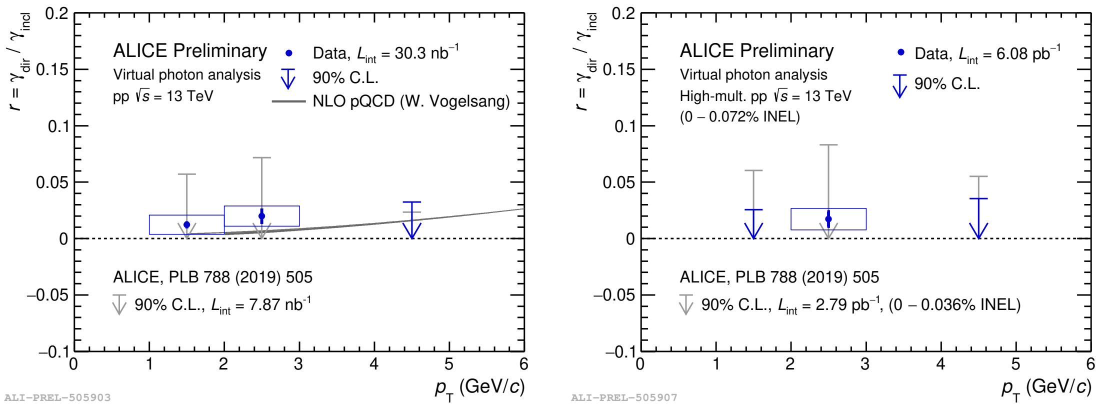

Figure 1: Direct photon fraction vs. p_{T} in pp collisions at $\sqrt{s}$ = 13 TeV in MB events (left) and in HM events (right).

Figure 2 (left) shows the m_{ee} spectrum in 0–10 % central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. It is compared with two different hadronic cocktails. The first one is based on the measured dielectron m_{ee} spectrum from HF hadron decays in pp collisions at $\sqrt{s}$ = 5.02 TeV [2] scaled by the number of binary nucleon-nucleon collisions N_{coll}. The data in the IMR are reproduced by the cocktail but at the lower edges of its uncertainties as shown by Figure 2 (left, middle panel), where the HF suppression is expected to affect the spectrum. In the second approach, the HF contribution was modified by a weighting procedure, taking as input the measured nuclear modification factor R_{AA} of single electrons from HF hadron decays [6] and CNM calculations based on EPS09 [7] to include CNM effects and parton energy-loss. This improves the description in the IMR and the data points

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are consistent with the HF suppression and the thermal radiation from the QGP [8, 9]. However, the uncertainties of the modified HF cocktail are larger due to the uncertainties of additional inputs from the single electrons measurement.

At $m_{\mathrm{ee}} < 0.5$ GeV/c^2, the m_{ee} spectrum shows indications of an excess above the hadronic cocktail compatible with predictions for thermal radiation from the hot medium [8, 9]. Also in this region, the direct photon fraction can be extracted with the same technique as presented in the pp analysis. Figure 2 (right) shows the first measurement of direct photon excess ratio $R_\gamma = 1/(1-r) = \gamma_{\mathrm{dir}}/\gamma_{\mathrm{decay}}$ as a function of p_{T} in 0–10 % central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (black). The results are in good agreement with those from the real photon analysis (red) while showing smaller systematic uncertainties at low p_{T}.

