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Status of the quark gluon plasma search

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Abstract. A selection of results are discussed that support the conclusion that strongly interacting quark gluon plasma is produced in heavy-ion collisions at the Relativistic Heavy Ion Collider at BNL.

Keywords. Quark gluon plasma; PHENIX; hydrodynamics; direct photons; hadron suppression.

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1. Introduction

The main impetus for the field of relativistic heavy-ion collisions since its inception with nuclear beams at the AGS and SPS more than 20 years ago has been to study the properties of nuclear matter under conditions of extremely high density and pressure. As QCD became recognized as the appropriate theory of the strong interaction it was realized that at nuclear densities of $\epsilon \sim 1$ GeV/fm^3 or temperatures of $T \sim 170$ MeV a hadronic picture of matter would breakdown and the matter should more appropriately be described as existing in a deconfined quark gluon plasma state [1].

Figure 1 illustrates current theoretical expectations on the structure of the phase diagram of strongly interacting matter in temperature versus baryon chemical potential, μ_{baryon}, variables [2]. It is expected that central collisions of relativistic heavy ions may provide the opportunity to produce and study matter in the quark gluon plasma phase in the high temperature and low baryon density region of the phase diagram. Other exotic phases, such as a color superconductor phase, or a color-flavor locked condensate may exist at low temperature and high baryon density in the interior of neutron stars [2].

In this note, we present a brief selection of evidence in support of the conclusion that quark gluon plasma has been produced in experiments at the Relativistic Heavy Ion Collider, highlighting results of the PHENIX experiment. This is a personal perspective and does not necessarily reflect that of the PHENIX collaboration. A thorough discussion of this topic from the PHENIX collaboration can be found in ref. [3].

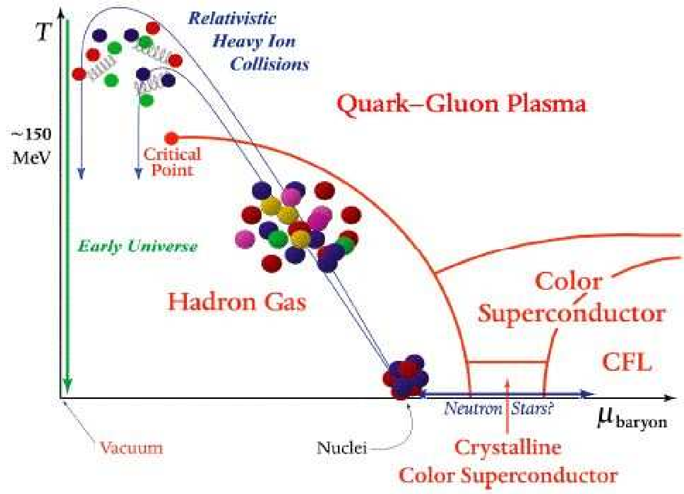

Figure 1. The phase diagram of strongly interacting matter.

2. Inferences from the final state

The duration of a relativistic heavy-ion collision is extremely short. While the matter may be in a highly excited, dense, quark-gluonic phase shortly after the many nearly simultaneous initial partonic collisions have occurred, the system will expand and eventually hadronize or freeze-out into hadrons, possibly leaving little trace of the early phase of the collision. To draw conclusions on the phase structure of strongly interacting matter from measurements of relativistic heavy-ion collisions, it is important to address the question of to what extent the produced matter has interacted, and possibly thermalized, at least locally.

While reflecting only the late freeze-out stage of the collision, the transverse momentum spectra of identified hadrons [4,5] provide a clear indication that the characteristics of the system change as the extent of nuclear overlap increases, as shown in figure 2. The p_{T} spectra of the various hadron species can be simultaneously fit by a hydrodynamical model-inspired parametrization [6] to extract a freeze-out temperature and average transverse flow velocity $\langle\beta_{\mathrm{T}}\rangle$. Figure 2 indicates that as the nuclear overlap increases, characterized by the number of participating nucleons, the parameters that characterize the hadron spectra change. The extracted average transverse flow velocity increases while the freeze-out temperature decreases as the initial overlap volume increases. The result suggests that due to the larger initial density and volume of the system as the nuclear overlap increases, interactions occur over a longer time interval and transfer random thermal motion to collective expansion more effectively.

