EPJ Web of Conferences **222**, 02001 (2019) https://doi.org/10.1051/epjconf/201922202001
*QFTHEP 2019*

# Direct photon production in pp, p-Pb and Pb-Pb collisions: results from ALICE

*Dmitry* Blau for the ALICE collaboration[1,*]

[1]NRC "Kurchatov Institute", Kurchatov sq. 1, 123182, Moscow

**Abstract.** Direct photon measurements provide a tool for testing QCD predictions in pp collisions and valuable information about properties of the quark-gluon matter created in nucleus-nucleus collisions. Comparing direct photon production in pp, p-Pb and Pb-Pb collisions, one can check the scaling with the number of binary collisions expected at high transverse momentum and get insight into the hot and cold hadronic matter properties with soft photons. The elliptic flow of direct photons is another unique possibility to trace the collective flow formation and space-time evolution of the fireball.
We present the latest measurements of direct photon production in pp, p-Pb and Pb-Pb collisions and of the elliptic flow in Pb-Pb collisions at the LHC energies. Comparison to recent theory predictions will be also discussed.

## 1 Introduction

By measuring different properties of particles created in the ultra-relativistic nucleus-nucleus collisions, one can study hot quark-gluon matter commonly referred to as quark-gluon plasma (QGP) [1]. Direct photons are those not originating from hadronic decays, but produced in electromagnetic interactions in the course of the collision. Unlike hadrons, photons do not interact strongly with hot matter and thus provide information about all stages of the collision as they are created at different times. At early times of the collision, prompt direct photons are produced in hard processes such as Compton scattering, annihilation, bremsstrahlung of incoming partons, and parton fragmentation. After thermalization of the system, thermal direct photons are radiated by the QGP. Thermal photons having almost exponential spectrum mainly occupy low-$p_{\mathrm{T}}$ part of the spectrum (below 2-3 GeV/$c$), while prompt photons with power-law spectrum dominate high-$p_{\mathrm{T}}$. Another source of photons detected experimentally are from decays of hadrons. The fraction of direct photons out of total inclusive photon yield could be as low as a few percent setting up a challenge to measure them experimentally.

In pp collisions, direct photons provide a tool to test QCD, as their production cross section is defined by parton distribution functions (PDF), cross sections of parton scattering processes and fragmentation functions. Studying high-$p_{\mathrm{T}}$ part of direct photon spectra in p-A and A-A collisions one can probe the initial conditions of this collisions, e.g. PDF modification in nuclei or violation of scaling with number of binary nucleon-nucleon collisions ($N_{\mathrm{coll}}$).

ALICE (A Large Ion Collider experiment) [2] at the Large Hadron Collider (LHC) ring is dedicated to study the QGP properties. Its good tracking and PID capabilities are coupled

*e-mail: dmitry.blau@cern.ch

with electromagnetic calorimetry provided by the EMCal and PHOS detectors. Different methods are used in ALICE to reconstruct direct photons: those based on the calorimeters (EMCAL and PHOS) and Photons Conversion method (PCM) using ALICE tracking system. These methods have their advantages at different $p_T$ ranges.

ALICE took part in all LHC data taking periods and data samples of Pb-Pb, Xe-Xe, p-Pb and pp collisions at different collision energies were collected during 2009-2013 years (LHC Run 1) and 2015-2018 years (LHC Run 2). Here we present results of direct photon measurements with ALICE detector using data from LHC Run 1.

### 1.1 Direct photon extraction method

Direct photons extraction is based on subtraction method (for example, see [3]) which is performed via statistical subtraction of decay photon yield out of total inclusive photon yield, see Eq. (1). Decay photon yield is calculated by decay simulation from measured or $m_T$-scaled hadron spectra.

$$\gamma_{\text{dir}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = (1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}})\gamma_{\text{inc}} = (1 - \frac{1}{R_\gamma})\gamma_{\text{inc}} \tag{1}$$

where $R_\gamma$ is the ratio of inclusive photons over decay ones, also called as direct photon excess ratio:

$$R_\gamma = \gamma_{\text{inc}}/\gamma_{\text{decay}} \approx \gamma_{\text{inc}}/\pi^0 \Big/ \gamma_{\text{decay}}/\pi^0_{param} \tag{2}$$

The approximation of $R_\gamma$ using so called double ratio to measured and simulated $\pi^0$ yield is advantageous as it cancels out some large systematic uncertainties since $\pi^0$ is the largest source of decay photons (about 80-90%).

