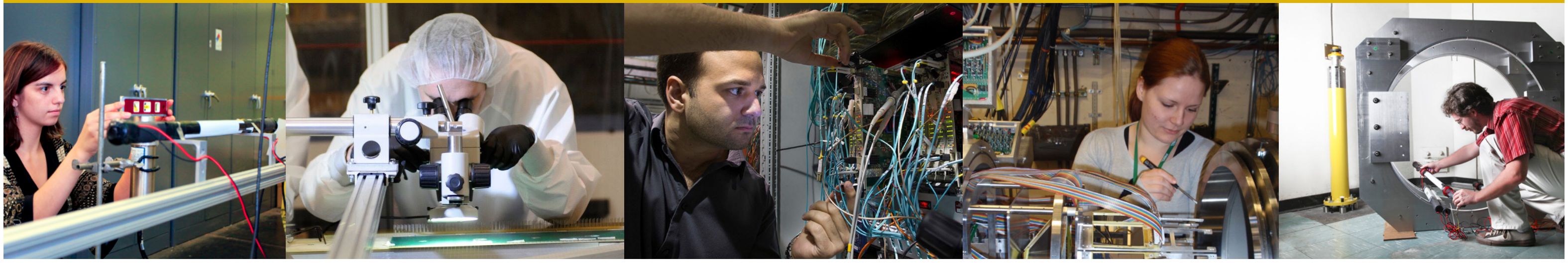
REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NSF

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Preface

Explorers, inventors, and scientists are constantly striving to reach to the horizon and beyond. Wilbur and Orville Wright made flight in a powered, heavier-than-air machine a reality in the winds of Kitty Hawk, North Carolina. Today, nuclear science is at a stepping-off point in reaching for the horizon. The exploration of nuclear science has been guided by a series of long range plans prepared by the Nuclear Science Advisory Committee (NSAC) at the request of the Department of Energy (DOE) Office of Science and the National Science Foundation (NSF) Directorate of Mathematical and Physical Sciences. In a letter dated 23 April 2014, NSAC was again charged to conduct a new study of the opportunities and priorities for United States nuclear physics research and to recommend a long range plan that will provide a framework for the coordinated advancement of the Nation's nuclear science program over the next decade.

While the charge was given to NSAC, the entire community of nuclear scientists in the U.S. actively contributed to developing the plan in a series of town meetings and white papers under the leadership of the American Physical Society Division of Nuclear Physics. Ideas and goals, new and old, were examined, and community priorities were established. A long range plan working group composed of 58 members from across the field and with international participation gathered in Kitty Hawk in April 2015 to converge on the long range plan.

The last long range plan in 2007 was created at a time when there was a commitment to double the funding for physical science research over the next decade. It followed the 2000–2007 time period where no new major construction had occurred, and the focus was on operating the then-new facilities we had built. The 2007 plan's recommendations focused on major new initiatives, and these could be accommodated with this doubling budget assumption. In the past seven years, this increasing budget scenario has not been realized, and, in 2013, NSAC responded to a charge to advise how to implement the 2007 plan under flat budget scenarios.

The charge for the 2015 Long Range Plan asked what resources and funding levels would be required to maintain a world-leadership position in nuclear physics research and what the impacts and priorities should be if the funding available provides for a constant level of effort. The 2015 plan will involve hard choices if we are to go forward with constrained budget scenarios. Our vision was to create a plan that would address the important scientific questions while requiring only modest growth in the nuclear science budgets of DOE and NSF. Realizing this vision is possible with careful staging of new initiatives while fully exploiting the opportunities of our past investments and taking into account complementary international initiatives.

Inspired by the symbolism of the Wright brothers' great leap forward in the winds of Kitty Hawk, the new plan, *Reaching for the Horizon*, offers the promise of great leaps forward in our understanding of nuclear science and new opportunities for nuclear science to serve society. Following its guidance, the United States will continue as a world leader in nuclear science.

1. Summary and Recommendations

From the hot dense soup of quarks and gluons in the first microseconds after the Big Bang, through the formation of protons and neutrons beginning the evolution of the chemical elements, to the awesome power of nuclear fission, bringing both strength and complicated nonproliferation issues to our national security, the physics of nuclei is fundamental to our understanding of the universe and, at the same time, intertwined in the fabric of our lives. Nuclear physicists and chemists are creating totally new elements in the laboratory and producing isotopes of elements that, hitherto, have only existed in stellar explosions or in the mergers of neutron stars. They develop new tools like accelerators and detectors that find broad applications in industry, medicine, and national security. The United States, with the support of the National Science Foundation (NSF) and the Department of Energy (DOE), has world-leading programs in nuclear science, from forefront basic research to the development of important new applications for society.

Since 1979, progress in nuclear science has been guided by a series of six Nuclear Science Advisory Committees' (NSAC) long range plans, the last one created in 2007. In April 2014, NSAC was charged by the DOE Office of Science and the NSF Directorate of Mathematical and Physical Sciences to conduct a new study of the opportunities and priorities for United States nuclear physics research and to recommend a long range plan that will provide a framework for the coordinated advancement of the Nation's nuclear science program over the next decade. The plan should indicate what resources and funding levels would be required to maintain a world-leadership position in nuclear physics research and what the impacts and priorities should be if the funding available provides for constant level of effort from the fiscal year (FY) 2015 President's Budget Request into the out-years. The full text of the charge is given in Appendix A.1. The Isotope Program of the DOE Office of Nuclear Physics is explicitly excluded from the charge, as it is the subject of a separate charge to NSAC.

NSAC created a Long Range Plan working group of 58 members (Appendix A.2), including scientists from Europe and Canada and with international observers representing associations of nuclear scientists from Europe and Asia. In a nine-month-long process, the Division of Nuclear Physics of the American Physical Society organized broad input for the working group, including several town meetings (listed in Appendix A.3) and white papers (available at https://www.phy.anl.gov/nsac-lrp/). The working group held two meetings, an organizational meeting in November 2014, and a resolution meeting (see Appendix A.4) in April 2015, to establish recommendations and priorities. 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 Congress. This 2015 Long Range Plan also involves hard choices to go forward with constrained budget scenarios.

THE SCIENCE QUESTIONS

Nuclear science is a broad and diverse subject. The National Research Council Committee on the Assessment of and Outlook for Nuclear Physics 2013 report, *Nuclear Physics, Exploring the Heart of Matter*, (NP2010 Committee) framed the overarching questions "that are central to the field as a whole, that reach out to other areas of science, and that together animate nuclear physics today:

1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?"

The progress in nuclear science since the last long range plan in 2007, as well as new questions that now demand to be answered, will be identified in the science sections of this report. The 2007 plan has served the community and the funding agencies extremely well as a blueprint for the future. Indeed, given the size and the decade-long time scales for major construction projects, in some cases, we are only now poised to reap the benefits of these initiatives. In other cases, anticipated upgrades were achieved at a small fraction of the cost estimated in 2007, and we are harvesting the benefits earlier than expected. All of our current four national user facilities, the Continuous Electron Beam Accelerator Facility (CEBAF), the Relativistic Heavy Ion Collider (RHIC), the Argonne Tandem Linac Accelerator System (ATLAS), and the NSF-supported National Superconducting Cyclotron Laboratory (NSCL), were significantly upgraded in capability during this period. A fifth national user facility, the DOE-supported Holifield Radioactive Ion Beam Facility, was closed down. Care was always taken to leverage U.S. investments in an international context while maintaining a world-leadership position.

Here are the recommendations of the 2015 Long Range Plan.

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.

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.

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 EIC 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 vision of an EIC was already a powerful one in the 2007 Long Range Plan. The case is made even more compelling by recent discoveries. This facility can lead to the convergence of the present world-leading QCD programs at CEBAF and RHIC in a single facility. This vision for the future was expressed in the 2013 NSAC report on the implementation of the 2007 Long Range Plan with the field growing towards two major facilities, one to study the quarks and gluons in strongly interacting matter and a second, FRIB, primarily to study nuclei in their many forms. Realizing the EIC will keep the U.S. on the cutting edge of nuclear and accelerator science.

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.

These NSF funding mechanisms are an essential component to ensure that NSF-supported scientists have the resources to lead significant initiatives. These programs are competitive across all fields, and an increase in the funds available in these funding mechanisms would benefit all of science, not just nuclear physics.

With both funding agencies, small- and mid-scale projects are important elements in increasing the agility of the field to react to new ideas and technological advances. The NP2010 Committee report also made a recommendation addressing this need. With the implementation of projects, there must be a commitment to increase research funding to support the scientists and students who will build and operate these projects and achieve the science goals. Close collaborations between universities and national laboratories allow nuclear science to reap the benefits of large investments while training the next generation of nuclear scientists to meet societal needs.

NSAC is asked to identify scientific opportunities and a level of resources necessary to achieve these. So, 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.

INITIATIVES

A number of specific initiatives are presented in the body of this report. Two initiatives that support the recommendations made above and that will have significant impact on the field of nuclear science are highlighted here.

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 EIC 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 EIC.*

WORKFORCE, EDUCATION, AND OUTREACH

A workforce trained in cutting-edge nuclear science is a vital resource for the Nation. Exciting research is intimately tied with attracting talented graduate students to any science, including nuclear science. Workforce surveys show that the total number of Ph.D. graduates in nuclear science has been constant for the past decade, which is consistent with the U.S. continuing to attract the best and brightest students for graduate education and research, both from the U.S. and abroad. However, compared to the patterns 10 years ago, a higher percentage of nuclear physics faculty at universities and national laboratories and of faculty recipients of prestigious early career awards received their Ph.D.s from universities outside the U.S. There is a continuing vital need to enhance the development of a talented U.S. workforce by increasing the participation of U.S. students in the opportunities in basic and applied nuclear science. To increase the number of U.S. students prepared for successful graduate studies and research in nuclear science requires opportunities for undergraduates to be engaged in forefront nuclear science research and studies. Graduate students are also inspired by highly visible postdoctoral positions to which they can aspire.

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 Experiences 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.*

Research in theory, experiment, and computation as well as instrumentation initiatives from university groups and laboratories provide a unique education and training environment that must be nurtured.

RESOURCES

The working group carefully considered the budgetary implications of its recommendations. The construction funding of FRIB will be winding down in FY 2020–2021. It is expected that project selection for a ton-scale neutrinoless double beta decay experiment will occur in a few years, and then this project will commence. An EIC is envisioned to start construction after FRIB construction is completed and to be operational by the end of the 2020s. With this sequencing, an effective and efficient program in nuclear science can be accomplished with a DOE nuclear science budget that increases by 1.6% in spending power above cost of living per year for the ten years of this plan. This is consistent with the scenario advocated in the 2013 NSAC report, *Implementing the 2007 Long Range Plan*. Under this constraint, some important science would rely on international efforts, and a number of promising avenues cannot be pursued, but the U.S. program will be strong, vital, and world leading. 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. 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. Nonetheless, a constant effort budget can fund a sustainable program for nuclear science, one of the elements of the charge.

For the NSF, it is anticipated that the operations budget of the NSCL will terminate once FRIB operations commence. 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 a slightly increasing total NSF nuclear physics funding from FY 2015 as new instrumentation and mid-scale projects led by NSF-supported scientists emerge to address the recommendations above.

The balance of the report begins with presenting the frontiers and accomplishments in each of the sub-disciplines of nuclear science: understanding nuclei in terms of the fundamental quarks and gluons; the structure and reactions of nuclei; the intimate relation between nuclear physics and astrophysics; and unique nuclear science searches for the new Standard Model of particles and interactions. The following four chapters point out cross-cutting issues in nuclear theory, place the domestic facilities and tools that enable much of this research in an international context, discuss issues of the scientific workforce and education, and highlight the broader impacts of nuclear science on other sciences and society. The plan concludes with a discussion of the budgets required to continue U.S. world leadership in nuclear science.

2. Quantum Chromodynamics: The Fundamental Description of the Heart of Visible Matter

It was just under a hundred years ago that Lord Rutherford uncovered the existence of the proton as one of the basic building blocks of the atomic nucleus. The discovery of the other building block, the neutron, came more than a decade later. By the middle of the twentieth century, many features of nuclear physics were well established, including the strong force that binds protons and neutrons within an atomic nucleus. A multitude of other strongly interacting particles, named hadrons, had also been discovered. But, even as applications of nuclear physics were developed, a fundamental understanding of the underlying laws of physics was missing. This ultimately changed when quantum chromodynamics (QCD) was established as the fundamental theory governing nuclear matter and all hadrons.

QCD holds that protons, neutrons, and all other hadrons are made from quarks, their antimatter siblings (antiquarks), and particles called gluons that carry the force binding quarks to each other. Protons and neutrons can be thought of as containing three so-called valence quarks, immersed in a shimmering cloud of quarks, antiquarks, and gluons, all continually winking into and out of existence according to the laws of quantum mechanics. Similarly, quarks and gluons are the building blocks of all hadrons. No single quark or gluon, however, can be observed in isolation. One says that they are *confined* within a hadron. Confinement is a hard pill to swallow when our experience tells us that we should be able to disassemble an object that has composite parts. Confinement means that any process by which one rips a quark out of a proton or neutron makes new hadrons, without ever isolating a single quark

Gluons carry the force between quarks in much the same way that electromagnetic forces are carried by the photon. There is, however, a hugely important difference. Photons interact with objects that have charge but do not carry charge themselves. This means that photons do not interact with each other. In contrast, gluons interact with objects that carry color charge, and they also carry color charge themselves. Thus, gluons can interact among themselves and even spawn additional gluons, a phenomenon that has bizarre consequences. For example, the force between two quarks becomes *small* when they move close together but grows *large* when they move apart, the opposite of the case in electromagnetism!

All of these unusual features of QCD result in a structure for the proton and neutron that is quite remarkable. It turns out that the intrinsic mass of the three valence quarks in the nucleon comprises only a small fraction of the nucleon's total mass. The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. Since protons and neutrons account for nearly all the mass of atoms, nearly all of the mass of the visible matter in the universe is due to these seemingly exotic QCD effects. And while these general features of nuclear matter are well established, a detailed understanding of how this all comes about from QCD is only now emerging.

The fundamental laws of QCD are elegantly concise; however, understanding the structural complexity of protons and neutrons in terms of quarks governed by those laws is one of the most important challenges facing physics today, a challenge that motivates the newest generation of experimental facilities, supercomputers, and nuclear scientists. There has been impressive progress. Scientists have taken important first steps toward understanding how nuclei are built from quarks. Recent advances in calculational power now allow for precise calculations of the masses of hadrons (Sidebar 2.1). These same calculations predict that because gluons interact with gluons there should be as-yet undiscovered hadrons in which gluons play as central a role as the valence quarks. A new experimental search for these novel exotic particles, using cutting-edge instrumentation now being commissioned, will soon be underway. Another outstanding challenge is the understanding of how protons get their spin: does it come entirely from the intrinsic spin of quarks and gluons? Very recently, we have learned that the spins of the gluons do make an important contribution. But is orbital motion of constituents within the proton important? Do quarks, antiquarks, and gluons all swirl in the same direction? Here, too, new measurements and new calculations are much anticipated.

