Eur. Phys. J. A **39**, 1–4 (2009)
DOI 10.1140/epja/i2008-10700-9

THE EUROPEAN
PHYSICAL JOURNAL A

Letter

Letter

Negative elliptic flow of J/ψ's: A qualitative signature for charm collectivity at RHIC

D. Krieg[a] and M. Bleicher

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany

Received: 21 August 2008 / Revised: 9 December 2008

Communicated by T. Bíró

Abstract. We discuss one of the most prominent features of the very recent preliminary elliptic flow data of J/ψ-mesons from the PHENIX Collaboration (PHENIX Collaboration (C. Silvestre), arXiv:0806.0475 [nucl-ex]). Even within the rather large error bars of the measured data a negative elliptic flow parameter (v_2) for J/ψ in the range of $p_T = 0.5$–2.5 GeV/c is visible. We argue that this negative elliptic flow at intermediate p_T is a clear and qualitative signature for the collectivity of charm quarks produced in nucleus-nucleus reactions at RHIC. Within a parton recombination approach we show that a negative elliptic flow puts a lower limit on the collective transverse velocity of heavy quarks. The numerical value of the transverse flow velocity β_T for charm quarks that is necessary to reproduce the data is $\beta_T(\text{charm}) \sim 0.55$–$0.6c$ and therefore compatible with the flow of light quarks.

PACS. 25.75.Ld Collective flow – 12.38.Mh Quark-gluon plasma – 14.20.Lq Charmed baryons

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 the observation of constituent quark number scaling of the elliptic flow $v_2^{\text{hadron}}(p_T^{\text{hadron}}) = n_q v_2^q(p_T^{\text{hadron}}/n_q)$, with n_q being the number of constituent quarks in the respective hadron as well as the observation of jet quenching at intermediate transverse momenta [4–6]. Together with the "standard" hydrodynamical interpretation this implies a rapid thermalization and a strong collective flow of the QCD matter created at RHIC. However, open questions remain: how can one obtain a consistent description of the high-p_T suppression and the elliptic flow of heavy flavour quarks and hadrons. *I.e.* is the collectivity at RHIC restricted to light quarks (up, down, strange) or do even charm (bottom) quarks participate in the collective expansion of the partonic system and reach local kinetic equilibrium?

Previously, it was assumed that local equilibrium of (heavy) quarks could not be achieved within pQCD transport simulations. In fact, older studies [7] based on a parton cascade dynamics restricted to $2 \leftrightarrow 2$ parton interactions seemed to indicate that the opacity needed to achieve local equilibrium would be at least an order of magnitude higher than pQCD estimates. However, recent state-of-the-art parton cascade calculations (including $2 \leftrightarrow 3$ parton interactions) have clearly shown that pQCD cross-sections are sufficient to reach local (gluon) equilibrium and allow to describe the measured elliptic flow data [8–11].

The aim of the present letter is to investigate whether also the charm quark does locally equilibrate and therefore follows the flow of the light quarks. Here we will focus on the J/ψ because it reflects the momentum distribution of the charm quarks directly, in addition first experimental data on the J/ψ elliptic flow just became available. We will show that the recently measured negative elliptic flow of J/ψ's provides a unique *lower* bound on the charm quark's collective velocity.

Under the assumption of local equilibration of light quarks a hydrodynamic parametrization of the freeze-out hyper-surface to parametrize the quark emission function, namely the blast-wave model, can be employed. For the charm quarks, the same emission function is used, however, with the transverse collective velocity as a free parameter to be determined by the preliminary PHENIX data. To calculate J/ψ's from the charm quark emission function, we apply the well-known parton recombination approach [12–14]. Details (like the exact form of the freeze-out hyper-surface) of the specific approach employed here

---

[a] e-mail: `krieg@th.physik.uni-frankfurt.de`

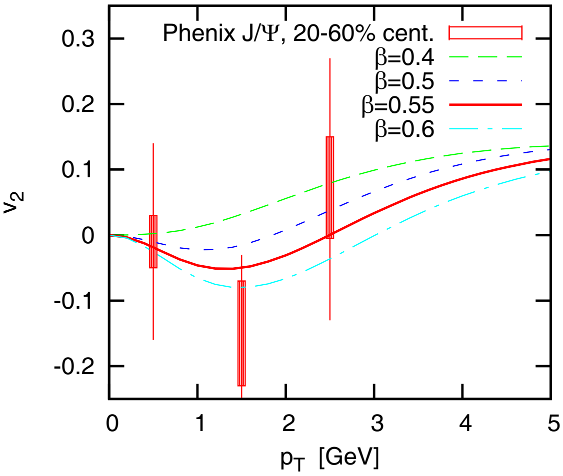

Fig. 1. Elliptic flow (v_2) of J/ψ's for $b = 9$ fm for different mean transverse expansion velocities (lines) compared to preliminary data from the PHENIX Collaboration [15]. While the v_2 of J/ψ's is smaller than for light hadrons, the mean transverse velocity for the best-fit case ($\beta = 0.55c$ for charm quarks) is the same as for light quarks.

