Recent Results from Relativistic Heavy Ion Collider (RHIC)

Outline

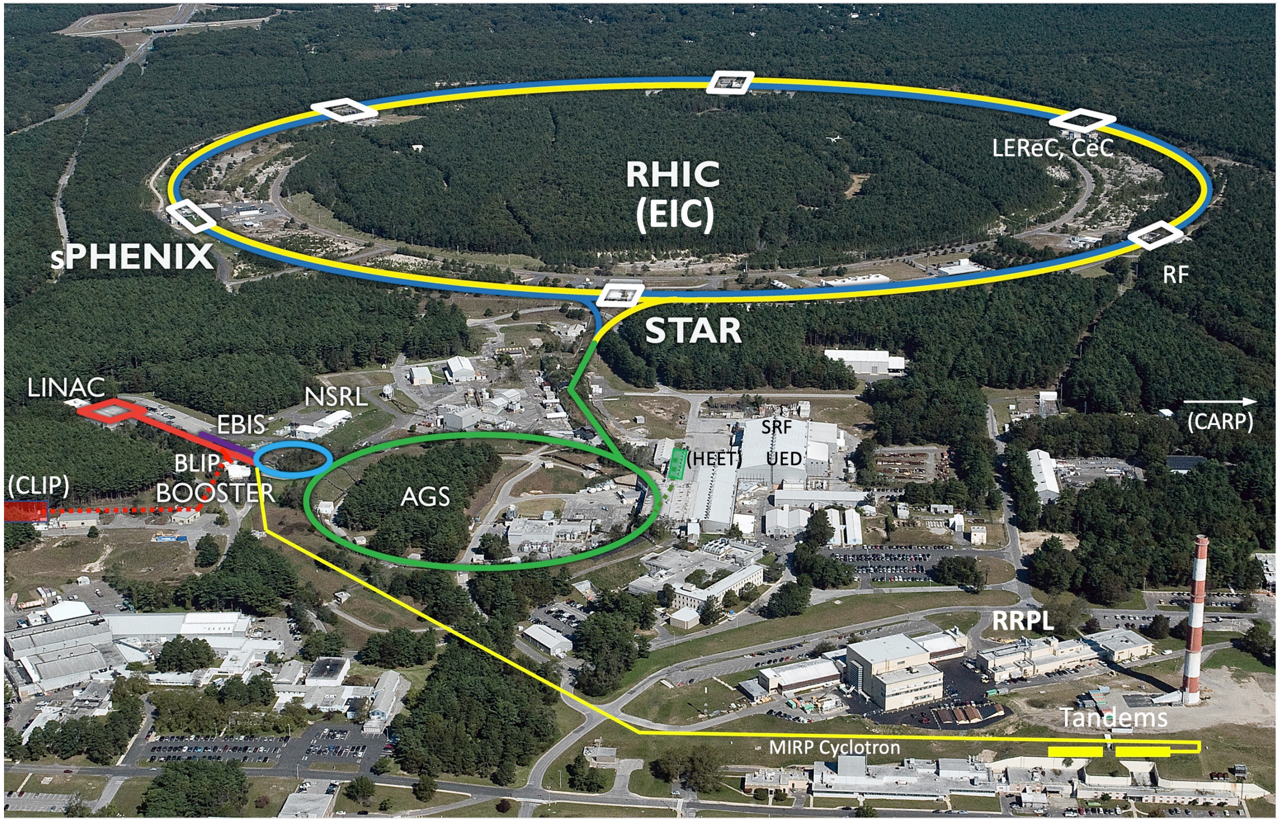
- Introduction of RHIC Complex and Applications program
- Highlights of RHIC hot and cold QCD results
- Completing the RHIC science mission
- Summary

Haiyan Gao

Nuclear and Particle Physics, BNL

September 5-9, QNP 2022

Relativistic Heavy Ion Collider (RHIC) Complex

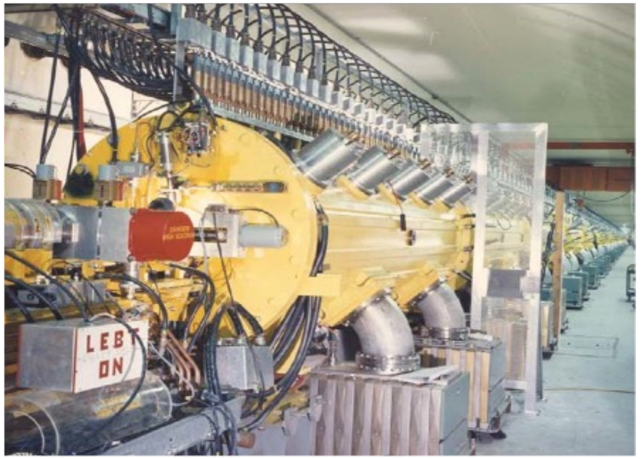


- ➢ Uniquely flexible and only hadron collider in the United States for exploration of QCD phase diagram and proton spin
- ➢ Injectors also used for application programs
  - Linac/BLIP for isotope production
  - Booster/NSRL for space radiation studies
  - Tandem for industrial/academic users
- ➢ R&D for future facilities and application (sources, cooling, pol. beams, …)

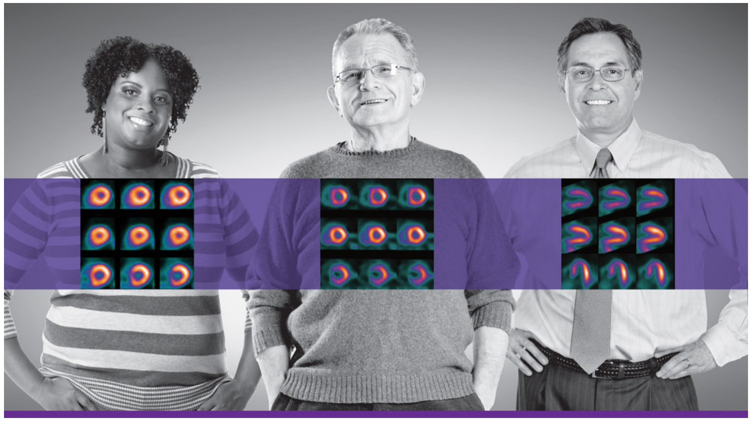
Brookhaven Linac Isotope Producer (BLIP)

50th anniversary

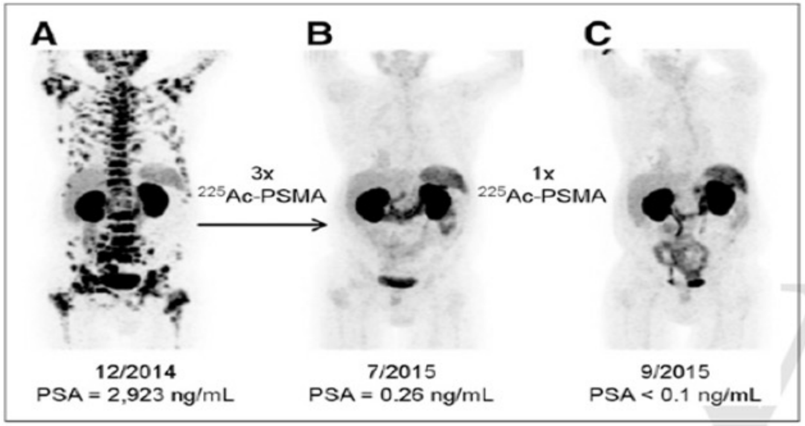
Official Use Only



- Target irradiation with 116 – 200 MeV, 160 mA proton beam
- Production of medical radio-isotopes for U.S.:
  - Mainly Sr-82, shared between LANL and BNL
  - R&D of new radio-isotopes for diagnosis and therapy (Ac-225, needs ~ 200 MeV protons)
- Significant expansion is underway:
  - BLIP target and proton beam intensity upgrades
  - Refurbishment of additional hot cells for Ac-225 processing
  - Bringing up a low-energy Cyclotron for supplying radionuclides currently available only from foreign suppliers, and an alternative Ac-225 production route with radium targets (Ac-225 without Ac-227 contamination)



Sr-82: coronary artery disease diagnosis, used under rest and stress conditions



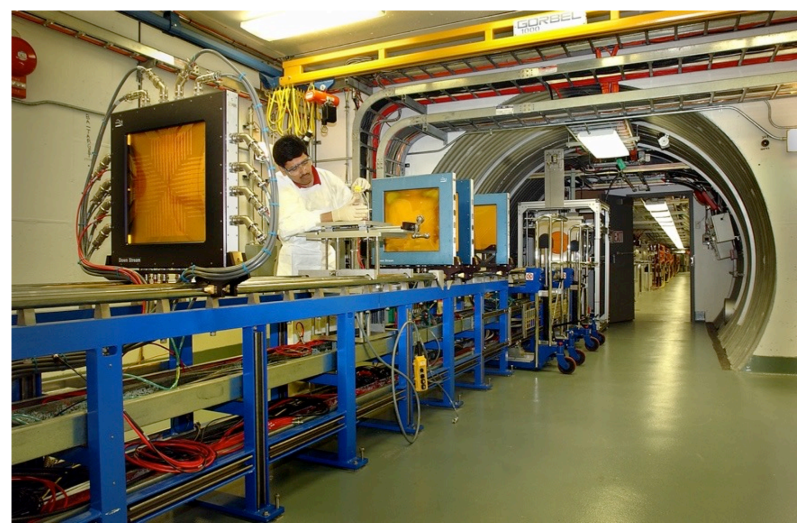
Ac-225: Alpha emitter for treatment of metastatic prostate cancer