## 2 Direct photon production in pp collisions

### 2.1 Direct photon production

Direct photon spectra in pp collisions at $\sqrt{s}$ = 2.76 and 8 TeV were measured using PCM, EMCal, and hybrid PCM-EMC method where meson spectrum needed for obtaining $R_\gamma$ is measured using pair of photons, one of which is taken from PCM and another from EMCal. The details about reconstruction techniques, systematic uncertainties evaluation can be found in [4]. The measured $R_\gamma$ are shown in Fig. 1. The direct photon excess at high $p_T$ (> 3 − 4 GeV) is described by NLO pQCD calculations [5]. At both collision energies no thermal photon excess at low-$p_T$ region is visible within uncertainties.

### 2.2 Isolated photon production

At high $p_T$, direct photons can be identified with the help of isolation criterion, which is introduced to separate them from jet fragments usually accompanied by hadronic activity in a cone of some radius. The spectrum of isolated photons was measured by CMS [6] and ATLAS [7] experiments in pp collisions in a wide range of transverse momenta, from 15 to 1000 GeV/$c$. Thanks to low material budget of its detectors, ALICE was able to extend the spectrum of isolated photons in pp collisions at $\sqrt{s}$ = 7 TeV down to even lower transverse momentum, exploring the range $10 < p_T < 60$ GeV/$c$ [8]. The measurement was done using electromagnetic calorimeter EMCal to reconstruct photons and the central tracking system (ITS and TPC) to detect charged hadrons. The isolation criterion was chosen based on the

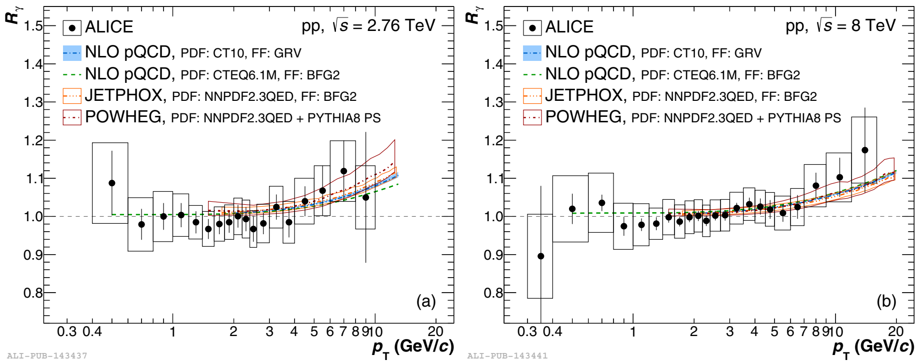


**Figure 1.** Direct photon excess ratio $R_\gamma$ measured in pp collisions at $\sqrt{s} = 2.76$ (left) and 8 (right) TeV compared to NLO pQCD calculations [4].

isolation momentum, $p_T^{iso}$, which is the sum of transverse momenta of all particles in a cone of radius $R$ with the axis at the high-$p_T$ photon trajectory:

$$p_T^{iso} = \sum p_T^{cluster} + \sum p_T^{track} \tag{3}$$

For this analysis, the set of parameters $R < 0.4$ and $p_T^{iso} < 2$ GeV/$c$ was chosen. The measured spectrum of isolated photons in pp collisions at $\sqrt{s} = 7$ TeV is presented in Fig. 2. The theory predictions calculated with JETPHOX [9] are consistent with the measurement. The comparison of measurements performed by ALICE, ATLAS and CMS with theoretical calculations performed with same isolation criteria as in experiments is shown in Fig. 2 (right). All measurements agree with pQCD predictions within experimental and theoretical uncertainties.

