# Probes of QCD Properties of Matter at RHIC

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**Abstract.** We present experimental features of hadronization from a partonic matter created at RHIC whose particle formation scheme is distinctly different from fragmentation phenomenology in elementary collisions. Multi-parton dynamics, such as quark coalescences or recombinations, appear to be essential to explain the experimental measurements at the intermediate transverse momentum of 2-5 GeV/c. We also present the measurement of charm quark production cross section and the $D$ meson transverse momentum distribution. Future measurements to probe QCD properties of the dense matter created at RHIC will be discussed.

## 1. Features of Hadronization From Bulk Matter

Figure 1 shows the nuclear modification factor $R_{CP}$ of $K^{\pm}$, $K_S$, $K^*$, $\phi$, $\Lambda$, $\Xi$ and $\Omega$ as a function of $p_T$ from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the STAR collaboration, where the $R_{CP}$ ratio is derived by dividing the yield from the most central 5% to that from the peripheral $40-60\%$ collision centralities [1, 2]. The dashed line is the $R_{CP}$ of charged hadrons for reference. In the low $p_T$ region soft particle production is dominated by the number of participant scaling. In the intermediate $p_T$ region of 2 to 5.5 GeV/c the $p_T$ dependence of $R_{CP}$ falls into two groups, one for mesons and one for baryons. Despite the large mass differences between $K_S$ and $K^*/\phi$, and between $\Lambda$ and $\Xi$ little difference among the mesons and among the baryons has been observed within statistical errors. Particle dependence in the nuclear modification factor seems to disappear above a $p_T$ of 6 GeV/c or so, consistent with the expectation from conventional fragmentation processes. The unique meson and baryon dependence in the intermediate $p_T$ region indicates the onset of a production dynamics very different from both fragmentation at high $p_T$ and hydrodynamic behavior at low $p_T$.

The azimuthal angular distribution can be described by a Fourier expansion

$$\frac{d^2n}{dp_T d\phi} \propto (1 + 2\sum_n v_n \cos n(\phi - \Psi_R))$$

where $\phi$ is the particle azimuthal angle, $\Psi_R$ is the reaction plane angle and $v_2$ has been called elliptic flow [3]. Figure 2 shows the $v_2$ as a function of $p_T$ for $\pi$, $K$, $p$, $\Lambda$ and $\Xi$ from PHENIX [4] and STAR [1] measurements. The angular anisotropy $v_2$ reveals three salient features: 1) particles exhibit hydrodynamic behavior in the low $p_T$ region – a

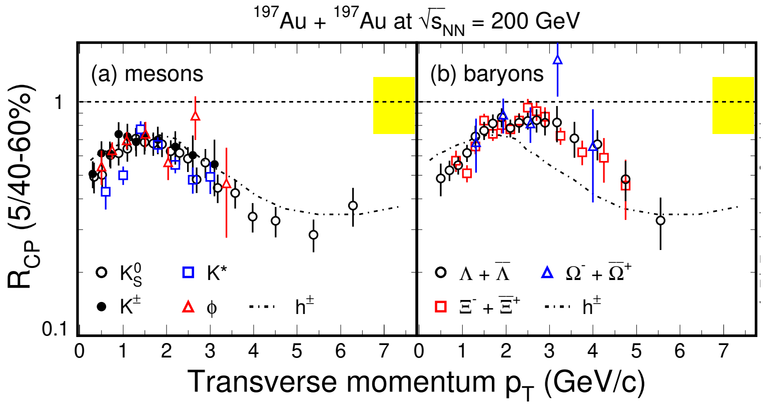


**Figure 1.** $R_{CP}$ of $K^{\pm}$, $K_S$, $K^*$, $\phi$, $\Lambda$, $\Xi$ and $\Omega$ in comparison with charged hadron in dashed line. Distinct meson and baryon groups are observed.

common expansion velocity may be established from the pressure of the system and the heavier the particle the larger the momentum from the hydrodynamic motion leading to a decreasing ordering of $v_2$ from $\pi$, to $K$ and $p$ for a given $p_T$; 2) $v_2$ values do not depend strongly on $p_T$ at the intermediate $p_T$ region in contrast to the strong $p_T$ dependence in the yield of particles; 3) the saturated $v_2$ values for baryons are higher than those for mesons and there is a distinct grouping among mesons and baryons.

