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Jet energy loss and bulk parton collectivity in nucleus-nucleus collisions at RHIC

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Abstract Nucleus-nucleus collisions at RHIC produce high temperature and high energy density matter which exhibits partonic degrees of freedom. We will discuss measurements of nuclear modification factors for light hadrons and non-photonic electrons from heavy quark decays, which reflect the flavor dependence of energy loss of high momentum partons traversing the dense QCD medium. The dense QCD medium responds to energy loss of high momentum partons in a pattern consistent with that expected from a hydrodynamic fluid. The hadronization of bulk partonic matter exhibits collectivity with effective partonic degrees of freedom. Nuclear collisions at RHIC provide an intriguing environment, where many constituent quark ingredients are readily available for possible formation of exotic particles through quark coalescence or recombinations.

Key words relativistic, heavy ion collision

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1 Introduction

Lattice Quantum ChromoDynamics (QCD) predicted that at high temperature and/or high baryon density quarks and gluons are deconfined and a new state of matter, the Quark-Gluon Plasma (QGP), is formed. The nature of the transition from hadrons to the QGP has not been established. Theoretical calculations indicate that there may be a critical point at finite baryon density. Below the critical baryon density the quark-hadron transition may be a smooth cross-over while above the critical baryon density a first-order phase transition may take place. More details may be found in Ref. [1] and references therein.

High energy nucleus-nucleus collisions have been used to study QCD at the extreme conditions of temperature and density and to search for the new state of matter. Experimental results at RHIC have demonstrated that matter of extremely high energy density has been produced in central Au+Au collisions[2]. In this paper we will discuss the flavor dependence of the parton energy loss in dense medium, QCD medium responses to jet energy loss, characteristics of hadronization for bulk partonic matter and possible formation of exotic particles from nuclear collisions at RHIC.

2 Parton energy loss in dense QCD medium

Hard scatterings of incoming partons in nuclear collisions involve large momentum transfer and can generally be calculated within perturbative Quantum Chromodynamics (pQCD) framework. Bjorken[3] first proposed that jets from pQCD processes may lose energy in Quark-Gluon Plasma (QGP) and can be used to probe properties of the QGP. X. N. Wang and M. Gyulassy[4] further developed the idea of partons radiating energy off in a high temperature dense matter and studied jet quenching phenomenology. Nuclear modification factors,

$$R_{\rm AA}=\frac{\left[\dfrac{{\rm d}n}{{\rm d}p_{\rm T}}\right]_{\rm AA}\Big/N_{\rm coll}}{\left[\dfrac{{\rm d}n}{{\rm d}p_{\rm T}}\right]_{\rm pp}}$$

and

$$R_{\rm CP}=\frac{\left[\dfrac{{\rm d}n}{{\rm d}p_{\rm T}}\right]_{\rm Cen}\Big/N_{\rm coll}^{\rm Cen}}{\left[\dfrac{{\rm d}n}{{\rm d}p_{\rm T}}\right]_{\rm Per}\Big/N_{\rm coll}^{\rm Per}},$$

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have been defined to quantitatively describe the change in the transverse momentum (p_{T}) spectra due to energy loss of high momentum partons in the dense medium, where N_{coll} denotes the number of binary inelastic nucleon-nucleon collisions in central/peripheral (Cen/Per) nucleus-nucleus (AA) collisions. These factors would be unity if nucleus-nucleus collisions are a superposition of independent nucleon-nucleon collisions. Experimental observations of a strong suppression of high p_{T} particles (R_{AA} or $R_{\mathrm{CP}} \sim 0.2 \ll 1$) in central Au+Au collisions have been one of the most exciting discoveries at RHIC, which established that the presence of dense matter created in central Au+Au collisions significantly changes the yields of high p_{T} hadrons produced from partons traversing the dense medium.

Recent experimental studies of high p_{T} physics at RHIC focus on questions of 1) whether the suppression of high p_{T} particles in central Au+Au collisions is mainly due to energy loss in partonic, not hadronic, evolutions; 2) whether there are experimental consequences due to differences in quark and gluon energy losses; 3) whether there is a difference in partonic energy loss between light and heavy quarks; and 4) possible experimental signatures associated with QCD medium response to energy loss of high momentum partons.