For heavy-ion collisions at non-zero impact parameter, the overlap volume has an almond shape that breaks azimuthal symmetry with respect to the reaction plane. Azimuthal correlations between particles, or between particles and an estimate of the reaction plane can be analyzed to extract the second Fourier coefficient, v_2, of the azimuthal correlation, also referred to as the elliptic flow parameter. At RHIC

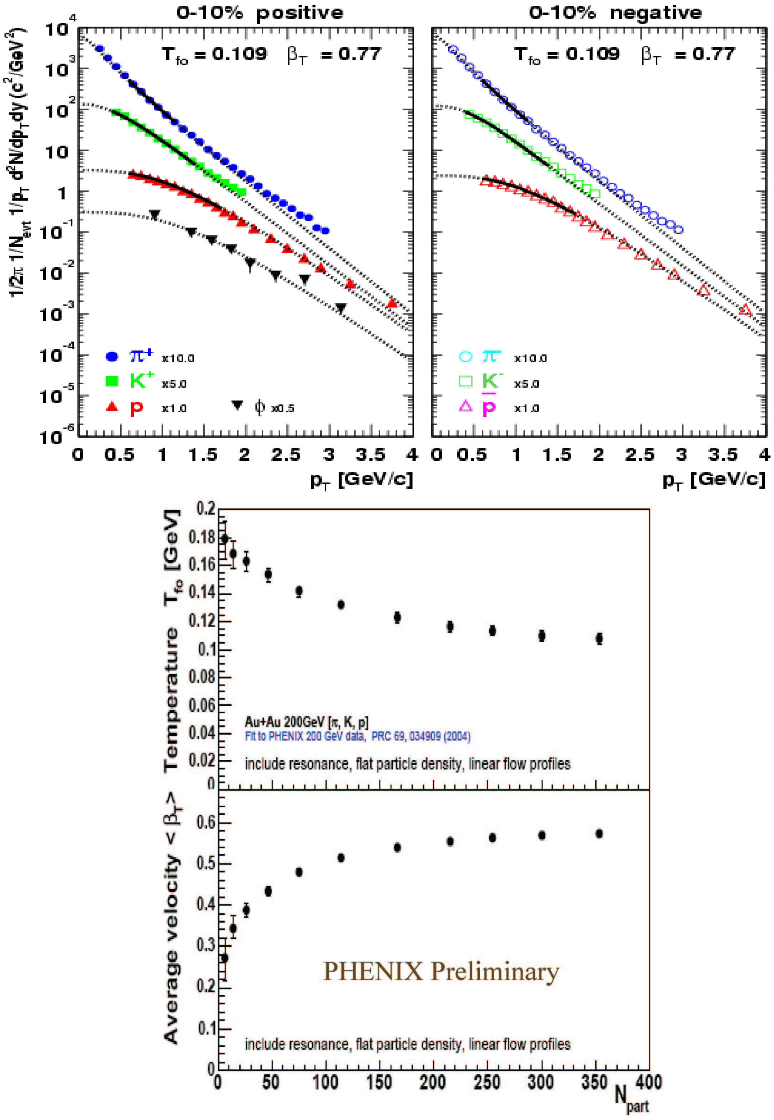

Figure 2. Top: Simultaneous fit to transverse momentum spectra of π, K, and p (left: positive charge, including ϕ, right: negative charge) for central Au+Au collisions. Bottom: The dependence of the freeze-out temperature and average transverse velocity fit parameters as a function of centrality, characterized by the number of participant nucleons for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

the v_2 coefficients are found to depend on p_{T} and particle type with a strength that is greater than that observed at the SPS and AGS [7,8]. The fact that the particle yields correlate strongly with the reaction plane demonstrates unambiguously that the produced particles interact strongly with one another.

