Elliptic Flow in Heavy-Ion Collisions from AGS to RHIC

Yu. B. Ivanov

1Kurchatov Institute, Moscow RU-123182, Russia

The integrated elliptic flow of charged particles, \( v_2(\text{charged}) \), and that of identified hadrons from \( \text{Au+Au} \) collisions are computed in a wide range of incident energies \( 2.7 \text{ GeV} \leq \sqrt{s_{NN}} \leq 39 \text{ GeV} \). The simulations are performed within a three-fluid model employing three different equations of state (EoS’s): a purely hadronic EoS and two versions of EoS involving the deconfinement transition— the first-order phase transition and a smooth crossover one. The present simulations demonstrate that \( v_2(\text{charged}) \) is insensitive to the EoS. All considered scenarios equally well reproduce recent STAR data on \( v_2(\text{charged}) \) for mid-central \( \text{Au+Au} \) collisions and properly describe its change of sign at the incident energy decrease below \( \sqrt{s_{NN}} \approx 3.5 \text{ GeV} \). This good reproduction of \( v_2(\text{charged}) \) indicates that the viscosity is small even at low incident energies. The predicted integrated elliptic flow of various species exhibits a stronger dependence on the EoS. A noticeable sensitivity to the EoS is found for anti-baryons and, to a lesser extent, for \( \phi \) and \( K^- \) mesons. In particular, the \( v_2 \) excitation functions of anti-baryons and \( \phi \) mesons exhibit a strong non-monotonicity within the deconfinement scenarios that was predicted by Kolb, Sollfrank and Heinz. However, low multiplicities of anti-baryons and \( \phi \) mesons at \( \sqrt{s_{NN}} \leq 10 \text{ GeV} \) may result in large fluctuations of their \( v_2 \) which wash out this non-monotonicity.

PACS numbers: 25.75.-q, 25.75.Nq, 24.10.Nz

Keywords: relativistic heavy-ion collisions, elliptic flow, hydrodynamics, deconfinement

I. INTRODUCTION

The Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) pursues the major goal of exploring the QCD phase diagram of the strongly interacting matter. The main questions addressed in this research are: At which energy does onset of deconfinement happen? What is the order of the deconfinement transition at high baryon densities? Is there a critical end point in the phase diagram? The BES program at RHIC provides us with a unique opportunity to study systematically the collision energy dependence of a large number of observables. The present study is inspired by recent papers of the STAR Collaboration \[1,2\] on the beam-energy dependence of the elliptic flow \( (v_2) \) in the BES region.

The beam-energy dependence of the collective flow has been recently studied within several different models \[3,13\] with the main emphasis on search of signals of the onset of deconfinement. A non-monotonicity of the transverse-momentum integrated \( (p_t\text{-integrated}) \) \( v_2 \) was predicted in Ref. \[3\] which is related to the quark-hadron phase transition and the corresponding softening of the EOS in the transition region. However, later it was stated \[4\] that in the experimental data this phase transition signature will be washed out by strong viscous effects in the late hadronic phase, where the fireball spends most of its time. As a result, the experimentally measured integrated elliptic flow \( v_2 \) should rise monotonically with the center-of-mass energy, \( \sqrt{s_{NN}} \), approaching the ideal fluid limit only at or above RHIC energies.

On the other hand, in Ref. \[14\] it was found that the hadron resonance gas with a large baryon density is closer to the ideal fluid limit than the corresponding gas with zero baryon density. Moreover, a nonzero baryon chemical potential serves not only to reduce the effect of dissipative terms of the first order in gradients but also of the second-order terms. This effect of the baryon chemical potential was noticed even earlier in Ref. \[13\]. The latter suggests that the system created at lower collision energies may display a fluid-like behavior with an effective fluidity close to that found at RHIC top-energy collisions, thus explaining why the differential elliptic flow measured at lower RHIC energies is close to that observed at the top RHIC energies. Indeed, an effective fluidity extracted from experimental data on collective flow \[16\] indicates that the viscosity at lower BES-RHIC energies is only slightly higher than that at the top RHIC energy. Above findings were supported by actual simulations within a hybrid model \[7\]. It was found that the triangular flow provides the clearer signal for the formation of low-viscous fluid in heavy ion collisions. Moreover, the kinetic phase produces additional elliptic flow rather than destroy it which also testify in favor of low-viscous fluid at low BES energies.