Brookhaven National Laboratory

NASA Space Radiation Laboratory (NSRL)

- Started in 2003, simulates galactic radiation for human space flight
  - Heavy ion beams from AGS Booster
  - Electron Beam Ion Source (EBIS) provides all necessary ion beams
  - New laser ion source for EBIS allows for rapid species switching to simulate energy and species spectrum of deep space radiation field

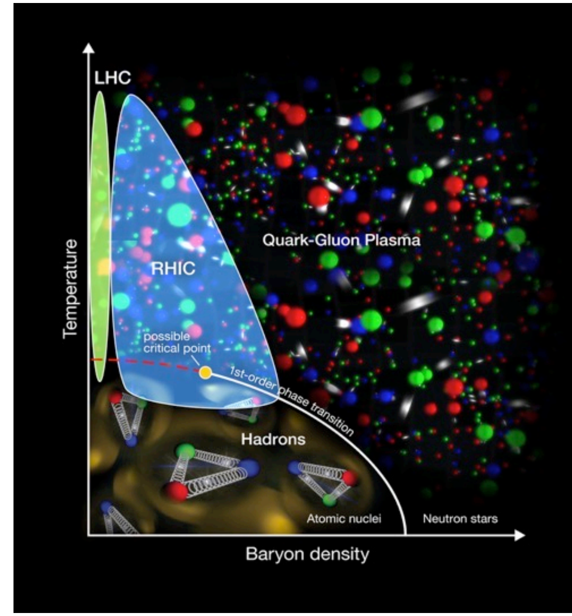
- Additional uses of NSRL
  - **Radiation effects studies (rapidly growing demand for satellite electronics testing)**
  - R&D of ion beam cancer treatment
  - Agreement with NASA in place for non-NASA users ("non-designated user facility")

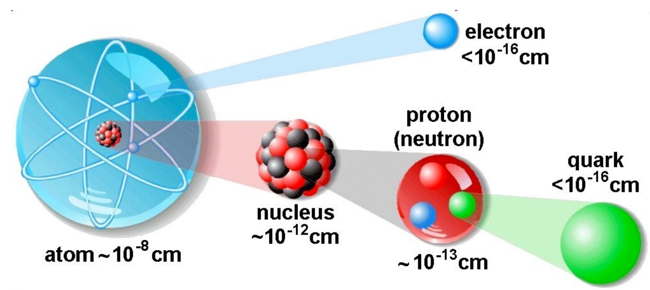


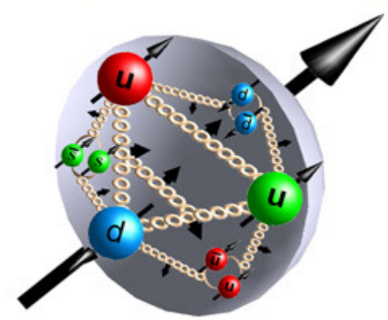
Brookhaven National Laboratory

RHIC – a Unique Research Tool

- Heavy ion collisions
  - Explore new state of matter: Quark Gluon Plasma
  - Highest collision rates and collide many different ion species
- Polarized proton collisions
  - Only collider of spin polarized protons to explore the internal spin structure of protons.
  - Gluons carry part of proton spin







Brookhaven National Laboratory

Quark-gluon plasma as "perfect liquid" discovered at RHIC

25

The News of the QGP Hit the Streets

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

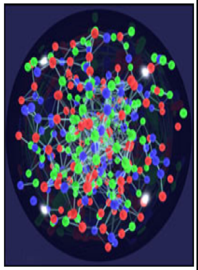
The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms. BBC NEWS

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.



The impression is of matter that is more strongly interacting than predicted

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

Early Universe was a liquid

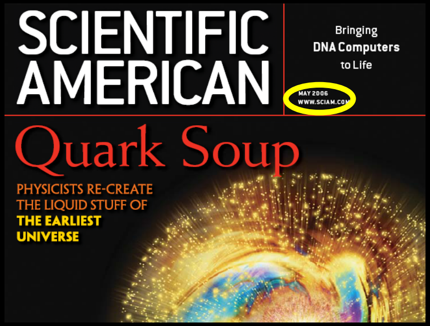
Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

nature

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.



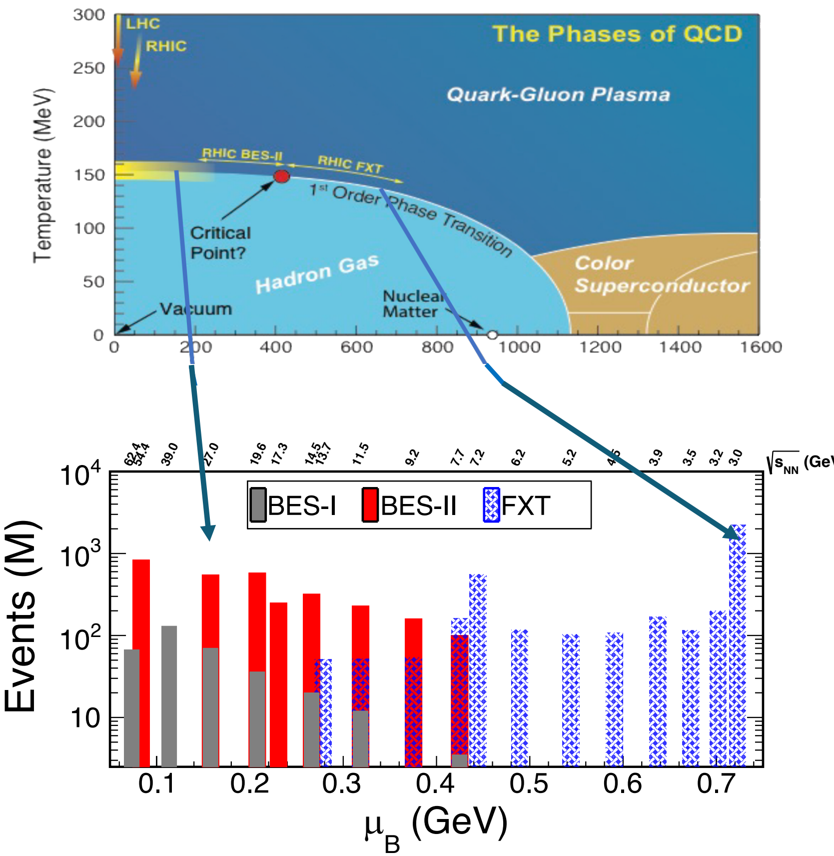
John Harris (Yale) | 20th Anniversary of RHIC | BNL-Online, June 12, 2020

Brookhaven National Laboratory

RHIC in the 2015 NSAC Long Range Plan

"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."**

LEReC = Low Energy RHIC electron Cooling
First-ever electron cooling with bunched beams
Test case for electron cooling at EIC



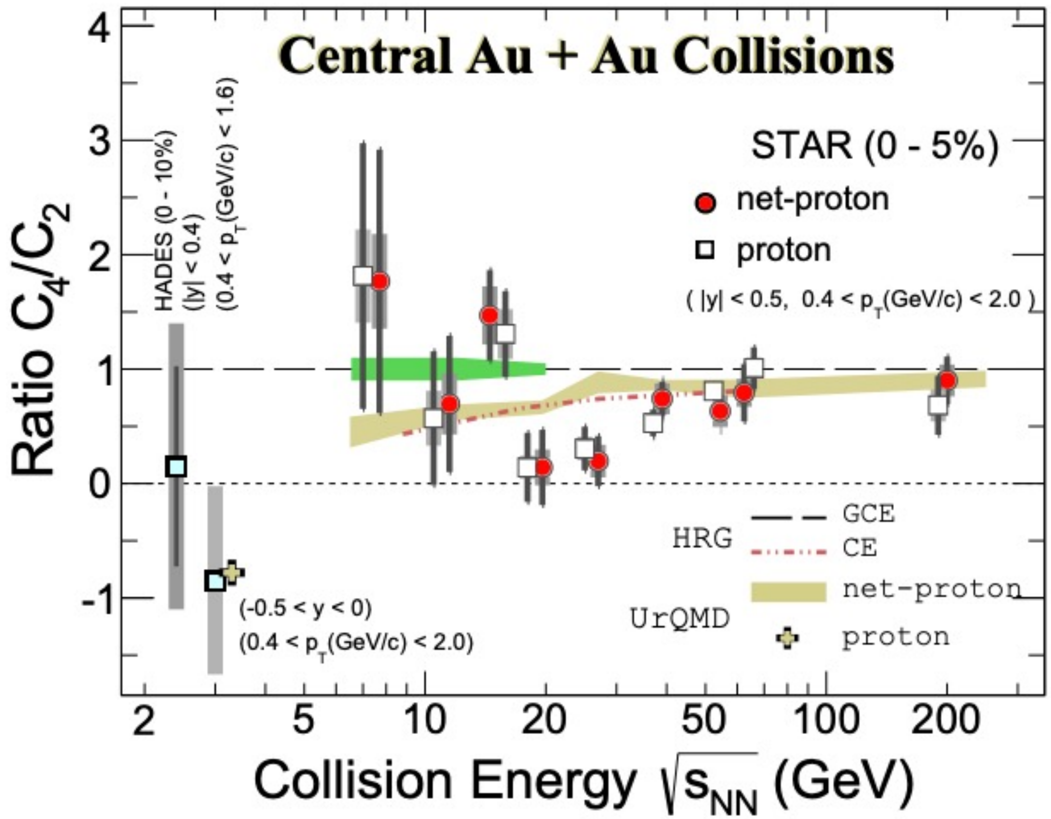
Beam Energy Scan

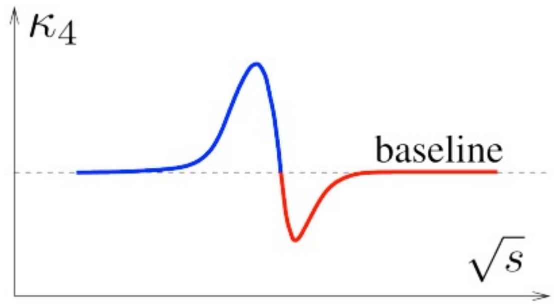
- What is the phase boundary of ordinary nuclear matter?
- Is there a critical point in the QCD phase diagram? If so, where?

