Formation of Dense Partonic Matter in High Energy Heavy-Ion Collisions: Highlights of RHIC Results

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Abstract. I review some important results from RHIC experiments. They were obtained in a unique environment for studying QCD bulk matter at temperatures and densities that surpass the limits where hadrons can exist as individual entities, raising the quark-gluon degrees of freedom to prominence. These findings support the major experimental observations from measuring the bulk properties of particle production, particle ratios and chemical freeze-out conditions, elliptic flow followed by hard probes measurements: di-jet fragment azimuthal correlations, high-pT-hadron suppression, and heavy-flavors probes. I present the measurements as a function of collision centrality, energy, system size and for different particle species. These results reveal that a dense strongly interacting medium was created in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV: the RHIC discovery. Further, they suggest that this medium is partonic. However, the discoveries so far observed at RHIC are far from being understood fully. Accordingly, the focus of the experiments has shifted from the discovery phase to the detailed exploration phase of the properties of this medium.

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1 Physics motivation and RHIC achievements

Quantum Chromodynamics (QCD) is considered the fundamental theory for strong interactions. According to it, hadronic matter under extreme dense and hot conditions must undergo a phase transition [1] to form a Quark Gluon Plasma (QGP) in which quarks and gluons no longer are confined to the size of a hadron. Recent results from lattice QCD at finite temperature [2,3] reveal a rapid increase in the number of degrees of freedom associated with this deconfinement of quarks and gluons from the hadronic chains. The transition point is at a temperature $T \approx 170$ MeV and energy density $\epsilon \approx 1$ GeV/fm$^3$. Under the same conditions, chiral symmetry is restored [2]. Therefore, experiments search for signatures of both QGP formation and the in-medium effects of hadron properties. It was proposed that the required high densities could be achieved via relativistic heavy ion collisions [4].

Under RHIC (Relativistic Heavy Ion Collider) project, an accelerator was constructed at Brookhaven National Laboratory (BNL) from 1991 to 1999. RHIC was designed as a heavy-ion machine, able to support the collision of a wide range of nuclei over a large range of energies. Already, gold–gold, copper–copper and deuter-on–gold collisions have been attained at energies from $\sqrt{s_{NN}} = 19.6$ to 200 GeV. Further, a polarized capability was added to RHIC allowing transverse and longitudinal polarized protons to collide at energies from $\sqrt{s_{NN}} = 200$ to 410 GeV. By now, RHIC has made a major physics discovery, namely the creation in high-energy central gold-gold collisions of a new form of matter; dense and strongly interacting, called the strongly coupled quark-gluon plasma, or sQGP. This finding was rated the top physics story of 2005 and the four experiments at RHIC, BRAHMS, PHENIX, PHOBOS, and STAR, published, in white papers, evidence of the existence of this new form of matter [6]. RHIC accelerator also met and surpassed its specifications; namely, it attained its energy goals, and exceeded the heavy-ion luminosity goals by factor of 2, and polarized proton luminosity by a factor of 5. Table 1 summarized the achievements of RHIC over the last eight years.

In this article, I highlight the recent RHIC results underlying the major experimental observations, i.e., “discoveries”. I start with discussions of bulk particle production and the initial conditions, followed by particle ratios and chemical freeze-out conditions. I then present our measurements of elliptic flow that are an indirect signature of the existence of partonic matter, followed by hard-probe measurements: di-jet fragment azimuthal correlations, high-pT-hadron suppression, and heavy-flavors probes. These measurements of hard probes afford direct
signatures of highly interacting dense matter created in central Au + Au collisions at √sNN = 200 GeV. The measurements, for different particle species, are given as a function of collision centrality, energy, and system sizes.