A the same time in Ref. \[5\] it was pointed out a strong influence of initial conditions for the hydrodynamic evolution on the observed \( v_2 \) values, thus questioning the standard interpretation that the hydrodynamic limit is only reached at RHIC energies. The integrated and differential elliptic flow for charged particles at SPS energies was found to be mostly sensitive to viscosity rather than to the EoS \[5\]. Thus, the situation is somewhat controversial and needs further investigation.

In the present paper I report results on the collision en-
ergy dependence of the integrated elliptic flow of charged particles produced in these collisions and predict that for various species using a model of the three-fluid dynamics (3FD) employing three different equations of state (EoS): a purely hadronic EoS [15] (hadr. EoS) that was used in calculations of the collective flow so far [20–22] and two versions of EoS involving the deconfinement transition [10]. These two versions are an EoS with the first-order phase transition and that with a smooth crossover transition. I report results of simulations in the energy range from 2.7 GeV to 39 GeV in terms of √sNN. This domain goes beyond the range of the RHIC BES program and also covers energies of the Alternating Gradient Synchrotron (AGS) at BNL and the Super Proton Synchrotron (SPS) of the European Organization for Nuclear Research (CERN). The reported results are also relevant to newly constructed Facility for Antiproton and Ion Research (FAIR) in Darmstadt and the Nuclotron-based Ion Collider Facility (NICA) in Dubna. Details of these calculations are described in Ref. [23] dedicated to analysis of the baryon stopping.

I would like to mention explicitly that no tuning (or change) of 3FD-model parameters has been performed in this study as compared to previous simulations [12, 23–27] in which various bulk observables were considered.

II. THE 3FD MODEL

The three-fluid approximation is a minimal way to simulate a finite stopping power of colliding nuclei at high incident energies. Within this approximation a generally nonequilibrium distribution of baryon-rich matter is modeled by counter-streaming baryon-rich fluids initially associated with constituent nucleons of the projectile (p) and target (t) nuclei. In addition, newly produced particles, populating the mid-rapidity region, are associated with a separate baryon-free fluid which is called a “fireball” fluid (f-fluid), following the Frankfurt group [28, 29]. A certain formation time τ is allowed for the fireball fluid, during which the matter of the fluid propagates without interactions. The formation time is associated with a finite time of string formation. It is similarly incorporated in kinetic transport models such as UrQMD [30] and HSD [31]. Each of these fluids (the f-fluid after its formation) is governed by conventional hydrodynamic equations which contain interaction terms in their right-hand sides. These interaction terms describe mutual friction of the fluids and production of the fireball fluid. The friction between fluids was fitted to reproduce the stopping power observed in proton rapidity distributions for each EoS, as it is described in Ref. [23] in detail.

The elliptic flow is proportional to the spatial anisotropy [32, 33] usually described by an eccentricity ε defined as

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\sqrt{\langle y^2 \rangle + \langle x^2 \rangle}},$$  \hspace{1cm} (1)

where $\langle x^2 \rangle$ and $\langle y^2 \rangle$ are mean square values of spatial transverse coordinates out of the reaction plane and in the reaction plane, respectively. These mean values are usually calculated with either the wounded-nucleon (WN) or the binary-collision (BC) weights, for details see Ref. [34]. These calculations are based on the usual Woods–Saxon profile of the nuclear density

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R_A)/d]},$$ \hspace{1cm} (2)

where $\rho_0$ is the normal nuclear density, $R_A = 1.12A^{1/3}$ is the radius of a nucleus with a mass number $A$, and $d$ is a diffuseness of the nuclear surface. As long as the eccentricity is small, elliptic flow should be directly proportional to the eccentricity. For numerically large eccentricities the direct proportionality could break in principle, but as was shown in the very first hydrodynamic calculation by Ollitrault [32] the proportionality holds well even for rather large values of $\varepsilon$.