can be found in [13,14]. Different from there we used a linear increasing transverse flow rapidity instead of a constant one, but the mean value has been preserved.

Here we summarize the most important features: in a coalescence process the quarks contribute equally to the hadrons momentum, so it inherits its azimuthal asymmetry directly from its constituents. Therefore in recombination the elliptic flow of J/ψ's emerges directly from a negative v_2 of the charm quark. To incorporate the asymmetry, the transverse expansion rapidity η_T depends on the azimuthal angle ϕ and the radial coordinate $\rho = \frac{r}{R}$ as

$$\eta_T(\phi,\rho) = \eta_T^0 \cdot \frac{3}{2}\rho\,(1 + \varepsilon f(p_T)\cos(2\phi)) \qquad (1)$$

with the eccentricity ε and $f(p_T) = 1/\left(1 + (p_T/p_0)^2\right)$ to model the damping at high p_T. With the factor $\frac{3}{2}$ we recover η_T^0 as the mean transverse rapidity after integrating over ρ.

By applying the definition of the elliptic flow one obtains [13]

$$v_2^q(p_T) = \frac{\int \cos(2\phi) I_2\left[a(\phi,\rho)\right] K_1\left[b(\phi,\rho)\right]\,\mathrm{d}\phi\,\rho\,\mathrm{d}\rho}{\int I_0\left[a(\phi,\rho)\right] K_1\left[b(\phi,\rho)\right]\,\mathrm{d}\phi\,\rho\,\mathrm{d}\rho} \qquad (2)$$

with $a(\phi,\rho) = p_T\sinh(\eta_T(\phi,\rho))/T$, $b(\phi,\rho) = m_T\cosh(\eta_T(\phi,\rho))/T$ and the modified Bessel functions I_n and K_n. For a more general hydrodynamical hyper-surface one could assume a dependence of freeze-out time τ on the radial coordinate ρ. This would lead to additional terms involving $\frac{\partial\tau}{\partial\rho}$ and Bessel functions of other orders. We have checked that the modifications are only minor and therefore neglect the contributions in this letter for brevity.

Let us investigate the elliptic flow of the J/ψ at midrapidity as a function of the transverse momentum for various transverse flow velocities as shown in fig. 1. The lines from top to bottom indicate calculations with a charm quark mass $m_c = 1.5$ GeV$/c^2$ for different mean expansion velocities $\tanh(\eta_T^0) = \beta_T = 0.4c, 0.5c, 0.55c, 0.6c$, the data by the PHENIX Collaboration are shown as symbols with error bars indicating a negative elliptic flow for J/ψ's at intermediate transverse momenta. The calculation shows that with increasing transverse flow a negative v_2 at low p_T (above $p_T \sim 2.5$ GeV, the elliptic flow values turn positive again) develops for the J/ψ, posing a lower bound of $\beta_T \geq 0.5c$ for the charm quarks flow. The best fit to the data is obtained with a mean charm flow velocity of $\beta_T = 0.55c$ equal to the light quark flow velocity extracted from previous fits within the same model.

In fig. 2 we use $\beta_T = 0.55c$ and compare the elliptic flow to other heavy mesons; fig. 3 shows the same for

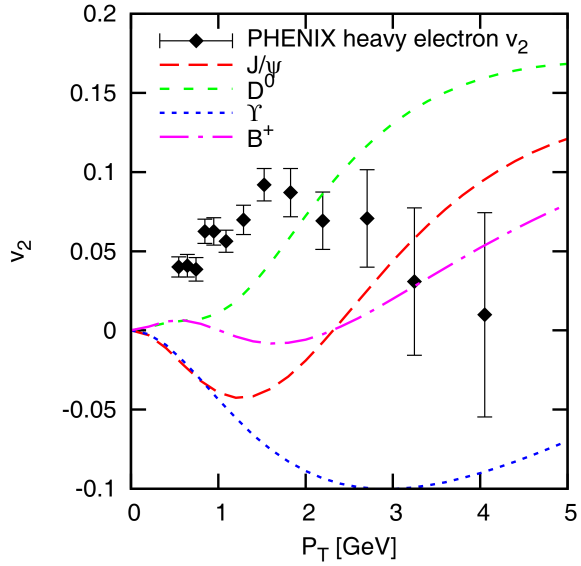

Fig. 2. Comparison of the elliptic flow (v_2) for J/ψ, D^0, Υ and B^+ at $b = 9$ fm with $\beta = 0.55c$ to data of non-photonic electrons from the PHENIX Collaboration [16].

