

# Relativistic Heavy-Ion Collider (RHIC) physics overview

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*Received January 20, 2010; accepted February 8, 2010*

The results from data taken during the last several years at the Relativistic Heavy-Ion Collider (RHIC) will be reviewed in the paper. Several selected topics that further our understanding of constituent quark scaling, jet quenching and color screening effect of heavy quarkonia in the hot dense medium will be presented. Detector upgrades will further probe the properties of Quark Gluon Plasma. Future measurements with upgraded detectors will be presented. The discovery perspectives from future measurements will also be discussed.

**Keywords** Quark Gluon Plasma, jet quenching, partonic collectivity, number of constituent quark scaling, baryon enhancement, color screening effect

**PACS numbers** 25.75.Ag, 25.75.Bh, 25.75.Cj, 25.75.Dw, 25.75.Gz, 25.75.Ld, 25.75.Nq, 25.75.-q, 13.85.Ni

## Contents

1	Introduction	205
2	The hot and dense medium created at RHIC	206
2.1	Bulk properties	206
2.2	Hard probes and medium properties	206
2.3	Intermediate $p_T$ physics: number of constituent quark scaling (NCQ) and baryon enhancement	207
3	Several selected recent highlights from RHIC	208
3.1	Further measurements of partonic flow and NCQ scaling	208
3.2	The characteristics of jet quenching	208
3.3	Color screening effect on high $p_T$ $J/\psi$ ?	209
4	Future upgrades and the related key measurements	209
4.1	Heavy flavor collectivity and energy loss	210
4.2	Quarkonia production mechanisms, color screening, collectivity and energy loss	210
4.3	Dilepton measurements in the future: vector meson properties and continuum	210
4.4	Direct photons and jet reconstruction	210
5	Energy scan: looking for the critical point	211
6	Discovery possibilities	211
7	Conclusion	212
	Acknowledgements	212
	References	212

the Relativistic Heavy-Ion Collider (RHIC) has created a strongly interacting hot, dense medium with partonic degrees of freedom, the Quark Gluon Plasma (QGP) in central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [1–4]. Such matter is believed to have existed a few microseconds after the big bang. Understanding the properties of this matter, such as the colored degrees of freedom and the equation of state is the physics goal of RHIC and of broad interest. I will review the experimental results which were used to identify the existence of the hot, dense medium, followed by the measurements of its properties. Future upgrades that are essential to understand the fundamental properties of the medium will be discussed as well.

RHIC at Brookhaven National Laboratory is the first hadron accelerator and collider consisting of two independent rings. It is designed to operate at high collision luminosity over a wide range of beam energies and particle species ranging from polarized proton to heavy ion [5, 6], where the top energy of the colliding center-of-mass energy per nucleon-nucleon pair is  $\sqrt{s_{NN}} = 200$  GeV. The RHIC facility consists of two rings with superconducting magnets, each with a circumference of 3.8 km, which focus and guide the beams. There are four experiments at RHIC, BRAHMS [7], PHENIX [8], PHOBOS [9], and STAR [10]. BRAHMS and PHOBOS are relatively small experiments. They have finished their experimental program and were decommissioned after year 2008. STAR and PHENIX, the two large detectors, are still in operation.

## 1 Introduction

Data taken in the last few years have demonstrated that

## 2 The hot and dense medium created at RHIC

In 2000, the experiments started to take data. In 2005, the four experiments published white papers summarizing what has been discovered. The details can be found in all four white papers [1–4]. The focus of RHIC was to identify the existence of the QGP. Below, I will review two probes used to identify QGP: bulk probes and penetrating probes. Bulk probes include measurements of the majority of produced particles at low  $p_T$  ( $p_T < 2$  GeV/ $c$ ) to address the energy density and collectivity, and freeze out properties of hot, dense medium. Penetrating probes are the measurements of the rarely produced particles such as heavy flavor, jets and identified particles at high  $p_T$  ( $p_T > 6$  GeV/ $c$ ) to see the medium effect on their productions and thereby are used to deduce medium properties. The measurements at intermediate  $p_T$  ( $2 < p_T < 6$  GeV/ $c$ ) probe the interplay between bulk and hard components and reveal some unique interesting features of the collisions at RHIC.

