Latest results from RHIC + Progress on determining $qL$ 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.

1 Introduction

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, $\sim$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.

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

*Research supported by U. S. Department of Energy, de-sc0012704
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 (Fig. 1). Perhaps more convincing is the list of the many Nobel Prize winners from New York City High School graduates (Fig. 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.

| Number of laureates by secondary school | Class | Name of laureate       | Award and year          | University                |
|-----------------------------------------|-------|------------------------|--------------------------|----------------------------|
| 8 The Bronx High School of Science     | 1947  | Leon N. Cooper         | Physics                   | Brown University           |
| Bronx, New York City, NY               | 1950  | Elbert Hinkleston      | Physics                   | Columbia University        |
|                                          | 1965  | Warren Weiler         | Physics                   | City University            |
|                                          | 1949  | Natie Schwartz       | Physics                   | Columbia University        |
|                                          | 1966  | Russell Hudson        | Physics                   | Princeton University       |
|                                          | 1955  | N. David Pulitzer     | Physics                   | California Institute of Technology |
|                                          | 1941  | Ray Glauber          | Physics                   | Harvard University         |
|                                          | 1959  | Robert Lehrman       | Chemistry                 | Columbia University        |
| 4 James Madison High School             | 1939  | Stanley Cohrs         | Medicine                  | Vanderbilt University      |
| Brooklyn, New York City, NY            | 1940  | Richard Roll         | Economics                 | Massachusetts Institute of Technology |
|                                          | 1943  | Martin Lewis Perl     | Physics                   | University of Michigan     |
|                                          | 1947  | Gary Becker          | Economics                 | University of Chicago     |
| 4 Skye High School, Manhattan, New York | 1941  | Joshua Lederberg      | Medicine                  | Rockefeller University     |
| City, NY                                | 1954  | Roald Hoffman         | Chemistry                 | Cornell University         |
|                                          | 1944  | Robert Fossey         | Economics                 | Cornell University         |
|                                          | 1965  | Richard Axel          | Medicine                 | Columbia University        |
| 5 Abraham Lincoln High School           | 1933  | Arthur Komberg       | Medicine                  | Stanford University        |
| Brooklyn, New York City, NY            | 1943  | Paul Berg            | Chemistry                 | Stanford University        |
|                                          | 1933  | Jerome Kere            | Chemistry                | City College of New York  |
| 1 Far Rockaway High School              | 1935  | Richard Feynman       | Physics                   | California Institute of Technology |
| Queens, New York City, NY              | 1948  | Burton Richter        | Physics                   | Stanford University        |
|                                          | 1948  | Edward Mandell        | Medicine                  | University of Pennsylvania |
| 3 Townsend Harris High School           | 1933  | Herbert A. Hauptman   | Chemistry                 | City College of New York  |
| Brooklyn, New York City, NY            | 1933  | John Finkbeiner       | Physics                   | Harvard University         |
|                                          | 1936  | Karl von Archenhold  | Economics                 | City College of New York  |
| 2 Brooklyn Technical High School       | 1934  | Alice Penfield        | Physics                   | City College of New York  |
| Brooklyn, New York City, NY            | 1932  | George Wall            | Biology                   | Harvard University         |
| 2 Vassar High School, Poughkeepsie, NY  | 1919  | Barbara McCrea        | Medicine or Physiology    | Cold Spring Harbor Laboratory |
|                                          | 1944  | Eric Kendal           | Medicine or Physiology    | Columbia University        |
| 2 Hastings High School (New York)      | 1951  | Edmund St. P. Whipple | Economics                 | Columbia University        |
| 2 Hastings High School (New York)      | 1946  | Robert C. Merkin      | Economics                 | A&T Sloan School of Management |
| 2 Martin Van Nort High School, Queens, | 1967  | Frank Wislocki        | Physics                   | University of Chicago, Princeton University |
| New York                                | 1967  | Alvin Rothbug        | Economics                 | Columbia University, Stanford University |
| 2 Wilson High School, Bronx, New York, NY | 1941  | Balmir Scrinchyl      | Medicine and Physiology   | Hunter College             |
|                                          | 1933  | Charlotte S. Blakley  | Medicine and Physiology   | Chicago University         |
|                                          | 1916  | Isadore Isaac Mills   | Physics                   | Columbia University        |
| 2 Schenley High School, Brooklyn, NY    | 1933  | Robert Hilsenbeck    | Physics                   | Stanford University        |
| 1 James Monroe High School, Bronx, NY  | 1939  | Leon Max Lederman    | Physics                   | Columbia University        |
| 1 New Trier High School, Winnetka, Evan | 1938  | Jack Steinberger    | Physics                   | Columbia University        |
| 1 Regis High School, Manhattan, New York City, NY | 1957  | John O'Keefe         | Medicine                  | City College of New York, McGill University |

