Phases of QCD:
Summary of the Rutgers Long Range Plan
Town Meeting, January 12-14, 2007

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1   Executive Summary

This White Paper summarizes the outcome of the Town Meeting on Phases of QCD that took place January 12-14, 2007 at Rutgers University, as part of the NSAC 2007 Long Range Planning process. The meeting was held in conjunction with the Town Meeting on Hadron Structure, including a full day of joint plenary sessions of the two meetings. Appendix A.1 contains the meeting agenda.

This Executive Summary presents the prioritized recommendations that were determined at the meeting. Subsequent chapters present the essential background to the recommendations. While this White Paper is not a scholarly article and contains few references, it is intended to provide the non-expert reader with a complete and nuanced case supporting the recommendations.

The prioritized recommendations of the Phases of QCD community are as follows:

1. Our central goal is a dramatic advance in our understanding of QCD Matter, through quantitative comparison of theory and experiment to determine the properties of the strongly interacting Quark-Gluon Plasma discovered in the initial phase of RHIC operations, and through further exploration of the QCD phase diagram at non-zero baryon density where a critical point has been predicted. The essential requirements for the success of this scientific program are therefore our highest priorities:

   - Effective utilization of the RHIC facility and completion of the ongoing detector upgrade program;
   - The RHIC II luminosity upgrade, which will enable quantitative study of key rare processes;
   - Strong support for the ongoing theoretical studies of QCD matter, including finite temperature and finite baryon density lattice QCD studies and phenomenological modeling, and an increase of funding to support new initiatives enabled by experimental and theoretical breakthroughs.

2. We strongly recommend significant and timely participation of U.S. groups in the LHC heavy ion program, which will study QCD matter at the highest energy densities and temperatures available in the

laboratory. This program will test and extend the insights reached in the RHIC program, and has the potential to make important new discoveries about QCD Matter.

3. An Electron-Ion Collider (EIC) facility is the highest priority of the QCD community for new construction after the JLab 12 GeV and the RHIC II luminosity upgrades. EIC will address compelling physics questions essential for understanding the fundamental structure of matter:

   - Precision imaging of sea-quarks and gluons to determine the full spin, flavor and spatial structure of the nucleon;
   - Definitive study of the universal nature of strong gluon fields manifest in nuclei.

   This goal requires that R&D resources be allocated for expeditious development of collider and experimental design.

4. Nuclear theorists play an essential role in the development of future research directions, the interpretation of experiments, and the articulation of their impact to the broader physics community. In many cases, significant contributions originate from our young scholars. In addition to the continuing success of this sustained effort, a number of key theoretical challenges remain. Meeting these challenges through targeted new investments is critical to realizing the full impact of the scientfic program outlined in this Long Range Plan.

   - We strongly recommend new investments in the next generation of nuclear theorists who are critical to the future of the field, and targeted support for initiatives to solve the key scientific problems identified in this LRP

5. Education and Outreach are of crucial importance to the Nuclear Physics community and to the nation as a whole. We strongly support the efforts of NSAC, the funding agencies, and other bodies, to expand education and outreach activities in Nuclear Physics at all levels, from elementary school through graduate education, and to help ensure a scientifically literate citizenry.

6. We support the creation of a coordinated national program in Accelerator Science and Technology, including a PI-driven program targeted at technologies that will enable major advances in Nuclear Physics.

2   Phases of QCD: Current Status

The RHIC accelerator complex and its complement of detectors have exceeded their initial scientific promise. When the RHIC physics program was planned, the hope was that collisions of heavy nuclei at energies up to 200 GeV per nucleon pair would result in the formation of a new type of strongly interacting matter, the quark-gluon plasma. A further hope was that the collisions would produce sufficient evidence of the nature of this matter to explore its physical properties and address the fundamental question: What is the structure of matter at the highest energy densities? Additionally, some speculated that the matter would be weakly coupled (describable perturbatively) and that indications of a strong first order phase transition might be observed. As a result of the experiments at RHIC, we now know that the matter is far from weakly coupled and a strong first-order phase transition can be excluded. Perhaps even more exciting, we know for certain that a new type of strongly interacting thermalized matter is, indeed, produced in nuclear collisions, and we have begun quantitative measurements of its structure and properties.

In the first six runs (2000-2006), BRAHMS, PHENIX, PHOBOS and STAR have collected data from Au+Au, d+Au, Cu+Cu, and p+p collisions, with Au+Au collisions having been studied at four collision energies ($\sqrt{s_{NN}} =$ 19.6, 63, 130 and 200 GeV). The largest data samples were collected at the highest energy of $\sqrt{s_{NN}} = 200$ GeV. The ability to study proton-proton, deuteron-nucleus, and nucleus-nucleus collisions with identical center-of-mass energies at the same facility has been the key to systematic control of the measurements. Nearly all observables have been studied as a function of collision centrality and of the emission angle relative to the reaction plane, thereby providing complete control over the collision geometry. It is noteworthy that the results obtained by the four RHIC experiments are overall in excellent quantitative agreement.

2.1 The RHIC Discoveries

Results from the first five years of RHIC operations with heavy ions have provided evidence for the creation of a new state of thermalized matter at unprecedented energy densities (more than 100 times larger than that of normal, cold nuclear matter) which appears to exhibit almost perfect hydrodynamical collective behavior. Among this evidence, four fundamental new discoveries stand out:

- **Near-Perfect Liquid**: The measured hadron spectra and their angular distributions bear witness to the enormous collective motion of the medium. In addition, measurements of non-photonic electrons, attributed to the decays of open charm hadrons, indicate that even heavy quarks flow with the bulk medium. These observations are in agreement with the hydrodynamic behavior of a nearly inviscid, i. e. viscosity-free, liquid – often characterized as a "perfect liquid" – and point to a rapid thermalization and equilibration of the matter.

- **Jet Quenching**: The strong quenching of jets, observed in central Au+Au collisions via the suppression of particle production at high transverse momentum and the dramatic modification of jet correlations, are evidence of the extreme energy loss of partons traversing matter containing a large density of color charges.

- **Novel Hadronization**: The large, unexpected enhancement of baryon and anti-baryon production, relative to meson production, at intermediate transverse momentum, together with the observed scaling of the collective motion of hadrons with the number of valence quarks, suggests that hadrons form by parton recombination after the collective flow pattern is established.

- **Novel phenomena at high parton density**: The RHIC experiments have observed low multiplicity of produced particles, compared to most expectations, together with a suppression in the production of high-transverse momentum particles at forward rapidity in deuteron-gold interactions. These phenomena may be the first indications of parton saturation inside the colliding nuclei.

These discoveries stand out, but many other results have been obtained which contribute important facets to the overall picture of the formation of an

equilibrated QCD medium of unprecedented energy density and endowed with novel and unexpected properties.

The RHIC experiments confirmed with high statistics and often better systematics important features of ultra-relativistic heavy-ion collisions that were previously discovered at lower energies. For example, all hadron abundance ratios are characterized by a chemical equilibrium distribution with chemical freeze-out temperature $T_{\mathrm{ch}} = 160 - 170$ MeV, a value that is observed to be independent of the collision system and the collision centrality. First results on charmonium production reveal a striking similarity of suppression in the medium to results at much lower beam energy, contrary to many expectations. Direct photon production at high transverse momentum has been measured and is in excellent agreement with pQCD expectations. Direct photon measurements at lower transverse momentum where significant thermal radiation contributions may be seen are underway.

2.2   Detailed Discussion: Experiment and Theory

We now present these results and their implications in more detail.

2.2.1   Near-Perfect Liquid

A "perfect" liquid is one that obeys the equations of ideal hydrodynamics without shear or bulk viscosity. In practice, any liquid must have a nonvanishing viscosity, because the mean free path of thermal excitations cannot be zero. Quite generally, a low shear viscosity implies a large transport cross section and thus strong coupling. One of the exciting theoretical discoveries of the past few years is the insight that there may exist a lower bound on the dimensionless ratio between the shear viscosity and entropy density of any fluid ($\eta/s \geq 1/4\pi$, see Section 2.3.3). Thus, in reality, a perfect liquid is a fluid that attains this lower bound. As we discuss in the following, measurements of the hadronic collective flow indicate that the matter produced at RHIC is, indeed, not far from this bound on η/s.

The abundances of the produced hadrons at midrapidity with transverse momenta below about 2 GeV/c, the shapes of their transverse momentum spectra, and the elliptic flow of these hadrons can be very well described by relativistic hydrodynamics for a perfect liquid with an equation of state similar to the one predicted by lattice QCD (Fig. 1). While strong collective flow had been observed previously in lower energy heavy-ion collisions,
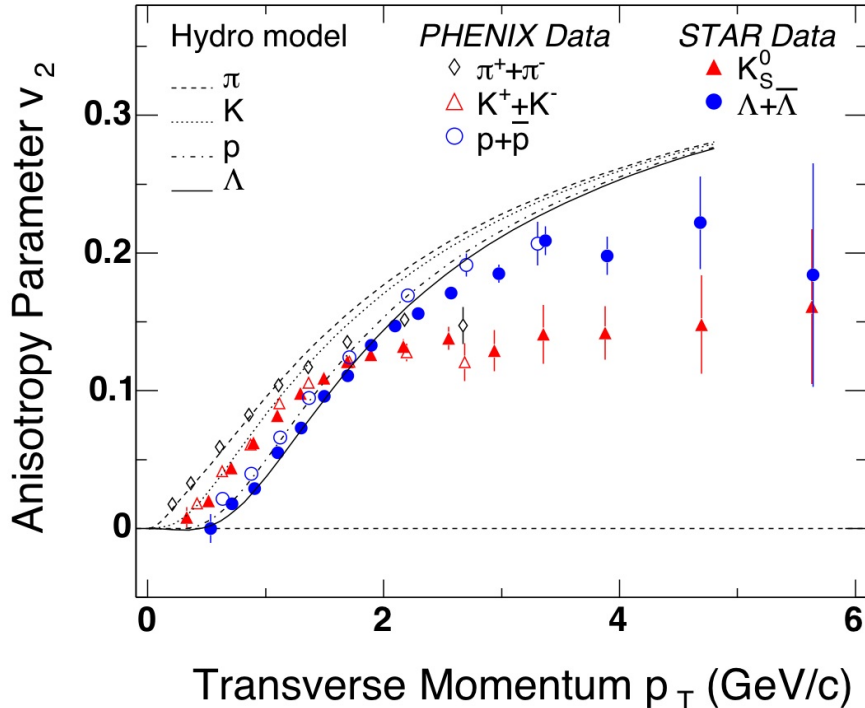
Figure 1: Compilation of STAR and PHENIX data on elliptic flow v_2 for identified hadrons, plotted as a function of transverse momentum p_T and compared with hydrodynamic predictions [1]. The elliptic flow is a measure of the anisotropic pressure-driven expansion in off-center collisions. Note that the bulk of the particle production occurs at less than 2 GeV/c. Collective motion of hadrons is expected to disappear above $p_T > 1.5 - 2$ GeV/c.

hydrodynamic models were never before able to provide an equally successful quantitative description of the data. The best overall description of the RHIC data is obtained if the ideal hydrodynamical evolution of a quark-gluon plasma during the early expansion stage is combined with a realistic hadronic cascade after hadronization, and if an equation of state like that obtained from lattice QCD is employed. To reproduce the magnitude of the observed radial and elliptic flow it is necessary to assume that the produced matter thermalizes very quickly, on a time scale of less than 1 fm/c, and builds up thermodynamic pressure whose gradients drive the collective expansion.

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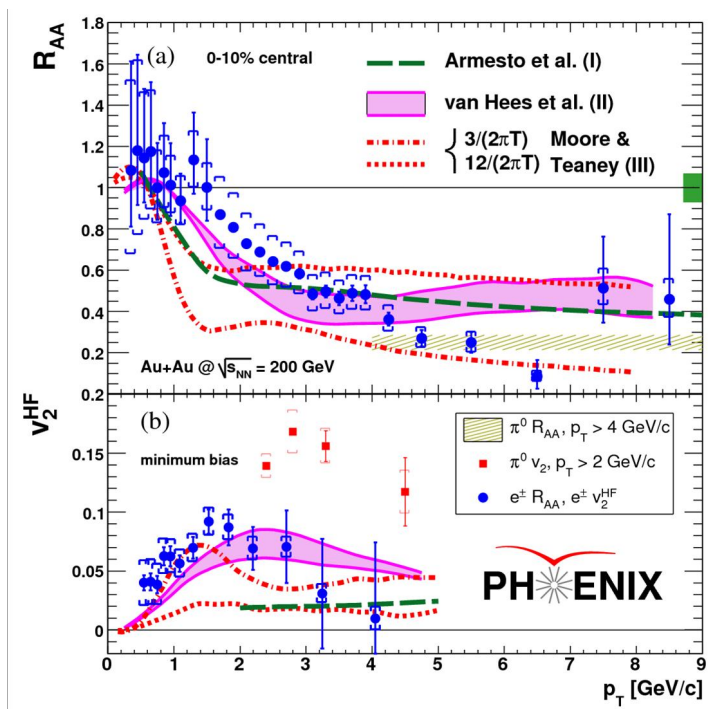
Figure 2: Figure from [2]. (a) The nuclear modification factor R_{AA} of heavy-flavor electrons in 0-10% central Au+Au collisions compared with π^0 data and model calculations. The nuclear modification factor is the ratio of the cross section per nucleon-nucleon collision measured in a heavy ion collision divided by the cross section measured in p+p collisions. If there were no nuclear effects it would be unity. (b) v_2 of heavy-flavor electrons in minimum bias collisions compared with π^0 data and the same models.

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Hydrodynamic calculations that reproduce the experimental data indicate that at thermalization time the energy densities must be at least 15 GeV/fm^3, i. e. 15 times the energy density needed for color deconfinement. In fact, even if one applies only the principle of energy conservation to the measured produced transverse energy in the collision, neglecting any energy lost to longitudinal work during the expansion, and uses any reasonable estimate for the initial volume of the fireball at thermalization, one also obtains a lower limit for the initial energy density which is about an order of magnitude above the critical value for deconfinement.

The evidence for fast thermalization, the observation of large elliptic flow even for multi-strange (anti-) baryons and charmed hadrons, and the good agreement of ideal hydrodynamical models assuming a vanishing shear viscosity of the matter during the early phase of its expansion, indicate that the extremely hot and dense medium created in the collision is a strongly coupled medium with the properties suggestive of a nearly perfect liquid. Its apparently almost complete absence of viscosity contrasts strongly with intuitive expectations by many scientists in the field that the quark-gluon plasma would exhibit perturbative, gas-like behavior characterized by weakened interactions among its partonic constituents.

The unanticipated success of ideal relativistic hydrodynamics to describe the collective flow imprinted on the hadron spectrum from nuclear collisions at RHIC has made it possible to develop a compelling foundation for the dynamical treatment of almost the entire collision process (except for the process of thermalization itself), which can serve as a basis for future, more refined treatments. In this framework, the densest stage of the collision, in which the matter is in the quark-gluon plasma phase, is described in terms of ideal relativistic hydrodynamics. The inputs for this description are the equation of state of the matter and the initial conditions, given in terms of the energy density of the matter at the moment of thermalization. The final, much more dilute hadronic stage of the collision is described by a Boltzmann cascade of binary hadronic interactions, which is tracked up to the disintegration of the matter into individual, free-streaming hadrons. Two independently developed implementations of this concept have had remarkable success in describing the global features of the heavy ion reactions (spectra, flow anisotropies, hadron ratios, etc.).

2.2.2 Jet Quenching

The medium created in collisions at RHIC shows evidence of strong interactions not only among its constituents, but also with hard colored penetrating probes, such as energetic quarks and gluons created at the very beginning of the collision and propagating outward through the reaction zone. High transverse momentum hadrons, which arise from the fragmentation of such hard partons, are found to be suppressed in central Au+Au collisions by a factor of up to five relative to the experimental proton-proton baseline (when normalized to the number of pairwise nucleon-nucleon interactions)(Fig. 3).
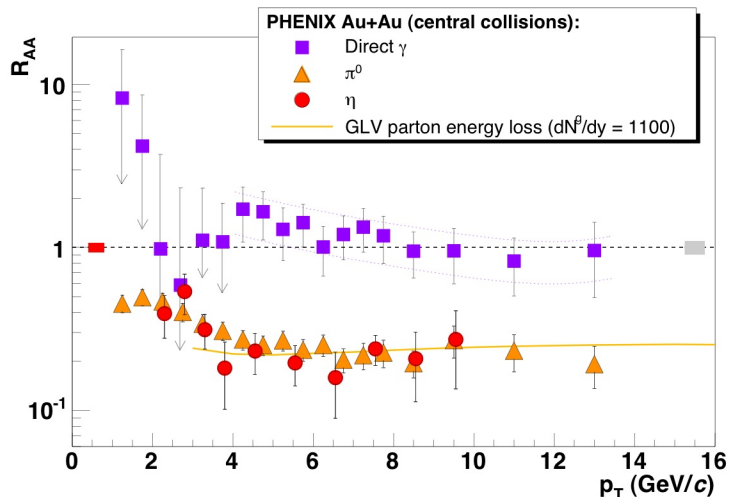
Figure 3: Nuclear modification factor $R_{AA}(p_T)$ for photons (γ), π^0 and η mesons in central Au+Au collisions [3]. The nuclear modification factor is the ratio of the cross section per nucleon-nucleon collision measured in a heavy ion collision divided by the cross section measured in p+p collisions. If there were no nuclear effects it would be unity. Note the strong suppression of the mesons and the lack of suppression for the photons, which do not interact with the final state medium.

In contrast, the production rates and spectra of direct photons, which escape from the collision without further interaction, agree well with expectations based on perturbative QCD. Confirmation of this interpretation comes from two other experimental observations: (1) The strong suppression of high p_T hadrons is not observed in d+Au collisions, which rules out initial state effects associated with possible modifications of the parton distributions

Figure 4: Dihadron correlations in azimuthal angle. Left: pairs of high momentum hadrons, showing suppression of leading recoil particles in central Au+Au relative to pp and dAu collisions [4]. Right: high momentum trigger and low momentum associated hadron, showing enhanced yield of recoiling soft jet fragments in Au+Au [5].

