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Decreasing elliptic flow at the CERN Large Hadron Collider: Calculations in a parton recombination approach

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We apply the parton recombination approach to study the energy dependence of the elliptic flow, v_2, in heavy ion collisions from BNL Alternating Gradient Synchrotron (AGS) to CERN Large Hadron Collider (LHC) energies. The relevant input quantities (T, μ_B, η_T) at the various center of mass energies are obtained from fits to the available data. The model yields a good description of the integrated v_2 data for charged particles at midrapidity from AGS to BNL Relativistic Heavy Ion Collider (RHIC) energies. In stark contrast to the current expectations, we observe a decrease of the integrated v_2 values above the highest RHIC energy. Thus, we predict a decrease of v_2 at LHC energies compared to the RHIC results. This drop is attributed to negative v_2 values for the underlying parton distributions at low to moderate transverse momenta that develop if the transverse flow velocity is high enough. At energies above the LHC regime, the present approach predicts even negative values for the integrated v_2.

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The main goal of the current and past heavy ion programs is the search for a new state of matter called the Quark-Gluon-Plasma (QGP) [1]. Major breakthroughs for the potential discovery [2,3] of this new state of matter were (i) the experimental discovery of a large elliptic flow (v_2) at BNL Relativistic Heavy Ion Collider (RHIC) [this led to the conclusion that the matter formed in the early stage of a heavy ion reaction at RHIC behaves like a nearly perfect liquid (i.e., a liquid with a low viscosity) ([4] and references therein)] and (ii) the observation of constituent quark number scaling $v_2^{\text{hadron}}(p_T^{\text{hadron}}) = n_q v_2^q(p_T^{\text{hadron}}/n_q)$, meaning that the elliptic flow of baryons (three quarks, $n_q = 3$) versus mesons (two quarks, $n_q = 2$) scales like 3:2 at the hadron transverse momentum p_T^{hadron}. While the details of this scaling are still under discussion [5–9], one might generally see this scaling as evidence for a recombination-like hadronization process for the transition of partonic matter to hadronic matter [10–14].

In this article, we apply the recombination approach to explore the energy dependence of the elliptic flow in massive (Pb + Pb/Au + Au) nucleus-nucleus reactions from the BNL Alternating Gradient Sychrotron (AGS) energies to the highest CERN Large Hadron Collider (LHC) energy. For complementory explorations of the elliptic flow at LHC within transport approaches the reader is referred to Refs. [15–17]. Elliptic flow is a well-chosen observable for the exploration of the energy dependence of flow observables because it exhibits a self-quenching effect and is therefore mostly sensitive to the early (partonic) stage of the reaction, even at rather low beam energies. The structure of this article is as follows: We start with a summary of the energy dependence of the input parameters, then we discuss briefly the relevant recombination formulas, and finally we present the results for the elliptic flow excitation function and the predictions for LHC.

To apply this model to energies other than RHIC energies ($\sqrt{s} = 200$ GeV) one has to model the dependence of the temperature T, the baryo-chemical potential μ_B, and the transverse flow rapidity $\eta_T = \text{atanh}(\beta_T)$ at the hadronization surface as a function of the center of mass energy. Details of the parametrizations can be found in the appendices. The values for RHIC energies and below are fitted to previously extracted flow velocities; at LHC energies, we obtain the values (for $\sqrt{s_{NN}} = 5.5$ TeV): $T = 175$ MeV, $\mu_B \simeq= 0$ MeV, and $\beta_T = 0.75c$, which are in line with previous estimates [18].

With these parameters we predict the elliptic flow of hadrons using the collinear recombination approach [14]. Because we are presently only interested in bulk (i.e., low p_T quantities, we apply the recombination prescription in the low to intermediate p_T range, from 0 to about 3 GeV at RHIC and about 5–6 GeV at LHC, respectively. Above this momentum, fragmentation will dominate the underlying quark distribution. Comparing the yields to experiment the formalism seems applicable down to $p_T \sim 1$ GeV at RHIC, which is approximately 3% of the matter produced, and we expect this lower limit to rise slightly to $p_T \sim 1.2$ GeV at LHC. Therefore using the recombination approach down to $p_T \to 0$ seems questionable; however, a part of the uncertainty in the recombination mechanism at low p_T, introduced by the violation of energy conservation, cancels after taking the ratios in Eq. (6). Thus, the recombination formalism seems to give valid results for v_2 down to transverse momenta of several hundred MeV [14]. Further justification about the validity of our results can be found in the paragraph about the mean v_2.