Figure 3 shows the proton and pion p_{T} spectra and dependence of v_2 on p_{T} with comparisons to several hydrodynamic model calculations with different assumptions on the equation-of-state (EOS) or hadronic phase evolution [3]. From these comparisons the following observations may be drawn.

1. A purely hydrodynamic treatment with an EOS that includes QGP reproduces all observables well, except the proton p_{T} spectrum.
2. A purely hydrodynamic treatment with an EOS that includes QGP, but allows only partial chemical equilibrium (PCE) (chemical freeze-out occurs at hadronization but is not allowed to evolve further in equilibrium) reproduces the proton and pion spectra, but predicts too much v_2 for protons and pions.
3. Assumption of an EOS with a resonance gas (RG) rather than QGP is too hard and produces too much v_2 for protons.
4. A hydrodynamic treatment with an EOS that includes QGP for the partonic stage followed by a relativistic quantum molecular dynamics (RQMD) transport calculation for the hadronic stage reproduces all observables best.

These calculations imply initial energy densities of 15–25 GeV/fm^3, far above the critical energy density expected for the QGP phase transition.

From these observations one may conclude that ideal non-viscous hydrodynamics describes the partonic phase of the collision well, but not the hadronic phase. If the hadronic phase is allowed to evolve without dissipation, then the results presented in figure 3 demonstrate that either the hadron yields are predicted incorrectly, if the system is allowed to evolve in chemical equillibrium, or, if chemical ratios are frozen at the time of hadronization, then the elliptic flow is predicted incorrectly. The interpretation of the results is that artificially enforced early chemical freeze-out removes energy from the system that would otherwise allow interactions to continue longer and increase the amount of radial expansion, boosting the apparent v_2 to larger p_{T} [13]. Only by a dissipative treatment of the hadronic phase, as in a hadron cascade calculation, can the hadron yields and v_2 be simultaneously reproduced.

As discussed in ref. [13] and shown in figure 4, the shear viscosity, η, is in fact larger in the partonic phase, above the critical temperature T_{c}, than in the hadronic phase. However, because the specific entropy, s increases dramatically above T_{c}, the $\eta(T)/s(T)$ ratio, which is the quantity of relevance for the importance of dissipative effects, is very small which allows an ideal hydrodynamical treatment of the partonic phase. The good agreement with the ideal hydrodynamical treatment of the partonic phase has led to the realization that near T_{c} the quark-gluon matter behaves as a strongly interacting fluid, and hence denoted by sQGP. In fact, for strongly coupled Yang–Mills theories it has recently been conjectured that the value of η/s approaches the perfect fluid value of $1/4\pi$ [14], as the RHIC results suggest.

3. Probing the QGP

Although there are many indications that the energy densities attained at RHIC exceed the critical energy density of the QGP phase transition, it is highly desirable to have a direct measurement of the attained initial temperature. Since photons are