BES-2 Completed as of June 7, 2021!

Brookhaven National Laboratory

Energy Dependence of (Net-) Proton High Moments



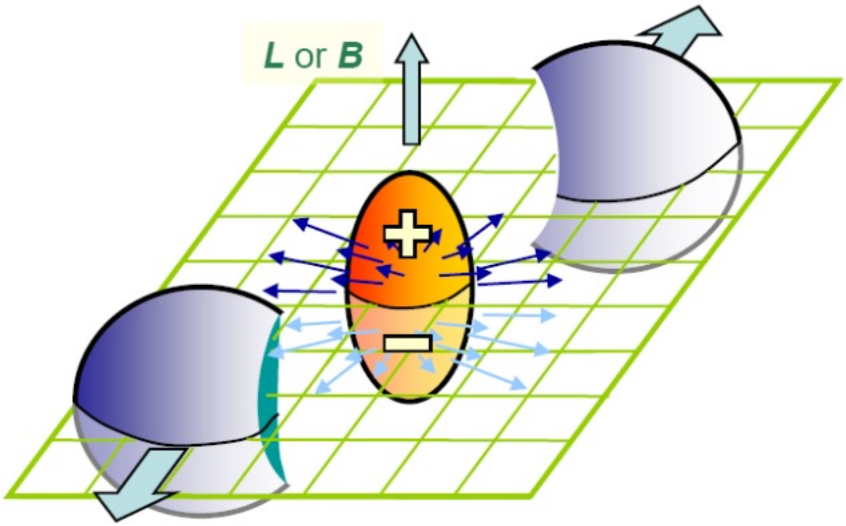


- Non-monotonic energy dependence in central Au+Au collisions (3.1σ)
- Strong suppression in proton C_4/C_2 at 3 GeV
  - *consistent with UrQMD hadronic transport model calculation*

BES-I: PRL 126 (2021) 092301
3 GeV data: PRL 128 (2022) 202303

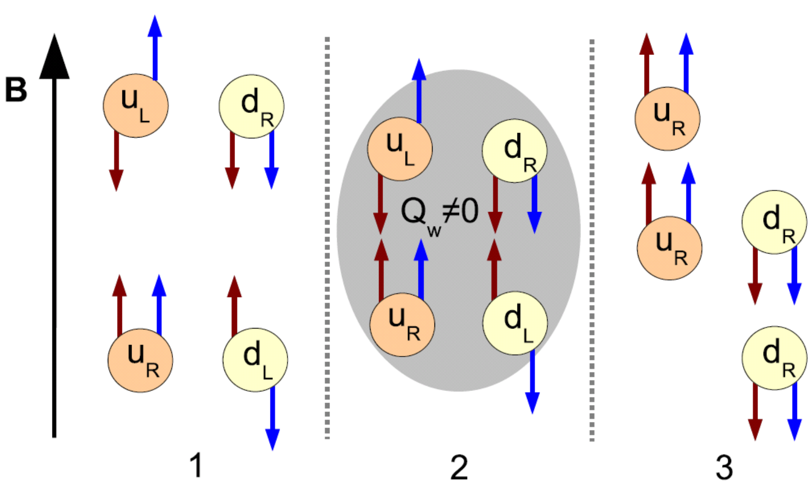
BES-II data collected at RHIC cover a broad and interesting range of μ_B for the critical point search

Chiral Magnetic Effect



Non head-on heavy ion collisions generate large magnetic field (peaked at 10^{15} T)

In QGP, massless quark interactions with gluon-field topological charge leads to chiral imbalance (non-zero μ_A)



charge separation caused by anomaly induced chiral imbalance and large magnetic field

$$\vec{J}_V = \frac{eN_C}{2\pi^2}\mu_A \vec{B}$$

D. Kharzeev

Brookhaven National Laboratory

Blinding Analysis of CME Search with Isobar Data

Mock data challenge
Test data structure
(27 GeV files)

Isobar-Mixed Analysis
QA, physics & code freezing
(One run is Ru+Zr)

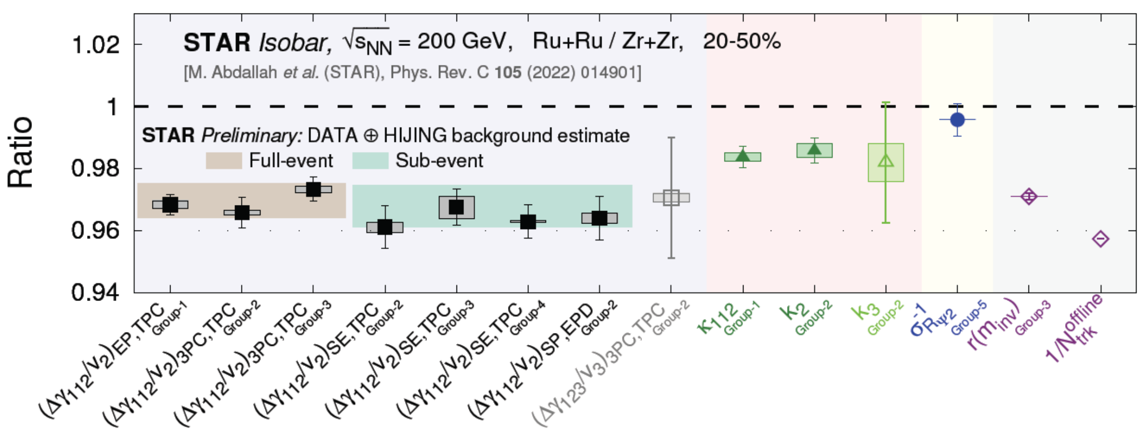
Isobar-Blind Analysis
Run-by-run QA, full analysis
(One run is Ru/Zr)

Isobar-Unblind Analysis
Full analysis
(Ru and Zr separated)

→ **Publication of Blind Analysis**

STAR, PRC 105 (2022) 014901

Pre-defined signature of CME: $\dfrac{\langle \text{Observable} \rangle_{\text{Ru+Ru}}}{\langle \text{Observable} \rangle_{\text{Zr+Zr}}} > 1$



Updated estimate on non-flow combining data/HIJING consistent with isobar data of $\Delta\gamma/v_2$

Hints of signals in Au+Au 200GeV:
PRL 128 (2022) 092301
arXiv: 2006.05035

Discoveries of Breit-Wheeler process and vacuum birefringence

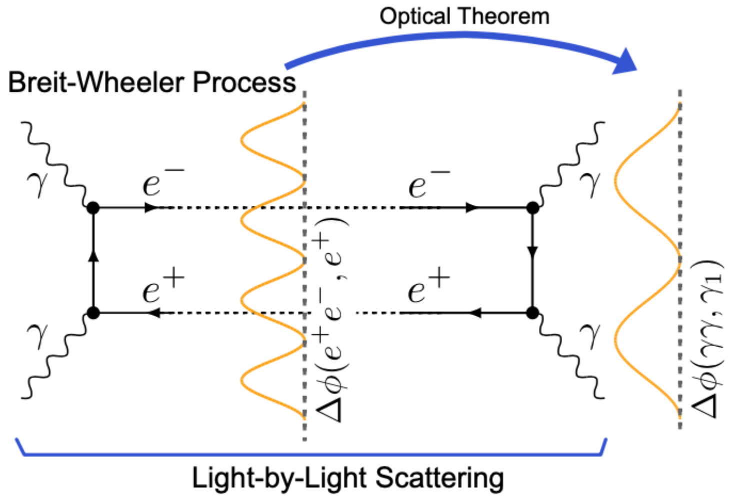
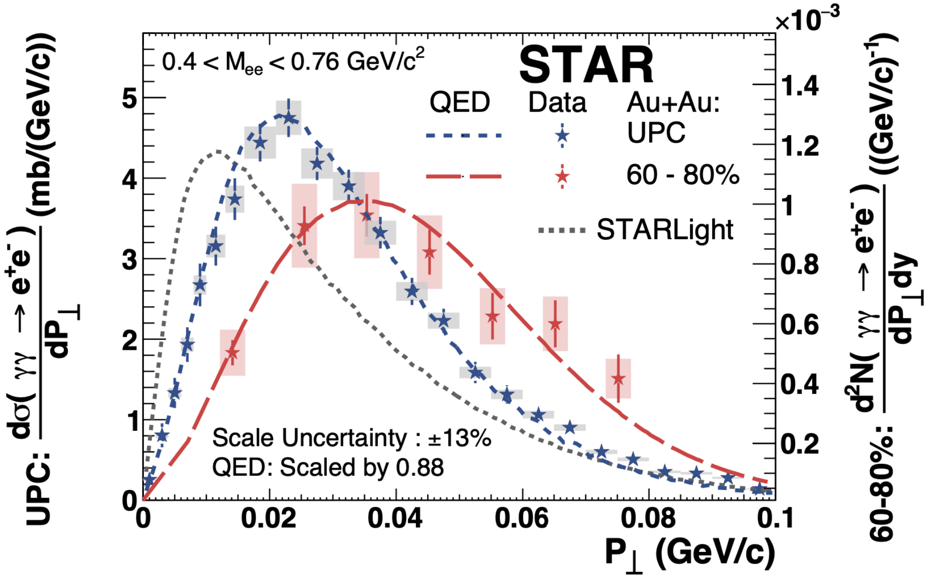


