Pion-kaon femtoscopy in Pb–Pb collisions at √s_{NN} = 2.76 TeV modeled in (3+1)D hydrodynamics coupled to Therminator 2 and the effect of delayed kaon emission

Adam Kisiel

Faculty of Physics, Warsaw University of Technology, ul. Koszykowa 75, PL-00662, Warsaw, Poland

Non-identical particle femtoscopy measures the size of the system emitting particles (“radius”) in heavy-ion collisions as well as the difference between mean emission space-time coordinates of two particle species (“emission asymmetry”). The system created in such collisions at the LHC behaves collectively and its dynamics is well described by hydrodynamic models. A significant emission asymmetry between pions and kaons, coming from collective flow, enhanced by contribution from flowing resonances is predicted. We present calculations within the (3+1)D viscous hydrodynamic model coupled to statistical hadronization code Therminator 2, corresponding to Pb–Pb collisions at √s_{NN} = 2.76 TeV. We obtain femtoscopic radii and emission asymmetry for pion-kaon pairs as a function of collision centrality. The radii grow linearly with cube root of particle multiplicity density. The emission asymmetry is negative and comparable to the radius, indicating that pions are emitted closer to the center of the system and/or later than kaons. Recent ALICE Collaboration measurements of identical kaon femtoscopy shows that kaons are emitted, on average, 2.1 fm/c later than pions. We modify our calculation by introducing such delay and find that the system source size is only weakly affected. In contrast the pion-kaon emission asymmetry is directly sensitive to such delays and the modified calculation shows significantly lower values of asymmetry. Therefore we propose the measurement of the pion-kaon femtoscopic correlation function as a sensitive probe of the time delays in particle emission.

PACS numbers: 25.75.-q, 25.75.Dw, 25.75.Ld

Keywords: relativistic heavy-ion collisions, femtoscopy, collective flow, emission asymmetry, non-identical particles

I. INTRODUCTION

The system created in collisions of heavy-ions at ultra-relativistic energies is dynamically expanding and cooling. In the early stages of the evolution it is thought to be in a deconfined phase (the Quark-Gluon Plasma), where the matter behaves as a strongly coupled liquid with small specific viscosity [1–4]. Models which employ hydrodynamic equations to describe this behavior are successful in reproducing many of the observables in such collisions. The most common are the transverse momentum spectra and elliptic flow, which are also modified by event-by-event fluctuations. This behavior of the system in momentum space is driven by space-time characteristics of the source – its size and gradients in pressure. Therefore, the correct description of the momentum space observables must be accompanied by a proper simulation of its space-time structure and its dynamics. The basic principles of such description have been established at RHIC [5, 6]. They have then been applied at the LHC [7–11] to describe the data on identical particle femtoscopy [12–15]. They include significant pre-thermal flows, an Equation of State that does not include the first-order phase transition, a careful treatment of strongly-decaying resonances as well as possible addition of viscosity.

The femtoscopic radii obtained from identical pion analysis agree well with model calculations [14], indicating that the dynamics of the system at the LHC is well described. Similar data for kaons show novel features [15]. The femtoscopic radii for kaons are larger than expected from the naive “m_T scaling” argument. The radii are also larger than predicted by Therminator 2 model, which includes hydrodynamic evolution of the system followed by the statistical hadronization. A second calculation presented in [15] is based on hydrodynamical model coupled to the hadronic rescattering code [11] and is able to reproduce the larger values of the kaon radii. The increase is attributed to the delay of the emission time of kaons, coming from the rescattering via the K^* meson. Experimental analysis with the theoretical formalism proposed in [11] shows that on average kaons are emitted later than pions by 2.1 fm/c. This result is then interpreted as evidence for the extended “rescattering” phase in the evolution of the heavy-ion collision. Confirmation of the existence of such phase has profound consequences for modeling such collisions and experimental data interpretation.

