RHIC
Overview and Future Program

8th Workshop on
Hadron Physics in China
CCNU

Berndt Mueller

August 8, 2016

BROOKHAVEN
NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

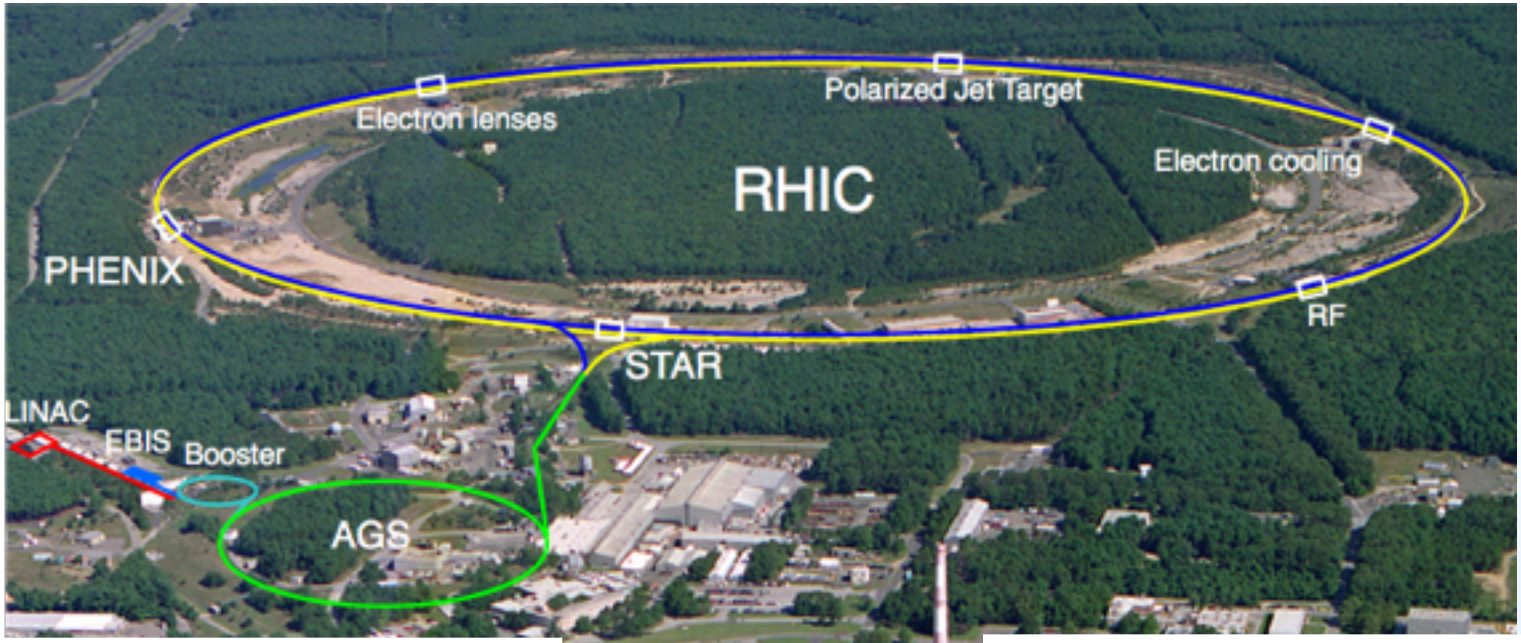
2015 NSAC Long Range Plan

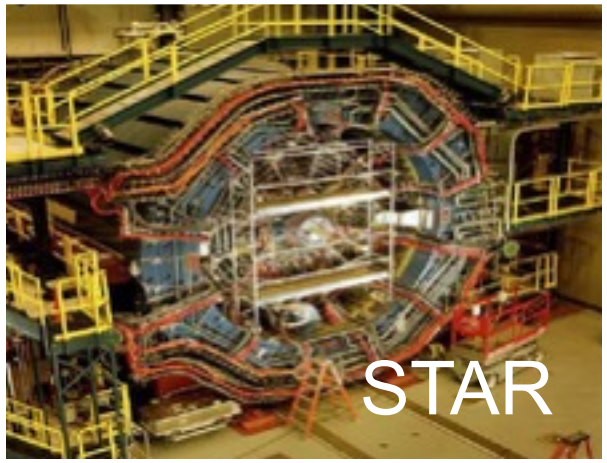
RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

