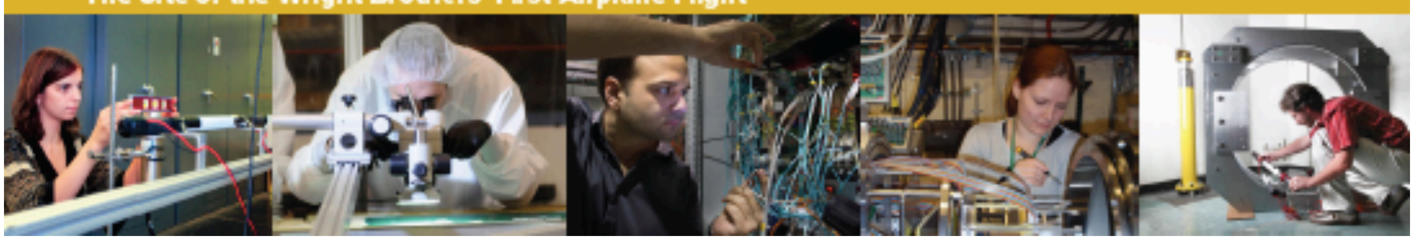
REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

LRP Schedule

- ✓ Charge delivered at 24 April 2014 NSAC Meeting
- ✓ LRP Working Group formed in early June ~ 60 members
  - Observers for nuclear physics associations in Europe and Asia
- ✓ Community organization summer 2014
- ✓ DNP town meetings in the July/September 2014
- ✓ Joint APS-DNP-JPS Meeting Oct 7-11, 2014
- ✓ Working Group organizational meeting Nov 16, 2014
- ✓ White papers submitted by end of January
- ✓ Cost review of EIC – Report at April 3 NSAC meeting
- ✓ Most of text of report assembled by April 10
- ✓ Resolution meeting of Long Range Plan working group April 16-20, 2015 in Kitty Hawk, NC
- ✓ Second draft of full report by May 18
- ✓ Draft report reviewed by external wise women and men
  - Balantekin, Jacak, Redwine, Seestrom, Symons, Tribble,
- ✓ LRP final report due October 2015 – NSAC Meeting and Public Presentation

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

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*
- *Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.*
- *The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

Realizing world-leading nuclear science also requires robust support of experimental and theoretical research at universities and national laboratories and operating our two low-energy national user facilities —ATLAS and NSCL— each with their unique capabilities and scientific instrumentation.

The ordering of these four bullets follows the priority ordering of the 2007 plan.

the magnitude of the EMC effect in that same nucleus, illustrated by the straight line in Figure 2.8. This result seems to indicate that both of these effects may depend on local nuclear density or, perhaps, that nucleons in correlated high-momentum pairs have the most strongly modified quark distributions. At JLab 12-GeV, high-precision experiments will be performed to further study both of these effects in a wide variety of nuclei. Furthermore, by "tagging" some of the participants in short-range collisions, it will be possible to directly explore the connection between those two phenomena. With these data and concurrent theoretical development, we are poised to greatly improve our understanding of the interplay between nuclear binding and QCD.

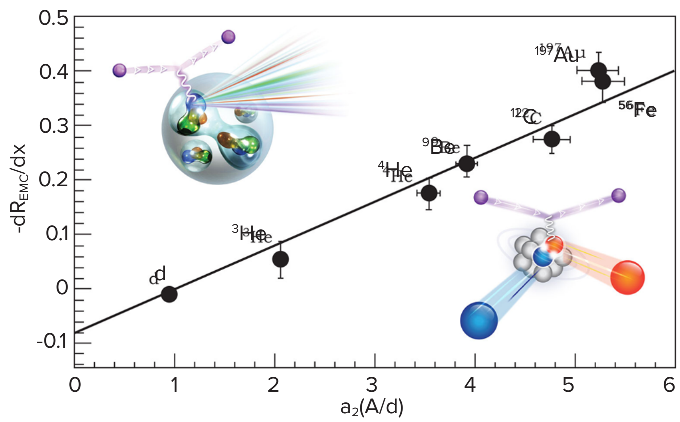


Figure 2.8: This plot illustrates, for a sample of eight nuclei, the apparent linear relationship between a parameter that characterizes the number of two-nucleon correlated pairs, $a_2(A/d)$, and the strength (i.e., the slope) of the EMC effect. A clear correlation is evidenced by the straight line that all eight nuclei fall on.

2.2 QCD and the Phases of Strongly Interacting Matter

Nuclear collisions at the RHIC and the LHC produce matter with temperatures in the trillions of degrees. In this way, scientists are recreating the matter that filled the microseconds-old universe for the purpose of characterizing its properties and understanding how it works. It was understood in the 1970s that ordinary protons and neutrons could not exist at temperatures above two trillion degrees Celsius. The predicted new form of matter, which can be recreated by heating protons and neutrons until they "melt," was named quark-gluon plasma (QGP). RHIC was built for the purpose of recreating QGP and has been doing so since 2000; the LHC was built to look for the Higgs boson and possible physics beyond the Standard Model and, at the same time, has provided the highest temperature QGP starting in 2010. Through measurements made at RHIC and the LHC and critical advances in theory, we now have a good idea of what QGP is and how it behaves.

A huge surprise at RHIC was the discovery that QGP is a liquid, a result then confirmed at the LHC. And not just any liquid: it flows with the lowest specific viscosity (characterized in terms of the ratio of shear viscosity to entropy density η/s) of any liquid known, for example, more than ten times smaller than that of water. Over the past five years nuclear physicists have begun to quantify just how perfect the QGP liquid is by virtue of enormous progress on two primary fronts.

The tools available to produce and characterize the liquid have been dramatically enhanced. The energy range over which QGP can be studied has been extended upward by a factor of 14 with the launch of the LHC and downward by a factor of 25 with the operation of RHIC below its maximum energy. The rate of collisions at both facilities has been improved by an order of magnitude, at RHIC via an accelerator upgrade that was accomplished at 1/7th the cost anticipated at the time of the last Long Range Plan. The precision and versatility of the detector capabilities have been correspondingly upgraded.

The comparison of more extensive and sophisticated data with more advanced theory has facilitated quantitative characterization of QGP properties. The theoretical treatment of relativistic fluids, including viscosity and ripples in the initial matter density, has been developed and has successfully described the features seen in large and diverse data sets. Such comparisons have not only constrained the magnitude of η/s but are also beginning to teach us about its temperature dependence and about the nature of the ripples in the matter density originating from the colliding nuclei. Similar advances are now being made in understanding how energetic quark and gluon "probes" propagate through QGP and how the liquid responds to their passage.

As a result of these recent advances, we now know that the η/s of QGP is very close to a fundamental quantum limiting value deduced for the extreme hypothetical case when the quarks and gluons have infinitely strong interactions—an extreme that can, remarkably, be theoretically related to the physics of gravitons falling into a black hole. While QCD does, of course, describe quark and gluon interactions, the emergent phenomenon that a macroscopic volume of quarks and gluons at extreme temperatures would form a nearly perfect liquid came as a complete surprise and has led to an intriguing puzzle. A perfect liquid would not be expected to have particle excitations, yet QCD is definitive in predicting that a microscope with sufficiently high resolution would reveal quarks and gluons interacting *weakly* at the shortest distance scales within QGP. Nevertheless, the η/s of QGP is so small that there is no sign in its macroscopic motion of any microscopic particlelike constituents; all we can see is a liquid. To this day, nobody understands this dichotomy: how do quarks and gluons conspire to form strongly coupled, nearly perfect liquid QGP?

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

This section is organized in three parts: characterization of liquid QGP, mapping the phase diagram of QCD by doping QGP with an excess of quarks over antiquarks, and high-resolution microscopy of QGP to see how quarks and gluons conspire to make a liquid.

EMERGENCE OF NEAR-PERFECT FLUIDITY

The emergent hydrodynamic properties of QGP are not apparent from the underlying QCD theory and were, therefore, largely unanticipated before RHIC. They have been quantified with increasing precision via experiments at both RHIC and the LHC over the last several years. New theoretical tools, including LQCD calculations of the equation-of-state, fully relativistic viscous hydrodynamics, initial quantum fluctuation models, and model calculations done at strong coupling in gauge theories with a dual gravitational description, have allowed us to characterize the degree of fluidity. In the temperature regime created at RHIC, QGP is the most liquidlike liquid known, and comparative analyses of the wealth of bulk observables being measured hint that the hotter QGP created at the LHC has a somewhat larger viscosity. This temperature dependence will be more tightly constrained by upcoming measurements at RHIC and the LHC that will characterize the varying shapes of the sprays of debris produced in different collisions. Analyses to extract this information are analogous to techniques used to learn about the evolution of the universe from tiny fluctuations in the temperature of the cosmic microwave background associated with ripples in the matter density created a short time after the Big Bang (see Sidebar 2.3).

There are still key questions, just as in our universe, about how the rippling liquid is formed initially in a heavy-ion collision. In the short term, this will be addressed using well-understood modeling to run the clock backwards from the debris of the collisions observed in the detectors. Measurements of the gluon distribution and correlations in nuclei at a future EIC together with calculations being developed that relate these quantities to the initial ripples in the QGP will provide a complementary perspective. The key open question here is understanding how a hydrodynamic liquid can form from the matter present at the earliest moments in a nuclear collision as quickly as it does, within a few trillionths of a trillionth of a second.