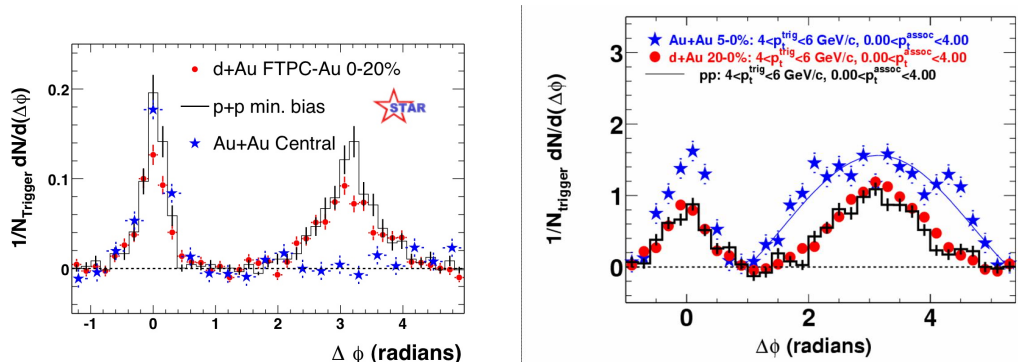in heavy nuclei; (2) when triggering on a high-p_T hadron with transverse momentum of up to 10 GeV/c, the data show its opposite partner jet even more strongly quenched in central Au+Au collisions.

The large momentum scale associated with the primary jet production vertex combined with enhanced momentum transfer to the jet on its way out by the dense medium permit a rigorous formulation of jet quenching in the framework of perturbative QCD. Although the formalism can be cast in several different forms, all formulations assign the quenching power of the medium to a unique transport coefficient, the jet quenching parameter $\hat{q}$, which measures the transverse momentum broadening of a hard parton propagating through the medium. The parameter $\hat{q}$ is a measure of the stopping power of the medium and has a similar importance for the characterization of the matter as does the shear viscosity for bulk transport.

The relation between jet quenching observables (for sufficiently energetic jets) and the parameter $\hat{q}$ is described within perturbative QCD; the value of $\hat{q}$ itself is determined by nonperturbative dynamics of the strongly interacting medium. An important insight developed recently is that a nonperturbative and gauge invariant definition can be given in terms of the expectation value of a light-like Wilson loop. This definition has enabled new calculational approaches to $\hat{q}$ (e. g. in strongly coupled QCD-like theories, see Section 2.3.3). Several groups have undertaken detailed analyses of the RHIC data
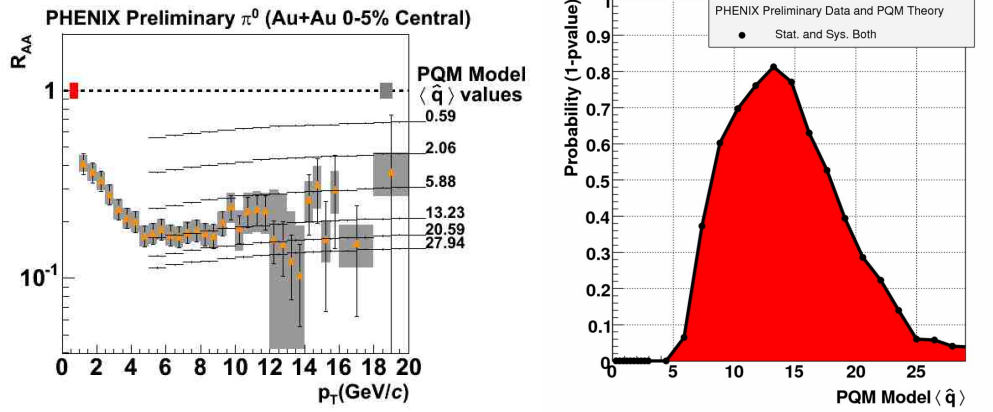
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Figure 5: Left: R_{AA} for π^0 compared to the PQM jet quenching model calculation for various values of model parameter $\hat{q}$. Right: χ^2 probability distribution for $\hat{q}$. Figures from [6].

in terms of the parameter $\hat{q}$, finding values more than 10 times larger than the stopping power of normal nuclear matter. The results of these analyses still differ considerably from each other, probably due to different approximations and oversimplifications made in the modeling of the collision geometry and dynamics. A specific example of a fit to RHIC data on the suppression of single hadrons and back-to-back hadron pairs is shown in Fig. 5.

Detailed correlation measurements have shown that the yield of high-p_T particles correlated with the trigger particle but on the opposite side is reduced by an additional factor of 4 or more, while its energy is found to be carried away by enhanced production of soft hadrons in the direction opposite to the trigger hadron (Fig. 4). The average momentum of these soft hadrons approaches that of the thermalized medium as the collisions become more central and the fireball size increases. In addition, dramatic modification in the angular and p_T structure of the opposite side jet point to a possible collective or hydrodynamic response of the dense medium to the energy and momentum deposited by the quenched jet (for example a Mach cone).

While not all of these features are understood quantitatively, theoretical estimates of the initial gluon density present in the medium which are necessary to explain the observed high-p_T hadron suppression are compatible with the values of the initial energy and entropy density required for the successful hydrodynamic description of the bulk of the matter. The important observa-

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tion of an angular dependence of jet quenching relative to the reaction plane
has opened the opportunity to use this process as a tomographic probe for
the properties of the dense medium created at RHIC.

2.2.3 Novel Hadronization

The kinetic freeze-out temperature T_{f} (determined by the disappearance of
elastic scattering) and the collective flow extracted from the final hadron
spectra depend on collision centrality. More central collisions freeze out later,
at lower temperature and with larger radial flow than peripheral collisions,
consistent with theoretical ideas that describe kinetic freeze-out as a com-
petition between local scattering and global expansion rates. On the other
hand, the chemical decoupling temperature T_{ch} (defined by the disappear-
ance of abundance changing interactions) extracted from the hadron yield
ratios is found to be independent of collision centrality and thus insensitive
to the expansion rate. This observation, combined with the value of T_{ch} near
T_c, strongly suggests that chemical freeze-out is not controlled by inelastic
hadronic rescattering processes, but by a phase change in which the hadrons
are born by a statistical process directly into a state which is relatively dilute
and expands so rapidly that most abundance-changing hadronic interactions
are ineffective. Even hadrons with suppressed inelastic interactions cross sec-
tions (for example the ϕ and Ω) follow the same freeze-out and flow patterns.

Further evidence for an active role of deconfined, thermalized and collec-
tively flowing quarks in hadron production comes from the observed valence
quark number scaling of hadron yields and elliptic flow at intermediate p_T
(Fig. 6). While the perfect liquid description gradually breaks down for
$p_T \geq 1.5 - 2$ GeV/c, the broadening of the baryon spectra by the strong
radial flow remains visible at even larger transverse momenta.

A theoretical basis for the process of hadron formation at momenta in
the "intermediate p_T" range 2 GeV/c $< p_T <$ 5 GeV/c has been developed.
The model describes the formation of hadrons in this momentum range as
sudden recombination of collectively flowing valence quarks to form mesons or
baryons. This process imprints the hydrodynamic flow characteristics of low-
momentum quarks onto the hadrons emitted with intermediate momenta.

As a result, hydrodynamic bulk particle production at low p_T is sepa-
rated from perturbative hard particle production at high p_T by a novel and
unexpected intermediate p_T region where the parton recombination and frag-
mentation mechanisms of hadron formation compete with each other. The

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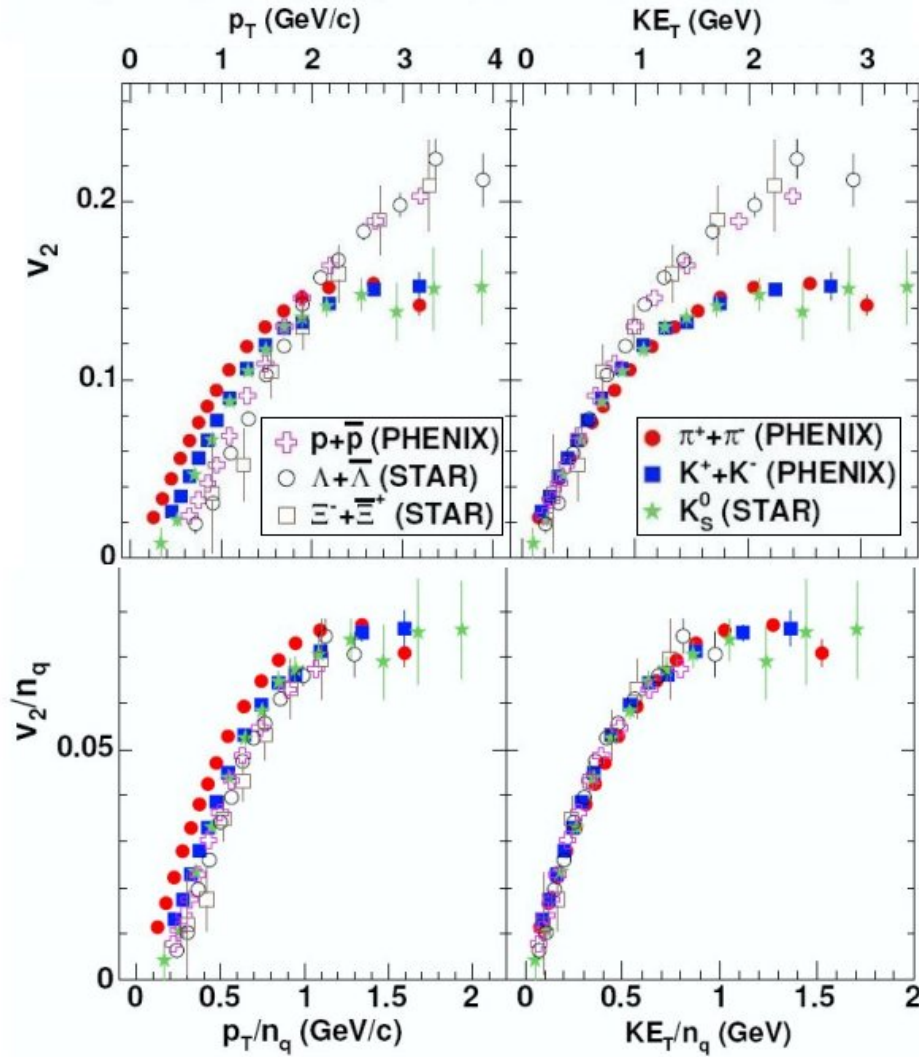
Figure 6: Figure from [7]. Upper panels: The elliptic flow parameter v_2 plotted versus hadron transverse momentum p_T (left) or hadron transverse energy $E_T = \sqrt{p_T^2 + m^2}$ (right). At low transverse momentum/energy all hadrons behave alike, indicating a common hydrodynamic origin of the elliptic flow. At higher momentum/energy the data show a distinct difference between mesons and baryons. Lower panels: Elliptic flow per valence quark v_2/n_q versus transverse momentum per valence quark p_T/n_q (left) or transverse energy per valence quark E_T/n_q. The collapse of all data into a single curve in the lower right panel indicates that the collective flow originates as a hydrodynamical phenomenon at the valence quark level.
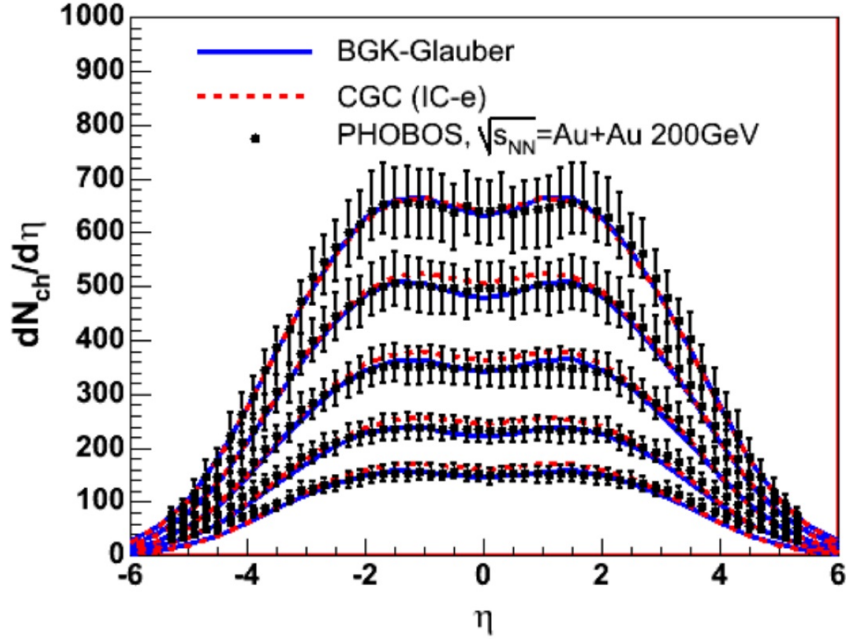
Figure 7: dNch/dη as function of pseudo-rapidity η for variety of collision centralities [8], together with a fit using the Color Glass Condensate model in which the saturation of the density of gluonic matter in the initial state leads to lower than expected particle multiplicity for central Au+Au collisions at RHIC energy.

recombination model successfully describes the excess emission of baryons at intermediate transverse momenta, the characteristic difference between mesons and baryons in the momentum dependence of the elliptic flow parameter, and the suppression of the production of p-wave baryons.

2.2.4 Saturated Gluon Density

At high energies, the wave functions of hadrons and nuclei contain many quarks and gluons – this is because high energy (large x) partons successively emit softer (smaller x) daughter partons in a self–similar radiation cascade. Therefore, at small x the density of partons in the transverse plane becomes large. In this regime, the softer gluons can recombine into harder ones, and this recombination limits the growth of parton distributions, causing them to saturate. The area density of partons defines a new dimensionful parameter,

the saturation momentum Q_s, which grows with the size of the nucleus like $Q_s^2 \sim A^{1/3}$. If the saturation momentum is large compared to the confinement scale, asymptotic freedom dictates that the coupling constant, and hence quantum effects, are small: $\alpha_s(Q_s^2) \ll 1$. At $Q^2 \leq Q_s^2$ the dynamics of gluon fields then becomes quasi-classical and highly non-linear. The classical color fields in a highly energetic hadron or nucleus appear frozen in time by Lorentz dilatation. This component of the wave function is thus called the "color glass condensate," and it is predicted to become *universal*, i.e. the same for all hadrons and nuclei, at very high energies.

This assumption can be probed in d+A collisions by concentrating on kinematic regions sensitive to the small-x gluon wave function of the Au nucleus. Measurements performed at RHIC have, indeed, shown a distribution of high transverse momentum particles at forward rapidity whose dependence on rapidity, transverse momentum and centrality are consistent with the Color Glass Condensate hypothesis. These observations are the first indication that gluon saturation effects play an important role in our understanding of nuclear structure at small x and of the pre-equilibrium stages of heavy ion collisions. A second indication for the validity of the color glass condensate picture is derived from the observed dependence of the particle multiplicity in Au+Au collisions on centrality and beam energy (Fig. 7), which can be understood as arising from such a high-density state of gluonic matter present in the colliding Au nuclei even at moderately small values of x. This growing body of evidence has led to the expectation that strong color fields will determine the pre-equilibrium dynamics of heavy ion collisions at the LHC. Many facets of this physics have unique manifestations also in electron–nucleus scattering, which can be studied at a future electron-ion collider (EIC).

2.3 Theoretical Advances

We have described many recent advances in theory in Section 2.2. Here, we discuss four more theoretical developments that bear on the interpretation of and context for RHIC data, as we build our understanding of the phases of QCD matter.
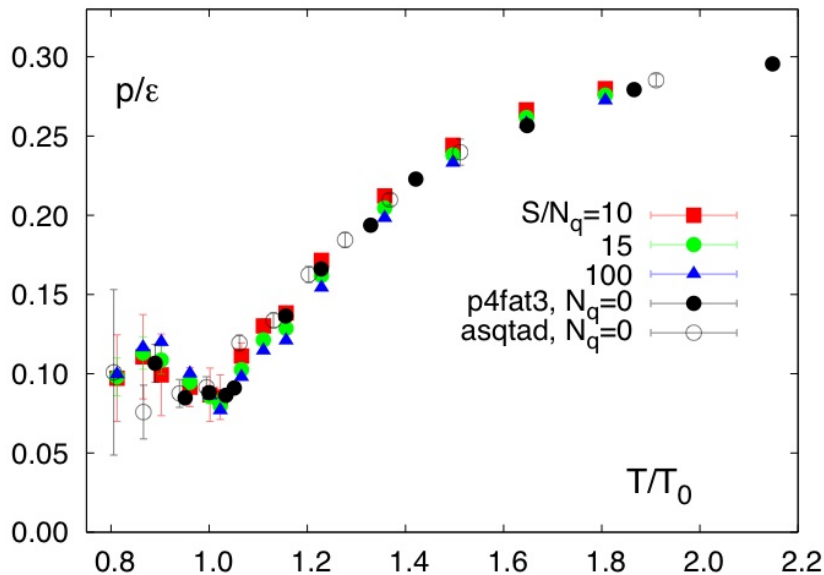
Figure 8: Recent lattice results for the ratio p/ε in unquenched QCD, which is an important input into the hydrodynamical simulations of relativistic heavy ion collisions. The small value $p/\varepsilon \ll 1/3$ near T_c implies that the quark-gluon plasma is characterized by a soft equation of state in the temperature range relevant to RHIC [9, 10].

2.3.1 Lattice QCD at Finite Temperature and Density

In recent years, significant progress has been made in studying the phase diagram and bulk properties of QCD at finite temperature and density. Previous lattice calculations were limited to zero net baryon density, but several methods have recently been developed to study the phase diagram, equation of state and various susceptibilities at nonzero net baryon density. There is now solid evidence that the transition from hadron gas to quark-gluon plasma at zero net baryon density is a rapid crossover, not a true phase transition. However, there exist general theoretical arguments and some indications from lattice QCD that a critical end-point of a first-order transition line exists at nonzero net baryon density.

