Highlights from RHIC

Outline

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

Haiyan Gao

Nuclear and Particle Physics, BNL

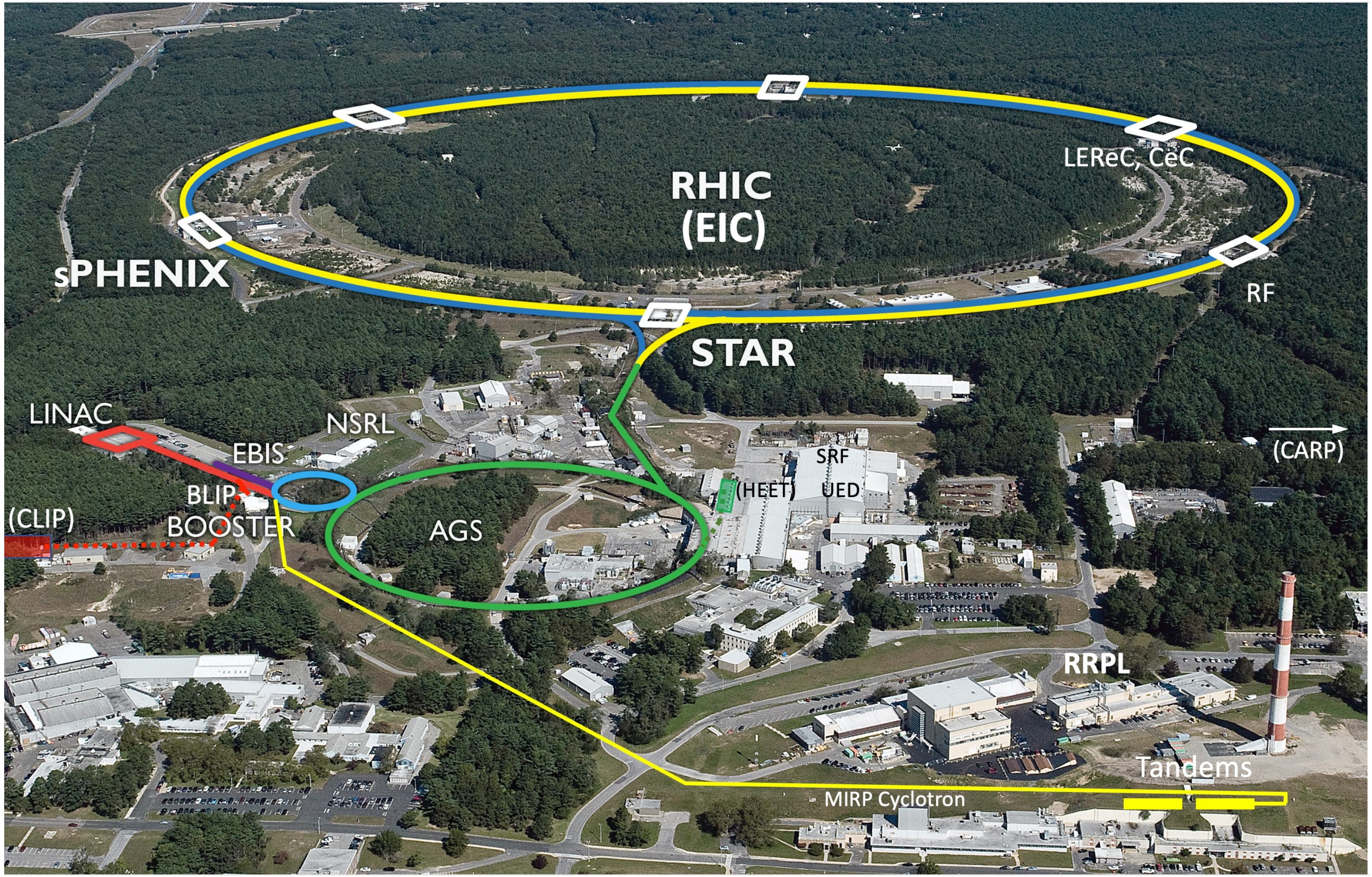
June 5-9, Hadron 2023

Relativistic Heavy Ion Collider (RHIC) Complex

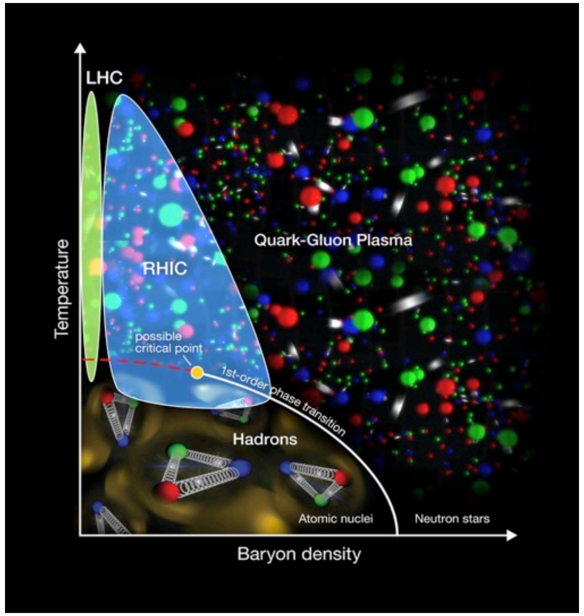
Uniquely flexible and only hadron collider in US for exploration of QCD phase diagram and proton spin

Injectors also used for application programs:
- Linac/BLIP for isotope production
- Booster/NSRL for space radiation studies
- Tandem for industrial/academic users

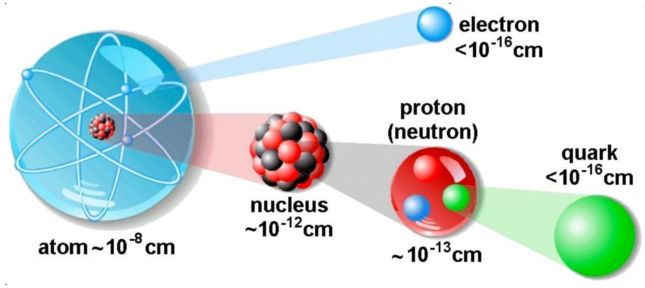
R&D for future facilities and application
sources, cooling, pol. beams, …

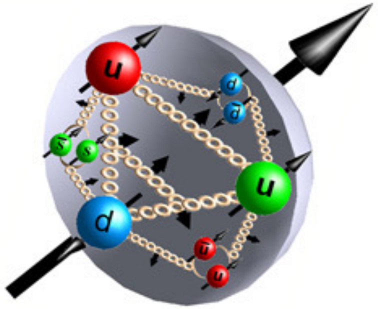


RHIC – a Unique Research Tool



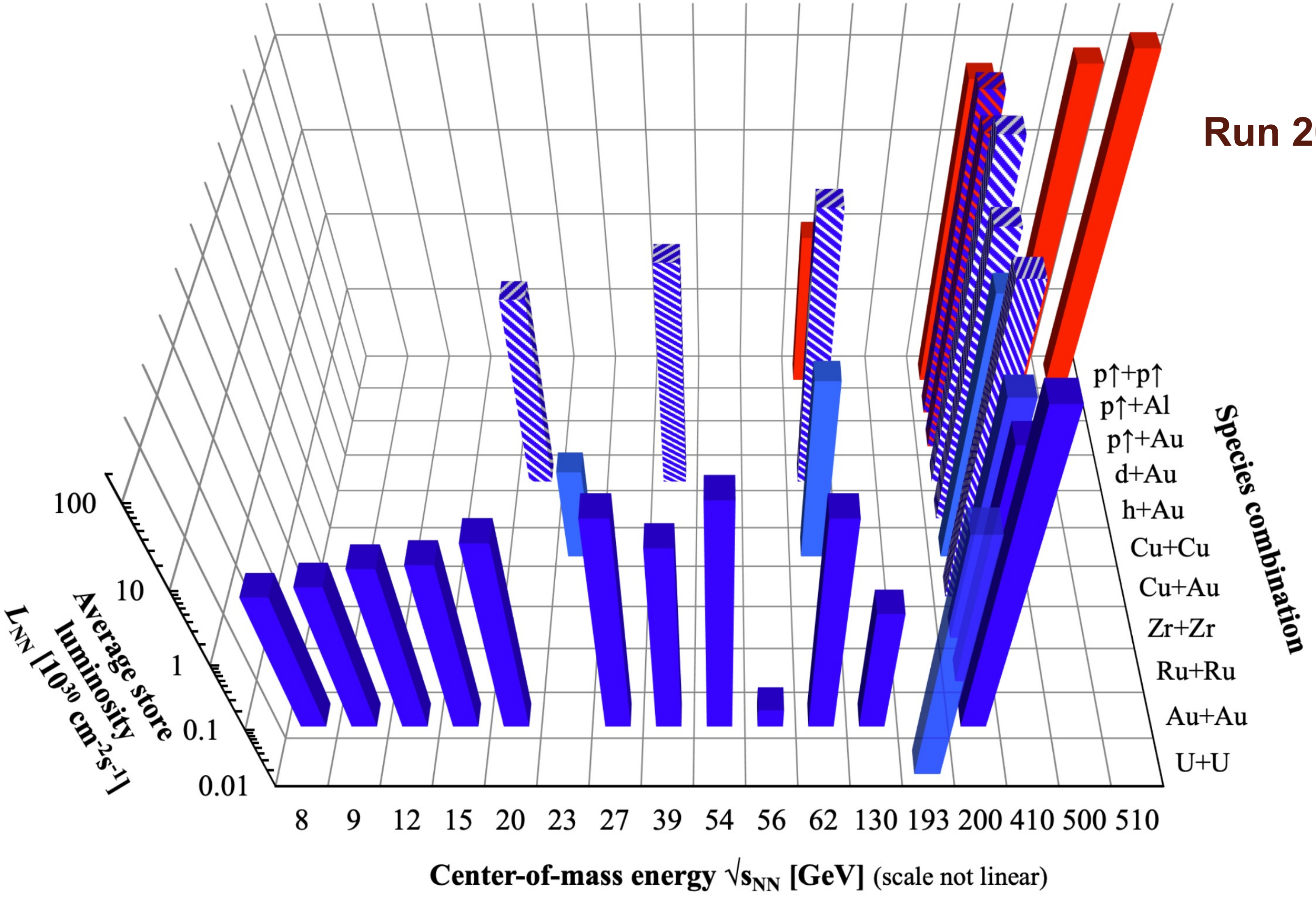
- Heavy ion collisions
  - Explore new state of matter: Quark Gluon Plasma
  - Highest collision rates and collide many different ion species
- Polarized proton collisions
  - Only collider of spin polarized protons to explore the internal spin structure of protons.
  - Gluons carry part of proton spin





Brookhaven National Laboratory

RHIC – high flexibility with wide range of energies and ion combination, including asymmetric; only spin-polarized proton beam collider