Femtoscopic technique is not limited to pairs of identical particles. For pairs of non-identical particles, the correlation arises from then the Final State Interactions (FSI), that is Coulomb when both particles in the pair are charged and Strong interaction when both particles are hadrons. The original motivation for the formulation of the non-identical particle femtoscopy formalism was to measure the difference in average time of the emission of various types of particles [16], which was called “emission asymmetry”. It was later realized that spatial

*Electronic address: kisiel@if.pw.edu.pl
emission asymmetry will produce equivalent asymmetry signal [17, 18]. Such spatial asymmetry arises naturally in a hydrodynamically expanding system, where thermal and flow velocities are comparable. Heavy-ion collisions produce such a system. In a detailed analysis of the non-identical particle correlations at RHIC energies [10], the emission asymmetry between pions, kaons, and protons was studied in detail. It was found that the emission asymmetry coming from the radial flow in the system is enhanced, for pion-kaon and pion-proton pairs, by additional non-trivial effects coming from the decay of flowing resonances. A complete set of emission asymmetries for three pair types was presented. Also the formalism was introduced and its validity was tested. The results show that the same formalism should be applicable in heavy-ion collisions at LHC.

The work is organized as follows. In Sec. II the model used in this work is described and the datasample which was analyzed is characterized. In Sec. III the formalism of the non-identical particle correlations is briefly introduced. Sec. IV discusses the main results of this work – the pion-kaon femtoscopic correlation functions as well as system sizes and emission asymmetries which were extracted from their analysis.

II. (3+1)D HYDRO AND THERMINATOR 2 MODELS

The model used in this work is composed of two parts. The collective expansion is modeled in the (3+1)D viscous hydrodynamics. The details of the implementation and the formalism of the model is presented in [20–22]. The particle emission is implemented in the statistical hadronization and resonance propagation and decay simulation code Therminator 2 [23].

In particular the calculations presented in this work have been intentionally performed on exactly the same generated model dataset, which was used in our previous work on identical particle femtoscopy [7]. These calculations were later used by the ALICE Collaboration for comparison with experimental data for identical kaon femtoscopy [15]. The discrepancies between our model calculation and data are an explicit scientific motivation for the studies in this work. We refer the reader to the works mentioned above for details of the model calculations. Here we only briefly mention the important features.

We use the viscous hydrodynamic model, following the second order Israel-Stewart equations [24]. Hard equation of state is used [5, 6], in particular a parametrization interpolating between lattice QCD results [25] at high temperatures and the hadron gas equation of state at low temperatures. All chemical potentials are set to zero. We use smooth initial conditions for the hydrodynamic evolution, given by the Glauber model. The initial time for the hydrodynamic evolution is 0.6 fm/c, viscosity coefficients are $\eta/s = 0.08$ and $\zeta/s = 0.04$, and the freeze-out temperature $T_f = 140$ MeV.

The calculation is performed for five sets of initial conditions, corresponding to impact parameter $b$ values (in fm) for the Pb–Pb collisions at the $\sqrt{s_{NN}}$=2.76 TeV: 3.1, 5.7, 7.4, 8.7, and 9.9 fm. They correspond, in terms of the average particle multiplicity density $\langle dN_{ch}/d\eta \rangle$, to given centrality ranges at the LHC [26]: 0–10%, 10–20%, 20–30%, 30–40%, and 40–50%.

Therminator 2 [23] code then performs a statistical hadronization on the freeze-out hypersurfaces obtained from the hydro model via the Cooper-Frye formalism. Chemical and kinetic freeze-outs are equated. Importantly the model does not include hadronic rescattering. It does however implement the propagation and decay (in cascades if necessary) of all known hadronic resonances. The final output from the model is a set of events, each composed of final-state particles, with information on the particle identity, momentum and space-time freeze-out coordinates provided for each of them.

III. NON-IDENTICAL PARTICLE FEMTOSCOPY FORMALISM

The formalism for non-identical particle femtoscopy is described in great detail in [18, 19]. Here we only briefly
introduce the main concepts.

The femtoscopic correlation function measures the conditional probability to measure two particles of a given type at a certain relative momentum $q$. In order to eliminate the trivial dependence on particle acceptance, such probability is normalized to the product of probabilities to measure each particle separately. Experimentally in heavy-ion collisions the measurement consists of constructing the distribution of pairs of particles of given types $X$ and $Y$ coming from the same event and storing their relative momenta in the distribution $A_{XY}(q)$. Then similar procedure is repeated, but the two particles come from two different events, giving the reference distribution $B_{XY}(q)$. The correlation function is then:

$$C(q) = A_{XY}(q)/B_{XY}(q) \quad (1)$$

For a pair consisting of a charged pion and a charged kaon, the femtoscopic correlation arises from the Strong and Coulomb Final State Interaction. Currently no model of heavy-ion collisions implements such interactions, therefore it must be introduced ‘a posteriori’ via the so-called “afterburner” procedure [18]. The pairs of particles are obtained from model events, and samples $A_{XY}$ and $B_{XY}$ are constructed in a procedure resembling the experimental one as closely as possible. However for each model pair going into the $A_{XY}$ sample an additional weight corresponding to the square of the module of the Bethe-Salpeter amplitude $\Psi_{XY}$ of the pair is added [18]. The correlation function is then a ratio of the weighted $A_{XY}$ sample to the $B_{XY}$ sample. The amplitude $\Psi_{XY}$ will be described in detail later in the manuscript.