The picture that one quark and one antiquark (or three quarks) with collinear momenta can recombine to form a meson (baryon) leads one to an integral over the product of the constituent-quark densities w_a times the Wigner function of the hadron Φ_h^W with the freeze-out hyper-surface Σ and its normal vector u^ν [14]:

$$E\frac{d^3N_h}{dp^3} = \int_\Sigma \frac{d\sigma\, P_\nu u^\nu(\sigma)}{(2\pi)^3} \int \prod_a \frac{dx_a}{(2\pi)^3} \times \Phi_h^W(x) w_a(R; x_a P)\delta\left(1 - \sum_a x_a\right), \quad (1)$$

where the quark a carries the fraction x_a of the hadron momentum P.

We use the parametrizations from Ref. [14] with a pure thermal spectrum for the recombining quarks and do not include the power-law-tail, which is only relevant for fragmentation. At higher c.m. energies recombination is expected to be dominant up to even higher p_T [18]; therefore, we neglect the contributions from fragmentation for the present considerations. Following Ref. [14] we obtain the elliptic flow for noncentral reactions from the asymmetry of the overlap region. To model peripheral collisions the asymmetry α of the collision depends on the geometric width and height of the transverse overlap zone,

$$h(b) = \sqrt{R_A^2 - (b/2)^2}, \quad w(b) = R_A - (b/2), \tag{2}$$

as

$$\alpha = \frac{h(b) - w(b)}{h(b) + w(b)}. \tag{3}$$

We have compared this simple asymmetry parameter with the eccentricity from other parametrizations in Fig. 1. One observes that the α parameter used (solid line) is quantitatively close to the Glauber model (short-dashed line) calculation for the relevant impact parameters. It has also been speculated that a much "sharper" Color Glass Condensate (CGC) initial distribution might be present in the initial state, and this parametrization is depicted by the long-dashed line. The CGC values for the eccentricity are slightly higher and lead to a small quantitative change of the final v_2 values; however, the qualitative feature of a v_2 decrease at high energies is not affected.

This spatial asymmetry is translated into a velocity asymmetry in the parton phase by

$$\eta_T(\phi) = \eta_T^0(1 + \alpha f(p_T)\cos(2\phi)). \tag{4}$$

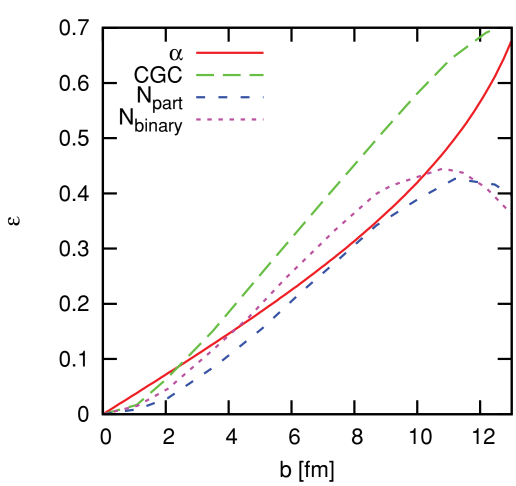

FIG. 1. (Color online) Comparison of our asymmetry parameter α with the eccentricity from CGC and the Glauber model [19].

To account for the fact that faster partons will experience this anisotropy less than slower ones, we define

$$f(p_T) = \frac{1}{1 + (p_T/p_0)^2}, \tag{5}$$

with the parameter $p_0 = 1.1$ GeV taken from Ref. [14]. The elliptic flow is then given by

$$v_2 = \langle\cos(2\Phi)\rangle = \frac{\int \cos(2\Phi)\frac{dN}{dp_t^2}\,d\Phi}{\int \frac{dN}{dp_t^2}\,d\Phi} \tag{6}$$

and is calculated for the individual quark species as [14]

$$v_2^q(p_T) = \frac{\int \cos(2\phi) I_2[a(\phi)]K_1[b(\phi)]d\phi}{\int I_0[a(\phi)]K_1[b(\phi)]d\phi}, \tag{7}$$

with

$$a(\phi) = p_T \sinh(\eta_T(\phi))/T, \quad b(\phi) = m_T \cosh(\eta_T(\phi))/T,$$

and the modified Bessel functions I_n and K_n. Replacing $w_a(R; p)$ in Eq. (1) with

$$w_a'(R; p) = w_a(R; p)(1 + 2v_2(p_T)\cos(2\Phi)) \tag{8}$$

and again applying the definition for v_2 yields the hadronic elliptic flow.