Figure 2: From Wikipedia (edited), Physicists in blue + Roald Hoffman a classmate of mine from Columbia.
There also have been many discoveries and Nobel Prizes at BNL (Fig. 3).

In particular, Leon Lederman who made many discoveries at BNL 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/do/10.1063/PT.6.4.20181010a/full/
2 Why RHIC was built: to discover the QGP.

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

Figure 5: View along the beam direction of central collision events in Au+Au collisions in the PHENIX and STAR 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 Fig. 6 which finished data taking in 2005.

Figure 6: View of RHIC location from the air. The positions of the 4 original detectors, PHENIX, STAR PHOBOS and BRAHMS are indicated as well as the AGS (with 3 Nobel Prizes shown in Fig. 3).
2.1 The first major RHIC experiments

The two major experiments at RHIC were STAR (Fig. 7), which is still operating, and PHENIX (Fig. 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**

- 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 φ separation up to p_T ~ 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 π⁰ → γ + γ 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 (Fig. 9).

![sPHENIX SC-Magnet Test (off-MIE)](image)

**Figure 9:** BABAR superconducting solenoid now in operation at BNL

The design of the sPHENIX experiment is moving along well (Fig. 10) with a notable addition of a hadron calorimeter based on the iron return yoke of the solenoid.

![sPHENIX MIE](image)

**Figure 10:** Conceptual design of sPHENIX with major features illustrated.

The conceptual design of sPHENIX is based on 3 principles:

- Design a detector to meet the Science Mission of measurements of Jets and Upsilons in RHIC environment
- Maximize cost effectiveness and utilize modern technologies where appropriate (SiPM, fast TPC readout)
- Build on existing $20M+ PHENIX infrastructure
Critical Decision Level 1 MIE Schedule

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

Multi-year run plan for sPHENIX

| Year | Species | Energy [GeV] | Phys. Wks | Rec. Lum. | Samp. Lum. | Samp. Lum. All-Z |
|------|---------|--------------|-----------|-----------|------------|-----------------|
| Year-1 | Au+Au | 200 | 16.0 | — | 87 nb⁻¹ | 34 nb⁻¹ |
| Year-2 | p+p | 200 | 11.5 | — | 48 pb⁻¹ | 267 pb⁻¹ |
| Year-3 | Au+Au | 200 | 11.5 | — | 0.33 pb⁻¹ | 1.46 pb⁻¹ |
| Year-4 | p+p | 200 | 23.5 | 14 nb⁻¹ | 26 nb⁻¹ | 88 nb⁻¹ |
| Year-5 | Au+Au | 200 | 23.5 | 14 nb⁻¹ | 149 pb⁻¹ | 783 pb⁻¹ |

sPHENIX 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 Fig. 11a, and the planned multi-year RHIC runs indicated in Fig. 11b. The present sPHENIX collaboration and its evolution is shown in Fig. 12.

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 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 Fig. 13. The 2018 JLab and BNL EIC designs are shown in Figs. 14, 15.

Figure 13: 2014 Cost estimate: BNL $755.9M; Temple NSAC subcommittee cost estimate $1.5B
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.
2.3.1 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 (Fig. 16a). Fig. 16b is the main Linac cryo module made from superconducting RF cavities. Fig. 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).