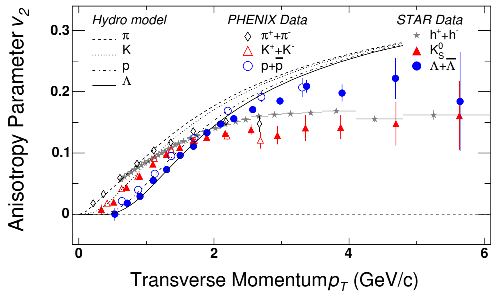


**Figure 2.** Azimuthal angular anisotropy $v_2$ as a function of $p_T$ for identified particles. The hydrodynamic calculation is provided by P. Huovinen et al [5].

The absence of a strong $p_T$ dependence at the intermediate $p_T$ region is an intriguing phenomenon for the angular anisotropy of particle emission. A very plausible scenario would be to relate the $v_2$ in this $p_T$ region with the geometrical shape of the emitting particle source. A surface emission pattern from the almond shaped participant volume would naturally lead to a saturation of $v_2$. A surface emission scenario is possible if particles are produced from a dense bulk matter and the hadronization duration is relatively short.

Parton energy loss in the dense medium created in nucleus-nucleus collisions was proposed as a possible mechanism for generating an angular anisotropy $v_2$. High energy partons are quenched inside the dense medium and lead to an effective particle emission from a shell area of the participating volume [6]. Gyulassy and Vitev proposed the parton energy scenario as a mechanism to explain the deviation of $v_2$ from hydrodynamic behavior at moderate $p_T$ [7]. While this scenario may be important for the considerable $v_2$ magnitude for charged hadrons at a $p_T$ greater than 6 GeV/c or so measured by STAR [8], it cannot explain the particle dependence in both the nuclear modification factor and the angular anisotropy $v_2$ at the intermediate $p_T$ region. Within the parton energy loss scenario the larger $v_2$ of baryons implies a higher energy loss than that of mesons; the larger nuclear modification factor of baryons, however, is only consistent with a smaller energy loss than that of mesons.

An empirical quark number scaling has also been observed [9]. Figure 3 presents the $v_2/n$ as a function of $p_T/n$ for $\pi$, $K$, $p$, $\Lambda$ and $\Xi$ from Au+Au collisions, where the line is a fit to the data points excluding the $\pi$ data. The $n$ is 2 for mesons and 3 for baryons, equivalent to the number of constituent quarks in the hadron. The bottom panel shows the ratio of data points to the fit. At the intermediate $p_T$ region ( $0.6 < p_T/n < 2$ GeV/c) all meson and baryon data points fall onto an uniform curve. In the lower $p_T$ region there is a particle dependent deviation from the fit curve presumably due to the hydrodynamic flow as a function of mass of particles. The $\pi$ data are significantly above the $v_2$ of other mesons. The large fraction of resonance decay contribution to the $\pi$ yield is known to enhance the $v_2$ of $\pi$ at a given $p_T$ [10].

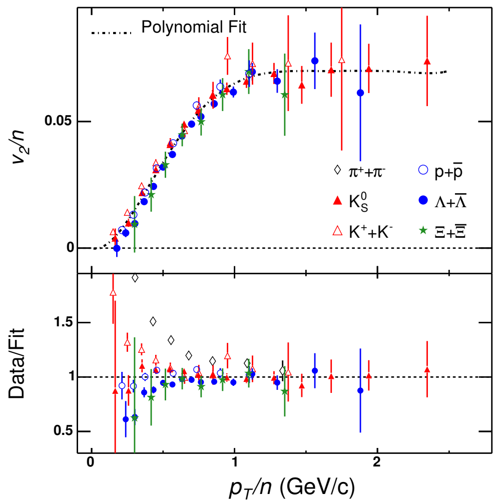


**Figure 3.** Azimuthal angular anisotropy $v_2/n$ as a function of $p_T/n$ for identified particles where n is the number of constituent quarks. The line is a fit to the data points excluding the $\pi$ data and the bottom panel shows the deviation from the fit line.

The quark number scaling hints at dynamics for the hadron formation at the intermediate $p_T$ which is very different from fragmentation at high $p_T$ and from thermal statistical descriptions at low $p_T$. The scaled azimuthal angular anisotropy ($v_2/n$) may be interpreted as the constituent quark anisotropy just prior to the hadron formation.

