Latest results from BNL and RHIC + Progress on determining q-hat in RHI collisions using di-hadron correlations

For previous years with more details see:

2009: IJMPA 26 (2011)5299 1406.0830

2011-2013: IJMPA 29 (2014)1430017 1406.1100

2014: arXiv1504.02771

2015: arXiv1604.08550

2016: arXiv1705.07925

2017: arXiv1805.02692

How hadron collider experiments contributed to the development of QCD arXiv:1801.08969

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA

18th Zimanyi School
Budapest, Hungary
December 3-7, 2018
The Relativistic Heavy Ion Collider (RHIC) at BNL is 1 of the 2 remaining hadron colliders and the first and only polarized p+p collider.
New York City region nurtures science
Many Nobel Prize winners from NYC High Schools
<table>
<thead>
<tr>
<th>Number of laureates by secondary school</th>
<th>Class</th>
<th>Name of laureate</th>
<th>Award and year</th>
<th>University</th>
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<tbody>
<tr>
<td></td>
<td>1941</td>
<td>Roy Glauber[1][5]</td>
<td>Physics 2005</td>
<td>Harvard University</td>
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<tr>
<td></td>
<td>1940</td>
<td>Robert Solow[16]</td>
<td>Economics 1987</td>
<td>Massachusetts Institute of Technology</td>
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<td></td>
<td>1943</td>
<td>Martin Lewis Perl[17]</td>
<td>Physics 1995</td>
<td>University of Michigan</td>
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<td></td>
<td>1944</td>
<td>Robert Fogel[20][22]</td>
<td>Economics 1993</td>
<td>Cornell University</td>
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<td>1933</td>
<td>Jerome Karle[31][32]</td>
<td>Chemistry 1985</td>
<td>City College of New York</td>
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<td>1935</td>
<td>Richard Feynman[33][34]</td>
<td>Physics 1965</td>
<td>California Institute of Technology</td>
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<td>1948</td>
<td>Burton Richter[34][35]</td>
<td>Physics 1976</td>
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<td>Year</td>
<td>School Name</td>
<td>Year of Graduation</td>
<td>Subject</td>
<td>Year Received</td>
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<td>1942</td>
<td>Baruch Blumberg[34]</td>
<td>1976</td>
<td>Medicine</td>
<td>University of Pennsylvania</td>
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<td>Herbert A. Hauptman[45]</td>
<td>1965</td>
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<td>Julian Schwinger[45]</td>
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<td>Kenneth Arrow[45]</td>
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<td>1954</td>
<td>Arno Penzias</td>
<td>1978</td>
<td>Physics</td>
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<td>1922</td>
<td>George Wald</td>
<td>1987</td>
<td>Biology</td>
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<td>1919</td>
<td>Barbara McClintock[52]</td>
<td>1983</td>
<td>Medicine or Physiology</td>
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<td>Eric Kandel[53]</td>
<td>2000</td>
<td>Medicine or Physiology</td>
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<td>1951</td>
<td>Edmund S. Phelps</td>
<td>2006</td>
<td>Economics</td>
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<td>1962</td>
<td>Robert C. Merton</td>
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<td>MIT Sloan School of Management</td>
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<td>Frank Wilczek[57]</td>
<td>2004</td>
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<td>1967</td>
<td>Alvin Roth[58]</td>
<td>2012</td>
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<td>Issidor Isaac Rabi</td>
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<td>1931</td>
<td>Robert Hofstadter</td>
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<td>1939</td>
<td>Leon Max Lederman</td>
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<td>1957</td>
<td>John O'Keefe</td>
<td>2014</td>
<td>Medicine</td>
<td>City College of New York McGill University</td>
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</tbody>
</table>
Add another to the list

One of this year’s Nobel Prize winners in Physics
Arthur Ashkin graduated James Madison High school in 1940, Columbia College in 1947 [delay because of WWII] and PhD from Cornell in 1952
Also many Discoveries & Nobel Prizes at BNL

1952 Strong Focusing
Brookhaven physicists—including Ernst Courant and Harland

1953 Nobel Prize-winning Discovery: Parity Violation

1957

1958

1959

KL discovered

1962 Nobel Prize-winning Discovery: The Muon-Neutrino

1964 Nobel Prize-winning Discovery: CP Violation

1964 Ω−

1964 Nobel Prize-winning Discovery: The J/Psi Particle

1974

2002 Nobel Prize-winning Discovery: Cosmic Neutrinos

2003 Nobel Prize-winning Discovery: Chemistry of the Cell
Rodrick MacKinnon, M.D., a visiting researcher at Brookhaven

2005 The "Perfect" Fluid sQGP
Scientists discover quark-gluon plasma, a "perfect" liquid 190,000 times hotter than the center of the sun and so hot that protons and

2009 Nobel Prize-winning Discovery: Atomic-Level "Pictures" of Protein

Zimanyi School 2018

M. J. Tannenbaum
Leon Lederman died this year at the age of 96

Leon was the most creative and productive high-energy physics experimentalist of his generation and also 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/
Discovery of the **QGP**: Why RHIC was built

The surprise is that it is a perfect liquid

*Fluid sQGP*

**The 'Perfect'**

Scientists discover quark-gluon plasma, a "perfect" liquid 100,000 times hotter than the center of the sun and so hot that protons and
Brookhaven National Laboratory (BNL)
Now only one experiment at RHIC: STAR