The model procedure described above produces a correlation function with femtoscopic effects as well as all the other event-wide correlations present in the model. Some additional non-femtoscopic correlations were studied in the previous works [27, 28] and were found to be significant for pion-kaon pairs. However, it was also shown that such correlation can be efficiently corrected for with a data-driven procedure. Since this work focuses on the analysis of the femtoscopic effect, we do not study these additional correlations. Instead we employ a modified procedure, where the $B_{XY}$ sample is simply the $A_{XY}$ sample without femtoscopic weights. In such calculation the non-femtoscopic correlations are not present [18, 27].

The theoretical interpretation of the correlation function assumes that it is expressed as:

$$C(k^*) = \frac{\int S(r^*, k^*)|\Psi_{XY}(r^*, k^*)|^2}{\int S(r^*, k^*)} \quad (2)$$

where $r^* = x_1 - x_2$ is a relative space-time separation of the two particles at the moment of their creation. $k^*$ is the momentum of the first particle in the Pair Rest Frame, so it is half of the pair relative momentum in this frame (for identical particles $q = 2k^*$). $S$ is the source emission function and can be interpreted as a probability to emit a given particle pair from a given set of emission points with given momenta.

For a charged pion-charged kaon pair $\Psi_{\pi K}$ contains contributions from the Strong and Coulomb interaction [18]. However for this particular pair, the Strong interaction is expected to be small. The femtoscopic signal is dominated by the Coulomb interaction, especially for the emission asymmetry signature. Therefore in this work we use a simplification: we only consider the Coulomb part of the interaction. We use it self-consistently first to calculate the model correlation functions and later in the fitting procedure to extract the the system size and emission asymmetry. With this modification we have:

$$\Psi_{XY} = \sqrt{A_C(\eta)} e^{-ik^*r^*} F(-i\eta, 1, i\xi) \quad , \quad (3)$$

where $A_C$ is the Gamov factor, $\xi = k^*r^*(1 + \cos \theta^*)$, $\eta = 1/(k^*a_C)$, and $F$ is the confluent hypergeometric function. $\theta^*$ is the angle between $k^*$ and $r^*$ and $a_C$ is the Bohr radius which is equal to $\pm 248.52$ fm for the pion-kaon pair. The correlation function then shows a positive correlation effect for unlike-sign pion-kaon pairs, and a negative correlation effect for like-sign pairs. This $\Psi_{\pi K}$ is used as a basis to calculate the weight for the model correlation function calculation and in the fitting procedure.

This “afterburner” procedure employing weights, as described above, is used to calculate the femtoscopic cor-
relation functions for all charge combinations of charged pion-charged kaon pairs. The functions are stored in the Spherical Harmonics representation [29]. We only analyze the two components of this representation, the \( l = 0, m = 0 \) and the real part of the \( l = 1, m = 1 \). It was shown in [19] that these two components contain the relevant signals for the system size and emission asymmetry. The pions and kaons were selected in the \( p_T \) range of 0.15 to 2.5 GeV/c and pseudorapidity range \( |\eta| < 1.0 \), which corresponds to the reconstruction and PID acceptance of the ALICE detector. Two example correlation functions, one for like-sign another for unlike-sign pion-kaon pair, are shown in Fig. 1. A positive(negative) correlation effect, coming from the Coulomb attraction(repulsion) for unlike-sign(like-sign) pion-kaon can be clearly seen. Similarly the \( \Re C_1 \) clearly deviates from zero, indicating a non-zero emission asymmetry between pions and kaons.