For the first time the transition temperature in QCD has been calculated with controlled continuum and chiral extrapolations using the improved staggered fermion action. One recent calculation of the transition temperature

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gives $T_c = 192(7)(4)$MeV which is larger than other published values of T_c and the chemical freezout temperature. If confirmed, this result would have important implications for the phenomenology of heavy-ion collisions. The calculations of the equation of state can now be performed with quark masses near their physical values, and definitive results for thermodynamic quantities with dynamical quarks in the continuum limit appear to be in reach.

Figure 8 shows results based on recent calculations of the QCD equation of state with dynamical fermions described by an improved lattice action. The figure shows the ratio of the pressure p to the energy density ε as a function of the temperature. This quantity, which would have the value $1/3$ for a perturbative gas of massless quarks and gluons or for a strongly coupled liquid that is conformal (i.e. scale-invariant), is closely related to the speed of sound c_s in the plasma $(c_s^2 = \partial p/\partial \varepsilon)$ and is thus relevant to hydrodynamical calculations of the expansion of the matter formed in heavy ion collisions.

2.3.2   Lattice Spectral Functions

For a long time lattice QCD has been used only to calculate static properties of the quark-gluon plasma, such as the transition temperature, equation of state and screening lengths. In recent years significant progress has been made in calculating the temporal meson correlators and spectral functions using the *Maximum Entropy Method*. Charmonium spectral functions have been calculated by several groups indicating that the ground state charmonium (J/ψ) can survive up to temperatures at least as high as $1.6\ T_c$. These findings differ from early estimates based on the perturbative color screening scenario, which predicted that the charmonium ground state would dissolve soon above T_c. Charmonium correlators calculated on the lattice thus become an essential input for phenomenological models aimed at understanding charmonium production at RHIC and for any theoretical approach addressing color screening in the quark-gluon plasma.

2.3.3   Strong coupling results from AdS/CFT correspondence

There is now a significant body of experimental evidence for the discovery that the quark-gluon plasma produced in RHIC collisions is a strongly coupled liquid with low viscosity, not a near-ideal gas. Lattice QCD is the proper tool for understanding the equilibrium thermodynamics of such a strongly coupled quark-gluon plasma, but the discovery poses a challenge to the theo-

retical analysis of its transport properties. The theoretical tools of choice for the understanding of observable phenomena, such as the strong jet quenching, which involve dynamics rather than just thermodynamics, have long been built upon perturbative QCD and are thus based upon the premise that interactions are essentially weak. This assumption does not apply to the matter produced at RHIC. The search for new tools to study the transport properties of matter described by strongly coupled, relativistic gauge theories has thus become an urgent necessity.

Recently, theorists have calculated the shear viscosity/entropy ratio η/s, the jet quenching parameter $\hat{q}$, the drag coefficient describing the energy loss of a heavy quark, the photon emission rate, and the velocity dependence of the color screening length for the strongly coupled plasmas of many gauge theories that differ in detail from QCD. The calculations are made possible by the fact that large classes of strongly coupled, thermal gauge theories are equivalent to string theories in curved 5-dimensional space-times containing black holes. This "AdS/CFT correspondence" was discovered by string theorists hoping to use gauge theories to learn about string theory. Nuclear theorists are now putting it to profitable use in the opposite direction. These calculations yield new insights: for example, there may be a fundamental lower bound on the ratio of shear viscosity η to entropy density s; for example, $\hat{q}$ scales with the square root of the number of degrees of freedom; for example, heavy quark energy loss may occur via drag rather than via the gluon radiation which dominates in the high-jet-energy limit and which is described by $\hat{q}$. In several instances (η/s and $\hat{q}/T^3$, for example) the AdS/CFT results obtained at strong coupling yield results which are in semi-quantitative agreement with those inferred from RHIC data, even though they are not calculations done in QCD.

2.3.4 Cold Dense Quark Matter

Theoretical advances have shown that QCD provides rigorous analytical answers, leaving no unresolved gaps in our understanding even at a nonperturbative level, to the question: "What are the properties of matter squeezed to arbitrarily high density?" It has long been known that cold dense quark matter, as may occur at the center of neutron stars, must be a color superconductor. Recent theoretical effort has made this subject both richer and more quantitative. An analytic, ab-initio calculation of the pairing gap and critical temperature at very high densities has now been done, and the prop-

erties of quark matter at these densities have been determined. The material is a color superconductor but admits a massless "photon" and behaves as a transparent insulator; it is a superfluid with spontaneously broken chiral symmetry. At densities that are lower but still above that of deconfinement, color superconducting quark matter may in a particular sense be crystalline, with a rigidity several orders of magnitude greater than that of a conventional neutron star crust.

3   Phases of QCD: Future Prospects

We are poised at the beginning of a new era in the quantitative experimental exploration of thermal QCD. This is made possible by dramatic detector and accelerator advances at RHIC and the opening of a new energy frontier at the LHC, which extends the experimental exploration of the phase diagram to yet higher temperatures. RHIC (and eventually the FAIR facility) will also explore the new region of finite baryon density, where lattice QCD calculations predict a critical point that is potentially accessible to RHIC.

This chapter presents the plans of the Heavy Ion community to address the challenges and opportunities. We first discuss the upgrades of the RHIC accelerator and detectors and the heavy ion capabilities of the LHC detectors, followed by discussion of important aspects of the physics scope of these upgraded and new facilities.

3.1   Facilities

3.1.1   RHIC

The initial suite of RHIC detectors comprised two large, general purpose experiments (PHENIX and STAR) and two small specialized experiments (BRAHMS and PHOBOS). BRAHMS and PHOBOS have completed their physics programs. Substantial upgrades to the PHENIX and STAR detectors are now in progress, at a total cost of about $30M. These upgrades will enable the detectors to address the key questions enumerated in this document, through extended particle identification capabilities (including heavy flavor mesons and baryons) and kinematic coverage, as well as improved triggering and data recording capabilities. Many new measurements require large data samples, to have sensitivity to processes that occur at the level of once per hundred million Au+Au reactions. The RHIC accelerator complex is also

being upgraded, in response to the physics needs for high luminosity and a broader range of available species and energies. This upgrade program is detailed in the "Mid-Term Strategic Plan for RHIC" [11].

The major detector upgrades for **PHENIX** are:

- Hadron Blind Detector: Ring Imaging Cerenkov detector for high signal/background measurements of low mass electron pairs, to study thermal radiation and medium-induced modification of mesons, which may be sensitive to chiral symmetry restoration;

- Central and forward silicon trackers: high precision detectors for resolved-vertex studies of heavy flavor production and electron-pair production over broad acceptance;

- Muon trigger upgrade: enhanced capability to trigger on $W^{\pm} \to \mu^{\pm}$, to measure the sea-quark contribution to nucleon spin;

- Nose-Cone Calorimeter: a forward tungsten-silicon calorimeter measuring photons and electrons, to study heavy quark spectroscopy and forward jet production at low x.

- Data acquisition upgrade to accomodate high data volume from new detectors

The major detector upgrades for **STAR** are:

- Forward Meson Spectrometer: large acceptance forward lead-scintillator calorimeter to measure forward meson, photon, and heavy quark production at low x;

- Time of Flight: highly segmented, MRPC-based detector covering the central STAR acceptance, to identify hadrons and electrons over broad kinematic interval; substantially improved measurements of event-by-event fluctuations and heavy flavor and vector meson production;

- Heavy Flavor Tracker: high precision silicon detectors for resolved-vertex studies of heavy flavor production and electron-pair production over broad acceptance;

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- Forward Tracker: GEM-based detector in same acceptance as STAR Endcap EM Calorimeter, to measure the sea-quark contribution to nucleon spin via $W^{\pm} \to e^{\pm}$;

- High-speed Data Acquisition: increase of STAR event readout speed by a factor 10, to 1 kHz, to enable recording of very large datasets needed for high precision event-by-event and heavy flavor studies.

The short term upgrade to the RHIC accelerator facility is the Electron Beam Ion Source (EBIS) (Fig. 9, upper panel). EBIS is currently under construction and will be commissioned and operational in 2010. It will replace the 35-year-old Tandem Van de Graaffs as the RHIC ion source, providing more reliable and cost-effective operation. EBIS makes new species available in RHIC, notably polarized Helium-3 and Uranium. Measurements of U+U collisions are of particular interest, because the large ground-state quadrupole deformation can be exploited to generate initial energy density about 30% higher than that achievable in Au+Au collisions at RHIC. This lever arm may provide significant systematic checks of hydrodynamic flow and jet quenching.

As discussed in Sect. 3.2, one of the key open questions for the field is the existence and location of a critical point on the QCD phase diagram. RHIC will explore this question, varying the baryo-chemical potential μ_B by lowering the collision energy as far down as $\sqrt{s_{NN}} = 5$ GeV. Effective use of such an energy scan, for instance to measure the event-by-event fluctuations that characterize the vicinity of the critical point at multiple energies within a single running period, requires the completion of detector upgrades underway, in particular the STAR Time of Flight upgrade. Discoveries from such a scan could be studied in greater detail with substantial improvement to the luminosity at low energy, which can be achieved at moderate cost through electron cooling in the AGS. This would increase the luminosity below $\sqrt{s_{NN}} \sim 20$ GeV by a factor up to 30.

In the longer term, the required high luminosity at RHIC II will be achieved by electron cooling of the full energy beams (Fig. 9, lower panel), the first such implementation in a high energy collider. Cooling will increase the heavy ion luminosity by a factor 10 at high energy and make RHIC the first collider in which luminosity is limited by the interactions themselves. Cooling at injection energy will increase polarized proton luminosity by a factor 2-3. Proof of principle of electron cooling at RHIC has been established through detailed simulations benchmarked at the existing high energy
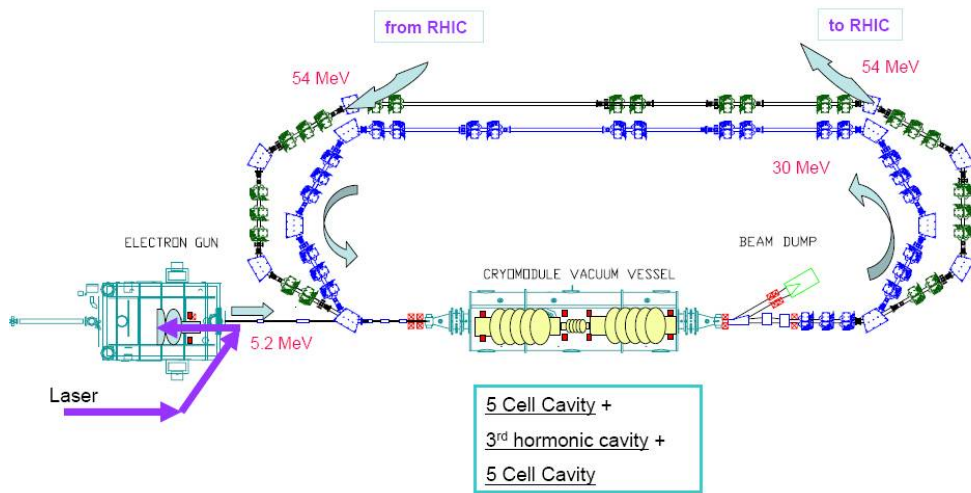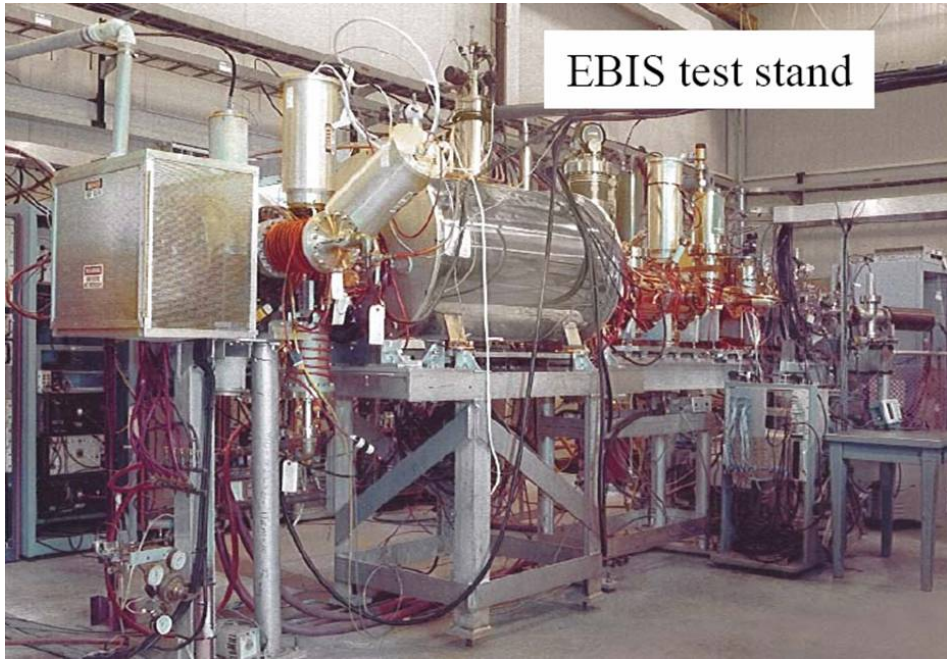
Figure 9: Upper: EBIS test stand. Lower: Schematic layout of electron cooling. Location in RHIC ring is shown in Fig. 17.

electron cooler at Fermilab. Major components of the RHIC electron cooler will be tested in a scaled test facility that is currently under construction. Commissioning of the full system could technically be completed by 2012.

RHIC computing capabilities must accomodate the large increase in data volume and complexity resulting from the increased RHIC II luminosity and upgrades to detectors. Detailed estimates indicate that the expected decrease in the cost of computing capacity with time offsets the increase in demand. Consequently, no significant increase in funding level for computing is required for the on-site RHIC Computing Facility and off-site satelite facilities to keep pace, in order to analyze the data in a timely fashion.

3.1.2 LHC

The LHC physics program includes four weeks of heavy ion physics running per year. The primary collision system is Pb+Pb at 5.5 TeV per nucleon pair, which is a factor 30 greater collision energy than at RHIC. Other systems under consideration are p+Pb (achievable at LHC despite the two-in-one magnet design) and 5.5 TeV p+p, to provide accurate reference data for heavy ion collisions measurements. The LHC is currently expected to begin commissioning with proton collisions in late 2007, with heavy ion beams commisioned in late 2008 and the first significant heavy ion running in 2009.

LHC heavy ion collisions are expected to generate matter with much higher initial energy density than RHIC collisions, with a long-lived fireball in the deconfined phase. The enormous collision energy results in large rates for a wide variety of hard probes over a very broad kinematic range (for instance, jets exceeding 300 GeV in transverse energy), which will complement and extend the successful hard probes measurements at RHIC and will in addition enable qualitatively new measurements.

Three LHC experiments - ALICE, ATLAS and CMS - will participate in heavy ion running, with extensive capabilities to measure the full spectrum of heavy ion observables. The ability to study similar probes of hot QCD matter generated from the vastly different initial conditions at RHIC and the LHC promises a rich physics program for the two facilities in the coming years.

We outline here the heavy ion physics capabilities of the LHC detectors:

- **ALICE** is the dedicated heavy ion experiment at the LHC. ALICE contains the main elements of both STAR and PHENIX. Its central detector, with acceptance $|\eta| < 0.9$, has a large Time Projection Chamber

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in a moderate solenoidal field (0.5 T), augmented by silicon tracking and highly segmented electron and hadron particle ID detectors. A muon arm in the forward direction is based on a large-aperture dipole. The US hardware contribution to ALICE is a large Electromagnetic Calorimeter covering one third of the central acceptance, which enables jet quenching measurements in ALICE over a broad kinematic range.

- **ATLAS** is a large acceptance, multi-purpose detector, with silicon and TRD-based tracking and highly segmented electromagnetic and hadronic calorimeters within a 2 T solenoid magnet. Muons are detected in large air-core toroids surrounding the central detector. US groups provide the physics leadership of the overall ATLAS Heavy Ion effort, while the US heavy ion hardware contribution is a modest-scale project to provide the Zero-Degree Calorimeters.

- **CMS** is a large acceptance, multi-purpose detector, with silicon-based tracking and and highly granular electromagnetic and hadronic calorimeters within a 4 T solenoid magnet. Muon detectors are embedded in the flux return iron yoke of the magnet. The very forward direction is covered by CASTOR and the Zero-Degree Calorimeters. US insitutions provide physics leadership of the overall CMS heavy-ion physics program, trigger preparation, and ZDC construction.

While ALICE is the only LHC detector that was designed from the outset for high performance tracking the high multiplicity environment expected in heavy ion collisions, subsequent studies of CMS and ATLAS have shown that they can also track robustly in such an environment. All experiments have good capabilities for heavy ion jet quenching and photon and quarkonium production measurements. Dimuon mass resolution is expected to be sufficient to separate the various quarkonium states. Extensive forward coverage will enable jet and photon measurements at moderate Q^2 down to $x \sim 10^{-6}$ (ATLAS) or even $x \sim 10^{-7}$ (CMS), which is of particular interest in p+Pb collisions.

3.2   The QCD Critical Point

Measurements using the RHIC detectors and complementary lattice calculations that each extend into the regime of nonzero baryon density can revo-

lutionize our quantitative understanding of the QCD phase diagram by discovering the QCD critical point.

What is the nature of the transition between Quark-Gluon Plasma and ordinary hadronic matter? Lattice calculations show that in a matter-antimatter symmetric environment, this transition occurs smoothly, with many thermodynamic properties of QCD matter changing dramatically within a narrow range of temperatures, but with all these changes occurring continuously. Collisions at the highest RHIC energies produce matter that is close to matter-antimatter symmetric, as did the big bang. RHIC data and cosmological observations are consistent with the prediction that the transition undergone by quark-gluon plasma as it cools occurs continuously.

In contrast, upon squeezing nuclear matter to higher and higher densities without heating it up — a feat accomplished in nature within the cores of neutron stars — we expect one or more first order phase transitions (at which thermodynamic properties change discontinuously as the pressure is increased) between various phases of nuclear matter and color superconducting quark matter (Fig. 10, left panel). Furthermore, the phase transition between cold dense color superconducting quark matter and hot quark-gluon plasma must, on very general grounds, be a first order transition.