Figure 1 shows measurements of nuclear modification factors R_{AA} for neutral π^0 and η from PHENIX[6] and R_{CP} for protons and charged pions from STAR[7]. The boxes on STAR data are systematic errors and the PHENIX errors contain point-by-point statistical and systematic errors. These measurements of nuclear modification factors indicate no significant differences between π^0 and η, between charged π and protons (anti-protons) in the region of p_{T} greater than 6 GeV/c. Therefore, the dominant energy loss process must have taken place before the formation of these particles. Otherwise, these hadrons would have very different magnitude of energy losses because their hadronic scattering cross sections are very different. These data have experimentally confirmed that the energy loss dynamics must be due to partons, which have long been assumed in theoretical calculations of jet quenching[8—10]. More importantly there is no significant difference between baryons and mesons as shown by the STAR data. Gluon and quark jet fragmentations tend to contribute differently to baryons and mesons, and generally anti-baryons at high p_{T} tend to originate more from gluon fragmentations[11]. The large difference expected theoretically for gluon and quark energy loss in QCD medium does not manifest in the high p_{T} suppression of baryons and mesons from central Au+Au collisions. One possible explanation for the experimental observation is that quarks and gluons convert to each other rapidly during the propagation in the medium such that there would be no pure quark or pure gluon energy loss, only the average of quarks and gluons. Recently Liu, Ko and Zhang calculated the quark-gluon jet conversion rate in the QGP using the lowest order pQCD and they found that a conversion rate much larger than the pQCD cross-section is needed in order to explain the STAR measurement[12]. Questions remain open whether and by what dynamics high p_{T} gluons would immediately convert to quark pairs when traversing the QGP and the gluon degrees of freedom do not explicitly manifest in the suppression of hadron spectra at high p_{T}. More experimental measurements with tagging on flavors will be needed to shed more light on the quark and gluon propagation in the QCD color medium.

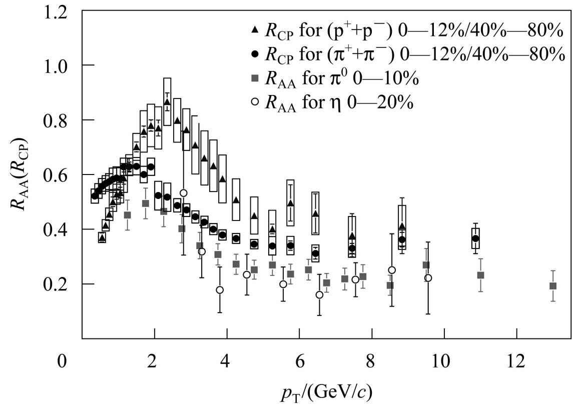

Fig. 1. Nuclear modification factors R_{AA} for π^0 and η from PHENIX and R_{CP} for π^{+}+π^{-} and proton ($\mathrm{p}+\bar{\mathrm{p}}$) from STAR. The differences in R_{AA} between π^0 and η, in R_{CP} between π and proton disappear above p_{T} of 6 GeV/c indicative of parton energy loss before the hadron formation.

Figure 2 shows the STAR[13] and PHENIX[14] measurements of nuclear modification factor for non-photonic electrons in comparison with that of charged hadrons[5] from central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}=$ 200 GeV. The boxes (bars) on STAR and PHENIX electron data indicate the size of systematic (statistical) errors. Note due to decay kinematics the heavy quark meson p_{T} is on average significantly higher than that of the decay daughter electron. Although there is a large discrepancy, approximately a factor of two difference, in the non-photonic electron spectra between the STAR and the PHENIX data, the STAR and PHENIX measurements of nuclear modification factors for non-photonic electrons are consistent with each other within statistical and systematic errors. There appears an overall scale factor in non-photonic electron measurements for both p+p and Au+Au collisions between STAR and PHENIX, which has not been understood yet. In our present discussion we assume that the $R_{\rm AA}$ measurements are correct and will not be affected by an overall normalization factor. These measurements imply that the energy loss of heavy quarks is not significantly different from that of light quarks, in contradiction with theoretical expectations that heavy quarks would loss much less energy due to the dead-cone effect suppressing gluon radiation for heavy quarks[15]. Recent theoretical calculations cannot explain the non-photonic electron and light hadron $R_{\rm AA}$ measurements with a consistent dynamical picture[16, 17]. The parton energy loss mechanism in dense QCD medium and the significance of elastic collisional energy loss are under re-examination now. It appears that in addition to medium-induced gluon radiation elastic collisional energy loss may also contribute significantly to the total magnitude of parton energy loss[18, 19].