A. Correlation function fitting

The model correlation function is then analyzed in a procedure closely resembling an experimental one. First it is assumed that the source is an ellipsoid with a Gaussian density profile. It has different widths in three directions defined in the Longitudinally Co-Moving System (LCMS), where the total longitudinal momentum of the pair vanishes. The directions are: “long” along the beam axis, “out” along the pair transverse momentum and “side” perpendicular to the other two. From the symmetry of the heavy-ion collision it is expected that the emission asymmetry between particles arises only in the “out” direction [17–19]. Its magnitude is another model parameter. The final form of the assumed emission function is then:

\[
S(r) \propto \exp \left( -\frac{[r_{\text{out}} - \mu_{\text{out}}]^2}{2\sigma_{\text{out}}^2} - \frac{r_{\text{side}}^2}{2\sigma_{\text{side}}^2} - \frac{r_{\text{long}}^2}{2\sigma_{\text{long}}^2} \right),
\]

where \( \sigma \) are the sizes of the system in the three directions and \( \mu \) is the emission asymmetry. The correlation function for non-identical particles is only weakly sensitive to the details of the three-dimensional shape of \( S \). Such details were much more precisely studied through identical particle femtoscopy [12–15]. We limit the number of independent fitting parameters by fixing \( \sigma_{\text{side}} = \sigma_{\text{out}} \) and \( \sigma_{\text{long}} = 1.3\sigma_{\text{out}} \). The values of the scaling coefficients are based on corresponding values of system sizes from identical pion femtoscopy [14]. In this work we focus instead on the emission asymmetry, which is not accessible in that technique. As a result we have only two independent fit parameters: \( \sigma_{\text{out}} \) characterizing the overall system size as well as \( \mu_{\text{out}} \) containing information of the pion-kaon emission asymmetry.

For a given set of \( \sigma_{\text{out}} \) and \( \mu_{\text{out}} \) values a “fit” correlation function is calculated according to Eq. (4) with \( \Psi \) given by Eq. (3). Then a \( \chi^2 \) value is calculated between this function a the “experimental-like” one calculated for Therminator 2 data. The calculation is repeated for all combinations of \( \sigma_{\text{out}} \) and \( \mu_{\text{out}} \) values in pre-defined ranges. An example result of such calculation is shown in Fig. 2. The minimization procedure is then employed to find the \( \sigma_{\text{out}} \) and \( \mu_{\text{out}} \) values that minimize the \( \chi^2 \) value. This set is the result of the fit. The procedure is implemented in the CorrFit software [30]. The fitting procedure also accounts for the so-called “purity” of the sample, or the percentage of the pairs that form the Gaussian core of the system. The values for this purity parameter depend mostly on the percentage of pions and kaons that come from strongly decaying resonances. Their abundances depend on the temperature of the chemical freeze-out. This temperature is very similar for RHIC and LHC calculations in Therminator, therefore in this work we have used the values estimated in the previous work for RHIC [19]. The \( \chi^2 \) landscape shown in Fig. 2 also reveals very small correlation between the \( \sigma_{\text{out}} \) and \( \mu_{\text{out}} \) fitting results. This has been observed consistently for all performed fits. In indicates that uncertainties of \( \sigma_{\text{out}} \) and \( \mu_{\text{out}} \) are uncorrelated.

IV. RESULTS

We calculate the femtoscopic correlation for all four charge combination of the pion-kaon pair: \( \pi^+K^+, \pi^0K^0, \pi^-K^+, \) and \( \pi^-K^- \). All correlations are fitted independently. At the end the result is averaged between all four charge combinations. The calculation has been performed for the event samples obtained from the (3+1)D hydrodynamic code coupled to Therminator 2 statistical hadronization, resonance propagation and decay code. The five samples used correspond to Pb–Pb collisions at the selected centralities. On the figures data for the five samples are plotted at the corresponding \( \langle dN_{ch}/d\eta \rangle^{1/3} \).

The standard calculation is performed on the generated events directly. Following the experimental in-
We also performed the calculations with a specific modification. For each kaon its emission time is modified by adding a delay $\Delta \tau$, distributed according to a Gaussian, with a certain width and mean. Firstly a calculation with a mean time delay of 2.1 fm/c and a width of 2 fm/c was performed. Then three other calculations were done, one with the mean changed to 1 fm/c, next with the mean changed to 3.2 fm/c and the last one with the width changed to 0.3 fm/c. The results of the fits to all the calculated correlation functions are presented in Fig. 3.