Geometry and Small Droplets

Connected to the latter question is the question of how large a droplet of matter has to be in order for it to behave like a macroscopic liquid. What is the smallest possible droplet of QGP? Until recently, it was thought that protons or small projectiles impacting large nuclei would not deposit enough energy over a large enough volume to create a droplet of QGP. New measurements, however, have brought surprises about the onset of QGP liquid production.

Measurements in LHC proton-proton collisions, selecting the 0.001% of events that produce the highest particle multiplicity, reveal patterns reminiscent of QGP fluid flow patterns. Data from p+Pb collisions at the LHC give much stronger indications that single small droplets may be formed. The flexibility of RHIC, recently augmented by the EBIS source (a combined NASA and nuclear physics project), is allowing data to be taken for p+Au, d+Au, and ^{3}He+Au collisions, in which energy is deposited initially in one or two or three spots. As these individual droplets expand hydrodynamically, they connect and form interesting QGP geometries as shown in Figure 2.9. If, in fact, tiny liquid droplets are being formed and their geometry can be manipulated, they will provide a new window into the earliest pre-hydrodynamic physics. Alternative explanations of the data from these experiments will also be tested.

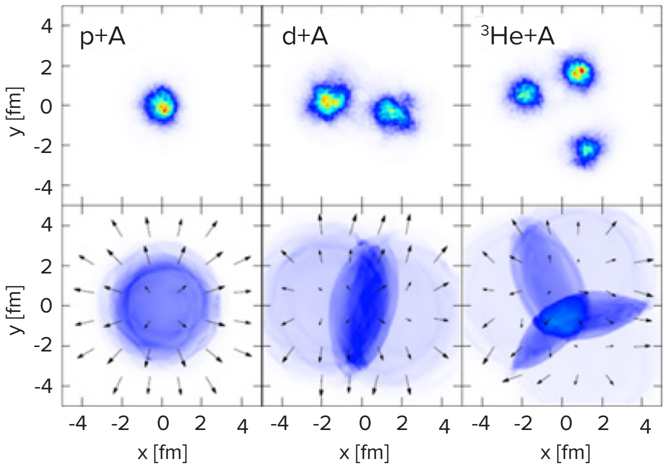


Figure 2.9: *Simulated initial energy deposition for individual collisions of protons, deuterons, and helium-3 on large nuclei (above) and the QGP geometry resulting from hydrodynamic flow (below).*

Geometry Engineering

Varying the geometry of the initial conditions—either by colliding ions of different shapes, including Cu+Au and U+U at RHIC, or by new methods used to select shape fluctuations—has enabled physicists to test models of the initial nuclear wave function in subtle ways, again complementary to future EIC measurements.

Tracers in the Flowing Liquid

In RHIC and LHC collisions, in addition to producing QGP, one produces pairs of charm–anticharm and bottom–antibottom quarks. These quarks, referred to as heavy quarks, are produced at the first moment of the collision and are only very rarely created or destroyed thereafter. They serve as test buoys in the liquid QGP. Measurements of particles containing charm quarks indicate that heavy quarks with moderate energy do, in fact, get swept up in the flowing and expanding QGP droplet. Evidence supporting this conclusion includes charm mesons having highly modified momentum distributions and having a similar elliptic flow pattern as light-quark hadrons. RHIC experiments have recently installed new cutting-edge silicon detectors that enable precision measurements of particles containing heavy quarks. In addition, key detector upgrades at LHC with strong U.S. involvement will enable higher statistics measurements in the lower momentum region where flow effects are the largest. As a result, the uncertainties in these unique measurements will soon be reduced significantly. Measuring the flow patterns of charm and the much heavier bottom quarks separately provides important new information due to the large mass difference between them.

From Characterization to Understanding

The field has made substantial strides in the experimental characterization of liquid QGP, and new measurements and new discoveries are anticipated in the coming few years. Pursuing these directions will yield quantitative characterization of the properties of liquid QGP and of how it ripples and flows.

Advancing from characterization to understanding requires progress on two fronts. To put the properties of QGP in their natural context, we need to map the phase diagram of QGP by doping it with an excess of quarks over antiquarks and observing any changes. And to understand how quarks and gluons that interact only weakly when they are close to each other correlate in such a way that they conspire to form a nearly perfect liquid, we must probe liquid QGP at varying length scales. We need to do high resolution microscopy on QGP.

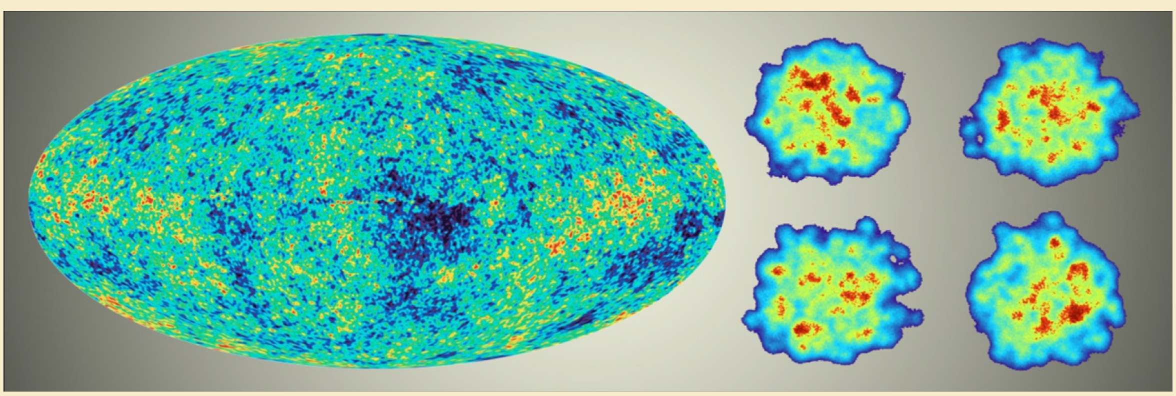
DOPING QGP WITH QUARKS TO MAP ITS PHASE DIAGRAM

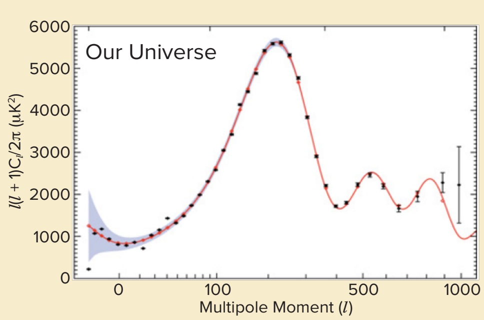
In the highest energy RHIC and LHC collisions and in the early universe, liquid QGP contains almost as many antiquarks as quarks. In the language of condensed matter physics, this is undoped QGP. It would be impossible to understand strongly correlated electron systems in condensed matter physics if all we knew were their properties in the absence of doping, with equal numbers of electrons and holes. Here too, if our goal is understanding, we must map the phase diagram of QCD as a function of both temperature and doping, in this case doping QGP with an excess of quarks over antiquarks.

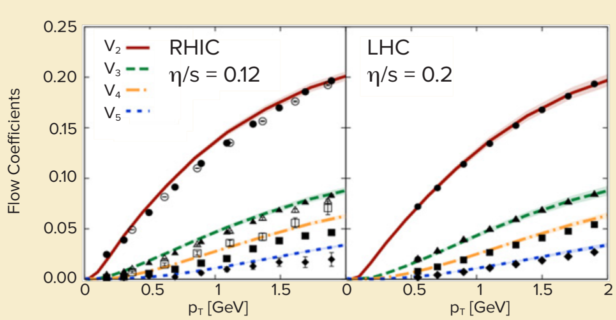
Rigorous theory calculations using lattice QCD tell us that the transition in which undoped QGP cools and forms hadrons is a rapid but smooth crossover. In contrast, QGP that is doped may experience instead a sharp first order phase transition as it cools, with bubbles of QGP and bubbles of hadrons coexisting at a critical temperature, much as bubbles of steam and water coexist in a boiling pot. At very large values of the

Sidebar 2.3: Fluctuations in the Big and Little Bangs

Fluctuations from after the Big Bang around the time atoms were first forming are preserved in time until the image at the top left is taken. Cosmologists' quantitative analysis of precise measurements (bottom-left graph) made from this image of the one Big Bang tell us key properties of the universe, for example, how much dark matter it contains. In heavy-ion collisions, nuclear physicists produce billions of "little bangs" and study their average properties and how they vary as an ensemble. These experiments, which reproduce tiny droplets of Big Bang matter for laboratory analysis, answer questions about the material properties of this liquid that cannot be accessed by astronomical measurements. The top-right images are theoretical calculations of ripples in the matter density expected in the earliest moments of four of the billion little bangs. One of the signatures of the extraordinary liquidity of QGP comes in the form of fluctuations in the patterns of particles emerging from RHIC and LHC collisions, fluctuations traced to the survival of the matter density ripples with which the QGP is born. The bottom-right figure shows a suite of precise measurements that describes the shape (elliptical, triangular, quadrangular, pentagular) of the exploding debris produced in the little bangs, together with a quantitative theoretical analysis that describes these data and tells us key properties of QGP, for example its specific viscosity η/s. All the curves in each panel come from one theoretical calculation, with initial ripples and η/s specified. Ripples, as in the top-right figure, originate from gluon fluctuations in the incident nuclei; if QGP had a specific viscosity as large as that of water, though, these ripples would dissipate so rapidly as to disappear before they could be measured. The fact that they survive and can be seen and characterized in the shapes of the debris from the collisions, as at the bottom right, tells us about the origin of the ripples and the smallness of η/s in QGP. These data and theoretical calculations in concert show that the QGP produced at both RHIC and the LHC is a much more nearly perfect liquid than water and hint that it becomes somewhat less liquid (has a somewhat larger η/s) at the higher temperatures reached by the LHC. An increase in η/s in going from RHIC energies (and temperatures) to those of the LHC is expected: the defining characteristic of the strong interaction is that quarks and gluons interact less strongly at higher energies and temperatures, meaning that hotter QGP is expected to become a less perfect liquid.







doping, and at lower temperatures, quarks pair up with each other, forming a color superconductor. The point where the doping becomes large enough to instigate a sharp transition is referred to as the QCD critical point. It is not yet reliably known whether QCD has a critical point, nor where on its phase diagram it may reside. Lattice calculations for doped QGP are progressing but remain an outstanding challenge.