Many studies which seek to put these facts and expectations together into a map of the QCD phase diagram predict that the continuous crossover being explored in heavy ion collisions at the highest RHIC energies will become discontinuous if the excess of matter over antimatter, typically parametrized by a chemical potential μ_B for baryon number, can be increased above some critical value. The critical point where the transition changes its character is a fundamental landmark on the phase diagram of QCD. Within the last five years, new methods in lattice QCD have opened the door to an *ab initio* theoretical determination of its location (Fig. 10, right panel). If it lies at a μ_B which is not more than 500 MeV, as several of the pioneering lattice calculations indicate, then there is every expectation that as these calculations are pushed to finer lattice spacings over the coming few years the QCD prediction for the location of the critical point will become as solid as that for T_c, the temperature of the matter-antimatter-symmetric crossover, is today.

At present we have only a tentative sketch of the QCD phase diagram based on what we know at $\mu_B = 0$, together with models, inferences, and the pioneering lattice QCD calculations. The discovery of experimental evidence for the existence, and hence the location in (μ_B, T), of either the QCD critical point itself or the first order phase transition that lies beyond it at higher

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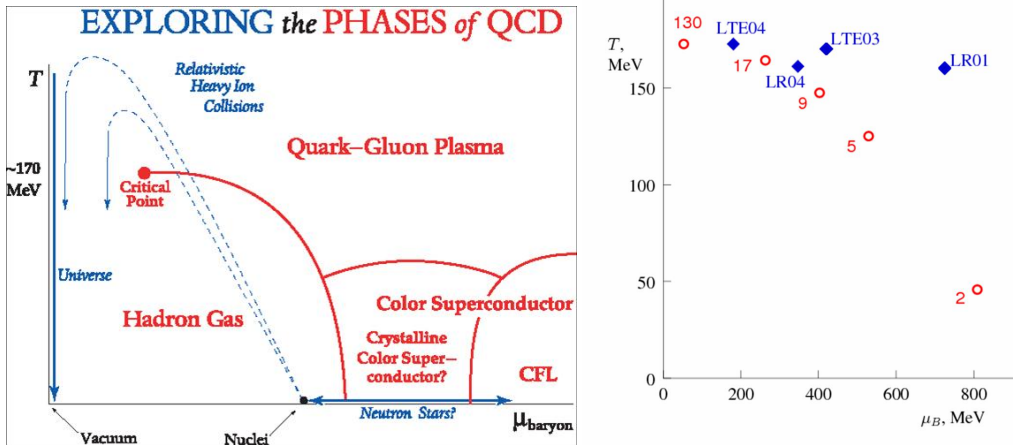
Figure 10: **Left panel:** a sketch of the QCD phase diagram as a function of temperature T and baryon chemical potential μ_B. The early universe cooled slowly down the vertical axis — it was filled with quark-gluon plasma for the first microseconds after the big bang. Heavy ion collisions reproduce matter last seen in nature at this early cosmological epoch. The transition between quark-gluon plasma and ordinary hadronic matter is a crossover at small μ_B, and is thought to become first order for μ_B greater than that of a critical point in the phase diagram. Cold dense quark matter, as may occur within neutron stars, is in one of several possible color superconducting phases. **Right panel:** searching for the QCD critical point [12]. The blue diamonds mark the location of the critical point found in four pioneering lattice QCD calculations (done in the years indicated, using the "Lattice Reweighting" or "Lattice Taylor Expansion" methods). Each was done at a single lattice spacing; extrapolation to the continuum limit is a current challenge. The red circles, labeled by $\sqrt{s}$, indicate the location in the phase diagram where heavy ion collisions with various collision energies freeze out. By scanning $\sqrt{s}$ over a range extending down to 5 GeV, and by virtue of its favorable collider geometry and detectors, RHIC can look for the entire suite of event-by-event fluctuations expected to characterize collisions which freezeout after passing near the critical point if the critical point has $\mu_B < \sim 500$ MeV.

μ_B, would transform this sketch into a solid, quantitative map in which we have full confidence. Increasing μ_B (i.e. increasing the excess of matter over antimatter) in a heavy ion collision is accomplished by reducing the collision energy $\sqrt{s}$. By doing heavy ion collisions at a sequence of energies with $\sqrt{s}$ between 5 and 50 GeV, RHIC will be able to explore the character of the QCD transition with μ_B between 30 and about 550 MeV, meaning that it can find the QCD critical point if it lies within this broad regime.

Heavy ion collisions that cool in the vicinity of the QCD critical point are expected to be characterized by enhanced event-by-event fluctuations of all observables that depend either on the matter-antimatter asymmetry or on the degree of chiral symmetry breaking. Both these quantities fluctuate with large amplitudes and over long length scales only near the critical point, and many properties of these fluctuations can be calculated from first principles. Examples of observables which have been studied include the event-by-event fluctuations of the number of protons minus antiprotons, of the mean transverse momentum p_T of all the soft pions in an event, and of the kaon-to-pion and proton-to-pion ratios.

Earlier experiments at the SPS have found an intriguing and as yet unexplained enhancement in the fluctuations of the kaon-to-pion ratio at $\sqrt{s} = 6 - 8$ MeV, corresponding to $\mu_B = 400 - 500$ MeV. The proton-to-pion fluctuations are not enhanced, and the p_T fluctuations were not measured. RHIC will be able to make comparative measurements over a range of energies in collider geometry, and with the same detectors, offering a considerable advantage because most systematic effects will remain constant, in contrast to the situation for fixed target measurements. Recent studies indicate that, in a single running period, RHIC could significantly improve both the statistical and systematic errors on those observables where there are existing data at SPS energies, while at the same time making the whole suite of relevant event-by-event fluctuation measurements over the entire relevant energy range for the first time. The feasibility of this program depends crucially on the completion of detector upgrades currently underway and depends on the capability of RHIC to provide adequate luminosity at low $\sqrt{s}$. There was considerable discussion of these feasibility issues at a recent workshop held at BNL [13]. It was concluded that there are no apparent barriers for operation of RHIC at 5-50 GeV, allowing RHIC to access the entire range 30 MeV$< \mu_B <$550 MeV. The possibility of implementing electron cooling to increase the luminosity at low energies is being pursued. This would make it possible to study any newly discovered features of the QCD phase diagram

with greater precision, for example by permitting the high-statistics runs needed to see dileptons or by facilitating varying nuclear size A along with $\sqrt{s}$.

When the FAIR facility, with its CBM detector, comes on line in Germany in 2015, it will study matter with $\sim 400 < \mu_B < 650$ MeV. If RHIC discovers the QCD critical point, experiments at FAIR will be well-positioned to study the spatially inhomogeneous final state of heavy ion collisions which cool through a first order phase transition. If RHIC discovers that the QCD critical point lies at $\mu_B > 400$ MeV, the FAIR facility will seek to confirm this discovery directly.

Locating the critical point where the transition changes its character is of fundamental importance for understanding QCD. This provides RHIC with significant new discovery potential as it explores the poorly charted reaches of our current map of the QCD phase diagram. As is the case in the complementary effort to use RHIC to gain new and more quantitative understanding of the properties of quark-gluon plasma, ramping up corresponding theoretical efforts are crucial to the success of the experimental program. The experimental search for the QCD critical point will require the phenomenological studies of the properties and experimental signatures of matter near the critical point to be taken to a new level, ultimately in an interplay with data as it comes in. Furthermore, in order for an experimental discovery to have maximum impact, the recent advances in lattice QCD that have opened this regime to *ab initio* calculations must be pursued and capitalized upon. Lattice QCD calculations and RHIC experiments are in a race to locate the QCD critical point. The resulting scientific accomplishment will have the greatest impact only if both parties win.

3.3 Hard Probes at RHIC and LHC

Hard (high Q^2) probes, in particular energetic jets, heavy quarks, and quarkonia, have provided key insights into the QCD matter generated in high energy nuclear collisions (Sect. 2.2.2). The great utility of hard probes for quantitative measurement of the transport properties of dense matter is due to several factors:

- hard probe production rates in nuclear collisions can be established using perturbative calculations and measurements in p+p and p/d+A collisions;

- interactions of hard probes in dense matter are seen experimentally to be very strong;

- these interactions are theoretically calculable within perturbatively-based frameworks.

The most notable success thus far in the area of hard probes at RHIC is jet quenching. Measurements of quarkonium suppression are now coming to maturity and promise as great an impact on our understanding of QCD matter. Here we discuss prospects for both classes of measurement in the coming years at RHIC and the LHC, and the developments necessary to realize them.

3.3.1 Jet Quenching

Measurements of high p_T hadron production and correlations give direct evidence that extraordinarily large gluon densities (and correspondingly large energy densities) are generated in head-on collisions of heavy nuclei (Sect. 2.2.2). However, quantitative interpretation of these data in terms of gluon densities and transport properties of the medium requires comparison to detailed phenomenological models. The systematic uncertainties of the extracted quantities therefore depend not only on the precision of the data, but also on the validation of the theoretical models and the full exploration of their parameter space. As the following discussion illustrates, jet quenching provides an example of striking experimental discoveries whose importamce and implications can be fully realized only by a combination of more discriminating, differential measurements and significant progress in theoretical understanding of the underlying processes.

Measurement of transport properties: Significant recent progress has been made in the quantitative comparison of jet quenching data with detailed theoretical calculations. Models incorporating radiative energy loss reproduce accurately the systematic behavior of hadron production and correlations as a function of hadron momentum and system size. High p_T pion suppression constrains the transport coefficient $\hat{q}$ in such models to within a factor two (Fig. 5), while the additional consideration of back-to-back leading hadron suppression from a pair of recoiling jets can reduce the systematic uncertainty further. However, due to the large partonic energy loss, the core
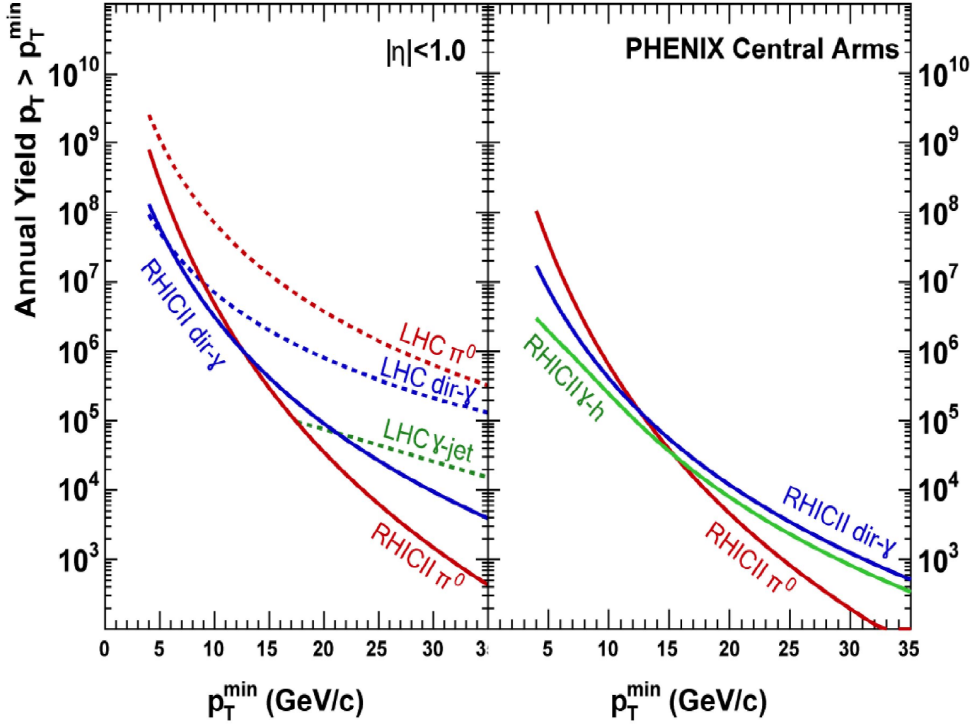
Figure 11: Annual yields at RHIC II and LHC for π^0, direct γ, and γ+jet above a p_T cut, for STAR (left) and PHENIX (right) acceptances. ATLAS and CMS have larger acceptance than left panel, ALICE has slightly smaller acceptance. Yields from RHIC I, prior to the luminosity upgrade, are a factor ~ 10 smaller than RHIC II yields.

of the fireball is largely opaque to moderate energy jets. Precise determination of medium properties in this framework requires systematic checks over a much broader dynamic range, which are possible only for dihadron correlation measurements at substantially higher momentum. Such measurements require RHIC II luminosities and the higher collision energy at the LHC.

These results are striking, and represent a major success of the RHIC program. However, the primacy of radiative energy loss is challenged by measurements of non-photonic electrons, which arise from the semi-leptonic decay of heavy flavor mesons (charm and bottom). The magnitude of radiative energy loss is expected on general grounds to be reduced for massive quarks, with a large difference predicted between charm and bottom quarks in the kinematic range currently accessible for non-photonic electron mea-

surements at RHIC ($p_T < 10$ GeV/c). Surprisingly, RHIC measurements show that non-photonic electron production in central nuclear collisions is suppressed at the same level as light hadron production (a factor ~ 5), leading to an apparent inconsistency for calculations in which only radiative energy loss is considered.

Resolution of the heavy flavor suppression puzzle at RHIC is crucial to establish a fully self-consistent picture of jet quenching. One proposed solution is the introduction of additional energy loss mechanisms, in particular elastic channels. However, the magnitude of the actual discrepancy depends on the relative contribution of charm and bottom mesons to the non-photonic electron yield, which at present is not well known. Perturbative QCD calculations unfortunately do not provide meaningful constraints on these contributions. The essential missing ingredient is the measurement of charm and bottom suppression separately, which requires the vertex detector upgrades to PHENIX and STAR that are currently in progress.

γ+jet and Z+jet measurements: Due to large partonic energy loss, the core of the fireball is effectively opaque to jets, and the hadronic measurements described above are dominated by jets generated at its periphery. This geometric bias limits sensitivity to the hottest and densest matter at the core of the fireball, and transport properties deduced from such measurements therefore have significant model dependence. The QCD Compton process, where a jet recoils from a hard direct photon (or Z-boson at the LHC), does not suffer from this geometric bias since the trigger photon/Z does not carry color charge and therefore does not lose energy in the medium. This process probes the full volume of the fireball, with the direct γ/Z providing an accurate measurement of the energy of the recoiling jet. Though challenging in terms of rate and signal/background, these measurements will provide the most precise, model-independent measurements of jet quenching available. Both PHENIX and STAR have reported initial steps in this direction, but current data are very limited statistically. High quality measurements require a luminosity upgrade. Figure 11 shows the annual yield of direct photons, π^0s and γ+jet/hadron coincidences in heavy ion collisions at RHIC II and the LHC. The kinematic reach of the RHIC detectors following the RHIC II luminosity upgrade is significant for γ+hadron coincidences, extending well beyond 30 GeV/c. At the LHC a similar range is expected for statistically significant Z+jet measurements, while the γ+jet measurement will extend farther.

Novel jet quenching phenomena: As discussed in Section 2.2.2, the detailed study of jet structure in nuclear collisions continues to reveal surprising new phenomena. Low momentum particles recoiling from a trigger hadron are distributed in a broad cone, perhaps indicating the generation of shock waves or Cerenkov radiation in the medium. Intra-jet correlations, measured using hadron pairs at small angular separation, are elongated in the beam direction, perhaps due to coupling of medium-induced radiation to the longitudinally expanding fireball. Neither of these features is understood theoretically at present, but they appear to probe the dynamics of the medium in new and sensitive ways and must be understood. Three-particle correlations promise to discriminate clearly among the proposed physics scenarios, but they are statistically very demanding. High quality multi-hadron correlation measurements require an order of magnitude more data than currently available, which can only be achieved with the RHIC II luminosity and detector upgrades. The large jet yields at the LHC will enable similar measurements. Detector upgrades and high statistics datasets will also generate much more detailed investgation of the "intermediate p_T" region, where identified particle measurements (especially correlations) probe the interaction of jets with the medium.

Fully reconstructed jets: The inclusive jet spectrum in heavy ion collisions at the LHC will reach $E_T \sim 400$ GeV, while at RHIC II (following the luminosity upgrade) it will extend beyond $E_T \sim 60$ GeV. At such large jet energies, infrared-safe jet reconstruction (recovery with good resolution of the full energy of hard-scattered partons) can be carried out even in the presence of the large underlying event in heavy ion collisions. Full jet reconstruction is, per definition, insensitive to details of the fragmentation. Full jet reconstruction, similar to the γ/Z+jet measurements discussed above, will therefore be free of geometric biases intrinsic to the leading particle analyses currently being carried out. The full range of modifications of jet structure can therefore be studied, with qualitatively new observables. The broad jet energy range will probe the medium over a broad variation in resolution scale, analogous to study of the Q^2 evolution of nucleon structure in DIS measurements. The jet physics program in heavy ion collisions at the LHC and RHIC II is still being developed, but such measurements have the potential to provide deep and qualitatively new insights into partonic interactions in QCD matter.

$q\bar{q}$	J/ψ	$\chi_c(1P)$	$\psi\prime$	$\Upsilon(1S)$
T_{dissoc}/T_c	1.7-2.0	1.0-1.2	1.0-1.2	~ 5

$q\bar{q}$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_{dissoc}/T_c	~ 1.6	~ 1.4	~ 1.2	~ 1.2

Table 1: Dissociation temperatures of various quarkonium states relative to the deconfinement temperature, from recent finite temperature lattice calculations in both quenched and two-flavor QCD.

3.3.2 Quarkonium Suppression and Deconfinement

One hallmark of the Quark-Gluon Plasma is *deconfinement*, the dissociation due to color screening of hadronic states that are bound in vacuum. Twenty years ago, Matsui and Satz proposed that deconfinement could be observed through strong J/ψ suppression. Such suppression has indeed been observed at the SPS by the NA50 experiment. It is not directly interpretable in terms of deconfinement, however, since absorption in cold nuclear matter also contibutes to the observed suppression and its effect must be disentangled through a systematic study of A+A, p+A, and p+p collisions. Quarkonium suppression is nevertheless *the* essential signature of deconfinement, and measurement of quarkonium production in A+A, p+A and p+p collisions is a key element of the RHIC and LHC heavy ion programs.

