Studies of Hot Dense Matter with the PHENIX Detector at RHIC

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Abstract

The PHENIX experiment at RHIC carries out studies of hot dense matter produced in heavy ion collisions and studies of the proton spin from polarized proton collisions. In this talk I concentrate on our present picture of the quark-gluon plasma as revealed in collisions of Au and other nuclei.

Keywords: *RHIC; PHENIX; QGP; perfect liquid; elliptic flow; R_{AA}; QGP temperature*

1 Introduction

The Relativistic Heavy Ion Collider (RHIC) was built at Brookhaven National Laboratory (BNL) and the first collisions of beams of 130 GeV/A Au nuclei were observed in June 2000. PHENIX and STAR are two large detector systems built to study these collisions. In the first collisions flow was observed. In the summer of 2001 experiments with collisions of Au beams at the full RHIC energy of 200 GeV/A were undertaken. After extensive analysis of the results of runs from 2000–2004 a white paper [1] was published where evidence was given for the production of a Quark–Gluon Plasma (QGP). The plasma was designated sQGP in illusion to the strong coupling observed. In addition the sQGP behaved not as a gas as many expected but like a liquid with almost zero viscosity, the so called "perfect liquid". In 2010 the first collisions of Pb nuclei were observed at the Large Hadron Collider (LHC) at a much higher energy density than at RHIC.

In this talk I will discuss the suppression of particles in the hot dense nuclear medium created at RHIC which gives evidence that the QGP is strongly coupled. Next I will discuss the evident that the QGP flows indicating that the plasma acts like a liquid rather than a gas. Finally I will discuss recent measurements at PHENIX in an attempt to measure the temperature of the QGP.

2 Suppression of particles in the sQGP

In order to produce a QGP you need not only high energies but large volumes. This is necessary to sustain high energy densities and temperatures for a sufficiently long time. Before the collision the nuclei can be pictured as two relativistically flattened "pancakes" of quarks and gluons. In the initial collision products of hard scattering are created followed by the creation of large numbers of quarks and gluons out of the vacuum to produce a dense partonic medium. This medium can initially be the QGP but as it cools and expands it evolves into a hadronic gas phase. For 200 GeV/A Au collisions of the order of 10^4 particles are created. This process is illustrated in Fig. 1.

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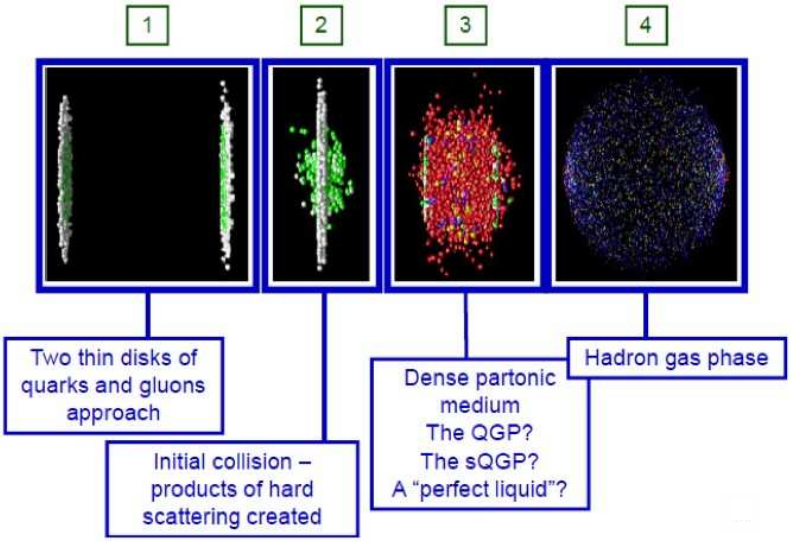

Figure 1: Stages in a relativistic heavy ion collision.

In order to study the properties of the QGP, particles that traverse the hot dense medium serve as a probe of its properties. In order to study the effects of the medium we introduce a Nuclear Modification Factor

$$R_{AA} = \frac{dN_{AA}^{J/\Psi}/dy}{N_{coll}\, dN_{pp}^{J/\Psi}/dy}.$$

In this factor the yield in nucleus-nucleus collisions is divided by the yield in p+p collisions but scaled by the appropriate number of binary collisions N_{coll} which is calculated using the Glauber model. We do not expect to produce the QGP in p+p collisions. Thus if the particles are not modified by the medium we expect $R_{AA} = 1$. In Fig. 2 the concept of participating nucleons is illustrated along with a plot of the number of binary collisions for Au collisions as a function of impact parameter.