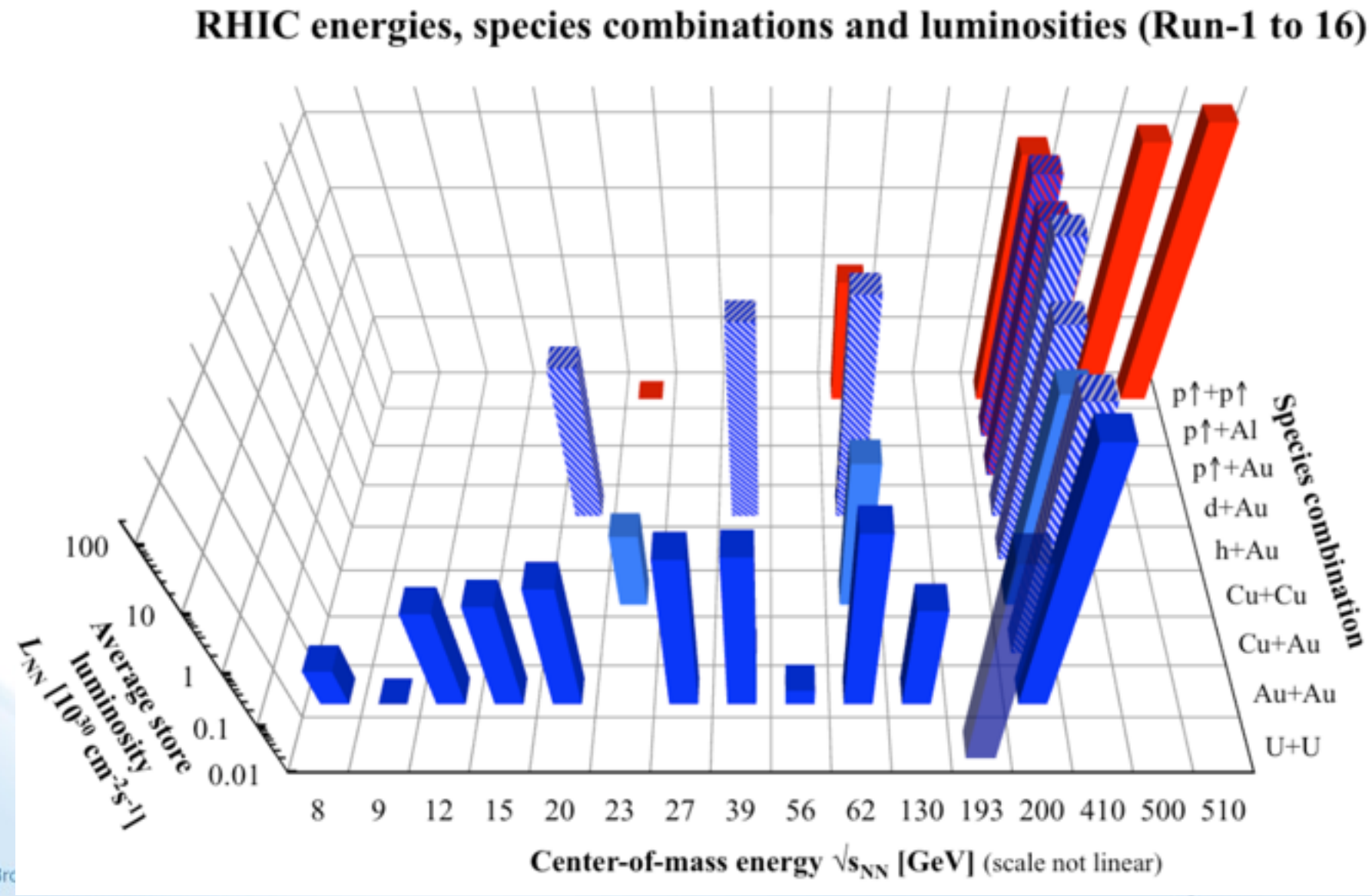
- *Complete the CEBAF 12 GeV upgrade and execute its program*
- *Complete construction of FRIB at MSU*
- *Run a targeted program in neutrinos and fundamental symmetries*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