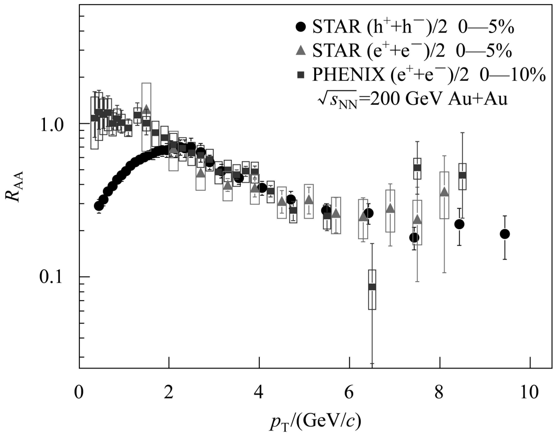

Fig. 2. Measurements of nuclear modification factor of non-photonic electrons from heavy quark semi-leptonic decays by STAR and PHENIX in comparison with that of charged hadrons by STAR. The magnitudes of suppression for hadrons and non-photonic electrons approach each other at high $p_{\rm T}$.

Both charm and bottom quarks contribute to non-photonic electrons through semi-leptonic decays. Bottom quarks, because of much heavier mass, are expected to suffer less energy loss than charm quarks. Such a difference in energy loss would lead to variations in the $R_{\rm AA}$ as a function of $p_{\rm T}$ for non-photonic electrons depending the relative bottom and charm quark yields[17, 20]. The charm and bottom quark production at high $p_{\rm T}$ has not been measured directly through hadronic decays, which is a major scientific goal of next generation of vertex detector upgrades for STAR and PHENIX at RHIC. The relative D and B decay contributions to the non-photonic electrons remain an experimental challenge. It has been proposed to use electron and hadron azimuthal angular correlations from D and B decays to study the relative D and B contributions[21]. Preliminary STAR results indicate that charm and bottom quarks have comparable contributions to non-photonic electrons at a $p_{\rm T}$ of 6 GeV/c[22]. If bottom quarks do contribute significantly to non-photonic electrons at $p_{\rm T}$ 6 GeV/c, the large suppression as shown in Fig. 2 would imply that bottom quarks suffer considerable energy loss while traversing the dense QCD medium created in central Au+Au collisions. The flavor dependence of parton energy loss continues to be a subject of both experimental and theoretical investigations.

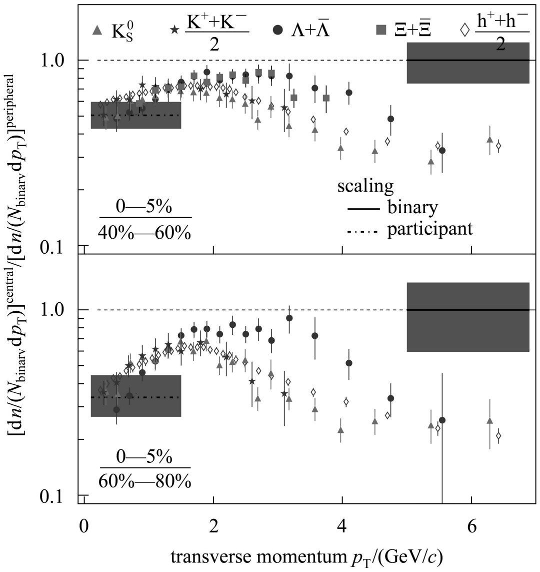

Fig. 3. Measurements of nuclear modification factor, $R_{\rm CP}$ for Kaons, Λ, Ξ and charged hadrons. In the intermediate $p_{\rm T}$ region the $R_{\rm CP}$ values are grouped in two bands, one for baryons and one for mesons.

