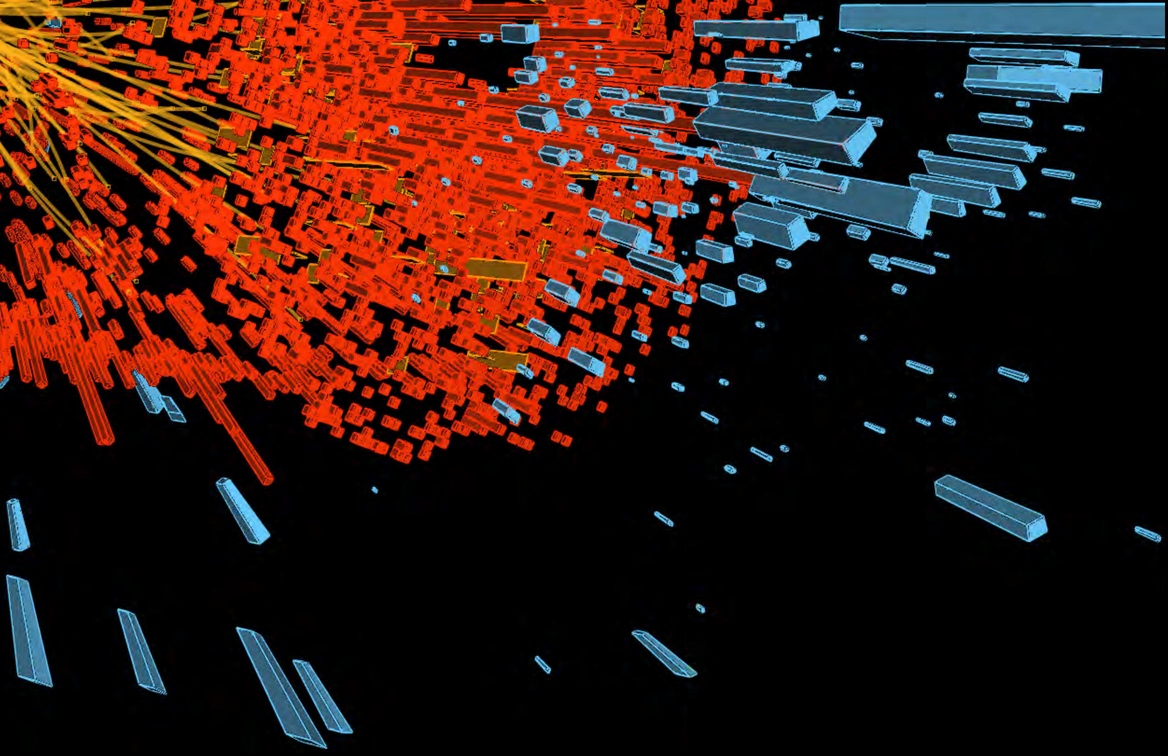
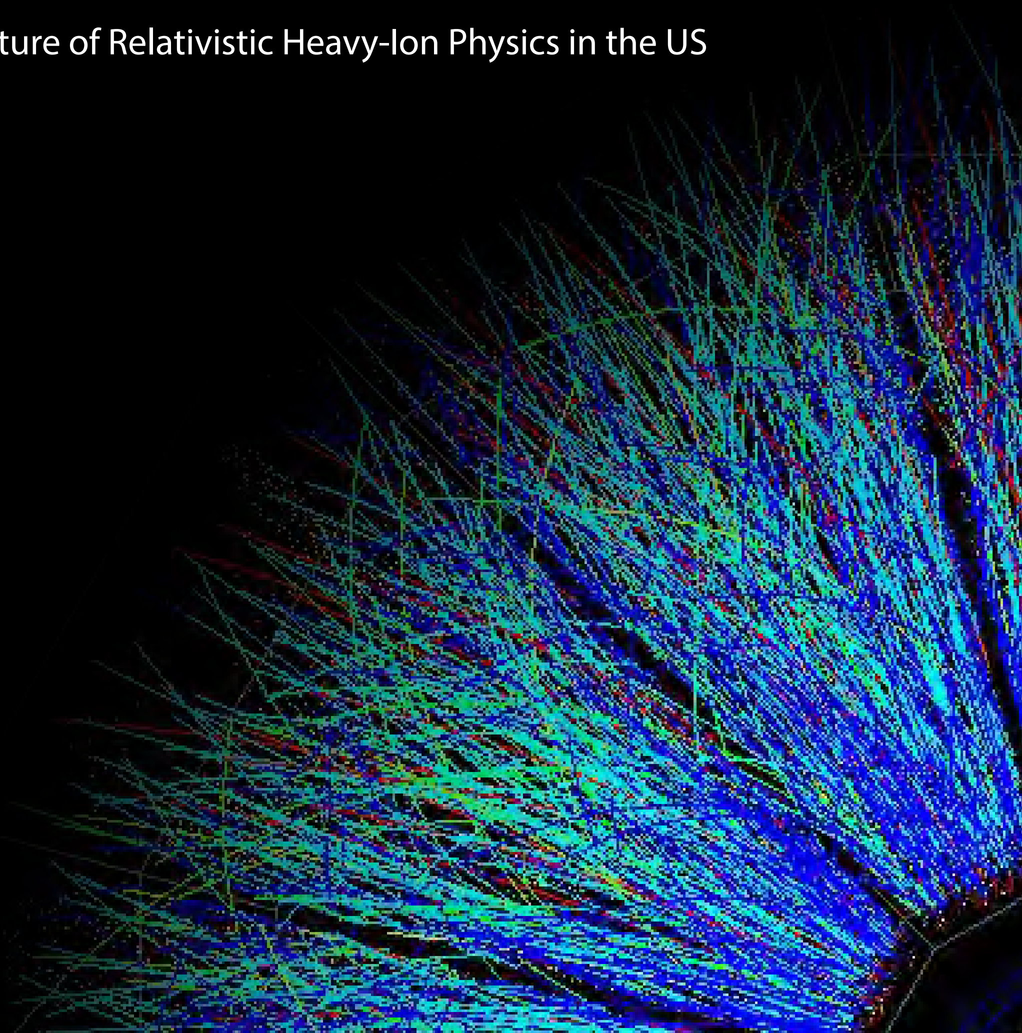


Hot and Dense QCD Matter

Unraveling the Mysteries of the Strongly Interacting Quark-Gluon-Plasma

A Community White Paper on the Future of Relativistic Heavy-Ion Physics in the US



Executive Summary

This document presents the response of the US relativistic heavy-ion community to the NSAC Subcommittee, chaired by Robert Tribble, that is tasked to recommend optimizations to the US Nuclear Science Program over the next five years.

The study of the properties of hot and dense QCD matter is one of the four main areas of nuclear physics research described in the 2007 NSAC Long Range Plan. The US nuclear physics community plays a leading role in this research area and has been instrumental in its most important discovery made over the past decade, namely that hot and dense QCD matter acts as a strongly interacting system with unique and previously unexpected properties. The US relativistic heavy ion program has now entered a crucial phase, where many of the fundamental properties of the strongly interacting QCD plasma are approaching precision measurements ($\sim 10\%$), sufficient to determine whether the conjectured lower bound of viscosity to entropy is achieved and to identify the primary energy loss mechanisms for hard partons traversing the plasma. And yet there are still important discoveries to be made in the search for a tri-critical point in the phase diagram and in seeking to understand the mysterious behavior of heavy quarks in the plasma. This document lays out the quantifiable deliverables and open questions the US relativistic heavy-ion program is going to address over the next several years, with the goal of gaining a comprehensive understanding of the dynamics and properties of this strongly interacting QCD matter, the long sought after Quark Gluon Plasma.

The execution of this scientific program will require a number of detector and accelerator upgrades as well as a significant amount of data taking, that have all been outlined in *The Case for Continued RHIC Operations* by Steve Vigdor. This document should be regarded as complementary to *The Case for Continued RHIC Operations* and focuses on the science goals of the US Heavy-Ion community.

The US relativistic heavy-ion program, including the research program outlined in this document, fully utilizes the complimentarity of the Relativistic Heavy-Ion Collider (RHIC) and Large Hadron Collider (LHC) accelerator facilities: the LHC provides access to high energy probes such as jets and high momentum leptons in the baryon free regime beyond the reach of RHIC. However, RHIC provides unique access to high energy probes in kinematic regions at lower energy, given sufficient luminosity, and with leveraging longer heavy-ion operation times in its favor. Jets of similar energy and characteristics produced at RHIC and LHC are sensitive to different aspects of the system evolution. Most importantly, however, RHIC can explore a much wider region of the QCD phase diagram (critical point, phase structure, baryon density) than is possible at the LHC.

The next 5–10 years of the US relativistic heavy-ion program will deliver:

- a beam-energy scan program to establish the properties and location of the QCD critical point.
- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependent shear-viscosity to entropy-density ratio $\eta/s(T)$, and the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.
- a jet physics program to study parton energy loss and the quasi-particle nature of the QGP.
- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium
- a systematic forward physics program to study the nature of gluon saturation and establish the foundation for the future Electron Ion Collider research program and facility.

This research program will ensure the continuing leadership of the US in relativistic heavy-ion physics and will optimally leverage the significant scientific investment the US government has made over the past two decades in this field of research.

1 Introduction

The study of the properties of hot and dense QCD matter, in particular its deconfined Quark Gluon Plasma (QGP) state, is one of the four main areas of nuclear physics research described in the 2007 NSAC Long Range Plan. The most important discovery made in this area over the past decade is that the QGP acts as a strongly interacting system with unique and previously unexpected properties.

We know of four systems in nature which permit a study of the bulk properties of strongly interacting matter: the interior of the atomic nucleus as well as the nucleon, the interior of a neutron star, and the Quark Gluon Plasma created in heavy-ion collisions. The US nuclear physics community plays a leading role in this research area through experiments at Thomas Jefferson National Laboratory (studying the interior of the nucleus as well as the nucleon) and Brookhaven National Laboratory (discovery and study of the Quark Gluon Plasma as well as the RHIC-Spin program[1] for studying the structure of the nucleon). In recent years, this leading role has extended to the heavy-ion program at the Large Hadron Collider. The study of the strong interaction in bulk is at the cutting edge of human understanding and is also a natural extension of the interests, talents, and traditions of classical nuclear physics and physicists. The US leadership role in this arena serves to advance related fields including particle physics, condensed matter physics, and ultra-cold atomic physics.