The phase diagram of QCD is illustrated in Sidebar 2.4. Nuclear scientists have the outstanding opportunity of both mapping it experimentally and relating it directly and quantitatively to our fundamental description of nature, the Standard Model.

A major effort to use heavy-ion collisions at RHIC to survey the phase diagram of QCD is now underway. Doped QGP is produced by colliding large nuclei at lower energies, where the excess of quarks over antiquarks in the incoming nuclei dominates. If a critical point exists within the experimentally accessible region, an energy scan can find it. The RHIC machine is uniquely suited for this doping scan because of the reach in chemical potential μ_B (a parameter reflecting the degree of doping) that its flexibility makes accessible, along with technical advantages of measuring fluctuation observables at a collider. RHIC is uniquely positioned in the world to discover a critical point in the QCD phase diagram if nature has put this landmark in the experimentally accessible region. RHIC completed the first phase of such an energy scan (Beam Energy Scan I, BES-I) in 2014, producing droplets of QGP with eight values of the doping. The region of the phase diagram being mapped out is shown in Sidebar 2.4 (upper right). In the longer term, the FAIR facility at GSI will extend this search to even higher μ_B if its lower collision energies produce matter at the requisite temperatures.

Data from BES-I provide qualitative evidence for a reduction in the QGP pressure, with consequences for flow patterns and droplet lifetimes that have long been anticipated in collisions that form QGP not far above the crossover region. (See second panel of Figure 2.10.) A key obstacle to drawing quantitative conclusions is that, of necessity to date given the small samples of collisions at each of the lower energies, each measurement averages over collisions with a wide range of impact parameters.

The experimental search for the QCD critical point hinges on the fact that matter near such a point exhibits well understood critical fluctuations, which in terrestrial examples turn a clear liquid opalescent. The collision energy dependence of a fluctuation observable that is particularly sensitive to the critical point is shown in the third panel of Figure 2.10. As the doping increases, the fluctuations near a critical point are predicted to make this observable swing below its baseline value of 1.0 as the critical point is approached, then going well above, with both the dip and the rise being greatest in head-on collisions and in analyses that record as many particles as possible in each event. The new data are tantalizing, with a substantial drop and intriguing hints of a substantial rise for the lowest energy collisions. This may be indicative of the presence of a critical point in the phase diagram of QCD, although the uncertainties at present are too large to draw conclusions.

The present reach of LQCD calculations is illustrated by the yellow band on the phase diagram in Sidebar 2.4. These calculations become more challenging with increased doping, but they do indicate that the critical point is not found in the region of the phase diagram with low doping (μ_B below 200 MeV), corresponding to collisions with energy above 20 GeV. This behavior, together with the intriguing non-monotonic collision energy dependence of various observables seen at lower collision energies, corresponding to higher doping, provides strong motivation for the second phase of the RHIC Beam Energy Scan (BES-II), which will focus on building up much larger samples of collisions with energies at and below 20 GeV.

RHIC accelerator physicists are upgrading the machine to use electrons to “cool” lower energy beams in the machine (keeping the bunches of nuclei in them compact) in order to increase the luminosity at BES-II energies by about a factor of 10. The detector upgrades planned for BES-II focus on maximizing the fraction of the particles in each collision that are measured, which is particularly important for fluctuation observables. The top panel in Figure 2.10 shows the projected increases in the number of events, and the lower panels show the improved statistical precision for flow and fluctuation observables that result from the statistics together with the extended coverage from targeted detector improvements.

The trends and features in BES-I data provide compelling motivation for a strong and concerted theoretical response, as well as for the experimental measurements with higher statistical precision from BES-II. The goal of BES-II is to turn trends and features into definitive conclusions and new understanding. This theoretical research program will require a quantitative framework for modeling the salient features of these lower energy heavy-ion collisions and will require knitting together components from different groups with experience in varied techniques, including LQCD, hydrodynamic modeling of doped QGP, incorporating critical fluctuations in a dynamically evolving medium, and more.

Experimental discovery of a critical point on the QCD phase diagram would be a landmark achievement. The goals of the BES program also focus on obtaining a quantitative understanding of the properties of matter in the crossover region of the phase diagram, where it is neither QGP nor hadrons nor a mixture of the two, as these properties change with doping.

Additional questions that will be addressed in this regime include the quantitative study of the onset of various signatures of the presence of QGP. For example, the chiral symmetry that defines distinct left- and right-handed quarks is broken in hadronic matter but restored in QGP. One way to access the onset of chiral symmetry restoration comes via BES-II measurements of electron-positron pair production in collisions at and below 20 GeV. Another way to access this, while simultaneously seeing quantum properties of QGP that are activated by magnetic fields present early in heavy collisions, may be provided by the slight observed preference for like-sign particles to emerge in the same direction with respect to the magnetic field. Such an effect was predicted to arise in matter where chiral symmetry is restored. Understanding the origin of this effect, for example by confirming indications that it goes away at the lowest BES-I energies, requires the substantially increased statistics of BES-II.

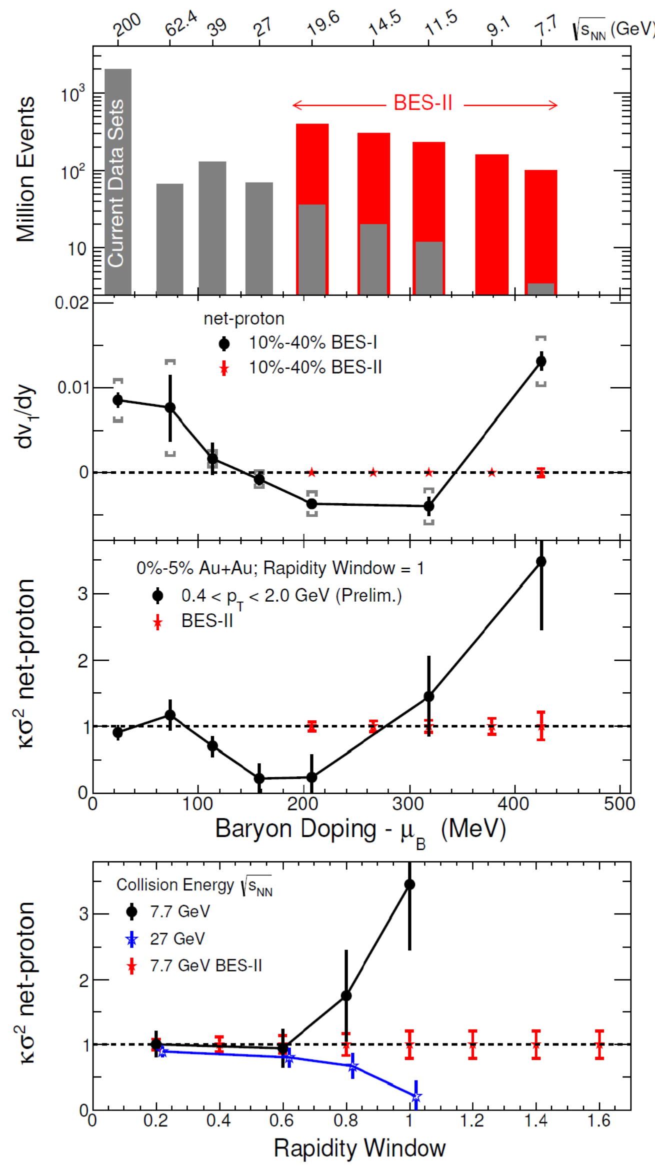


Figure 2.10: *The top panel shows the increased statistics anticipated at BES-II; all three lower panels show the anticipated reduction in the uncertainty of key measurements. RHIC BES-I results indicate nonmonotonic behavior of a number of observables; two are shown in the middle panels. The second panel shows a directed flow observable that can encode information about a reduction in pressure, as occurs near a transition. The third panel shows the fluctuation observable understood to be the most sensitive among those measured to date to the fluctuations near a critical point. The fourth panel shows, as expected, the measured fluctuations growing in magnitude as more particles in each event are added into the analysis.*