A large number of measurements have been carried out at PHENIX to measure the response of various particles to passage through the hot dense medium created

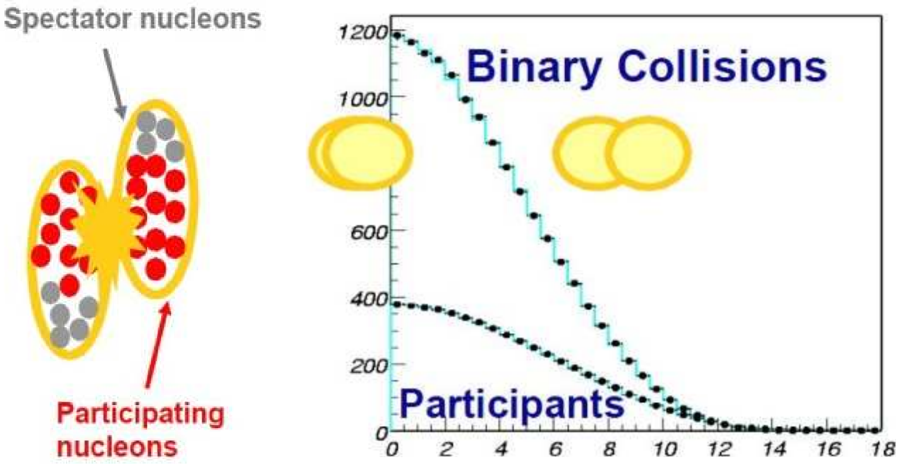

Figure 2: Concept of nuclear modification factor. On the left the concept of participant nucleons is illustrated and to the right a plot of participants and binary collisions as a function of impact parameter for Au collisions is shown.

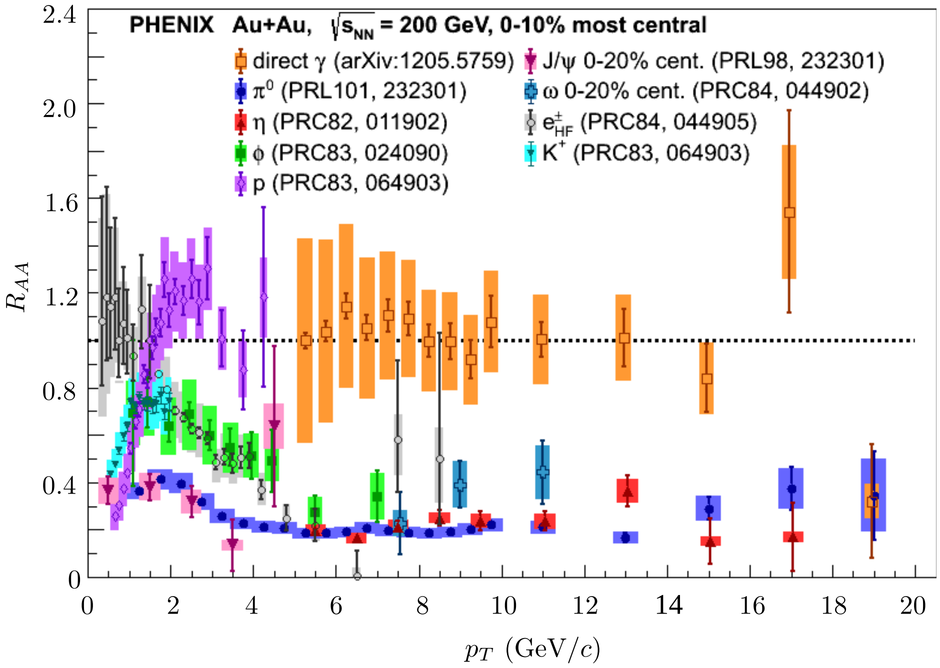

Figure 3: Plots showing R_{AA} for the 0 to 10% most central 200 GeV/A Au+Au collisions for a wide variety of mesons, protons and direct photons, and particle transverse momenta up to 19 GeV/c. Note the large suppression for hadrons but not for direct photons.