Recent lattice QCD calculations predict a hierarchy of dissociation temperatures for different quarkonium states, as shown in Table 1. χ_c, $\psi\prime$, and $\Upsilon(3S)$ are loosely bound and dissociate near the deconfinement transition temperature T_c temperature, while $\Upsilon(1S)$ is most tightly bound and survives well above the transition temperature. There are still significant theoretical uncertainites in these estimates, but the general features present in the table suggest that systematic study of multiple quarkonium states may provide a powerful *differential* probe of color screening and deconfinement.

Quarkonium production cross sections are generally much smaller than jet cross sections, and quarkonium measurements at RHIC are only now coming to maturity. PHENIX has found the same magnitude of J/ψ suppression in nuclear collisions at RHIC as was seen by the NA50 collaboration at the SPS, a result which is surprising in light of the larger energy density measured by jet quenching at RHIC. This may be due to large opacity of the fireball in both cases, leading to similar geometric bias and a geometry-driven suppression factor; to a conspiracy at RHIC of larger initial suppression and
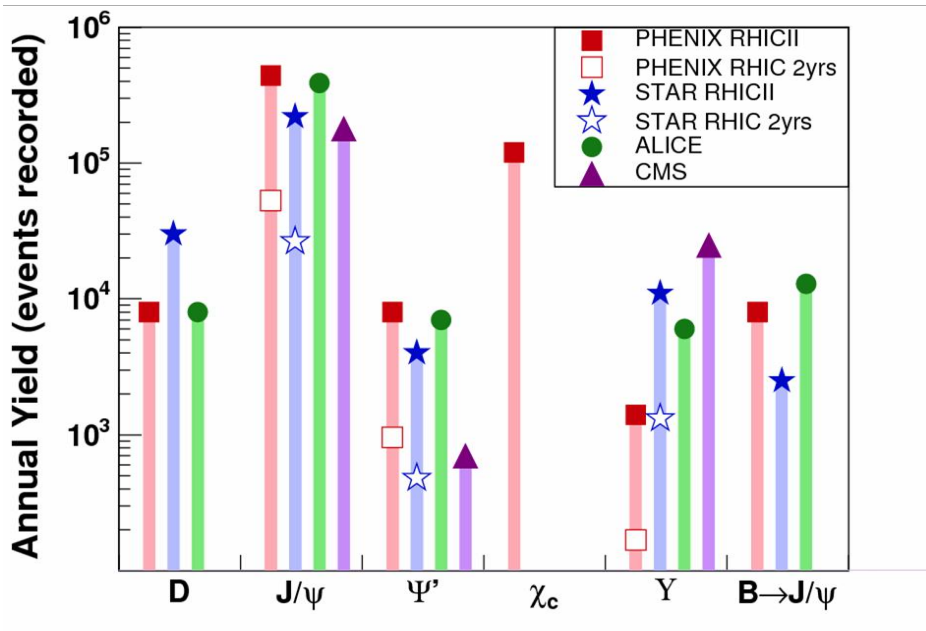
Figure 12: Annual yields for heavy flavor production at RHIC II and the LHC. Open symbols indicate expected total yields for the near-term RHIC runs in 2007 and 2009, prior to the luminosity upgrade.

significant production via coalescence at a later stage of the fireball evolution; or to preferential dissociation of χ_c at moderate temperatures near the phase transition, suppressing its feed-down contribution to the observed J/ψ signal while the J/ψ itself survives (Table 1). Additional measurements, such as elliptic flow and the rapidity and transvere momentum dependence of the suppression, will provide strong constraints on the possible underlying mechanisms. While the PHENIX measurement has prompted new theoretical activity to model the various effects, a clear resolution to this puzzle requires measurements of additional quarkonium states.

The RHIC II luminosity upgrade is required for significant measurements of all states in the Table except J/ψ. A crucial experimental test of the relative importance of initial production vs. coalescence is the collision energy dependence of the suppression, which can only be studied with the upgraded RHIC luminosity.

Figure 12 shows the expected yield of various heavy flavor states for one year of heavy ion running at RHIC II and the LHC (annual rates are roughly

independent of collision system), together with expectations for near-term RHIC running prior to the luminosity upgrade. In all channels except J/ψ, the luminosity upgrade turns statistically marginal (or worse) measurements into robust probes of the medium.

The larger cross sections at the higher LHC energy are approximately balanced by the increased luminosity and running times at RHIC II, so that the heavy flavor yields per year are similar. Thus the types and quality of measurements that can be made at the two facilities will also be similar. However, there will be a significant difference in the physics environments at the two facilities that will make the programs complementary. The higher initial energy density at the LHC means that the QGP will be created at a significantly higher temperature. In addition, the factor of 10 increase in charm pairs and the factor of 100 increase in bottom pairs per central collision at the LHC will have a major impact on the interpretation of heavy flavor measurements.

At the LHC, all of the charmonium states may be unbound at the highest temperatures. Thus the prompt charmonium yields at the LHC should be large and be dominated by coalescence and feed-down ($B \rightarrow$ J/ψ), with relatively little contribution from the primordial J/ψ production. Because of its higher binding energy, bottomonium at the LHC should behave similarly to charmonium at RHIC. The $\Upsilon(1S)$ may remain bound at the highest temperatures at the LHC while the other bottomonium states will melt. RHIC II and LHC therefore provide a number of complementary probes of quarkonium suppression, enabling detailed, differential study of color screening and deconfinement.

3.4   Future prospects: summary

The RHIC community has embarked on a series of integrated upgrades to the detectors and the accelerator complex, which will provide broad new capabilities that address the fundamental questions raised by the first generation of RHIC experiments. Most importantly, these upgrades, together with significant progress in theory, will provide dramatic progress in the *quantitative* understanding of hot QCD matter. Progress in this direction has already been made, in particular in the measurement of the transport parameter $\hat{q}$. Definitive measurements of $\hat{q}$, η/s, and other fundamental quantities require the upgrades and progress in theory discussed in this chapter.

The LHC will soon begin operation, not only with p+p collisions but also

with heavy ion collisions for four weeks per year. The simultaneous operation of heavy ion experiments at RHIC and LHC offers an unprecedented opportunity to understand QCD matter in great depth. Each facility has its strengths, in terms of flexibility in beams and energies and kinematic reach of hard probes. Equally important, however, is the ability to carry out the *same* jet quenching or elliptic flow measurements on physical systems evolving from vastly different initial states. The comparison of RHIC and LHC measurements promises to give deep insights into the nature of the experimental probes and their interactions with the medium, and consequently the hot QCD medium itself.

4 The Emerging QCD Frontier: The Electron-Ion Collider

Much of the focus in contemporary nuclear physics research is on mapping and understanding the emergent phenomena from QCD that determine the unique properties of strongly interacting matter: the breaking of chiral symmetry that gives light-quark hadrons most of their mass; the spin, flavor, space and momentum structure of hadrons; the nearly perfect liquid behavior of the hot matter created in RHIC collisions; possible color superconductivity in the dense interior of compact stars. A key to understanding the rich panoply of QCD phenomena is identifying conditions under which the theory is amenable to controlled solution. Numerical solutions on a space-time lattice have made impressive advances in the treatment of strongly interacting matter in equilibrium at both low and high temperatures. A perturbative expansion in powers of the running QCD coupling constant α_s is successful in describing hadron dynamics in high-energy processes involving large momentum transfer. Interactions of pions and nucleons at low momentum have been successfully analyzed via chiral effective field theories.

Recent theoretical advances have introduced a new QCD regime that may be amenable to a quite different effective field theory approach. This new interpretability frontier occurs in matter probed at moderate momentum transfers, where the QCD coupling is still relatively weak, but at gluon densities high enough to produce extremely strong color fields that can be treated by classical field theory. This regime is dominated by direct manifestations of the defining feature of QCD: the self-interaction of gluons. Gluon splitting

and gluon recombination are predicted to reach a competitive balance, leading to a saturation of gluon density that should be universal to all strongly interacting matter probed under suitable conditions. Hints of this saturation have been extracted from measurements of electron-proton collisions at HERA and of deuteron-nucleus and nucleus-nucleus collisions at RHIC. Saturated gluon densities would have a profound influence on heavy-ion collisions at the LHC, and may well be the source of certain general features of high-energy hadron cross sections. In order to tie these phenomena together and map the universal properties of gluon-dominated matter, one needs to probe partonic structure at very low values of Bjorken x, where individual partons carry $<\sim 0.1\%$ of a nucleon's overall momentum, but within a "sweet spot" in momentum transfer (Q^2) where the color interaction is neither too weak nor too strong.

The ideal accelerator to test this classical field theory approach well into the gluon saturation regime with an *a priori* understood probe is an Electron-Ion Collider, EIC. Coherent contributions from many nucleons within a heavy-ion beam particle at such a collider amplify gluon densities, thereby broadening the Q^2 "sweet spot" and extending the effective reach to small x-values by about two orders of magnitude, in comparison with e-p collisions at the same energy per nucleon. In addition to providing precocious entry into the anticipated universal saturation regime, how does the nuclear environment affect the *path* to saturation? Do the momentum and space distributions of gluons in nuclei differ in non-trivial ways from those in nucleons, as has been found for quarks? Are there small clumps of gluons, or are they more uniformly distributed? These questions will be addressed by a combination of deep inelastic inclusive scattering and vector meson production from nucleons and nuclei.

The addition of *polarized* proton and light-ion beams to collide with polarized electrons and positrons at EIC would dramatically expand our understanding of the nucleon's internal wave function. It would greatly extend the kinematic reach and precision of deep inelastic scattering measurements of nucleon spin structure. The contribution of gluons and of sea quarks and antiquarks of different flavor to the nucleon's spin would be mapped well into the gluon-dominated region. The study of Generalized Parton Distributions (GPD's) in deep exclusive reactions will be pushed far beyond presently accessible energies at JLab, HERA and CERN, extending three-dimensional spatial maps of the nucleon's internal landscape from the valence quark region down into the region dominated by sea quarks, antiquarks and gluons.

This extension may be critical for completing the picture of how the nucleon gets its spin, by providing sensitivity via GPD's to the orbital motion of sea partons.

High-energy scattering from nucleons in a collider environment lends itself specifically to study how the creation of matter from energy is realized in QCD when an essentially massless (and colored) quark or gluon evolves into massive (and color-neutral) hadrons. Numerical solutions of QCD on a space-time lattice cannot provide guidance for the dynamical process by which the scattered parton picks up other colored partners from either the QCD vacuum or the debris of the high-energy collision. Rather, we rely on experiment to map the result of these parton fragmentation dynamics. The availability of a high-energy, high-luminosity polarized electron-ion collider, using high-efficiency detectors with good particle identification, will facilitate experiments to measure new features of the fragmentation process, such as its dependence on quark spin, flavor and motion, and on passage through nuclear matter.

In short, EIC is a machine that would expand the intellectual horizons of nuclear physics research into the non-linear heart of QCD, where gluon self-interactions dominate. It would address the following fundamental science questions:

- Does the self-limiting growth of color field strengths in QCD lead to universal behavior of all nuclear and hadronic matter in the vicinity of these limits?

- How does the nuclear environment affect the distribution of gluons in momentum and space?

- What is the internal landscape of a nucleon in the region dominated by sea quarks and gluons?

- How do hadronic final states form from light quarks and massless gluons in QCD?

It would build on the scientific and technical expertise developed over decades at the nation's two premier QCD laboratories at Jefferson Lab and RHIC, but would add new state-of-the-art accelerator technology to reach its design goals.

In this section, we highlight several of the science programs that EIC would foster and outline two design options under consideration, referring the reader to the more detailed White Papers [14, 15] that have been written on EIC alone. We also describe briefly below the R&D necessary to demonstrate feasibility of various aspects of accelerator and detector design for such a facility.

4.1 Physics of Strong Color Fields

With its wide range in energy, nuclear beams, high luminosity and clean collider environment, the EIC will offer an unprecedented opportunity for discovery and for the precision study of a novel universal regime of strong gluon fields in QCD. The EIC will allow measurements, in a wide kinematic regime, of the momentum and spatial distribution of gluons and sea-quarks in nuclei, of the scattering of fast, compact probes in extended nuclear media, and of the role of color neutral (Pomeron) excitations in scattering from nuclei. These measurements at the EIC will deepen and corroborate our understanding of the formation and properties of the strongly interacting Quark Gluon Plasma (QGP) in high energy heavy ion collisions at RHIC and the LHC.

Strong color fields in nuclei. One of the major discoveries of the last decade was just how dominant a role gluons play in the wave function of a proton viewed by a high-energy probe with high spatial resolution (*i.e.*, with large 4-momentum transfer squared Q^2). HERA deep inelastic scattering data revealed that the density of partons, especially gluons, in the plane transverse to the probe momentum grows rapidly with decreasing parton momentum fraction x. This growth is attributable in QCD to the successive emission of soft partons by higher-momentum partons. The resulting gluon field can be treated linearly within QCD when x and Q^2 are not too small. But for given x, the dynamics of the gluon fields becomes highly non-linear below a certain saturation momentum scale Q_s^2. At low x, where parton densities are quite high, the recombination of soft gluons into harder ones sets in as the leading non-linear interaction to tame further growth of the parton densities. If the saturation momentum is large on a typical QCD scale, $Q_s \gg \Lambda_{\mathrm{QCD}}$, then the coupling strength $\alpha_s(Q_s^2) \ll 1$ and the gluon dynamics can be described with weak-coupling techniques. The occupation number of gluon field modes with transverse momenta below Q_s saturates at values $\sim 1/\alpha_s(Q_s^2) \gg 1$, so that the probe sees a very strong, essentially classical, color field frozen by time dilation, a system often referred to as the

"color glass condensate" (CGC). A goal of theoretical treatments of this high-density QCD matter is to establish a rigorous effective field theory approach for controlled inclusion of higher-order effects beyond the CGC limit.
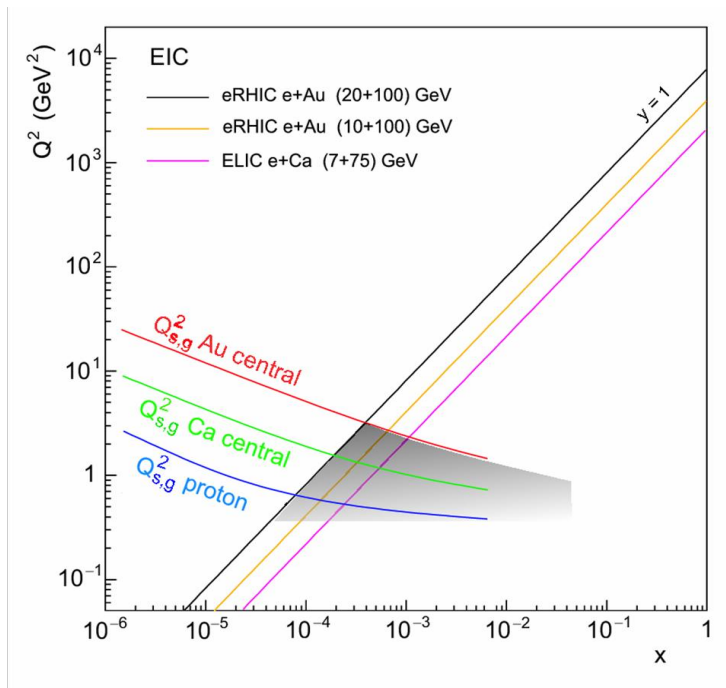
Figure 13: Kinematic acceptance and exposure of the predicted gluon saturation regime in the (x, Q^2) plane for the EIC. The accessible regions fall to the right of the three diagonal straight lines, representing different choices for beam energies (per nucleon in the case of ion beams) and maximum mass of the ion beams. Curves showing the gluon saturation scale Q_s^2 for protons and for central collisions with Ca and Au nuclei are superposed on the kinematic acceptance. The shaded area indicates the kinematically accessible region of saturated gluon density that should be reached in the maximum-energy e+Au collisions considered.

Since the saturation momentum grows slowly with decreasing x (see Fig. 13), so does the window ($\Lambda_{\mathrm{QCD}} \ll Q \ll Q_s$) into the CGC regime. However, a much more effective opening of this window can be arranged by exploiting the Lorentz contraction of a fast-moving nucleus, which amplifies the parton density in proportion to the nuclear diameter, so that $Q_s^2 \propto A^{1/3}$.

Thus, as illustrated in Fig. 13, one can enter the predicted saturation regime in e-Au collisions at x-values a couple of orders of magnitude larger than what would be required in e-p collisions at the same Q^2. An electron-ion collider thus represents the most robust and cost-effective approach to study the physics of these strong color fields. Can a clear saturation scale be identified experimentally? Are the properties of partonic matter in the saturation regime indeed *universal* to all hadrons and nuclei? Are these properties consistent with inferences from particle multiplicities and momentum spectra observed at RHIC and with dynamics soon to be explored in heavy-ion collisions at the LHC? Can the properties of saturated gluon fields in heavy nuclei provide a natural explanation for the very rapid thermalization inferred from analysis of relativistic heavy-ion collisions? These questions will be addressed via deep inelastic scattering (DIS) and other cleanly interpretable electromagnetic processes at EIC, as explained in more detail below.

Measurements of momentum distributions of gluons and sea quarks in nuclei. Gluon momentum distributions overwhelm their quark counterparts in the proton for $x <\sim 0.01$. DIS experiments have established that quark and gluon distributions in nuclei exhibit "shadowing": they are modified significantly relative to their distributions in the *nucleon* wavefunction. However, the detailed nature of gluon shadowing at $x <\sim 0.01$ is *terra incognita* in QCD. This physics, bearing directly on the universality of gluon saturation, can be fully studied in electron–nucleus scattering at the EIC, over the broad kinematic coverage shown in Fig. 13.

