Ultrarelativistic quantum molecular dynamics calculations of two-pion Hanbury-Brown–Twiss correlations in central Pb-Pb collisions at sqrt[s_{NN}]=2.76 TeV

Qingfeng Li, G. Gräf, and Marcus Bleicher

Phys. Rev. C **85**, 034908 — Published 26 March 2012

DOI: 10.1103/PhysRevC.85.034908

UrQMD calculations of two-pion HBT correlations in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

Qingfeng Li [1,2,4*], G. Gräf [2,3] and Marcus Bleicher [2,3]

1) School of Science,
Huzhou Teachers College,
Huzhou 313000, P. R. China
2) Frankfurt Institute for Advanced Studies (FIAS),
Johann Wolfgang Goethe-Universität,
Ruth-Moufang-Str. 1,
D-60438 Frankfurt am Main, Germany
3) Institut für Theoretische Physik,
Johann Wolfgang Goethe-Universität,
Max-von-Laue-Str. 1,
D-60438 Frankfurt am Main, Germany
4) Institute of Theoretical Physics,
Chinese Academy of Sciences,
Beijing 100080, P. R. China

---

* E-mail address: liqf@hutc.zj.cn

Abstract

Two-pion Hanbury-Brown-Twiss (HBT) correlations for central Pb-Pb collisions at the Large-Hadron-Collider (LHC) energy of $\sqrt{s_{NN}} = 2.76$ TeV are investigated for the first time with the microscopic transport model UrQMD (Ultra-relativistic Quantum Molecular Dynamics). The transverse momentum dependence of the Pratt-Bertsch HBT radii is extracted from a three dimensional Gaussian fit to the correlator in the longitudinal co-moving system (LCMS). Qualitative agreement with the ALICE data is obtained, however R_{out} is overpredicted by nearly 50%. The LHC results are also compared to data from the STAR experiment at RHIC. For both energies we find that the calculated R_O/R_S ratio is always larger than data, indicating that the emission in the model is less explosive than observed in the data.

PACS numbers: 25.75.-q, 24.10.Lx, 25.75.Gz

I. INTRODUCTION

In order to shed light on a large number of unsolved questions in fundamental physics [1–3], the Large Hadron Collider (LHC) at CERN had been designed, installed, tested, and repaired in the past two decades and finally, started normal operation in the end of the year 2009. Since then, a tremendous amount of experimental data in various aspects of high energy physics has been obtained and received much attention by theoretical physicists. Although the most exciting prediction, the *Higgs* boson, has not been observed in the data from the LHC experiments [4], the extracted bulk properties of the high temperature fireball created in such ultra-relativistic collisions have provided unprecedented information for fundamental investigations of the phase diagram of Quantum Chromodynamics (QCD). Here we want to explore the expansion properties of the created matter by investigating the spatial shape of the fireball. Although it is known that one can not measure the emission time pattern and/or the spatial profile of the source directly, a well-established technique, called "femtoscopy" or "HBT" (see e.g. [5] and references therein) can be employed to obtain this information. Femtoscopy has been extensively used in the heavy ion community since it provides the most direct link to the lifetime and size of nuclear reactions. The ALICE collaboration has published first results of two-pion Bose-Einstein correlations in both p-p [6] and central Pb-Pb [7] collisions at LHC energies in the beginning of the year 2011. These experimental results have attracted the research interest of several theoretical groups [7–10], whose models are based on hydrodynamic/hydrokinetic and hadronic microscopic approaches.

In this paper we show for the first time results for the HBT radii of two-pion correlations from central ($< 5\%$ of the total cross section σ_T) Pb-Pb collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV from the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [11–14]. The calculations are compared to ALICE data as well as to those at the RHIC energy $\sqrt{s_{NN}} = 200$ GeV. The UrQMD calculation results for p-p collisions at LHC energies are presented in [15].

The paper is arranged as follows: In Section 2, a brief description of the UrQMD model and the treatment of the HBT correlations as well as the corresponding Gaussian fitting procedure is shown. Section 3 gives the main results of the model calculations. Finally, in Section 4, a summary is given.

II. BRIEF DESCRIPTION OF THE URQMD MODEL AND THE HBT GAUSSIAN FITTING PROCEDURE

UrQMD [13, 14] is a microscopic many-body approach to p-p, p-A, and A-A interactions at energies ranging from SIS up to LHC. It is based on the covariant propagation of mesons and baryons. Furthermore it includes rescattering of particles, the excitation and fragmentation of color strings, and the formation and decay of hadronic resonances. At LHC, the inclusion of hard partonic interactions in the initial stage is important and is treated via the PYTHIA [16] model.