This document will describe the quantifiable deliverables and open questions the US relativistic heavy-ion program will address within the next 5-10 years. All of these are geared towards gaining a comprehensive understanding of the dynamics and properties of strongly interacting QCD matter, in particular the long sought after Quark Gluon Plasma, which was created well above the transition temperature for the first time at RHIC in 2000. RHIC is the only machine that can systematically probe the plasma in the vicinity of the transition by varying both temperature and baryon density. Without the continued operation of RHIC, the characterization of the fundamental properties of the Quark Gluon Plasma will be incomplete, and the full promise of the heavy-ion program will remain unfulfilled. The execution of this scientific program will require a number of detector and accelerator upgrades as well as a significant amount of data taking, that have all been outlined in *The Case for Continued RHIC Operations* by Steve Vigdor [1]. The timelines for the scientific program described here have been set up to take the projected detector and accelerator upgrades and data-taking schedules outlined in that document into account. Improvement of the RHIC facilities and detectors are already in full swing, others such as the sPHENIX upgrade proposal, have just undergone a successful internal review at BNL prior to submission to DOE, and the new EBIS source and luminosity upgrade to the accelerator have delivered huge improvements to the quality and versatility of the beam.

The next several years of the US relativistic heavy-ion program will deliver:

- a beam-energy scan program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out the transition region from hadronic to deconfined matter.

- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependence of the shear-viscosity to entropy-density ratio η/s (including an assessment of whether the conjectured lower bound has been reached to within a precision of 10%), and that of the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.

- a jet physics program to study the nature of parton energy loss and the quasi-particle nature of the QGP.

[1]this document does not address the RHIC-Spin program, which is topic of a separate White Paper

- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium (i.e. the "heavy-flavor puzzle"), as well as quarkonia measurements that will provide standard candles for the temperatures obtained in the early stages of a heavy-ion reaction.

- a systematic forward physics program to study the nature of gluon saturation. This program will build the foundation for the future Electron Ion Collider research program and facility.

RHIC and LHC facilities are complementary when it comes to successfully executing the outlined research program: the LHC provides access to high energy probes (quarkonia, high energy jets, W/Z/γ) beyond the reach of RHIC and the continuing participation of the US in the LHC heavy-ion program is crucial for the success of the program outlined here. RHIC has complementary access to high energy probes in kinematic regions at lower energy, given sufficient luminosity, and can leverage longer heavy-ion operation time with beams in its favor. Jets of similar energy and characteristics produced at RHIC and LHC will be sensitive to different aspects of the system evolution. Most importantly, however, RHIC can explore a much wider region of the QCD phase diagram (critical point, phase structure, baryon density) than is possible at the LHC. Without the benefit of RHIC, many of the goals of the field, such as the discovery of the critical point, the temperature dependence and minimum value for η/s, and the solution to the heavy-flavor puzzle will be difficult, if not impossible to achieve.

The document is organized in three main sections, detailing the success of the US relativistic heavy-ion program, the current Standard Model of relativistic heavy ion collisions that has emerged from these discoveries, and finally laying out a program for the next several years to quantify the properties of the Quark Gluon Plasma and gain insight into the physics driving the discoveries made previously. Clearly, the primary physics goal for the next decade of the US program is to characterize the properties of the Quark Gluon Plasma via the quantitative extraction of important medium parameters from precision measurements of sensitive observables. In addition, the discoveries over the past decade have led to compelling new questions, and without answers to these questions, our understanding of the strongly coupled QGP will be left incomplete:

- What is the nature of QCD matter at low temperature but high gluon density, and how does it affect plasma formation?

- How does the plasma thermalize so rapidly?

- The QCD plasma is strongly coupled, but at what scales? Does it contain quasiparticles, or does the strong coupling completely wipe out long-lived collective excitations?

- What impact does the coupling have on color screening? Is there a characteristic screening length, and if so, what is it?

- What is the mechanism for parton-plasma interactions, and how does the plasma respond to energy deposited in it?

The research program outlined in this document will ensure that the above questions about the nature of hot and dense QCD will be addressed quantitatively over the next 5–10 years, yielding another important milestone in the US relativistic heavy-ion program. Due to the abbreviated and general nature of this document, technical details have been mostly omitted – we refer the reader to the extensive list of references provided in order to follow-up on the pertinent details of the described measurements and theoretical calculations.

2 Major Discoveries and Scientific Advances

The physics program at the Relativistic Heavy Ion Collider began in the summer of 2000 and has yielded a series of fascinating discoveries [2, 3, 4, 5] that have intrigued nuclear physicists and captured the imagination of the public. Starting in 2010, the range of collision energies has been extended even higher energies in Pb+Pb collisions at the CERN Large Hadron Collider [6, 7, 8, 9, 9, 10, 11, 12]. The measurements by the four original experimental collaborations at RHIC have established, and the recent data from the LHC have confirmed, a novel quantitative framework for the theoretical description of QCD matter at energy densities in excess of 1 GeV/fm^3 (more than six times normal nuclear energy density) as a strongly coupled plasma of quarks and gluons, which behaves as a nearly inviscid liquid and is highly opaque to energetic colored probes [13, 14].

This research has had broad impact across multiple physics disciplines and can be rightly identified as the source of several new sub-fields of physics research, such as relativistic viscous fluid dynamics or the application of gauge-gravity duality to strongly coupled Quantum Field Theories. The RHIC physics program has successfully measured or bracketed parameters that characterize the initial state of the reaction (such as the initial energy-density ϵ_{init}, its initial temperature T_{init}, etc.) and also properties of fundamental physical importance to QCD (specific shear-viscosity η/s, momentum broadening transport coefficient $\hat{q}$, etc.). The measurements of these fundamental properties of the plasma are in various stages, but as will be described in Sec. 4, all require additional data from RHIC and LHC combined with advances in theory to achieve significant advances in our understanding of the Quark Gluon Plasma.

In this section we review the discoveries made, the theoretical and phenomenological advances motivated by these discoveries, and the plasma properties quantified during the first 12 years of the RHIC program and the first few years of the LHC program.

2.1 Discoveries

- **High-Momentum Hadron Suppression**
  A long-anticipated signature of a color-opaque medium, suppression by a factor-of-five for high-momentum hadron production in Au+Au collisions compared to a proton-proton collision base-line ("jet quenching") [15, 16], was observed following the first RHIC run [17, 18]. It was later uniquely identified as a final-state effect via control measurements including prompt photon production [19] and the absence of suppression in d+Au collisions [20, 21].

- **Away-Side Jet Modification (Tomography)**
  The azimuthally back-to-back character of di-jet production allowed experiments to tag the production of an "away-side-jet" by the coincident observation of the "near-side-jet" [21, 22, 23, 24, 6]. Such studies allowed the jet's trajectory through the medium to be controlled, thereby furthering jets as a tomographic probe of the medium [25, 26, 27, 28].

- **Elliptic Flow at the Hydrodynamic Limit**
  Ideal hydrodynamics had long been proposed as a tentative, but rarely quantitatively accurate description of nuclear collisions. Measurements of elliptic (second Fourier moment) flow at RHIC [29, 30, 31, 32, 7], matched the maximally achievable collective flow predicted by ideal hydrodynamics (i.e. the hydrodynamic limit) [33] and provided the first indication that the medium (later dubbed the strongly interacting QGP acknowledging its strongly-interacting character) behaved as a fluid with a shear viscosity to entropy density ratio at or near the quantum lower bound.

- **Valence Quark Scaling of Elliptic Flow**
  The varied elliptic flow patterns of identified hadrons were discovered to have a universal underlying scaling character driven by the valence quark count of the final state hadron [34, 35, 36]. This scaling identified the collective sQGP behavior as being established during the partonic phase of the system evolution and serves as a direct signature for deconfinement [37, 38, 39].

- **Density-Fluctuation-Driven High Order Flow Moments**
  Odd Fourier flow moments must vanish on average for central-rapidity particle production in a symmetric colliding system. In contrast, they were discovered to persist to the final state via two-particle correlation measurements [40, 7]. Driven by the non-uniformity of the initial-state, these unanticipated observations of minute variations imposed onto the final-state momentum distribution of produced particles provide not only tight constraints on the transport properties of the medium, but also information about the quantum fluctuations of the initial state at the nucleon and sub-nucleon scale [41].

- **Suppression & Flow of Heavy Quarks**
  Kinematic modifications to heavy quark (charm & bottom) projectiles were anticipated to be limited both by their mass and the "dead-cone effect" [42]. Startling results demonstrated heavy quark spectral modification at a level comparable to light quarks [43, 44, 45, 46], indicating near perfect color-opacity of the medium.

- **Sequential Melting of Heavy Quarkonia**
  Heavy quarkonia ($c\bar{c}$, $b\bar{b}$), exhibiting well understood energy(mass) levels and physical size comparable to the sQGP Debye screening length, were observed to sequentially dissociate ordered by their physical size [9, 47].

- **Charge Correlations Suggesting Chiral-Magnetic Effect**
  Instanton (tunneling) and sphaleron (hopping) transitions between QCD vacuum states of differing Chern-Simons winding number generate local imbalances of chirality. The "Chiral-Magnetic Effect" reveals this underlying topology as a finite electric dipole moment induced in any color-deconfined state exposed to a strong external magnetic field. Measurements of charge sign correlations [48, 49] are qualitatively consistent with expectations of the Chiral-Magnetic Effect [50, 51], disappearing with either the absence of deconfinement (low collision energy) or a magnetic field (central U+U collisions).

- **Suppression of particle production in the low-x coherent regime**
  Contrary to the naive extrapolation of the mid-rapidity Cronin enhancement in d+Au collisions, RHIC experiments conclusively established large suppression of particle production at forward rapidities [52, 53, 54]. Measurements of low Bjorken $x_{\rm Au}$ di-jet production in the d+Au system exhibit both a suppression by a factor of ten and back-to-back decorrelation [55]. Such modifications are anticipated in a very high gluon density "saturation regime", where the low-x nuclear structure consists of a Color-Glass Condensate (CGC) [56, 57, 58].

- **New Anti-Nuclei and Hyper-Nuclei created**
  The detection of the first ever observed anti-hypernucleus, a $\bar{p}\bar{n}\bar{\Lambda}$ bound state, and eighteen of the heaviest anti-particles ever identified, antihelium-4, opened a new direction of exploration in the nuclear chart. Confirmation that antimatter is produced at a rate consistent with statistical coalescence expectations provides an important benchmark for possible future cosmic radiation observations [59].

2.2 Theoretical and Phenomenological Advances

Discoveries made at RHIC and more recently at LHC have necessitated broad advances in theory and phenomenology to aid in our understanding and interpretation of the data. In some cases entire new areas of theoretical research have been created to address the RHIC data.

