THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Possible explanation of the irregular energy dependence of the rapidity width of ϕ mesons observed in Pb+Pb collisions

Tom Reichert[1,2,3], **Jan Steinheimer**[2,4], **Marcus Bleicher**[1,3,4,a]

[1] Institut für Theoretische Physik, Goethe-Universität Frankfurt, Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany

[2] Frankfurt Institute for Advanced Studies (FIAS), Ruth-Moufang-Str. 1, D-60438 Frankfurt am Main, Germany

[3] Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung GmbH, Campus Frankfurt, Max-von-Laue-Str. 12, 60438 Frankfurt am Main, Germany

[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, D-64291 Darmstadt, Germany

Abstract Experimental data from the NA49 collaboration show an unexpectedly steep rise of the rapidity width of the ϕ meson as function of beam energy, which was suggested as possible interesting signal for novel physics. In this work we show that the Ultra-relativistic Quantum-Molecular-Dynamics (UrQMD) model is able to reproduce the shapes of the rapidity distributions of most measured hadrons and predicts a common linear increase of the width for all hadrons. Only when following the exact same analysis technique and experimental acceptance of the NA49 and NA61/SHINE collaborations, we find that the extracted value of the rapidity width of the ϕ increases drastically for the highest beam energy. We conclude that the observed steep increase of the ϕ rapidity width may be a problem of limited detector acceptance and the simplified Gaussian fit approximation.

1 Introduction

A promising observable for the understanding of strongly interacting matter created in heavy ion collisions is the production of ϕ mesons. Being a $\bar{s}s$ state with zero net-strangeness it has a small hadronic cross section and may therefore transport information directly from hadronisation. Being at the same time a multi-strange hadron and net strangeness neutral it is further sensitive to different realizations of strangeness suppression in peripheral collisions, either via canonical strangeness suppression or via a γ_s strangeness suppression factor. It has been further found that many transport simulations have substantial problems to describe the yields of ϕ mesons, which may hint to hith-

erto unknown production channels. For the production of ϕ mesons in hadronic and partonic matter many mechanisms have been proposed, such as thermal production [1], OZI suppressed reactions [2], kaon coalescence [3], catalytic reactions [4,5] or from heavy resonance decays [6].

The production of ϕ mesons has been studied extensively in experiments at the CERN-LHC [7], RHIC [8–10], CERN-SPS [11–13], BNL-AGS [14] and at GSI [15–17]. Especially deep sub-threshold production of strangeness in the ϕ and Ξ hadrons has been subject of low energy and large baryon density experiments e.g. at HADES [16–18] accompanied by theoretical efforts [5,6].

The NA49 collaboration at the CERN-SPS has reported on the rapidity widths of several hadrons ranging from π^-, $K^\pm$ to $\overline{\Lambda} + \overline{\Sigma}^0$ and to the ϕ meson for central Pb+Pb collisions in the energy range from $E_{\text{lab}} = 20A$ GeV to $E_{\text{lab}} = 158A$ GeV [12]. Recently, additional measurements in p+p collisions in the same energy range have been reported by the NA61/SHINE experiment [13]. The general observations for π^-, $K^\pm$ and $\overline{\Lambda} + \overline{\Sigma}^0$ was that the rapidity widths increase linearly as a function of the beam rapidity both in Pb+Pb and in p+p collisions in the investigated energy regime and that the rapidity widths in Pb+Pb and p+p are very similar to each other. These results are summarized as open (p+p) and filled (Pb+Pb) symbols in Fig. 1. The ϕ seems to follow this linear trend in p+p collisions, but shows a stark difference in Pb+Pb collisions. For Pb+Pb collisions the data suggest a dramatic deviation from the trend observed for all other hadrons, namely a much broader rapidity width of the ϕ meson for the highest collision energy.

In this article we aim to explore the reason for this apparent broadening of the rapidity width of the ϕ in Pb+Pb collisions at $158A$ GeV using microscopic transport simulations.