In the present study, the cascade mode of the latest version (v3.3) of UrQMD is used (for details of version 3.3. see [13, 14]). Some predictions and comparison works with data from reactions at LHC have already been pursued based on this version and showed encouraging results for the bulk properties [17, 18].

To obtain HBT radii, first, about 200 and 10000 central events are calculated for Pb-Pb collisions at LHC and for Au-Au at RHIC, respectively. Then, all particles with their phase space distributions at their respective freeze-out time (last collisions) from UrQMD are put into an analyzing program using the formalism of the well known "correlation after-burner" (CRAB) [19]. At last, the constructed two-pion HBT correlator (regardless of charge) in the longitudinally co-moving system (LCMS) [20, 21] without influence of residual interactions is fitted (using the χ^2 method) with a three-dimensional Gaussian form expressed as

$$C(\mathbf{q},\mathbf{K}) = 1 + \lambda(\mathbf{K})\mathrm{exp}\left[-\sum_{i,j=O,S,L} q_i q_j R_{ij}^2(\mathbf{K})\right]. \tag{1}$$

In Eq. (1), λ represents the fraction of correlated pairs [5] and q_i is the pair relative momentum $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$ in the i direction, p_i being the momenta of the particles. L is the longitudinal direction along the beam axis, O the outward direction along the transverse component of the average momentum $\mathbf{K}$ of two particles ($\mathbf{k}_T = |\mathbf{p}_{1T} + \mathbf{p}_{2T}|/2$) and S the sideward direction perpendicular to the afore mentioned directions. The effect of cross terms with $i \neq j$ on the HBT radii is found to be negligible in the present fits when a pseudorapidity cut $|\eta| < 0.8$ is used, as in experiments, and is not discussed in this paper.

For central collisions, the HBT radii are, except for an implicit $\mathbf{K}_T$ dependence, related

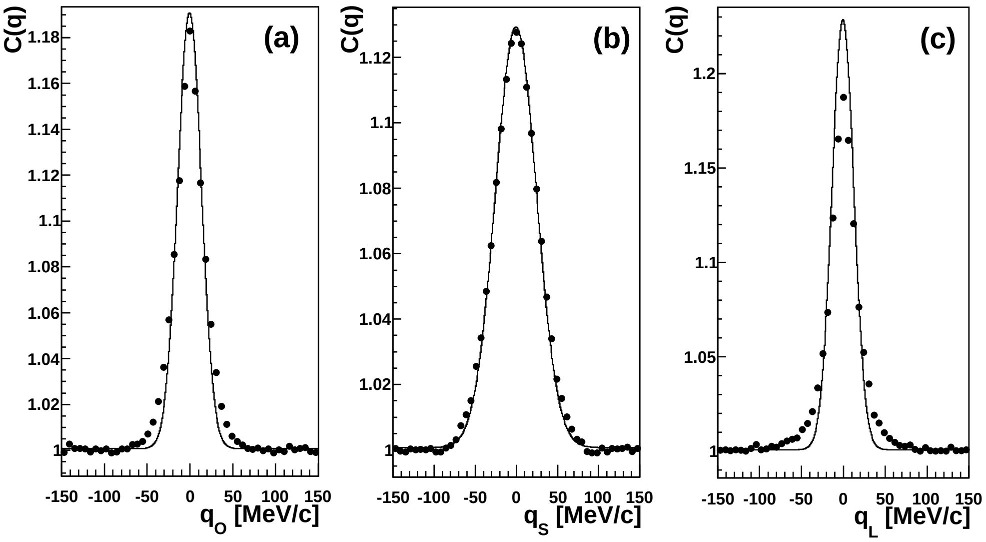

FIG. 1: Projections of the three-dimensional correlation function (points) and of the respective fit (lines) for the k_T bin $200-300$ MeV/c and $|\eta| < 0.8$. When projecting on one axis the other two components are restricted to the range (-30 $< q <$ 30) MeV/c.

