PROCEEDINGS OF SCIENCE

The Future of RHIC

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This article describes recent results and future plans for the Relativistic Heavy Ion Collider.

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1. The Relativistic Heavy Ion Collider

The nearly simultaneous discoveries of the cosmic microwave background radiation and the exponentially growing hadron mass spectrum in 1965 raised several questions: What kind of matter filled the early universe at its hot beginning? Is there an upper limit to the temperature of matter or does hadronic matter dissolve into quarks and gluons above a certain critical temperature? The Relativistic Heavy Ion Collider (RHIC) was constructed to answer these questions by exploring the properties of nuclear matter under the extreme conditions of the early universe.

The phase diagram of nuclear matter extends in two dimensions described by the intensive variables, temperature and baryon chemical potential. Temperature T measures the average excitation energy per degree of freedom, the baryon chemical potential μ_B is a measure of the excess of baryons over antibaryons. In nature, the temperature axis was explored in the early universe immediately after the Big Bang, when the cosmos was filled with hot matter characterized by very high temperature ($T \gg 10^{10}$ K) and a negligibly small baryon surplus; the chemical potential axis is explored in atomic nuclei and collapsed stars, where μ_B can exceed the nucleon mass ($\mu_B > 1$ GeV).

Colliding nuclei at its highest energy (100 GeV per nucleon in each beam), RHIC has been shown to be able to produce matter at a temperature $T \approx 4 \times 10^{12}$ K ($T > 350$ MeV) and very small μ_B, but unforeseen to its designers, has also been able to produce matter far into the dense regime of the nuclear phase diagram by lowering its beam energy down to 5 GeV per nucleon. The full range of variability of RHIC is shown as the shaded yellow region in the phase diagram in Fig. 1. It has recently been shown that the range of coverage of RHIC can be extended to even higher values of μ_B by colliding one of the beams with an internal fixed target. This technique will allow RHIC to explore nearly all of the interesting range of conditions in the nuclear matter phase diagram that is accessible in heavy ion collisions.

The versatility of RHIC does not only concern the thermodynamic conditions of the matter produced. RHIC can also vary the size and shape of the hot matter droplets that are created by changing the combination of nuclei that collide. In recent years, RHIC has collided protons (p+p), protons with various heavier nuclei (p+Al, p+Au), deuterons and helium-3 with gold nuclei (d+Au and ^{3}He+Au), and the nuclear combinations Cu+Cu, Cu+Au, Au+Au, and U+U. Because RHIC can accelerate and collide polarized protons in any desired polarization state — it is the world's first and only polarized proton collider — it has also turned out to be a powerful tool to explore the dynamics of spin in quantum chromodynamics (QCD). In this talk I will not discuss the goals and results of the polarized proton program and focus on the heavy ion physics program.

Over the past several years, RHIC has seen various upgrades that increased its luminosity and versatility: a new ion source (EBIS), the implementation of three-dimensional stochastic cooling, and electron lenses to compensate for the beam-beam effect in p+p collisions, to name just a few. At top energy RHIC has now exceeded its original design luminosity in the Au+Au mode by more than 40 times. The achieved luminosities over the full range of collision systems and energies achieved at RHIC is shown in Fig 2.

The scientific program of RHIC in recent years has been carried out by two large detectors, PHENIX and STAR. Both devices are operated by international collaborations of more than 500 scientists from over 10 countries. The detectors have been upgraded in recent years by the addition