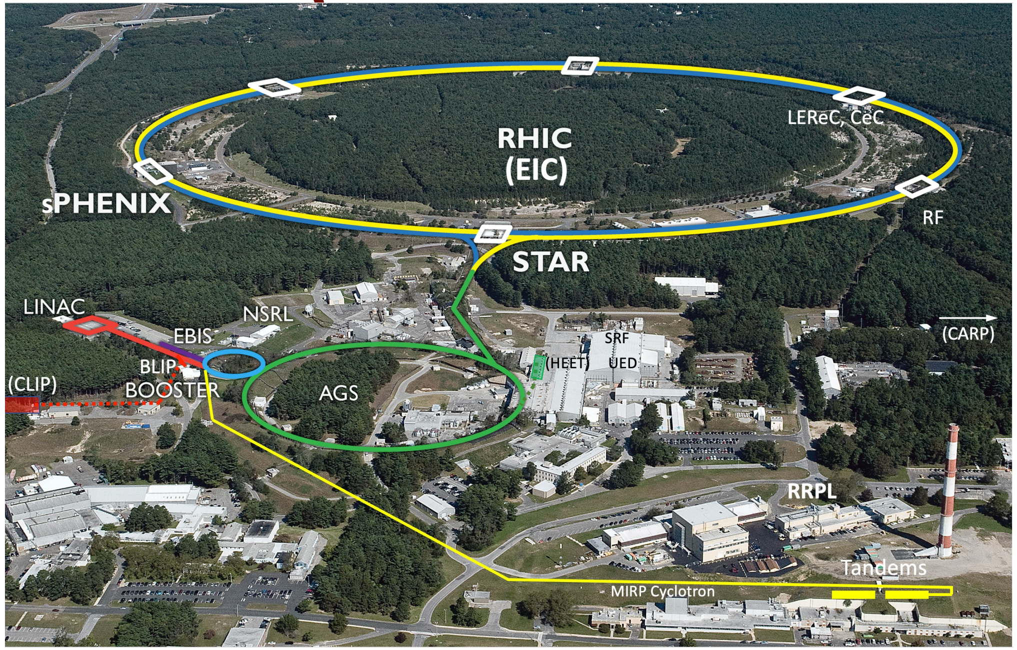


Run 2023 started May 2023

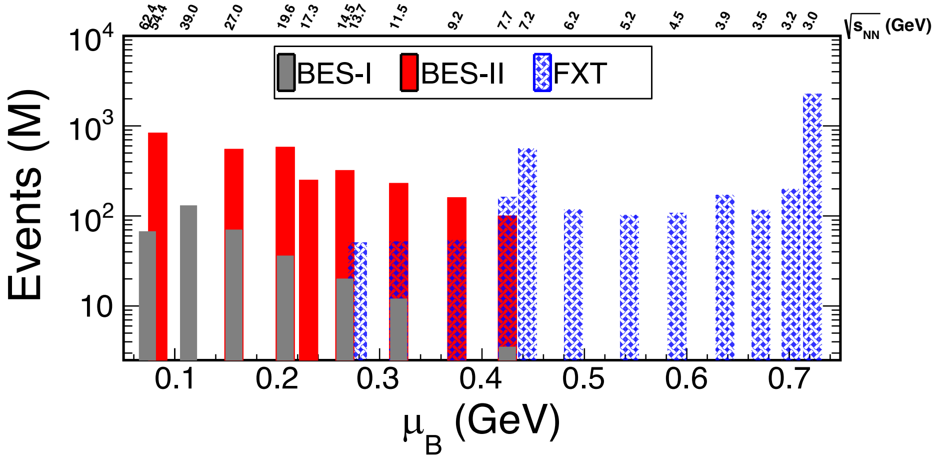
Quark-gluon plasma as "perfect liquid" discovered at RHIC

Complete RHIC Science Mission (2015 NSAC 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.” (completed data taking in 2021)**

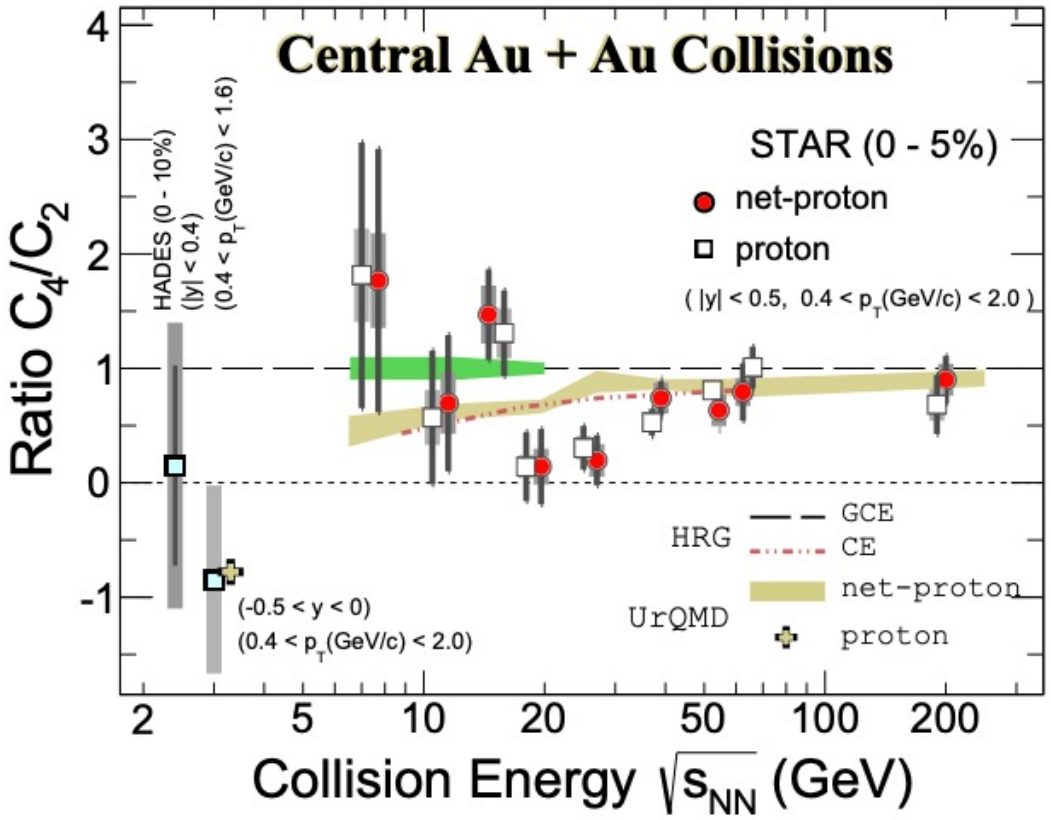


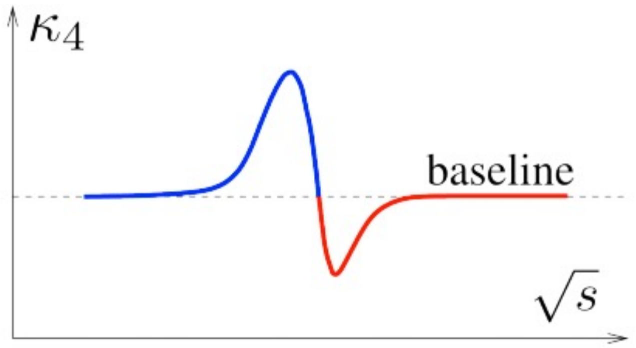
Exceeded STAR data taking goals



Run 2021: last, lowest (~40% of nominal injection energy), and most difficult colliding Au+Au BES-II energy –second year with low-energy electron cooler (LEReC)

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

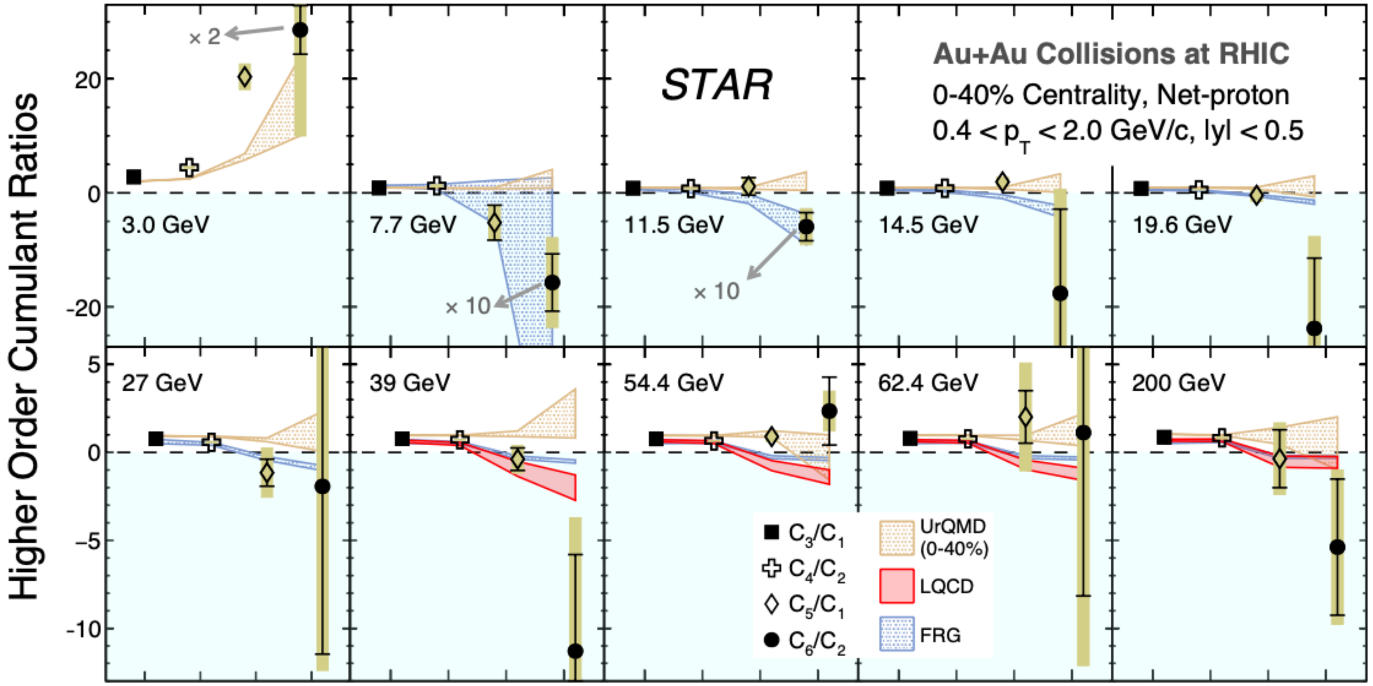
BES-II data collected at RHIC cover a broad and interesting range of μ_B for the critical point search

Higher order net-proton number fluctuations

2207.09837, PRL **130**, 082301 (2023)

Calculations with a cross-over quark-hadron transition (LQCD and FRG) predict a particular ordering of susceptibility ratios:

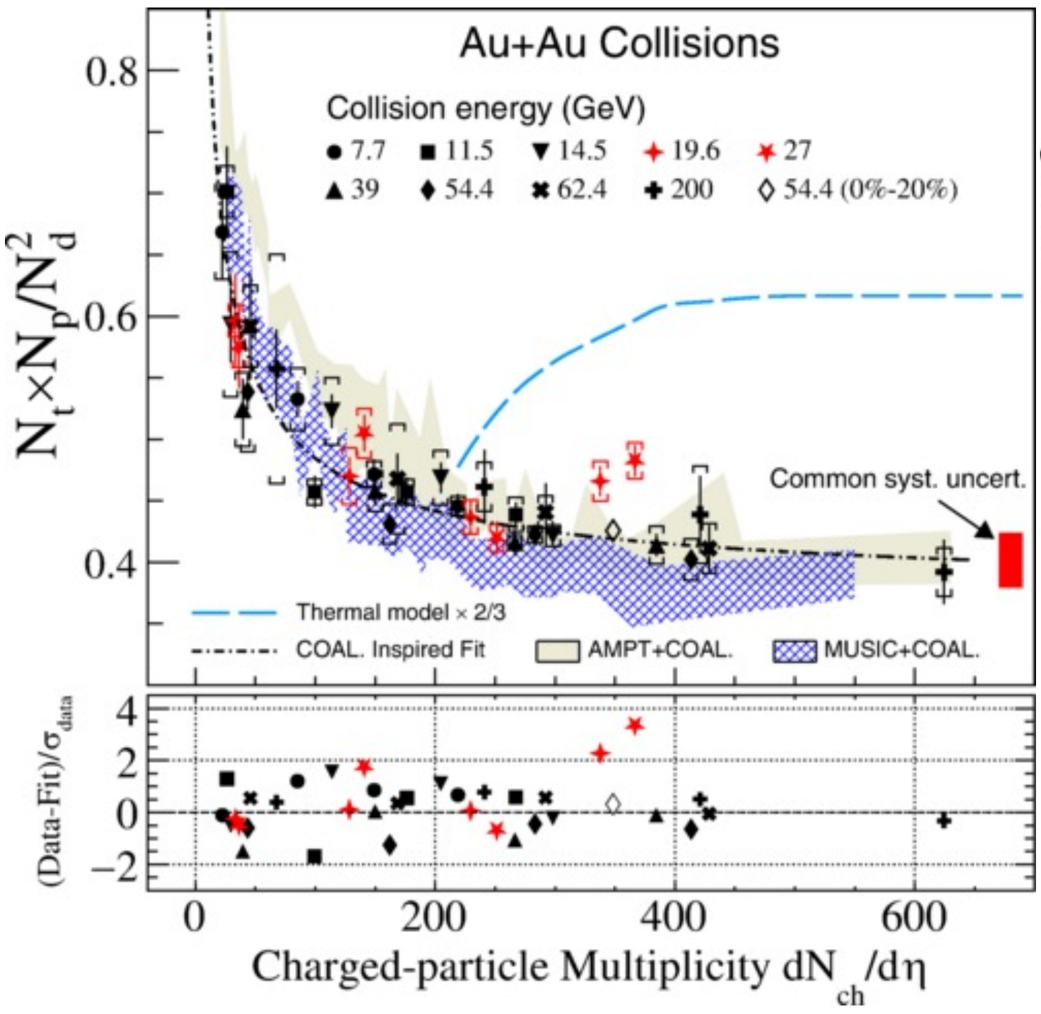
$$\chi_3^B/\chi_1^B > \chi_4^B/\chi_2^B > \chi_5^B/\chi_1^B > \chi_6^B/\chi_2^B$$

