Salient Features of Hadronization, Deconfinement and Heavy Quark Probes at RHIC

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Abstract. We present experimental features of identified particle production from nucleus-nucleus collisions at RHIC. These features reflect hadronization from a deconfined partonic matter 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. Constituent quarks seem to be the dominant degrees of freedom at hadronization and gluon degrees of freedom are not explicitly manifested in the hadronization scheme. This physical scenario is consistent with recent Lattice QCD calculations that near the critical temperature hadrons do not melt completely and quasi-particles may provide an effective degrees of freedom to describe the partonic matter. Heavy quark production and other future experimental measurements to quantify the QCD properties of the produced matter at RHIC will be discussed.

1. Introduction

The advent of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) has ushered in a new area in searches for the Quark Gluon Plasma (QGP). Recent measurements by all four RHIC experiments have established that a dense medium has been created in central Au+Au collisions at RHIC and the energy loss of partons leads to a suppression of high transverse momentum ($p_T$) particles [1 2 3 4]. The QCD nature of the dense matter created at RHIC and whether the current experimental evidence proves the discovery of the QGP have been under debate within the heavy ion physics community [5 6 7]. We will attempt to address three specific questions: 1) features of hadronization and evidence for a color deconfined bulk partonic matter; 2) QCD properties of the matter at hadronization from experimental data and from Lattice QCD calculations; and 3) heavy quark production and other future experimental measurements which would further quantify the QCD properties at the phase boundary.
2. Features of Hadronization From Bulk Matter

QCD color charges are confined and hadrons exist in color singlet state. The hadronization of quarks and gluons (partons) has not been understood based on QCD principles. Phenomenologically hadron formation in elementary $e^+e^-$ and nucleon-nucleon collisions has been described by fragmentation processes. In the pQCD domain physical processes are factorized into parton distribution functions, parton interaction processes and fragmentation functions for hadron formation. The fragmentation function is assumed to be universal and can be obtained from $e^+e^-$ collisions. A typical Feynmen-Field fragmentation process involves a leading parton of momentum $p$, which fragments into a hadron of momentum $p_h$ whose properties are mostly determined by the leading parton. The fragmentation function is a function of variable $z = p_h/p$, where $z$ is between 0 and 1. Baryon production is found to be significantly suppressed compared to the production of light mesons: the baryon to pion ratio increases with $z$, but never exceeds 20% [9].

In the soft (low $p_T$) particle production region, the pQCD framework and factorization break down – particles are believed not to be from fragmentation of partons. String fragmentation models were inspired by the QCD description of quark and anti-quark interaction. The Lund string model is one of the popular hadron formation models which has been successfully implemented in Monte Carlo description of $e^+e^$, p+p and nuclear collisions [10]. In string fragmentation models the baryon production is also suppressed because the baryon formation requires the clustering of three quarks [11].

Baryon production from nucleus-nucleus collisions, especially for multi-strange hyperons, has been measured to be much larger than theoretical model calculations. The hyperon production per number of participant pairs from nucleus-nucleus collisions at the SPS is significantly enhanced in comparison with the value from p+p collisions. The enhancement factor increases from $\Lambda$ to $\Omega$ hyperons and with the collision centrality. The large production of strange hyperons cannot be described by string fragmentation models. In nucleus-nucleus collisions a large number of strings would overlap and lead to a much stronger string tension. A theoretical model to describe multiple strings as a rope has been proposed [12]. Strange hyperon production would be increased from ropes or strings with a larger tension. The large enhancement in the strange baryon production with respect to the number of participant scaling from p+p collisions has been proposed as evidence for the formation of the QGP at the SPS [13]. However, there is no direct experimental measurement linking the hyperon production with the QGP hadronization. Furthermore, theoretical calculations based on chiral properties of hadrons at high density [14] or strong color fields [15] can also provide an explanation for the large hyperon production.