STAR Detector

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

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

- **On-going/future upgrades**
  - iTPC (2019+): $|\eta| < 1.5$
  - eTOF (2019+): $-1.6 < \eta < -1$
  - FCS (2021+): $2.5 < \eta < 4$
  - FTS (2021+): $2.5 < \eta < 4$

Normal Solenoid, TPC, TOF, EMCalorimeter, VTX detector, $\mu$ detector
“Mike, is there a ‘real collider detector’ at RHIC?”---J. Steinberger about PHENIX 2002

- 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% $X_0$
  - EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger
  - $\gamma \pi^0$ separation up to $p_T \sim 25$ GeV/c
  - EMCAL and precision TOF for $h^{\pm}$ pid

Comparison to scale with a wedge of CMS
Last PHENIX run was 2016
PHENIX has Silicon Vertex Detector upgrade
Separate c from b with single e trigger

PHENIX Silicon Vertex Detector, VTX & FVTX

VTX installed in 2011
|y|<1.2, \( \phi \sim 2\pi \) : 4 layers (2 pixels + 2 strips)

FVTX installed in 2012
1.2<|y|<2.2, \( \phi = 2\pi \) : 4 layers

• Purpose
  • Measure DCA for charm-bottom separation
    • Proportional to decay length
      • \( B^0 : 455 \) \( \mu m \), \( D^0 : 123 \) \( \mu m \)
  • VTX : Collision vertex determination
  • FVTX: Event plane : twice higher resolution

Collision vertex
DCA
The new experiment sPHENIX is moving along well
Successful DOE Major Item of Equipment review

sPHENIX MIE

The conceptual design of sPHENIX is based on 3 principles:
• Design a detector to meet the Science Mission of measurements of Jets and Upsilon in RHIC environment
• Maximize cost effectiveness and utilize modern technologies where appropriate (SiPM, fast TPC readout)
• Build on existing $20M+ PHENIX infrastructure

WBS  sPHENIX MIE Project Elements
1.1  Project Management
1.2  Time Projection Chamber
1.3  Electromagnetic Calorimeter
1.4  Hadron Calorimeter
1.5  Calorimeter Electronics
1.6  DAQ-Trigger
1.7  Minimum Bias Trigger Detector

To counting house
Ansaldo-Babar-sPHENIX superconducting Soleniod ramped to 105% full current

sPHENIX SC-Magnet Test (off-MIE) sPHENIX

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

SC-Magnet ramped and held at 105% Full Current
DOE approves with a few minor issues 05/25/18

Critical Decision Level 1 MIE Schedule

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

Also See Gunther Roland’s talk at Hard Probes 2018

Multi-year run plan for sPHENIX

<table>
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</thead>
<tbody>
<tr>
<td>2023</td>
<td>Year-1</td>
<td>Au+Au</td>
<td>200</td>
<td>16.0</td>
<td>7 nb⁻¹</td>
<td>8.7 nb⁻¹</td>
<td>34 nb⁻¹</td>
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<tr>
<td>2024</td>
<td>Year-2</td>
<td>p+p</td>
<td>200</td>
<td>11.5</td>
<td>—</td>
<td>48 pb⁻¹</td>
<td>267 pb⁻¹</td>
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<tr>
<td>2024</td>
<td>Year-2</td>
<td>p+Au</td>
<td>200</td>
<td>11.5</td>
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<td>0.33 pb⁻¹</td>
<td>1.46 pb⁻¹</td>
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<tr>
<td>2025</td>
<td>Year-3</td>
<td>Au+Au</td>
<td>200</td>
<td>23.5</td>
<td>14 nb⁻¹</td>
<td>26 nb⁻¹</td>
<td>88 nb⁻¹</td>
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<tr>
<td>2026</td>
<td>Year-4</td>
<td>p+p</td>
<td>200</td>
<td>23.5</td>
<td>—</td>
<td>149 pb⁻¹</td>
<td>783 pb⁻¹</td>
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<tr>
<td>2027</td>
<td>Year-5</td>
<td>Au+Au</td>
<td>200</td>
<td>23.5</td>
<td>14 nb⁻¹</td>
<td>48 nb⁻¹</td>
<td>92 nb⁻¹</td>
</tr>
</tbody>
</table>
If you are interested in joining/contributing contact Dave Morrison (BNL) or Gunther Roland (MIT)
Next U.S. Nuclear Physics Facility
Electron-Ion Collider
Need for EIC approved by U.S. National Academy of Sciences
July 24, 2018
Statement by Brookhaven Lab, Jefferson Lab, and the Electron-Ion Collider Users Community on National Academy of Sciences Electron-Ion Collider 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.
eRHIC first BNL design—(ISSP2014)

FFAG Recirculating Electron Rings

1.3-5.3 GeV

6.6-21.2 GeV

Energy Recovery Linac, 1.32 GeV

Coherent Electron Cooler

Polarized Electron Source

Detector I

electrons

hadrons

Detector II

From AGS

Beam Dump

100 meters

ERL Cryomodules

Cost estimates
BNL $755.9M
NSAC $1.5B

NSAC Sub-Committee Review of the EIC (Electron Ion Collider) Cost Estimates
L Edward Temple, Jr. Chairman

Zimanyi School 2018
Jefferson Lab Design

JLEIC Concept, Jefferson Lab, VA

Temple committee cost estimate also $1.5B but no new accelerator technology required
eRHIC design progress 2017