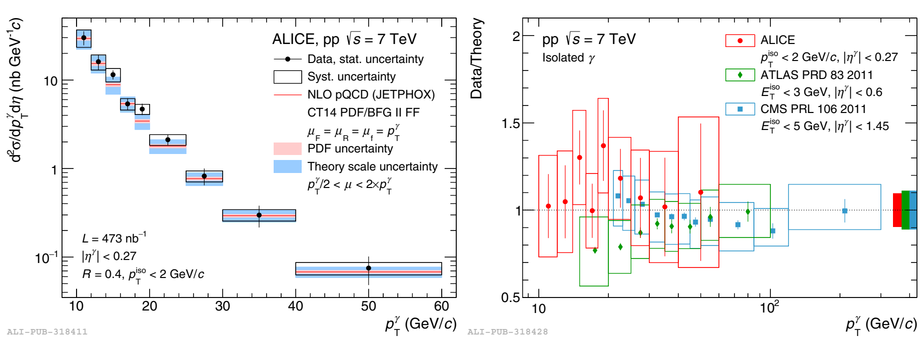


**Figure 2.** Left: The isolated photon spectrum measured in pp collisions at $\sqrt{s} = 7$ TeV [8] compared to JETPHOX calculations [9]. Right: the ratio of data to theory (JETPHOX calculations) for data points from ALICE [8], CMS [6] and ATLAS [7] experiments.

# 3 Direct photon production in p-Pb collisions

## 3.1 Direct photon production

Direct photon spectrum in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV was measured using four methods: PCM, EMCal, PHOS and PCM-EMC. Thanks to large amount of collected data, it was possible to measure the multiplicity dependence of the direct photon spectrum. The multiplicity classes were based on signal of V0A detector located at rapidity $2.8 < \eta < 5.1$. The measured $R_\gamma$ are shown in Fig. 3 for minimum bias collisions (left) and the highest multiplicity class 0-20% (right), both compared to NLO pQCD calculations scaled with the number of binary collisions. Both measurements are consistent with the theory predictions at high $p_{\rm T}$ and show no thermal photon excess at low $p_{\rm T}$ within uncertainties.

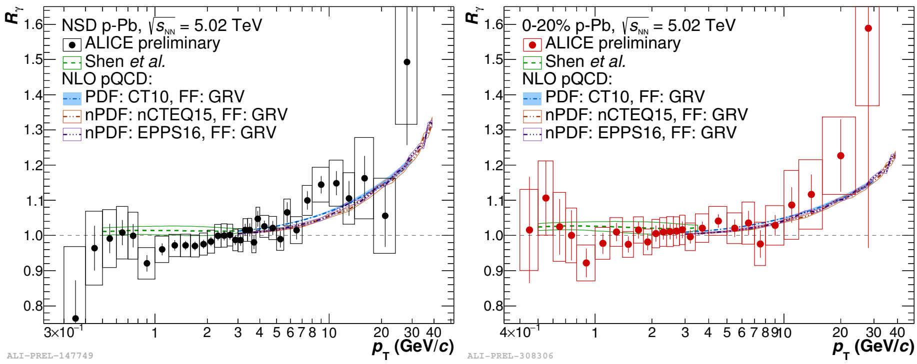


**Figure 3.** Left: Direct photon excess ratio $R_\gamma$ measured in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to NLO pQCD calculations and predictions of hydrodynamic model. Right: the same in the highest multiplicity class 0-20%.

## 3.2 Isolated photon production

Isolated photon spectrum in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV was measured with the same technique as discussed in section 2.2. The $p_{\rm T}^{\rm iso}$ criterion was modified to take into account underlying event (UE) contribution to the $p_{\rm T}^{\rm iso}$:

$$p_{\rm T}^{\rm iso} - UE < 2{\rm GeV}/c \tag{4}$$

The measured isolated photon spectrum in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is shown in Fig. 4. The measurement is consistent with NLO pQCD calculations scaled with the number of binary collisions.