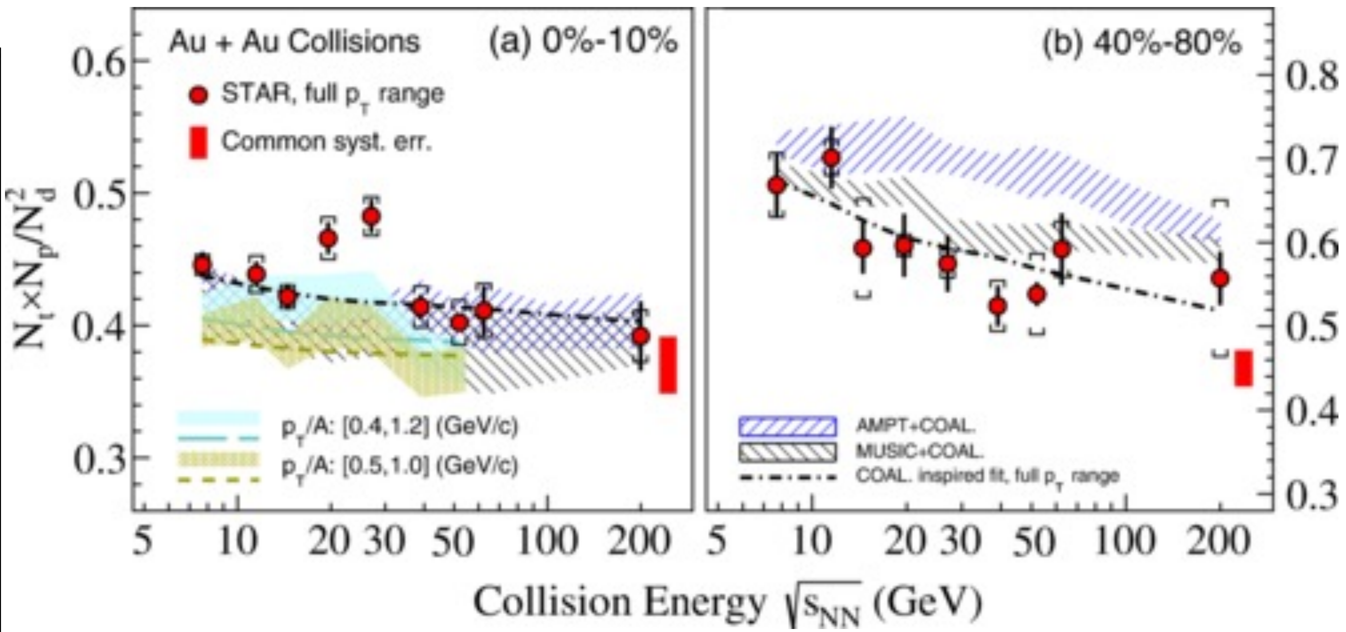


- At 7.7-200 GeV, net-proton cumulant ratios consistent with the ordering predicted by LQCD and FRG:
  $$C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$$
- The 3 GeV data show a reversing trend

The structure of QCD matter at high baryon density μ_B ~750 MeV starkly different from those at vanishing μ_B

Beam Energy Dependence of Triton Production and Yield Ratio ($N_t \times N_p / N^2_d$) in Au+Au Collisions at RHIC



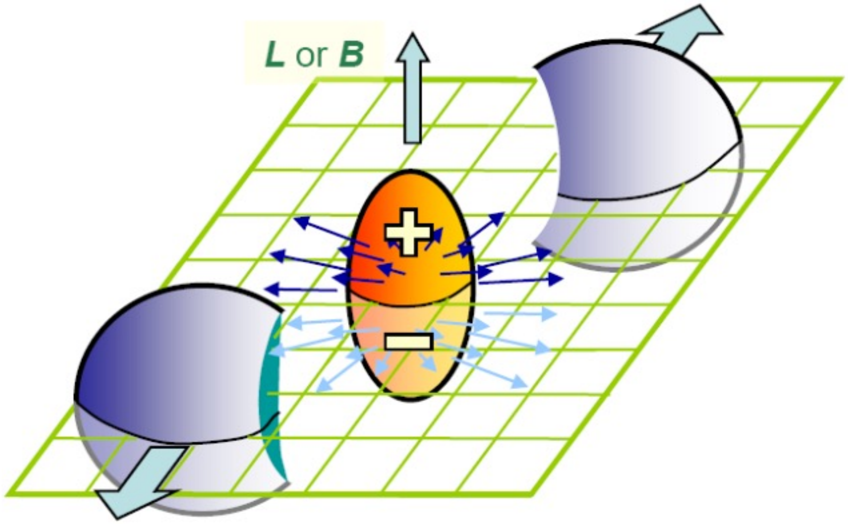


PRL **130**, 202301 (2023)

- The yield ratio shows a monotonic decrease with increasing charged-particle multiplicity and exhibits a scaling behavior (via nucleon coalescence).
- In the 0%-10% most central collisions, at 19.6 and 27 GeV, the ratio shows enhancements relative to the coalescence baseline with a significance of 2.3σ and 3.4σ, respectively.
- Enhancements are due to large baryon density fluctuations near the critical point?

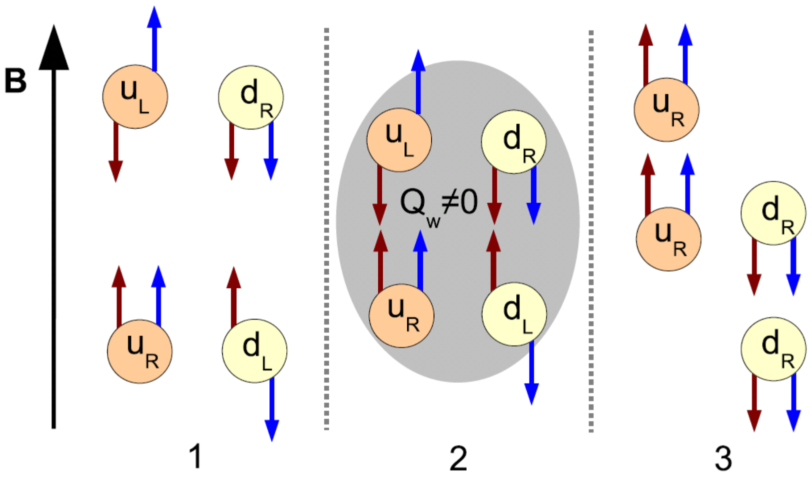
Brookhaven National Laboratory

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)



D. Kharzeev

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

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

Brookhaven National Laboratory

Blinding Analysis of CME Search with Isobar Data

STAR

Mock data challenge
Test data structure (27 GeV files)

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

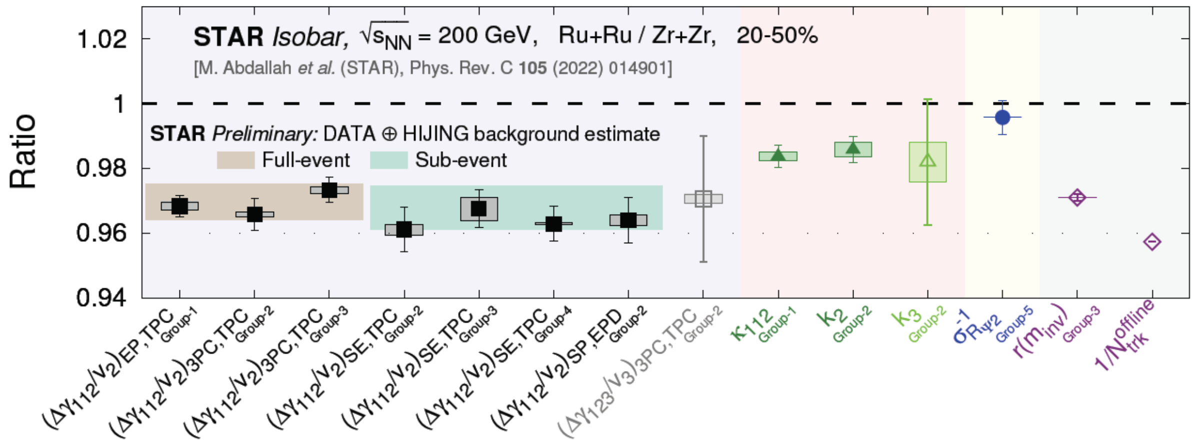
Isobar-Blind Analysis
Run-by-run QA, full analysis (One run is Ru/Zr)

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

→ **Publication of Blind Analysis**

STAR, PRC 105 (2022) 014901

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



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

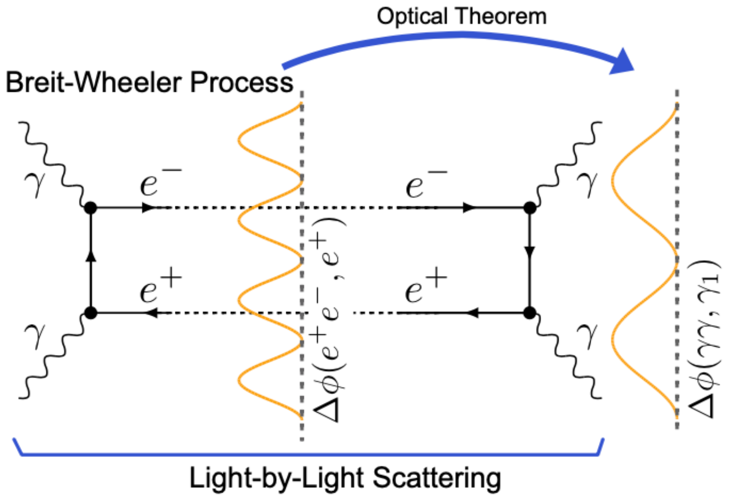
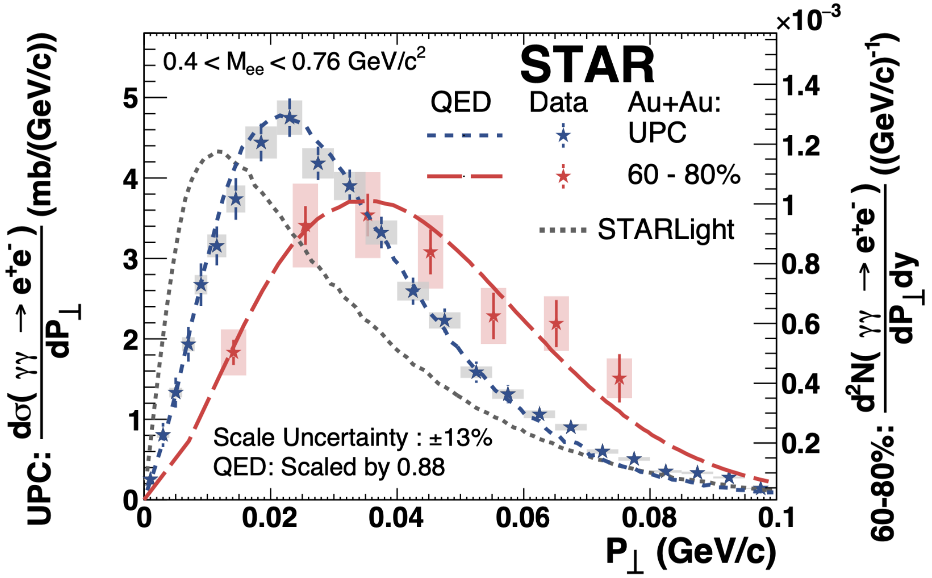
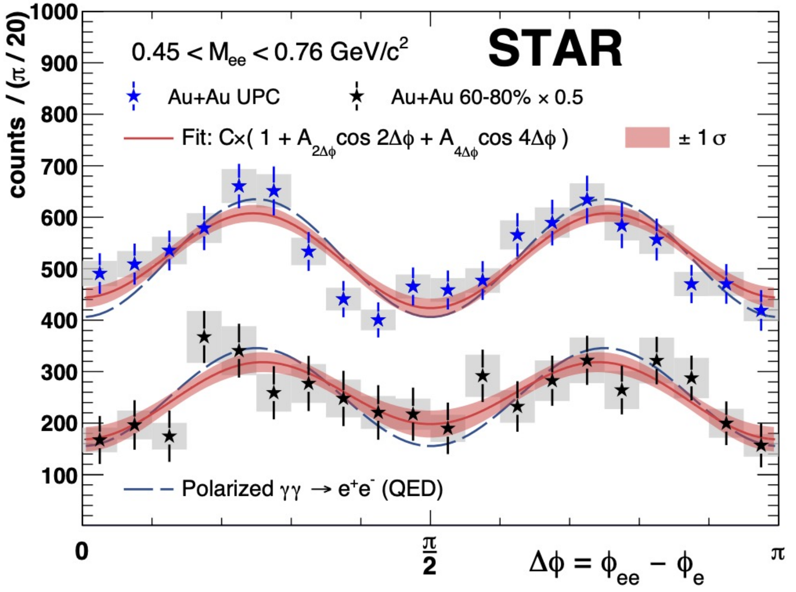


FIG. 1. A Feynman diagram for the exclusive Breit-Wheeler process and the related Light-by-Light scattering process illustrating the unique angular distribution predicted for each process due to the initial photon polarization.