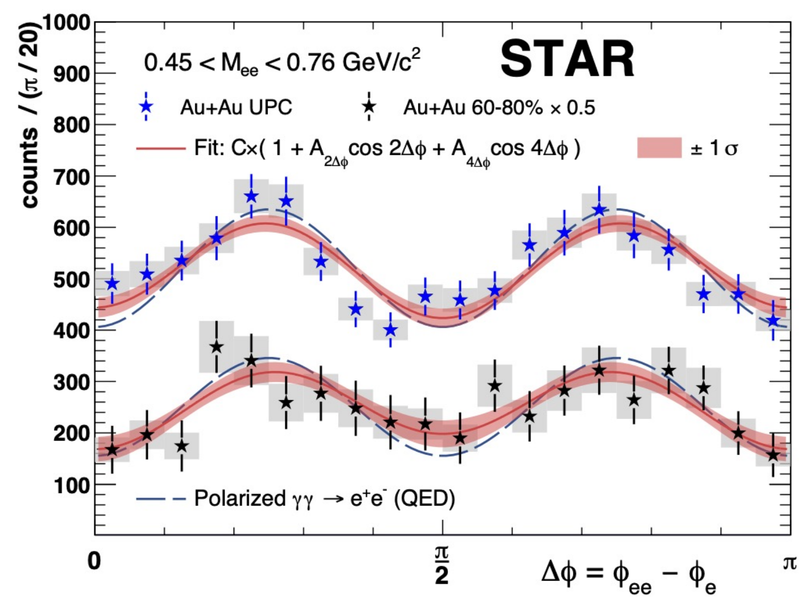
FIG. 1. A Feynman diagram for the exclusive Breit-Wheeler process and the related Light-by-Light scattering process illustrating the unique angular distribution predicted for each process due to the initial photon polarization.



Observation of Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, p_T, angle)

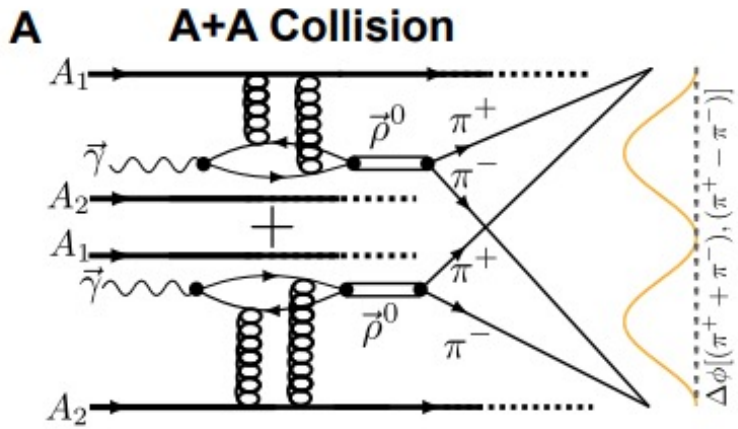
Dielectron p_T spectrum: broadened from large to small impact parameters

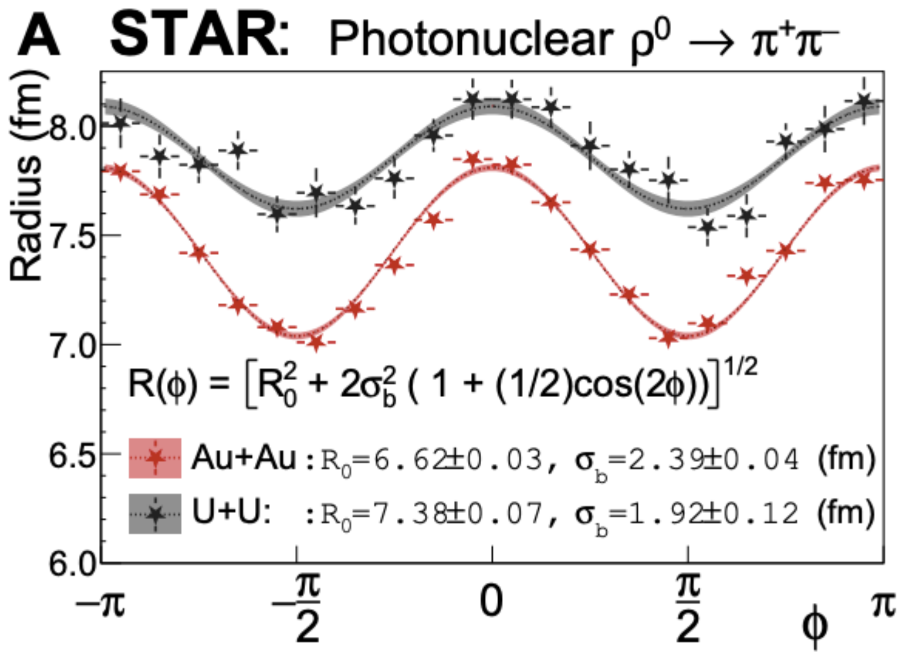
Observation of vacuum birefringence: 6.7σ in Ultra-peripheral collisions



PRL127 (2021) 52302

Tomography of Ultra-relativistic Nuclei with Gamma + A Collisions





Quantum interference enabled nuclear tomography:

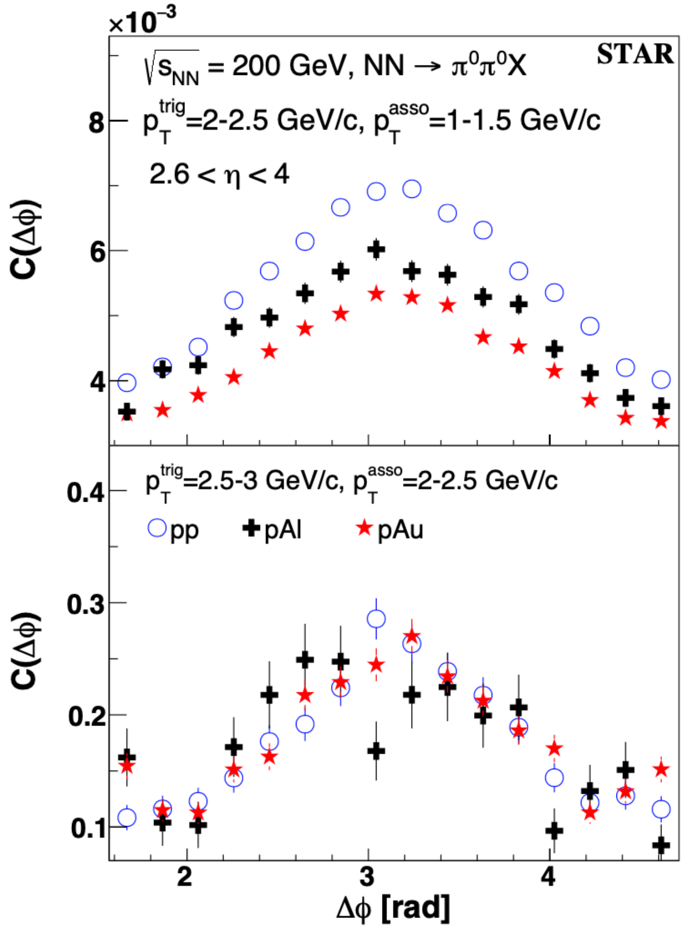
- A novel approach to extract the strong-interaction nuclear radii, which were found to be larger than the nuclear charge radii

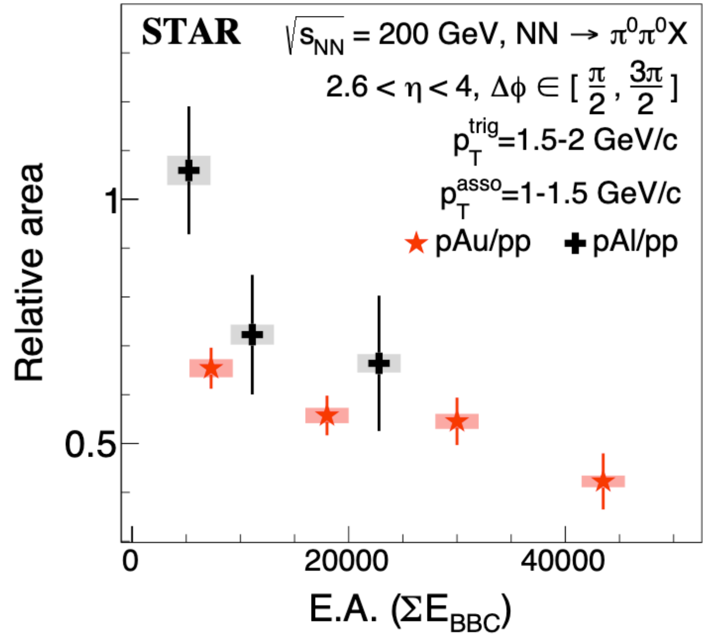
2204.01625, submitted to Science Advances

Brookhaven National Laboratory

QCD Non-linear Effects

Phys. Rev. Lett. **129**, 092501





Run-15 di-π^0 correlation:
away side area suppressed significantly, while the pedestal and away side widths change very little.

