The *2023 Long Range Plan for Nuclear Science*
Heavy Ion Perspective

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Lijuan Ruan, BNL

The 39th Winter Workshop on Nuclear Dynamics,
February 14, 2024

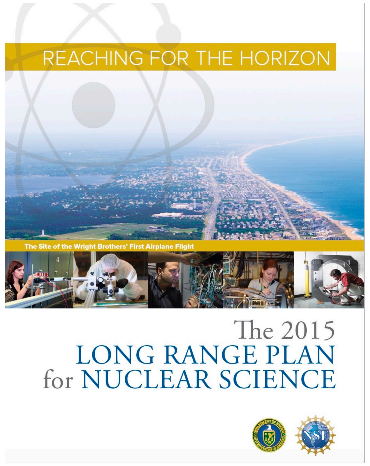
@BrookhavenLab

Successful History of Long Range Planning in Nuclear Science

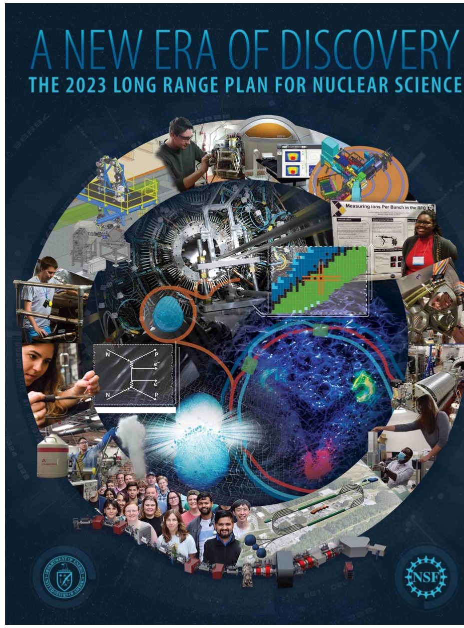
Since 1979 the Department of Energy Office of Science and the National Science Foundation periodically have charged the Nuclear Science Advisory Committee, NSAC, to provide a framework for coordinated advancement of the Nation's nuclear science research program.

- A consistent, strategic plan for investments was developed every 5 – 7 years
- NSAC engaged the community through town meetings organized by the Division of Nuclear Physics of the American Physical Society

2015



2023



Broad Community Input Organized by Division of Nuclear Physics, American Physical Society

2022 Town Hall Meeting on Hot and Cold Quantum Chromodynamics

September 23–25, 2022 Massachusetts Institute of Technology

Conveners:
Bjoern Schenke (Brookhaven National Laboratory)
Anne Sickles (University of Illinois)
Feng Yuan (Lawrence Berkely National Laboratory)
Xiaochao Zheng (University of Virginia)

Website: https://indico.mit.edu/event/538/

Fundamental Symmetries, Neutrons, and Neutrinos Town Meeting

December 13–15, 2022 University of North Carolina at Chapel Hill

Conveners:
Leah Broussard (Oak Ridge National Laboratory)
Vincenzo Cirigliano (University of Washington)
Jon Engel (University of North Carolina at Chapel Hill)
Lindley Winslow (Massachusetts Institute of Technology)

Website: https://indico.phy.ornl.gov/event/209/

NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions, and Astrophysics

November 14–16, 2022 Argonne National Laboratory

Conveners:
Alex Gade (Michigan State University)
Sofia Quaglioni (Lawrence Livermore National Laboratory)
Grigory Rogachev (Texas A&M University)
Rebecca Surman (University of Notre Dame)

Website: https://indico.phy.anl.gov/event/22/

2023 Long Range Plan Working Group Members

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Calvin R. Howell, *Duke University*
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Dean Lee, *Michigan State University*
Shelly Lesher, *University of Wisconsin–La Crosse*
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Jorge Piekarewicz, *Florida State University*
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Xiaochao Zheng, *University of Virginia*

International Observers

Byungsik Hong, Korea University and ANPhA
Marek Lewitowicz, GANIL and NuPECC

RECOMMENDATION 1

The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

RECOMMENDATION 1 requires

- Increasing the research budget that advances the science program through support of theoretical and experimental research across the country, thereby expanding discovery potential, technological innovation, and workforce development to the benefit of society.
- Continuing effective operation of the national user facilities ATLAS, CEBAF, and FRIB, and completing the RHIC science program, pushing the frontiers of human knowledge.
- Raising the compensation of graduate researchers to levels commensurate with their cost of living—without contraction of the workforce—lowering barriers and expanding opportunities in STEM for all, and so boosting national competitiveness.
- Expanding policy and resources to ensure a safe and respectful environment for everyone, realizing the full potential of the US nuclear workforce.