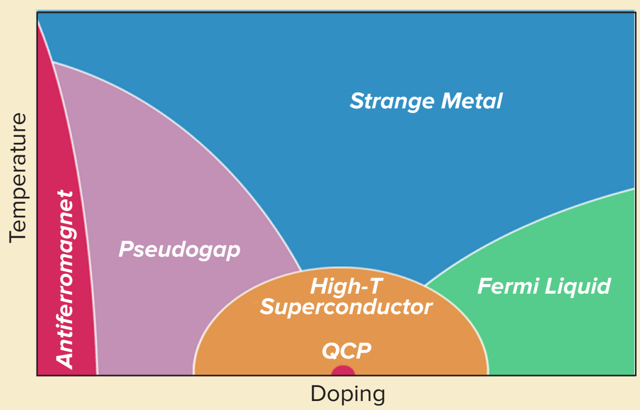
NEW MICROSCOPES ON THE INNER WORKINGS OF QGP

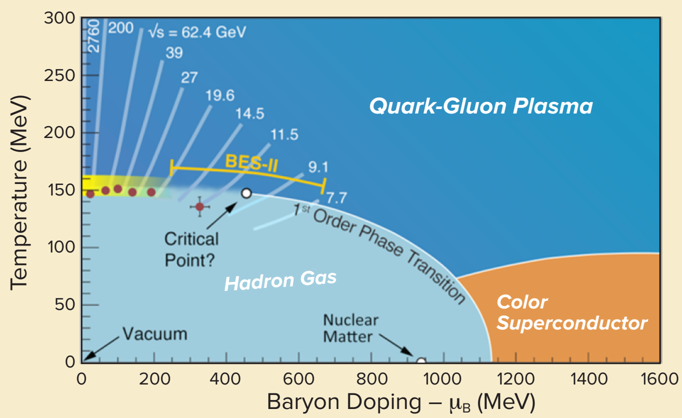
To understand the workings of QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid.

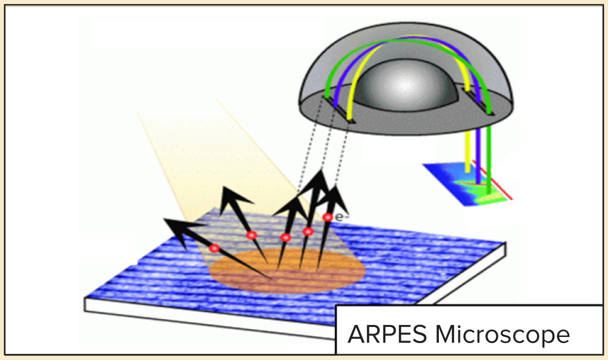
Microscopy requires suitable messengers that reveal what is happening deep within QGP, playing a role analogous to light in an ordinary microscope. The

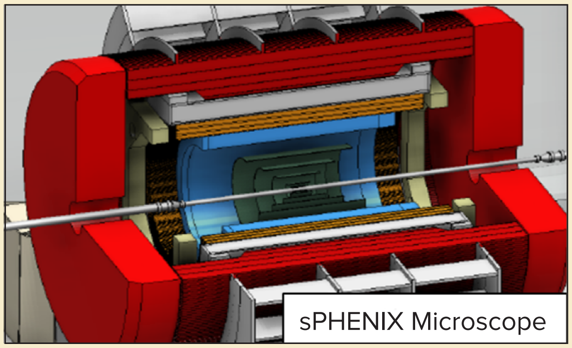
Sidebar 2.4: The States of QCD Matter

The study of states of matter governed by the strong force parallels progress in other fields of matter in which surprising "emergent phenomena," striking macroscopic phenomena in no way apparent in the laws describing the interactions between microscopic constituents, have been discovered. High temperature superconductivity is an emergent phenomenon arising in strongly correlated, electromagnetically interacting matter. The first goals after its discovery included the mapping of its phase diagram, shown at the upper-left, and the characterization of the newly found phases of matter, including the strange metal phase. As with QGP, there is no known way to describe its structure and properties particle by particle; understanding strange metals remains a central challenge. Experimental progress can come by changing the material doping—adding more holes than electrons—and by probing the material at shorter wavelengths—for example, with the angle resolved photo emission spectroscopy (ARPES) technique, shown on the lower left—with the goal of understanding how strong correlations result in the emergence of the surprising macroscopic phenomena. Near perfect fluidity is an equally exciting and unexpected emergent phenomenon, in this case arising in strongly interacting matter in the QGP phase. Doping QGP, adding more quarks than antiquarks, is done via changing the collision energy and enables a search for a possible critical point in the phase diagram shown in the upper right. The reach of the RHIC BES-II program that will be enabled by new instrumentation at RHIC is shown, as are the trajectories on the phase diagram followed by the cooling droplets of QGP produced in collisions with varying energy. The microscopy of QGP is enabled by new "microscopes," such as sPHENIX, shown in the lower right, and upgraded detectors and luminosities in the combined RHIC and LHC program.









messengers we describe here are heavy quark bound states which characterize the nature of QGP on three different length scales, as well as jets, which further characterize the liquid and provide the best path to true microscopy that is presently envisioned.

Characterizing QGP on Three Length Scales at Once

Bound states of a heavy quark and antiquark, referred to as quarkonia, are particularly interesting because if they are small enough in size, which is to say if they are sufficiently tightly bound, they are predicted to survive immersion in QGP. If they are larger, however, the QGP that gets between the quark and antiquark is predicted to make the quarkonia melt away, analogous to the way molecules dissociate in electromagnetic plasmas. Studying the survival probabilities of quarkonia of different sizes characterizes QGP on different length scales. In the case of the J/ψ, the most bound state of a charm and anticharm quark, there is a large suppression of these particles in RHIC collisions as expected. In the higher temperature QGP created in LHC collisions, the suppression is less. This represents very strong evidence that, despite melting at early times, new J/y mesons re-form between new partner charm and anticharm quarks late in the collision.

The newly-won understanding of charm-anticharm quarkonia sets the table for the case of bottom and antibottom quarks that bind to form upsilon particles. Three different upsilon states, with three different sizes, can be measured in heavy-ion collisions using the same techniques. First measurements of these upsilon states at the LHC follow the ordering expected if the QGP produced in LHC collisions is unable to melt the smallest upsilons but can melt the larger ones. Higher statistics measurements to come will enable checks of how these patterns depend upon the momentum of the quarkonia and the collision geometry.

Upsilons have also been detected at RHIC, and their measurement will be improved by new upgrades to the STAR detector in the near future. Ultimately, one will need very precise data, as shown in Figure 2.11, which are enabled by the sPHENIX detector. The comparison with similarly precise data from the LHC will allow us to cleanly detect the temperature dependence of how QGP screens the quark-antiquark force on three different length scales.

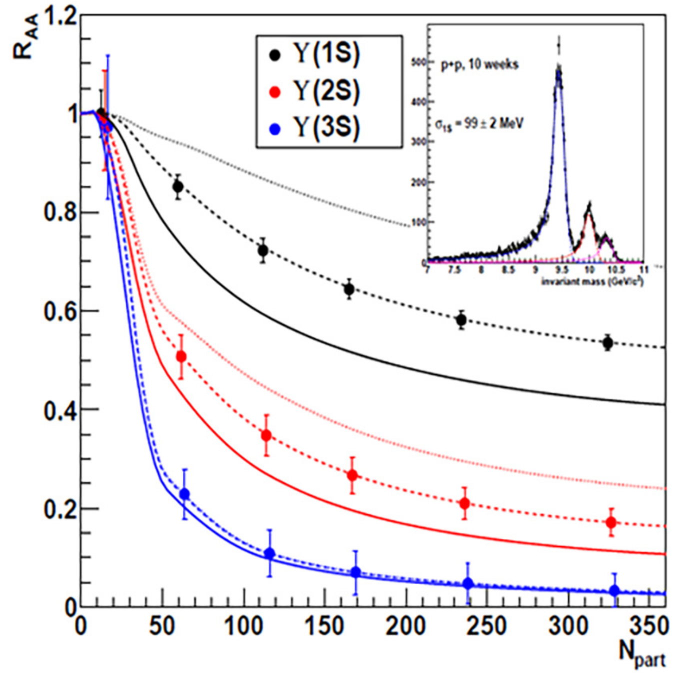


Figure 2.11: The projected sPHENIX mass separation of the three upsilon states (in the inset) and the projected accuracy of measuring their nuclear suppression in collisions with varying impact parameters. Three sets of theory curves show the melting dependence on the degree of fluid perfection.

Jets as Probes of QGP

At the earliest moment of a heavy-ion collision, occasionally two quarks or gluons have a "hard scattering" in which they are kicked in opposite directions that are very different from the direction of the beam in which they flew in. These quarks and gluons find themselves moving at very high velocities through the liquid QGP made in the collision, thus providing crucial characterizations of its properties. Early in the RHIC program, it was a major discovery that these partons lose significant energy as they pass through QGP, a phenomenon referred to as "jet quenching." The name comes from the fact that if these partons were produced in vacuum, they would fragment into a collimated spray, or "jet," of hadrons.

At the LHC, the higher rate of these hard scattering events combined with detectors with large acceptance yielded the first results for heavy-ion collisions where the energy carried by all the hadron fragments could be assembled to fully reconstruct the jets. Figure 2.12 shows the power of the large coverage and the clear energy imbalance between one jet and its barely visible partner jet, suggesting an event in which the two back-to-back partons had to traverse differing lengths of QGP.