While it is impossible to observe a single quark in isolation, that does not mean that quarks are necessarily always confined. A spectacular example of unconfined quarks can be found in the behavior of matter at temperatures above three trillion degrees Fahrenheit, the matter that filled the universe in the first microseconds after it came into existence in the Big Bang. The enormously large thermal energy in these conditions makes hadrons literally melt and form quark-gluon plasma (QGP). Quarks can roam throughout a large droplet of QGP; within it, they are not confined into hadrons. In fact, the protons, neutrons, and other hadrons that condensed out of QGP as the universe cooled below QGP temperatures were the first complex structures ever to form. With the highest energy accelerators in the world, scientists are today recreating tiny droplets of the hot QGP matter that filled the universe before hadrons existed and studying their properties in the laboratory. Although the quarks in QGP are not confined to individual hadrons, they are also far from isolated: recreating QGP in the laboratory yielded the surprising discovery that QGP is a nearly perfect liquid, that is, a fluid whose viscosity is about as low as is theoretically possible. How quarks and gluons conspire to form such a liquid is not yet understood. Unraveling how the perfect fluid works, how it emerges from the simple underlying laws of QCD, requires probing QGP with “microscopes” with varying resolving power and changing its makeup by doping it with more quarks than antiquarks.

We are still far from a comprehensive and quantitative understanding of how the many properties of protons and nuclei arise from quarks and gluons and their interactions or of how these interactions conspire to create the hottest, and most “liquid,” liquid ever seen in the universe. This Long Range Plan lays out the path by which U.S. nuclear science can lead the worldwide quest to unravel these mysteries and gain new fundamental understanding of QCD in all its manifestations. The investigative tools for this quest are particle accelerators, including two newly upgraded facilities: CEBAF at the Thomas Jefferson National Accelerator Facility (TJNAF or JLab), whose energy doubling upgrade is just being completed; and RHIC at Brookhaven National Laboratory (BNL), recently upgraded to increase its beam intensity by a factor of ten. In addition to searching for novel exotic particles, CEBAF will map out the valence quark structure of protons and neutrons in unprecedented detail, creating exquisite images of how the quarks in them are distributed in space and how they are moving. RHIC will use very heavy or energetic quarks to probe the properties of liquid QGP with varying resolving power and will map out how the transition between liquid QGP and ordinary matter changes with doping, searching for a distinctive critical point in the phase diagram of QCD. Accelerators at Fermilab are also important as are international endeavors such as the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN).

That said, today’s tools will leave fundamental questions related to the role of gluons within protons, neutrons, and nuclei unanswered. As scientists examine protons and neutrons more and more closely, the importance of the role of gluons in their structure is becoming increasingly apparent. Furthermore, understanding how QGP forms when two nuclei collide is thought to be connected to understanding how it is that many gluons within a single nucleus can act in concert like a classical wave rather than as many individual particles. A complete understanding of how protons and nuclei are built and of how QGP forms will require a powerful new experimental tool, a polarized EIC. The EIC will make it possible to resolve the gluon structure of the proton and of nuclei with the same precision with which CEBAF will map their quark structure. The EIC will perform precise measurements to complete our picture of how the proton’s spin is generated by quarks and gluons. And it will explore how the interactions among gluons themselves serve to prevent the numerous gluons within fast-moving nuclei from clustering into arbitrarily dense states. Ultimately, the EIC will provide the data that will help us understand the mass and other fundamental properties of protons and neutrons from first principles. Together with anticipated advances in our ability to solve the equations of QCD, these experimental explorations will help us explain how the properties of nuclear matter can arise from complex solutions to simple equations. The EIC will take a critical step in the study of QCD by opening a new window into the crucial role played by gluons in all matter.

In the chapter ahead, we examine the many achievements since the 2007 Long Range Plan, describe what can be accomplished in the future with existing facilities, and look ahead to the discovery potential of an EIC.

2.1 QCD and the Structure of Hadrons and Nuclei

THE QUARK STRUCTURE OF HADRONS

Understanding the structure of hadrons in terms of QCD's quarks and gluons is one of the central goals of modern nuclear physics. This endeavor is profoundly difficult, however, since we cannot simply think of hadrons as being solely composed of their valence quarks but must fold in the roles played by both the gluons that bind quarks and the quark-antiquark pairs associated with quantum fluctuations.

Despite considerable challenges, however, through both theoretical and experimental progress, physicists have begun to tease out the structure of hadrons. Facilities such as CEBAF and RHIC have provided tools of unprecedented capability. Theoretical techniques such as lattice QCD and increasingly realistic models are providing new and deeper understanding of experimental observations. Our knowledge of the spatial distribution and the motion of the quarks has become more detailed, and we are now starting to unfold the dynamics that give hadrons their basic properties. This quest is still at an early stage, but the progress that has been made since the 2007 Long Range Plan is considerable, and the next decade promises to be one of increasingly sophisticated understanding and discovery.

A New Era in the Theory of Hadron Structure

While quantum mechanics made it possible to compute the structure of atoms, using QCD to compute the structure of hadrons has long been an elusive goal. That, however, is rapidly changing. It can truly be stated that we are entering a new era in our theoretical understanding of hadron structure. Lattice QCD (see Sidebar 2.1) can now be used to compute certain properties of hadrons, and even light nuclei, from first principles with a precision that is well quantified and only limited by available computational resources.

Furthermore, effective field theories and increasingly realistic models are describing hadron structure in a manner that advances our understanding of the underlying physics. These include both models in which quarks are treated as constituent degrees of freedom with effective masses and QCD-inspired field theories in which the effective mass of the quark is dynamically generated. Much progress has been made since the 2007 LRP, and the promise of future breakthroughs in understanding is truly exciting.

The Size, Shape and Makeup of Hadrons

Form Factors—The Closest Thing We Have to a Snapshot

With such theoretical predictions in hand, one can essentially construct a snapshot of a particle and compare to experiment. These properties can be experimentally determined by extracting “form factors” from the elastic scattering of electrons, scattering in which the object being struck recoils but remains intact. The resolution of the image, or **resolving power**, is determined by the momentum that is transferred to the object—the higher the momentum transfer, the higher the resolution. From the first measurement of the size of the proton by Hofstadter in the 1950s, to some of the most important discoveries to emerge from JLab, form factors have played a critical role in our evolving understanding of hadron structure.

The Strange-Quark Form Factors of the Nucleon

While the three valence quarks of the proton are two up (u) quarks and one down (d) quark, there are also quark-antiquark pairs—termed sea quarks—due to quantum fluctuations. For many years, there were both theoretical and experimental reasons to believe that the strange sea quarks might play a significant role in the nucleon's structure; a better understanding of the role of strange quarks became an important priority.

Two notable accomplishments presented in the 2007 LRP were constraints on the contributions of strange quarks to the electric and magnetic properties of the proton obtained through the study of parity violation in electron scattering. In such measurements, polarized electrons are scattered from unpolarized targets, and one looks for tiny changes in the scattering of electrons when the beam spin is reversed. Such changes represent a violation of the parity (or “mirror”) symmetry and are due to the weak force, the only force that behaves differently in a “looking glass” world. These experiments measure the weak-force equivalent of the charge and magnetism distributions, which can be combined with precision electromagnetic data to disentangle the strange-quark contributions. The time period since the 2007 LRP has seen the successful conclusion of this experimental program, which conclusively shows that strange-quark contributions to nucleon form factors are consistent with zero and not more than a few percent.

Parity-violating electron scattering is an important part of JLab's program and will continue to be so in the future. Examples include the Qweak experiment, which measured the "weak charge" of the proton, and PREX, which measured the radius of the neutron distribution in lead. Future proposed experiments include PREX-II, CREX, MOLLER, and a program utilizing the SoLID detector. These experiments are covered in Chapters 3–5.

Flavor Separated Form Factors of the Nucleon

At the time of the 2007 LRP, the elastic form factors of the proton were known to much higher momentum transfer than was the case for the neutron. A lingering discrepancy also remained between the determinations of the proton form factors between two experimental methods, ascribed to the probability that two photons rather than one were exchanged in the electron scattering process. The latter hypothesis has been the topic of experiments comparing electron and positron scattering and appears correct. Furthermore, the range over which the neutron's form factors are known has now more than doubled. This, together with the aforementioned constraints on strange-quark form factors, has made it possible to extract the form factors associated with u and d quarks individually by combining data from both the proton and the neutron.

The results are illustrated in Figure 2.1. Surprisingly, the u- and d-quark contributions differ with increasing Q^2 or resolving power. Several theoretical interpretations of their behavior seem to suggest the presence of *diquark-like structures* within the nucleon, structures in which two of the quarks in the nucleon are much closer to one another than they are to the third quark. Such diquark-like structures have long been hinted at by baryon spectroscopy (see the "Hadron Spectroscopy" section), so it is exciting to see possible evidence for them in a very different context.

One of the important goals of JLab's 12-GeV upgrade is to push our knowledge of the elastic nucleon form factors into new territory. For the proton, the range of momentum transfer will be significantly increased, and the precision will be dramatically improved. For the neutron, the range of momentum transfer will be nearly tripled. The "Super Bigbite Spectrometer" (SBS) under construction in JLab's Hall A will be critical here. Given the important discoveries that have already emerged from form-factor measurements at JLab, the discovery potential of these new measurements is considerable.

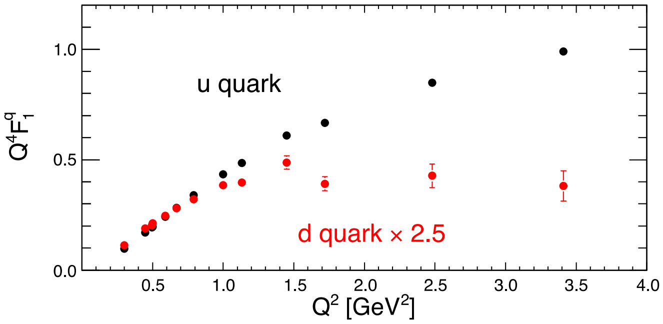


Figure 2.1: *The u- and d-quark contributions to the nucleon form factors and their surprising difference. The extraction of these quantities was made possible by measuring the neutron form factors to high values of momentum transfer. The range will be tripled with JLab's 12-GeV Upgrade.*

A Puzzle Surrounding the Size of the Proton

Physicists around the world are seeking a solution to a puzzle concerning the charge radius of the proton. Recent results from precise atomic spectroscopy using muonic hydrogen found the radius to be seven standard deviations smaller than the previous accepted value extracted from a combination of form-factor measurements using electron scattering and atomic spectroscopy using conventional hydrogen. Theorists are exploring ways to explain this discrepancy, including the possibility that it is due to physics beyond the Standard Model. New generations of precise experiments are planned to address the mystery, including the PRad experiment at JLab (electron scattering at very small angles) and the muon-scattering MUSE experiment at the Paul Scherrer Institut (PSI).

The Charged Pion Form Factor

The pion plays a unique role in nature. It is the lightest quark system, with a single valence quark and a single valence antiquark. It is also the particle responsible for the long range character of the strong interaction that binds the atomic nucleus together. Physicists believe that the underlying rules governing the strong interaction are left-right—that is, chirally—symmetric. If this were completely true, the pion would have no mass. But the chiral symmetry of massless QCD is broken dynamically by quark-gluon interactions and explicitly by inclusion of light quark masses, giving the pion mass. Thus, the pion is seen as key to confirm the mechanisms that dynamically generate nearly all of the mass of hadrons and central to the effort to understand hadron structure.

With such strong theoretical motivation, the study of the pion form factor is one of the flagship goals of the JLab 12-GeV Upgrade. It will be studied using a new instrument, the "Super-High Momentum Spectrometer"

Sidebar 2.1: Solving the Structure of Hadrons and Light Nuclei with Lattice QCD

The building blocks of nuclei, protons and neutrons, are comprised of quarks and gluons. Quantum chromodynamics (QCD), the theory describing the interactions of quarks and gluons, is well known, and its equations can be written down in an elegant manner. QCD has had tremendous successes, for example, it allows direct comparisons of its predictions with experiments at high energies, where "deep inelastic scattering experiments" have beautifully revealed the quark and gluon substructure of protons, neutrons, and nuclei. However, precise descriptions of many low-energy properties of even the simplest systems, such as protons and neutrons, have remained elusive. A top priority of nuclear physics has been to develop first-principles predictive capabilities for low-energy processes described by QCD.

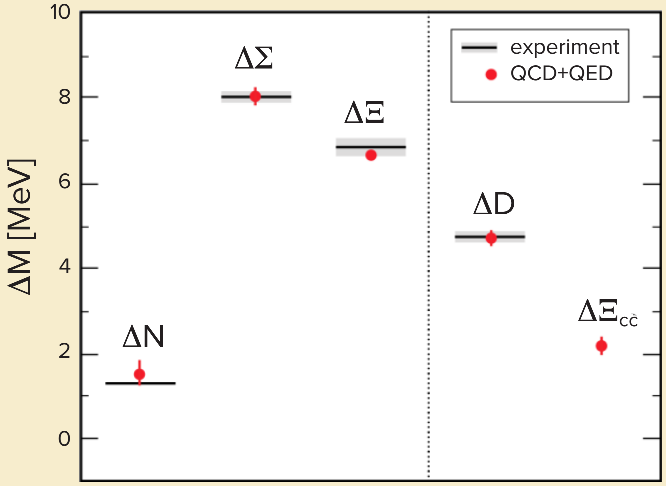


Figure 1: *Shown are the mass differences between "isospin pairs" of baryons, such as a proton and a neutron (ΔN), and other unstable isospin pairs. Experimental values (gray bands) are compared with LQCD, including electromagnetic effects (red points). It is remarkable that differences in these baryon masses at the level of one part in a thousand can now be precisely calculated from first principles.*

To achieve predictive capability, a numerical technique to perform QCD calculations has been developed: lattice QCD (LQCD). LQCD combines breathtaking advances in high-performance computing, innovative algorithm and software development, and conceptual breakthroughs in nuclear theory. In LQCD, space and time are described as points on a grid. Quarks and gluons are also defined on this grid, and their interactions with one another can be calculated numerically. Next, a widely used set of approaches to computer simulations, known as Monte Carlo methods, is employed. Basically, a large number of computer-generated configurations of the quantum fields are created and analyzed, and out of this process the true behavior of the quarks and gluons emerges. In principle, any level of accuracy can be obtained, limited only by computational resources and available work force.

The progress in LQCD calculations since the 2007 Long Range Plan has been dramatic. For the first time, calculations are being performed using the physical quark masses rather than the artificially increased masses that were needed previously. The effects of electromagnetism are being included as well. In Figure 1, the impressive agreement of calculated and measured mass differences between isospin partners amongst the hadrons confirms that QCD provides an accurate description of strongly interacting matter.

Underscoring this huge progress, LQCD plays an essential role in guiding experimental work. GlueX at JLab, one of the flagship experiments of the 12-GeV Upgrade, is designed to search for exotic particles where the "glue" is in an energetically excited state. Initial LQCD calculations motivated the experiment and guided its design. Recent LQCD results confirm the mass range of the predicted particles. And in the future, LQCD calculations of hadron dynamics will play a critical role in the analysis of the data.

Tremendous progress has been made in the calculation of hadron-hadron scattering probabilities. Phase shifts and mixings describing the low-energy scattering behavior have been successfully calculated for elastic pion-pion scattering, including mapping out the shape of the rho resonance, and, recently, for multi-channel scattering. The mixing is highlighted in the extraction of resonance information in pion-kaon scattering when the inelastic eta-kaon channel also contributes. These studies illustrate the practicality of extracting physical scattering (S-matrix) elements from LQCD and have opened a whole new era of lattice computations of hadron dynamics.

