1 Introduction

Since the AGS and SpS fixed target heavy-ion programs began operations in 1986, BNL and CERN have been the principal laboratories for measurements of high energy nucleus-nucleus collisions which create nuclear matter in conditions of extreme temperature and density [1, 2]. The kinetic energy of the incident projectiles is dissipated in the large volume of nuclear matter involved in the reaction. At large energy or baryon densities, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of “deconfined” (from their individual nucleons) quarks and gluons, in chemical and thermal equilibrium, covering a volume that is many units of the confining length scale. This state of nuclear matter was originally given the name Quark Gluon Plasma (QGP) [3], a plasma being an ionized gas.

The startup of the Relativistic Heavy Ion Collider (RHIC) at BNL in the year 2000 provided a major advance in the field, leading to the discovery of the QGP at RHIC, which was announced on April 19, 2005. The results at RHIC [4] indicated that instead of behaving like a gas of free quarks and gluons, the matter created in heavy ion collisions at nucleon-nucleon c.m. energy $\sqrt{s_{NN}} = 200$ GeV appears to be more like a liquid. This matter interacts much more strongly than originally expected, as elaborated in peer reviewed articles by the 4 RHIC experiments [4, 5, 6, 7], which inspired the

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theorists [8] to give it the new name “sQGP” (strongly interacting QGP). These properties were quite different from the properties of the CERN SpS fixed-target heavy ion results which led to the claim of “new state of matter”, in a press-conference [9] on February 10, 2000, that was neither peer-reviewed nor published. However, results in the past two years from Pb+Pb measurements at the CERN-LHC at $\sqrt{s_{NN}} = 2760$ GeV (2.76 TeV) confirm the RHIC discoveries [1, 2] and add some new information—notably with fully reconstructed jets [10, 11].

J/Ψ suppression, proposed by Matsui and Satz in 1986 [12] as the ‘gold-plated’ signature for deconfinement, suffered from the significant J/Ψ suppression observed in the Cold Nuclear Matter (CNM) of p+A collisions [13] ($A^{0.92}$) relative to the point-like scaling ($A^{1.0}$) from p-p collisions expected for the large mass scale. Although, “anomalous” J/Ψ suppression, i.e. more than the estimated CNM effect, was discovered at the CERN SPS heavy ion program and is its main claim to fame, the later development of J/Ψ measurements has not been concerned with J/Ψ suppression as a signature of deconfinement, but rather with the strong c.m. energy dependence of the CNM effect and the possibility of regeneration of J/Ψ from recombination of the large number of c and $\bar{c}$ quarks produced in the QGP (e.g. see ref. [1]). Nevertheless, the search for J/Ψ suppression (as well as thermal photon/dilepton radiation from the QGP) drove the design of the RHIC experiments [14] and the ALICE experiment at the LHC [15].

2 The RHIC machine in 2012

With the shutdown of the Tevatron at FERMILAB, on September 30, 2011 after 28 years of operation, RHIC at Brookhaven National Laboratory (Fig. 1) is the only hadron collider in the U.S. and one of only two hadron-colliders in the world, the other being the CERN-LHC. Also RHIC is the world’s first and only polarized proton collider. RHIC is composed of two independent rings, of circumference 3.8 km, containing a total of 1,740 superconducting magnets. RHIC can collide any species with any other species and since beginning operation in the year 2000 has provided collisions at 15 different values of nucleon-nucleon c.m. energy, $\sqrt{s_{NN}}$, and six different species combinations. The performance history of RHIC with A+A and polarized p-p collisions is shown in Fig. 2.

This past year, the performance was even more outstanding than usual thanks to the new EBIS source and 3-dimensional stochastic cooling [16]. For the first time in a collider, Cu+Au and U+U collisions at $\sqrt{s_{NN}} = 200$
Figure 1: Aerial view of the RHIC facility [14]. The six crossing points are labelled as on a clock. The two principal experiments still running are PHENIX and STAR. Two smaller experiments PHOBOS [5] and BRAHMS [4] have been completed; a test run, AnDy, occupies the former location of BRAHMS. The LINAC is the injector for polarized protons into the Booster/AGS/RHIC chain; with the Jet Target used for precision beam polarization measurements. The TANDEM injector for Ions has been replaced by the Electron Beam Ion Source (EBIS) starting with the 2012 run.

