Beam Energy Scan and Future Plans of RHIC

Rachid Nouicer
Brookhaven National Laboratory

XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece
August 29th to September 3rd, 2016

Many Thanks to:
- Berndt Mueller (ALD NP)
- David Morrison
- Wolfram Fischer
- Elke-Caroline Aschenauer
Jet Quenching is the major discovery at RHIC as well at LHC
Motivation: Perfect Liquid Major Discovery

RHIC and LHC precision measures of higher moments

\[
\frac{dN}{d\phi} = 1 + 2v_2 \cos[2(\phi - \Psi_2)] + 2v_3 \cos[3(\phi - \Psi_3)] + 2v_4 \cos[4(\phi - \Psi_4)] + 2v_5 \cos[5(\phi - \Psi_5)] + \ldots
\]

- Medium is strongly interacting (the large amplitude of \(v_2\))
- Comparisons with models hydrodynamic viscous with RHIC and LHC data seem to support very small values for \(\eta/s\). This implies that the nuclear matter created is almost perfect fluid.
Validation of the crossover transition leading to the QGP

→ Necessary requirement for CEP
Strategy for RHIC BES-I

- Map turn-off of QGP signatures
- Location of the Critical End Point (CEP)?
- Location of phase coexistence regions?
- 1st order phase transition signs
- Detailed properties of each phase?

\[ \frac{\eta}{s} (T, \mu), \frac{\zeta}{s} (T, \mu), c_s (T), \hat{q}(T), \alpha_s (T), \text{etc} \]
Phases of QCD matter
• How do we map the QCD phase diagram?

**RHIC has access to different collision systems and a broad domain of the \( (\mu_B, T) \)-Plane**

We can vary \( \sqrt{S_{NN}} \) and explore the \( (\mu_B, T) \) plane for experimental signatures.

**RHIC established a physics program for Beam Energy Scan-I (BES-I):**
7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, 200 GeV
Phases of QCD matter

- How do we map the QCD phase diagram?

- Vary the collision energy over the full range accessible at RHIC

$$\left( \mu_B, T \right)$$ at chemical freeze-out

J. Cleymans et al.
Phys. Rev. C73, 034905
Phases of QCD matter

• How do we map the QCD phase diagram?

• Vary the collision energy over the full range accessible at RHIC

• Do we observe signatures of a phase transition and/or critical end point?
  
    – Elliptic and directed flow: indicators of the “softest point” in momentum space
  
    – Azimuthally-sensitive HBT: indicator of the “softest point” in coordinate space

• Do we observe turn off of the new phenomena that have been observed in full-energy RHIC collisions?
  
    – Jet quenching in central collisions
The RHIC Facility

The RHIC Facility is a multi-purpose particle accelerator located at the Brookhaven National Laboratory in Upton, New York. It is designed to study the fundamental properties of matter under extreme conditions, such as those created in the early universe or in high-energy collisions.

The RHIC QCD Machine, shown in the diagram, includes several key components such as the RHIC ring, PHENIX and STAR detectors, and electron lenses. The RHIC is a synchrotron that accelerates protons and ions to high energies before they are collided at the center of the ring. The PHENIX and STAR detectors are used to measure the properties of the resulting collisions, allowing scientists to study the structure of matter and the forces that hold it together.

Lattice QCD is a theoretical framework used to study the behavior of quarks and gluons, the fundamental constituents of protons and neutrons. It is used in conjunction with experiments at RHIC to help interpret the data and further our understanding of the strong force that binds quarks together.

Rachid Nouicer
BES-I: Directed Flow ($v_1$)

- Generated during the nuclear passage time ($2R/\gamma$) – sensitive to EOS

- Minimum in slope of directed flow ($d v_1 /dy$) as a function of beam energy for baryons and double sign-change for net baryons suggest sudden softening of EOS - sign of the 1st order phase transition

- Proton $v_1$ probes interplay of baryon transport and hydro behavior
Non-monotonic behavior in net-proton $v_1$ indicate 1st order phase transition?