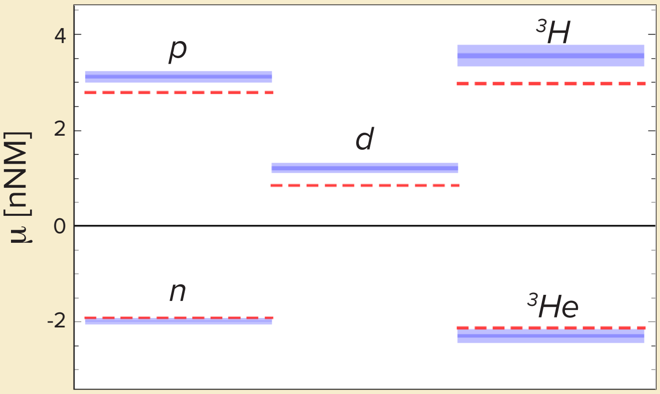


Figure 2: *In an impressive tour-de-force, scientists have now calculated the properties and structure of light nuclei with LQCD. Shown here are the magnetic moments of the proton, neutron, deuteron, ^{3}He, and triton. The red dashed lines show the experimentally measured values. The solid bands are the result of LQCD calculations with a pion mass of 805 MeV.*

It has even become possible to calculate the properties of light nuclei. Nuclear scientists have managed to extract the magnetic moments of the lightest nuclei from LQCD calculations, with reasonable agreement with experimental values as shown in Figure 2. We anticipate, within the next several years, precision calculations of light nuclei, their properties, their structure, and their reactions.

With the growing capability to perform precise LQCD calculations of many quantities of crucial importance to the mission of nuclear physics, including the properties and structure of hadrons and light nuclei and the forces between them, we are truly entering a golden era.

(SHMS) in Hall C. As is illustrated in Figure 2.2, SHMS will nearly quadruple the momentum transfer over which the pion form factor is known. These measurements will probe a broad regime in which the phenomenology of QCD begins to transition from large- to short-distance-scale behavior.

Expressions of Chiral Dynamics in Hadrons

The special status of pions and kaons in QCD and their marked impact on the long-distance structure of hadrons can be systematically encoded in an effective theory, applicable to processes at low energy. This effective theory, as well as emerging LQCD calculations, can provide benchmark predictions for so-called polarizabilities that parameterize the deformation of hadrons due to electromagnetic fields, spin fields, or even internal color fields. Great progress has been made in determining the electric and magnetic polarizabilities. Within the next few years, data are expected from the High Intensity Gamma-ray Source (HIγS) facility that will allow accurate extraction of proton-neutron differences and spin polarizabilities. JLab also explores aspects of this physics. The most precise measurement of the neutral-pion decay rate, exactly calculable from fundamental constants, was already done at JLab, and with the 12-GeV Upgrade the pion polarizability and decays of other light pseudoscalar mesons will be measured.

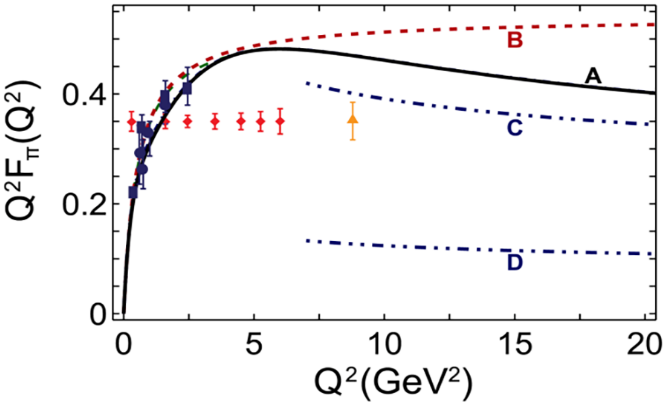


Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

The 1D Picture of How Quarks Move within a Hadron

Whereas form factors provide a picture of hadrons as a whole, a technique called deep inelastic scattering (DIS) is used to access their quark substructure. In DIS, high-energy electrons scatter hard off individual quarks, and the proton or neutron is essentially destroyed in the collision. By measuring the angle of the scattered electron and the energy it loses in the collision, it is possible to discern the fraction of the nucleon's momentum that was carried by the struck quark. This fraction is referred to as the *longitudinal* momentum fraction x. The probability of finding a quark with a specific momentum fraction x is what is referred to as a parton distribution function (PDF). In short, the PDFs provide us with a one-dimensional (1D) picture describing the motion of the quarks within the hadron.

In DIS, the momentum fraction x of the quark off which an electron scatters provides insight into whether the quark was most likely a valence quark (larger values of x) or a sea quark (smaller values of x). Naively, if a hadron were composed of three quarks, we might expect each quark to carry about 1/3 of the momentum. Because the quarks are bound and exchanging gluons, however, they can carry a momentum fraction anywhere from 0 to 1. JLab turns out to be an excellent place to study the valence-quark region, very roughly from around 0.1 up to values approaching unity.

The Quark Valence Structure

One feature of the valence quark structure that is of particular interest is the ratio d(x)/u(x) in the limit of the momentum fraction x approaching one. Here d(x) and u(x) are the PDFs for the d and u quarks, respectively. While in general it is not yet possible to calculate PDFs from first principles, near x=1, there are some definite model predictions for the ratio of d/u, making such a measurement a powerful test of our understanding of hadronic structure within QCD.

The ratio d/u will be measured (see Figure 2.3) using the 12-GeV upgraded CEBAF in multiple ways. In the early years, it will be measured by comparing scattering from the mirror nuclei ^{3}He and ^{3}H, as well as by handpicking events where the scattering takes place off a near-free neutron in ^{2}H. Later, the ratio can be accessed by measuring the aforementioned parity-violating effect in DIS with the foreseen SoLID detector.

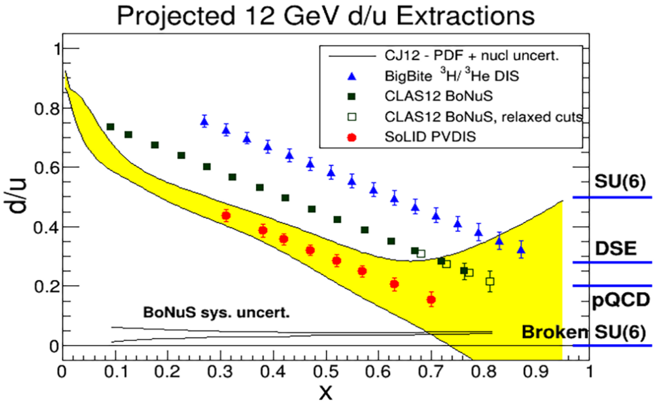


Figure 2.3: *Projected uncertainties (offset for display) for JLab 12-GeV measurements of the ratios of the PDFs for the d and u quarks at large momentum fraction x. The yellow band represents the uncertainty in the existing measurements under several theoretical assumptions. Various predictions for this ratio in the limit of x = 1 are given by the blue lines.*

Of similar interest are the spin-dependent PDFs, $\Delta u(x)$ and $\Delta d(x)$, that quantify the orientation of the spin of u and d quarks. Both $\Delta u(x)/u(x)$ and $\Delta d(x)/d(x)$ are predicted to approach unity as the momentum fraction x approaches 1. Whether this is the case or not, and, if true, the manner in which they do so, provides important insight on nucleon structure. Measurements of these quantities at JLab provided early hints that quark orbital angular momentum plays an important role in nucleon structure. With the 12-GeV Upgrade, the spin structure of the valence region will be mapped out in exquisite detail.

The Sea Quark and Gluon Structure

In atomic systems, the particle-antiparticle pairs induced by quantum fluctuations play a relatively minor role. In contrast, in strong interactions, quark-antiquark pairs are readily produced as a result of the relatively large magnitude of the strong force, and they form an integral part of the nucleon's structure.

While JLab will measure the ratio d/u for the valence quarks, other experiments will measure a similar ratio for the light (sea) antiquarks, $\bar{d}/\bar{u}$. This ratio was originally assumed to be unity, as quantum fluctuations are creating both. Experiments using the Drell-Yan process (in which a quark from one nucleon annihilates with a sea antiquark from another nucleon) observed $\bar{d}$ quarks to be more prevalent than $\bar{u}$ quarks, a smoking gun for a definite role of sea quarks in nucleon structure. SeaQuest at Fermi National Accelerator Laboratory (FNAL) exploits this process to measure $\bar{d}/\bar{u}$ to higher values of x, a region where $\bar{u}$ may well become prevalent. A proposal is being discussed to upgrade SeaQuest with a polarized beam and target that could point to whether light sea quarks have orbital angular momentum.

At RHIC, the production of W bosons in polarized proton-proton collisions serves as an elegant tool to study both the unpolarized and the spin-dependent PDFs for intermediate regions of the momentum fraction x. The data from RHIC have provided the first evidence that the spin carried by $\bar{u}$ quarks ($\Delta\bar{u}$) differs from that of $\bar{d}$ quarks ($\Delta\bar{d}$) as evidenced in Figure 2.4, which shows a global analysis incorporating RHIC data. This asymmetry between u and d quarks in the sea again underscores the role of sea quarks in nucleon structure. As discussed in Sidebar 2.6 of the EIC subchapter, the RHIC program has also led to our first real glimpse of the quantity known as ΔG, the fraction of the proton spin carried by the intrinsic spin of the gluons. This important development, indicating that ΔG is nonzero and positive, represents the first fruit of more than a decade of effort in this direction.

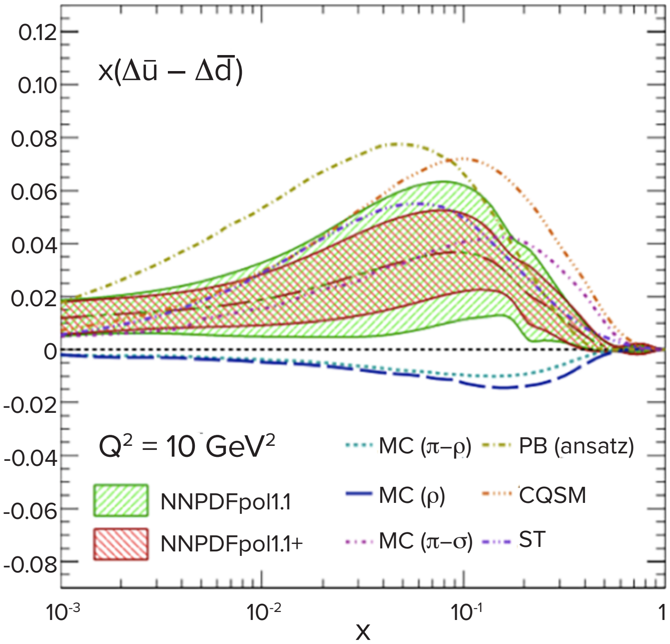


Figure 2.4: *The difference between the $\Delta\bar{u}$ and $\Delta\bar{d}$ spin functions as extracted from the NNPDF global analysis. The green (red) band shows the present (final expected) uncertainties from analysis of the RHIC W data set. Various model calculations are also shown.*

A Multidimensional View of Nucleon Structure

"With 3D projection, we will be entering a new age. Something which was never technically possible before: a stunning visual experience which 'turbocharges' the viewing." This quotation from film director J. Cameron could just as well describe developments over the last decade or so in hadron physics, in which a multidimensional description of nucleon structure is emerging that is providing profound new insights. Form factors tell us about the distribution of charge and magnetization but contain no direct dynamical information. PDFs allow us to access information on the underlying quarks and their longitudinal momentum but tell us nothing about spatial locations. It has now been established, however, that both form factors and PDFs are special cases of a more general class of distribution functions that merge spatial and dynamic information. Through appropriate measurements, it is becoming possible to construct "pictures" of the nucleon that were never before possible.

3D Spatial Maps of the Nucleon: GPDs

Some of the important new tools for describing hadrons are Generalized Parton Distributions (GPDs). GPDs can be investigated through the analysis of *hard exclusive processes*, processes where the target is probed by high-energy particles and is left intact beyond the production of one or two additional particles. Two processes are recognized as the most powerful processes for accessing GPDs: deeply virtual Compton scattering (DVCS) and deeply virtual meson production (DVMP) where a photon or a meson, respectively, is produced.

One striking way to use GPDs to enhance our understanding of hadronic structure is to use them to construct what we might call 3D spatial maps (see Sidebar 2.2). For a particular value of the momentum fraction *x*, we can construct a spatial map of where the quarks reside. With the JLab 12-GeV Upgrade, the valence quarks will be accurately mapped.

GPDs can also be used to evaluate the total angular momentum associated with different types of quarks, using what is known as the Ji Sum Rule. By combining with other existing data, one can directly access *quark orbital angular momentum*. The worldwide DVCS experimental program, including that at Jefferson Lab with a 6-GeV electron beam and at HERMES with 27-GeV electron and positron beams, has already provided constraints (albeit model dependent) on the total angular momentum of the u and d quarks. These constraints can also be compared with calculations from LQCD. Upcoming 12-GeV experiments at JLab and COMPASS-II experiments at CERN will provide dramatically improved precision. A suite of DVCS and DVMP experiments is planned in Hall B with CLAS12; in Hall A with HRS and existing calorimeters; and in Hall C with HMS, the new SHMS, and the Neutral Particle Spectrometer (NPS). These new data will transform the current picture of hadronic structure.

3D Momentum Maps of the Nucleon: TMDs

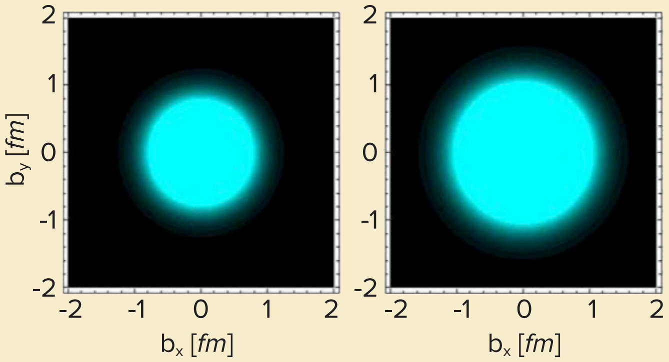
Other important new tools for describing nucleon structure are transverse momentum dependent distribution functions (TMDs). These contain information on both the longitudinal and transverse momentum of the quarks (and gluons) inside a fast moving nucleon. TMDs link the transverse motion of the quarks with their spin and/or the spin of the parent proton and are, thus, sensitive to orbital angular momentum. Experimentally, these functions can be investigated in proton-proton collisions, in inclusive production of lepton pairs in Drell-Yan processes, and in *semi-inclusive deep inelastic scattering* (SIDIS), where one measures the scattered electron and one more meson (typically a pion or kaon) in the DIS process.

Sidebar 2.2: The First 3D Pictures of the Nucleon

A computed tomography (CT) scan can help physicians pinpoint minute cancer tumors, diagnose tiny broken bones, and spot the early signs of osteoporosis. Now physicists are using the principles behind the procedure to peer at the inner workings of the proton. This breakthrough is made possible by a relatively new concept in nuclear physics called generalized parton distributions.

