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Recent Heavy Ion Results from STAR

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Over the past decade the STAR experiment at Relativistic Heavy Ion Collider had successfully collected data at a number of center-of-mass energies with a variety of beam species. This allowed our diverse scientific program to flourish. In this work a review of selected recent results in three major areas of STAR's experimental studies is presented: new developments in the studies of medium properties with hard penetrating probes; current status and future plans for the STAR heavy flavor program; and the progress of the ongoing search for the QCD critical point.

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1. Introduction

The beginning of experimental operations at the Relativistic Heavy Ion Collider (RHIC) has opened a new era for studies of nuclear matter. The unprecedented energy densities first achieved at RHIC in heavy ion collisions provided the environment to study QCD medium under extremes of high temperature and energy density. Multiple signatures, attributed to the strongly interacting Quark-Gluon Plasma (sQGP), have been seen across all accessible kinematic regions [1, 2, 3, 4]. The matter formed in nuclear collisions at RHIC's top energy of 200 GeV per nucleon pair (for heavy ion beams) is found to exhibit strong collective behavior. The collective features are apparent across many observables in the bulk sector (at low momenta). The relative hadron production rates are well described by statistical models based on thermalization assumption. The strength of azimuthal correlations with respect to reaction plane (commonly referred to as *elliptic flow*), particularly for strange and multi-strange hadrons, are also found consistent with thermalization across the u, d, and s quark families. Another novel phenomenon discovered at RHIC and redefined completely the original notion of weakly interacting plasma is the jet quenching. It was first observed via the suppression of the high transverse momenta hadrons with respect to a binary-scaled reference measurement form pp collisions at the same energy. The suppression level of about factor of 5 for most central Au+Au collisions at 200 GeV signaled the strength of the jet-quenching effects and lead to the emergence of the concept of the strongly-coupled medium instead. It has been also found that in the hard sector the jet remnants appeared to be unmodified with respect to the vacuum-like pp reference [5]. It required the development of multi-dimensional analyses to understand the details of jet-medium interaction mechanisms and to quantify the energy loss effects. Unexpected discoveries have also been made in the kinematic regime between the soft and the hard domains, e.g. the intermediate transverse momenta $\sim 2-6$ GeV/c. These include the constituent quarks scaling in the measurements of relative baryon to meson production rates and, particularly, in the strength of elliptic flow for various flavors of baryons and mesons. The first observation of the long-range pseudo-rapidity correlations (the *ridge*), and pronounced shape modification of the associated hadron distributions for high-p_T trigger hadrons [6, 7] also came from this sector.

STAR experimental contributions to these discoveries were made possible by the two major advantages of the detector - uniform azimuthal acceptance over sufficiently extended pseudo-rapidity range, and advanced particle identification capabilities afforded by the set of complimentary detectors. Combining the information from the Time-projection Chamber (TPC) and the Time-of-Flight (TOF) detectors allows identification of common particle species ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, $e^{\pm}$) from the lowest recorded momenta of about 200 MeV/c to 10 GeV/c and above at mid-rapidity. At forward rapidities, Photon Multiplicity Detector (PMD) allowed photon identification, and Forward Meson Spectrometer (FMS) mea-

