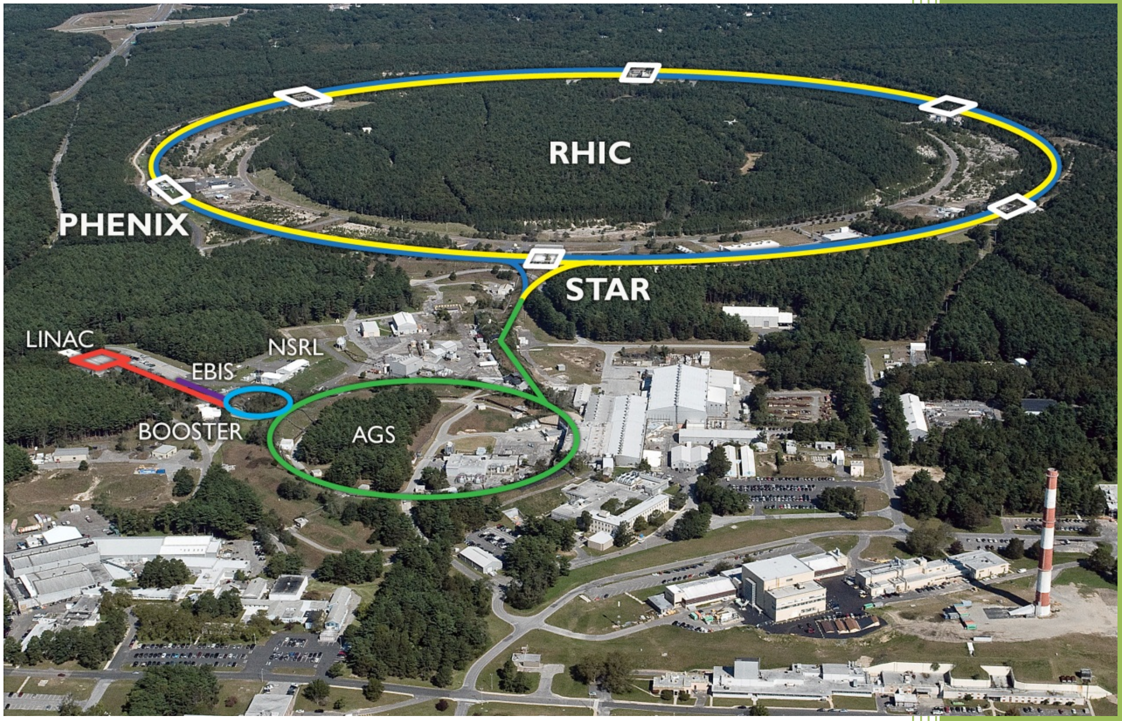
2012

The Case for Continuing RHIC Operations



Drafted by Steve Vigdor

Revised with extensive feedback from RHIC user and support community

9/2/2012

The Case for Continuing RHIC Operations

Table of Contents

1. The Case in a Nutshell

RHIC has, by almost any measure, been one of the greatest successes of the U.S. Nuclear Physics research program. It has been a pioneering facility: the first to observe clearly the transition to quark-gluon matter; in addition, the world's only polarized collider. It is the world's most versatile collider: the wide range of beam energies and colliding beam species has been crucial in facilitating a series of definitive discoveries in an important regime of nuclear matter. It has been extremely productive: the first decade of operation produced more than 300 refereed papers, cumulatively earning more than 30,000 citations, and more than 300 Ph.D.'s; many more of each category are currently in the pipeline, with no rate falloff in sight. Young scientists whose research programs have been primarily focused on RHIC have gone on since the year 1997 to fill over 150 tenured or tenure-track faculty and laboratory staff positions worldwide, with many in some of the most prominent Physics Departments. The point of this White Paper is that RHIC is in its prime: it is poised to address a host of compelling science questions that remain or have been raised by the important discoveries to date; the facility performance continues to improve dramatically; the user base remains energized and committed; the Nuclear Physics community's visions for the long-term future of QCD-related research are best realized using RHIC as a primary base.

> *RHIC is in its prime: it is poised to address a host of compelling science questions that remain or have been raised by the important discoveries to date; the facility performance continues to improve dramatically; the user base remains energized and committed; the Nuclear Physics community's visions for the long-term future of QCD-related research are best realized using RHIC as a primary base.*

The most important reasons for continuing RHIC operations despite budget constraints are:

- **RHIC has pioneered a vibrant new subfield – laboratory study of condensed QCD matter physics – and has led the rapid climb up a steep learning curve marked by continuing science and technology breakthroughs.** A signature discovery is that matter created at the extreme temperatures characteristic of the universe a few micro-seconds after the Big Bang behaves, in marked contrast to expectations before RHIC, like a nearly friction-free liquid assembled from quarks and gluons. This finding, in turn, opens the door to future discoveries. By terminating RHIC operations, the U.S. would unilaterally cede leadership in this high-impact field that has attracted many talented young scientists.

- **Discoveries and techniques at RHIC have established deep intellectual connections to other physics forefronts.** Connections to String Theory, Cosmology, Condensed Matter and Low Temperature Physics have given RHIC unusually broad impact for Nuclear Physics research. Strong interest in the results has extended beyond non-nuclear physicists to the public at large, through wide media coverage.

- **Critical directions for future research in this subfield involve quantifying hot QCD matter properties as a function of temperature from below to above the transition to Quark Gluon Plasma (QGP).** This transition appears to occur within the RHIC range, at energies not accessible at the LHC. Measurements at both facilities are essential to map QGP behavior as a function of temperature. The LHC heavy-ion program complements RHIC by extending the temperature and kinematic ranges for the study of early-universe QCD matter, but it cannot supplant RHIC. Condensed QCD matter physics is *not* Energy Frontier science!

- **RHIC has now essentially completed major performance upgrades that facilitate the next decade's science. It also provides quite possibly the only cost-realizable path to the next QCD frontier with an Electron-Ion Collider (EIC).** The RHIC-II era has been launched during the 2012 run, five years sooner than projected in the 2007 Long Range Plan (LRP) and at one-seventh the projected collider upgrade cost, thanks to technology breakthroughs at RHIC. RHIC is the only facility in the world that has demonstrated polarized proton beam acceleration to energies needed for EIC and built a strong research program on this capability. Crisis management for U.S. Nuclear Physics in the current decade must preserve a viable path to a vibrant future in the next decade.

We elaborate on the above points in this White Paper, while making several additional essential points in passing here. First, as the only operating U.S. collider facility, RHIC serves as an important base for cutting-edge accelerator R&D. That R&D has underpinned RHIC's critical versatility, has greatly reduced the cost of RHIC upgrades, and is crucial to achieve the performance desired for EIC. Synergies in accelerator R&D across BNL's multiple program missions greatly enhance the impact, providing facilities to test new accelerator concepts, opportunities to exploit the same technology to meet different scientific and application goals, and creative options to reduce the cost of an EIC. More generally, RHIC's impact is magnified by connections that arise at a single multi-mission laboratory housing world-leading efforts in accelerator science and technology, nuclear theory, lattice QCD and cutting-edge instrumentation development, in addition to experimental nuclear and particle physics.

Second, RHIC has a deeply engaged international user community. The RIKEN Institute of Japan, established in 1997, has contributed over $100M to support RHIC hardware and (theoretical as well as experimental) science. It has just extended support for the RIKEN-BNL Research Center for another six years, 2012-2018, to continue outstanding physics research highlighted by the number of Fellows who have to date filled nearly 60 tenured nuclear physics positions worldwide (see Appendix D). China, India and South Korea are making important in-kind contributions and seeking ways to enhance their involvement, as part of expansive national plans to build up fundamental science research efforts.

Third, the RHIC facility and accelerator physics program bring important ancillary benefits to society. Beams from the RHIC pre-injectors serve heavily subscribed programs to develop and produce medical radioisotopes and to study (with NASA funding) radiation hazards of deep space travel. RHIC accelerator physicists are working with industry to develop next-generation hadron radiotherapy facilities, based on Rapid Cycling Medical Synchrotrons and low-mass gantries. High-temperature superconducting magnet technology, developed in part for superconducting radiofrequency electron guns at RHIC, is being adapted for use in energy storage systems. Tests of a high-current electron Energy Recovery Linac needed for EIC are partially funded by the Office of Naval Research for their potential defense applications. All of these auxiliary benefits would suffer serious, quite possibly fatal, collateral damage if RHIC operations were terminated.

Finally, history teaches us that funding "freed" from termination of a major operating facility at one laboratory seldom, if ever, becomes available for construction of new projects at other laboratories, within the same field. Cautionary tales in this regard from not-too-distant history include nuclear physics operations at LAMPF and high-energy physics operations at SLAC. Termination of RHIC operations would lead with certainty to a devastating loss of U.S. scientific leadership, and in all likelihood simultaneously to a significant loss of funding for the U.S. Nuclear Physics research program.

2. Hot QCD Matter: RHIC's Intellectual Challenges and Greatest Hits To Date

In recreating, in microcosm, and studying quark-gluon matter under thermodynamic conditions akin to those of the universe a few microseconds after the Big Bang, RHIC has pioneered a vibrant new subfield of nuclear physics research: laboratory study of condensed QCD matter. This subfield is driven by a number of overarching and ongoing deep intellectual and technical challenges related to those at other contemporary physics forefronts, for example:

RHIC collisions have produced deconfined quark-gluon plasma matter that behaves as a nearly perfect relativistic fluid.

- What techniques can be used to pump and probe condensed strongly interacting matter that lives for only ~10^{-23} seconds after a collision?
- What are the unique emergent phenomena for matter governed by QCD?
- How did these emergent phenomena influence the evolution of the early universe?
- What roles do quantum fluctuations play in the evolution of the "mini-universe" created in each RHIC collision?
- Are there lessons to be learned from QCD matter that can inform our understanding of other non-Abelian matter (e.g., that at the ElectroWeak phase transition in the infant universe) that is more difficult or not possible to subject to laboratory investigation?

RHIC's first decade of hot QCD matter research revealed a number of compelling discoveries:

- The matter produced in near-central RHIC collisions flows as a nearly viscosity-free fluid ("perfect liquid"), in marked contrast to early expectations of ideal (asymptotically free) gas behavior for the quark-gluon plasma (QGP).
- Quantitatively, studies of elliptic flow of the matter have revealed a ratio of shear viscosity to entropy density (η/s) close to a lower quantum bound ($1/4\pi$ in natural units) predict-

ed via String Theory treatments of black holes and the Maldacena (AdS/CFT) duality between weakly coupled gravitational theories and strongly coupled QCD-like theories.

- The yields and flow of mesons vs. baryons establish a scaling behavior that points to collective flow established at the quark level, with hadrons subsequently formed by coalescence of already flowing quarks.
- The spectra of thermal photons radiated during the collisions, in combination with hydrodynamics calculations, indicate that the matter equilibrates at an initial temperature >~300 MeV (or 4 trillion Kelvin, about twice the QGP transition temperature predicted by lattice QCD), and in no more time than it takes light to traverse a proton.
- The QGP is nearly opaque to moderate-energy quarks and gluons traversing it, but transparent to photons. The quenching of particle jets spawned by such quarks and gluons is attributed to rapid parton energy loss, with the lost momentum shared among many softer outgoing hadrons distributed broadly in angle surrounding the jet axis.

Collectively, these discoveries establish that RHIC collisions have produced deconfined QGP matter that behaves as a nearly perfect relativistic fluid. The low viscosity, the strong jet quenching, and the very rapid thermalization all suggest that the fluid's constituents are quite strongly correlated. The discoveries to date also raise a number of more pointed questions to be explored in the coming decade, both experimentally at RHIC and LHC, and theoretically:

- How does strongly correlated liquid behavior arise from an asymptotically free theory?
- How close does η/s come to the AdS/CFT bound, and how does it vary as one goes from temperatures below to well above the deconfinement transition?
- What are the values of other transport coefficients in the QGP as a function of temperature, and how do they compare to expectations from lattice QCD?
- How does the QGP matter respond to the absorption of energy from traversing partons? Can we learn about the transition from weak to strong coupling by studying jet quenching and QGP response as a function of jet and collision energy?
- How does the matter thermalize so rapidly, and how is the rapid thermalization influenced by details of the gluon-dominated initial state in the collisions?
- Do heavy (c and b) quarks participate fully in the thermalization, the collective flow and the energy loss phenomena established so far for lighter quarks?
- How is the color force that binds quarks together screened, over distances comparable to hadron sizes, by the presence of colored QGP matter?

Recent breakthroughs summarized in the next section have made progress in addressing some of these questions, but also posed new profound questions for the coming decade.

3. Recent Breakthroughs and RHIC's Versatility Inform the Path Forward

Laboratory study of condensed QCD matter is a young subfield, at the dawn of its second decade, and making vigorous progress up the learning curve. In this section, we elaborate on five illustrative recent developments that pave a path toward future quantification of QGP properties and toward additional discoveries. We summarize the developments briefly here, before proceeding to a more detailed explanation of each:

1) The measurement of higher Fourier components in collective flow patterns, combined with a new generation of event-by-event relativistic viscous hydrodynamics calculations, points the way toward precision determinations of η/s and other transport coefficients of the QGP. The same analyses also promise to constrain the nature of quantum fluctuations in the initial state density. The approach is analogous in a number of ways to studies of the power spectrum of cosmic microwave background fluctuations and the quest to understand the inflationary period quantum fluctuations believed to have seeded the large-scale structure observed in today's universe. Heavy-ion collisions offer the advantages of observing billions of events and exercising control over initial conditions.
2) The surprisingly strong suppression observed in ion-ion collisions for electrons and positrons at high transverse momentum, where yields are dominated by decay daughters from heavy-flavor hadrons, shows that heavy quarks lose energy almost as rapidly as light quarks in traversing QGP. This result has led to significant re-thinking about the mechanisms for parton energy loss, but is not yet well understood theoretically. Further insights will be provided by micro-vertex detector upgrades to both PHENIX and STAR, which will allow the collaborations to distinguish effects from *c vs. b* quarks.
3) Another result of the close interplay between theory and experiment is the elaboration of several testable signatures of an important, if exotic, emergent phenomenon in hot non-Abelian matter: high-temperature excited vacuum fluctuations (so-called sphalerons) like the EW ones speculated to be the source of baryon-antibaryon asymmetry in the infant universe. Several recent measurement results resemble predicted effects of QCD sphalerons in the presence of the extremely strong magnetic fields in heavy-ion collisions. Establishing discovery potential here rests on ongoing and future experiments aimed at distinguishing these signals from more mundane backgrounds associated with collective flow.
4) A beam energy scan carried out at RHIC in 2010-11 has provided first indications that the transition from hadronic to quark-gluon degrees of freedom occurs within the energy range spanned at RHIC, offering a unique opportunity to probe QCD matter properties from below to above the transition. The same scan also reveals fluctuation phenomena suggesting approach toward an anticipated critical endpoint in the phase diagram, a unique fixed point in the landscape of QCD matter.
5) The installation of six planes of stochastic cooling equipment in 2012 dramatically improved the heavy-ion luminosity. At the same time, completion of a new Electron Beam Ion Source (EBIS) allows for new colliding beam species (e.g., U+U, Cu+Au) that offer additional controls of initial collision geometry in elucidating QGP behavior.

> *The combination of an energy "sweet spot," the enhanced versatility in colliding beam species, targeted detector upgrades, and the focus to dedicate ample time and integrated luminosity to heavy ion collision experiments all promise to keep RHIC at the forefront in answering the compelling open science questions…*

The combination of an energy “sweet spot,” the enhanced versatility in colliding beam species, targeted detector upgrades, and the focus to dedicate ample time and integrated luminosity to heavy ion collision experiments all promise to keep RHIC at the forefront in answering the compelling open science questions mentioned near the end of Sec. 2.

1) The early focus on *elliptic* flow in RHIC collisions – measuring the amplitude of the quadrupole pattern in the azimuthal dependence of emerging hadrons – was based on a simplifying assumption that the overlap region of the colliding nuclei could be characterized by a smooth, ellipsoidal density distribution. But the low viscosity of the QGP allows features in the emerging particle patterns to also reflect any lumpiness or asymmetry caused by event-to-event density fluctuations in the initial state. In particular, fluctuation-driven asymmetries seed *odd* flow multipoles, which are needed to account for interesting features (referred to previously as the “ridge” and the “Mach cone”) in observed di-hadron angular correlations. The sensitivity to higher flow multipoles provides, simultaneously, a method to quantify the viscosity and new discovery potential regarding the nature of the initial state density and quantum fluctuations.

New hydrodynamics calculations by a number of groups track event-by-event time evolution of QGP in three spatial dimensions, incorporating initial density fluctuations, viscosity and, in some cases, matching to a hadronic final state. These simulations demonstrate clearly (Fig. 1) that higher flow harmonics are progressively damped by shear viscosity. The shape of the flow power spectrum then becomes a well-tuned tool to quantify viscosity. For example, comparing these hydrodynamics predictions to recent RHIC results for n=2, 3 and 4 flow multipoles (Fig. 2) narrows down the possible range of η/s values to within a factor of 2—3 of the proposed quantum lower limit.

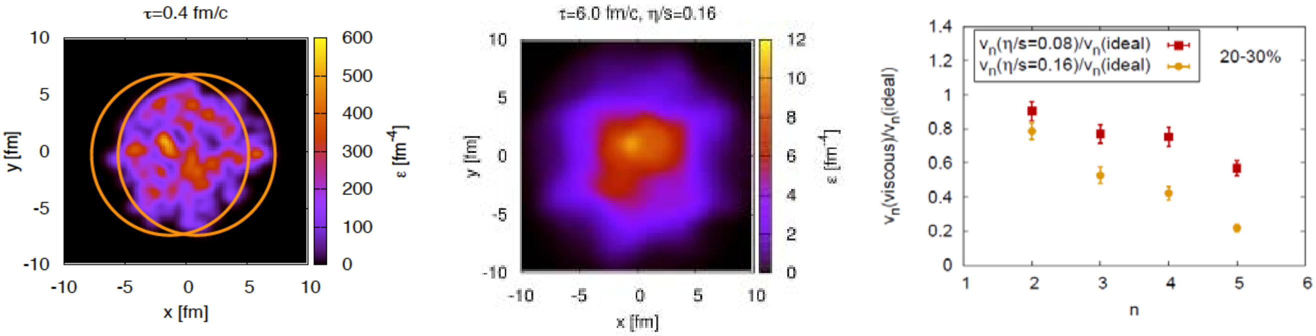


Figure 1. *3+1-dimensional event-by-event viscous hydrodynamics calculation results from B. Schenke, et al. [Phys. Rev.* ***C 85,*** *024901 (2012)]. The left two frames illustrate the evolving QGP matter density for a single event and given viscosity (twice the quantum limit), at an early (left) and a late (middle) time, with initial density fluctuations included. The blurring of the fluctuations over time reflects the higher damping of higher harmonics. The extent of damping is shown quantitatively in the right frame, via flow amplitude vs. harmonic number, for two different viscosities: equal to (red) or twice (gold) the quantum limit. In a later publication, Schenke, Tribedy and Venugopalan [Phys. Rev. Lett.* ***108,*** *252301 (2012)] also treat the influence of different models of initial density fluctuations on the shape of the flow power spectrum.*

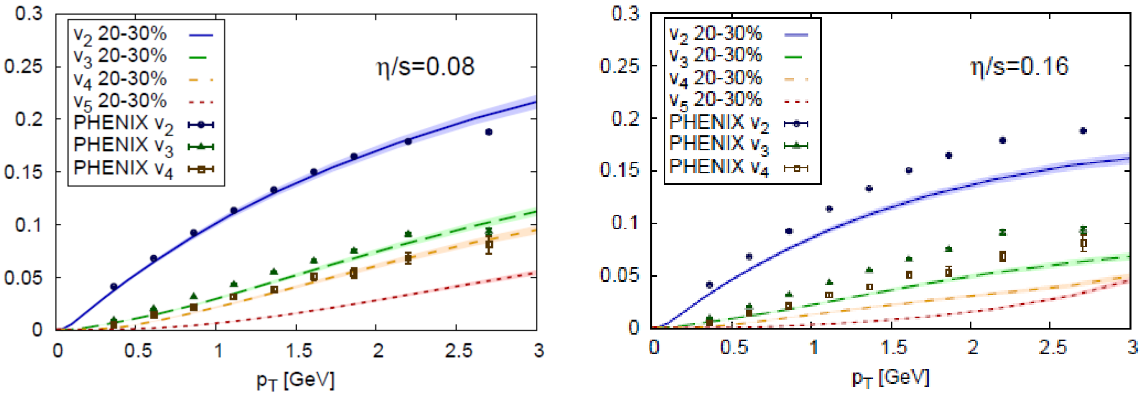


Figure 2. *Comparison of viscous hydrodynamics calculations from Schenke et al. to recent PHENIX experimental results [Phys. Rev.* ***C 85,*** *024901 (2012)] for the n=2, 3 and 4 flow multipoles in* $\sqrt{s_{NN}}$ *= 200 GeV Au+Au collisions, as a function of hadron transverse momentum. The results are shown for one particular collision centrality bin (spanning 20-30% of the total collision cross section) and assumed fluctuation model, but for different values of shear viscosity: η/s at the quantum limit (left) and twice the quantum limit (right).*

The same hydrodynamics calculations have now been extended at BNL to evaluate the effect of different initial density models, comparing fluctuations in initial nucleon positions only to models that add quantum fluctuations in an initial saturated-density gluon field. Different models lead to different length scales and rapidity-dependence of the fluctuations, affecting odd and even flow multipoles distinctly (see Sec. 6). These theoretical and experimental breakthroughs from 2011-12 point the way toward a systematic set of measurements of the flow power spectrum, outlined in Sec. 6, that can **constrain the nature of the initial state fluctuations and lead, over the coming decade, to ~±10% determinations of η/s and other QGP transport coefficients.**

It is important to see how the QCD transport properties evolve with temperature. Some conventional fluids (*e.g.*, water, liquid nitrogen, liquid helium) exhibit sharp η/s minima (still at values far above the quantum bound) near phase transitions; does QCD matter behave similarly? Studying the temperature-dependence relies on measurements over a very broad √s range, as the expansion and cooling of the matter produced at any one collision energy integrates over a range of temperatures. Comparison of flow results all the way from the apparent QGP onset at RHIC up to the maximum LHC energy will allow us to vary the initial equilibration temperature of the matter over a factor of 2—3, in order to meaningfully constrain models and test anticipated next-generation lattice QCD calculations of the temperature-dependence of QGP properties.