to regions of homogeneity by [22]

$$R_O^2 = \left\langle (x-\beta_T t)^2 \right\rangle = \left\langle x^2 \right\rangle - 2\left\langle \beta_T t x \right\rangle + \left\langle \beta_T^2 t^2 \right\rangle , \tag{2}$$

$$R_S^2 = \left\langle y^2 \right\rangle , \tag{3}$$

$$R_L^2 = \left\langle (z-\beta_L t)^2 \right\rangle = \left\langle z^2 \right\rangle - 2\left\langle \beta_L t z \right\rangle + \left\langle \beta_L^2 t^2 \right\rangle , \tag{4}$$

where x, y, z and t are the spatio-temporal separation of the particles in a pair and $\boldsymbol{\beta}= \mathbf{K}/K_0$. If no space-momentum correlations are present the regions of homogeneity and the source size coincide. In central collisions the relation $\langle x^2\rangle \simeq \langle y^2\rangle$ is satisfied. Thus R_O^2 and R_S^2 differ mainly in the last two terms of Eq. (2). The first of these two terms is dependent on the strength of the correlation of emission time and transverse emission position, while the second one is especially sensitive to the particle emission duration.

III. RESULTS

The correlation functions are studied in bins of the transverse momentum $k_T = |\mathbf{k}_T|$. Fig. 1 shows the projections of the three-dimensional correlation function (points) and of the respective fit (lines) for the k_T bin $200-300$ MeV/c. It is seen clearly that the correlator

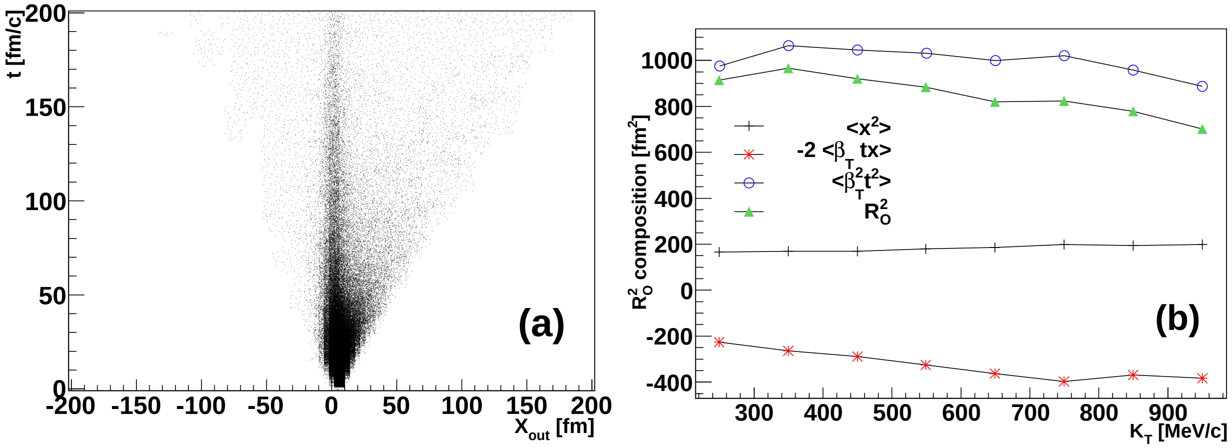

FIG. 2: (Color online) (a) the transverse position x_{out} versus emission time distribution of pions with cuts $|\eta| < 0.8$, $200 < k_T < 300$ MeV/c, $|q_i| < 100$ MeV/c, and $t_{freezeout} < 199$ fm/c. (b) the contribution of terms $< x^2 >$ (line with crosses), $-2 < \beta_T tx >$ (line with asterisks), and $< \beta^2 t^2 >$ (line with open circles) in Eq. (2), to R_O^2 (line with triangles) with same cuts as for (a).

in sideward direction can be described by a Gaussian form fairly well. However, it deviates slightly from a Gaussian in the other two directions, especially in the longitudinal direction, as found and discussed in previous publications for HICs at lower energies [23]. At LHC, the fraction of excited unstable particles is much larger than at lower beam energies, therefore, the non-Gaussian effect is more pronounced in the current calculations. At RHIC energies, the non-Gaussian effect was also seen in the experimental HBT correlator, especially in the longitudinal direction [24]. Furthermore, when comparing our fitting result in Fig. 1 with that observed in experiment (in Fig. 1 of Ref. [7]), it is seen that the non-Gaussian effect is stronger in our calculations than in experiment. This might be due to the omission of all potential interactions between particles in the current cascade calculations. Support for this interpretation was found in Ref. [23], where the consideration of a mean-field potential plus Coulomb potential significantly reduced the non-Gaussian effect on correlators of pions from HICs at AGS energies. Therefore, both a dynamic treatment of the particle transport with a proper equation of state (EoS) for the QGP phase and the hadron phase, and further theoretical development of the fitting formalism are equally important for a more precise extraction of spatio-temporal information of the source [25].