- **Statistical Hadronization**
  Yields of all hadronic states created from a decaying quark-gluon-plasma follow a statistical distribution. The Statistical Model of hadro-chemistry describes the hadronic species distribution via thermodynamic variables (T, μ_B, $\mu_{\rm isospin}$) remarkably well over all accessible beam energies [60, 61, 62, 63, 64].

- **Parton Recombination**
  Hadronization can be understood as a statistical process of assembling constituent quarks into hadronic bound states of these quarks. The parton recombination model successfully explains the anomalously large baryon/meson ratios at intermediate transverse momentum and the observed quark number scaling law of elliptic flow [37, 38, 65, 39, 66].

- **Relativistic Viscous Hydrodynamics**
  RHIC data has driven the development of a mature and reliable theory for Event-by-Event Three Dimensional Viscous Relativistic Hydrodynamics [67, 68, 69, 70, 71, 72].

- **AdS/CFT Modeling of Strongly-Coupled Media**
  The duality between N=4 supersymmetric Yang-Mills theory (serving as a model for QCD) and 5D Anti de Sitter space superstring theory, allows for the calculation of various QCD-like transport coefficients and properties (including heavy quark energy loss and shock waves) in the strong-coupling limit that are otherwise computationally not accessible [73, 74, 75, 76, 77, 78]. It has made the study of strongly coupled gauge plasma dynamics increasingly important in the string theory community.

- **Transport of pQCD Probes Through Strongly Interacting Matter**
  Propagation of partons and hadrons of various masses and initial energies through the strongly-interacting medium has stimulated the development of innovative many-body perturbative QCD approaches [79, 80, 81, 82, 83, 84, 85, 86, 87]. Theoretical "jet tomography" tools, driven by precise experimental data, have emerged to quantitatively measure the complex sQGP properties [16, 88, 89, 90, 91, 92, 93].

- **Lattice QCD**
  Lattice calculations in QCD Thermodynamics are closely coupled to the RHIC experimental program, receiving guidance from and providing theoretical input to the experimental community. Past accomplishments include the determination location and nature of the chiral transition, now well established as a crossover, calculations of the Equation of State with sufficient precision to be used in hydrodynamic calculations, and the determination of melting temperatures for charmonium bound states within the plasma. Future lattice calculations combined with experiment will be used to establish the existence and location of a QCD critical point, and to understand the origin of fluctuations in the final state particle distributions [94, 95, 96, 97, 98, 99].

- **Small-x Physics and the Color Glass Condensate**
  Hadron multiplicities and initial attempts at alternative explanations of high momentum hadron suppression include the recognition that nature must exhibit a "Saturation Scale" which can

influence RHIC initial state gluon density and must influence parton distribution functions at sufficiently low Bjorken-x [100, 56, 101, 57, 102, 103, 58, 104],.

2.3 Quantitative Estimates of QGP Properties:

A rigorous phenomenological analysis in conjunction with precision data and theoretical advances has lead to quantitative estimates for some of the most important quantities characterizing the formation and transport properties of the QGP:

- **Initial State Characterization:**
  The initial energy density ϵ_{init}, initial temperature T_{init}, and formation time of the Quark-Gluon-Plasma τ_{init} have been determined to lie within the following ranges: 300 MeV $\lesssim T_{\mathrm{init}} \lesssim$ 600 MeV, 0.2 fm/c $\lesssim \tau_{\mathrm{init}} \lesssim$ 1.2 fm/c (the ranges are correlated – a higher initial temperature goes hand in hand with an earlier formation time: $\epsilon_{\mathrm{init}}^{1/4}\tau_{\mathrm{init}} = const.$).

- **Shear-Viscosity / Entropy-Density (η/s)**
  Expressed in dimensionless units, the effective value for the shear viscosity to entropy density ratio in the QGP phase near T_C has been found to be $\eta/s = (1-2)\frac{1}{4\pi}$ [70, 105] Figure 1 shows how the availability of precision data and advances in theory have resulted in increasingly better constraints on that quantity.

- **Momentum & Energy Transport coefficients**
  The medium-induced part of the energy-loss transport coefficient $\hat{q}$ at the very early stage in the evolution ($\tau = 0.6$ fm) of Au+Au collisions has been determined to $\hat{q} = 2$–10 GeV^2/fm [16, 106]. Figure 2 shows the availability of precision data and advances in theory have resulted in increasingly better constraints on $\hat{q}$ and projects the anticipated improvement due to further measurements by the end of this decade.

3 A "Standard Model" of Heavy Ion Collisions

Prior to the first collisions at RHIC in 2000, expectations for the properties of the system formed in high energy nuclear collisions were varied. One widely-held view was that the extremely high temperatures reached in a RHIC collision would lead to a weakly coupled system of partons (due to asymptotic freedom) that would thermalize and then behave like an ideal gas and expand isotropically. The very first experimental results from RHIC showed that this view was wrong: the particles emerging from heavy ion collisions showed an unmistakable azimuthal anisotropy. This first result led to much more extensive and precise measurements as well as to striking new theoretical developments. Within a handful of years this process resulted in what could be called a "Standard Model": a view of the key elements of the physics of high energy heavy ion collisions that is well supported by experimental evidence and widely accepted. It provides a foundation for relating the many observables relevant to the physics. The example of the anisotropy of particle emission provides a case study of the evolution of our understanding, involving new concepts, quantitative measurement, and theoretical modeling that is underway in many areas of heavy ion physics.

The measurement of "elliptic flow", an event-by-event azimuthal modulation in the emission of hadrons from the collision, characterized by the second Fourier coefficient v_2, was one of the earliest results from RHIC. It was found to be nearly 50% larger than that measured at the SPS ($\sqrt{s_{NN}}$=17.3 GeV), which provided the highest energy heavy ion collisions before RHIC. More importantly, the elliptic flow, averaged over transverse momentum, was found to agree with ideal hydrodynamic calculations initialized to account for the measured multiplicity and transverse momentum spectra [33, 107, 108]. Ideal hydrodynamic calculations are only possible in a purely classical continuum limit where no particle degrees of freedom are evident. Already, this measurement implied a strongly-coupled system far different than naive expectations before RHIC. Follow-up measurements from the other RHIC experiments confirmed the STAR results and catalyzed enormous efforts from the theory community to develop both, more sophisticated hydrodynamic calculations, as well as to explore the microscopic conditions for hydrodynamics to be valid.

One area of particular interest at RHIC was the measurement of v_2 for identified hadrons, over a wide range of masses. Ideal hydrodynamics predicted a characteristic dependence of v_2 on the transverse momentum of the emitted particles, since the presence of the different particles sharing a velocity field would lead to a clear mass splitting. The observation of this "fine structure" in the flow data, which was straightforwardly incorporated into theoretical calculations, provided further evidence that the hydrodynamic paradigm was the most efficient way to understand the wide range of soft hadron measurements emerging from RHIC.

Despite these successes, early on it was noticed that at higher transverse momenta p_T, above 2 GeV, the different hadrons failed to show as much v_2 as predicted from the calculations. Moreover, it was observed that the heavier baryons (protons, lambdas) had a much larger v_2 at the same p_T than was seen for mesons like pions and kaons. A striking scaling was discovered in 2002 when it was proposed by several groups to consider the possibility that the hot, dense medium did not form hadrons directly but rather via a gas of dressed "constituent quarks" which carry their parent quark's quantum numbers [37, 65, 39]. Constituent quark scaling provided a simple way to unify an even larger range of data, from low p_T to high p_T, although alternate descriptions have been proposed, and early data from the LHC suggest that some scaling violations occur at higher energies.

The importance of incorporating viscosity into the theoretical description of heavy ion collisions was never completely ignored but had been neglected in the early years of RHIC both by the apparent successes of ideal hydrodynamics in a large phase space regime, and by the lack of a straightforward formalism to incorporate it into practical relativistic hydrodynamic calculations. However, it was the realization in late 2003 that AdS/CFT calculations could be used to calculate the ratio of viscosity over entropy density in strongly-coupled systems, in a regime where standard kinetic theory was known to break down, that brought a real sense of urgency to the community. These calculations predicted that the viscosity of a strongly-coupled quantum system could never be zero, but were bounded below by $\eta/s = 1/4\pi$, a value that can be rationalized by the argument that excitations can't be localized with a precision smaller than their thermal wavelength, but which had not been reliably calculated previously.

While the theoretical community wrestled with how to systematically incorporate viscous corrections into hydrodynamics, experiments discovered the importance of fluctuations in the initial geometric configuration of nucleons in the colliding nuclei. The motivation for colliding copper ions at RHIC in 2005 was to provide a small system even in central events, one in which many of the interesting physics effects at RHIC might be found to turn off. Instead it was found that the v_2 measured in central events was quite large, a surprising finding if the initial eccentricity of the overlap region was assumed to arise from the convolution of two smooth average densities. The puzzle was resolved by the invention of "participant eccentricity" where the shape of the overlap region was not calculated relative to the classical impact parameter, but relative to an axis determined by the participants themselves. This was the first indication that the fluctuations in the initial state survived the dynamical evolution before freeze-out, itself suggestive of a small viscosity. Subsequent measurements of flow fluctuations reinforced this viewpoint, that the initial state of a nuclear collision was not a smooth density, but varied event to event. RHIC's capability of colliding different nuclear systems was instrumental to the discovery of the role of these fluctuations.

Before 2010, it had been assumed that odd harmonics of the Fourier expansion should not be present in the collision of symmetric nuclei, from the two-fold x-y reflection symmetry of the overlap of two spherically symmetric densities. However, these symmetries are not present event-by-event, as was realized in the work of Alver and Roland in 2010 [109]. Those authors proposed the existence of triangular flow based on the presence of a finite $\cos(3\phi)$ modulation observed in the two-particle correlation functions measured by the RHIC experiments. This term provided a succinct, elegant explanation for two phenomena previously though to be unrelated, a long range rapidity correlation leading to an enhanced distribution in the near-side azimuthal distribution of particles relative to a trigger, referred to as "the ridge", and opposite-side enhancement in the azimuth referred to as "the cone" First results on higher-order harmonic flow, beyond elliptic flow, by the RHIC and LHC experiments appeared just before and at the Quark Matter 2011 conference, where significant contributions from $\cos(\phi)$ to $\cos(6\phi)$, each with their own amplitudes and reaction plane angles, were found to exist. Most importantly, the higher order harmonics were shown to have a weak centrality dependence, characteristic of initial state geometric fluctuations. However they have a very strong dependence on the order n, as expected from the presence of viscosity during the system evolution, which more efficiently damps out higher order (smaller wavelength) fluctuations.