The inclusive DIS structure functions $F_2^A(x, Q^2)$ and $F_L^A(x, Q^2)$ offer the most precise determination of quark and gluon momentum distributions in nuclei. Independent extraction of F_2^A and F_L^A is only possible via measurements over a range of center of mass energies, an essential requirement of the EIC. The F_2^A structure function is directly sensitive to the sum of quark and anti-quark momentum distributions in the nucleus; at small x, these are predominantly sea quarks. Information on the gluon distribution in the nucleus, $G^A(x, Q^2)$, can be indirectly garnered from the well-known logarithmic scaling violations of F_2^A with Q^2, $\partial F_2^A/\partial \ln(Q^2)$. In Fig. 14 we show projections for the normalized ratio of $F_2^A(x, Q^2)$ in gold relative to deuterium from a saturation (CGC) model in comparison to the usual linear evolution of perturbative QCD for three models incorporating differing amounts of shadowing. Saturation of gluon densities in the CGC model is manifested by the weak x- and Q^2-dependence of the slope $\partial F_2^{Au}/\partial \ln(Q^2)$ at low x and moderate Q^2. The projected statistical precisions attainable for inclusive DIS
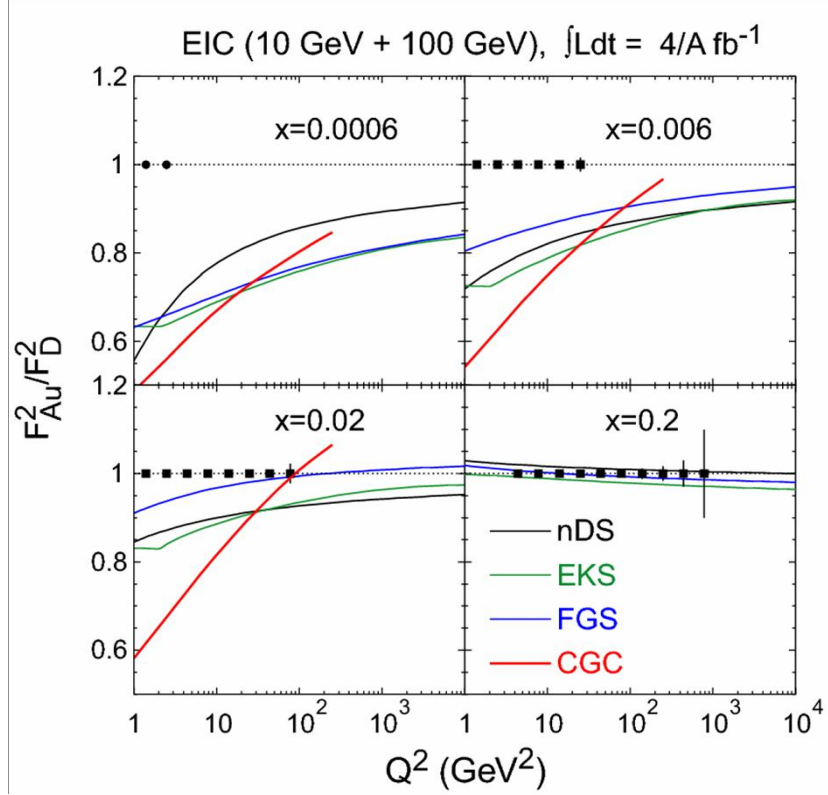
Figure 14: The ratio of the structure function F_2^{Au} in Au nuclei relative to the structure function F_2^{D} in deuterium nuclei as a function of Q^2 for several bins in x. The filled circles and error bars correspond respectively to the estimated kinematic reach in F_2 and the statistical uncertainties for a luminosity of $4/\mathrm{A}\,\mathrm{fb}^{-1}$ with the EIC. The curves labeled nDS, EKS and FGS correspond to different parameterizations of parton distributions at the initial scale for pQCD evolution, while the one labeled CGC corresponds to a Color Glass Condensate model prediction applicable at small x.

measurements with $10\,\mathrm{GeV}$ electrons on $100\,\mathrm{GeV}$/nucleon Au nuclei and an integrated luminosity of $4/\mathrm{A}\,\mathrm{fb}^{-1}$, also shown in Fig. 14, suggest that EIC data can readily distinguish among differing model predictions.

The structure function $F_L^A \equiv F_2^A - 2xF_1^A$ for absorption of longitudinal photons by the proton vanishes in the naive parton model, but in QCD it is proportional at small x to the gluon momentum distribution. Hence, its measurement will allow a new and independent direct determination of

$G^A(x, Q^2)$ in the low-x region where little is presently known. The high precision attainable for both F_2 and F_L at EIC will facilitate definitive tests of the universality of saturated gluonic matter. Measurements for different nuclei, x and Q^2 values can be combined in a single plot of the structure functions vs. $Q^2 x^\gamma / A^\delta$ to search for values of the adjustable powers γ and δ that yield a universal curve, and hence define the x- and A-dependence of the saturation scale $Q_s^2(x, A)$.

Additional strong sensitivity to gluon densities in nuclei will be provided by semi-inclusive and exclusive final states. An example of the former is di-jet production in e-A collisions, which is dominated at EIC energies by the photon-gluon fusion process. An exclusive example is elastic vector meson production $e + A \longrightarrow (\rho, \phi, J/\psi) + A$, where forward cross sections for longitudinal virtual photons depend on the square of the gluon density.

The gluon spatial distribution. The spatial distribution of gluons in a nucleus provides a complementary handle on the physics of strong color fields and has important ramifications for a wide range of final states in hadronic and nuclear collisions. Information on the spatial distribution can be inferred from forward vector meson production in e-A, which can be viewed at small x as the result of coherent interactions of quark-antiquark fluctuations of the virtual photon with the nucleus. The differential cross section for the vector mesons, as a function of momentum transfer t along the proton line, can be analyzed to extract a survival probability of these small color dipole fluctuations as a function of impact parameter b at which the dipole traverses the nucleus. The survival probability is, in turn, sensitive to the strength of the gluon field seen. Systematic studies of vector meson production over a wide range of kinematic conditions and for several ion species can thereby illuminate the b-dependence as well as the A-dependence of the saturation scale.

Color neutral (Pomeron) excitations in scattering off nuclei. Another predicted manifestation of strong gluon fields in QCD is an enhanced probability for a high-energy probe to interact with a color-neutral multi-gluon excitation of the vacuum – an excitation that may be associated with the so-called Pomeron – leaving the target nucleus intact. These interactions lead to diffractive final states that may dominate forward scattering. At HERA, an unexpected discovery was that diffraction accounted for 15% of the total $e + p$ cross-section. This is a striking result implying that a proton at rest remains intact one seventh of the time when struck by a 25 TeV electron. The effect may be even more dramatic in nuclei. Several models of

strong gluon fields in nuclei suggest that large nuclei will remain intact nearly 40% of the time in EIC collisions, in comparison to the quantum mechanical black disk limit of 50%. Measurements of coherent diffractive scattering on nuclei are easier in the collider environment of EIC than in fixed-target experiments, but nonetheless place strong demands on the forward acceptance of detectors. With suitable detectors, EIC measurements should be able to distinguish the onset of non-linear dynamics for the gluon field, leading to a weak x-dependence but strong Q^2-dependence of the ratio of diffractive structure functions for heavy *vs.* light nuclei. These dependences are distinct from those expected in non–perturbative ("soft" Pomeron) models of diffractive scattering.

Fast probes of an extended gluonic medium. How are the propagation of fast partons and their space-time evolution into hadrons affected by traversal of nuclear matter characterized by strong gluonic fields? Semi-inclusive DIS (SIDIS) experiments at EIC, with high-momentum hadrons detected in coincidence with scattered electrons for a wide range of kinematic conditions and ion species, will use nuclei as femtometer-scale detectors to study these issues in cold nuclear matter. These experiments will provide an essential complement to studies of jet quenching in the hot matter produced in RHIC heavy-ion collisions. The RHIC jet quenching studies have produced a series of striking and surprising results: a strong suppression of high-momentum hadrons usually attributed to rapid energy loss of partons traversing matter of high color charge density, but little apparent dependence of the suppression factor on quark flavor, in sharp contrast to expectations from perturbative QCD models of the parton energy degradation. SIDIS on *fixed* nuclear targets has so far revealed an analogous but weaker suppression of light hadron production in cold nuclear matter. EIC will enormously expand the virtual photon energy range in such studies, from 2–25 GeV in the HERMES experiment at HERA to $10 \, \text{GeV} < \nu < 1600 \, \text{GeV}$, thereby providing access to the kinematic region relevant for LHC heavy-ion collisions and to such important new issues as the suppression of heavy-flavor mesons travelling through cold nuclear matter.

One of the basic physics questions to be answered here concerns the time scale on which the color of the struck quark is neutralized, acquiring a large inelastic cross-section for interaction with the medium. The parton energy loss models used to interpret RHIC results assume long color neutralization times, with "pre-hadron" formation outside the medium and quark/gluon energy loss as the primary mechanism for hadron suppression. Alternative

models assume short color neutralization times with in-medium "pre-hadron" formation and absorption as the primary mechanism. There do exist hints of short formation times from HERMES data and JLab preliminary data, but these must be pursued over the wider kinematic range and much broader array of final-state channels that can be explored at EIC.

4.2   A New Era of Hadronic Physics

The EIC will provide definitive answers to compelling physics questions essential for understanding the fundamental structure of hadronic matter. It will allow precise and detailed studies of the nucleon in the regime where its structure is overwhelmingly due to gluons and to sea quarks and anti-quarks. Some of the scientific highlights at the EIC in this area would be: (1) definitive answers to the question of how the proton's spin is carried by its constituents, (2) determination of the three-dimensional spatial quark and gluon structure of the proton, (3) precision study of the proton's gluon distribution over a wide range of momentum fractions, and (4) maps of new spin-dependent features of the quark fragmentation process. In the following we briefly address three of these highlights of future research in hadronic physics.

The spin structure of the proton. Few discoveries in nucleon structure have had a bigger impact than the surprising finding that quarks and anti-quarks together carry only about a quarter of the nucleon's spin. Determining the partonic source of the "missing" spin in this complex composite system has developed into a world-wide quest central to nuclear physics. The sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

states that the proton spin projection along its momentum is the sum of the quark and gluon intrinsic spin ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) contributions. EIC with its unique high luminosity, highly polarized electron and nucleon capabilities, and its extensive range in center-of-mass energy, will allow DIS access to quark and gluon spin contributions at substantially lower momentum fractions x than important current and forthcoming experiments at RHIC, DESY, CERN and JLab. A key measurement at the EIC would be of the spin-dependent proton structure function $g_1(x, Q^2)$ of the proton over a wide range in Q^2, and down to $x \sim 10^{-4}$. Studies of the scaling violations of $g_1(x, Q^2)$ prove to be a most powerful and clean tool to determine the spin contribution by gluons. This is demonstrated by Fig. 15,
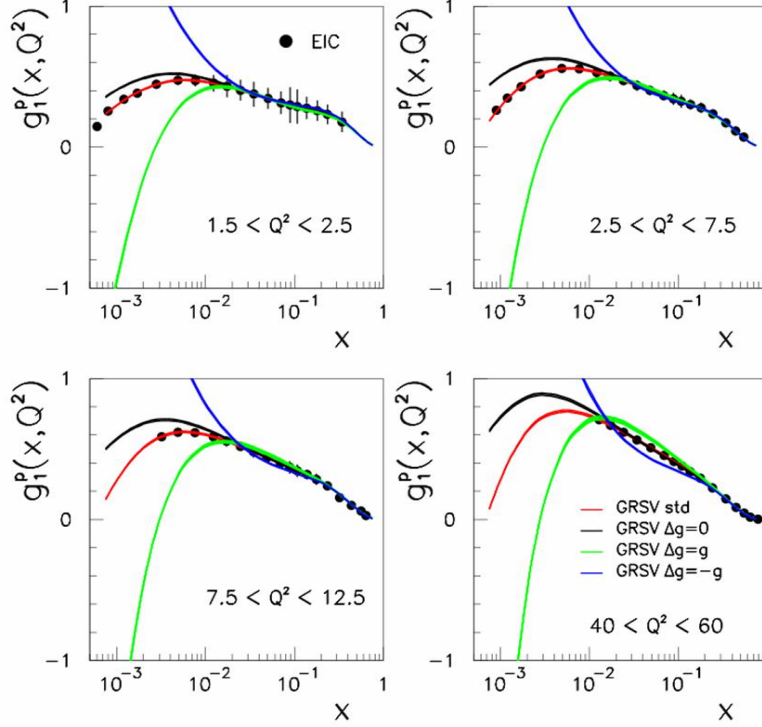
Figure 15: Projected EIC data for the proton structure function $g_1(x, Q^2)$ as a function of x in four Q^2 bins, for 7 GeV electrons colliding with 150 GeV protons at an integrated luminosity of $5\,\mathrm{fb}^{-1}$. The curves show theoretical predictions based on different sets of spin-dependent parton distribution functions that mostly differ in the gluon helicity distribution.

which shows projections for EIC measurements of $g_1(x, Q^2)$ in comparison with four model predictions that make different assumptions regarding the sign and magnitude of the gluon spin contribution to the proton spin. Each of these models is compatible with the currently available polarized fixed-target DIS data. While data from polarized proton collisions at RHIC are already beginning to establish preferences among these particular four models at $x > \sim 0.01$, the RHIC data will not be able to constrain the shape of the gluon helicity distribution at lower x, where the density of gluons rapidly increases. The great power of the EIC in providing precise information on $\Delta G(x < \sim 0.01)$ is evident.

With polarized ^{3}He beams at an EIC, measurements of g_1 would also be possible off polarized neutrons, allowing a precision test of the fundamental Bjorken sum rule, which relates the proton and neutron spin structure via the axial weak coupling strength measured in neutron beta-decay. Furthermore, semi-inclusive DIS measurements, for which a specific hadron is detected from the struck quark jet, would provide information with unprecedented detail on the individual contributions by quark and anti-quark spins to the proton spin, testing models of nucleon structure and lattice QCD calculations.

There are various avenues for investigating the role of orbital angular momenta in nucleon structure. One of them is the study of correlations of the transverse momentum of a parton in the nucleon with the nucleon spin transverse to its momentum. Such correlations produce characteristic patterns of azimuthal-angular dependences for final-state hadrons in SIDIS experiments. Initial experimental results from fixed-target SIDIS indicate the presence of such correlations. Measurements at an EIC would allow precision studies of such orbital effects. An alternative approach will utilize deep exclusive reactions to extract generalized parton distributions (GPDs), to which we turn next. The GPDs provide unique access to the total – spin plus orbital – angular momentum contributions of quarks and gluons, as well as to many other important aspects of nucleon structure. While initial maps of GPDs in the valence-quark region will be carried out with the 12 GeV upgrade at JLab, access to orbital contributions associated with virtual mesons in the nucleon wave function will require the EIC kinematic reach well into the region of the quark-antiquark sea.

Measurements of Generalized Parton Distributions. GPDs may be viewed as the Wigner quantum phase space distributions of the nucleon's constituents – functions describing the simultaneous distribution of particles with respect to position and momentum in a quantum-mechanical system, representing the closest analog to a classical phase space density allowed by the uncertainty principle. In addition to information about spatial density (form factors) and momentum density (parton distribution), these functions describe correlations of the two, i.e., how the spatial shape of the nucleon changes when one probes quarks and gluons of different wavelengths. The concept of GPDs has revolutionized the way scientists visualize nucleon structure, in the form of either two-dimensional tomographic images (analogous to CT scans in medical imaging) or genuinely six-dimensional phase space images. In addition, GPDs allow us to quantify how the angular momenta of partons in the nucleon contribute to the nucleon spin.
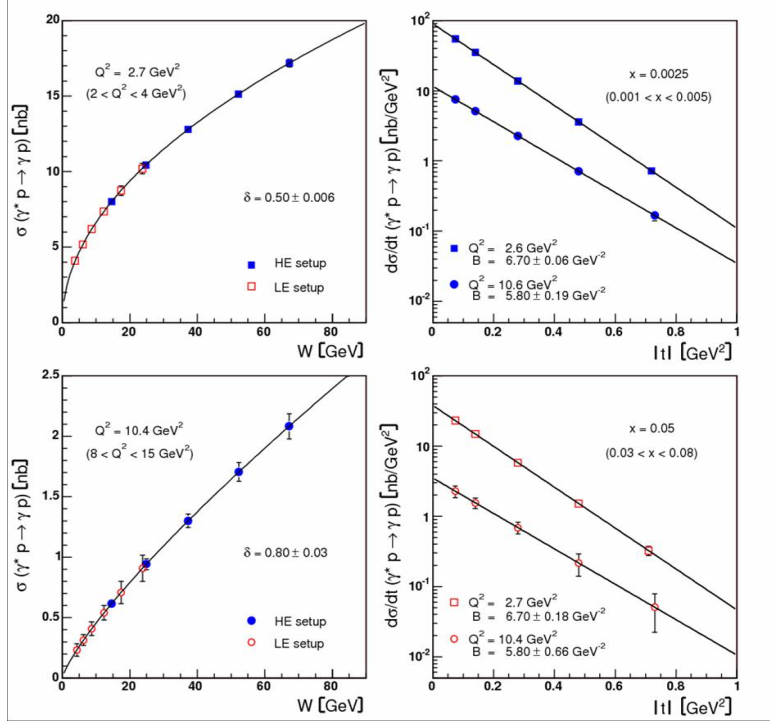
Figure 16: Left: projected results for total DVCS cross section measurements with an EIC, as a function of invariant γ^*p mass W, for two values of Q^2. Right: t differential DVCS cross section for two representative values of x and Q^2. The projections assume a high-energy setup (10 GeV on 250 GeV), with an integrated luminosity of $530\,\mathrm{pb}^{-1}$ for the smaller x-value, and a low-energy setup (5 GeV on 50 GeV) with $180\,\mathrm{pb}^{-1}$ for the larger x-value. The estimates of the event rates here assume 100% detector acceptance.

Measurements of GPDs are possible in hard exclusive processes such as deeply virtual Compton Scattering (DVCS), $\gamma^*p \to \gamma p$. The experimental study of these processes is typically much more challenging than of traditional inclusive DIS. In addition to requiring substantially higher luminosities (because of small cross sections) and the need for differential measurements, the detectors and the interaction region have to be designed to permit full reconstruction of the final state.