An intense beam of high-energy electrons can be used as a microscope to look inside the proton. The high energies tend to disrupt the proton, so one or more new particles are produced. Physicists often disregarded what happened to the debris and measured only the energy and position of the scattered electron. This method is called inclusive deep inelastic scattering and has revealed the most basic grains of matter, the quarks. However, it has a limitation: it can only give a one-dimensional image of the substructure of the proton because it essentially measures the momentum of the quarks along the direction of the incident electron beam. To provide the three-dimensional (3D) picture, we need instead to measure all the particles in the debris. This way, we can construct a 3D image of the proton as successive spatial quark distributions in planes perpendicular to its motion for slices in the quark's momentum, just like a 3D image of the human body can be built from successive planar views.

An electron can scatter from a proton in many ways. We are interested in those collisions where a high-energy electron strikes an individual quark inside the proton, giving the quark a very large amount of extra energy. This quark then quickly gets rid of its excess energy, for instance, by emitting a high-energy photon. The quark does not change identity and remains part of the intact target proton. This specific process is called deeply virtual Compton scattering (DVCS). For the experiment to work, the scientists need to measure the speed, position, and energy of the electron that bounced off the quark, of the photon emitted by the quark, and of the reassembled proton. From this information the 3D picture of the proton can be constructed.



The first 3D views of the proton: the spatial charge densities of the proton in a plane (bx, by) positioned at two different values of the quark's longitudinal momentum x: 0.25 (left) and 0.09 (right).

Very recently, using the DVCS data collected with the CLAS detector at JLab and the HERMES detector at DESY/Germany, the first nearly model-independent images of the proton started to appear. The result of this work is illustrated in the figure, where the probabilities for the quarks to reside at various places inside the proton are shown at two different values of its longitudinal momentum x (x = 0.25 left and x = 0.09 right). This is analogous to the "orbital" clouds used to depict the likely position of electrons in various energy levels inside atoms. The first 3D pictures of the proton indicate that when the longitudinal momentum x of the quark decreases, the radius of the proton increases.

The broader implications of these results are that we now have methods to fill in the information needed to extract 3D views of the proton. Physicists worldwide are working toward this goal, and the technique pioneered here will be applied with Jefferson Lab's CEBAF accelerator at 12 GeV for (valence) quarks and, later, with a future EIC for gluons and sea quarks.

In these experiments, the quark struck in the scattering process must, as it cannot exist in isolation, join with an antiquark partner or two quark partners to form new hadrons. The latter process is called fragmentation. The hadron resulting from the fragmentation process retains a memory of the original transverse motion of the quark and can, thereby, present new information about the transverse momentum dependence of the quark within the nucleon. The correlations of spin and the transverse momentum of quarks give rise to asymmetries in the distributions of the produced particles. One source of such asymmetries is the correlation between the transverse momentum of the quark and the transverse spin of the parent proton, the so-called Sivers function.

A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum. Indeed, it has been measured to be nonzero in the HERMES and JLab experiments. Figure 2.5 shows the unique potential of the JLab 12-GeV program to map the Sivers function for the up quark. The Sivers function has a quite intriguing property predicted by QCD. When measured in SIDIS, it will have one sign, yet when measured in a collision with a proton or pion beam, it should have the opposite sign. This sign change is due to the nature of QCD color interactions and provides an important test of our understanding. It is imperative that the quark Sivers functions that will be measured in SIDIS are also accurately measured with hadron beams, such as the proton beams available at RHIC or Fermilab and the pion beams used by the COMPASS-II experiment at CERN.

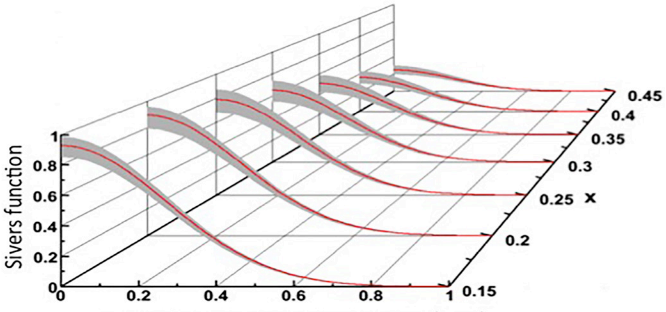


Figure 2.5: *Maps of the Sivers function for up quarks as a function of transverse momentum and at different values of the longitudinal momentum fraction x, as projected for 12-GeV JLab data.*

Pioneering SIDIS experiments from JLab, HERMES, and COMPASS have provided initial information about TMDs and hint that valence u and d quarks differ in their transverse momentum distributions. This behavior is independently suggested by LQCD calculations that also point to a flavor and spin dependence of transverse momentum. The JLab 12-GeV era can move this field to a new level of sophistication. Precision measurements in semi-inclusive pion and kaon production from unpolarized, as well as longitudinally and transversely polarized proton and neutron targets, will allow access to both flavor and spin dependent transverse momentum distributions in the valence quark region. Multiple instruments bring essential elements to this campaign: SBS, CLAS12, HMS-SHMS, and the proposed NPS. Finally, the proposed multipurpose SoLID detector (see Figure 2.6) would realize the full potential of the upgraded CEBAF. RHIC will contribute by utilizing transversely polarized beams to make the first measurements in hadronic collisions to probe antiquark and gluon TMDs with the forward upgrades proposed for STAR and PHENIX. These efforts will benefit from the polarized and unpolarized fragmentation results to be extracted from the e^+e^- collision data from Belle, Belle II, and Babar.

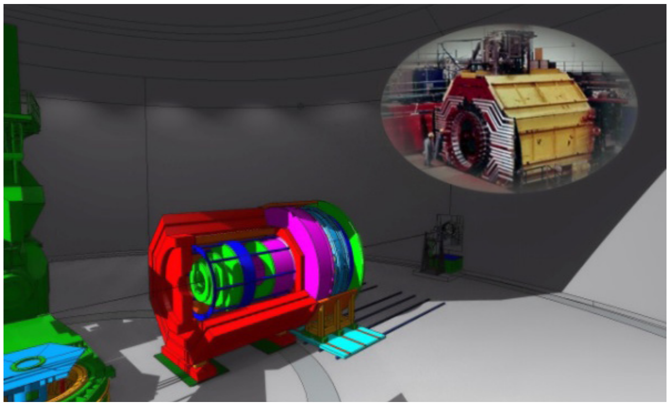


Figure 2.6: *The envisioned SoLID experiment in Hall A is centered around the CLEO-II magnet (insert) that will be relocated to JLab to enable a rich multipurpose science program. SoLID boasts large acceptance detection with operability at extremely high luminosities and offers unprecedented opportunities to provide precision 3D imaging of the motion of valence quarks in the nucleon and to probe the Standard Model.*

HADRON SPECTROSCOPY

Atomic spectroscopy has been a crucial tool for studying the electromagnetic interactions that bind electrons to the nucleus. Likewise, hadron spectroscopy illuminates the QCD interaction that binds quarks. While the proton and neutron contain the two lightest valence quarks (up and down), other hadrons composed of these light quarks or of more massive quarks (strange, charm, and bottom) and their corresponding antiquarks can be created in energetic collisions produced by particle accelerators. Once produced, these hadrons decay promptly, allowing one to measure only a few of their properties, such as their mass, charge, and angular momentum. Studying patterns of hadrons classified by these properties provides insight into and provokes questions about the inner workings of QCD.

The observed patterns of states suggest, perhaps surprisingly, that almost all hadrons fall into two classes: baryons that contain three valence quarks, like the proton and neutron, and mesons that contain a valence quark and a valence antiquark. In principle, QCD allows hadrons made of two quarks and two antiquarks (tetraquarks), four quarks and an antiquark (pentaquarks), and infinitely many other configurations. Recently, physicists studying the spectrum of heavy mesons formed with charm and bottom quarks have uncovered evidence that supports the existence of tetraquark and pentaquark hadrons. Understanding the properties of these new states of QCD may illuminate why nature prefers hadrons with relatively few quarks.

The Three-Quark Arena: Chasing the Missing Baryons
A major experimental initiative continues to be the search for the so-called “missing baryons.” If each of the three quarks in a baryon interacted equally, one would predict the existence of more baryons than observed by experiments. The experimental data are, therefore, suggestive of a more intricate manifestation of QCD in baryons. For example, two quarks may strongly bind with each other, forming a “diquark” that interacts more weakly with the third quark. Determining whether the missing baryons really do not exist or are just not yet discovered will guide our understanding.

Jefferson Lab has been engaged in a vigorous program to search for these missing states by trying to produce them in photon-induced collisions, in contrast to most of the earlier searches using hadron beams. Analysis of recent data from JLab has substantiated the existence of five additional excited baryon states that now appear in the compilation of known hadrons published in the *Review of Particle Physics*. This breakthrough was enabled by the polarized beam and polarized target capabilities of JLab. The new capabilities of the 12-GeV era facilitate a detailed study of baryons containing two and three strange quarks. Knowledge of the spectrum of these states will further enhance our understanding of the manifestation of QCD in the three-quark arena.

The Gluon: Force Mediator and Constituent Particle?
One of the most intriguing puzzles of QCD is understanding the role that gluons play in hadrons. Gluons mediate the strong force; quarks in hadrons interact with each other by emitting and absorbing gluons. However, gluons also interact with each other, suggesting that gluons could bind together like quarks. The consequences of this unique self-interacting property of gluons should give rise to new states of matter composed entirely of gluons or quark-gluon hybrids. Recent breakthroughs in theoretical techniques have enabled physicists to perform LQCD calculations of the complete spectrum of both the conventional and experimentally elusive hybrid mesons. These calculations indicate, for the first time, that the gluonic component of hybrid mesons has specific dynamical properties, an understanding that can be tested with experimental data.

The GlueX experiment in Hall D at JLab has been designed to utilize the unique photon beam capability of the 12-GeV Upgrade to search for these hybrid mesons formed with light quarks. The JLab spectroscopy program, which is well underway with the successful operation of the GlueX detector in 2014, will be augmented by the multi-purpose CLAS12 apparatus in Hall B. Planned future detector upgrades are essential to enable a complete study of hadrons composed of all three flavors of light quarks: up, down, and strange.

The 12-GeV Upgrade of JLab will permit a detailed exploration of light quark hadrons and is the centerpiece of experimental hadron spectroscopy in the U.S. in the next decade. Collaboration with complementary facilities abroad to study hadrons composed of heavier quarks is a critical ingredient in a complete study of the spectrum. In addition, a theory-based initiative, like the Joint Physics Analysis Center at JLab, geared at developing techniques for conducting a global data analysis, will augment the experimental knowledge of the hadron spectrum. These experimental observations can then be compared to emerging QCD-based theoretical calculations to understand the role that gluons play in the structure of matter.

QCD AND NUCLEI

Nuclei are bound systems of nucleons (protons and neutrons), much like molecules are assembled from atoms. Many aspects of nuclear binding can be described quite well through various effective interactions. However, to fully understand and predict nuclear properties, we need to find out how the binding forces between nucleons emerge from the fundamental theory of QCD and give rise to nuclei. Impressive progress in this direction has recently been achieved with LQCD (Sidebar 2.1). In addition, we need to find out how the internal QCD structure of nucleons is related to, and in turn, is affected by nuclear binding.

The Short-Range Structure of Nuclei

Of particular interest is the interaction of nucleons that are relatively close to each other, so that their internal structure might be expected to come into play. This "short-range interaction" is responsible for the fact that most nuclei have roughly the same density, and ultimately determines the stability and size of neutron stars. While nucleons mostly move at moderate speeds inside nuclei (up to 30% of the speed of light), their short-range encounters can impart significantly higher momentum to each of them and make them move swiftly in opposite directions. Such high-momentum correlations, long predicted by nuclear theory, provide an excellent way to study the short-range part of the nucleon-nucleon interaction and have recently been identified and characterized in detail by experiments at JLab.

In these experiments a fascinating feature came to light. Nearly all of the observed correlations are between two nucleons of the opposite type—one proton and one neutron—while proton-proton and neutron-neutron correlations are ten times less likely. This leads to the somewhat paradoxical result that even in heavy nuclei, where neutrons are more common than protons, the "minority" protons are more likely to be part of a high-momentum pair than the neutrons. This incredibly important feature of the nucleon-nucleon interaction has implications for the behavior of cold, dense nuclear matter in general, such as that found in a neutron star.

Quark Properties in Nuclei—The EMC Effect

If we want to understand the role of QCD in nuclei, one obvious question is how the nuclear environment affects the quark-structure of nucleons. One answer is provided by the EMC effect, named after the European Muon Collaboration that first observed it 30 years ago. They found that the probability of DIS off a quark inside a large nucleus decreases significantly with the momentum fraction x carried by the quark over the range $x = 0.3–0.7$, relative to the same probability inside a free nucleon. This result indicates that valence quarks tend to carry a smaller fraction of the momentum of nucleons tightly bound in nuclei than in free nucleons. A full understanding of this striking EMC effect has remained elusive until now.

Recent precise data from JLab on this probability ratio in light nuclei, as shown in Figure 2.7, show a striking feature. It has long been known that the EMC effect becomes more pronounced for heavier nuclei, which seemed to indicate that it might depend on A, the total number of nucleons in the nucleus, or on the *average* nuclear density. The JLab data indicate, however, that the EMC effect depends on the *local* nuclear density. This is illustrated strikingly in the case of ^{9}Be, which can be described as two "alpha clusters" (4-nucleon configurations similar to ^{4}He nuclei) and one extra neutron. These three subunits essentially orbit in a fairly large volume, giving ^{9}Be a relatively small *average* nucleon density. Most of the nucleons off of which an electron can scatter, however, are contained in one of the two clusters, where there is a relatively high *local* nucleon density. The pronounced EMC effect in ^{9}Be strongly suggests that it is the local density that drives the modification.

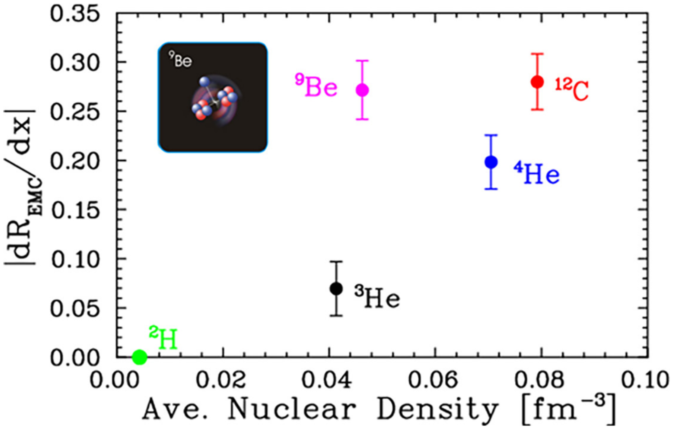


Figure 2.7: *Results from precise measurements at JLab of the slope of the EMC effect in light nuclei. They reveal that the fairly "dilute" nucleus of beryllium behaves more like the dense carbon nucleus than the similarly dilute ^{3}He nucleus, suggesting the quark distributions depend on the local rather than the average nuclear environment.*

This observation led scientists to a fascinating connection between the aforementioned two-nucleon correlations and the EMC effect in a nucleus. Put simply, the number of two-nucleon correlated pairs found in a given nucleus appears to be directly proportional to 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.