[a] e-mail: bleicher@itp.uni-frankfurt.de (corresponding author)

We will first calculate the rapidity distributions and widths directly from the UrQMD simulations and then proceed with the analysis following the experimental procedure to extract σ_y of the ϕ meson.
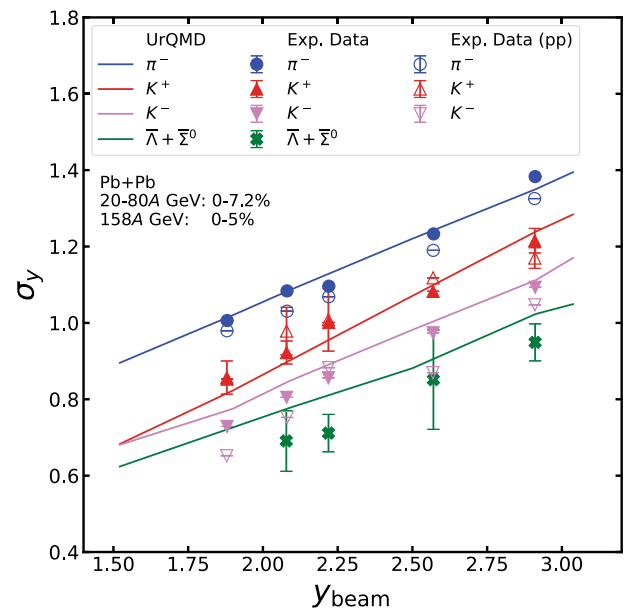
2 The UrQMD model and resonance reconstruction

The Ultra-relativistic Quantum Molecular Dynamics model (UrQMD) [19–21] is based on the covariant propagation of hadrons and their resonances in phase space. As a QMD-type model it keeps track of all n-body correlations providing a realistic time evolution for the n-body phase space distribution function. In its current version UrQMD includes mesonic and baryonic hadrons and resonances up to 4 GeV in mass. Their binary interactions are modeled via measured or derived cross sections, while additional QMD potentials can be switched on but will not be used in the present work.

Experimentally, unstable resonances like the ϕ are reconstructed from the invariant masses of their decay products. The NA49 collaboration, in particular, use the $\phi \to K^+ K^-$ channel for the reconstruction in an invariant mass analysis and correct for the branching ratio of 49.1% [12]. This means, from the invariant mass distributions of the measured $K^+ K^-$-pairs, the yield of the ϕ is obtained by fitting a relativistic Breit-Wigner distribution in the mass range of the m_ϕ after subtracting the uncorrelated background. Thus, only ϕ mesons where both decay daughter particles escape without interaction from the fireball can be reconstructed experimentally. Therefore, in the simulation, measurable resonances are identified by tracing their daughter particles and counting only those ϕ mesons for which both daughter particles escape without further interactions. This method is well established and has been extensively tested at various collision energies and resonances [22–28]. We note that in the model calculation we use all $\phi \to \overline{K}K$ decays independent of the charge in order to have better statistics.[1]

3 Results

All results have been obtained by calculating 0–7.2% central Pb+Pb collisions at the lower energies and 0–5% central Pb+Pb collisions at 158A GeV, in accordance with the experimental centrality cuts [12]. We select the centrality by an impact parameter cut chosen to match the number of wounded nucleons which NA49 reports [12]. All calculations are done with UrQMD (v3.4) in cascade mode. We reconstruct ϕ mesons in the $\phi \to \overline{K}K$ channel (independent of charge) by following the daughter particles through the evo-

_____
[1] We have checked that this does not influence the yield and spectra.

Fig. 1 Comparison between experimental results [11–13,29–34] of the rapidity widths of π^- (blue), K^+ (red), K^- (magenta) and $\overline{\Lambda} + \overline{\Sigma}^0$ (green) in p+p (open symbols) and Pb+Pb (filled symbols) collisions and UrQMD simulations for Pb+Pb reactions (solid lines) in the energy range from $E_{\text{lab}} = 20A$ GeV to $E_{\text{lab}} = 158A$ GeV