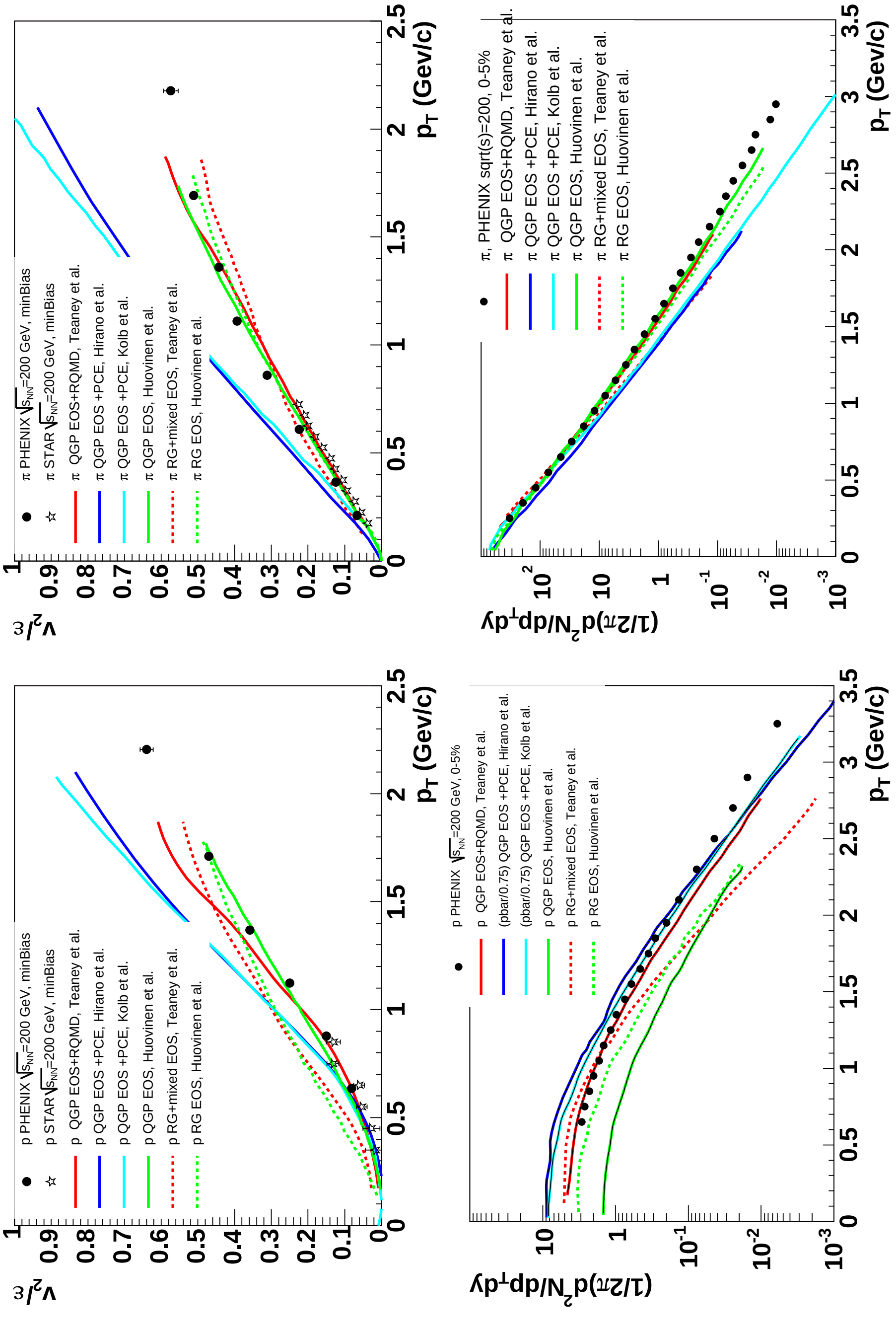

Figure 3. Simultaneous fits to proton (left) and π (right) azimuthal asymmetry v_2 (scaled to the initial overlap eccentricity) [8] and transverse momentum spectra (bottom) [4] compared to various theoretical models [9–12].

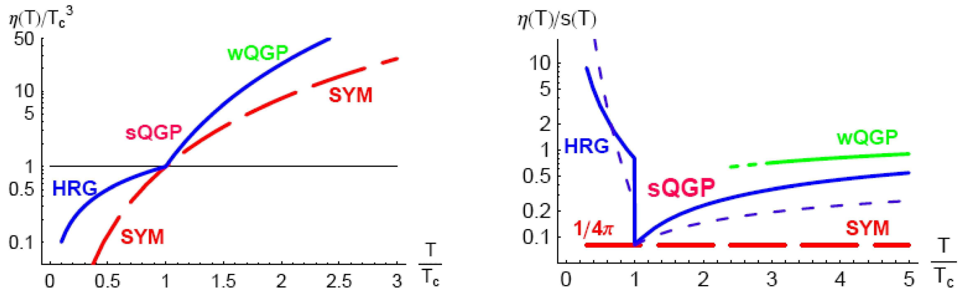

Figure 4. The temperature and phase dependence of the shear viscosity η scaled by the critical temperature T_c^3 (left) or specific entropy $s(T)$ (right) [13].