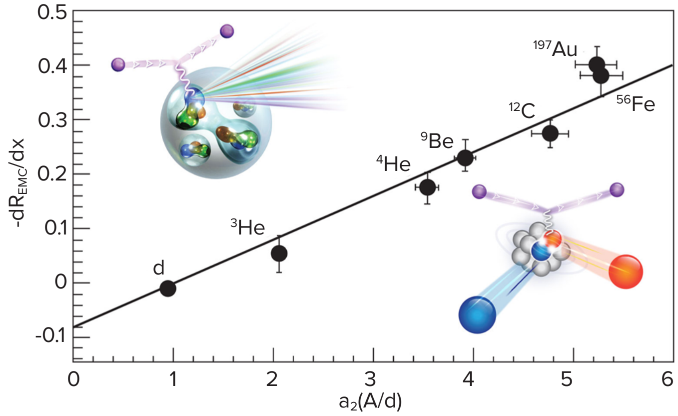


Figure 2.8: *This plot illustrates, for a sample of eight nuclei, the apparent linear relationship between a parameter that characterizes the number of two-nucleon correlated pairs, $a_2(A/d)$, and the strength (i.e., the slope) of the EMC effect. A clear correlation is evidenced by the straight line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

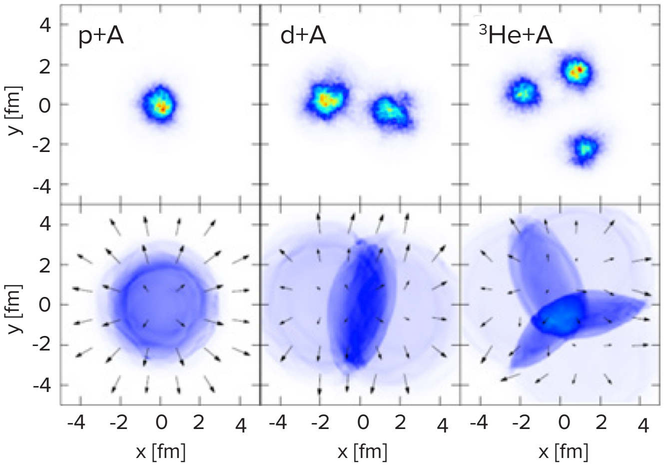


Figure 2.9: *Simulated initial energy deposition for individual collisions of protons, deuterons, and helium-3 on large nuclei (above) and the QGP geometry resulting from hydrodynamic flow (below).*

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.

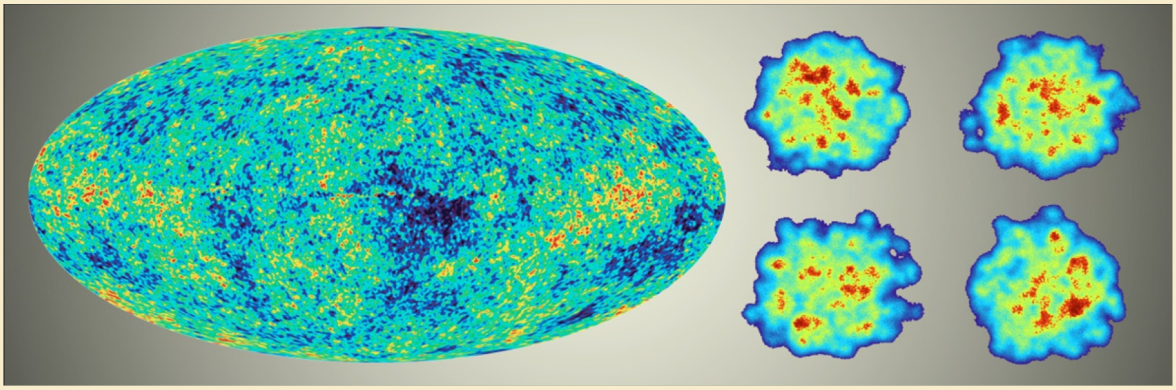
DOPING QGP WITH QUARKS TO MAP ITS PHASE DIAGRAM

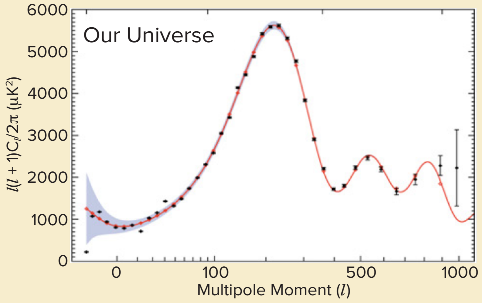
In the highest energy RHIC and LHC collisions and in the early universe, liquid QGP contains almost as many antiquarks as quarks. In the language of condensed matter physics, this is undoped QGP. It would be impossible to understand strongly correlated electron systems in condensed matter physics if 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.

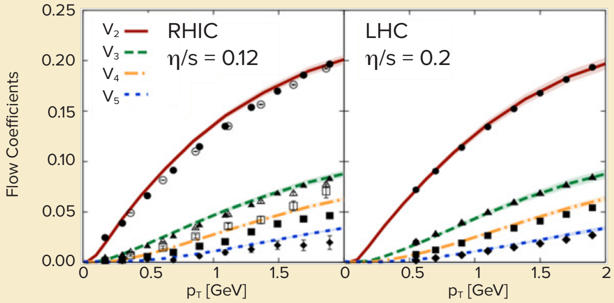
Rigorous theory calculations using lattice QCD tell us that the transition in which undoped QGP cools and forms hadrons is a rapid but smooth crossover. In contrast, QGP that is doped may experience instead a sharp first order phase transition as it cools, with bubbles of QGP and bubbles of hadrons coexisting 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 (figure, 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.

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.

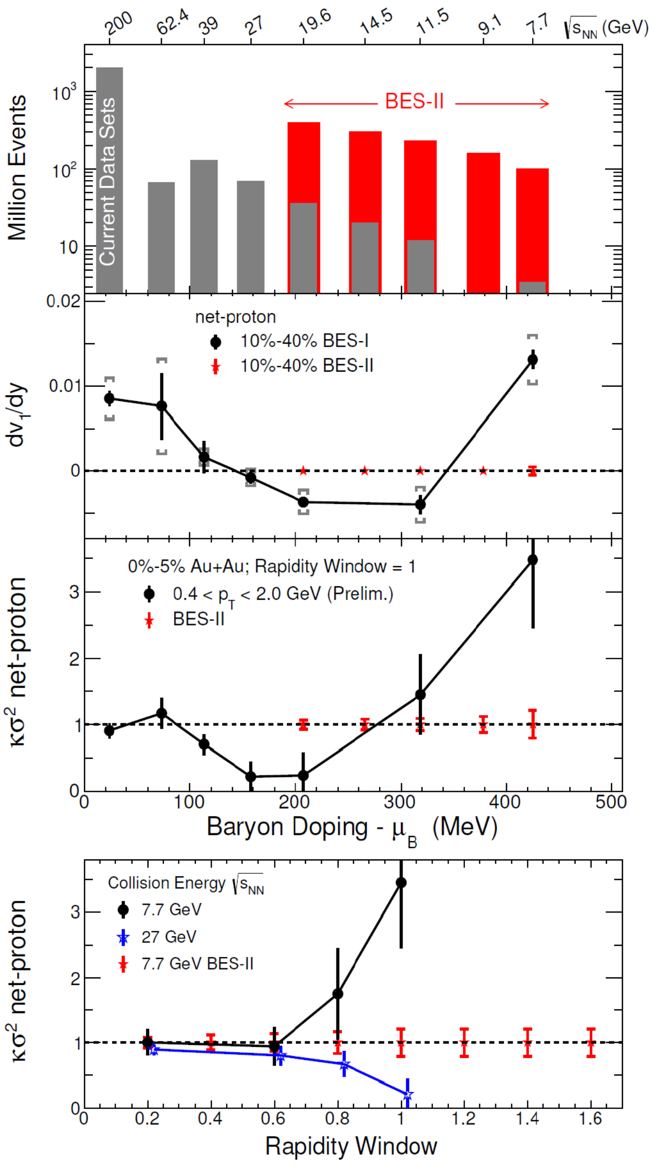
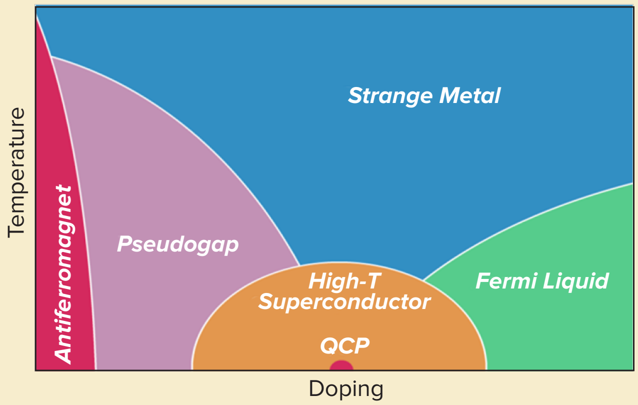


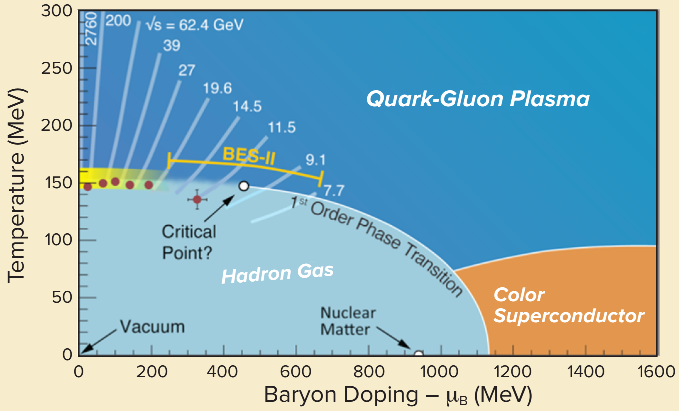
Figure 2.10: *The top panel shows the increased statistics anticipated at BES-II; all three lower panels show the anticipated reduction in the uncertainty of key measurements. RHIC BES-I results indicate nonmonotonic behavior of a number of observables; two are shown in the middle panels. The second 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.*

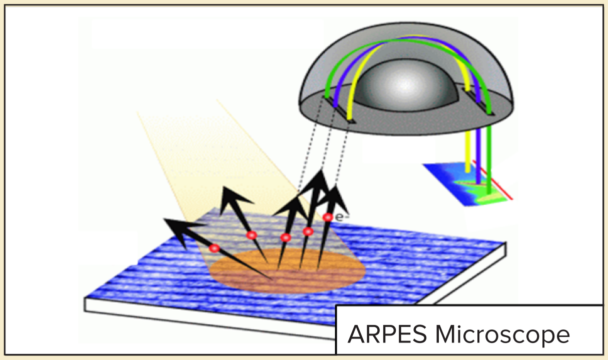
Microscopy requires suitable messengers that reveal what is happening deep within QGP, playing a role analogous to light in an ordinary microscope. The

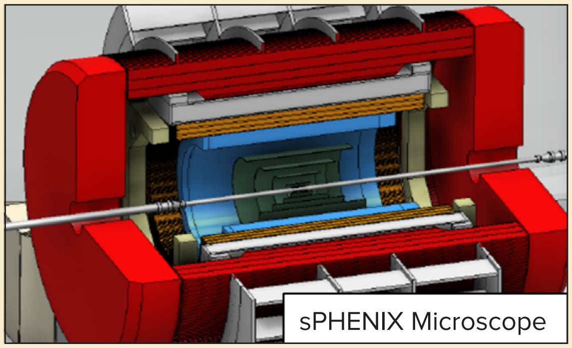
Sidebar 2.4: The States of QCD Matter

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.

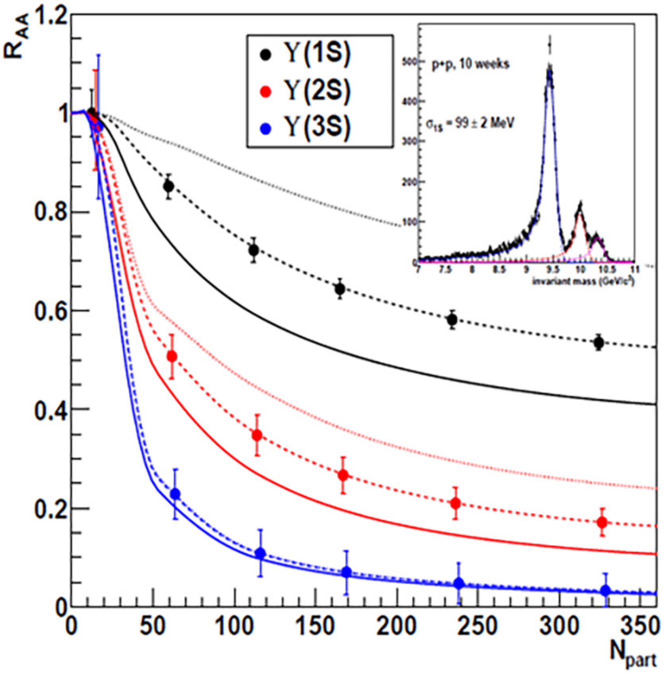


Figure 2.11: *The projected sPHENIX mass separation of the three upsilon states (in the inset) and the projected accuracy of measuring their nuclear suppression in collisions with varying impact parameters. Three sets of theory curves show the melting dependence on the degree of fluid perfection.*

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.

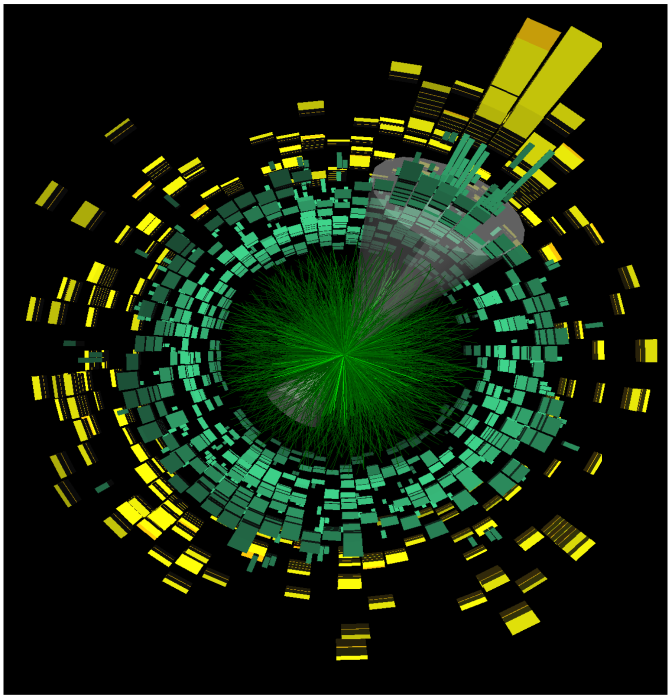


Figure 2.12: *A single LHC heavy-ion collision with one high energy jet (upper right) and no apparent partner jet—because it has been quenched by the QGP produced in the collision.*

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.