PRL127 (2021) 52302

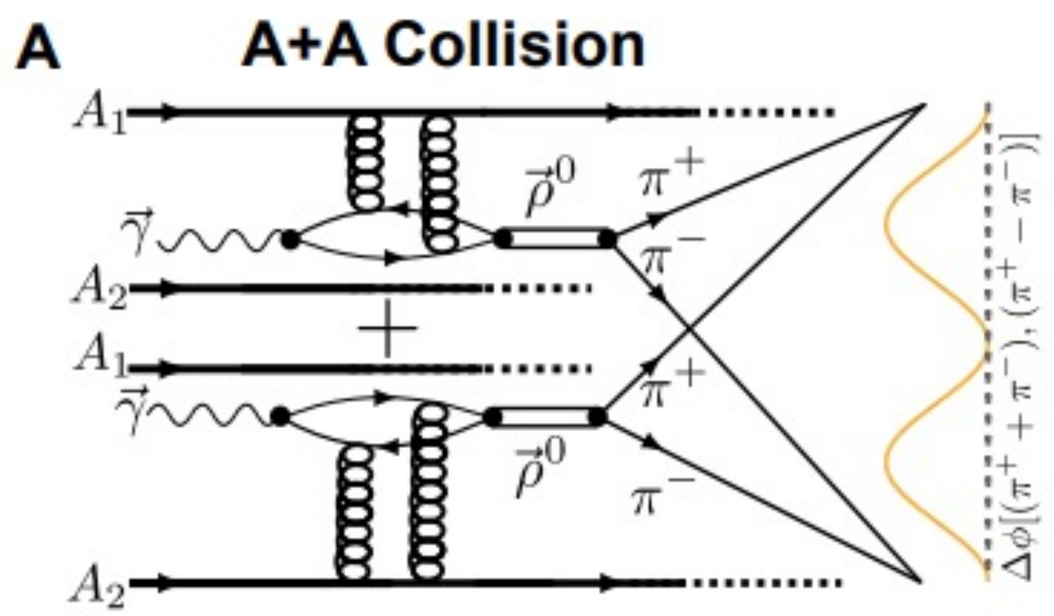
Observation of Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, p_T, angle)

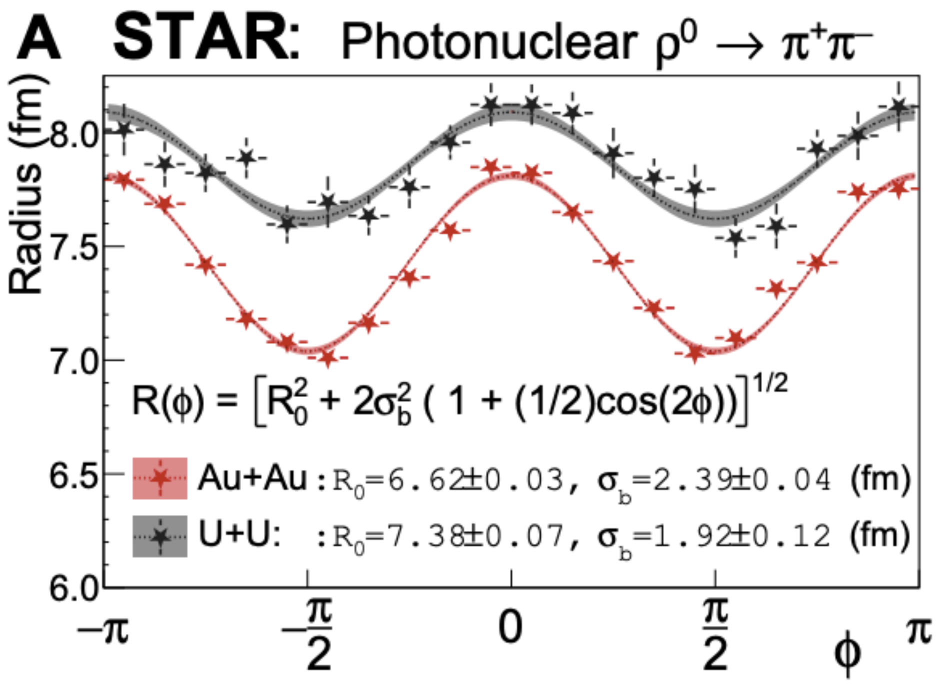
Dielectron p_T spectrum: broadened from large to small impact parameters

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

Brookhaven National Laboratory

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, Science Advances 9 (2023) 3903

Global spin alignment of vector mesons

Λ-like (-10^-5)

Electric field (10^-5)

$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

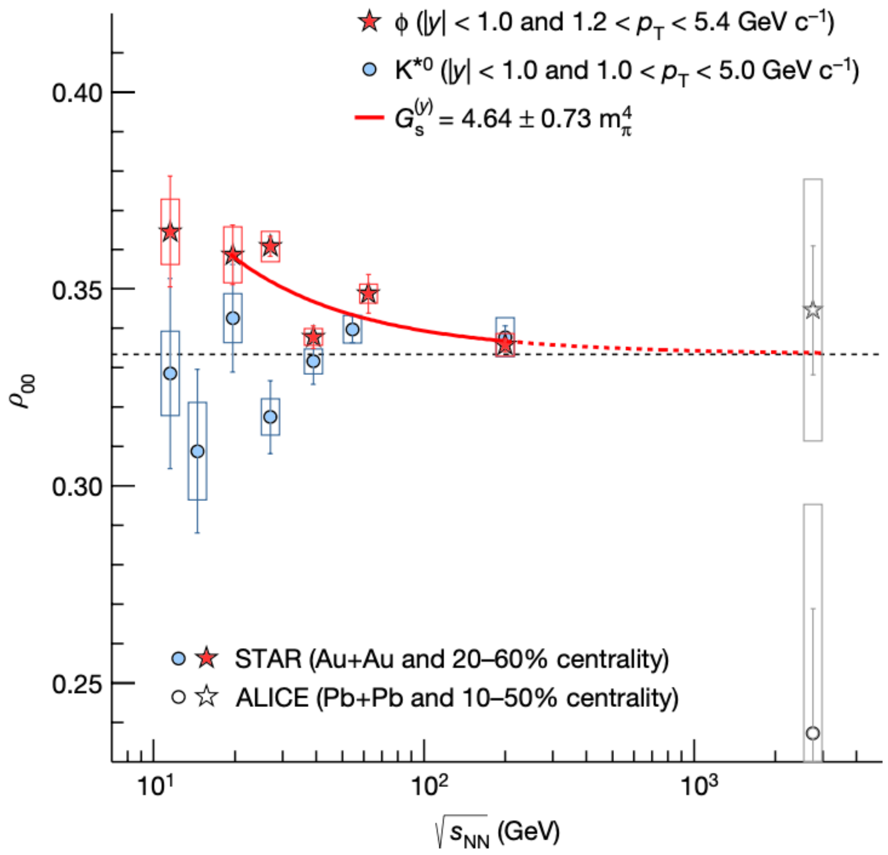
Vorticity tensor (-10^-4)

Vector meson field

Surprising pattern observed:
ϕ–meson $\rho_{00} > 1/3$ by 7.4σ

Possible explanation with a strong vector meson field;

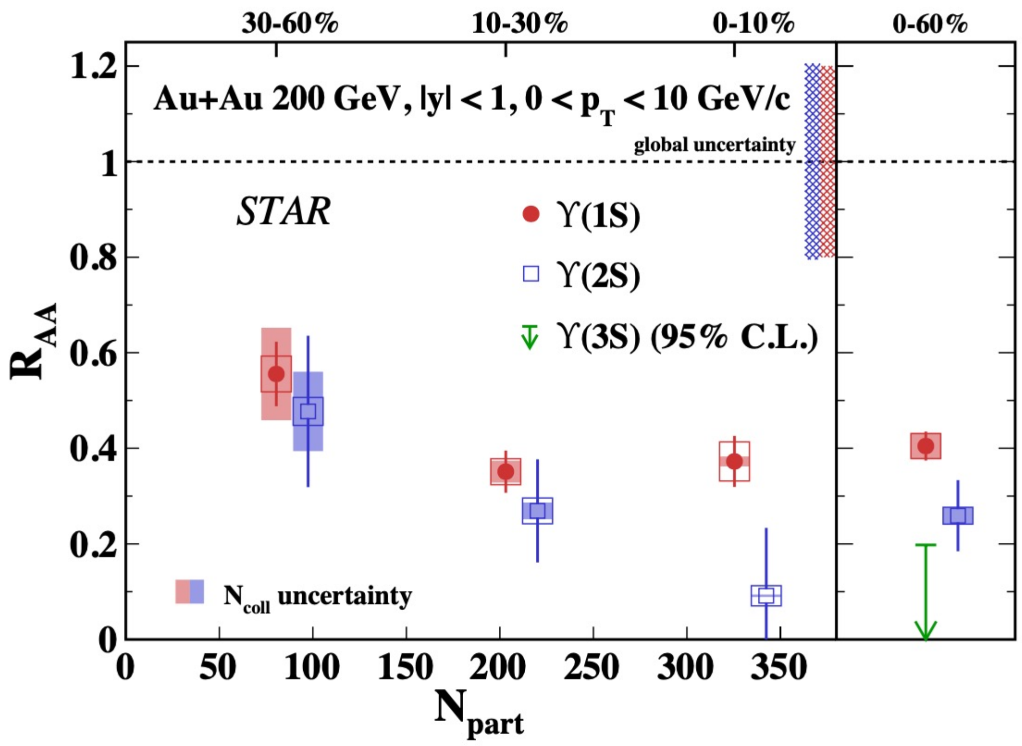
Provides a potential new avenue for understanding the strong interaction at work at the subnucleon level



2204.02302, Nature 614 (2023) 244

Brookhaven National Laboratory

Sequential Upsilon suppression



2207.06568, PRL **130**, 112301 (2023)

ϒ(1S), ϒ(2S), ϒ(3S) sizes: 0.28, 0.56, 0.78 fm

Negligible contribution from b and bbar recombination at RHIC

A better probe to study color screening feature of QGP.