### 2.1 Bulk properties

Many measurements at RHIC have studied the bulk properties of the collisions, including low  $p_T$  identified particle transverse momentum and rapidity distributions in different collision centralities, system sizes and collision energies. The measurements indicate that RHIC has created a hot and dense partonic medium which expands and cools down hydrodynamically. Hadrons freeze out chemically at close to critical temperature ( $T_c$ ) and then freeze out kinetically at lower temperature. Below are several important measurements that point to the existence of a hot, dense medium and its freeze-out features.

- The rapidity dependence of particle multiplicity demonstrates that the 26-TeV energy has been dumped in the system to produce particles in 200-GeV central Au+Au collisions [11]. The energy density is much higher than normal nuclear matter density; thus, it is believed that partonic matter is formed in such collisions [12].
- The measurements of elliptic flow  $v_2$ , the second harmonic coefficient of a Fourier expansion of the final momentum-space anisotropic azimuthal distribution, show mass dependence at low  $p_T$  consistent with hydrodynamic behaviors with quark gluon plasma equation of state [13, 14]. The quantitative consistency between data and hydrodynamic model calculations is lacked and complicated by initial conditions, hadronization and freeze-out processes. However, the magnitude of the elliptic low

can be reproduced only when partonic interactions are included in the calculations.

- The identified particle  $p_T$  distributions were measured and fit with the blast-wave model using thermal-like distribution or Tsallis-like distributions [15–18]. The latter include the fluctuation and non-equilibrium effects in the system and can be applied in p+p collisions also. The thermal-like fit indicates that the kinetic freeze-out temperature  $T_{\text{kin}}$  decreases from p+p to peripheral Au+Au to central Au+Au collisions while the velocity profile increases. This indicates that the system is cooling with expansion.
- The identified particle ratios measured in Au+Au collisions at different centralities were fit with thermal model distributions [15, 19–23]. The fit indicates that the chemical freeze-out temperature ( $T_{\text{chemical}}$ ) is about 160 MeV and that there is no significant centrality or system size dependence. This value of  $T_{\text{chemical}}$  is very close to the critical temperature  $T_c$  calculated by Lattice QCD [24, 25].
- The measurements of resonance to stable particle ratios and Hanbury Brown–Twiss (HBT) interferometry of two particle Bose–Einstein correlations indicate that the time interval between chemical and kinetic freeze out is about 3–10 fm/ $c$  [26–28].

The above measurements are consistent with the physics picture in which partonic matter is created at RHIC, expands and cools down, and hadronizes into a system of hadrons that freeze out chemically shortly after at a fixed temperature, followed by further expansion and cooling down until kinetic freeze-out.

### 2.2 Hard probes and medium properties

Beside bulk probes, hard probes such as identified particles at high  $p_T$ , jets and heavy flavor are thought to be ideal probes for quark gluon plasma. They are thought to be well calibrated since they are believed to be produced from hard processes with high  $Q^2$  transfer and thus can be calculated in perturbative Quantum Chromodynamic (pQCD) framework [29, 30]. In pQCD calculations, identified particle production can be described as a convolution of parton distribution functions, parton parton interaction cross sections and parton fragmentation functions. When hard partons traverse the hot and dense medium created in the collision, they lose energy by gluon radiation and/or collide elastically with surrounding partons [31–37]. This phenomenon is also called jet quenching. Jet quenching leads to a softening of the final measured hadron spectra at high  $p_T$ . The amount of energy loss can be calculated in QCD and is expected to be different for energetic gluons, light quarks and heavy quarks [38, 39]. In experiments, in order to

quantify the effect of the medium, the nuclear modification factors ( $R_{AB}$  or  $R_{CP}$ ) are measured, where the invariant yield in A+B collisions is divided by that in p+p or peripheral A+B collisions, scaled by their respective numbers of binary nucleon–nucleon collisions. If there was no nuclear medium effect, the ratio would be 1 at high  $p_T$ . Any deviation from unity therefore indicates nuclear medium effects. This is similar to medical imaging techniques, where the picture of a human body can be obtained through the calibrated gamma ray interaction. Below, several important results are listed to illustrate the properties of the medium through the change in hard probes in central heavy-ion collisions compared to peripheral and to p+p collisions.