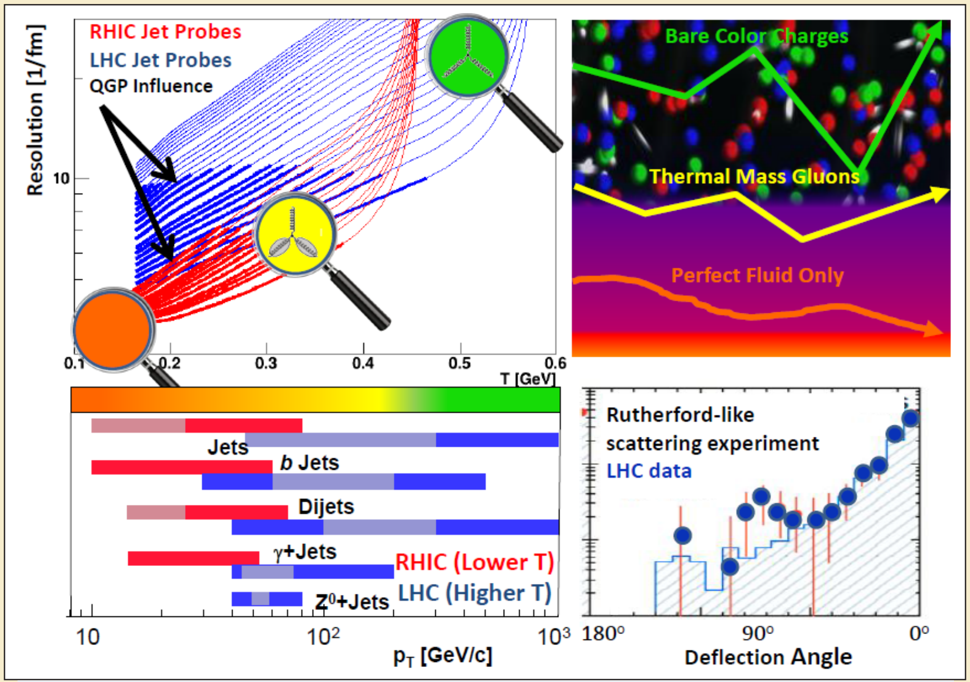
One path to realizing the potential of jets as microscopes is illustrated in Sidebar 2.5. The pointlike quarks and gluons that become visible if the microscopic structure of QGP can be resolved make it more likely that jets, or

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.

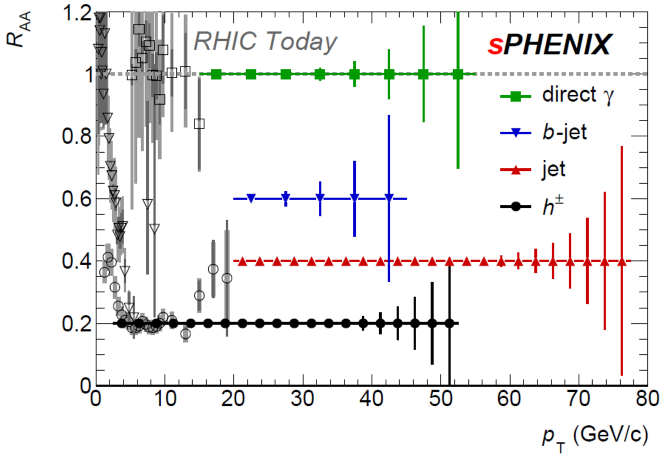


Figure 2.13: *Future reach of four precision measurements via jets for probing the most strongly coupled liquid with sPHENIX, in color, compared to current measurements from RHIC where available, in grey.*

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 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 and protons—indeed, nearly all the mass of the visible universe—can be built up from an assembly of massless gluons and nearly massless quarks.

In order to understand how the properties and structure of nuclear matter emerge from the dynamics encoded in QCD, it is essential to precisely image gluons and sea quarks and to understand the role they and their interactions play in protons, neutrons, and nuclei. For example, we do not know how gluons are distributed in space; are they confined to the same volume as the quarks within protons and neutrons? Understanding how the gluons are distributed in space and in momentum in the nucleon will offer the first dramatic glimpse of the gluon's orbital angular momentum contribution to the nucleon's spin (see Sidebar 2.6) and provide essential clues toward understanding the important QCD phenomenon of confinement.

Gluons are special in that they can split into two or more gluons that share the parent gluon's momentum. This splitting leads to a proliferation of low-momentum gluons in normal nuclear matter: the lower the momentum of the constituents observed, the larger the number of gluons we see (see Sidebar 2.7). These low-momentum gluons are so abundant that they can make significant cumulative contributions to such static properties of the proton and neutron as mass and spin, even if each individual gluon contributes little.

The gluon proliferation has to be bounded in order to prevent runaway growth in the probability of neutron and proton interactions at high energy. QCD provides a natural self-defense mechanism because two or more gluons can also recombine. It is predicted that, at very high gluon densities, the probability for gluons to recombine will counterbalance the probability for gluons to split, leading to saturation of the gluon density and to a form of gluonic matter with universal properties that occurs inside nucleons and other hadrons, as well as inside all nuclei. When the density saturates, the gluons are anticipated to act collectively, rather than independently, presenting themselves as an intense color field to a high-energy probe.

It seems counterintuitive that electron scattering, long used to great effect in the study of nuclear structure, should also provide a precise probe for gluons and gluon-dominated matter, which carry no electric charge. But both the photon exchanged in the electron scattering process and the gluons can fluctuate into quark-antiquark pairs, which can interact either through their electric or color charges. The interactions via these intermediary quark-antiquark pairs are now understood sufficiently well to permit the precise extraction of the distributions of gluons.

Thus, in order to probe the role of gluons and sea quarks and discover if nature adheres to the predictions of dense, and ultimately saturated, gluon matter, a new accelerator facility is required: the Electron Ion Collider. The EIC must make a qualitative leap in technical capabilities beyond previous electron scattering programs. It must reach collision energies far higher than are available at the upgraded CEBAF. It will surpass the earlier electron-proton collider HERA at DESY in Hamburg, Germany, by providing the following capabilities:

- Spin-polarized proton and light ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin;
- Heavy-ion beams to reach much higher gluon densities than with proton beams, providing the essential discovery potential to approach and reach the gluon saturation regime;
- Extensive energy variability to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter;
- Collision rates (luminosity) 100–1000 times higher, allowing unprecedented three-dimensional imaging of the gluon and sea quark distributions in order to explore correlations among them.

By precisely imaging gluons and sea quarks inside the proton and nuclei, the EIC will address some of the deepest issues regarding the emergence of nuclear properties from QCD:

- How are the gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of sea quark and gluon orbital motion in building the nucleon spin?
- What happens to the gluon density in nuclei at high energy? Does it saturate, giving rise to a gluonic matter component with universal properties in all nuclei, even the proton?

- How do gluons and sea quarks contribute to the nucleon-nucleon force, as manifested in the internal landscape of light nuclei?

- How does the nuclear environment affect quark and gluon distributions and interactions inside nuclei? Do the abundant low-momentum gluons remain confined within nucleons inside nuclei?

- How does nuclear matter respond to a fast moving color charge passing through it? How do quarks of different flavor dress themselves in nuclear matter to emerge as colorless hadrons? What does this dressing process tell us about the mechanisms by which quarks are normally confined inside nucleons?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide them. The new experimental capabilities will be complemented by theoretical advances in LQCD calculations and in effective field theory approaches that are being developed explicitly for the gluon-dominated regime.

SCIENCE HIGHLIGHTS AT THE ELECTRON ION COLLIDER

The EIC, with high energy and high luminosity polarized beams, will unite and extend the scientific programs at CEBAF and RHIC in dramatic and fundamentally important ways, as illustrated in the following subsections by highlights of relevant theoretical calculations and simulations under realistic experimental conditions.

The Proton as a Laboratory for QCD

How are the gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of sea quark and gluon orbital motion in building the nucleon spin?

How Does the Proton Get Its Spin?

The decomposition of the proton's overall intrinsic spin into quark and gluon contributions remains a fascinating open question (see Sidebar 2.6). State-of-the-art QCD analyses of recent measurements at RHIC have shown that individual gluons that carry more than a few percent of a proton's momentum have a preference to align their own intrinsic spins along that of the proton's overall spin, thereby accounting for approximately 30–40% of the total. This contribution is similar to that from quarks and antiquarks. But even with anticipated further polarized proton collision runs, RHIC does not have the kinematic reach to meaningfully constrain the extrapolation of gluon spin preferences to the abundant lower-momentum gluons. Consequently, there is still a large uncertainty in the *net* contribution of gluons to the proton's spin, as reflected in the vertical extent of the blue band in Figure 2.14. Our knowledge of the gluon spin contribution, and to a smaller extent the net quark spin contribution, is limited by the limited range in parton momentum fraction (*x*) explored so far. The EIC would greatly increase the kinematic coverage in *x* and resolving power Q^2 for polarized deep inelastic scattering experiments, as shown in Figure 2.15. By probing the abundant lower-momentum gluons and sea quarks, EIC experiments will reduce the spin contribution uncertainties dramatically, as shown by red and yellow bands in Figure 2.14, providing a much clearer picture of how the proton's spin emerges from QCD.

Motion of Quarks and Gluons in a Proton

In addition to contributions to the overall proton spin from preferential spin orientations of quarks and gluons, there can be contributions from the orbital motion of quarks and gluons within the proton (see Sidebar 2.6). Such orbital contributions can be probed by orienting the spin of the beam protons perpendicular to their direction of motion and then looking for preferences for the partons inside to move toward one side or the other (see Figure 2.16). Such transverse motional preferences would be revealed precisely by EIC measurements, where one detects the scattered electron in coincidence with an emitted hadron emerging near the direction of the struck parton. For example, the contours in Figure 2.16 illustrate how such measurements could reveal a preference for up sea quarks to move toward the right within a proton that is itself moving out of the page at nearly light speed, with its spin pointing upward. Such unprecedented images illuminate correlations among partons that help to produce such emergent properties as the proton's spin. These images are simply unattainable without the polarized electron and proton beams and the high collision rates of the EIC.

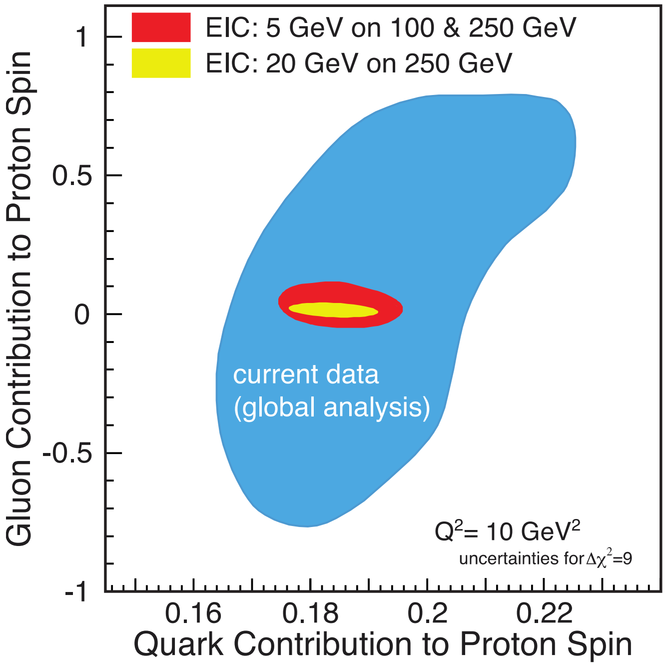


Figure 2.14: *The projected reduction in the uncertainties of the net gluon and net quark spin contributions to the proton's spin for EIC electron energies of 5 (red) and 20 (yellow) GeV.*

Tomographic Images of the Proton

Deep inelastic scattering (DIS) experiments carried out at EIC collision rates will provide for the first time 3D images of gluons in the proton's internal landscape. Of particular interest are exclusive measurements, where one detects an outgoing meson in coincidence with the scattered electron with sufficient resolution to confirm that the proton has been left intact by the scattering process. For example, the detection of exclusive J/ψ meson production would provide unprecedented maps (Figure 2.17) showing how the gluons are distributed in space within a plane perpendicular to the parent proton's motion. These particular maps encode vital information, inaccessible without the EIC, on the amount of proton spin associated with the gluons' orbital motion.

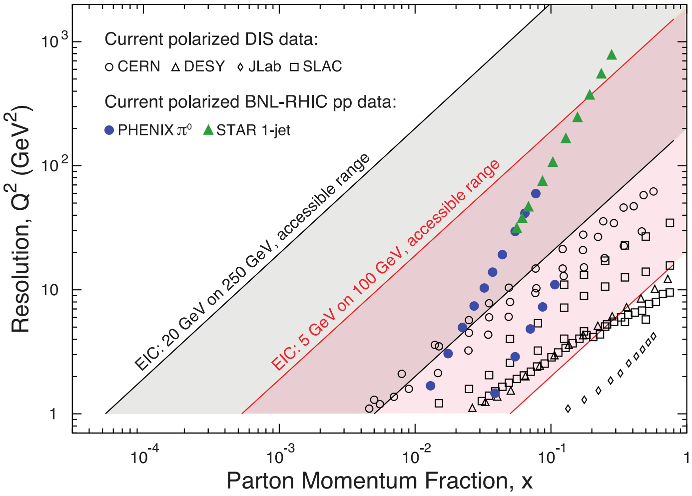


Figure 2.15: *The increased coverage (colored bands) over existing experiments (point symbols) that EIC polarized electron-proton collisions will provide in parton momentum fraction and resolving power.*

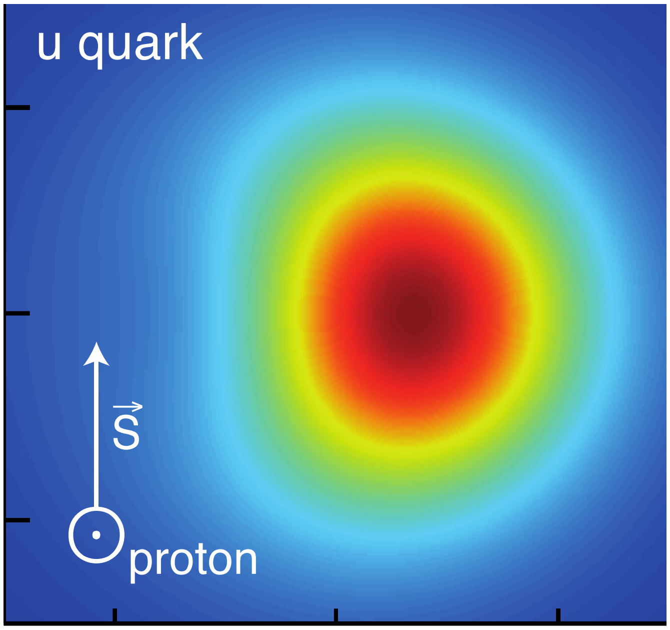


Figure 2.16: *A simulation based on projected EIC data of the transverse motion preferences of an up sea quark within a proton moving out of the page, with its spin pointing upward. The color code indicates the probability of finding the up quarks.*

Proton Spin at the EIC and Lattice QCD

The ability of LQCD calculations to reproduce many features of the hadron spectrum is a testimony to striking recent advances in our treatment of quark and gluon interactions from first principles. An important recent breakthrough in LQCD methodology now provides the promise of precision future comparisons of theory with such detailed EIC measurements of proton spin structure as the images and distributions in Figures 2.16 and 2.17. Such comparisons will not only bring deep insight into the origin of the spin but will also shed light on the role the abundant gluons play in generating the proton's mass and confining quarks and gluons inside the proton.