lution. Only if both kaons escape without further interaction, we consider the ϕ reconstructable.
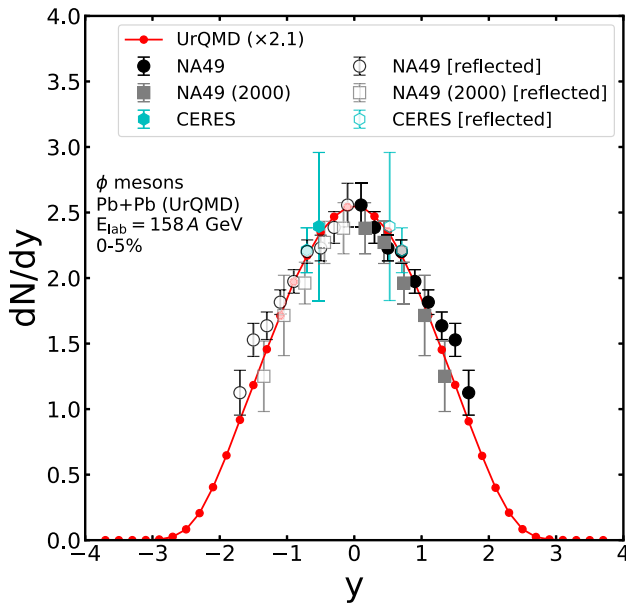
To establish the baseline for the investigation, we first compare the rapidity widths of π^-, $K^\pm$ and $\overline{\Lambda} + \overline{\Sigma}^0$ in Pb+Pb reactions with those presented in the NA61/SHINE article [13]. For this purpose we calculate the rapidity distributions of π^-, K^+, K^- and $\overline{\Lambda} + \overline{\Sigma}^0$ and extract the width of the rapidity distribution σ_y from the simulated data precisely by $\sigma_y^2 = \langle y^2 \rangle - \langle y \rangle^2$. Figure 1 shows the comparison of the rapidity widths calculated from UrQMD (solid lines) to the experimental data [11–13,29–34] of π^- (blue), K^+ (red), K^- (magenta) and $\overline{\Lambda} + \overline{\Sigma}^0$ (green) in Pb+Pb (filled symbols) collisions. The experimental data in p+p collisions are also shown as open symbols.

One observes that the transport model calculations of σ_y agree very well with the experimentally measured data for all investigated hadron species. Both model and data show a linear increase of the width of the rapidity distributions with increasing beam rapidity, with a roughly constant slope across all hadron species.

As reported in [12] the σ_y of the ϕ seems to not follow this behavior, especially close to $\sqrt{s_{\text{NN}}} = 17.3$ GeV.

Before calculating the width of the rapidity distribution of the ϕ, the rapidity density should be compared directly between the model calculation and the experimental data to confirm the ability of the model to describe the shape of the rapidity distribution. Figure 2 shows the rapidity distribution of reconstructable ϕ mesons in 0–5% central Pb+Pb
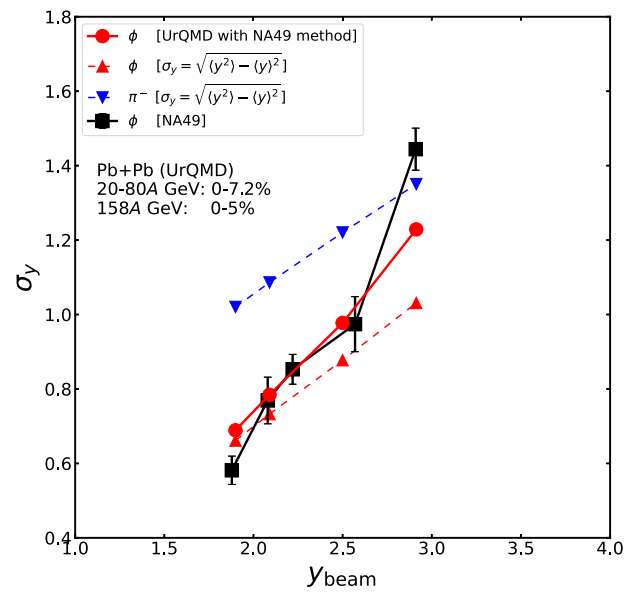
Fig. 2 Rapidity distributions of reconstructable ϕ mesons in 0–5% central Pb+Pb collisions at $E_{\text{lab}} = 158A$ GeV (red, scaled by 2.1) from UrQMD in cascade mode. The symbols represent experimental data taken at $E_{\text{lab}} = 158A$ GeV ($\sqrt{s_{\text{NN}}} = 17.3$ GeV) by NA49 [12] (black circles), earlier by NA49 [11] (grey squares) and by CERES [35] (cyan hexagons, Pb+Au). The reflected experimental data is shown by brighter symbols and colors