# 4 Direct photon production in Pb-Pb collisions

Direct photon spectrum in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV was measured using PHOS and PCM methods [10]. The measured $R_\gamma$ is shown in Fig. 5 (left) in 3 centrality classes and compared to NLO pQCD calculations scaled with $N_{\rm coll}$. For all three centrality classes, measurements are consistent with NLO pQCD calculations within uncertainties for $p_{\rm T} \gtrsim 3$ GeV/$c$. At low $p_{\rm T}$ (< 3 GeV/$c$), the excess of $R_\gamma$ above unity and NLO pQCD calculations is clearly seen with the significance of 2.6 $\sigma$ for 0-20% and 1.5 $\sigma$ for 20-40% centrality

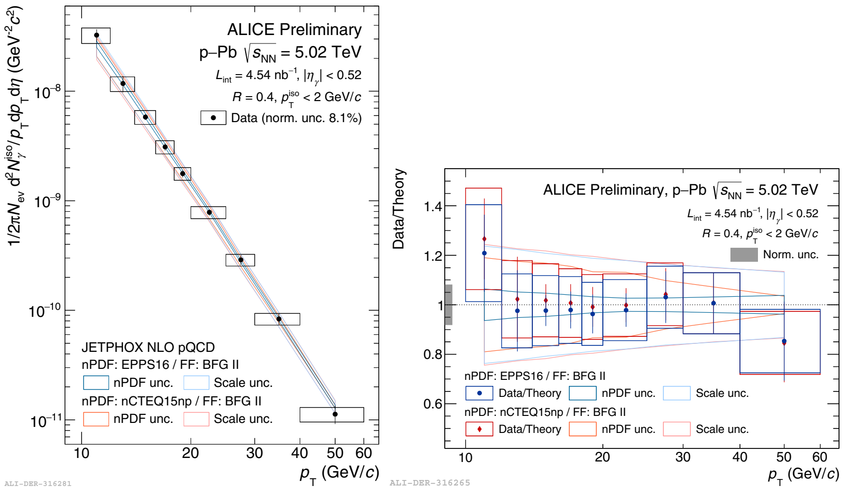


**Figure 4.** Left: The isolated photon spectrum measured in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to NLO pQCD calculations. Right: the ratio of data to theory.

classes. This indicates the presence of the thermal radiation from QGP created in heavy-ion collisions. The effective temperature of these thermal photons can be obtained as the inverse of the slope of the exponential functon that best fits to the $p_{\rm T}$ distributions in the low $p_{\rm T}$ region, as shown in Fig. 5 (right). For ALICE measurements in 0-20% centrality class $T_{\rm eff}$ is found to be 297 $\pm$ $12^{\rm stat}$ $\pm$ $41^{\rm syst}$ MeV, a temperature greater than that obtained in Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [11].

Figure 6 shows the comparison of the measured direct photon spectra and calculations within hydrodynamic models which incorporate thermal radiation from QGP and hadronic phases emitted during the collision evolution as well as prompt photons from hard processes in the initial phase. All models describe the measured spectra in all centrality classes although tend to be at the low edge of the uncertainties for the 0-20% centrality class in the low-$p_{\rm T}$ part.

## 5 $x_{\rm T}$ scaling of direct photon spectra

The observation of $x_{\rm T} = 2p_{\rm T}/\sqrt{s}$ scaling of high-$p_{\rm T}$ hadron production [12] led to conclusion of the importance of higher-twist processes [13]. Unlike hadrons, photons are believed to be produced mainly through $2 \rightarrow 2$ processes and thus should obey scaling with power law exponent $n \approx 4$. The $x_{\rm T}$-scaled spectra of world data including results of ALICE are shown in the Fig. 7. Approximately, spectra in all kinds of collision systems (pp, p-A and A-A) follow the same trend when scaled by $\sqrt{(s/\mathrm{GeV})^n}$, with $n = 4.5$.