Let us start by comparing the transverse momentum dependence of the elliptic flow for pions, kaons, protons, and Ω-baryons in midperipheral Au + Au reactions at the RHIC with the distributions obtained in midperipheral Pb + Pb reactions at the LHC as shown in Fig. 2. For comparison, Fig. 3 shows the elliptic flow of light and strange quarks. A first striking observation is that the $v_2(p_T)$ values at each given p_T are always lower at the LHC than at the RHIC. A similar pattern was also observed within a parton transport approach, if the viscosity was set to the Anti-deSitter space (ADS) and conformal field theory (CFT) limit [16]. Even more surprising, we find strong out-of-plane emission of (multi-)strange particles, i.e., negative values of v_2. These negative values of the elliptic flow parameter for heavy particles have also been found in previous exploratory studies and seem to be a general feature of the blast-wave-like flow profile at high transverse velocities [21–24]. The negative v_2 values have also be seen within a blast-wave fit of the proton elliptic flow to STAR data [25] and they have also been experimentally observed by the NA49 Collaboration [26]. These results are supported by the recent preliminary data on J/ψ elliptic flow from PHENIX [27]. It reflects the depletion of the low p_T particle abundance, when the source elements are highly boosted in the transverse direction. At higher p_T and/or lower transverse flow velocities, the opposite effect dominates and results in a more pronounced emission in-plane again. The details depend on the underlying transverse flow parametrization as discussed in Ref. [24]. One might argue that negative elliptic flow values are an artifact of the blast-wave parametrization; however, transport simulations indicate slightly negative v_2 values for heavy particles at very low p_T [28] and the A multiphase transport model (AMPT) model predicts a negative v_2 at least for heavy charm and bottom quarks [15]. Thus, the qualitative behavior of a negative

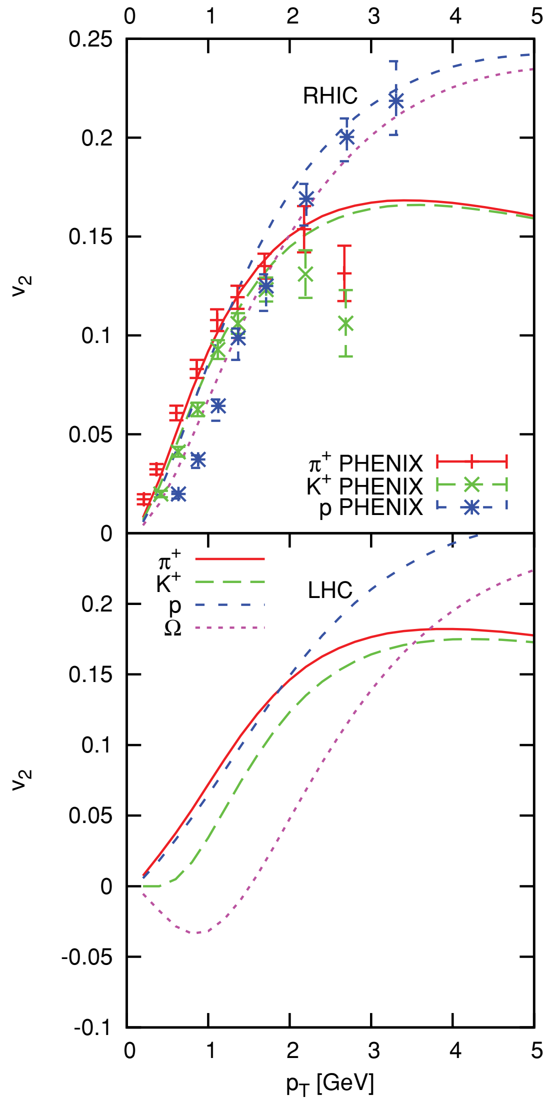

FIG. 2. (Color online) Elliptic flow parameter v_2 as a function of the transverse momentum p_t for midcentral ($b = 8$ fm) Au + Au/Pb + Pb reactions as obtained from the recombination approach. The lines indicate the calculations for π^+, K^+, p, and Ω^-. (Top panel) v_2 at RHIC ($\sqrt{s} = 200$ GeV) compared with PHENIX data [20]. (Bottom panel) Prediction for LHC ($\sqrt{s} = 5.5$ TeV).

