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Review of particle spectrum data at RHIC

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The particle spectra from the last several years at the Relativistic Heavy-Ion Collider (RHIC) will be reviewed in the paper. Several selected highlights on recent progress to further our understanding of freeze-out properties and jet quenching will be discussed.

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[*] Speaker.

[†] A footnote may follow.

1. Introduction

Data taken in the last few years have demonstrated that 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, 2, 3, 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. Particle spectrum data have been one of the pillars which were used to identify the existence of the hot, dense medium, followed by the measurements of its properties. I will review several aspects of identified particle spectrum data with emphasis on 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, 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. Overview of published particle spectrum results

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. 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 [5]. The energy density is much higher than normal nuclear matter density thus it is believed that partonic matter is formed in such collisions [6].

- The identified particle p_T distributions were measured and fit with the blast-wave model using thermal-like distribution [1, 7, 8]. The thermal-like fit indicates that the kinetic freeze out temperature T_{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. In central Au+Au collisions, T_{kin} is higher and velocity profile is lower for multi-strange hadrons and ϕ compared to non-strange hadrons, indicating they freeze out earlier, consistent with the picture that multi-strange hadrons and ϕ have smaller interaction cross sections at hadronic stage.

- The identified particle ratios measured in Au+Au collisions at different centralities were fit with thermal model distributions [7, 9]. The fit indicates that the chemical freeze out temperature ($T_{chemical}$) is about 160 MeV and that there is no significant centrality or system size dependence. This value of $T_{chemical}$ is very close to the critical temperature T_c calculated by Lattice QCD [10].
- The measurements of resonance to stable particle ratios indicate that the time interval between chemical and kinetic freeze out is about 3-10 fm/c [11].

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.

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2.2 Hard probes and medium properties

Beside bulk probes, hard probes such as identified particles at high p_T 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 [12]. 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 colliding elastically with surrounding partons [13, 14, 15]. 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 [16, 17]. 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.

The R_{AA} of inclusive hadrons in central Au+Au collisions at 200 GeV at mid-rapidity shows a factor of 5 suppression with respective to unity at $p_T > 6$ GeV/c [14, 15]. The pQCD calculation with gluon density $dN_g/dy = 1000$ and with radiative energy loss can describe the suppression [13]. The R_{dAu} of inclusive charged hadrons in d+Au collisions shows enhancement at intermediate p_T and equals to unity at high p_T [18]. 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) [19] at mid-rapidity. These measurements indicate that the suppression on R_{AA} of high p_T particles in central Au+Au collisions are consistent with partonic energy loss picture.

2.3 Intermediate p_T physics: 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. At intermediate p_T, R_{CP} (R_{AA})

for baryons is larger than that for mesons, indicating strong baryon enhancement in Au+Au collisions [20]. In central Au+Au collisions, the p/π ratio reaches unity, which is much larger than that from elementary p+p collisions. Coalescence or recombination models [21], in which two or three constituent quarks are combined into mesons or baryons, were proposed to explain the data. This 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.

The measurements of particle spectra on bulk properties, hard penetrating probes and at intermediate p_T at RHIC indicate that RHIC has created a hot, dense matter. Next, I will highlight several recent results on identified particle spectra to further our understanding of freeze-out properties and the details of jet quenching.

3. Two selected highlights

3.1 Freeze-out properties derived from the Tsallis-like blast-wave model fit

The thermal-like blast-wave model [8] has been used in heavy-ion and p+p collisions by the RHIC community very successfully. However, there are several disadvantages of this model. There is a strong assumption on local thermal equilibrium. The p_T range of the spectra for the fit is limited and the choice is arbitrary. Besides, the average transverse flow velocity profile is about 0.2 c in p+p collisions, which is very hard to explain. Recently, Tsallis-like blast-wave model [22] was proposed to replace thermal-like blast-wave model. There are non-extensive quantities such as q variable to describe the evolution from p+p to central Au+Au collisions. q characterizes the degree of non thermal equilibrium. If q is 1, Tsallis-like is the same as thermal-like. Using the Tsallis-like blast-wave model fit, the velocity profile is zero in p+p and peripheral Au+Au collisions [22]. By fitting to the spectra of strange hadrons and non-strange hadrons, it was found that strange hadrons have a higher freeze out temperature and a similar flow velocity profile compared to non-strange hadrons. Besides, the q variable for strange hadrons is around 1 while deviates from 1 for non-strange hadrons, as shown in Fig. 1. This seems to indicate that strange hadrons decouple earlier. Hadron re-scattering at hadronic phase does not produce a collective radial flow, instead, it drives the system off equilibrium. It also indicates that in central collisions, partons achieve thermal equilibrium [23].