Figure 16: a) CBETA (Cornell-Brookhaven Energy Recovery Linac (ERL)) b) Main Linac cryo module c) FFAG permanent loop return loop.
BNL’s future plan 2017 still works in 2018

| Years | Beam Species and | Science Goals | New Systems |
|-------|------------------|---------------|-------------|
| 2014  | Au+Au at 15 GeV  | Heavy flavor flow, energy loss, thermalization, etc. | Electron lenses 56 MHz SRF STAR HFT STAR MTD |
|       | Au+Au at 200 GeV | Quarkonium studies QCD critical point search  |  |
|       | 3He+Au at 200 GeV|  |  |
| 2015-16 | p+Au at 200 GeV | Complete heavy flavor studies Sphaleron tests | PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test |
|       | p+Au at 200 GeV | Parton saturation tests |  |
|       | p+Au at 200 GeV | Extract n(s)(T) + constrain initial quantum fluctuations |  |
|       | p+Au at 200 GeV |  |  |
|       | p+Au at 15 GeV  |  |  |
|       | p+Au at 200 GeV |  |  |
|       | p+Au at 62 GeV  |  |  |
|       | d+Au at 200 GeV |  |  |
|       | 200, 62, 39, 20 GeV |  |  |
| 2017  | p+p at 510 GeV  | Transverse spin physics Sign change in Sivers function | Coherent e-cooling final |
| 2018  | No Run isobars | 96Zr+96Zr and 96Au+96Ru to test chiral magnetic effect on observed Au+Au charge separation effects | Low energy e-cooling install. STAR ITPC upgrade |
| 2019-20 | Au+Au at 200 GeV (BES-2) | Search for QCD critical point and onset of deconfinement | Low energy e-cooling |
| 2022-23 | Au+Au at 200 GeV | Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics | sPHENIX Forward upgrades ? |
| 2024-26 | p+p at 5-20 GeV | Complete above measurements | Transition to eRHIC |

This color is sPHENIX proposed run plan

Figure 17: RHIC run plan 2014-2023 (2026?).
3.1 2018 RHIC run is $^{40}\text{Zr}^{96} + ^{40}\text{Zr}^{96}$ and $^{44}\text{Ru}^{96} + ^{44}\text{Ru}^{96}$, why?

In order to determine whether the separation of charges in the flow, $v_2$, of $\pi^+$ and $\pi^-$ shown in Fig. 19 is due to a new phenomenon called the Chiral Magnetic Effect (Fig. 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 (Fig. 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 will indicate that the charge asymmetry is the Chiral Magnetic Effect.

![Figure 19: Article by Karen McNulty Walsh in BNL news June 8,2015](image)

![Figure 20: a) schematic of A+A collision. b) sketch of the stronger magnetic (B) field in Ru+Ru.](image)
3.2 Vorticity: an application of particle physics to the QGP

It was observed at FERMILAB [PRL 36 (1976) 1113] that forward $\Lambda$ were polarized in $p+\text{Be}$ collisions, where the proton in the $\Lambda \rightarrow p + \pi^-$ decay is emitted along the spin direction of the $\Lambda$. In the A+A collision (Fig. 21a), the forward going beam fragments are deflected outwards so that the event plane and the angular momentum $\hat{J}_{\text{sys}}$ of the QGP formed can be determined. STAR claims that the $\Lambda$ polarization, $P_\Lambda$, is parallel to the angular momentum $\hat{J}_{\text{sys}}$ of the QGP everywhere so that the vorticity $\omega = k_B T (P_\Lambda + P_\Xi)/\hbar$ 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 [Nature 548 (2017) 62-65]. Another interesting thing to note is that the largest vorticity is at $\sqrt{s_{NN}} = 7.6 - 19$ GeV where the CERN fixed target experiments measure. Does this mean that their fluid (with no QGP) is also perfect?!!!

Figure 21: a) Schematic of STAR vorticity detection. b) Polarization $P_H = P_\Lambda$ or $P_\Xi$ vs $\sqrt{s_{NN}}$

STAR Team Receives Secretary’s Achievement Award

Recognition for role in enabling discovery of fastest swirling matter at U.S. Department of Energy Office of Science user facility for nuclear physics research

Figure 22: STAR receives an award for vorticity in 2018 BUT Michael Lisa isn’t there!!?
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 (Fig. 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.