2 Global properties of hadron production

Measurements of charged-particle multiplicity and transverse energy distributions, and of azimuthal anisotropies in heavy-ion interactions afford information on the initial energy density and the entropy production during the system’s evolution, and are sensitive to a variety of physics processes responsible for generating multiparticle production. This knowledge is important for constraining model predictions and indispensable for understanding and estimating the accuracy of the more detailed measurements of, for example, jet or quarkonia production. Figure 1a shows the measured distribution of charged-hadrons produced in the 15% most central Au + Au collisions at √sNN = 200 GeV. The distribution illustrates a “bulk” and “tail” that are respectively related to “soft” and “hard” parton-parton scattering. We clearly observed that the “bulk” constitutes the dominant part of charged-hadron production. However, there is no clear separation between “soft” and “hard” processes. For this reason, an analysis undertaken as a function of centrality, transverse momentum, energy, and system sizes is required for better understanding particle production.

2.1 Charged-particle density distributions and initial conditions

One important observable in heavy-ion interactions is the number of charged-particles produced in a collision, called the charged-particle pseudorapidity density dNch/dη. This number (dNch/dη) is proportional to the entropy density at freeze-out and, since entropy cannot be destroyed (even in non-equilibrium systems), pseudorapidity density provides information on the initial state of parton density, and any further entropy produced during subsequent evolution [8].

Fig. 1b) shows the charged particle densities near the mid-rapidity region, dNch/dη|<1/⟨Npart⟩/2, where ⟨Npart⟩ is the average number of nucleon participant pairs, for Au + Au (RHIC: 19.6, 62.4, 130 and 200 GeV), Cu + Cu (RHIC: 22.4, 62.4 and 200 GeV), Pb + Pb (SPS: 8.83, 12.28 and 17.26 GeV) and Au + Au (AGS: 2.63, 3.28, 3.84, 4.29, 4.86 GeV): they present the 6% most central collisions as a function of center-of-mass collision energy (√sNN) [8, 9, 10, 11]. The results in this figure (see Fig. 1b) suggest that the particle density rises approximately logarithmically with energy. Comparing the finding for Cu + Cu and Au + Au indicates that, for the most central events in symmetric nucleus-nucleus collisions, the particle density per nucleon participant-pair does not depend on the size of the two colliding nuclei but only on the collision’s energy [10, 11].
Based on the data presented in the Fig. 1b, we can establish two types of fits to predict (extrapolate) the results of $dN_{ch}/d\eta$ at the mid-rapidity region in Pb + Pb collisions at the LHC energy 5.5 TeV:

1. The logarithmic quadratic fit of the RHIC data is shown as the solid curve in Fig. 1b and its fit function is:

$$f^Q_{AA} = 3.11 - 1.07 \ln(\sqrt{s_{NN}}) + 0.23(\ln(\sqrt{s_{NN}}))^2$$

2. The logarithmic linear fit of the data from the AGS, SPS and RHIC is shown by the dashed line in Fig. 1b, and has the fit function:

$$f^L_{AA} = -0.33 + 0.75 \ln(\sqrt{s_{NN}})$$

With this fit equation, we extrapolated the scaled particle density per nucleon participant pair at the mid-rapidity region to LHC energy, $\sqrt{s_{NN}} = 5.5$ TeV:

$$\frac{1}{(N_{part}/2)} \times \frac{dN_{ch}}{d\eta}(Pb + Pb at 5.5$ TeV) = 6.1$$

For $N_{part} = 365.5$ obtained via the Glauber model calculation (using $\sigma_{NN} = 64$ mb) for 6% central Pb + Pb collisions at 5.5 TeV, this yielded:

$$\frac{dN_{ch}}{d\eta}(central : 0 - 6\%, Pb + Pb at 5.5$ TeV) = 1120$$

The prediction of the Color Glass Condensate model (CGC model) [12] for $dN_{ch}/d\eta|_{|\eta|<1}/(N_{part}/2)$ in Pb + Pb collisions at LHC energy, $\sqrt{s_{NN}} = 5.5$ TeV, agrees very well with the results of extrapolation obtained with the logarithmic quadratic fit, as shown in Fig. 1b.