2) The quenching of jets in RHIC collisions was first predicted to result from enhanced gluon radiation of partons traversing matter of high color charge density. Destructive interference effects suppress such gluon radiation within a “dead cone” whose angle depends on the ratio of the parent quark mass to its total energy. It was thus predicted that heavy quark jets should be much less suppressed than light quark jets of the same energy. However, the experimental results shown in Fig. 3(a) do not support this prediction: electrons with transverse momenta p_T ~ 5 GeV/c have yields suppressed by nearly as large a factor as pions. In this momentum range the electrons arise predominantly from the decays of hadrons containing *c* or *b* quarks. Furthermore,

the RHIC results on electron yields (after subtraction of electrons associated with photon conversion in the detectors or $e^+e^-\gamma$ decays of light neutral mesons) are confirmed by recent LHC measurements of reconstructed D-meson yields in the same transverse momentum range.

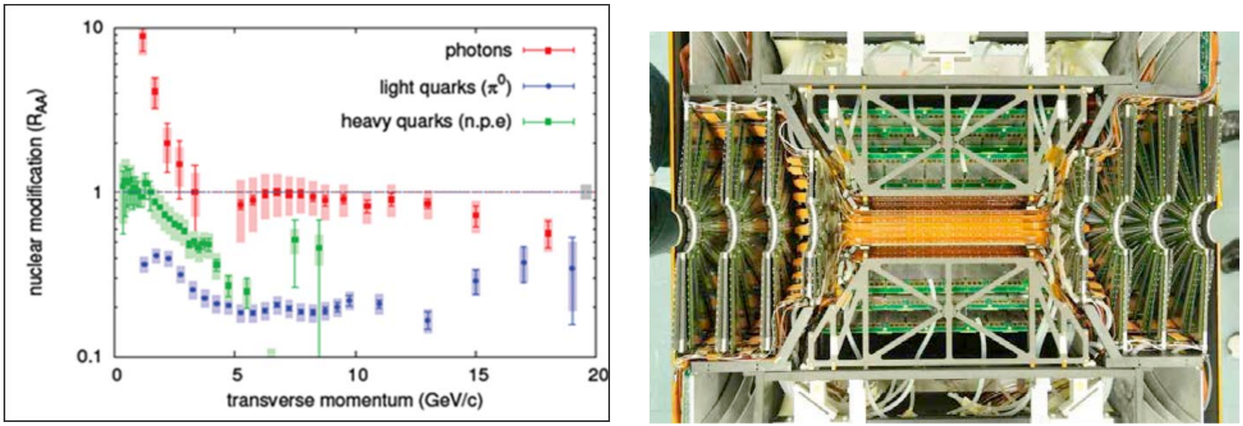


Figure 3. *(Left) Particle production cross sections in* $\sqrt{s_{NN}}$ *= 200 GeV Au+Au collisions measured by PHENIX, and scaled to expectations for independent nucleon-nucleon collisions, reveal strong suppression of light (blue) and heavy (green) quark mesons, while direct photons (red) are unsuppressed. The green points reflect yields of non-photonic electrons (n.p.e.), after subtraction of contributions from photon conversion in the detector and from Dalitz decays of light mesons. (Right) Photograph of one-half of the new silicon microvertex detector installed in PHENIX for the 2011 (barrel) and 2012 (forward wheels) runs, to enhance identification of the displaced decay vertices for heavy-quark hadrons.*

These results for heavy flavors suggest that energy loss arising from collisions of partons in the QGP contributes at least comparably to that from gluon radiation. To test models quantitatively it is important to separate the contributions associated with *c vs. b* quarks. This is one of the goals of a new generation of micro-vertex detectors, utilizing silicon pixel sensors as well as strip detectors and hybrids of the two, installed recently in PHENIX (see Fig. 3b) and to be installed in STAR for the 2014 run. These will provide resolution on decay vertex locations at the level of tens of μm, suitable to select the weak decays of heavy-flavor mesons. The STAR upgrade will further facilitate the direct reconstruction of D-mesons and Λ_c baryons, to measure suppression as a function of full hadron transverse momentum and to see if the quark-number scaling observed for light hadrons extends to the heavy-quark sector. The participation of heavy quarks in the rapid thermalization and collective flow of the QGP will also be investigated.

Still more pointed tests of parton energy loss models can be carried out by measuring yields, energies, composition, shapes and flow of fully reconstructed jets. Of particular interest are measurements of the energy imbalance between pairs of coincident jets or between a jet and a coincident high-energy photon. Such measurements are just beginning in earnest. Initial di-jet energy asymmetry measurements from the LHC detectors have helped to stimulate a new round of jet quenching theoretical calculations. Different models tuned to reproduce LHC results make different predictions at RHIC energies, so measurements are needed at both facilities. Full jet reconstruction at RHIC energies, in the midst of the high-multiplicity collision environment, is challenging, and will require further upgrades (see Sec. 6) to the PHENIX detector, in particular.

We seek to understand how the interactions of quarks and gluons in the QGP depend not only on the parton flavor, but also on parton energy. In the high-energy limit we expect the interactions to tend toward the weak coupling characteristic of asymptotic freedom. Thus, the energy-dependence of jet quenching may illuminate how interactions evolve from asymptotic freedom toward the strong effective coupling characteristic of the perfect fluid QGP. It is also a long-term goal to probe how the medium itself responds to the energy lost in it. This is challenging because it requires distinguishing correlations of modest-momentum particles spawned by quenched jets from an underlying event background reflecting dominant correlations associated with collective flow.

3) Non-Abelian gauge theories admit degenerate vacuum-state solutions related to one another by non-trivial topological transitions. In QCD (Fig. 4a), neighboring energy minima are related by leftward or rightward "twists" in the gluon field. In a high-temperature quark bath, such as that formed in RHIC collisions, quantum fluctuations ("sphalerons") among these minima can lead to spatially localized "bubbles" marked by a chiral imbalance between left-handed and right-handed quarks. Within such bubbles, symmetries (parity and CP) obeyed globally by QCD can be locally violated. Analogous bubbles created at the electroweak phase transition in the very early universe are speculated to be the site of baryon number violation needed to account for the matter-antimatter asymmetry in our universe. Because sphalerons play such a critical role in modern cosmology, it would represent a very important contribution if we could discover and characterize their effects in the evolution of the hot QCD matter produced at RHIC.

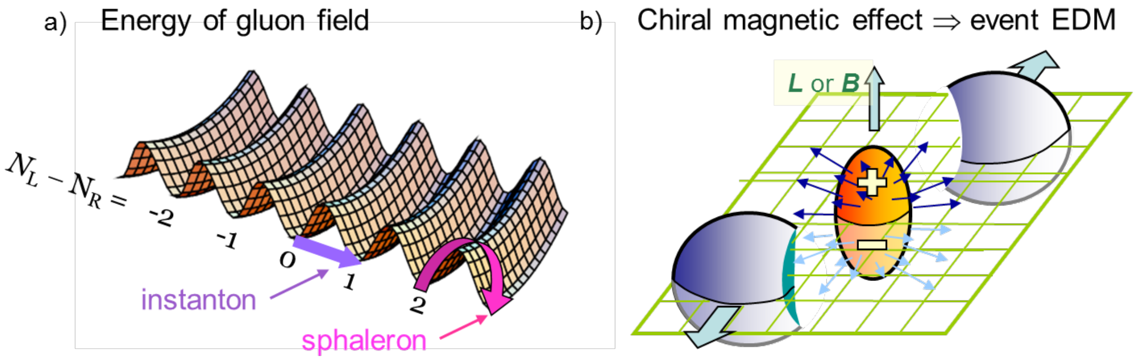


Figure 4. *a) Schematic illustration of gluon field energy in QCD, indicating instanton (tunneling) and sphaleron (high temperature) transitions that can lead to bubbles with a chiral imbalance* ($N_L - N_R \neq 0$)*. (b) In the presence of a very strong magnetic field in a non-central collision, the chiral imbalance can produce an event electric dipole moment (EDM), whose influence must be distinguished from effects correlated only with the elliptic flow induced by the almond-like shape of the overlap region.*

The challenge, and the subject of important recent progress, has been to determine a suite of observables that might distinguish sphaleron influence in the complex collision environment. In a series of papers Kharzeev and collaborators have suggested a number of consequences when the chiral imbalance in QCD bubbles is combined with the extremely strong ($\sim 10^{17}$ Gauss) magnetic fields set up by passing heavy nuclei in early stages of non-central RHIC collisions. One result is a Chiral Magnetic Effect (CME) that can lead to an event electric dipole moment (EDM) in the produced matter (Fig. 4b), but one whose sign can fluctuate, along with the direction of the sphaleron transition, from event to event [D. Kharzeev *et al.*, *Nucl. Phys.* **A803**, 227

(2008)]. Thus, explicitly P- or CP-odd observables one might normally associate with an EDM vanish when averaged over many events. Voloshin [*Phys. Rev.* **C 70,** 057901 (2004) and *Phys. Rev. Lett.* **106,** 172301 (2010)] has suggested measurable P-even correlation signals that should still bear the CME imprint.

Additional consequences arise when the bubbles occur in ambient matter with a net non-zero electric charge or baryon density. The former situation can produce an event electric quadrupole moment resulting in opposite π^+ *vs.* π^- dependences of elliptic flow on the fractional net charge imbalance detected in each event [Y. Burnier *et al., Phys. Rev. Lett.* **107,** 052303 (2011)]. In QGP matter that begins with a significant net quark minus antiquark density (*i.e.,* with baryochemical potential $\mu_b \neq 0$), the QCD triangle anomaly responsible for CME should lead also to a *baryon* current correlated with the EDM-causing electric current [D. Kharzeev and D.T. Son, *Phys. Rev. Lett.* **106**, 062301 (2011)]. All of these signals rely on the restoration of chiral symmetry in the QGP, in order for the bubble's chiral imbalance to survive passage through the surrounding matter.

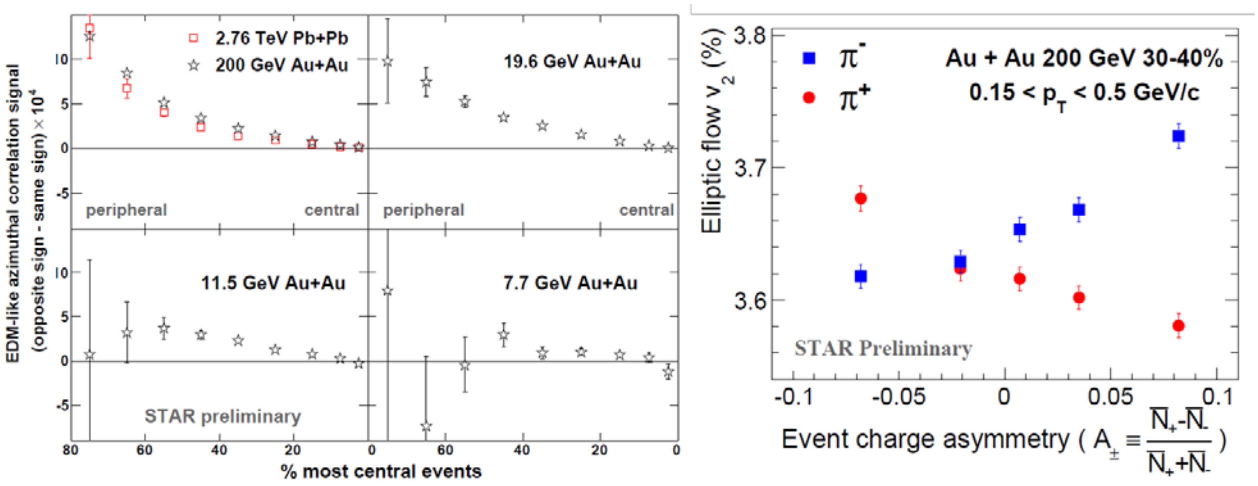


Figure 5. *a) STAR [Phys. Rev. Lett.* ***103****, 251601 (2009)] and ALICE [arXiv:1207.0900] measurements of charge-dependent azimuthal correlations at five collision energies, with potential sensitivity to an EDM that fluctuates in sign from event to event. Positive values of the correlation imply that particle pairs of like sign emerge on the same side (above or below) of the event reaction plane more often than unlike signs. The observed signal is stable over two orders of magnitude in energy from LHC down to the middle of the RHIC range, but then appears to vanish rapidly below* $\sqrt{s_{NN}} \approx 20$ *GeV. At all energies, the signal decreases for the most central collisions, where both elliptic flow and magnetic field strength tend toward zero. (b) The measured correlation of elliptic flow for charged pions with the event asymmetry between all positive and negative charges detected at mid-rapidity. The difference in slopes between* π^+ *and* π^- *is a potential signature for an event electric quadrupole moment of chiral magnetic origin.*

A discovery of sphaleron effects would have to rely on observing all of these basic predicted signals. That, in turn, will demand that the theoretical concepts be embedded in state-of-the-art hydrodynamics calculations to make more quantitative predictions, while various background contributions are also carefully evaluated. In the meantime, the RHIC and LHC experiments have made measurements that whet one's appetite, despite current controversy over their interpretation. Figure 5a shows recent STAR and ALICE results for a parity- and CP-even charged-particle correlation that an event EDM would produce: like-sign charges emerge preferentially on the same side (either up or down), and unlike signs on opposite sides, of the reaction plane, with the preference growing toward more peripheral collisions, with stronger magnetic fields. The figure shows the difference between the like- and unlike-sign correlations for several collision energies. Figure 5b reveals a sign difference in the slopes of π^+ *vs.* π^- elliptic flow variation with event charge asymmetry, consistent with chiral magnetic expectations.

The correlations in Fig. 5 represent small signals teased out from large backgrounds of more mundane origin, and one can question whether subtle aspects of the backgrounds may account for the results. For example, the observable in Fig. 5a could potentially arise from non-exotic sources of charge-dependent particle correlations (nicely summarized by Bzdak, Koch and Liao in *arXiv:1207.7327*) coupled with elliptic flow, which introduces natural non-magnetic differences between correlations within and perpendicular to the event reaction plane. As Bzdak *et al.* conclude: “the most important next step is the experimental separation of elliptic flow and magnetic field,” which both increase with impact parameter in heavy ion collisions. In fact, there are now two observations in which the apparent CME signal vanishes while elliptic flow is still appreciable. The first is for the lowest RHIC energies in Fig. 5a, where the CME might vanish if QGP is no longer formed in the collisions. The second is for highly central uranium + uranium collisions, where the magnetic field should vanish but the deformed nuclear shape can still produce significant flow. The first U+U results are shown under item (5) below.

The bottom line is that a program of future measurements, primarily at RHIC, can be defined to test the chiral magnetic expectations more thoroughly (see Sec. 6). **It is RHIC’s responsibility to resolve this issue, as it concerns a unique emergent phenomenon in hot non-Abelian matter that is of critical interest for the early history of the universe.**

4) The data in Fig. 5a represent some of the early results from a first beam energy scan carried out at RHIC in 2010-11, extending even to energies where RHIC had to be used to *decelerate* the beam from injection. The primary goal was to search for evidence of an anticipated critical endpoint in the QCD phase diagram and of the onset of the deconfinement transition. As seen in Fig. 6a, the critical point would represent a unique and important fixed point in the QCD landscape, separating a locus of first-order discontinuous phase transitions at sizable μ_b from the region of continuous, though rapid, crossover transitions encountered at small μ_b (i.e., at top RHIC and LHC energies). Various theoretical arguments make the existence of a critical point plausible, but lattice QCD calculations so far provide little useful guidance regarding its location, because the Monte Carlo evaluation of lattice integrals is strictly applicable only at μ_b=0.

At each energy studied and in each collision centrality bin, hadrons freeze out from the produced matter at a well-defined average temperature and μ_b value. The measured freezeout conditions shown for various collision energies in Fig. 6b illustrate how the energy scan explores the phase diagram. If freezeout occurs near a critical point, one expects enhanced non-statistical fluctuations in event-by-event distributions of conserved quantities, such as charge or baryon number. These are sought via excursions in the energy dependence of higher moments of the distributions, which are increasingly sensitive to the coherence length associated with the critical point. The examples of data in Fig. 7a reveal significant deviations from Poisson expectations in the neighborhood of 20 GeV, which would benefit from improved statistics and additional energy points in future runs. Theoretical arguments [M.A. Stephanov, *Phys. Rev. Lett.* **107,** 052301 (2011)] suggest that the fourth moment, *kurtosis* (κ in Fig. 7a), should *universally* undergo a negative excursion as one approaches a critical point from the crossover transition side, followed by a positive excursion as one passes the critical point. More precise data in the 5-20 GeV range should aid greatly in clarifying whether the observed deviations reflect this anticipated critical point excursion.

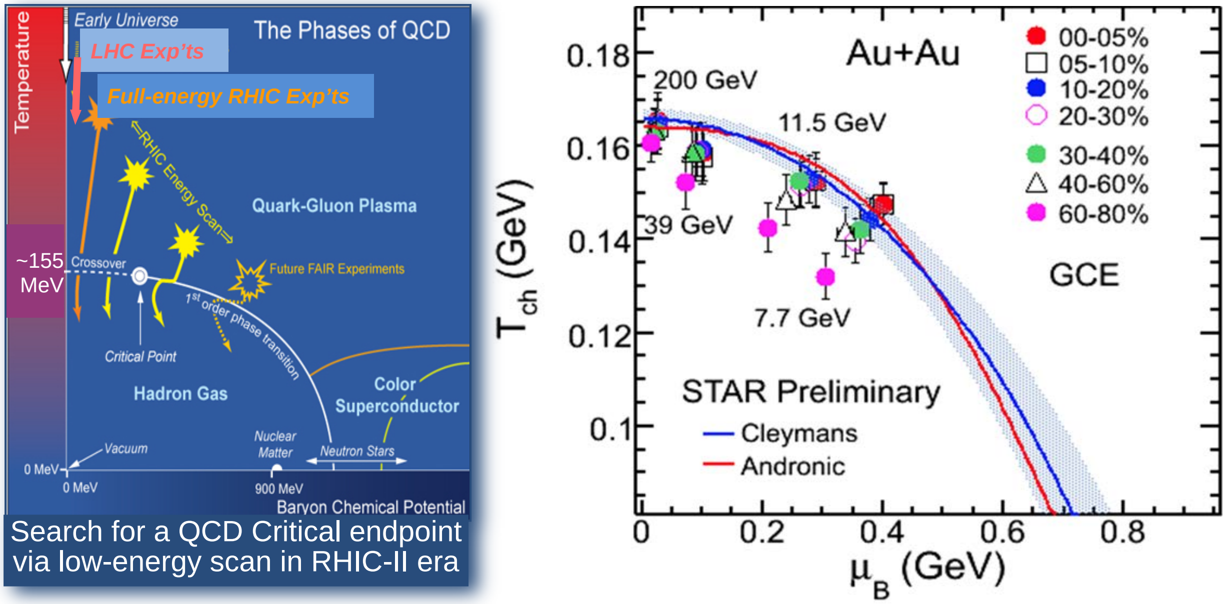


Figure 6. *Left frame: schematic illustration of the QCD phase diagram, showing a possible critical point and how measurements at a variety of RHIC energies could scan across it. Right frame: the measured chemical freezeout temperatures (T_{ch}) and baryochemical potentials (μ_B) for various Au+Au centrality bins at four of the $\sqrt{s_{NN}}$ values covered in the RHIC beam energy scan. The results, extracted from thermal model fits to the observed hadron species yields, are compared to two models of the freezeout curve. A critical point that falls near the freezeout conditions should be manifested in fluctuation analyses of data at the corresponding energies.*

The energy scan has revealed rapid changes in behavior for a number of observables that we associate with possible QGP signatures, at energies between $\sqrt{s_{NN}}$ = 11.5 and 27 GeV, while they are surprisingly stable at higher energies all the way to LHC. The correlations in Fig. 5a are among these observables, but significant changes are also seen, for example, in the suppression of high transverse momentum hadrons (Fig. 7b), the production of strangeness (Fig. 7c), and the quark number scaling of elliptic flow. These are likely **hints that the initial equilibration point for the QCD matter formed in RHIC collisions is falling near or below the QGP transition locus at the lower end of the RHIC energy range.** If so, we don't know yet if this onset of deconfinement occurs to the left or to the right of the critical point in Fig. 6a, but it may restrict the possibility of finding the critical point to the RHIC range. If it occurs near the lowest end of RHIC's reach, then eventual measurements at the new FAIR and NICA facilities in Europe may help to pin down its location.