in Au+Au collisions. Using both Au+Au and p+p data measured at PHENIX R_{AA} for a number of different particles has been measured and the results are shown in Fig. 3. Particularly striking is the large suppression of π^0 mesons [2] all the way out to 19 GeV/c. In addition large suppression of η and ω mesons [3, 4] were observed. This is evidence for strong suppression of mesons composed of the light u and d quarks in the sQGP.

We also measured the suppression of ϕ and K^+ mesons that contain a heavy s quark. It is interesting to note that for these mesons the suppression was less but still [5, 6] significantly below an R_{AA} of 1.0. It might be expected that photons produced in direct interactions with the colliding quarks and gluons would not be suppressed by the sQGP since they only interact electromagnetically with the hot dense medium. This can be seen in the results in Fig. 3 for direct photons [7] where their R_{AA} is 1.0 within the error. We conclude that the sQGP strongly suppresses mesons made up of light u and d quarks but still significant suppression occurs when the meson is composed of a heavier s quark. As expected direct photons are little effected by the sQGP.

An important question is how does suppression in the QGP change if we reduce the collision energy or the centrality of the collision. We would thus expect less suppression both for lower collision energy and more peripheral collisions. Au+Au collisions were studied at 39 and 62.4 GeV/A and the results are compared with those at 200 GeV/A in Fig. 4.

The suppression for a collision energy of 62.4 GeV/A is very similar to that for 200 GeV/A except that the suppression is slightly lower at 62.4 GeV/A for π^0 momenta below 6 GeV/c. By contrast when the collision energy is lowered to 39 GeV/A the π^0 is still suppressed but to a lesser extent than at 62.4 GeV/A. It would be of interest to determine how far can we go down in collision energy and still see significant suppression. The data in Fig. 4 also shows that π^0 suppression is still