Fig. 2 plots the measured $dN_{ch}/d\eta$ of primary charged particles over a broad range of pseudorapidity, $|\eta| < 5.4$,..
for Au + Au [8,9] and Cu + Cu [10,11] collisions under a variety of collision centralities and RHIC energies. The 
\( d + Au \) [13,14,15] and \( p + p \) [13] data at RHIC energies also are shown. The \( Cu + Cu \), \( Au + Au \) \( d + Au \) and \( p + p \) data at all energies were obtained with the same detector setup in the PHOBOS experiment [10]. This is optimal because common systematic errors cancel each other out in the ratio. With this configuration, we were able to examine comprehensively particle production in \( Cu + Cu \) and \( Au + Au \) collisions for the same number of nucleon participant pairs, for the same fraction of total inelastic cross sections, and for the same geometry in both systems [11]. Both the height and width of the \( dN_{ch}/dy \) distributions increase as a function of energy in both systems. Comparing the results revealed an interesting feature, namely that the best agreement of \( dN_{ch}/(N_{part}/2) \) distributions over the full coverage, \( |y| < 5.4 \), for central and for peripheral \( Cu + Cu \) and \( Au + Au \) collisions is obtained for centrality bins selected to yield a similar geometry, i.e., a comparable value of \( N_{part}/2A \) (where \( A \) is the atomic number) in both systems [11].

One question to be asked is whether mechanisms in the limiting fragmentation region (i.e., high \( |y| \)) are distinct from those at mid-rapidity (\( |y| < 1 \)). From the results shown in Fig.2 for \( Au + Au \), \( Cu + Cu \), \( d + Au \), and \( p + p \) collisions, there is no obvious evidence for two separate regions at any of the RHIC energies [10]. However, to date no such anomalies have been noted, at the AGS, SPS, or RHIC. So far, all results on particle pseudorapidity densities point to a rather smooth evolution in centrality and \( \sqrt{s_{NN}} \). This of course, does not necessarily imply the absence of a phase transition, but rather, might indicate the insensitivity of these observables to the early phase of the collision and/or might suggest a second order phase transition (or a cross-over) [17]. We note that charged-particle production mechanisms for \( dN_{ch}/dy \) shown in Fig.2 are mostly obtained from the “soft” processes (see Fig.1a).

2.2 Particle ratios and chemical freeze-out conditions

The chemical freeze-out point is the stage in the evolution of the hadronic system when inelastic collisions cease and the relative particle ratios become fixed; this point, is defined by the temperature chemical freeze-out, \( T_{ch} \), and also by the baryon chemical potential, \( \mu_B \). These parameters, \( T_{ch} \), and \( \mu_B \) determine the particle composition of the hadronic final state. After chemical freeze-out, the particle composition inside the fireball is fixed, but elastic
Fig. 3a compares the RHIC's experimental particle ratios and statistical thermal model calculations for Au + Au collisions at 130 and 200 GeV [19]; note that the measurements were taken in the mid-rapidity region $|\eta| < 1$. They demonstrate quantitatively the high degree of equilibration achieved for hadron production in central Au+Au collisions at RHIC energies. Values were obtained for $(T_{ch}, \mu_B)$ of $(174 \pm 7, 46 \pm 5)$ and $(177 \pm 7, 29 \pm 6)$ at 130 and 200 GeV, respectively. The model matches well with these results, and there is no indication of a significant change in $T_{ch}$ at the two energies, 130 and 200 GeV. There is a drop in $\mu_B$ from $\sim 46$ MeV, at $\sqrt{s_{NN}} = 130$ GeV to 29 MeV at $\sqrt{s_{NN}} = 200$ GeV. We note that ratios involving multi-strange baryons are well reproduced, as is the $\phi/h^-$ ratio. Even relatively wide resonances such as the $K^*$s fit well with the picture of a chemical freeze-out.