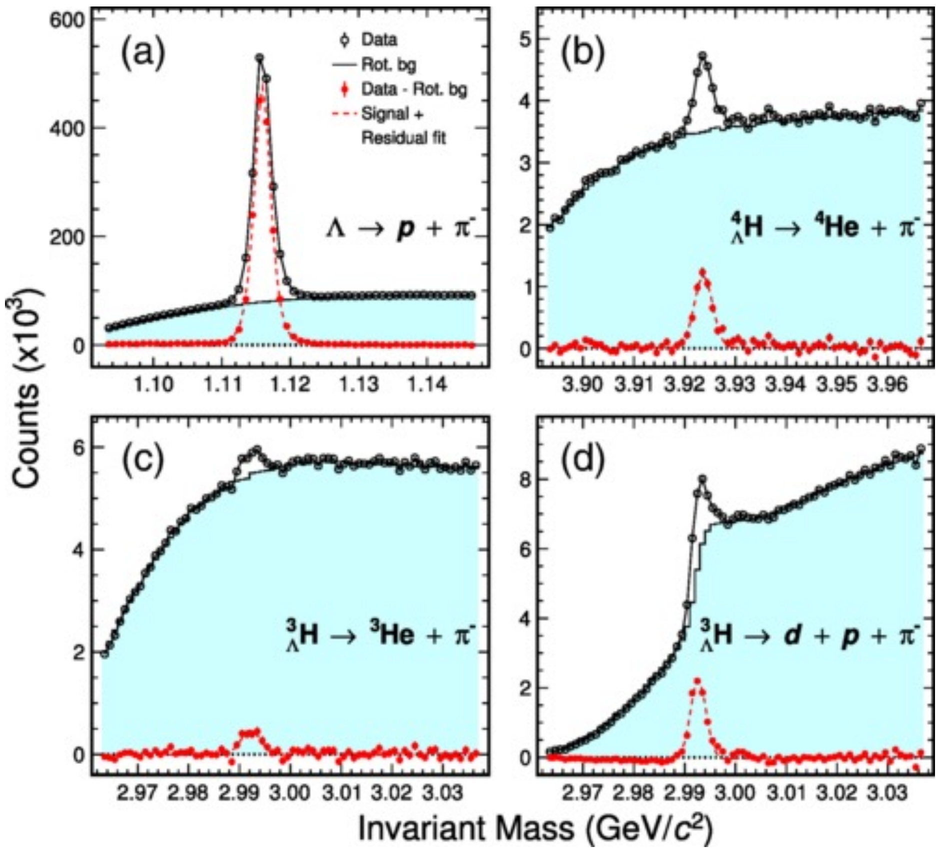
ϒ(1S) R_{AA} = 0.40 ± 0.03 (stat.) ± 0.03 (sys.) ± 0.07 (norm.)

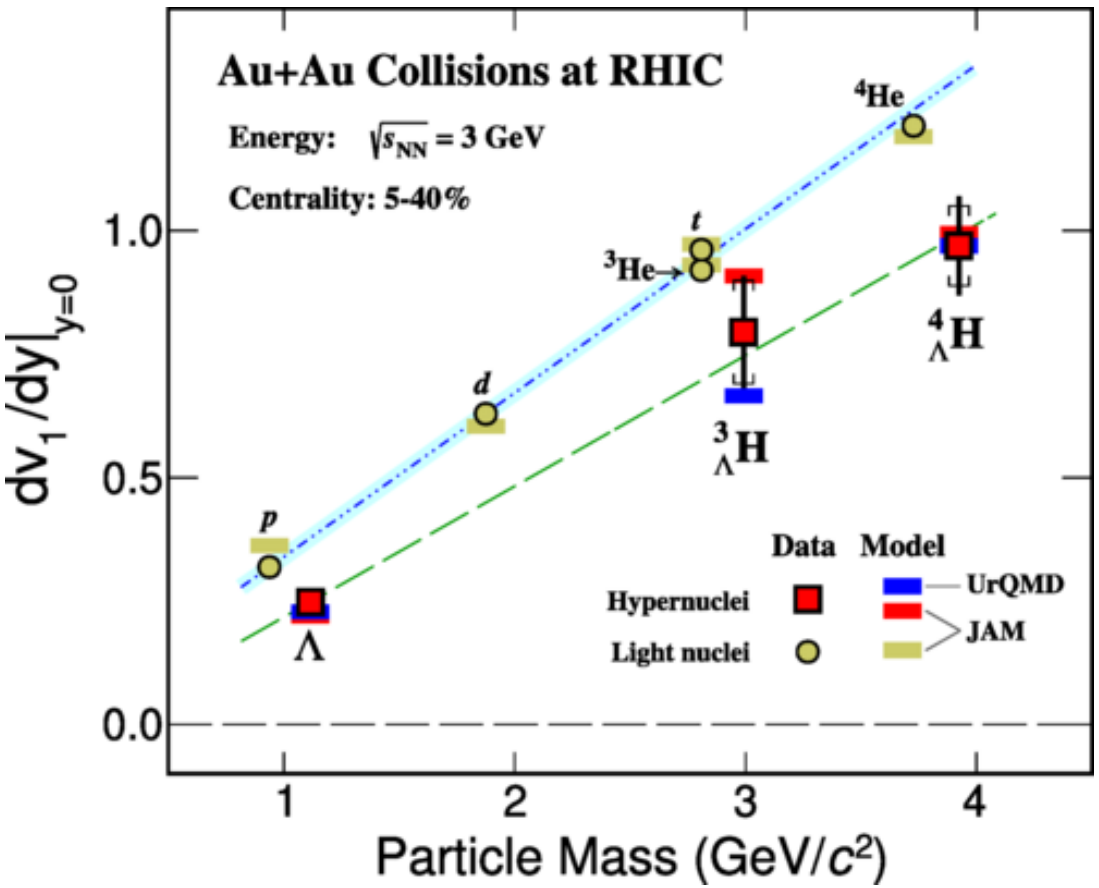
ϒ(2S) R_{AA} = 0.26 ± 0.07 (stat.) ± 0.02 (sys.) ± 0.04 (norm.)

ϒ(3S) R_{AA} upper limit: 0.20 at a 95% confidence level

Sequential ϒ suppression at RHIC

First Measurements of Hypernuclei Flow at RHIC





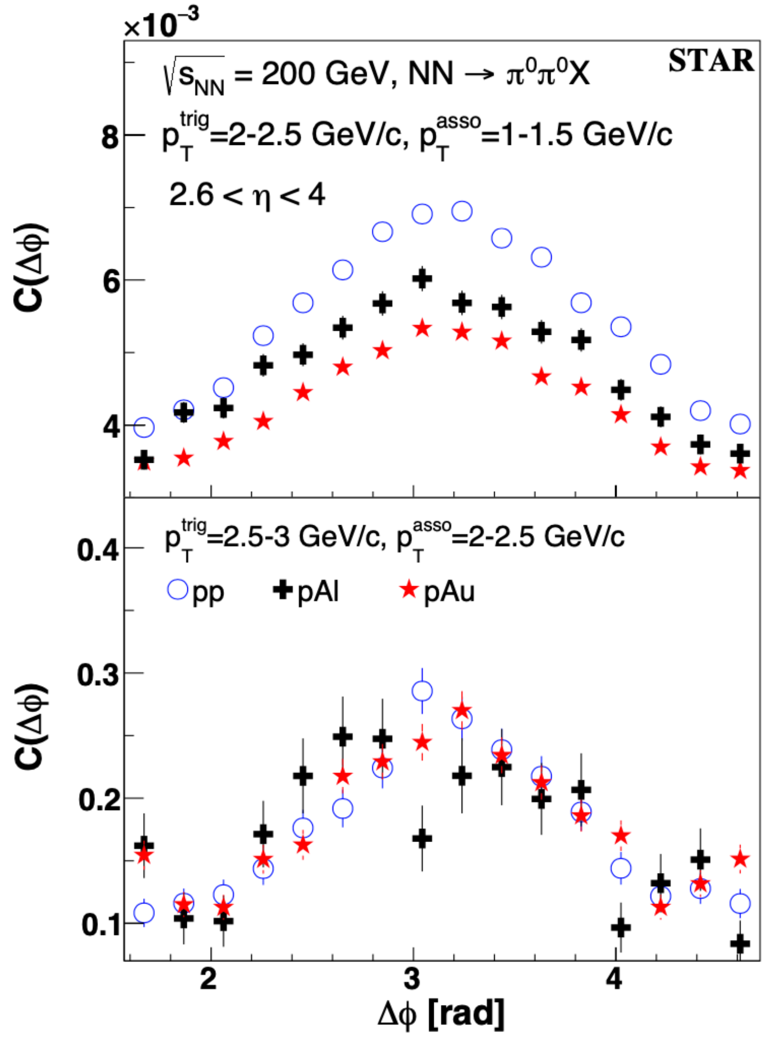
- These hypernuclei exhibit significant directed flow, follow mass-scaling pattern
- The coalescence is the dominant mechanism for these hypernuclei production in the 3 GeV Au+Au collisions.

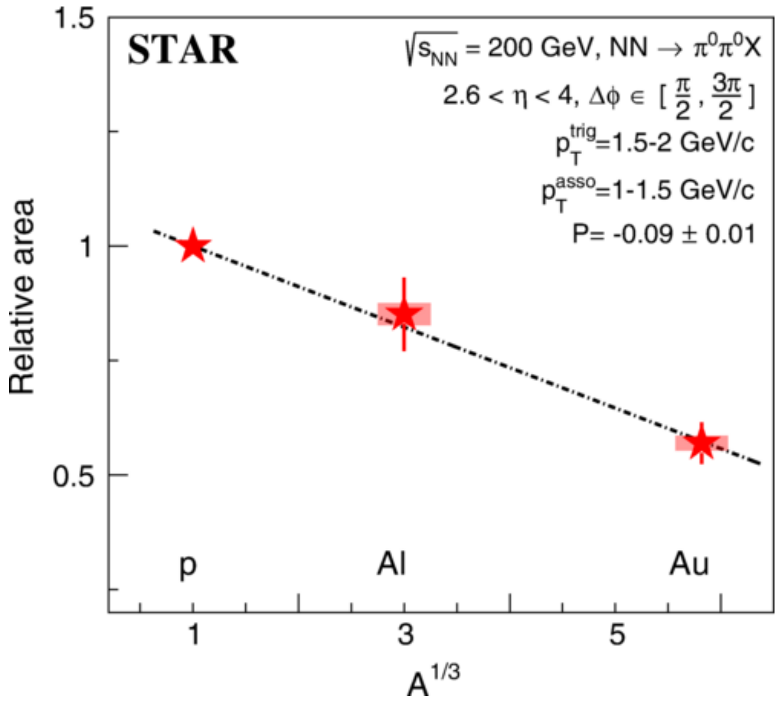
Phys. Rev. Lett. **130**, 212301 (2023)

Brookhaven National Laboratory

QCD Non-linear Effects

Phys. Rev. Lett. **129**, 092501 (2022)





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}

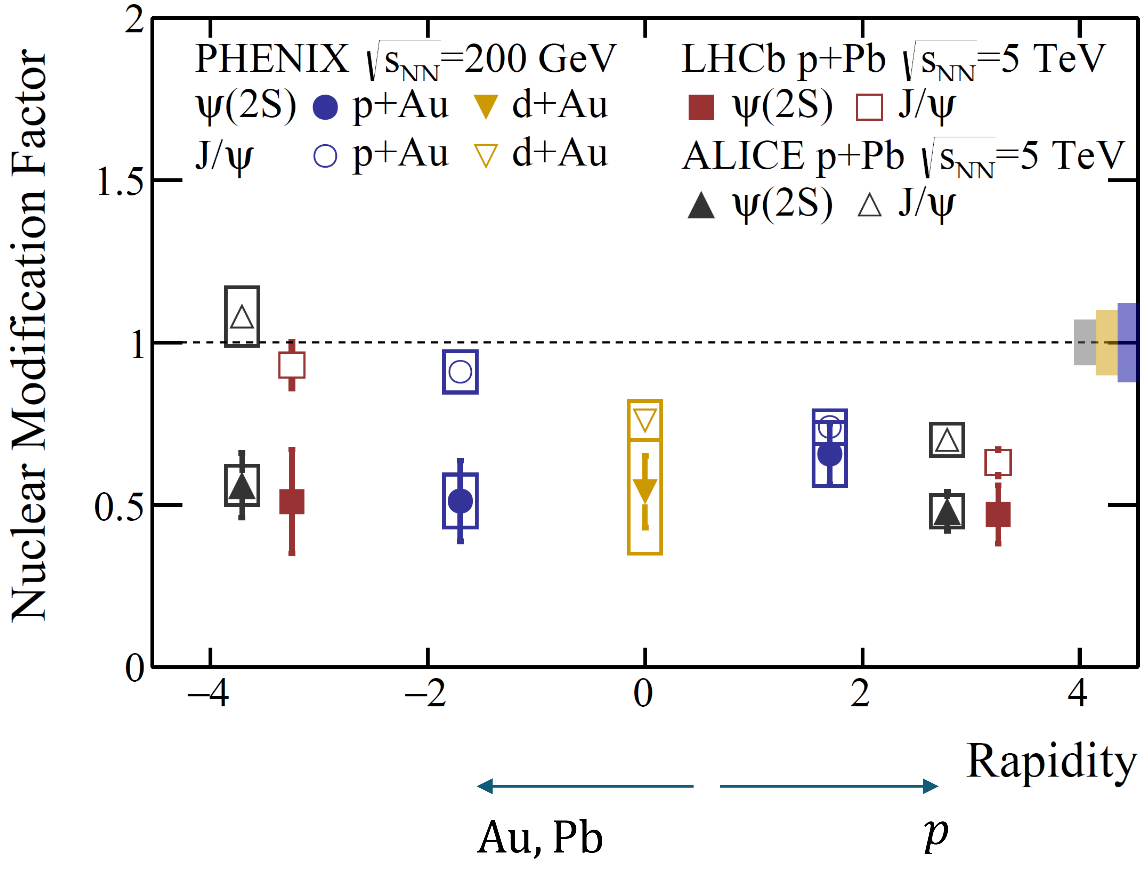
STAR forward upgrades will characterize non-linear effects with charged di-hadrons, γ-jet, di-jet

