Vol. 1 (2008) *Acta Physica Polonica B Proceedings Supplement* No 3

# COLLECTIVE FLOW FROM QGP HYDRO + HADRONIC CASCADE*

Tetsufumi Hirano

Department of Physics, University of Tokyo
Tokyo 113-0033, Japan

*(Received October 16, 2008)*

Current status of a study for dynamics of relativistic heavy ion collisions is reported by focusing on hadronic rescattering effects on elliptic flow. We show mass splitting behavior of differential elliptic flow for non-strange hadrons is generated mainly during the late hadronic rescattering stage. $\phi$ mesons which undergo less scattering due to small cross-section do not follow mass ordering of differential elliptic flow predicted by ideal hydrodynamics.

PACS numbers: 25.75.–q, 25.75.Nq, 12.38.Mh, 12.38.Qk

## 1. Introduction

Recently, it is debated whether the quark–gluon plasma (QGP) created in relativistic heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) behaves like a perfect fluid [1]. Elliptic flow [2], which is an anisotropic momentum distribution in the azimuthal direction with respect to the reaction plane in non-central collisions, is a key observable to study transport properties of the produced QCD matter. Ideal hydrodynamics is quite successful in description of elliptic flow at RHIC, which leads to the press release of the "discovery of perfect liquid" [1]. Now the paradigm of strongly coupled/interacting/correlated QGP is prevailing among many fields. However, ideal hydrodynamics fails to reproduce elliptic flow data at larger impact parameter and in forward/backward rapidity regions [3] where the multiplicity is small. In order to understand the deviation from ideal hydrodynamics we have developed a hybrid model [4]: The early QGP stage, including its hadronization, is described by full 3-dimensional ideal hydrodynamics [3], whereas, in the dilute hadronic rescattering stage, we employ a hadronic

* Presented at the XXXVII International Symposium on Multiparticle Dynamics, Berkeley, USA, August 4–9, 2007.

cascade JAM [5]. We have shown that a large fraction of these deviations from ideal hydrodynamics is due to "late viscosity" caused by dissipative effects in the dilute hadronic rescattering stage. In this paper, we show new results from the hybrid model focusing our attention on a detailed investigation of hadronic rescattering effects on differential elliptic flow.

## 2. Mass ordering

Observed mass splitting behavior of elliptic flow parameter $v_2 = \langle \cos 2\phi \rangle$ for identified hadrons in low $p_{\mathrm{T}}$ region at RHIC [7, 8] is considered as an important evidence of perfect fluidity since its pattern is almost perfectly reproduced by ideal hydrodynamics [6]. Here we focus on how mass ordering of elliptic flow parameter appears during evolution of the system.

In our hybrid model simulations we switch from ideal hydrodynamics to a hadronic cascade model at the switching temperature $T_{\mathrm{sw}} = 169\,\mathrm{MeV}$. The subsequent hadronic rescattering cascade is modeled by JAM [5], initialized with hadrons distributed according to the hydrodynamic model output, calculated with the Cooper–Frye formula [9] along the $T_{\mathrm{sw}} = 169\,\mathrm{MeV}$ hypersurface rejecting inward-going particles.

### *2.1. Pions and protons*

To understand the origin of the mass ordering in $v_2(p_{\mathrm{T}})$, we compare in Fig. 1 (left), for a selected impact parameter of $b = 7.2$ fm, the above hybrid model result with a calculation where all hadronic rescatterings are turned off, allowing only for decay of the unstable hadron resonances. Whereas just

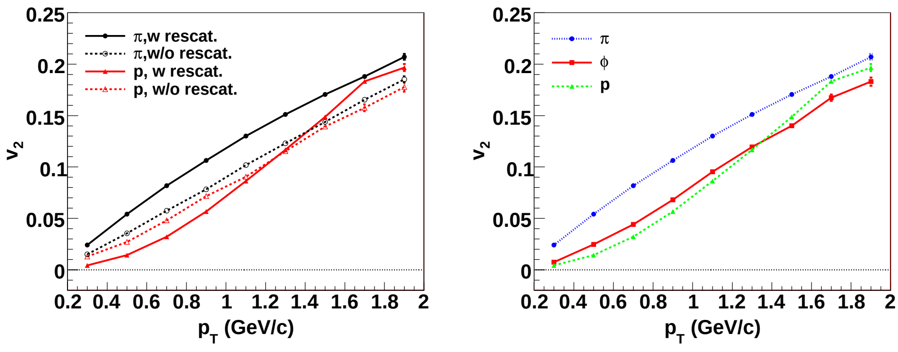


Fig. 1. Transverse momentum dependence of the elliptic flow parameter $v_2(p_{\mathrm{T}})$ at $b = 7.2$ fm. (Left) $v_2(p_{\mathrm{T}})$ for pions and protons. Solid (dashed) lines are with (without) hadronic rescattering. (Right) $v_2(p_{\mathrm{T}})$ for pions (dotted), protons (dashed) and $\phi$ mesons (solid).

after hadronization the differential elliptic flow $v_2(p_{\rm T})$ for pions and protons looks very similar, the mass splitting gets strongly enhanced by hadronic rescattering.