expected to be radiated throughout the history of the heavy-ion collision, measurement of the thermal spectrum of direct photon radiation would provide valuable information on the initial temperature. Figure 5 shows the direct photon spectra, after subtraction of photons from long-lived resonance decays (mostly π^0s and ηs), for various centrality selections [15]. The results are seen to be in good agreement with NLO pQCD predictions [16] scaled by the number of binary nucleon–nucleon collisions calculated for the corresponding centrality selection. The NLO pQCD predictions are in agreement with the measured direct photon yield in $p+p$ collisions at $\sqrt{s} = 200$ GeV [17].

The direct photon yield for central Au+Au collisions is shown separately in figure 6. The scaled NLO pQCD prediction is again shown together with various predictions for the thermal photon yield. The calculations make various assumptions on the initial thermalization time with corresponding initial temperatures ranging from 300 to 600 MeV [18–22]. The measured direct photon yield is consistent with all thermal yield predictions, but also consistent with no thermal photon contribution. Thus, it is not possible to draw useful conclusions on the initial temperature of the system, with the current level of experimental uncertainty on the direct photon yield.

The produced matter may be probed by particles produced in hard collisions during the initial stage of the collision as they must then propagate through the surrounding matter before propagating through vacuum. Photons are expected to interact rarely, and therefore should not be affected by the produced matter, while colored objects might be expected to interact strongly [23].

Hard processes with small cross section are expected to occur as an incoherent process and therefore should scale with the number of binary nucleon–nucleon collisions in A+A collisions, as was observed in figure 5 for the direct photon production. The nuclear medium effects on particle production can be quantified by the nuclear modification factor, $R_{\rm AB}$, defined for collisions of A+B as the ratio of invariant yield in A+B to that of $p+p$, scaled by the number of binary collisions.

$$R_{\rm AB}(p_{\rm T}) = \frac{(1/N_{\rm AB}^{\rm evt})\,{\rm d}^2N_{\rm AB}/{\rm d}\eta{\rm d}p_{\rm T}}{\langle N_{\rm coll}\rangle/\sigma_{pp}^{\rm inel}{\rm d}^2\sigma_{pp}/{\rm d}\eta{\rm d}p_{\rm T}} = \frac{(1/N_{\rm AB}^{\rm evt})\,{\rm d}^2N_{\rm AB}/{\rm d}\eta{\rm d}p_{\rm T}}{\langle T_{\rm AB}\rangle{\rm d}^2\sigma_{pp}/{\rm d}\eta{\rm d}p_{\rm T}},$$