Figure 2: a)(left) Au+Au performance, where the nucleon-pair luminosity is defined as $L_{NN} = A \times B \times L$, where $L$ is the luminosity and $A$, $B$ are the number of nucleons in the colliding species. b) (right) Polarized p-p performance. Courtesy Wolfram Fischer.
GeV were studied, with the purpose of: i) $J/\Psi$ suppression with no-corona in central collisions (Cu+Au); ii) a large eccentricity of the overlap zone in central collisions by using a very large deformed nucleus with a prolate shape, like a rugby ball (U+U). Also, the polarized p-p runs in 2012 included both $\sqrt{s} = 200$ and 510 GeV with improved polarization and luminosity for the purposes of: iii) comparison data for the new silicon vertex detectors (200 GeV); iv) flavor-identified parton spin distribution functions using the parity violating single spin asymmetry in $W^\pm$ production (500 GeV) [17].

3 Issues in A+A versus p-p collisions

The principal difference in dealing with collisions of relativistic heavy ions, e.g. Au+Au, compared to p-p or e-p (or e-A) collisions at the same nucleon-nucleon c.m. energy, $\sqrt{s_{NN}}$, is that the particle multiplicity is $\sim A$ times larger in A+A central collisions than in p-p collisions as shown in actual events from the STAR and PHENIX detectors at RHIC (Fig. 3). This year, both experiments have benefitted from incremental upgrades, with STAR at present making use of an EM calorimeter with a shower-maximum detector; and PHENIX with central and “forward” silicon vertex detectors for event-by-event identification of $c$ and $b$ quarks.

A schematic drawing of a collision of two relativistic Au nuclei is shown in Fig. 4. In the center of mass system of the nucleus-nucleus collision, the two Lorentz-contracted nuclei of radius $R$ approach each other with impact parameter $b$. In the region of overlap, the “participating” nucleons interact with each other, while in the non-overlap region, the “spectator” nucleons simply continue on their original trajectories and can be measured,
in principle, by Zero Degree Calorimeters (ZDC), so that the number of participants, \( N_{\text{part}} \), can be directly determined. The degree of overlap is called the centrality of the collision, with \( b \sim 0 \), being the most central and \( b \sim 2R \), the most peripheral. The impact parameter \( b \) can not be measured directly, so the centrality of a collision is defined in terms of the upper percentile of \( n_{\text{ch}} \) distributions, e.g. top 10%-ile, upper 10 – 20%-ile, from which \( b \) and \( N_{\text{part}} \) can be deduced.

The energy of the inelastic collision is predominantly dissipated by multiple production of soft particles (\( \langle p_T \rangle \approx 0.36 \text{ GeV/c} \)), where \( n_{\text{ch}} \), the number of charged particles produced, is directly proportional to the number of participating nucleons (\( N_{\text{part}} \)) as sketched on Fig. 4a. Figure 4b shows the measured distributions [18] of the charged particle multiplicity, \( n_{\text{ch}} \), at mid-rapidity at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) for all the combinations of A+B collisions measured at RHIC. The increase of \( n_{\text{ch}} \) with both \( A \) and \( B \) is evident.

### 3.1 Collective Flow

Another unique feature of A+A collisions compared to either p-p or p+A collisions is the “flow” observed, which is a collective effect that can not be obtained from a superposition of independent N-N collisions. Immediately after an A+A collision, the overlap region defined by the nuclear geometry of participants is roughly almond shaped (see Fig. 5a); with the shortest axis roughly along the impact parameter vector, which together with the
Figure 5: a) (left) Almond shaped overlap zone generated just after an A+A collision where the incident nuclei are moving along the ±z axis and the impact parameter vector is along the x axis. b) (right) Measurements of elliptical-flow ($v_2$) and triangular flow ($v_3$) for identified hadrons plotted as $v_k$, divided by the number of constituent quarks $n_q$ in the hadron raised to the power $k/2$, as a function of $KE_T/n_q$ [19].