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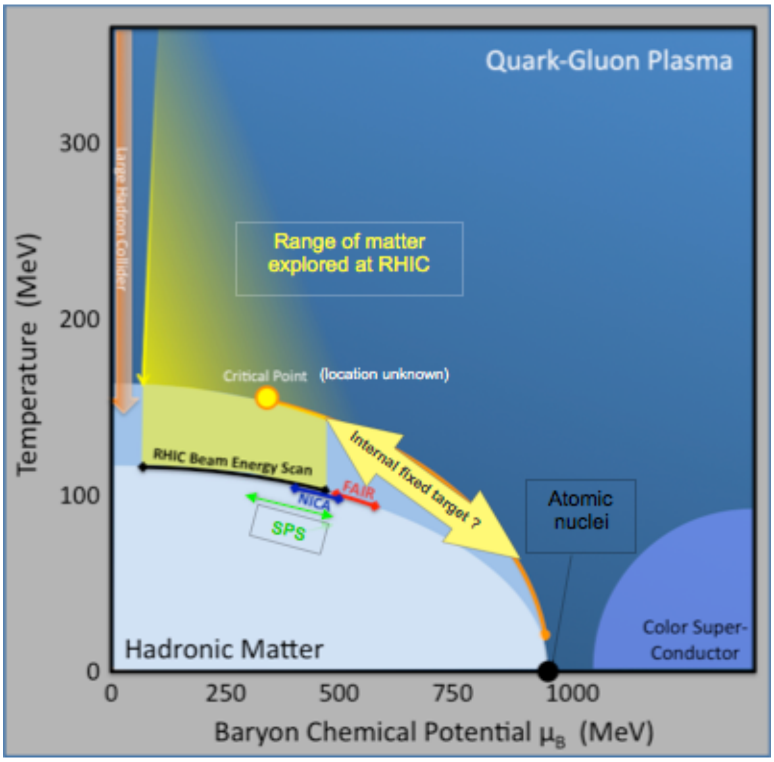

Figure 1: QCD phase diagram showing the range covered by colliding beam and internal fixed target experiments at RHIC.

of silicon vertex detectors (VTX and FVTX in PHENIX, the HFT in STAR), Roman pots and a forward meson spectrometer (FMS) with pre-shower detector in STAR, and the MPS-extension in PHENIX. The new silicon vertex detectors have enabled the direct identification of mesons, and potentially baryons, containing heavy (c and b) quarks. The forward detectors make it possible to measure processes that are sensitive to the parton structure of nuclei at small values at Bjorken x.

2. Recent Results

One of the most exciting recent results from RHIC made use of its ability to collide different collision systems. Following up on indications from p+p and p+Pb experiments at the LHC that a collectively expanding quark-gluon plasma (QGP) may be produced even in collisions creating a hot fireball with the transverse size of a single proton, RHIC explored p+Au, d+Au and ^{3}He+Au collisions at its top energy. Because transverse shape of the collision region is very different in these three systems, with a strong elliptical shape in d+Au and triangular shape in ^{3}He+Au, the elliptical and triangular components of the transverse collective flow field (v_2 and v_3) are differently seeded in these systems. Assuming the formation of a transversely expanding QGP with the same fluid properties in all three systems, unambiguous predictions for the flow components $v_2(p_T)$ and $v_3(p_T)$ can be made. The RHIC data revealed remarkable agreement with these predictions [1] (see Fig. 3), providing strong confirmation of the hypothesis that a QGP with the initial size of a proton behaves collectively as matter.

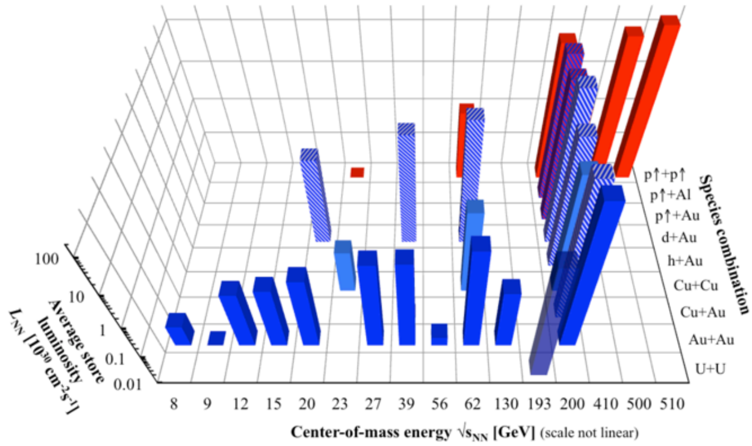

Figure 2: Range of collision systems and center-of-mass energies explored at RHIC with achieved luminosities.