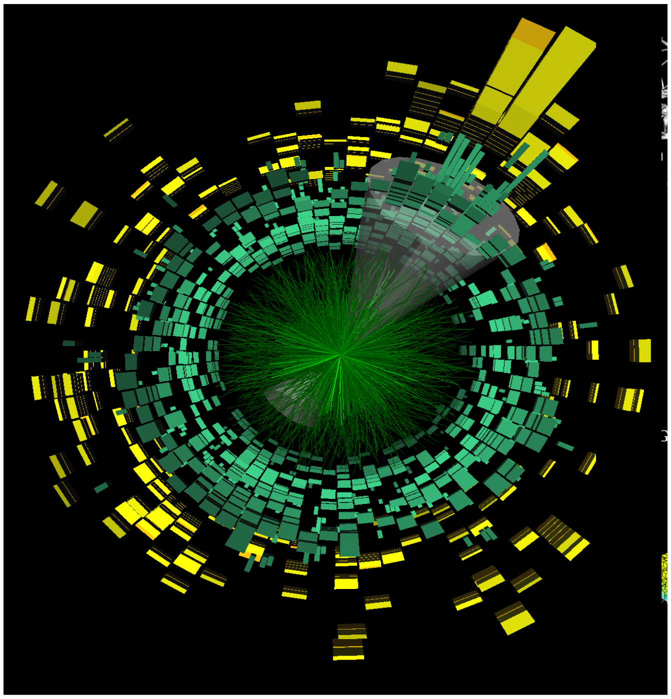


Figure 2.12: A single LHC heavy-ion collision with one high energy jet (upper right) and no apparent partner jet—because it has been quenched by the QGP produced in the collision.

The combined RHIC and LHC results on single hadron suppression (the fate of the most energetic particle emerging from the jet) have, in concert, been a powerful tool. Keys to their utility include: (i) the fact that the measurement ranges are complementary but overlap, (ii) the different physics from different temperature QGP created in collisions with different energies, and (iii) the different kinematics of the jets. These results have been compared with theoretical calculations where the leading parton loses energy via induced radiation. As the parton traverses the medium, it is jostled and, just as electric charges that undergo acceleration radiate photons, jostled color charges radiate gluons. The jostling and the consequent radiation and energy loss are parameterized via the same “jet quenching parameter”; a recent major accomplishment has been to reduce the uncertainty on this parameter by an order of magnitude, revealing stronger jostling in the QGP produced at RHIC than in the hotter QGP at the LHC. This analysis required a substantial theoretical effort involving the development and deployment of state-of-the-art calculations of the dynamics of the expanding droplet and of parton energy loss. A DOE Topical Collaboration played a key role by bringing people with varied, and needed, expertise together effectively, with common goals to attack these problems. Further steps in the direction of true microscopy require the analysis of a wealth of fully reconstructed jet observables, to which we now turn.

Jets as Microscopes on the Inner Workings of QGP

Just as condensed matter physicists seek to understand how strange metals with no apparent particulate description arise from interacting electrons, nuclear physicists must understand how a nearly perfect liquid arises from matter which, at short distance scales, is made of weakly interacting quarks and gluons. This will require new microscopes trained upon QGP together with theoretical advances. Jets provide tools of great potential for microscopy because their modification as they travel through QGP is influenced by the structure of the medium at many length scales. However, measuring the modifications to the “shapes” of jets and extracting information about the structure of QGP at different length scales from such data present both experimental and theoretical challenges.

Although the full promise of jets as microscopes has yet to be realized, the qualitative lessons learned to date from fully reconstructed jets at the LHC are encouraging. These studies have shown that the interaction of a jet with the medium does not detectably alter the direction of the jet as a whole and that while the energy loss is substantial, the depleted jets that emerge from the droplet are not substantially modified in other respects. They have shown that the energy lost by the jet as it traverses liquid QGP ends up as many low-momentum particles spread over angles far away from the average jet direction, i.e., as a little bit more QGP. At a qualitative level, these observations are consistent with expectations for how jets should behave in strongly coupled plasma, expectations that are based upon calculations done in model systems that can be analyzed via mapping questions about jets onto questions about strings in an equivalent gravitational description. At the same time, many attributes of the jets that emerge from QGP are described very well at weak coupling, for example, the fact that they have quite similar fragmentation patterns and angular shapes as jets that form in vacuum. This makes us optimistic that jets encode information about the structure of QGP over a wide range of length scales.

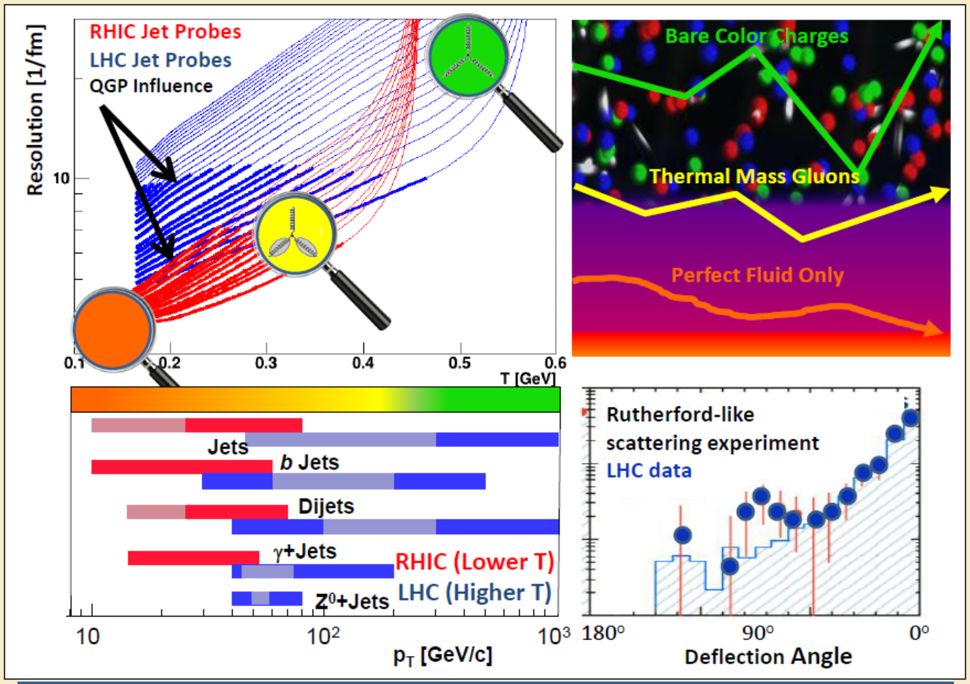
One path to realizing the potential of jets as microscopes is illustrated in Sidebar 2.5. The pointlike quarks and gluons that become visible if the microscopic structure of QGP can be resolved make it more likely that jets, or

Sidebar 2.5: Jetting through the Quark-Gluon Plasma

Understanding how quark-gluon plasma (QGP) works requires new microscopy using energetic quark probes called “jets,” generated in the initial interaction of the colliding beams. These high-energy quarks are initially able to “see” the very short distance structure of the medium they traverse. As they propagate, they rapidly shed energy by splitting off lower energy partons and, as this happens, the length scale that they “see” grows rapidly. The combination of all these partons eventually forms the hadrons that together make up a jet. The curves in the top-left panel illustrate how the resolving power (inverse of length scale) of jets at the LHC and RHIC decreases (symbolically, from green to yellow to orange) as they propagate and as the QGP in which they are propagating cools. The highest energy jets at the LHC probe very short wavelengths, where they should resolve the individual weakly coupled “bare” quarks and gluons (green). A key area is the lowest energy jets, optimally measured at RHIC, that probe longer wavelengths toward the scale of the nearly perfect liquid itself (orange). The curves are heavier in the regime where the resolving power of the jets is determined largely by the medium itself. The bottom-left panel shows the momentum range, related to the resolving power, of many jet observables in current measurements (muted red and blue) and the enormously increased reach at both RHIC (bright red) and the LHC (bright blue) enabled by upgrades including the sPHENIX microscope at RHIC.

A century ago, Ernest Rutherford discovered atomic nuclei by aiming a beam of alpha particles at a gold foil and observing that they were sometimes scattered at large angles. The simplest way to “see” pointlike quarks and gluons within QGP is, as Rutherford would have understood, to look for evidence of jets, or partons within jets, scattering off individual quarks and gluons as they plow through QGP. As the top-right panel illustrates, partons that can resolve the microscopic structure of QGP are more likely to be deflected by larger angles than the partons with less resolving power that only see the nearly perfect liquid. First exploratory measurements of the jet deflection angle are now being carried out at the LHC (lower-right, where the sharp peak at the right-hand edge of the plot corresponds to undeflected jets) and at RHIC. Full exploitation of Rutherford-like scattering experiments requires the capabilities of sPHENIX at RHIC as well as upgrades to the LHC and its detectors.

Understanding the evolution of the microscopic substructure of QGP as a function of scale will complete the connection between the fundamental laws of nature, QCD, and the emergent phenomena discovered at RHIC.



at least partons within jets, are occasionally deflected by larger angles than would be the case if the liquid had no particulate structure on any length scale. Seeing such an effect will require precise measurements of modifications of the jet structure in angular and momentum space. It can be seen by selecting particles within a narrow range of momenta within a jet of a given initial energy and measuring how their angular distribution differs from that in jets in vacuum with the same initial energy. This program requires large samples of jets in different energy regimes, with tagging of particular initial states, for example, in events with a jet back-to-back with a photon. As Sidebar 2.5 indicates, the full power of this new form of microscopy will only be realized when it is deployed at both RHIC and the LHC, as jets in the two regimes have complementary resolving power and probe QGP at different temperatures, with different values of the length scale at which bare quarks and gluons dissolve into a nearly perfect liquid.

