Review

Latest Results from RHIC + Progress on Determining $\hat{q}L$ in RHI Collisions Using Di-Hadron Correlations

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Abstract: Results from Relativistic Heavy Ion Collider Physics in 2018 and plans for the future at Brookhaven National Laboratory are presented.

Keywords: RHIC qhat dihadron correlations

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is one of the two remaining operating hadron colliders in the world, and the first and only polarized p+p collider. BNL is located in the center of the roughly 200 km long maximum 40 km wide island (named Long Island), and appears on the map as the white circle which is the berm containing the Relativistic Heavy Ion Collider (RHIC). BNL is 100 km from New York City in a region which nurtures science with Columbia University and the Bronx High School of Science indicated (Figure 1). Perhaps more convincing is the list of the many Nobel Prize winners from New York City High School graduates (Figure 2) which does not yet include one of this years Nobel Prize winners in Physics, Arthur Ashkin who graduated from James Madison High school in 1940 and Columbia U. in 1947.

Figure 1. NASA infra-red photo of Long Island and the New York Metro Region from space. RHIC is the white circle to the left of the word BNL. Manhattan Island in New York City, ~100 km west of BNL, is also clearly visible on the left side of the photo, with Columbia U. and Bronx Science High School indicated.
<table>
<thead>
<tr>
<th>Class</th>
<th>Name of laureate</th>
<th>Award and year</th>
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<td>Stefan Gledhow</td>
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<td>1957</td>
<td>John O'Keefe</td>
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<td>2014</td>
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Figure 2. From Wikipedia (edited), Physicists in blue and Roald Hoffman a classmate of mine from Columbia.

There also have been many discoveries and Nobel Prizes at BNL (Figure 3).

In particular, Leon Lederman, who made many discoveries at BNL (Figure 4), died this year (2018) at the age of 96. Leon was the most creative and productive high energy physics experimentalist of his generation as well as the physicist with the best jokes. He was also my PhD thesis Professor. For more details, see [https://physicstoday.scitation.org/doi/10.1063/PT.6.4.20181010a/full/](https://physicstoday.scitation.org/doi/10.1063/PT.6.4.20181010a/full/).
2. Why RHIC Was Built: To Discover the Quark Gluon Plasma (QGP)

Figure 5 shows central collision particle production in the PHENIX and STAR detectors, which were the major detectors at RHIC.

At the startup of RHIC in the year 2000, there were two smaller more special purpose detectors PHOBOS and BRAHMS, as shown in Figure 6, which finished data taking in 2005.
Discovery of the QGP: Why RHIC was built

The surprise is that it is a perfect liquid

Zimanyi School 2018 M. J. Tannenbaum

Fluid

2005

Figure 5. View along the beam direction of tracks of charged particles from central collision events in Au+Au collisions in the PHENIX and STAR detectors at RHIC.

Figure 6. View of RHIC location from the air. The positions of the four original detectors, PHENIX, STAR PHOBOS and BRAHMS are indicated as well as the AGS (with three Nobel Prizes shown in Figure 3).

2.1. The First Major RHIC Experiments

The two major experiments at RHIC were STAR (Figure 7), which is still operating, and PHENIX (Figure 8), which finished data taking at the end of the 2016 run.
STAR Detector

- Tracking and PID (full 2π)
  - TPC: |η| < 1
  - TOF: |η| < 1
  - BEMC: |η| < 1
  - EEMC: 1 < η < 2
  - HFT (2014-2016): |η| < 1
  - MTD (2014+): |η| < 0.5

- MB trigger and event plane reconstruction
  - BBC: 3.3 < |η| < 5
  - EPD (2018+): 2.1 < |η| < 5.1
  - FMS: 2.5 < |η| < 4
  - VPD: 4.2 < |η| < 5
  - ZDC: 6.5 < |η| < 7.5

- On-going/future upgrades
  - iTPC (2019+): |η| < 1.5
  - eTOF (2019+): −1.6 < |η| < −1
  - FCS (2021+): 2.5 < |η| < 4
  - FTS (2021+): 2.5 < |η| < 4

Figure 7. STAR is based on a normal conductor solenoid with Time Projection Chamber for tracking, an EM Calorimeter, Vertex detector and µ detector behind the thick iron yoke.

- PHENIX was a special purpose detector designed and built to measure rare processes involving leptons and photons at the highest luminosities.
  - possibility of zero magnetic field on axis
  - minimum of material in aperture 0.4% X₀
  - EMCAL RICH e± i.d. and lvl-1 trigger
  - γ ± separation up to pT ~ 25 GeV/c
  - EMCAL and precision TOF for h±pid

Comparison to scale with a wedge of CMS

Last PHENIX run was 2016

Figure 8. As indicated on the figure, PHENIX is a special purpose detector for electrons and photons but also measures charged hadrons and notably \( \pi^0 \rightarrow \gamma + \gamma \) at mid-rapidity and muons in the forward direction.

