Dilepton measurements with the ALICE experiment at the LHC

Elisa Meninno on behalf of the ALICE Collaboration
Stefan Meyer Institute for Subatomic Physics, Boltzmannasse 3, 1090, Wien
E-mail: elisa.meninno@cern.ch

Abstract. The production of low-mass dielectrons and dimuons is a powerful tool for the understanding of the properties of the quark–gluon plasma (QGP) created in ultra-relativistic heavy-ion collisions. Since such pairs do not interact strongly and are emitted during all stages of the collisions, they provide information about the full time evolution and dynamics of the medium created. Measurements in pp and p–Pb collisions are the necessary reference for heavy-ion studies. In addition, they can be used to extract charm and beauty cross sections.

In this contribution, we present the latest measurements of \( e^+e^- \) and \( \mu^+\mu^- \) pair production in pp, p–Pb and Pb–Pb collisions performed by ALICE at different energies.

1. Introduction

Photons and lepton pairs (electrons or muons) are penetrating probes that allow us to investigate the full time evolution and dynamics of the dense and hot medium created in ultra-relativistic heavy-ion collisions, since they don’t undergo strong interactions in the final state. Dileptons can be emitted during all the stages of the collision and a differential study as a function of the invariant mass \( m_{l^+l^-} \) and transverse momentum \( p_{T,l^+l^-} \) (with \( l = e, \mu \)) allow one to disentangle the various sources. At low invariant masses (\( m_{ee} < 1 \text{ GeV}/c^2 \)) Dalitz decays of pseudoscalar mesons (\( \pi^0, \eta, \eta' \)) and direct decays of vector mesons (\( \rho, \omega, \phi \)) are the main dilepton sources. Measurements of \( \phi \) mesons, due to their \( s\bar{s} \) quark content, are useful to study the strangeness production, which is one of the key observables for the QGP. Studying hadron production in different transverse momentum (\( p_T \)) regions gives important information on the hadronization processes. Strangeness production, indeed, can be studied in two regions. While at high \( p_T \) it is dominated by hard QCD processes, such as partonic scattering, which can be described by perturbative calculations, at low \( p_T \) is dominated by soft non-perturbative processes, described by phenomenological models. The \( \rho \) meson is potentially sensitive to chiral symmetry restoration, which is expected to happen close to the phase transition to the QGP in heavy-ion collisions [1]. This meson has a shorter lifetime than that of the medium. Therefore, its spectral function, which can be inferred from the study of its dielectron decay channel, is affected by the dense medium and the predicted restoration of chiral symmetry. Also the \( \phi \) meson may be sensitive to the chiral symmetry restoration, that could be observed by measuring a broadening of its spectral function, although no evidence of such an effect has been observed so far. Dileptons also originate from thermal QGP radiation from the medium in heavy-ion collisions. The thermal radiation, from both the QGP and the hadronic phase, contributes over a broad mass range. At intermediate mass ranges (IMR) (\( 1 < m_{ee} < 3 \text{ GeV}/c^2 \)) measurements...
of thermal radiation are very challenging, because of the large contribution of dileptons from semileptonic decays of correlated heavy-flavour hadrons [2]. Therefore, it is important to improve the knowledge of the contribution from charm- and beauty-hadron decays. Measurements in small systems, pp and p–Pb collisions, are the necessary reference for studies in Pb–Pb collisions. In addition to dileptons produced by hadronic interactions, also coherent photo-production of dileptons via electromagnetic interactions plays a role. This process is usually studied in ultra-peripheral collisions, where no strong interactions between colliding nuclei take place and the condition of coherence, i.e. the assumption that the produced electromagnetic field probes the whole nucleus, is easier to be maintained.

2. Experimental apparatus and data samples
ALICE [3, 4] is the heavy-ion dedicated experiment at CERN with an apparatus characterized by unique capabilities for Particle Identification (PID) and tracking at low transverse momenta, aimed to study the properties of the QGP. The detector consists of a central barrel at mid-rapidity, a muon spectrometer at forward rapidity and a set of detectors (forward and backward rapidity) for global collision characterization and triggering purposes.