The BRAHMS collaboration reported interesting results on particle ratios as a function of rapidity [20]. Figure 3b shows the $\pi^-/\pi^+$, $K^-/K^+$ and $\bar{p}/p$ ratios as a function of this parameter. We observe that the $\pi^-/\pi^+$ ratio is consistent with unity over the considered rapidity range, while the $K^-/K^+$ ratios drop almost by 30% at $y = 3$ from its mid-rapidity value, and the $\bar{p}/p$ ratio by almost 70%. Fig. 3c and d show thermal model fit temperature and baryon potential at chemical freeze-out as a func-
tion of collision centrality \((N_{\text{part}})\) in Au + Au, Cu + Cu and p + p collisions at \(\sqrt{S_{NN}} = 200\) GeV [21]. Temperature seems constant as a function of \((N_{\text{part}})\) and apparently independent of system size (Au + Au and Cu + Cu systems). The baryon chemical potential exhibits small variations as a function of system size (Au + Au and Cu + Cu systems). The baryon chemical potential exhibits small variations as a function of system size (Au + Au and Cu + Cu systems). The baryon chemical potential exhibits small variations as a function of system size (Au + Au and Cu + Cu systems). The baryon chemical potential exhibits small variations as a function of system size (Au + Au and Cu + Cu systems). The baryon chemical potential exhibits small variations as a function of system size (Au + Au and Cu + Cu systems).

3 Evidence of partonic matter at RHIC

3.1 Anisotropic flow of hadrons

The anisotropic flow of hadrons has been studied extensively in nucleus-nucleus collisions at the SPS and RHIC as a function of pseudorapidity, centrality, transverse momentum and energy [6,22,29]. In non-central collisions of heavy ions at high energy, the configuration space anisotropy is converted into a momentum space anisotropy. The dynamics of the collision determine the degree of this transformation. For a symmetric system, like Au + Au, the second Fourier expansion is a good parameterization of the anisotropy. At RHIC, a strong anisotropic flow \((v_2)\) was observed for all hadrons measured suggesting that a strongly interacting system was created in the collisions.

Hydrodynamic models that assume the formation of a QGP were used to model the behavior of the medium so created [23]. Comparison of the data obtained at midrapidity region presented by the STAR, PHOBOS, and PHENIX collaborations [6,29] to the hydrodynamic model [23] affords strong evidence that the originated medium behaves as a near ideal fluid.

Fig. 4 shows the anisotropic flow distributions, \(v_2\), for identified hadrons \(\pi\), \(K_0^*\), \(p\), \(\Lambda\), \(\Xi\), \(\Omega\) and \(\phi\) [24]. Calculations from a hydrodynamic model are depicted in dashed lines, while the dot-dashed lines represent the results of fit for quark number scaling \(n_q\) (for mesons, \(n_q = 2\); and, for baryons: \(n_q = 3\)). In the lower \(p_T\) region, \(p_T \leq 2\) GeV/c, the value of \(v_2\) is inversely related to the mass of the hadron, that is, characteristic of hydrodynamic collective motion in operation, see Fig. 4a and b. At the intermediate \(p_T\) region, the dependence is different. Instead of a mass dependence, there seems to be a hadron type dependence, Fig. 4b. An interesting result concerns the \(\phi\) meson, whose mass is close to that of p and \(\Lambda\). The \(v_2\) distribution illustrated as circles in Fig. 4a, is the same as the \(v_2\) for \(p\) and \(\Lambda\). It is known that the \(\phi\) meson does not participate as strongly as others do in hadronic interactions, nor can \(\phi\) mesons be formed via the coalescence-like \(K^+ + K^-\) process in high energy collisions [25]. Hence, the strong \(v_2\) we recorded must have developed before hadronization. This observation, together with the \(\Omega\) \(v_2\) results offer clear evidence for partonic collectivity [26]. To demonstrate the scaling properties of \(v_2\), the following transformation have been performed. The measured \(v_2\) was scaled by the number of valence quarks in a given hadron. For mesons and baryons, respectively, they are \(n_q = 2\) and \(3\). The \(p_T\) also was scaled with the same \(n_q\). The results are shown in Fig. 4. To include the effect of the collective motion, the \(p_T\) was transfered to the transverse kinetic energy \(K_{T} \equiv m_T - \text{mass} = \sqrt{p_T^2 - m^2} - m\) scaled by \(n_q\), where \(m\) mass of the particle. The outcome is depicted in Fig. 4b. All of the hadron \(v_2\) scaled nicely up to \((m_T - \text{mass})/n_q \sim 1.2\). Hydrodynamic calculations [27], shown as dashed-lines in the plot, also are scaled in the low \(p_T\) region. At high-\(p_T\), the values of \(v_2\) appear to fall. These observations about scaling reveal that before hadronization, quarks already have acquired the collective motion \(v_2\), and that when they coalesce, the \(v_2\) is passed...
to newly formed hadrons. Again this observation verifies
partonic collectivity.