2.2. The New Major RHIC Experiment sPHENIX

sPHENIX is a major improvement over PHENIX with a superconducting thin coil solenoid which was surplus from the BABAR experiment at SLAC and is now working at BNL and has reached its full field (Figure 9).
The SC-Magnet has last been operated 10 years ago and has since been moved from SLAC to BNL. The full current cold test in Jan-Feb 2018 tested:

- Magnet Integrity
- The Power Supply to be used by sPHENIX
- The Quench Protection and Magnet controls that will be used by sPHENIX
- The new extension to the cryo chimney

The SC-Magnet has been approved by the U.S. Department of Energy (DoE) as a Major Item of Equipment (MIE) with the schedule of critical decisions shown in Figure 11a, and the planned multi-year RHIC runs indicated in Figure 11b. The present sPHENIX collaboration and its evolution is shown in Figure 12.
Critical Decision Level 1 MIE Schedule

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<th>Milestone</th>
<th>Schedule Date</th>
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<td>CD-0, Approve Mission Need</td>
<td>9/27/2016</td>
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<tr>
<td>CD-1/3A, Approve Alternative Selection and Cost Range. Long Lead Procurements</td>
<td>Q4 FY 2018</td>
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<tr>
<td>CD-2/3, Approve Performance Baseline</td>
<td>Q4 FY 2019</td>
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<tr>
<td>CD-4, Approve Project Completion</td>
<td>Q1 FY 2023</td>
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</table>

Multi-year run plan for sPHENIX

sPHENIX collaboration evolution

Figure 11. (a) DoE Critical Decision Schedule; and (b) multi-year run plan for sPHENIX.

Figure 12. List of the sPHENIX collaboration members in June 2018 together with photos showing the evolution since December 2015. Dave Morrison (BNL) and Gunther Roland (MIT) are spokespersons.
2.3. Following RHIC in U.S. Nuclear Physics: the Electron Ion Collider (EIC)

Statement by Brookhaven Lab, Jefferson Lab, and the Electron-Ion Collider Users Community on National Academy of Sciences Electron-Ion Collider (EIC) Report

July 24, 2018

On July 24, 2018, a National Academy of Sciences (NAS) committee issued a report of its findings and conclusions related to the science case for a future U.S.-based Electron-Ion Collider (EIC) and the opportunities it would offer the worldwide nuclear physics community.

The committee’s report—commissioned by the U.S. Department of Energy (DOE)—comes after 14 months of deliberation and meetings held across the U.S. to gather input from the nuclear science community. The report’s conclusions include the following:

- The committee concludes that the science questions regarding the building blocks of matter are compelling and that an EIC is essential to answering these questions.
- The answers to these fundamental questions about the nature of the atoms will also have implications for particle physics and astrophysics and possibly other fields.
- Because an EIC will require significant advances and innovations in accelerator technologies, the impact of constructing an EIC will affect all accelerator-based sciences.
- In summary, the committee concludes that an EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading and will ensure global U.S. leadership in nuclear science as well as in the accelerator science and technology of colliders.

The first BNL EIC design in 2014 is shown in Figure 13. The 2018 JLab and BNL EIC designs are shown in Figures 14 and 15.
Figure 13. The 2014 cost estimate: BNL $755.9M; Temple NSAC subcommittee cost estimate $1.5B.

Figure 14. JLab EIC Concept. Temple committee cost estimate also $1.5B but no new accelerator technology required.
The two new designs of the JLab (JLEIC) and BNL (eRHIC) both satisfy the Temple committee cost estimate of $1.5B, but R&D of the novel first BNL design is not idle.

Research and Development (R&D) for an Improved Less Expensive BNL Machine Is Ongoing

BNL and Cornell are in the process of experiments studying an energy recovery linac ERL (Figure 16a). Figure 16b is the main Linac cryo module made from superconducting RF cavities. Figure 16c is a return loop made from fixed-field alternating-gradient (FFAG) optics made with permanent Halbach magnets to contain four beam energies in a single 70 mm-wide beam pipe, designed and prototyped at Brookhaven National Laboratory (BNL).
Small Accelerator Promises Big Returns

Under construction in the US, the CBETA multi-turn energy-recovery linac will pave the way for accelerators that combine the best of linear and circular machines.

March 16, 2018

Figure 16. (a) CBETA (Cornell-Brookhaven Energy Recovery Linac (ERL)); (b) Main Linac cryo module; and (c) FFAG permanent loop return loop.

3. RHIC Future Run Plan (Figure 17) and the Present RHIC Run in 2018 (Figure 18)

3.1. 2018 RHIC Run Is $^{40}\text{Zr}^{96} + ^{40}\text{Zr}^{96}$ and $^{44}\text{Ru}^{96} + ^{44}\text{Ru}^{96}$, Why?