Electrons are reconstructed and identified at mid-rapidity using the Inner Tracking System (ITS) [5] (for vertexing and tracking), the Time Projection Chamber [6] (for tracking and PID) and the Time-Of-Flight [7] (for PID). Low-mass dimuon production is studied with the muon spectrometer [8] at forward rapidity.

Dilepton measurements have been performed by ALICE in different collision systems (pp, p–Pb and Pb–Pb collisions) at different centre-of-mass energies. In this contribution, the most recent dielectron measurements in pp and p–Pb collisions at √sNN = 5.02 TeV, in pp collisions at √s = 13 TeV and in Pb–Pb collisions at √sNN = 5.02 TeV are presented. At √s = 13 TeV pp collisions were collected with a particular detector setup, characterized by a reduced solenoidal magnetic field to explore dielectron regions at very low pT, ee and mee, which was not accessible with higher magnetic field. Results related to the production of φ mesons, studied through its decay in muon pairs, in Pb–Pb collisions at √sNN = 2.76 TeV and in pp collisions at different centre-of-mass energies (√s = 2.76, 5.02, 8 and 13 TeV) are also presented.

3. Analysis strategy
First of all, selections on the track quality in the reconstruction procedure are applied. Electron candidates are selected from tracks reconstructed in the ITS and in the TPC. Electrons are identified using information on specific energy loss in the TPC and time-of-flight measurements in the TOF detector. For the dimuon analysis, tracks are reconstructed in the muon spectrometer. Tracks reconstructed in the muon tracking chambers have to match track segments reconstructed in the trigger chambers.

An opposite-sign invariant mass distribution is created combining e+ (μ+) and e− (μ−) tracks. This distribution contains not only signal, but also background from combinatorial pairs, as well as residual correlations from jets and from electron-positron pairs from photon conversion in the detector material. The background contribution is estimated from the distribution of same-sign pairs from the same event in the dielectron analysis, as explained in [20], or using the event mixing technique, combining muon tracks from different events [9]. The signal is then extracted subtracting the background contribution, corrected for the different acceptance of opposite-sign and same-sign pairs (in the dielectron analysis), from the opposite-sign spectrum. Photon conversion pairs are removed, for example, with selections on the opening angle of the pairs relative to the magnetic field. The dilepton measurement is compared with the expected contributions from light and heavy-flavour hadron contributions, the so-called hadronic cocktail.
4. Production of $\phi$ mesons in pp collisions

The production of $\phi$ mesons has been studied via the dimuon decay channel in pp collisions at $\sqrt{s} = 5.02$, 8 and 13 TeV at forward rapidity ($2.5 < y < 4$). In Fig. 1 the dimuon invariant mass spectrum in pp collisions at $\sqrt{s} = 13$ TeV after the subtraction of the combinatorial background is shown. The spectrum is fitted with a superposition of the hadronic cocktail (light-flavour resonances) and a continuum contribution due to semi-muonic decays of charm and beauty hadrons, described with an empirical function. For each $p_T$ and rapidity interval, the raw number of $\phi$ mesons is determined via a fit procedure based on a $\chi^2$ minimisation.

![Figure 1. Dimuon invariant mass spectrum in pp collisions at $\sqrt{s} = 13$ TeV, at forward rapidity, fitted with the hadronic cocktail.](ALICE-PREL-149249)

The $p_T$-differential $\phi$-meson production cross section is shown in Fig. 2 in different rapidity intervals, compared with two model calculations, PYTHIA8 [10] and PHOJET [11], and previous measurements at mid-rapidity [12,13]. Cross sections are fitted with a Levy-Tsallis function. In general, a softening of the $p_T$ spectra with increasing rapidity is observed. PYTHIA8 provides a quite good description of the different $p_T$ distributions, in all rapidity ranges while PHOJET is in agreement with the data only for $1 < p_T < 2$ GeV/$c$. The energy dependence of the $\phi$-meson production cross section has been also studied, as it can be seen in Fig. 3, where the $\phi$-meson production cross section integrated in $1.5 < p_T < 5$ GeV/$c$ is plotted as a function of $\sqrt{s}$. PHOJET describes quite well the energy dependence, while PYTHIA significantly underestimates the data. A hardening of the $p_T$ spectra with increasing energy is observed [14].