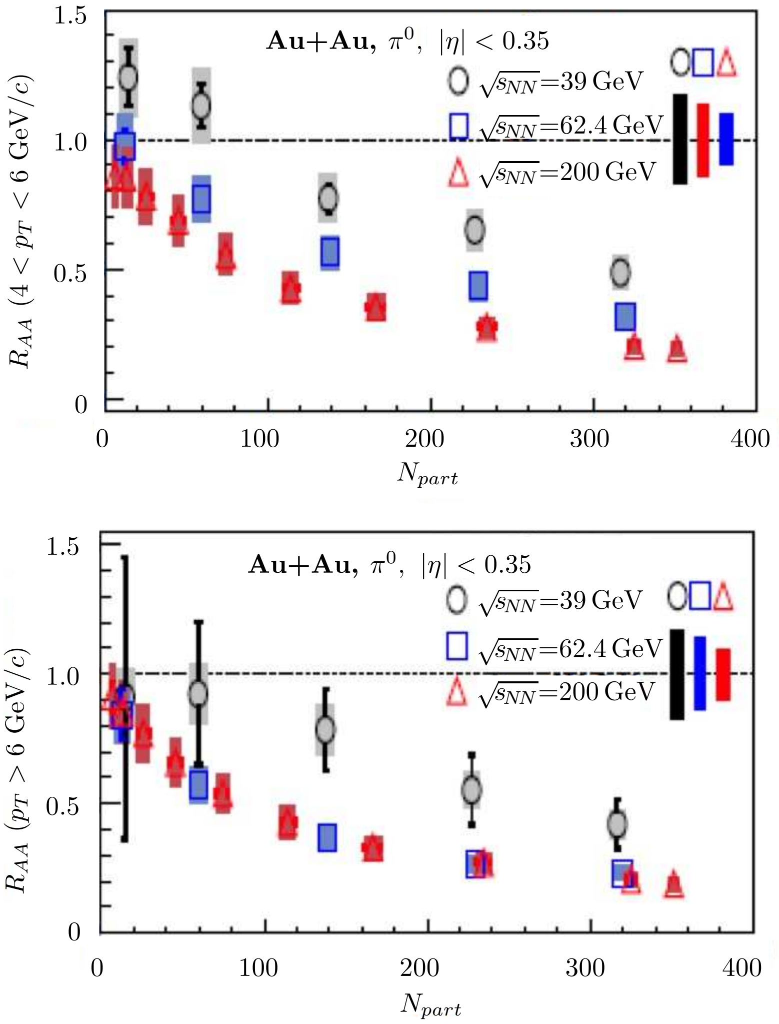

Figure 4: R_{AA} results for π^0 mesons for collision energies of 62.4 and 39 GeV/A. Particle numbers from 0 to 400 indicate a range from the most central to the most peripheral collisions.

significant at all three collision energies [8] down to peripheral collisions where of the order of 50 particles are emitted.

The LHC has produced Pb+Pb interactions with a collision energy of 2.76 TeV/A. R_{AA} for the production of π^0 and + and − charged hadrons was measured. These results for R_{AA} are compared with those from Au+Au collisions at PHENIX [9] at a collision energy of 200 GeV/A in Fig. 5.

From Fig. 5 it is observed that there is very little difference in the suppression of the π^0 even though the collision energies at ALICE are much greater. One might expect a higher suppression due to the greater energy densities at ALICE but many more particles are produced so the effects of recombination must be taken into account.

The suppression of u, d and s quarks in the sQGP is significant so it is interesting to test to what extent the much heavier c and b quarks are suppressed. To study this the R_{AA} for Au+Au collisions at 200 GeV/A were measured for electrons and positrons from decay of open charm and beauty. The R_{AA} for these particles is shown in the top part of Fig. 6 and compared [10] with results from π^0. For the most central collisions electrons with p_T greater than 2.0 GeV/c are significantly suppressed.

From the study of the suppression of various particles emitted in Au+Au collisions