To determine whether the separation of charges in the flow, $v_2$, of $\pi^+$ and $\pi^-$ shown in Figure 19 is due to a new phenomenon called the Chiral Magnetic Effect (Figure 20a), the 2018 measurements are made with collisions of Zr+Zr and Ru+Ru, which have the same number of nucleons but different electric charges (Figure 20b). If the effect is larger in Ru+Ru with stronger charge and magnetic field compared to Zr+Zr with the same number of nucleons, it would indicate that the charge asymmetry is a magnetic effect, possibly the Chiral Magnetic Effect.
### BNL’s future plan 2017 still works in 2018

<table>
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<th>Years</th>
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<td>Au+Au at 15 GeV</td>
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<td>Au+Au at 200 GeV</td>
<td>Heavy flavor flow, energy loss, thermalization, etc.</td>
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<td>He+Au at 200 GeV</td>
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<td>STAR MTD</td>
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<tr>
<td>2015-16</td>
<td>p⁺p⁻ at 200 GeV</td>
<td>Extract n(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests</td>
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<td></td>
<td>p⁺p⁻ at 200 GeV</td>
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<td>STAR FMS preshower</td>
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<td>d+Au at 200 GeV</td>
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<td>Coherent e-cooling test</td>
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<td>Coherent e-cooling final</td>
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<td>2022-23</td>
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<td>Jet, di-jet, y-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin &amp; initial state physics</td>
<td>sPHENIX</td>
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<td>2024-26</td>
<td>Factor of 10 increase Au+Au No Runs</td>
<td>Complete above measurements</td>
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<td>2022-23</td>
<td>Factor of 4 increase p+p</td>
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This color is sPHENIX proposed run plan

**Figure 17.** RHIC run plan 2014–2023 (2026?).

**Figure 18.** The 2018 RHIC run schedule.
3.2. Vorticity: An Application of Particle Physics to the QGP

It was observed at FERMILAB [1] that forward Λ were polarized in p+Be collisions, where the proton in the $\Lambda \rightarrow p + \pi^-$ decay is emitted along the spin direction of the Λ. In the A+A collision (Figure 21a), the forward going beam fragments are deflected outwards so that the event plane and the angular momentum $\vec{J}_{\text{sys}}$ of the QGP formed can be determined. STAR claims that the Λ polarization, $P_{\Lambda}$, is parallel to the angular momentum $\vec{J}_{\text{sys}}$ of the QGP everywhere so that the vorticity $\omega = k_B T (P_{\Lambda} + P_{\Sigma}) / \hbar$ can be calculated, a good exercise for the reader to see if you can get the $\omega \sim 10^{22}/s$ which is $10^5$ times larger than any other fluid [2]. Another interesting thing to note is that the largest vorticity is at
\( \sqrt{s_{NN}} = 7.6 - 19 \text{ GeV} \) where the CERN fixed target experiments measure. Does this mean that their fluid (with minimal if any QGP) is also perfect?

STAR team receives secretary’s achievement award for vorticity in 2018 (Figure 22).

\[ P_{H} = \mathcal{P}_{\Lambda} \text{ or } \mathcal{P}_{\bar{\Lambda}} \text{ vs. } \sqrt{s_{NN}} \text{ [3].} \]

Figure 21. (a) Schematic of STAR vorticity detection; and (b) polarization \( P_{H} = \mathcal{P}_{\Lambda} \text{ or } \mathcal{P}_{\bar{\Lambda}} \text{ vs. } \sqrt{s_{NN}} \text{ [3].} \)

4. The Search for the Quark Gluon Plasma at RHIC

High energy nucleus–nucleus collisions provide the means of creating nuclear matter in conditions of extreme temperature and density, the Quark Gluon Plasma QGP (Figure 23). At large energy or baryon density, 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 covering a volume that is many units of the confinement length.
4.1. Anisotropic (Elliptical) Transverse Flow—An Interesting Complication in all A+A Collisions (Figure 24)

Figure 23. Sketch of nucleus–nucleus collision producing a QGP.

Figure 24. Sketch and definitions of elliptical flow, $v_2$.

Figure 25 shows that Elliptical flow ($v_2$) exists in all A+A collisions measured. At very low $\sqrt{s_{NN}}$, the main effect is from nuclei bouncing off each other and breaking into fragments. The negative $v_2$ at larger $\sqrt{s_{NN}}$ is produced by the effective “squeeze-out” (in the $y$ direction) of the produced particles by slow moving minimally Lorentz-contracted spectators, which block the particles emitted in the reaction plane. With increasing $\sqrt{s_{NN}}$, the spectators move faster and become more contracted so the blocking stops and positive $v_2$ returns.

4.2. Flow Also Exists in Small Systems and Is Sensitive to the Initial Geometry

Figure 26 shows that flow exists in small p+Au, d+Au, $^3$He+Au systems with preliminary sensitivity of $v_3$ to the initial geometry. Figure 27 (Top) shows that $v_2$ is about the same in all three systems
but $v_3$ is much larger in $^3\text{He}+\text{Au}$, clearly indicating the sensitivity of flow to the initial geometry of the collision. Figure 27 (Bottom) shows that there is mass ordering in the flow which is strong evidence for hydrodynamics in these small systems. The solid red and dashed blue lines represent hydrodynamic predictions. These hydrodynamical models, which include the formation of a short-lived QGP droplet, provide the best simultaneous description of the measurements, strong evidence for the QGP in small systems.