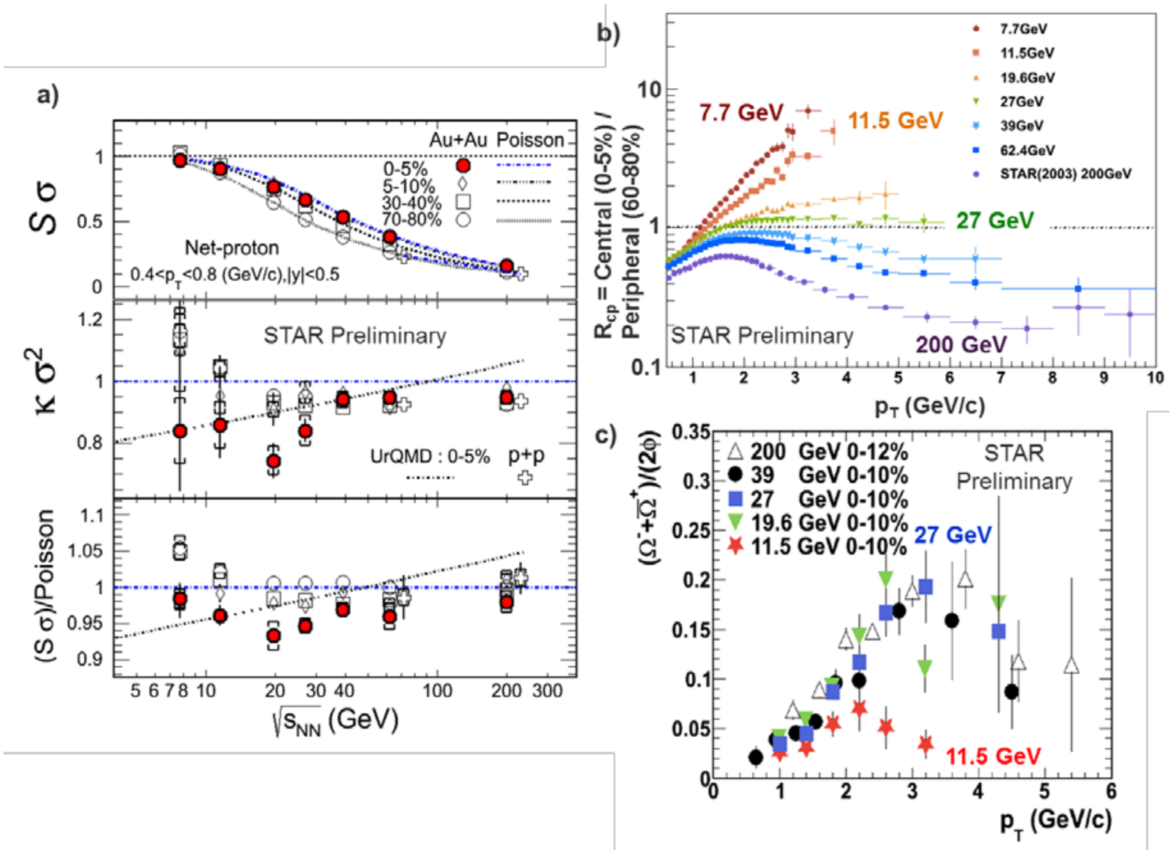


Figure 7. *Preliminary STAR results from the beam energy scan, shown at the Quark Matter 2012 conference. (a) The dependence on collision energy of the 2nd (variance σ), 3rd (skewness S) and 4th (kurtosis κ) moments of the event-to-event distribution of net proton number among detected mid-rapidity products from Au+Au collisions. Results for three centrality bins (0-5% most central, 30-40% mid-central and 70-80% peripheral) are compared to Poisson statistical expectations and to relativistic quantum molecular dynamics (UrQMD) calculations for the most central bin. A significant negative deviation from expectations is seen for central collisions, especially in the kurtosis, in the vicinity of* $\sqrt{s_{NN}} = 20$ *GeV. (b) The ratio of central-to-peripheral collision yields as a function of hadron transverse momentum, showing a change from high-*p_T *suppression at the higher energies to enhancement (expected from the so-called Cronin multiple scattering effect) below 27 GeV. (c) The ratio of* Ω*-baryon to* ϕ*-meson yields as a function of* p_T *and collision energy, indicating a rapid reduction in strangeness production below 27 GeV.*

5) In order to study rarer probes and more subtle aspects of the QGP, heavy-ion collision luminosities at RHIC have had to be increased, overcoming limitations imposed by intra-beam Coulomb scattering. Most of the needed gain has now been accomplished (Fig. 8) by installation in 2010-12 of three planes of pickups and kickers for each of the RHIC rings, allowing continuous correction of three-dimensional deviations from the central momentum vector within each bunch. This pioneering realization of bunched-beam stochastic cooling relied on breakthroughs in high-frequency pickup and kicker technology, achieved with RHIC R&D in 2007.

The remaining component needed to complete this system is a 56 MHz superconducting RF cavity, to be installed for the 2014 run to ameliorate the transverse-cooling-driven migration of beam into satellite RF buckets during a fill. **In combination with other incremental improvements to the RHIC lattice, development of stochastic cooling will have increased full-energy heavy-ion luminosity by a factor ~20 from the original machine design, for a total cost of about $14M**, in comparison with the $95M projection for an electron cooling solution made in the 2007 LRP. A history of RHIC luminosity improvements is shown in Appendix A.

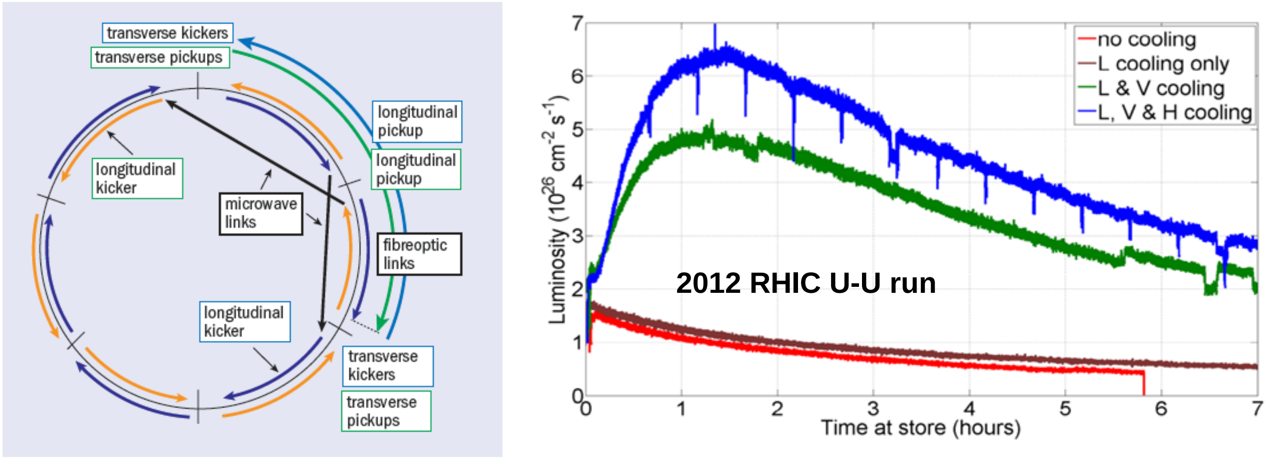


Figure 8. *Schematic layout (left) and impact (right) of the RHIC stochastic cooling system. Deviation signals from the pickups are sent along paths that beat the light-speed beams to the location of kickers, which act to reduce the longitudinal and transverse momentum spread in each beam bunch. The change from the red to the blue curve in the right frame shows the factor ~5 increase in time-averaged luminosity and store length achieved for U+U collisions in 2012 when all the stochastic cooling planes were turned on. In combination with other recent improvements to the RHIC lattice, this upgrade provides full-energy heavy ion collisions with 15 times the original design luminosity and highly efficient beam usage, with burn-off rates from the heavy ion collisions themselves dominating the intensity decay. The spikes in the blue curve on the right are artifacts from the periodic turn-on of the RHIC orbit feedback system.*

A second recently completed major upgrade to RHIC's machine capabilities (partially funded by NASA) is EBIS, now being used instead of BNL's tandem Van de Graaff accelerators as the RHIC heavy ion pre-injector. It has provided uranium ion collisions for the first time in 2012, **permitting exploitation of the deformed nuclear shape to add new controls on the initial collision geometry.** For example, even head-on collisions of prolate nuclei can, for some orientations of the deformation axes, lead to an almond-shaped overlap region, hence, to significant elliptic flow. The effect is seen in Fig. 9a, where the 1% most central U+U collisions yield comparable flow to the most central 5% of Au+Au events, despite the significantly smaller average impact parameters sampled in the U+U bin. But in contrast to the Au+Au bin, the charge separation signal of Fig. 5a is seen to vanish for the U+U bin. This is the expected outcome for the Chiral Magnetic Effect, because the magnetic field vanishes for head-on collisions, but not for flow-related background contributions to that signal. This does not yet settle the CME issue but it illustrates one value of the new control over collision geometry.

Another EBIS application that will enhance geometry control to distinguish interesting signals from background is the extraction of two different beam species for asymmetric RHIC collisions. This capability was also first used in 2012 for Cu+Au collisions. Such asymmetric collisions allow odd flow harmonics even in the absence of initial density fluctuations. Asking hydrodynamics calculations to account simultaneously for the flow power spectra in symmetric and asymmetric collisions should thus test the robustness of our quantitative understanding of initial geometry effects on flow. Furthermore, Cu+Au will illuminate the normally intertwined dependences of parton energy loss on energy density and path length through the QGP, by providing geometries inaccessible to symmetric systems. It can also help to unravel various initial- and final-state influences from color screening effects on the production of bound $q\bar{q}$ systems. First Cu+Au results shown at Quark Matter 2012 (Fig. 9b) already indicate that the suppression of J/ψ production differs for the Cu- *vs.* Au-going directions.

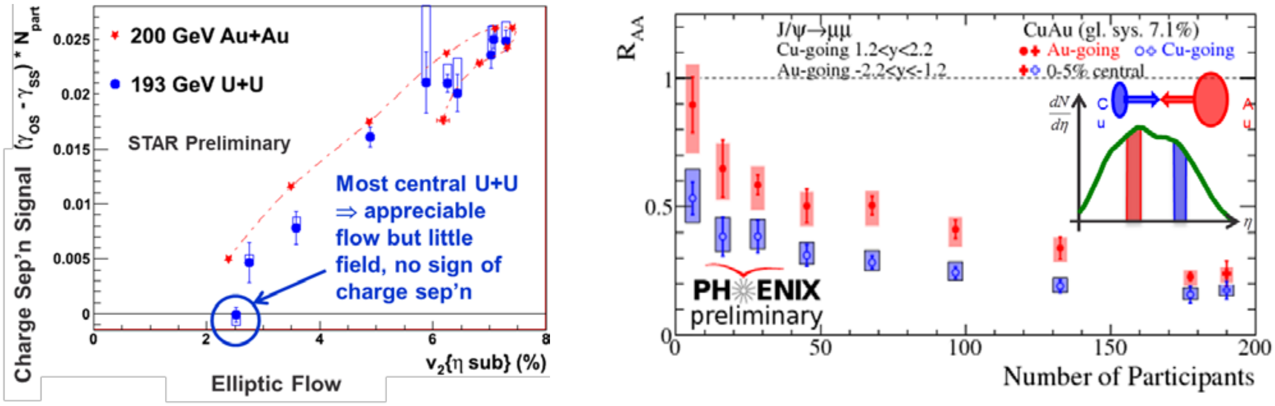


Figure 9. *Preliminary results from the first uranium-uranium and copper-gold collision runs at RHIC in 2012. The left frame compares U+U with Au+Au data on the correlation between the charge separation signal sensitive to the chiral magnetic effect and the elliptic flow. Different points correspond to different centrality bins: the leftmost point represents 0-5% centrality for Au+Au but 0-1% for U+U. These two bins exhibit similar flow, but the charge separation signal vanishes for the U+U, as might be expected if the signal arises primarily from the magnetic field. The right frame shows the difference in suppression factors (with respect to expectations based on p+p) for forward J/ψ production in Cu+Au when the meson emerges in the Cu-going vs. Au-going directions. The inset in the right frame illustrates the fore-aft asymmetry in particle multiplicity for central collisions in this asymmetric system.*

4. Unanticipated Intellectual Connections

RHIC's visibility and impact have been amplified by unexpected ties between its studies of hot QCD matter and other forefront areas of physics research. Some of the most profound connections are summarized here:

RHIC thus becomes a testing ground for concepts whose applicability extends well beyond QCD matter.

- String theory studies of black hole behavior led to the prediction of a quantum lower bound on η/s for relativistic fluids, a prediction best borne out by QGP behavior revealed at RHIC (*e.g.*, see C.V. Johnson and P. Steinberg, *Physics Today* **63,** 5, 29 (May 2010)).

- Ultra-cold atomic Fermi gases, trapped at temperatures 19 orders of magnitude lower than that of the QGP, have also been found to exhibit nearly perfect liquid behavior (*e.g.*, see J.E. Thomas, *Physics Today* **63,** 5, 34 (May 2010)).
- Similar strongly correlated behavior has been observed and studied in a number of condensed matter systems of intense interest, including organic superconductors (*e.g.*, see J. Quintanilla and C. Hooley, *Physics World* (June 2009)).
- The Chiral Magnetic Effect offered as a possible explanation for the RHIC correlation data in Fig. 5 is analogous to sphaleron effects predicted at the infant-universe electroweak phase transition, the speculated origin of baryon-antibaryon asymmetry in both leptogenesis and electroweak baryogenesis models (*e.g.*, see V.A. Rubakov and M.E. Shaposhnikov, *hep-ph/9603208*). The CME may even have condensed matter applications, where it has been recently considered [A. Zyuzin *et al., Phys. Rev.* ***B 85,*** *165110 (2012);* D. Kharzeev and H.-U. Yee, *arXiv:1207.0477*] to provide a mechanism for non-dissipative transport of information and energy in Weyl semi-metals.
- The power spectrum analysis of flow to constrain QGP viscosity and the nature of initial density fluctuations is analogous to the power spectrum analysis of cosmic microwave background fluctuations, used to constrain baryon acoustic oscillations and the nature of Dark Energy (*e.g.*, see A.P. Mishra *et al.*, *Physical Review* **C77,** 064902 (2008)). Furthermore, there are emerging theoretical connections in the spectrum of quantum fluctuations between models of inflation-era density perturbations in the universe and models of initial density perturbations in RHIC collisions.

These connections illustrate an emerging unifying theme that runs across multiple areas of contemporary many-body physics: the behavior of strongly coupled fluids without apparent quasi-particles. Conventional condensed matter systems that fall within this class include “strange metals” (*e.g.*, high-T_c superconductors above T_c), quantum spin liquids and matter at quantum critical points. Laboratory study of QGP properties holds the promise of illuminating the physics of many such systems, thanks to two distinct advantages: 1) we can produce the fluid of interest in the lab without extraneous degrees of freedom and, by combining RHIC and LHC, over a broad range of initial conditions; 2) we can pump/probe the system with jets over a wide range of energies (hence, distance scales and anticipated QCD coupling strengths), hopefully to observe how the strongly coupled fluid emerges from well understood (quark and gluon) quasi-particle behavior at short distances. In the case of new discovery potential from explorations of possible sphaleron effects and initial quantum density fluctuations as well, **RHIC thus becomes a testing ground for concepts whose applicability extends well beyond QCD matter**.

As further evidence of the broad impact and connections of RHIC research, we compile in Appendix C a list of articles and features by RHIC scientists or about RHIC science, written in journals for a broad scientific audience. RHIC results have led to cover story articles in *Physical Review Letters* (January 14, 2002 and August 15, 2003), *Scientific American* (May 2006) and *Physics Today* (October 2003 and May 2010). In addition to these, there has been broad coverage (well over 1000 news items) of RHIC results in worldwide media for a lay audience.

5. Cold QCD Matter Studies at RHIC

In parallel with the program outlined above, RHIC has carried out experiments with deuteron-nucleus (d+A) and proton-proton collisions that provide essential baselines to distinguish cold from hot QCD matter effects observed in the heavy ion collisions. But the cold matter studies themselves address critical issues regarding the dominant roles of soft gluons in QCD matter.

RHIC's cold matter studies themselves address critical issues regarding the dominant roles of soft gluons in QCD matter.

A primary focus in the d+A collisions has been on the forward (near the deuteron beam direction) production of hadrons at moderate transverse momentum. The underlying process for such production often involves collisions with a soft gluon in the heavy nucleus, and is hence sensitive to the possible saturation of gluon densities in nuclear matter. HERA deep inelastic scattering data have clearly revealed that, among partons that carry less than about 20% of a nucleon's momentum, gluons dominate. Their density rises very rapidly toward lower momentum fraction x. The rise, however, cannot continue untamed or it would eventually lead to a violation of unitarity in high-energy scattering processes. The mechanism for eventual saturation of the gluon density is built into QCD: at high gluon densities the recombination of two gluons into one competes favorably with the splitting of a single gluon into two. If this saturation condition is reached at moderate four-momentum transfer Q^2, as sketched in Fig. 10a, we enter a unique regime where very intense color fields are combined with weak QCD coupling. That regime, though characterized by highly non-linear aspects of QCD, is amenable to treatment in an effective theory (so-called "Color Glass Condensate" or CGC) approach starting from a semi-classical treatment of the intense gluon field.

Reaching well into the gluon saturation regime in p-p or e-p collisions would require a very high-energy collider, exceeding the reach of HERA. But in collisions with heavy nuclei, a light probe can coherently sample all the gluons available through the (relativistically contracted) thickness of the nucleus. This coherence permits access to the saturation regime at much higher x-values (hence, much lower center-of-mass energy) than for a proton. In RHIC d+Au collisions, the observation of strong suppression of forward hadron production, and especially of forward two-hadron coincidences (see Fig. 10b), is consistent with gluon saturation setting in at $x{\sim}10^{-3}$. In particular, the scattering of a parton from the deuteron on a coherent gluon field inside the gold nucleus would greatly reduce the normal back-to-back hadron signature of two-body parton-parton scattering. But the saturation interpretation is not unique, and needs to be tested further by focused experiments capable of mapping gluon densities quantitatively. At RHIC we envision future d+A and p+A (requiring a small reconfiguration of RHIC magnets) runs focusing on the production of high-energy forward photons, which arise predominantly from quark-gluon collisions. At LHC a relevant (and technically challenging) p+Pb collision run is scheduled for early 2013. But, as we discuss in Sec. 7, the crucial gluon density maps await an Electron-Ion Collider.

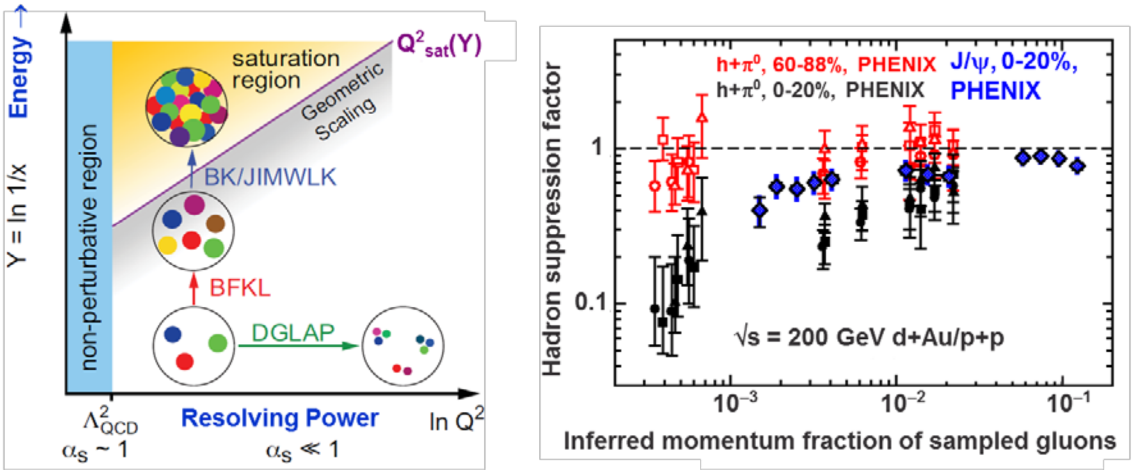


Figure 10. *Schematic illustration (left) of the gluon density saturation region reached by lowering momentum fraction x (upward in the figure) at moderate probe resolution Q^2. The right frame shows RHIC results that suggest that gluon saturation may be reached in the middle of a light-speed gold nucleus probed by a 100 GeV/nucleon deuteron beam. The strong suppression (relative to p+p yields) observed for forward J/ψ production (blue points) and forward di-hadron coincidences (black points) in central d+Au collisions indicate that gluon densities below $x \sim 10^{-3}$ in the gold nucleus fall far short of linear QCD scaling from their values in an isolated proton. The di-hadrons are not suppressed in peripheral collisions (red points).*

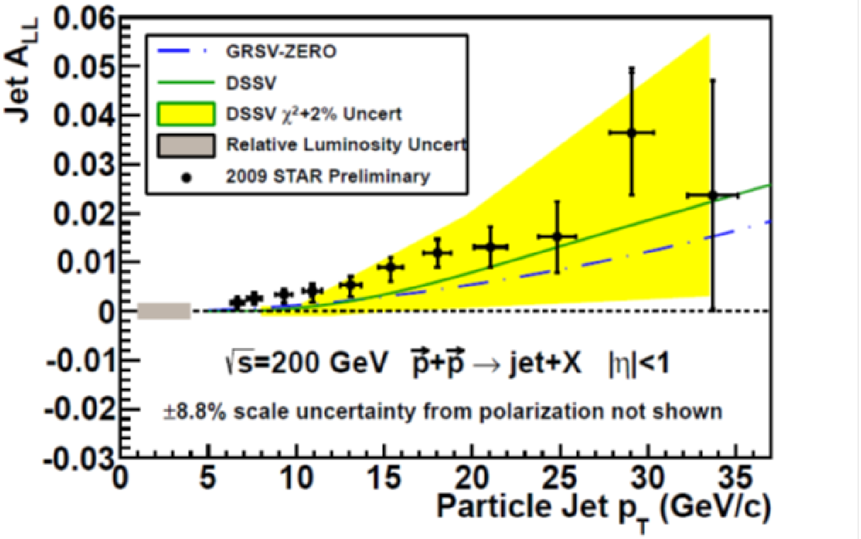


Figure 11. *STAR data from the 2009 RHIC run for the two-spin helicity asymmetry of inclusive jet production in $\sqrt{s}$=200 GeV polarized proton collisions. Comparison with the blue curve, which assumes zero gluon polarization at an initial scale, reveals clearly non-zero gluon helicity preferences in a longitudinally polarized proton. The green curve and yellow uncertainty band reflect earlier theoretical fits to a database that included RHIC p+p data through 2006. A preliminary fit including the newer data in this figure suggest that the sampled gluons contribute ~20% of the overall proton spin.*

The unique polarized proton capability at RHIC has been used to explore gluon contributions to the proton's spin. Three decades of deep inelastic scattering experiments, where polarized electron or muon beams interact with fixed polarized targets, have revealed that only ~30% of the proton's spin can be attributed to preferential spin orientation among all the proton's quarks and antiquarks. Since gluons are so abundant, even a slight gluon spin preference might also contribute significantly. The latest relevant RHIC measurements (Fig. 11) indeed reveal, for the first time, a gluon spin preference, enough to account in preliminary fits for roughly 20% of the proton's spin over the kinematic range covered so far. **In other words, it appears that quark and gluon spin preferences contribute comparably to the spin of the proton.**

The data in Fig. 11 are from 200 GeV p-p collisions. Continuing efforts at RHIC, focusing on 500 GeV and on asymmetries for di-jets and di-hadrons, as well as on inclusive jet and hadron production, will provide more detailed information on how the gluon spin preference varies with momentum fraction for x >~ 10^{-2}. We thus expect further RHIC running to quantify the non-zero gluon contribution to proton spin over the range of momentum fractions accessible at RHIC. However, in order to pin down the *net* gluon contribution to proton spin, one will need an EIC to access the even more abundant softer gluons beyond RHIC's kinematic reach.