Design Choice Validation Review
April 5-6, 2017 Ferdinand Willeke

Injector
Linac
3 GeV

Polarized Electron Source,
Pre-Injector
and Accumulator

Injector
Loops

Storage Ring
5-18 GeV

AGS

100 meters

eRHIC

Detector I

Detector II

Electrons

Ions

(Polarized) Ion Source

National Academy of Sciences: US based electron ion collider Science Assessment 2/1/17-7/31/18

Zimanyi School 2018

PHOENIX

M. J. Tannenbaum

23
Novel design not idle: BNL-Cornell study of energy recovery linac (ERL), superconducting RF cavities and FFAG return loop which uses permanent magnets.
Berndt Mueller showing Secretary of Energy eRHIC plan at BNL Oct. 26, 2018
<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and</th>
<th>Science Goals</th>
<th>New Systems</th>
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<tbody>
<tr>
<td>2014</td>
<td>Au+Au at 15 GeV</td>
<td>Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies</td>
<td>Electron lenses 56 MHz SRF STAR HFT STAR MTD</td>
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<td>Au+Au at 200 GeV</td>
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<td>³He+Au at 200 GeV</td>
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<td>2015-16</td>
<td>p↑+p↑ at 200 GeV</td>
<td>Extract η/s(T) + constrain initial quantum fluctuations</td>
<td>PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test</td>
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<tr>
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<td>p↑+Au, p↑+Al at 200 GeV</td>
<td>Complete heavy flavor studies Sphaleron tests Parton saturation tests</td>
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<td>High statistics Au+Au</td>
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<td>Au+Au at 62 GeV ?</td>
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<td>d+Au @ 200, 62, 39, 20 GeV</td>
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<td>2017</td>
<td>p↑+p↑ at 510 GeV</td>
<td>Transverse spin physics Sign change in Sivers function</td>
<td>Coherent e-cooling final</td>
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<td>2018</td>
<td>No Run isobars</td>
<td>96Zr+96Zr and 96Ru+96Ru to test chiral magnetic effect on observed Au+Au charge separation effects</td>
<td>Low energy e-cooling install. STAR iTPC upgrade</td>
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<td>2019-20</td>
<td>Au+Au at 5-20 GeV (BES-2)</td>
<td>Search for QCD critical point and onset of deconfinement</td>
<td>Low energy e-cooling</td>
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<td>2022-23</td>
<td>Au+Au at 200 GeV</td>
<td>Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism</td>
<td>sPHENIX</td>
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<td>2024-22</td>
<td>p↑+p↑ , p↑+Au at 200 GeV</td>
<td>Color screening for different quarkonia Forward spin &amp; initial state physics</td>
<td>Forward upgrades ?</td>
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<td>2024-26</td>
<td>Factor of 10 increase Au+Au</td>
<td>Complete above measurements</td>
<td>Transition to eRHIC</td>
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<td>≥ 2023 ?</td>
<td>No Runs Factor of 4 increase p+p</td>
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This color is sPHENIX proposed run plan
# RHIC running FY2018

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<th>Program Element</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
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<td>AGS-Booster/EBIS Startup</td>
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<td>RHIC CrvO Cooldown to 45 K</td>
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<td>RHIC CrvO Cooldown/Warm-up</td>
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<tr>
<td>RHIC CrvO Operation</td>
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<tr>
<td>RHIC CrvO off</td>
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<td>RHIC setup/commissioning (3/9 – 3/18)</td>
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<td>RHIC Research with ( v_s = 200 \text{ GeV/n Zr} )</td>
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<tr>
<td>Setup &amp; RHIC Research with ( v_s = 200 \text{ GeV/n Ru} )</td>
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<td>Setup &amp; RHIC Research with ( v_s = 27 \text{ GeV/n Au} )</td>
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<tr>
<td>LeReC commissioning</td>
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<td>CeC POP Experiment E = 26.5 GeV/u Au</td>
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<td>NSRL (NASA Radiobiology)</td>
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<td>BLIP isotopes</td>
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<tr>
<td>Shutdown (RHIC)</td>
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<tr>
<td>Au run = 33 days (1 setup + 26 “physics” + 3 FXT + 3 CeC)</td>
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</tbody>
</table>

“physics” = physics + APEX + maintenance

**Dates for first three CeC periods are approximate**
(early April, early and late May)

**CeC parasitic commissioning =**

**CeC Dedicated running =**

(Total of 14 days)

---

N.B. “Physics” running was declared on 3/14, STAR started Physics data on 3/15.
WHY Isobars

$^{40}\text{Zr}^{96} + ^{40}\text{Zr}^{96}$

$^{44}\text{Ru}^{96} + ^{44}\text{Ru}^{96}$

Dates Back to 2015 result and press release
Scientists See Ripples of a Particle-Separating Wave In Primordial Plasma

Key sign of quark-gluon plasma (QGP) and evidence for a long-debated quantum phenomenon

\[ v_2 \text{ is elliptical transverse flow} \]

\[ r = 3.1985 \pm 0.2903 \]

30-40% Au+Au200

\[ A_{ch} = \frac{(N_+ - N_-)}{(N_+ + N_-)} \]

How does one prove what it is?
Separation of charges in $v_2$ of $\pi^+ \pi^-$ in previous run. Is this a Chiral Magnetic effect?