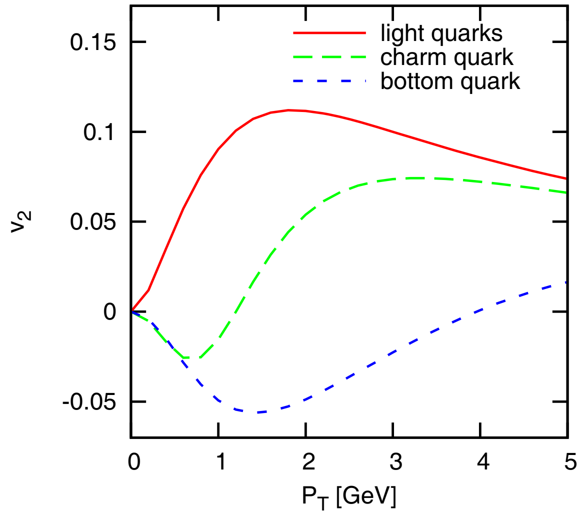

Fig. 3. Elliptic flow (v_2) of light, charm and bottom quarks at $b = 9$ fm with $\beta = 0.55c$.

the quarks. The value for Υ, with a bottom quark mass of $m_b = 4.7$ GeV/c^2, is negative in the whole range of applicability. In contrast to J/ψ , the v_2 of D^0 stays positive. This is due to the positive light quark v_2, which competes with the negative one for the charm quark, and results in nearly zero elliptic flow at low p_T. While the B^+-meson follows the D^0 flow for $p_T < 1$ GeV, it is much more suppressed at higher p_T due to the strong negative flow of the bottom quark and approximately zero up to $p_T \sim 2.5$ GeV.

Data on the D-meson elliptic flow is not yet available. When comparing it to the non-photonic electron v_2, our calculations fail to predict the data [17]. These two observables have been predicted to be similiar [18], since the non-photonic electrons are mainly from D-meson decays, but with a small contribution of B-meson decays. But the electron elliptic flow is no straightforward probe for the D^0 v_2. Since the electron is not the only decay product, the decay kinematics might smear out the resulting elliptic flow of the electrons. At low p_T, the increase of the D^0 flow is similiar to the electron data, but shifted to higher transverse momenta. Above $p_T = 2$ GeV the electron v_2 starts to decrease which might be due to contributions from the B-mesons or an early onset of the fragmentation regime.

Direct measurements on the elliptic flow of heavy mesons will be available in the near future with the heavy-flavor tracker for STAR, which will allow a better analysis. Therefore the presented results are based only the J/ψ elliptic flow data.

These results provide strong evidence for a substantial collectivity and transverse expansion of the charm quarks in nucleus-nucleus reactions at RHIC. Due to the large error bars this has to be verified when more precise data is available. Note that our present findings are different from previous approaches that assume incomplete thermalization of the charm [18–21]. We also verified our findings within a Boltzmann approach to coalescence [20] using our parametrizations and received similar results.

One should also note that the observation of negative elliptic flow of heavy particles is well known in the literature (even if not conclusively observed experimentally up to now). It appears due to an interplay between transverse expansion and particle mass, the more flow and the heavier the particle the more negative values does the elliptic flow reach. *E.g.*, negative values of the elliptic flow parameter for heavy hadrons 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 [22–26]. This reflects the depletion of the low-p_T particle abundance, when the source elements are highly boosted in the transverse direction. The difference to the present study is that, here, v_2 is already negative on the quark level. Negative elliptic flow values will even be encountered for light quarks at asymptotically high bombarding energies as discussed in [14]. One might argue that this is an artefact of the blast-wave peak and will not survive in more realistic calculations, however also transport model calculations show slightly negative v_2 values for heavy particles at low transverse momenta [27].