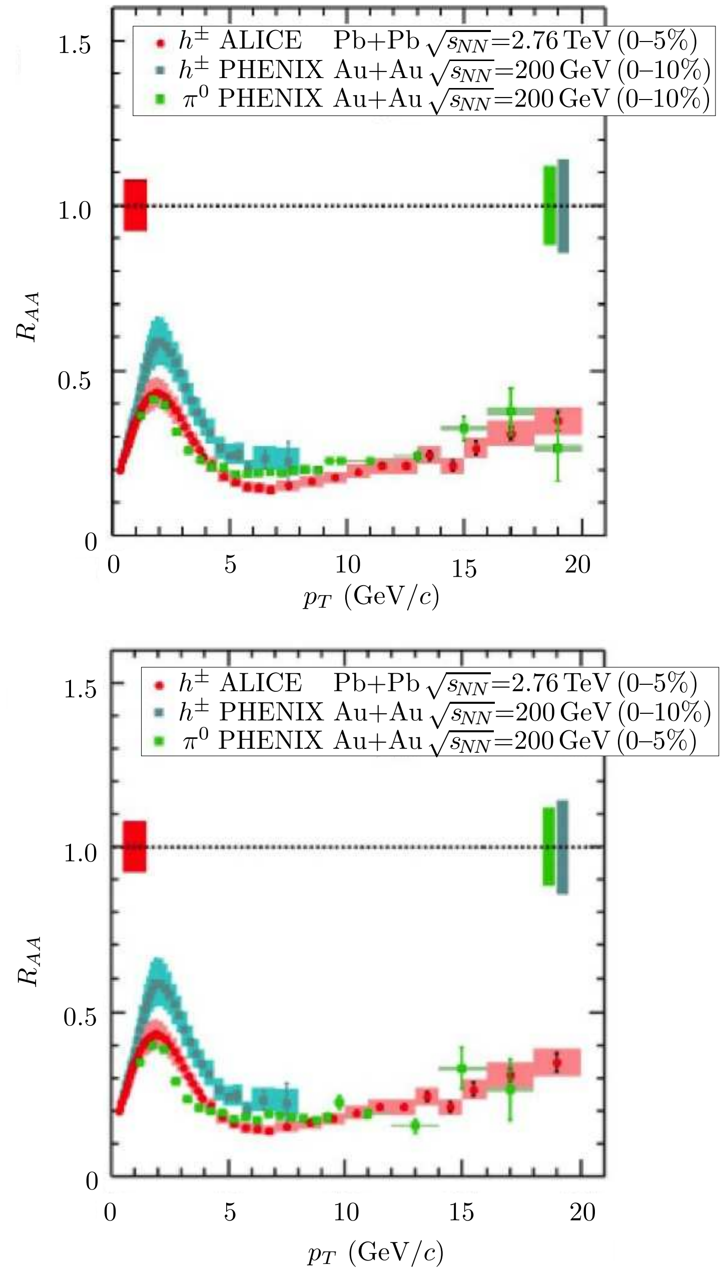

Figure 5: Plots showing R_{AA} for 200 GeV/A collisions at PHENIX and 2.76 TeV/A Pb+Pb collisions at ALICE.

we have reached the following conclusions:

A. In Au+Au collisions we have created a color opaque medium called the sQGP.

B. Suppression of particles in the medium is prominent for collision energies down to 39 GeV/A.

C. The level of suppression at the higher energy densities at the LHC is similar to that at RHIC.

D. The level of suppression is still very significant for the heavy c and b quarks.

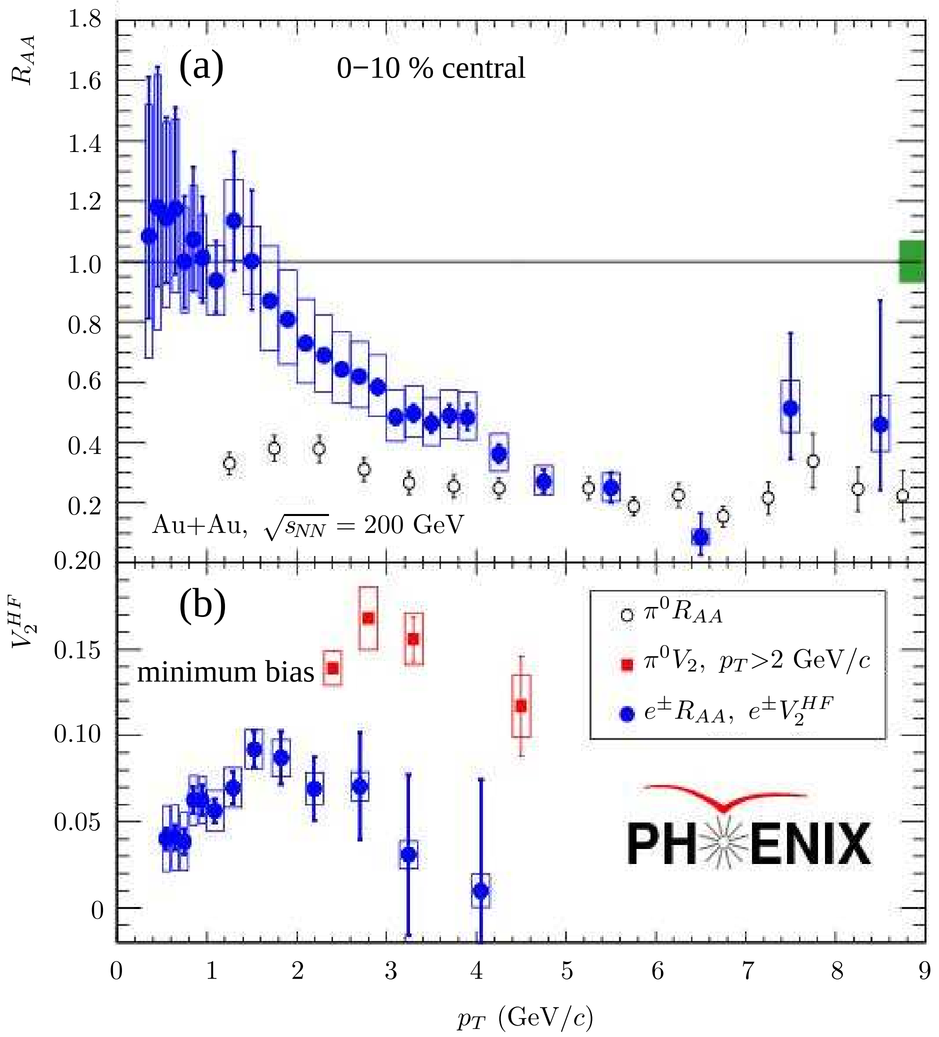

Figure 6: Plots of R_{AA} and v_2 in parts (a) and (b), respectively, for electrons from the decay of open charm and beauty. The data is for Au+Au collisions at 200 GeV and the 10% most central collisions.