v_2 is a well-known observation. The magnitude, however, of this effect and the particle species affected by it depend on the mass, the amount of transverse flow, and the decoupling hypersurface of this individual particle species. Therefore, we suggest that in the case of the AMPT approach the transverse flow is not sufficient to allow for a negative v_2 for the light strange quarks, but only for the heavier charm and bottom quarks. It might be interesting to test if a modified AMPT with higher transverse flow would also show negative elliptic flow for strange quarks. We conclude that the surprising observation in the present work is not the existence of the elliptic "antiflow" but the quantitative strength and influence on the light quark sector of this effect at LHC.

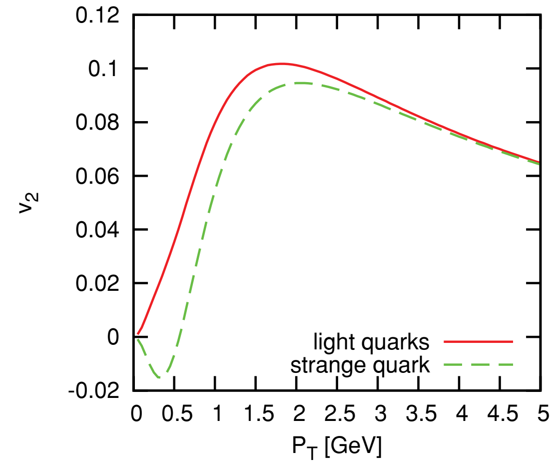

FIG. 3. (Color online) Elliptic flow parameter v_2 for light and strange quarks as a function of the transverse momentum p_t for midcentral ($b = 8$ fm) Pb + Pb reactions as given by Eq. (7) at $\sqrt{s} = 5.5$ TeV.

From these arguments we conclude that the blast-wave flow profile is responsible for the negative v_2 on the quark level, which then enters the hadron elliptic flow via the parton recombination. To understand this effect in more detail we go to the thermal quark-spectrum [14] with the energy

$$E(R, p) = m_T \cosh(\eta - y) \cosh \eta_T(\phi) - p_T \cos(\phi - \Phi) \sinh \eta_T(\phi). \tag{9}$$

For simplicity we look at midrapidity ($y = 0$) and for high η the spectrum is very low, so we consider the region around $\eta = 0$. For high c.m. energies, when the source is highly boosted transversally, the particles will mainly be emitted in the direction in which the fireball flies, so we can simplify even more and set $\phi = \Phi$. Because we have no longitudinal momentum we can replace the momentum with the transverse rapidity of the parton: $p_T = m \sinh \eta_T^q$ and $m_T = \sqrt{m^2 + p_T^2} = m\sqrt{1 + \sinh^2 \eta_T^q} = m \cosh \eta_t^q$. Therefore, the energy of the quark in the transverse moving source is

$$E = m \cosh\left[\eta_T^0(1 + \alpha f(p_T)\cos(2\phi)) - \eta_T^q\right]. \tag{10}$$

For a fixed quark rapidity $\eta_T^q < \eta_T^0$ (low p_T) the energy of the quarks emitted in-plane is higher than the energy of quarks emitted out-of-plane. With the thermal spectrum more energy means less particles, therefore, a negative v_2. At $\eta_T^q = \eta_T^0$ one would expect the zero crossing and above a positive v_2.

In this way one can visualize our predicted negative elliptic flow for low p_T at LHC. At RHIC this picture cannot be applied, because the simplification $\phi = \Phi$ is only valid for high η_T^0 (high c.m. energies).