Is the $v_2$ asymmetry a Chiral Magnetic effect which depends on the electric charge or a nucleon effect. This run is now in progress.
New or Improved Physics Results 2017-2018
Au+Au Vorticity: something for a plumber or Hydrodynamics theorist to love

Forward $\Lambda$ are polarized in p+Be collision
STAR claims that this effect in Au+Au is new
because $\Lambda$ polarization is parallel to the angular momentum of the QGP $J_{\text{sys}}$ everywhere

See CERN 86-07 for T.D.Lee’s story of how Jack Steinberger missed parity violation of $\Lambda$ decay


Vorticity Formula. See if you can get $\omega \sim 10^{22}/s$, $10^{15}$ times larger than any other fluid. But note, largest vorticity is at $\sqrt{s_{NN}}=7.6--19\text{GeV}$ where CERN fixed target measures---is their fluid also perfect or ???
Au+Au Vorticity: something for a plumber or Hydrodynamics theorist to love 2018

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See CERN 86-07 for T.D.Lee’s story of how Jack Steinberger missed parity violation of $\Lambda$ decay

$$\omega = k_B T \left( \overline{P}_\Lambda + \overline{P}_{\Lambda^*} \right) / \hbar$$

Vorticity Formula. See if you can get $\omega \sim 10^{22}/s$, $10^{15}$ times larger than any other fluid. But note, largest vorticity is at $\sqrt{s_{NN}} = 7.6--19\text{GeV}$ where CERN fixed target measures---is their fluid also perfect or ???
STAR receives an award for vorticity
BUT Michael Lisa isn’t there

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

PHENIX and Collectivity
but first why we are doing A+A experiments at RHIC:
Searching for the Quark Gluon Plasma
High Energy Nucleus-Collisions provide the means of creating Nuclear Matter in conditions of Extreme Temperature and Density the **QGP**

> 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 scale.
Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions

- Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane
  - $v_2$ is the 2nd harmonic Fourier coefficient

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

- spatial anisotropy $\Rightarrow$ momentum anisotropy

Directed flow zero at midrapidity
Elliptical flow dominant at midrapidity
Flow exists in all A+A collisions: evidence of a collective effect of nucleons (quarks?)
Is this an indication of QGP?

Nuclei bounce off each other and break into fragments.

Here slow moving Nuclei make particles but block particles emitted in event plane which squeeze out vertically.
Flow is sensitive to the initial geometry

Flow is sensitive to the initial geometry. The dependence of flow on the initial geometry can be quantified by comparing different systems and energies. Here are some key observations:

- **p+Au**
  - Flow is sensitive to the initial geometry, with $v_2^{p+Au}$ not directly comparable to other systems.

- **d+Au**
  - Similar to p+Au, flow is sensitive to the initial geometry, with $v_2^{d+Au}$.

- **$^3$He+Au**
  - Flow is sensitive to the initial geometry, with $v_2^{^3$He+Au}$.

- **$v_2^{dAu} < v_2^{3He+Au}$**
  - $v_2$ is plotted against $p_T$ for different energy bins, showing a decrease in magnitude for $d+Au$ compared to $^3He+Au$.

- **$v_3^{dAu} < v_3^{3He+Au}$**
  - $v_3$ is also plotted against $p_T$, showing a similar trend as $v_2$.

- **Non-flow effects**
  - Non-flow effects increase with decreasing $\sqrt{s}$, as indicated by the extrapolation and systematic errors.

- **Extrapolation**
  - Extrapolated values with $\pm 35\%$ and $\pm 48\%$ systematic errors are shown for different energy bins.

- **Global Systematics**
  - $v_2$ central vs $\sqrt{s}$

**Graphical Representation**

- The graphs show $v_2$ and $v_3$ for different systems and energies, with $p_T$ on the x-axis and $v_2$ or $v_3$ on the y-axis.

**Inference**

The sensitivity of flow to the initial geometry is demonstrated through the comparison of $v_2$ and $v_3$ for different systems at varying energies. The decrease in $v_2$ and $v_3$ for $d+Au$ compared to $^3He+Au$ highlights the impact of initial geometry on flow observables.
Conclusion: Flow in small systems 2018

Final state correlations in lowest energy suggests short-lived QGP droplets

PRC 96, 064905 (2017) and PRL 120, 062302 (2018)

Mass ordering strengthens case for QGP droplets

arXiv:1710.09736

Flow is geometric

arXiv:1805.02973

• The collection of measurements best description is by hydro which includes QGP
• Strong evidence for QGP in small systems
What are the minimal conditions for collectivity?

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

For the case of e+e− collisions utilizing the AMPT framework and a single color string. The results indicate only a modest number of parton-parton scatterings and no observable collectivity signal.

Additional Special Case – 2 Strings

However, a simple extension to two color strings which represent a simplified geometry in p + p collisions predicts finite long-range two-particle correlations (i.e., the ridge) and a strong v2 with respect to the initial parton geometry.
Unlike an electric or magnetic field between two sources which spreads over all space, in QCD as proposed by Kogut and Susskind PRD9(1974)3501 the color flux lines connecting two quarks or a q-qbar pair 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-qbar pair. This led to the Cornell potential PRL 34(1975)369 which combined the Coulomb 1/r

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

dependence at short distances from vector-gluon exchange with a linearly rising string-like potential at large distances which provided confinement. Fragmentation is produced by the string breaking.
OK since the latest discovery claims ‘flow’ in small systems is from the QGP, how did we find the QGP in the first place
The gold-plated signature for the QGP 
J/ψ Suppression-1986

• In 1986, T. Matsui & H. Satz PL B178, 416 (1987) said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the cc-bar 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 [Satz 2000]:

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

where $\mu_D = \mu_D(T) = 1/r_D$ is the Debye screening mass [Satz 2000]. 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 [Soltz 2015].