**Figure 25.** Values of elliptical flow ($v_2$) as a function of $\sqrt{s_{NN}}$ from all A+A collision measurements.

**Figure 26.** (Top) Published PHENIX $v_2$ measurements in p+Au, and 0-5% central d+Au and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV, with preliminary $v_2$ and $v_3$ for the d+Au and $^3\text{He}+\text{Au}$ compared on the right. (Bottom) PHENIX preliminary $v_2$ in d+Au collisions as a function of $\sqrt{s_{NN}}$ with the centrality indicated illustrating that non-flow effects increase with decreasing $\sqrt{s_{NN}}$. 

4.2.1. It Takes Two Color Strings for Collectivity—Nagle, J.; et al. [6]

This is an answer to the interesting question of the minimal conditions for collectivity in small systems. For the case of $e^+e^-$ collisions in Figure 28 utilizing the AAMPT framework and a single color string, the results indicate only a modest number of parton–parton scatterings and no observable collectivity signal.

$$e^+e^- \rightarrow Z_0 \rightarrow q\bar{q}$$

Figure 28. A fundamental point about QCD and the string tension between the $q$ and $\bar{q}$.

However, a simple extension to two color strings (Figure 29), which represent a simplified geometry in $p+p$ collisions, predicts finite long-range two-particle correlations (known as the ridge) and a strong $v_2$ with respect to the initial parton geometry.

Figure 29. Additional special case—two Strings.
4.2.2. A Fundamental Point about QCD and the String Tension

Unlike an electric or magnetic field between two sources which spreads over all space, in QCD as proposed by Kogut and Susskind [7] the color flux lines connecting two quarks or a $q - \bar{q}$ pair as in Figure 28 are constrained in a thin tube-like region because of the three-gluon coupling. Furthermore, if the field contained a constant amount of color-field energy stored per unit length, this would provide a linearly rising confining potential between the $q - q$ or $q - \bar{q}$ pair.

This led to the Cornell string-like confining potential [8], which combined the Coulomb $1/r$ dependence at short distances from vector-gluon exchange with QCD coupling constant $\alpha_s(Q^2)$, and a linearly rising string-like potential, with string-tension $\sigma$,

$$V(r) = -\frac{\alpha_s}{r} + \sigma r$$

which provided confinement at large distances (Equation (1)). Particles are produced by the string breaking (fragmentation).

4.3. The Latest Discovery Claims “Flow” in Small Systems Is From the QGP How Did We Find the QGP in the First Place?

4.3.1. $J/\psi$ Suppression, 1986

In 1986, T. Matsui and H. Satz [9] said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the $c - \bar{c}$ could not bind. With increasing temperature, $T$, in analogy to increasing $Q^2$, the strong coupling constant $\alpha_s(T)$ becomes smaller, reducing the binding energy, and the string tension, $\sigma(T)$, becomes smaller, increasing the confining radius, effectively screening the potential [10]

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + \sigma r \to -\frac{4}{3} \frac{\alpha_s}{r} e^{-\mu_D r} + \sigma \frac{1 - e^{-\mu_D r}}{\mu_D}$$

where $\mu_D = \mu_D(T) = 1/r_D$ is the Debye screening mass. For $r < 1/\mu_D$, a quark feels the full color charge, but, for $r > 1/\mu_D$, the quark is free of the potential and the string tension, effectively deconfined. The properties of the QGP cannot be calculated in QCD perturbation theory but only in Lattice QCD Calculations [11].

$J/\psi$ suppression eventually didn’t work because the free $c$ and $\bar{c}$ quarks recombined to make $J/\psi$’s [12]. See Alice publication [13].

4.3.2. Jet Quenching by Coherent LPM Radiative Energy Loss of a Parton in the QGP, 1997

In 1997, Baier, Dokshitzer, Mueller, Peigne, Schiff and Zakharov (BDMPSZ) [14] said that the energy loss from coherent Landau–Pomeranchuk–Migdal (LPM) radiation for hard-scattered partons exiting the QGP would result in an attenuation of the jet energy and a broadening of the jets (Figure 30).

As a parton from hard-scattering in the A+B collision exits through the medium, it can radiate a gluon; and both continue traversing the medium. It is important to understand that “Only the gluons radiated outside the cone defining the jet contribute to the energy loss”. In the angular ordering of QCD [15], the angular cone of any further emission will be restricted to be less than that of the previous emission and will end the energy loss once inside the jet cone. This does not work in the QGP so no energy loss occurs only when all gluons emitted by a parton are inside the jet cone. In addition to other issues, this means that defining the jet cone is a big issue—so watch out for so-called trimming.
Jet quenching

4.4. BDMPSZ: The Cone, the Energy Loss, Azimuthal Broadening, Is the QGP Signature

The energy loss of the outgoing parton, \(-dE/dx\), per unit length (x) of a medium with total length L, is proportional to the total four-momentum transfer-squared, \(q^2(L)\), and takes the form:

\[
\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \mu^2 L / \lambda_{\text{mfp}} = \alpha_s \hat{q} L
\]

where \(\mu\) is the mean momentum transfer per collision, and the transport coefficient \(\hat{q} = \mu^2 / \lambda_{\text{mfp}}\) is the four-momentum-transfer-squared to the medium per mean free path, \(\lambda_{\text{mfp}}\).