![FIG. 1: Spatial eccentricity $\varepsilon$ as a function of impact parameter in Au+Au collisions for different surface diffusenesses ($d$) of the Au nucleus and different weights of averaging: the wounded-nucleon (WN) and the binary-collision (BC) weights [34]. The results on $\varepsilon_{\text{part}}$ [2] \hspace{1cm} (see Eqs. 3 \hspace{1cm} and 4 \hspace{1cm}) \hspace{1cm} are also displayed. Theses are calculated in Ref. 1 within the Monte-Carlo Glauber model and Color Glass Condensate (CGC) model.](image)

Within the 3FD model the initial nuclei are represented by sharp-edged spheres, i.e. the zero diffuseness ($d = 0$). This is done for stability of the incident nuclei before collision. However, this approximation essentially affects the eccentricity. The results obtained with $d = 0$ and the realistic value of $d = 0.6$ fm calculated with BC weights are shown in Fig. 1. As seen, the ($d = 0$)-result noticeably exceeds the eccentricity for the realistic value of $d = 0.6$ fm. The ($d = 0.6$ fm)-result with BN weights practically coincides with the eccentricity calculated with WN weights that is accepted as a default eccentricity in the experimental analysis [34]. The overestimation of $\varepsilon$ in the 3FD model naturally causes a respective overestimation of the elliptic flow. In order to resolve this problem,
the calculated values of $v_2$ are rescaled with the factor of $\varepsilon_{BN}(d = 0.6 \text{ fm})/\varepsilon_{BN}(d = 0)$. In the earlier works on the elliptic flow with the purely hadronic EoS \[20-22\] this rescaling was not applied, because the need of it was realized only recently.

Figure II also displays the root-mean-square participant eccentricity, $\varepsilon_{\text{part}}(2)$, defined as \[1\]

$$
\varepsilon_{\text{part}} = \frac{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}{\sigma_y^2 + \sigma_x^2}, \quad \varepsilon_{\text{part}}(2) = \sqrt{\langle \varepsilon_{\text{part}}^2 \rangle} \quad (3)
$$

$$
\sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2, \quad \sigma_y^2 = \langle y^2 \rangle - \langle y \rangle^2, \quad \sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle, \quad (4)
$$

where the curly brackets denote the average over all participants per event, while $\langle \ldots \rangle$, the average over events, and $x$ and $y$ are the positions of participant nucleons. Thus defined eccentricity takes into account event-by-event fluctuations with respect to the participant plane caused by a finite number of participant particles. The results displayed in Fig. II are calculated in Ref. [1] with the Monte-Carlo Glauber model \[35, 36\] and Color Glass Condensate (CGC) model \[37-39\]. Correspondence between experimental centrality and impact parameter are taken from Ref. [40] where the mean values of the impact parameter were obtained using a Monte-Carlo Glauber calculation.

The displayed results on $\varepsilon_{\text{part}}(2)$ demonstrate two points. First, there is an uncertainty related to the rescaling described above. Only for mid-central collisions ($b = 5-9$), $\varepsilon_{BN}(d = 0.6 \text{ fm})$ is close to $\varepsilon_{\text{part}}(2)$ (Glauber). At smaller and bigger impact parameters the difference is substantial. Second, possible effects of the fluctuations resulting from a finite number of participant particles could be significant beyond the range of mid-central collisions. Certainly, such kind of fluctuations are beyond the scope of the 3FD model because it deals only with continuous-medium quantities.

III. INTEGRATED ELLIPTIC FLOW OF CHARGED PARTICLES

Calculations of the integrated elliptic flow of charged particles were performed at fixed impact parameters $b$ which relate to experimental centralities as described above \[40\]. The integration over transverse momentum ($p_t$) was cut from above, $p_t < 2 \text{ GeV/c}$. This constraint was chosen because the STAR data were taken with this acceptance. Another reason is that the hydrodynamic treatment becomes inapplicable at high transverse momenta, as claimed in Ref. \[49\], already at $p_t > 1.5 \text{ GeV/c}$.

Comparison of the integrated elliptic flow of charged particles at midrapidity calculated within different scenarios with STAR data \[1\] for different centralities is presented in Fig. II. Only the $v_2\{EP\}$ subset of data is presented because other data subsets are quite indistinguishable from the former one within the scale of this figure. As seen, all different scenarios give almost identical results which perfectly agree with the data for mid-central collisions (centralities 5-30% or $b = 4-6 \text{ fm}$). The agreement is even too perfect because it leaves no room for viscosity effects. However, in view of above discussed uncertainties of the eccentricity rescaling, this agreement should be considered as simply good.