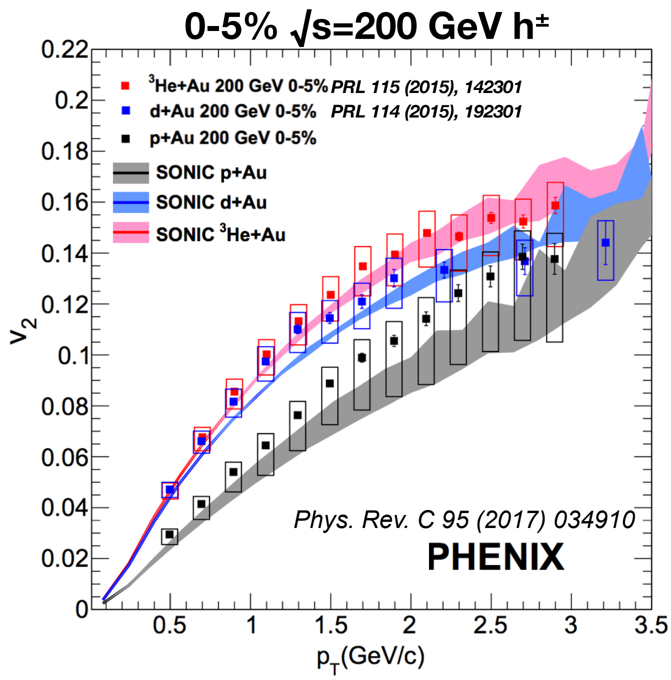

Figure 3: Elliptic flow in p+Au, d+Au and ^{3}He+Au collisions at top RHIC energy in comparison with the predictions of a viscous hydronamics model.

The new vertex detectors in STAR and PHENIX have made it possible to make the first unambiguous measurements of the transport properties of heavy quarks inside the QGP. PHENIX data that separate the contributions from c and b quark semi-leptonic decays to the single electron spectrum show that both contributions exhibit similarly strong suppression at electron transverse momenta above 5 GeV/c, indicating strong energy loss in the QGP even for b-quarks [2]. STAR data (Fig. 4) for the elliptic flow of identified D^0 mesons show a clear presence of collective flow with the same amplitude as for hadrons only composed of light quarks [3].

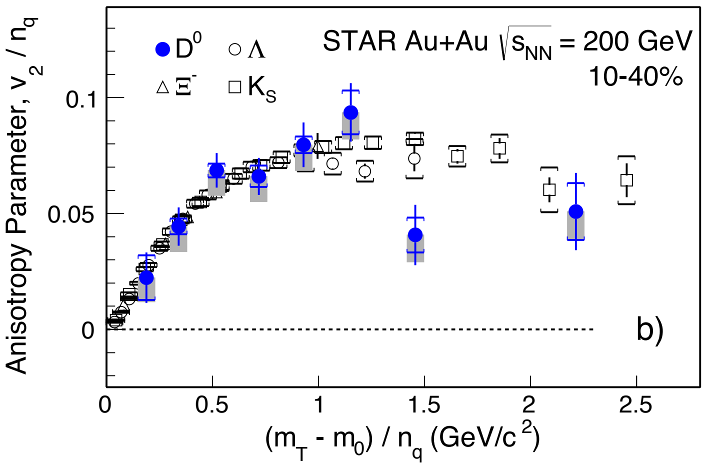

Figure 4: Elliptic flow of D^0 mesons in 200 GeV Au+Au collisions in comparison with elliptic flow measured for hadrons containing light and strange quarks scaled by valence quark number.

Another interesting recent result is the direct measurement of the force between two antiprotons using identical particle correlations in final states by STAR. The relative momentum correlation function between two antiprotons is affected by quantum statistics, Coulomb repulsion, and the nuclear force. Using data from Au+Au collisions, STAR deduced the scattering length f_0 and effective range d_0 between two antiprotons and determined that both parameters agree with those for a pair of protons within statistical errors [4]. Although not unexpected, this is constitutes a remarkable confirmation of the CPT symmetry of nature.

3. Future RHIC Science Program

The scientific program of RHIC over the next 7–10 years is described in the 2015 NSAC Long Range Plan for Nuclear Science [5], which recommended the exploitation of the expanded capabilities of the RHIC detectors in combination with the increased luminosity of the collider. The three-year campaign mainly aimed at measurements of hadrons containing heavy quarks was completed with the 2016 RHIC run. The focus of the 2017 RHIC run will be a sufficiently precise measurement of the Sivers function in transverse polarized p+p collisions to confirm the predicted sign change between gluon exchange contributions in the initial state (observable in deep-inelastic scattering) and contributions involving interactions between the initial and the final state (observable in lepton-pair or W-boson production). Preliminary results from earlier runs indicate that this will be possible with the recently achieved luminosity.