Besides the non-Gaussian effect, the contribution of the correlation between the emission time and position to the HBT radii, especially in the outward direction, has been paid more attention in recent years since it closely relates to the stiffness of the EoS of nuclear matter especially at the early stage of the whole dynamic process [26–28]. In Fig. 2 (a) we show the calculated emission time versus transverse position x_{out} of pions. The cuts $|\eta| < 0.8$ and $200 < k_T < 300$ MeV/c are adopted to have the same acceptance as for the extraction of the HBT radii. At the same time, since the correlation function and thus the HBT radii are mainly sensitive to pairs with small momentum difference, a cut on the relative pair momentum $|q_i| < 100$ MeV/c is applied as well. Further, in order to remove the contribution of long-lived resonances, a cut on the freeze-out time ($t_{freezeout} < 199$ fm/c) is used. It is found that, even in the cascade calculation, there exists a visibly positive correlation between the emission time and position. To further analyze the importance of the $x - t$ correlation, we quantitatively calculate all three terms in Eq. (2) and show them in Fig. 2 (b) as a function of k_T. As a whole, although the magnitude of the $x - t$ correlation term ($-2\langle \beta_T t x \rangle \approx$ -300 fm^2) is as big as that of the emission region term ($\langle x^2 \rangle \approx 200$ fm^2), the most important contribution to R_O comes from the emission duration term ($\langle \beta_T^2 t^2 \rangle \approx$ 1000 fm^2). It implies that both a shorter duration time and a stronger $x - t$ correlation lead to a smaller R_O value, which will be further discussed in Fig. 3 specialized for the result of HBT radii. Here, it is interesting to see that the direct computation of R_O leads to a value of ≈ 30 fm which is larger than the value extracted from the Gaussian fit to the correlation function by about a factor of three, as was also observed in the AMPT model calculations for Au-Au collisions at RHIC [26].

Fig. 3 shows the k_T dependence of the HBT radii R_O, R_S, and R_L, as well as the ratio R_O/R_S, extracted from the Gaussian fit to the two-pion correlators. The UrQMD cascade calculations for central Pb-Pb collisions at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV (lines with crosses) and central Au-Au collisions at RHIC energy $\sqrt{s_{NN}} = 200$ GeV (lines with up-triangles) are compared to corresponding experimental data by ALICE/LHC (open stars) and STAR/RHIC (open diamonds). A strong decrease of the three HBT-radii with k_T is seen both in experiments and in the UrQMD calculations for HICs. This implies a substantial expansion of the source and is qualitatively captured by the UrQMD dynamics. Following experimental results, the calculated HBT radii for Pb-Pb at LHC are found to be larger than those for Au-Au at RHIC. The largest increase exists in the longitudinal direction, which is also seen by the experiments. Although the comparison of the calculated HBT radii R_L and R_S with corresponding data at RHIC is fairly well, it gets worse when going to the higher