From these observations and our previous studies on importance of hadronic dissipation [4, 10] we conclude that the large magnitude of the integrated $v_2$ and the strong mass ordering of the differential $v_2(p_{\rm T})$ observed at RHIC result from a subtle interplay between perfect fluid dynamics of the early QGP stage and dissipative dynamics of the late hadronic stage.

### *2.2. $\phi$-mesons*

$\phi$ mesons have considerably smaller scattering cross-sections than non-strange hadrons [11]. They are therefore expected to show larger dissipative effects in our hybrid model and not to fully participate in the additional radial flow generated during the hadronic rescattering stage. The $\phi$ mesons decouple from rest of the system earlier than other, non-strange hadrons [12], thereby possibly opening a window to extract direct information on collective phenomena in the partonic stage from $\phi$-meson spectra [11].

Fig. 1 (right) shows the effects of hadronic rescattering: while the $v_2(p_{\rm T})$ curves for pions and protons separate (at low $p_{\rm T}$ the pion curve moves up while the proton curve moves down), $v_2(p_{\rm T})$ for the $\phi$ meson remains almost unchanged after its hadronization [13]. As a result of rescattering the proton elliptic flow ends up being smaller than that of the $\phi$ meson, $v_2^p(p_{\rm T}) < v_2^\phi(p_{\rm T})$ for $0 < p_{\rm T} < 1.2\,{\rm GeV}/c$, even though $m_\phi > m_p$. Hadronic dissipative effects are seen to be particle specific, depending on their scattering cross-sections which couple them to the medium. The large cross-section difference between the protons and $\phi$ mesons in the hadronic rescattering phase leads to a violation of the hydrodynamic mass ordering at low $p_{\rm T}$ in the final state.

## 3. Conclusion

We have studied effects of hadronic dissipation on differential elliptic flow of pions, protons and $\phi$ mesons from Au+Au collisions at RHIC, using a hybrid model which treats the early QGP phase macroscopically as a perfect fluid and the late hadronic phase microscopically with a hadronic cascade. Differential elliptic flow for $\phi$ mesons remains almost unaffected by hadronic rescattering. The net result of dissipative hadronic rescattering is that the differential elliptic flow $v_2(p_{\rm T})$ of protons *drops below* that of the $\phi$ mesons, in violation of the hydrodynamic mass-ordering.

An accurate extraction of the value for transport coefficients of the QGP created at RHIC requires a proper accounting for effects from late hadronic viscosity. Here, an attempt has been made to do this, by coupling the hydrodynamic model to a hadronic cascade.

This work was done in collaboration with U. Heinz, D. Kharzeev, R. Lacey and Y. Nara. The work is partly supported by JSPS Grant-in-Aid for Scientific Research No. 19740130.

## REFERENCES

[1] `http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=05-38`

[2] J.Y. Ollitrault, *Phys. Rev.* **D46**, 229 (1992).

[3] T. Hirano, *Phys. Rev.* **C65**, 011901 (2002); T. Hirano, K. Tsuda, *Phys. Rev.* **C66**, 054905 (2002).

[4] T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, *Phys. Lett.* **B636**, 299 (2006); *J. Phys.* **G34**, S879 (2007).

[5] Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba, *Phys. Rev.* **C61**, 024901 (2000).

[6] For theoretical reviews see P. Huovinen, in *Quark–Gluon Plasma 3*, R.C. Hwa, X.-N. Wang eds. World Scientific, Singapore, 2004, p. 600 `[nucl-th/0305064]`; P.F. Kolb, U. Heinz, in *Quark–Gluon Plasma 3*, R.C. Hwa, X.-N. Wang eds. World Scientific, Singapore, 2004, p. 634 `[nucl-th/0305084]`.

[7] J. Adams *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **92**, 052302 (2001).

[8] S.S. Adler *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **91**, 182301 (2003).

[9] F. Cooper, G. Frye, *Phys. Rev.* **D10**, 186 (1974).

[10] T. Hirano, M. Gyulassy, *Nucl. Phys.* **A769**, 71 (2006).

[11] A. Shor, *Phys. Rev. Lett.* **54**, (1985) 1122.

[12] H. van Hecke, H. Sorge, N. Xu, *Phys. Rev. Lett.* **81**, 5764 (1998).

[13] J.H. Chen *et al.*, *Phys. Rev.* **C74**, 064902 (2006).