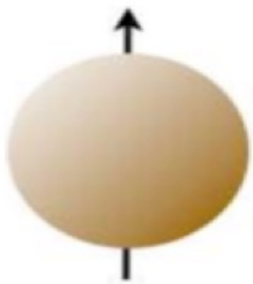
probe x down to 10^{-3}

STAR forward upgrades will characterize non-linear effects with charged di-hadrons, γ-jet, di-jet

Brookhaven National Laboratory

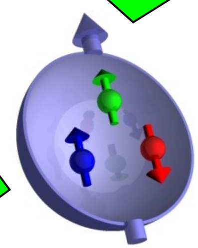
The incomplete nucleon: spin puzzle

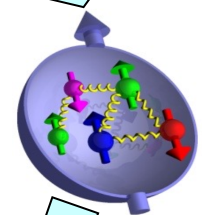
Jaffe-Manohar, 90
Ji, 96

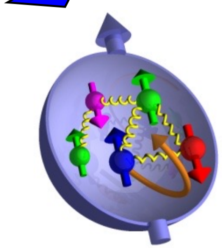


Proton Spin

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







Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

~40% (RHIC Spin data)
At Q^2 =10 GeV^2

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

Brookhaven National Laboratory

Helicity PDFs: ΔG

Golden probes for Δg:

Double spin asymmetry A_{LL} for jets, di-jets and π^0

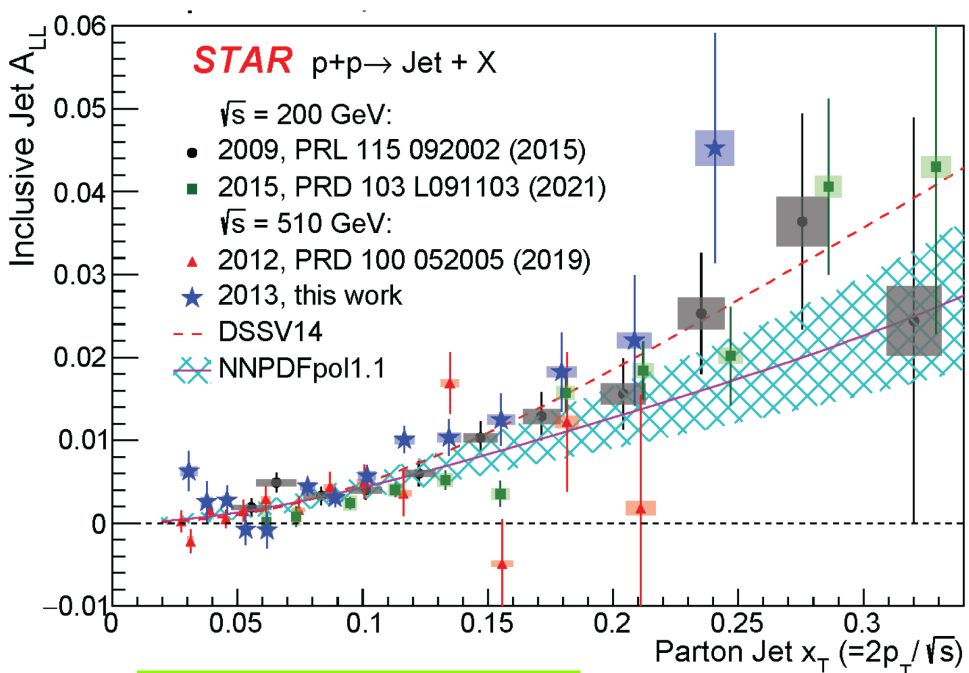
to increase x-range covered: go to higher √s (200 GeV → 500 GeV)

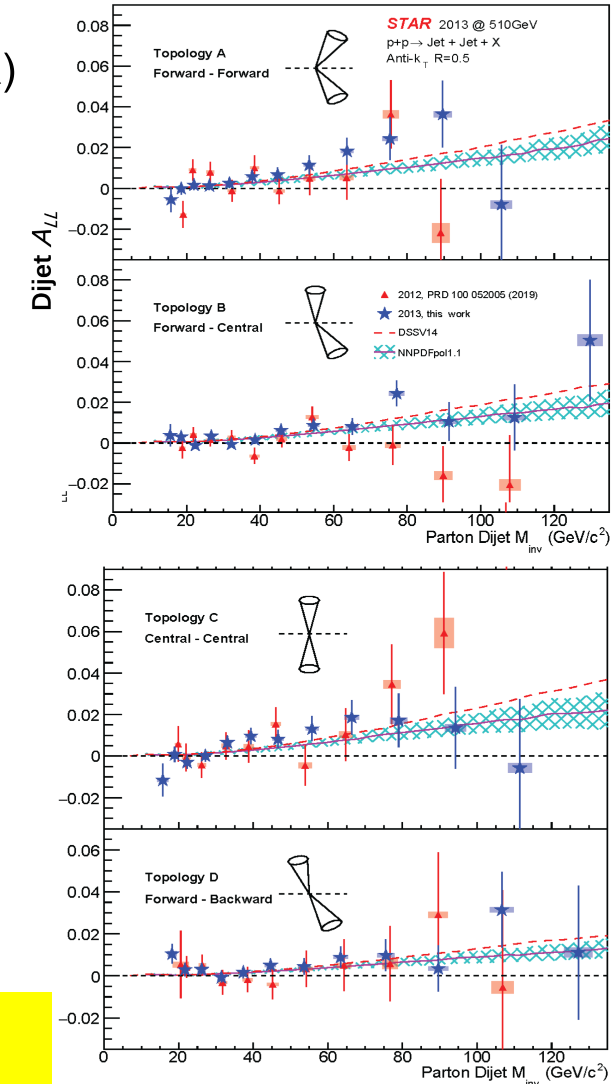
or

go to higher rapidity: $-1<\eta<1$ → $-1<\eta<1.8$ ($-1<\eta<4$ with fSTAR)

or both

Di-jets: constrain the shape of the $\Delta g(x,Q^2)$





PRD 105 (2022) 092011

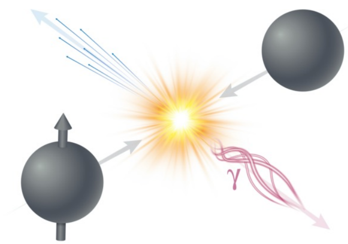
Complement and improve the precision of previous measurements for $0.015 < x < 0.25$

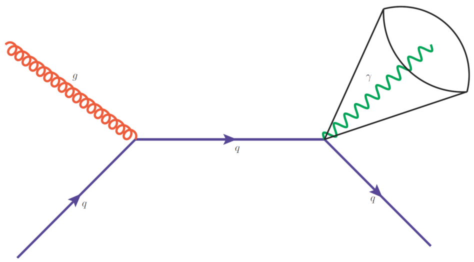
Spin highlights from direct photons

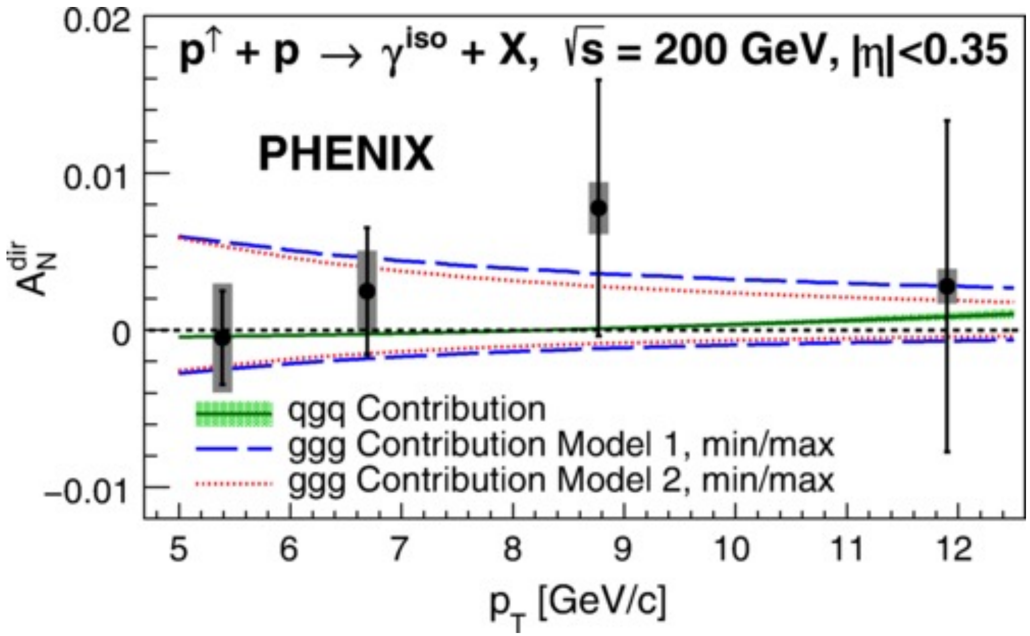
PRL 127, 162001 (2021)