- The  $R_{AA}$  of inclusive hadrons in central Au+Au collisions at 200 GeV at mid-rapidity shows a factor of 5 suppression with respect to unity at  $p_T > 6$  GeV/c [33–37]. The pQCD calculation with gluon density  $dN_g/dy = 1000$  and with radiative energy loss can describe the suppression [31, 32]. The  $R_{dAu}$  of inclusive charged hadrons in d+Au collisions shows enhancement at intermediate  $p_T$  and is equal to unity at high  $p_T$  [40–43]. This indicates that the strong suppression observed in  $R_{AA}$  in central Au+Au collisions is due to final state effects and not due to an initial wave function difference such as a possible color glass condensate (CGC) [44–48] at mid-rapidity.
- Two particle azimuthal angle correlations show that in central Au+Au collisions, away side particle production at  $p_T > 2$  GeV/c disappears or is suppressed significantly compared to that in p+p and d+Au collisions with respect to a high  $p_T$  trigger ( $p_T > 6$  GeV/c) [1, 49]. When the  $p_T$  was lowered for associate particles, enhancement of particle production on the away side was observed compared to p+p and d+Au collisions, and the transverse momentum distribution on the away side is softened and approaches the inclusive particle distribution [50]. This indicates that the energy loss by the jet on the away side might be thermalized by the system.

The above measurements indicate that the suppression on  $R_{AA}$  of high  $p_T$  particles in central Au+Au collisions is consistent with the partonic energy loss picture.

### 2.3 Intermediate $p_T$ physics: number of constituent quark scaling (NCQ) and baryon enhancement

Between low  $p_T$  where the physics is dominated by bulk properties and high  $p_T$  where the particle production is by jet fragmentation, there is also rich physics which can be used to explore the properties of the medium created in heavy ion collisions. Below, several interesting results are presented.

- The identified particle elliptic flow measurements for  $\pi$ , K,  $p$ ,  $\Xi$ ,  $\Omega$  and  $\phi$  indicate that the flow pattern at intermediate  $p_T$  seems to follow a simple scaling governed by the fact that mesons (baryons) have two (three) constituent quarks [51–54]. Even though multi-strange hadrons or  $\phi$  have smaller interaction cross sections at hadronic stage, they have a similar flow pattern as non-strange hadrons. This indicates that the elliptic flow is mainly developed at the partonic stage where the light-strange quark difference is insignificant. Coalescence or recombination models [55–58], in which two or three constituent quarks are combined into mesons or baryons, were proposed to explain the data.
- At intermediate  $p_T$ ,  $R_{CP}$  ( $R_{AA}$ ) for baryons is larger than that for mesons, indicating strong baryon enhancement in Au+Au collisions [59, 60]. In central Au+Au collisions, the  $p/\pi$  ratio reaches unity, which is much larger than that from elementary p+p collisions. The coalescence or recombination model can qualitatively reproduce the feature. The parton density at RHIC is significant so that parton recombination into hadrons is efficient. In the same  $p_T$  region, the parton  $p_T$  for baryons is effectively lower than that for mesons; thus, the baryon over meson ratio can be significantly enhanced in the intermediate  $p_T$  region in central Au+Au collisions.

At intermediate  $p_T$ , elliptic flow and baryon over meson ratio measurements are consistent with the recombination or coalescence picture in which partons recombine into hadrons at hadronization.

To summarize this section, the measurements on bulk properties, hard penetrating probes and at intermediate  $p_T$  at RHIC indicate that RHIC has created a dense and rapidly thermalizing matter characterized by: 1) initial energy densities far above the critical values predicted by lattice QCD for formation of a QGP; 2) opacity to jets; and 3) nearly ideal fluid flow, which is marked by constituent interactions of very short mean free path, established most probably at a stage preceding hadron formation [1].

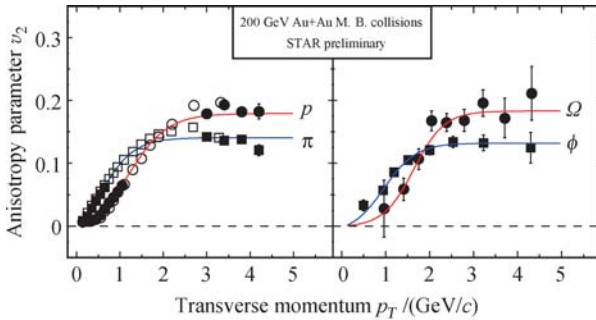
The next objective is to study the properties of the created matter in detail in terms of the equation of state and colored degrees of freedom. For example, one would like to know the temperature, the chemical composition and the velocity of sound of the hot and dense matter. One would also like to further understand or test jet quenching and NCQ scaling and to study other signatures of the quark gluon plasma such as color screening effects.