Fig. 3 The rapidity width σ_y as a function of the beam rapidity of the ϕ calculated using the experimental technique (red filled circles) and calculated directly from the data set (red triangles-up) in 0−7.2%/0–5% central Pb+Pb collisions at different energies from UrQMD. The UrQMD calculations of the width of the π^- (blue triangles-down) are shown as a comparison. Experimental results for the ϕ [12] in Pb+Pb are shown as black squares with error bars

collisions at 158A GeV (red, scaled by a factor 2.1) from UrQMD. The symbols represent experimental data by the NA49 collaboration [12] (black circles), earlier data by the NA49 [11] (grey squares) and by the CERES[2] experiment [35] (cyan hexagons). The reflected experimental data is shown by lighter/open symbols.

We note that describing the yield of ϕ mesons produced in nuclear reactions is often a challenging task for transport approaches as well as for thermal models. This is mainly due to the fact that it is not a priori clear whether a ϕ should be treated as a double-strange or zero-strange hadron. It might further be accounted for as evidence for hitherto unknown production channels or medium modifications, see [36,37] and references therein. Therefore the UrQMD simulations have been scaled for better comparison by a factor of 2.1 (obtained through a fit to the available data) such that the integrated yield of the ϕ matches the experimental value. We explicitly state that this scaling does, however, neither affect the shape nor width of the calculated rapidity distribution.

The shape of the rapidity density of ϕ mesons calculated with UrQMD describes the measured rapidity density very well, especially in terms of the width. This is also quantified in the reduced chi-squared $\tilde{\chi}^2 \equiv \chi^2/d.o.f.$ of the UrQMD-

Data comparison which evaluates to $\tilde{\chi}^2_{\text{UrQMD}} = 0.16$ for UrQMD and to $\tilde{\chi}^2_{\text{Gauss}} = 0.10$ for a single Gaussian fit to the data. The quality of both fits is hence very good and both can be considered a good description of the available data.[3]
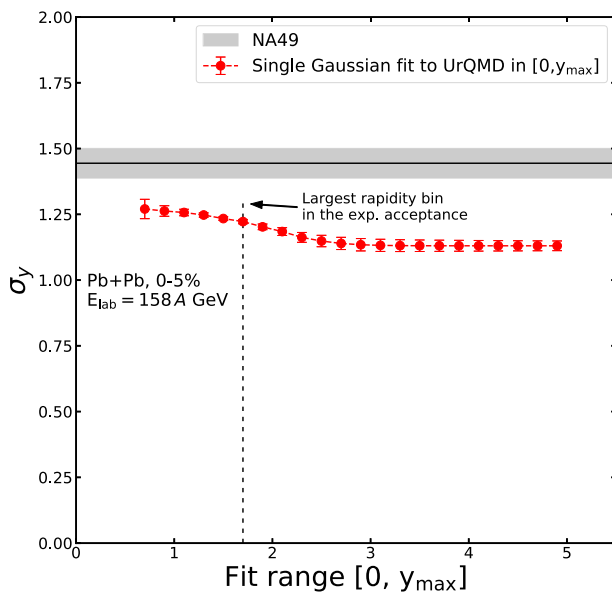
To calculate the width of the ϕ rapidity density σ_y two different methods can be employed:

1. The width is directly calculated, assuming full rapidity acceptance, as $\sigma_y = \sqrt{\langle (\delta y)^2 \rangle} = \sqrt{\langle y^2 \rangle - \langle y \rangle^2}$ from the simulated data set as it was done for the comparison of the π^-, $K^\pm$ and $\overline{\Lambda} + \overline{\Sigma}^0$ widths in Fig. 1.
2. We employ the method used by the NA49 collaboration, i.e. we fit the rapidity density with a Gaussian (2) and/or a double Gaussian[4] (3) in the rapidity acceptance of the NA49 detector.[5] Following the experimental analysis as described in [12, p. 9], we then extrapolate the rapidity width from the UrQMD calculations

---

[2] Note that CERES has measured ϕ mesons in a slightly asymmetric system, i.e. in Pb+Au collisions. The results are thus not necessarily one to one comparable with the measurements in Pb+Pb.