New instrumentation at RHIC in the form of a state-of-the-art jet detector (referred to as sPHENIX) is required to provide the highest statistics for imaging the QGP right in the region of strongest coupling (most perfect fluidity) while also extending the kinematic reach at RHIC (as illustrated in Figure 2.13) to overlap that for jets at LHC energies. Upgrades to the LHC luminosities and detector and measurement capabilities are keys to providing a complete picture, as are new experimental techniques being developed to compare how light quark jets, heavy quark jets, and gluon jets "see" QGP. In general, using common, well-calibrated, jet shape observables in suitably tagged fully reconstructed jets at RHIC and the LHC will be critical to using the leverage in resolution and temperature that the two facilities provide in concert (see Sidebar 2.5) to relate observed modifications of jets to the inner workings of QGP.

OUTLOOK

The discoveries of the past decade have posed or sharpened questions that are central to understanding the nature, structure, and origin of the hottest, most nearly perfect form of liquid matter ever seen in the universe. Much remains to be learned about how the remarkable properties of this liquid change across its phase diagram and how they emerge from interactions of individual quarks and gluons. A program to complete the search for the critical point in the QCD phase

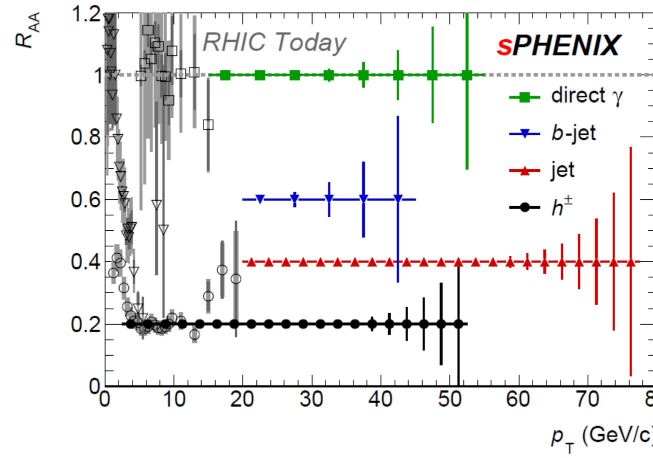


Figure 2.13: *Future reach of four precision measurements via jets for probing the most strongly coupled liquid with sPHENIX, in color, compared to current measurements from RHIC where available, in grey.*

diagram and to exploit the newly realized potential of exploring QGP structure and properties at multiple length scales at RHIC and the LHC, enabled by targeted new experimental capabilities and critical advances on a range of theoretical frontiers, places key answers within reach.

2.3 Understanding the Glue That Binds Us All: The Next QCD Frontier in Nuclear Physics

Nuclear matter in all its forms—from protons and neutrons, to atomic nuclei, to neutron stars, to quark-gluon plasma—is a teeming many-body system of quarks, antiquarks, and gluons interacting with one another via nature's strongest force. In atomic, molecular, and condensed matter systems, where the electrically charged constituents interact by exchanging photons, it is not necessary to consider the photons themselves as important constituents of the matter. In sharp contrast, the force carriers in QCD—the gluons—are constituents that play a pivotal role in determining how the properties of nuclear matter emerge from the underlying theory

The difference arises because the gluons, in addition to being exchanged between quarks, possess the intrinsic property—color charge—that is responsible for the QCD interaction, while photons are free of electric charge. The gluons thus interact among themselves and can spawn more gluons or quark-antiquark pairs (sea quarks), a fundamental feature of QCD. The emergent interactions of quarks and gluons are, for example, responsible for the fact that massive neutrons

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.

Neutrinoless Double Beta Decay Context

- We are aiming for U.S. leadership of the most promising ton-scale experiment, and expecting significant international and interagency collaboration. For the highest cost options, we only projected about 60% funding from U.S.

- If a positive result is seen, it needs to be confirmed on another isotope and with another technique. We expect secondary U.S. involvement in at least one other international effort would go ahead with a similar time scale.

- Total integrated budgets for two projects ~ $250M in $FY15

- Ongoing NSAC Subcommittee activities

RECOMMENDATION III

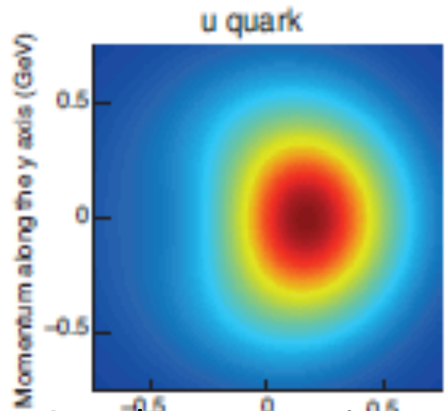
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new Electron Ion Collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

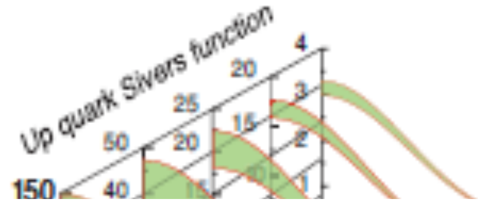
We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

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

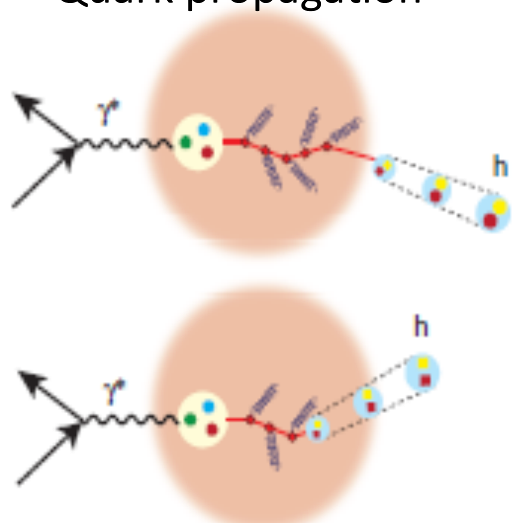
The Science Questions for the EIC as laid out by the community

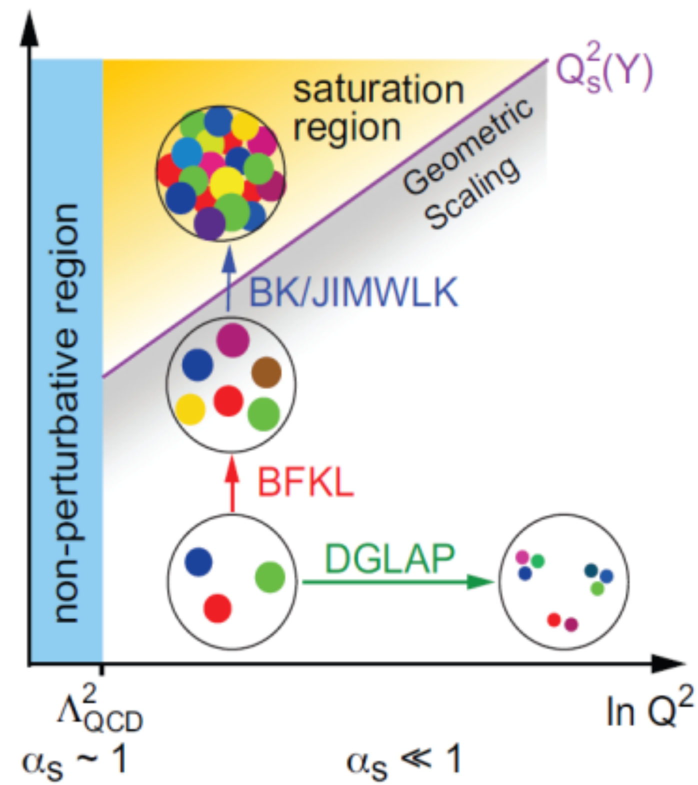
- **How are the sea and momentum** distributions cor direction? **What gluons in buildi**
- **Where does the** boundary that s matter? If so, ho crosses the bour properties in the light?
- **How does the n gluons and thei** distribution of g matter respond response differe



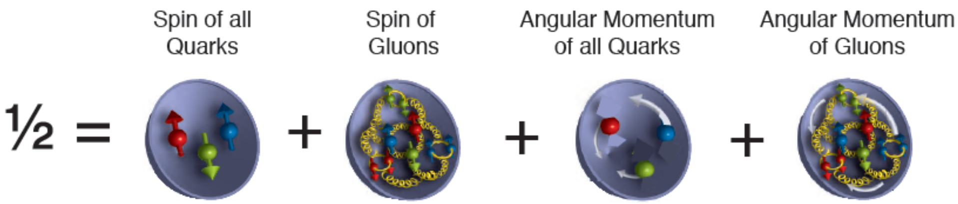


Quark propagation





Why isn't the Spin Settled by JLAB and RHIC?