4 Signatures of dense matter at RHIC

4.1 Di-jet fragment azimuthal correlations

The study of high transverse momentum hadron production in heavy ion collisions at RHIC provides an experimental probe of the QCD matter in the most dense stage of the collisions, wherein quark-gluon deconfinement is likely to occur [28]. In particular, two-hadron azimuthal correlations support the assessment of back-to-back, hard-scattered partons that propagate in the medium before fragmenting into jets of hadrons, thereby serving as a tomography probe of the medium.

Fig. 6 shows measurements of two-particle correlations [30] given a trigger particle $p_{T}^{(t)}$ under the condition $4 < p_{T}^{(t)} < 6$ GeV/c, along with an associated particle with $p_{T}^{(a)}$: 1) for $2 < p_{T}^{(a)} < p_{T}^{(t)}/2$ GeV/c as shown in Fig. 5a, and 2) for $0.15 < p_{T}^{(a)} < 2$ GeV/c as shown in Fig. 5b. The two-particle correlation are presented as a function of the dif-

Fig. 6. Compilation of data of nuclear modification factor $R_{AA}$ from Au + Au collisions and $R_{dA}$ of d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV using Refs. [34]. Panel a) compares $R_{AA}$ with $R_{dA}$ for charged hadrons, $(h^+ + h^-)/2$, from minimum bias Au + Au and d + Au collisions. Panel b) compares $R_{AA}$ with $R_{dA}$ for $\pi^0$ and $\eta$ from central Au + Au and d + Au collisions. Panel c) compares the $R_{AA}$ of Direct $\gamma$ with $R_{AA}$ of $\pi^0$, $\eta$ and $\pi^0$ in central Au + Au collisions. The error bars correspond to the statistical errors. For clarity, the systematic errors are shown as vertical bands.
ference between the azimuthal angles of the two particles \((\Delta \phi)\) produced in Au + Au, d + Au and p + p collisions at \(\sqrt{s_{\text{NN}}} = 200\) GeV. These measurements were made at the mid-rapidity region \(0 < |\Delta \eta| < 1.4\).

Fig. 5h demonstrates that the trigger-side correlation peak in central Au + Au collisions apparently is the same as that measured in p + p and d + Au collisions but the away-side jet correlation in Au + Au has vanished. This observation is consistent with a large energy loss in the medium causing it to be opaque to the propagation of high momentum partons. However, it is noticeable in Fig. 5b, which has a wide \(p_{T}^{(a)}\), 0.15 < \(p_{T}^{(a)}\) < 2 GeV/c, that the away side jets have not really disappear, but simply lost energy so that the away-side correlation peak has become much wider than that of the p + p and d + Au collisions. These collective measurements, from p + p, d + Au and Au + Au of two-particle correlations, point to the creation of a dense medium in central Au + Au collisions at \(\sqrt{s_{\text{NN}}} = 200\) GeV.

4.2 High-\(p_{T}\), hadron suppression: jet-suppression

In heavy ion collisions (from AGS to RHIC energies) hadron production at the mid-rapidity region \((|\eta| < 1.5)\) rises with increasing collision energy. At RHIC, the central zone is almost baryon free \([31]\). Particle production is large and dominated by pair production, and the energy density seems to exceed significantly that required for QGP formation \([6]\).