Brookhaven National Laboratory

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

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

Editors' Suggestion

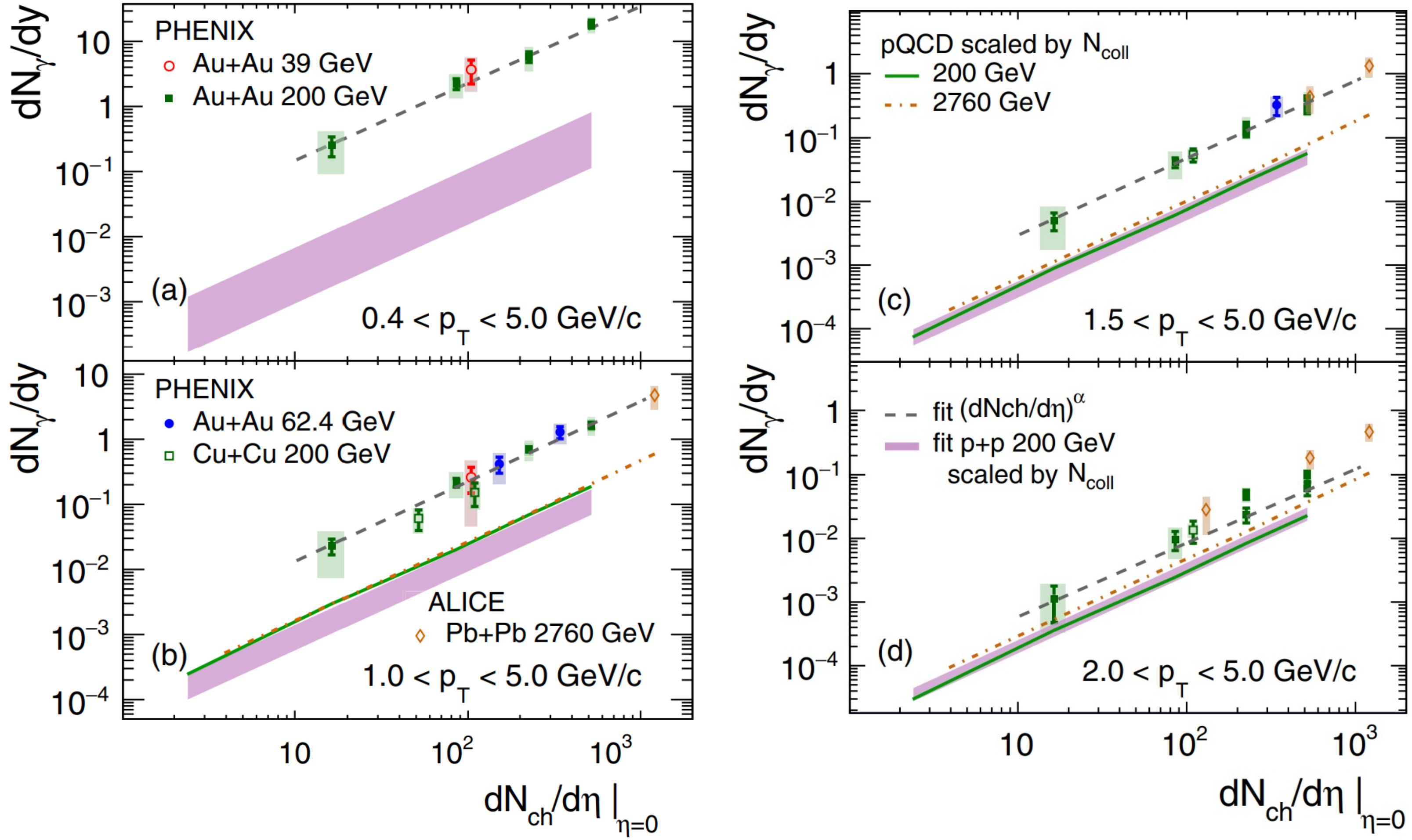


- Nuclear modification of $\psi(2S)$ in $p + \mathrm{Al}$, and $p + \mathrm{Au}$
- Forward (p-going):similar suppression of J/ψ and $\psi(2S)$

  → 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

Low pT direct photon at 39 and 62 GeV

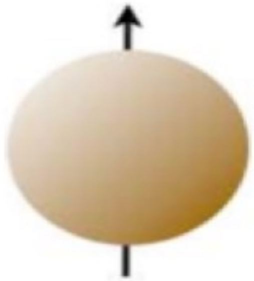


arXiv:2203.12354 (2022),
PRC **107**, 024914 (2023)

- Systematic study of low p_T direct photon production at 39 and 62 GeV and comparison with higher collisions energy
- Photon yield scaled with $dN/d\eta$ for all systems
- PRC Editor's suggestion

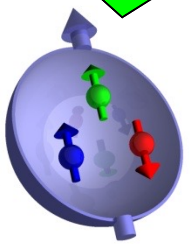
The incomplete nucleon: spin puzzle

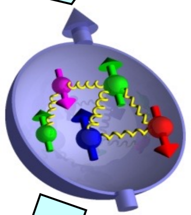
Jaffe-Manohar, 90
Ji, 96

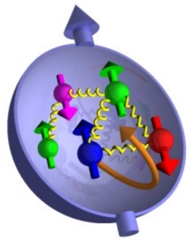


Proton Spin

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







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

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

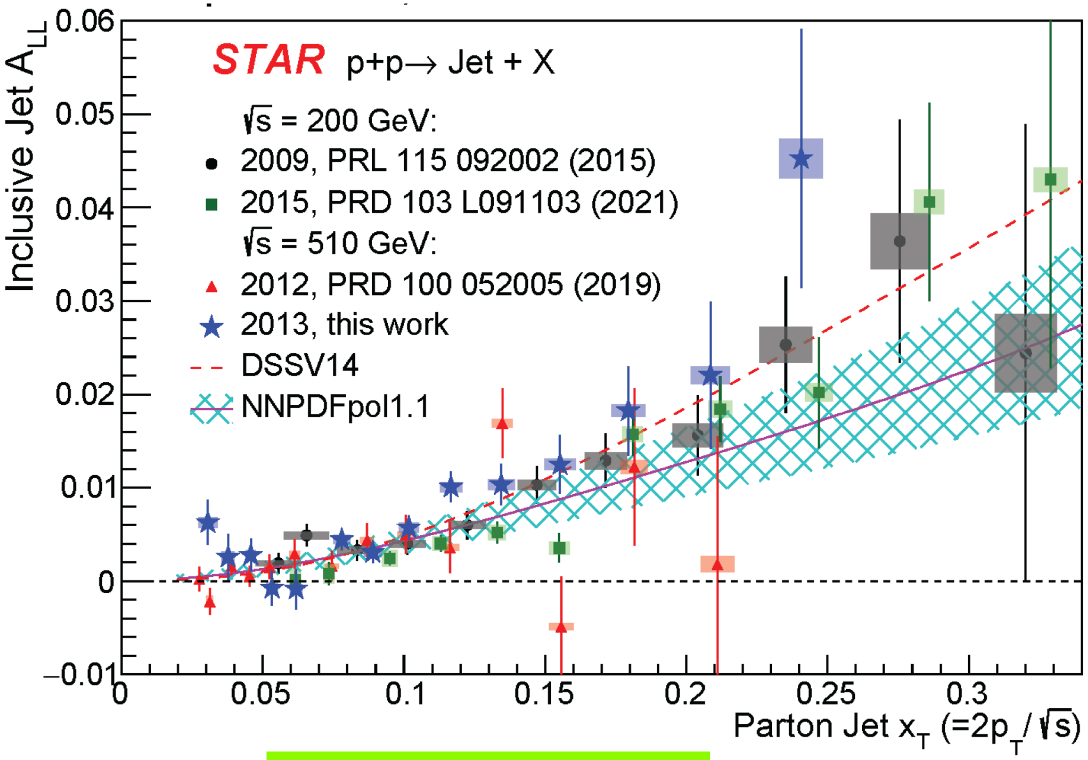
~40% (RHIC Spin data)
At Q^2 =10 GeV^2

Orbital Angular Momentum of quarks and gluons
Little known

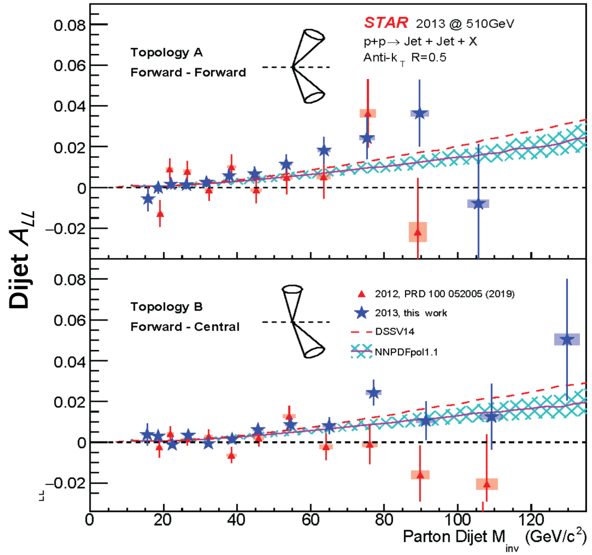
Net effect of partons' transverse motion?