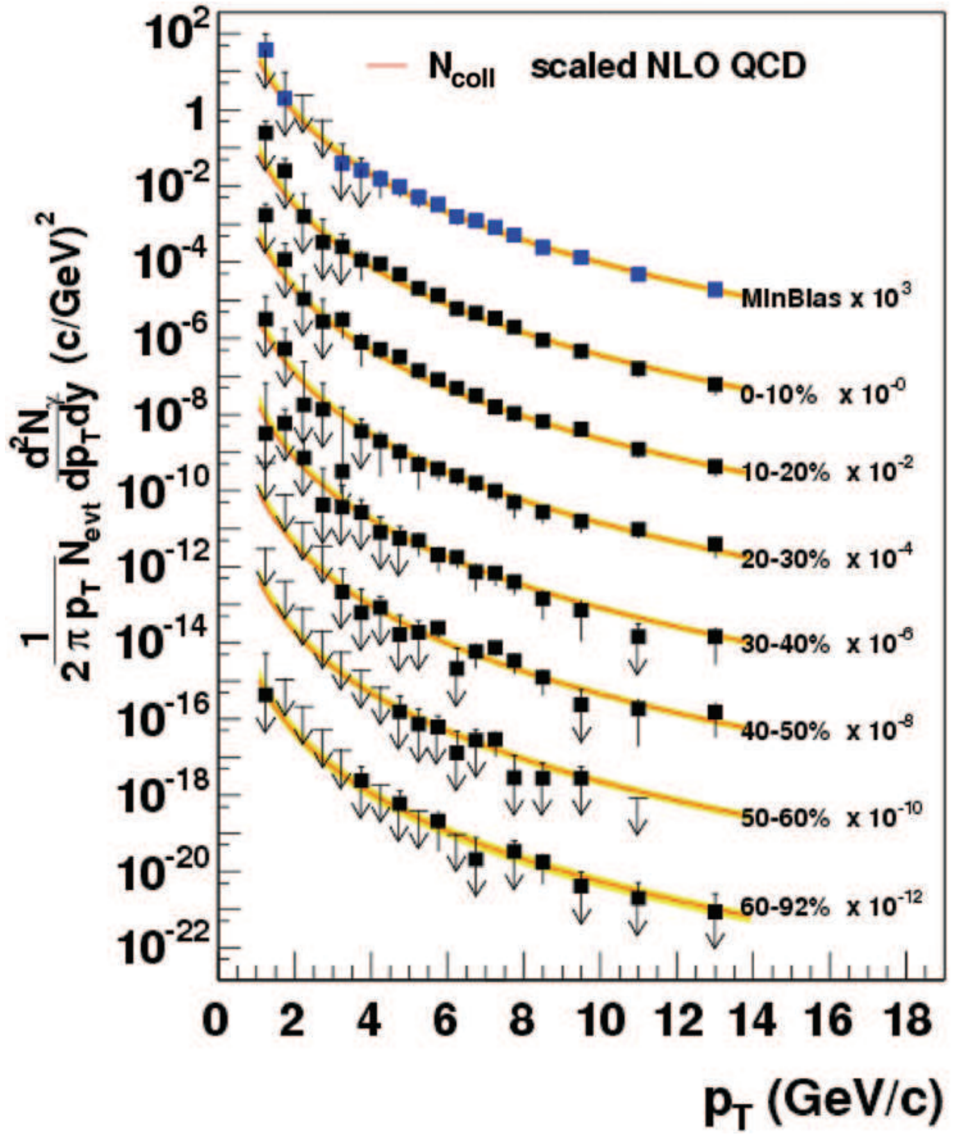

Figure 5. Transverse momentum spectra of direct photons for various centrality selections (0–10% being most central) in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The expectation from pQCD calculations scaled by the number of binary nucleon collisions are shown by the solid curves.

where $\langle N_{\rm coll}\rangle$ is the average number of inelastic nucleon–nucleon collisions per event, and $\langle T_{\rm AB}\rangle = \langle N_{\rm coll}\rangle/\sigma_{pp}^{\rm inel}$ is the average of the nuclear overlap function, which is determined purely from the nuclear geometry. Thus $\langle T_{\rm AB}\rangle$ represents the parton luminosity and $\langle T_{\rm AB}\rangle {\rm d}^2\sigma_{pp}/{\rm d}\eta {\rm d}p_{\rm T}$ gives the expected yield for the experimentally selected nuclear geometry, assuming no nuclear effects.

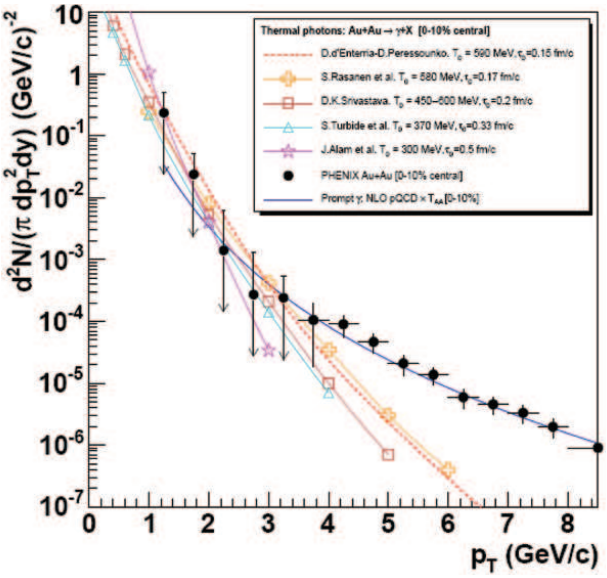

Figure 6. Direct photon transverse momentum spectrum for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared to predictions of pQCD and various thermal photon predictions [18–22].