The contribution of initial state fluctuations to the average values of the various Fourier coefficients naturally suggests that the coefficients should vary strongly event to event. The fluctuations of elliptic flow had been inferred by the measurements of flow cumulants, which combined the event-wise measurement of multiple particles (2,4 and 6) into estimates of v_2 which also contained contributions from flow fluctuations. It had also been directly measured by the PHOBOS experiment using its large charged particle acceptance. Subsequently, the LHC provided the large acceptance spectrometers missing at RHIC to provide the first direct measurements of $v_2 - v_4$ with large acceptance in both pseudorapidity and transverse momentum, which could be compared to theoretical predictions tuned on the previous-available event-averaged data. At Quark Matter 2012 these predictions, from the BNL/McGill group incorporating subhadronic quantum fluctuations, were compared to new data from ATLAS with remarkable success.

After twelve years of steady progress, a "Standard Model" for heavy ion collisions has emerged, which provides a generally adopted framework, in which detailed dynamical questions can be phrased and addressed.

- The initial state is understood to fluctuate event by event, with contributions from the nucleons themselves, as well as the energy deposit per nucleon-nucleon collisions, which fluctuates according to classical color dynamics relevant at subhadronic size scales (resulting from gluon saturation). These are usually of negative binomial form.

- There is a rapid changeover from the glue-field dominated initial off-equilibrium stage of the reaction to its hydrodynamic evolution at a "thermalization" time, estimated between 0.15 fm/c and 1fm/c after the nuclei cross. There is debate whether transverse velocity fields can develop before this time and whether the system fully thermalizes or merely becomes isotropic in the transverse direction. The shorter the thermalization time, the higher the initial temperature at thermalization time. The actual mechanism of thermalization is still unknown and represents one of the open questions to be addressed in the coming years.

- The dynamical evolution of the liquid proceeds using second order viscous hydrodynamic equations. Currently, 2+1 boost-invariant hydrodynamics codes are common but the state-of-the-art is rapidly progressing towards a consistent use of 3+1 dimensional codes.

- The equation of state is taken from lattice QCD calculations. At temperatures below the deconfinement transition temperature, the lattice QCD equation of state resembles that of a hadron gas. Partial chemical equilibrium needs to be implemented in the equation of state for the hadronic phase to account for the cessation of inelastic flavor-changing reactions prior to the kinetic break-up of the system.
- The kinetic break-up of the system (freeze-out) occurs at temperatures well below the deconfinement transition temperature. From the transition temperature to freeze-out the system evolves as an expanding hadron gas that is optimally and reliably described with a microscopic transport calculation based on the Boltzmann equation.

4 Discovery Potential, Quantifiable Deliverables and Open Questions

After little more than a decade of operation, many of the initial discoveries at RHIC have lead to precision measurements of Quark Gluon Plasma properties. Yet, due to advances spurred by these initial discoveries and new measurements at higher $\sqrt{s_{NN}}$ provided by the LHC, there are aspects of the RHIC program that are still in a discovery phase. The RHIC beam energy scan serves as prime example that RHIC, even with the LHC operational, remains the only facility in the world capable of providing the necessary collision energies in order to execute a program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out the transition region from hadronic to deconfined matter.

The significant progress towards precision physics of strongly interacting QCD matter under extreme conditions (QGP), as outlined for the case of η/s in the previous chapter, is a success in its own right of the experimental and theoretical community, but it is only a stepping stone in the overall goal of characterizing the QGP via its transport properties (η/s, $\hat{q}$, $\hat{e}$, ...), including their temperature dependence. These transport coefficients η/s and $\hat{q}$ and their temperature dependence serve as examples of precision measurements of the RHIC program for the next 5-10 years. To facilitate such a program, the unique collision energy and system size coverage of RHIC is essential and will be discussed in more detail in the following sections.

Another important aspect of the outlined programs is that it is not only confined to increase the precision to which we determine certain QGP properties, but that it will also add fundamental knowledge to our understanding of QCD matter, such as the precise nature of quasi-particles in the QGP phase and the determination of the stopping power $-dE/dx$ of a hot and dense QGP for colored partons. This determination of the stopping power will provide us with information that is analogous to our precise knowledge of the stopping power of ordinary matter for electrically charged particles [110, 111, 112].

The previously discussed Standard Model of heavy-ion physics based on the hydrodynamic paradigm is still incomplete at present. It requires additional new insights, such as the detailed nature of the initial state, in particular how to describe the nuclear wave function at low Bjorken x, as well as the determination of the fundamental process which allows fast thermalization at early times to occur in heavy-ion collisions. In the following sections we will discuss in more detail additional important aspects of the discovery potential, quantifiable deliverables, and open questions of the future US heavy-ion physics program in the coming years.

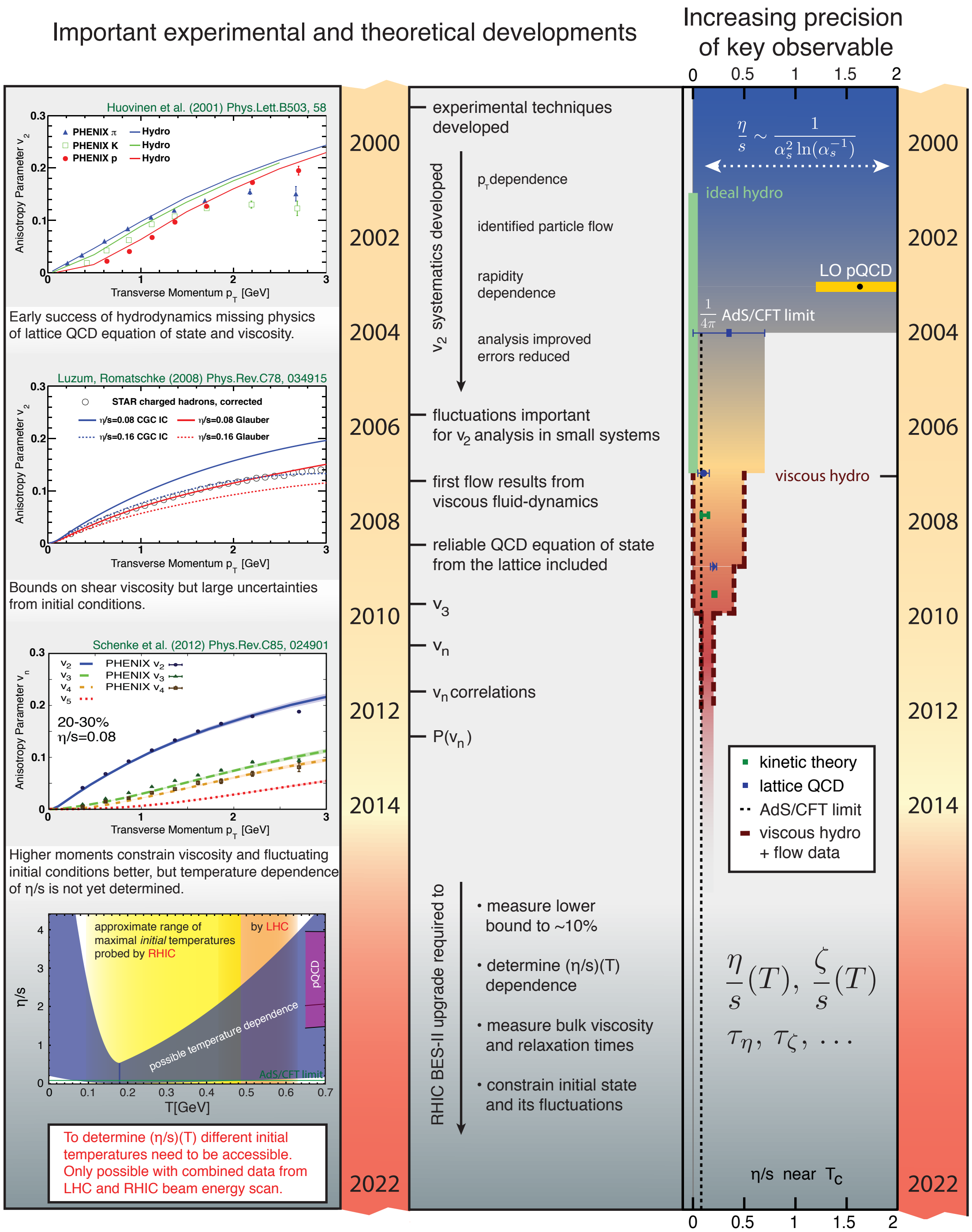


Figure 1: Timeline of important experimental and theoretical developments leading towards increasingly precise understanding of flow, transport properties of the quark-gluon plasma, and the initial state and its fluctuations. The three key figures are taken from [113, 70, 114]. On the right, the increasing precision in one key observable, the shear viscosity to entropy density ratio η/s near its minimal value, is illustrated. Shown results were obtained in [115] (pQCD) [73] (AdS/CFT limit) [116, 117, 118] (lattice QCD - pure glue at $\sim 1.6\,T_c$, $1.24\,T_c$, and $1.58\,T_c$, respectively) [119, 120] (ideal hydrodynamics) [121, 122] (perturbative QCD/kinetic theory) [123, 70, 124, 105] (viscous hydrodynamics constrained by flow measurements).