The increase in the baryon production from nucleus-nucleus collisions has become much more prominent at RHIC energies. Figure 1 shows the ratios of $\bar{p}/\pi$ and $\Lambda/K_S$ from central Au+Au collisions at $\sqrt{s_{NN}} = 130, 200$ GeV measured by PHENIX [16] and STAR [17, 18, 19]. The apparent difference between the STAR and PHENIX ratios
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can be explained by the fact that the STAR $\bar{\Lambda}$ data include the electromagnetic decay contribution from $\Sigma^0$ and the PHENIX data are corrected for weak decay contributions. The STAR $\bar{\Lambda}$ data have been corrected for feeddown contributions from multi-strange hyperon decays. Some early data, for example \cite{20}, were not included because these data were not corrected for weak decay contributions. The large baryon to meson ratio cannot be accommodated by the fragmentation scheme. The large ratio at the intermediate $p_T$ region is the first indication that particle formation dynamics in nucleus-nucleus collisions at RHIC are distinctly different from the hadron formation mechanism via fragmentation processes in elementary $e^+e^-$ and nucleon-nucleon collisions.

![Figure 1. Ratios of $\bar{\Lambda}$ to $K_S$ from Au+Au and p+p collisions (STAR) and $\bar{p}$ to $\pi$ from Au+Au collisions (PHENIX) as a function of transverse momentum ($p_T$). The $\bar{\Lambda}$ data include contributions from $\Sigma^0$ decays and the $\bar{p}$ data are corrected for weak decays of hyperons.](image)

Measurements on nuclear modification factors and azimuthal angular anisotropy for identified particles have provided essential insight into hadronization in nucleus-nucleus collisions. The nuclear modification factor is defined as

$$R_{AA} = \frac{[\text{yield}]^{AA}}{N_{\text{bin}} \times [\text{yield}]^{pp}}$$

where $N_{\text{bin}}$ is the number of binary nucleon-nucleon collisions. The $[\text{yield}]^{AA}$ and $[\text{yield}]^{pp}$ are particle yields ($d^2n/dp_Tdy$) from A+A and p+p collisions, respectively. The nuclear modification factor has also been defined using peripheral and central collisions

$$R_{CP} = \frac{[\text{yield}/N_{\text{bin}}]_{\text{central}}}{[\text{yield}/N_{\text{bin}}]_{\text{peripheral}}}.$$  

A $R_{AA}$ or $R_{CP}$ of unity implies that particle production from nucleus-nucleus collision is equivalent to a superposition of independent nucleon-nucleon collisions. Hard scattering
processes within the pQCD framework are believed to follow approximately binary scaling in the kinematic region where the nuclear shadowing of parton distribution function and the Cronin effect are not significant. Measurements of charged hadrons and neutral pions have revealed a strong suppression at high $p_T$ region in central Au+Au collisions \[21, 22, 23, 24\]. Recent d+Au measurements \[1, 2, 3, 4\] have demonstrated that the large suppression of high $p_T$ particles in central Au+Au collisions is mainly due to energy loss, presumably of partons traversing the dense matter created in these collisions.

Figure 2 shows the $R_{CP}$ 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 from the most central 5\% to the peripheral 40 – 60\% collision centralities. 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 disappears only above a $p_T$ of 6 GeV/c, 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

$$\frac{d^2 n}{d p_T dp_T d\phi} \propto (1 + 2 \sum_n v_n \cos n(\phi - \Psi_R))$$
where $\phi$ is the azimuthal angle of the particle, $\Psi_R$ is the reaction plane angle and $v_2$ has been called elliptic flow \cite{25}. Theoretical calculations indicate that $v_2$ is generated mostly at the early stage of the nuclear collision. There are two dynamical mechanisms responsible for $v_2$: hydrodynamic and geometrical phase space of emitting source. In a non-central nucleus-nucleus collision the overlapping participants form an almond shaped particle emission source. The reaction plane is defined by the vectors $x$ (impact parameter direction) and $z$ (beam direction). The pressure gradient is greater and particles would experience larger hydrodynamic expansion along the short axis direction (in plane) than these along the long axis (out plane), resulting an ellipsoid in transverse momentum space in the final state. Particle production from a dense matter could lead to a surface emission pattern with higher particle density in the reaction plane than that out of the reaction plane. Figure 3 shows a schematic diagram for two scenarios of generating azimuthal angular anisotropy $v_2$ in non-central collisions.