RHIC: Champion of versatility





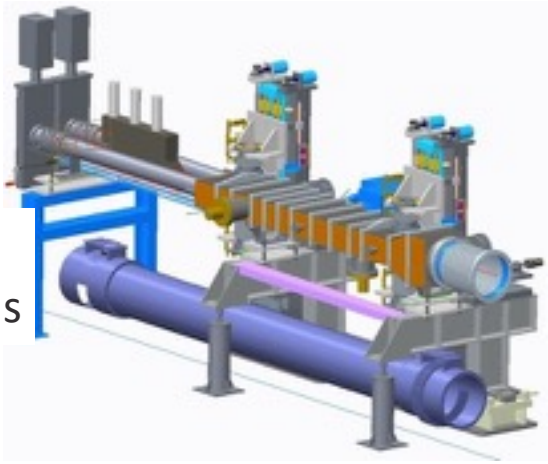
You want it - you can have it!

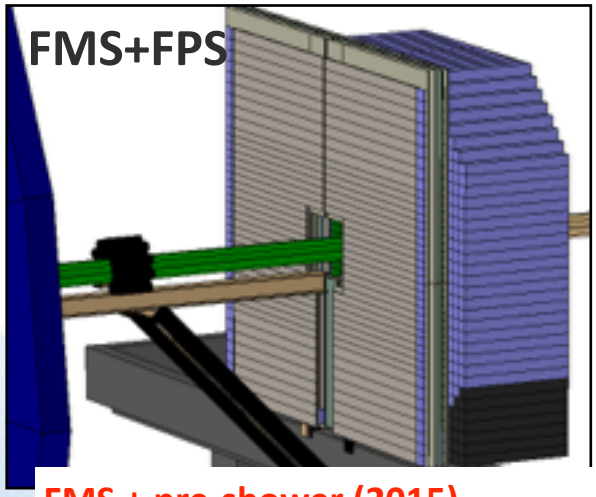


Recent Detector Upgrades

Trigger/DAQ x2 throughput

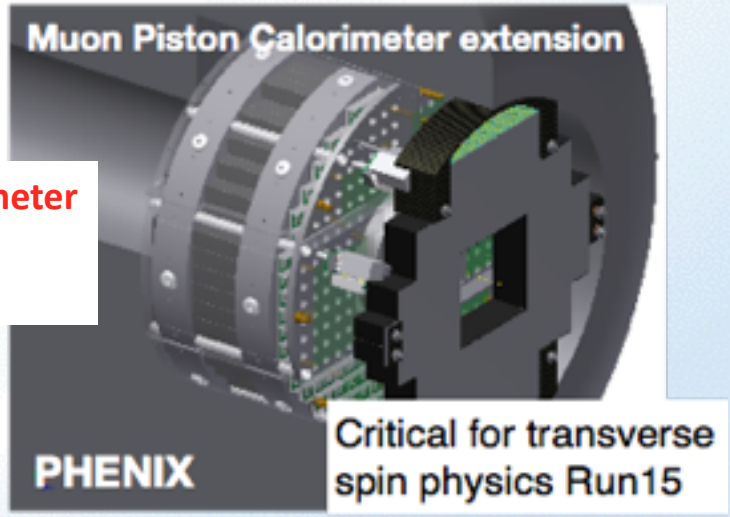
Roman Pots (2015)
Tag diffractive protons





FMS + pre-shower (2015)
A_N photon, jets, Drell-Yan; ridge, fluctuation, spectators