A different way to obtain an analytic expression that explains the negative v_2 is to consider only the in-plane ($\phi = 0$) and out-of-plane ($\phi = \pi/2$) directions (similar to the analysis performed in Ref. [22]). The ϕ integration breaks down and the elliptic flow is then given by

$$v_2^q(p_T) = \frac{I_2[a(0)]K_1[b(0)] - I_2[a(\pi/2)]K_1[b(\pi/2)]}{I_0[a(0)]K_1[b(0)] + I_0[a(\pi/2)]K_1[b(\pi/2)]}. \tag{11}$$

For $p_T \to 0$ the argument of the Bessel functions I_n goes to zero and I_n becomes constant with $I_2 \to 0$ and $I_0 \to 1$. Therefore they are independent of the angle. This leads to

$$\lim_{p_T \to 0} v_2^q(p_T) = \frac{I_2[a(0)]}{I_0[a(0)]} \frac{K_1\left[m \cosh\left(\eta_T^0(1+\alpha)\right)\right)/T\right] - K_1\left[m \cosh\left(\eta_T^0(1-\alpha)\right)\right)/T\right]}{K_1\left[m \cosh\left(\eta_T^0(1+\alpha)\right)\right)/T\right] + K_1\left[m \cosh\left(\eta_T^0(1-\alpha)\right)\right)/T\right]}. \tag{12}$$

Because K_1 is a monotonically decreasing function, the numerator and thus the elliptic flow are negative (for some small transverse momenta). The specific values depend on the mass, the mean flow rapidity η_T^0, and the temperature. For increasing mass, or increasing transverse flow rapidity or decreasing temperature, the elliptic flow will become more negative.

Folding the distributions for $v_2(p_T)$ with the corresponding transverse momentum distributions yields the integrated v_2 at midrapidity for each particle species, see Fig. 4. A first observation is the apparent good description of the available charged particle v_2 data from the AGS to the RHIC energy regime. However, when going above the highest RHIC energy, we predict that the integrated elliptic flow saturates and then starts to *decrease* in the LHC energy range. This finding is in stark contrast to the current expectations in the heavy ion community (compare, e.g., with the linear extrapolations toward LHC by Borghini and Wiedemann [29]).

A rather critical assumption in this study is the applicability of the recombination approach for the elliptic flow for small transverse momenta on the order of $p_T < 1$ GeV. We want to emphasize that our result of the decreasing mean elliptic flow $\langle v_2 \rangle$ at LHC is not affected by the validity of this assumption, because $\langle v_2 \rangle \approx v_2(\langle p_T \rangle)$ and $\langle p_T \rangle > 1$ GeV in the LHC regime. However, to show the robustness of the prediction, Fig. 5 depicts the elliptic flow at a fixed p_T as a function of $\sqrt{s}$. With $p_T = 1$, 1.5, and 2 GeV the elliptic flow exhibits the same drop as the mean v_2 from Fig. 4.

In contrast to other more general, dynamical recombination models, the model employed in this article is an analytical collinear approach, which only allows comoving quarks to form hadrons. Without this constraint, the predicted scaled hadron elliptic flow v_2^h/n_q seems to be smaller [30,31]. So one may argue that also the amplitude of the negative v_2 might also be smaller or even negligible. To study this, we have verified the present results using a dynamical coalescence model based on a transport equation [32], using our blast-wave parametrization for the quark density as input. Indeed, this approach without the assumption of collinearity indicates a slight decrease of the amplitude of the negative v_2, but the magnitude remains sizable.

We have calculated the energy dependence and transverse momentum dependence of the elliptic flow parameter v_2 for midcentral Au + Au/Pb + Pb collisions from AGS to LHC energies within a parton recombination approach. We find a reasonable description of the v_2 data over the whole inspected energy regime, indicating that the measured v_2 values are consistent with the assumption that a major part of the elliptic flow was created in the partonic stage. We predict that the integrated v_2 of charged particles at midrapidity will *decrease* from RHIC to LHC energies, due to the strong transverse flow. In detail, we link this to the prediction of a negative v_2 component developing at low transverse momenta