The essence of this hadron formation dynamics is very different from the fragmentation picture where the leading parton plays a dominant role in determining properties of hadron. The measured features for intermediate $p_T$ hadrons produced at RHIC require that all quark ingredients (n=2 for mesons and 3 for baryons) play an approximately equal role in hadron formation and that the hadron properties are determined by the sum of partons.

Recent theoretical models of quark coalescence [11, 12] and recombination [13, 14] all have the essence of multi-parton dynamics for hadron formation despite significant differences in details. The recombination models provided a satisfactory description of the particle yields, in particular, the large production of baryons in the intermediate $p_T$ region. The formation of a dense partonic system provides a parton density dependent increase in baryon yield as a function of collision centrality through the coalescence mechanism. More importantly the particle dependence in $v_2$ requires a $v_2$ distribution at the constituent quark level. The establishment of the quark collectivity $v_2$ would be an unambiguous signal for deconfinement in bulk partonic matter.

## 2. Charm Production Cross Section at RHIC

The total charm quark pair production cross section ($\sigma_{c\overline{c}}$) is an important constraint on the collision dynamics and the heavy quark evolution. Both STAR and PHENIX have presented results on the $\sigma_{c\overline{c}}$ measurement of p+p collisions from charm semi-leptonic decays. In addition, STAR has also derived an equivalent $\sigma_{c\overline{c}}$ for p+p collisions based on direct reconstruction of hadronic decays of charm mesons from d+Au collisions. Figure 4 shows the $p_T$ spectra of electron and $D^0$ from STAR. The PHENIX preliminary non-photonic electron data are represented by the fitted line with a reported $\sigma_{c\overline{c}}$ measurement of $709 \pm 85$(stat)$+332 - 281$(sys) $\mu b$ [15]. STAR has measured a cross section of $1300 \pm 200 \pm 400$ $\mu b$ and a mean transverse momentum for $D^0$ of $1.32 \pm 0.08$ GeV/c from direct $D^0$ reconstruction [16]. A next-to-leading order pQCD calculation of charm quark production cross section [17] yielded 300 to 450 $\mu b$, significantly below the STAR measurement and at the lower end of the PHENIX range of uncertainty.

Several comments on the cross section measurements are in order. When measuring the charm cross section through semi-leptonic decay, the quality of the electron data below a $p_T$ of 1 GeV/c or so is significantly deteriorated because of a large combinatorial background. An electron of $p_T \sim 1$ GeV/c typically comes from the decay of a $D$ meson with $p_T \sim 2$ GeV/c, which is significantly beyond the average $p_T$ of $1.32 \pm 0.08$ GeV/c reported by STAR. Therefore, one has to extrapolate to the low $p_T$ region by over a factor of two to obtain the total charm cross section. Such an extrapolation is often model dependent and has a large uncertainty. The semi-leptonic decay branching ratios for $D^0$, $D^*$, $D^{\pm}$ and $D_S$ are different. The electron yield from decays of these $D$ mesons depends on the relative yield which is another important contribution to the uncertainties of the charm production cross section derived from electron measurement. The direct reconstruction of the $D$ decay kinematics provides a broad coverage of $p_T$ and

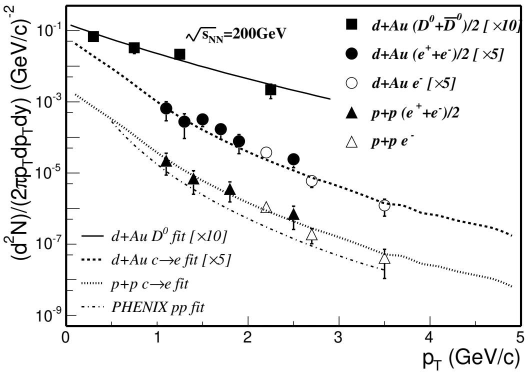


**Figure 4.** $p_T$ distribution of $D^0$ mesons and non-photonic electrons from semi-leptonic decays of charm mesons.

does not suffer from the same uncertainties as the leptonic decay electron measurement. However, present STAR measurements of $D$ meson yields using event-mixing methods from TPC tracks suffer from limited statistics [18]. A future vertex detector upgrade capable of measuring the $D$ decay vertex displacement is essential for both STAR and PHENIX heavy flavor physics programs.