RECOMMENDATIONS 2 and 3

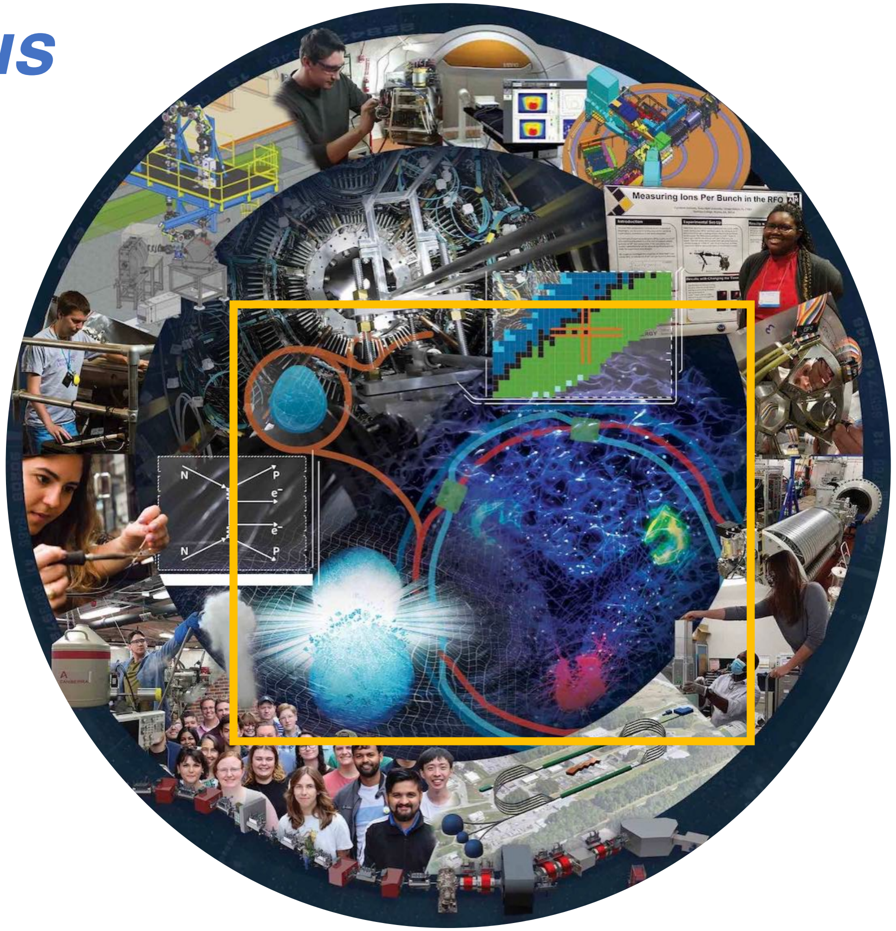
Next, we reaffirm the exceptionally high priority of the following two investments in new capabilities for nuclear physics. The Electron–Ion Collider (EIC), to be built in the United States, will elucidate the origin of visible matter in the universe and significantly advance accelerator technology as the first new particle collider to be constructed since the LHC. Neutrinoless double beta decay experiments have the potential to dramatically change our understanding of the physical laws governing the universe.

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

RECOMMENDATION 3

We recommend the expeditious completion of the EIC as the highest priority for facility construction.



RECOMMENDATION 4

We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Strategic Opportunities

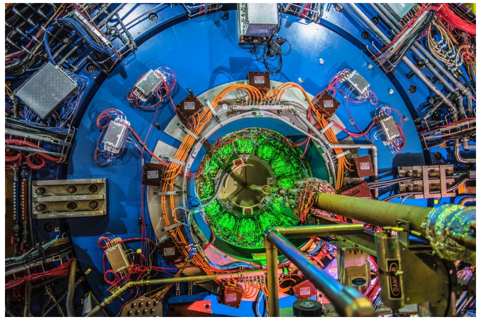
- Projects that lay the foundation for the discovery science of tomorrow
  - Examples: FRIB400, SoLID, LHC upgrades, EDM, ν mass measurements
- Detector and accelerator R&D
- Emerging technologies: computing and sensing
  - Quantum information science and technology
  - Artificial intelligence and machine learning
  - High performance computing
- Multidisciplinary centers
- Nuclear data

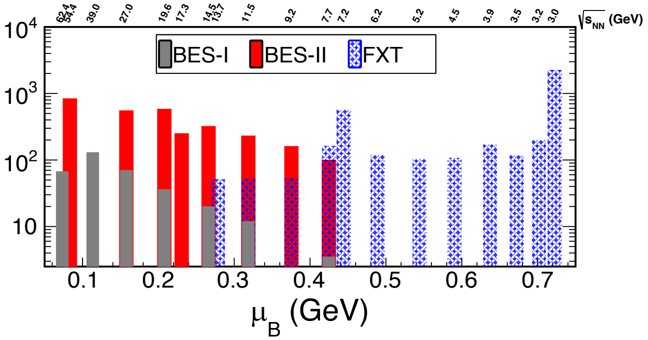
Progress since last LRP

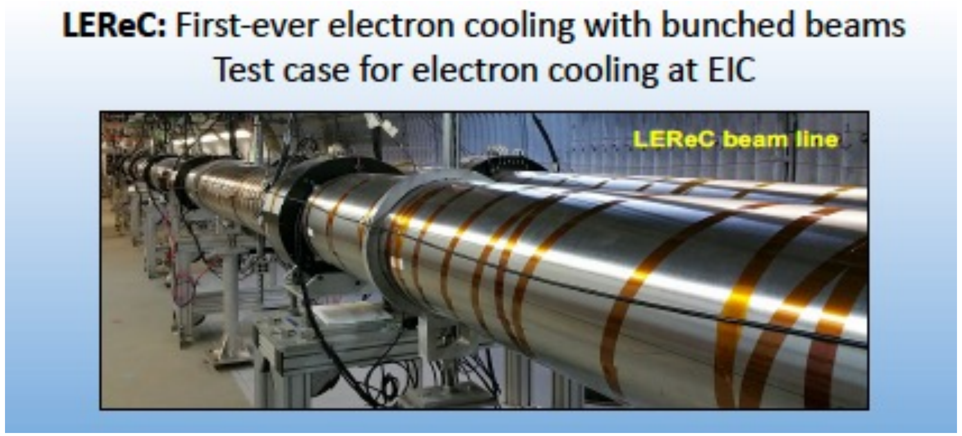
In 2015 LRP:
“There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.”**