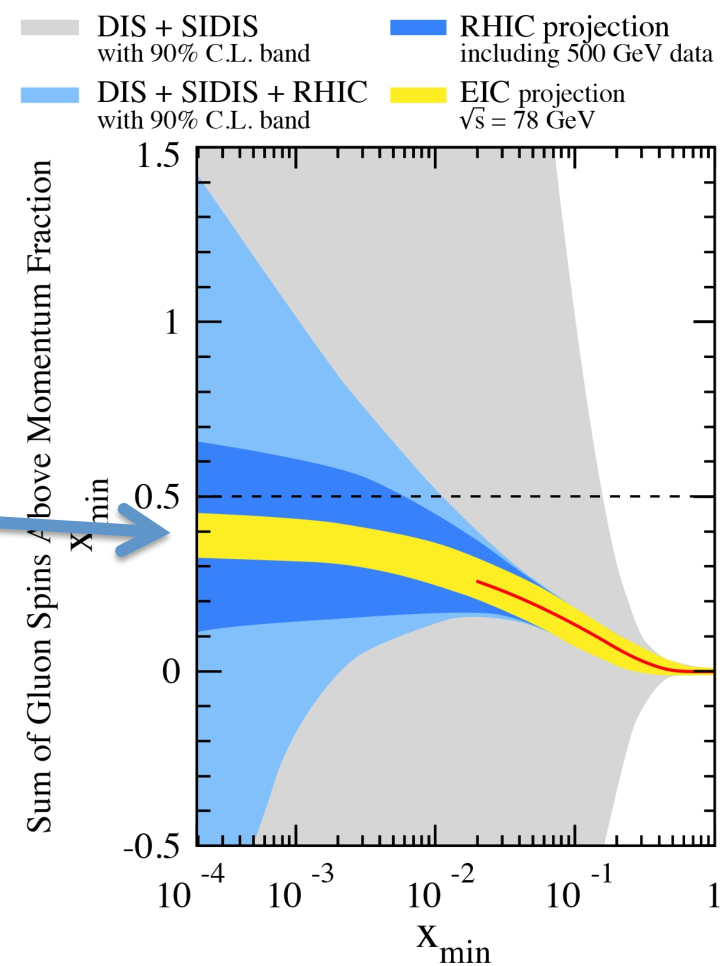
Done

CEBAF

EIC

Valuable Information from RHIC

Requires EIC to fully answer



RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

Innovative research and initiatives in instrumentation, computation, and theory play a major role in U.S. leadership in nuclear science and are crucial to capitalize on recent investments. The NSF competitive instrumentation funding mechanisms, such as the Major Research Instrumentation (MRI) program and the Mathematical & Physical Sciences mid-scale research initiative, are essential to enable university researchers to respond nimbly to opportunities for scientific discovery. Similarly, DOE-supported research and development (R&D) and Major Items of Equipment (MIE) at universities and national laboratories are vital to maximize the potential for discovery as opportunities emerge.

The Role of the NSAC Long Range Plan in Projects

NSAC is asked to identify scientific opportunities and a level of resources necessary to achieve these. The recommendations express priorities. But, except for the largest-scale facilities, projects named in this report are given as examples to carry out the science. The funding agencies have well-established procedures to evaluate the scientific value and the cost and technical effectiveness of individual projects. There is a long-standing basis of trust that if NSAC identifies the opportunities, the agencies will do their best to address these, even under the constraints of budget challenges.

In this way our charge is different than that of the HEP Particle Physics Prioritization Panel which considers individual projects.

A: Theory Initiative

Advances in theory underpin the goal that we truly understand how nuclei and strongly interacting matter in all its forms behave and can predict their behavior in new settings.

To meet the challenges and realize the full scientific potential of current and future experiments, we require new investments in theoretical and computational nuclear physics.

- *We recommend new investments in computational nuclear theory that exploit the U.S. leadership in high-performance computing. These investments include a timely enhancement of the nuclear physics contribution to the Scientific Discovery through Advanced Computing program and complementary efforts as well as the deployment of the necessary capacity computing.*
- *We recommend the establishment of a national FRIB theory alliance. This alliance will enhance the field through the national FRIB theory fellow program and tenure-track bridge positions at universities and national laboratories across the U.S.*
- *We recommend the expansion of the successful Topical Collaborations initiative to a steady-state level of five Topical Collaborations, each selected by a competitive peer-review process.*

B: Initiative for Detector and Accelerator Research and Development

U.S. leadership in nuclear physics requires tools and techniques that are state-of-the-art or beyond. Targeted detector and accelerator R&D for the search for neutrinoless double beta decay and for the Electron Ion Collider is critical to ensure that these exciting scientific opportunities can be fully realized.

- *We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the Electron Ion Collider.*

Workforce, Education, and Outreach

A workforce trained in cutting-edge nuclear science is a vital resource for the Nation.

Our Nation needs a highly trained workforce in nuclear science to pursue research, develop technology, and ensure national security. Meeting this need relies critically on recruiting and educating early career scientists.

We recommend that the NSF and DOE take the following steps.

- *Enhance programs, such as the NSF-supported Research Experience for Undergraduates (REU) program, the DOE-supported Science Undergraduate Laboratory Internships (SULI), and the DOE-supported Summer School in Nuclear and Radiochemistry, that introduce undergraduate students to career opportunities in nuclear science.*
- *Support educational initiatives and advanced summer schools, such as the National Nuclear Physics Summer School, designed to enhance graduate student and postdoctoral instruction.*
- *Support the creation of a prestigious fellowship program designed to enhance the visibility of outstanding postdoctoral researchers across the field of nuclear science.*

Budgets

It is well recognized that resources are always limited, and hard choices have been made concerning parts of the program that could not go forward in a realistic budget scenario. For example, the 2013 NSAC report *Implementing the 2007 Long Range Plan* responded to a more constrained budget picture than was originally expected. The resulting focused plan has been widely supported by the community, the Administration and the Congress. This 2015 Long Range Plan also involves hard choices to go forward with constrained budget scenarios.

Project Sequencing

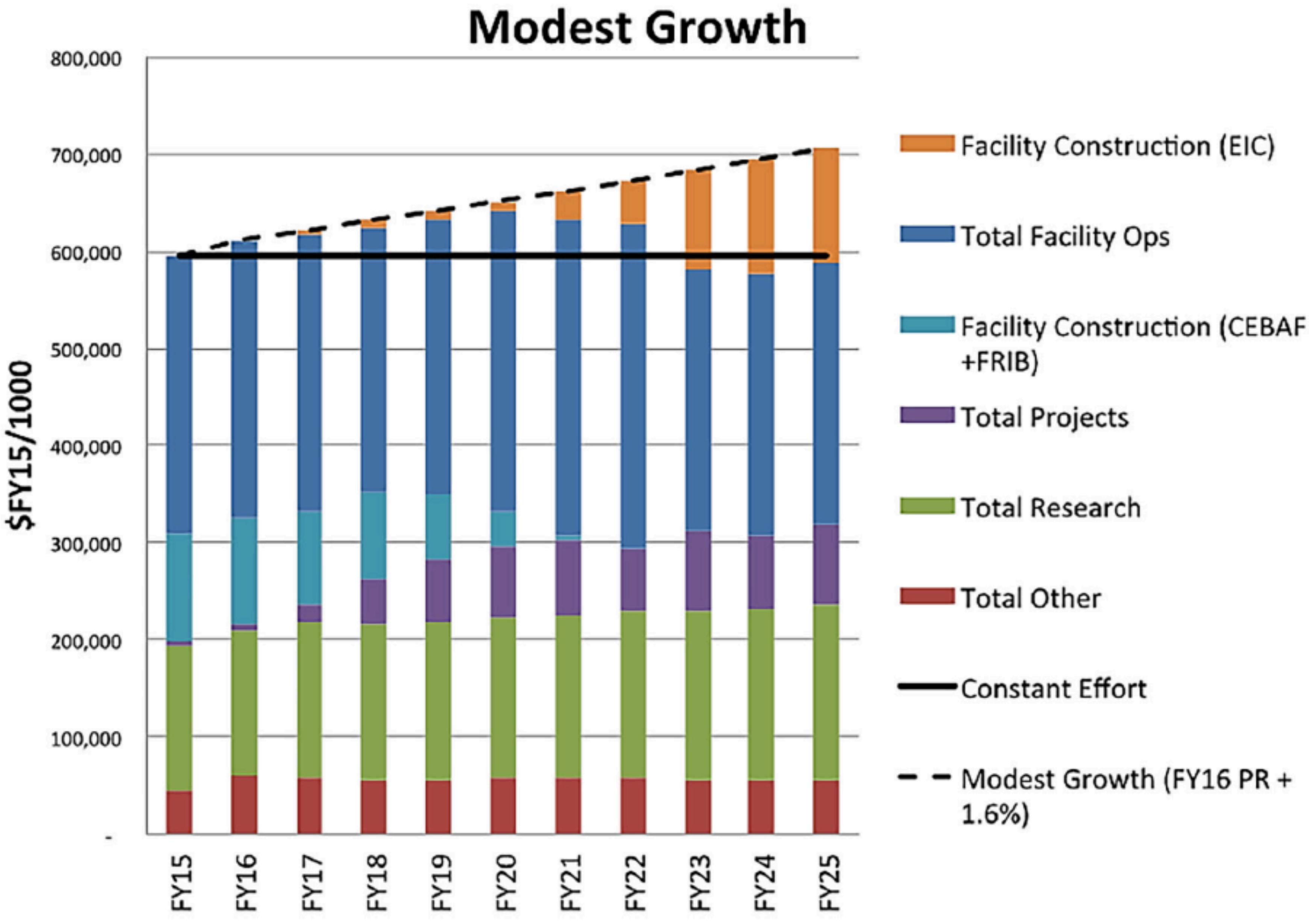
- FY15-18 as in 2013 Implementation Plan and consistent with the FY16 President's budget request
- Ton-scale neutrinoless double beta decay starts near end of the decade after FRIB peak.
  - Need for demonstration projects to show what they can do and need for more R&D
  - A standing NSAC subcommittee is providing advice.
- EIC construction after completion of FRIB construction.
  - Time scale set, in part, by exciting physics at current facilities, by R&D required, and, in part, to avoid the need for large sudden budget increase.
  - Significant redirection from existing facilities when construction begins

Other Budget Priorities

- Increased small-scale and mid-scale projects including theory computing. This was temporarily sacrificed in 2013 implementation plan to start construction program.