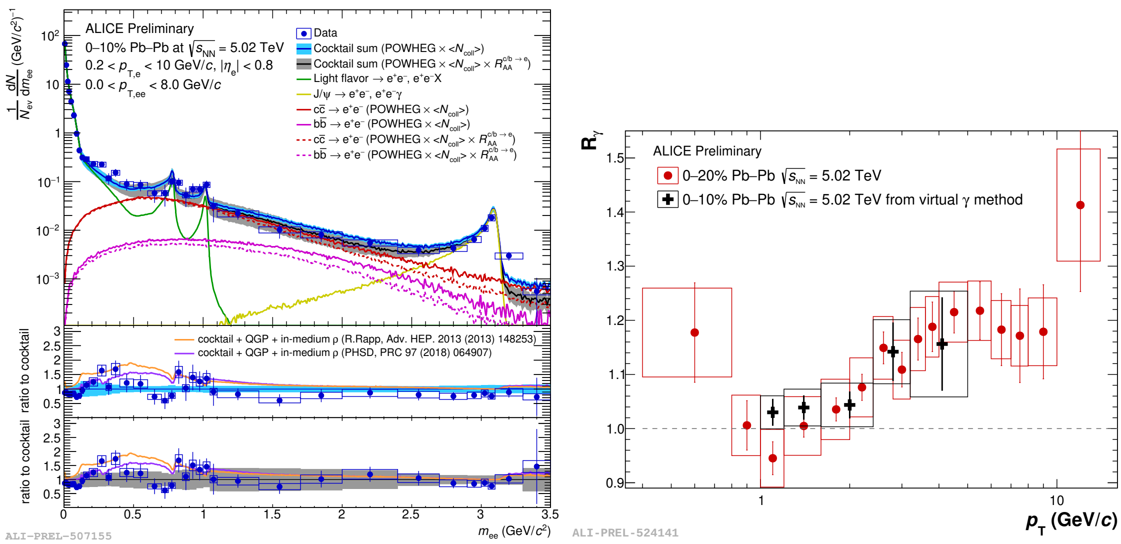

Figure 2: Dielectron invariant mass m_{ee} spectrum (left) and direct photon excess ratio R_γ (right) measured with virtual (black) and real photons (red) in 0–10% central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

The p_{T} spectrum of the direct photons is determined as $\gamma^{\mathrm{dir}} = r \times \gamma^{\mathrm{inc}}_{\mathrm{PCM}}$ using the measured real inclusive photon spectrum with PCM as shown by Figure 3 (left). The data is consistent with pQCD calculations with a hint for an excess at low p_{T}. Comparing the measurement to theory calculations including pre-equilibrium, thermal and pQCD photons, models tend to overestimate the data at low p_{T}. The integrated direct photon yield dN/dy is consistent within the large uncertainties with an universal scaling behavior as a function of the charged-particle multiplicity $dN_{\mathrm{ch}}/d\eta$ postulated by PHENIX [10].

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 access the early stage of the collision. Prompt and non-prompt dielectron sources can be separated based on their decay topology. For that purpose, the distance-of-closest approach (DCA) to the primary vertex for the $\mathrm{e^+e^-}$ pair is introduced as

$$DCA_{\mathrm{ee}} = \sqrt{\frac{(DCA_1/\sigma_1)^2 + (DCA_2/\sigma_2)^2}{2}}, \tag{2}$$

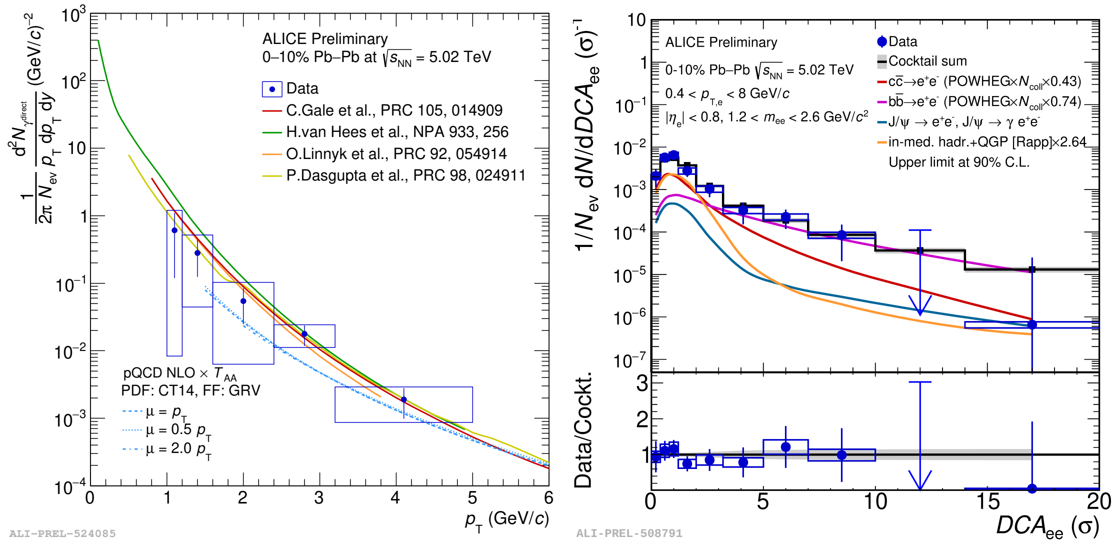

Figure 3: Direct photon p_T spectrum (left) and dielectron DCA_{ee} spectrum of direct photons (right) in 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