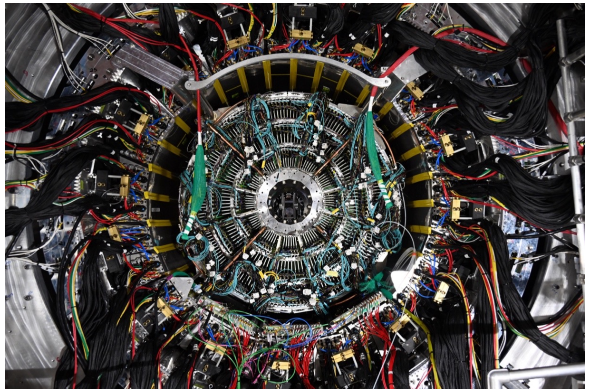
- STAR completed Beam Energy Scan (BES) data collection that benefited from Low Energy RHIC electron Cooling (LEReC)

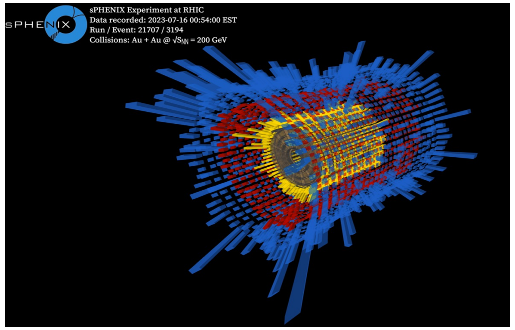
- Completed sPHENIX construction and installation, sPHENIX commissioning with RHIC beams started in Run 2023











Progress since last LRP

- Discovery of Breit-Wheeler process, vacuum birefringence, quantum interference enabled nuclear tomography to extract strong-interaction nuclear radii
- Observation of flow-like signatures in small-sized systems
- Observation of global Lambda hyperon polarization in nuclear collisions: evidence for the most vortical fluid
- Achieved the most precise measurement of any heavy ion collisions experiments in search of chiral magnetic effect with isobar collisions
- Stringent constraints of jet quenching with jet-substructure measurements
- Observation of baryon enhancement in the heavy flavor sector
- Observation of sequential Upsilon suppression
- …

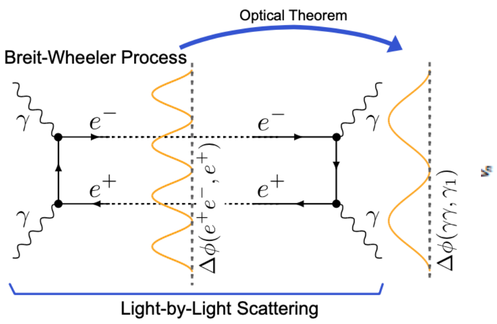
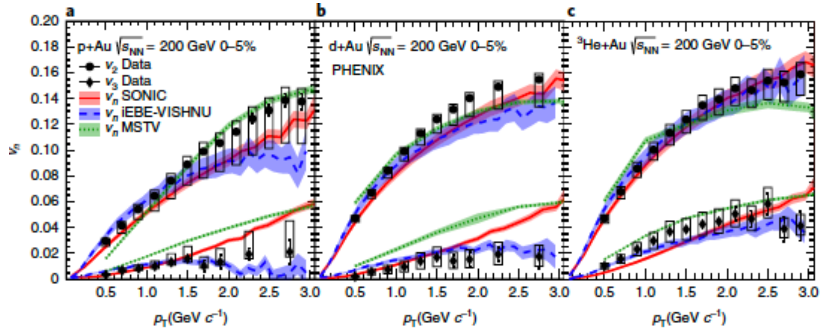
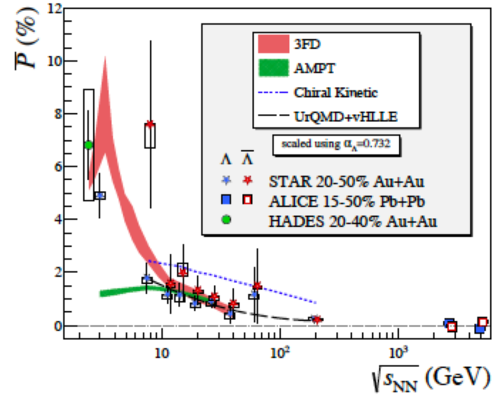
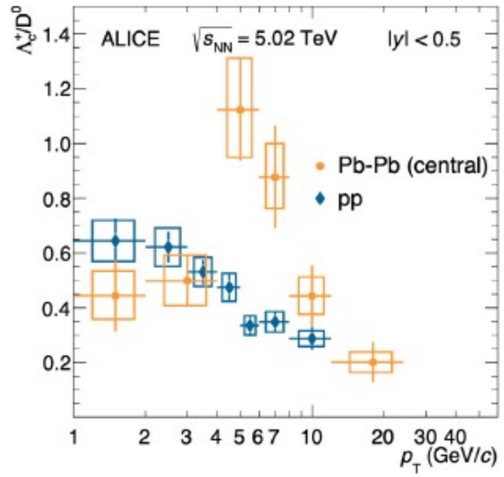
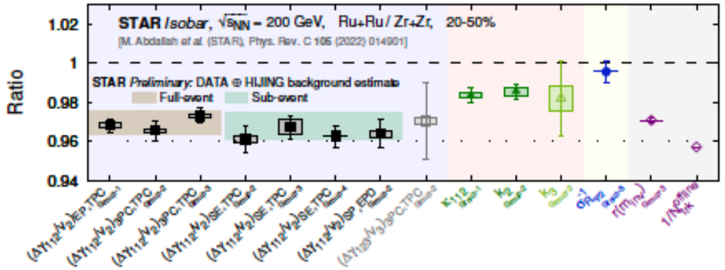


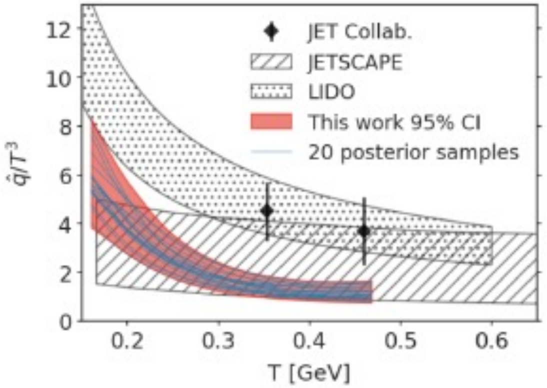
FIG. 1. A Feynman diagram for the exclusive Breit-Wheeler process and the related Light-by-Light scattering process illustrating the unique angular distribution predicted for each process due to the initial photon polarization.