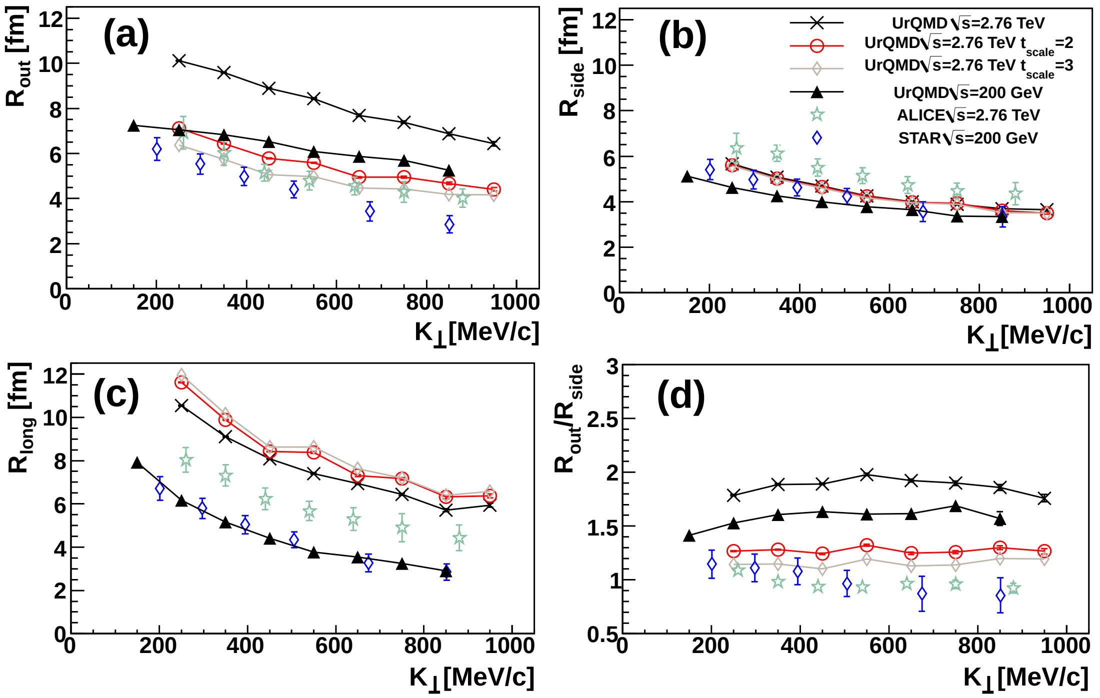

FIG. 3: (Color online) k_T dependence of pion HBT radii R_O [panel (a)], R_S [(b)], and R_L [(c)], as well as the ratio R_O/R_S [(d)], for central ($\sigma/\sigma_T < 5\%$) Pb-Pb collisions at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV. For comparison, parameters for central ($\sigma/\sigma_T < 5\%$) Au-Au collisions at RHIC energy $\sqrt{s_{NN}} = 200$ GeV are also shown. Lines with up-triangles and crosses are for model calculations while scattered symbols are for experimental data of STAR/RHIC and ALICE/LHC collaborations taken from [7, 24]. Lines with circles and diamonds show results with an artificially decreased emission duration by a factor of $t_{scale} = 2$ and 3, separately, in the analysis of correlation function.

LHC energy. At LHC the calculated R_S values at all k_T are found to be slightly smaller than data, while R_L and R_O values are larger than data. Together with large calculated R_O, the emission time related quantity R_O/R_S is found to be markedly larger than the data.

From Eq. (2) and Fig. 2 (b) it is clear that the value of R_O is strongly dependent on the emission duration of the particles. To further investigate the contribution of the emission duration to the HBT radii, we artificially decrease it by rescaling the relative time t to the "effective source center time" $\bar{t}$ ($=< t_i >$) by $t = t_i - \bar{t} \to t' = (t_i - \bar{t})/t_{scale}$ in the calculation of the correlation function at LHC energies. This effectively changes Eq. (2) to

$$R_O'^2 = \langle (x - \beta_T t')^2 \rangle = \langle x^2 \rangle - 2\frac{\langle \beta_T t x \rangle}{t_{scale}} + \frac{\langle \beta_T^2 t^2 \rangle}{t_{scale}^2}. \qquad (5)$$

The results for this calculation are presented as lines with circles ($t_{scale} = 2$) and with diamonds ($t_{scale} = 3$) in Fig. 3. The artificially decreased emission duration leads to smaller R_O values in all k_T bins but leaves R_S unchanged, as expected. Overall it results in an improved agreement with the data of R_O/R_S ratio. From Fig. 3 it is also found that R_L is overestimated at LHC. Since R_L is mainly related to the lifetime of the source, it implies that this lifetime is also overestimated by UrQMD. Other calculations in [7, 29] show that UrQMD overestimates the source lifetime by a factor of $\sim 2 - 3$ when compared to LHC data. The overestimation of both R_O and R_L can be attributed to the known fact that the pressure in the early stage is not strong enough in the cascade model calculations. A higher pressure would lead to a more explosive expansion, a stronger phase-space correlation, and a faster decoupling of the system, thus leading to smaller regions of homogeneity. For more discussion we refer the reader to [25, 27]. With the improved integrated Boltzmann + hydrodynamics hybrid approach [14, 18, 30, 31], where various EoS of nuclear matter during the hydrodynamic evolution may be treated consistently and a decoupling supplemented by realistic 3d hypersurfaces we hope to get a satisfactory solution in the near future.