First direct photon A_N extracted at RHIC

- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function as well
- High precison measurement of Direct photon A_N
- 50-fold improvement over the only previous measurement



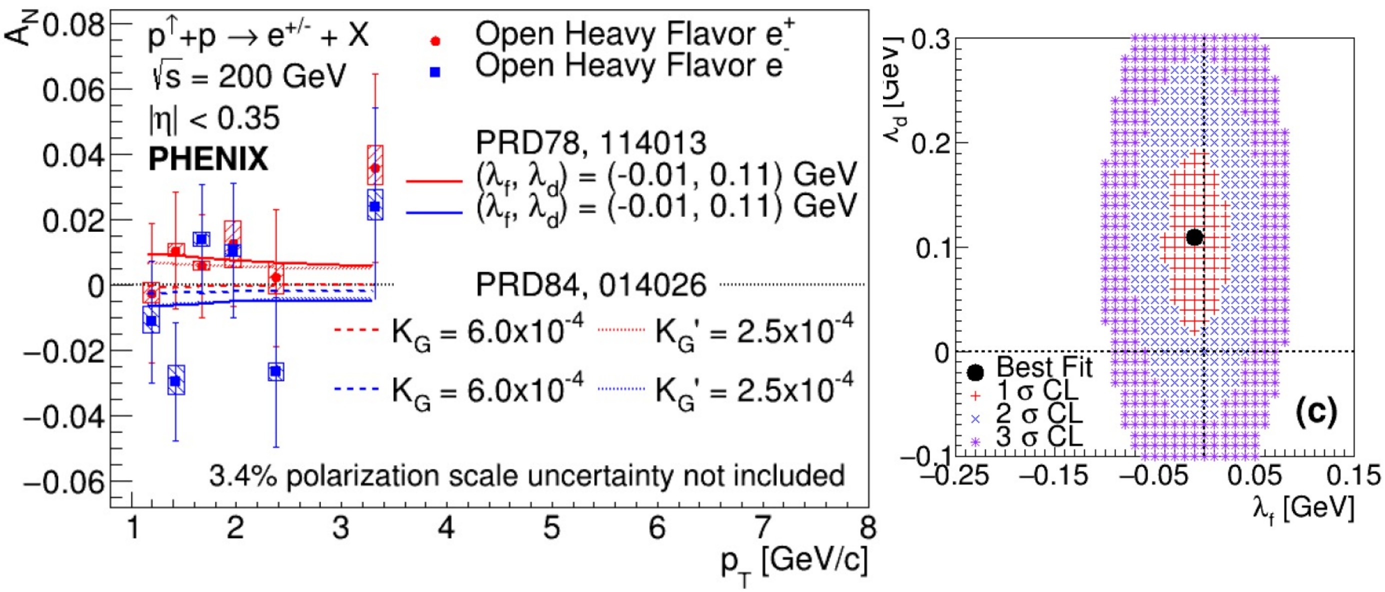




Spin Physics highlights

PHENIX

arXiv:2204.12899 (2022)



$A_N(p^{\uparrow}+p \to HF(e^{+/-}) + X)$

$\sqrt{s}$ = 200 GeV

$|\eta| < 0.35$

PHENIX

Theory: PRD78, 114013

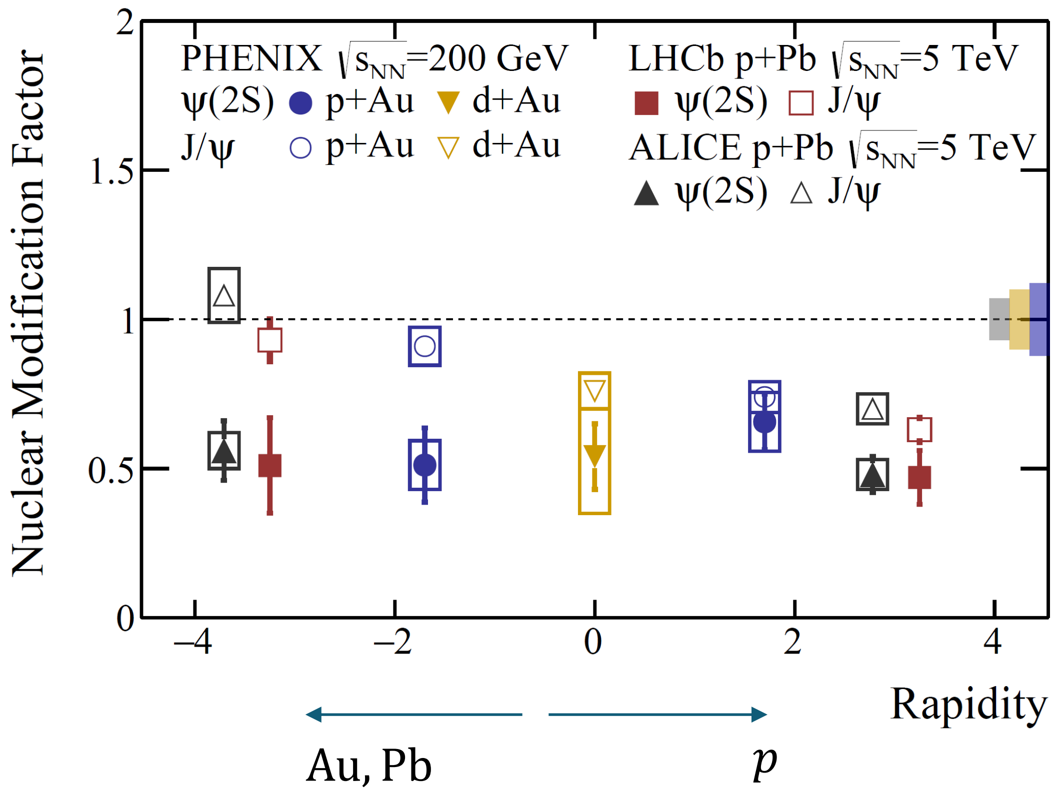
$A_N^{D^0/\overline{D}^0 \to e^{+/-}}(\lambda_f,\lambda_d)$

- Measurement of A_N of heavy-flavor decay electrons
- **Constraints on parameters of Tri-Gluon correlation model by Z.Kang and J.W.Qiu**
  - **The first measurement on the model parameters (λ_f, λ_d) of the model**

$\psi(2S)$ suppression in p+Al, and p+Au

PHYSICAL REVIEW C **105**, 064912 (2022)

Editors' Suggestion



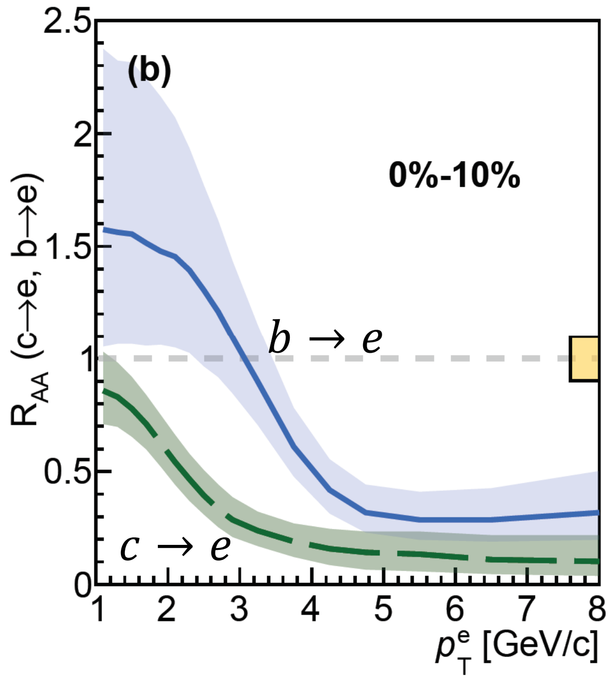
- Nuclear modification of $\psi(2S)$ in $p+$Al, and $p+$Au
- Forward (p-going):similar suppression of J/ψ and $\psi(2S)$

  → Shadowing dominance
- Backward (A-going): Stronger suppression of $\psi(2S)$ than J/ψ suggests **presence of final state effects in $p+A$**
- PRC Editor's suggestion