The figure shows the set of predictions for the pion-kaon source size and asymmetry in heavy-ion collisions at the LHC energy. The system size grows with event multiplicity, the dependence is to a good approximation linear. This is expected and understood, as similar increase has been consistently observed in all measurements for identical pion femtoscopy. The pion-kaon system size is a convolution of the size of the system emitting pions and kaons at a given velocity. Therefore, it is mostly influenced by the source radius which is larger, which usually is the one for pions.

The emission asymmetry in the default calculation is universally negative. This means that pions are emitted closer to the center of the system and/or later than kaons. This emission asymmetry is relatively large, comparable to the system size. It was shown in [19] that it is coming from the spatial asymmetry produced by a flow of primordial pions and kaons. This asymmetry is further enhanced by the qualitative difference in the way that resonance decays influence the emission pattern of pions and kaons. The pion decay momentum for most common resonances is close to or larger than a pion mass. The direction of the velocity of such pion is heavily randomized, and is no longer strongly influenced by the flow field. As a result the average emission point of pions from resonances is close to the geometrical center of the source. In contrast for kaons the decay momentum is usually small compared to the kaon mass. The parent resonance is usually quite heavy, therefore it is strongly pushed by the flow field. After decay the kaon velocity direction is still strongly correlated with the parent one. Therefore the average emission point for kaons is strongly pushed by the flow to the edge of the source, producing a large emission asymmetry with respect to pions.

When a time delay is introduced for kaons, the fit results are visibly changed. The overall system size is only slightly affected. It grows by approximately 0.5 fm for all calculations. The increase is larger when the introduced time delay is larger. The width of the time delay distribution has a smaller but still visible effect on size. The calculation with time delay distribution width of 0.3 fm/c gives a size about 0.1–0.2 fm smaller than the calculation with the time delay width of 2 fm/c.

The kaon emission time delay has a direct and strong effect on the pion-kaon emission asymmetry. As expected the delay significantly decreases the emission asymmetry. When the time delay is increased to 3.2 fm the emission asymmetry even turns positive for most peripheral collisions. The value of introduced time delay is shifting the extracted emission asymmetry and the value of this shift

FIG. 3: (Color online) Source size (upper panel) and pion-kaon emission asymmetry (lower panel) from pion-kaon correlation functions calculated in the Therminator 2 model for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for selected centralities. Blue open points show default calculation. Red closed points, orange open squares, green closed squares and violet open diamonds show calculations with selected values of additional time delay for kaons (see text for details). Some points were shifted slightly in the $x$-direction for clarity.

FIG. 4: (Color online) The difference in the extracted pion-kaon emission asymmetry between the default calculation for the Therminator 2 model for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and the calculations with additional kaon emission time delay, plotted as a function of the value of additional shift. Some points were shifted slightly in the $x$-direction for clarity.
is independent of centrality (and therefore system size).

In Fig. 3 the difference in the extracted emission asymmetry between the default calculation and the calculations with the kaon emission time delay is plotted as a function of the value of this introduced delay. The dependence between the two seems to be a direct one-to-one correspondence, independent of the system size. In other words this calculation shows that pion-kaon emission asymmetry is directly and linearly sensitive to any delays in emission time of kaons. The calculation shows that the experimental measurement of the pion-kaon emission asymmetry can be a very sensitive cross-check of the model interpretation of identical pion and kaon femtoscopy data given in [15]. In particular if the interpretation given in this work is correct, than ALICE should observe pion-kaon emission asymmetry of approximately $-4\text{ fm}$ in most central collisions, instead of $-6\text{ fm}$ predicted by the default Therminator 2 calculation.

It should be noted that the analysis of the kaon emission time presented in [15] are given for central events only. It is postulated that the emission delay is a result of rescattering via the $K^*$ resonance. If that is the case (and given that the chemical freeze-out temperature and consequently the relative abundance of this resonance changes little with centrality), then the value of the delay should be similar at other centralities too. This work shows the predictions for them as well. On the other hand if the experimentally observed asymmetry will be different at other centralities, the calculations shown in Fig. 3 can be used to estimate the kaon emission time delay from the data.

V. SUMMARY

We have presented the first calculations of pion-kaon femtoscopic correlation function for Pb–Pb collisions at the $\sqrt{s_{NN}}=2.76$ TeV at selected collision centralities. System size and emission asymmetry was extracted for each pion-kaon charge combination and collision centrality separately. The extracted system size is observed to linearly increase with cube root of the charged particle multiplicity density. The emission asymmetry is large and negative, indicating that pions are emitted closer to the center of the source and/or later than kaons. Such asymmetry is naturally expected in a hydrodynamically flowing medium, where large fraction of particles is produced via resonance decay. The results are also qualitatively consistent with the calculations at top RHIC collision energies.