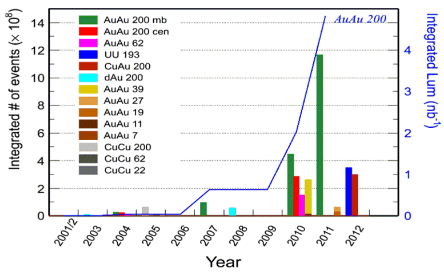


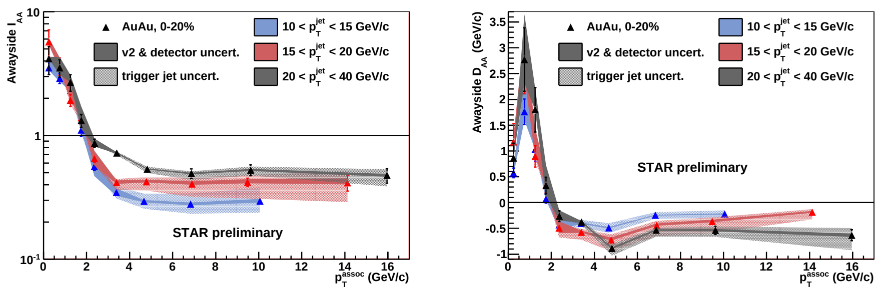
Figure 1: (Color online) Integrated luminosity recorded by STAR detector since the beginning of RHIC operations. Histogram bars represent various data sets. Integrated luminosity is shown as a line.

sures the mesons. New STAR upgrade - Muon Telescope Detector (MTD) - adds muon identification at mid-rapidity to these capabilities. Well-equipped for a wide variety of physics measurements, STAR experiment is taking full advantage of the versatility of RHIC machine to study systematically the properties of the strongly-coupled plasma. Over the years RHIC machine increased dramatically the beam luminosity and delivered collisions of many different types. Figure 1 presents all the beam energies and species collided by RHIC together with the integrated luminosity recorded by STAR. The high integrated luminosity recorded for the top energy Au+Au collisions in recent years has enabled advances in the hard sector and rare probe studies. The delivered data from collisions of various ion species (p, d, Cu, Au, and last year U) allowed detailed studies of the system size effects on medium properties. New data samples at lower beam energies have also allowed systematic studies of sQCP as function of energy and further exploration of the phase structure of nuclear matter. In the following, selected results for STAR experiment are presented to discuss recent advances in the quantitative assessment of in-medium energy loss via full-jet reconstruction and multi-particle correlation techniques. Tests of heavy quark collectivity and medium response to heavy penetrating probes are also presented. Finally, first results from the the ongoing search for the QCD critical point are discussed.

2. Jet-medium interactions studies

Di-hadron correlation measurements with high-p_T hadrons provide access to jets and are recognized as a valuable tool for jet-medium interaction studies. Identification of the observed correlation structures with the specific pQCD processes is not trivial in the relativistic heavy ion environment, where collective effects produce variety of complex correlation structures as well. Deployment of the hardware-based high-tower trigger, that preselects events with neutral energy above some specific threshold in the Barrel Electromagnetic Calorimeter (BEMC), significantly extended the kinematic reach of the data available for hard sector studies. These data-sets allowed the development of more differential jet-quenching probes for additional constraints on models describing the medium effects and their interplay with jets. Most of the new jet-related analyses developed in STAR in recent years involve some form of multi-particle correlations.

Full jet reconstruction was used as a tool for parton studies in high energy physics for many years, but was not envisioned as a tool for nuclear physics. STAR experiment has implemented successfully the full jet reconstruction, achieving a closer access to the initial parton energy. Jets are reconstructed statistically from combination of neutral towers in the BEMC and the charged tracks recorded by TPC using anti-k_T algorithm from the FastJet package [8, 9]. The reconstructed jet axis is then used to construct the correlation with all the tracks in the event in order study jet shapes and the fate of the recoil jet partner. It is expected in theory [10] and confirmed by the experimental measurements [5, 11] that the jet triggered by high-p_T track or high-energy tower is surface-biased, and the most of the medium is traversed by a recoil parton on the away-side. Medium effects in this study are thus quantified by comparing with matching measurements from pp collisions via the binary-scaled ratio of associated hadron yields on the away-side of the trigger jet, I_{AA}, quantifying the jet suppression; and the p_T-weighted ratio, D_{AA}, that measures the difference in the energy distribution between Au+Au and pp data.



(a) (b)

Figure 2: (Color online) a) The transverse momentum dependence of the away-side $I_{\rm AA}$ from jet-hadron correlations. b) The away-side $D_{\rm AA}$ illustrates the extent of the energy balance between the suppressed high-p_T associated hadrons and excess of such particles at low momenta.