### 3 Several selected recent highlights from RHIC

In this section, several selected recent results will be presented that further our understanding of partonic flow, NCQ scaling and jet quenching. New results on possible color screening effects of QGP are also presented.

#### 3.1 Further measurements of partonic flow and NCQ scaling

With the high statistics data from Au+Au collisions taken in year 2007, STAR measured  $v_2$  of  $\phi$  and  $\Omega$  with high precision, as shown in Fig. 1. The  $\Omega$  and  $\phi$   $v_2$  at intermediate  $p_T$  is close to the proton and pion  $v_2$ , respectively. This indicates that  $v_2$  observed at RHIC is dominantly due to partonic collectivity [61]. With high precision measurements, STAR and PHENIX both showed that there is significant deviation from NCQ scaling for  $v_2$  measurements at intermediate  $p_T$  [62–65], which can be understood as the hard component from jet fragmentation starting to play a role in the corresponding  $p_T$  region.



**Fig. 1**  $v_2$  as a function of  $p_T$  for  $\pi$ ,  $p$ ,  $\Omega$  and  $\phi$  in 200-GeV minimum bias Au+Au collisions. Open symbols are from PHENIX [66], and the solid symbols are from STAR. Lines represent NCQ-inspired fit [67]. The figure is taken from Ref. [61].

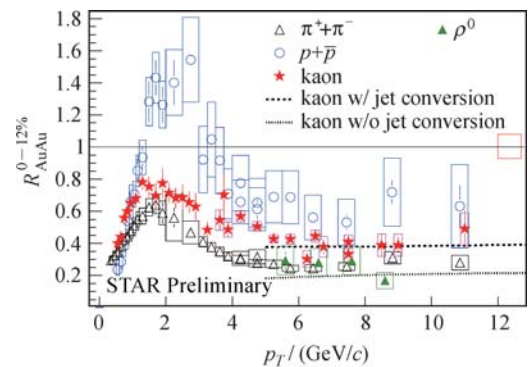
#### 3.2 The characteristics of jet quenching

To further understand energy loss mechanisms and medium properties, nuclear modification factors for direct photons were measured. The  $R_{AA}$  from direct photons, which are the inclusive photon yields subtracting hadronic decay contributions, is consistent with no suppression at high  $p_T$  [68]. This confirms that the suppression observed in the  $R_{AA}$  for hadrons is due to jet quenching, rather than initial wave function change which would affect the direct photons as well.

In addition, nuclear modification factors for protons, pions, and non-photonic electrons from heavy flavor decay were also measured to test color charge or flavor dependence of energy loss. For example, gluons carry different Casimir factor from quarks. The coupling of gluons to the medium is stronger than the coupling of

quarks to the medium; thus, gluons are expected to lose more energy than quarks when traversing the medium. At RHIC energy, the gluon jet contribution to protons is significantly larger than to pions at high  $p_T$  [38, 69–71]. Therefore, protons are expected to be more suppressed than pions in  $R_{AA}$  or  $R_{CP}$  measurement. Experimentally, protons and pions show similar magnitudes of suppression in  $R_{CP}$  [72, 73]. One of the proposed mechanisms is the jet conversion mechanism [74], in which, a jet can change flavor or color charge after interaction with the medium. With much larger jet conversion cross sections compared to that in the Leading Order (LO) calculation, the proton and pion suppression magnitudes are similar. Using the same factor scaling the LO QCD calculations, kaons are predicted to be less suppressed than pions since the initially produced hard strange quarks are much fewer than the strange quarks in a hot, dense medium [75]. Alternatively, enhanced parton splitting in the medium will also lead to a change of the jet hadron chemical composition in Au+Au collisions compared to that in p+p collisions [76].

The new measurements of strange hadrons can test further these mechanisms. Recently, STAR showed the invariant yields of  $\pi$ , K and  $p$  up to  $p_T$  of 15 GeV/c in 200-GeV p+p collisions at mid-rapidity, which can further constrain light flavor separated quark and gluon fragmentation functions and serves as a baseline for the prediction of Au+Au collisions at high  $p_T$ . The preliminary results of  $R_{AA}$  in central Au+Au collisions indicated  $R_{AA}(K_S^0, K^\pm, p + \bar{p}) > R_{AA}(\pi^+ + \pi^-) \sim R_{AA}(\rho^0)$ , as shown in Fig. 2 [77–80]. This provides additional constraints on energy loss calculations. A full comparison between data and calculations requires consideration of quantitative modelling and calculations incorporating 3-D hydro in an expanding medium [81] and proper light flavor-separated quark and gluon fragmentation functions. Experimentally, high  $p_T$  strange hadron measurements in d+Au, its centrality dependence of  $R_{AA}$  in Au+Au and elliptic flow  $v_2$  measurements will shed more light on our understanding of energy loss mechanisms.