Again relying on discussion in the previous section, the observed underestimation of the elliptic flow at $b = 2 \text{ fm}$ is a consequence of fluctuations resulting from a finite number of participant particles. Indeed, the calculated $v_2$ is approximately 40% as low as compared with data. This calculated $v_2$ was rescaled with factor $\varepsilon_{BN}(d = 0.6 \text{ fm})/\varepsilon_{BN}(d = 0)$ that amounts to 0.5 at $b = 2 \text{ fm}$. This implies that without this rescaling the calculation well reproduces the data. The eccentricity $\varepsilon_{\text{part}}(2)$, that takes fluctuations into account, indicates that the above rescaling should be at least omitted, see Fig. II.

The observed overestimation of the elliptic flow at $b = 8 \text{ fm}$ is expected. At large impact parameters, the number of particles in the participant zone becomes small. Therefore, the applicability of the hydrodynamics becomes worse. In practice, this manifests itself in growing importance of dissipative effects, i.e. effective viscosity. At $b > 8 \text{ fm}$ the overestimation is even stronger because of disregarding of both the effective viscosity and fluctu-
tions which are in fact two sides of the same coin, i.e. a small number of particles in the participant zone.

As for the predicted non-monotonicity of the integrated $v_2$ as a function of $\sqrt{s_{NN}}$, it indeed takes place for first-order-transition scenario; see a weak peak at $\sqrt{s_{NN}} \approx 8$ GeV and the subsequent fall. Although, this non-monotonicity is very weak for charged particles. It is not observed in data.

In Fig. 2 FOPI data for $Z=1$ particles \cite{41}, as well as E877 \cite{12} and CERES \cite{43} data for charged particles are also displayed. The CERES data appreciably differ from those of the STAR collaboration. Recently there were published new CERES data \cite{13}, however, only on differential $v_2$. The FOPI data are included because $Z=1$ particles dominate among charged particles in the respective energy range. As seen from Fig. 2 all considered scenarios properly describe the change of sign of the elliptic flow at the incident energy decrease and approach the FOPI data. It is even better seen in Fig. 3 where proton $v_2$ is presented with additional experimental data. These negative values are a consequence of the squeeze-out effect resulting from blocking of the expanding central fireball by the spectator matter from above and below the reaction plane.

IV. INTEGRATED ELLIPTIC FLOW OF IDENTIFIED HADRONS

Let us turn to the elliptic flow integrated over transverse momentum for various species within different scenarios. Results of such calculations are presented in Figs. 3 and 4 for mid-central collisions of Au+Au ($b = 6$ fm). The integration over transverse momentum ($p_t$) is again cut from above, $p_t < 2$ GeV/c. Excitation functions of anti-baryons and heavy hyperons are displayed starting from energies above threshold of their production in the nucleon-nucleon collision. Below this threshold the hydrodynamic treatment of these species is inapplicable. Here, predictions of alternative scenarios differ from each other to a different extent depending on a particle. Results of the simulations presented in Fig. 3 are confronted to available data on elliptic flow of protons, pions and lambdas. Data on elliptic flow of charged particles are also displayed to guide an eye.

As seen from Figs. 3 and 4 the energy evolution of the mid-rapidity $v_2$ exhibits two basic patterns which also take place in excitation functions of the inverse slopes and mean transverse masses \cite{27}. The first pattern (pattern I) is characteristic of baryons which populate all regions (both central and peripheral) of the excited system. In terms of the 3FD model, they originate predominately from the baryon-rich fluids. Within this pattern, $v_2$ rises with energy sometimes beginning from negative values at low energies. These negative values are a consequence of the squeeze-out effect resulting from blocking of the expanding central fireball by the spectator matter from above and below the reaction plane.

The second pattern (pattern II) is characteristic of anti-baryons which are predominately produced in the central region of the excited system. In terms of the 3FD model, they originate from the net-baryon-free f-fluid. The energy evolution of the anti-baryon $v_2$ is very distinct in purely hadronic and deconfinement scenarios. This distinction results from the difference in dynamical evolution of the f-fluid that have already been discussed in Ref. \cite{25} devoted to analysis of transverse-momentum spectra.

