Probing the Big Bang at the Relativistic Heavy Ion Collider (RHIC) (or Probing the Big Bang 13.7 billion years later)

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Abstract. The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory in the USA is a variable energy proton-proton and ion-ion collider that is the first accelerator capable of colliding heavy ions. RHIC was designed to do experiments that provide important information about the Standard Model of particle physics, Quantum Chromodynamics (QCD). QCD predicts that in the early part of the Universe just after the Big Bang the world consisted of a Quark Gluon Plasma, a weakly interacting collection of quarks and gluons. At RHIC we can recreate the conditions of the early Universe by colliding heavy ions at 200 GeV. This paper will give a general overview of the physics motivation for studying the QGP, how our experiments are designed to study the QGP, what we have learned over the last 9 years, and what the future holds.

Introduction
The goal of heavy ion physics is to study QCD under extreme temperatures and energy densities with a great emphasis on the discovery of the quark-gluon plasma (QGP). The QGP is the nuclear medium where the neutrons or protons (baryons) are no longer bound states of quarks but instead the quark and gluon constituents of the neutrons and protons are in a deconfined state. This new state of matter has been predicted for many years but never observed [1,2,3]. The QGP is thought to be the primary form of matter that occurred within 10 µs after The Big Bang, the event that caused the formation of our universe. As such the study of the QGP is important in cosmology, astrophysics, and nuclear physics. Very quickly after the formation of the QGP, the universe cooled and the quarks and gluons bound together to remain that way for the next 13.7 billion years. The bound quarks and gluons formed hadrons and anti-hadrons but they quickly annihilate so by about 1 sec after the Big Bang only the hadrons remain. Later in time, light atoms were formed, then came the formation of stars and heavy nuclei, and finally the universe of today with galaxies and solar systems began about 8-9 billion years after the Big Bang. One of the mysteries of the universe is why we have a predominance of matter over anti-matter.

Ordinary nuclear matter is a system composed of interacting neutrons and protons that form the nucleus in the center of a much larger atomic system that includes the nucleus and electrons. The neutrons and protons, also collectively called hadrons, are composed of three quarks and gluons, the force carrier that binds the quarks together. Physicists have learned that there are six types of quarks and anti quarks. Only two are found in the universe today and they are called the up and the down
quark. Protons are made of two up quarks and one down quark and the neutrons are made of two down quarks and one up quark. The other heavier quarks, the strange, charm, bottom, and the top, are not found naturally but are produced in energetic collisions of high energy particles. Hadron is a term that identifies particles that are made of quarks and are held together by the strong force. There are two types of hadrons, baryons and mesons. Mesons are not naturally occurring but are formed by the collisions of energetic particles. Mesons are composed of a quark and an anti-quark and baryons are composed of three quarks. In highly energetic collisions of particles many additional hadrons and mesons are produced some composed of the heavier quarks.

The Relativistic Heavy Ion Collider at the Brookhaven National Laboratory in the USA was constructed with one of its goals to study QCD under extreme conditions and search for evidence of the QGP. Beginning in 2000, the RHIC collider has run successfully with a variety of beam conditions and energies and shed light on the sought after QGP but also discovered many puzzles.

The Relativistic Heavy Ion Collider (RHIC)
RHIC is a variable energy heavy ion collider facility that can collide 100 GeV/nucleon Au ion beams together with the goal of producing a new state of matter called the quark gluon plasma (QGP). The accelerator complex is shown in figure 1. Gold ions are produced in an ion source and accelerated to \( \sim 1 \text{ MeV/nucleon} \) in the Tandum Van de Graaf accelerator with a charge state of \(+32\) and then transported to the Booster accelerator where they are accelerated to \( 95 \text{ MeV/nucleon} \) with a charge state of \(+77\). The AGS (Alternating Gradient Synchroton) takes the output of the Booster and accelerates the Au ions to \( 8.9 \text{ GeV/nucleon} \) with a charge state of \(+79\) and then the ions are transported to the RHIC ring where they are accelerated to \( 100 \text{ GeV/nucleon} \). In the RHIC accelerator there are two independent counter rotating beams that are focused to collide at six intersecting positions around the ring. The ring is 3.8 km in diameter, contains 1740 superconducting magnets operating at 3.5 Tesla, and has a luminosity of \( 2 \times 10^{30} \text{cm}^{-2}\text{s}^{-1} \).