Additionally, the accumulated momentum-squared, \(\langle p_{\perp W}^2 \rangle\), transverse to a parton traversing a length \(L\) in the medium is well approximated by

\[
\langle p_{\perp W}^2 \rangle \approx \langle q^2(L) \rangle = \hat{q} L
\]

5. Jet Quenching at RHIC, the Discovery of the QGP

The energy loss of an outgoing parton with color charged fully exposed in a medium with a large density of similarly exposed color charges (i.e., a QGP) from Landau–Pomeranchuk–Migdal (LPM) coherent radiation of gluons was predicted in QCD by BDMPSZ [14].

Hard scattered partons (Figure 31a) lose energy going through the medium so that there are fewer partons or jet fragments at a given \(p_T\). The ratio of the measured semi-inclusive yield of, for example, pions in a given A+A centrality class divided by the semi-inclusive yield in a p+p collision times the number of A+A collisions \(N_{\text{coll}}\) in the centrality-class is given by the nuclear modification factor, \(R_{AA}\) (Figure 31b), which equals 1 for no energy loss.

\[
R_{AA}(p_T) = \frac{d^2N_{\pi}^A / p_T dp_T dy N_{\text{inel}}^{AA}}{\langle N_{\text{col}}^{AA} \rangle d^2N_{\pi}^p / p_T dp_T dy N_{\text{inel}}^{pp}}
\]

Figure 30. Jet Cone of an outgoing parton with energy \(E\) [14].

Figure 31. (a) Hard quark-quark scattering in an A+A collision with the scattered quarks passing through the medium formed in the collision; and (b) nuclear modification factor \(R_{AA}(p_T)\).
PHENIX discovered jet quenching of hadrons at RHIC in 2001 [16] (Figure 32). Pions at large $p_T > 2$ GeV/c are suppressed in Au+Au at $\sqrt{s_{NN}}=130$ GeV compared to the enhancement found at the CERN SpS at $\sqrt{s_{NN}}=17$ GeV. This is the first regular publication from a RHIC experiment to reach 1000 citations.

Figure 32. (left) Hadron suppression $R_{AA}$ in Au+Au at $\sqrt{s_{NN}}=130$ GeV by PHENIX at RHIC compared to enhancement at $\sqrt{s_{NN}}=17$ GeV in Pb+Pb at the CERN SpS; and (right) plot is from the cover of PRL [16].

5.1. Status of $R_{AA}$ in Au+Au at $\sqrt{s_{NN}}=200$ GeV

Figure 33 shows the suppression of all identified hadrons, as well as $e^\pm$ from $c$ and $b$ quark decay, with $p_T > 2$ GeV/c measured by PHENIX until 2013. One exception is the enhancement of protons for $2 < p_T < 4$ GeV/c, which are then suppressed at larger $p_T$. Particle Identification is crucial for these measurements since all particles behave differently. The only particle that shows no-suppression is the direct single $\gamma$ (from the QCD reaction $g + q \rightarrow \gamma + q$) which shows that the medium produced at RHIC is the strongly interacting QGP since $\gamma$ rays only interact electromagnetically.
5.2. Recent Measurements to Test the Second BDMPSZ Prediction

(1) The energy loss of the outgoing parton, \(-\frac{dE}{dx}\), per unit length (\(x\)) of a medium with total length \(L\), is proportional to the total four-momentum transfer-squared, \(q^2(L)\), and takes the form:

\[
\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \mu^2 L/\lambda_{\text{mfp}} = \alpha_s \hat{q} L
\]

where \(\mu\) is the mean momentum transfer per collision, and the transport coefficient \(\hat{q} = \mu^2/\lambda_{\text{mfp}}\) is the four-momentum-transfer-squared to the medium per mean free path, \(\lambda_{\text{mfp}}\).

(2) Additionally, the accumulated momentum-squared, \(\langle p_{T}^2 \rangle_{W}\) transverse to a parton traversing a length \(L\) in the medium is well approximated by

\[
\langle p_{T}^2 \rangle_{W} \approx \langle q^2(L) \rangle = \hat{q} L
\]

\[
\langle \hat{q} L \rangle = \langle k_T^2 \rangle_{AA} - \langle k_T^2 \rangle_{pp}.
\]

Although only the component of \(\langle p_{T}^2 \rangle_{W}^{\perp}\) to the scattering plane affects \(k_T\) (Figure 34), the azimuthal broadening of the di-jet is caused by the random sum of the azimuthal components \(\langle p_{T}^2 \rangle_{W}^{\perp}\) from each outgoing di-jet or \(\langle p_{T}^2 \rangle_{W}^{\perp} = \hat{q} L\).