3 Flow and evidence for a liquid sQGP

Early in experiments at RHIC it was observed that particles were not emitted isotropically in Au+Au collisions. This effect is shown in Fig. 7.

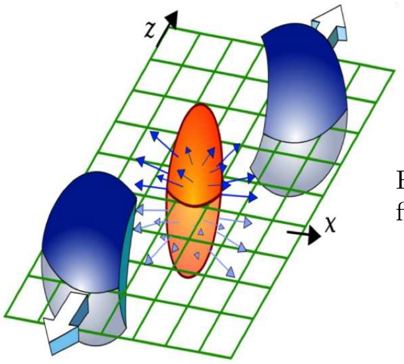

Figure 7: Figure illustrating the concept of elliptic flow.

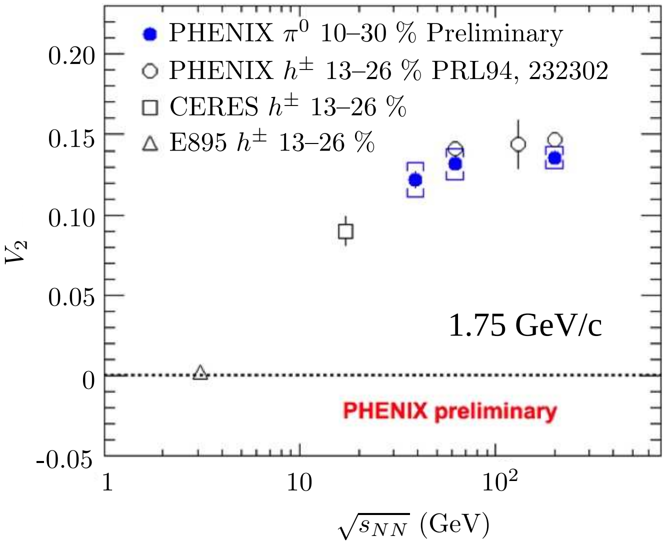

Figure 8: v_2 as a function of collision energy.

It was observed in RHIC experiments that when two heavy ions collided hot matter flowed. The colliding region is almond shaped due to the overlap of the colliding nuclei that have been flattened to "pancake" shapes due to relativistic effects. The regions of high density in the center exert a greater pressure resulting in the expansion of an elliptically shaped region (elliptic flow). The particle angular distribution can be described as:

$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos(2\phi).$$

For a spherically symmetric distribution v_2 is 0.

A plot of v_2 for Au+Au collisions at RHIC [11] is shown in Fig. 8. It is evident that the hot dense matter flows at both the lowest and highest RHIC energies. Also v_2 appears to saturate at the highest energies. There is also evidence that open charm and bottom particles flow but not as strongly as for the lighter quarks. See the (b) part of Fig. 6.

Once elliptic flow was established an important question was how did it scale with valence quark count. The v_2 was thus studied [12] for a large number of both baryons and mesons. The results are shown in Fig. 9.

The plot of v_2 on the upper part of Fig. 9 shows the results for both baryons and mesons for a number of different particle energies. If the v_2 values in the left plot are divided by the quark number the results are shown in the plot in the lower part. This result shows that v_2 scales as the quark number.

The observation of quark scaling is significant in that it establishes that collective behavior has been established during the partonic phase of the system since the degrees of freedom are partonic. This is a direct signature of deconfinement.