![Figure 1. The RHIC accelerator complex.](image-url)
Four detectors are positioned at the intersecting regions, PHENIX, STAR, BRAHMS, and PHOBOS. The two detectors, PHENIX and STAR, are designed to cover large areas of rapidity and angle with STAR focusing on hadron detection and PHENIX focusing on rare events and leptons. The other two smaller detectors are more specific with PHOBOS measuring large amounts of untriggered data and BRAHMS covering a large range of rapidity but with limited angular range. All of the experiments are complimentary to each other and still provide overlap in key areas. The two smaller detectors finished taking data in 2006.

The STAR detectors’ main feature is a large Time Projection Chamber (TPC) for measuring the tracks of the charged particles emanating from the collision vertex. The detector is shown in figure 2, idealized in the left panel and as built in the right panel. The TPC is a large cylindrical gas volume where the charged particles leave ionization tracks that drift to a wire grid array at either end that detects the ionization track. Surrounding the TPC are other types of detectors that are used to help identify the charged particles. A typical heavy ion collision event in the STAR detector is shown in figure 3.

The PHENIX detector consists of four large analyzing spectrometers that are designed to measure the properties of the particles coming out of the collisions of heavy ions. The detector is shown in figure 4, idealized in the left panel and as built in the right panel. PHENIX is designed specifically to
measure direct probes of the collisions such as electrons, muons, and photons. The two beams enter the detector via a beam pipe shown in the left panel running from the upper left to the lower right and collide at the center of the detector in the center of the central magnet (depicted in the left panel with a darker blue color). The two conical shaped magnets that surround the upstream and downstream portion of the beam pipe are designed to measure the momentum of the muons coming from the collisions and the series of panels in the back portion of the conical magnets identify the muons. Surrounding the central portion of the detector is the central magnet that is used for momentum analysis of the charged particles and to provide a lower momentum threshold for charged particle detection. Centered at 90 degrees to the beam line are two large detector carriages with a number of subdetectors for measuring particles trajectories, drift chambers and pad chambers, electromagnetic calorimeters to measure the electron and photon energies, cherenkov detectors to identify electrons and time-of-flight detectors to identify charged hadrons.

![Image](image_url)

**Figure 4.** The left panel is an artist view of the PHENIX detector and the right panel is a photo of the actual detector. In the right panel one of the detector carriages has been moved out of view.

Both the PHENIX and STAR detectors have hundreds of thousands of signals coming from all of the subdetectors for each event and all of that information must be processed electronically and recorded for further analysis. Various electronic triggers are used to filter the raw data to reduce the extremely high data volume before it is finally archived on computer disks. The raw data volume from the PHENIX detector exceeds 700 Mbits/s, but only a small fraction of the data is important for each collision event. Before data analysis files can be produced the raw data files are preprocessed to produce condensed files for analysis and this process can take up to a year following the data run. The subsequent analysis of the data involves determining which particles in the ~1000 particle event are important (perhaps 1-3 particles). This can take a few minutes per event so many months are needed to analyze the stored data. Many different analyses are done to look at different physics processes so this time consuming process is repeated many times and in fact sometimes physics analysis are still being done 3-5 years after the yearly data run.

**A Brief Review of the Quark Model**

The quark model was independently proposed by physicists Murray Gell-Mann[4] and George Zweig[5] in 1964. The quark model is a part of the Standard Model of Physics. Their idea was that protons and neutrons as well as other particles that were discovered were not elementary but made up of smaller constituents which they called quarks. Their model consisted of three quarks, up, down, and strange, which explained much of the known particles at that time. Over the next decade more types of
quarks were proposed and all of the quarks were finally experimentally found by 1995 with the discovery of the top quark at FNAL[6]. Figure 5 left panel [7] shows the current state of our picture of the quark model and the right panel shows the constituents of a He$^4$ atom[8]. There are 6 lepton, 6 quarks, and 4 force carriers. The particles in the first column in the left panel, generation I, are the only particles that are found in the natural world today. Columns 2 and 3, generations II and III, are produced in high energy collisions at man-made accelerators or in high energy cosmic ray interactions and do not exist normally in nature. All of the elementary particles have a corresponding antiparticle. The force carriers are the particles that are responsible for the forces between the elementary particles. The gluon is responsible for the strong force that holds quarks together in the nucleus, the photon is responsible for the force due to electromagnetic charge, and the W, Z are responsible for the weak force that governs radioactive decay and neutrino interactions. The gravitational force is not part of the Standard Model of Physics. In the right panel is a He$^4$ atom showing how the nucleus of an atom is made up of quarks and electrons. In the nucleus of the atom are the protons and neutrons and each are composed of three quarks bond together by the gluon force carrier.