Recently, RHIC experiments revealed suppression of the high transverse momentum component, \(p_{T}\), of hadron spectra at the mid-rapidity region in central Au + Au collisions compared to scaled momentum spectra from p + p collisions at the same energy, \(\sqrt{s_{\text{NN}}} = 200\) GeV \([6]\). This effect, originally proposed by Bjorken, Gyulassy and others \([32]\) rests on the expectation of a large energy loss of high momentum partons scattered in the initial stages of collisions in a medium with a high density of free color charges. According to QCD theory, colored objects may lose energy by the bremsstrahlung radiation of gluons \([33]\). Such a mechanism would strongly degrade the energy of leading partons, reflected in the reduced transverse momentum of leading particles in the jets emerging after fragmentation into hadrons. The STAR experiment established that the topology of high-\(p_{T}\), hadron emission is consistent with jet emission, so that jet-suppression is a valid concept.

Fig. 6 shows compilation of data using Refs. 24 for the nuclear modification factors measured for different collisions systems at RHIC energies. The nuclear modification factor is defined as:

\[
R_{\text{AA}}(p_{T}) = \frac{\text{yield per } A + A \text{ collisions}}{N_{\text{bin}} \times (\text{yield per } p + p \text{ collisions})}
\]

\[
= \frac{d^{2}N_{A+A}^{p_{T}}}{N_{\text{bin}} \frac{d^{2}N_{pp}^{p_{T}}}{d^{2}p_{T}d\eta}}
\]

It involves scaling measured distributions of nucleon-nucleon transverse momentum by the number of expected incoherent binary collisions, \(N_{\text{bin}}\). In the absence of any modifications due to the ‘embedding’ of elementary collisions in a nuclear collision, we expect \(R_{\text{AA}} = 1\) at high-\(p_{T}\). At low \(p_{T}\), where particle production follows a scaling with the number of participants, the above definition of \(R_{\text{AA}}\) leads to \(R_{\text{AA}} < 1\) for \(p_{T} < 2\) GeV/c.

In d + Au collisions at RHIC energy (\(\sqrt{s_{\text{NN}}} = 200\) GeV) as shown in Fig. 6a, the \(R_{\text{dA}}\) for charged hadrons \((h^{+} + h^{-})/2\) is enhanced. This enhancement was expected as a consequence of Cronin enhancements, now understood as an initial state effect \([36]\) which also is seen in pA collisions. The Cronin effect is associated with the initial multiple scattering of high momentum partons. In contrast, RHIC experiments discovered a factor of 4–5 suppression, in central Au + Au (at \(\sqrt{s_{\text{NN}} = 200}\) GeV). In the same context, the \(R_{\text{dAu}}\) of \(\pi^{0}\) and \(\eta\) in central d + Au collisions exhibits no suppression of high-\(p_{T}\), in contrast with the \(R_{\text{AA}}\) of \(\pi^{0}\) and \(\eta\) in central Au + Au collisions that is suppressed, as shown in Fig. 6b. At \(p_{T} \sim 4\) GeV/c, we find a ratio \(R_{\text{dAu}}/R_{\text{AA}} \approx 5\). Indeed, the \(R_{\text{dA}}\) distribution shows the Cronin type enhancement observed at lower energies as in Pb + Pb collisions at 17.3 GeV/c \([37]\).

Fig. 6c summarizes the present status of \(R_{\text{AA}}\) for direct photons, \(\pi^{0}\) and \(\eta\) in central Au + Au collisions at \(\sqrt{s_{\text{NN}}} = 200\) GeV. The \(R_{\text{AA}}\) for direct photons are not suppressed because they do not interact strongly with the medium. The \(R_{\text{AA}}\) for both \(\pi^{0}\) and \(\eta\)’s mesons exhibit the same suppression relative to the point-like scaled p + p data by a factor of \(\sim 5\) which appears to be constant for \(p_{T} > 4\) GeV/c while the \(\eta\) mass is much larger than that of \(\pi^{0}\). This observation combined with Fig. 4 is clearly an indication of partonic nature of suppression.