This eventually didn’t work because the free $c$ and $c$-bar quarks recombined to make J/ψ’s. Ask somebody from ALICE for more details.
Jet Quenching: by coherent LPM radiative energy loss of a parton in the QGP-1997

In 1997, Baier, Dokshitzer, Mueller Peigne, Schiff also Zakharov, see ARNPS 50, 37 (2000), said that the energy loss from coherent LPM radiation for hard-scattered partons exiting the QGP would “result in an attenuation of the jet energy and a broadening of the jets”.

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 doesn’t 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—watch out for so-called trimming.
The energy loss of the original outgoing parton, $-dE/dx$, per unit length ($x$) of a medium with total length $L$, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, with 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 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 the parton from its collisions traversing a length $L$ in the medium is well approximated by

$$\langle p_{\perp W}^2 \rangle \approx \langle q^2(L) \rangle = \hat{q} L.$$
Jet Quenching: a parton-medium effect
First QCD-based prediction BDMPSZ c. 1997

- Energy loss of an outgoing parton with color charge fully exposed in a medium with a large density of similarly exposed color charges (i.e. a QGP) from LPM coherent radiation of gluons is predicted in QCD by BDMPSZ.

Hard scattered partons lose energy going through the medium so that there are fewer partons or jet fragments at a given $p_T$. The ratio of measured $AA$ to scaled $pp$ cross section which = 1 for no energy loss is:

$$R_{AA}(p_T) = \frac{d^2 N_{AA}^{\pi_0}}{dp_T dy N_{AA}^{inel}} \frac{\langle N_{coll_{AA}} \rangle d^2 N_{pp}^{\pi_0}}{dp_T dy N_{pp}^{inel}}$$

Lots of evidence for jet Quenching, discovered at RHIC for $\pi^0$ and $h^\pm$

PHENIX PRL 88, 022301 (2002) >1000 cites

$\langle N_{coll} \rangle$ is the number of collisions
PHENIX discovered Jet Quenching at RHIC 2001

PHENIX at Quark Matter 2018

Our third paper (now well over 200 papers)


HEP

1 records found

1. Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}} = 130$-GeV

DOI: 10.1103/PhysRevLett.88.022301
e-Print: nucl-ex/0109003 | PDF

First regular paper from RHIC experiment to reach 1000 citations

Pions at large $p_T > 2.5$ GeV/c suppressed in Au+Au at $\sqrt{s_{NN}}=130$ GeV compared to enhancement at CERN SpS $\sqrt{s_{NN}}=17$ GeV
Status of $R_{AA}$ in AuAu at $\sqrt{s_{NN}}=200$ GeV

Notable are that ALL particles are suppressed for $p_T>2$ GeV/c (except for direct-$\gamma$), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)
Back to Jet Quenching and BDMPSZ.
The BDMPSZ model has 2 predictions

(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, $\langle p_{\perp W}^2 \rangle$ transverse to a parton traversing a length $L$ in the medium is well approximated by

$$\langle p_{\perp W}^2 \rangle \approx \langle q^2(L) \rangle = \hat{q} L \quad \langle \hat{q} L \rangle = \langle k_T^2 \rangle_{AA} - \langle k_T'^2 \rangle_{pp}$$

Although only the component of $\langle p_{\perp W}^2 \rangle$ perpendicular to the scattering plane affects $k_T$, the azimuthal broadening of the di-jet is caused by the random sum of the azimuthal components $\langle p_{\perp W}^2 \rangle/2$ from each outgoing di-jet or $\langle p_{\perp W}^2 \rangle = \hat{q} L$
The BDMPSZ model has 2 predictions

(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:

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From $R_{AA}$ observed at RHIC (after 12 years) the JET Collab. PRC 90 (2014) 014909 has found that $\hat{q} = 1.2 \pm 0.3$ GeV$^2$/fm at RHIC, $1.9 \pm 0.7$ at LHC at initial time $\tau_0=0.6$ fm/c but nobody has yet measured the azimuthal broadening predicted in (2)!
The key new idea \( k'_{T} \) gives elegant Solutions

The di-hadron correlations of \( p_{Tt} \) with \( p_{Ta} \) 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. 

\[
x_{h} = \frac{p_{Ta}}{p_{Tt}} \quad \hat{x}_{h} = \frac{\hat{p}_{Ta}}{\hat{p}_{Tt}} \quad \langle z_{t} \rangle = \frac{p_{Tt}}{\hat{p}_{Tt}}
\]

The same values of \( \hat{x}_{h} \), and \( \langle z_{t} \rangle \) in Au+Au and p+p gives the cool result:

\[
\langle \hat{q}L \rangle = \left[ \frac{\hat{x}_{h}}{\langle z_{t} \rangle} \right]^{2} \left[ \frac{\langle p_{out}^{2} \rangle_{AA} - \langle p_{out}^{2} \rangle_{pp}}{x_{h}^{2}} \right]
\]