6. RHIC Program for the Coming Decade; Complementarity with LHC

RHIC's second decade is devoted to quantifying properties of the QGP and features of the QCD phase diagram, and continuing explorations of the role of soft gluons in cold nuclear matter. In parallel with quantification, the envisioned program will also pursue new discovery potential associated with the location of a possible QCD critical point, the nature of initial-state quantum fluctuations, and effects of QCD sphalerons.

As we emphasize in this section, the complementarity of RHIC and the LHC heavy-ion program is an essential tool for progress on the quantification and quantum fluctuation goals. For roughly the next five years (FY2013-2018), RHIC research will exploit the facility's versatility and unique capabilities, especially those added with recent and ongoing upgrades, to advance answers that only RHIC can provide to the driving intellectual challenges outlined in Section 2. Beyond the next five years, both PHENIX and STAR detectors will likely need further upgrades to complete our picture of how a strongly coupled liquid emerges from an asymptotically free theory. Those upgrades will also move both detectors along a path toward the longer-term future of an Electron-Ion Collider (eRHIC) at RHIC, a future outlined in the next section. In addition, RHIC luminosity for low-energy heavy-ion collisions, where stochastic cooling is ineffective, will have to be improved to sharpen the pursuit of the QCD critical point and the onset of deconfinement.

RHIC and LHC are complementary. Both are needed to explore the temperature-dependence of QGP properties. RHIC has unique reach to search for the QGP onset, unique ion species versatility and unique polarized proton capability, until EIC is realized.

In order to explain why a full second decade is needed, it is useful to start by considering the set of ten illustrative basic questions in Table 1, which were each posed before RHIC started making the relevant measurements. The questions are not all-inclusive, and many, but not all, of them have been discussed in earlier sections. As seen from the answers to date in Table 1, several of these have definitive answers. There are a number of "hints," which are significant: they indicate cases where the interpretation of hints in the existing data remains open to questions that can be addressed by well-defined future measurement programs. This situation is analogous to that of question 1 regarding QGP formation itself, where the RHIC collaborations indicated in their renowned 2005 White Papers [*Nucl. Phys.* **A757** (2005), entire volume] that the hints were not yet definitive, but they have been extended since to yield a clear 'yes.' For only one of the questions in Table 1, associated with W-boson production in 500 GeV polarized p-p collisions, is the data acquired to date insufficient in statistics to extract hints, though the existing data clearly demonstrate RHIC's ability to answer the question with improved statistics and recent upgrades. **It is the responsibility of RHIC and LHC to design measurements to address the more quantitative 2nd-generation questions emerging from the definitive answers in Table 1, and to resolve the hints surrounding the others.**

Table 1. *Basic questions going into the RHIC era and answers from RHIC to date*

Basic questions going into the RHIC era	RHIC/LHC answers to date
1) Is RHIC's kinematic reach sufficient to create matter in the anticipated Quark-Gluon Plasma (QGP) phase?	Yes
2) Is the QGP weakly coupled, with approximately ideal gas (i.e., asymptotic freedom) behavior?	No
3) Can we experimentally demonstrate the transition from hadronic to quark-gluon degrees of freedom in reaching QGP?	Hints[a)]
4) Do partons lose energy rapidly in traversing QGP?	Yes
5) Does color screening in the QGP suppress the formation of quarkonium (i.e., bound states of same flavor quark-antiquark systems)?	Strong Hints[a)]
6) Can we find evidence of high-temperature excited QCD vacuum fluctuations, analogous to the electroweak sphalerons postulated as the source of the universe's baryon asymmetry?	Hints[a)]
7) Is there a locus of first-order phase transitions and a Critical Point in the QCD phase diagram?	Hints[a)]
8) Do we see evidence of gluon density saturation in cold nuclear matter at low Bjorken x?	Strong Hints[a)]
9) Do gluon spin preferences account for a significant part of the "missing" proton spin?	Yes
10) Is there a significant flavor-dependence in sea quark polarizations within a polarized proton?	Insufficient data to date

a) "Hints" implies that significant data have been collected, hinting at a definitive answer. However, questions of interpretation remain, with clear follow-up measurements proposed (and outlined in Sec. 6) to resolve the ambiguities.

A set of eight second-decade questions following up on those in Table 1 is listed in Table 2, together with the facilities needed to answer them. These are questions that connect the intellectual drivers listed in Sec. 2 with specific measurement programs outlined below. The comments in Table 2 point out issues of timeline at RHIC, needed upgrades, particular advantages of one facility or another, etc. The main conclusions from Table 2 are the following:

- ***RHIC and LHC are complementary. Both are needed to explore the temperature-dependence of QGP properties. RHIC has unique reach to search for the QGP onset, unique ion species versatility and unique polarized proton capability, until EIC is realized.***
- ***Addressing the questions in Table 2 requires an ~10-year program of A+A (various ion species), p+p and p/d + A runs at various RHIC energies.***

Table 2. *Second-decade questions and the facilities needed to address them.*

Question	Facilities	Comments	Table 1 Question #'s on which these follow
1) How perfect is "near-perfect" liquid?	RHIC & LHC	Flow power spectra, next 5 years	1 + 2
2) Nature of initial density fluctuations?	RHIC, LHC & EIC	Benefits from asymmetric ion collisions at RHIC	2 + 8
3) How does strong coupling emerge from asymptotic freedom?	RHIC & LHC	Following 5 years @ RHIC; jets need sPHENIX upgrade	2 + 4
4) Evidence for onset of deconfinement and/or critical point?	RHIC; possible follow-up @ FAIR, NICA	Phase 2 E scan in following 5 years, needs low-E electron cooling	3 + 7
5) Sequential melting of quarkonia?	RHIC & LHC	LHC mass resolution a plus; RHIC det. upgrades help; $\sqrt{s}$-dependence important	5
6) Are sphaleron hints in RHIC data real?	Mostly RHIC	Exploits U+U and $\mu_B \neq 0$ reach at RHIC	6
7) Saturated gluon densities?	RHIC, LHC & EIC	Want to see onset at RHIC; need EIC to quantify	8
8) Where is missing proton spin?	RHIC & EIC	EIC will have dramatic impact	9 + 10

A rough timeline for the next decade at RHIC is given in Table 3, assuming that RHIC would operate for 15-20 cryo-weeks per year, as currently planned for FY2013. (Running for only 15 weeks every year would be highly inefficient in light of setup overheads; at corresponding budget levels we would probably combine runs across fiscal years in some cases.) The programs indicated for 2013 and 2014 have already received scrutiny and priority from the RHIC Program Advisory Committee. The timelines beyond 2014 are less sharp, but are largely dictated by the anticipated availability of various collider and detector upgrades indicated in the “new systems” column. The major division between 2015-17 and 2018-21 is the time needed for the low-energy heavy-ion beam cooling and the major PHENIX and STAR upgrades discussed below.

Table 3. *Approximate timeline for next-decade RHIC science program. The science goals are illustrative; many others will also be pursued with same colliding beam species and energies. Species, goals and subsystems in blue are aimed primarily at the cold nuclear matter program.*

Years[a]	Beam Species and Energies	Science Goals	New Systems Commissioned	Comments
2013	500 GeV $\vec{p}+\vec{p}$; 15 GeV Au+Au	Sea antiquark and gluon polarization; QCD critical point search	Electron lenses; upgraded pol’d source; STAR Heavy Flavor Tracker (HFT) prototype	15 GeV Au+Au completes phase 1 of beam energy scan
2014	200 GeV Au+Au and baseline data via 200 GeV p+p (needed for new det. subsystems)	Heavy flavor flow, energy loss, thermalization, etc.; quarkonium studies	56 MHz SRF; full HFT; STAR Muon Telescope Detector; PHENIX Muon Piston Calorimeter Extension (MPC-EX)	Separation of c and b-quarks now possible for both STAR & PHENIX; high-energy luminosity upgrade completed
2015-2017	High statistics Au+Au at 200 and ~40 GeV; U+U/Cu+Au at 1-2 energies; 200 GeV p+A; 500 GeV $\vec{p}+\vec{p}$	Precision extraction of $\eta/s(T)$ and constraints on initial quantum fluctuations; gluon densities and saturation (p+A); continued heavy flavor studies; sphaleron tests @ $\mu_B \neq 0$; complete p+p W production program	Coherent Electron Cooling (CeC) test; Low-energy electron cooling; STAR inner TPC pad row upgrade	CeC test for eRHIC R&D; low-E electron cooling and STAR TPC upgrade ready by end of this period; p+A exploits MPC-EX
2018-2021	5-20 GeV Au+Au (beam energy scan phase 2); long 200 GeV + 1-2 lower energies Au+Au with upgraded dets.; 500 GeV $\vec{p}+\vec{p}$; 200 GeV $\vec{p}+A$; baseline data @ 200 GeV and lower energies	Order of magnitude increase in sensitivity to signals of QCD critical point and onset of deconfinement; jet, di-jet, γ-jet quenching probes of energy loss mechanism; color screening for different quarkonium states; transverse spin asymmetries for Drell-Yan and gluon saturation	sPHENIX; forward physics upgrades	Other collider upgrade options under consideration for this time period include: polarized ^{3}He beams; additional Siberian Snakes; higher frequency stochastic cooling

a) After roughly 2021, we envision the eRHIC construction era beginning.

We now elaborate briefly on each of the eight second-decade questions in Table 2:

1) ***How perfect is the near-perfect liquid QGP, as a function of its temperature?*** As seen in Fig. 12a, a number of more conventional liquids each exhibit a sharp minimum in η/s (still much above the string theory bound) at or near a phase transition. Is the same true of QGP? There is currently a wide range of model predictions for the variation with temperature above T_c. The path to quantify η/s involves power spectrum measurements of collective flow, and relies on advances in event-by-event viscous hydrodynamics, as described in Sec. 3. Measurements at both RHIC and LHC are required to constrain the temperature-dependence. Results at a given collision energy average over a range of temperatures crossed during the matter's evolution, and this leads to the limited sensitivity to the temperature-dependence of η/s seen in Fig. 12b. However, the combination of RHIC (including energies down to $\sqrt{s_{NN}} \sim 20$ GeV, as well as 200 GeV) and LHC should allow us to cover a range of initial temperatures varying by a factor of 2—3, providing much improved sensitivity.

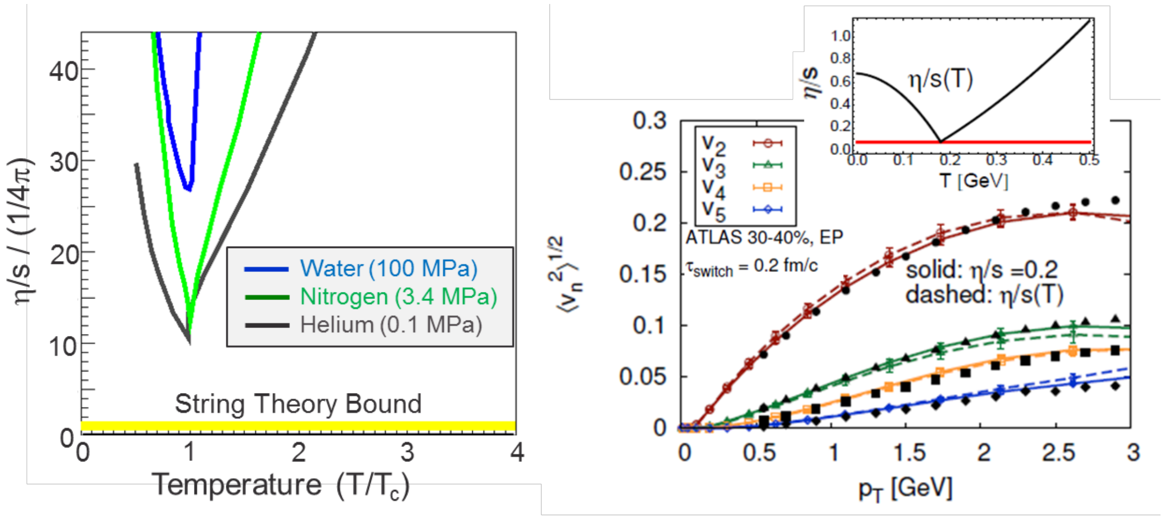


Figure 12. *Left: Ratio of shear viscosity to entropy density for various liquids as a function of temperature in the vicinity of a phase transition, and in comparison to the String Theory bound at* $1/4\pi$*. Right: Comparison of LHC measured [ATLAS Collaboration, Phys. Rev.* ***C 86,*** *014907 (2012)] flow harmonic amplitudes with 3+1-dimensional viscous hydrodynamic calculations [B. Schenke, et al., talk at Quark Matter 2012] including and excluding the inset model temperature-dependence of* η/s*. In contrast to the calculations in Fig. 2, these include initial fluctuations in the color charge density as well as in nucleon positions. Sensitivity to the temperature-dependence of* η/s *(comparing solid and dashed curves) is weak for measurements at a single collision energy, and masked by other theoretical uncertainties.*

The temperature-dependence of QGP viscosity is one among a number of theoretical ambiguities being addressed in the latest generation of hydrodynamics calculations. The important sensitivity to the nature of the initial geometry and density fluctuations will be discussed further below. Examples of other issues are related to the possibility of flow contributions from before attainment of local equilibrium or after hadronization of the QGP, non-linear hydrodynamic evolution, and the different time-dependences of radial and anisotropic flow. It is the combination of the rapidly improving sophistication of the theory and the impressive experimental precision, binning and control now becoming possible at both RHIC and LHC that make ~±10% determinations of η/s a worthy, though ambitious, goal. The potential impact of such quantification can extend far beyond nuclear physics. 1/4π is the value predicted for η/s by AdS/CFT for QCD-*like* gauge theories dual to *classical* gravity. Deviations from 1/4π in actual QCD matter could illuminate effects in the as yet undiscovered *quantum* gravitational theory to which QCD is dual.

Detailed considerations of where the hydrodynamics calculations are likely to be five years from now, and of what experimental data will be needed to constrain their ambiguities and parameters to the desired precision, lead [Ulrich Heinz, private communication] to a future measurement program highlighting the following:

- the collective flow power spectrum for at least a few identified hadrons, as well as for all charged hadrons, to as high a harmonic as possible, as a function of transverse momentum and collision centrality, and at multiple collision energies;
- $v_2(p_T)$ to 1-3% relative experimental precision for light and singly strange hadrons and to 5-10% precision for multi-strange hadrons (including ϕ-mesons);
- control over initial geometry via comparisons of measurements for Au+Au, Cu+Au, Cu+Cu and U+U at one or two collision energies;
- high statistics samples for ultra-central (0-1%, with even finer centrality binning) collisions to provide enhanced sensitivity to the influence of initial density fluctuations;
- distribution measurements of event-by-event fluctuations in several flow harmonics;
- angular correlations among the event planes associated with different flow harmonics.

Data in several of these categories have begun to emerge already at the Quark Matter 2012 conference, along with impressive preliminary fits, but the bulk of the needed measurements will take several years to carry out. We anticipate great progress in the quest to quantify η/s in the next five years at both RHIC (see Table 3) and LHC (following the planned long shutdown in 2013-14). We also want to determine how heavy (*c* and *b*) quarks share in the flow, exploiting the recent and ongoing micro-vertex detector upgrades to PHENIX and STAR. The proposed measurement program is also needed to quantify other transport coefficients and characteristic relaxation times of the QGP, but we will have to make further progress on η/s before we can determine realistic precision goals for those.

2) ***What is the nature of the initial density fluctuations in the matter prior to QGP formation?*** The path to quantify shear viscosity also establishes discovery potential to determine the nature of the quantum fluctuations in the initial state. The initial density fluctuations leave their imprint on the evolution of a RHIC collision in much the same way that quantum fluctuations during the inflationary stage of the universe are assumed to have seeded the large-scale structure we observe in today's universe. But in studying these early fluctuations, heavy ion collisions carry opportunities unavailable in cosmic microwave background measurements, to observe billions of

> *But in studying these early fluctuations, heavy ion collisions carry opportunities unavailable in cosmic microwave background measurements, to observe billions of events and exercise some experimental control over the initial conditions.*

events and exercise some experimental control over the initial conditions.

Although we have clearly seen the legacy of the initial fluctuations in odd flow harmonics for collisions of identical heavy ions, we do not yet know if it is just nucleon positions that fluctuate, or also the initial color charge (*i.e.*, gluon field) distributions. The two possibilities are characterized by different length scales and rapidity dependence of the fluctuations, as illustrated by simulations in Fig. 13. Experimentally, we can constrain the nature of the fluctuations by comparing odd vs. even flow harmonics in theory and experiment, and by focusing on ultra-central collisions where even elliptic flow is dominated by the fluctuations. This must be done in conjunction with pinning down η/s as described in measurement program (1) above. Our understanding of the odd vs. even flow systematics can be benchmarked by RHIC measurements for non-identical (*e.g.*, Cu+Au) ion collisions, as the asymmetry in these permits odd flow multipoles even without density fluctuations. Ultimately, the most incisive "snapshots" of quantum fluctuations in gluon densities in heavy nuclei at relevant Bjorken *x*-values may come from observations of the broadening of particle p_T-distributions in e+A *vs.* e+p collisions at EIC.