[3] Although the overall normalization of the UrQMD curve underestimates the measured ϕ yields, the $\chi^2/d.o.f.$ of the scaled curve suggests that the kinematics of the ϕ production are handled properly, hence allowing to reliably calculate the width of the rapidity distribution.

[4] Note, that in case of a double Gaussian the width of the distribution is not equal to the parameter in the denominator, hence we renamed it as ϖ to avoid confusion. The standard deviation of the double Gaussian is then $\sigma = \sqrt{\varpi^2 + a^2}$.

[5] The rapidity acceptances vary with energy. We have chosen the rapidity windows for our analysis in accordance with NA49 [?, Tab. III]

Fig. 4 The rapidity width σ_y of ϕ mesons calculated with the experimental method using a single Gaussian to extrapolate the ϕ rapidity density from $0 \leq y \leq y_{max}$ to the full rapidity range (red circles with error bar) in 0–5% central Pb+Pb collisions at $E_{lab} = 158A$ GeV from UrQMD. The experimental results [12] in Pb+Pb are shown as a black line with error band

in the respective rapidity acceptance to the full acceptance using the single (2) and/or double (3) Gaussian fits (at 158 GeV only the single Gaussian is used) to the UrQMD calculations in the rapidity acceptance and then calculate the rapidity width ($\equiv \sigma_{Exp.}$) as the average $\sigma_{Exp.} = 0.5\left(\sigma_{extrap.}^{single\ Gauss} + \sigma_{extrap.}^{double\ Gauss}\right)$ of the extrapolated widths. The extrapolated rapidity width is obtained as shown below in (1)

$$\sigma_{extrap.} = \sqrt{\frac{\sum_i y_i^2 \left(\frac{dN}{dy}\right)_i \Delta y_i + \int_a^b y^2 f_{fit}(y) dy}{\sum_i \left(\frac{dN}{dy}\right)_i \Delta y_i + \int_a^b f_{fit}(y) dy}}, \qquad (1)$$

where the sum runs over the rapidity bins, y_i is the rapidity of the i-th bin, $(dN/dy)_i$ is the rapidity density of the i-th bin, Δy_i is the width of the i-th bin and the integral integrates the region not covered by the acceptance (note that this does not only cover the forward rapidity, but might also cover the midrapidity region at certain energies [12]) in which $f_{fit}(y)$ is the single and/or double Gaussian fit to the UrQMD calculations fitted in the rapidity acceptance.

$$\frac{dN}{dy} \propto \exp\left[-\frac{y^2}{2\sigma^2}\right] \qquad (2)$$

$$\frac{dN}{dy} \propto \exp\left[-\frac{(y+a)^2}{2\varpi^2}\right] + \exp\left[-\frac{(y-a)^2}{2\varpi^2}\right] \qquad (3)$$

Figure 3 compares the calculated rapidity widths σ_y (red triangles-up) and $\sigma_{Exp.}$ (red filled circles) of the ϕ from UrQMD, in $0-7.2\%$ and $0-5\%$ central Pb+Pb collisions at different energies, as a function of the beam rapidity. The UrQMD calculations of the width of the π^- (blue triangles-down) are shown as a comparison. Experimental results for the ϕ [12] in Pb+Pb are shown as black squares with error bars.

