Heavy-Flavor Collectivity – Light-Flavor Thermalization at RHIC

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Abstract. Flow measurements of multi-strange baryons from Au+Au collisions at RHIC energies demonstrate that collectivity develops before hadronization, among partons. To pin down the partonic EOS of matter produced at RHIC, the status of thermalization in such collisions has to be addressed. We propose to measure collective flow of heavy-flavor quarks, e.g. charm quarks, as an indicator of thermalization of light flavors (u,d,s). The completion of the time of flight barrel and the proposed upgrade with a μ Vertex detector for heavy-flavor identification in STAR are well suited for achieving these goals.

Keywords: Ultra-relativistic nuclear reactions, quark-gluon plasma, collectivity, thermalization, heavy-flavor quarks

PACS: 25.75.Dw, 25.75.Ld

INTRODUCTION

Quantum Chromo–Dynamics (QCD) is the theory of strong interactions. Lattice calculations of QCD predict that at a critical temperature of $T_c \approx 170$ MeV a phase transition of ordinary nuclear matter to a deconfined state of quarks and gluons occurs. Quarks and gluons are not confined in hadrons any more; they become asymptotically free. Under the same conditions, chiral symmetry is approximately restored and quark masses are reduced from their large effective values in hadronic matter to their small bare masses.

In ultra–relativistic nuclear collisions, a system with a temperature larger than the critical temperature $T_c$ is expected to be created. The development of collectivity at the partonic level (among quarks and gluons) and the degree of thermalization are closely related to the equation of state of partonic matter: Re-scattering among constituents and the density profile lead to the development of collective flow. In case of sufficient re-scattering, the system might be able to reach local thermal equilibrium.

In this paper, we show by means of flow measurements of multi-strange baryons that at RHIC energies collectivity develops before hadronization, among partons. We further suggest to measure heavy-flavor (c,b) collective flow to probe thermalization of light quarks.
MULTI-STRANGE HADRON FLOW - PARTONIC COLLECTIVITY

In ultra-relativistic nuclear collisions, measured final-state transverse–momentum spectra can be fit within a hydrodynamically motivated approach, with a kinetic freeze-out temperature $T_{\text{fo}}$ and a mean collective flow velocity $\langle b_T \rangle$ as the relevant parameters [2]. Figure 1 shows results of those fits from Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV at RHIC in the $T_{\text{fo}}$-$\langle b_T \rangle$ plane. Dashed and solid lines represent 1-$\sigma$ and 2-$\sigma$ contours, respectively.

As the collisions become more and more central, the bulk of the system dominated by the yields of $p$, $K$, $p$ appears to be cooler and develops stronger collective flow, representing a strongly interacting system expansion. At the most central collisions, the temperature parameter and the velocity are $T_{\text{fo}} \sim 100$ MeV and $\langle b_T \rangle \sim 0.6$ (c), respectively.

On the other hand, for the same collision centrality, the multi-strange hadrons $\phi$ and $\Omega$ freeze-out at a higher temperature $T_{\text{fo}} \sim 180$ MeV, close to the point at which chemical freeze-out occurs [5]. A similar behavior was also observed in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 130$ GeV [6].

Multi-strange hadrons might have smaller hadronic cross sections [7] and therefore decouple from the fireball early, perhaps right at the point of hadronization. This would explain the low $\langle b_T \rangle$ and higher temperature parameter. Most importantly, the finite value of $\langle b_T \rangle$ therefore must be cumulated prior to hadronization - via partonic interactions.

Elliptic flow, due to its self-quenching nature, is an early stage signal [8]. In non-central nuclear collisions, the initial overlap zone between the colliding nuclei is spatially deformed. If the matter produced in the reaction zone re-scatters efficiently, this spatial anisotropy is transferred into momentum space and the initial, locally isotropic, momentum distribution develops anisotropies. This anisotropy in momentum space is quantified by the second Fourier coefficient $v_2$, the elliptic flow parameter. Results on elliptic flow measurements at RHIC are shown in Fig. 2, (a) for $\pi, K^0_S, p$ and $\Lambda + \bar{\Lambda}$ [9, 10].