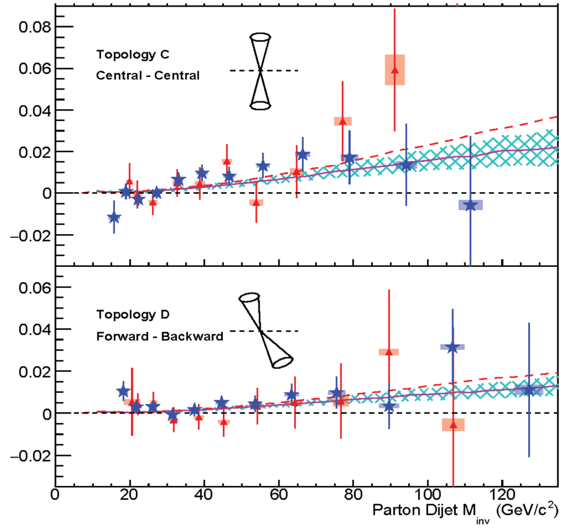
Helicity PDFs: ΔG

Golden probes for Δg: Double spin asymmetry A_{LL} for jets, di-jets and π^0
to increase x-range covered: go to higher $\sqrt{s}$ (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 $0.015 < x < 0.25$

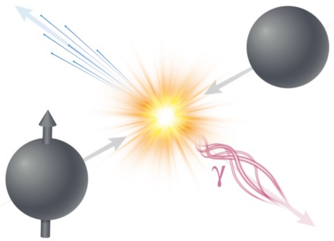
Brookhaven National Laboratory

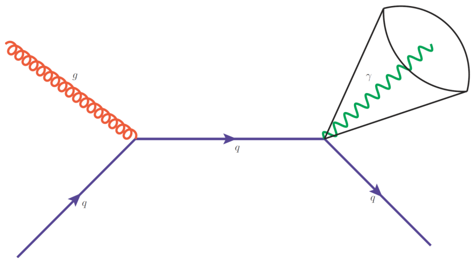
Spin highlights from direct photons

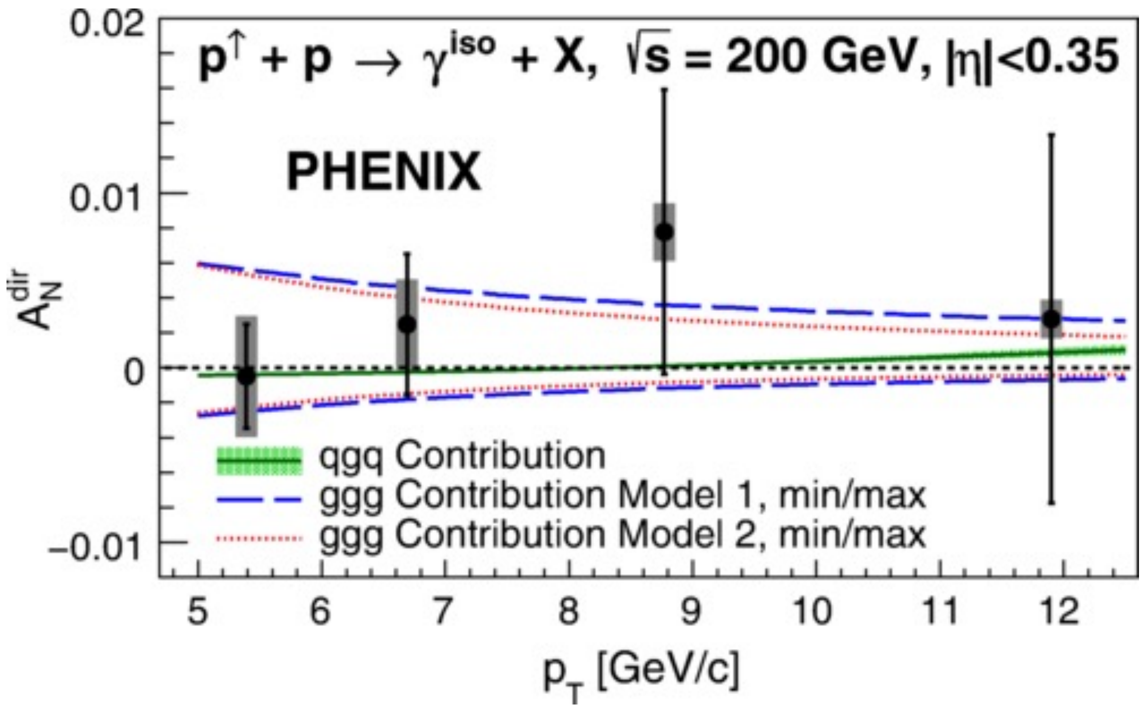
PRL 127, 162001 (2021)

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

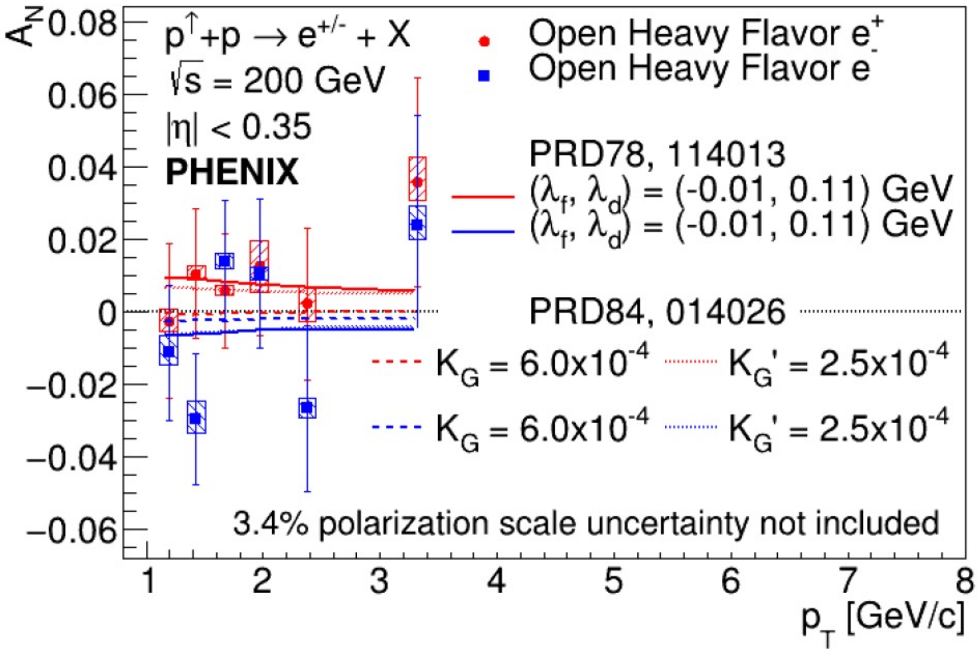


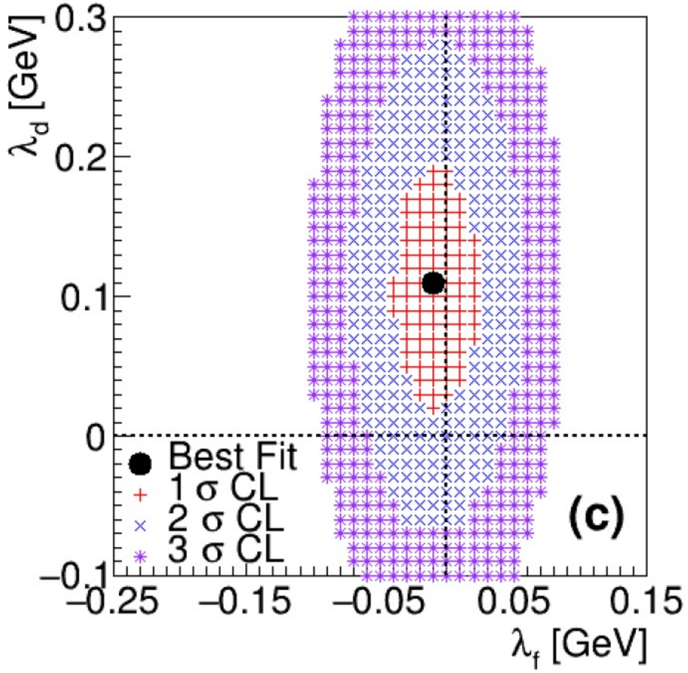




Spin Physics highlights

arXiv:2204.12899 (2022)





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

$\sqrt{s}$ = 200 GeV

$|\eta| < 0.35$

PHENIX

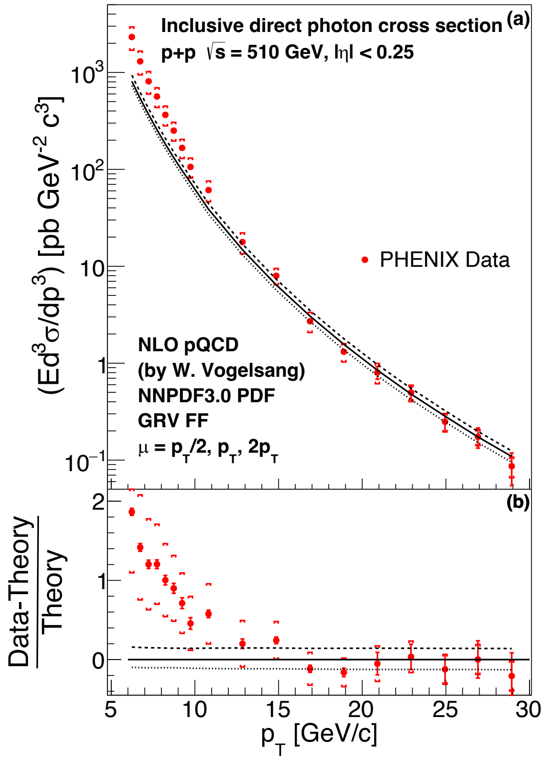
Theory: PRD78, 114013

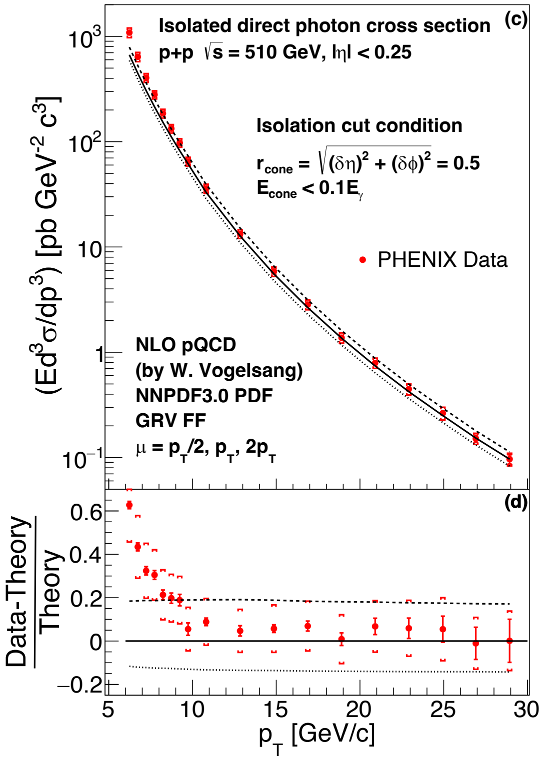
$A_N^{D^0/\overline{D}^0 \rightarrow e^{+/-}}(\lambda_f,\lambda_d)$

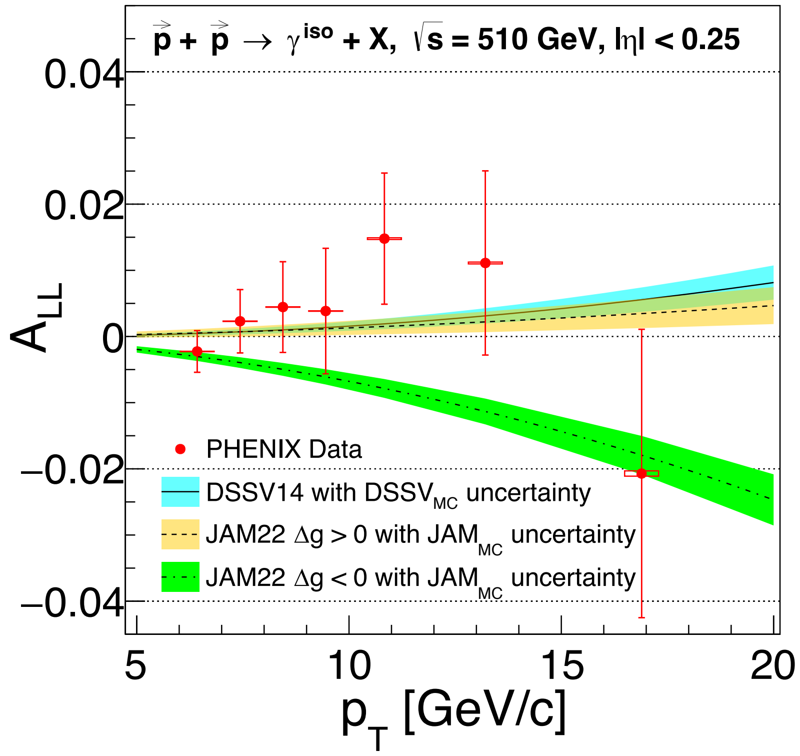
- Measurement of A_N of heavy-flavor decay electrons
- **Constraints on parameters of Tri-Gluon correlation model by Z.Kang and J.W.Qiu**
  - **The first measurement on the model parameters (λ_f, λ_d) of the model**