In 2018 it is planned to compare the size of the observed fluctuations in charge asymmetry effects with respect to the collision plane between two isobaric systems differing by four units of the nuclear charge, ^{96}Zr ($Z = 40$) and ^{96}Ru ($Z = 44$). If the fluctuating charge asymmetries observed in Au+Au collisions are caused by *chiral magnetic effects* (CME), as various features of the observed effects indicate, one expects a 14% difference in magnitude between the two system on account of their different nuclear charge, because the CME grows with the square of the magnetic field strength. With 1.2×10^9 recorded events for each system, a CME contribution as small as 6% of the observed effects could be identified. If the CME effect could be unambiguously established, it would not only constitute the discovery of predicted topological gauge field transitions in the QGP, but also provide for a direct observation of chiral symmetry restoration in the QGP.

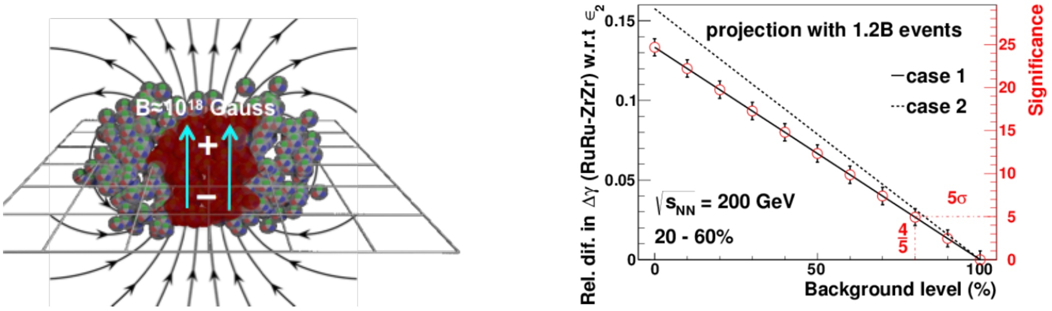

Figure 5: Left: High energy collisions of heavy nuclei create short-lived magnetic fields perpendicular to the collision plane that can drive anomalous electric currents (chiral magnetic effect). Right: Difference in charge asymmetry fluctuations expected in the isobar comparison run as a function of background.

Also in 2018, it is planned to complete the installation of low-energy electron cooling that will increase the achievable luminosity at the lowest RHIC energies (beam energies below 10 GeV per nucleon) by approximately an order of magnitude. In addition, the STAR TPC will be upgraded by fully instrumenting its inner sectors, which will extend its pseudorapidity coverage to $|\eta| \leq 1.6$ and improve particle identification, especially at small p_T. STAR also plans to install a dedicated event plane detector (EPD) that will improve the event plane resolution threefold (see Fig. 6). These upgrades will enable a high statistics beam energy scan (BES-II) covering the range of collision energies in which tantalizing hints of critical fluctuations in the net proton number distribution have been found in the exploratory beam energy scan ($\sqrt{s_{\rm NN}} < 20$ GeV).

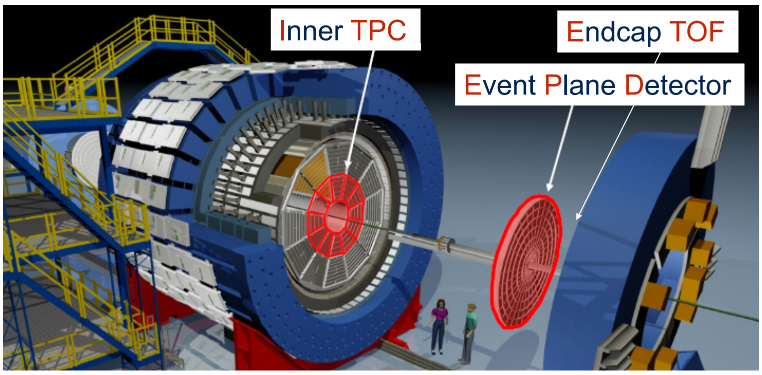

Figure 6: Upgrades of the STAR detector in preparation for the high statistics beam energy scan: Increase in the rapidity coverage of the TPC (iTPC upgrade), event plane detector (EPD), and forward time-of-flight detector (ETOF).