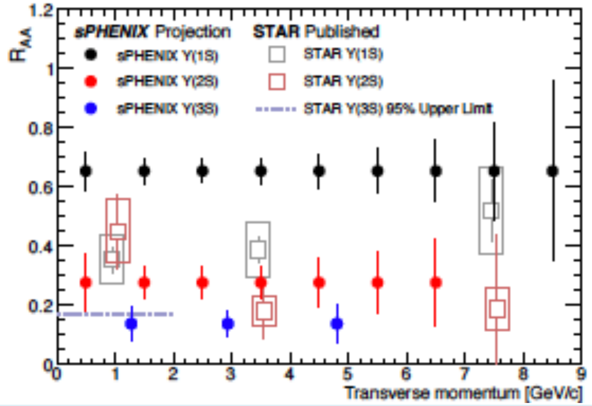






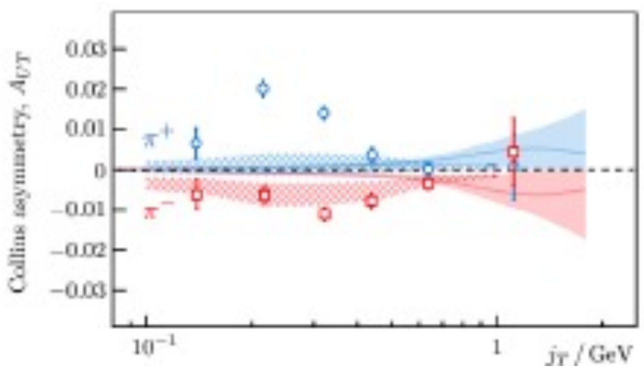


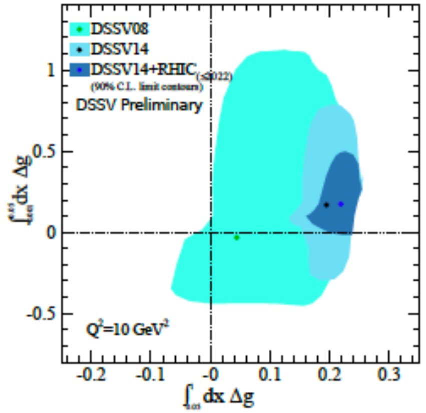


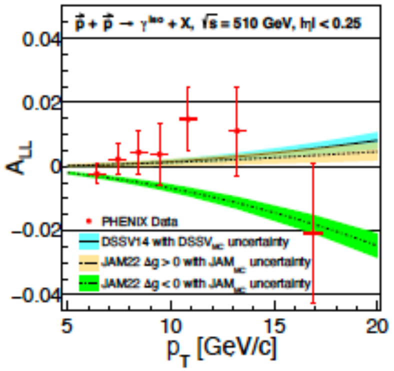


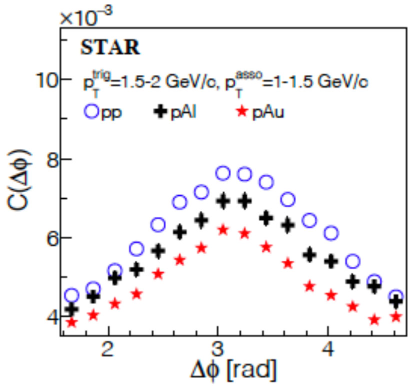
Progress since last LRP

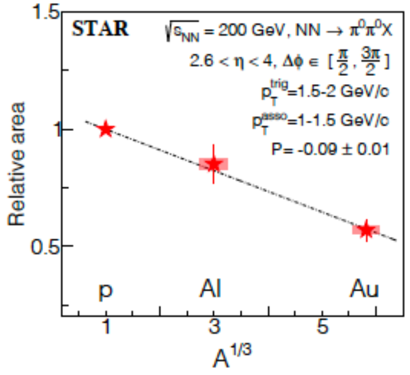
- Observation of a nonzero spin-momentum correlation in hardon production in jets with transversely polarized proton-proton collisions
- Established gluons’ helicity contribution to the proton spin, and they align in the same direction as that of the proton spin
- Improved the constraints on ubar and dbar polarization
- Observed non-linear QCD effect in di-hadron correlations
- …