The dynamical evolution of the f-fluid is determined by three factors: a degree of stopping of colliding nuclei (i.e. the friction between them), the formation time ($\tau$) of the f-fluid, and the EoS itself. The friction specifies the initial conditions, i.e. the energy deposit into the f-fluid. The formation time determines the beginning of the hydrodynamical expansion. Before it a collisionless expansion takes place. The EoS controls the character of the hydrodynamical expansion. The first two quantities, the friction and $\tau$, were chosen on the condition of the best reproduction major part of bulk observables for each EoS, see Ref. \cite{25, 28}. The hadronic scenario is characterized by considerably longer formation time ($\tau = 2$ fm/c) and stronger friction as compared to the deconfinement scenarios ($\tau = 0.17$ fm/c). Therefore, in the hadronic scenario the f-fluid exercises a longer collisionless expansion during which the spatial eccentricity of the system drops while the elliptic flow is not formed. The hydrodynamical expansion starts from essentially less deformed configuration as compared with that in the deconfinement scenarios. Thus, the hydrodynamically generated elliptic flow turns out to be lower than in the deconfinement scenarios at $\sqrt{s_{NN}} \lesssim 10$ GeV. At higher energies, two other factors (the friction and EoS) come into game. The energy deposit into the f-fluid turns out to be higher in the hadronic scenario than that for the deconfinement ones, which, in particular, is manifested in overestimation of anti-baryon and, somewhat later, meson production within the hadronic scenario \cite{25}. Besides, the deconfinement EoS’s reduce the elliptic flow because of the softening caused by the mixed phase, as described in Ref. \cite{28}. As a result, the elliptic flow within the hadronic scenario becomes higher than that in the deconfinement ones.

Mesons demonstrate intermediate (between patterns I and II) behavior depending on whether they predominately produced in the central region or originate from both central and peripheral regions. Mesons, which require lower energy deposit for their production (pions and positive kaons), exhibit the $v_2$ behavior more similar to that of baryons (pattern I). At the same time, mesons, for production of which a higher energy deposit is needed ($\phi$ mesons and negative kaons), predominately originate from highly excited central region and hence their $v_2$ excitation functions are more similar to that of anti-baryons (pattern II). This similarity is stronger, the heavier the meson is.

As has been already mentioned, the difference between
predictions of the purely hadronic scenario and deconfinement ones is substantial for hadrons exhibiting pattern-II behavior. In particular, in this case $v_2$ indeed exhibits a strong non-monotonicity within the deconfinement scenarios that was predicted in Ref. [3]. The reason is the same as that discussed in Ref. [12] concerning the difference proton and antiproton $v_2$. The proton $v_2$ at midrapidity is formed by particles from both the spatially central and peripheral regions of the nuclear system. This happens because the nuclear stopping is already quite strong at $\sqrt{s_{NN}} \lesssim 10$ GeV, and hence the mid-rapidity quantities are determined not only by particles newly produced near the spacial center. The center and peripheral regions differently contribute to the mid-rapidity elliptic flow of different species, because they have different $v_2$ patterns. The interference between different $v_2$ patterns washes out the non-monotonicity inherent in a separate pattern. As seen from Figs. 3 only an extremely weak non-monotonicity is left in $v_2$ of pattern-I particles. At the same time, antiprotons are mostly produced from the central region with a definite $v_2$ pattern that survives in its mid-rapidity excitation function. This
is also applicable to other antibarions, the φ mesons and, to a lesser extent, to negative kaons.

However, the multiplicities of anti-baryons and φ mesons are low at $\sqrt{s_{NN}} \leq 10$ GeV. This results in large fluctuations of their $v_2$ which are, of course, beyond the scope of the 3FD model. This fluctuations can reduce the observable $v_2$ and thus wash out the non-monotonicity. A possible destructive role of these fluctuations was indicated in Ref. 13. It was shown that local fluctuations of the baryon number may lead to a biased determination of the event plane which may result in artificial reduction of antiproton $v_2$. The same mechanism of reduction is applicable to all other species of low multiplicity. The data on yet differential $v_2$ of antiprotons recently published by STAR Collaboration 2 apparently testify in favor of such scenario.