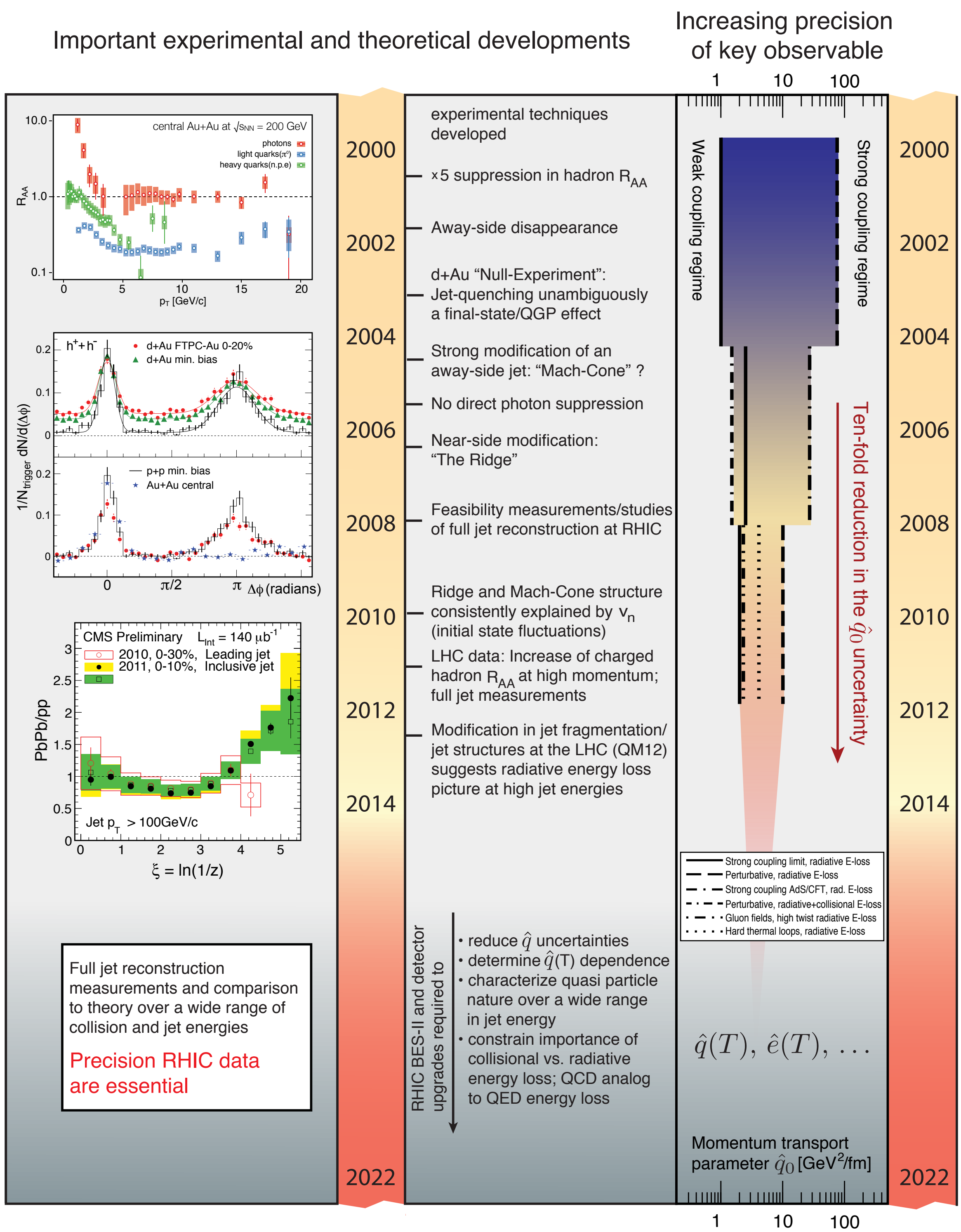


Figure 2: Timeline of important experimental and theoretical developments leading towards the increasingly precise understanding of jet energy-loss mechanisms and its related transport coefficients ($\hat{q}$) as illustrative example on the r.h.s.). The future determination of the temperature dependence of $\hat{q}(T)$ and $\hat{e}(T)$ relies on the proposed detector upgrades to STAR and PHENIX as well as the BES-II program and future LHC measurements.

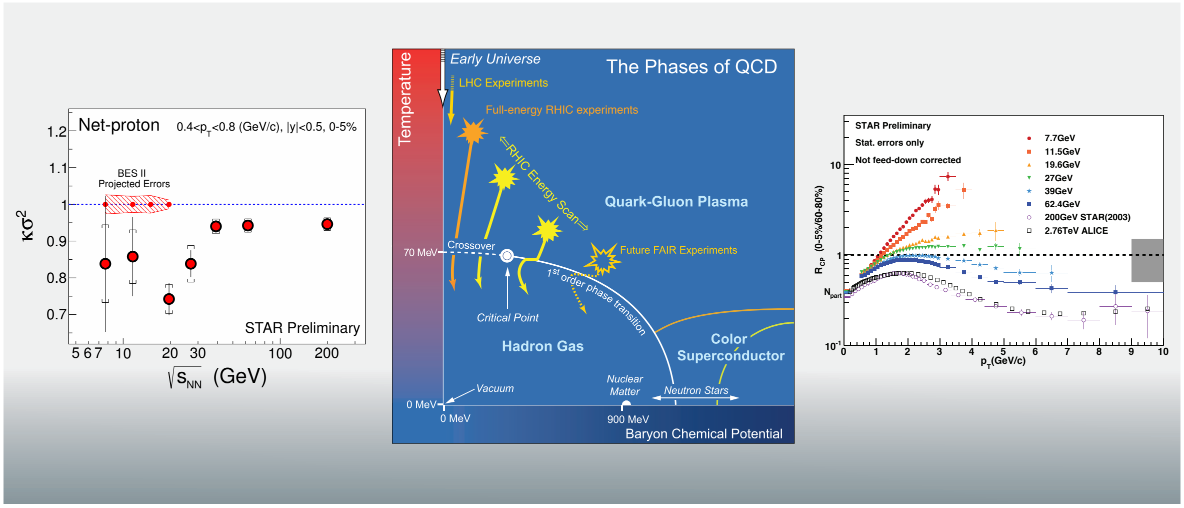


Figure 3: Left: current and projected uncertainties on the net-proton kurtosis $\times$ variance, a measure of the shape of the event-by-event distribution of net protons. Center: illustration of the phase-diagram of QCD matter, including the area of the phase diagram probed by the beam energy scan. Right: nuclear modification factor R_{AA} in central Au+Au collisions measured for different collision energies during phase #1 of the beam energy scan demonstrating the transition from confined to deconfined matter.

4.1 Search for the QCD Critical Point: Beam Energy Scan Phase II

Bulk matter in which the interactions are governed by QCD has a rich phase structure, as shown in the center frame of Figure 3, which can be explored by varying the collision energy between heavy nuclei. In collisions of two nuclei, versus collisions of nuclei with their antimatter partner, the matter is formed with a net baryon density, or baryochemical potential (μ_b), which decreases with increasing collision energy. At zero baryochemical potential, lattice gauge calculations have firmly established that the transition from normal nuclear matter to the Quark Gluon Plasma is of the crossover type, in which no thermodynamic quantity diverges even in the infinite volume limit. At high baryochemical potential and low temperature, the transition is strongly first order, which leads to the conjecture that there must be a critical endpoint in the QCD phase diagram. In recent years lattice calculations have been extended to finite baryochemical potential, with many of these calculations finding a critical endpoint, though its location (and even its existence) are highly uncertain due to the difficulty of performing lattice calculations in this regime. The identification of the QCD critical point is therefore presently an experimental question: should it be found, its location and existence would provide a unique landmark in the understanding of the QCD phase diagram from first principles.

The collision energies currently available at heavy ion colliders span almost three orders of magnitude, from the lowest center of mass energy per nucleon $\sqrt{s_{NN}}$ of 7.7 GeV first performed at RHIC in 2010, to 5.5 TeV eventually available at the LHC. A first-phase scan over the lower end of this range was performed in 2010 and 2011. This scan indicates that RHIC sits at a "sweet spot" in energy, in which rapid changes occur in a number of signatures for energies up to approximately 30 GeV, while remaining surprisingly stable beyond that over the two orders of magnitude to the LHC. As an illustrative example, the right frame of Figure 3 shows the hadron suppression R_{CP} in central collisions for $\sqrt{s_{NN}}$ from 7.7 GeV to 2.76 TeV, in which it is clear that the strongest changes occur at the lowest energies. Combined, these measurements provide a substantial hint that collisions at energies at the lower range available at

RHIC probe a region of non-trivial structure in the QCD phase diagram. The disappearance of many key signatures of deconfined matter as the collision energy is lowered hints that the matter is moving from one with partonic degrees of freedom to one with hadronic degrees of freedom as the initial temperature decreases.

However, many of these measurements are of limited statistical power. In order to convert these into conclusive statements, more luminosity is needed. A cooling upgrade to RHIC can provide an order of magnitude higher luminosity for $\sqrt{s_{NN}} < 20$ GeV, on the timescale of 2017. Figure 3, shows the current and projected uncertainties on the net-proton kurtosis $\times$ variance, a measure of the shape of the event-by-event distribution of net protons. As one passes through a critical point from high to low energies, this quantity is expected to first go below unity, and then become large as the correlation length diverges near the critical point. The uncertainties in the current measurements do not allow for an identification of this behavior, clearly more precise measurements are needed, especially at the lower energies.

4.2 Parity-Violating Fluctuations

QCD matter created in relativistic heavy-ion collisions may possess a very rich set of features, reflecting the fundamental symmetries (and violations thereof) of QCD. Among the more intriguing features which are currently being searched for is the presence of the Chiral Magnetic Effect (CME) [50, 51, 125, 126]: the QCD Lagrangian in principle permits the existence of a so-called θ-term which violates time-reversal and thus CP symmetry. While precision measurements of the electric dipole moment have not found any indications of CP violation, the presence of a strong external magnetic field can be used to probe the CP-odd sector of QCD which otherwise may not be accessible. As was pointed out in [50], non-central heavy-ion collisions create a coherent magnetic field that may convert topological charge fluctuations in the QCD vacuum into global electric charge fluctuations with respect to the reaction plane.

While initial measurements of charge sign correlations [48, 49] are qualitatively consistent with expectations of the Chiral-Magnetic Effect [50, 51], the uncertainties associated with these measurements remain large and preclude any definitive assessment. Since the CME should disappear with either the absence of deconfinement (i.e. at low collision energy) or the absence of a magnetic field (as in very central U+U collisions), the planned Beam Energy Scan Phase II as well as extended runs with U+U provide a unique discovery potential for this effect. We should note that the search for the CME has the virtue of being the only known means of testing in the laboratory the gauge theory dynamics that might (in its SU(2) incarnation) be responsible for the matter/antimatter excess in the universe and is thus of highly significant theoretical importance [51].

4.3 Differential Measurements of Transport Properties of the sQGP

4.3.1 Precision Measurement: Temperature dependence of η/s and other bulk transport parameters

Given the outlined success of hydrodynamics and the *Standard Model of heavy ion physics* the next natural step is to systematically measure the temperature dependent values of bulk transport parameters. In addition to $(\eta/s)(T)$ these include the temperature dependent bulk viscosity over entropy density ratio $(\zeta/s)(T)$ as well as corresponding relaxation times. With the development of comprehensive event-by-event viscous relativistic hydrodynamic simulations coupled to hadronic cascade models, theoretical simulations are just reaching the necessary maturity to undertake such investigations. At the same time, a differential measurement of $(\eta/s)(T)$ requires experimental control over the initial temperature. Thus, high precision measurements of higher harmonic flow coefficients v_n, that are sensitive to $(\eta/s)(T)$, at both LHC and varying RHIC energies are absolutely essential. The behavior of $(\eta/s)(T)$ near the critical temperature T_c, where typical liquids (e.g. ^{4}He and even water) show rapid changes in η/s, is particularly useful to establish a deeper understanding of the nature of QCD matter. Furthermore, to establish effects of non-zero bulk viscosity, one has to utilize the strength of RHIC by exploring a broad variety of both collision energies and system sizes. The phase II of the RHIC Beam Energy Scan is crucial for these measurements.