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) \( \langle p_{out}^{2} \rangle = \hat{p}_{Ta}^{2} \sin^{2}(\pi - \Delta \phi) \). This reduces the formula for di-jets to:

\[
\langle \hat{q}L \rangle = \left[ \langle p_{out}^{2} \rangle_{AA} - \langle p_{out}^{2} \rangle_{pp} \right] = \hat{p}_{Ta}^{2} \left[ \langle \sin^{2}(\pi - \Delta \phi) \rangle_{AA} - \langle \sin^{2}(\pi - \Delta \phi) \rangle_{pp} \right]
\]
Does the formula give the same answer for $q^L$ from the above predictions at RHIC for 35 GeV Jets?
I got 9.7 GeV$^2$ and 21.5 GeV$^2$ respectively for the 8 GeV$^2$ and 20 GeV$^2$ plots.
Find di-jet info from di-hadrons and $<z_t>$

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

This is well known to older PHENIXians who have read PRD74(2006)072002, or my book [Rak & Tannenbaum, High pT physics in the Heavy Ion Era –Cambridge 2013] as outlined below

• A) Bjorken parent-child relation and `trigger-bias’ gives $<z_t>$
• B) The energy loss of the trigger jet from p+p to Au+Au can be measured by the shift PRC87(2013) 034911
• C) $\hat{x}_h$ the ratio of the away-jet to the trigger jet transverse moments can be measured by the away particle $p_{Ta}$ distribution for a given trigger particle $p_{Tt}$

\[ n=8.1 \text{ for } 200 \text{ GeV} \]
$\hat{x}_h$ from fits to the PX PRL104 data

**PHENIX $\pi/6 \pi0$--$h$ pp $p_T=4\text{--}5$ GeV/c**

**PHENIX $\pi/6 \pi0$--$h$ AuAu0020 $p_T=4\text{--}5$ GeV/c**

Solid:2--component; Dashed:1--component

<table>
<thead>
<tr>
<th>N</th>
<th>$\hat{x}_h$</th>
<th>$N_p$</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.53±0.02</td>
<td>1.06±0.02</td>
<td></td>
<td>1.1/3</td>
</tr>
<tr>
<td>1.1±0.4</td>
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<td>1.6$_{-0.8}^{+1.8}$</td>
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<td>3.1$_{-2.1}^{+3.4}$</td>
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<td>0.13±0.09</td>
<td>AuAu/pp</td>
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</tbody>
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**PHENIX $\pi/6 \pi0$--$h$ AuAu0020 $p_T=7\text{--}9$ GeV/c**

Solid:2--component; Dashed:1--component

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>0.94±0.03</td>
<td>0.86±0.03</td>
<td></td>
<td>2.7/3</td>
</tr>
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Zimanyi School 2018

PHENIX M. J. Tannenbaum 56
\( \hat{x}_h \) from fits to the PX PRL104 data

**PHENIX** \( \pi/6 \pi0-h \) \( pp \) \( p_t=4-5 \) GeV/c

**PHENIX** \( \pi/6 \pi0-h \) AuAu0020 \( p_t=4-5 \) GeV/c

Solid:2–component; Dashed:1–component

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<tr>
<td>●</td>
<td>0.53±0.02</td>
<td>1.06±0.02</td>
<td>1.1/3</td>
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<tr>
<td>●</td>
<td>1.1±0.4</td>
<td>0.47±0.07</td>
<td>3.0/3</td>
</tr>
<tr>
<td>■</td>
<td>1.6^{+1.8}_{-0.8}</td>
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AuAu/pp

**PHENIX** \( \pi/6 \pi0-h \) \( pp \) \( p_t=7-9 \) GeV/c

**PHENIX** \( \pi/6 \pi0-h \) AuAu0020 \( p_t=7-9 \) GeV/c

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</tr>
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</table>

AuAu/pp
Results from STAR PLB760(2016)689 as given by MJT in PLB771(2017)553 with a few corrections

Table 18: Tabulations for $\hat{q}$-STAR $\pi^0$-h: $12 < p_{Tt} < 20$ GeV/c 00-12% Centrality

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sqrt{s_{NN}}$ = 200</th>
<th>$\langle p_{Tt} \rangle$</th>
<th>$\langle p_{Ta} \rangle$</th>
<th>$\langle z_t \rangle$</th>
<th>$\hat{x}_h$</th>
<th>$\langle p_{out}^2 \rangle$</th>
<th>$\sqrt{\langle k_T^2 \rangle}$</th>
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</thead>
<tbody>
<tr>
<td>p+p</td>
<td>14.71</td>
<td>1.72</td>
<td>$0.80 \pm 0.05$</td>
<td>$0.84 \pm 0.04$</td>
<td>0.263</td>
<td>$0.113$</td>
<td>$2.34 \pm 0.34$</td>
</tr>
<tr>
<td>p+p</td>
<td>14.71</td>
<td>3.75</td>
<td>$0.80 \pm 0.05$</td>
<td>$0.84 \pm 0.04$</td>
<td>0.576</td>
<td>$0.167$</td>
<td>$2.51 \pm 0.31$</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>1.72</td>
<td>$0.80 \pm 0.05$</td>
<td>$0.36 \pm 0.05$</td>
<td>0.547</td>
<td>$0.163$</td>
<td>$2.28 \pm 0.35$</td>
</tr>
<tr>
<td>Au+Au 00-12%</td>
<td>14.71</td>
<td>3.75</td>
<td>$0.80 \pm 0.05$</td>
<td>$0.36 \pm 0.05$</td>
<td>0.851</td>
<td>$0.203$</td>
<td>$1.42 \pm 0.22$</td>
</tr>
<tr>
<td>p+p comp</td>
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</tbody>
</table>

The errors on the STAR $\langle \hat{q}L \rangle$ GeV$^2$ are much larger than stated in my publication using the STAR data [15] because I made an error by incorrectly calculating Eq. 44 which is correct. Interestingly neither referee caught this because all they had to do was use Eq. 5 since the necessary information with correct errors was given in the Tables. For the present work, the errors are correct. Also, the new values reflect that Eq. 5 defines $\langle \hat{q}L \rangle$ not $\langle \hat{q}L \rangle /2$. 