Figure 5 presents the STAR preliminary transverse momentum spectrum of $D$ mesons from d+Au collisions normalized by the number of binary collisions, where the $p_T$ shapes of $D^*$ and $D^{\pm}$ are assumed to be the same as that of $D^0$ [18]. The shape of the $p_T$ distribution coincides with the bare charm quark $p_T$ distribution from the Fixed-Order-Next-Leading-Log (FONLL) pQCD calculation from M. Cacciari et al [19]. If a fragmentation function such as the Lund fragmentation scheme [20] or the Peterson function [21] is introduced for $D$ meson production, the resulting $p_T$ distribution will be significantly below the measurement at the high $p_T$ region. This observation raises an outstanding question regarding the $p_T$ distribution and the formation mechanism of $D$ mesons in hadro-production. Recently a $k_T$ factorization scheme has been found to significantly change the $D$ meson $p_T$ distribution from nuclear collisions as well [22].

The fact that the $D$ meson $p_T$ distribution can be better described by the $p_T$ of bare charm quarks from pQCD calculations has been observed in previous fixed target experiments [23]. With a fragmentation function such as the Peterson function the $D$ meson $p_T$ distribution is too steep to explain the measured $p_T$ distribution. In order to match the calculation with the data one has to introduce a $k_T$ kick to the parton distribution. The scale of $< k_T^2 >$ is on the order of 1 $(\mathrm{GeV/c})^2$, much larger than the typical $\Lambda_{QCD}$ scale for the strong interaction. Furthermore, the Feynman $x_F$ of the $D$ meson distribution was also found to coincide with the bare charm quark $x_F$ distribution [23]. The fragmentation function will have a large impact on the $x_F$ distribution from bare charm quark to $D$ meson, which cannot be negated by introducing any $k_L$ longitudinal boost of reasonable scale as in the case for $k_T$ kick in the transverse momentum direction.

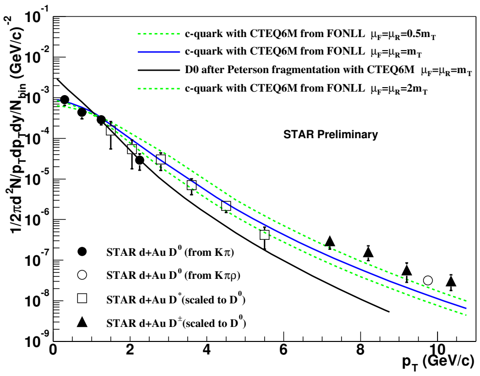


**Figure 5.** STAR preliminary measurement of $p_T$ distribution of $D$ mesons from d+Au collisions normalized by the number of binary collisions. The shape of the $p_T$ distribution is compared to pQCD FONLL calculations.

The transverse momentum distribution of particles produced at RHIC energies are considerably flatter than those at lower energies. The $k_T$ kick scheme does not change the shape of the $p_T$ distribution significantly. The STAR measurement of the $D$ meson $p_T$ distribution suggests either that the charm quark fragmentation may be close to a delta function or that a charm formation mechanism such as the recombination model may be important in hadro-production. The recombination model takes a charm quark and combines it with a light quark, presumably of low $p_T$, to form a charmed meson. Therefore, the $p_T$ of the meson is not significantly different from that of the bare charm quark. Measurements of charmed meson production provide unique probes for the hadron formation dynamics and for the transport dynamics of heavy quarks in the dense medium created at RHIC.

## 3. Recombination Mechanism and Heavy Quark Measurements

The experimental evidence of bulk partonic matter formation and its collectivity comes from the elliptic flow $v_2$ of partons based on constituent quark scaling in the $v_2$ measurement of mesons and baryons. Therefore, one critical test of the idea is to measure many more particles and resonances over a much broader $p_T$ region. In particular, we need to push the $p_T$ coverage above 6 GeV/c or so to reach the fragmentation region. The meson and baryon difference in the nuclear modification factor and the angular anisotropy $v_2$ is expected to vanish in the fragmentation region.