Split of net-p and net-K $v_1$ below 14.5 GeV.

D.H. Rischke et al. HIP1, 309(1995)
J. Steinheimer et al., arXiv:1402.7236
P. Konchakovski et al., arXiv:1404.276
Surprisingly consistent as the energy changes by a factor ~400
- Initial energy density changes by nearly a factor of 10
- No evidence from $v_2$ of charged hadrons for a turn off of the QGP
  How sensitive is $v_2$ to QGP?
- Substantial particle-antiparticle split at lower energies
- The number of quark scaling in elliptic flow is broken

STAR results show that $v_3$ vanishes for peripheral collisions at lowest RHIC BES energy. Minimum are observed for centralities bins in 0-50% collisions for $v_3^2/n_{ch,pp}$. STAR: PRL 116, 112302 (2016)
Energy Dependence of HBT signals

HBT radii are sensitive to the expansion dynamics

- These non-monotonic patterns signal an important change in the reaction dynamics; CEP?

\[ R_{\text{side}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T}^2} \]
\[ R_{\text{out}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T}^2} + \frac{2}{T} \left[ \frac{m_T}{T} \right]^2 \]
\[ R_{\text{long}}^2 \approx \frac{T}{m_T}^2 \]

PHENIX: arXiv:1410.2559

Hung, Shuryak, PRL. 75 (95) 4003
Chapman, Heinz, PRL. 74 (95) 4400
Makhlin, Sinyukov, ZPC. 39 (88) 69

Hung, Shuryak, PRL. 75 (95) 4003
Chapman, Heinz, PRL. 74 (95) 4400
Makhlin, Sinyukov, ZPC. 39 (88) 69
Jet quenching

$R_{CP}$ for hadrons can provide a measure of partonic energy loss in the medium.

Insufficient reach to search for evidence of high $p_T$ suppression below 19.6 GeV.
Beam Energy Scan-I required more statistic and it is carried out by many interesting results. Beam Energy Scan-II (BES-II) is necessary.
# Future Science Plan of RHIC 2017-2020

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>High statistics Pol. p+p at 510 GeV</td>
<td>Transverse spin physics</td>
<td>Coherent e-cooling test II</td>
</tr>
<tr>
<td>2018</td>
<td>$^{96}$Zr+$^{96}$Ru at 200 GeV Au+Au at 27 GeV (?)</td>
<td>Establish chiral magnetic effect</td>
<td>Low energy e-cooling upgrade</td>
</tr>
<tr>
<td>2019-20</td>
<td>7.7-20 GeV Au+Au (BES-2)</td>
<td>Search for QCD critical point and onset of deconfinement</td>
<td>STAR iTPC upgrade EPD upgrade CBM TOF test</td>
</tr>
</tbody>
</table>

**Strongly endorsed by 2016 RHIC PAC**
RECOMMENDATION 1

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- Complete and run CEBAF 12 GeV upgrade
- Complete FRIB at MSU
- Targeted program in neutrinos and fundamental symmetries
- The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.
Transverse Polarized p+p Collisions (Run-17)

Talk by Elke-Caroline Aschenauer: “The RHIC Spin Program”; Thursday at 17:00 PM

Visualize Color interactions in QCD

Sivers function

\[ \sin(\phi_h - \phi_s) \]

- correlation of nucleon's transverse spin with the \( k_T \) of an unpolarized quark
- measures spin-orbit correlations
- link to parton orbital motion (through models)
- reveals non-trivial aspects of QCD color gauge invariance

Measure non-universality of sivers-function

**QCD:**

**DIS:**
- \( \gamma q \)-scattering
- attractive FSI

**pp:**
- \(qq\bar{q} \)-anihilation
- repulsive ISI

\[ Sivers_{\text{DIS}} = - (Sivers_{\text{DY}} \text{ or } Sivers_{W} \text{ or } Sivers_{Z0}) \]
Analysis of Run-15 data demonstrates viability of definitive measurement

**STAR:** PRL 116 (2016) 132301

- Will provide data to constrain TMD evolution
- Sea-quark Sivers fct → y-dependence
- Test sign-change if TMD evolution ~ 5 or less.