3.2 The details 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 [24]. 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, 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 Casmir factor from quarks. The coupling of gluons to the medium is

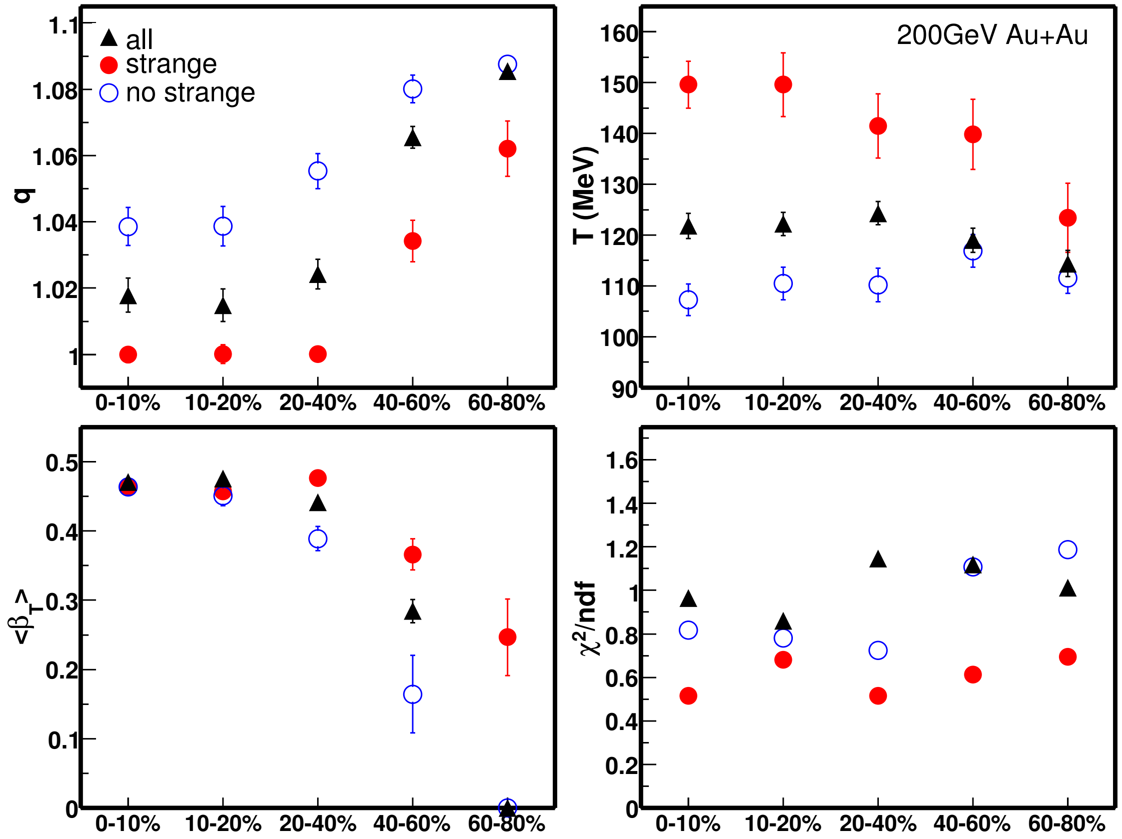

Figure 1: (Color Online) q, T, β and χ^2/nDoF as a function of centrality for different groups of hadrons from the Tsallis-like blast-wave model fit to spectra in Au+Au collisions at 200 GeV. Open and solid circles represent the fit results to non-strange and strange hadrons separately. Triangles represent the fit results to all the hadrons (strange and non-strange hadrons) simultaneously. The figure is taken from ref. [23].

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 (especially for anti-protons) is significantly larger than to pions at high p_T [16, 25, 26]. Therefore, protons, especially anti-protons, are expected to be more suppressed than pions in R_{AA} or R_{CP} measurement. Experimentally, protons, anti-protons and pions show similar magnitudes of suppression in R_{CP} [27]. One of the proposed mechanisms is the jet conversion mechanism [28], 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 [29]. 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 [30].

