THERMAL RADIATION AND DIRECT PHOTON PRODUCTION IN Pb–Pb AND *pp* COLLISIONS WITH DIELECTRONS IN ALICE*

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Received 11 September 2022, accepted 12 October 2022,
published online 14 December 2022

Dielectrons are a unique tool to study the space-time evolution of the hot and dense matter created in ultrarelativistic heavy-ion collisions. They are produced by a variety of processes during all stages of the collision with negligible final-state interactions. At low invariant mass (m_{ee}), thermal radiation from the hot hadron gas (HG) contributes to the spectrum while at larger m_{ee}, thermal radiation from the quark–gluon plasma (QGP) carries information about the early temperature of the medium. The latter is nevertheless dominated by a large background of correlated heavy-flavour (HF) hadron decays affected by energy loss and flow in the medium. At very low m_{ee} ($m_{ee} \to 0$), the fraction of direct photons, including thermal contributions, can be extracted from the dielectron spectrum as a function of transverse momentum ($p_{\mathrm{T},ee}$). In proton–proton (pp) collisions, such measurement serves as a fundamental test for perturbative QCD calculations and a baseline for the studies in heavy-ion collisions. We report on the latest ALICE results on dielectron studies in Pb–Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s} = 13$ TeV, respectively. The results are compared to 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 (HM) pp collisions is discussed.

DOI:10.5506/APhysPolBSupp.16.1-A124

1. Introduction

In relativistic pp and heavy-ion collisions, dielectrons are emitted from several sources which can be separated via the invariant mass of the e^+e^- pair. In the intermediate-mass region (IMR) above $1.1\,\mathrm{GeV}/c^2$ and below

* Presented at the 29th International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

$2.7\,\mathrm{GeV}/c^2$, the dielectron spectrum is dominated by correlated semi-leptonic decays of open heavy-flavour hadrons, while at masses below 1.1 GeV/c^2, pseudoscalar and vector mesons mainly shape the spectrum via their resonance and Dalitz decays. In addition to these sources already present in *pp* collisions, cold nuclear matter (CNM) and the hot and dense medium created in heavy-ion collisions provide further contributions and modify the spectrum compared to the vacuum expectation. At higher masses, the contribution of open-charm and open-beauty hadrons is sensitive to the suppression and modification of HF production, while an additional signal of virtual photons from the QGP is expected. Going to lower masses, thermal radiation from the hadron–gas contributes to the dielectron spectrum via decays of ρ mesons, whose spectral function is modified in heavy-ion collisions and is sensitive to chiral-symmetry restoration. Therefore, measurements in *pp* collisions are essential as a vacuum baseline for the studies in Pb–Pb collisions.

Recently, also HM *pp* collisions have been found to exhibit interesting phenomena showing similarities with those in heavy-ion collisions. Low-mass dielectrons could provide additional information regarding the underlying physics processes in such collisions.

2. Data analysis

The presented results are based on data recorded by ALICE during the LHC Run 2. The full Run 2 data sample at $\sqrt{s} = 13$ TeV, corresponding to integrated luminosities of $L_{\mathrm{int,MB}} = 30.3\ \mathrm{nb}^{-1}$ and $L_{\mathrm{int,HM}} = 6.08\ \mathrm{pb}^{-1}$, was analysed. This results in an increase in the number of reconstructed events by a factor of 3.8 for minimum bias (MB) and by a factor of 4.4 for the HM trigger than reported in Ref. [1]. Furthermore, the estimation of e^+e^- pairs from hadronic sources (hadronic cocktail) was improved by incorporating a new independent measurement of the π^0 and η mesons by ALICE at the same center-of-mass energy and in the same multiplicity intervals using the photon-conversion method (PCM) and calorimeters. The Pb–Pb data at $\sqrt{s_{NN}} = 5.02$ TeV was collected in 2018 with a centrality trigger accumulating an integrated luminosity of 10 $\mu\mathrm{b}^{-1}$ in 0–10% most-central events.

3. Results

In MB *pp* collisions at $\sqrt{s} = 13$ TeV, the invariant-mass spectrum of dielectrons with $p_{\mathrm{T},ee}$ above 1 GeV/c was measured. The spectrum is well described by only hadronic sources establishing that the vacuum baseline is well understood. For HM *pp* events, the cocktail uncertainties of the multiplicity-dependent HF production are still rather large and no sign of thermal radiation can be observed. Finally, the direct-photon fraction r can be extracted both in MB and HM events. For this purpose, a fit of the m_{ee} spectra is performed at low masses

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

where $f_{\rm LF}$ and $f_{\rm HF}$ denote the templates for the light- and heavy-flavour hadron contributions, respectively, and $f_{\rm dir}$ represents the direct-photon contribution estimated using the Kroll–Wada formula [2]. The fit parameter r, corresponds to $r = \frac{\gamma^*_{\rm dir}}{\gamma^*_{\rm incl}} = \frac{\gamma_{\rm dir}}{\gamma_{\rm incl}}$ and links the virtual- to the real-photon yield. However, fitting the spectrum above the pion mass allows to reduce the systematic uncertainties compared to the real-photon measurement.