Figure 23: sketch of Nucleus-Nucleus collision producing a QGP

4.1 Anisotropic (Elliptical) Transverse flow—an interesting complication in all A+A collisions (Fig. 24)

![Diagram of Anisotropic Elliptical Transverse Flow](image)

\[
\frac{E d^3 N}{dp^3} = \frac{d^3 N}{p_T dp_T dy d\phi} = \frac{d^3 N}{2\pi p_T dp_T dy} \left[ 1 + 2v_1 \cos(\phi - \Phi_R) + 2v_2 \cos(2(\phi - \Phi_R) + \cdots \right]
\]

*Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane

\( v_1 = \langle \cos \phi \rangle \)

\( v_2 = \langle \cos 2\phi \rangle \)

Directed flow zero at midrapidity

Elliptical flow dominant at midrapidity

Figure 24: Sketch and definitions of Elliptical flow, \( v_2 \)
Figure 25: Values of Elliptical flow ($v_2$) as a function of $\sqrt{s_{NN}}$ from all A+A collision measurements.

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 to 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: (top) Published PHENIX $v_2$ measurements in p+Au, and 0-5% central d+Au and $^3$He+Au collisions at $\sqrt{s_{NN}}$ =200 GeV, with preliminary $v_2$ and $v_3$ for the d+Au and $^3$He+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 $\sqrt{s_{NN}}$. 
bution, as pointed out in Ref. [13]. However, a broader understanding of the presence of a common radial flow field with deposited energy around each nucleon-nucleon collisions, where the splitting can be understood in terms of 2- and 3-body nucleon correlations in the PHENIX event plane method and find these variations. We have additionally analyzed these parton transport models, for example A Multi-drodynamic evolution, the translation occurs via parton-particle azimuthal momentum anisotropy. Instead of hydrodynamical models, the initial conditions generated from a nucleon Glauber model. Theoretical calculations from central systems but not significantly change the sensitivity of \( v_2 \) to the initial geometry. Fig. 27a shows that \( v_2 \) is about the same in all 3 systems but \( v_3 \) is much larger in \(^3\)He+Au clearly indicating the sensitivity of flow to the initial geometry of the collision. Fig. 27b shows that there is mass ordering in the flow which is strong evidence for the QGP 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.

4.2.1 “It takes two to tango”. — J. L. Nagle et al. PRC 97 (2018) 024909

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 Fig. 28 utilizing the AAMPT framework and

\[
e^+e^- \rightarrow Z_0 \rightarrow q\bar{q}
\]

Figure 28: A fundamental point about QCD and the string tension between the \( q \) and \( \bar{q} \) a single color string, the results indicate only a modest number of parton-parton scatterings and no observable collectivity signal.
However, a simple extension to two color strings 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–2 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 [PRD 9 (1974) 3501] the color flux lines connecting two quarks or a $q - \bar{q}$ pair as in Fig. 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 [PRL 34 (1975) 369], 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 (Eq. 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 [PLB 178 (1987) 416] said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the $c\bar{c}$ couldn’t 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 [Rep. Prog. Phys. 63 (2000) 1511]

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

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 can not be calculated in QCD perturbation theory but only in Lattice QCD Calculations [Ann. Rev. Nucl. Part. Sci. 65 (2015) 379].

$J/\psi$ suppression eventually didn’t work because the free $c$ and $\bar{c}$ quarks recombined to make $J/\psi$’s [PLB 490 (2000) 196]. Ask somebody from ALICE for more details.
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 also Zakharov (BDMPSZ), see [Ann. Rev. Nucl. Part. Sci. 50 (2000) 37], 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. (Fig. 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, 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.

4.4 BDMPSZ—the cone, the energy loss, azimuthal broadening, is THE QGP signature.

![](https://example.com/diagram.png)

**Figure 30:** Jet Cone of an outgoing parton with energy $E$ [BSZ arXiv:hep-ph/0002198v2]

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 4-momentum transfer-squared, $q^2(L)$, and takes the form:

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

where $\mu$, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2 / \lambda_{\text{mfp}}$ is the 4-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 \[\text{arXiv:hep-ph/0002198v2}\].