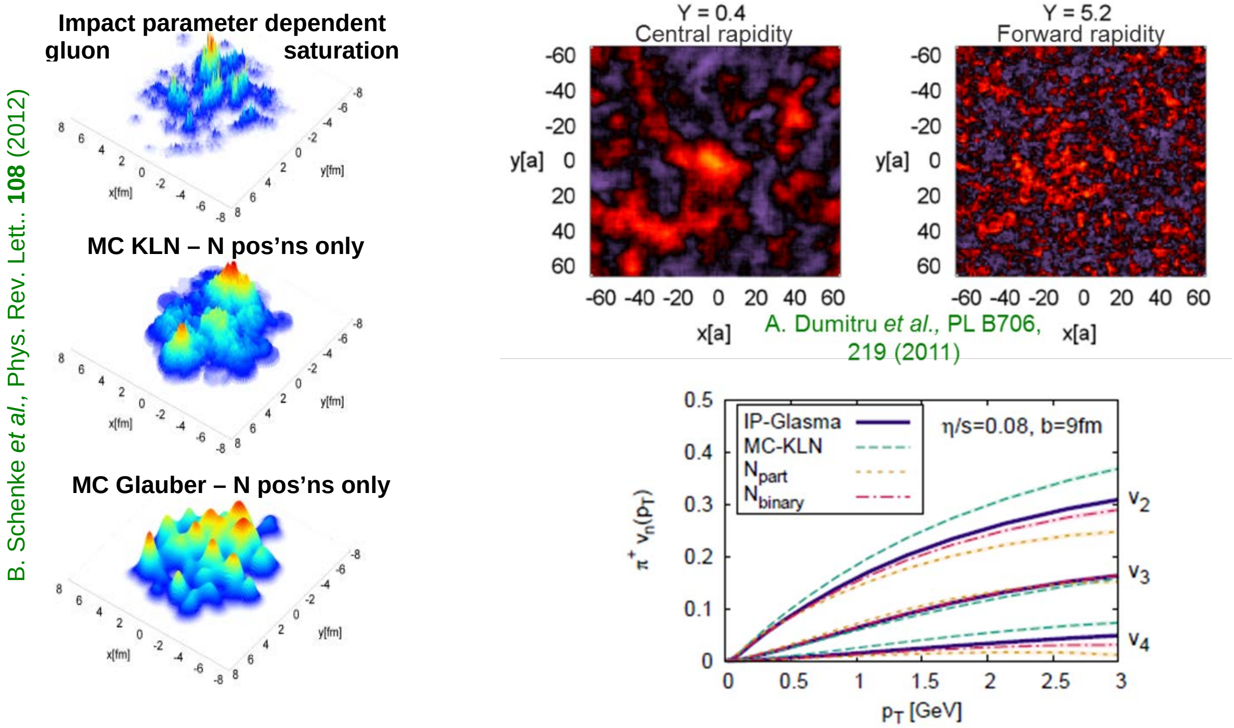


Figure 13. *Theoretical simulations of initial density fluctuations and their impact in heavy-ion collisions. The left frame shows simulated fluctuations for three different models, only the uppermost of which includes quantum fluctuations in the color charge density. The lower right frame illustrates the effects of these different models on collective flow harmonics for a particular choice of shear viscosity and impact parameter. Both figures are taken from B. Schenke et al., Phys. Rev. Lett.* ***108,*** *252301 (2012). The upper right frames, from A. Dumitru et al., Phys. Lett.* ***B706,*** *219 (2011), illustrate how the length scale of color charge density fluctuations changes under conditions relevant to mid-rapidity vs. forward particle production. This variation should be reflected in a rapidity-dependence of the flow power spectrum.*

3) ***How does a strongly coupled liquid emerge from an asymptotically free theory?*** As seen in Fig. 14, the near perfection of the QGP corresponds to very strong effective coupling among constituents, far from the originally anticipated perturbative QCD regime. The energy loss of partons traversing the QGP, characterized by a transport coefficient $\hat{q}$ (describing the variance of the distribution of momentum transfer between the parton and the medium), is independently sensitive to the effective strength of the coupling. Majumder, Müller and Wang [*Phys. Rev. Lett.* **99,** 192301 (2007)] have shown that these two different QGP properties are completely correlated functions of temperature T in the weak coupling limit ($\eta/s = 1.25\,T^3/\hat{q}$), but that the correlation breaks down for strong coupling. They conclude: *"An unambiguous determination of both sides of [the above relationship] from experimental data would thus permit a model-independent, quantitative assessment of the strongly coupled nature of the quark-gluon plasma produced in heavy ion collisions."*

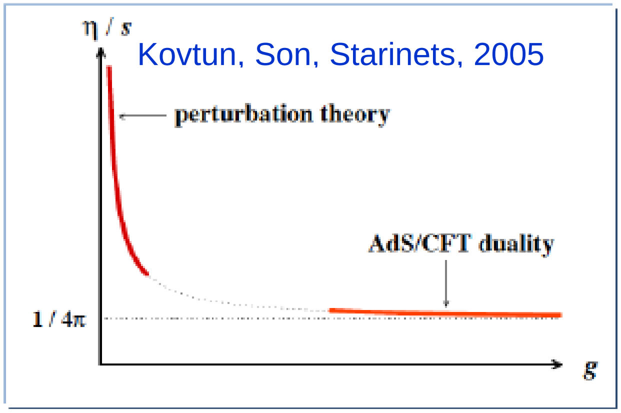


Figure 14. *Schematic illustration from P. Kovtun, D.T. Son and A.O. Starinets [Phys. Rev. Lett.* ***94****, 111601 (2005)] of the variation in shear viscosity to entropy density ratio with coupling strength among the constituents of a relativistic fluid, with asymptotic freedom on the left and the effectively infinite coupling of AdS/CFT on the right.*

Appropriate determinations of $\hat{q}$ rely on jet quenching measurements at both RHIC and LHC, again to cover a suitable range of initial temperatures. Furthermore, to explore how the coupling strength depends on scale, one wants measurements over a wide range of jet energies, including di-jet coincidences with flavor tagging (especially to distinguish c from b quark energy loss) and photon-jet coincidences (using the photon to determine the initial coincident parton energy). Such coincidence measurements benefit greatly from the upgraded RHIC luminosities, while the flavor tagging is made possible by the new micro-vertex detectors. In order to distinguish among contemporary models of parton-medium interactions, one needs measurements not only of jet yields and energies, but also of the distribution of the fragments within a jet in angle, momentum and hadron species, to compare with data from p+p collisions.

There is also uncertainty regarding the path length (L) dependence of parton energy loss. In perturbative QCD models, the dependence is linear when energy loss is dominated by parton collisions within the medium, but quadratic when gluon radiation is the dominant mechanism. In the strongly coupled AdS/CFT limit, the expected dependence is cubic. Experimental constraints on the L-dependence are just beginning to emerge from measurements of apparent elliptic flow for high-p_T hadrons and jets as a function of collision centrality, as this probes energy loss differences between partons emerging within or beyond the event-by-event reaction plane. The in- *vs.* out-of-plane path length differences vary with centrality, but so do other parameters, such as energy density, radial flow, and freezeout conditions. The intertwined dependences, along with effects biasing detected jet samples toward ones produced near the surface of the matter, can be at least partially unraveled via jet quenching studies in asymmetric (*e.g.*, Cu+Au) collisions at RHIC, where even significantly non-central events have the smaller nucleus occluded by the larger. High-p_T flow measurements are needed with flavor-tagging, since the balance among energy loss mechanisms is likely to differ for heavy *vs.* light quarks.

Jet reconstruction in heavy-ion collision environments at RHIC requires a significant upgrade to the PHENIX detector, described below, and is thus a program primarily for the second half of the decade ahead (see Table 3). The proposed PHENIX upgrade includes a hadron, as well as an electromagnetic, calorimeter, whereas STAR, without a hadron calorimeter, has already demonstrated its capability in p-p collisions to reconstruct the charged hadron contribution to full jet energies via tracking in its TPC. Figure 15 illustrates different predictions for RHIC di-jet energy asymmetries from models that fit LHC data, and simulations demonstrating the ability to reconstruct the underlying asymmetry from jet measurements with the upgraded PHENIX.

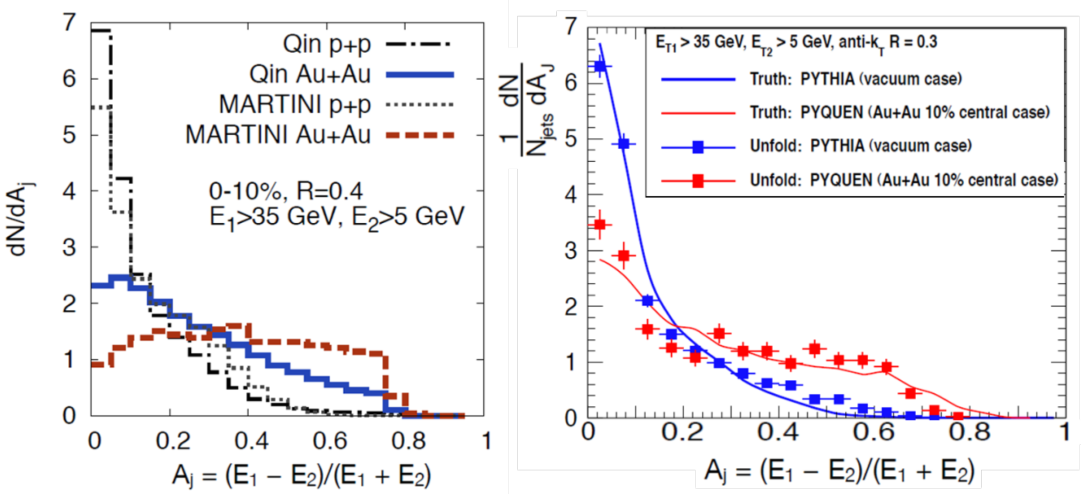


Figure 15. *(Left) Predictions for the energy asymmetry between the two members of a di-jet pair at RHIC* $\sqrt{s_{NN}}$ *= 200 GeV by different models that fit analogous LHC Pb+Pb data at* $\sqrt{s_{NN}}$ *= 2.76 TeV. (Right) Simulations of the ability of the proposed upgraded PHENIX detector (sPHENIX) to reconstruct full jets in the presence of realistic heavy-ion event background and detector acceptance and resolutions, and to perform unfolding of the detector and background effects to recover the underlying di-jet asymmetry modeled with (red) or without (blue) jet quenching.*

4) ***Do we observe evidence for the onset of deconfinement and/or a QCD Critical Point?*** The evidence discussed in Sec. 3 (see Figs. 5 and 7) hints at interesting, possibly profound, changes in behavior and degrees of freedom of QCD matter in the vicinity of RHIC collision energies $\sqrt{s_{NN}} \approx 20$ GeV. Significant discovery potential rests on pursuing these hints at RHIC in a second phase of the beam energy scan, which will collect order of magnitude larger data samples at the lowest energies. Much improved statistical precision below 20 GeV is needed, for example, for measurements of: elliptic flow for multi-strange hadrons, to characterize the apparent breakdown in the scaling with number of valence quarks; event-to-event fluctuations in net baryon number and net charge, in searching for a QCD critical point; and the charge-

dependent correlations sensitive to the chiral magnetic effect, to further distinguish among competing interpretations of these data.

The efficiency of such measurements will be greatly increased if we can raise low-energy heavy-ion luminosities by electron cooling (Fig. 16). Options involving electron acceleration with rf cavities being developed for other purposes at BNL, or with a Pelletron that was used for electron cooling studies at Fermilab, are under consideration. Such an accelerator upgrade project, while modest (~$5M) in scope, would require a few years to complete, making the bulk of further low-energy measurements a program for the second half of the decade ahead. There is also a shorter-term need, to be addressed in 2013-14, to fill in one more first-phase Au+Au point near $\sqrt{s_{NN}} \approx 15$ GeV, where there is currently a gap in μ_B coverage in Fig. 7a that is potentially wide enough to hide the positive lobe of a bipolar kurtosis excursion indicative of passage through a critical point. If the critical point turns out to be very near the low end ($\sqrt{s_{NN}} =$ 5 GeV) of the RHIC energy range, then the new European fixed-target heavy-ion facilities at FAIR and NICA may have strong roles to play in mapping it.

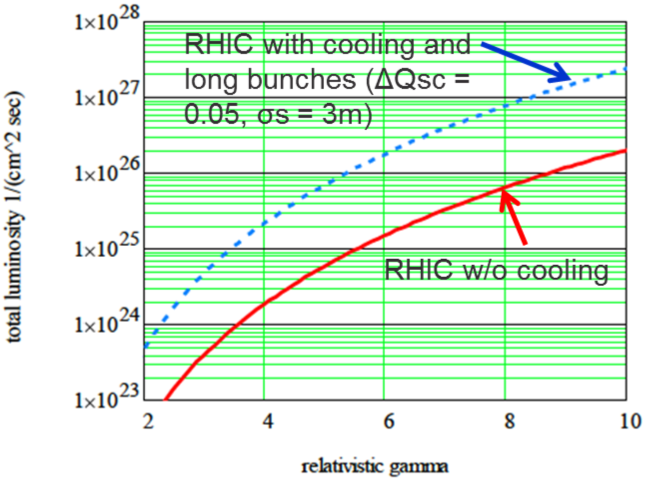


Figure 16. *Simulation of the anticipated order of magnitude improvement in low-energy Au+Au collision luminosity by the addition of low-energy electron cooling and the use of lengthened beam bunches in RHIC.*

5) ***Do we observe sequential melting of different quarkonium states?*** The interaction between a heavy quark and antiquark inside the QGP should be subject to screening by the intervening colored (deconfined) matter. This effect should be manifested by a distinctive pattern of sequential "melting" of heavy-flavor quarkonia, with the smallest, most tightly bound $q\bar{q}$ systems surviving to the highest temperatures, as suggested by the schematic thermometer in Fig. 17. If measured survival probabilities for various quarkonium states, over a wide range of collision energy, reveal the anticipated pattern, this would provide a clear signature for deconfinement and a new method for determining QGP temperature.

At Quark Matter 2012, the CMS Collaboration released preliminary results for the yields of various quarkonium states in Pb+Pb collisions at LHC (Fig. 17, middle frame), which show the anticipated suppression pattern at least qualitatively. In particular, the excited $b\bar{b}$ states ϒ(2s) and ϒ(3s) and the excited $c\bar{c}$ state ψ′(2s) are clearly more strongly suppressed than the corresponding ground states, in comparison to expectations from p+p collisions. However, new data released by PHENIX at the same conference (right frame in Fig. 17) show much stronger suppression of ψ′ than of J/ψ even in d+Au collisions, where QGP is not formed. The PHENIX results emphasize the complexity of influences on quarkonium production and survival, and the vital importance of cold matter baseline measurements before clear interpretations can be made.

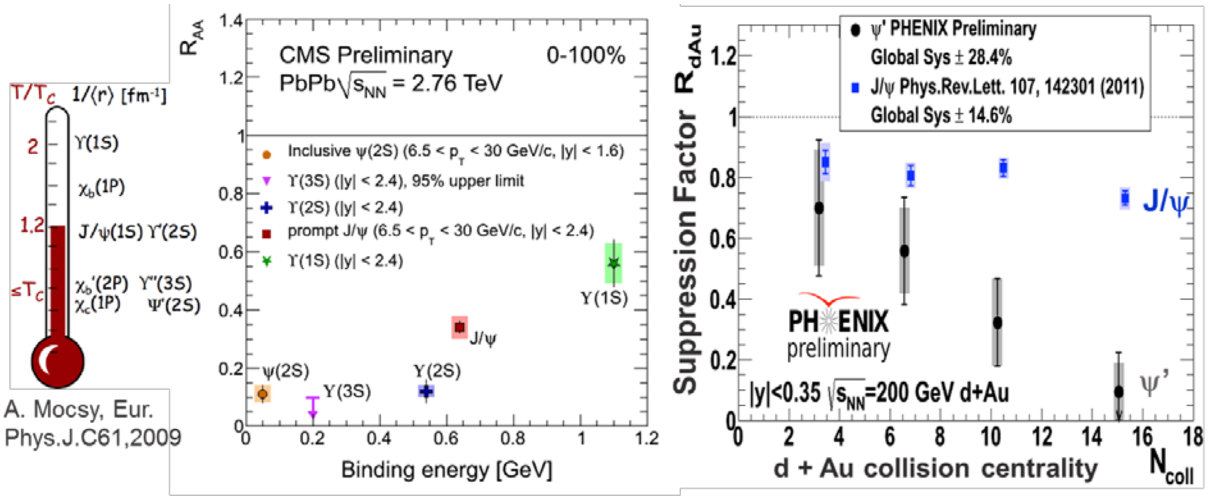


Figure 17. *Left: the thermometer [A. Mocsy, Phys. J.* ***C61, 705*** *(2009)] schematically illustrates the different "melting" points expected for quarkonium systems of different binding energy and size embedded within QGP. Middle: CMS preliminary results [G. Roland, talk at Quark Matter 2012] for the suppressed production of various quarkonium states in 2.76 TeV Pb+Pb collisions at LHC, with respect to expectations from p+p collisions. The suppression pattern appears qualitatively consistent with the anticipated sequential melting in QGP. Right: Preliminary PHENIX results [T. Sakaguchi, talk at Quark Matter 2012] for J/*ψ *and* ψ' *suppression in 200 GeV d+Au collisions at RHIC shows enhanced* ψ' *suppression even in cold nuclear matter.*

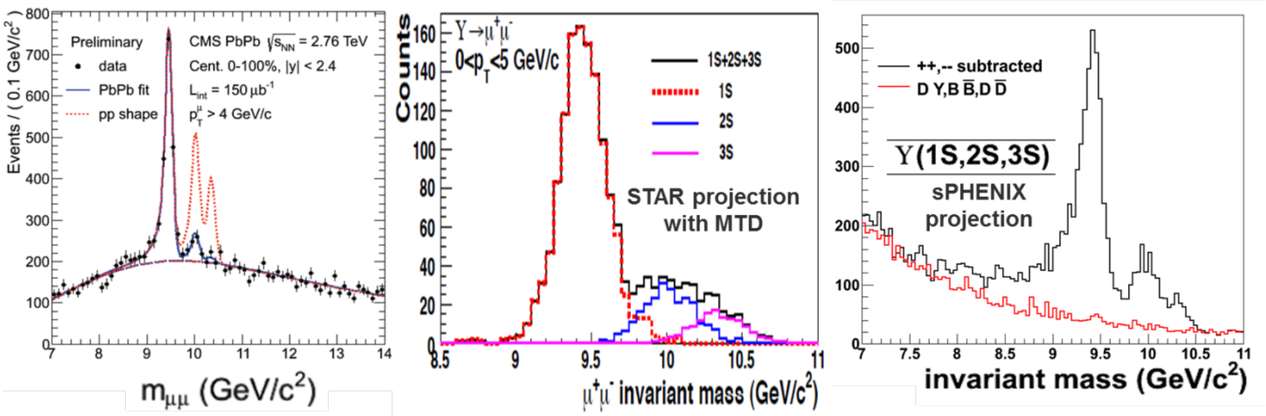


Figure 18. *Di-lepton spectra showing upsilon resolution as measured in Pb+Pb collisions at CMS (left) and as simulated for Au+Au with upgraded STAR (middle) and PHENIX (right) detectors. Comparison of the data to the dashed red (p+p) curves in the left frame illustrates the enhanced suppression of the excited upsilon states vs. the ground state.*

Quarkonium yields are affected by competing phenomena: color screening, initial-state shadowing of parton distribution functions, final-state regeneration and absorption in cold nuclear matter. These have different dependences on quarkonium state, √s, colliding beam species and collision centrality. It is imperative to measure the yields as a function of all of these, in order to provide a definitive test of our understanding of the in-medium $q\bar{q}$ interaction. The upsilon states are of particular interest, not only because of their different binding, but also because $b\bar{b}$ regeneration is considered unlikely at the temperatures reached at either RHIC or LHC. The middle and right frames of Fig. 18 illustrate, respectively, simulated upsilon spectra obtainable with STAR after its muon detection upgrade (to be completed by the 2014 run) and with sPHENIX, showing the resolved ground state in each. Despite the challenge in matching the di-muon resolution already attainable with CMS (left frame in Fig. 18), RHIC measurements for various heavy ion species, and for p/d+A as well, remain crucial to unravel the competing influences on the production mechanism and to determine the temperature-dependence of color screening effects.

6) ***Are the hints of sphaleron effects seen in the data to date real?*** As already discussed in Sec. 3, the interpretation of the suggestive results shown in Fig. 5 is best tested at RHIC. One approach is to test flow-related background explanations more stringently by improving statistics for ultra-central U+U (see Fig. 9a) and lowest RHIC energy (Fig. 5a) collisions, where the charge separation signal appears to vanish despite still appreciable elliptic flow. Equally important is the search for other predicted manifestations of the chiral imbalance allowed in localized spatial regions by excited QCD vacuum fluctuations and the QCD triangle anomaly responsible for the Chiral Magnetic Effect. One such predicted phenomenon [D. Kharzeev and D.T. Son, *Phys. Rev. Lett.* **106**, 062301 (2011)] is a baryon current correlated with the CME charge current, which should become visible when the matter produced has a net baryon density ($\mu_B \neq 0$). This effect could be sought via Λ-$\pi^+$and $\overline{\Lambda} - \pi^-$ event-by-event azimuthal correlations at a mid-range RHIC energy, *e.g.,* $\sqrt{s_{NN}} \approx 40$ GeV, where the CME signal in Fig. 5a is still strong but μ_B deviates significantly from zero. It also pays to search for π^+ *vs.* π^- elliptic flow differences, such as those in Fig. 5b, at RHIC's lower energies.

If the sphaleron interpretation is confirmed, it will be important to see if the magnitude of the observed EDM-like particle correlations can be quantitatively understood. This will require embedding excited QCD vacuum fluctuation effects and the strong magnetic fields in state-of-the-art hydrodynamics calculations. This development is anticipated as a feature of the pre-equilibrium "glasma" incorporation that is also being used to constrain the initial density fluctuations discussed under item (2) above.

7) ***Do we reach saturated gluon densities in RHIC d/p+A collisions?*** A number of observations in both heavy-ion and d+Au collisions at RHIC, including those in Fig. 10, are consistent with expectations based on the saturation of gluon densities in the colliding cold nuclei. Alternative multiple-scattering explanations for some of these observations have been offered, although these have an as yet undetermined degree of overlap with saturation models. The CGC-based approaches, including the glasma stage intermediate between the cold nuclei and the establishment of thermalized QGP, provide a unified approach to calculation of not only the initial densities but also the incorporation of quantum fluctuations of various sorts. More insight may come from the first p+Pb collision run planned at LHC for early 2013. Even if the LHC experiments observe a strong suppression of forward hadron and di-hadron production that argues further for gluon saturation, one wants to understand where the saturation sets in as a function of Bjorken x, resolving power Q^2 and nuclear mass A.

Further RHIC measurements focusing especially on forward direct photon production in d+A or p+A collisions can help to map low-x gluon densities in heavy nuclei. The photon production is dominated by quark-gluon scattering, with a moderate- to high-x quark from the deuteron or proton interacting with a soft gluon from the heavy nucleus. By 2014 both PHENIX and STAR will have good forward photon calorimetry installed, and the relevant p/d+A runs can take place within the coming five years. Even more direct information on the location of the saturation surface may be provided by polarized proton collisions with heavy ions. Kang and Yuan have recently [*arXiv:1106.1375*] pointed out that the ratio of transverse spin asymmetries measured for far forward hadron production in p+A *vs.* p+p collisions depends directly on the saturation momentum Q_s^2 in the proton *vs.* that in the nucleus. An appropriate set of spin measurements on several different nuclei is probably best carried out in the second half of the decade, after forward detector upgrades proposed by both RHIC collaborations.

On the other hand, the cleanest maps of soft gluon densities in heavy nuclei require e+A collisions at an EIC. One of the major goals of EIC will be to map the saturation surface that separates the dilute parton gas and Color Glass Condensate regimes, as a function of x, Q^2 and A (see Sec. 7 and Fig. 21).