![Figure 5](image-url)  
**Figure 5.** The left panel lists the elementary particles and the force carriers that form the Standard Model of Physics and the right panel shows how the quarks and electrons make up a nucleus, in this case He$^4$ atom.

The quarks are not free to roam around the nucleus but are constrained to be part of the 3 quark triplet that identifies the hadron. The only way to break up the hadron is to put the atom under extreme temperature and pressure or to collide the nuclei at very high energies in an accelerator.

**Relativistic Heavy Ion Collisions**

In attempting to create the Quark Gluon Plasma in the laboratory we collide two beams of heavy ions traveling at close to the speed of light. At RHIC we use Au ions accelerated to 100 GeV. A schematic representation of these collisions [9] is shown in figure 6. In the left panel the two Au ions are traveling towards each other at 99.995% of the speed of light. Due to this relativistic velocity the Au ions Lorentz contract in the direction of motion and take on a pancake shape. The consequence of this is that the quarks and gluons are more dense. In the second panel the collision takes place and some high energy collisions produce high energy particles that can be used to probe the nuclear medium. In the third panel the quarks and gluon that were part of the hadrons in the Au nucleus are released to...
form the high temperature and high density fire ball. In the fourth panel the resulting plasma begins to cool down and the quarks and gluons recombine to produce many particles and antiparticles. The particles that result from the recombination can be used to probe the plasma.

**Figure 6.** A heavy ion collision where in the first panel the Lorentz contracted Au ion beams a moving toward each other at 99.995% of the speed of light; in the second panel the two beams collide; in the third panel the quarks and gluons are freed; in the fourth panel the plasma is beginning to cool.

Not all heavy ion collisions are head-on as depicted in figure 6. Collisions that are head-on or near head-on are called central collisions and produced the greatest density of free quarks. When the two Au ions collide off axis with a smaller overlap, we call that a peripheral collisions. In peripheral collisions only some of the nucleons participate in the reaction and the other nucleons that don’t participate are called spectator nucleons. By measuring the spectator nucleons we can determine the amount of energy available to the collision out of the total 39.4 TeV that is available. In all of the collisions, central or peripheral, not all of the participating nucleons actually collide so another term is used and that is colliding nucleons. The number of colliding nucleons is determined by a Glauber calculation.

**Signatures of the Quark Gluon Plasma**
The signatures of the QGP that are commonly considered are jet suppression, J/PSI suppression, collective flow, strangeness enhancement, and high pt suppression of hadrons. In jet suppression the two jets formed in the collision process travel back to back through the dense QGP. The near side jet (the jet closest to the surface of the plasma) is detected and the far side jet (the jet in the opposite direction that transverse most of the plasma) is suppressed because of the absorption and energy loss in the dense QGP. A representation of this is shown in figure 7.

**Figure 7.** A descriptive example of jet suppression. The near side jet in red is detected while the far side jet in green is lost to the dense QGP medium.

In J/psi suppression we expect the color screening to suppress the bound states of charmonium (the charm-anticharm meson which is the J/psi). This is similar to Debye screening in electrostatics. Color screening is a property of quarks and the strong force much in the same way that charge is an
electrostatic property of charged particles. A pictorial representation [10] of this is shown in figure 8. Normally the quark-antiquark pair bound together by the strong force but when they are in a plasma of many other quarks and antiquarks of different color they are unable to remain bound together and therefore the number of J/psi’s are suppressed.

![Perturbative Vacuum](image1.png) ![Color Screening](image2.png)

**Figure 8.** A description of J/psi color screening. In the left panel the J/psi quark – antiquark pair are held together by the strong force but in the right panel the quark and antiquark pair are shielded by the other quarks and the binding is broken.