In conclusion, we have shown that the recent preliminary PHENIX data exhibiting a negative elliptic flow at low p_T can be explained within a parton recombination approach using a blast-wave–like parametrization. We point out that studying $v_2(p_T)$ from J/ψ offers the possibility to put a lower limit on the charm quark transverse velocity. From the present quantitative analysis we expect the transverse velocity of charm quarks to be above $\beta_T \geq 0.4c$. Within the limits of the present model the best description of the data is obtained for a charm transverse velocity equal to the light quark velocity of $\beta_T = 0.55c$. So if more precise data will still support the negative v_2, we conclude from this observation that charm quarks reach a substantial amount of local kinetic equilibration.

This work was supported by Gesellschaft für Schwerionenforschung, Darmstadt (GSI) and by the LOEWE initiative of the State of Hessen through the Helmholtz International Center for FAIR.

References

1. S.A. Bass, M. Gyulassy, H. Stoecker, W. Greiner, J. Phys. G **25**, R1 (1999) [arXiv:hep-ph/9810281].
2. PHENIX Collaboration (K. Adcox *et al.*), Nucl. Phys. A **757**, 184 (2005) [arXiv:nucl-ex/0410003].
3. STAR Collaboration (J. Adams *et al.*), Nucl. Phys. A **757**, 102 (2005) [arXiv:nucl-ex/0501009].
4. X.N. Wang, Acta Phys. Hung. A **24**, 307 (2005).
5. I. Vitev, Phys. Lett. B **639**, 38 (2006) [arXiv:hep-ph/0603010].
6. N. Armesto, A. Dainese, C.A. Salgado, U.A. Wiedemann, Phys. Rev. D **71**, 054027 (2005) [arXiv:hep-ph/0501225].
7. D. Molnar, M. Gyulassy, Nucl. Phys. A **697**, 495 (2002); **703**, 893 (2002)(E) [arXiv:nucl-th/0104073].
8. Z. Xu, C. Greiner, Phys. Rev. C **76**, 024911 (2007) [arXiv:hep-ph/0703233].
9. Z. Xu, C. Greiner, arXiv:0710.5719 [nucl-th].
10. Z. Xu, C. Greiner, H. Stocker, arXiv:0711.0961 [nucl-th].
11. A. El, Z. Xu, C. Greiner, arXiv:0712.3734 [hep-ph].
12. J. Zimanyi, T.S. Biro, T. Csorgo, P. Levai, Phys. Lett. B **472**, 243 (2000) [arXiv:hep-ph/9904501].
13. R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, Phys. Rev. C **68**, 044902 (2003) [arXiv:nucl-th/0306027].
14. D. Krieg, M. Bleicher, Phys. Rev. C **78**, 054903 (2008).
15. PHENIX Collaboration (C. Silvestre), arXiv:0806.0475 [nucl-ex].
16. PHENIX Collaboration (A. Adare *et al.*), Phys. Rev. Lett. **98**, 172301 (2007) [arXiv:nucl-ex/0611018].
17. PHENIX Collaboration (S. Sakai), J. Phys. G **34**, S753 (2007).
18. V. Greco, C.M. Ko, R. Rapp, Phys. Lett. B **595**, 202 (2004) [arXiv:nucl-th/0312100].
19. L. Yan, P. Zhuang, N. Xu, Phys. Rev. Lett. **97**, 232301 (2006) [arXiv:nucl-th/0608010].
20. L. Ravagli, R. Rapp, Phys. Lett. B **655**, 126 (2007) [arXiv:0705.0021 [hep-ph]].
21. O. Linnyk, E.L. Bratkovskaya, W. Cassing, arXiv:0801.4282 [nucl-th].
22. S.A. Voloshin, Phys. Rev. C **55**, 1630 (1997) [arXiv:nucl-th/9611038].

23. P. Huovinen, P.F. Kolb, U.W. Heinz, P.V. Ruuskanen, S.A. Voloshin, Phys. Lett. B **503**, 58 (2001) [arXiv:hep-ph/0101136].
24. S.A. Voloshin, arXiv:nucl-th/0202072.
25. F. Retiere, M.A. Lisa, Phys. Rev. C **70**, 044907 (2004) [arXiv:nucl-th/0312024].
26. S. Pratt, S. Pal, Nucl. Phys. A **749**, 268 (2005); Phys. Rev. C **71**, 014905 (2005) [arXiv:nucl-th/0409038].
27. M. Bleicher, H. Stoecker, Phys. Lett. B **526**, 309 (2002) [arXiv:hep-ph/0006147].