There are two $p_{\rm T}$ scales, approximately 2 GeV/c and 6 GeV/c, which separate distinct features in the $R_{\rm AA}/R_{\rm CP}$ data presumably corresponding to different applicable dynamics in nucleus-nucleus collisions. These features were first noted by STAR[23] in the measurement of $R_{\rm CP}$ and elliptic flow v_2 for identified strange particles. Fig. 3 shows the STAR measurements of nuclear modification factors $R_{\rm CP}$ for $\rm K_S$, charged K, Λ, Ξ and charged hadrons. Below the $p_{\rm T}$

scale of 2 GeV/c, there is a particle mass dependence in both the $R_{\rm CP}$ and the v_2 measurements[23]. Such a mass dependence is consistent with hydrodynamical calculations[24]. Detailed comparisons between experimental measurements and hydrodynamical models have led to the suggestion that partons in the dense QCD matter formed in nucleus-nucleus collisions may be strongly coupled with each other and the fluid matter may possess a minimum viscosity[25—27]. In the intermediate $p_{\rm T}$ region of 2—6 GeV/c between two scales, measured features in $R_{\rm CP}$ and v_2 seem to depend on particle types, grouped in baryons and mesons. These features have been related to multi-parton dynamics in the hadronization of bulk partonic matter, which we will discuss in the next section. Only above the $p_{\rm T}$ scale of 6 GeV/c, the particle dependence in the $R_{\rm CP}$ and $R_{\rm AA}$ measurements disappears. The jet quenching picture where partons lose energy in the QCD color medium and hadronization takes place outside the medium is only valid above the $p_{\rm T}$ scale of 6 GeV/c. Future measurements of nuclear modification factors and v_2 for Ω and heavy quark mesons will test if the $p_{\rm T}$ scales depend on quark masses.

High momentum jets from hard scatterings lose considerable amount of energy in the dense QCD color medium created in central Au+Au collisions at RHIC. How the energy is dissipated in the medium and how the medium responds to the traversing of partons are key questions for experimental and theoretical investigations. Experimentally the azimuthal angular distribution of associated particles opposite to the direction of the triggered high $p_{\rm T}$ particle (away-side) is significantly broadened in central Au+Au collisions[28]. Detailed studies of di-hadron angular correlations show that particles on the away-side of the high $p_{\rm T}$ triggered hadron are preferentially emitted in a cone[29]. Fig. 4 shows the di-hadron azimuthal angular distributions for charged hadrons from STAR and PHENIX. Note the ranges of $p_{\rm T}$ for associated particles are different for the STAR and the PHENIX data. It appears that the conic emission pattern becomes more prominent if the softest particles with $p_{\rm T}$ below 1 GeV/c are excluded. H. Stocker proposed that the broadening of the away-side di-hadron correlation is due to the supersonic wake created when a high speed jet traversing the dense partonic matter with a speed exceeding that of the sound[30]. J. Casalderrey-Solana et al. calculated the Mach cone response from a hydrodynamical description of the dense medium created in nucleus-nucleus collisions at RHIC[31]. Ruppert and Muller proposed a Mach cone generation mechanism from collective excitation of plasmon wave when a jet traversing the Quark-Gluon Plasma (QGP)[32]. The expanding of the QGP can also affect the conic pattern of the emitted particles[33]. G. L. Ma et al. demonstrated that parton cascade processes from jet quenching can also generate a Mach-like structure in the partonic medium[34]. A recent review of theoretical ideas related to the experimental observation of conic emission pattern can be found in reference[35].

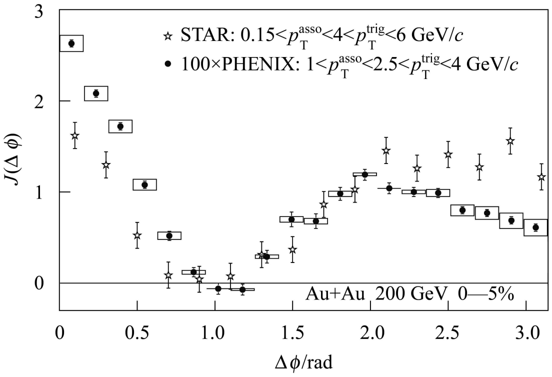

Fig. 4. Di-hadron azimuthal angle correlations between a triggered high $p_{\rm T}$ particle and associated particles. Note that the STAR and PHENIX data cover different $p_{\rm T}$ region for associated particles leading to different prominence in the conic emission pattern.