Following the experimental results for identical kaon femtoscopy the calculation has been modified by introducing an emission time delay for kaons. The pion-kaon asymmetry is shown to be directly and linearly sensitive to such delay. The introduction of a time delay of $2.1\text{ fm}$ reduced the pion-kaon asymmetry to approximately $-4\text{ fm}$ for central collisions, compared to approximately $-6\text{ fm}$ for default calculation. Such difference should be measurable in the ALICE experiments. The experimental data on pion-kaon emission asymmetry can be a direct and sensitive test of the existence of emission time delay for kaons. The confirmation of its existence would be a strong and independent argument for the importance of the hadronic rescattering phase at the LHC.

Acknowledgment

This work has been supported by the Polish National Science Centre under grant No. UMO-2014/13/B/ST2/04054.

[1] J. Adams et al. (STAR), Nucl. Phys. A757, 102 (2005).
[2] K. Adcox et al. (PHENIX), Nucl. Phys. A757, 184 (2005).
[3] B. B. Back et al., Nucl. Phys. A757, 28 (2005).
[4] I. Arsene et al. (BRAHMS), Nucl. Phys. A757, 1 (2005).
[5] W. Broniowski, M. Chojnacki, W. Florkowski, and A. Kisiel, Phys.Rev.Lett. 101, 022301 (2008).
[6] S. Pratt, Nucl. Phys. A830, 51c (2009).
[7] A. Kisiel, M. Gaayn, and P. Bozek, Phys. Rev. C90, 064914 (2014), 1409.4571.
[8] P. Bozek, Phys. Rev. C95, 054909 (2017), 1702.01319.
[9] I. Karpenko, Y. Sinyukov, and K. Werner, Phys.Rev. C87, 024914 (2013), 1204.5351.
[10] A.A. Karpenko and Yu. M. Sinyukov, Phys. Rev. C81, 054903 (2010), 1004.1565.
[11] V. M. Shapoval, P. Braun-Munzinger, I. A. Karpenko, and Yu. M. Sinyukov, Nucl. Phys. A929, 1 (2014), 1404.4501.
[12] K. Aamodt et al. (ALICE Collaboration), Phys.Lett. B696, 328 (2011).
[13] J. Adam et al. (ALICE), Phys. Rev. C92, 054908 (2015), 1506.07884.
[14] J. Adam et al. (ALICE), Phys. Rev. C93, 024905 (2016), 1507.06842.
[15] S. Acharya et al. (ALICE), Phys. Rev. C96, 064915 (2012).
[16] R. Lednicky, V. L. Lyuboshits, B. Erazmus, and D. Nouais, Phys. Lett. B373, 30 (1996).
[17] R. Lednicky, in International Workshop on the Physics of the Quark Gluon Plasma Palaiseau, France, September 4-7, 2001 (2001), nucl-th/0112011.
[18] R. Lednicky, Phys. Part. Nucl. 40, 307 (2009), nucl-th/0501065.
[19] R. Lednicky, Phys. Rev. C81, 064906 (2010), 0909.5349.
[20] P. Bozek, Phys.Rev. C85, 034901 (2012).
[21] P. Bozek and I. Wyskiel-Piekarska, Phys. Rev. C85, 064915 (2012).
[22] P. Bożek, Phys. Rev. C89, 044904 (2014).
[23] M. Chojnacki, A. Kisiel, W. Florkowski, and W. Broniowski, Comput. Phys. Commun. 183, 746 (2012).
[24] C. Gale, S. Jeon, B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013).
[25] S. Borsanyi et al., JHEP 11, 077 (2010).
[26] K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. 106, 032301 (2011).
[27] A. Kisiel, Acta Phys. Polon. B48, 717 (2017).
[28] K. Graczykowski, A. Kisiel, M. A. Janik, and P. Karczmarczyk, Acta Phys. Polon. B45, 1993 (2014), 1409.8120.
[29] A. Kisiel and D. A. Brown, Phys. Rev. C80, 064911 (2009).
[30] A. Kisiel, Nukleonika 49, s81 (2004).