Though the experimental value of the width σ_y of the ϕ at 158A GeV is still larger than the widths of the ϕ, calculated from the simulated UrQMD events, one notices that the width of the rapidity density of the ϕ calculated by following exactly the experimental technique shows also a much larger value than the direct calculation of σ_y in the model. One should also keep in mind that this large variation of the rapidity width σ_y occurs for two different, but statistically very likely (i.e. both the scaled UrQMD calculation and the single and/or double Gaussian fit to the rapidity density dN/dy have a low χ^2, cf. Figure 2), descriptions of the data. In general one notices that extracting the rapidity width σ_y by extrapolating to the full rapidity range using single and/or double Gaussian fits yields larger widths than the direct calculation in the model, also at the lower energies. The dependence on the beam rapidity remains, however, linear but with a slightly increased slope. The UrQMD model calculation of $\sigma_{Exp.}$ of the ϕ meson employing the experimental technique comes very close to the experimental values though the true value of the width σ_y shows the same linear trend with the same slope as the other hadrons. We, however, also point out that at 158A GeV the $\sigma_{Exp.}$ extracted from UrQMD using a Gaussian fit still does not reach the value extracted by NA49. Also the measured rapidity width at the lowest energy (20A GeV) is slightly better described by the direct calculation of σ_y than by using the Gaussian fits.

To better understand the systematics of the strong increase of $\sigma_{Exp.}$, Fig. 4 shows the rapidity width σ_y of ϕ mesons calculated with the experimental method using a single Gaussian to extrapolate the ϕ rapidity density from $0 \leq y \leq y_{max}$ to the full rapidity range (red circles with error bar) in 0–5% central Pb+Pb collisions at $E_{lab} = 158A$ GeV from UrQMD. The experimental results [12] in Pb+Pb are shown as a black line with error band.

The rapidity width $\sigma_{Exp.}$ from the UrQMD calculation shows a strong dependence on the considered fit range (i.e. the acceptance of the experimental detector). Smaller acceptance windows artificially increase the extracted rapidity width. This can be attributed to the extrapolation of the employed fit function to large forward and backward rapidities, which deviates from the actual tails of the simulated distributions, simply because the distribution does not

exactly resemble a double Gaussian. This phenomenon is not observed at lower collision energies because the acceptance in beam rapidity allowed the single or double Gaussian fit to capture the whole distribution, constraining it also at higher forward and backward rapidities.

Again, we want to emphasize that all fits will provide a low $\tilde{\chi}^2$ as the fit usually does not put much emphasis on the tails of the distributions. In conclusion it is not clear whether the systematic error, given by the experiment, is sufficient to capture the uncertainties arising from fitting a double Gaussian in an incomplete acceptance. Therefore also the interpretation of the steep increase of the width as a signal for new physics remains an open question.

4 Conclusion

In the present article we have employed the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model to calculate 0-5% and $0-7.2\%$ central Pb+Pb collisions and extract the rapidity distributions of reconstructable ϕ mesons. The NA49 collaboration observed a strong increase of the width of the rapidity density of ϕ mesons around $\sqrt{s_{NN}} = 17.3$ GeV. We have demonstrated that this increase in σ_y may arise as an artifact from the limited rapidity coverage of the detector being extrapolated with a function which may not be able to capture the tails of the distributions correctly. The rapidity width calculated directly from the simulated data set of the ϕ follows the same linear trend as seen for the π^-, $K^\pm$ and $\overline{\Lambda} + \overline{\Sigma}^0$ while the width extracted following the experimental technique, i.e. calculated directly from the (transport model) data within the experimental acceptance and extrapolated to the full rapidity range employing the same fit function, shows a steeper slope with respect to the beam rapidity. This brings the rapidity width of the ϕ closer to the value measured by NA49. A discrepancy between the NA49 data and the UrQMD calculation following their technique is, however, still remaining.

Data Availibility Statement Data will be made available on reasonable request. [Author's comment: Generated data set are not available. The model to create the data sets is available from the corresponding author on reasonable request.]

Code Availability Statement Code/software will be made available on reasonable request. [Author's comment: The code/software generated during and/or analysed during the current study is available from the corresponding author on reasonable request.]