Collective flow provides information on the properties of the medium, in this case the QGP, such as viscosity, equation of state, thermalization, etc. By measuring the elliptic flow we can determine whether the QGP is a strongly or weakly interacting system.

High energy quarks propagating through matter are predicted to lose energy via induced gluon radiation, with the total energy loss strongly dependent on the color charge density of the medium. This process is expected to be very sensitive to the hot dense matter created in relativistic heavy ion collision.

A Systematic Approach to the Study of the QGP

In order to study the QGP it is very important to understand the basic nucleon-nucleon interactions and nucleon-nucleus interactions so that we don’t infer an effect to nucleus-nucleus collisions that is in fact due to the more simple nucleon-nucleon and nucleon-nucleus interactions. To accomplish this collider runs over the last 9 years have included Au-Au collisions at 200 GeV, d-Au collisions at 200 GeV, and p-p collisions at 200 GeV. The p-p collisions are used to understand the differences that are due to nuclear effects in the QGP in Au-Au collisions and between a superposition of independent nucleon-nucleon collisions. The analysis uses a term called the nuclear modification factor and is described by the following formula,

\[
R_{AA}(p_T) = \frac{d^2N_{AA}^{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{NN}/dp_Td\eta}
\]

where the numerator is the yield in Au-Au collisions and the denominator is the yield in p-p collisions multiplied by \(T_{AA}\), the number of binary collisions in Au-Au collisions as calculated by the Glauber Model. In the Glauber Model the nucleons in each Au nucleus is treated as nucleon that travels in a straight line and only undergoes binary scattering. If the Au-Au collisions behave according to the Glauber Model and are just a superposition of many nucleon-nucleon collisions, then the nuclear modification factor will be unity. Departure from unity indicates nuclear matter effects either due to the QGP( sometimes referred to as hot nuclear matter) or due to nucleon-nucleus interactions(sometimes referred to as cold nuclear matter effects) and not due to the QGP. To separate out the cold nuclear matter effects another form of the nuclear modification factor is used where
instead of using the Au-Au yield in the numerator, the d-Au yield is used. Here, unity also means that there are no cold nuclear matter effects and a departure from unity indicates cold nuclear matter effects. Comparing the nuclear modification factor for the Au-Au and for d-Au we can understand how much is due to the QGP.

Some important results
Over the last 9 years the RHIC community has learned much about what is formed in the collisions of Au-Au nuclei. Some of what we have learned at RHIC are that,

- There is jet suppression in Au-Au collisions
- There is a very large amount of flow
- There is evidence of shock wave dynamics
- There is excessive numbers of electrons
- There are more high momentum protons than expected.

All of these point to the creation of a new form of matter that behaves like a near perfect liquid. Unlike the original expectations of the QGP being a weakly interacting plasma of quarks and gluons, this near perfect liquid is strongly interacting.

Jet suppression has been one of the most important indicators that a new form of dense matter has been formed in the Au-Au collisions. Figure 9 shows the results for all types of runs, Au-Au, d-Au, and p-p at 200 GeV.[11] In this figure the near side jet is seen at 0 radians and the backward away side jet is at 3.14 radians. The far side jet is clearly visible for the p-p collisions and the d-Au collisions but is absent for the Au-Au collisions. This indicates that the far side jet is absorbed by the nuclear medium. The fact that the far side jet is seen for the d-Au collisions indicates cold nuclear matter effects are not the cause of the jet suppression seen in Au-Au collisions.

Figure 9. Jet suppression observed in the STAR experiment. The far side jet is suppressed in Au-Au collisions.

Figure 10 shows the energy dependence of jet suppression.[12] In experiments at the CERN ISR (Intersecting Storage Ring) at 31.0 GeV and at the CERN SPS (Super Proton Synchrotron) at 17.3 GeV jet suppression is not seen. This clearly indicates that the results from RHIC are unique and indicative of a new regime in high density nuclear physics.
Figure 10. The nuclear Modification Factor for different collision energies.