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

Figure 31: a) Hard quark-quark scattering in an A+A collision with the scattered quarks passing through the medium formed in the collision. b) Nuclear modification factor \(R_{AA}(p_T)\)

Hard scattered partons (Fig. 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 \(\langle N_{coll} \rangle\) in the centrality-class is given by the nuclear modification factor, \(R_{AA}\) (Fig. 31b), which equals 1 for no energy loss.

PHENIX discovered Jet Quenching of hadrons at RHIC in 2001 [PRL 88 (2002) 022301] (Fig. 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. (right) Plot is from the cover of PRL.
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, $-dE/dx$, per unit length ($x$) of a medium with total length $L$, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, and takes the form:

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

where $\mu$, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{mfp}$.

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

$$\langle p_{\perp}^2 \rangle \approx \langle q^2(L) \rangle = \hat{q} L \quad \langle \hat{q} L \rangle = \langle k_{T}^2 \rangle_{AA} - \langle k_{T}^2 \rangle_{pp} \quad (3)$$

Although only the component of $\langle p_{\perp}^2 \rangle$ perpendicular to the scattering plane affects $k_T$ (Fig. 34) the azimuthal broadening of the di-jet is caused by the random sum of the azimuthal components $\langle p_{\perp}^2 \rangle /2$ from each outgoing di-jet or $\langle p_{\perp}^2 \rangle = \hat{q} L$. 
From the values of $R_{AA}$ observed at RHIC (after 12 years) the JET Collaboration [Phys. Rev. C 90 (2014) 014909] has found that $\hat{q} = 1.2 \pm 0.3$ GeV$^2$/fm at RHIC, $1.9 \pm 0.6$ at LHC at an initial time $\tau_0 = 0.6$ fm/c; but 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 in [NPB 129 (1977) 1] as the transverse momentum of a parton in a nucleon (Fig. 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. Also $x_E = p_{Ta} \cos(\pi - \Delta \phi)/p_{Tt}$.

The formula for calculating $k_T$ from di-hadron correlations is given in [PRD 74 (2006) 072002].

5.2.1 The key new idea of $\langle k'^2_T \rangle_{pp}$ instead of $\langle k^2_T \rangle_{pp}$ in Eq. 3

The di-hadron correlations of $p_{Ta}$ with $p_{Tt}$ (Fig. 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 dihadron 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 [PLB 771 (2017) 553]:

$$\langle \hat{q}_L \rangle = \left[ \frac{\hat{x}_h}{\langle z_t \rangle} \right]^2 \left[ \frac{\langle p^2_{out} \rangle_{AA} - \langle p^2_{out} \rangle_{pp}}{x_h^2} \right]$$  (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; iii) $\langle p^2_{out} \rangle = \hat{p}^2_{Ta} \sin^2(\pi - \Delta \phi)$. This reduces the formula for di-jets to:

$$\langle \hat{q}_L \rangle = \left[ \langle p^2_{out} \rangle_{AA} - \langle p^2_{out} \rangle_{pp} \right] = \hat{p}^2_{Ta} \left[ \langle \sin^2(\pi - \Delta \phi) \rangle_{AA} - \langle \sin^2(\pi - \Delta \phi) \rangle_{pp} \right]$$  (5)
5.2.2 A test of Eq. 5 for $\langle \hat{q}L \rangle$

Al Mueller et al. [PLB 763 (2016) 208] gave a prediction for the azimuthal broadening of dijet angular correlations for 35 GeV jets at RHIC (Fig. 35). To check my Eq. 5 I measured the half width at half maximum (HWHM), which equals 1.175σ for a Gaussian, for each curve in Fig. 35 and calculated $(\sigma \times 35)^2$ to get $\langle p_{\text{out}}^2 \rangle$ for each $\hat{q}L$, and used Eq. 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 from Fig. 35 with a pencil and ruler.