This data of \(R_{\text{AA}}\) were described by theoretical calculations of parton energy loss in the matter created in Au + Au collisions \([35]\). From these theoretical frameworks, we have learned that the gluon density d\(N_{g}/dy\) must be approximately 1000 \([39]\), and the energy density of the matter created in the most central collisions must be approximately 15 GeV/fm\(^{3}\) to account for the large suppression observed in the data \([40]\).

5 Heavy-flavors as probes for dense medium

As discussed above, RHIC has produced in high-energy central Au + Au collisions at \(\sqrt{s_{\text{NN}}} = 200\) GeV a new form of matter that is dense, strongly interacting and can be partonic, called sQGP. This new state of strongly interacting matter can closely resemble a “perfect” fluid, with very low viscosity and high opacity explained by the equations of hydrodynamics \([23]\). The research focus now has shifted from this initial discovery to a detailed exploration of partonic matter. Particles carrying a heavy flavor, i.e., charm or beauty quarks, are powerful tools for studying the properties of the hot, dense medium created in high-energy nuclear collisions: they are generated early in the reaction, and subsequently diffuse in the putative sQGP.

The study of heavy flavor in relativistic nuclear collisions follows two different approaches: 1) The direct reconstruction of the heavy flavor meson, and 2) the identification of electrons and muons from semi-leptonic de-
At RHIC, two methods are utilized to measure heavy flavor production via semi-leptonic decays: 1) Identification of electrons from the decays of D and B—mesons, and 2) identification of muons from D—meson decays. The PHENIX and STAR experiments pursue the analysis of non-photonic electrons (from heavy flavor). Electron identification in PHENIX largely is based on using the Ring Imaging Chernkov detector (RICH) in conjunction with a highly granular EMC (electromagnetic calorimeter). Their momentum is derived from the curvature of the track (due to a magnetic field up to 1.15 Tesla) reconstructed from drift and pad chambers. STAR identifies of electrons is done using information on dE/dx and momentum gleaned from the Time Projection Chamber (TPC) and the Time of Flight (ToF) data for the low to moderate pT (pT < 4-5 GeV/c) electrons. The barrel electromagnetic calorimeter’s (EMCAL’s) data is used for moderate to high-pT (pT > 1.5 GeV/c) electrons. A major difficulty in both collaborations’ electron analyzes is the fact that there are many sources of electrons other than the semi-leptonic decays of heavy flavor mesons. The main sources of background are photon conversion in the detector material (less significant in PHENIX that has a lesser amount of material than STAR), and π0 and η Dalitz decays. Other sources of background such as ω, φ and ρ decays also must be taken into account. The background sources usually are called photonic electrons.

Fig. 7a shows compilation of data using Refs. [34,41,42] of the nuclear modification factors and elliptic flow measured for Au + Au collisions systems at √sNN = 200 GeV. Fig. 7b compares the nuclear modification factor RAA of heavy flavor electrons to π0 data, and to π± data obtained from central Au + Au collisions at √sNN = 200 GeV. We
observe clear suppression of heavy flavor electrons in central events in high-\(p_t\). For \(p_t > 4\) GeV/c, the \(R_{AA}\) of heavy flavors is surprisingly similar to that for \(\pi^0\) and \(\pi^\pm\). Fig. 7b illustrates the distribution of the anisotropy of heavy flavors electrons (\(v_2^{HF}\)) as a function the particles’ transverse momentum, \(p_T\), in minimum bias Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV. Collective behavior is apparent in heavy-flavor electrons (\(v_2^{HF} > 0\)); however, it is lower than \(v_2\) of \(\pi^0\) for \(p_T > 2\) GeV/c.

This data presented in Fig 7 indicates that heavy flavors strongly coupled with the medium. The observed suppression at high-\(p_T\), > 4 GeV/c can be explained in terms energy loss from the heavy-flavors into the medium. Ref. [11] offers different theoretical predictions for heavy-flavor electrons in central Au + Au collisions, considering different energy loss mechanisms. However, I note that in Fig. 7b, the data extend only to around \(p_T \approx 4\) GeV/c, and there are large statistical errors in the \(v_2^{HF}\). This implies that we can reach a comprehensive conclusion about \(R_{AA}^{HF}\) and \(v_2^{HF}\) only when we have more data on Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV is needed and an upgrade of PHENIX and STAR detectors is required. Furthermore, we need measurements of the particles identified as decay products from charm or beauty flavors using the displacement of their trajectories from the collision vertex (measuring the distance of closest approach, DCA). Fortunately, both detectors PHENIX and STAR already were upgrade by building silicon vertex trackers for heavy flavors [42,43].