where 1(2) denotes e^- (e^+) and σ is DCA resolution. This gives the possibility to disentangle prompt contribution such as thermal radiation from the non-prompt signal of correlated semileptonic HF hadron decays. The dielectron spectrum as a function of DCA_{ee} is compared to templates extracted from Monte Carlo simulations and scaled with the N_{coll} for HF contributions. It can be seen that beauty dominates the spectrum at high DCA_{ee} while the charm contribution defines the spectrum at low DCA values. Overall, the data are below the HF expectation indicating a HF suppression. The description of the data can be improved by including an additional (thermal) prompt contribution and fitting the templates to the data as shown in Figure 3 (right). The extracted HF scaling factors amount to $0.74 \pm 0.24(\text{stat.}) \pm 0.12(\text{syst.})$ for beauty and $0.43 \pm 0.40(\text{stat.}) \pm 0.22(\text{syst.})$ for charm with respect to N_{coll} scaling. For the thermal prompt component, a scaling factor of $2.64 \pm 3.18(\text{stat.}) \pm 0.29(\text{syst.})$ with respect to the calculation of R.Rapp [8] 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. Conclusion

ALICE reported the analysis of the full Run 2 data set in pp collisions at $\sqrt{s}$ = 13 TeV. There is a significant reduction of both statistical and systematic uncertainties of the dielectron results compared to the previous publication [5]. This large data set allows us to extract direct photon fraction as a function of p_T in MB and HM events for the first time. The extracted direct photon fraction r is found to be similar between MB and HM pp events at $\sqrt{s}$ = 13 TeV. Furthermore, ALICE measured the first dielectron production in 0–10 % Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The predicted prompt photon contribution with pQCD calculations is at the lower edge of the data uncertainties. On the other hand, theoretical models including thermal radiation tend to overpredict the measured direct photon yields. Finally, a first feasibility study for a topological separation between thermal radiation and the correlated e^+e^- pairs from HF hadron decays using the DCA_{ee} was presented. The DCA_{ee} results will benefit from the recent upgrade of the ALICE detectors and the larger integrated luminosity of 13 nb^{-1} MB Pb–Pb collisions to be collected during the LHC Run 3 and 4. Especially, the improved vertex resolution will give us better topological separation between prompt and non-prompt sources.

References

[1] Norman M. Kroll and Walter Wada. Internal pair production associated with the emission of high-energy gamma rays. *Phys. Rev.*, 98:1355–1359, 1955.

[2] Shreyasi Acharya et al. Dielectron production in proton-proton and proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. *Phys. Rev. C*, 102(5):055204, 2020.

[3] K. Aamodt et al. The ALICE experiment at the CERN LHC. *JINST*, 3:S08002, 2008.

[4] Betty Bezverkhny Abelev et al. Performance of the ALICE Experiment at the CERN LHC. *Int. J. Mod. Phys. A*, 29:1430044, 2014.

[5] Shreyasi Acharya et al. Dielectron and heavy-quark production in inelastic and high-multiplicity proton–proton collisions at $\sqrt{s_{NN}}$ = 13TeV. *Phys. Lett. B*, 788:505–518, 2019.

[6] Shreyasi Acharya et al. Measurement of electrons from semileptonic heavy-flavour hadron decays at midrapidity in pp and Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. *Phys. Lett. B*, 804:135377, 2020.

[7] K. J. Eskola, H. Paukkunen, and C. A. Salgado. EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions. *JHEP*, 04:065, 2009.

[8] Ralf Rapp. Dilepton Spectroscopy of QCD Matter at Collider Energies. *Adv. High Energy Phys.*, 2013:148253, 2013.

[9] Taesoo Song, Wolfgang Cassing, Pierre Moreau, and Elena Bratkovskaya. Open charm and dileptons from relativistic heavy-ion collisions. *Phys. Rev. C*, 97(6):064907, 2018.

[10] U. A. Acharya et al. Nonprompt direct-photon production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. 10.48550/arXiv.2203.17187.