4.3.2 Precision Measurement: Jets – The Physics of Partonic Energy Loss

The emission of hadrons with large transverse momentum is observed to be strongly suppressed in central collisions of heavy nuclei [17, 18] compared to proton-proton interactions. The origin of this phenomenon, commonly referred to as *jet-quenching*, can be understood in the following way: during the early pre-equilibrium stage of the relativistic heavy-ion collision, scattering of partons which leads to the formation of deconfined quark-gluon matter often engenders large momentum transfers which leads to the formation of two back-to-back hard partons. The interaction of these partons with the surrounding medium leads to significant energy loss, and is sensitive to the structure of the QGP and its transport properties.

Compared to the bulk medium dynamics described in the previous sections, the physics of partonic energy loss in the QGP [79, 127, 128, 80, 81, 82, 83, 84, 85, 86, 77, 78, 87] is not yet in a similarly advanced state. Nevertheless, significant progress in constraining the underlying microscopic processes has been made, with RHIC pioneering this field [17, 18, 21, 22, 23, 24].

One of the parameters that characterizes the interaction of an energetic jet with the QGP medium is the momentum transport parameter $\hat{q}$, defined as the typical momentum transfer squared per unit length incurred by the hard parton in the strongly interacting medium [127, 128]. It depends on the coupling regime (strong versus weak) at the scale of the interaction, the nature of the plasma (quasi-particle-dominated versus quasi-particle-less) and the micro-physics of many-body QCD in strongly-interacting matter. The measurement of $\hat{q}$ relies on an interplay between experiment and theory, since it is not a directly measurable quantity. $\hat{q}$ is commonly extracted via a comparison between data, e.g. on the nuclear modification factor R_{AA} or two particle correlation functions, and theoretical calculations of the same quantities with $\hat{q}$ as parameter of the calculation. The extraction of $\hat{q}$ thus inherently is not only dependent on experimental uncertainties, but also on the model assumptions that go into the respective theoretical calculation. A significant fraction of the $\hat{q}$ uncertainties quoted here stem from these theoretical uncertainties. The measurement of correlation observables at high precision will not only reduce experimental uncertainties, but also significantly constrain the theory calculations, thus reducing their systematic uncertainties as well.

Over the past decade considerable progress has been made at RHIC in constraining the value of $\hat{q}_0$, the value of $\hat{q}$ at the formation time of the QGP τ_0, as illustrated in Figure 2. Shown in the right hand side is the value of the momentum transfer parameter at time $\tau_0 = 0.6$ fm, typical of the formation time of the QGP at RHIC. Most of the constraints are based on (single particle) light hadron measurements [129, 130]. Initial $\hat{q}_0$ estimates covered a staggering two orders of magnitude, ranging from the weak coupling [16, 88] to the strong coupling limit, where nuclear matter created in RHIC collisions transitions from a completely opaque core to a fully transparent corona [131, 132]. This significant uncertainty in the value of $\hat{q}_0$ was due in part to the large experimental uncertainties in the early days of RHIC.

Initial theoretical attempts to constrain $\hat{q}_0$ concentrated mainly on radiative energy loss. Subsequent efforts have included both radiative and collisional energy loss in the QGP [133, 134] resulting in a new definition of the lower bound. On the strong coupling side, the AdS/CFT correspondence has been used to calculate $\hat{q}_0$ as well [77] and can be interpreted as an upper limit for that quantity. This resulted in a reduction in the uncertainties of $\hat{q}$ by a factor of three. The latest analysis of increasingly more precise RHIC measurements decreased the allowed range of $\hat{q}_0$ from 2 GeV^2/fm to 10 GeV^2/fm [130, 135].

Concurrent developments in theory and experiment have allowed to reduce the uncertainty of the momentum transport parameter at RHIC by an overall factor of twenty. The continuing improvement in the precision determination of $\hat{q}$ is a remarkable progress and success of the field, but the remaining uncertainty of roughly of a factor of five still hinders the precise determination of the medium transport properties. In particular, the QGP response to different jet energies and the temperature dependence of the transport parameter cannot be constrained at this stage with sufficient precision. A program of RHIC upgrades with optimal kinematic coverage is expected to reduce these uncertainties to a factor of two in 2020 and key aspects will be discussed in the following:

- **Study of low energy jets in medium:**
  The interactions of the full parton shower (i.e. the full jet) with the medium probes the transport properties of the QGP at scales that range from the bulk scale set by the temperature $\sim T$, to a scale $\sim \sqrt{E_T T}$ (with E_T being the transverse energy of the shower). The measurement of jets at relatively small jet energies around 40-50 GeV will allow for the mapping of the energy and momentum transport coefficients in the most interesting and least understood region between the weak and strong coupling limits. Reconstruction of these jets of relatively small energies can be achieved at RHIC with higher efficiency than at the LHC, due to the underlying background at RHIC being smaller than at LHC.

- **Temperature dependence of $\hat{q}$:**
  The measurement of the temperature dependence of $\hat{q}$ is of analogous importance to to the future studies of temperature dependence of η/s. Since the expected scaling of $\hat{q}$ with temperature is a strong function of T [16, 77, 136, 137], jet quenching measurements are sensitive to the earliest times and highest temperatures. In order to achieve sensitivity to temperatures around 1 - 2 T_C, measurements at RHIC are needed for different colliding systems and smaller center of mass energies as opposed to LHC energies, where larger initial temperatures are produced.

- **Probing the coupling strength of the medium:**
  Both the *soft* η/s bulk transport parameter and the *hard* partonic energy loss parameters such as $\hat{q}$ (and analogously $\hat{e}$, defined as the longitudinal momentum transfer per unit length) are sensitive to the underlying coupling of the matter, but in different ways. If precise measurements of bulk and jet observables are accessible, one can utilize the relationship between the energy and momentum transfer parameters (for example in weak coupling $\hat{q} = 1.25T^3/(\eta/s)$ [137]), to test the nature and coupling strength of the QGP medium.

- **Testing the quasi-particle nature of the QGP:**
  It is expected that at some sufficiently large momentum scale a quasiparticle picture of the QGP must be valid, even though on its natural length scale it is a strongly coupled fluid. To determine this scale and the detailed nature of the quasi particles, jet measurements over a wide range of energies and with different medium temperatures (RHIC complementary to LHC) are essential. Even though recent measurements at the LHC suggest that a strongly coupled AdS/CFT like picture at the scales currently accessible is not favored [138], precision jet measurements at RHIC will allow to map out the currently unexplored regime closer to the strongly coupled limit.

- **Radiative vs. elastic energy-loss:**
  The exact nature of what the parton is scattering off in the medium is tied directly to the balance between radiative energy loss and inelastic collisional energy loss in the medium and will allow to measure the relative importance of these processes. In QED, the stopping power of matter for electrically charged particles is known to within a few percent. At the LHC, in the $E_T > 50$ GeV regime, jet modification appears to be dominated by radiative energy loss. RHIC can provide the necessary kinematic coverage to study the relative significance of collisional and radiative processes, thereby advancing our understanding of dense QCD matter at high energies. Therefore RHIC and LHC combined will allow to map out the stopping power $-dE/dx$ of hot and dense QGP for colored patrons [139] in analogy to our precise knowledge of the stopping power of ordinary matter for electrically charged particles [110, 111, 112].

4.3.3 Heavy Flavor and Quarkonia

Heavy quark observables promise enormous potential for insight into the dynamics of the QGP. Because charm and bottom quarks are so massive, they must be produced in the very earliest stages of the collision. Once produced, heavy quarks act as identifiable test particles, navigating the entire evolution of the medium, participating in and being affected by its dynamics. Produced as $q\bar{q}$ pairs, the heavy flavor may emerge together as quarkonia (closed heavy flavor) or in separate hadrons (open heavy flavor). As tomographic probes of strongly-interacting matter, heavy flavors provide a well-defined physical scale against which the temperature of the medium can be gauged via the pattern of quark diffusion. Due to their different Lorentz boost factor at a given momentum transfer, heavy quarks shed light on the mechanisms of collisional and radiative energy loss in the QGP. Furthermore, the large D and B meson masses suggest early hadronization and have stimulated a fresh look in the in-medium fragmentation and dissociation of open and closed heavy flavor. Charm and beauty quarks are also sensitive to resonant states just above the QCD chiral transition temperature.

The small production cross sections involved mean that heavy flavor measurements require high luminosity and extremely capable detectors. Interestingly, now that RHIC is effectively operating at the luminosities forseen for the RHIC II project, the statistics expected for produced heavy flavor at RHIC and at LHC are comparable [140]. The higher b and c production cross sections at the LHC are largely compensated by the higher heavy ion luminosity and longer per year running time of RHIC. In any case, a complete program to investigate the QGP using heavy flavor probes will be a multi-year program of integrating luminosity and performing necessary reference measurements.

Measurements of heavy flavor at RHIC already present an intriguing puzzle to the high-energy nuclear physics community. Early theoretical expectation was that heavy quarks would lose considerably less energy in their passage through the medium than light quarks do, but PHENIX and STAR measurements of the suppression of non-photonic electrons coming from the decays of D and B mesons indicate that heavy quarks do, in fact, lose a considerable amount of energy in the QGP. Furthermore, the elliptic flow of non-photonic electrons suggests heavy quarks have largely thermalized in the medium. This surprising behavior of heavy mesons has recently been observed to be even more pronounced at the LHC.