- Increased research funding. It has fallen over the past few years to less than 30% of total in 2015 in DOE-NP.

DOE Budget Projections



NSF Nuclear Physics Budget

- FRIB begins operation at the mid-point of this LRP and NSCL transitions from NSF stewardship. Before the transition , NSCL will remain the premier national user facility for rare isotope research in the U.S., with unique rare isotope reacceleration capabilities following fast beam fragmentation.

- We project increasing mid-scale funding at NSF and believe NP can compete well across the Physics Division for new initiatives. This is essential to ensure NSF-supported scientists have the resources to lead significant initiatives. We did not specifically associate any one initiative with NSF except as significant partners/leaders in neutrinoless double beta decay and neutron EDM where they already play important roles.

- We project a total NSF nuclear physics funding increasing slightly each year in line with the modest growth scenario.

Impacts of Constant Effort Budget

Under a budget that represents constant effort at the level of the appropriated FY 2015 budget, the decisions become more difficult. Promising opportunities will be lost. The technology choices for some of the major projects may become driven more by cost rather than by optimizing the science reach. This could affect the international competitiveness of the ton-scale neutrinoless double beta decay experiment. While the FRIB facility operations can be maintained, completion of experimental equipment needed to fully utilize FRIB beams would be stretched out in time. There would be less scope to follow up new discoveries at FRIB, CEBAF, and RHIC. The EIC must begin more slowly. U.S. leadership would be maintained in some areas but would be given up in others.

The most difficult choices would occur at or beyond the mid-point of time window of this LRP.

Nonetheless, a constant effort budget can fund a sustainable program for nuclear science, one of the elements of the charge.

Summary

- We have an exciting science program
- There are broader impacts to technology and medicine as well as other sciences such as astrophysics, HEP, material science and chemistry.
- New powerful world leading tools are coming on-line and being constructed
- We see two important major initiatives for the future.
- The recommendations were developed by consensus. There was unanimous agreement among the working group for the recommendations and the report. The community will unite to support this vision of the future.
- This is a sustainable world-leading nuclear science program.
- I thank all of you for your help in creating this plan.

A.2 The Long Range Plan Working Group Membership

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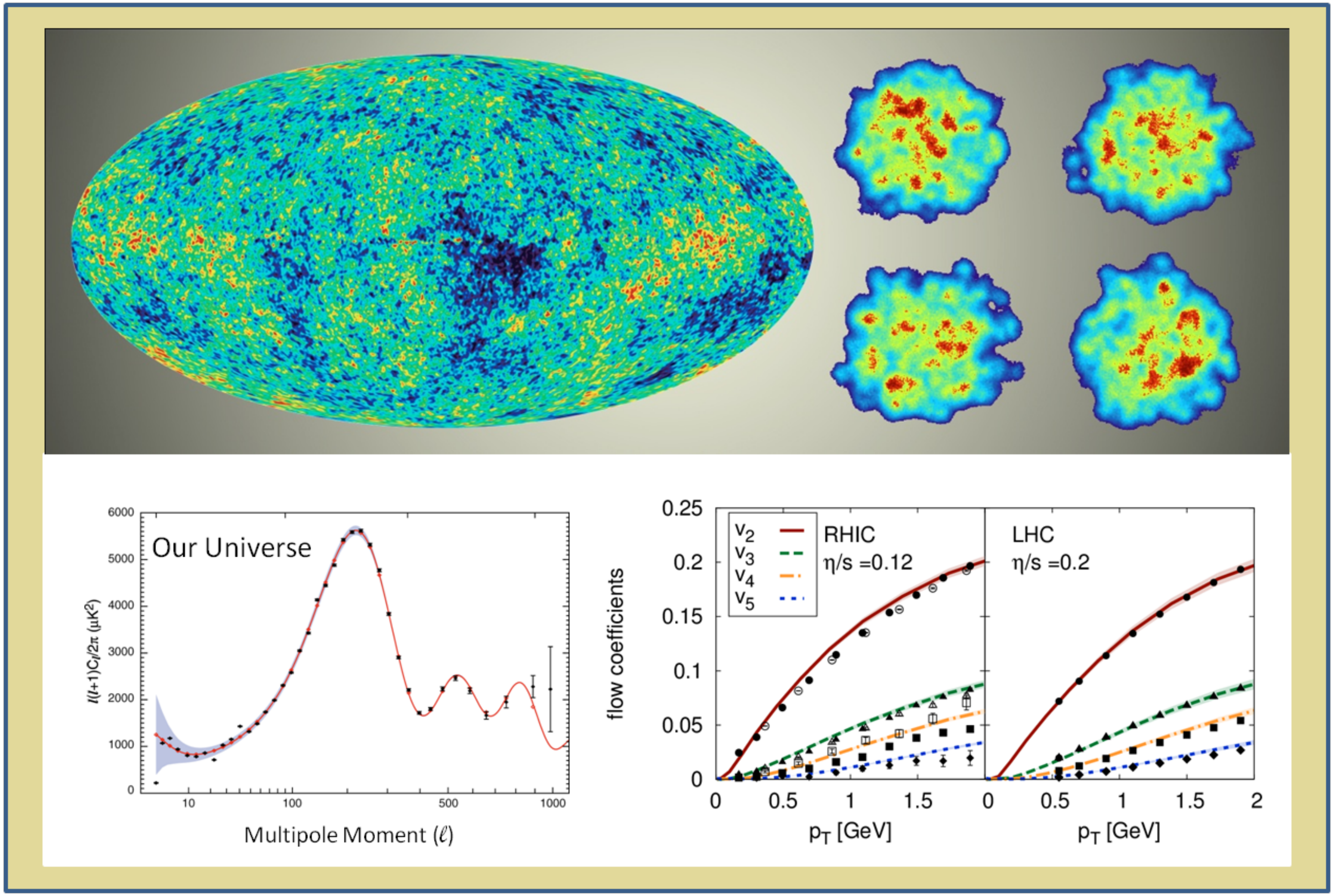
Charge to NSAC to Develop a New Long Range Plan

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required (including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment) to maintain a world-leadership position in nuclear physics research and what the impacts are and priorities should be if the funding available provides for constant level of effort from the FY 2015 President's Budget Request into the out-years (FY 2016-2025), with constant level of effort defined using the published OMB inflators for FY 2016 through FY 2025. A key element of the new NSAC LRP should be the Program's sustainability under the budget scenarios considered.

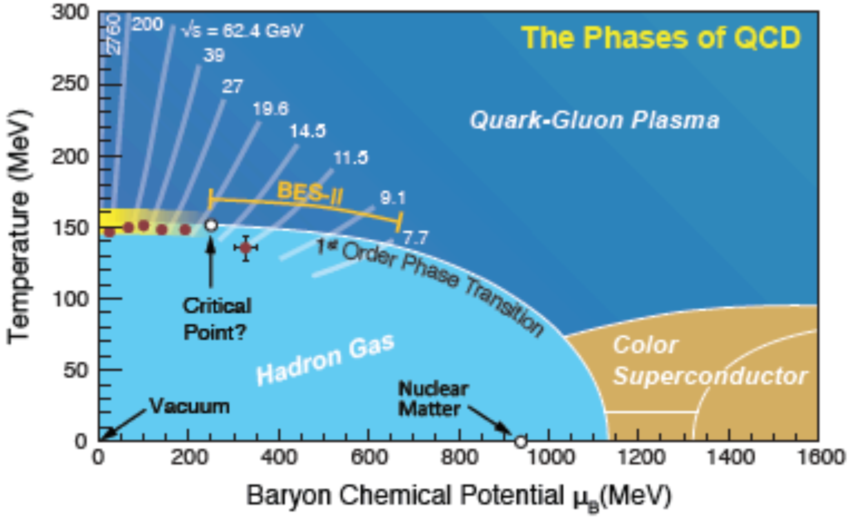
The extent, benefits, impacts and opportunities of international coordination and collaborations afforded by current and planned major facilities and experiments in the U.S. and other countries, and of interagency coordination and collaboration in cross-cutting scientific opportunities identified in studies involving different scientific disciplines should be specifically addressed and articulated in the report. The scientific

RHIC and the LHC
The Big Bang vs Lots of Little Bangs



In both cases the measurements at later time reveal the fluctuations in the initial conditions which are remarkably preserved during the expansion.

Toward critical fluctuations



Model independent structure of net baryon number kurtosis