## 6 Direct photon elliptic flow

Measurement of azimuthal anisotropy of particle production is a powerful tool to study initial conditions, time-space evolution and transport properties of the system. Collective flow is described with Fourier series coefficients $v_n$ of particle yield with respect to the reaction plane angle. The elliptic flow quantified by the second order coefficient $v_2$ is originated from the

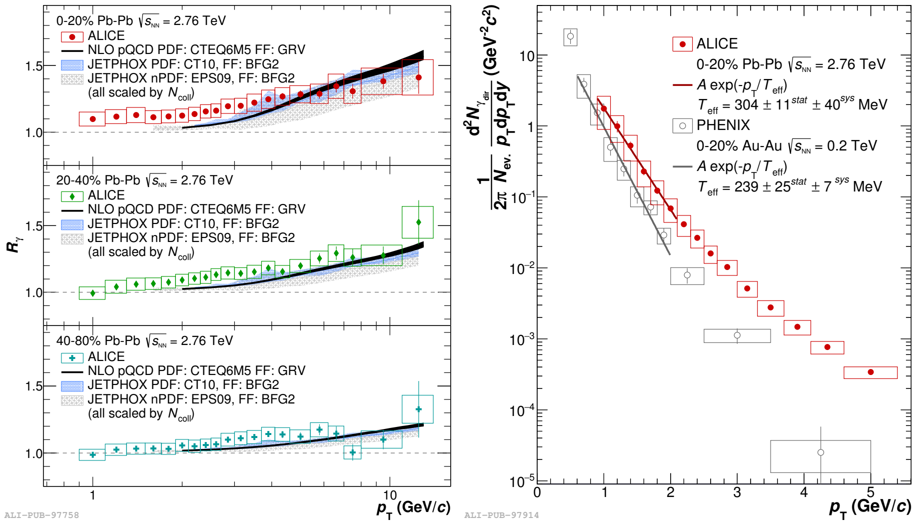


**Figure 5.** Left: The direct photon excess ratio $R_\gamma$ measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to NLO pQCD calculations scaled with $N_{\rm coll}$. Right: the spectrum of direct photons in 0-20% centrality class measured by ALICE [10] and PHENIX [11] experiments with exponential fits.

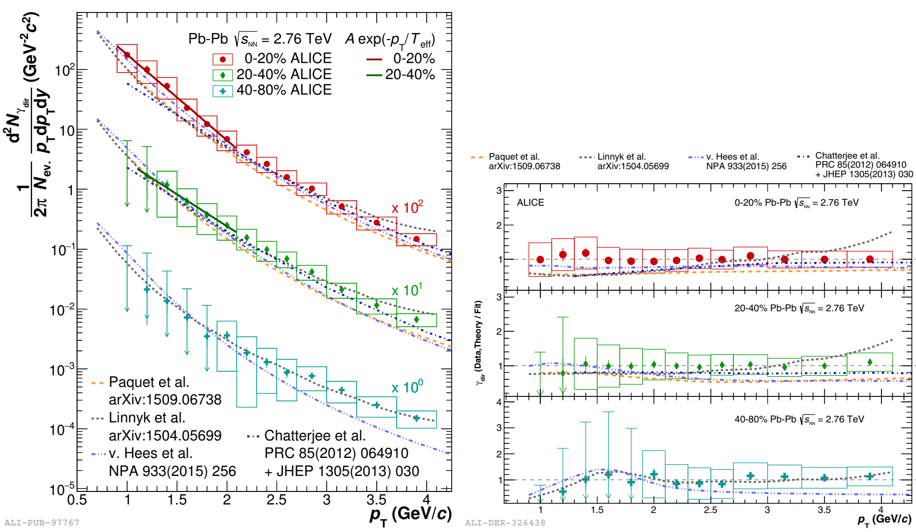


**Figure 6.** Left: The direct photon spectrum measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [10] compared to hydrodynamic and transport models. Right: the ratio of data and theoretical predictions to the fit to data.

fact that the initial spacial anisotropy of the colliding nuclei is transformed to final anisotropy in momentum space via strong interactions in the dense matter.