For heavy-ion collisions R_{AB} is expected to be below unity at low p_{T} where the bulk of the particle production is due to soft processes which scale like the overlap volume, or the number of participant nucleons $\langle N_{\mathrm{part}}\rangle$, rather than as $\langle N_{\mathrm{coll}}\rangle$. At high p_{T} however, R_{AB} should be unity in the absence of nuclear medium effects.

One of the earliest and most exciting results from RHIC was obtained during the first year of RHIC operation. Despite very modest integrated luminosity and consequent limits on the extent of the p_{T} measurements, the yield of hadrons in central Au+Au collisions at moderately large transverse momenta was observed to be significantly suppressed [24], in qualitative agreement with expectations that it was a consequence of parton energy loss, or jet quenching in the QGP matter [23].

The suppression effect as observed in the PHENIX experiment is shown in figure 7 where the π^0, η, and direct photon R_{AA} are shown for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [15,25]. It is observed that while the direct photon Au+Au result is consistent with the scaled $p+p$ direct γ results ($R_{\mathrm{AA}} \approx 1$), the π^0 and η yields for central Au+Au are significantly below the scaled expectations, indicating a strong nuclear suppression of the π^0 and η yields.

Although the suppression of the high p_{T} hadron yields in central A+A collisions was a predicted consequence of energy loss of partons produced in initial hard scatterings as they traverse the hot-dense matter produced in a central A+A collision [23], it was alternatively suggested that the suppression could be due to a decreased number of initial hard scatterings due to a reduction, or saturation, of the initial gluon density in heavy nuclei [26]. Because photons produced in the initial Compton-like quark-gluon scatterings are sensitive to the initial gluon density, but will hardly be affected by the surrounding dense matter in the central heavy-ion

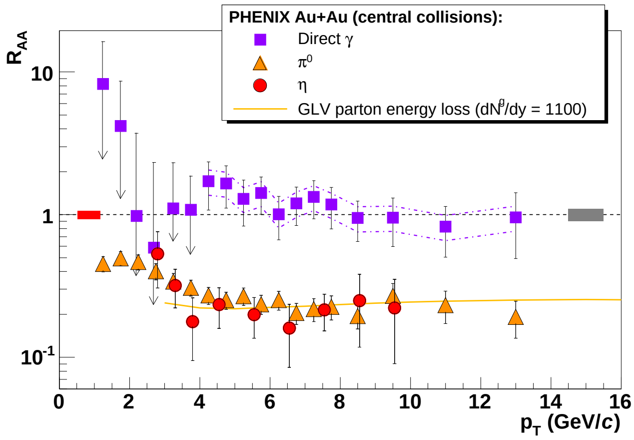

Figure 7. Nuclear modification factor $R_{\mathrm{AA}}(p_{\mathrm{T}})$ for π^0, η, and photons in central Au+Au at $\sqrt{s_{NN}} = 200$ GeV. The error bars include all point-to-point experimental (p+p, Au+Au) errors. The shaded bands represent the fractional uncertainties in $\langle T_{\mathrm{AuAu}}\rangle$ and in the π^0 and η yields normalization added in quadrature, which can move all the points up or down together.

collision, the observation that the direct photon yield is in agreement with expectations (i.e. $R_{\mathrm{AA}} \sim 1$ as seen in figure 7) demonstrates that there is no appreciable saturation of the initial gluon density. The conclusion that gluon saturation effects cannot explain the hadron suppression is also supported by the observation that high p_{T} particles in d+Au collisions are not suppressed [27]. The direct photon and d+Au results strongly indicate that the hadron suppression in central Au+Au collisions is not an initial state effect, but instead is a final state effect due to energy loss in the produced dense medium.