This second beam energy scan will exploit the unique capability of RHIC to explore the high density-high temperature region of the QCD phase diagram where theoretical arguments locate a possible critical endpoint of a first-order line separating the phases of QCD matter with dynamically broken and unbroken chiral symmetry. It is also the region of the phase diagram where the speed of sound reaches a minimum (the "softest point") revealed by a long life-time of the fireball and a minimum in the collective flow. The most model independent signature of a critical point would be a change in sign in the fourth-order cumulant (kurtosis) of the net baryon number fluctuations as the trajectory followed by the system moves from the cross-over region into the first-order transition region. Because only net-proton fluctuations are measurable, which exhibit a much diluted signal, high statistics data will be needed to establish this effect, which is tentatively present in the BES-I data. As shown in Fig. 7, the extended η coverage of the upgraded TPC will also strongly enhance the kurtosis signal, which grows as $(\Delta\eta)^3$.

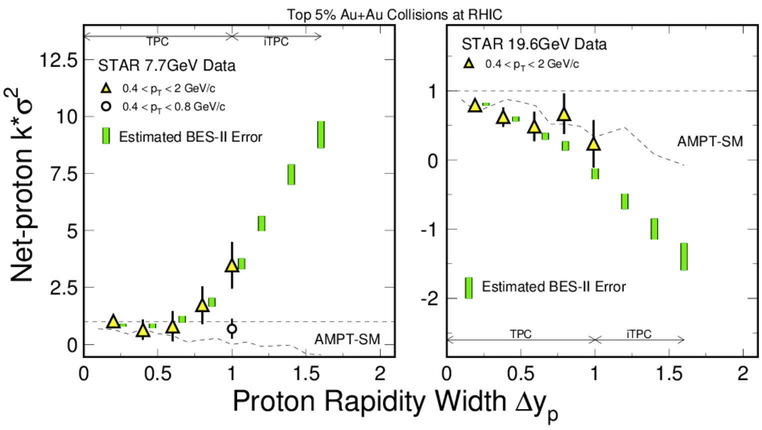

Figure 7: Expected precision of the measurement of the fourth cumulant (kurtosis) of event-by-event net-proton fluctuations over the expanded rapidity range enabled by the STAR iTPC upgrade.

The most ambitious upgrade currently underway at RHIC is the construction of the sPHENIX detector shown in the left panel of Fig. 8. The purpose of the sPHENIX upgrade is to perform high-statistics, high-resolution measurements of fully resolved jet and resolved Upsilon states. The detector will combine electromagnetic and hadronic calorimeters covering the pseudorapidity range $-1 \leq \eta \leq 1$ with charged particle tracking detectors (high-rate TPC, silicon strip detectors, MAPS vertex detector). sPHENIX will be able to sample more than 500 biliion Au+Au collisions per year increasing the kinematic range in p_T of jet and single particle measurements at RHIC by a factor $3-4$ (left panel of Fig. 8). The increased kinematic range will allow for significant overlap with similar measurements at the LHC and thus enable the comparison of medium modifications of hard QCD probes for different initial conditions. sPHENIX will also resolve all three Upsilon bound states enabling a precision study of the medium effects on their production.

The goal of these measurements is to probe the structure of the "perfect fluid" quark-gluon plasma at different scales. Jets probe the medium at a range of length scales below the thermal scale. Precise measurements are expected to map the transition from weakly coupled partonic constituents at the shortest length scales to the composite structures responsible for the hydrodynamic behavior of the quark-gluon plasma at thermal length scales. Upsilon states are sensitive to the color screening in the plasma, which depends on the temperature and thus is expected to exhibit difference between RHIC and LHC.

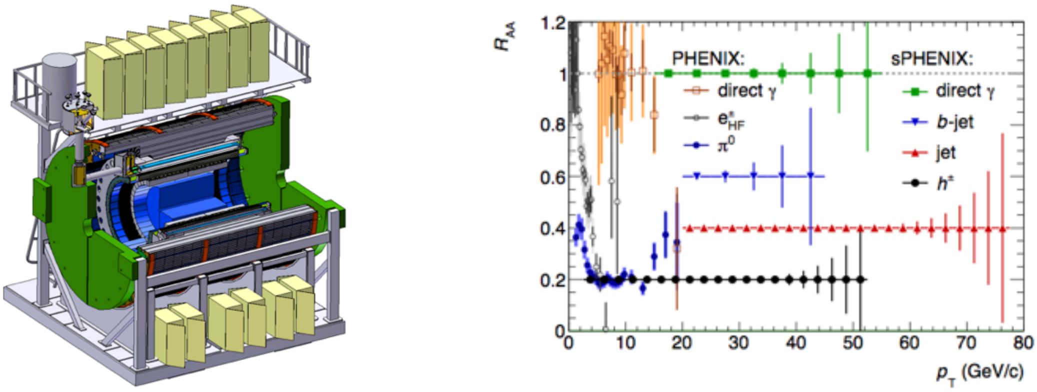

Figure 8: Left: Schematic view of the sPHENIX detector. Right: Kinematic reach of the sPHENIX detector for resolved jet and single particle measurements.