Preliminary results of this study are shown in Fig. 2. The p_T-dependence of $I_{\rm AA}$ and $D_{\rm AA}$ from the jet-hadron correlations indicate significant quenching of the away-side jet evident in associated yield suppression and energy depletion at high-p_T. These losses in the hard sector are compensated by the excess of yield and energy in soft associated hadrons. Such trends are consistent with the expectation from in-medium energy loss resulting in additional soft hadrons that are not fully thermalized with the medium. Jet shape studies also indicate significant broadening of the jet peak in Au+Au collisions compared to *pp* reference [8], indicating that the angular correlation of soft hadrons with the original parton direction is weakened by the medium presence.

To gain additional insight into the path-length dependence of jet-quenching, another multi-particle correlation technique has been deployed [11, 12]. To gain control over the surface-bias effects and vary the path-lengths traversed in the medium, we investigates associated hadron distributions with respect to a di-jet axis approximated by pair of back-to-back high-p_T hadrons ("2+1" correlations). Correlation functions, spectra, and energy difference between two sides of such di-jet from central Au+Au collisions are compared to the d+Au data at the same energy. We observed that the correlation functions from central Au+Au events are dominated by jet-like structures on both near- and away-sides, with similar shape/magnitude to those of d+Au collisions. This observation, contrasting the strongly modified shapes seen in di-hadron correlation, stresses the strength of the jet-medium interaction, as the away-side jet rarely emerges from deep in the medium led by a hard hadron. Rather, the back-to-back hard hadrons trigger predominantly on

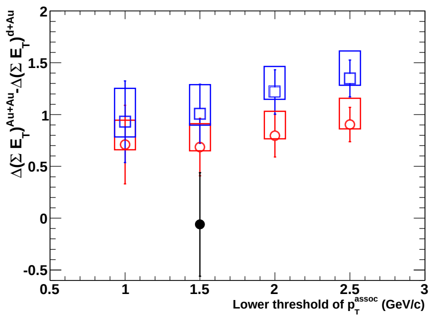


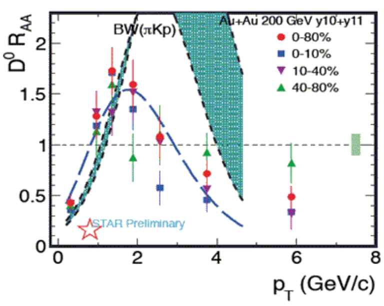
Figure 3: (Color online) The relative di-jet energy imbalance for primary triggers of 8 to 10 GeV (open circles), 10 to 15 GeV (squares), and 5 to 10 GeV (solid point). The back-to-back trigger partner is required to be above 4 GeV/c in all cases. The x-axis shows lower threshold of the transverse momentum selection for associated hadrons.

tangentially scattered partons. Kinematic reach afforded by the collected data allows to vary the asymmetry in transverse momentum between the two back-to-back trigger hadrons, and thus the degree of the surface bias. The resulting variations in the in-medium path-lengths are studied through the imbalance of the final energies of each side of a di-jet.

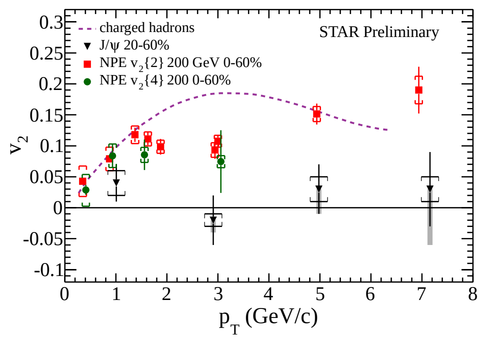
The jet energy is estimated by a sum of trigger and all associated hadrons p_T within the jet peak; and the side-to-side difference is taken by direct subtraction of the correlations. To remove the contributions due to known k_T effects, the base-line obtained from d+Au collisions is also subtracted. The observed energy imbalance for different trigger selections from [12] is shown in Fig. 3. Larger imbalance is found for larger trigger asymmetry, as expected by the models, however the measured values of the relative energy imbalance are found smaller than the theoretical prediction of in-medium energy deposition [13]. The results seem to favor a stronger surface bias than expected in theory, which in turn indicate a stronger path-length dependence of energy loss. It has been also observed that the relative imbalance is decreasing for correlations constructed with softer associated hadrons. We find this trend consistent with the observations from jet-hadron correlations of jet fragmentation softening and/or displacement of soft fragmentation products to larger angles with respect to jet axis (e.g. broadening).