6 Conclusions

I discussed measurements from RHIC collisions on bulk particle production, the initial conditions of the collisions, particle ratios and chemical freeze-out conditions, flow anisotropy of particles, di-jet fragment azimuthal correlations, high-\(p_T\) hadron suppression and heavy-flavors probes as a function of collision centrality, energy, system sizes and for different particle species. The measurements suggest that RHIC discovered a new state of matter in central Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV. This new form of matter is a hot, dense, strongly interacting and is called “sQGP”. Whilst this material, and its discovery, is far beyond our current understanding, the focus of the RHIC experiments has shifted from the discovery phase to a detailed exploration phase of the properties of the medium. The hope is that Pb + Pb collisions at LHC energies (LHC energy is approximately 30 times higher than RHIC’s maximum energy: LHC–energy/RHIC–energy = 5500/200 = 27.5) will create a medium with an initial temperature high enough so that the interaction weakens sufficiently to generate a gaseous QGP.

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Table 1. RHIC operating modes and total integrated luminosity delivered to all experiments for each run [5].

| Run  | Species       | Total particle energy: $\sqrt{s_{NN}}$ [GeV/nucleon] | Total delivered luminosity | Average Store polarization |
|------|---------------|-------------------------------------------------------|---------------------------|---------------------------|
| Run 1 | Au+Au         | 55.8                                                  | < 0.001 $\mu$b$^{-1}$    | -                         |
|      | Au+Au         | 130.4                                                 | < 20 $\mu$b$^{-1}$       | -                         |
| Run 2 | Au+Au         | 200.0                                                 | < 258 $\mu$b$^{-1}$      | -                         |
|      | Au+Au         | 19.6                                                  | < 0.4 $\mu$b$^{-1}$      | -                         |
|      | pol. p+p      | 200.0                                                 | < 1.4 $\mu$b$^{-1}$      | 15%                       |
| Run 3 | d+Au          | 200.0                                                 | 73 nb$^{-1}$              | 34%                       |
|      | pol. p+p      | 200.0                                                 | < 5.5 pb$^{-1}$           | -                         |
| Run 4 | Au+Au         | 200.0                                                 | 3530 pb$^{-1}$            | -                         |
|      | Au+Au         | 62.4                                                  | 67 $\mu$b$^{-1}$          | -                         |
|      | pol. p+p      | 200.0                                                 | 7.1 $\mu$b$^{-1}$         | 46%                       |
| Run 5 | Cu+Cu         | 200.0                                                 | 42.1 $\mu$b$^{-1}$       | -                         |
|      | Cu+Cu         | 62.4                                                  | 1.5 $\mu$b$^{-1}$        | -                         |
|      | Cu+Cu         | 22.4                                                  | 0.02 $\mu$b$^{-1}$       | -                         |
|      | pol. p+p      | 200.0                                                 | 29.5 pb$^{-1}$            | 46%                       |
|      | pol. p+p      | 409.8                                                 | 0.1 pb$^{-1}$             | 30%                       |
| Run 6 | pol. p+p      | 200.0                                                 | 88.6 pb$^{-1}$            | 58%                       |
|      | pol. p+p      | 62.4                                                  | < 1.05 pb$^{-1}$          | 50%                       |
| Run 7 | Au+Au         | 200.0                                                 | 7250 pb$^{-1}$            | -                         |
|      | Au+Au         | 9.2                                                   | test only                 | -                         |
| Run 8 | d+Au          | 200.0                                                 | 437 nb$^{-1}$             | -                         |
|      | pol. p+p      | 200.0                                                 | 38.4 pb$^{-1}$            | 45%                       |

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