beam (z) axis defines the reaction plane. Fluctuations in the distribution of participants from event-to-event do not respect the average symmetry of the almond, $\phi \rightarrow \phi + \pi$, so that the event plane of the participants, with angle $\Psi_k$, is relevant in the Fourier decomposition of the azimuthal distribution:

$$Ed^3N/dp^3 = (d^3N/2\pi p_Tdp_Tdy)[1 + \sum_{k \geq 1} 2v_k \cos k(\phi - \Psi_k)]$$

(1)

which is no longer restricted to even harmonics $v_k$ by symmetry so that odd harmonics such as $v_3$ can be produced [1], which was observed (Figs. 5b).

The flow can also be seen in two-particle correlations. The fact that the flow persists for $p_T > 1$ GeV/c [20] and that the higher harmonics are not strongly damped [21, 22] implies that the viscosity is small, perhaps as small as a quantum viscosity bound from string theory [23], $\eta/s = 1/(4\pi)$ where $\eta$ is the shear viscosity and $s$ the entropy density per unit volume. This has led to the description of the “sQGP” produced at RHIC as “the perfect fluid” [8]. It was observed that the flow is not dominated by final state hadrons but is proportional to the number of constituent quarks $n_q$ in the mesons and baryons, in which case $v_2/n_q$, as well as $v_3/n_q^{3/2}$ [19], as

\[\text{If two particles } A \text{ and } B \text{ are correlated to the event plane but not otherwise correlated, the analog of Eq. 1 is } dN^{AB}/d\phi^A d\phi^B \propto [1 + \sum_{k \geq 1} 2v_k^A v_k^B \cos k(\phi^A - \phi^B)].\]
a function of the transverse kinetic energy per constituent quark, $KE_T/n_q$, would be universal, as shown in Fig. [5], where the power $k/2$ and the transverse kinetic energy, $KE_T ≡ m_T - m_0$, are suggested by the relativistic hydrodynamics of “ideal” fluids [24, 25].

4 Old and New RHIC results

One of the most important innovations at RHIC was the use of hard scattering as an in-situ probe of the medium produced in A+A collisions by the effect of the medium on outgoing hard-scattered partons produced by the initial A+A collision. Measurements in p+A (or d+A) collisions, where no (or negligible) medium is produced, allow correction for any modification of the nuclear structure function from an incoherent superposition of proton and neutron structure functions.

Hard-scattering of partons in p-p collisions was discovered at the CERN-ISR in 1972 as shown at the ICHEP 1972 conference [26] by observation that the $e^{-6p_T}$ dependence for pion production at low $p_T$ breaks to a power-law for $p_T > 2$ GeV/c with a characteristic $\sqrt{s}$ dependence (Fig. 5b) which is more evident from the log-log plot of subsequent $\pi^0$ data (Fig. 6b). This plot, as a function of $x_T = 2p_T/\sqrt{s}$ (Fig. 6b), shows that the cross section for hard-processes (Fig. 6c) obeys the scaling law, called “$x_T$-scaling”:

$$E \frac{d^3\sigma}{d^3p} = \frac{1}{p_T^{n_{\text{eff}}}} F(\frac{p_T}{\sqrt{s}}) = \frac{1}{\sqrt{s}^{n_{\text{eff}}}} G(x_T)$$ (2)

for $\sqrt{s} \geq 53.1$ GeV, $x_T \geq 0.3 (p_T \geq 7$ GeV/c), where $n_{\text{eff}}(x_T, \sqrt{s}) \sim 4 - 6$ gives the form of the force-law between constituents as predicted by Quantum Chromodynamics (QCD) with non-scaling structure and fragmentation functions and running coupling constant [1].

Figure 6a provided the first evidence that the electrically charged partons of e-p deeply inelastic scattering (DIS) interacted with each other much more strongly than electromagnetically [2]. Note that the parton degrees of freedom in p-p collisions become evident only for parton-parton scattering
at large $Q^2 \approx 2p_T^2 \gtrsim 5 - 8$ (GeV/c)$^2$, while in DIS, only $Q^2 > 1$ (GeV/c)$^2$ is required.