3. Heavy Flavor measurements

Studies of heavy flavor quarks are actively pursued in the field as ideal probes for sQGP medium. Due to their large masses, the charm and bottom are expected to be primarily produced in the initial hard parton interactions, and thus could be sensitive to the entire evolution of the system. Large masses also allow for their production cross-sections to be well determined in pQCD, and thus modification of the differential production cross sections of heavy flavor quarks in heavy ion collisions is attributed to the sQGP effects. Studies on heavy flavor production and collectivity have been carried by the STAR collaboration via direct and indirect measurements, such as non-



(a)



(b)

Figure 4: (Color online) a) Transverse momentum dependence of D^0 nuclear modification factor for different centrality bins of 200 GeV Au+Au data compared with Blast-wave model. b) Elliptic flow results from two different methods as function of p_T for non-photonic electrons from 200 GeV Au+Au collisions ($v_2\{2\}$ in closed squares, $v_2\{4\}$ is closed circles). J/ψ v_2 as function of p_T is also shown (triangles). Dashed line shows inclusive charged hadron measurement for the reference.

photonic electrons from heavy flavor semi-leptonic decays and hadronic decay channels of open charm mesons ($D^0 \longrightarrow K\pi$, $D^* \longrightarrow K\pi\pi$, etc.).

Recent STAR measurements confirm the two unexpected early observations: heavy mesons show similar suppression patters at high p_T to that of the light hadrons, and they exhibit a non-zero elliptic flow. These findings are crucial for establishing of collectivity for charm and, possibly, bottom. Figure 4 *a* shows nuclear modification factor measurements for D^0-mesons from four centrality bins of Au+Au collisions at 200 GeV [14]. With the increasing collision centrality the high-p_T yields of D^0-mesons become more and more suppressed, approaching the $R_{AA} \approx 0.3$ for 0-10% most central collisions at $p_T \sim 6$ GeV/c. In addition, an enhancement is observed at the intermediate transverse momentum range. The shape of the intermediate-p_T enhancement is captured well by the models incorporating radial flow picked up by D^0 from the expanding medium [15]. Blast-wave fits to the D^0 spectra (shown as a dashed line in Fig. 4 *a*) lead to a sizable radial flow velocity parameter, though not as high as given by the Blast-wave fits to the light hadron (π, K, p) spectra (filled band). This smaller radial flow may not necessarily reflect the lesser degree of charm thermalzation, but result form the fact that charm is unaffected by the hadronic phase. Collective behavior of the heavy flavor is evident in another flow, elliptic. Non-photonic electrons v_2 measured via two different methods is presented in Fig. 4 *b* as a function of transverse momenta for 200 GeV Au+Au collisions. Charged hadron v_2 from the same data-set is also shown for comparison. We observe significant non-photonic electron v_2 in 200 GeV Au+Au data for all accessible momenta. Below 2 GeV/c the magnitude of non-photonic electron elliptic flow is comparable with that of charged hadrons, indicating that charm quarks (a dominant source of non-photonic electrons in this kinematic range) are thermalized with the partonic medium created.