**Fig. 2** Nuclear modification factors of pion, kaon, and proton and rho in Au+Au collisions. The bars and boxes represent statistical and systematic uncertainties. The figure is taken from Refs. [77–80].

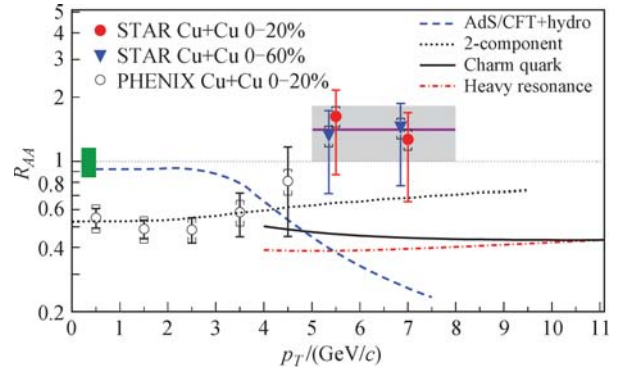
On the other hand, non-photonic electrons, which come from heavy flavor charm and bottom decay, show a similar magnitude of suppression as light hadrons [82–84]. The pQCD calculations, including collisional and radiative energy loss, show a systematically higher  $R_{AA}$  value than experimental data [85, 86]. Further calculations indicate that with the charm contribution only, non-photonic electrons are expected to reproduce the data [86]. Using the azimuthal angle correlations between non-photonic electrons and charged hadrons ( $e$ - $h$ ) and between non-photonic electrons and  $D^0$  ( $e - D^0$ ), the bottom contribution factor to non-photonic electrons were measured [87–89]. It was found that at  $p_T > 5$  GeV/ $c$ , the bottom contribution is very significant. This together with non-photonic electron  $R_{AA}$  measurements challenges the pQCD energy loss model calculations; they may indicate that collisional dissociation of heavy mesons [90], in-medium heavy resonance diffusion [91], and multi-body mechanisms [92] might play an important role for heavy quark interactions with the medium.

### 3.3 Color screening effect on high $p_T$ $J/\psi$ ?

The dissociation of quarkonia due to color screening in a QGP is a classic signature of de-confinement in relativistic heavy-ion collisions [93]. Results at RHIC show that the suppression of the  $J/\psi$  as a function of centrality (the number of participants) is similar to that observed at the SPS, even though the energy density reached in collisions at RHIC is significantly higher [94, 95]. Possible production mechanisms such as sequential suppression [96, 97], and  $c\bar{c}$  recombination [98–101] were proposed to explain this. Recent Lattice QCD calculations indicate that direct  $J/\psi$  is not dissociated in the medium created at RHIC, while the suppression observed for  $J/\psi$  comes from the dissociation of  $\chi_c$  and  $\psi'$  [102–104]. However, the direct  $J/\psi$  might be dissociated at RHIC at high  $p_T$ , which was predicted in the hot wind dissociation picture, in which the AdS/CFT approach was used, and the dissociation temperature for  $J/\psi$  was predicted to decrease as a function of  $J/\psi$   $p_T$  [105]. The AdS/CFT approach was applied to hydro framework and predicted that  $J/\psi$   $R_{AA}$  decreases versus  $p_T$  [106].

Figure 3 shows  $J/\psi$   $R_{AA}$  as a function of  $p_T$  in 0–20% and 0–60% Cu+Cu collisions from STAR [107, 108] and 0–20% Cu+Cu collisions from PHENIX [109]. The average of two STAR 0–20% data points at high  $p_T$  is  $R_{AA} = 1.4 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})$ . Compared to low  $p_T$  PHENIX measurements, the results indicate that  $R_{AA}$  of  $J/\psi$  increases from low  $p_T$  to high  $p_T$  at the 97% confidence level (C. L.). The  $R_{AA}$  of high  $p_T$   $J/\psi$  is in contrast to strong suppression for open charm [85, 90, 110, 111], indicating that  $J/\psi$  might be dominantly produced through color singlet configuration. However, even though there is significant improvement from the next-