The results of R_{AA} in central Au+Au collisions were obtained for η [31], and ϕ [32] and preliminary for kaons and protons [33] at high p_T. η shows a similar magnitude of suppression compared to π^0 [31]. The current systematic uncertainties or statistical errors on kaons, protons

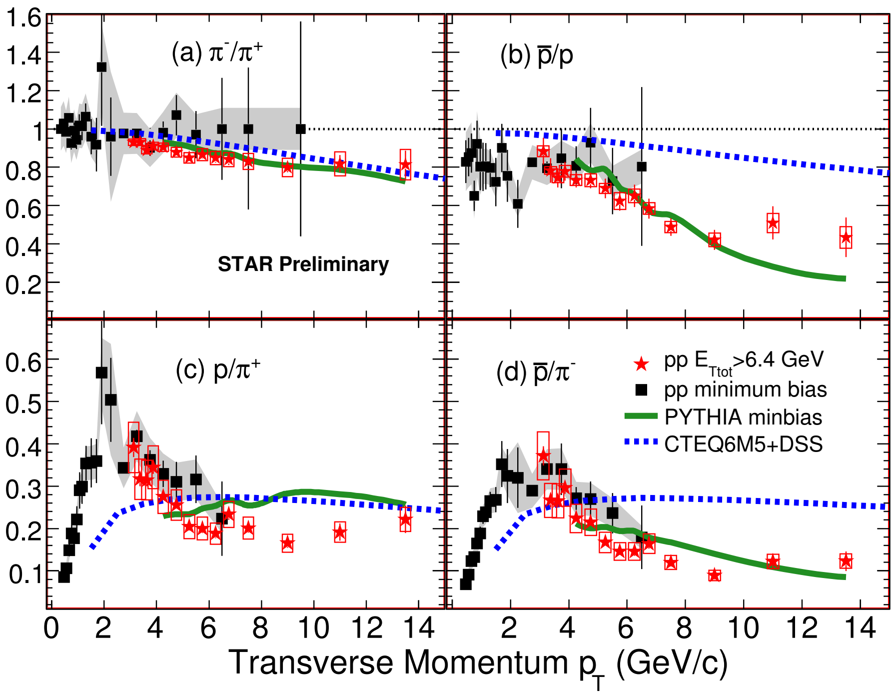

Figure 2: Ratios of π^-/π^+, $\bar{p}/p$, p/π^+ and $\bar{p}/\pi^-$ as a function of p_T in 200 GeV p+p collisions, DSS NLO calculations, and PYTHIA simulation. The bars and boxes represent statistical and systematic uncertainties. The figure is taken from ref. [33].

and ϕ at high p_T are large. The precise measurement in the future, for example, from year 2010 will improve our understanding of jet quenching and provide additional constraints on energy loss calculations. However, to understand the jet quenching in detail, a precise understanding of our reference p+p data is crucial. Recently, STAR showed the invariant yields of π, K and p up to p_T of 15 GeV/c in 200 GeV p+p collisions at mid-rapidity [33]. The preliminary results indicate that in p+p collisions, the $\pi^{\pm}$ spectra are in good agreement with the calculations from NLO perturbative QCD models, which fail to reproduce the K and $p(\bar{p})$ spectra at high p_T [33]. Shown in Fig. 2 are particle ratios of π^-/π^+, $\bar{p}/p$, p/π^+ and $\bar{p}/\pi^-$ as star symbols at mid-rapidity as a function of p_T. Also shown are ratios from minimum bias p+p collisions (square symbols) published in [26] and predictions from PYTHIA (solid line), and DSS (dashed line) pQCD calculations. Interestingly, leading order pQCD calculation PYTHIA can generally reproduce particle ratios, while showing significant deviations from spectra. The NLO pQCD [34] calculations lead to better agreement with measured spectra but deviate from ratios of $\bar{p}/p$, p/π^+ and $\bar{p}/\pi^-$. This indicates that light flavor separated quark and gluon FFs used in NLO pQCD calculations need better constraints. The precise measurement in p+p collisions 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 understanding of p+p data has important consequences on the predictions of jet quenching at high p_T and coalescence at intermediate p_T.

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 [35, 36]. The pQCD calculations including collisional and radiative energy loss show a systematically higher R_{AA} value than experimental data [37, 38]. Further calculations indicate that with the charm contribution only, non-photonic electrons are expected to reproduce the data [38]. 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 [39]. 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 challenge the pQCD energy loss model calculations; they may indicate collisional dissociation of heavy mesons [40], in-medium heavy resonance diffusion [41], and multi-body mechanisms [42] might play an important role for heavy quark interactions with the medium.

4. Summary

The particle spectrum results from RHIC serve as one of the pillars for the discovery of a hot, dense medium at RHIC. The recent results from the Tsallis-like Blast-wave model fit and the identified particle measurements at high p_T are highlighted to further our understanding of freeze-out properties and the details of jet quenching. The understanding of p+p reference data, which is crucial to probe the details of jet quenching and coalescence, needs more exploration.

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