Direct photon elliptic flow was measured for the first time in Au-Au collisions at $\sqrt{s_{NN}} =$ 200 GeV by PHENIX collaboration [14] and was found to be similar in magnitude to the elliptic flow of hadrons. This similarity can not be explained within current hydrodynamic

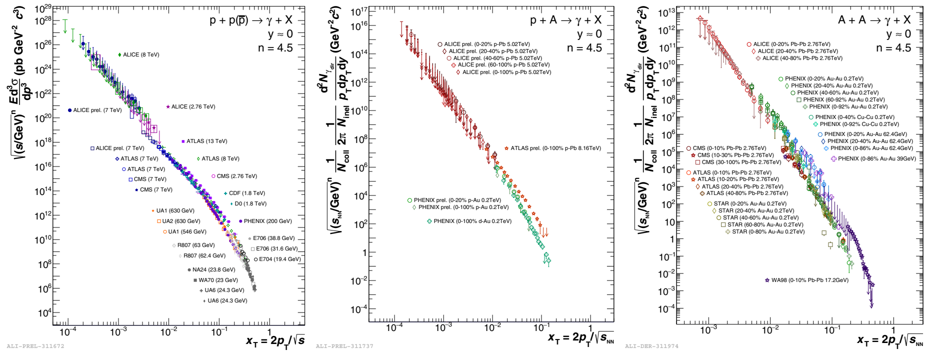


**Figure 7.** World data compilation of $x_T$-scaled direct and isolated photons spectra in pp(p̄) (left), p-A (middle) and A-A (right) collisions.

models which commonly predict significantly lower values of $v_2$ for direct photons. This finding, usually referred to as "direct photon puzzle", is widely debated in the literature [15].

ALICE measured direct photon elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV in two centrality classes, 0-20% and 20-40% [16]. The $v_2$ of direct photons was determined as:

$$v_2^{\gamma,\mathrm{dir}} = \frac{v_2^{\gamma,\mathrm{inc}} R_\gamma - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1} \quad (5)$$

where $R_\gamma$ is direct photon excess ratio discussed in section 4, $v_2^{\gamma,\mathrm{inc}}$ and $v_2^{\gamma,\mathrm{dec}}$ are the elliptic flow of inclusive and decay photons, respectively. $v_2^{\gamma,\mathrm{inc}}$ was measured using scalar product method [17] with reference particles detected in V0-A and V0-C detectors. $v_2^{\gamma,\mathrm{dec}}$ was obtained from simulations using measured or $m_T$-scaled $v_2$ of hadrons as an input.

The direct photon elliptic flow measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV is shown in Fig. 8. Direct photon elliptic flow was found to be similar in magnitude to elliptic flow of decay photons and systematically larger than predictions from hydrodynamic or transport models, although large systematic uncertainties of the measurements prevent us from drawing strong conclusions.

## 7 Conclusions

We presented overview ALICE results on direct and isolated photon production in pp, p-Pb and Pb-Pb collisions at LHC energies, and direct photon elliptic flow at Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. In pp and p-Pb collisions no significant direct photon excess was observed in the thermal photon region ($p_T < 2-3$ GeV/$c$), while at higher $p_T$ the results are consistent with $N_{\mathrm{coll}}$ scaled NLO pQCD calculations. In Pb-Pb collisions direct photon excess was observed for $p_T < 3$ GeV/$c$ with 2.6 $\sigma$ significance for 0-20% and 1.5 $\sigma$ significance for 20-40% centrality classes. In this $p_T$ range the spectra can be described by hydrodynamic models. At high transverse momentum ($p_T > 4$ GeV/$c$) the spectra are consistent with $N_{\mathrm{coll}}$ scaled NLO pQCD predictions. Direct photon elliptic flow was measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV for two centrality classes. Both in the 0-20% and 20-40% centrality classes, $v_2^{\gamma,\mathrm{dir}}$ has similar magnitude to the charged hadron elliptic flow and inclusive photon elliptic flow, but it is compatible with 0 within $\approx 1\sigma$ for $0.9 < p_T < 2.1$ GeV/$c$. This measurement confirms the creation of hot matter in Pb-Pb collisions with a subsequent significant collective