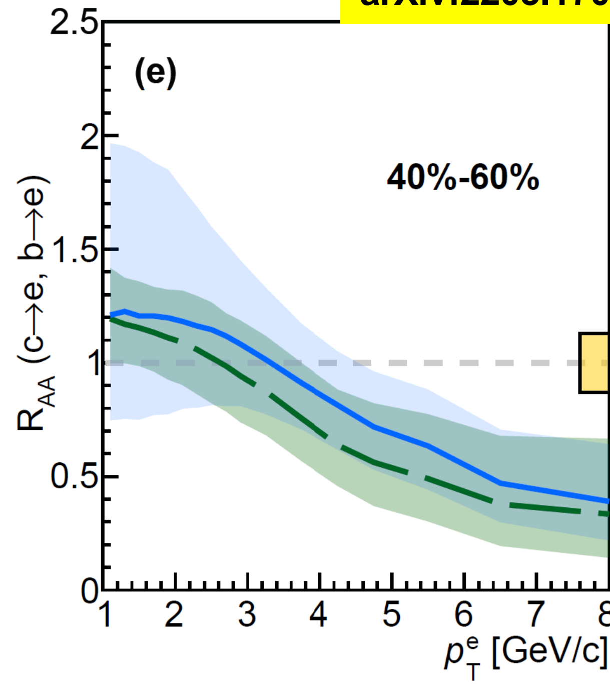
Brookhaven National Laboratory

R_{AA} of $b \to e$ and $c \to e$

PHENIX



arXiv:2203.17058



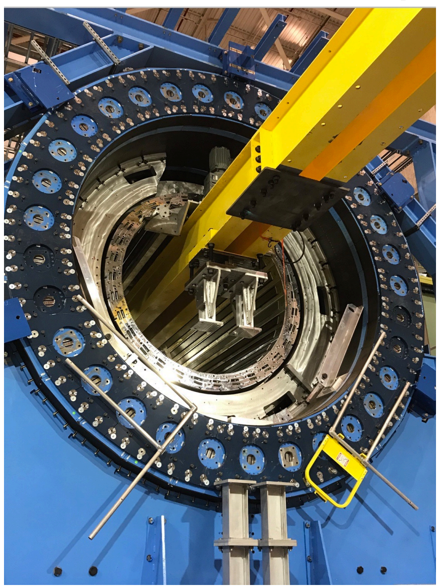
- R_{AA} of $b \to e$ and $c \to e$ at midrapidiy from 20B Au+Au data
- **Clear difference of charm and bottom suppression is seen**

Brookhaven National Laboratory

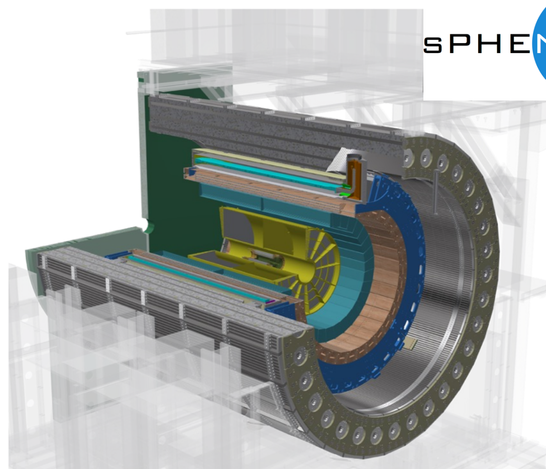
Completing the 2nd RHIC Goal in 2015 LRP

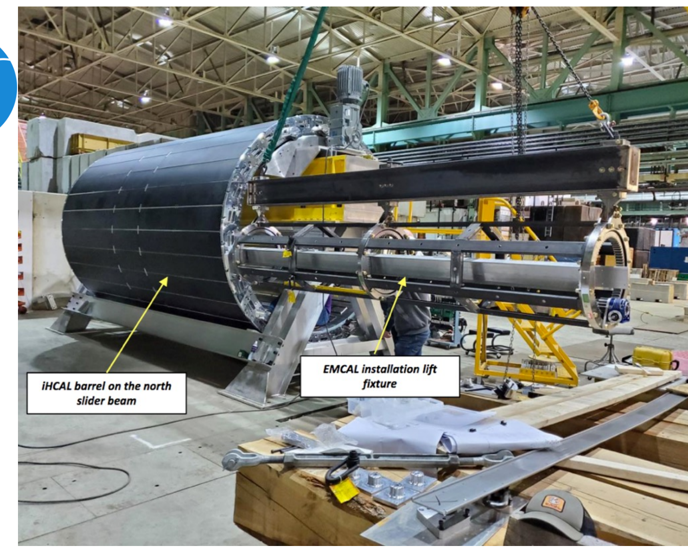
sPHENIX: **Study QCD phenomena discovered at RHIC** on different scales with unprecedented precision – How does the structureless "perfect fluid" emerge from the underlying asymptotically free gauge theory?

- Extend RHIC kinematic reach and capabilities for direct comparison with the LHC
- Focus on hard probes (jets and heavy flavor)



sPHENIX



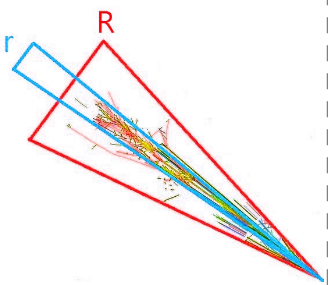


RHIC data taking scheduled for 2023–2025
sPHENIX upgrade will fully utilize the enhanced (~50 times AuAu design) luminosity of RHIC together with STAR

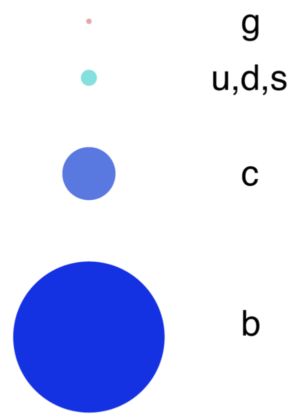
sPHENIX Science

State-of-the-art collider detector technology

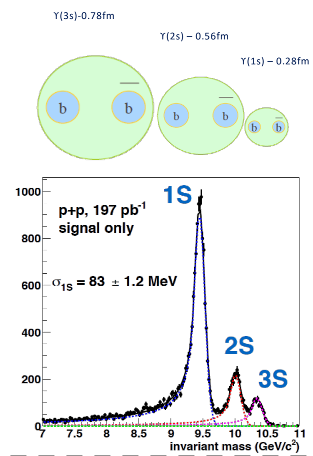
Jet cor. & substructure
Vary momentum/angular size of probe



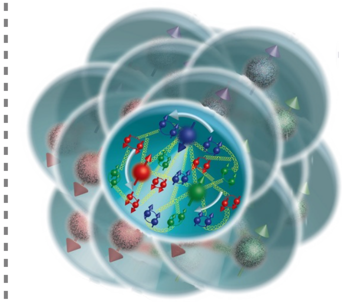
Parton energy loss
Vary mass/momentum of probe



Upsilon spectroscopy
Vary size of the probe



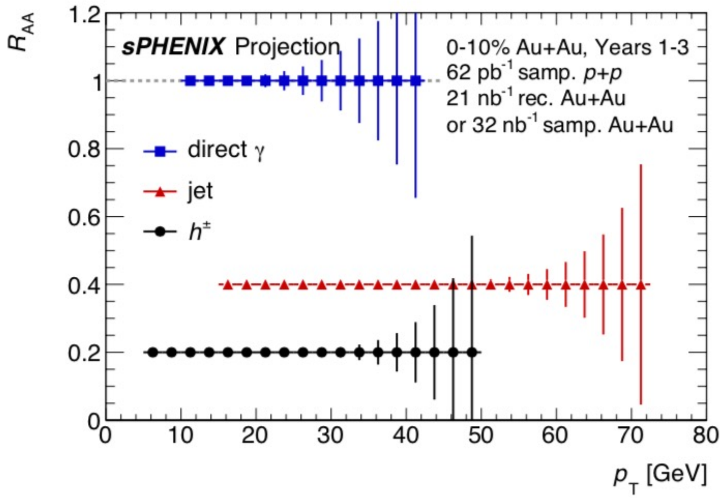
Cold QCD
Vary temperature of QCD matter



Mission: **Study QCD phenomena discovered at RHIC** on different length scales with unprecedented precision – Where and how does plasma transitions from (quasi)particles to structureless "perfect" fluid?

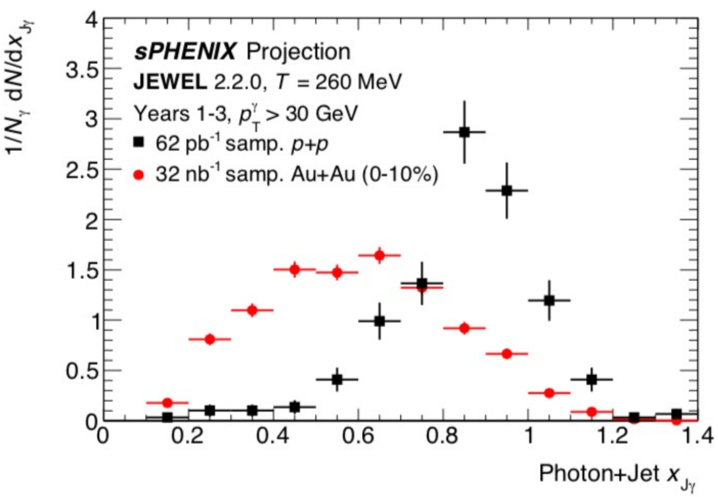
- Focus on **hard probes** (jets and heavy flavor)
- Kinematic reach and capabilities to allow **direct comparison with LHC**