References

1. V. Vovchenko, V.V. Begun, M.I. Gorenstein, Phys. Rev. C **93**(6), 064906 (2016). https://doi.org/10.1103/PhysRevC.93.064906. [arXiv:1512.08025 [nucl-th]]
2. W.S. Chung, G.Q. Li, C.M. Ko, Nucl. Phys. A **625**, 347–371 (1997). https://doi.org/10.1016/S0375-9474(97)00198-X. [arXiv:nucl-th/9704002 [nucl-th]]
3. C.M. Ko, B.H. Sa, Phys. Lett. B **258**, 6–10 (1991). https://doi.org/10.1016/0370-2693(91)91199-6
4. E.E. Kolomeitsev, B. Tomasik, J. Phys. G **36**, 095104 (2009). https://doi.org/10.1088/0954-3899/36/9/095104. [arXiv:0903.4322 [nucl-th]]
5. B. Tomasik, E.E. Kolomeitsev, Acta Phys. Polon. Supp. **5**, 201–206 (2012). https://doi.org/10.5506/APhysPolBSupp.5.201. [arXiv:1112.1437 [nucl-th]]
6. J. Steinheimer, M. Bleicher, J. Phys. G **43**(1), 015104 (2016). https://doi.org/10.1088/0954-3899/43/1/015104. [arXiv:1503.07305 [nucl-th]]
7. B.B. Abelev et al., [ALICE]. Phys. Rev. C **91**, 024609 (2015). https://doi.org/10.1103/PhysRevC.91.024609. [arXiv:1404.0495 [nucl-ex]]
8. S.S. Adler et al., [PHENIX]. Phys. Rev. C **72**, 014903 (2005). https://doi.org/10.1103/PhysRevC.72.014903. [arXiv:nucl-ex/0410012 [nucl-ex]]
9. B.I. Abelev et al., [STAR]. Phys. Lett. B **673**, 183–191 (2009). https://doi.org/10.1016/j.physletb.2009.02.037. [arXiv:0810.4979 [nucl-ex]]
10. B.I. Abelev et al., [STAR]. Phys. Rev. C **79**, 064903 (2009). https://doi.org/10.1103/PhysRevC.79.064903. [arXiv:0809.4737 [nucl-ex]]
11. S.V. Afanasiev et al., [NA49]. Phys. Lett. B **491**, 59–66 (2000). https://doi.org/10.1016/S0370-2693(00)01023-6
12. C. Alt et al., [NA49]. Phys. Rev. C **78**, 044907 (2008). https://doi.org/10.1103/PhysRevC.78.044907. [arXiv:0806.1937 [nucl-ex]]
13. A. Aduszkiewicz et al., [NA61/SHINE]. Eur. Phys. J. C **80**(3), 199 (2020). https://doi.org/10.1140/epjc/s10052-020-7675-6. [arXiv:1908.04601 [nucl-ex]]
14. B.B. Back et al., [E917]. Phys. Rev. C **69**, 054901 (2004). https://doi.org/10.1103/PhysRevC.69.054901. [arXiv:nucl-ex/0304017 [nucl-ex]]
15. A. Mangiarotti et al., [FOPI]. Nucl. Phys. A **714**, 89–123 (2003). https://doi.org/10.1016/S0375-9474(02)01366-0. [arXiv:nucl-ex/0209012 [nucl-ex]]

16. G. Agakishiev et al., [HADES]. Phys. Rev. C **80**, 025209 (2009). https://doi.org/10.1103/PhysRevC.80.025209. [arXiv:0902.3487 [nucl-ex]]

17. J. Adamczewski-Musch et al., [HADES]. Phys. Lett. B **778**, 403–407 (2018). https://doi.org/10.1016/j.physletb.2018.01.048. [arXiv:1703.08418 [nucl-ex]]

18. G. Agakishiev et al., [HADES]. Phys. Rev. Lett. **103**, 132301 (2009). https://doi.org/10.1103/PhysRevLett.103.132301. [arXiv:0907.3582 [nucl-ex]]

19. S.A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, M. Hofmann, S. Hofmann, J. Konopka et al., Prog. Part. Nucl. Phys. **41**, 255–369 (1998). https://doi.org/10.1016/S0146-6410(98)00058-1. [arXiv:nucl-th/9803035 [nucl-th]]