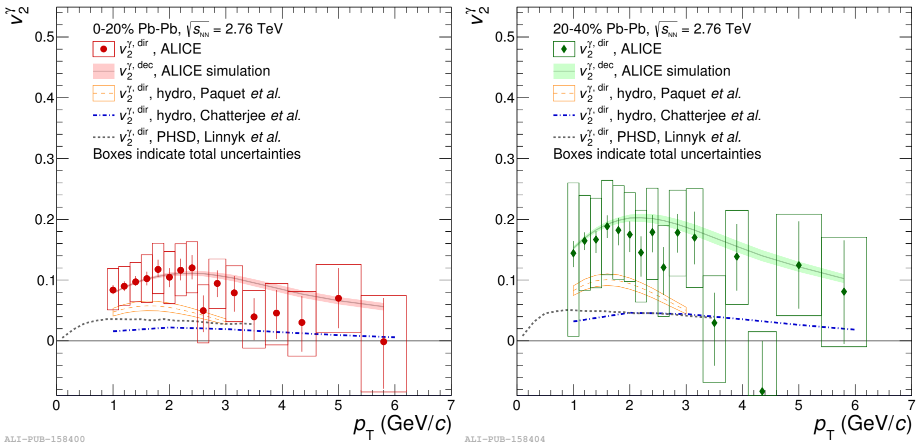


**Figure 8.** Left: The direct photon elliptic flow measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [16] compared to hydrodynamic models calculations in 0-20% (left) and 20-40% (right) centrality classes.

expansion. The measured magnitude of $v_2^{\gamma,\rm dir}$ tends to be larger than predictions of theoretical models albeit with large systematic uncertainties.

## Acknowledgments

This research was supported by the Russian Science Foundation grant 17-72-20234.

## References

[1] E.V. Shuryak, Phys.Lett. B **78**, 150 (1978), Sov.J.Nucl.Phys. **28**, 408 (1978), Yad.Fiz. **28** 796-808 (1978)
[2] ALICE Collaboration, JINST **3**, S08002 (2008)
[3] WA98 Collaboration, [arxiv:nucl-ex/0006007]
[4] ALICE Collaboration, Phys. Rev. C **99**, 024912 (2019)
[5] M. Klasen, C. Klein-Bösing, and H. Poppenborg, J. High Energy Phys. **03**, 081 (2018)
[6] CMS Collaboration, Phys. Rev. Lett. **106**, 082001 (2011)
[7] ATLAS Collaboration, Phys. Rev. D **83**, 052005 (2011)
[8] ALICE Collaboration, [arXiv:nucl-ex/1906.01371]
[9] P. M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, et al., Phys. Rev. D **78**, 013004 (2008)
[10] ALICE Collaboration, Phys. Lett. B **754**, 235-248 (2016)
[11] PHENIX Collaboration, Phys. Rev. C **91** no. 6, 064904 (2015)
[12] S. M. Berman, J. D. Bjorken, and J. B. Kogut, Phys. Rev. D **4**, 3388–3418 (1971); J.F. Gunion, R. Blankenbecler, S.J. Brodsky, Phys. Rev. D **18**, 900 (1978)
[13] F. Arleo, S. J. Brodsky, D. Sung Hwang, and A. M. Sickles, Phys. Rev. Lett. **105**, 062002 (2010)
[14] PHENIX Collaboration, Phys. Rev. Lett. **109**, 122302 (2012)
[15] G. David, [arXiv:nucl-ex/1907.08893]
[16] ALICE Collaboration, Phys. Lett. B **789**, 308 (2019)
[17] STAR Collaboration, Phys. Rev. C **66**, 034904 (2002)