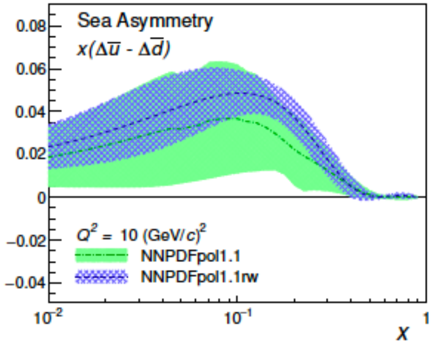












Impact of 2023 Long Range Plan – hot QCD

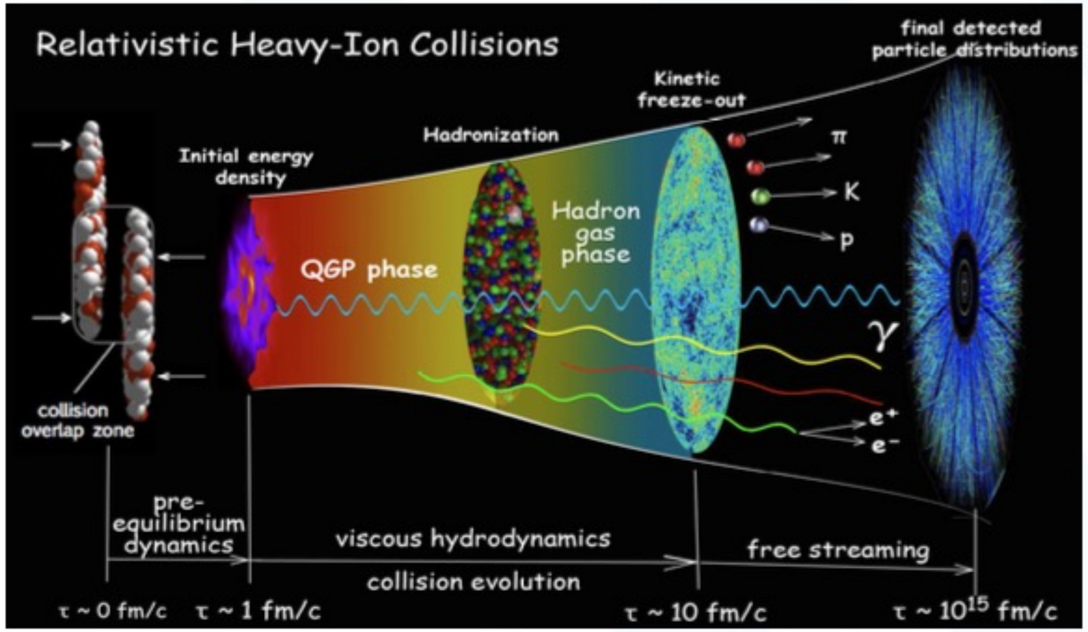
Our vision for the future builds on the ongoing, world-leading US program in nuclear science, which includes exploring the nature of quark–gluon matter and the spin structure of the nucleon at the RHIC facility and through leadership across the heavy ion program at the Large Hadron Collider (LHC).

In the highest priority, there is a special shout out to completing the RHIC science program.

Strategic opportunities include targeted upgrades for the LHC heavy ion program.

Essential questions:

1. How do the fundamental interactions between quarks and gluons lead to the perfect fluid behavior of the quark-gluon plasma?
2. What are the limits on the fluid behavior of matter?
3. What are the properties of QCD matter?
4. What is the correct phase diagram of nuclear matter?



High temperature frontier

The newly built sPHENIX detector and upgraded STAR detector at RHIC, together with increased luminosity at the LHC and upgraded ALICE, ATLAS, CMS and LHCb detectors, will enable a multi-messenger era for hot QCD based on the combined constraining power of low-energy hadrons, jets, electro-magnetic radiation, heavy quarks, and exotic bound states.

Successful theory collaborations offer breakthroughs in the next decade. State-of-the-art numerical simulations, assisted by ML techniques, will provide quantified uncertainties on the viscosities, jet transport coefficients, and other properties of this novel plasma and their dependence on temperature.

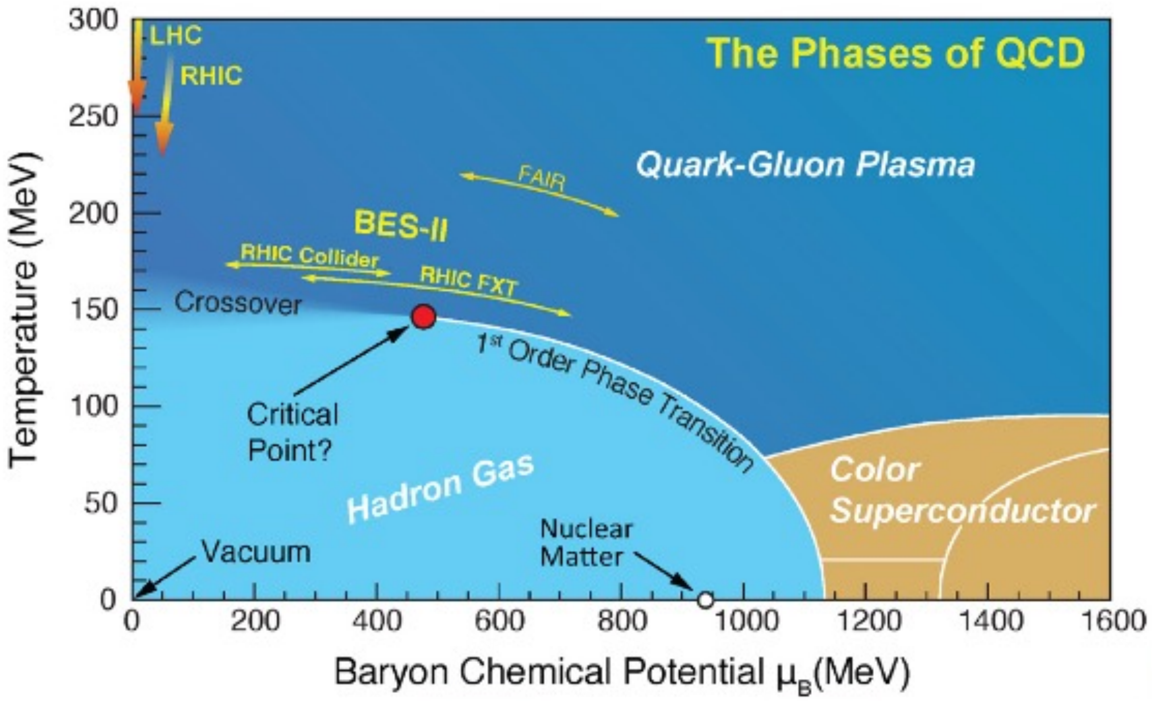
High baryon density frontier

Lattice QCD: crossover chiral transition at $\mu_B < 2$ T

At top RHIC and LHC energies, measurements consistent with a smooth crossover chiral transition