Muon Piston Calorimeter Extension (2015)
Forward photons ID



Exploring the Phases of Nuclear Matter

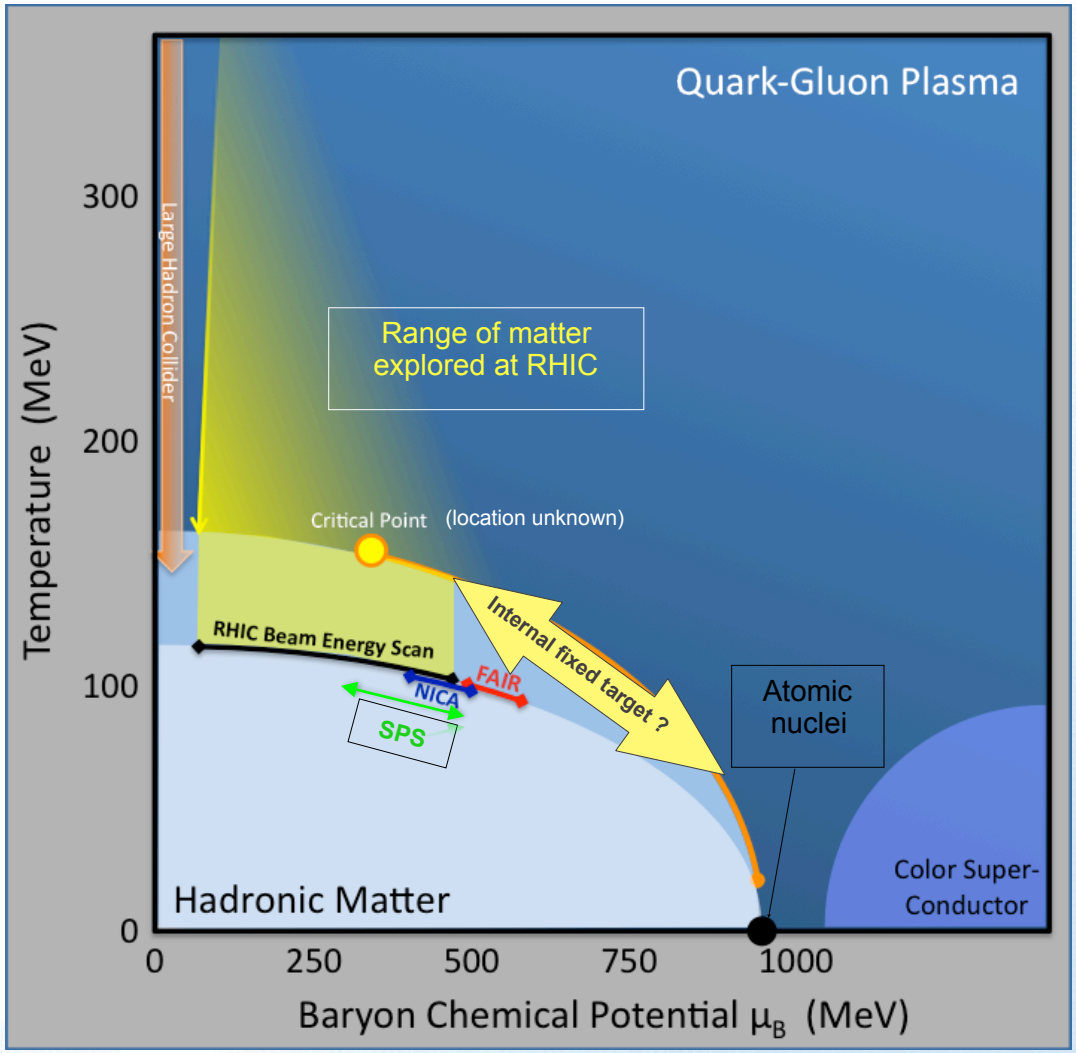
RHIC is ideally suited to explore the Quark-Gluon Plasma and map the QCD matter phase diagram.

RHIC has defined a multi-year program to execute its scientific mission. We just completed Year 3.

Major components of this program are:

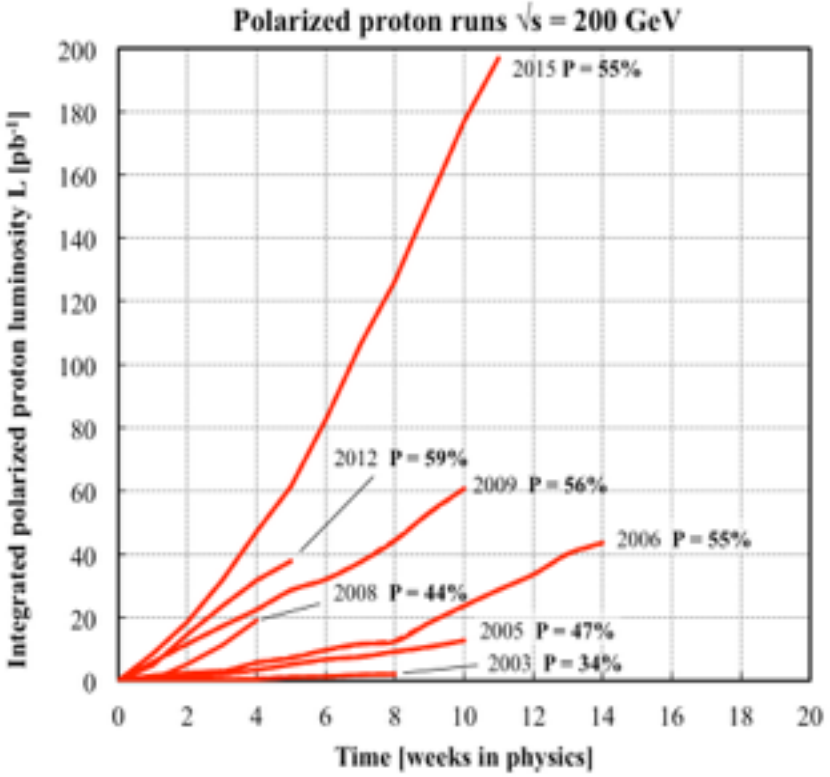
- ***Search for a possible critical point in the QCD phase diagram***
- ***Find unambiguous evidence for the restoration of chiral symmetry***
- ***Discover novel phenomena caused by topological QGP excitations***
- ***Unravel the mechanism behind the near "perfect" fluidity of the QGP discovered at RHIC***

In addition, RHIC is the first and only polarized proton collider in the world. It is uniquely positioned to elucidate the dynamics of spin in QCD. RHIC has already discovered that gluons make up part of the spin of the proton.

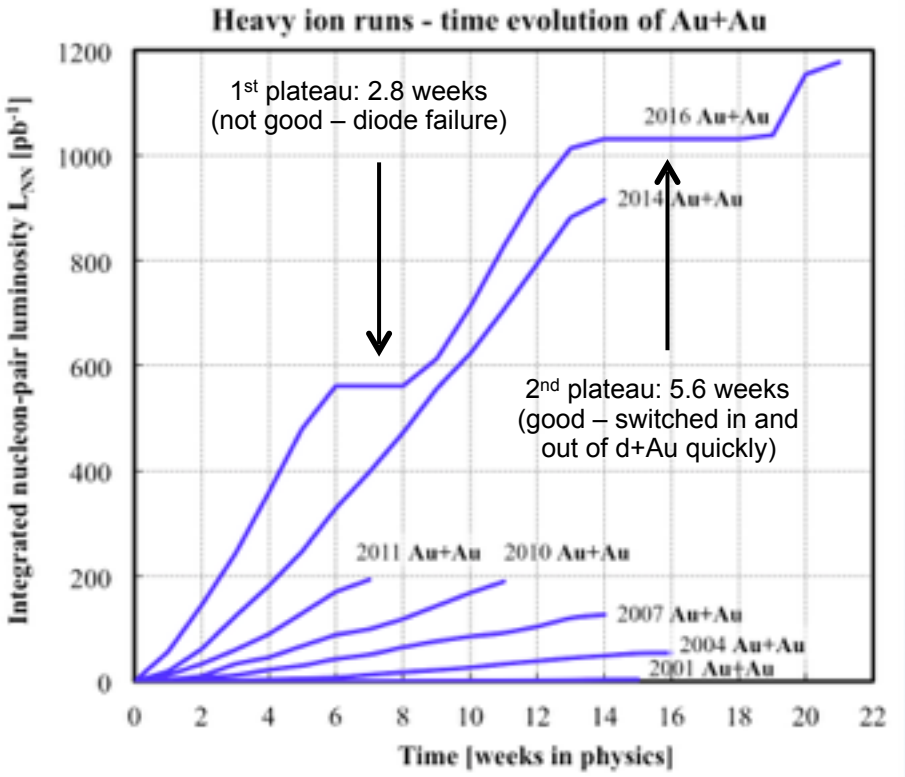


RHIC sets new records …

Run-15 integrated luminosity at $\sqrt{s}$ = 200 GeV exceeds sum of all previous runs