Measurements of $\phi$-meson production in Pb–Pb collisions have been performed at $\sqrt{s_{NN}} = 2.76$ TeV [15] and more recently at 5.02 TeV. Also in this case, results at forward and mid-rapidity have been compared. Their compatibility hints to similarities in the interaction of
Figure 3. $\phi$ meson-production cross section for $1.5 < p_T < 5 \text{ GeV}/c$ and $2.5 < y < 4$, in pp collisions as a function of the centre-of-mass energy, compared with PHOJET and PYTHIA8 models.

Figure 4. Nuclear modification factor $R_{AA}$ of $\phi$ mesons, measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward rapidity, in 0–10% and 40–60% centrality intervals.

the $\phi$ meson with the medium in the two rapidity ranges at intermediate $p_T$. Figure 4 shows the nuclear modification factor $R_{AA}$ measured in two different centrality classes. In peripheral collisions, the $R_{AA}$ is compatible with unity within uncertainties, as expected in the case that these collisions behave as a superposition of incoherent pp collisions. In most central collisions, $R_{AA}$ at forward rapidity is reduced to about 0.65, showing a clear suppression with respect to the pp reference in the intermediate $p_T$ region.

5. Dilepton production in pp and p-Pb collisions
Recently, dilepton production has been measured in pp and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16]. In Fig. 5 the dilepton production cross section in pp collisions is shown, as a function of the invariant mass $m_{ee}$ (left panel) and transverse momentum of the pair (right panel). Charm and beauty cross sections are estimated by fitting the $m_{ee}$ and $p_{T,ee}$ distributions in the IMR with templates obtained with two different event generators, the leading-order parton shower generator PYTHIA [17] and the next-to-leading order generator POWHEG [18], for which hadronization of c- and b-quarks and decays of heavy-flavour hadrons are still implemented with PYTHIA. The two generators differ in the implementation of heavy-quark production mechanisms. Cocktails obtained with both calculations reproduce quite well the data, although POWHEG provides a slightly better description of the measurement at low $m_{ee}$.

The charm- and beauty-production cross sections evaluated with the two event generators are in agreement with previous measurements, performed through the reconstruction of single heavy-flavour hadron decays [19]. The difference in the cross section values obtained with the two models is compatible with the difference already observed in previous measurements, performed in pp collisions at 7 TeV [20] and 13 TeV [21]. As already observed in these previous publications, this difference reflects the sensitivity of the dilepton measurement to production mechanisms implemented in the Monte Carlo generators. A summary plot of the measurements of charm and beauty cross sections performed at different centre-of-mass energies is shown in Fig. 6.

The nuclear modification factor $R_{pPb}$ is shown in Fig. 7 as a function of $m_{ee}$ and for $p_{T,ee} < 8$ GeV/c. Data are compared with the $R_{pPb}$ of the hadronic cocktail. Two additional models for the cocktail are taken into account and compared with the data. One includes cold-
Figure 5. Dielectron cross section as a function of $m_{ee}$ (left) and $p_{T,ee}$ (right). Data in the IMR are fitted, in $m_{ee}$ and $p_{T,ee}$, with two different templates for open charm and beauty contributions, obtained using, respectively, POWHEG and PYTHIA event generators.

Figure 6. Charm and beauty production cross sections measured at midrapidity, as a function of $\sqrt{s}$ in pp collisions.

nuclear-matter (CNM) effects on the production of dielectrons from semileptonic decays of charm hadrons. CNM effects are estimated using EPS09 nuclear parton distribution functions (nPDF) [22]. The second model includes thermal radiation effects [23, 33]. The measured $R_{pPb}$ stays below the theory expectations for $m_{ee} < 1.1 \text{ GeV}/c^2$, where the fraction of dielectrons from light-flavour hadron decays is not negligible. The $R_{pPb}$ is instead consistent with unity in the IMR, and the behavior is reproduced by the hadronic cocktail, where no CNM effects are taken into account. The calculation with included CNM effects seems to describe better the data for $m_{ee} < 1.1 \text{ GeV}/c^2$, while, for the IMR, data are on the upper edge of the systematic uncertainties of the calculation, suggesting negligible CNM effects. Calculations including
thermal radiation from hadronic and partonic phases are quite compatible with data within uncertainties, meaning that this source cannot be excluded.