The use of hard-scattering to probe the thermal or “soft” medium produced in RHI collisions was stimulated by pQCD studies \cite{28} of the energy loss of partons produced by hard scattering, “with their color charge fully exposed”, in traversing a medium “with a large density of similarly exposed color charges”. The conclusion was that “Numerical estimates of the loss suggest that it may be significantly greater in hot matter than in cold. *This makes the magnitude of the radiative energy loss a remarkable signal for QGP formation*” \cite{28}. In addition to being a probe of the QGP the fully exposed color charges allow the study of parton-scattering with $Q^2 \ll 1 - 5$ (GeV/c)$^2$ in the medium where new collective QCD effects may possibly be observed.

The discovery, at RHIC \cite{29}, that $\pi^0$’s produced at large transverse momenta are suppressed in central Au+Au collisions by a factor of $\sim 5$ compared to point-like scaling from p-p collisions is arguably the major discovery in Relativistic Heavy Ion Physics. For $\pi^0$ (Fig. 7a) \cite{30} the hard-scattering in p-p collisions is indicated by the power law behavior $p_T^{-n}$ for the invariant cross section, $Ed^3 \sigma / dp^3$, with $n = 8.1 \pm 0.05$ for $p_T \geq 3$ GeV/c. The Au+Au
Figure 7: a) (left) Log-log plot of invariant yield of $\pi^0$ at $\sqrt{s_{NN}} = 200$ GeV as a function of transverse momentum $p_T$ in p-p collisions multiplied by $\langle T_{AA} \rangle$ for Au+Au central (0–10%) collisions compared to the Au+Au measurement [30]. b) (right) $R_{AA}(p_T)$ for all identified particles so far measured by PHENIX in Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV.

data at a given $p_T$ can be characterized either as shifted lower in $p_T$ by $\delta p_T$ from the point-like scaled p-p data at $p'_T = p_T + \delta p_T$, or shifted down in magnitude, i.e. suppressed. In Fig. 7, the suppression of the many identified particles measured by PHENIX at RHIC is presented as the Nuclear Modification Factor, $R_{AA}(p_T)$, the ratio of the yield of e.g. $\pi$ per central Au+Au collision (upper 10%-ile of observed multiplicity) to the point-like-scaled p-p cross section, where $\langle T_{AA} \rangle$ is the average overlap integral of the nuclear thickness functions:

$$R_{AA}(p_T) = \frac{d^2N_{AA}^\pi/dp_TdyN_{AA}}{\langle T_{AA} \rangle d^2\sigma_{pp}^\pi/dp_Tdy} . \tag{3}$$

The striking differences of $R_{AA}(p_T)$ in central Au+Au collisions for the many particles measured by PHENIX (Fig. 7) illustrates the importance of particle identification for understanding the physics of the medium produced at RHIC. Most notable are: the equal suppression of $\pi^0$ and $\eta$ mesons by a constant factor of 5 ($R_{AA} = 0.2$) for $4 \leq p_T \leq 15$ GeV/c, with suggestion of an increase in $R_{AA}$ for $p_T > 15$ GeV/c; the equality of suppression of direct-single $e^\pm$ (from heavy quark ($c$, $b$) decay) and $\pi^0$ at $p_T \gtrsim 5$ GeV/c; the non-suppression of direct-$\gamma$ for $p_T \geq 4$ GeV/c; the exponential rise of $R_{AA}$ of direct-$\gamma$ for $p_T < 2$ GeV/c [31], which is totally and dramatically different from all other particles and attributed to thermal photon production by many authors (e.g. see citations in reference [31]). For $p_T \gtrsim 4$ GeV/c, the hard-scattering region, the fact that all hadrons are suppressed,
but direct-$\gamma$ are not suppressed, indicates that suppression is a medium effect on outgoing color-charged partons likely due to energy loss by coherent Landau-Pomeranchuk-Migdal radiation of gluons, predicted in pQCD [28], which is sensitive to properties of the medium. Measurements of two-particle correlations [1] confirm the loss of energy of the away-jet relative to the trigger jet in Au+Au central collisions compared to p-p collisions. However, there are still many details which remain to be understood, such as the apparent suppression of direct-$\gamma$ for $p_T \gtrsim 18$ GeV/c, approaching that of the $\pi^0$. Interesting new results this year extend and clarify these observations.