RHIC Beam Energy Scan Phase I (BES-I) measurements imply the QCD critical point, if exists, should be accessible in the center of mass energy region 3-20 GeV

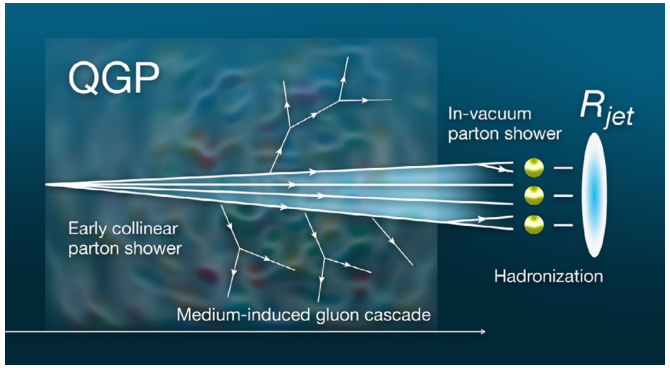
BES-II data taking (energy range 3 - 19.6 GeV) completed in 2021, physics analyses under active pursuit need to be completed

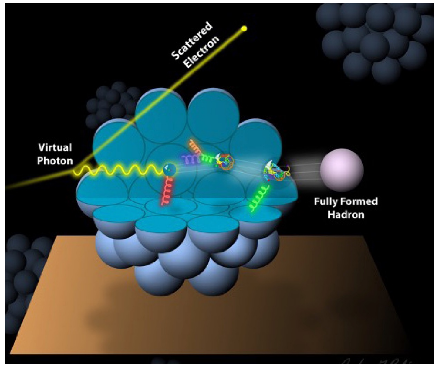


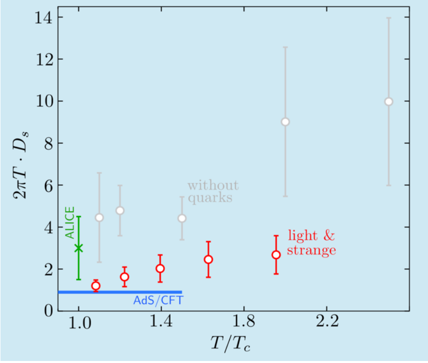
Future experiments, such as CBM at FAIR in Germany will provide additional high statistics and high-resolution data for low-energy collisions and high μ_B

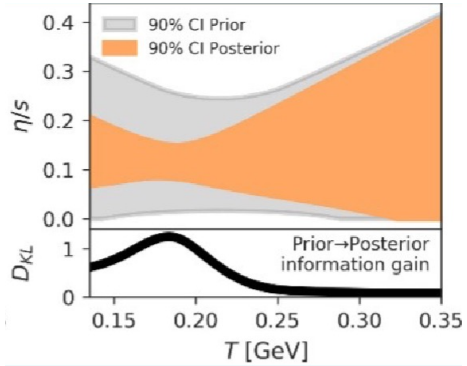
Impact of 2023 Long Range Plan

- Nuclear Theory and computing are well represented in the 2023 LRP:
  - Recommendation 1: "***Increas[e] the research budget that advances the science program through support of theoretical and experimental research across the country, […]"***
  - Recommendations 2 and 3 highlight the importance of theory. Recommendation 3: ***"To achieve the scientific goals of the EIC, a parallel investment in […] QCD theory is essential, as recognized in the 2018 NAS report. […] To maximize the scientific impact of the facility and to prepare for the precision expected at the EIC, theory must advance on multiple fronts, and new collaborative efforts are required."***
  - Recommendation 4 discusses QIS, AI/ML, nuclear data, and HPC. It states: ***"As we enter the era of exascale computing, with increasing numbers of communities within nuclear physics poised to take advantage of HPC, enhanced support will maximize scientific progress."*** and calls out SciDAC.
  - Theory is highlighted throughout the science chapter. Among others, sidebars feature jet evolution in the medium, hadronization, lattice QCD (hot and cold), and the need for complex modeling frameworks









Impact of 2023 Long Range Plan

- The EIC Science Chapter (Ch. 3.4) discusses the proposed EIC Theory Alliance:
  "EIC theory includes many interdisciplinary components best addressed through a broad alliance." […] "The EIC-TA will raise the visibility of EIC-related theory and obtain the resources needed for adequate support of the EIC, including for workforce development. The long timeframe of EIC construction (>10 years), combined with the prospect of decades of operation, requires a strategic plan to ensure a robust program is in place. Targeted funding of a theory alliance, in addition to the base theory funding, throughout the lifetime of the facility, is an excellent way to achieve these goals."

- There is a dedicated Theory Chapter (Ch. 7). Some of its main points include:
  - **"The core nuclear theory program as implemented at universities and national laboratories is the mainstay of the entire theory effort."** reemphasizing Recommendation 1 for increasing the research budget.
  - Bringing theorists together: A section that calls out Topical Collaborations, the INT, EIC Theory alliance
  - Section on QIS, AI/ML and HPC and connection to theory
  - Section on growing the **workforce**: Apart from a "Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) Theory Consortium" and a "Nuclear Physics Quantum Connection", it mentions the EIC Theory Alliance again, saying ***"A timely investment in an EIC theory alliance, unifying these research areas, creating theory fellow and bridge permanent positions at universities to allow for graduate student training, expanding the efforts on EIC theory beyond national laboratories, would accelerate the pace of discovery."***