next-to-leading order (NNLO) pQCD calculations with the color singlet model, the calculation still fails to reproduce the high  $p_T$  part [112, 113]. The  $R_{AA}$  trend of  $J/\psi$  is contradictory to AdS/CFT+hydrodynamic calculations at the 99% C. L.. This might indicate two things: 1) Cu+Cu system is not big enough so that the calculation is not applicable. The larger system produced in Au+Au collisions may be necessary to observe or exclude the effect predicted by AdS/CFT; 2) the formation time effect for high  $p_T$   $J/\psi$  is important since the AdS/CFT+hydrodynamic calculation shown in Fig. 3 requires that the  $J/\psi$  be produced as an on-shell  $J/\psi$  fermion pair, almost instantaneously, at the initial impact with no formation time. A calculation combining effects of  $J/\psi$  formation time, color screening, hadronic phase dissociation, statistical  $c\bar{c}$  coalescence and B meson feed-down contribution can describe the data [114]. The calculation suggests a slight increase in the  $R_{AA}$  at higher  $p_T$ .



**Fig. 3**  $J/\psi$   $R_{AA}$  versus  $p_T$ . The box about unity on the left shows  $R_{AA}$  normalization uncertainty, which is the sum in quadrature of p+p normalization and binary collision scaling uncertainties. The solid line and band show the average and uncertainty of the two 0–20% data points. The curves are model calculations described in the text. The uncertainty band of 10% for the dotted curve is not shown. Figure is taken from Refs. [107, 108].

In summary, the recent measurements further confirm that a partonic, hot and dense medium is created in central Au+Au collisions at RHIC. The strong suppression in  $R_{AA}$  for hadrons is due to jet quenching. However, even though the framework of jet quenching might be valid, the details of how jets interact with the medium and lose energy need more detailed theoretical assessments, and coherent modelling is required. To understand possible color screening effects of quarkonia, it is necessary to understand their production mechanisms in elementary p+p collisions. Nuclear modification factors for heavy quarkonia can help further constrain their production mechanisms as well.

## 4 Future upgrades and the related key measurements

STAR and PHENIX recently updated their data acqui-

sition and trigger systems, which will help sample RHIC II luminosity. With several detector upgrades, heavy flavor collectivity and energy loss, color screening effects, QGP thermal radiation [115–117] and jet quenching will be studied with better precision at RHIC.

#### 4.1 Heavy flavor collectivity and energy loss

The non-photonic electron analyses suffer from big systematic uncertainties, which are related to photonic background reconstruction and/or subtraction from hadronic decays. In the future, with the Heavy Flavor Tracker upgrade at STAR, the direct topological reconstruction of heavy flavor hadron decays will be feasible, and direct charmed hadron measurements will be obtained with good precision [118, 119]. With the Silicon Vertex Detector upgrades, PHENIX will be able to measure non-photonic electrons from charm and bottom decay separately [120]. These measurements are crucial to understand heavy flavor energy loss and thus further constrain the details of jet quenching. The collectivity measurements from heavy flavor will be important to understand the thermalization for light flavor.

#### 4.2 Quarkonia production mechanisms, color screening, collectivity and energy loss

To further understand the production mechanisms of quarkonia, color screening effects and medium properties, the precise measurements of the following are needed: nuclear modification factors of  $J/\psi$  from low to high  $p_T$  in Au+Au and d+Au collisions,  $J/\psi$   $v_2$ , forward and backward  $J/\psi$  production to address intrinsic charm contributions at large  $x_F$  [121],  $J/\psi$ - $h$  correlations to access the feeddown contribution, the spin alignment of  $J/\psi$  [122], higher charmonia states and different  $\Upsilon$  states [123–125]. The  $\Upsilon$  states are also ideal tools to study the effect of color screening in hot and dense QCD matter since its ground state and excited states melt at different temperatures, and all of them decay to dileptons [97, 98]. Furthermore, since the  $b\bar{b}$  cross section at RHIC energy is expected to be much smaller compared to  $c\bar{c}$  cross section from FONLL calculations [126], the recombination contribution from QGP phase might be negligible to bottomonia production. This makes the  $\Upsilon$  even a better probe for studying the color screening effect in QGP if sufficient statistics can be achieved experimentally. The Time of Flight system [127–129], fully installed in the summer of 2009, will enhance the  $J/\psi$  capability at low  $p_T$  significantly at STAR. RHIC II luminosity enables the  $\Upsilon$   $R_{AA}$  measurements with good precision. With the possible Muon Telescope Detector upgrade, STAR can cleanly separate the ground state from the excited states even with the additional material from the upgraded inner tracker since the muons