From the values of \(R_{AA}\) observed at RHIC (after 12 years), the JET Collaboration [17] has found that \(\hat{q} = 1.2 \pm 0.3\) GeV²/fm at RHIC, \(1.9 \pm 0.6\) at LHC at an initial time \(t_0 = 0.6\) fm/c; however, nobody has yet measured the azimuthal broadening predicted. Before proceeding, one has to know the meaning of \(k_T\) defined by Feynman, Field and Fox [18] as the transverse momentum of a parton in a nucleon (Figure 34).
Figure 34. Sketch of a di-jet looking down the beam axis. The $k_T$ from the two jets add randomly and are shown with one $k_T$ perpendicular to the scattering plane, which makes the jets acoplanar in azimuth, and the other $k_T$ parallel to the trigger jet, which makes the jets unequal in energy. In addition, 

$$x_E = p_{Ta} \cos(\pi - \Delta \phi)/p_{Tt}.$$ 

The formula for calculating $k_T$ from di-hadron correlations is given in Ref. [19].

5.2.1. The Key New Idea of $\langle k_T^2 \rangle_{pp}$ Instead of $\langle k_T^2 \rangle_{pp}$ in Equation (3)

The di-hadron correlations of $p_{Ta}$ with $p_{Tt}$ (Figure 34) are measured in $p+p$ and $Au+Au$ collisions. The parent jets in the original $Au+Au$ collision as measured in $p+p$ will both lose energy passing through the medium but the azimuthal angle between the jets should not change unless the medium induces multiple scattering from $\hat{q}$. Thus, the calculation of $k'_T$ from the di-hadron $p+p$ measurement to compare with $Au+Au$ measurements with the same di-hadron $p_{Tt}$ and $p_{Ta}$ must use the value of $\hat{x}_h$ and $\langle z_t \rangle$ of the parent jets in the $A+A$ collision. The variables are $x_h \equiv p_{Ta}/p_{Tt}, \hat{x}_h \equiv \hat{p}_{Ta}/\hat{p}_{Tt}, \langle z_t \rangle \equiv p_{Tt}/\hat{p}_{Tt}$, where, e.g., $p_{Tt}$ is the trigger particle transverse momentum and $\hat{p}_{Tt}$ means the trigger jet transverse momentum.

The same values of $\hat{x}_h$ and $\langle z_t \rangle$ in $Au+Au$ and $p+p$ give the cool result [20]:

$$\langle \hat{q}_L \rangle = \left[ \frac{\hat{x}_h}{\langle z_t \rangle} \right]^2 \left[ \frac{\langle p_{out}^2 \rangle_{AA} - \langle p_{out}^2 \rangle_{pp}}{\hat{x}_h^2} \right].$$

(4)

For di-jet measurements, the formula is even simpler:

(i) $x_h \equiv \hat{x}_h$ because the trigger and away “particles” are the jets; (ii) $\langle z_t \rangle \equiv 1$ because the trigger “particle” is the entire jet not a fragment of the jet; and (iii) $\langle p_{out}^2 \rangle = \hat{p}_{Ta}^2 \sin^2(\pi - \Delta \phi)$. This reduces the formula for di-jets to:

$$\langle \hat{q}_L \rangle = \left[ \langle p_{out}^2 \rangle_{AA} - \langle p_{out}^2 \rangle_{pp} \right] = \hat{p}_{Ta}^2 \left[ \frac{\sin^2(\pi - \Delta \phi)}{\langle z_t \rangle_{AA}} - \frac{\sin^2(\pi - \Delta \phi)}{\langle z_t \rangle_{pp}} \right].$$

(5)

5.2.2. A Test of Equation (5) for $\langle \hat{q}_L \rangle$

Al Mueller et al. [21] gave a prediction for the azimuthal broadening of di-jet angular correlations for 35 GeV jets at RHIC (Figure 35).
To check my Equation (5), I measured the half width at half maximum (HWHM), which equals $1.175\sigma$ for a Gaussian, for each curve in Figure 35, and calculated $(\sigma \times 35)^2$ to get $\langle p^2_{\text{out}} \rangle$ for each $qL$, and used Equation (5) to get 9.6 GeV$^2$ and 21.5 GeV$^2$, respectively, for the 8 GeV$^2$ and 20 GeV$^2$ plots. This is an excellent result considering that I had to measure the HWHMs in Figure 35 with a pencil and ruler.

5.2.3. How to Calculate $qL$ with Equation (4) from Di-Hadron Measurements

The determination of the required quantities is well known to older PHENIXians who have read Ref. [19] or my book [22] as outlined below:

(A) $\langle z_t \rangle$ is calculated from the Bjorken parent–child relation and “trigger bias” [23] (cf. Ref. [24]).

(B) The energy loss of the trigger jet from p+p to Au+Au can be measured by the shift in the $p_T$ spectra [25].