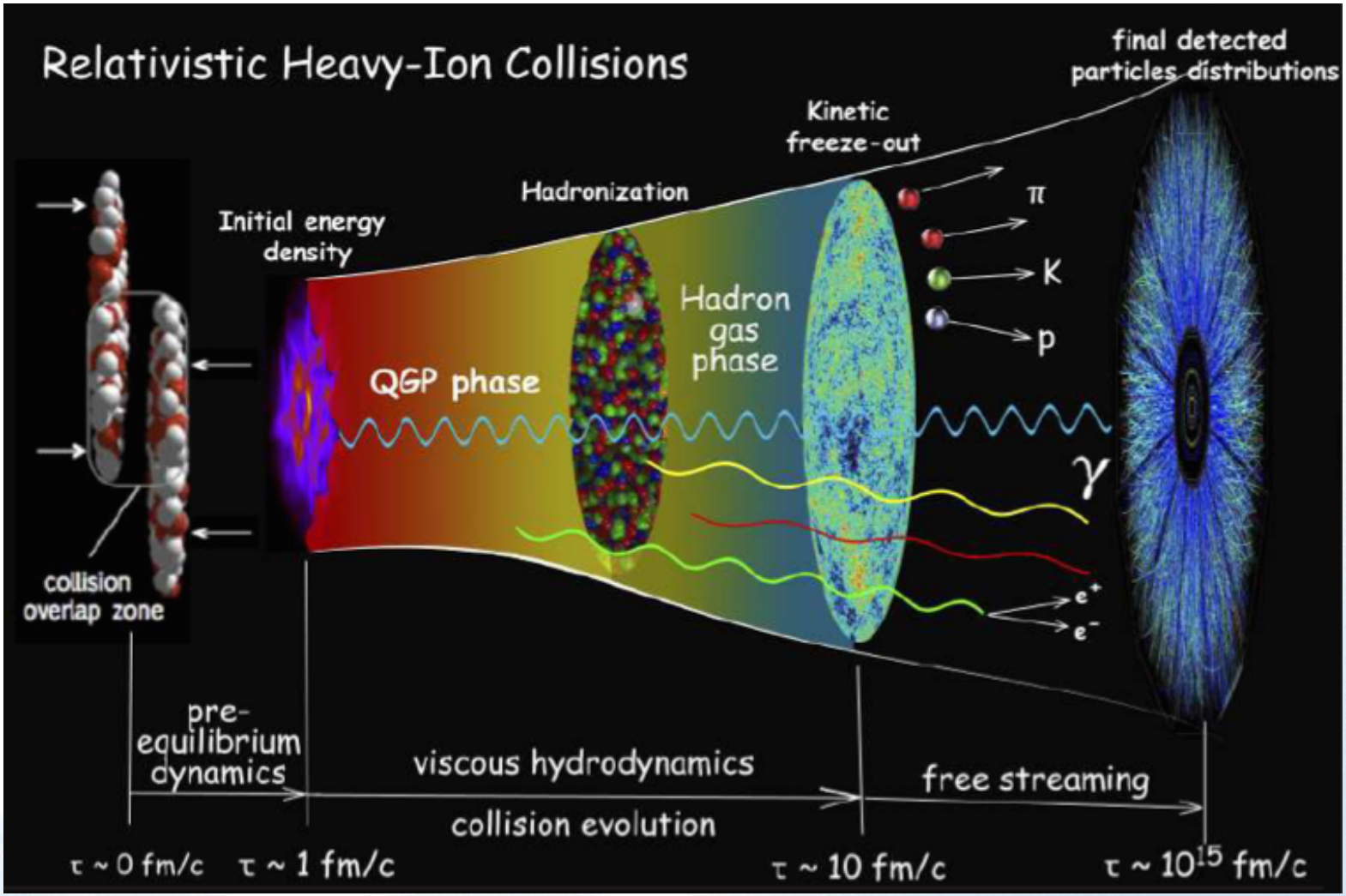


Run-16 luminosity +33% vs. 2014

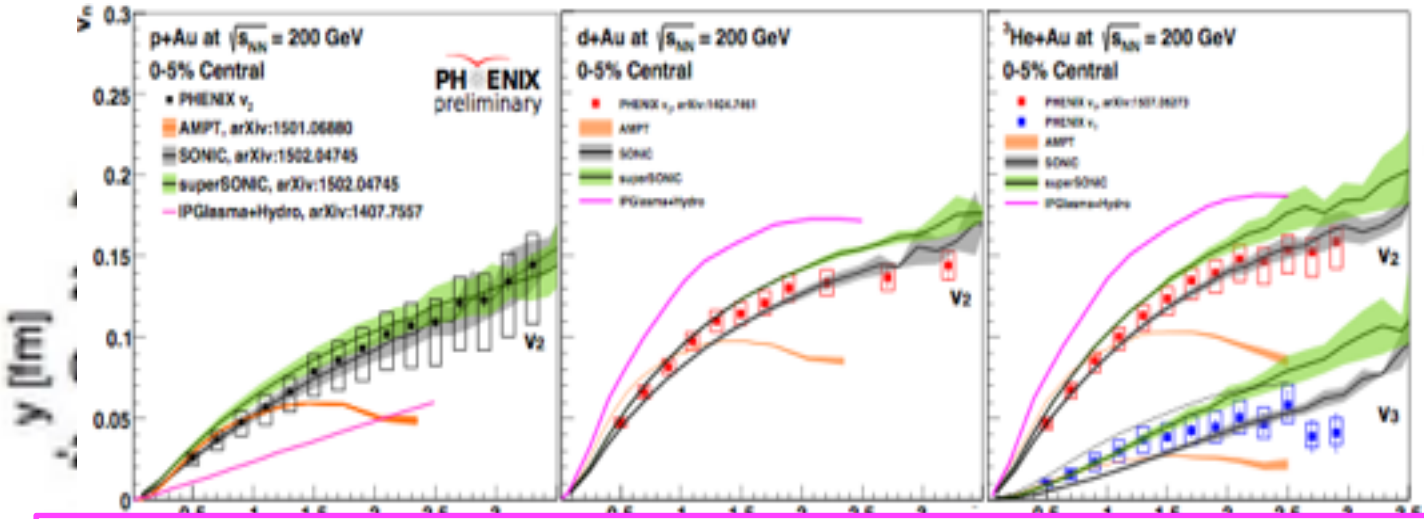


d+Au reached same number of collisions in 1 week as 2008 run in 8 weeks

Standard model of the "Little Bang"



Tiny drops of QGP?