A properly designed collider is much better suited for this purpose than a fixed-target experiment. A collider also achieves momentum transfers of the order $Q^2 \sim 10$ GeV^2, where higher-twist QCD corrections in the GPD analysis are under control. The EIC would allow unique access to the gluon

and sea-quark and anti-quark GPDs, entirely complementary to what will be achieved by the 12-GeV upgrade program at JLab. This would be possible through study of a variety of exclusive final states, ranging from photons to pions, kaons and J/ψ. As an example of the potential of an EIC in this area, we show in Fig. 16 the expected uncertainties of measurements of the DVCS cross section. In particular, we show the cross section differential in t, the momentum transfer on the nucleon line. By a Fourier transform, the t-dependence encodes the information about the transverse spatial distribution of partons in the proton. One can see that excellent statistics can be obtained in fully differential measurements in x, Q^2 and t, and over a wide kinematic range. This will allow for precise extraction of information about the nucleon GPDs and for numerous detailed studies, for example, of their Q^2-evolution.

Spin-dependent Quark Fragmentation. Semi-inclusive DIS experiments at a high-luminosity polarized EIC will map the spin-dependence of the process by which quarks transform to jets of hadrons. Recoiling quarks from a polarized proton will initiate the fragmentation process with a spin orientation preference. How does this preference affect the yields, momenta and spin preferences of various types of hadronic fragments, and what do such effects teach us about the fragmentation dynamics? It is already apparent from measurements in electron-positron collisions and in fixed-target SIDIS that there are correlations between the momentum components of hadron fragments transverse to the jet axis and any quark spin preference transverse to its momentum. In addition to systematic exploration of these initial hints at EIC, it may be possible for selected final-state hadrons – e.g., ρ-mesons – reconstructed from their decay daughters to correlate their density matrices with the spin orientation of the fragmenting quark. In combination with the study of in-medium fragmentation in e-A collisions at EIC, such measurements are likely to launch a new stage in modeling how quarks accrete colored partners from the vacuum or their environment to form colorless hadrons.

4.3 Accelerator Designs

A high luminosity (at or above 10^{33} cm^{-2}s^{-1}) Electron-Ion Collider, covering the full range of nuclear masses A with variable center-of-mass energy in the range of 20 to 100 GeV/nucleon, and the additional capability of colliding polarized protons and light-ions with polarized electrons and positrons, appears to be the ideal accelerator to explore these fundamental questions of QCD and expand nuclear physics research into the gluon-dominated regime. Presently there are two distinct design approaches to an EIC: eRHIC, based on the RHIC ion complex, and ELIC, using CEBAF as a full energy injector into an electron storage ring. Research and development needed for a detailed design of each approach is outlined in this section.

eRHIC Two accelerator design options for eRHIC were developed in parallel and presented in detail in the 2004 Zeroth-Order Design Report[16]. Presently the most promising option is based on the addition of a superconducting Energy Recovery Linac (ERL) to provide the polarized electron beam. This ERL-based design option can achieve peak luminosity of 2.6×10^{33} cm^{-2}s^{-1} for e-p collisions, with the potential for improvement. The peak luminosity per nucleon for electron-Au collisions is 2.9×10^{33} cm^{-2}s^{-1} for 100 GeV/N gold ions colliding with 20 GeV electrons. R&D for a high-current polarized electron source and high-energy and high-current ERL are needed to achieve these design goals. A second option is based on the addition of an electron storage ring to provide polarized electron or positron beams. This option is technologically more mature and promises peak e-p luminosity of 0.47×10^{33} cm^{-2}s^{-1}. The general layout of the ERL-based design option of the eRHIC collider is shown in Fig. 17. A polarized electron beam is generated in a photo-injector and accelerated to the energy of the experiment in the ERL. After colliding with the hadron beam in as many as four detector locations, the electron beam is decelerated to an energy of a few MeV and dumped. Positron beam is possible with the addition of a conversion system and a compact storage ring, at one quarter of the RHIC circumference, for positron accumulation, storage and self-polarization. In the present design, the ERL provides electrons in the energy range from 3 to 20 GeV, leading to a center-of-mass energy range from 25 to 140 GeV in combination with RHIC proton beams.
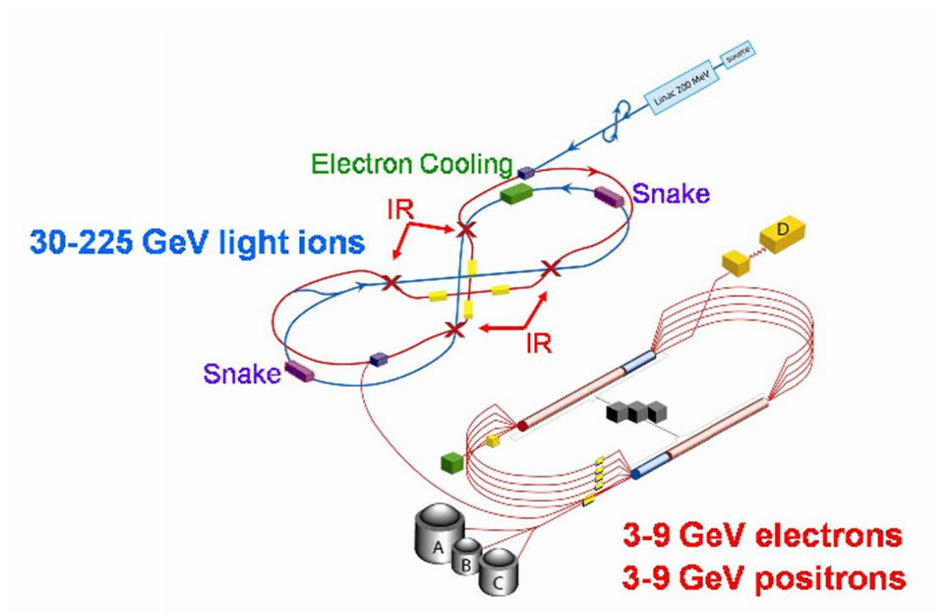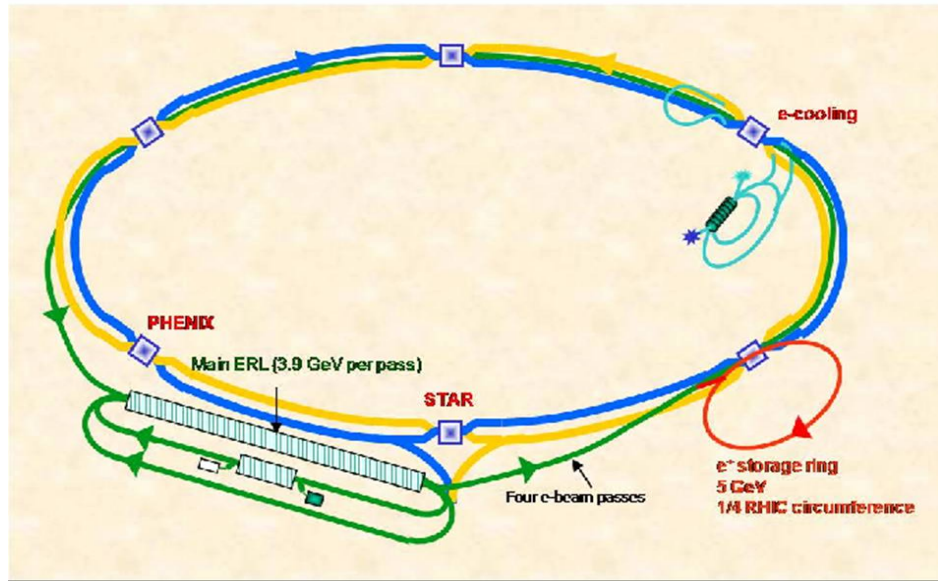
Figure 17: Design layouts of the ERL-based eRHIC, and the CEBAF-based ELIC colliders.

The main highlights of the ERL-based eRHIC design are:

- luminosity of 10^{33} cm^{-2}s^{-1} and higher in electron-hadron collisions

- high electron beam polarization ($\sim$80%)

- full polarization transparency at all energies for the electron beam

- multiple electron-hadron interaction points (IPs) and detectors

- $\pm$3m "element-free" straight section(s) for detector(s)

- ability to take full advantage of electron cooling of the hadron beams

- easy variation of the electron bunch frequency to match it with the ion bunch frequency at different ion energies

ELIC ELIC is an electron-ion collider with center of mass energy of 20 to 90 GeV and luminosity up to 8×10^{34} cm^{-2}s^{-1} (at a collision frequency of 1500 MHz). It is described in detail in the 2007 Zeroth Order Design Report [17] and shown schematically in Fig. 17. This high-luminosity collider is envisioned as a future upgrade of CEBAF, beyond the 12 GeV Upgrade, and compatible with simultaneous operation of the 12 GeV CEBAF (or a potential extension to 24 GeV) for fixed-target experiments. The CEBAF accelerator with polarized injector is used as a full-energy injector into a 3-9 GeV electron storage ring. A positron source is envisioned as an addition to the CEBAF injector for generating positrons that can be accelerated in CEBAF, accumulated and polarized in the electron storage ring, and collide with ions with luminosity similar to the electron-ion collisions. The ELIC facility is designed for a variety of polarized light ion species: p, d, ^{3}He and Li, and unpolarized light to heavy (up to A $\sim$ 200) ion species. To attain the required ion beams, an ion facility must be constructed, a major component of which is a 30-225 GeV collider ring located in the same tunnel and below the electron storage ring. A critical component of the ion complex is an ERL-based continuous electron cooling facility, anticipated to provide low emittance and simultaneously very short ion bunches. ELIC is designed to accommodate up to four intersection points (IP's), consistent with realistic detector designs. Longitudinal polarization is guaranteed for protons, electrons, and positrons in all four IP's simultaneously and for deuterons in up to two IP's simultaneously.

An alternate design approach for ELIC is based on the linac-ring concept, in which CEBAF operates as a single-pass ERL providing full energy electrons for collisions with the ions. Although this approach promises potentially higher luminosity than the ring-ring option, it requires significant technological advances and associated R&D. The main highlights of the ELIC design are:

- "Figure-8" ion and lepton storage rings ensure spin preservation and ease of spin manipulation

- spin transparency to energy for all species

- unprecedented luminosity at the 10^{35} cm^{-2}s^{-1} level

- four interaction regions with ± 2m element-free region

- the present JLab DC polarized electron gun routinely delivers $\sim 85\%$ polarization and meets the beam current requirements for filling the storage ring

- the 12 GeV CEBAF accelerator can serve as an injector to the ring

- collider operation remains compatible with 12 GeV CEBAF operation for a fixed-target program

R&D Required

I. Common R&D Topics In order for either eRHIC or ELIC to reach luminosity at or above 10^{33} cm^{-2}s^{-1} level, R&D on high energy electron cooling and on the production of polarized ^{3}He beams is required. Electron cooling is required to achieve the design transverse emittances, to counteract the effects of intrabeam scattering, and in the case of ELIC to reach short ion bunches. An electron cooling system based on ERL technology is presently under development for RHIC-II, intended to lead to an order of magnitude higher ion-ion luminosities in RHIC. The same system will be used for eRHIC. ^{3}He ions have not yet been used for experiments. EBIS, the new ion source under construction at BNL, will provide the ability to produce polarized ^{3}He beams, given a ^{3}He source. In addition, R&D will be required on a variety of detector and polarimetry items, such as the development of cost-effective and compact high-rate tracking and associated readout systems, small angle

detector instrumentations, multi-level trigger systems and precision ion polarimetry.

II. R&D Required for eRHIC R&D applicable to both ERL and ring-ring options for eRHIC is required in order to increase the number of bunches in RHIC from 111 to 166, and for better understanding of the machine tolerances required for ^{3}He polarization preservation in RHIC and its injectors. In addition, the ERL eRHIC design requires R&D on high-current polarized electron sources and on high-energy and high-current energy recovery. To achieve the design eRHIC luminosities, 260 mA average current is required from a polarized electron source. The best existing source, at JLab's CEBAF accelerator, operates at approximately 0.3 mA of average current (1 mA is expected to be reached shortly) with current densities of about 50 mA/cm^2. The development of large cathode guns should provide a path to electron currents of tens to hundreds of milliamps. The eRHIC ERL is envisioned to employ state-of-the-art 703.75 MHz 5-cell SRF cavities. The cavity design was developed at BNL in the course of the electron cooling project and allows the minimization and efficient damping of the higher-order modes, opening a way for higher electron currents. Simulations of multi-bunch and multi-pass breakup instabilities showed that the design eRHIC currents can be achieved in an ERL based on this cavity.

III. R&D Required for ELIC With the exception of electron cooling, no additional R&D is necessary for ELIC at the luminosity level of 10^{33} cm^{-2}s^{-1}. To achieve the ELIC design luminosity of 10^{35} cm^{-2}s^{-1}, R&D is critical in the areas of crab crossing, stability of intense ion beams accumulated at stacking, and electron cooling using a circulator ring. For the former, R&D is required for the design of a 1500 MHz multi-cell crab cavity, for understanding the beam dynamics with crab cavities in both rings, and for achieving phase and amplitude stability requirements. Understanding beam stability of intense ion beams in boosters and the collider ring also requires R&D. One approach is to overcome space charge at injection by increasing the beam size while preserving the 4D emittance, using a circular painting technique for stacking similar to the technique proposed at SNS. An alternate approach is to admit a large beam emittance in the pre-booster and cool it after injection in the collider ring using stochastic cooling for coasting beam. ELIC's electron cooling concept is unique, in that it relies on the use of a circulator ring to ease requirements on the average current from the electron source and on the

ERL. Simulation studies are required to establish beam stability conditions and to optimize the beam and cooling ring operating parameters. Lastly, the ELIC design requires a dedicated R&D effort to develop the high-speed data acquisition and trigger systems that would be needed to accommodate the high collision frequencies.

5 Theory Opportunities and Initiatives

5.1 Phenomenology

The high quality of the RHIC data provides a solid basis for the quantitative interpretation of the measurements in terms of fundamental properties of the matter produced in nuclear collisions. An essential prerequisite for all analyses of this kind is the sophisticated modeling of the collision dynamics, which must provide for a detailed description of the evolution of the matter in space and time. Such a description would start with the initial conditions, determined by a detailed quantitative theory of strong color fields, and would require a theoretical understanding of the thermalization dynamics leading into the stage of hydrodynamical expansion.

While relativistic ideal hydrodynamics augmented by hadronic Boltzmann transport constitutes a solid basis for such modeling efforts, more sophisticated descriptions involving three-dimensional viscous relativistic hydrodynamics, as well as detailed simulations of the propagation of hard probes through the matter and their effect on the medium will be required to enable quantitative comparisons with the data. The efforts of a broad community of theorists interested in interpreting the data in terms of basic material properties, such as the equation of state, viscosity, stopping power, heavy quark diffusion constant, and color screening length will increasingly rely on the availability of sophisticated and validated modeling tools of this kind.

In addition, further progress in extracting quantitative values for thermodynamic and transport properties of the medium will require the systematic refinement of the existing treatments of hard probes of hot and dense matter. Examples of such needs include the next-to-leading order treatment of radiative parton energy loss, a unified treatment of elastic and inelastic energy loss mechanisms, and a comprehensive description of the interaction of heavy

quarkonium states with the medium. These goals are within reach, but will require substantial investment in theoretical development, discussed below.

5.2 Lattice QCD

There are many new opportunities in lattice QCD. These include: a fully controlled calculation of the equation of state, a better understanding of the chiral aspects of the finite temperature transition, detailed study of microscopic properties of QCD matter such as fluctuations of conserved charges, density correlations, plasma excitations and transport coefficients. It will become feasible to map out the phase diagram of QCD at finite temperature and moderate net baryon density and determine the location of the critical end-point in the (T, μ) plane. This information will be vital for the success of a future low energy RHIC run, as well as for the experimental program at GSI/FAIR. Detailed lattice studies of the temperature region $T_c < T < 3T_c$ will be important benchmarks for the comparison of data from the RHIC and LHC experiments.

Lattice calculations of the spectral functions are still in their infancy. To date, almost all such calculations have been done in the quenched approximation (i.e. neglecting the effect of dynamical quarks). To have a quantitative impact on RHIC phenomenology such calculations must be done with dynamical light quarks. This will soon become feasible due to the expected increase in the computer resources (the 100 Teraflop Blue Gene supercomputer at BNL and the 1 Petaflop Blue Gene installation at ANL).

Improved calculations of the meson correlators will also permit quantitative estimates for some transport coefficients, in particular, the heavy quark diffusion constant. Up to now, meson correlators have been studied at zero spatial momentum. In principle, it is straightforward to extend these calculations to nonzero momenta $\vec{p}$, where the corresponding spectral functions have a contribution for energies $\omega < |\vec{p}|$. This component of the spectral function is related to the scattering of on-shell quarks in the plasma. Thus lattice calculations may provide for a non-perturbative insight into the physics of the heavy quark energy loss. The study of meson correlators at nonzero momentum could also clarify the dependence of quarkonium suppression on its velocity with respect to the plasma.

5.3   Analytical Approaches to Strong Coupling

In view of the paucity of analytical methods for dynamical problems in strongly coupled quantum field theories, the value of AdS/CFT calculations as a tool for gaining qualitative insights is already well established. Perhaps the semi-quantitative agreement with some experimental results is a hint that certain properties of strongly interacting gauge theories are "universal" among large classes of such theories, whereas others are "microscopic details", yielding important differences in vacuum but unimportant in a strongly interacting quark-gluon plasma which has no quasiparticles. This question must be addressed by extending AdS/CFT calculations to more observables and to more, and more QCD-like, gauge theories.

If evidence that the strongly interacting quark-gluon plasmas of QCD and of theories with a dual string theory description are in the same universality class accumulates, allowing a better understanding of what quantities are universal and what quantities are not, the motivation to address more challenging calculations in strongly interacting quark-gluon plasmas via AdS/CFT methods will increase. A nonzero chemical potential can be added. One can envision implementing finite volumes of quark-gluon plasma with more and more realistic geometries, incorporating longitudinal and radial expansion and elliptic flow. Finally, equilibration can be studied at strong coupling.