**FIGURE 1.** 1–$\sigma$ (dashed lines) and 2–$\sigma$ (solid lines) contours for the transverse radial flow velocity $\langle b_T \rangle$ and the kinetic freeze-out temperature parameter $T_{\text{fo}}$ derived from hydrodynamically motivated fits to particle spectra. The results for $\pi, K$ and $p$, are numbered from 1 (most central) to 9 (most peripheral) Au+Au collisions and $p+p$ collisions [3]. Results for the multi-strange hadrons $\phi$ and $\Omega$ are shown in the top of for most central Au+Au collisions only. The numbers on the top give the fraction of total hadronic cross section for centrality bins 1-9. This figure has been taken from [4].
(b) double-strange $\Xi^- + \Xi^+$ [11] and (c) triple-strange $\Omega^- + \Omega^+$ [11]. The elliptic flow parameter increases with $p_T$ and then saturates at larger $p_T$. In the lower $p_T$ region, a mass ordering is observed with lighter particles exhibiting larger elliptic flow parameters. The shaded bands show results from hydrodynamical calculations for $\pi$ (upper edge) to $\Omega$ (lower edge), assuming zero mean free path length and therefore infinitely fast re-scattering which leads to instantaneous local thermal equilibrium distributions. These calculations qualitatively describe the experimental results in the lower $p_T$ region, especially the observed mass ordering. As can be seen in Fig. 2, even the multi-strange baryons $\Xi^- + \Xi^+$ (b) and $\Omega^- + \Omega^+$ (c) do significantly flow. This suggests that collective flow of multi-strange baryons $\Xi^- + \Xi^+$ and $\Omega^- + \Omega^+$ indeed develops before hadronization - among partons.

In the intermediate $p_T$ region (2-6 GeV/c), the calculations overshoot the data. At these momenta, the mean free path length is relatively large leading to deviations from hydrodynamic behavior. In this region, the saturation level depends on particle type: Baryons saturate at larger values than mesons. The dash-dotted lines are results from empirical fit-functions [12]. This particle type dependence is accounted for in quark coalescence models [13]. In these hadronization models, hadrons are dominantly formed by coalescing massive constituent quarks from a partonic system with the intrinsic assumption of collective flow among these partons. These models predict a universal scaling of the observed elliptic flow $v_2$ and the hadron transverse momentum $p_T$ with the number of constituent quarks $n$ (meson, $n = 2$, baryon, $n = 3$). The accordingly $n$-scaled values for $v_2$ versus $p_T$ are shown in Fig. 2(d). Above a parton momentum $p_T/n > 0.7$ GeV/c, the predicted universal scaling holds within experimental uncertainties. An exception might be $\pi$ which can be attributed to the contribution of feeddown

FIGURE 2. Results on elliptic flow measurements at RHIC for (a) $\pi, K^0, p$ and $\Lambda + \bar{\Lambda}$ [9, 10], (b) double-strange $\Xi^- + \Xi^+$ [11] and (c) triple-strange $\Omega^- + \Omega^+$ [11]. Values for $v_2$ versus $p_T$ both scaled by the number $n$ of constituent quarks are shown in panel (d). The shaded bands show results from hydrodynamical calculations for $\pi$ (upper edge) to $\Omega$ (lower edge). The dash-dotted lines are results from empirical fit-functions [12] for baryons (upper) and mesons (lower).
from resonances with $\pi$ in the decay channel $[12]$. The successful prediction of quark coalescence models further supports the idea that collectivity develops at the partonic stage at RHIC. The important question and maybe the final step to a QGP discovery at RHIC is the status of thermalization of light quarks.

HEAVY-FLAVOR COLLECTIVITY AS A PROBE OF LIGHT-FLAVOR THERMALIZATION

Heavy-flavor quarks are special probes because of their heavy mass. If chiral symmetry is restored in a QGP, light quarks obtain their small current masses. On the other hand, heavy quarks get almost all their mass from their coupling to the Higgs field $[14]$. Thus, heavy quarks stay heavy - even in a QGP. The observation of heavy-quark collective flow indicates multiple interactions among partons. This would suggest that light quarks are thermalized.

![Elliptic Flow Measurements](image)

**FIGURE 3.** Results of elliptic flow measurements on electrons from heavy-flavor semileptonic decays $[17]$ as a function of $p_T$ from STAR (closed squares) and PHENIX (open circles). The curves show results from a quark coalescence model $[18]$ assuming identical flow of heavy and light quarks (solid) and no heavy quark flow (dotted) and microscopic calculations using different partonic cross sections $[19]$ of 10 mb (dashed) and 3 mb (dash-dotted).