IV. SUMMARY

To summarize, the two-pion HBT correlations (in the LCMS system) for central Pb-Pb collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV are calculated for the first time with the microscopic transport model UrQMD. The non-Gaussian effect is seen especially in both longitudinal and outward directions. Both the transverse momentum k_T dependence and the beam energy (from RHIC to LHC) dependence of the HBT radii R_O, R_S, and R_L, extracted from a three dimensional Gaussian fit to the correlator, exhibit qualitatively the same behaviour as found in the experiments. However, the calculated R_O/R_S ratios at all k_T bins are found to be larger than in the data, both at RHIC & LHC. We traced this finding back to the explosive dynamics of the fireball at LHC which results in both a shorter emission duration and a stronger time-space correlation than modeled here.

Acknowledgments

We would like to thank S. Pratt for providing the CRAB program. This work was supported by the Helmholtz International Center for FAIR within the framework of the

LOEWE program launched by the State of Hesse, GSI, and BMBF. Q.L. thanks the financial support by the key project of the Ministry of Education (No. 209053), the NNSF (Nos. 10905021, 10979023), the Zhejiang Provincial NSF (No. Y6090210), and the Qian-Jiang Talents Project of Zhejiang Province (No. 2010R10102) of China. G.G. thanks the Helmholtz Research School for Quark Matter Studies (H-QM) for support. Computational resources were provided by the LOEWE-CSC.

---

[1] G. Weiglein *et al.* [LHC/LC Study Group], Phys. Rept. **426**, 47 (2006).

[2] F. Gianotti, Phys. Rept. **403**, 379 (2004).

[3] A. J. Baltz *et al.*, Phys. Rept. **458**, 1 (2008).

[4] G. Brumfiel, Nature **475**, 434 (2011).

[5] S. Pratt, R. Soltz and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55** (2005) 357.

[6] K. Aamodt *et al.* [ALICE Collaboration], arXiv:1101.3665 [hep-ex].

[7] K. Aamodt *et al.* [ALICE Collaboration], Phys. Lett. B **696**, 328 (2011).

[8] Yu. A. Karpenko and Yu. M. Sinyukov, J. Phys. G **38**, 124059 (2011).

[9] T. J. Humanic, arXiv:1011.0378 [nucl-th].

[10] K. Werner, K. Mikhailov, I. Karpenko and T. Pierog, arXiv:1104.2405 [hep-ph].

[11] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998).

[12] M. Bleicher *et al.*, J. Phys. G **25**, 1859 (1999).

[13] H. Petersen, M. Bleicher, S. A. Bass and H. Stocker, arXiv:0805.0567 [hep-ph].

[14] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C **78**, 044901 (2008).

[15] G. Graef, Q. Li, M. Bleicher, submitted.

[16] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP **0605**, 026 (2006).

[17] M. Mitrovski, T. Schuster, G. Graf, H. Petersen and M. Bleicher, Phys. Rev. C **79**, 044901 (2009).

[18] H. Petersen, Phys. Rev. C **84**, 034912 (2011).

[19] S. Pratt *et al.*, Nucl. Phys. A **566**, 103C (1994).

[20] S. Pratt, Phys. Rev. D **33**, 1314 (1986).

[21] G. Bertsch, M. Gong and M. Tohyama, Phys. Rev. C **37**, 1896 (1988).

[22] U. A. Wiedemann, U. W. Heinz, Phys. Rept. **319**, 145-230 (1999).

[23] Q. Li and M. Bleicher, J. Phys. G **36**, 015111 (2009).

[24] J. Adams *et al.* [STAR Collaboration], Phys. Rev. C **71**, 044906 (2005).

[25] S. Pratt, Acta Phys. Polon. **B40**, 1249-1256 (2009).

[26] Z. W. Lin, C. M. Ko and S. Pal, Phys. Rev. Lett. **89**, 152301 (2002).

[27] Q. Li, M. Bleicher and H. Stöcker, Phys. Lett. B **659**, 525 (2008).

[28] Q. Li, J. Steinheimer, H. Petersen, M. Bleicher and H. Stocker, Phys. Lett. B **674**, 111 (2009).

[29] G. Graef, Q. Li, M. Bleicher, to be submitted.

[30] J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G **38**, 035001 (2011).

[31] J. Steinheimer, M. Bleicher, Phys. Rev. **C84**, 024905 (2011).