(C) $\hat{x}_h$, the ratio of the away-jet to the trigger jet transverse momenta can be measured by the away particle $p_{T_h}$ distribution for a given trigger particle $p_{T_t}$ taking $x_E = x_h \cos \Delta \phi \approx x_h = p_{T_h} / p_{T_t}$ [19]:

$$
\left. \frac{dP_n}{dx_E} \right|_{p_{T_t}} = N (n - 1) \frac{1}{\hat{x}_h} \frac{1}{(1 + \frac{x_h}{\hat{x}_h})^n}.
$$

5.2.4. Example: $\hat{x}_h$ from Fits to the PHENIX Data from Ref. [26]

The fits in Figure 36 work very well, with excellent $\chi^2$/dof. However, it is important to notice that the dashed curve in Au+Au does not fit the data as well as the solid red curve which is the sum of Equation (6) with free parameters + a second term with the form of Equation (6) but with the $\hat{x}_h$ fixed at the p+p value. It is also important to note that the solid red curve between the highest Au+Au data points is notably parallel to the p+p curve. A possible explanation is that, in this region, which is at a fraction $\approx 1\%$ of the $dP/dx_E$ distribution, the highest $p_{T_h}$ fragments are from jets that do not lose energy in the QGP.
5.2.5. Results from STAR $\pi^0 - h$ and $\gamma - h$ Correlations [27]

Figure 37 is a table of results of my published calculation [20] of $\langle \hat{q}L \rangle$ from the STAR data. The errors on the STAR $\langle \hat{q}L \rangle$ here (with the *) are much larger than stated in my published calculation because I made a trivial mistake, which is corrected here. In addition, the new values of $\langle \hat{q}L \rangle$ reflect that Equation (4) defines $\langle \hat{q}L \rangle$ not $\langle \hat{q}L \rangle / 2$.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\langle p_{T1} \rangle$ (GeV/c)</th>
<th>$\langle p_{T\nu} \rangle$ (GeV/c)</th>
<th>$\langle z_2 \rangle$</th>
<th>$\hat{x}_h$</th>
<th>$\langle p_{out}^2 \rangle$ (GeV/c)</th>
<th>$\sqrt{\langle k^2 \rangle}$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>14.71</td>
<td>1.72</td>
<td>0.80 ± 0.05</td>
<td>0.84 ± 0.04</td>
<td>0.263 ± 0.113</td>
<td>2.34 ± 0.34</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>3.75</td>
<td>0.80 ± 0.05</td>
<td>0.84 ± 0.04</td>
<td>0.576 ± 0.167</td>
<td>2.51 ± 0.31</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>3.75</td>
<td>0.80 ± 0.05</td>
<td>0.36 ± 0.05</td>
<td>0.547 ± 0.163</td>
<td>2.28 ± 0.35</td>
</tr>
<tr>
<td>p+p comp</td>
<td>14.71</td>
<td>3.75</td>
<td>0.80 ± 0.05</td>
<td>0.36 ± 0.05</td>
<td>0.851 ± 0.203</td>
<td>1.42 ± 0.22</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>3.75</td>
<td>0.80 ± 0.05</td>
<td>0.36 ± 0.05</td>
<td>0.263 ± 0.113</td>
<td>1.006 ± 0.18</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>3.75</td>
<td>0.80 ± 0.05</td>
<td>0.36 ± 0.05</td>
<td>0.576 ± 0.167</td>
<td>1.076 ± 0.18</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>1.72</td>
<td>4.21 ± 3.24*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>3.75</td>
<td>0.86 ± 0.87*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3. Some $\langle \hat{q}L \rangle$ Results from PHENIX [26]

The away widths from PHENIX $\pi^0 - h$ correlations [26] are shown in Figure 38 with the calculated $\hat{q}L$ values for $\pi^0 - h$ $\sqrt{s_{NN}} = 200$ GeV, 20–60% centrality, $5 < p_{T1} < 7$ GeV/c shown in Figure 39 and $7 < p_{T1} < 9$ GeV/c in Figure 40.
Figure 38. Away widths from $\pi^0 - h$ correlations as function of partner $p_T$, i.e., $p_T^{\text{Tar}}$, in Au+Au 0–20% and 20–60% and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV for four ranges of trigger $p_T^{\text{Tar}}$ indicated [26].