An improved measurement of $\pi^0$ production in Au+Au and p-p collisions by PHENIX [32] now clearly shows a significant increase of $R_{AA}$ (decrease in suppression) with increasing $p_T$ over the range $7 < p_T < 20$ GeV/c for 0-5% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (Fig. 8a). Interestingly, despite more than a factor of 20 higher $\sqrt{s_{NN}}$, the ALICE $R_{AA}$ data from LHC [33] are nearly identical to the RHIC measurement for $5 < p_T < 20$ GeV/c. However, since the exponent of the power-law at LHC ($n \approx 6$) is flatter than that at RHIC ($n \approx 8$, Fig. 7a), a $\sim 25\%$ larger shift $\delta p_T / p_T$ in the spectrum from p-p to A+A is required at LHC to get the same $R_{AA}$ (Fig. 8b), likely indicating $\sim 25\%$ larger fractional energy loss at LHC in this $p_T$ range.

Measurements by STAR (Fig. 9a) [34] of the evolution of charged hadron suppression with $\sqrt{s_{NN}}$ in Au+Au collisions, using the variable $R_{CP} = (R_{AA}^{0-5\%}/R_{AA}^{60-80\%})$ which does not require the p-p cross section (see Eq. 3).

Figure 8: a) (left) $R_{AA}$ of $\pi^0$ in $\sqrt{s_{NN}} = 200$ GeV central (0-5%) Au+Au collisions [32] at RHIC compared to charged hadron $R_{AA}$ in $\sqrt{s_{NN}} = 2.76$ TeV central (0-5%) Pb+Pb collisions at LHC. b) (right) Shift of $p_T$ spectrum $S_{loss} = \delta p_T / p_T$ vs. $p_T$ (p-p) calculated by PHENIX [32] for RHIC and LHC.
but is usually smaller than $R_{AA}$ \cite{4}, show the transition from suppression ($R_{CP} < 1$) to enhancement ($R_{CP} > 1$) for $\sqrt{s_{NN}} > 27$ GeV.

Figure 9: a) (left) STAR $R_{CP}(p_T)$ for $h^\pm$ as a function of $\sqrt{s_{NN}}$ in Au+Au collisions \cite{34}. b)(right) PHENIX $R_{AA}(p_T)$ of direct-$\gamma$ in d+Au and Au+Au minimum bias collisions at $\sqrt{s_{NN}} = 200$ GeV \cite{35}.
Figure 10: a)(left) $\sqrt{s}^{n_{\text{eff}}} \times E d^{3} \sigma / d p^{3}$, as a function of $x_T = 2p_T / \sqrt{s}$, with \( n_{\text{eff}} = 4.5 \), for direct-$\gamma$ measurements in p-p and $\bar{p}$-$p$ experiments at the ($\sqrt{s}$ GeV) indicated. [36]. b)(right) same as (a) with $n_{\text{eff}} = 4.0$

universal curve in Fig. 10(a) (and from pQCD) is claimed to be due to the $k_T$ effect (transverse momentum of the quarks in a nucleon).