Workforce

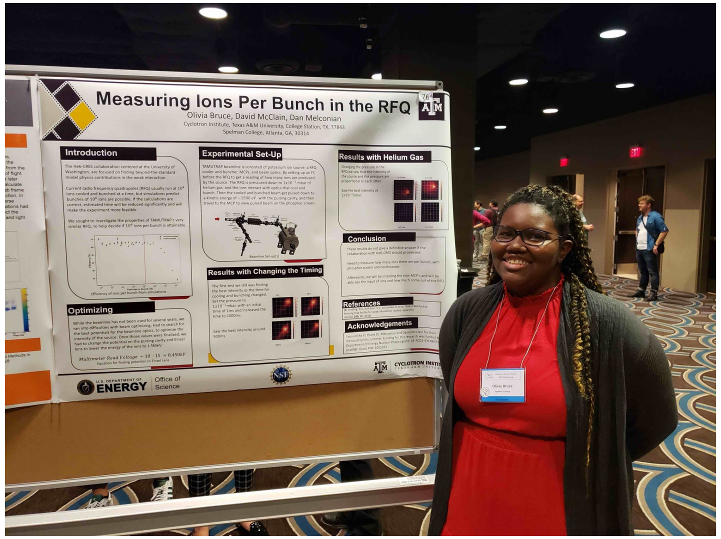
People are essential to accomplishing the goals in all areas of physics described in the Long Range Plan.

Programs such as the NSF REU and DOE SULI are essential to attracting talented students to nuclear science.

Central to our proposals is the necessity to reduce barriers to participation in nuclear science.

Our community is committed to establishing and maintaining an environment where all feel welcome and are treated with respect and dignity.

The training our students receive is very valuable in industry, national labs, and in critical areas of national need, such as nuclear nonproliferation and security

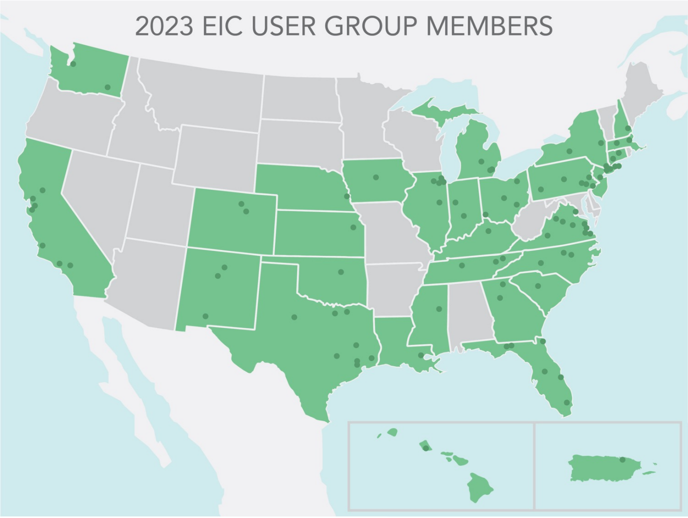


EIC Network for Discovery Science and Workforce Development

An EIC network would empower discovery science at the EIC while strengthening and building nuclear physics research at U.S institutions, especially those with limited research capacities, and supporting training of a STEM workforce for the nation from a broad pool of talent.

The network promotes partnerships between U.S. national labs and universities and supports students and postdoctoral fellows. The network would promote collaborations between experimentalists and theorists, organize traineeships, and provide mentoring and career development programs for students and postdocs.

In addition to discovery science, the nation benefits from a highly skilled STEM workforce for advances in fields such as energy, environment, health, and national security.



We deeply appreciate the enormous efforts and enthusiasm from the community.

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Observation of $0\nu\beta\beta$ would mean that the neutrino is its own antiparticle.

It would also mean that lepton number is not conserved.

It would mean that matter can be created and help explain why the universe has more matter than antimatter.

The rate of $0\nu\beta\beta$ has implications for neutrino masses.

Regular beta decay:

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

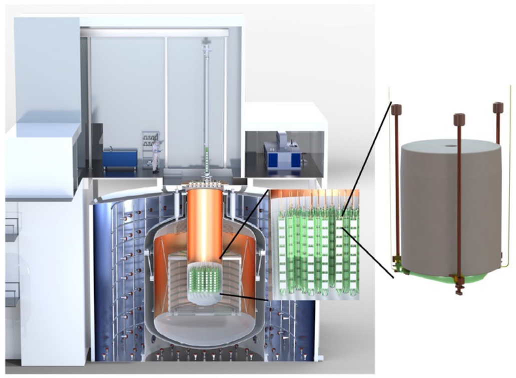
Double beta decay (DBD):

$$2n \rightarrow 2p + 2e^{-} + 2\bar{\nu}_e$$

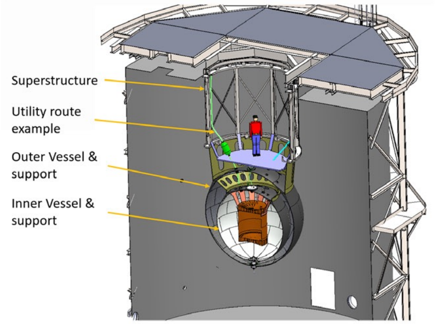
Neutrinoless DBD:

$$2n \rightarrow 2p + 2e^{-}$$

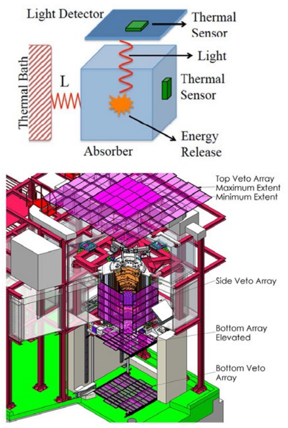
Major discovery potential!