The heavy quark diffusion coefficient is a quantity that the heavy flavor program at RHIC will determine over the next several years to a precision of $\sim$10–15%: In the quasi-particle picture, heavy quarks lose energy in the QGP medium through both elastic collisions and gluon emission. The first process dominates at the low to intermediate heavy quark momenta predominantly accessible at RHIC while the latter dominates at the large heavy quark momenta mostly accessible at the LHC. In the domain dominated by collisional energy loss, heavy quark evolution can be described as a diffusion process with

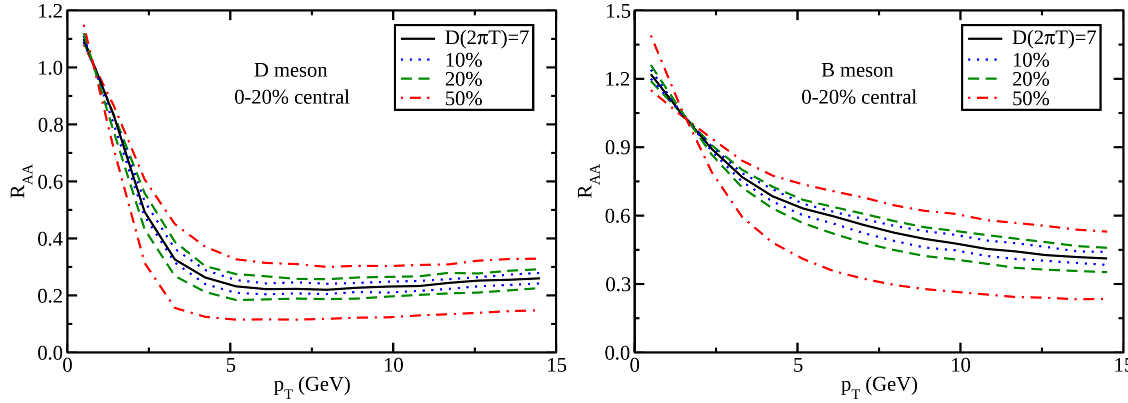


Figure 4: Diffusion calculation of the nuclear modification factor R_{AA} for D-mesons (left) and B-mesons (right) in central Au+Au collisions at RHIC. Shown is how a $\pm 10\%, \pm 20\%$ and $\pm 50\%$ variation in the diffusion coefficient translates into a respective change of the nuclear modification factor. For a determination of the diffusion coefficient within $\pm 10\%$, the nuclear modification factor needs to measured with similar precision.

the heavy quark diffusion coefficient as the governing transport coefficient [141, 142]. The precision with which the diffusion coefficient can be determined scales directly with the uncertainties of the experimental measurements for the nuclear modification factor R_{AA} and elliptic flow coefficient v_2 of D and B mesons; if these quantities can be measured with an uncertainty of ∼10% this will translate into a determination of the diffusion coefficient to similar precision (Fig. 4).

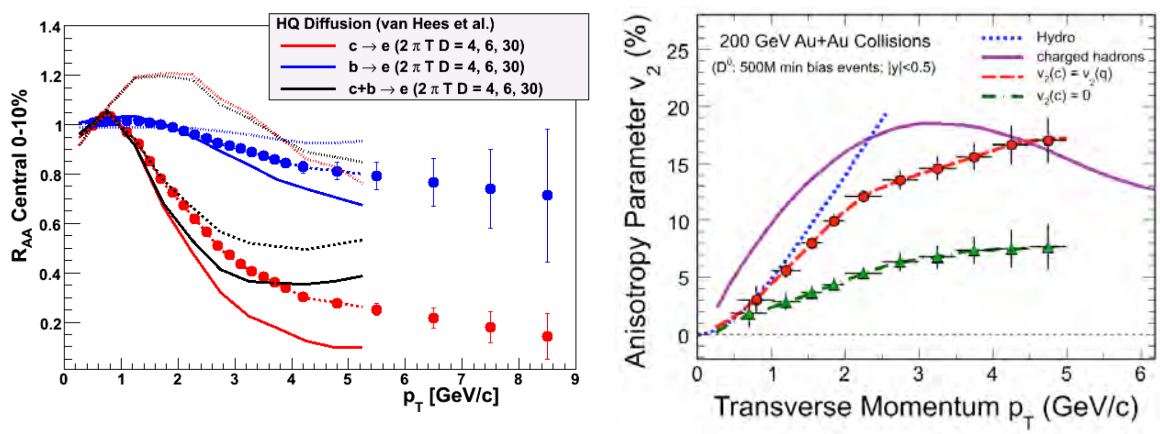


Figure 5: Projected uncertainties for the determination of flavor separated R_{AA} for the most central 10% of 4.3 nb^{-1} of Au+Au collisions and 14.8 pb^{-1} of p+p collisions (left). Also shown are diffusion calculations by van Hees et al Projected uncertainties for D^0 v_2 measurement using the STAR detector in a 10 week 200 GeV Au+Au RHIC run (right).

Measuring heavy quarks by their semi-leptonic decay alone does not distinguish between the decays of D and B mesons [43] and represents and admixture of information about charm and bottom quarks. Since bottom quarks are more than three times as massive as charm quarks, making them much less abundant than charm quarks, but also leading to significant differences in their dynamical behavior [143], separating the two signals has clear significance. One can employ various techniques to decompose the separate contributions of charm and bottom [144], but to make direct measurements both STAR and PHENIX have developed a physics program for the next several years centered around sophisticated vertex detectors that are able to distinguish the different decay lengths of the D and B mesons. The PHENIX VTX and STAR HFT are barrel detectors near mid-rapidity; the PHENIX FVTX is an endcap detector. The PHENIX VTX has recently demonstrated first results for c/b separation in heavy ion collisions. The left panel of Figure 5 shows the projected uncertainties one would obtain on the nuclear modification factor, R_{AA}, with a high statistics Au+Au run and two years of accumulated p+p data.

The identification of heavy flavor through its semi-leptonic decay is well complemented by a direct measurement of topologically reconstructed D mesons. This technique has some very positive features, especially at low transverse momentum, as one does not need to unfold the spectrum of a decay electron to obtain the momentum of the parent meson. The right panel of Figure 5 shows the projected uncertainties one would obtain for the v_2 of charm quarks under two different assumptions in a ten week Au+Au run. The v_2 for charm flow from reconstructed D mesons has also been measured by ALICE [145], and a measurement at RHIC would enable a statement about the temperature dependence of the coupling of charm to the flowing medium.

Measurements of quarkonia provide different information about the propoerties of the QGP. At high temperatures one expects the emergence of Debye screening of the interaction between quarks and gluons. This leads to the dissolution of hadronic bound states [146]. A particularly interesting subset of hadronic states consists of those comprised of heavy quarks since the spectrum of low lying states can be found using potential-based non-relativistic treatments. Based on such potential models there were early predictions [147, 148] that J/ψ production would be suppressed in heavy ion collisions relative to the corresponding production in proton-proton collisions scaled by the number of nucleons participating in the collision. In recent years there have been important theoretical advances in the understanding of heavy quark states at finite temperature using analytic techniques [149, 150, 151, 152, 153, 154, 155, 156, 157] and lattice QCD [158, 159, 160, 161, 162, 163, 164].

Practitioners are, for the first time, using realistic viscous hydrodynamical models to describe the evolution of the matter in which the heavy quark bound states are embedded [165, 166, 167]. With these advances, the study of heavy quarkonium suppression has moved into a new quantitative era, in which precise comparison of experimental data and theoretical predictions is vitally important. The measurement of the suppression of the ground and excited states of heavy quarkonium will enable the determination of key plasma properties such as the initial temperature, degree of momentum space anisotropy, and the shear viscosity to entropy ratio. RHIC's ability to perform beam energy and system size scan are essential for these measurements.

Already there are results from CMS showing that the higher mass states of the upsilon are relatively more suppressed in Pb+Pb collisions at 2.76 TeV than in control p+p collisions [9]. STAR's muon telescope detector (MTD) will enable measurements at RHIC energies of the upsilon family of states, and the right panel of Figure 6 shows the uncertainties one could achieve within a few years.

Quarkonia can be produced directly, but there is also the possibility of producing a $q\bar{q}$ state through recombination of a quark and an anti-quark from different initially produced pairs. The degree to which recombination plays a role can be controlled by studies of the $c\bar{c}$ and $b\bar{b}$ systems at RHIC and LHC.

ALICE J/ψ measurement [168] compared to PHENIX data is shown in the left panel of Figure 6. The J/ψ in central Pb+Pb at 2.76 TeV are relatively less suppressed that is the case in central Au+Au at 200 GeV. Charm is so abundant at the higher collision energy of LHC that recombination of independently produced charm quarks into quarkonia may be responsible for the difference. This is a particular example where complementary measurements at the LHC and RHIC illuminate the physics of the QGP.

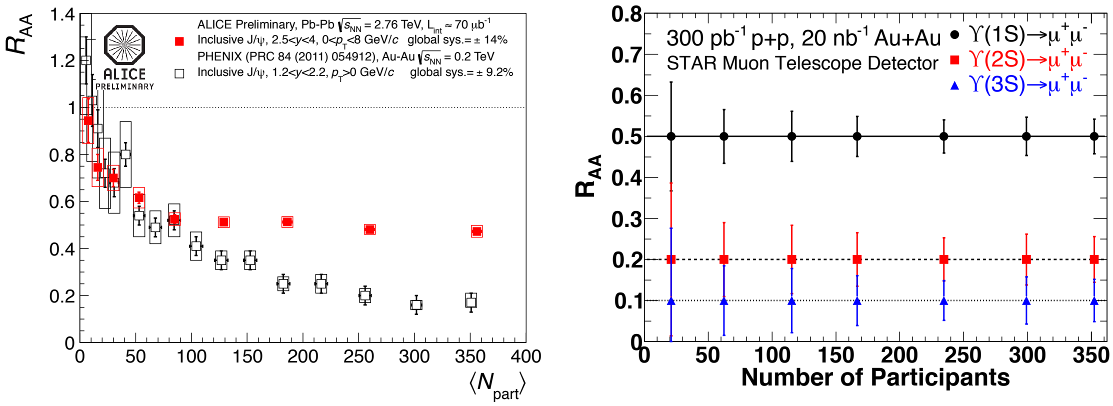


Figure 6: left) A comparison of ALICE results for J/ψ suppression versus centrality compared to the results obtained by PHENIX. The relatively weaker suppression in central collisons may be due to recombination of charm from abundantly produced $c\bar{c}$ pairs at the LHC. (right) Projected uncertainties for the suppression of the different mass states of the upsilon family.

4.4 Pre-Equilibrium Physics

One of the fundamental open questions in the study of the Quark Gluon Plasma is to what extent the system that is produced in relativistic heavy ion collisions achieves local isotropic thermal equilibrium and at what timescale this may occur. Immediately after the initial nuclear impact, the Quark Gluon Plasma is not a thermal isotropic plasma. The constituents must interact for some period of time in order to reach a (quasi)-thermal state. In the high-energy limit the incoming nuclei are dominated by small-x gluons whose occupation numbers are large, $n \sim 1/\alpha_s$ [169]. The question then becomes, how does one connect such a coherent nuclear state to an incoherent plasma of quarks and gluons on the fm/c timescale. The answer to this question is highly relevant for Quark Gluon Plasma phenomenology since a key component of the Standard Model of heavy-ion collisions described in section 3 is the viscous hydrodynamic evolution of the QGP phase, which requires local isotropization of the Quark Gluon Plasma. Standard hydrodynamical fits to RHIC elliptic flow data suggested that the Quark Gluon Plasma has a thermalization and isotropization time on the order of 0.2 – 1.0 fm/c. However, some recent viscous hydrodynamic analyses have shown that the pre-equilibrium phase of the Quark Gluon Plasma evolution can last for up to 2 - 3 fm/c after the initial nuclear impact [70, 170].