![Figure 3](image)

Figure 3. Schematic diagram to show two dynamical origins of angular anisotropy, one from hydrodynamical expansion and the other from surface geometrical phase space.

Figure 4 shows the $v_2$ as a function of $p_T$ for $\pi$, $K$, $p$, $\Lambda$ and $\Xi$ from PHENIX \cite{26} and STAR \cite{27} measurements. The angular anisotropy $v_2$ reveals three salient features: 1) particles exhibit hydrodynamic behavior in the low $p_T$ region – a 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.

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 [29]. Gyulassy and Vitev proposed the parton energy scenario as a mechanism to explain the deviation of $v_2$ from hydrodynamic behavior at moderate $p_T$ [30]. 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 [31], 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.

Shuryak [32] has pointed out that the magnitude of the measured $v_2$ is significantly larger than what can be accommodated based on particle emission from a geometrical ellipsoid source within an energy loss scenario. Using a more realistic Wood-Saxon description of the colliding nuclei for the ellipsoid source the predicted theoretical $v_2$ is much smaller than that from a hard-sphere model of the colliding nuclei, leading to a greater discrepancy between the measurement and the theoretical expectation. The magnitude and the particle dependence of $v_2$ at the intermediate $p_T$ region cannot have a dynamical origin either from hydrodynamic flow or from parton energy loss alone.

An empirical constituent quark number ($n$) scaling has also been observed [33]. Figure 5 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 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 \( p_T \) \cite{33,35}.

![Figure 5. 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.](image)

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 the low \( p_T \) region. 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 \cite{36,37} and recombination \cite{38,39} 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.
3. Color Deconfined Matter and its QCD Properties at Hadronization

The fact that for hadron formation at intermediate $p_T$ all quark constituents must contribute almost equally to hadron properties does not depend on details of theoretical models. Recombination or coalescence models provide a useful theoretical framework to derive quantitative quark level properties. However, these models do not constitute unambiguous evidence for deconfined partonic matter. The recombination model developed by Hwa and Yang, for example, works for p+p and d+Au collisions as well. These models provide an alternative hadronization scheme which, though different from fragmentation, has been demonstrated to be more suitable for hadron formation at the intermediate $p_T$ region from nucleus-nucleus collisions at RHIC. The unique evidence for a color deconfined quark matter comes from the fact that constituent quarks must have a collective $v_2$ distribution in order to explain the measured particle dependence of azimuthal angular anisotropy.

The particle dependences in the nuclear modification factor and in the angular anisotropy $v_2$ have demonstrated that two distinct groups: mesons and baryons, characterize the particle dependence at the intermediate $p_T$ region. The quark number scaling in the $v_2$ indicates that constituent quarks have developed a collective angular anisotropy distribution $v_2$ in transverse momentum space by the time of hadronization and hadrons are formed through coalescence or recombination of constituent quarks. The dominant degrees of freedom at hadronization seem to be in the constituent quarks. Based on nuclear parton distribution functions and quark versus gluon interaction cross sections, the initial conditions of nucleus-nucleus collisions at mid-rapidity at RHIC are expected to be dominated by gluon degrees of freedom. We do not know how the colliding system evolves from the initially gluon-dominated matter to a constituent quark dominated system just prior to hadronization. The dominance of the constituent quark degrees of freedom and the collective $v_2$ distribution at the constituent quark level are the most direct experimental evidence for a color deconfined matter, despite the lack of our understanding on the dynamics of nuclear matter evolution. The saturation of $v_2$ can be related to the geometrical shape of the particle emitting source at the time of hadron formation, which supports the notion of bulk partonic matter of constituent quark degrees of freedom.