4. Summary and Outlook

Ongoing upgrades to the RHIC accelerator and detectors will enable a series of definitive measurements of properties of the quark-gluon plasma over the coming years. The most exciting among these are high statistics studies of the QGP in the baryon dense region of the QCD phase diagram, which hold the promise of a possible discovery of a critical point, the measurement of anomalous electric current fluctuations that would provide unambiguous evidence for chiral symmetry restoration at high temperature, and investigations of the scale dependent color structure of the quark-gluon plasma using the high rate capabilities of the future sPHENIX detector.

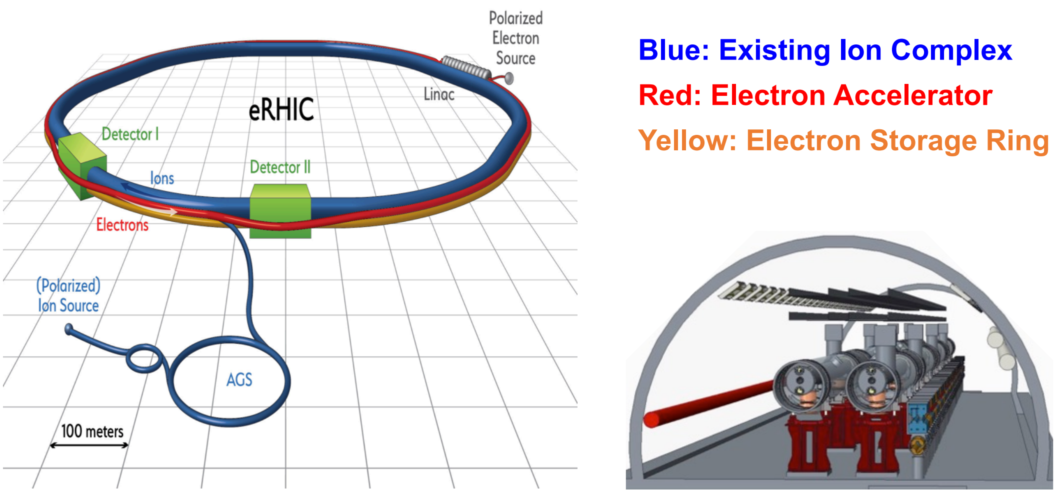

Figure 9: Left: Schematic view of the eRHIC facility. One possible design adds a multi-pass linac electron injector (red) and an electron storage ring (yellow) to the existing hadron physics complex (shown in blue). Right: The electron recirculation rings using the fixed field-alternating gradient concept and the electron storage ring are shown in the RHIC tunnel next to the existing hadron rings.

The next compelling upgrade of the RHIC/AGS accelerator complex would be to add an electron accelerator to convert the RHIC into a polarized Electron Ion Collider (eRHIC). The radius of the existing RHIC tunnel limits the range of reachable electron energies to approximately 20 GeV before synchrotron radiation becomes excessive. Two different design options are under consideration: In the Linac-Ring option, the electrons would be accelerated in a multi-pass superconducting energy recovery linac (ERL) and made to collide only once with the stored ion beam before deceleration. In the Ring-Ring option, the electrons would be stored in a storage ring after acceleration, either in a multi-pass superconducting linac or in a rapid cycling synchrotron. In both cases the maximal center-of-mass energy in e+p collisions would be approximately 140 GeV. Luminosities of order $10^{33}\text{cm}^{-2}\text{s}^{-1}$ can be reached with existing technologies; luminosities in the range of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ or above require strong hadron cooling, which has not yet been demonstrated. The science program such an electron ion collider has been described in the EIC White Paper [6], and the Nuclear Science Advisory Committee (NSAC) has recommended the construction of an EIC as the next major research facility for nuclear physics in its 2015 Long Range Plan [5].

5. Acknowledgments

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