Figure 11. The Nuclear Modification Factor for different centrality bins. The top panels are for peripheral collisions and the bottom panels are for the most central collisions.
The results for the nuclear modification factor further reinforces the notion that we have observed the QGP. Figure 11 shows the nuclear modification factor for two centrality bins, peripheral and central.[13] In the top panels the peripheral bins are shown for both Au-Au(70-80%) and d-Au(60-88%) collisions. Here, because the collision is so peripheral, we don’t expect to be able to produce the QGP in the Au-Au collisions and the two panels are very similar. In the bottom two panels are plotted the data for the central collisions. Here, we do expect to produce the QGP in Au-Au collisions and indeed we observe a dramatic suppression for $R_{AA}$. The enhancement for the d-Au data at central collisions is due to a known cold nuclear matter effect.

Another measure of the $R_{AA}$ for direct photons and hadrons show the same suppression for the hadrons from jets but no suppression from photons. We expect hadrons from the jet will be suppressed but photons will not because photons will not interact in the QGP. This is shown in figure 12.[14][15][16]

![Figure 12. The Nuclear Modification Factor for direct photons and mesons.](image)

Figure 13 is a calculation [17] of the flow parameter $v_2$ compared to data[18]. The large $v_2$ indicates that the quarks flow and the calculation fits the data only if the viscosity is very small. This is the criteria for a near perfect liquid.

![Figure 13. The flow parameter $v_2$ for baryons and mesons. The red and blue are calculations by Kolb, et. Al. [17]](image)
In addition to these results we have also had some unexpected surprises. Figure 14 shows the proton to pion ratio and the antiproton to pion ratio for a variety of trigger conditions.[19] This ratio of baryons/mesons is completely unexpected. The ratio changes most rapidly when the collision process becomes more central. We do not know the reason for this result.

![Figure 14](image-url) The baryon to pion ratio for different collision systems.

**The future at RHIC and the LHC**

The main effort at RHIC in the future is to further elucidate the properties of the QGP. RHIC is now in the regime where instead of discovery, it is in the determination of the details. To do this we look at different ways to probe the nuclear medium. One way to do this is to use heavy quark probes. Heavy quarks are formed in the early part of the formation of the plasma so are ideal to use as a probe of the QGP. In addition, because the heavy quarks are more massive, the theoretical calculations are more reliable. To date the identification of the heavy quarks at RHIC have been hampered by large backgrounds in the analysis and an inability to determine if the leptons have a displaced vertex from the semileptonic decay of the heavy quarks. To remedy this, the two large detectors at RHIC have embarked on an upgrade program to install new detector systems in the vertex region to accurately track the particles from the heavy ion collisions and determine which have a displaced vertex. Figure 15 illustrates the definition of a displaced vertex. The D+ meson (contains a charm quark) decays to a muon that is detected in the muon arm. The decay length of the D+ meson is of the order of a few hundred microns while the decay of the π meson has a decay length of the order of a few cm. By measuring the decay length we can identify the heavy quark decay (charm and bottom) from the prompt muons and the π meson decays. Figure 16 shows an example of this type of new detector.
Figure 15. An illustration of the definition of a displaced vertex. The D meson travels a short distance and the decays semi-leptonically to a muon and neutrino.

Figure 16. The new Silicon Vertex Tracker (SVT) upgrade for the PHENIX detector.

The SVT is designed to measure all of the particles emanating from the heavy ions collisions. It does this by having four layers of silicon pixel and strip detectors in the barrel region and forward regions. It has ~5.3 million channels of electronic information that must be filtered and processed for each event. The detector support structure is made of carbon fiber composite material for light weight and stable operation. The technical challenges are the need for ~ 50 micron vertex resolution, stability to ~25 micron, and a heat load ~4 kWatts.

The heavy ion program at the Large Hadron Collider (LHC) will be getting under way in the coming year. This program pushes the energy regime from 200 GeV center-of-mass/nucleon to 5.5 TeV center-of-mass/nucleon and opens the door to investigations of the QGP at higher densities and
temperature. It will extend the discovery potential beyond RHIC and perhaps find a weakly interacting QGP. This ambitious program utilizes the large complex at CERN and will operate in conjunction with the proton-proton collider program. A view of the CERN complex is shown in figure 17 in the left panel and the ALICE dedicated heavy ion detector in the right panel.[20]

![CERN complex](image)

**Figure 17.** The CERN complex is shown in the left panel and the ALICE dedicated heavy ion detector is in the right panel.

The LHC-Heavy Ion program promises to be as exciting as the RHIC program and when the beams are operational later this year will yield many interesting results and probably a few surprises.

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