The extracted r values as a function of $p_{\rm T}$ are shown in Fig. 1. The new results have significantly reduced uncertainties, both statistical and systematic, compared to the previous publication [1]. In MB *pp* events, the measurement is in good agreement with the expectation from pQCD calculations, while the HM *pp* results do not show an increase in r compared to MB *pp* events within uncertainties.

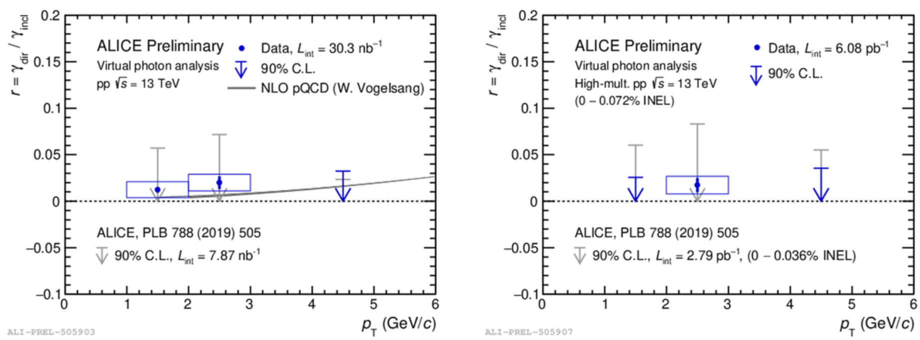

Fig. 1. Direct-photon fraction r as a function of $p_{\rm T}$ in *pp* collisions at $\sqrt{s} = 13$ TeV in MB events (left) and HM events (right).

The left panel of Fig. 2 shows the m_{ee}-differential dielectron yield in 0–10% most-central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The spectrum is compared to different hadronic cocktails. For the HF contribution to the cocktail, two different approaches are assessed. In the first one, the HF measurement in *pp* collisions at $\sqrt{s} = 5.02$ TeV [3] scaled with the number of binary nucleon–nucleon collisions $N_{\rm coll}$ was used as a vacuum baseline. In this case, the data in the IMR are at the edge of the lower uncertainties of the cocktail expectation indicating the HF suppression. As a second approach, the HF contribution was modified by weighting it with the measured R_{AA} of single HF electrons [4] to include the effects of cold and hot nuclear medium. This improved the description in the IMR and the data points are consistent with HF suppression and thermal radiation from the QGP [5, 6]. However, the uncertainties of the modified cocktail are larger due to the uncertainties of additional inputs.

At lower invariant masses, the dielectron spectrum shows indications of an excess above the hadronic cocktail compatible with predictions for thermal radiation from the hadron–gas phase [5, 6]. Also in this region, the direct-photon fraction can be extracted with the same technique as presented in the pp analysis. The right panel of Fig. 2 depicts the first measurement of $R_\gamma = \frac{1}{1-r}$ as a function of p_{T} in 0–10% most-central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The results are in good agreement with the real-photon measurement while showing smaller systematic uncertainties at lower momenta.

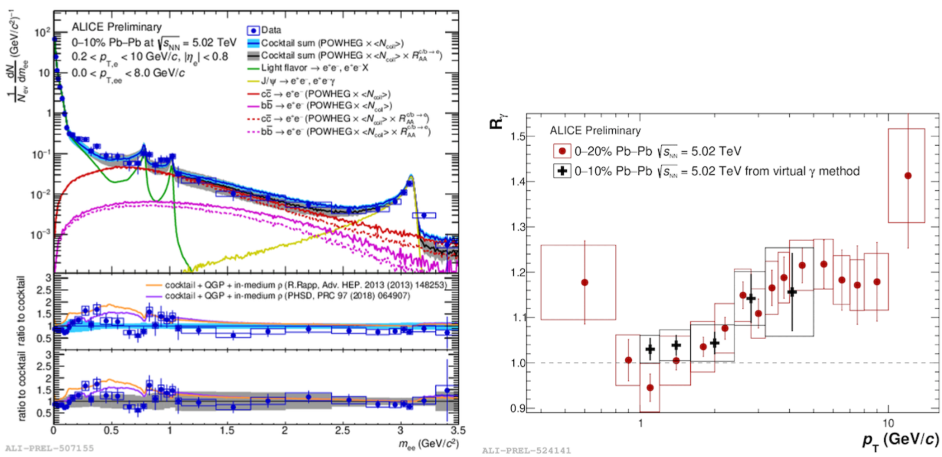

Fig. 2. Dielectron production as a function of m_{ee} in 0–10% most-central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to different hadronic cocktails (left) and comparison of R_γ (see the text) as a function of p_{T} measured with virtual and real photons (right).