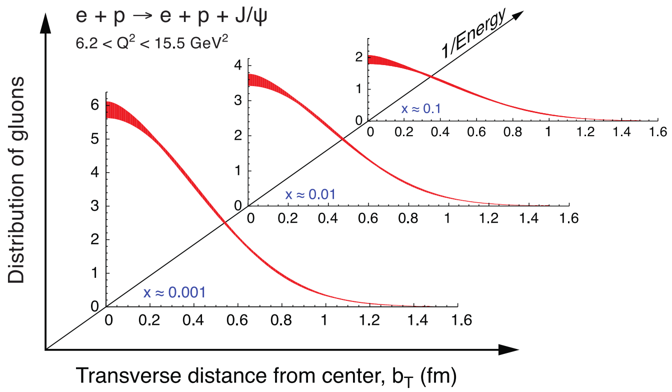


Figure 2.17: *Projected measurement precision for gluon distributions in transverse space inside a proton, obtained from exclusive J/ψ production at the EIC. Projections are shown for three different bins in the fraction of the proton's momentum carried by the gluons.*

Nuclei as a Laboratory for Emergent QCD Phenomena

How do gluons and sea quarks contribute to the nucleon-nucleon force, as manifested in the internal landscape of light nuclei?

The ability of the EIC to collide electrons with nuclei, from light to heavy and at varying energies, presents us with new and exciting ways to study and understand nuclear matter. The use of light nuclei with 2 to 12 nucleons, whose nuclear structure is experimentally well studied and well described by existing models, will allow us to *study* the nucleon-nucleon force at short distances but from the point of view of quarks and gluons. The recently discovered intriguing correlation between the quark motion inside the nucleus and the nucleon-nucleon force at short distance would be further elucidated by such studies at the EIC. Detection of spectators (those nuclear fragments that do not participate in the DIS process) from a nucleus can identify the active nucleon and study the nuclear binding effects and what role the partons play in them.

QCD Matter at Extreme Gluon Density

What happens to the gluon density in nuclei at high energy? Does it saturate, giving rise to a gluonic matter component of universal properties in all nuclei, even the proton? How does the nuclear environment affect quark and gluon distributions and interactions inside nuclei? Do the abundant low-momentum gluons remain confined within nucleons inside nuclei?

When fast-moving hadrons are probed at high energy, the low-momentum gluons contained in their wave functions become experimentally accessible (see Sidebar 2.7). By colliding electrons with heavy nuclei moving at near light speed, the EIC will provide access to an uncharted regime of all nuclear matter, where abundant gluons saturate in density and dominate its behavior. This regime, falling below the colored surface in Figure 2.18, is accessible with *heavy-ion* beams at the EIC, while much higher collision energies would be required to reach it in electron-proton collisions. The nuclear “oomph” experienced by a high-energy probe arises due to the coherent effects of gluons contributed by many nucleons. The probe no longer resolves individual quarks and gluons in the nucleus but rather samples strongly correlated matter. Gluons in the matter are as closely packed as possible; strong interactions, among the strongest in nature, ensure nuclei are stable against endless gluon proliferation.

This maximal close packing allowed by nature in collisions with certain energy establishes a resolution scale, denoted by Q_s, corresponding to sizes smaller than those of hadrons. The existence of this scale allows theorists to compute the properties of this remarkable matter, describing it as a color glass condensate (CGC). Previously, quarks and gluons were believed to form a nearly free gas of weakly interacting partons at very high resolution Q^2 and very strongly interacting confined matter on lower, hadron-size, resolution scales. As illustrated in Figure 2.18, gluon saturation suggests a new emergent regime in QCD where matter is not easily characterized as weakly or strongly interacting but has aspects of both.

A striking prediction of the CGC theory is that at very high energies, the properties of gluon matter in a nucleus are independent of its detailed structure; they can be expressed entirely in terms of ratios of Q_s and the resolution momentum scale Q of the external probe. Because of the claim that it controls the bulk of strong interaction phenomena at high energies, the study of this conjectured universal gluon matter is of high scientific interest and curiosity. At an EIC, theory predictions for the evolution of collective gluon dynamics toward this remarkable universal state can be explored and tested with precision by varying the energy, resolution, and atomic number for a large number of measurements. These will span, to the widest extent ever, the space

Sidebar 2.6: Nucleon Spin: So Simple and Yet So Complex

The simple fact that the proton carries spin 1/2, measured in units of Planck's famous constant, is exploited daily in thousands of magnetic resonance imaging images worldwide. Because the proton is a composite system, its spin is generated from its quark and gluon constituents. Physicists' evolving appreciation of how the spin might be generated, and of how much we have yet to understand about it, is an illustrative case study of how seemingly simple properties of visible matter emerge from complex QCD interactions.

Quarks are also spin 1/2 particles, and at any given moment an individual quark may spin in the same or the opposite direction of its proton host, respectively, making a positive or negative contribution to the total proton spin. Physicists originally expected the sum of quark spins to account for most of the proton's spin but were quite surprised when experiments at CERN and other laboratories showed that the spins of all quarks and antiquarks combine to account for no more than about 30% of the total. This result has led nuclear scientists to address the more daunting challenges involved in measuring the other possible contributions to the spin illustrated in Figure 1. The gluons also have an intrinsic spin (1 unit) and might be "polarized" (i.e., might have a preferential orientation of their spins along or opposite the proton spin). And just as the earth orbits around the sun while simultaneously spinning about its own axis, the quarks and gluons in a proton could have orbital motion that would also contribute to the overall proton spin.

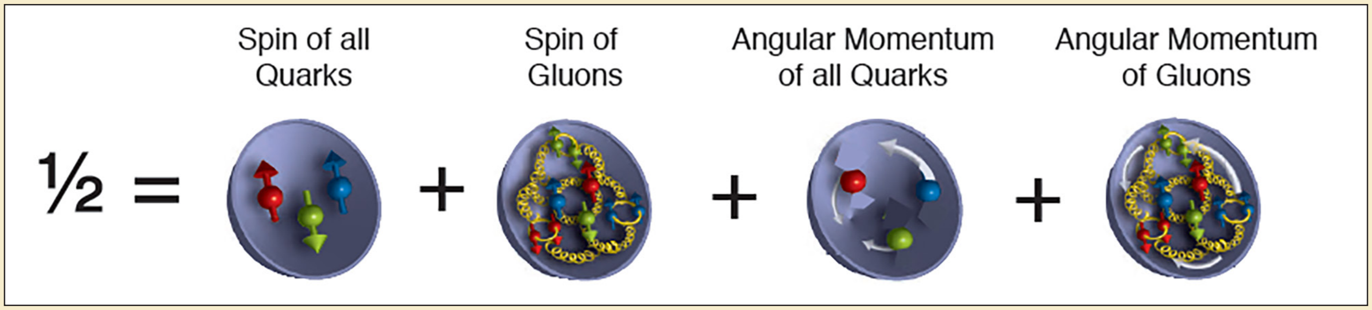


Figure 1: *A schematic view of the proton and its potential spin contributions.*

So how much of the spin comes from the spin of gluons? The first important constraints have come from recent measurements at RHIC, which provides the world's first and only polarized proton collider capability at high energy. There, the STAR and PHENIX experiments have used the polarized quarks in one proton as a scattering probe to reveal that the gluons in the other proton are indeed polarized. Just as critical has been the development of the theoretical framework to integrate the RHIC measurements into a global QCD analysis to constrain both quark and gluon spin preferences. Results of those analyses are shown in Figure 2.

The protons at RHIC move at nearly the speed of light, and each quark and gluon inside carries a fraction x of the proton's overall momentum. The widths of the colored bands in Figure 2 illustrate the uncertainties in the summed spin of all gluons that carry more than a fraction x_{min} of the proton's momentum, with the value of x_{min} indicated on the horizontal axis. For each dataset, the uncertainties grow significantly at low x_{min} as the contributions have not been directly measured there.

In a significant breakthrough, the RHIC results to date (light blue band in Figure 2) indicate that the gluon spins do indeed have a non-negligible orientation preference for x above 5%. But they tell us very little about whether the much more abundant lower-momentum gluons may reinforce or counterbalance this preference. This leaves a large uncertainty in the total gluon spin contribution, indicated at the left edge of the plot, which can be reduced by analysis of anticipated RHIC polarized proton data (the darker blue band). However, this still would leave the overall uncertainty at a level that remains larger than the entire proton spin itself. Only an EIC (yellow band) can uniquely settle how much of the overall spin is contributed by the spins of quarks, antiquarks, and gluons combined.

If this summed spin contribution is not enough to account for the total, orbital angular momentum of quarks and/or gluons must come to the rescue. Here again, the EIC will provide a wealth of relevant data. Orbital angular momentum depends on the correlation between positions and momenta of the quarks and gluons, information contained within unprecedented three-dimensional images of the sea quark and gluon distributions that will become available with the EIC.

The quest to understand how the proton gets its spin has led us naturally to study the distributions of quarks and gluons—in space, in momentum, and in spin preference—from low to high resolution scales, providing important clues on the inner structure of the proton in terms of the dynamics of quarks and gluons. Experiments at RHIC, at the 12-GeV Upgraded CEBAF at Jefferson Lab, and the COMPASS experiment at CERN all provide some pieces of this puzzle. However, *only* a future EIC can fully reveal what makes up the proton spin.

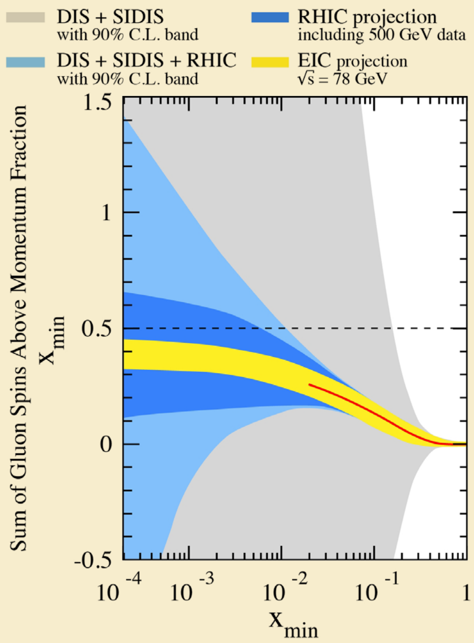


Figure 2: *Constraints on the spin sum of gluons carrying more than a fraction x_{min} of the proton's momentum. The width of each band represents the range of values allowed by existing and projected DIS and RHIC spin data.*

illustrated in Figure 2.18 to confirm the existence of and, hence, extract the properties of saturated gluon matter.

Evidence regarding the saturation regime can be obtained at an early stage of EIC operations by measuring diffractive cross sections. In these measurements, the nucleus remains intact despite the enormous energy of its collision with the electron. When combined with the total DIS cross-section (in electron+proton and electron+nucleus collisions), diffractive measurements at the EIC, as shown in Figure 2.19, will be able to distinguish between CGC models containing the saturation window shown in Figure 2.18 and those that do not. The EIC will, therefore, provide the first unambiguous evidence for whether the transition from a dilute gas of quarks and gluons to the closely packed regime of proliferated gluons has been achieved.

Further, the wavelike features of quantum mechanics can be exploited in such measurements to extract essential information on where the saturated gluons are localized in nuclei. Visualize the electron beam exchanging a photon with the nucleus and that this photon can fluctuate into a quark-antiquark pair, which acts as a microscope sensitive to the gluons in the nucleus. Because of the wave-particle duality of quantum mechanics, the quark-antiquark system can scatter as a wave off gluon locations in the nucleus, producing diffraction patterns analogous to those produced by light waves. Thus, just as light waves inform us about spatial distributions in a diffraction grating, the reconstituted quark-antiquark system (for example, a phi-meson) leaving the nucleus intact provides fundamental information on where gluons are localized. Such measurements of exclusive production of the phi or other mesons in electron-nucleus collisions are unique to an EIC and are an extraordinarily powerful tool, providing spatial information to complement the energy and resolution landscape in Figure 2.18, both above and below the saturation surface.

Relevance of EIC Measurements to LHC/RHIC Results

Besides its fundamental interest, information from the EIC on the location, fluctuations, and correlations within saturated gluon matter in the nuclear wave functions will provide a unique perspective—complementary to what can be learned from heavy- ion collisions—on two aspects of results from RHIC and LHC. These aspects are how the perfect liquid QGP is formed so rapidly, and how spatial inhomogeneities in the colliding gluon fields are imprinted on the QGP and then transported to the final state by the perfect liquid. With regard to the former, recent experiments at RHIC and LHC provide surprising evidence of collective behavior in rare high multiplicity configurations generated even when light ions collide with heavy ions. It is possible that this evidence reflects collective behavior that was already present in the initial saturated gluon states of the colliding nuclei, in which case analogous DIS measurements at the EIC should show similar features. Alternatively, the RHIC and LHC evidence might indicate the formation of small QGP droplets even in light-ion-heavy-ion collisions, in which case EIC experiments should not show similar effects.

With regard to the second aspect mentioned above, highly precise data are becoming available from the RHIC and LHC heavy-ion collisions on anisotropic patterns in particle emission that reflect early QGP matter density distortions of progressively more complex geometry. Comparisons of these anisotropies to hydrodynamic models can be used to extract the transport properties of the QGP with precision and to constrain the shape distributions of the initial state. The complementary constraints on the initial state extracted from EIC measurements will help facilitate the high-precision extraction of the viscosity and other transport coefficients in the QGP liquid.

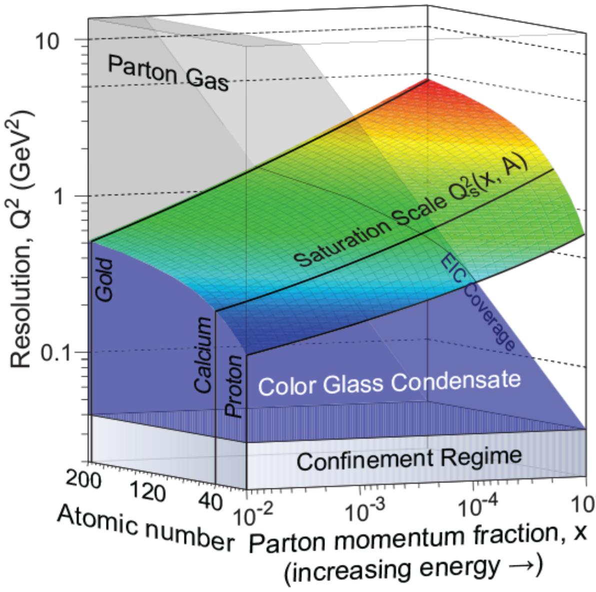


Figure 2.18: *The schematic QCD landscape in probe resolving power (increasing upward) vs. energy (increasing toward the right), as a function of the atomic number of the nucleus probed. Electron collisions with heavy nuclei at the EIC will map the predicted saturation surface (colored surface) with the CGC region below that surface. Spatial distributions extracted from exclusive reactions (see text) will help demarcate the CGC region from the confinement regime.*

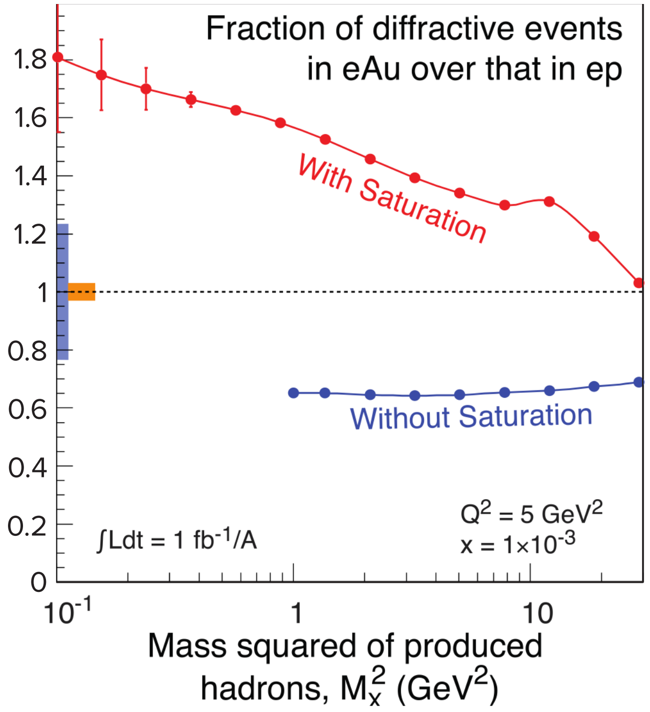


Figure 2.19: *The ratio of diffractive over total cross section for DIS on a gold nucleus normalized to DIS on a proton, for different values of the mass-squared of hadrons produced in the collisions, predicted with (red curve) and without (blue curve) gluon saturation. The projected experimental uncertainties are smaller than the plotted points while the range of each model's prediction (shaded bands on the left side) is smaller than the difference caused by saturation.*

Formation of Hadrons and Energy Loss

How does nuclear matter respond to a fast moving color charge passing through it? How do quarks of different flavor dress themselves in nuclear matter to emerge as colorless hadrons? What does this dressing process tell us about the mechanisms by which quarks are normally confined inside nucleons?