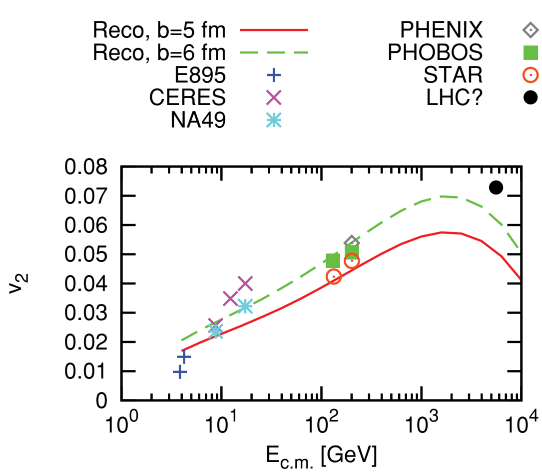

FIG. 4. (Color online) Comparison of $\langle v_2 \rangle$ for charged hadrons at midrapidity as a function of center of mass energy from the present recombination approach for Au + Au/Pb + Pb reactions at an impact parameter of $b = 5$–6 fm. Data points and the extrapolation to LHC are taken from Ref. [29].

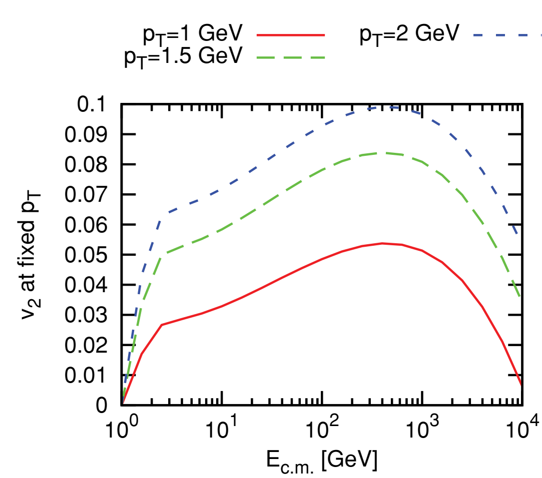

FIG. 5. (Color online) Elliptic flow v_2 of charged hadrons at $b = 5$–6 and fixed p_T as a function of $\sqrt{s_{NN}}$ for $p_T = 1$, 1.5, and 2 GeV.

to the blast-wave-like flow profile of the underlying quark distribution. Because this effect is strongest for heavy quarks it is most visible for (multi-)strange hadrons. Above the presently envisaged LHC energy for nucleus-nucleus reactions, we predict that the mean elliptic flow will even turn negative. It should be pointed out that the present prediction is in striking contrast to all former assumptions about the behavior of v_2 at LHC.

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APPENDIX A

To extract T and μ_B at the phase boundary we take the freeze-out values of the baryo-chemical potential from different accelerators [33] and fit them against their c.m. energy via

$$\mu_B^{\mathrm{Freeze}} = \frac{a}{1 + \sqrt{s_{NN}}^{\,b}/c}, \tag{A1}$$

with $a = 1.478$ GeV, $b = 0.802$, $c = 2.096$ GeV. Then we follow the isentropes from freeze-out to the phase boundary to connect this μ_B^{Freeze} to a μ_B value at the phase boundary (Fig. 6). In the relevant region, the connection is approximately linear with

$$\mu_B = d \cdot \mu_B^{\mathrm{Freeze}}, \quad d = 0.938. \tag{A2}$$

Because of the lack of lattice data at high baryo-chemical potentials, we calculate the phase transition line with a simple MIT-Bag model with a critical temperature of $T_C = 175$ MeV at vanishing chemical potential. The line of the phase transitions temperature is

$$T = \sqrt{-\left(\frac{\mu_B}{3}\right)^2 \frac{g_q}{C} + \sqrt{\left(\frac{\mu_B}{3}\right)^4 \frac{g_q}{C^2}\left(g_q - \frac{C}{\pi^2}\right) + T_C^4}}, \tag{A3}$$

with $C = \frac{\pi^2}{15}(7g_q + 4g_g)$, $g_q = 12$, $g_g = 16$. Details like the order and nature of the parton-hadron transition are not relevant for the present study. Because the fugacity $\gamma = \exp(\mu_B/T)$ does not enter in the equation for v_2 (in any case $\gamma \simeq 1$ for all relevant flavors at LHC energies), we neglect it in this article. The temperature, the baryo-chemical potential, and the fugacity at hadronization are shown in Fig. 7.