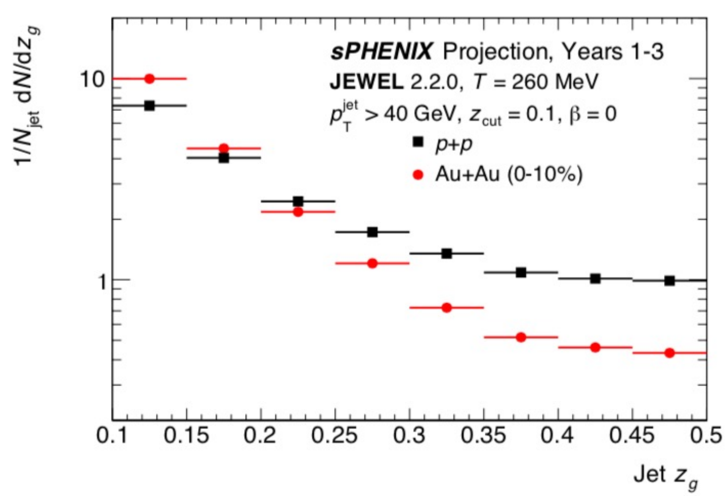
Promises and Deliverables: Jets and Photons

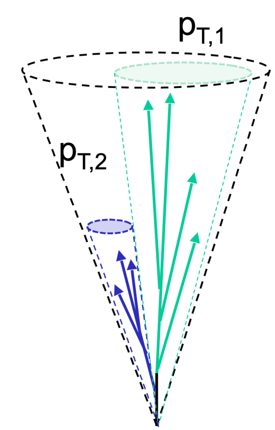


High statistics jets, photons, hadrons
No trigger bias in AuAu, no bias on the physics

Enables precision differential measurements

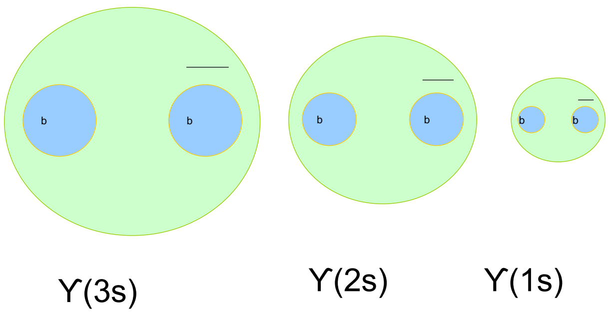






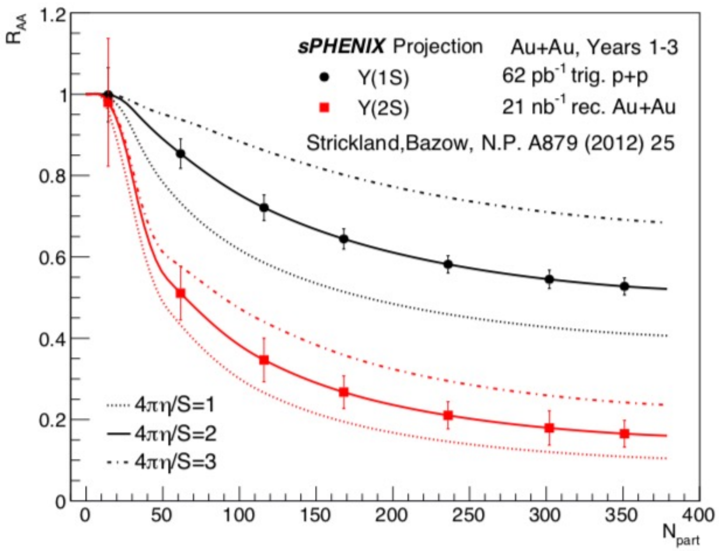
J. Nagle@PAC2020

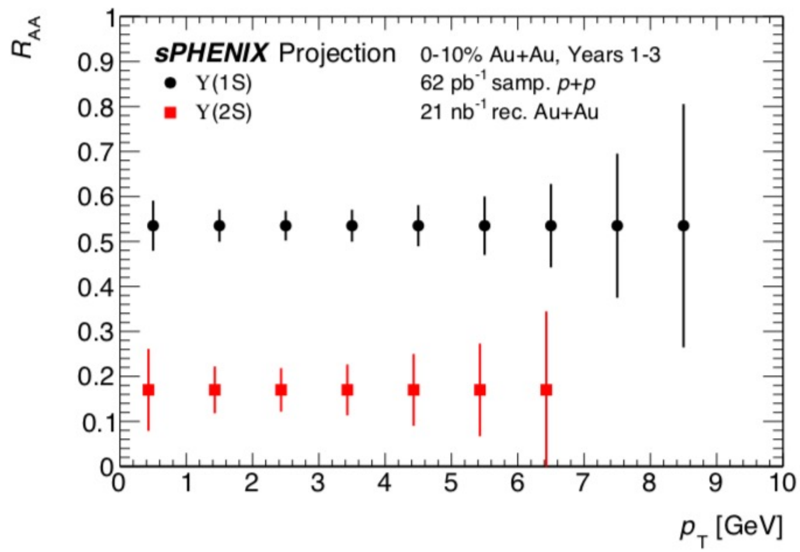
Promises and Deliverables: Closed Heavy Flavor



Upsilon QGP "thermometer" measurements

Precision 1s, 2s and 3s (depends on the level of suppression) in pp, pAu, AuAu





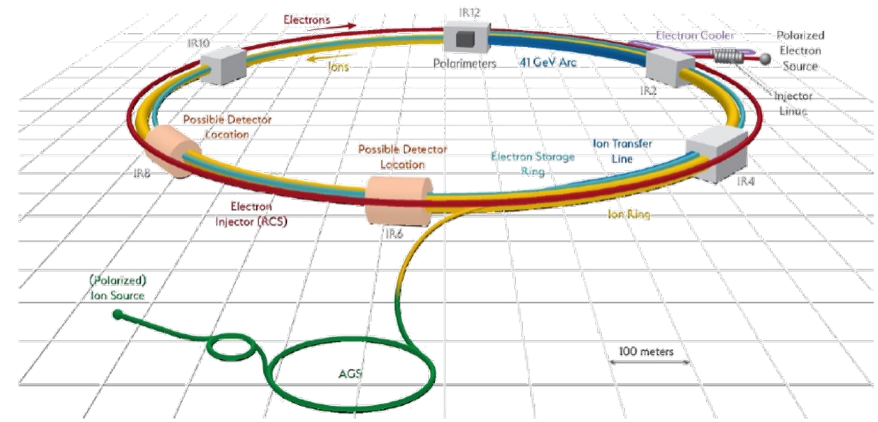
J. Nagle@PAC2020

Looking forward – The Electron-Ion Collider

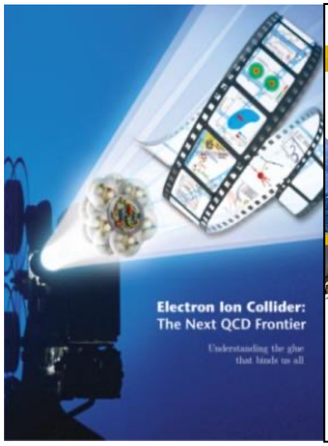
Project Design Goals

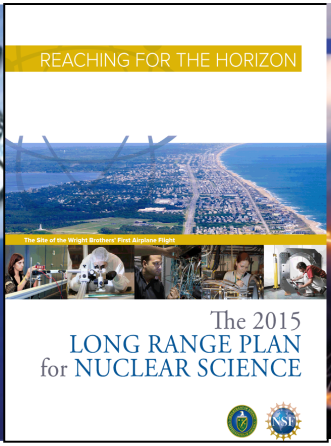
- High Luminosity: L= 10^{33}–10^{34}cm^{-2}sec^{-1}, 10–100 fb^{-1}/year
- Highly Polarized Beams: ~70%
- Large Center of Mass Energy Range: E_{cm} = 20–140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

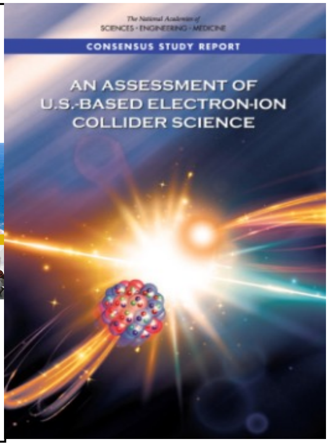
Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)



Double Ring Design Based on Existing RHIC Facility







Brookhaven National Laboratory

Major milestones: CD-0 December 2019; DOE EIC site (BNL) selection on Jan 9, 2020; CD-1 June 2021; EIC project detector reference design selected in March 2022

Summary

- After more than two decades, RHIC continues to produce exciting results
- STAR completed beam energy scan II data taking in 2021, and ran successfully (trans.) polarized proton-proton program in Run 2022 with forward upgrades
- sPHENIX commissioning with beam collisions will start in Run 2023
- sPHENIX and STAR with forward upgrade will complete the RHIC data taking in Run 2023 to Run 2025
- EIC is the next QCD frontier in US

Acknowledgement: PHENIX, STAR and sPHENIX collaborations, especially Yasuyuki Akiba and Lijuan Ruan

Brookhaven Lab's role in the work of the EIC and the work and operations at RHIC are supported by the DOE Office of Science (NP).
Brookhaven National Laboratory is supported by the U.S. Department of Energy's Office of Science.