Critical inputs for EIC!

**Talk by Elke-Caroline Aschenauer:**
“The Spin structure of the Proton: What RHIC and EIC can teach us” Saturday at 17:20 PM

**Recent theory paper:** Jin Huang et al. Phys. Rev. D 93, 014036 (2016)
The chiral anomaly of QCD creates fluctuating differences in the number of left and right handed quarks, characterized by a chiral chemical potential $\mu_5$.

In a chirally symmetric QGP, this imbalance generates an electric current along the magnetic field (chiral magnetic effect).

$\mu_5 > 0$

Chirality + magnetic field = current

Electric charge separation

$B \approx 10^{18}$ Gauss
Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation.

Isobar collisions will tell us what fraction of the charge separation is due to CME to within +/- 6% of the observed signal.
Breaking of chiral symmetry in QCD generates most of the visible mass of the universe. Is chiral symmetry restored in these collisions?

At low density, the phase transition between QGP and hadrons is smooth. Is there a 1\textsuperscript{st} order transition and a critical point at higher density?
BES-II: The STAR Upgrades

Major improvements for BES-II

**iTPC Upgrade:**
- Rebuilds the inner sectors of the TPC
- Full (azimuth) coverage
- Improves dE/dx
- Extends $\eta$ coverage from 1.0 to 1.7
- Lowers $p_T$ cut-in from 125 MeV/c to 60 MeV/c

**EndCap TOF Upgrade:**
- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program

**EPD Upgrade:**
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics
BES-II for search of critical point in QCD phase diagram

<table>
<thead>
<tr>
<th>Center-of-mass energy $\sqrt{s_{NN}}$ GeV</th>
<th>7.7</th>
<th>9.1</th>
<th>11.5</th>
<th>14.6</th>
<th>19.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events BES-I, actual</td>
<td>M</td>
<td>4.3</td>
<td>11.7</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>Events BES-II, min goal</td>
<td>M</td>
<td>80</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Events BES-II, full goal</td>
<td>M</td>
<td>100</td>
<td>160</td>
<td>230</td>
<td>300</td>
</tr>
</tbody>
</table>

General strategy to maximize integrated luminosity is to use:

- Cooling at the 3 lowest energies (4x gain in $L_{\text{avg}}$),
- No cooling at the 2 highest energies (3x gain in $L_{\text{avg}}$): demonstrated at 19.6 GeV in Run-16
- Increase cryo-time from 22 to 24 weeks/year
- Start BES-II at highest energies (machine ready w/o cooling)
- Interleave cooling commissioning with physics operation
- Finish BES-II at lowest energies (largest gain in $L_{\text{avg}}$ and time)
Low Energy RHIC electron Cooling (LEReC) Layout

Energies: 1.6, 2.0 (2.65) MeV
Avg. current $I_{av}$: 27 mA
Momentum $dp/p$: $5 \times 10^{-4}$
Luminosity gain: 4x

1st bunched beam electron cooler planned operation in 2019/2020

Commissioning Diagnostic Line 1
704 MHz Cu Cavity
9 MHz Cu Cavity
2.1 GHz Cu Cavity
704 SRF Booster Cavity
DC e- Gun

LEReC Solenoids
- Compensating (LF)
- Matching (HF)
- Merger/Transport

COOLING in Blue RHIC ring
COOLING in Yellow RHIC ring

180° Bending Magnet
20° Bending Magnets
Beam Dump

RHIC TRIPLET

Commissioning Diagnostic Line 2

Talk by Wolfram Fischer: “RHIC upgrades for the next decade”, Sunday at 14:30 PM
A. Fedotov et al.
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) Prove the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.
Complementarity of RHIC and LHC Measurements