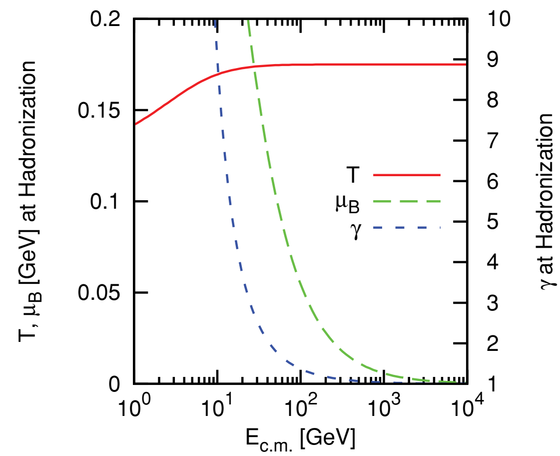

FIG. 7. (Color online) Temperature T and baryo-chemical potential μ_B (left y axis) and fugacity $\gamma = e^{(\mu_B/T)}$ (right y axis) at the phase transition as a function of the center of mass energy $\sqrt{s_{NN}}$.

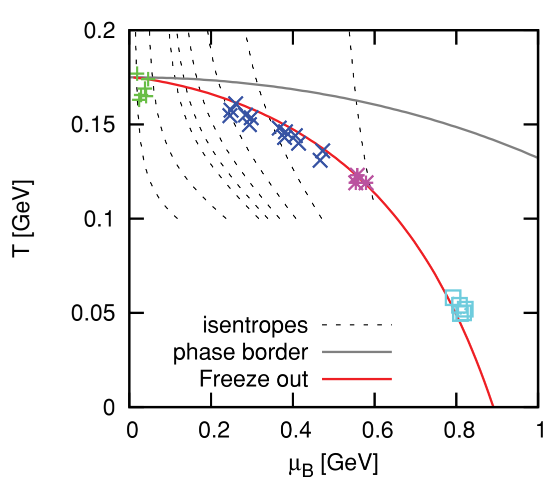

FIG. 6. (Color online) The QCD phase diagram with a freeze-out curve fitting the collider experiments (RHIC, SPS, SIS, AGS) and some isentropes to the MIT-Bad model phase boundary.

APPENDIX B

While the hadronization temperature shows only a weak dependence on energy, the transverse expansion rapidity η_T is strongly energy dependent. We fit the flow rapidities extracted

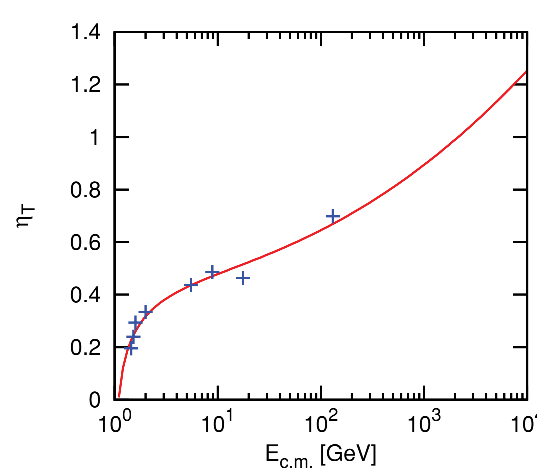

FIG. 8. (Color online) Parametrization of η_T (solid line) as a function of $\sqrt{s}$. The data at kinetic freeze-out (crosses) are taken from Ref. [34].

from the experimental data [34] at kinetic freeze-out. The data given in Ref. [34] is for mean transverse flow velocity β_T, but we use the rapidity $\eta_T = \tanh \beta_T$ to assure that the velocity stays less than the speed of light. To fit these values we choose

$$\eta_T^{\text{Freeze}}(\sqrt{s}) = a + bx + cx^2 + d \ln(x), \quad x = \ln(\sqrt{s}) \quad \text{(B1)}$$

with the constants $a = 0.418$, $b = -0.064$, $c = 0.012$, $d = 0.170$. As these values are extracted at freeze-out, we scale the obtained transverse rapidities by a constant factor $k = 0.85$ to obtain the transverse flow at the hadronization surface. Using these parameters our value for $v_T = 0.54$ at RHIC energies agrees with the value from Ref. [14]. For the LHC energy ($\sqrt{s} = 5.5$ TeV) we obtain a transverse flow velocity of $v_T = 0.75$ also in line with previous estimates [18]. Figure (8) depicts our fit (line) and the available data on η_T (crosses).

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