3 Hadronization of bulk partonic matter

Particle production from nucleus-nucleus collisions at RHIC has shown distinct $p_{\rm T}$ scales: $p_{\rm T}$ above 6 GeV/c or so where parton fragmentations become important and particle dependence in the nuclear modification factors disappears; $p_{\rm T}$ below 2 GeV/c where hydrodynamic calculations can describe $p_{\rm T}$ and elliptic flow v_2 distributions of π, Kaon, protons, Λ and Ξ particles[36]; and the intermediate $p_{\rm T}$ region of 2—6 GeV/c where unique particle type dependence on particle yield and elliptic flow v_2 has been observed[23]. Experimental features in both the nuclear modification factors and the elliptic flow at intermediate $p_{\rm T}$ have been related to hadron formation mechanisms from bulk partonic matter through multi-parton dynamics such as quark coalescence and recombinations.

A unique feature of constituent quark number scaling has been observed in experimental measurements of nuclear modification factors and elliptic flow v_2 at intermediate $p_{\rm T}$[23]. This scaling cannot be explained in the traditional parton fragmentation picture for hadron formation where a leading parton determines the properties of the produced hadron in nuclear collisions. Characteristics of hadrons at intermediate p_{T} produced in nucleus-nucleus collisions at RHIC necessarily require the existence of effective degrees of freedom for constituent quarks which carry an azimuthal angular anisotropy before hadronization. Fig. 5 shows elliptic flow v_2/n versus p_{T}/n, where n is the constituent quark number for identified particles from the STAR and PHENIX measurements[37]. At the intermediate p_{T} region the scaled data points fall approximately on a single curve. Deviations from the scaling in the low p_{T} region have been attributed to hydrodynamic behavior and detailed internal quark-gluon structures for various hadrons have been shown theoretically to contribute to deviations from the scaling as well[38]. The constituent quark number scaling has also been observed in the particle dependence of nuclear modification factors for π, Kaon, proton and hyperons.

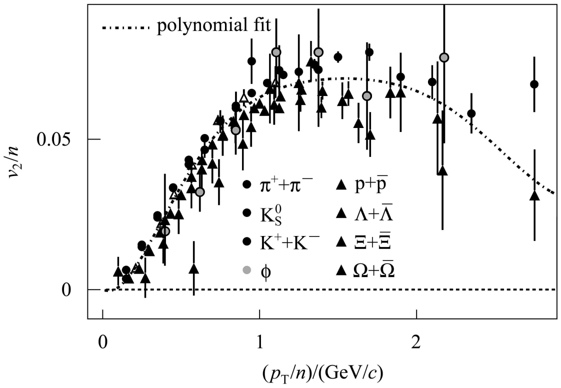

Fig. 5. v_2/n as a function of p_{T}/n for identified particles, where n is the number of constituent quarks. The dotted line is a polynomial fit to the available data. Systematic deviation as a function of particle masses at low p_{T} is largely due to hydrodynamic behavior. Internal structures of hadrons also contribute to deviations.

The measurement of ϕ mesons is considered an important test for physical mechanisms in different p_{T} regions. The mass of the ϕ is close to proton mass. Therefore, in the low p_{T} region where hydrodynamics work the ϕ meson should exhibit an elliptic flow close to that of the proton. In the intermediate p_{T} region where the constituent quark number scaling is valid, however, the ϕ meson should behave like a meson, unlike baryons. Recently measurements of nuclear modification factor and v_2 for ϕ mesons have revealed the hydrodynamic behavior at low p_{T} and the quark number scaling at intermediate p_{T}[39—41]. The ϕ measurements confirm the parton origin of the dynamics for the scaling behavior and imply parton collectivity among up, down and strange quarks in the hot and dense matter formed in nucleus-nucleus collisions at RHIC.

Quark coalescence or recombination models[42—45] can explain the experimental features at the intermediate p_{T}. The constituent quark number scaling reflects the fact that hadrons are formed from constituent ingredients readily available at the hadronization stage and the azimuthal angular anisotropy of hadrons is the sum from individual ingredients. We denote this feature the constituent quark number scaling because the number of constituents is 2 for mesons and 3 for baryons although the revelant entity may not necessarily be the constituent quarks in traditional quark model for hadrons.