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U.S. Department of Energy
Brookhaven National Laboratory
Zimanyi School 2018
PHOENIX M. J. Tannenbaum 58
Fig 2 from PHENIX PRL104,252301(2010) shows the away widths
Table 8: Tabulations for $\hat{q}$-PHENIX $\pi^0$-h: $5 < p_{Tt} < 7$ GeV/c 20-60% Centrality (Fig. 13)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sqrt{s_{NN}}$ (GeV/c)</th>
<th>$\langle p_{Tt} \rangle$ (GeV/c)</th>
<th>$\langle p_{T\alpha} \rangle$ (GeV/c)</th>
<th>$\langle z_t \rangle$ (GeV/c)</th>
<th>$\hat{x}_h$ (GeV/c)</th>
<th>$\langle p_{\text{out}}^2 \rangle$ (GeV/c)</th>
<th>$\sqrt{\langle k_{T}^2 \rangle}$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<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>
<td></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>
<td></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>
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</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>
<td></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>
<td></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>
<td></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>
<td></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>
<td></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>
<td></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>
<td></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>
<td></td>
</tr>
<tr>
<td>p+p comp</td>
<td>5.783</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>
<td></td>
</tr>
</tbody>
</table>

$\langle \hat{q}L \rangle$ .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           |
More qhatL results from PRL104 Fig2

Table 10: Tabulations for $\hat{q}$–PHENIX $\pi^0$-h: $7 < p_{Tt} < 9$ GeV/c 20-60% Centrality (Fig. 13)

<table>
<thead>
<tr>
<th>PHENIX PRL104</th>
<th>$\sqrt{s_{NN}} = 200$</th>
<th>$\langle p_{Tt} \rangle$</th>
<th>$\langle p_{Ta} \rangle$</th>
<th>$\langle z_t \rangle$</th>
<th>$\hat{x}_h$</th>
<th>$\langle p^2_{out} \rangle$</th>
<th>$\sqrt{\langle k^2_T \rangle}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>7.83</td>
<td>1.42</td>
<td>0.64 ± 0.06</td>
<td>0.86 ± 0.03</td>
<td>0.360 ± 0.017</td>
<td>2.98 ± 0.41</td>
<td></td>
</tr>
<tr>
<td>p+p</td>
<td>7.83</td>
<td>2.44</td>
<td>0.64 ± 0.06</td>
<td>0.86 ± 0.03</td>
<td>0.694 ± 0.048</td>
<td>2.99 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>p+p</td>
<td>7.83</td>
<td>3.76</td>
<td>0.64 ± 0.06</td>
<td>0.86 ± 0.03</td>
<td>1.213 ± 0.109</td>
<td>2.76 ± 0.32</td>
<td></td>
</tr>
<tr>
<td>p+p</td>
<td>7.83</td>
<td>5.82</td>
<td>0.64 ± 0.06</td>
<td>0.86 ± 0.03</td>
<td>2.177 ± 0.424</td>
<td>2.48 ± 0.38</td>
<td></td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>7.83</td>
<td>1.30</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>0.548 ± 0.107</td>
<td>3.35 ± 0.64</td>
<td></td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>7.83</td>
<td>2.31</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>0.803 ± 0.177</td>
<td>2.45 ± 0.46</td>
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<tr>
<td>Au+Au 20-60%</td>
<td>7.83</td>
<td>3.55</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>1.237 ± 0.232</td>
<td>2.08 ± 0.34</td>
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</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>7.83</td>
<td>5.73</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>1.300 ± 0.350</td>
<td>1.29 ± 0.27</td>
<td></td>
</tr>
<tr>
<td>p+p comp</td>
<td>7.83</td>
<td>1.30</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>0.360 ± 0.017</td>
<td>2.28 ± 0.33</td>
<td></td>
</tr>
<tr>
<td>p+p comp</td>
<td>7.83</td>
<td>2.31</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>0.694 ± 0.048</td>
<td>2.22 ± 0.28</td>
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</tr>
<tr>
<td>p+p comp</td>
<td>7.83</td>
<td>3.55</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>1.213 ± 0.109</td>
<td>2.05 ± 0.26</td>
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<tr>
<td>p+p comp</td>
<td>7.83</td>
<td>5.73</td>
<td>0.66 ± 0.06</td>
<td>0.62 ± 0.04</td>
<td>2.177 ± 0.424</td>
<td>1.76 ± 0.28</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\langle \hat{q}L \rangle$</th>
<th>$\langle \hat{q}L \rangle$ GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au 20-60%</td>
<td>9.3 ± 6.3</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>2.4 ± 2.2</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>1.0 ± 1.2</td>
</tr>
<tr>
<td>Au+Au 20-60%</td>
<td>−1.2 ± 1.0</td>
</tr>
</tbody>
</table>
Conclusion