The emerging physical picture implies that constituent quarks are the dominant degrees of freedom at the boundary of quark-hadron transition. The gluon degrees of freedom are not explicitly manifested in the hadron formation or in characterizing the hadron properties. It appears that the nuclear matter created in nucleus-nucleus collisions at RHIC would evolve naturally from a partonic gluon-dominated initial state towards a constituent quark or quasi-hadron state at the time of hadron formation. These experimental observations may provide useful insights on the QCD properties of the quark matter near $T_c$. Recent Lattice QCD (LQCD) calculations indicate that spectral functions of pseudoscalar and vector mesons have non-trivial shapes at a temperature above the critical $T_c$. In particular, heavy quarkonia such as J/ψ might...
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Survive at a temperature above $1.6T_c$ [42, 43]. Other theoretical calculations, for example reference [44], have also invoked the notion of quasi-hadrons to describe properties of the dense matter created at RHIC. It is a critical step to firmly connect the experimental insights on the properties of the quark matter at the boundary of hadronization with the LQCD calculations. The disappearance of the gluon degrees of freedom from the initial state and the emergence of constituent quarks at hadronization are some of the critical conceptual questions to be addressed. These questions will have a direct bearing on the nature of the quark hadron phase transition for which there is as yet no direct experimental evidence.

4. Charm Production Cross Section at RHIC

Heavy quarks are produced mostly in initial parton scattering or during the very high temperature phase of the collision. Therefore, heavy quark measurement can probe the initial parton flux, the dynamical evolution and the quark energy loss in dense medium. If heavy quarks are found to participate in the collective motion of the medium (radial or elliptic flow), this will lend further confirmation for parton collectivity. Features of charm meson production will also bear signatures of the partonic matter at the phase boundary. Both the STAR and PHENIX collaborations at RHIC have been pursuing vigorous heavy quark physics programs both in analyses of current data and in future detector upgrade plans to provide better capabilities for heavy quark measurements.

The total charm quark pair production cross section ($\sigma_{cc}$) is an important constraint on the collision dynamics and the heavy quark evolution. Both STAR and PHENIX have presented results on the $\sigma_{cc}$ measurement of p+p collisions from charm semi-leptonic decays. In addition, STAR has also derived an equivalent $\sigma_{cc}$ for p+p collisions based on direct reconstruction of hadronic decays of charm mesons from d+Au collisions. Figure 6 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 $\sigma_{cc}$ measurement of $709 \pm 85$ (stat) +332 −281 (sys) $\mu$b [45]. 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 [46]. A next-to-leading order pQCD calculation of the charm quark production cross section [47] has 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 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. 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 6 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 $D^0$ [15]. 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 [49]. If a fragmentation function such as the Lund fragmentation scheme [50] or the Peterson function [51] 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 [52].

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 [53]. 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 $1 \text{ (GeV/c)}^2$, much larger than the typical $\Lambda_{QCD}$ scale for 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 [53].
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.

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 nuclear medium produced at RHIC energies.

5. Recombination Mechanism and Heavy Quark Flow and Energy Loss

R.J. Fries et al \[38\] has argued that recombination dominates over the fragmentation production mechanism when the parton spectrum is a thermal distribution. The resulting hadron momentum distribution exhibits the same thermal distribution as the constituents. Only at sufficiently large $p_T$, where the underlying parton distribution is a power-law, does fragmentation overtake recombination. The recombination process is particularly effective for baryon production which recombines three readily available quarks while in fragmentation process the three quark production is suppressed. Since the low $p_T$ distributions of hadrons from $p+p$, $d+A$ and $A+A$ collisions at high energies such as RHIC are not drastically different quantitatively, the argument by R.J. Fries et al would imply that the recombination process should play a unique role at the
intermediate $p_T$ region for all these collisions if we interpret the soft particle production as from an underlying thermal parton distribution. Recombination model calculations by Hwa and Yang can fit Au+Au and d+Au data from RHIC reasonably well [40]. The fact that phenomenologically an underlying parton distribution is used for the recombination model does not necessarily mean the formation of partonic matter.

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 [54]. 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 [55].

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 [56, 57]. 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 [58]. Figure 8 shows preliminary STAR [59] and PHENIX [60] measurements of the $v_2$ for electrons from charm leptonic decays, which have been demonstrated to be closely correlated with charmed meson $v_2$ [35].

6. 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 the Lattice QCD results. Spectral function calculations have indicated that hadrons, particularly heavy quarkonia, do not melt completely at critical temperature. It appears plausible that the constituent quark degrees of freedom or quasi-particles play a dominant role at the hadronization of bulk partonic matter 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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