Since high p_{T} π^0s and ηs are produced predominantly in the fragmentation of gluons and light quarks, the suppressed high p_{T} yields of figure 7 are attributed to energy loss of the light quarks or gluons as they propagate through the dense matter resulting in π^0s and ηs of reduced p_{T}. Heavy quarks should similarly lose energy, but their interaction with the medium is predicted to be smaller than for light quarks as the phase space for gluon radiation is decreased due to their larger mass. This is the so-called 'dead cone' effect [28].

Information on heavy quark energy loss may be obtained from measurement of the p_{T} spectrum of 'non-photonic' electrons extracted as the inclusive electron yield minus the yield of electrons produced in 'photonic' processes of internal or external photon conversions. The yield of non-photonic electrons at high p_{T} is dominated by electrons from weak decays of D- and B-mesons that result from fragmentation of c- and b-quarks. Figure 8 shows $R_{\mathrm{AA}}(p_{\mathrm{T}})$ for non-photonic electrons for central Au+Au collisions [29,30]. The suppression at high p_{T} is observed to be large and comparable to the observed π^0 and η suppression. The implied large energy loss of heavy quarks is currently not understood, as indicated by theoretical predictions shown for comparison [31,32]. Calculations that include the electron yields from B-mesons are unable to reproduce the large suppression observed [32]. This result

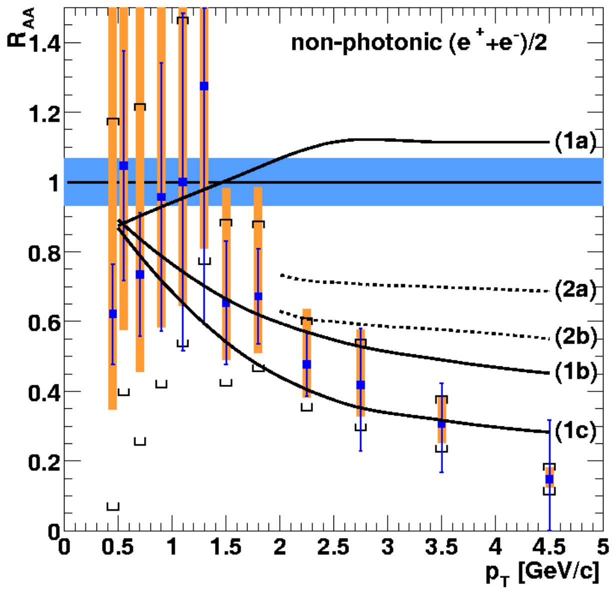

Figure 8. Nuclear modification factor $R_{\mathrm{AA}}(p_{\mathrm{T}})$ for electrons from heavy quark decays for central Au+Au at $\sqrt{s_{NN}} = 200$ GeV in comparison to models incorporating charm quark energy loss. Curves (1a)–(1c) and (2a), (2b) are taken from [31,32], respectively. Only curves (2a) and (2b) include contributions from B meson decays. The error bars are statistical errors only. Error brackets indicate the systematic errors on the experimental ($p+p$, Au+Au) measurements. The shaded band around unity represents the fractional systematic uncertainty in $\langle T_{\mathrm{AuAu}} \rangle$.

again indicates the strong interactions with the produced matter and that much remains to be learned about its characteristics.

4. Conclusions

A number of features of central heavy-ion collisions at RHIC, such as the centrality dependence of the hadron spectra at low transverse momenta, the correlations of particle emission with the reaction plane, and the large suppression of hadron yields at high p_{T}, indicate that the matter produced interacts strongly and behaves collectively. The collisions can be described by model calculations with an equation of state that includes a quark gluon plasma phase. The model calculations indicate that the initial energy densities are well above the QGP critical temperature and that the strongly interacting sQGP phase can be described with non-viscous hydrodynamics, while dissipative effects are important for the hadronic phase. Further studies will continue the investigation of the properties of sQGP.

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