20. M. Bleicher, E. Zabrodin, C. Spieles, S.A. Bass, C. Ernst, S. Soff, L. Bravina, M. Belkacem, H. Weber, H. Stoecker et al., J. Phys. G **25**, 1859–1896 (1999). https://doi.org/10.1088/0954-3899/25/9/308. [arXiv:hep-ph/9909407 [hep-ph]]

21. M. Bleicher, E. Bratkovskaya, Prog. Part. Nucl. Phys. **122**, 103920 (2022). https://doi.org/10.1016/j.ppnp.2021.103920

22. M. Bleicher, J. Aichelin, Phys. Lett. B **530**, 81–87 (2002). https://doi.org/10.1016/S0370-2693(02)01334-5. [arXiv:hep-ph/0201123 [hep-ph]]

23. M. Bleicher, Nucl. Phys. A **715**, 85–94 (2003). https://doi.org/10.1016/S0375-9474(02)01416-1. [arXiv:hep-ph/0212378 [hep-ph]]

24. S. Vogel, M. Bleicher, Phys. Rev. C **74**, 014902 (2006). https://doi.org/10.1103/PhysRevC.74.014902. [arXiv:nucl-th/0509105 [nucl-th]]

25. A.G. Knospe, C. Markert, K. Werner, J. Steinheimer, M. Bleicher, Phys. Rev. C **93**(1), 014911 (2016). https://doi.org/10.1103/PhysRevC.93.014911. [arXiv:1509.07895 [nucl-th]]

26. T. Reichert, P. Hillmann, A. Limphirat, C. Herold, M. Bleicher, J. Phys. G **46**(10), 105107 (2019). https://doi.org/10.1088/1361-6471/ab34fa. [arXiv:1903.12032 [nucl-th]]

27. A.G. Knospe, C. Markert, K. Werner, J. Steinheimer, M. Bleicher, Phys. Rev. C **104**(5), 054907 (2021). https://doi.org/10.1103/PhysRevC.104.054907. [arXiv:2102.06797 [nucl-th]]

28. T. Reichert, M. Bleicher, Nucl. Phys. A **1028**, 122544 (2022). https://doi.org/10.1016/j.nuclphysa.2022.122544. [arXiv:2206.00410 [nucl-th]]

29. N. Abgrall et al., [NA61/SHINE]. Eur. Phys. J. C **74**(3), 2794 (2014). https://doi.org/10.1140/epjc/s10052-014-2794-6. [arXiv:1310.2417 [hep-ex]]

30. S. Pulawski, Ph.D. thesis (2015), University of Silesia, Katowice, https://edms.cern.ch/ui/file/1550661/1/main.pdf

31. S.V. Afanasiev et al., [NA49]. Phys. Rev. C **66**, 054902 (2002). https://doi.org/10.1103/PhysRevC.66.054902. [arXiv:nucl-ex/0205002 [nucl-ex]]

32. C. Alt et al., [NA49]. Phys. Rev. C **77**, 024903 (2008). https://doi.org/10.1103/PhysRevC.77.024903. [arXiv:0710.0118 [nucl-ex]]

33. T. Anticic et al., [NA49]. Phys. Rev. Lett. **93**, 022302 (2004). https://doi.org/10.1103/PhysRevLett.93.022302. [arXiv:nucl-ex/0311024 [nucl-ex]]

34. C. Blume, [NA49]. J. Phys. G **31**, S685–S692 (2005). https://doi.org/10.1088/0954-3899/31/6/008. [arXiv:nucl-ex/0411039 [nucl-ex]]

35. D. Adamova et al., [CERES]. Phys. Rev. Lett. **96**, 152301 (2006). https://doi.org/10.1103/PhysRevLett.96.152301. [arXiv:nucl-ex/0512007 [nucl-ex]]

36. T. Song, J. Aichelin, E. Bratkovskaya, Phys. Rev. C **106**(2), 024903 (2022). https://doi.org/10.1103/PhysRevC.106.024903. [arXiv:2205.10251 [nucl-th]]

37. P. Gubler, M. Ichikawa, T. Song, E. Bratkovskaya, Phys. Rev. C **111**(3), 034908 (2025). https://doi.org/10.1103/PhysRevC.111.034908. [arXiv:2408.15364 [hep-ph]]