The particle mass dependence of v_2 in the low p_{T} region is indicative of pressure-induced hydrodynamic flow. A KE_{T} scaling in the low p_{T} region has been observed by PHENIX[46] using STAR and PHENIX data, where $KE_{\mathrm{T}}=m_{\mathrm{T}}-m$ and m_{T} is the transverse mass ($m_{\mathrm{T}}=\sqrt{p_{\mathrm{T}}^2+m^2}$) and m the rest mass of the particle. It appears that the measured v_2 is linearly proportional to KE_{T} for all particles including π, K, proton, Λ and Ξ in the low p_{T} region. The linear relationship between v_2 and KE_{T} also leads to constituent quark number scaling of v_2/n versus KE_{T}/n. The scaling in the low p_{T} region indicates the constituent quark-like degrees of freedom in the flowing matter and effective masses of these constituents determine the hydrodynamic flow[46]. We note that π mesons seem to follow the KE_{T} scaling in the low p_{T} region well. Previously it has been observed that π mesons deviate from hydrodynamic calculations and the deviation has been attributed to the fact that most π mesons are decay daughters of resonances. The resonance masses are higher than the π mass and the decay kinematics alter the particle v_2 distribution[47]. Measurements of ρ resonance v_2 are needed to shed more light on the nature of the puzzling behavior of KE_{T} scaling for π mesons.

The constituent quark number scaling in nuclear modification factors and elliptic flow for identified particles at intermediate p_{T} originates from partonic nature of the matter. Moreover, the partonic matter must exhibit parton collectivity such as v_2 in order to explain experimental measurements of v_2 at intermediate p_{T} for mesons and baryons including multi-strange hyperons. These data have provided most direct experimental evidence for deconfined partonic matter created in nucleus-nucleus collisions at RHIC.

Experimental data seem to imply that the effective degrees of freedom near the transition temperature for dense matter created in nucleus-nucleus collisions at RHIC are in the constituent quarks. Such a picture would be qualitatively consistent with the description of quark-antiquark quasi-hadron state just above the T_c by Brown, Gelman and Rho[48].

4 Exotic particle searches at RHIC

Experimental data at RHIC indicate that hadrons may be formed from coalescence or recombination of quarks, which are readily available from the dense partonic matter created in nuclear collisions at RHIC energies. Such a collision environment would be favorable for the formation of exotic particles if these particles do exist. Of course, searches for exotic particles in nuclear collisions with an overwhelming number of ordinary hadrons are both scientifically and technically challenging.

STAR reported a upper limit result on strangelet searches[49]. Pentaquark searches have also been carried out. An intriguing peak with $\sim 4\sigma$ statistical significance in $\mathrm{pK}^+ + \overline{\mathrm{p}}\mathrm{K}^-$ invariant mass distribution from 18.6 million d+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV has been observed. The observed peak position is at 1.53 GeV/c^2 and the width is consistent with detector resolutions. We denote this peak as θ^{++} for simplicity in our description. Note the observed peak is a different charge state than what has been called θ^+ as first reported by the LEPS collaboration[50]. Neither the θ^+ nor the θ^{++} states have been observed by the CLAS collaboration[51, 52] from analyses of recent data samples much larger than that was previously used in a report for positive signal[53]. Analyses of available STAR data from other colliding systems at RHIC neither confirm nor rule out the observation from d+Au collisions. Another d+Au run at RHIC will be needed to investigate the STAR observation. Details of the STAR analysis can be found in reference[54]. Future STAR detector upgrades, a barrel Time-of-Flight detector under construction and a Heavy Flavor Tracker, will significantly enhance the STAR capability for exotic particle searches.

5 Experimental outlook

Searches for possible critical point in the QCD phase diagram is another interesting topic that we did not cover in this paper. The nature of the order of possible phase transition has not been determined experimentally. In fact, we do not know how to address the order of QCD phase transition question experimentally though it is believed that studies on fluctuations are relevant. Direct measurement of open charm and beauty mesons will be necessary in order to understand heavy quark dynamics in dense QCD medium, for which measurements of relative B and D contributions, elliptic flow v_2 of D and B mesons and elliptic flow v_2 for quarkonia are critical. This will require future vertex detector upgrades for both STAR and PHENIX.

More measurements are needed in order to understand the QCD properties of matter near or above the T_c. Dileptons in the low to intermediate mass regions will provide new insight on the chiral properties of the dense matter[55]. Soft photons of tens MeV to GeV energy will be the shining lights from the dense matter and have remained an open experimental issue. And of course, our searches for exotic particles at RHIC may prove that RHIC is indeed an exotic particle factory which would allow us to study hadrons whose structure is beyond the conventional quark-antiquark and three-quark constituents.

In summary RHIC as a dedicated QCD machine has an exciting scientific program even when the energy frontier is pushed an order of magnitude higher at the LHC experiments.

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