Figure 7. Dielectron nuclear modification factor $R_{pPb}$, as a function of $m_{ee}$ measured in pp and p–Pb collisions at $\sqrt{s} = 5.02$ TeV. The measurement is compared with two cocktails, one including thermal radiation and the other one including CNM effects on the heavy-flavour production.

5.1. Soft-dielectron excess in pp collisions at $\sqrt{s} = 13$ TeV

Figure 8 shows the dielectron cross section in pp collisions at $\sqrt{s} = 13$ TeV as a function of $m_{ee}$ (on the left) and as a function of $p_{T,ee}$ (on the right), at very low $p_T$ and compared with the hadronic cocktail [25]. The $\eta$ meson gives the dominant contribution to the hadronic cocktail in the very low $p_T$ region under study. In order to estimate this contribution, ALICE measurements of $\eta/\pi^0$ performed in pp and p–Pb collisions have been parametrized and extended to low $p_T$ using measurements from CERES/TAPS [26] and assuming that this ratio does not depend on $\sqrt{s}$. In the mass region $0.15 < m_{ee} < 0.6$ GeV/$c^2$ and for $p_{T,ee} < 0.4$ GeV/$c$, an enhancement of a factor $1.69 \pm 0.14$ (stat.) $\pm$ (syst., data) $\pm$ (syst., cockt.) with respect to the hadronic cocktail is observed.

The multiplicity dependence of the observed excess has been investigated, as shown in Fig. 9, where the dielectron yield and the ratio data/cocktail are plotted as a function of the charged-particle multiplicity. In all the multiplicity intervals, the dielectron yield for $0.15 < m_{ee} < 0.6$ GeV/$c^2$ is always above the cocktail, however no conclusions can be drawn on the multiplicity trend of the excess. The $m_{ee}$ and $p_{T,ee}$ distributions of the excess, corrected for the detector acceptance, are shown in Fig. 10 compared with theoretical predictions. Calculations of bremsstrahlung from initial- and final-state hadrons are not able to describe data, as well as a calculation of thermal dielectron yield with a hadronic many-body model [23,33]. This important result needs confirmation with more precise measurements, which will be possible with the upgraded ALICE detector [32]. If confirmed by future measurements, this result could help to solve the "soft-photon puzzle", i.e. the question of an anomalous production of soft
photons (and leptons) in hadronic collisions observed by several experiments since decades and still awaiting for a clear explanation [28–31].

6. Dielectron production measurements in Pb–Pb collisions
Dielectron production has been measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [2] and 5.02 TeV. The left panel of Fig. 11 shows the dielectron invariant mass distribution measured in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared with the hadronic cocktail. There is a hint of enhancement at low $m_{ee}$ (< 0.5 GeV/$c^2$). This enhancement could be explained as a contribution from thermal radiation from the QGP and hadron gas. This effect looks more pronounced in central collisions, where the thermal radiation contribution is expected to be larger, with respect to peripheral collisions. Thermal radiation calculations by R. Rapp [23,33] are found to be compatible with the measurement. In the IMR, which is dominated by dielectrons from semileptonic heavy-flavour hadron decays, data are systematically below the hadronic cocktail, as can be observed in the left panel of Fig. 11. In the calculations for the cocktail, effects of open-charm hadron production modification due to cold-nuclear-matter effects are not taken into account. In the right panel of Fig. 11, EPPS16 nuclear parton distribution functions [24] are included in the calculations, without considering any hot-nuclear matter effects. As a consequence, the suppression is reduced and the data are better described by the hadronic cocktail. However, the statistical and systematic uncertainties of the measurement are still too large to allow us to constrain models and quantify the impact of CNM effects on the production of dielectrons from heavy-flavour hadron semileptonic decays. The Pb–Pb data sample collected
Figure 9. Dielectron yield per event in the excess region compared with the hadronic cocktail (top panel) and data/cocktail ratio in three $m_{ee}$ intervals (bottom panel), as a function of the charged-particle multiplicity.

in 2018 will help to improve the precision of the measurements.