STAR heavy flavor program includes measurements of heavy quarkonia [16]. Quarkonia suppression is one of the earliest proposed signatures of quark-gluon plasma, and has been studied extensively at RHIC and SPS. Open questions remain regarding quarkonia production mechanisms, particularly for J/ψ, due to observed similarity in the charmonium suppression levels at RHIC and SPS despite appreciable differences in the initial energy density. The models describing J/ψ nuclear modification factor at high p_T from RHIC data require sizable contributions from coalescence production [17]. To check if coalescence is indeed plays important role in J/ψ production we measure the magnitude of elliptic flow. It is expected that J/ψ formed through coalescence would pick up charm quark flow. Figure 4 *b* shows J/ψ elliptic flow as function of transverse momenta. We find that J/ψ v_2 is consistent with zero at high p_T, disfavoring large coalescence contributions in that kinematic region, however, statistical uncertainties do not allow to make a conclusive statement regarding the magnitude of v_2 below 2 GeV/c.

Going heavier, recent STAR results include a new, higher precision, measurement of Υ nuclear modification factors using 200 GeV Run-10 Au+Au and Run-9 *pp* data [18]. Successive melting of Υ states at different medium temperatures, expected in theory, makes it an important experimental probe for the source temperature. Additionally, production of Υ is expected to have smaller contributions from coalescence, compared to J/ψ, making it a cleaner probe of the medium properties. Figure 5 shows integrated Υ R_{AA} as function of centrality (expressed via N_{part}). Model calculations [19] describing best the centrality trend predict full melting of 3S-state and strong suppression of 2S yields.

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The open heavy quarks measurements suffer from large combinatorial background contribution because of the limited track pointing resolution of the TPC. In the near future Heavy Flavor Tracker (HFT) upgrade will address this issue, enhancing dramatically the heavy flavor capabilities of the STAR detector. The HFT is designed to provide excellent track impact parameter resolution for a wide range of track transverse momenta, essential for the direct reconstruction of the secondary vertices, and allowing statistical separation between charged leptons from charm quark decays and those from bottom. Completion of the MTD detector upgrade will also allow STAR to measure Υ $1S$, $2S$ and $3S$ states separately.

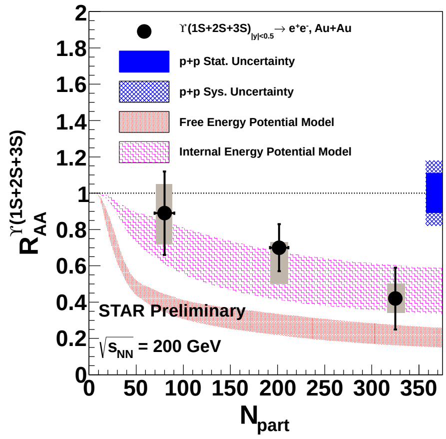
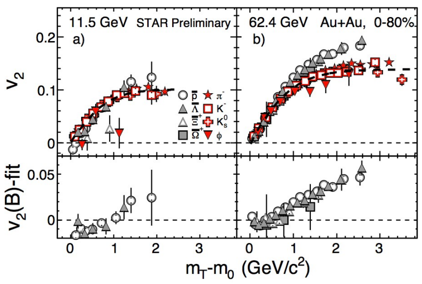


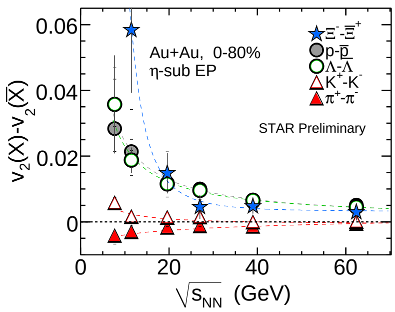
Figure 5: (Color online) Centrality dependence of Υ nuclear modification factor as function of centrality (N_{part}) compared with theoretical predictions.