PHENIX results on Direct-Photon Cross Section and Double-Helicity Asymmetry

arXiv:2202.08158, to appear in PRL







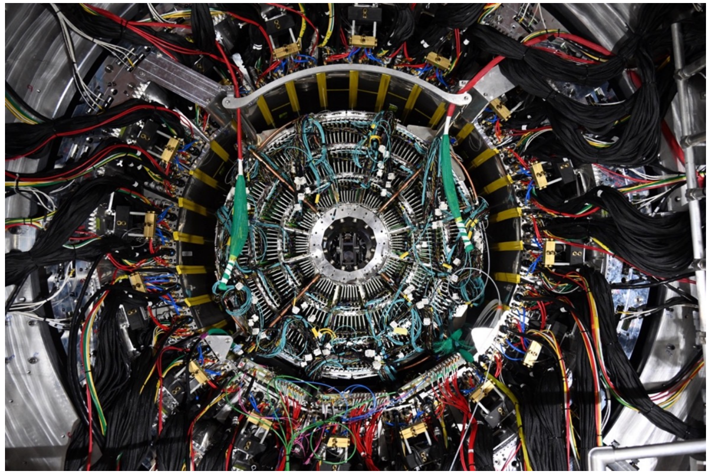
- The NLO pQCD calculations are consistent with the results except at lower p_T
- Data consistent with the positive gluon-spin contributions and strongly disfavor the negative gluon-spin scenario

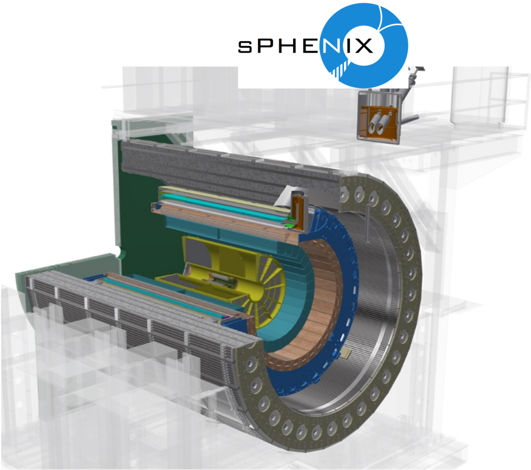
Brookhaven National Laboratory

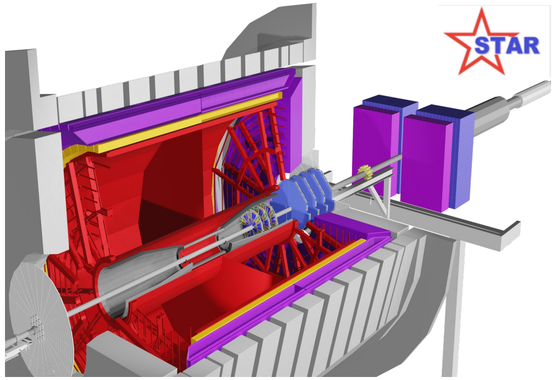
Completing the RHIC Mission with sPHENIX and STAR

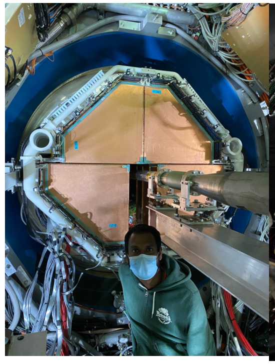
- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- sPHENIX outer hadron calorimeter will be part of the EIC project detector
- Detector (sPHENIX and STAR) removal and repurpose for EIC

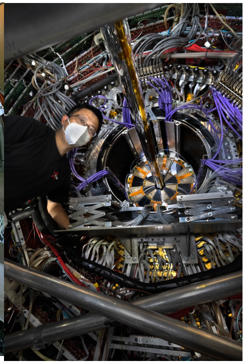
- STAR with forward upgraded detectors will understand the initial state of nucleon and nuclei from high to low x and the inner workings of QGP
- How are gluons and sea quarks distributed in space and momentum inside the nucleon?
- How does a dense nuclear environment affect quarks and gluons, their correlations, and their interactions and giving rise to non-linear effects?









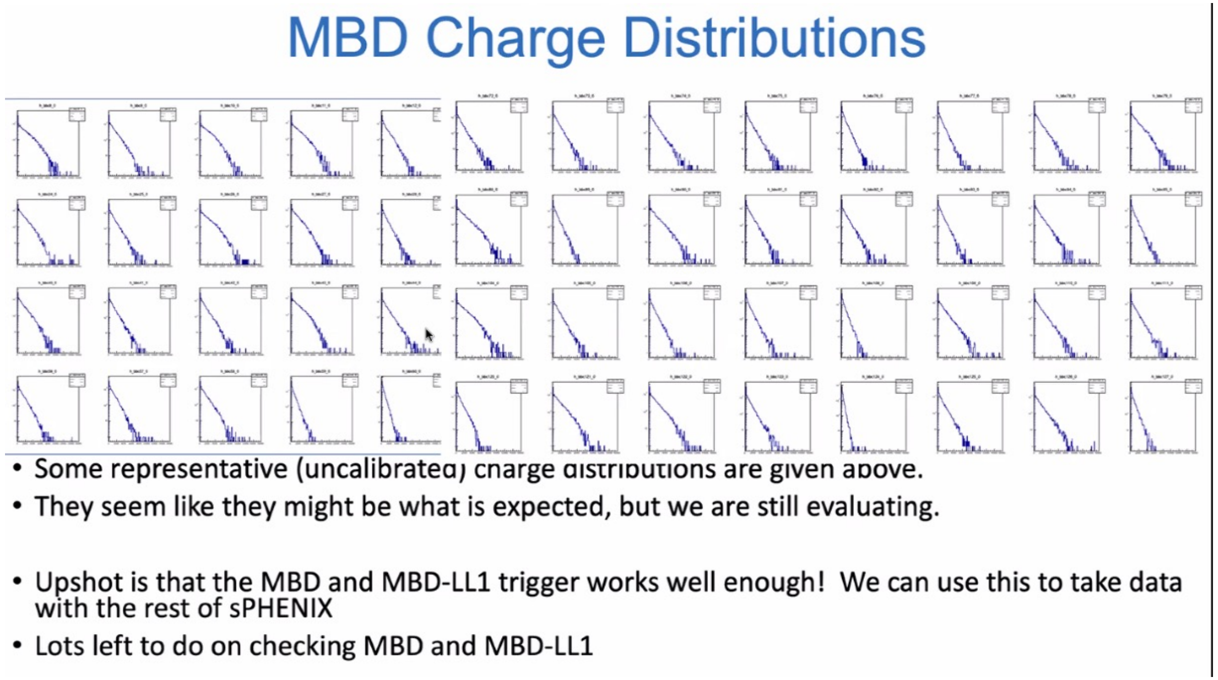


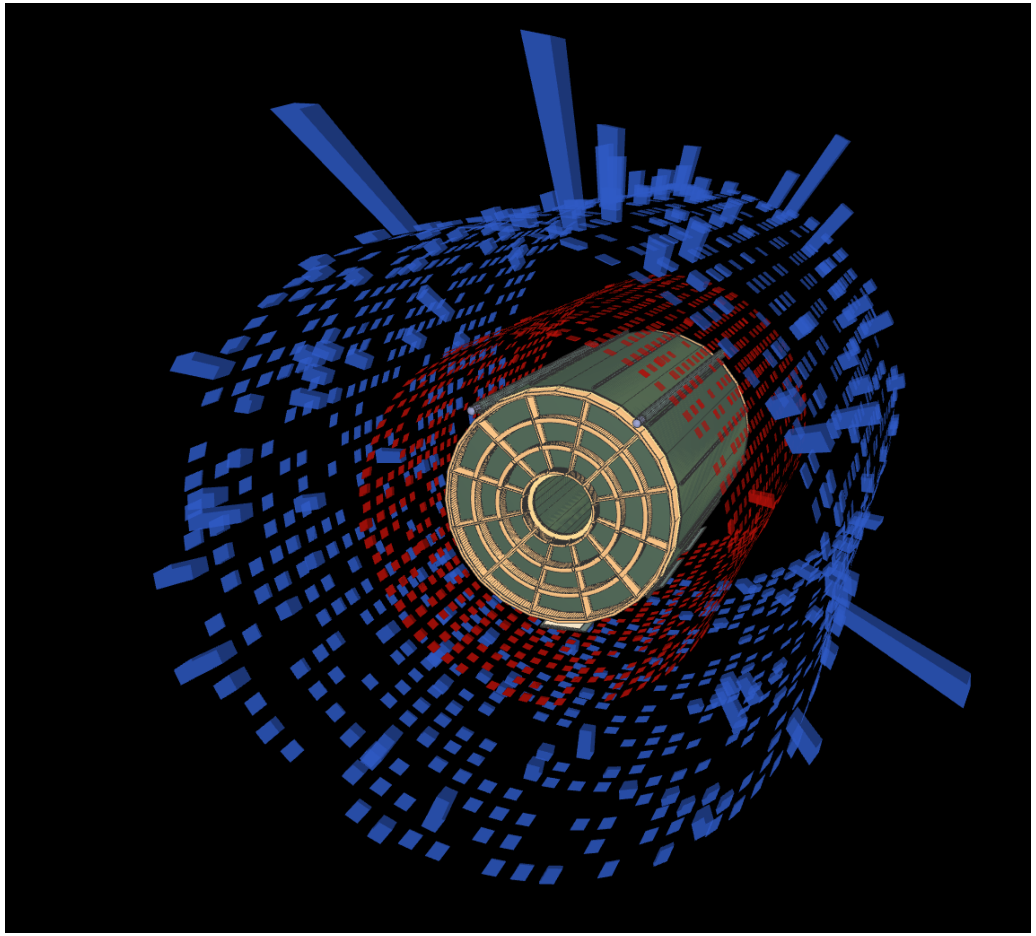
Synergies with the EIC science and contribute to EIC workforce development

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

Brookhaven National Laboratory

First collisions at sPHENIX just after midnight, May 18th, 2023!





MBD: minimum bias detector
Right: Event display from outer HCAL and inner HCAL for one collision event from a coincidence of 20 PMTs on the north and south MBDs forming a functional central "trigger"

Brookhaven National Laboratory

The Electron-Ion Collider

2015 NSAC LRP

"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

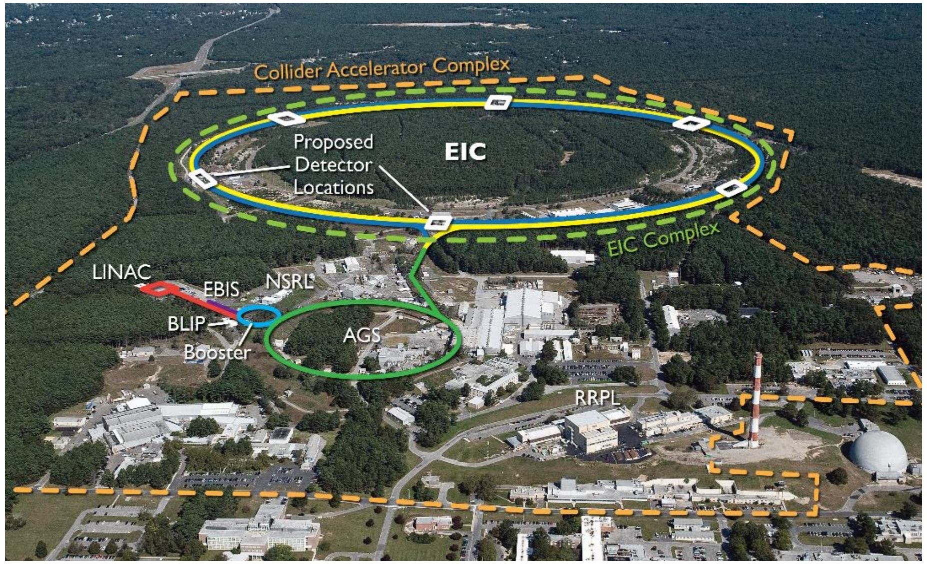
Project Design Goals

- 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)

An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the **mass** of the nucleon arise?
- How does the **spin** of the nucleon arise?
- What are the emergent properties of dense systems of gluons?



Double Ring Design Based on Existing RHIC Facility

Major milestones: CD-0 December 2019; DOE EIC site (BNL) selection Jan 2020; CD-1 June 2021; EIC project detector selected in March 2022; ePIC collaboration formed in July 2022 & spokesperson (John Lajoie) and deputy spokesperson (Silvia Dalla Torre) elected Feb 2023; EIC Resource Review Board (RRB) meeting April 2023

Thank you for your time and attention!

Brookhaven National Laboratory is supported by the U.S. Department of Energy's Office of Science.