8) ***Where is the missing proton spin?*** The first clear indication from RHIC of appreciable gluon polarization (Fig. 11) must be extended to lower Bjorken x-values, via not only inclusive jet and hadron production, but especially di-jet asymmetry measurements in polarized proton collisions at $\sqrt{s}$ = 500 GeV. However, RHIC will run out of kinematic reach for gluons below x~0.01 in p+p collisions. Access to the dominant softer gluons in a proton to assess their contribution to proton spin can only be gained via polarized e+p collisions at EIC.

A second important program for future 500 GeV polarized proton collisions at RHIC involves measurement of parity-violating helicity asymmetries in $W^{\pm}$ boson production to probe the chiral structure of the nucleon, by measuring the flavor dependence of sea antiquark polarizations. The electroweak process, dominated by $u\bar{d}$ $(d\bar{u})$ fusion for W^+ (W^-) production, provides theoretically clean access to the antiquark helicity preferences $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$. Both STAR and PHENIX have already published first results that prove their ability to detect and identify the W-bosons. Figure 19 shows simulations that reveal the complementary sensitivities of W production asymmetries to be measured by the two detectors, with statistical precision attainable in two long RHIC 500 GeV polarized proton runs. The needed 500 GeV runs should be completed within the coming few years.

There is also great interest in measuring transverse spin asymmetries for forward Drell-Yan dilepton production at RHIC, to test robust perturbative QCD predictions of a simple relationship with analogous asymmetries measured in SIDIS. The asymmetries in both cases are sensitive to spin-orbit correlations of quarks within the proton wave function, in particular to a transverse-momentum-dependent (TMD) parton distribution known as the Sivers function. However, the relevant Sivers functions are predicted to differ in sign between Drell-Yan and SIDIS, as a result of the fundamental color-dependence of QCD corrections to the processes, which come in as final-state interactions in SIDIS but as initial-state interactions in Drell-Yan. This program requires some upgrade to the forward detection capabilities at STAR and PHENIX, beyond ongoing projects, and would thus be done during the second half of the coming decade.

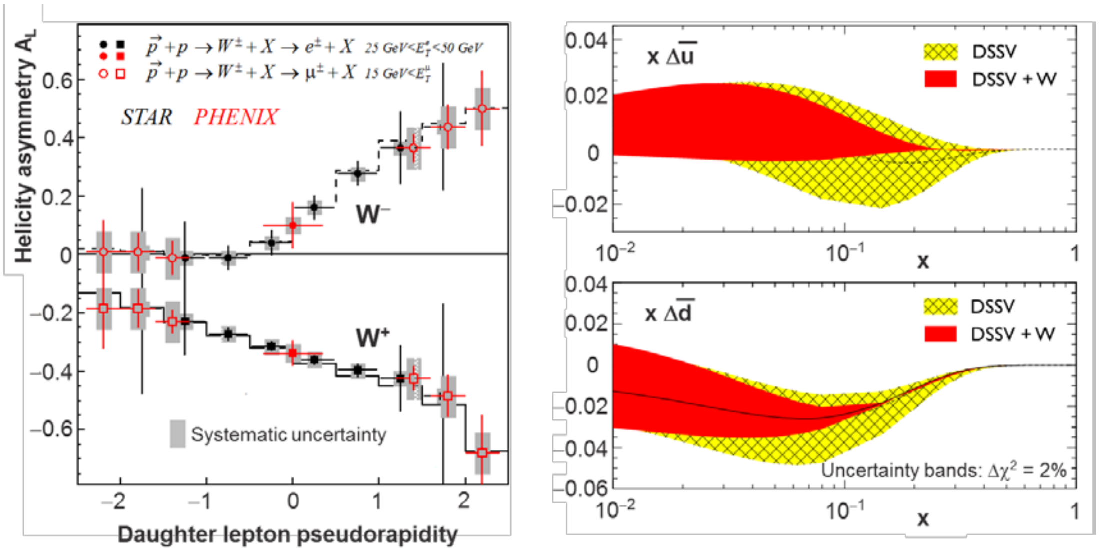


Figure 19. *Simulations of sensitivities to sea antiquark polarizations from parity-violating asymmetry measurements for W production with 250-300 pb*$^{-1}$ *sampled of 500 GeV polarized proton collisions at RHIC. The left frame shows* W^+ *and* W^- *asymmetries from PHENIX (red points) and STAR (black points) combined. The data are generated using the central fit values for antiquark polarizations from the existing DSSV perturbative QCD analysis of the polarized database. The comparison of red to yellow bands in the right frames shows the anticipated uncertainty reduction for the helicity preference of anti-up (top) and anti-down (bottom) quarks when the simulated RHIC W asymmetries are added to the DSSV fits.*

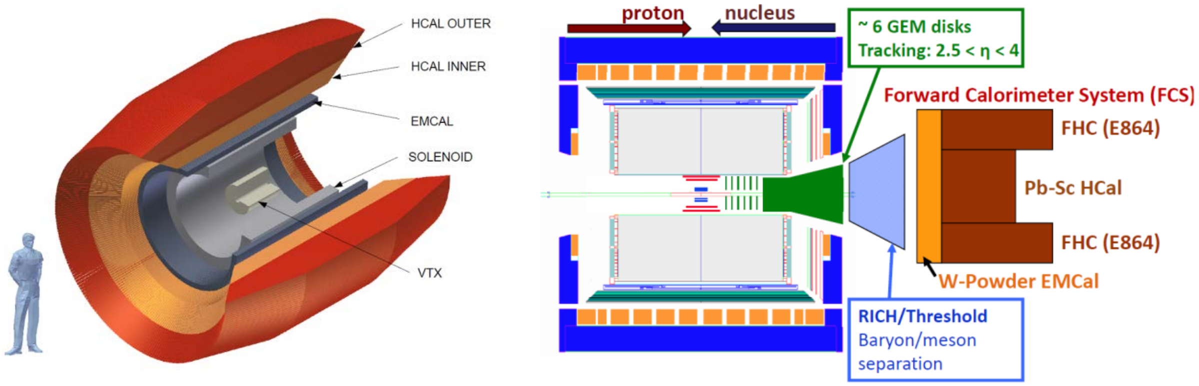


Figure 20. *Schematic layout of the proposed sPHENIX upgrade (left) and forward physics additions for STAR (right). sPHENIX would build around the now completed micro-vertex detectors with new, cost-effective solenoidal magnet and electromagnetic and hadronic calorimeters, to greatly increase the acceptance and jet reconstruction capabilities of the PHENIX detector. Additional tracking layers may be provided by foreign partners. The proposed STAR upgrades would add far forward tracking, particle identification and calorimetry subsystems to enhance cold nuclear matter studies, including measurement of transverse spin asymmetries for Drell-Yan and p+A processes. Both upgrades would have the detectors poised for subsequent additions that optimize their roles in a first stage of eRHIC (see Sec. 7).*

The measurement program outlined above exploits RHIC's full versatility in energy and colliding beam species. In addition to healthy facility operations, the parts of the program designated for the second half of the coming decade rely on some further upgrades. The low-energy electron cooling simulated in Fig. 16 can be carried out as a modest (< $5M) Accelerator Improvement Project. Figure 20 shows proposed significant upgrades to the PHENIX and STAR detectors, for which separate proposals will be written and evaluated by normal DOE processes.

7. The Path to EIC in RHIC's Third Decade

Gluon self-interactions give rise to unique emergent QCD phenomena in cold, as well as hot, matter. The gluons are the dominant "silent partners" in ordinary matter: they do not directly influence the quantum numbers of non-exotic hadrons, but their interactions are nonetheless the major contributors to light hadron masses. The splitting of a single gluon into two gluons that share the original momentum leads to a proliferation of soft gluons in the vicinity of any bare color charge, and it is this proliferation that accounts for nearly all of the mass of the visible universe ("mass without mass" in an evocative phrase first used by John Wheeler). When the color charges are confined in the tiny volume of a color-neutral hadron, this proliferation leads to very high internal color charge densities and to Nature's most intense fields. But QCD also provides a natural mechanism for the self-regulation of these extreme densities: the recombination of two soft gluons into one eventually competes favorably with gluon splitting, leading to an anticipated density saturation of the soft gluons inside all hadrons and nuclei when they are viewed at light speed. Understanding the properties and behavior of this high density, cold gluon-dominated matter is essential to the treatment of high-energy QCD processes, such as those studied at RHIC and LHC, and of the partonic substructure of nucleons and nuclei.

Understanding the properties and behavior of this high density, cold gluon-dominated matter is essential to the treatment of high-energy QCD processes, such as those studied at RHIC and LHC, and of the partonic substructure of nucleons and nuclei.

Electron-proton collisions at the HERA facility and ion collisions at RHIC and LHC provide initial glimpses into this gluon-dominated matter, but its quantitative characterization requires a future Electron-Ion Collider with capabilities far exceeding HERA's: two-to-three orders of magnitude improvement in collision luminosity; the availability of polarized nucleon beams and of heavy-ion beams up to A>200; wide energy variability to aid the separation of longitudinal from transverse response of the hadrons to the electromagnetic field carried by exchanged photons. The electron beam provides the probe precision of the electromagnetic interaction and its low-order QCD corrections, while heavy-ion beams provide precocious access to the density saturation regime, as described in Sec. 5 above. Advances in accelerator science since HERA was constructed now render these technical enhancements feasible, while results from HERA, RHIC, LHC and CEBAF highlight the need for such a new facility. The cost can be kept manageable by taking advantage of the existing heavy ion and polarized proton beams at RHIC.

EIC is envisioned as a high-resolution femtoscope for cold, gluon-dominated matter, to:

- Probe the momentum-dependence of the onset of gluon saturation in nuclei, an emergent phenomenon that clearly manifests the non-Abelian nature of QCD;
- Map the gluon densities and multi-dimensional distributions of confined partons in space, momentum, spin and flavor, within the gluon-dominated regime in nucleons and nuclei;
- Image the positions and motion of soft gluons and sea quarks transverse to a nucleon's direction, bearing on parton orbital angular momentum contributions to the nucleon spin;
- Test effective theory approaches (*e.g.*, CGC) to the highly non-linear, high density, strong field limit of QCD.

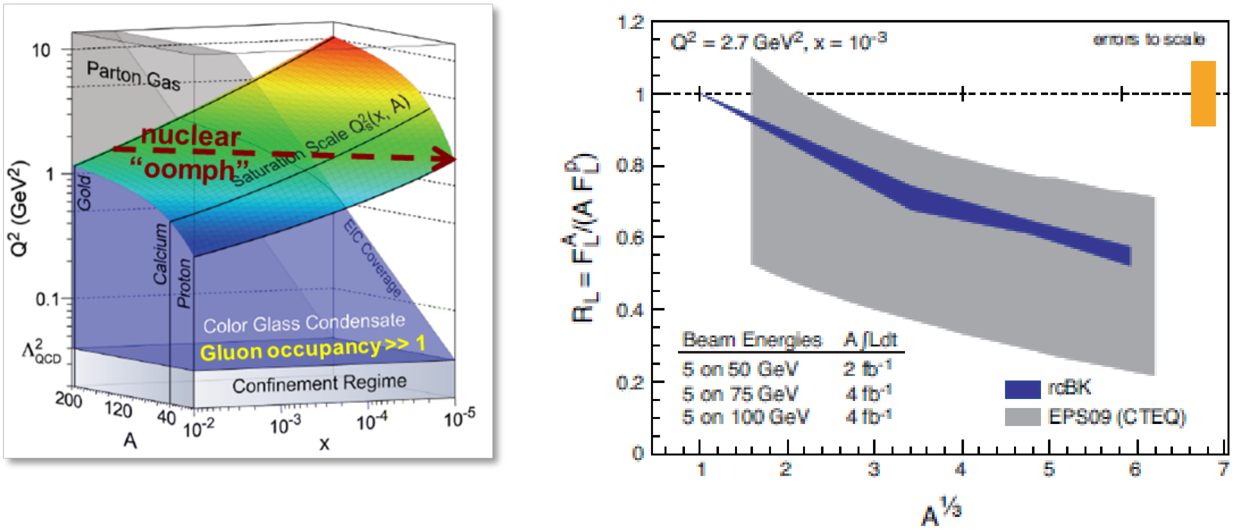


Figure 21. *Predicted aspects of gluon saturation in nuclei. The left frame shows the expected shape of the gluon density saturation surface that separates the dilute parton gas and Color Glass Condensate (CGC) regimes, as a function of Bjorken x, resolving power* Q^2 *and nuclear mass A. The brown dashed arrow illustrates the "nuclear oomph" factor: one can enter the CGC regime at given* Q^2 *(or given coupling strength* α_s*) at x-values ~A times larger (hence, at much lower* $\sqrt{s}$*) for a heavy nucleus than for a proton. The right frame shows expectations for the A-dependence of the longitudinal structure function* F_L*, divided by A times the corresponding value for the proton, at momentum fraction* $x=10^{-3}$ *and* $Q^2=2.7$ *GeV*^{2}*.* F_L *is measurable in deep inelastic e+A scattering carried out at multiple collision energies, and it probes gluon densities directly. The gray shaded band reflects present gluon density uncertainties, while the narrow blue band represents CGC-based predictions and the experimental uncertainties anticipated from early measurements with a first-phase EIC.*

The science program of an EIC has been detailed in the report (arXiv:1108.1713) from a 10-week Fall 2010 program at the Institute for Nuclear Theory, and is summarized in a separate EIC Science White Paper that will be available in Summer 2012. Here we provide (Figs. 21-24) only a small glimpse of prominent goals and measurement results desired from EIC, representing game-changing extensions of QCD physics that has been pursued at RHIC, CEBAF and HERA.

Figure 21 illustrates aspects of the anticipated saturation of gluon densities in nuclei. Deep inelastic scattering (DIS) of electrons from nuclei, never before accessible at collider center-of-mass energies, should allow us to map significant parts of the expected saturation surface in the left frame of the figure, and to observe the transition across it from a dilute parton gas regime to the CGC, where the occupancy of single-gluon states is large compared to unity. The shape of the saturation surface is constrained by what we know from HERA of the gluon density variation with momentum fraction x within a proton and by the $A^{1/3}$-dependence expected for the effective gluon density probed coherently at low x by a virtual photon interacting with a nucleus. These constraints give rise to the "nuclear oomph" factor illustrated in Fig. 21, characterizing the extent of precocious access to saturation. The right frame shows that the ratio of soft gluon densities in a heavy nucleus to that in a proton is essentially unknown at present. Early EIC measurement of longitudinal structure functions in e+A DIS will help to pin down soft gluon densities precisely to test CGC predictions, as illustrated by the narrow band in the figure. Measurements of the Q^2-dependence of the F_2 structure function will provide additional constraints. But these structure function measurements alone may not definitively distinguish CGC predictions from parton distribution fits that do not assume gluon saturation.

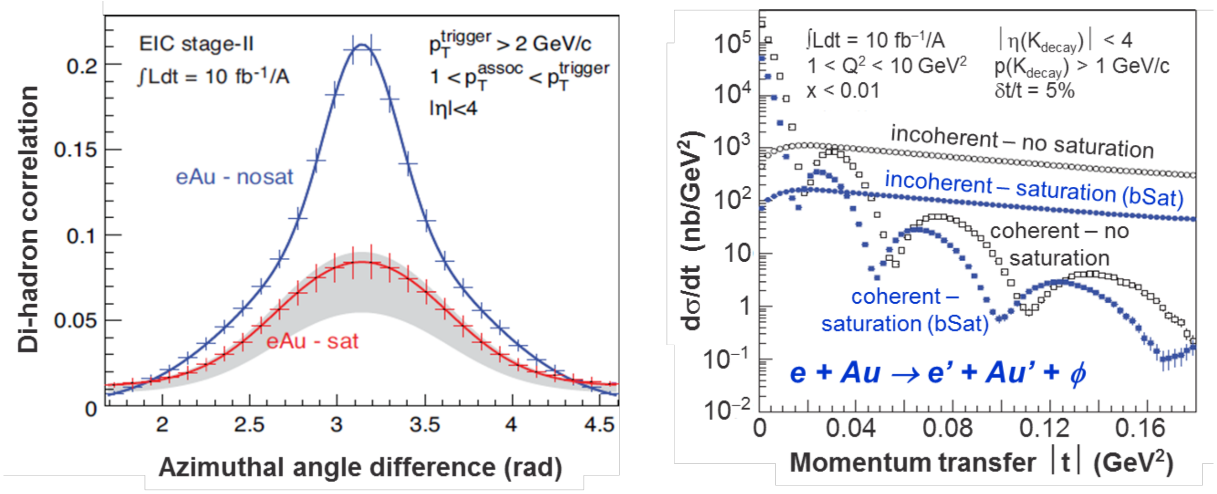


Figure 22. *Simulations highlighting two ways of observing gluon saturation effects clearly in e+Au collision runs of modest length (~10 fb^{-1}ep-equivalent integrated luminosity) at EIC. The left frame shows predictions with and without saturation for the azimuthal angle correlation between two hadrons, while the right shows the predicted effect on the novel "nuclear gluonic form factor" (related to the spatial distribution of gluons in the nucleus) in coherent diffractive ϕ-meson production. The experimental challenge to distinguish the latter from incoherent processes with nuclear breakup will require detecting breakup neutrons at far forward angles.*

The saturation of gluon densities should also be manifested strongly in di-jet production and diffractive forward particle production in e+A collisions, as illustrated in Fig. 22. The di-jet production is dominated by photon-gluon fusion processes ($\gamma + g \rightarrow q + \bar{q}$), and thus has a linear dependence on gluon density in the nucleus. Saturation should then lead to a strong, easily detected suppression of back-to-back di-hadron coincidences signaling di-jet production, as shown by predictions in the left frame of Fig. 22. This suppression is similar to, but much more cleanly interpretable than, forward di-hadron suppression seen in central d+Au collisions at RHIC. Diffractive processes are dominated by two-gluon exchange between the nucleus and $q\bar{q}$

fluctuations of the virtual photon, providing quadratic sensitivity to gluon densities. Exclusive diffractive vector meson production (see right frame in Fig. 22) is of special interest, because it can provide unprecedented access to the "gluonic form factor" of a nucleus. The Fourier transform of such form factors yields unprecedented information on the transverse spatial distribution of high-density gluons inside a nucleus. Does this simply mirror the distribution of nucleons in the nucleus, or is there a hint of the universal nature of saturated gluonic matter? The influence of saturation on the gluonic form factor is significant, as in Fig. 22, when the size of the produced vector meson is comparable to or greater than $1/Q_{\rm sat}$.

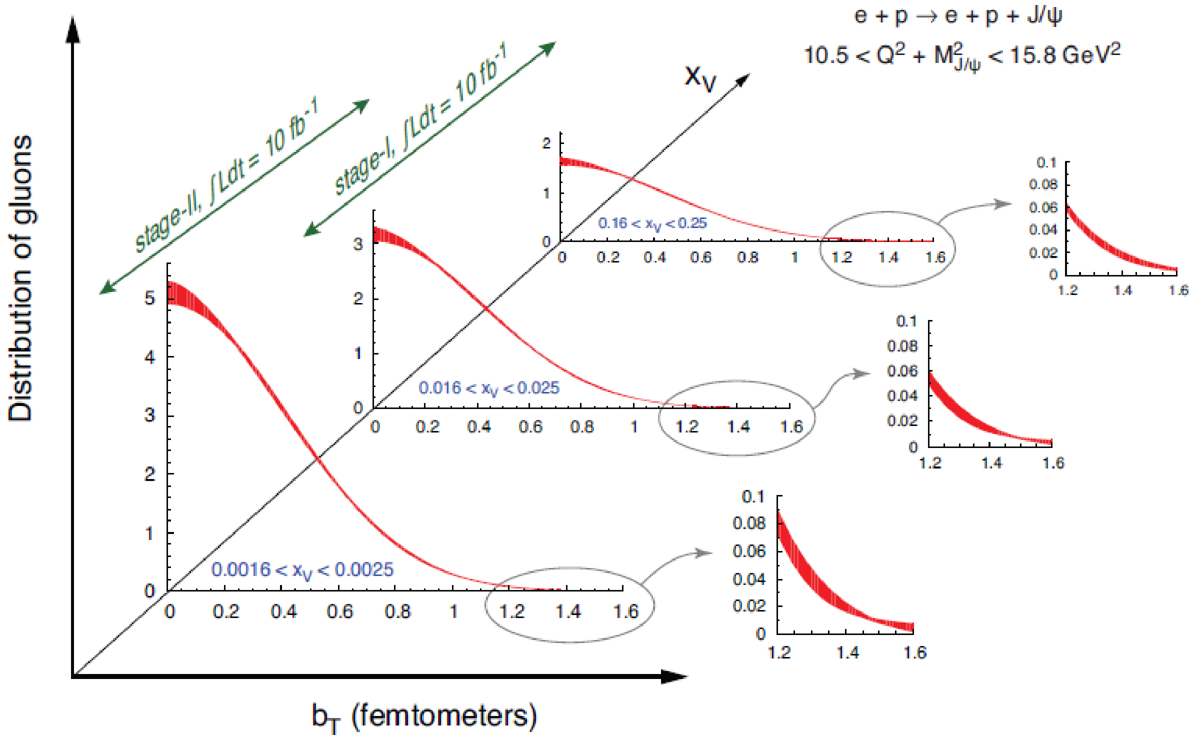


Figure 23. *Simulations illustrating the groundbreaking tomographic imaging capabilities of deep exclusive e+p reaction measurements at EIC. The curves represent the transverse spatial distributions of gluons extracted for various gluon longitudinal momentum fraction values* x_V *from simulated differential cross section (*$d\sigma/dt$*) data for exclusive* J/ψ *production.* b_T *is the transverse distance of the gluon from the center of the proton. The collision energies assumed for a stage-I and stage-II version of EIC are* E_e*=5 GeV,* E_p*=100 GeV and* E_e*=20 GeV,* E_p*=250 GeV, respectively. The widths of the red bands reflect systematic (±5% on* $d\sigma/dt$*) as well as statistical uncertainties projected for the measurements. The intermediate* x_V *bin is accessible with either energy setting and gives almost identical uncertainty bands in both cases.*

EIC luminosities will also facilitate measurement of exclusive reaction processes in polarized e+p collisions, such as Deeply Virtual Compton Scattering (DVCS, $e+p \rightarrow e'+p'+\gamma$) or meson production. These processes are sensitive to the Generalized Parton Distributions (GPDs) that connect electromagnetic form factors measured in elastic electron-nucleon scattering to parton distribution functions probed in DIS. The GPDs encode tomographic imaging information that allows groundbreaking visualizations of parton distributions inside a proton. For example, the simulations in Fig. 23 illustrate the precision with which one will be able to extract information from exclusive J/ψ production cross sections on the transverse spatial distribution of gluons as a function of x. Such images provide the baseline to which we can compare gluon spatial distributions in heavy nuclei, extracted from cross sections like those in Fig. 22b.