It appears that the method works and gives consistent results for all the data shown. In the lowest $p_{Ta} \sim 1.5$ GeV/c bin the results are all consistent with the JET collaboration [Phys. Rev. C90, 014909 (2014)] result, $\hat{q} = 1.2 \pm 0.3$ GeV$^2$/fm or $\hat{q}L \approx 8.4 \pm 2.1$ GeV$^2$ for $L = 7$fm, the diameter 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 that three orders of magnitude down in the $x_E$ aka (STAR $z_T$) distributions the A+A best fit is parallel to the p+p measurement which means no energy loss from the jets beyond this value. This is consistent with all the $I_{AA} = p_{Ta}/p_{Tt}$ distributions ever measured which decrease with increasing $p_{Ta}$ until $p_{Ta} \approx 3$ GeV/c and then become constant because the A+A and p+p distributions are parallel.
Some $I_{AA}$ distributions all flat for $p_{Ta}>3$ GeV/c
THE END

For More Info on the latest BNL results check Quark Matter 2018
https://qm2018.infn.it
My method and answer

The theorists don’t give numbers for the curves, so I assumed gaussians and measured the half width at half maximum, which for a gaussian is 1.177 \( \sigma \). i.e. \( \sigma = \text{hwhm}/1.177 \).

Assuming that the peak is symmetric about \( \pi \), I calculated \( <p_{\text{out}}^2> = (35 \times \sin \sigma)^2 \) and used

\[
\langle \hat{q}L \rangle = \left[ \langle p_{\text{out}}^2 \rangle_{AA} - \langle p_{\text{out}}^2 \rangle_{pp} \right]
\]

I got 9.7 GeV\(^2\) and 21.5 GeV\(^2\) for the 8 GeV\(^2\) and 20 GeV\(^2\) plots.
(QGP) Discoveries at RHIC

- Suppression of high $p_T$ hadrons from hard-scattering of initial state partons; also modification of the away-side jet
- Elliptic Flow at the Hydrodynamic limit as a near ideal fluid with shear viscosity/entropy density at or near the quantum lower bound $\eta/s \approx 1/(4\pi)$
- Elliptic flow of particles proportional to the number of the valence (constituent) quark count.
- Charged particle multiplicity proportional to the number of constituent quark participants
- Higher order flow moments proportional to density fluctuations of the initial colliding nuclei
- Suppression and flow of heavy quarks roughly the same as that of light quarks; QCD hard direct photons not suppressed, don’t flow.
- Production and flow of soft photons not seen in p+p collisions
The big discovery is that the soft photons, $p_T > 1.0$ GeV/c, also follow $N_{\text{coll}}$ scaling, but without the $\text{SY}(\sqrt{s_{NN}})$ i.e. they scale with $(dN_{\text{ch}}/d\eta)^{1.25}$ as a function of centrality for all $\sqrt{s_{NN}}$ measured.
The exponential soft photons, $p_T > 1$ GeV/c scale with $(dN_{ch}/d\eta)^{1.25}$ as a function of centrality for all $\sqrt{s_{NN}}$ measured.
AuAu & PbPb Direct single photon $p_T$ spectra normalized by $(dN_{ch}/d\eta)^{1.25}$

![Graphs showing AuAu & PbPb direct single photon $p_T$ spectra normalized by $(dN_{ch}/d\eta)^{1.25}$](image)

arXiv: 1805.04084

PHENIX
AuAu & PbPb Direct single photon $p_T$ spectra normalized by $(dN_{ch}/d\eta)^{1.25}$
The very big discovery
1) the soft photons, $p_T=1$-$3$ GeV/c, scale with $N_{coll}$ as a function of centrality like the hard photons.
2) the scaling is identical at all $\sqrt{s_{NN}}$ in the variable $(dN_{ch}/d\eta)^{1.25}$ as a function of centrality
3) the soft photons flow $v_2>0$, but the hard photons don’t flow (old news)
I don’t believe the so called QCD calculation used by PHENIX and the dashes from ALICE which has a 30% to 60% systematic error not shown but I do believe in JETPHOX.
All Direct $\gamma$ p-p data and pQCD c. 2007

PHENIX direct-$\gamma$ in p-p
PRL 98 (2007) 012002

JETPHOX fits all existing direct $\gamma$ data for $p_T$>4 GeV/c plus the new 2.76 TeV data
Final configuration a di-jet with $k_T'$ and fragments with $p_{out}$. 
The new experiment sPHENIX is moving along well
Successful DOE Major Item of Equipment review

sPHENIX MIE

<table>
<thead>
<tr>
<th>WBS</th>
<th>sPHENIX MIE Project Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Project Management</td>
</tr>
<tr>
<td>1.2</td>
<td>Time Projection Chamber</td>
</tr>
<tr>
<td>1.3</td>
<td>Electromagnetic Calorimeter</td>
</tr>
<tr>
<td>1.4</td>
<td>Hadron Calorimeter</td>
</tr>
<tr>
<td>1.5</td>
<td>Calorimeter Electronics</td>
</tr>
<tr>
<td>1.6</td>
<td>DAQ-Trigger</td>
</tr>
<tr>
<td>1.7</td>
<td>Minimum Bias Trigger Detector</td>
</tr>
</tbody>
</table>

The conceptual design of sPHENIX is based on 3 principles:
- Design a detector to meet the Science Mission of measurements of Jets and Upsilon in RHIC environment
- Maximize cost effectiveness and utilize modern technologies where appropriate (SiPM, fast TPC readout)
- Build on existing $20M+ PHENIX infrastructure