4 Temperature of the quark-gluon plasma

The temperature for formation of the QGP has been predicted to be around 170 MeV. It is thus important to measure the temperature of the hot hadronic matter produced at RHIC. The spectrum of photons is complex since they are generated in each stage of the collision. In the initial phase of the collision photons are emitted from the primary parton collisions. Next photons are emitted as the QGP forms, thermalizes and evolves into a mixed phase. Finally the mixed phase evolves into a hot hadron

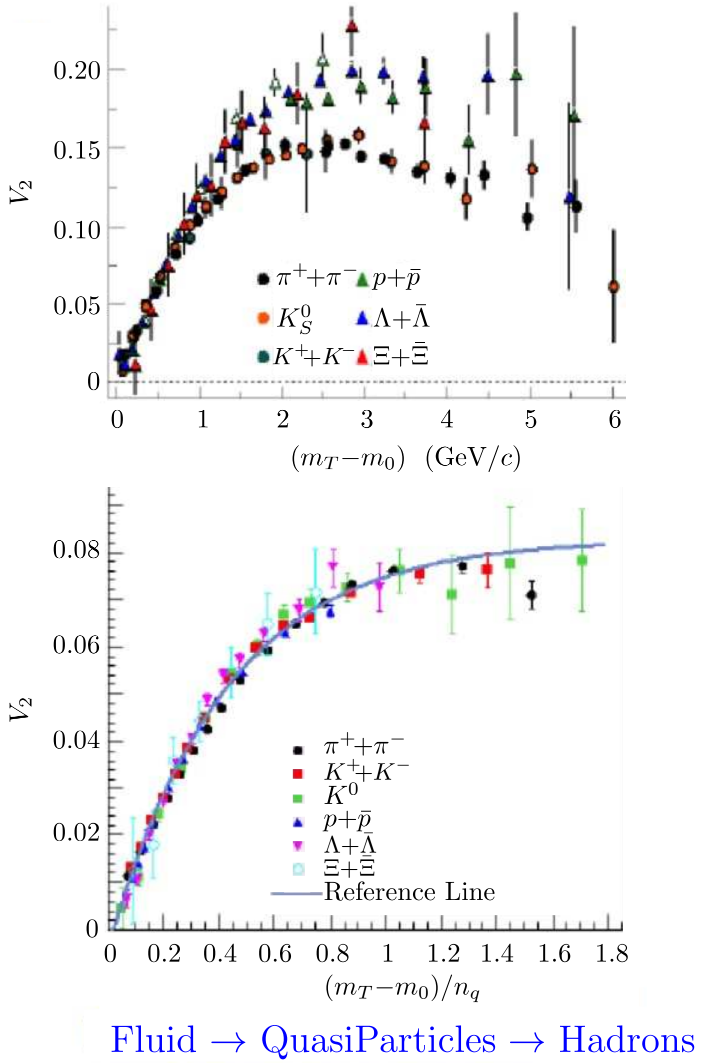

Figure 9: Scaling behavior of v_2 for baryons and mesons.

gas. This process is illustrated [13] schematically in Fig. 10. Note that the photon energy spectrum becomes softer at each stage.

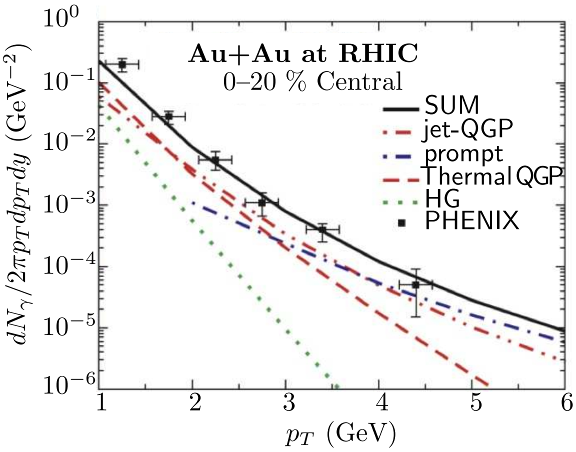

Figure 10: Photon yields from Au+Au collisions compared with calculated yields from different stages of the collision.