5.2.3 How to calculate $\hat{q}L$ with Eq. 4 from di-hadron measurements

The determination of the required quantities is well known to older PHENIXians who have read [PRD 74 (2006) 072002] or my book [Rak & Tannenbaum, High pT physics in the Heavy Ion Era-Cambridge 2013] as outlined below:

(A) $\langle z_t \rangle$ is calculated from the Bjorken parent-child relation and ‘trigger bias’ [Phys. Rep. 48 (1978) 285], also see PRD 81 (2010) 012002;

(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 [PRC 87 (2013) 034911];

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

$$\left. \frac{dP_x}{dx_E} \right|_{p_{T_t}} = N (n - 1) \frac{1}{\hat{x}_h} \frac{1}{(1 + \frac{x_E}{\hat{x}_h})^n}.$$ (6)
5.2.4 Example: $\hat{x}_h$ from fits to the PHENIX data from [PRL 104 (2010) 252301]

Figure 36: Fit to $x_E$ distributions for $\pi^0 - h$ correlation in p+p and Au+Au 0-20% central collisions using Eq. 6 with the results indicated: (left) $4 < p_{Tt} < 5$ GeV/c; (right) $7 < p_{Tt} < 9$ GeV/c;

The fits in Fig. 36 work very well, with excellent $\chi^2$/dof. However it is important to notice that the dashed curve in Au+Au doesn’t fit the data as well as the solid red curve which is the sum of Eq. 6 with free parameters + a second term with the form of Eq. 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 $pT_a$ fragments are from jets that don’t lose energy in the QGP.

5.2.5 Results from STAR $\pi^0 - h$ and $\gamma - h$ correlations [PLB 760 (2016) 689]

Table 1: $\langle \hat{q}L \rangle$ result table for STAR $\pi^0$-h: 12 $< p_{Tt} < 20$ GeV/c 00-12% Centrality

| Reaction           | $\langle p_{Tt} \rangle$ | $\langle p_{Tt} \rangle$ | $\langle z_t \rangle$ | $\hat{x}_h$ | $\langle p_\text{out} \rangle$ | $\langle \hat{q}L \rangle$ |
|--------------------|--------------------------|--------------------------|-----------------------|------------|-------------------------------|--------------------------|
| Au+Au 00-12%       | 14.71                    | 1.72                     | 0.80 ± 0.05           | 0.84 ± 0.04| 0.263 ± 0.113                 | 2.34 ± 0.34              |
| p+p comp           | 14.71                    | 3.75                     | 0.80 ± 0.05           | 0.84 ± 0.04| 0.576 ± 0.167                 | 2.51 ± 0.31              |
| Au+Au 00-12%       | 14.71                    | 1.72                     | 0.80 ± 0.05           | 0.36 ± 0.05| 0.547 ± 0.163                 | 2.28 ± 0.35              |
| Au+Au 00-12%       | 14.71                    | 3.75                     | 0.80 ± 0.05           | 0.36 ± 0.05| 0.851 ± 0.203                 | 1.42 ± 0.22              |
| p+p comp           | 14.71                    | 1.72                     | 0.80 ± 0.05           | 0.36 ± 0.05| 0.263 ± 0.113                 | 1.006 ± 0.18             |
| Au+Au 00-12%       | 14.71                    | 3.75                     | 0.80 ± 0.05           | 0.36 ± 0.05| 0.576 ± 0.167                 | 1.076 ± 0.18             |

Table 1 is a table of results of my published calculation [PLB 771 (2017) 553] 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. Also the new values of $\langle \hat{q}L \rangle$ reflect that Eq. 4 defines $\langle \hat{q}L \rangle$ not $\langle \hat{q}L \rangle /2$. 
5.3 Some $\langle qL \rangle$ results from PHENIX [PRL 104 (2010) 252301]

Figure 37: Away widths from $\pi^0-h$ correlations as function of partner $p_T$, i.e. $p_{Tq}$, in Au+Au 0-20% and 20-60% and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV for 4 ranges of trigger $p_T$ indicated.

The away widths from PHENIX $\pi^0-h$ correlations [PRL 104 (2010) 252301] are shown in Fig. 37 with the calculated $\hat{q}L$ values for $\pi^0-h$ GeV/c 20-60% centrality $5 < p_T < 7$ GeV/c shown in Table 2 and $7 < p_T < 9$ GeV/c in Table 3.