Figure 10. Dielectron excess as a function of $m_{ee}$ (left panel) and $p_{T,ee}$ (right panel), after subtraction of the hadronic cocktail. Calculations of bremsstrahlung and thermal dielectron production are also shown.

Figure 11. Dielectron invariant mass spectrum in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 0–20% centrality class, compared with the hadronic cocktail. In the right panel, nPDF(EPPS16) are included in the charm contribution to the hadronic cocktail.

6.1. Photo-production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Photo-production of dielectrons has been studied in the IMR, which does not contain vector mesons and it is dominated by charm and beauty semileptonic decay contributions [34]. In Fig. 12 the dielectron $p_{T,ee}$ spectra in Pb–Pb collisions in two different centrality intervals, 0–40% (left panel) and 70–90% (right panel) are shown.
Figure 12. Dielectron spectrum as a function of $p_{T,ee}$ in the centrality ranges 0–40% (left) and 70–90% (right), compared with models of thermal radiation and photo-production.

Three different photo-production models [35, 36] are compared to data, together to the hadronic cocktail and with a thermal radiation model by R. Rapp [37]. Effects of tracking resolution are not taken into account in the photo-production models, however they should play a minor role in the comparison with data. In the 0-40% centrality class the spectrum is in agreement with the cocktail, and neither photo-production nor thermal effects can be inferred, due to the limited precision of the measurement. In peripheral collisions (70–90%) photo-production is expected to contribute stronger to the dielectron production with respect to central collisions. In this centrality range, an excess of dielectrons with respect to the cocktail is observed for $p_{T,ee} < 0.1$ GeV/$c^2$. All the photo-production calculations are overall compatible with data.

7. Outlook

Future dilepton studies are expected to reach much higher precision than the current measurements, thanks to the upgrade of the ALICE detector [32]. The new ITS, with improved resolution in the determination of secondary vertices, and reduced material budget, will allow a better separation of prompt sources (thermal radiation) and electrons from semileptonic decays of correlated heavy-flavour hadrons. The improved read-out capability will increase the expected number of events in the central barrel detector by a factor of 100. This will allow us to measure precisely the QGP temperature, and study the in-medium modification of the $\rho$ meson.

The New Muon Forward Tracker (MFT) [38] will add vertexing capability to the muon spectrometer, thus allowing us to study at forward rapidity new observable like prompt/displaced $J/\psi$ and to separate the individual contribution of charm and beauty in the open heavy-flavour studies. Equipped with the MFT, the upgraded muon spectrometer will allow us to increase the precision of low- and intermediate-mass dimuon measurements via the improvement of both the invariant mass resolution and the signal over background ratio.

References

[1] F. Karsch and M. Lutgemeier, “Deconfinement and chiral symmetry restoration in an SU(3) gauge theory with adjoint fermions,” Nucl. Phys. B 550 (1999), 449-464 doi:10.1016/S0550-3213(99)00129-7 [arXiv:hep-lat/9812023 [hep-lat]].

[2] S. Acharya et al. [ALICE], “Measurement of dielectron production in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,” Phys. Rev. C 99 (2019) no.2, 024002 doi:10.1103/PhysRevC.99.024002 [arXiv:1807.00923 [nucl-ex]].

[3] K. Aamodt et al. [ALICE], “The ALICE experiment at the CERN LHC,” JINST 3 (2008), S08002 doi:10.1088/1748-0221/3/08/S08002
[4] B. B. Abelev et al. [ALICE], "Performance of the ALICE Experiment at the CERN LHC," Int. J. Mod. Phys. A 29 (2014), 1430044 doi:10.1142/S0217751X14300440 [arXiv:1402.4476 [nucl-ex]].