5.4   New Initiatives

In order to build and maintain a nuclear theory effort that allows us to reap the full scientific rewards of the experimental program in relativistic heavy ion collisions, sound and stable funding for a broad range of nuclear theory activities of outstanding quality is needed. In addition to adequate base program support for theorists addressing questions of fundamental importance for the experimental program described in Section 3, support for new initiatives targeting (a) problems of particular programmatic relevance and requiring the collaboration of theorists at several institutions, and (b) the rejuvenation of the theory community at the highest level of excellence, are urgently needed. Below we describe specific ideas for such targeted initiatives.

5.4.1 Programmatic Initiatives

The recent initiative aimed at providing the hardware needed to realize the opportunities in lattice QCD thermodynamics must be continued. The national lattice initiative demonstrates what can be accomplished by large, multi-institutional and multifaceted collaborations with several independent goals but common needs, when mechanisms and support for their collaborative organization are put into place. A similar opportunity has arisen for the theory community working on phenomenological aspects of relativistic heavy ion collisions.

The central challenge for the RHIC community now is to progress from qualitative statements to rigorous quantitative conclusions. The main obstacle on the path to achieving this goal is the inherently complex and highly dynamical nature of relativistic heavy-ion collisions. Quantitative conclusions require sophisticated modeling and thorough comparison of such models with data. The complexity of the modeling derives from the fact that reactions traverse two orders of magnitude of energy density and several distinct phases, each with different underlying degrees of freedom: a pre-equilibrated phase characterized by the presence of strong color fields, an approximately thermalized partonic phase with the characteristics of a nearly ideal liquid and, finally, a viscous hadronic phase. Experiments provide three classes of observables: spectra, correlations and fluctuations, and jets. Each class encompasses a host of hadronic and electromagnetic species which provide observational access to different stages of the collision. None of them, taken alone, yields complete and unambiguous information about any of these stages, but taken together they hold the promise of fully constraining the dynamics of the collision and permitting the quantitative extraction of key properties of the created quark-gluon matter.

Doing so will require a full account of the rapid dynamical evolution of the collision fireball, using sophisticated models which correctly describe all aspects and stages of its three-dimensional expansion. A successful quantitative interpretation of the heavy-ion data will not be possible without extensive and sophisticated modeling, requiring close collaboration of the experimental data analysis with the theoretical modeling effort. Without such an effort, the RHIC physics program cannot be successfully completed, and the synergies from the parallel LHC heavy-ion programs cannot be adequately brought to bear on the physics program of RHIC. In view of the rapid progress on the experimental side, the necessary tools for a comprehensive

and quantitative determination of the properties of the medium produced in relativistic heavy-ion collisions must developed with utmost urgency. This will require close collaboration between many different segments of the RHIC theory community, as well as between theory and experiment. The success of this effort mandates significant additional investment in theoretical resources in terms of focused collaborative initiatives.

The two established theoretical milestones[1] in the DOE performance measures for the RHIC program address limited aspects of the above challenge. Achievement of these milestones and, more broadly, realization of the opportunities described in Section 3 and above, are critical to the success of the scientific investments made in experimental facilities and research. A collaborative model organized around common goals like that adopted by the lattice community and in close coordination with the experimental community may serve many of these needs. More focused collaborative structures like topical centers organized around a specific research program can also be of value.

Any initiatives of this nature should be launched via a competitive bidding process, open to the participation of theorists and interested experimentalists from all universities and national laboratories. This will ensure that funding of such coordinated efforts targets phenomenology of the highest quality. It will also ensure that the theory community as a whole thinks creatively about the most effective means to accomplish its goals. The size, scientific scope, duration, degree of geographical localization, and organizational mechanisms of such initiatives should emerge as outcomes of a competitive process designed to engage all parts of the theory community.

5.4.2 Community Oriented Initiatives

Targeted support in various forms aimed at strengthening the nuclear theory community by nurturing the careers of creative theorists with already demonstrated accomplishment, and in this manner attracting the best theoretical graduate students to work on the rich trove of new problems which our successes are bringing to light, is critical for the future of nuclear physics. The initiatives we describe can easily be designed for the participation of the

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[1]2009: "Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow at RHIC.";

2010: "Complete realistic calculations of jet production in a high density medium for comparison with experiment."

entire nuclear physics community, including all subfields and including both theoretical and experimental physicists:

- We recommend the introduction of a national prize fellowship program for postdoctoral researchers in nuclear physics. Winning a prestigious fellowship in a national competition will raise the profile of a research career at an early stage and enhance the visibility of the brightest among our young scientists, and the best accomplishments of our field, in the larger academic world. Giving the winners both support and freedom as they launch their research careers will maximize the scientific impact of these future leaders of the field at the crucial time when their abilities are fully developed and their energies are devoted solely to research. Furthermore, the success and visibility of such a program will have positive impacts on many additional fronts: it will attract highly talented students to do graduate work in nuclear physics, retain the best as postdocs working within our field, raise the visibility of the field by winning the recognition of the broader physics community that its recipients are doing outstanding research and continuing onward to successful careers, and thus assist those seeking to make the case within their departments or laboratories for hiring of faculty or staff in nuclear physics.

- We recommend the introduction of a Nuclear Physics Graduate Fellowship, which would identify and support the best graduate students in the nation who intend to pursue nuclear physics research. The main objective of this initiative parallels that of the prize postdoctoral fellowship at one stage earlier, namely to attract the highest caliber undergraduate students to study nuclear physics.

- The nuclear physics Outstanding Junior Investigator (OJI) program has goals which parallel those of the postdoctoral fellowship, at a later career stage. This initiative of the DOE should be opened up to include recently hired staff members in tenure-track positions at the national laboratories.

The base program in nuclear theory must be raised to the point that outstanding theorists can earn grant support which allows him or her to build and then *maintain* a successful and productive research effort. The OJI program and the proposed postdoctoral and graduate fellowships are

part of a concerted effort to further enhance the excellence of theoretical nuclear physics research in the U.S., but they will not function as intended without a healthy base program. If implemented together with a healthy base program, these initiatives will yield the kind of breakthrough innovations that can come from creative research by talented individuals, while at the same time training people who go on to maximize the effectiveness of more targeted theoretical pursuits.

6 Workforce

The heavy ion community within the broader nuclear physics community in the United States has been very strong over the last five year period including the start up and full operational status of the Relativistic Heavy Ion Collider (RHIC). The challenge of constructing a new scale of Nuclear Physics experiments presented significant questions of labor force, commitment, and coordination amongst the experimental physics community. These challenges have been met and the results are the broad array of high quality precision data from the four experiments at RHIC (BRAHMS, PHENIX, PHOBOS, and STAR). Top young scientists getting their Ph.D's from the RHIC program and postdoctoral research scientists at the start of the RHIC program are now new leaders as tenured faculty at our nation's universities and research scientists at national laboratories. On the theory side, again great strides have been made in recruiting top young scientists and making major contributions in many areas to understand the experimental data and create a broader picture of the novel state of nuclear matter under investigation.

Currently the two large experiments (PHENIX and STAR) have over 500 members each (authors in good standing) and with over 100 institutions in all from around the world. The author lists have shown steady growth over the last five years as new institutions (within the United States and from around the world) have been added and a new graduate students join the effort. The smaller experimental groups BRAHMS and PHOBOS have also been quite successful, and have completed their programs as of 2006.

As the next phase at RHIC includes not only major detector and accelerator upgrades at RHIC (including RHIC II luminosity upgrades), but also the new energy frontier in heavy ion studies at the Large Hadron Collider (LHC), this labor force will meet new challenges. In the last year, both PHENIX and STAR have done a re-assessment of full time equivalent membership for the

next five year period (including a renewal of memorandum of understandings (MOU) within STAR). A modest number of groups will be leaving the RHIC program to focus on the LHC heavy ion effort and programs elsewhere such as JPARC. However, within the United States, few groups are leaving, but rather many will split their efforts in the future between RHIC and LHC. Both STAR and PHENIX project an approximate reduction of 20% of FTE personel over the next five year period (2006-2010). This maintains a strong program with excellent leadership at RHIC, though will present some issues for the timely completion of the full detector upgrades and maintaince of older detector systems.

This 20% FTE reduction is quite consistent with the increase in FTE projections from the ALICE, ATLAS, and CMS heavy ion collaborations in the United States. ALICE includes 12 US institutions and projects FTE labor growing from 24 in 2007 to 45 in 2011. The ALICE construction project of the Electromagnetic Calorimeter is a major undertaking that requires significant FTE's over many years. The ATLAS effort includes 4 US institutions presently and projects 12 FTE growing to 20 FTE in the next three years. The CMS effort includes 10 US institutions presently and projects of order 50 FTE by 2010. The ATLAS hardware effort is more targeted with construction limited to Zero Degree Calorimetry (ZDC), and the CMS effort with ZDC's and also significant contributions to the high level trigger (HLT). All groups expect to make substantial contributions to computing and trigger for heavy ion specific running. Although the heavy ion effort at the LHC only has projected beam time for 1 month each year, the heavy ion groups will be full members of the LHC experiments that take proton-proton data for approximately eight months per year.

Thus, the overall heavy ion effort in the United States will remain strong with a 20% FTE contingent working at the LHC heavy ion efforts and a more focussed effort at RHIC. This allows for a substantial contribution at the LHC without threatening the existing very strong program at RHIC. Overall the synergy between the LHC and RHIC projects will strengthen the heavy ion field and broaden the interests of the people involved.

7 Education and Outreach

Education and outreach are central to the missions of the Department of Energy and the National Science Foundation. They are the fundamental underpinnings that support the mandates of the agencies to advance the broad interests of society in academia, medicine, energy, national security, industry, and government, and to help ensure United States competitiveness in the physical sciences and technology.

Similarly, education and outreach are key components of any vision of the future of the field of nuclear physics. Education is critical to sustaining a diverse pool of talented nuclear physicists to carry out a world-leading program of fundamental and applied research, as well as to train future generations. In addition to these goals, nuclear science has a long tradition of educating physicists who ultimately make important contributions to a broad spectrum of societal needs including medicine, energy, and national security. This has most recently been documented in the NSAC Education Report [18], for which comprehensive surveys were conducted of nuclear science PhD degree recipients from 1992-1998. Of that cohort less than 40% remained in nuclear science careers in 2003, the remainder having found rewarding careers in other areas of society.

In order to meet the projected need for nuclear scientists in the future for basic research and higher education as well as national needs, the NSAC report recommended that the production of PhDs per year in nuclear science return to the level of production in the early 1990s, approximately 100 per year. At present the number of nuclear science PhDs granted per year is approximately 80 and is decreasing. Continuation of this trend will compromise U.S. leadership in nuclear science research, resulting in a sub-critical number of trained researchers, educators, and faculty to meets the nation's needs.

The collaborations at RHIC (BRAHMS, PHENIX, PHOBOS and STAR) have to date graduated more than 100 PhD students. These students, who represent a microcosm reflecting trends in the larger community, have gone on to postdoctoral fellowships and faculty positions all over the world, career positions at NNSA laboratories, software companies, and nuclear energy R&D; careers in medical physics, teaching, and on Wall Street. Many other students have received Masters degrees from work at RHIC, or interned as undergraduates.

In the past, the lack of adequate numbers of U.S. PhDs in nuclear sci-

ence has been addressed by recruiting from abroad. However, this traditional source of talent shows signs of drying up as an increasing number of attractive opportunities open up in Europe and Asia. Increasing the number of U.S. citizens who get PhDs in nuclear science will therefore almost certainly require increased participation from the full diversity of backgrounds within the U.S. population. It will also require introducing students to the concepts of nuclear science and its research before they start graduate school. These two points are most effectively addressed at the undergraduate level. Undergraduates are the wellspring of the pipeline, and the tools and talent exist within the nuclear science community to make a difference by attacking the problem at this pressure point. Such an effort best leverages the resources of our community, building on existing programs (e.g., REU, SULI, CEU, RUI) and the work of university departments, national laboratories, and individuals. Therefore, we endorse the first recommendation of the White Paper: A Vision for Nuclear Science Education and Outreach for the Next Long Range Plan: *The nuclear science community should increase its involvement and visibility in undergraduate education and research, so as to increase the number of nuclear science PhDs, and the number of scientists, engineers and physics teachers exposed to nuclear science.*

Assuming the success of this initiative, adequate support at the graduate level for students ultimately attracted to the field is another key component to insuring the nuclear science workforce of the future is adequate to the nation's needs.

Outreach to all of nuclear science's stakeholders is also essential. RHIC has made international headlines since the facility's commissioning in 1999. The very idea of probing the earliest microseconds after the Big Bang has sparked people's imaginations in many directions. RHIC physics is an excellent example of how new and exciting science can capture public interest if conveyed in an open, comprehensible way. Conveying this excitement to the public at large and to teachers and students at all levels is critical for the health of our field. We applaud Brookhaven National Laboratory's Community, Education, Government and Public Affairs directorate, which has worked collaboratively with members of the RHIC community to communicate the importance and excitement of RHIC science to a diverse community of stakeholders, skillfully managing perceived negatives (e.g. the possibility of creating black holes at RHIC) so as to turn potential controversy into an opportunity for dialogue. This effort serves as an excellent "best practice" model to the nuclear science community about how to outreach to its

stakeholders: the scientific community, funding agencies, elected officials, educators and students; the science-attentive public and general public; the science and mainstream media. We therefore also endorse the second recommendation of the White Paper: A Vision for Nuclear Science Education and Outreach for the Next Long Range Plan: *The nuclear science community should develop and disseminate materials and hands-on activities that illustrate and demonstrate core nuclear science principles to a broad array of audiences, so as to enhance public understanding and appreciation of nuclear science and its value to society.*

8   Accelerator R&D

The design and construction of new particle accelerators is essential to the future of nuclear physics. Increasingly, these accelerators are quite distinct in character from those planned for high energy physics. In addition, compact, low energy accelerators are widely used in applications of nuclear physics from medicine to cargo screening. Nuclear Physics has strongly supported large accelerator physics efforts at all of its user facilities over many decades and this will continue to be essential. However, the support for accelerator physics and technology at universities has been a very small ad-hoc effort and not an explicit part of the agencies' program mission. It is now time to develop an accelerator science and technology program that consists of a coordinated effort between the national laboratories and a modest PI-driven effort at universities supported by DOE and NSF nuclear physics. The program should be open to beam physics research activities relevant to all subfields of nuclear physics. This effort should be an explicit part of the DOE and NSF program mission as it would enhance nuclear science in the United States.

The need for an educational component within this effort was clearly articulated by the Office of Science within its Occasional Paper "Accelerator Technology for the Nation" (2003):

The role of university faculty and students should be expanded in all aspects of accelerator research from operating accelerators to advanced accelerator research. This will allow the breadth of knowledge and expertise that resides at the universities to be brought to accelerator research, and young scientists will have the opportunity to learn and become tomorrow's leaders.

The program at DOE and NSF would solicit proposals from PI's at universities to carry out research in accelerator physics relevant to the priorities of nuclear science. The proposals would be peer reviewed and evaluated within the context of the national accelerator science and technology program. The grants would support faculty summer salaries, students, post-docs and equipment.

A   Appendix

A.1   Program of the Phases of QCD Town Meeting

Web site is: http://www.physics.rutgers.edu/np/2007lrp-home.html

Friday January 12		
(QCD and Hadron Physics Town Meeting meets separately)		
9:00-9:05	Welcome	
9:05-9:35	Scientific status of RHIC HI program	P. Steinberg
9:35-10:05	Scientific challenges for the next decade I	U. Wiedemann
10:05-10:35	Scientific challenges for the next decade II	V. Koch
10:35-10:55	coffee break	
10:55-11:20	RHIC II: Hard Probes	A. Drees
11:20-11:45	RHIC II: Low energy	P. Sorensen
11:45-12:05	ATLAS-US Heavy Ions	B. Cole
12:05-12:25	ALICE-US	J. Harris
12:25-13:30	Lunch	
13:30-13:50	CMS-US Heavy Ions	D. Hofman
13:50-14:15	low-x/eA theory	R. Venugopalan
14:15-14:40	low-x/eA experiment	T. Ullrich
14:40-15:00	p/d+A opportunities	M. Leitch
15:00-15:20	Possible connections to String Theory	D. Son
15:20-15:40	coffee break	
15:40-16:00	Lattice QCD at Finite Temperature and Density	F. Karsch
15:40-16:00	Theory Initiatives	U. Heinz
16:30-18:30	Contributed presentations and discussion	P. Petreczky, J. Rafelski, J. Sandweiss

Saturday January 13		
(joint session with QCD and Hadron Physics Town Meeting)		
8:30-8:40	Welcome address	Dean David Madigan
8:40-9:25	JLab 12 GeV upgrade and science program	A. Thomas
9:25-10:10	RHIC II upgrade and science program	W. Zajc
10:10-10:30	coffee break	
10:30-10:50	International opportunities: LHC	B. Wyslouch
10:50-11:10	International opportunities: FAIR	W. Henning
11:10-11:30	International opportunities: J-PARC	N. Saito
11:30-11:40	International opportunities: discussion	
11:40-12:20	QCD Theory: challenges, opportunities and community needs	D. Kaplan
12:20-13:30	Lunch Break	
13:30-14:00	Computational QCD	J. Negele
14:00-14:35	Gluons at high density	Y. Kovchegov
14:35-15:10	Central questions in nucleon structure	W. Vogelsang
15:10-15:50	Opportunities in low-x physics	B. Surrow
15:50-16:10	Coffee Break	
16:10-16:50	Opportunities in hadron structure	R. Ent
16:50-17:30	e+p/A facilities	L. Merminga
17:30-18:45	Community input and discussion of priorities	

Sunday January 14 (QCD and Hadron Physics Town Meeting meets separately)		
9:00-9:20	American Competitiveness Initiative	E. Hartouni
9:20-9:40	Accelerator R&D at Universities	R. Milner
9:40-10:00	Status of Theory Support	X.-N. Wang
10:00-10:20	Computing for experiments	R. Soltz
10:20-10:40	Coffee Break	
10:40-11:00	Education and Outreach	T. Hallman
11:00-12:00	Discussion and White paper planning	
12:00-12:30	Lunch Break	
13:00-14:00	Discussion and White paper planning	

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