V. SUMMARY

The integrated elliptic flow of charged particles from Au+Au collisions was analyzed in a wide range of incident energies $2.7 \text{ GeV} \leq \sqrt{s_{NN}} \leq 39 \text{ GeV}$. The analysis was done within the three-fluid model 17 employing three different EoS’s: a purely hadronic EoS 18 and two versions of the EoS involving the deconfinement transition 19. These are an EoS with the first-order phase transition and that with a smooth crossover transition. It is found that all considered scenarios well reproduce recent STAR data 1 on the integrated elliptic of charged particles for mid-central Au+Au collisions. Moreover, all considered scenarios properly describe the change of sign of the elliptic flow at the incident energy decrease below $\sqrt{s_{NN}} \approx 3.5$ GeV. The problems met with central and peripheral collisions are naturally explained by restricted applicability of the 3FD model to those cases.

The 3FD model reproduces the major part of bulk observables, especially within deconfinement scenarios 12, 23–27. This model does not include viscosity in its formulation. The most sensitive quantity to the viscous effects is the elliptic flow. A good reproduction of the integrated elliptic flow indicates that the viscosity is small even at low incident energies. This conclusion agrees with that was done Ref. 7 and with the experimental estimate of the effective fluidity 10.

Applicability of hydrodynamics to low-energy heavy-ion collisions was vividly discussed approximately 30 years ago, e.g., see reviews 52 and first estimates of the nuclear viscosity 54. I would like to remind that this applicability was found quite acceptable (though not perfect) especially at high baryon densities achieved in the system. Recent calculations 14, 15 confirm that the nuclear viscosity of the matter at large baryon density is not high.

The present simulations demonstrated that the integrated elliptic flow for charged particles at AGS-SPS-RHIC energies is insensitive to the equation of state in agreement with the same observation made in Ref. [6] for the SPS energies. Even within the first-order-transition scenario the calculated elliptic flow of charged particles practically does not exhibit the non-monotonicity of the $v_2$ as a function of $\sqrt{s_{NN}}$ predicted in 3. This happens even in spite of non-viscous hydrodynamics applied in the present calculation. This is a consequence of the nuclear stopping that is already substantial at $\sqrt{s_{NN}} < 10$ GeV. Hence the mid-rapidity quantities are determined not only by particles newly produced near the spacial center. The center and peripheral regions differently contribute to the mid-rapidity elliptic flow of different species, because they have different $v_2$ patterns. The interference between different $v_2$ patterns washes out the non-monotonicity inherent in a separate pattern.

The integrated elliptic flow of various species from Au+Au collisions was also predicted in simulations with the same three EoS’s within the same energy range. A noticeable sensitivity to the EoS is found only for antibaryons and, to a lesser extent, for φ and $K^-$ mesons. In particular, in this case $v_2$ indeed exhibits a strong non-monotonicity within the deconfinement scenarios that was predicted in Ref. [3]. Anti-baryons (and, to a lesser extent, φ and $K^-$ mesons) are mostly produced from the central region with a definite $v_2$ pattern and their $v_2$ pattern is negligibly affected by interference with those of peripheral regions. However, the multiplicities of antibaryons and φ mesons are low at $\sqrt{s_{NN}} \leq 10$ GeV. This results in large fluctuations of their $v_2$. The fluctuations can reduce the observable $v_2$ and thus wash out the non-monotonicity. A possible destructive role of these fluctuations was indicated in Ref. [13]. The data on yet differential $v_2$ of anti-protons recently published by STAR Collaboration 2 apparently testify in favor of such scenario.

Acknowledgements

I am grateful to A.S. Khvorostukhin, V.V. Skokov, and V.D. Toneev for providing me with the tabulated 2-phase and crossover EoS’s. The calculations were performed at the computer cluster of GSI (Darmstadt). This work was supported by The Foundation for Internet Development (Moscow) and also partially supported by the Russian Ministry of Science and Education grant NS-215.2012.2.

[1] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 86, 054908 (2012) [arXiv:1206.5528 [nucl-ex]].
[2] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 88 14902 (2013) [arXiv:1301.2348].
[3] P. F. Kolb, J. Sollfrank and U. W. Heinz, Phys. Rev. C 62, 054909 (2000) [hep-ph/0006129].
[4] G. Kestin and U. W. Heinz, Eur. Phys. J. C 61, 545 (2009) [arXiv:0806.3530 [nucl-th]].