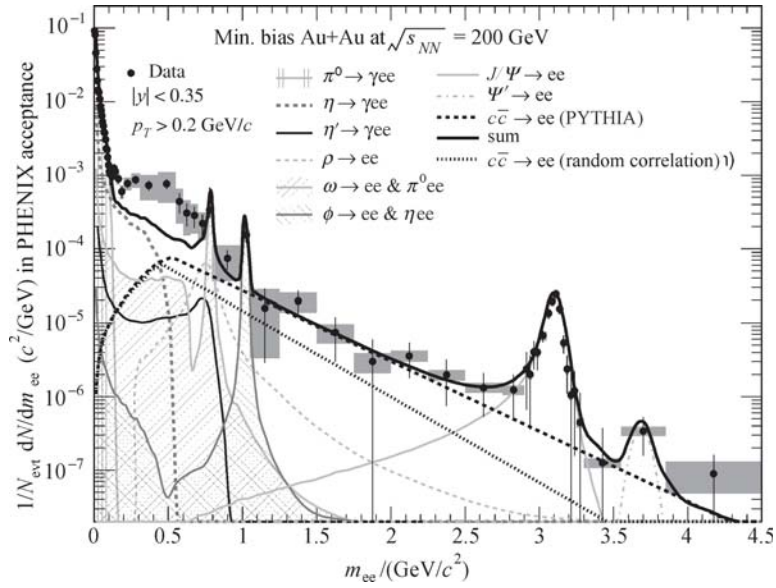
in  $\Upsilon \rightarrow \mu^+\mu^-$  do not suffer from Bremsstrahlung radiation [130–132]. With the Silicon Vertex Detector upgrade, PHENIX can measure different  $\Upsilon$  states as well through  $\Upsilon \rightarrow e^+e^-$  since the silicon vertex detector brings better mass resolution to quarkonia measurement. The different state  $\Upsilon$  measurements will shed more light on the study of the temperature of the QGP created at RHIC.

#### 4.3 Dilepton measurements in the future: vector meson properties and continuum

The dilepton spectra at intermediate mass range are directly related to thermal radiation of the QGP [115, 116]. At low mass range, we can study the vector meson in-medium properties through their dilepton decays, the observable of possible chiral symmetry restoration. For example, we can measure  $\phi \rightarrow e^+e^-$  and  $\phi \rightarrow K^+K^-$  in p+p and Au+Au collisions to see whether the yield ratios from these two decay channels are the same or not. We can measure  $\rho \rightarrow e^+e^-$  to see whether there is a mass shift or broadening and also compare the possible  $a_1 \rightarrow \gamma\pi$  measurements. These measurements will shed light on the study of chiral symmetry restoration. At the intermediate mass region, in order to get the signature of QGP thermal radiation, the  $c\bar{c}$  from heavy flavor decay must be subtracted. Figure 4 shows the dilepton invariant mass distribution after background subtraction. You can see at low mass region that there is significant enhancement [133]. Further study indicates that the enhancement is mainly at low  $p_T$ . From the low mass and higher  $p_T$  region, the direct photon measurements were obtained at  $1 < p_T < 5$  GeV/c. The average temperature of QGP at RHIC was obtained by PHENIX [134]. At the intermediate mass region, currently, there is no conclusion yet as to whether there is enhancement from thermal radiation or not. The current measurement suffered from large systematic uncertainties. In the future, the precise measurements of D mesons with the Heavy Flavor Tracker [118, 119] and non-photonic electrons from charm decay with the Silicon Vertex Detector [120] will help constrain the  $c\bar{c}$  background contribution. However, the measurement of  $c\bar{c}$  correlation is still challenging. The Muon Telescope Detector in STAR will provide  $\mu$ - $e$  correlation for the much needed independent measurements of heavy-flavor contribution to the dileptons [130–132].