4. Early finds of the Beam Energy Scan program

In the last three years a new physics program - the exploration of the QCD phase diagram via the Beam Energy Scan - has become one of the major focuses of experimental studies at RHIC. The phase diagram, defined in terms of temperature (T) and baryon chemical potential (μ_B), maps the location of different phases of nuclear matter and contains transition boundaries between them. In the lattice QCD calculations the order of the phase transition between the sQGP and hadronic matter is expected to change from a smooth cross-over to a first order phase transition with increasing μ_B (at sufficiently high temperatures). The location of this transition order change-over, the tri-critical point is not well-defined in theory due to luck of analytical solutions [20]. The BES program allows



(a)



(b)

Figure 6: (Color online) a) Elliptic flow results for identified (anti)particles from Au+Au collisions at 11.5 (left) and 62.4 GeV (right). The error bars are statistical only. b) The difference in v_2 between identified particles and anti-particles from Au+Au collisions as a function of beam energy.

experimental tests of theoretical predictions, essential for further advancement of our understanding of QCD. To move across the phase map in search of the critical point location a gradual decrease of the center-of-mass energies is explored to create a colder matter with higher baryon potential. The data taking for the Phase-I of the BES program has been completed earlier this year, providing Au+Au events at 39, 27, 19.6, 11.5, and 7.7 GeV [21]. This range of energies to a large extent covers a suggested region of (T, μ_B) for critical point location from most models. With these data STAR is investigating the evolution of the properties of created medium, looking for a turn-off of the partonic signatures on one side, and testing the theoretical predictions for the first-order phase transition on the other.

In the former category, the energy dependence of such novel phenomena as constituent quark scaling of the elliptic flow and hadron suppression at high-p_T is considered as potential sQGP turn-off signatures, as they believed to be related to partonic collectivity and partonic energy loss. Fourier decomposition of the identified particle distributions with respect to reaction plane has been performed for the BES data in order to test the scaling features of elliptic flow. Figure 6 shows preliminary results of these systematic studies. At higher energies (for example, in the 62.4 GeV data shown) the identified particle v_2 measurements as function of p_T form two distinct trends at the intermediate momenta, with baryons and mesons grouping together regardless of their masses. The relevance of the number of constituent quarks for the elliptic flow scaling behavior, is considered one of the important evidences of partonic collectivity. We observed that at lower energy, the distinct baryon-meson trends disappear, as illustrated by the anti-particle v_2 distributions from 11.5 GeV in Fig.6 *a*. Additionally, the differences between collective flow of particles and antiparticles, negligible at the top RHIC energy, become more pronounced with decreasing center-of-mass energy (see Fig.6 *b*), indicating a significant change in the contributions from the hadronic interactions. Other well-established sQGP signature, hard-sector hadron suppression, is found disappearing in the low end of the beam energies explored.

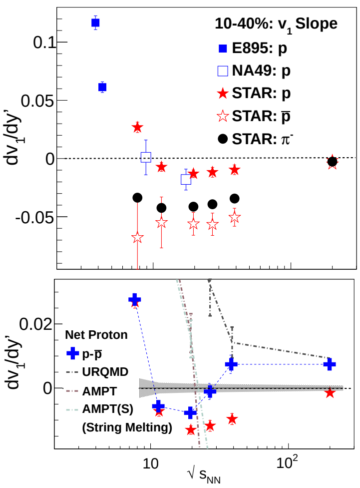


Figure 7: (Color online) Upper panel: midrapidity directed flow slope for various particles as function of $\sqrt{s_{\rm NN}}$ for Au+Au collisions at RHIC. Lower panel: Net-proton v_1 slope as function of the beam energy. The filled band shows the size of the systematic uncertainties. Corresponding proton v_1 slope is also shown for comparison. Expectations from AMPT and URQMD models shown do not reproduce the trend seen in the data.