In order to address the question of the precise thermalization and isotropization times of the Quark Gluon Plasma there are two prevailing approaches in the literature. The first is to take the high-energy limit in which the plasma is weakly-coupled and extrapolate the resulting perturbative series to the couplings relevant ($\alpha_s = 0.3$) for phenomenological applications [171, 172, 173, 174]. The second is to study the problem using the conjectured anti de Sitter space / conformal field theory (AdS/CFT) formalism in the infinitely strong coupling limit [175, 176, 177, 178, 179, 180, 181]. On the perturbative side we have learned in the last ten years that there exist non-Abelian plasma instabilities which help to accelerate the isotropization of the Quark Gluon Plasma. Such predictions began over two decades ago [182, 183, 184] but in the last decade we have seen tremendous advances in our ability to simulate the complicated dynamics of non-Abelian plasma instabilities [185, 186, 187, 188, 189, 190, 191, 192, 193]. Such studies are of key importance since it can be shown that plasma instabilities induce an anomalous shear viscosity in the plasma which is lower than what one obtains in a static thermally equilibrated Quark Gluon Plasma [194, 195]. The other important conceptual change due to the existence of non-Abelian plasma instabilities is that their dynamics naturally drives the system to a state which has

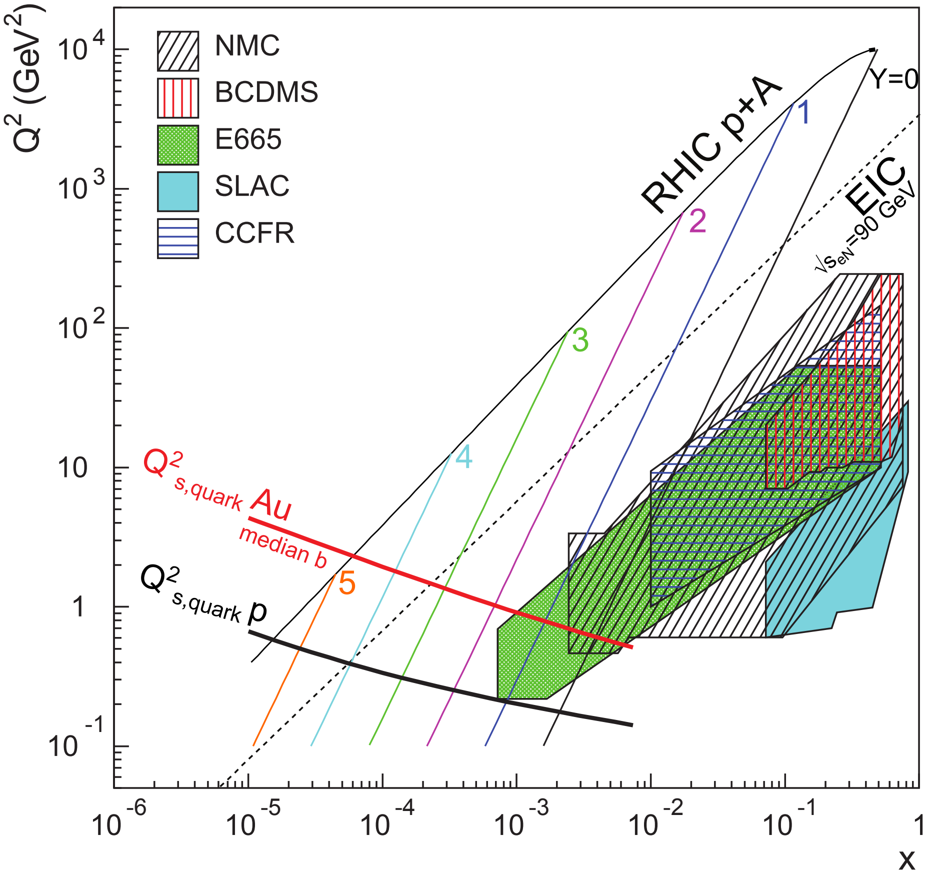


Figure 7: Kinematic coverage in the $x - Q^2$ plane for p+A collisions at RHIC, along with previous e+A measurements, the kinematic reach of an electron-ion collider (EIC), and estimates for the saturation scale Q_s in Au nuclei and protons. Lines are illustrative of the range in x and Q^2 covered with hadrons at various rapidities.

parametrically large field occupation numbers. Such large occupation numbers cause the system to interact strongly even though the coupling constant itself may not be large.

The cleanest and most sensitive probes to the pre-equilibrium phase of the heavy-ion collision are photons and leptons, since they do not interact with the concurrently forming QGP medium after their production [196, 197]. However, a very high precision is required for these measurements in order to de-convolute the pre-equilibrium photon and lepton emission from the subsequent thermal emission of these probes during the Quark Gluon Plasma evolution. The planned upgrades to the STAR and PHENIX detectors are designed to deliver the required precision in the measurement of leptons and photons that are crucial for the unraveling of the thermalization mechanism. These measurements have to be augmented by data from the LHC, since thermalization times are expected to be shorter at higher temperatures and energy-densities.

4.5 The Nature of the Initial State / Gluon Saturation

The nature of the initial state, in particular how to describe the nuclear wave function at low Bjorken x, is still an area with large experimental and theoretical uncertainties at the current stage of our understanding. Recent theoretical developments combine the color-glass-condensate framework to describe fluctuating gluon fields in highly energetic nuclei with a dynamic pre-equilibrium glasma stage immediately after the collision and viscous hydrodynamics to describe further evolution in heavy-ion collisions. This provides a promising framework for the study of the initial state and transport parameters of the quark-gluon plasma by analyzing higher harmonic flow coefficients v_n and their fluctuations [198, 199]. First comparisons to flow measurements at RHIC and LHC have been remarkably successful [41]. However, to access in more detail the subhadronic correlations and dynamics governed by saturation physics requires further measurements at small x, and therefore forward rapidities, with the cleanest measurements possible in p+A and e+A collisions.

Experiments at HERA have shown conclusively that as one probes to lower fractional momentum x in the wave function, the gluon density rises rapidly. This rise cannot continue forever, since it would eventually lead to a violation of unitarity in high-energy scattering processes. At some point, the nonlinear nature of QCD will enter to tame this rise, entering into a regime where occupation numbers are high enough that the process of gluon recombination competes with gluon splitting. The scale at which this happens is known as the saturation scale. Reaching this scale would open up a new and unique regime of tractable QCD calculations, in which weak coupling is combined with extremely intense gluon fields. There is no question that this regime exists somewhere in nature; the main question is whether it is experimentally accessible at the energies available at current colliders.

Current measurements at RHIC of the suppression of single hadrons [52, 54] and back-to-back di-hadron correlations [55] in d+Au collisions have been interpreted as strong hints that the saturation scale, and the onset of saturation effects, are accessible at forward rapidities at RHIC [200]. At this point, though, these interpretations are not unique, for two main reasons.

First, as shown in Figure 7, for the kinematic reach of RHIC energies the saturation scale is moderate, on the order of a few GeV^2, so measurements sensitive to the saturation scale are by necessity limited to semi-hard processes, and effects due to kinematic limits must be fully addressed. To some level this can be addressed at the LHC, where the larger energies allow for measurements deeper into the saturation regime, especially at forward rapidities. First measurements have been made at mid-rapidity by ALICE [201], which correspond approximately to y=3-4 at RHIC. This measurement shows no suppression of single hadrons for $p_T > 2\,\mathrm{GeV}$, as predicted by saturation models [202, 203], however, alternative models also predict this feature of the data [204]. Key tests at the LHC will come at more forward rapidities, where saturation effects are stronger and distinct from other descriptions [203, 204].

Second, and more importantly, in measurements to date in p+A collisions both the entrance and exit channels have components that interact strongly, leading to severe complications in the theoretical treatment. In p+A collisions, these complications can be ameliorated by removing the strong interaction from the final state, using photons and Drell-Yan electrons. Both PHENIX and STAR have upgrade plans to make these difficult measurements, which are planned to be in place for high precision towards the end of this decade. Beyond this, the possibility of using polarized protons at RHIC to probe saturation phenomena is just beginning to be explored [205], utilizing the large transverse single-spin asymmetries seen in p+p collisions at forward rapidity (which do not require a polarized ion beam) to explore the onset of saturation. In addition, measurements of direct photons at forward rapidities over a large Q^2 regime at the LHC could be used, with appropriate upgrades, to probe deeper into the saturation regime.

The ultimate level of precision can be obtained using an electron-ion collider, in which strong interactions are removed from the initial scattering, and in which the full kinematics can be reconstructed in the final state. The rich program available at an electron-ion collider is detailed in a separate White Paper. Besides the close match in instrumental capability necessary for both p+A and e+A collisions, the combination of a strong p+A and e+A program allows for detailed tests of universality within the saturation approach.

5 The Future of Relativistic Heavy Ion Physics

In this document we have outlined a research program that will address the most relevant open questions in the physics of strongly interacting hot and dense QCD matter. It will lead to the quantitative determination of the most important Quark Gluon Plasma properties, such as the temperature dependence of its transport coefficients, while also enabling new discoveries, such as the existence and location of the QCD critical point. This program relies on a number of detector and accelerator upgrades as specified in *The Case for Continued RHIC Operations* by Steve Vigdor [1].

The key pillars of this 5–10 year program are:

- a beam-energy scan program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out the transition region from hadronic to deconfined matter.
- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependence of the shear-viscosity to entropy-density ratio η/s (including an assessment of whether the conjectured lower bound has been reached to within a precision of 10%), and that of the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.
- a jet physics program to study the nature of parton energy loss and the quasi-particle nature of the QGP.
- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium, as well as quarkonia measurements that will provide standard candles for the temperatures obtained in the early stages of a heavy-ion reaction.
- a systematic forward physics program to study the nature of gluon saturation.

As noted earlier, the last bullet leads naturally to the physics program for the Electron Ion Collider. It is also important to note that this physics program cannot be pursued with data from the Large Hadron Collider. RHIC provides essential measurements that span the range above and below the transition region in temperature as well as regions of the phase diagram at higher baryon density. The science objectives presented in this document can only be achieved in a heavy ion program that includes the continued operation of the Relativistic Heavy Ion Collider in addition to continued participation in the LHC heavy ion program. The heavy ion program described herein will ensure continued leadership in the field and will complete the scientific investment the US government has made in seeking to discover and understand the bulk properties of strongly interacting matter.

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