Since the $p_T^\gamma$ of a direct-$\gamma$ can be measured very precisely, the fragmentation function of the jet from the away quark in the reaction $g + q \rightarrow \gamma + q$ can be measured by the direct-$\gamma - h$ correlations (where $h$ represents charged hadrons opposite in azimuth to the direct-$\gamma$) because the $p_T$ of the away-quark at production is equal and opposite to $p_T^\gamma$, thus known to high precision (modulo a small $k_T$-smearing effect). This year, improved measurements by PHENIX [37] in both p-p and Au+Au collisions (Fig. 11) now indicate a significant modification of the fragmentation function in Au+Au (0-40%) central collisions compared to p-p (Fig. 11), with an enhancement at large $\xi = -\ln z_T$ (low $z_T = p_T^h / p_T^\gamma$) and a suppression at small $\xi$ (large $z_T$) which is more clearly seen as $I_{AA}(\xi)$, the ratio of the fragmentation functions in Au+Au/pp (Fig. 11). As shown in Fig. 11,c,d, restricting the away-side azimuthal range reduces the large $\xi > 0.9$ ($p_T^\gamma \lesssim 3$ GeV/c) enhancement but leaves the suppression at small $\xi < 0.9$ relatively unchanged, which shows that the large $\xi$ enhancement is predominantly at large angles, similar to the effect observed by CMS with actual jets. [38].
Figure 11: a) $\xi = -\ln(p_T^h/p_T^\gamma) = -\ln z_T$ distributions of hadrons opposite in azimuth ($|\pi - \Delta \phi| < \pi/2$) to a direct-$\gamma$ trigger with $5 < p_T^\gamma < 9$ GeV/c in p-p and 0–40% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX [23]. b) Ratio of the two distributions, $I_{AA}(\xi)$. c) (right)-(top) $I_{AA}(\xi)$ as in (b) when the away-side azimuthal range is restricted as indicated. d) (right)-(bottom) Ratio of $I_{AA}$ for $|\pi - \Delta \phi| < \pi/2$ to $|\pi - \Delta \phi| < \pi/6$.

One of the most exciting discoveries at RHIC, now confirmed at the LHC, is the suppression of heavy quarks by the same amount as light quarks for $p_T \gtrsim 5$ GeV/c as indicated at RHIC (Fig. 7b) by direct single-$e^{\pm}$ from heavy quark ($c, b$) decay; and at the LHC by $D$ mesons from $c$-quarks [39], and non-prompt $J/\Psi$ from $b$-quarks [10] (Fig. 12a). The discovery at RHIC was a total surprise and a problem since it appears to disfavor the radiative energy loss explanation [28] of suppression (also called jet-quenching) because heavy quarks should radiate much less than light quarks or gluons.

Many explanations have been offered including some from string theory; but the explanation I prefer was by Nino Zichichi [41] who proposed that since the standard model Higgs Boson, which gives mass to the Electro-Weak vector Bosons, does not necessarily give mass to Fermions, “it cannot be excluded that in a QCD coloured world (a QGP), the six quarks are all nearly massless”. If this were true it would certainly explain why light and heavy quarks appear to exhibit the same radiative energy loss in the medium. This idea can, in fact, be tested because the energy loss of one hard-scattered parton relative to its partner, e.g. $g + g \rightarrow b + \bar{b}$, can be measured by experiments at RHIC and LHC using two particle correlations in which both
the outgoing $b$ and $\bar{b}$ are identified by measurement of the Distance of Closest Approach (DCA) of their displaced decay vertices in silicon vertex detectors. When such results are available, they can be compared to $\pi^0$-charged hadron correlations from light quark and gluon jets, for which measurement of the relative energy loss has been demonstrated at RHIC [1].

Of course, measurement of the Yukawa couplings to Fermions of the candidate 125 GeV Higgs Boson at the LHC may be available by the end of 2012; but, already this year, the first direct measurement of $b$-quarks in p-p and Au+Au collisions at RHIC by their displaced vertices was made in the new PHENIX Silicon VTX detector [42]. Figure 12b shows the measurement of the $b$-quark fraction $F_b = b \rightarrow e/(c \rightarrow e + b \rightarrow e)$ of direct single-$e^\pm$ in p-p and Au+Au from PHENIX measurement of the Distance of Closest Approach (DCA) of the displaced vertex.

The correct conditional DCA distribution requires the actual (modified) $b$-quark $p_T$ spectrum in Au+Au, which must be obtained by iteration. Once the iteration has converged, the $R_{AA}^p(p_T^e)$ can be calculated from the measured $R_{AA}(p_T^e)$ of the direct-single-$e^\pm$ by the relation $R_{AA}^p(p_T^e) = R_{AA}(p_T^e) \times F_{b}^{AA}/F_{b}^{pp}$. For example, if the final $F_{b}^{AA} = F_{b}^{pp}$ then $R_{AA}^p(p_T^e) = R_{AA}(p_T^e)$.
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