STAR preliminary measurement of $\Xi$ and its comparison with $\Lambda$ indicated that the strange quark dynamics in nuclear modification factor and the $v_2$ at the intermediate $p_T$ region is similar to these of light quarks: the constituent strange quarks have a similar $v_2$ as light up and down quarks [2]. The measurement of nuclear modification factor and $v_2$ of $\phi$ meson and $\Omega$ baryon covering the full $p_T$ range from recombination to fragmentation region in nucleus-nucleus collisions at RHIC will further test the strange quark dynamics in the hadronization of bulk partonic matter. Possible variation may come from the particle formation differences because the $\phi$ meson is a vector meson and $\Omega$ belongs to decuplet while what have been measured are for pseudo scalar mesons and octet baryons. Resonance measurement has also been proposed to test the production dynamics [24].

Charm quark transport dynamics in dense nuclear medium will provide unique probes to the QCD properties of the medium. If the initial temperature is very high, $T \sim 500$ MeV or higher, the yield of total charm quarks can also be increased through thermal gluon-gluon scatterings. Possible suppression of charm mesons at high $p_T$ will test the energy loss dynamics of charm quark propagation in a QCD medium. Theoretical calculations have predicted a reduced medium induced energy loss for heavy quarks and the high $p_T$ suppression of charmed hadrons should not be as strong as light hadrons [25, 26]. Observation of heavy quark hydrodynamic flow would indicate that heavy quarks, once created in the initial state, must have participated in the partonic hydrodynamic evolution over a sufficiently long period of time to reach a substantial flow magnitude. This would be a unique probe for the early stage of a partonic phase [27]. Figure 6 shows preliminary STAR [28] and PHENIX [29] measurements of the $v_2$ for electrons from charm leptonic decays, which have been demonstrated to be closely correlated with charmed meson $v_2$ [30].

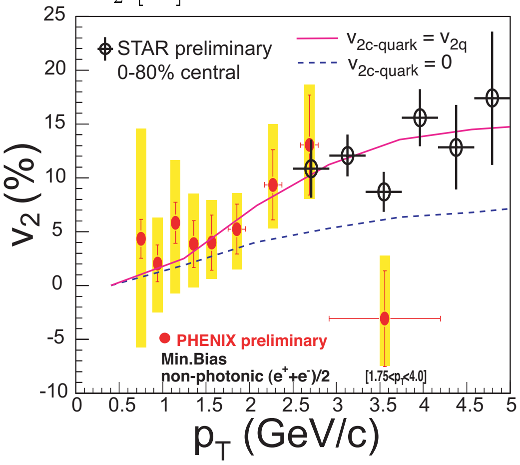


**Figure 6.** Preliminary measurement of non-photonic electron $v_2$ as a function of $p_T$ from PHENIX and STAR. The curves are from a calculation by V. Greco et al [27].

## 4. Summary

Characteristics in hadrons below a $p_T$ of 5 GeV/c or so from nucleus-nucleus collisions at RHIC have shown distinct features that are drastically different from fragmentation processes in elementary collisions. A salient feature of meson and baryon dependence has been observed in the nuclear modification factor and the angular anisotropy $v_2$ of $\pi$, $K^{\pm}$, $K_S$, $K^*$, $p$, $\Lambda$ and $\Xi$ particles at the intermediate $p_T$ of 2-5 GeV/c. A constituent quark number scaling has been observed for the $v_2$ measurement. These experimental measurements suggest that at the hadronization moment the effective degrees of freedom are the constituent quarks; the constituent quarks have developed a collective $v_2$ as a function of $p_T$; and the hadron formation at the intermediate $p_T$ is likely through multi-parton dynamics such as recombination or coalescence process.

The physical picture emerging from the experimental measurements complements Lattice QCD results. Spectral function calculations have indicated that hadrons, particularly heavy quarkonia, do not melt completely at critical temperature [31]. The constituent quark degrees of freedom or quasi-hadrons appear to play a dominant role at the hadronization though further confirmation of the picture from LQCD is needed. Despite intriguing experimental observations of hadronization from a deconfined bulk partonic matter, signatures for a quark-hadron phase transition remain elusive.

Heavy quark production and its transport dynamics in dense nuclear medium probe QCD properties of the matter. The charm quark flow measurement will provide a significant insight on recombination or coalescence hadronization mechanism and partonic collectivity of the dense matter. Future detector upgrades from STAR and PHENIX will greatly enhance their heavy quark measurement capabilities at RHIC.

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