Measurements with polarized electrons on polarized protons for various exclusive reaction processes will constrain different GPDs and provide even richer information on parton spatial distributions. For example, DVCS measurements of the spin asymmetry associated with proton beam transverse spin flip can reveal off-center shifts in sea quark distributions (with respect to those in an unpolarized proton), along a direction perpendicular to both the proton spin vector and its momentum. Such experiments will typically require about an order of magnitude more integrated luminosity than the modest demands for the cross section measurements represented in Fig. 23. From transverse spin sensitivities in semi-inclusive DIS (SIDIS), one can extract analogous images in momentum space (see Fig. 24a), mapping transverse momentum preferences for partons of different flavor, indicative of spin-orbit correlations in a transversely polarized proton. The exclusive reaction and SIDIS measurement programs will revolutionize our understanding of the proton's internal wave function, taking us from the present one-dimensional view of parton distribution functions of x to three-dimensional views sensitive to transverse parton position or parton orbital motion.

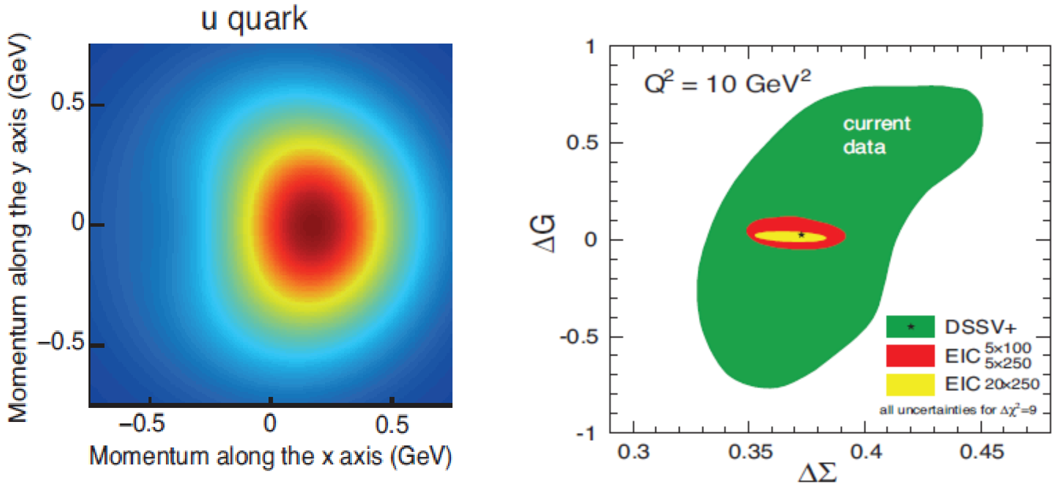


Figure 24. *Simulations of dramatic advances EIC polarized deep inelastic scattering (DIS) would bring to understanding the spin structure of the proton. The left frame shows the transverse momentum probability distribution for up quarks with x=0.1, reconstructed from simulated SIDIS spin asymmetry data for a proton moving in the z-direction and polarized in the y-direction. The right frame shows projected reductions from present (green, not yet including RHIC 2009 spin data) uncertainties on the integral gluon (vertical axis) and fractional quark (horizontal axis) contributions to the proton spin. The red band is based on fits to simulated DIS data for about two months of running with a first-stage (5 GeV electron energy) eRHIC facility; the yellow band shows the additional improvement possible at a 20 GeV second-stage facility.*

By greatly extending the kinematic reach of polarized *inclusive* DIS measurements, which up to now have been made only with fixed polarized targets, EIC will also dramatically advance understanding of the nucleon's spin structure. As shown in Fig. 24b, inclusive DIS measurements at low x with longitudinally polarized electron and proton beams will reduce present uncertainties on partonic spin contributions to proton spin by a large factor for gluons and by a factor ~2 for quarks. The uncertainties following early EIC experiments will then be small enough to determine definitively whether parton orbital angular momentum contributions are needed to account for the overall spin. The additional measurement of parity-violating asymmetries sensitive to proton helicity flip in charged-current DIS will provide unprecedented information on electroweak structure functions that will help to pin down precisely the flavor-dependence of sea quark helicity preferences in a polarized proton.

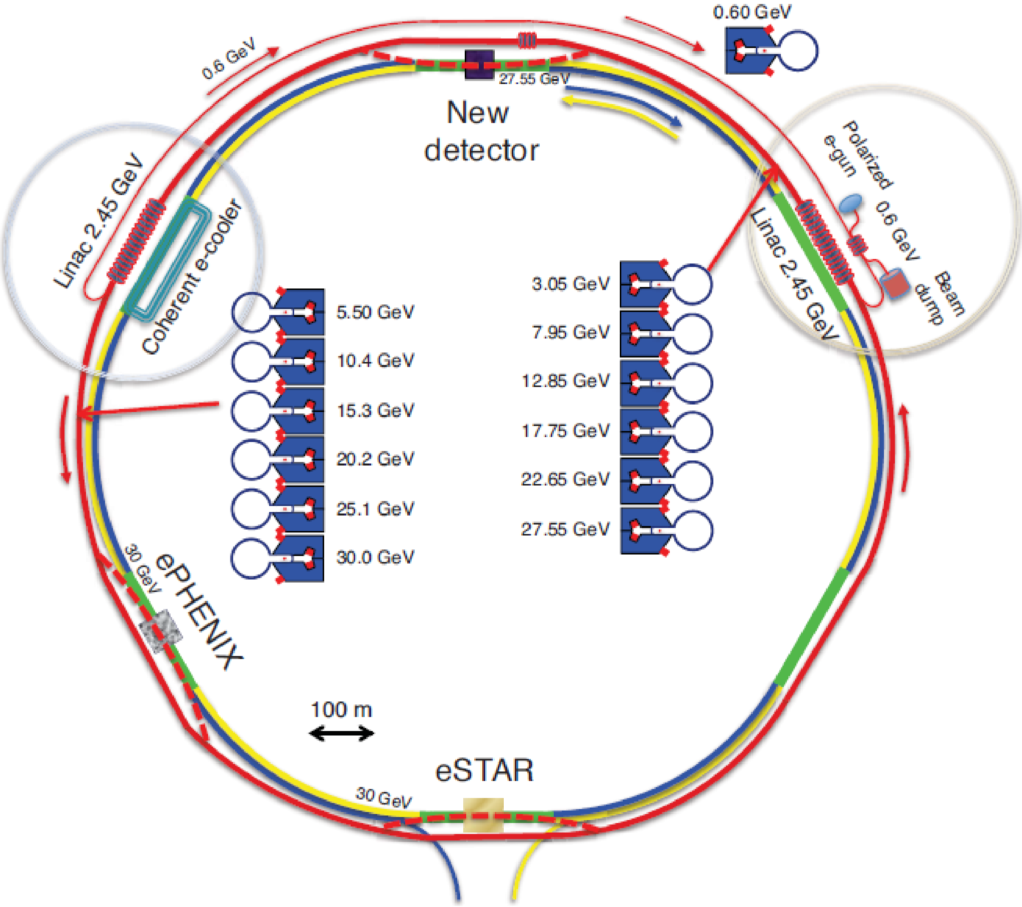


Figure 25. *Layout of the electron Energy Recovery Linac (in red) that would be added inside the RHIC tunnel to realize eRHIC. The polarized electron beam starts in a polarized gun and ends in a beam dump, both located in the 2 o'clock intersection region. The baseline design shown here assumes the electron beam is accelerated, and subsequently decelerated, through six vertically stacked passes with small gap normal conducting magnets. Alternative recirculation layouts are under consideration.*

Realizing the full range of energies and luminosities desired for EIC will be costly. The optimal strategy for getting there thus involves a staging approach, with a first phase that can accomplish a significant fraction of the science goals at a total project cost far under a billion dollars. RHIC provides a natural platform for such an approach. The eRHIC design we have developed, adding an electron Energy Recovery Linac (ERL) to the existing RHIC rings, and inside the RHIC tunnel, is shown in Fig. 25.

The first stage of eRHIC would add an ERL accelerating electrons to 5-10 GeV, with linac sections installed in two of RHIC’s existing intersection regions (IR’s at 2 and 10 o’clock). Subsequent upgrades to as much as 30 GeV electron energy would then proceed by adding superconducting rf cavities to these linac sections. The accelerated electron beam would be brought into collision with RHIC’s heavy ion or polarized proton beams at the existing locations of the PHENIX and STAR detectors, and possibly also at a new IR at 12 o’clock, before it undergoes deceleration in the ERL. Luminosities three orders of magnitude beyond HERA’s would be obtained by starting with a 50 mA multi-cathode polarized electron gun (the subject of current RHIC R&D), cooling the hadron beams via Coherent electron Cooling (currently under development at RHIC), exploiting advances already demonstrated in high-gradient superconducting quadrupole design with funding from the LHC Accelerator Research Program, and adding crab cavities to optimize beam bunch overlap with a small (10 mrad) beam crossing angle at the IRs.

The eRHIC design underwent a successful first technical review by an independent panel of accelerator physicists in August 2011. We are currently working on a bottom-up cost estimate and value engineering evaluation. The baseline design costed involves six vertically stacked recirculation passes through which the electron beam is accelerated to top energy, as indicated in Fig. 25. We are also evaluating other options, involving multiple electron passes through large acceptance permanent magnets, which might reduce cost while permitting attainment of higher first-stage electron energies. The goal is a total project cost for the accelerator ~$500M, with an additional ~$100M available for detector upgrades and/or installations.

It is considerably less costly to add an electron accelerator to the RHIC complex, taking advantage of the ~$2B replacement cost of RHIC, than to build a hadron facility from the ground up.

The eRHIC design would advance the accelerator state-of-the-art considerably, but is nonetheless a cost-effective approach for the following reasons:

- It reuses the RHIC tunnel and the existing detector halls, thereby minimizing civil construction costs.
- It reuses significant fractions of the existing STAR and PHENIX detectors (including the proposed upgrades in Fig. 20), which can provide reasonable science reach in a first-stage eRHIC.
- It exploits the already existing heavy ion beams at RHIC to provide precocious access to the regime of very high gluon densities.
- It exploits polarized proton beam capabilities and hardware that already exist.
- It is considerably less costly to add an electron accelerator to the RHIC complex, taking advantage of the ~$2B replacement cost of RHIC, than to build a hadron facility from the ground up.
- It provides for a straightforward upgrade path via the addition of superconducting rf linac cavities.
- It takes advantage of RHIC needs and of other accelerator research at Brookhaven:

    - For example, coherent electron cooling being developed for eRHIC could also boost RHIC p+p luminosities dramatically to enhance the RHIC spin program;
    - For example, FFAG (fixed-field alternating-gradient) accelerator design advanced at BNL as part of muon collider R&D (and also exploited for the patented design of low-mass gantries for hadron radiotherapy facilities) is now considered for possibly substantial cost savings on eRHIC recirculation arcs.

8. Summary: What Would Be Lost if RHIC Operations Were Terminated

As illustrated by examples in Sec. 3, and by publication documentation in Appendix B, the RHIC science program remains vibrant and highly productive. The facility continues to train a significant fraction of the Ph.D.'s in Nuclear Physics. As outlined in Secs. 6 and 7, RHIC has a well-defined vision addressing compelling open questions for both the short- and long-term future. If RHIC operations were to be terminated in the next few years, all of the following would be lost to the U.S. Nuclear Physics research effort:

The most sensible approach to a several-year budget crisis is to find creative ways to exploit the resources that have been built up by past investments, as long as they are still operating at full efficiency.

- The opportunity to map QCD matter properties as a function of temperature across the hadronic phase to QGP transition and to discover the possible QCD Critical Point.
- The unique polarized proton collider capability and the selective access it provides to address questions of nucleon spin structure.
- U.S. leadership in a vibrant Nuclear Physics subfield it pioneered and still leads.
- A major fraction of the productivity for U.S. Nuclear Physics research for the better part of a decade. The community will have to judge whether this loss is survivable.
- The unmatched track record of the RHIC-focused RIKEN-BNL Research Center in funding outstanding Fellows and helping to place them in high-profile tenured positions.
- The only operating U.S. collider facility, hence a critical attractor for talented accelerator scientists and cutting-edge R&D.
- Quite possibly the only cost-realizable path to a future Electron-Ion Collider, taking advantage of the ~$2B replacement cost of RHIC.
- The home research base for over 1000 domestic and foreign users.
- Very strong foreign (especially RIKEN) investment in a U.S. facility.
- Support for ~750 (direct plus indirect) FTE's at BNL.
- The cost-effectiveness and viability of many associated efforts that rely on RHIC's presence:
    - Lattice QCD thermodynamics leadership in the U.S.
    - Medical radioisotope production at BNL's BLIP facility (uses the RHIC linac pre-injector) would likely have to be terminated if forced to pay full operations costs.

    - NASA Space Radiation studies at BNL (uses RHIC's Booster) would likely have to be terminated if forced to pay full operations costs.
    - Application offshoots in accelerator physics, especially in next-generation hadron radiotherapy machine design.
- Probably a sizable chunk of DOE Nuclear Physics funding, as it will likely be siphoned off to other agencies or program offices.

The most sensible approach to a several-year budget crisis is to find creative ways to exploit the resources that have been built up by past investments, as long as they are still operating at full efficiency. Conversely, continuing health of the U.S. Nuclear Physics program would be gravely endangered by a strategy to terminate operations at its most productive facility based on the naïve assumption that the associated operations funds can be freely redirected as the community wishes. RHIC and the BNL staff who operate it are too important a resource for the U.S. Nuclear Physics community and the DOE Office of Science to waste.

Appendix A: History of RHIC Beam Performance

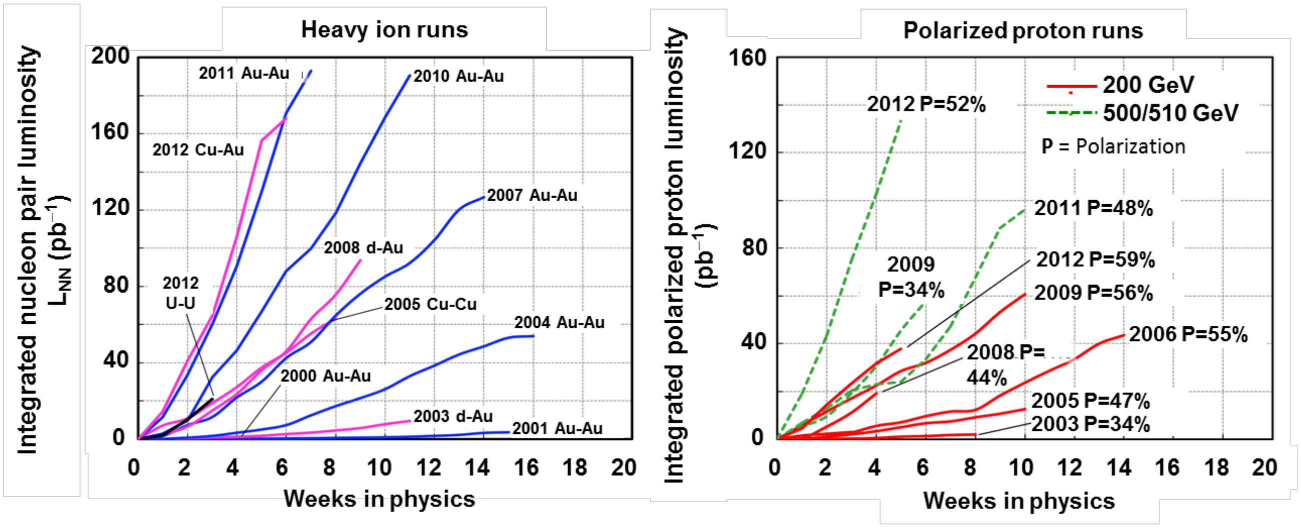


Figure A.1. *Delivered integrated luminosity vs. weeks in physics production over the years at RHIC for heavy-ion runs (left) and polarized proton runs (right). pp-equivalent luminosities are plotted to facilitate comparison for different species. The average beam polarizations measured online are also indicated in the right frame (usually, the beam polarization within collision constraints imposed by the STAR and PHENIX detectors is several percent higher). The steadily increasing slopes reflect incremental improvements over the years, including the installation of bunched beam stochastic cooling systems between 2007 and 2012. The installation of EBIS in 2012 facilitated first U-U collisions and first collisions of asymmetric (Cu-Au) heavy ion species.*

Table A.1. *Colliding beam species and energies run to date at RHIC, or contemplated for near-future running. The variety of configurations and energies illustrates RHIC's versatility.*

Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 31, 65, 100	195×10^{30} cm^{-2}s^{-1}
d+Au[a)]	100	100×10^{30} cm^{-2}s^{-1}
Cu+Cu	11, 31, 100	80×10^{30} cm^{-2}s^{-1}
p↑+p↑ (polarized)	11, 31, 100, 205, 250, 255	165×10^{30} cm^{-2}s^{-1} at 255 GeV
Cu+Au[a)]	100	230×10^{30} cm^{-2}s^{-1}
U+U	96	60×10^{30} cm^{-2}s^{-1}
Considered for future		
Au+Au	2.5, 7.5	
p+Au	100	
p↑+ ^{3}He↑ [a)]	166	

a) *Asymmetric rigidity configurations.*

b) *For comparison, we list best luminosity performance to date at other colliders, scaled ($L \propto \gamma$) to RHIC energies (255 GeV p, 100 GeV/A heavy ions): Tevatron $\bar{p}-p$ (110×10^{30} cm^{-2}s^{-1}); LHC unpolarized p-p (430×10^{30} cm^{-2}s^{-1} with 50 ns bunch spacing vs. RHIC's 107 ns); LHC Pb-Pb (1.6×10^{30} cm^{-2}s^{-1}).*

Appendix B: Publications, Citations, Ph.D.'s

Table B.1. *Some publication statistics for the four RHIC experiment collaborations, through July 8, 2012. Conference proceedings are not included in the refereed paper or citation figures. The White Papers refer to the detailed summary evaluations of the first three years' RHIC data that each collaboration published in Nucl. Phys.* ***A757*** *(2005). These four papers are among the 8 most cited nuclear physics papers written on any subject since 2001, when RHIC publications began (the other four report neutrino physics results from SNO and KamLAND).*

Collaboration	Total # Refereed Papers	Total # Citations for Refereed Papers	# PRL's	# Citations for 2005 White Paper	Position of 2005 White Paper Among Most Cited NP Papers 2001-12	# Papers with >250 Citations
PHENIX	126	13,292	57	1358	5	12
STAR	160	14,434	54	1382	4	15
PHOBOS[a)]	39	4057	15	1049	7	1
BRAHMS[b)]	22	2649	10	1040	8	3
Total =	**347**	**34,432**	**136**	**4829**		**31**

a) *PHOBOS was a small dedicated experiment that completed its mission in 2005.*

b) *BRAHMS was a small dedicated experiment that completed its mission in 2006.*

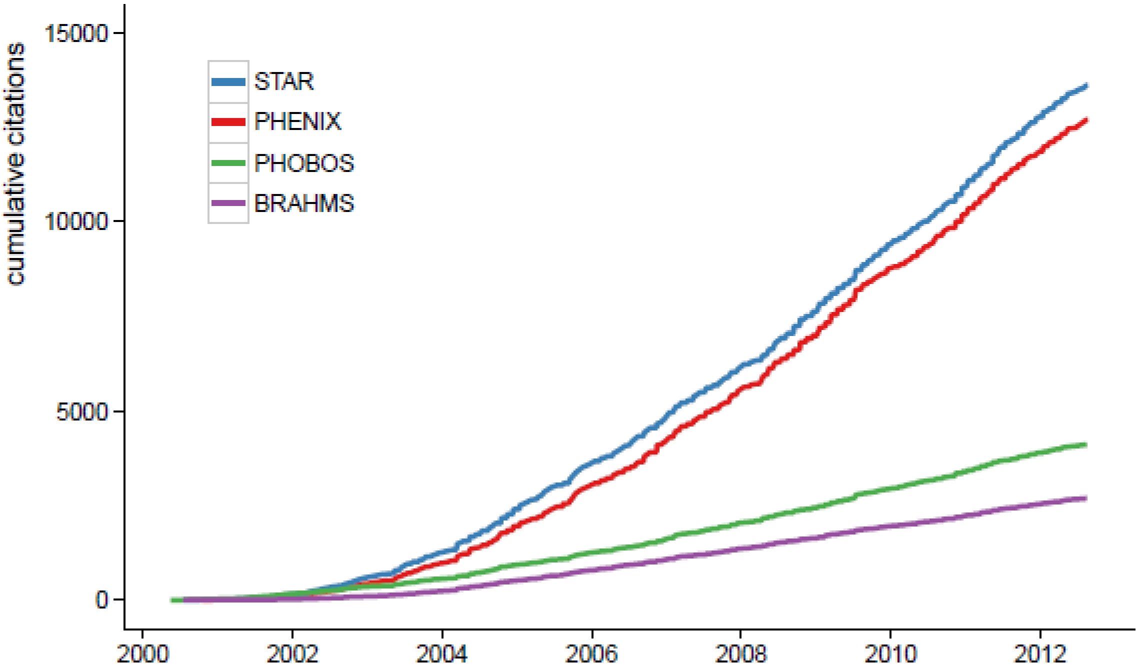


Figure B.1. *Number of citations vs. year to refereed papers (excluding instrumentation articles, which are included in Table B.1) written by the four RHIC experiment collaborations (from SPIRES database). The recent slopes of the STAR and PHENIX curves illustrate the absence of any falloff in interest in the RHIC experimental results.*