[5] K. Aamodt et al. [ALICE], "Alignment of the ALICE Inner Tracking System with cosmic-ray tracks," JINST 5 (2010), P03003 doi:10.1088/1748-0221/5/03/P03003 [arXiv:1001.0502 [physics.ins-det]].

[6] J. Alme et al., "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events," Nucl. Instrum. Meth. A 622 (2010), 316-367 doi:10.1016/j.nima.2010.04.042 [arXiv:1001.1950 [physics.ins-det]].

[7] A. Akindinov et al., "Performance of the ALICE Time-Of-Flight detector at the LHC," Eur. Phys. J. Plus 128 (2013), 44 doi:10.1140/epjp/i2013-13044-x

[8] C. Finck [ALICE Muon Spectrometer], "The muon spectrometer of the ALICE," J. Phys. Conf. Ser. 50 (2006), 397-401 doi:10.1088/1742-6596/50/1/056

[9] B. Abelev et al. [ALICE], "Light vector meson production in pp collisions at \(\sqrt{s} = 7\) TeV," Phys. Lett. B 710 (2012), 557-568 doi:10.1016/j.physletb.2012.03.038 [arXiv:1112.2222 [nucl-ex]].

[10] P. Skands, S. Carrazza and J. Rojo, "Tuning PYTHIA 6.4: the Monash 2013 Tune," Eur. Phys. J. C 74 (2014) no.8, 3024 doi:10.1140/epjc/s10052-014-3024-y [arXiv:1404.5630 [hep-ph]].

[11] R. Engel and J. Ranft, "Hadronic photon-photon interactions at high-energies," Phys. Rev. D 54 (1996), 4244-4262 doi:10.1103/PhysRevD.54.4244 [arXiv:hep-ph/9509373 [hep-ph]].

[12] S. Acharya et al. [ALICE], "K*(892)\^0 and \(\phi(1020)\) production at midrapidity in pp collisions at \(\sqrt{s} = 8\) TeV," [arXiv:1910.14410 [nucl-ex]].

[13] S. Acharya et al. [ALICE], "Multiplicity dependence of K*(892)\^0 and \(\phi(1020)\) production in pp collisions at \(\sqrt{s} = 13\) TeV," [arXiv:1910.14397 [nucl-ex]].

[14] A. Chauvin, "Low-Mass dimuon measurements in pp collisions with ALICE at the LHC," Poster presented at the conference "Strangeness in Quark Matter 2019".

[15] S. Acharya et al. [ALICE], "\(\phi\) meson production at forward rapidity in Pb-Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV," Eur. Phys. J. C 78 (2018) no.7, 559 doi:10.1140/epjc/s10052-018-6034-3 [arXiv:1804.08906 [nucl-ex]].

[16] S. Acharya et al. [ALICE], "Dielectron production in proton-proton and proton-lead collisions at \(\sqrt{s_{NN}} = 5.02\) TeV," [arXiv:2005.11995 [nucl-ex]].

[17] T. Sjostrand, S. Mrenna and P. Z. Skands, "PYTHIA 6.4 Physics and Manual," JHEP 05 (2006), 026 doi:10.1088/1126-6708/2006/05/026 [arXiv:hep-ph/0603175 [hep-ph]].

[18] S. Alioli, P. Nason, C. Oleari and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX," JHEP 06 (2009), 043 doi:10.1007/JHEP06(2009)043 [arXiv:1002.2581 [hep-ph]].

[19] S. Acharya et al. [ALICE], "Measurement of D-meson production at mid-rapidity in pp collisions at \(\sqrt{s} = 7\) TeV," Eur. Phys. J. C 77 (2017) no.8, 559 doi:10.1140/epjc/s10052-017-5090-4 [arXiv:1702.00766 [hep-ex]].

[20] S. Acharya et al. [ALICE], "Dielectron production in proton-proton collisions at \(\sqrt{s} = 7\) TeV," JHEP 09 (2018), 064 doi:10.1007/JHEP09(2018)064 [arXiv:1805.04391 [hep-ex]].