#### 4.4 Direct photons and jet reconstruction

Direct photons at high  $p_T$  are believed to be a golden probe to study jet quenching since photons do not interact with the medium [135]. For example, if we trigger on a direct photon and look at away side hadrons or identified particles, the fragmentation function can be



**Fig. 4** Invariant  $e^+e^-$ -pair yield compared to the yield from simulated hadron decays. The charmed meson decay contribution based on PYTHIA is included in the sum (solid black line). The charm contribution expected if the dynamic correlation of  $c$  and  $\bar{c}$  is removed is shown separately. Statistical (bars) and systematic (boxes) uncertainties are shown separately; the mass range covered by each data point is given by horizontal bars. The systematic uncertainty on the cocktail is not shown. Figure is taken from Ref. [133].

precisely studied and compared to theoretical calculations [136]. Both STAR and PHENIX measured the fragmentation functions in p+p and Au+Au collisions with respect to a direct photon trigger, and the results are consistent with most of the theoretical calculations [137, 138]. In the future, with RHIC II luminosity, precise measurements on the away side in both p+p and Au+Au will shed light on the path length dependence of energy loss [139], color charge dependence of energy loss [38] and jet conversion, etc.. Recently, the results for full jet reconstruction at RHIC were also shown [140, 141]. The preliminary results indicate a significant broadening of energy profile in Au+Au collisions. RHIC II luminosity will make the measurements more precise; thus, how the jet energy loss disperses in the medium will be better understood.

To summarize the section, detector upgrades together with RHIC II luminosity will enable the RHIC experiments to put further constraints on the characteristics of jet quenching. The study of color screening through different quarkonia states and precise dilepton measurements will also be enabled. Possible thermal radiation signatures may be obtained allowing the temperature of the QGP created at RHIC to be inferred. While the efforts mentioned above are mainly to study the properties of QGP in detail, an effort to understand phase transition and explore the phase diagram is also on-going at RHIC.

## 5 Energy scan: looking for the critical point

The baryon chemical potential ( $\mu_B$ ) at top energy at

RHIC is very close to zero [1, 15]. At top energy, the transition from hadronic to partonic matter was thought to be a cross-over transition [142, 143]. When we go to larger  $\mu_B$ , several calculations indicate that the transition might be first order [144–148]. To know where the first order phase transition ends is of great interest. The signature of a first-order phase transition such as long-range fluctuations in event-by-event observables will be measured. Together with the identified particle ratio measurements, the  $\mu_B$  and  $T_{\text{chemical}}$  freeze out temperature can be obtained.

At RHIC, a lower energy scan has been proposed to study the phase diagram and also to see at what energy, the signatures of QGP disappear such as jet quenching, large elliptic flow and NCQ scaling, etc. [149]. In 2007, RHIC had a test run at 9.2 GeV. STAR has analyzed the data, 3000 good events, for identified particle spectra, elliptic flow and HBT radii and submitted a paper with these results for publication [150]. Compared to a previous lower energy program at the SPS, RHIC experiments have uniform acceptance for all beam energies thus systematic uncertainties can be reduced. Also there will be less ambiguity when comparing the results in different energies. The large acceptance and excellent particle identification from the detectors at RHIC will enable significant qualitative and quantitative improvements in the measurements compared to SPS.

## 6 Discovery possibilities

Beside the major discovery of QGP created at RHIC, there are many other discovery possibilities. Recently,

the anti-hypertriton was measured at the STAR experiment. This is the first observation of an antimatter hypernucleus [151–153]. This opens the window to studying hyperon-baryon interactions. Also at RHIC, STAR collaborators found that the correlation between same (different) charged sign particles is positive (negative) [154, 155]. This is qualitatively consistent with the strong parity violation picture, which induces charge separation with respect to the reaction plane. The charge separation can occur if two possible scenarios exist: chiral symmetry restoration and a strong magnetic field in QGP [156–158]. Similar measurements at lower beam energies will help the understanding of this effect and determine if strong parity violation is the only explanation for the observation. In addition, the search for the CGC [44–48] and QCD critical point [149, 159] is important and along with ongoing programs at RHIC too.

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## 7 Conclusion

In summary, I have presented measurements that identify the existence of QGP at RHIC. Several recent new measurements are presented that further our understanding of partonic flow and NCQ scaling, jet quenching and the color screening effect in QGP. The future upgrades at RHIC will significantly enhance the capability for dilepton and heavy flavor measurements, which will further our understanding of the properties of QGP.

**Acknowledgements** The author would like to thank H. Z. Huang, B. Mohanty, Z. Tang, Y. Xu and Z. Xu for many valuable discussions. The author would also like to thank G. Eppley for proof reading. This work was supported in part by the U. S. Department of Energy under Contract No. DE-AC02-98CH10886. L. J. Ruan is supported in part by the Battelle Memorial Institute and Stony Brook University in the form of the Gertrude and Maurice Goldhaber Distinguished Fellowship.

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