LEGEND



nEXO



CUPID

The Electron-Ion Collider

Polarized electrons colliding with polarized protons, polarized light ions, and heavy ions will allow us to study sea-quarks and gluons to understand:

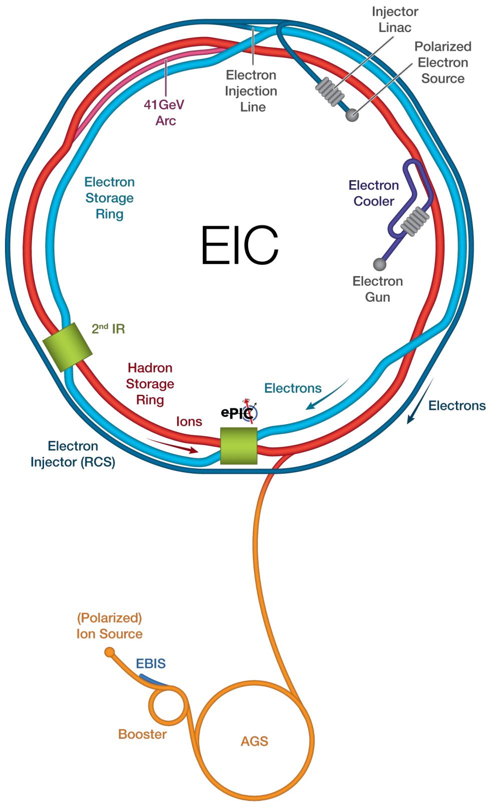
- mass and spin of the proton.
- spatial and momentum distribution of low-x partons
- Possible gluon saturation
- modifications of parton distribution functions when a nucleon is embedded in a nucleus
- hadron formation

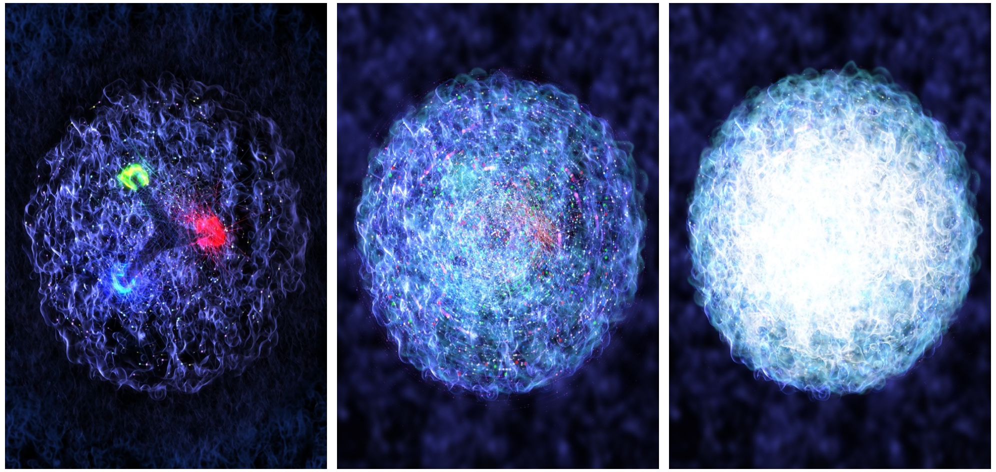
The EIC is a partnership between BNL and Jefferson Lab.

Project is aiming for CD2/3 in 2025

ePIC detector design is advanced. Significant international support and participation (160+ institutions, 24 countries).

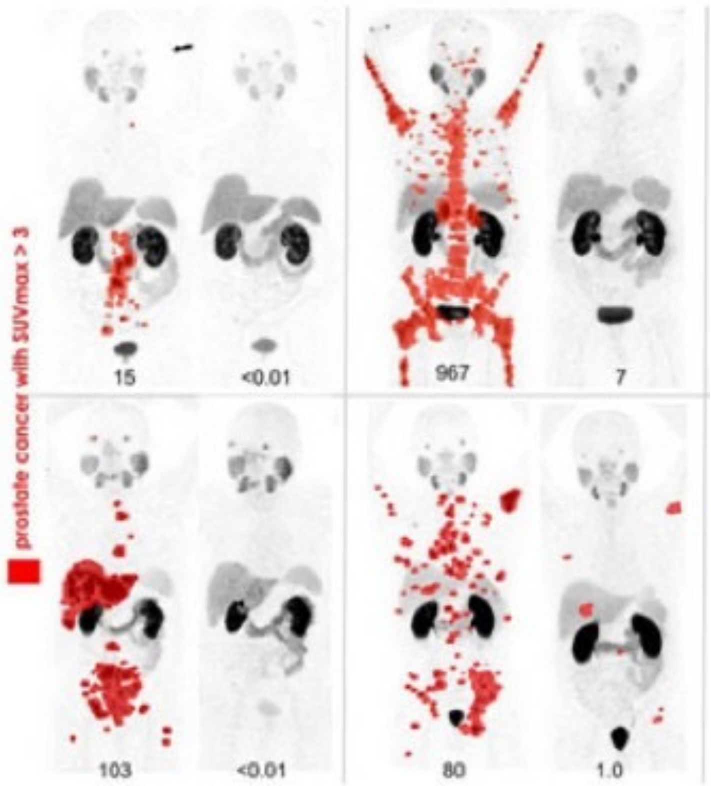
Major discovery potential!





Benefits to the nation

- Synergy and impact on other fields, such as high energy physics, astrophysics and cosmology, accelerator science, atomic physics, condensed matter physics …
- Trained nuclear workforce, affects many fields, including nuclear security, isotope production for medical and other needs
- Applications: energy, health care, environmental issues, radiation hardening for electronics, improved particle detection for homeland security
- Development of computational techniques



PET images using gallium-68 before (left) and after (right) treatment of prostate cancer with lutetium-177-PSMA-617