Table 2: $\hat{q}L$ result table for PHENIX $\pi^0-h$: $5 < p_T < 7$ GeV/c 20-60% Centrality

| PHENIX PRL104 | $\sqrt{s_{NN}} = 200$ | $\langle p_{Tq} \rangle$ | $\langle p_{Tq} \rangle$ | $\langle z_t \rangle$ | $\hat{z}_h$ | $\langle p_{out}^2 \rangle$ | $\sqrt{(k_T^2)}$ |
|---------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Reaction      | $p/p$                    | $5.78$                   | $1.42$                   | $0.60 \pm 0.06$          | $0.96 \pm 0.02$          | $0.434 \pm 0.010$        | $3.13 \pm 0.37$          |
|               | $p/p$                    | $5.87$                   | $2.44$                   | $0.60 \pm 0.06$          | $0.96 \pm 0.02$          | $0.394 \pm 0.031$        | $3.18 \pm 0.34$          |
|               | $p/p$                    | $5.78$                   | $3.76$                   | $0.60 \pm 0.06$          | $0.96 \pm 0.02$          | $1.523 \pm 0.061$        | $2.74 \pm 0.29$          |
|               | $p/p$                    | $5.87$                   | $5.82$                   | $0.60 \pm 0.06$          | $0.96 \pm 0.02$          | $3.339 \pm 0.351$        | $2.73 \pm 0.32$          |
| Au+Au 20-60%  | $5.78$                   | $1.30$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $0.867 \pm 0.116$        | $4.04 \pm 0.61$          | $4.04 \pm 0.61$          |
| Au+Au 20-60%  | $5.78$                   | $2.31$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $1.291 \pm 0.308$        | $2.88 \pm 0.54$          | $2.88 \pm 0.54$          |
| Au+Au 20-60%  | $5.78$                   | $3.55$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $1.370 \pm 0.249$        | $1.90 \pm 0.32$          | $1.90 \pm 0.32$          |
| Au+Au 20-60%  | $5.78$                   | $5.73$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $2.562 \pm 0.620$        | $1.66 \pm 0.31$          | $1.66 \pm 0.31$          |
| p+p comp      | $5.78$                   | $1.30$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $0.434 \pm 0.010$        | $2.39 \pm 0.32$          | $2.39 \pm 0.32$          |
| p+p comp      | $5.87$                   | $2.83$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $0.934 \pm 0.031$        | $2.34 \pm 0.29$          | $2.34 \pm 0.29$          |
| p+p comp      | $5.87$                   | $3.55$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $1.522 \pm 0.061$        | $2.03 \pm 0.25$          | $2.03 \pm 0.25$          |
| p+p comp      | $5.87$                   | $5.73$                   | $0.62 \pm 0.06$          | $0.69 \pm 0.05$          | $3.339 \pm 0.351$        | $1.93 \pm 0.26$          | $1.93 \pm 0.26$          |

$\langle qL \rangle$ GeV$^2$
5.4 Conclusions

It appears that the method works and gives consistent results for all the $\hat{q}L$ calculations shown (Tables 1,2,3). In the lowest $p_{Ta} \sim 1.5$ GeV/c bin the results are all consistent with the JET collaboration [PRC 90 (2014) 014909] result, $\hat{q} = 1.2\pm0.3$ GeV$^2$/fm or $\hat{q}L = 8.4\pm2.1$ GeV$^2$/fm 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 there is no evident suppression; or that jets with hard fragments close to the axis don’t lose energy in the QGP. I think that this also agrees with the observation in Fig. [38] that two or three orders of magnitude down in the $x_{h}$($\approx p_{Ta}/p_{Tt}$) distributions the A+A best fit is parallel to the p+p measurement which means that there is no energy loss from the jets beyond this value. This is consistent with all the $I_{AA} = p_{Ta}/p_{Tt}$ distributions ever measured (e.g. Figs. [38,39]) 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 38: PHENIX $I_{AA}$ distribution from [PRL 104 (2010) 252302]

Figure 39: (left) STAR $I_{AA}$ distribution from [PLB 760 (2016) 689]; (right) ALICE $I_{AA}$ distribution from [PLB 763 (2016) 238]