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}} = 200$</th>
<th>$\langle p_{TL} \rangle$</th>
<th>$\langle p_{TR} \rangle$</th>
<th>$\langle z_t \rangle$</th>
<th>$\bar{x}_h$</th>
<th>$\langle p_{out}^2 \rangle$</th>
<th>$\sqrt{\langle k_t^2 \rangle}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>GeV/c</td>
<td>GeV/c</td>
<td>GeV/c</td>
<td></td>
<td>GeV/c</td>
<td></td>
</tr>
<tr>
<td>p+p</td>
<td>5.78</td>
<td>1.42</td>
<td>0.60 ± 0.06</td>
<td>0.96 ± 0.02</td>
<td>0.434 ± 0.010</td>
<td>3.13 ± 0.37</td>
</tr>
<tr>
<td>p+p</td>
<td>5.78</td>
<td>2.44</td>
<td>0.60 ± 0.06</td>
<td>0.96 ± 0.02</td>
<td>0.934 ± 0.031</td>
<td>3.18 ± 0.34</td>
</tr>
<tr>
<td>p+p</td>
<td>5.78</td>
<td>3.76</td>
<td>0.60 ± 0.06</td>
<td>0.96 ± 0.02</td>
<td>1.523 ± 0.061</td>
<td>2.74 ± 0.29</td>
</tr>
<tr>
<td>p+p</td>
<td>5.78</td>
<td>5.82</td>
<td>0.60 ± 0.06</td>
<td>0.96 ± 0.02</td>
<td>3.339 ± 0.351</td>
<td>2.73 ± 0.32</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>5.78</td>
<td>1.30</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>0.867 ± 0.116</td>
<td>4.04 ± 0.61</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>5.78</td>
<td>2.31</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>1.291 ± 0.308</td>
<td>2.88 ± 0.54</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>5.78</td>
<td>3.55</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>1.370 ± 0.249</td>
<td>1.90 ± 0.32</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>5.78</td>
<td>5.73</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>2.562 ± 0.620</td>
<td>1.66 ± 0.31</td>
</tr>
<tr>
<td>p+p comp</td>
<td>5.78</td>
<td>1.30</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>0.434 ± 0.010</td>
<td>2.39 ± 0.32</td>
</tr>
<tr>
<td>p+p comp</td>
<td>5.78</td>
<td>2.31</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>0.934 ± 0.031</td>
<td>2.34 ± 0.29</td>
</tr>
<tr>
<td>p+p comp</td>
<td>5.78</td>
<td>3.55</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>1.522 ± 0.061</td>
<td>2.03 ± 0.25</td>
</tr>
<tr>
<td>p+p comp</td>
<td>5.78</td>
<td>5.73</td>
<td>0.62 ± 0.06</td>
<td>0.69 ± 0.05</td>
<td>3.339 ± 0.351</td>
<td>1.93 ± 0.26</td>
</tr>
</tbody>
</table>

$\langle \hat{q}L \rangle_{0.01}$ $\langle \hat{q}L \rangle$ GeV$^2$

| Au+Au 20-60%          | 5.78                 | 1.30                 | 6.9 ± 3.6            | 10.6 ± 3.8  |
| Au+Au 20-60%          | 5.78                 | 2.31                 | 2.3 ± 2.1            | 2.8 ± 2.4  |
| Au+Au 20-60%          | 5.78                 | 3.55                 | 0.35 ± 0.93          | −0.5 ± 0.9 |
| Au+Au 20-60%          | 5.78                 | 5.73                 | −0.75 ± 1.0          | −1.0 ± 0.9 |

Figure 39. $\hat{q}L$ result table for PHENIX $\pi^0 - h$, 5 < $p_T^{\text{Tar}}$ < 7 GeV/c 20–60% centrality.
5.4. Conclusions

It appears that the method works and gives consistent results for all the $\hat{q}L$ calculations shown (Figures 37, 39 and 40). In the lowest $p_{Ta} \sim 1.5$ GeV/c bin, the results are all consistent with the JET collaboration [17] result, $\hat{q} = 1.2 \pm 0.3$ GeV$^2$/fm or $\hat{q}L = 8.4 \pm 2.1$ GeV$^2$ for $L = 7$ fm, the radius of an Au nucleus. However, for $p_{Ta} > 2.0$ GeV/c, all the results are consistent with $\hat{q}L = 0$. Personally, I think that this is where the first gluon emitted in the medium was inside the jet cone, so that all further emissions were also inside the jet cone due to the angular ordering of QCD so that there is no evident suppression; or that jets with fragments with $p_T \geq 3$ GeV/c, which are distributed narrowly about the jet axis, are not strongly affected by the medium [28]. I think that this also agrees with the observation in Figure 36 that two or three orders of magnitude down in the $x_E = p_{Ta}/p_{Tt}$ distributions the A+A best fit is parallel to the p+p measurement, which means that these A+A fragments are from jets that have not lost energy. This is consistent with all the $I_{AA} = x_{E^A}^A/x_{E^p}^p = (p_{Tt}^{AA}/p_{Tt}^{pp})|_{p_{Tt}}$ distributions ever measured (e.g., Figures 41 and 42), which decrease with increasing $p_{Ta}$ until $p_{Ta} \approx 3$ GeV/c and then remain constant because the A+A and p+p distributions are parallel due to no jet energy loss for fragments in this range.
Figure 41. PHENIX $I_{AA}$ distribution [26].

Figure 42. (left) STAR $I_{AA}$ distribution [27]; and (right) ALICE $I_{AA}$ distribution [29].

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**Conflicts of Interest:** The author declares no conflict of interest.

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