Physics Requirements of sPHENIX at RHIC

Table:

<table>
<thead>
<tr>
<th>Physics goal</th>
<th>Detector requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>High statistics for rare probes</td>
<td>Accept/sample full delivered luminosity</td>
</tr>
<tr>
<td></td>
<td>Full azimuthal and large rapidity acceptance</td>
</tr>
<tr>
<td>Precision Upsilon spectroscopy</td>
<td>Hadron rejection &gt; 99% with good $e^+e^-$ acceptance</td>
</tr>
<tr>
<td></td>
<td>Mass resolution 1% @ mv</td>
</tr>
<tr>
<td>High jet efficiency and resolution</td>
<td>Full hadron and EM calorimetry</td>
</tr>
<tr>
<td></td>
<td>Tracking from low to high $p_T$</td>
</tr>
<tr>
<td>Control over parton mass</td>
<td>Precision vertexing for heavy flavor ID</td>
</tr>
<tr>
<td>Control over initial parton $p_T$</td>
<td>Large acceptance, high resolution photon ID</td>
</tr>
<tr>
<td>Full characterization of jet final</td>
<td>High efficiency tracking for $0.2 &lt; p_T &lt; 40$GeV</td>
</tr>
</tbody>
</table>

Talk by Gunther Roland (for sPHENIX S&T Review at BNL, August 2016):

https://indico.bnl.gov/conferenceDisplay.py?confId=2238
sPHENIX Capabilities: Jets & Upsilon states

Complete calorimetric jet spectroscopy

PHENIX:
- direct $\gamma$
- $e^+_{HF}$
- $\pi^0$

sPHENIX:
- direct $\gamma$
- $b$-jet
- jet
- $h^*$

Outer HCal
Magnet coil
Inner HCal
EMCal
Vertexer/Tracker

Completely resolved Upsilon spectroscopy

$R_{AA}$ vs $p_T$ (GeV/c)

$R_{AA}$ vs $N_{part}$

Y(1S), Y(2S), Y(3S)

Rachid Nouicer
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC’s unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.
Most compelling SCIENCE Questions

How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?

How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

- How does the transverse spatial distribution of gluons compare to that in the nucleon?
- How does matter respond to fast moving color charge passing through it?
- Is this response different for light and heavy quarks?

Where does the saturation of gluon densities set in?

- Is there a simple boundary that separates the region from the more dilute quark gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?
- Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?
BNL EIC Design: eRHIC

- Talk by Wolfram Fischer: “RHIC upgrades for the next decade”, Sunday at 14:30 PM
- Talk by Christoph Montag: “eRHIC Design Status and Plans”, Sunday at 15:15 PM

eRHIC ERL + FFAG ring design @ $10^{33}$-$10^{34}$/cm$^2$s
~20 GeV $e^-$ + 255 GeV $p$ or 100 GeV/u Au.

When completed eRHIC will be the most advanced and energy efficient accelerator in the world.

Note: new detectors for EIC fit in the existing RHIC tunnels.

Build a new detector: BeAST (Brookhaven eA Solenoidal Tracker)
Talk by Timothy J. Hallman  Associate Director for Nuclear Physics  DOE Office of Science

RHIC is Amazing QCD Machine
- Many Species, Many Energies, and High Luminosity and Stability

RHIC is planning a unique forefront science program with continued discovery potential as laid out in NSAC LRP:
- Quantify the transport properties of the QGP near $T_c$ using heavy quarks as probes
- Measure gluon and sea quark contributions to proton spin and explore transverse momentum-spin dynamics of QCD
- High statistics map of the QCD phase diagram, including search for a possible critical point
- Probe internal structure of the most liquid QGP using fully reconstructed jets and resolved Upsilon states as probes

Important machine and detector upgrades underway for BES II (LEReC, iTPC, EPD)

Major detector upgrade underway (sPHENIX)

Transition from RHIC to eRHIC in mid-2020s