Multiple observable have been suggested as promising signatures for the critical point. Divergences in specific heat, baryon number and net-charge susceptibilities, predicted by theory near critical points, are expected to lead to large fluctuations in mean-p_T, net-baryons, and /or particle ratios. Preliminary results from the BES program have not so far indicated presence of unusually large fluctuations in one of those physical quantities. Another promising theoretical prediction is related to the proton directed flow (v_1) excitation function. It has been proposed that the rapidity dependence of the proton v_1 may have sensitivity to the softening of the equation of state, with location of the softest point associated with the order change of the phase transition. To look for such softest point of equation of state, STAR has measured rapidity dependence of v_1 for the variety of identified particle species for each BES energy [23]. Preliminary results of these studies are presented in Fig. 7, where rapidity dependence of v_1 is expressed as a slope dv_1/dy', with scaled rapidity $y' = y/y_{\mathrm{beam}}$. It has been found that sign of the proton v_1 slope changes to negative above 7.7 GeV and remains negative up to RHIC's top energy. The rest of the identified species measured so far (charged pions and antiprotons) show no sign change and exhibit negative slope for the full range of measured energies. The slope for the net-proton v_1, calculated as a difference between the proton and antiproton slope parameters weighted by their corresponding yields, is also presented in Fig. 7 as a function of the center-of-mass energy. The sign of the net-proton v_1 changes twice in the energy range covered, forming distinct minimum between 11.5 and 19.6 GeV. This unexpected trend is not captured by any of the model calculations available as illustrated in the figure.

As mentioned, these early findings are the beginning of the detailed systematic studies for excitation functions of medium properties. Further investigation is necessary for conclusive statements about existence and location of the critical point, with the region of interest for this search constrained to below 19.6 GeV.

5. Summary

STAR experiment is carrying out a multi-faceted research program, taking advantage of the wide variety of colliding energies and beam species delivered by the RHIC machine. In recent years the focus of experimental program has naturally shifted from the sQGP discovery phase into detailed systematic studies of the matter created. We have discussed selected recent results from STAR experiment, focusing on penetrating probes, heavy flavor studies, and the experimental scan of QCD phase diagram.

At the top RHIC energy, integrated luminosity delivered provided ample grounds for advancing the hard sector studies and the measurements related to the heavy quark flavors. Results from systematic studies of jet-hadron and 2+1 correlations in central Au+Au collisions at 200 GeV indicate the softening of jet fragmentation through interactions with the medium. At lower momenta this softening is accompanied by broadening of away-side peaks seen in jet-hadron correlations. Both studies suggest that the suppression of away-side associated yields (or production rates for di-jets) is compensated to some degree by excess of yield/energy in soft hadrons.

Recent measurements in the heavy flavor sector give more quantitative information about c and b interactions with sQGP medium. Heavy quark energy loss comparable to that for light flavors is observed through a large suppression of heavy flavors at high-p_T in non-photonic electrons and D^0-meson R_{AA} measurements. The shape of D^0-spectra at intermediate momenta is consistent with the effects of radial flow, and thus c-quark collectivity. Interpretation of J/ψ results is complicated by the potential interplay between different production mechanisms, however, the dominance of the coalescence production contributions above 2 GeV/c is disfavored by the data. Centrality dependent "melting" of the Υ yields is observed in the nuclear modification factors. Theoretical model well-describing the trend predict complete melting of 3S and strong suppression 2S states.

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STAR has completed the first phase of the Beam Energy Scan program, exploring the QCD phase diagram at a number of (T, μ_B) points. The analysis of the data is underway, but a number of exciting features have been already observed in the preliminary results reported from the program. A turn-off of the sQGP signatures is seen in the disappearance of high-p_T hadron suppression and deviations from the NCQ-scaling trend, which are observed at higher $\sqrt{s_{\rm NN}}$. Novel features found at the lower energies might help to pin-point the location of the critical point. The change of the slope in proton v_1 measurements is seen between 7.7 and 11.5 GeV. In the same energy region the slope of net-proton v_1 has been found to have a distinct minimum. Different v_2 behavior between particles and anti-particles has also been observed. These initial findings constrain the region of interest for the critical point search to below 19.6 GeV and demand further detailed study at the low range of RHIC energies.

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