The emergence of hadrons from quarks and gluons is at the heart of the phenomenon of color confinement in QCD. The dynamical interactions of energetic partons passing through nuclei or QGP provide unique analyzers, probing the poorly understood evolution from colored partons to color neutral hadrons. As envisioned in Figure 2.20, a nucleus in a collision at the EIC would provide a femtometer size "detector" to monitor the evolution from partons to hadrons.

For example, EIC experiments will measure the difference between producing light π mesons (containing up and down quarks) and heavy D^0 mesons (containing a charm quark) in both electron+proton and electron+nucleus collisions. These measurements will provide critical information on the response of cold nuclear matter to fast moving quarks with different masses (compare π to D^0 production) and lengths of color neutralization (small versus large nucleus size). The dramatic difference between the production of a π and D^0 meson, shown in Figure 2.21, caused by the predicted mass-dependence of the quark energy loss, would be easily discernible at the EIC. The difference between model I and model II for light quarks reflects the current limits of our knowledge on the formation of a pion from a colored quark, commonly known as hadronization. Through the study of hadronization in DIS, the EIC presents us with the tools to dial with precision the formation of light and heavy hadrons inside or outside the nuclear medium. This will offer a fresh window into how quarks and gluons are confined in nuclear matter and in vacuum. The precision data that will become available at the EIC on the energy loss of quarks and gluons in cold nuclear matter will provide an important benchmark complementing similar studies of the response of the hot QGP to fast moving quarks.

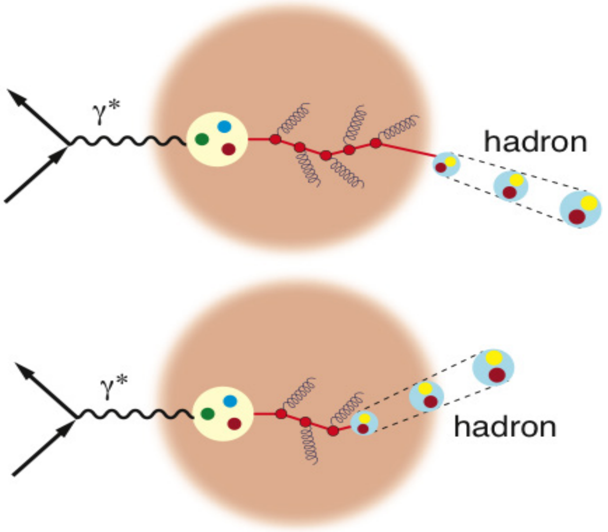


Figure 2.20: *A schematic illustrating the interaction of a struck parton moving through cold nuclear matter, with hadrons formed either outside (top) or inside (bottom) the nucleus.*

EIC: Why Now and Why in the U.S.?

Our view of the structure of atomic nuclei and the nucleons they contain has made quite a transformation in the last few decades. The most common picture found in textbooks shows a simple three-valence quark structure of the nucleon, yet we now know that the inside of the nucleon is rather a complex many-body system with a large number of gluons and sea quarks. There is unambiguous evidence that they both play surprisingly important roles for defining the structure of nuclear matter around us. Their quantitative study and understanding require a novel sophisticated tool, the EIC. The key machine parameters the EIC should have to address the compelling questions described above are well established.

- Polarized (~70%) electrons, protons, and light nuclei
- Ion beams from deuterons to the heaviest stable nuclei
- Variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV
- High collision luminosity ~10^{33-34} $cm^{-2}sec^{-1}$
- Possibly have more than one interaction region

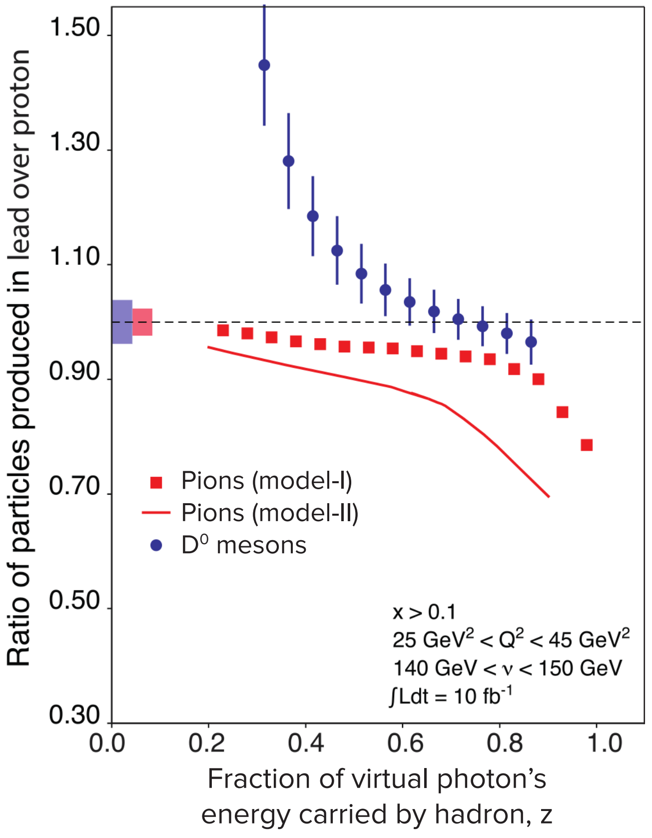


Figure 2.21: *Model predictions of the ratio of cross sections for producing a pion (light quarks, red) or a D^0 meson (heavy quarks, blue) in electron+Pb to electron+proton DIS collisions plotted as a function of z, the fraction of the virtual photon's momentum carried by the produced hadron. Projected measurement uncertainties are sufficient to clearly distinguish the effects of nuclear passage as a function of both momentum and energy transfer with the exchanged photon and struck quark mass.*

The realization of the EIC will require the same core expertise that led to the versatility of the polarized proton and heavy-ion beams at RHIC, at Brookhaven National Laboratory, and the unique polarized electron beam properties of CEBAF at Jefferson Lab. This expertise at the U.S. laboratories will be crucial in meeting the technical challenges to realize the versatile range of kinematics, the broad range in ion beam species, and the high luminosity and beam polarization at the EIC: all critical to addressing the most central questions for QCD matter, while at the same time maintaining U.S. leadership in the fields of nuclear and accelerator science.

A set of compelling physics questions related to the role of gluons and sea quarks in nuclear matter has been formulated, and a corresponding set of measurements at the EIC identified. A powerful formalism that connects those measurements to the QCD structure of hadrons and nuclei has been developed. We have articulated ways in which the EIC would provide unique and precise information on emergent dynamics of sea quarks and gluons in the structure of nuclear matter. However, if history of emergent phenomena in other subfields of physics is any guide, surprises and unanticipated novel directions of study can be expected with high probability. This is especially likely for the EIC since much of the gluon- and sea- quark dominated region it will explore in nuclei and polarized protons is *terra incognita*.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as “embodying the vision for reaching the next QCD frontier.” In 2013 the NSAC Subcommittee report on Future Scientific Facilities declared an EIC to be “absolutely essential in its ability to contribute to the world-leading science in the next decade.” The strong and worldwide interest in a U.S.-based EIC has been rapidly growing. Countries such as China, France, India, Italy, and Japan have expressed strong interest in collaborating on the physics, the detector, and the accelerator technologies. Now is the time to realize the EIC in the U.S.

Sidebar 2.7: An Evolving Picture of Nuclei

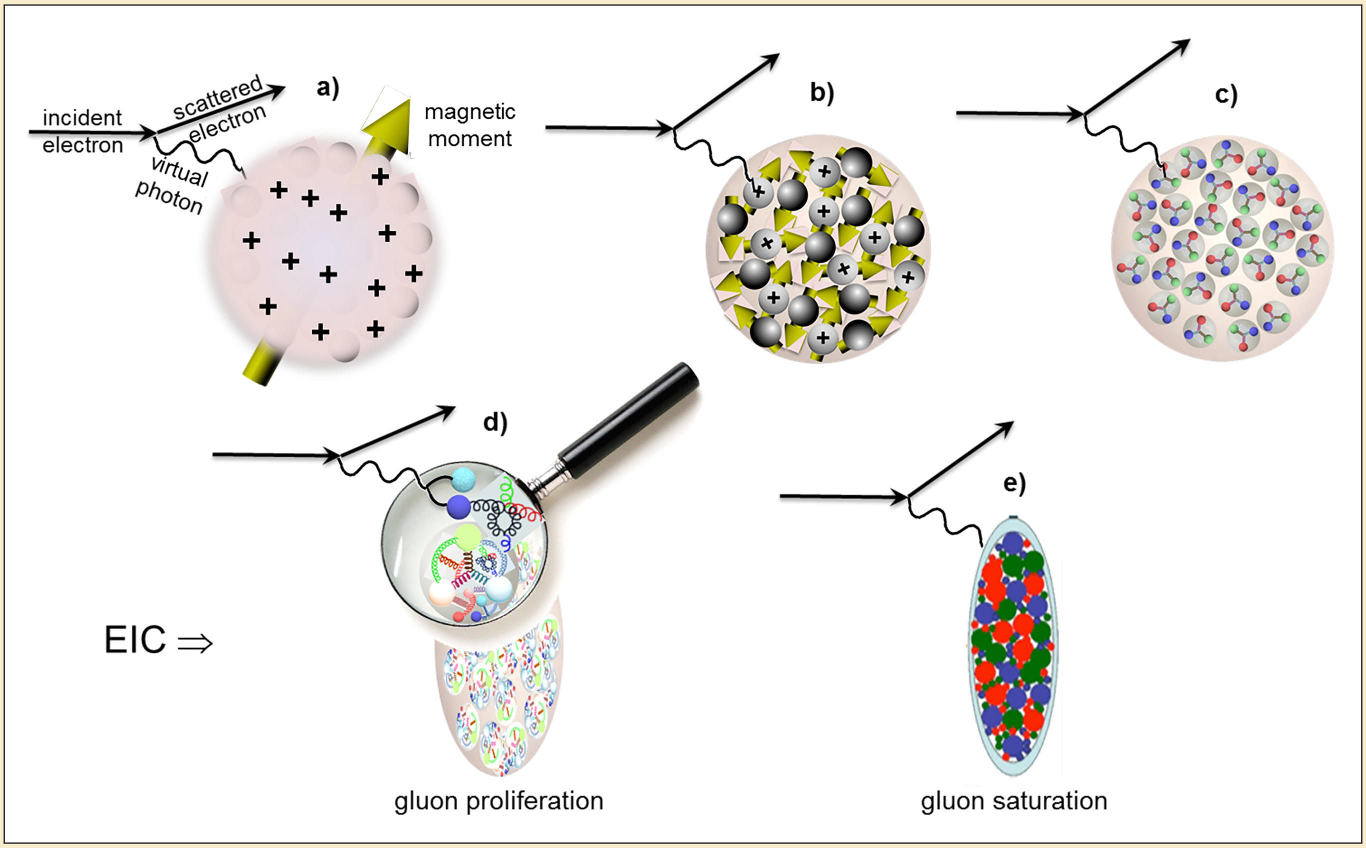
The nucleus is a tiny object, about 100,000 times smaller than a typical atom. A central goal of nuclear physics, since the birth of the subject, has been to image the internal landscape of nuclei in order to understand how they are assembled and how they interact. The strong interaction that binds the nucleus leads to a fascinating, multi-layered internal picture, as suggested by the five views shown in the figure.

The most precise information physicists have about the internal structure comes from scattering electrons, which interact with the nucleus by exchanging a virtual photon. The photon can transfer momentum and energy from the electron to the nucleus, and the layers of structure exposed change as one varies these quantities. At very low momentum transfer (see figure, frame a), the photon’s resolving power is insufficient to see any details; it just senses the nucleus’ overall electric charge and magnetic moment (which is zero for many nuclei). With increasing electron energy and momentum transfer, one begins (frame b) to resolve the spatial distribution of electric charge and magnetization inside the nucleus and senses how the protons inside are distributed. Robert Hofstadter won the 1961 Nobel Prize for using this technique to reveal that the proton itself also had a charge distribution.

With sufficient electron beam energy, the virtual photon can transfer enough energy and momentum to probe inside individual nucleons (frame c). Friedman, Kendall, and Taylor won the 1990 Nobel Prize for using this DIS process to demonstrate that virtual photons interact with pointlike fractionally charged particles inside the nucleon (i.e., with quarks). Currently, CEBAF uses DIS to study the distribution of valence quarks—the quarks that define the charge and magnetic moment—in individual nucleons and in nuclei.

If one holds the photon’s resolving power in the same range studied at CEBAF, but at dramatically increased electron-nucleus collision energy, one exposes nucleon constituents that each carry tiny fractions of the overall nuclear momentum. This is the basically unexplored region dominated by the proliferation (frame d) and eventual saturation (frame e) of gluons that is the focus of an EIC. Even though each gluon (represented by colored springs in frame d) carries no electric charge or magnetism itself, it can interact with a photon that splits into a quark and antiquark, each of which has both electric and color charge. If, for example, the quark and anti-quark recombine after the scattering to form a phi-meson, which one detects in coincidence with the scattered electron to reveal that the nucleus has been left intact, one can infer the spatial distribution of gluons in the nucleus—unprecedented information extending the work of Friedman, Kendall, and Taylor to a new layer of internal structure.

At sufficiently low momentum fraction, the density of gluons inside a nucleus must saturate, as in frame (e), in order to avoid violating fundamental physical principles. This can occur because at high density the probability for two gluons to recombine into one counterbalances the probability for one gluon to split into two. Before saturation is reached, an electron encountering a nucleus moving toward it near light speed sees a relativistically contracted object as in frame (d), with much higher gluon density than it would if colliding with a single proton. In fact, to attain comparable gluon densities, one would have to study electron-proton collisions at energies two orders of magnitude higher than in electron collisions with heavy nuclei. This is why the ion beams are so important in the EIC. They provide early access, allowing us to image nuclei as strongly correlated gluon systems with universal properties. This picture of nuclei—indeed, of all hadrons—determines their interactions at very high energies, whether in a terrestrial collider facility such as RHIC or LHC or in the highest energy radiation from cosmic sources. It is the ultimate picture of nuclei at their deepest level.



Schematic illustration of the evolving landscape in a nucleus as we alter the resolving power and energy of the electron scattering process used to probe it.