First results on heavy-flavor production at RHIC have been reported from observing electrons stemming from the decay of heavy-flavor quarks $[15, 16]$. Recent results of elliptic flow measurements on electrons from heavy-flavor semileptonic decays $[15, 17]$ are shown in Fig. 3 as a function of $p_T$ from STAR (closed squares) and PHENIX (open circles). The electron momentum range $p_T=0.5-2.0$ GeV/c corresponds to heavy-flavor hadron $p_T=1.0-4.0$ GeV/c. In this region, the values of $v_2$ are significantly different from zero. The curves show results from calculations within a quark coalescence model $[18]$ assuming identical flow of heavy and light quarks (solid) and no heavy quark flow (dotted) and microscopic calculations using different partonic cross sections $[19]$ of 10 mb (dashed) and 3 mb (dash-dotted). Both models support the idea of heavy-flavor collectivity at RHIC, while the unexpectedly large cross section needed to describe the experimental data comes as a surprise. It is possible, as argued by several theorists, that elliptic flow and energy loss of heavy quarks are correlated $[20, 21, 22, 23]$. It is therefore very interesting to study both elliptic flow and nuclear modification factors.
However, due to the decay kinematics, important information on heavy-flavor dynamics is smeared out \cite{24}. It seems that we do not fully understand the underlying mechanism of heavy-flavor interaction with the dense medium. At higher $p_T$, therefore, it is also important to measure distributions from directly reconstructed $D$-mesons in order to isolate the bottom contributions in collisions at RHIC.

![Image](image.png)

**FIGURE 4.** (a) The measured invariant yield of $D$-mesons from direct reconstruction through the invariant mass of decay-daughter candidates in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV as a function of $p_T$ \cite{25,26}. The dashed line shows the fit-result of a pQCD inspired power-law function. A prediction from hydro-dynamically inspired model calculations is shown by the solid line. (b) The modification of the $D^0$ spectrum as a function of average transverse momentum for three different flow velocities.

The measured invariant yield of $D$-mesons from direct reconstruction through the invariant mass of decay-daughter candidates in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV is shown in Fig. 4(a) as a function of $p_T$ \cite{25,26}. The spectrum steeply falls with increasing momentum, followed by a long tail at high $p_T$. The dashed line shows the fit-result of a pQCD inspired power-law function, describing the experimental data over the whole momentum range. A prediction from hydro-dynamically inspired model calculations is shown by the solid line. In these calculations, a kinetic freeze-out temperature $T_{fo}=160$ MeV and an average flow velocity $\langle b_T \rangle=0.4$ (in units of speed of light) was assumed. Both curves are normalized to the same yield in the momentum range $p_T=0-14$ GeV/c. The presence of collective flow modifies the spectrum, its shape changes from concave (no-flow in $d+Au$ collisions) to convex (flow in Au+Au collisions).

The modification of the $D^0$ spectrum is further quantified by taking the ratio $R_{AA}$ of the spectra expected from Au+Au collisions (flow) relative to $d+Au$ collisions (non-flow). Figure 4(b) shows the modification of the $D^0$ spectrum as a function of average transverse momentum for three different flow velocities with $\langle b_T \rangle=0.1$ (dotted), 0.2 (dashed) and 0.4 (solid). The modification is in the order of 30-50% with the maximum moving to larger momentum with increasing flow velocity.

Due to the large multiplicities of $\pi,K,p$ and the rather small production cross section for charm-hadrons, the combinatorial background in the invariant mass distribution is roughly 1000 times larger than the signal \cite{27}. Extending particle identification by time of flight information will improve the statistical significance by a factor of five. This large combinatorial background leads to systematic uncertainties of extracted charm-hadron yields in the order of 30%. On the other hand, elliptic flow modulates particle yields with respect to the reaction plane in the order of 10%. To overcome these large systematic uncertainties and make precise heavy-flavor elliptic flow measurements feasible, we propose to upgrade STAR with $\mu$-vertex capabilities to identify heavy-flavor hadrons through their displaced decay vertex \cite{28}.
SUMMARY

Elliptic flow measurements have demonstrated that partonic collectivity, collective flow of partons, develops in 200 GeV Au+Au collisions at RHIC. To pin down the partonic EOS of matter produced at RHIC, the status of thermalization in such collisions has to be addressed. Since the masses of heavy-flavor quarks, e.g. charm quarks, are much larger than the maximum possible excitation of the system created in the collision, heavy-flavor collective motion could be used to indicate the thermalization of light flavors ($u,d,s$). The completion of the time of flight barrel and the proposed upgrade with a $\mu$Vertex detector for heavy-flavor identification in STAR are well suited for achieving these goals.

ACKNOWLEDGMENTS

Discussions with Drs. X. Dong, J. Gonzalez, Y. Lu, H.G. Ritter, P. Sorensen, L. Ruan, N. Xu, Z. Xu and H. Zhang are gratefully acknowledged.

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