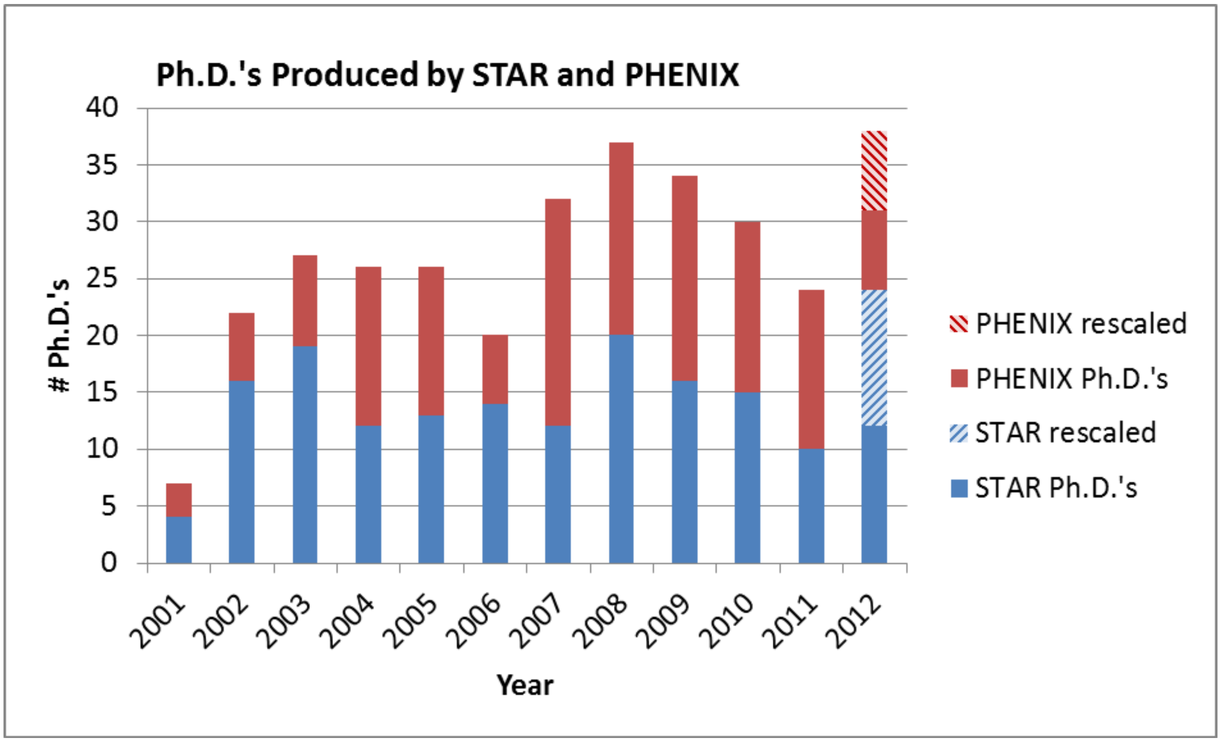


Figure B.2. *The number of Ph.D.'s produced per year by the two large RHIC collaborations. Note that the 2012 solid bars include only Ph.D.'s awarded during the first half of the calendar year; the cross-hatched bars extrapolate those numbers to a full year for comparison to earlier years. The continuing attractiveness of the field to young scientists is also manifested by the hundreds of students and post-docs who attend each Quark Matter conference, including the most recent one in August 2012.*

Appendix C: RHIC Publications and Coverage in Broad Science Journals

1) RHIC-related scholarly publications and features in broad-audience journals:

The Exploration of Hot QCD Matter, B.V. Jacak and B. Müller, invited review article, *Science* (July 2012)

Collaborative Physics: String Theory Finds a Bench Mate, Z. Merali, *Nature* **478,** 302 (October 2011)

The Limits of Ordinary Matter, B. Müller, *Science* **332,** 1513 (June 2011)

Observation of the Antimatter Helium-4 Nucleus, STAR Collaboration, *Nature* **473,** 353 (May 2011)

Creating the Perfect Liquid in Heavy Ion Collisions, B. Jacak and P. Steinberg, *Physics Today* **63,** 5, 39 (May 2010) – cover story

What Black Holes Teach About Strongly Coupled Particles, C.V. Johnson and P. Steinberg, *Physics Today* **63,** 5, 29 (May 2010) – cover story

The Nearly Perfect Fermi Gas, J.E. Thomas, *Physics Today* **63,** 5, 34 (May 2010) – cover story

Observation of an Antimatter Hypernucleus, STAR Collaboration, *Science* **328,** 58 (April 2010)

Of Gluons, Atoms and Strings, B. Jacak, *Physics World* (September 2009)

The Strong-Correlations Puzzle, J. Quintanilla and C. Hooley, *Physics World* **22,** 32 (June 2009)

Phase Diagram of Strongly Interacting Matter, P. Braun-Munzinger and J. Wambach, *Rev. Mod. Phys.* **81,** 1031 (2009)

Theoretical Physics: A Black Hole Full of Answers, J. Zaanen, *Nature* **448,** 1000 (August 2007)

The Quest for the Quark-Gluon Plasma, P. Braun-Munzinger and J. Stachel, *Nature* **448,** 302 (July 2007)

The Big Bang Machine, T. Folger, *Discover* cover story (February 2007)

The Order of the Quantum Chromodynamics Transition Predicted by the Standard Model of Particle Physics, Y. Aoki, G. Endrödi, Z. Fodor, S.D. Katz and K.K. Szabó, *Nature* **443,** 675 (October 2006)

Particle Physics: Did the Big Bang Boil?, F. Wilczek, *Nature* **443,** 637 (October 2006)

The First Few Microseconds, M. Riordan and W.A. Zajc, *Scientific American* **294,** 34 (April 2006) – cover story

High-Energy Physics: An Emptier Emptiness?, F. Wilczek, *Nature* **435,** 152 (May 2005)

Shattered Glass, D. Appell, *Scientific American* (April 2004)

What Have We Learned from the Relativistic Heavy Ion Collider?, T. Ludlam and L. McLerran, *Physics Today* **56,** 48 (October 2003) – cover story

The Glue That Holds the World Together, R. Kunzig, *Discover* (July 2000)

Review of Speculative "Disaster Scenarios" at RHIC, W. Busza, R. Jaffe, J. Sandweiss and F. Wilczek, *Reviews of Modern Physics* **72,** 1125 (2000)

Nuclear Physics: Taking Serious Risks Seriously, S.L. Glashow and R. Wilson, *Nature* **402**, 596 (December 1999)

2) Scientific News Coverage:

From first collisions in 2000 to results presented at the March 2012 American Physical Society (APS) meeting and the recent Guinness World Record, RHIC has generated headlines in more than 1,000 stories in major news outlets throughout the world.

RHIC made national news in January 2004, when results presented at the Quark Matter conference led to three stories in *The New York Times*, as well as coverage in many other major media outlets. This was just a prelude to the announcement during the April 2005 APS meeting of discovery of a "perfect liquid." The world learned of this news in hundreds of stories, including coverage in *The New York Times* (3 stories), *Wall Street Journal*, *Washington Post*, *USA Today*, *Science*, *Nature*, *BBC News*, CNN, MSNBC, *ABC News*, Associated Press, Reuters – and a cover story in *Scientific American* – reaching more than 700 million readers, viewers and listeners worldwide.

Partnering again with APS for the February 2010 announcement of finding high temperature "quark soup" that contains symmetry-violating "bubbles," Brookhaven Lab again saw global media attention to RHIC in more than 500 stories published in 40 countries. In addition to coverage in top-tier media that included *The New York Times*, *USA Today*, *Newsweek*, Reuters, *ABC News* and *Fox News*, the RHIC discoveries were disseminated widely through social and online media – including tens of thousands of blog posts, 800 "re-tweets" of BNL's Twitter feed, and nearly 80,000 page views of RHIC animation on the Lab's YouTube channel.

RHIC coverage continues to have a broad reach, with coverage by MSNBC, *CBS News* and *Los Angeles Times* (among many others) of the June 2012 awarding of a Guinness World Record to Brookhaven Lab for achieving the "Highest Man-Made Temperature" at RHIC.

3) Selection among top science research results:

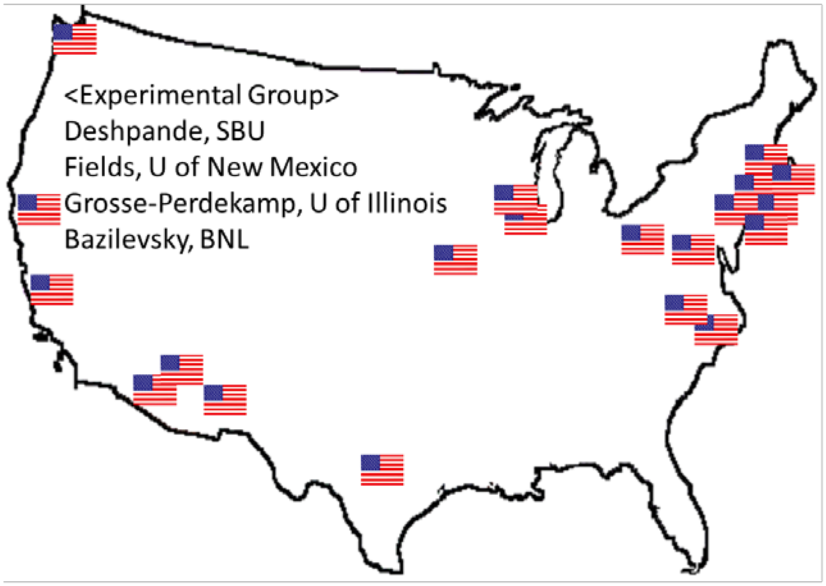
RHIC results have appeared four times since 2001 among the annual AIP compilation of the Top Ten Physics News Stories of the Year:

- **2004:** Evidence for Color Glass Condensate in d+Au collisions at RHIC
- **2005:** Evidence for "perfect liquid" matter in RHIC heavy-ion collisions
- **2010:** Initial temperatures > 4 × 10^{12}K measured for QGP at RHIC; hints of "symmetry-violating bubbles" in RHIC results
- **2011:** Discovery of antihelium-4 among RHIC collision debris – the heaviest antimatter found to date

In *Discover Magazine's* annual compilation of the top 100 science stories of the year, RHIC-related stories have three times been selected among the top 3 physics stories:

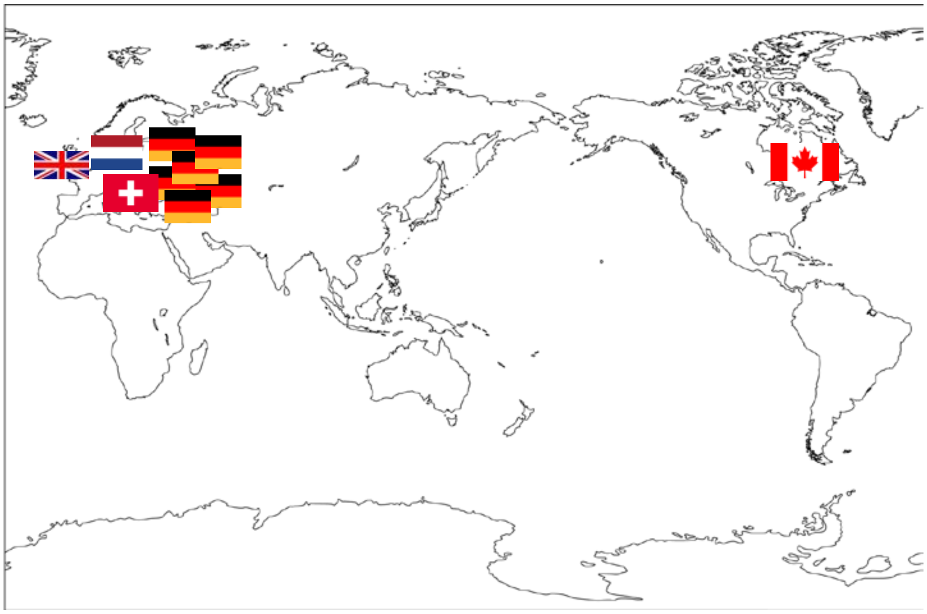
- **2001:** RHIC startup, without black hole formation or worldwide destruction
- **2005:** RHIC results indicating "perfect liquid" formation
- **2011:** Discovery of antihelium-4

Appendix D: Tenured Faculty and Research Positions Filled by RBRC (RIKEN-BNL Research Center) Fellows



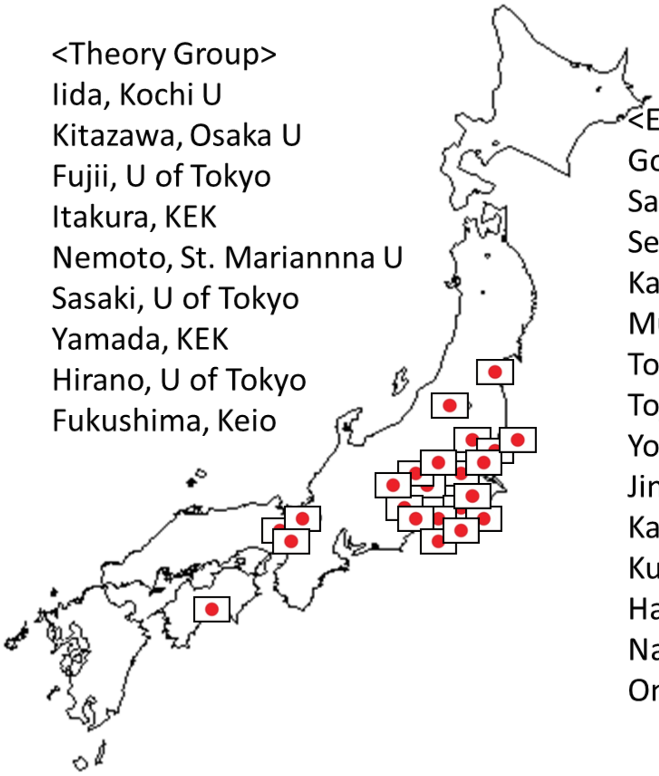
<Experimental Group>
Deshpande, SBU
Fields, U of New Mexico
Grosse-Perdekamp, U of Illinois
Bazilevsky, BNL

<Theory Group>
Bass, Duke U
Blum, U of Connecticut
Kharzeev, BNL
Son, U of Washington
Schaefer, NCSU
Stephanov, U of Illinois
Van Kolck, U of Arizona
Venugopalan, BNL
Tuchin, Iowa S U
Kusenko, UCLA
Fries, Texas A&M
Molnar, Purdue
Lunardini, Arizona State
Petreczky, BNL
Orginos, William & Mary
Yuan, Berkeley



<Experimental Group>
Heuser, GSI

<Theory Group>
Bodeker, Bielefeld U
Jeon, McGill U
Rischke, FIAS
Vogelsang, Tubingen U
Wettig, U of Regensburg
Boer, U of Groningen
Schaffner-Bielich, Heidelberg U
Wingate, Cambridge U
Wiedemann, CERN



<Theory Group>
Iida, Kochi U
Kitazawa, Osaka U
Fujii, U of Tokyo
Itakura, KEK
Nemoto, St. Mariannna U
Sasaki, U of Tokyo
Yamada, KEK
Hirano, U of Tokyo
Fukushima, Keio

<Experimental Group>
Goto, RIKEN
Saito, KEK
Seidl, RIKEN
Kawabata, Kyoto U
Murata, Rikkyo U
Togawa, Osaka U
Tojo, KEK
Yokkaichi, RIKEN
Jinnouchi, Titech
Kaneta, Tohoku U
Kurita, Rikkyo U
Hayashi, JAEA
Nakano, Titech
Onishi, RIKEN

Appendix E: Other Tenured or Tenure-Track Faculty and Research Positions Filled by RHIC Scientists Since 1997

Experimental faculty positions, US Institutes:
Abilene Christian – Rusty Towell, Michael Daugherity
Austin - Christina Markert
Baruch College- Stefan Bathe
BNL – Mickey Chiu, James Dunlop, Rachid Nouicer, Robert Pak, Takao Sakaguchi, Ann Sickles, Paul Sorensen, Peter Steinberg, Thomas Ullrich, Zhangbu Xu
Cal. Poly - Jennifer Klay
Colorado - James Nagle
UC Davis - Manuel Calderon de la Barca Sanchez
Georgia State - Murad Sarsour
Houston - Rene Bellwied; Anthony Timmins
Iowa State - John Lajoie, Craig Ogilvie, Marzia Rosati
Kansas - Michael Murray
Kentucky - Renee Fatemi
LANL - Gerd Kunde
LBNL - Xin Dong, Constantin Loizides, Matteusz Ploskon, Ernst Sichtermann
LLNL – Ron Soltz
MIT -Yen-Jie Lee
U. Michigan - Christine Aidala
Ohio Univ. - Justin Frantz
ORNL - David Silvermyr
Purdue - Fuqiang Wang, Wei Xie
Rice - Frank Geurts, Wei Li
Rutgers - Sevil Salur
Stony Brook - Abhay Deshpande, Jiangyong Jia, Joanna Kiryluk (hired from Spin now doing IceCube)
TAMU - Saskia Mioduszewski
Temple - Bernd Surrow
Tennessee - Christine Nattrass
UC Riverside - Ken Barish
UIC - Olga Evdokimov, Zhenyu Ye
USNA - Richard Witt
Vanderbilt - Julia Velkovska
Washington - Michael Miller (was hired into a Spin research Prof position but has since resigned and gone into industry)
Wayne State - Joern Putschke, Sergei Voloshin
Yale - Helen Caines

Experimental faculty positions, Brazilian Institutes:
UNICAMP - Jun Takahashi
Sao Paulo - Marcello Munhoz
Sao Paulo- Alexandre Suaide

Experimental faculty positions, Chinese Institutes:
CCNU - Jinghua Fu, Zhiming Li, Shusu Shi, Xiangming Sun
SINAP - Jinhui Chen, Wei Li, Guoliang Ma, Song Zhang, Chen Zhong
Sangdong - Jian Deng, Qinghua Xu
Tsinghua University - Xianglei Zhu, Yi Wang, Zigang Xiao
USTC - Ming Shao, Zebo Tang, Yifei Zhang

Experimental faculty positions, European Institutes:
CNRS Strasbourg - Boris Hippolyte
CNRS Saclay - Javier Castillo
CNRS Orsay - Christophe Suire
CNRS Nantes - Magalie Estiene, Sonia Kabana, Alexander Shabetai
CNRS Grenoble - Julien Faivre
CNRS Ecole Polytechnique - Matthew Nguyen (European Fellowship)
CNRS - Paris Sud - Mercedes Lopez-Noriega
Frankfurt Germany - Henner Buesching (PHd on data from PHENIX and WA98)
Warsaw U. Technology Poland - Adam Kisiel, Hanna Zbroszczyk
Weizmann Institue - Alexander Milov

Experimental faculty positions, Indian Institutes:
IIT Bombay - Sadhana Dash, Basanta K Nandi
NISER Bhubaneswar - Bedanga Mohanty
IIT Indore - Raghunath Sahoo
BARC Mumbai - Dipak K Mishra

Experimental faculty positions, Korean Institutes:
Pusan - Chang-Hwan Lee, In-Kwon Yoo

Theoretical faculty positions, U.S. Institutes (other than RBRC fellows):
Baruch – Adrian Dumitru, Jamal Jalilian-Marian
Colorado – Paul Romatschke
Gettysburg – Mike Strickland (now moving to Kent State)
Illinois, Chicago – Ho-Ung Yee
Indiana – Jinfeng Liao
LANL – Ivan Vitev
MIT – Krishna Rajagopal
Ohio State – Yuri Kovchegov
Pratt Institute – Agnes Mocsy
Stony Brook – Derek Teaney
Texas A&M – Ralf Rapp
Virginia – Peter Arnold
Wayne State – Sean Gavin, Abhijit Majumder

Theoretical faculty positions, European Institutes (other than RBRC fellows):
Belgrade - Magdalena Djordjevic
Bern – Mikko Laine
Bielefeld – York Schroeder
Darmstadt – Juergen Berges
Eotvos – Zoltan Fodor
Florence – Francesco Becattini
Frankfurt – Marcus Bleicher, Carsten Greiner
Jyvaskala – Kari Eskola
Mainz – Harvey Meyer
Matej Bel – Boris Tomasik
Saclay – Francois Gelis, Edmond Iancu
Santiago de Compostela – Nestor Armesto, Carlos Salgado
Torino – Claudia Ratti

Theoretical faculty positions, Japanese Institutes (other than RBRC fellows):
Kyoto - Masayuki Asakawa
Nagoya – Chiho Nonaka
Tsukuba – Yoshitaka Hatta

Theoretical faculty positions, Other Institutes Worldwide (other than RBRC fellows):
Capetown – Will Horowitz, Andre Peshier, Heribert Weigert, Spencer Wheaton
Johannesburg - Azwinndini Muronga
McGill – Guy Moore
Sao Paolo - Jorge Noronha