[21] S. Acharya et al. [ALICE], "Dielectron and heavy-quark production in inelastic and high-multiplicity proton-proton collisions at \(\sqrt{s_{NN}} = 5\) TeV," [arXiv:2005.11995 [nucl-ex]].

[22] K. Eskola, H. Paukku and C. Salgado, "EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions," JHEP 04 (2009), 065 doi:10.1088/1126-6708/2009/04/065 [arXiv:0902.4154 [hep-ph]].

[23] R. Rapp, "Signatures of thermal dilepton radiation at RHIC," Phys. Rev. C 63 (2001), 054907 doi:10.1103/PhysRevC.63.054907 [arXiv:hep-ph/0001010 [hep-ph]].

[24] K. J. Eskola, P. Paukkunen, H. Paukku and C. A. Salgado, "EPPS16: Nuclear parton distributions with LHC data," Eur. Phys. J. C 77 (2017) no.3, 163 doi:10.1140/epjc/s10052-017-4725-9 [arXiv:1612.05741 [hep-ph]].

[25] S. Acharya et al. [ALICE], "Soft-dielectron excess in proton-proton collisions at \(\sqrt{s} = 13\) TeV," [arXiv:2005.14522 [nucl-ex]].

[26] G. Agakichiev et al., Eur. Phys. J. C 4 (1998), 249-257 doi:10.1007/s100529800804

[27] R. Rapp, "Dilepton Spectroscopy of QCD Matter at Collider Energies," Adv. High Energy Phys. 2013 (2013), 148253 doi:10.1155/2013/148253 [arXiv:1304.2309 [hep-ph]].

[28] A. Beloglianti et al., "Observation of a soft photon signal in excess of QED expectations in p p interactions," Phys. Lett. B 548 (2002), 129-139 doi:10.1016/S0370-2693(02)02837-X

[29] A. Beloglianti et al., "Further analysis of a direct soft photon excess in p-p interactions at 280-GeV/c," Phys. Lett. B 548 (2002), 122-128 doi:10.1016/S0370-2693(02)02836-8

[30] J. Antos et al., "Soft photon production in 400-GeV/c p - Be collisions," Z. Phys. C 59 (1993), 547-554 doi:10.1007/BF01562546

[31] V. Balek, N. Pisutova and J. Pisut, "The Puzzle of Very Soft Photon Production in Hadronic Interactions,"
Acta Phys. Polon. B 21 (1990), 149 HU-TFT-89-33.

[32] Z. Citron et al. CERN Yellow Rep. Monogr. 7 (2019), 1159-1410 doi:10.23731/CYRM-2019-007.1159 [arXiv:1812.06772 [hep-ph]].

[33] R. Rapp, “Dilepton Spectroscopy of QCD Matter at Collider Energies,” Adv. High Energy Phys. 2013 (2013), 148253 doi:10.1155/2013/148253 [arXiv:1304.2309 [hep-ph]].

[34] S. Lehner [ALICE], “Dielectron production at low transverse momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE,” PoS LHCP2019 (2019), 164 doi:10.22323/1.350.0164 [arXiv:1909.02508 [nucl-ex]].

[35] M. Kusek-Gawenda, R. Rapp, W. Schfer and A. Szczeurek, “Dilepton Radiation in Heavy-Ion Collisions at Small Transverse Momentum,” Phys. Lett. B 790 (2019), 339-344 doi:10.1016/j.physletb.2019.01.035 [arXiv:1809.07049 [nucl-th]].

[36] W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, “Initial transverse-momentum broadening of Breit-Wheeler process in relativistic heavy-ion collisions,” Phys. Lett. B 800 (2020), 135089 doi:10.1016/j.physletb.2019.135089 [arXiv:1812.02820 [nucl-th]].

[37] H. van Hees and R. Rapp, “Dilepton Radiation at the CERN Super Proton Synchrotron,” Nucl. Phys. A 806 (2008), 339-387 doi:10.1016/j.nuclphysa.2008.03.009 [arXiv:0711.3444 [hep-ph]].

[38] B. Abelev et al. [ALICE], “Technical Design Report for the Muon Forward Tracker,” CERN-LHCC-2015-001. ALICE-TDR-018