The direct-photon yield can be constructed using the inclusive-photon spectrum from PCM via $\gamma^{\mathrm{dir}} = \gamma^{\mathrm{inc}}_{\mathrm{PCM}} \times r$ as depicted in the left panel of Fig. 3. The data is consistent with pQCD calculations with a hint for an excess at low p_{T}. Comparing the measurement to theory calculations including thermal and pQCD photons models tend to overestimate the data at low momenta. Overall, the integrated direct-photon yield is consistent within the large uncertainties with a universal scaling behaviour with the charged-particle multiplicity which was postulated by the PHENIX Collaboration [7]. 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 QGP radiation.

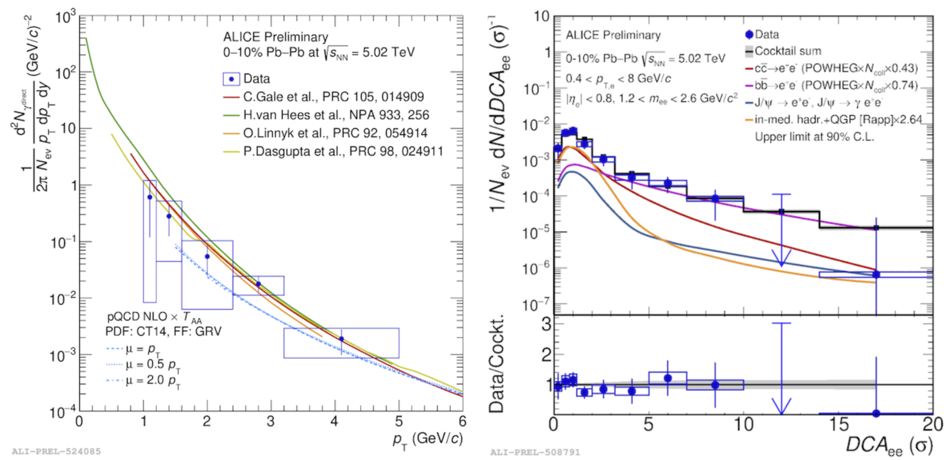

Fig. 3. Direct-photon yield as a function of p_T in 0–10% most-central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to theory and pQCD calculations (left) and dielectron production as a function of DCA$_{ee}$ in the IMR compared to fitted templates (right).

Prompt and non-prompt dielectron sources can be separated based on their decay topology. For that purpose, the distance-of-closest approach (DCA) of the electron (1) and positron (2) are combined as follows:

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

where σ denotes the DCA resolution. This gives the possibility to disentangle prompt contribution like thermal radiation from the non-prompt signal of correlated semi-leptonic HF decays. Comparing the dielectron spectrum as a function of DCA$_{ee}$ to templates extracted from the Monte Carlo simulations and scaled with the hadronic cocktail, it can be seen that beauty dominates the spectrum at high DCA$_{ee}$, while the charm contribution defines the spectrum at low DCA$_{ee}$ values. Overall, the data are below the HF expectation indicating the HF suppression. The description of the data can be improved by including an additional (thermal) prompt contribution and fitting the templates to the data shown in the right panel of Fig. 3. 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 $2.64\pm3.18(\text{stat.})\pm0.29(\text{syst.})$ with respect to the calculation of Rapp [5] was obtained. Compared to the cocktail-based approach, this method shows much smaller systematic uncertainties, allowing, with a larger data sample, an extraction of a thermal dielectron yield in the IMR.

4. Conclusion

We presented the analysis of the full Run 2 data set of pp collisions at $\sqrt{s} = 13$ TeV which shows a significant reduction of both the statistical and systematic uncertainties compared to the published results [1]. This allowed a first extraction of the direct-photon fraction as a function of p_{T} in minimum-bias and high-multiplicity events. No enhanced fraction of direct photons was observed in high-multiplicity events compared to minimum-bias events. Furthermore, we reported on the measurements of the dielectron production in 0–10% most-central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. These include a first measurement of the direct-photon yield and limits for the thermal radiation contribution. A hint for an excess compared to predictions of prompt photons was observed at low p_{T}. Calculations including additional thermal photon contributions tend to overestimate the results. Finally, we presented a first approach for a topological separation of the thermal radiation and the heavy-flavour background. The results are in agreement with the expectation from theory calculations. These results will benefit from the recent upgrade of the ALICE apparatus and the data sample of 13 nb^{-1} MB Pb–Pb events which are expected to be collected in the LHC Runs 3 and 4. Especially, the improved vertex-pointing resolution will further enhance the topological separation power between prompt and non-prompt sources.

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