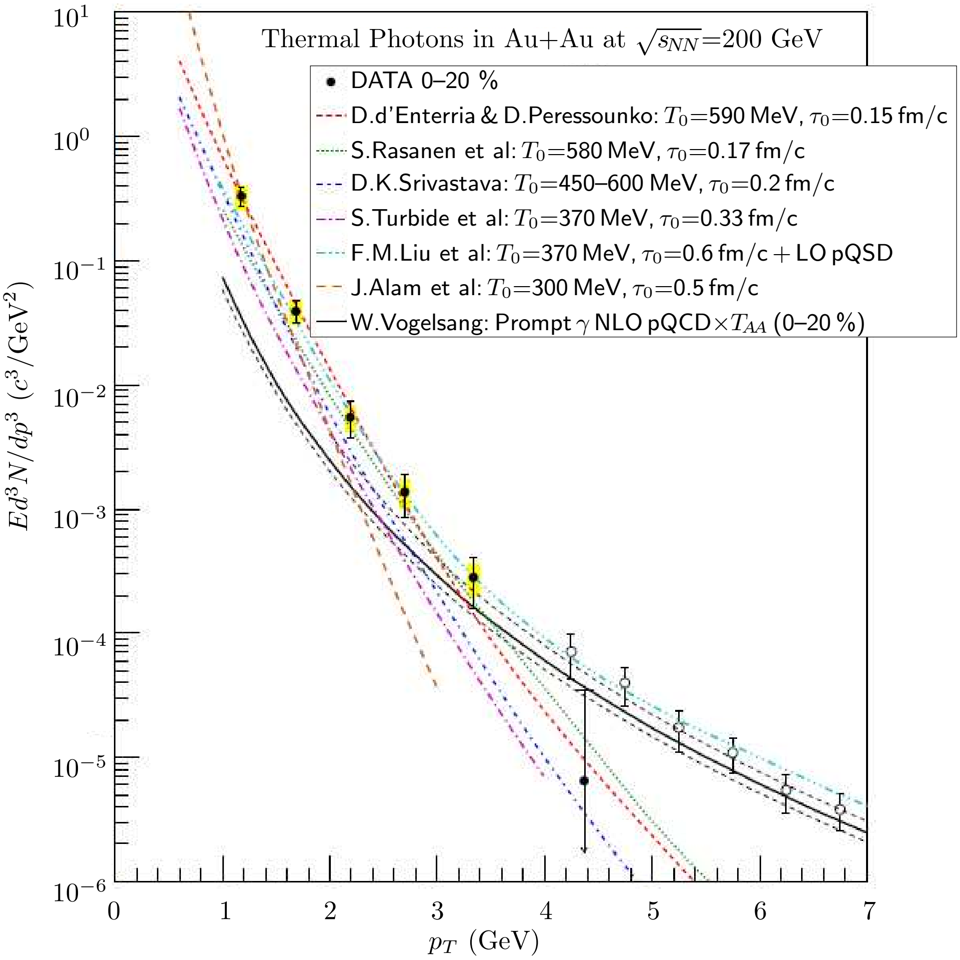

Figure 11: Spectrum of thermal photons from Au+Au collisions at 200 GeV/A compared with calculations assuming various values for formation energies and times.

In order to estimate the temperature of hot hadronic matter produced at RHIC, PHENIX measured dilepton production for 200 GeV/A Au and p collisions. This data was used to deduce the direct photon spectra shown in Fig. 11. The theoretical calculations shown in Fig. 11 assume a system with an initial temperature between 300 and 600 MeV and formation times between 0.6 and 0.15 fm/c. The PHENIX data [14] is in good agreement with calculations assuming initial temperatures above 300 MeV, which is well above the predicted formation temperature for the QGP of 170 MeV.

5 Summary and conclusions

Since the first collisions occurred at RHIC in 2000, the QGP has been produced using Au beams at RHIC and Pb beams at the LHC. This resulted in the formation of a very strongly interacting low viscosity liquid called the sQGP. Even heavy c and b quarks were stopped in the sQGP. At RHIC the temperature of the sQGP was deduced to be in the range of 300–600 MeV which is well above the proposed limit of 170 MeV for plasma formation. The transition from sQGP to hot hadronic matter is continuous rather than through a phase transition. The sQGP produced at the LHC has properties very similar to that produced at RHIC at a much lower energy density.

Acknowledgments

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Since this symposium is a celebration of the 70th birthday of James Vary I would like to point out that it has been almost 40 years since both James and I came to Iowa State in 1975. For many years I have valued James both as a colleague and especially as a friend. Happy 70th birthday, James.

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