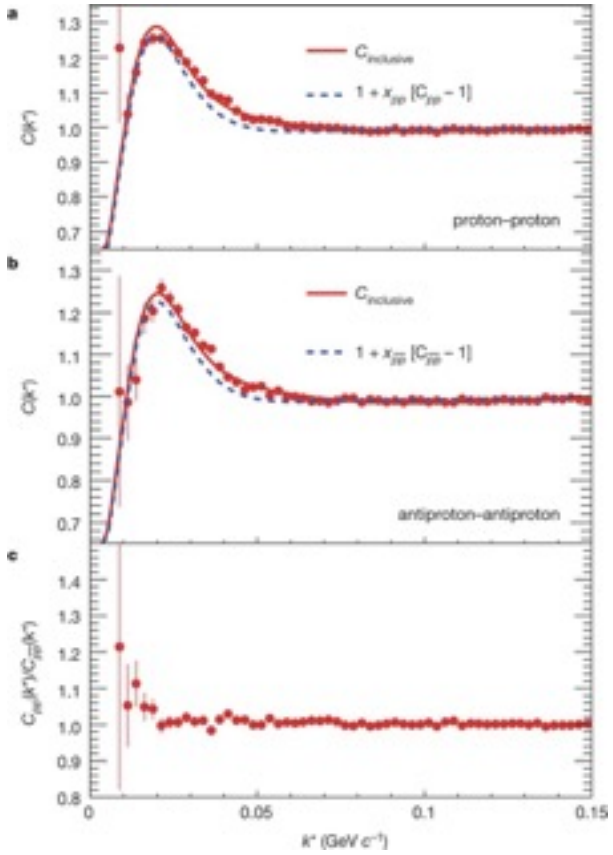


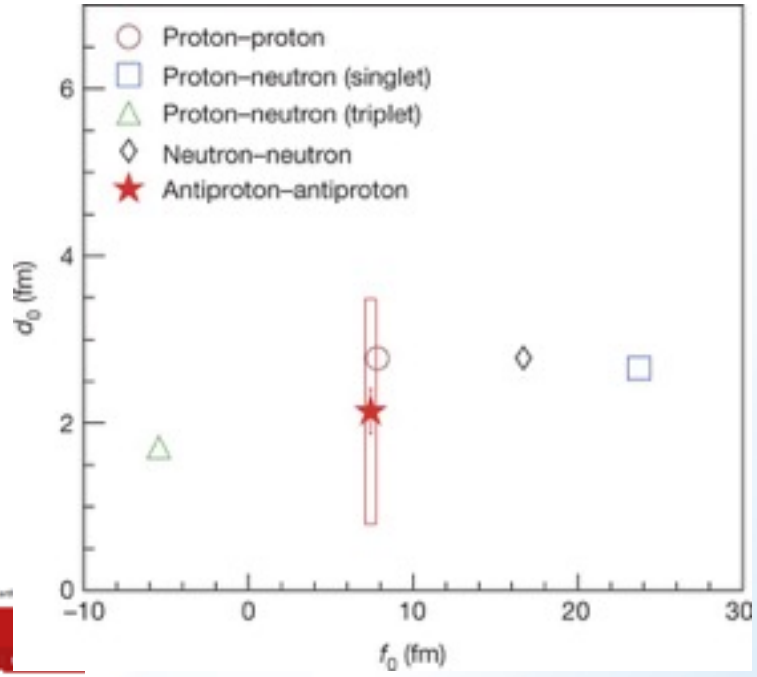
Data-Theory comparison confirms hydrodynamic collective flow

An opportunity for heavy ion theory being tackled now

Final state

Interaction between two antiprotons





Nature **527**, 345 (2015)

By applying a technique similar to Hanbury-Brown and Twiss intensity interferometry, we show that the force between two antiprotons is attractive.

We report two key parameters that characterize the corresponding strong interaction: the scattering length and the effective range of the interaction

Future Science 2017-20s

Run-17 Plan

- High luminosity 510 GeV transverse polarized p+p run (400 pb^{-1})
- Study scale evolution of the Sivers effect in W-boson production; possibly confirm sign change of the Sivers effect relative to DIS
- Cosmic ray fragmentation studies with RHICf (1 week)
- Proof of Principle test of coherent electron cooling (1 week)

Run-18 Plan

- Isobar system (^{96}Ru - ^{96}Zr) run (1.2B events each)
- Critical signature of Chiral Magnetic Effect
- 27 GeV Au+Au (2 weeks)

Strongly endorsed by 2016 RHIC PAC.

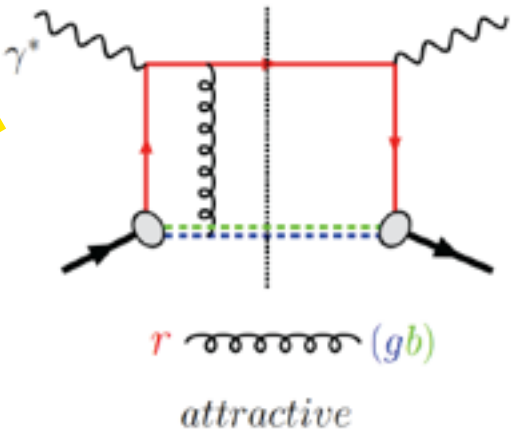
Transverse polarized p+p collisions

Access the dynamic structure of protons:

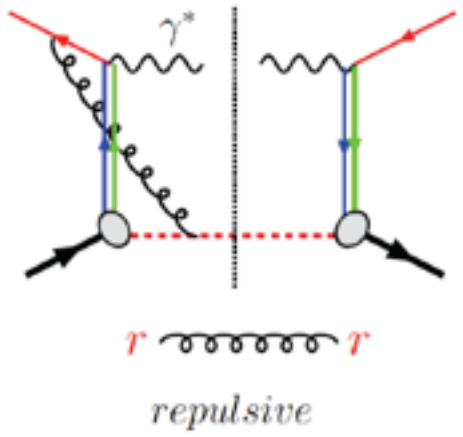
→ **Test and confirm QCD structure of color spin interactions**
- → **Non-universality of transverse momentum dependent functions**
- → **$Sivers_{DIS} = -Sivers_{pp}$**
  - → **Observable: A_N for Drell-Yan and $W^{+/-}$ production**

Will achieve NP Performance Milestone HP13 in Run 17

DIS:
γq-scattering attractive



pp:
qqbar-anhilation repulsive

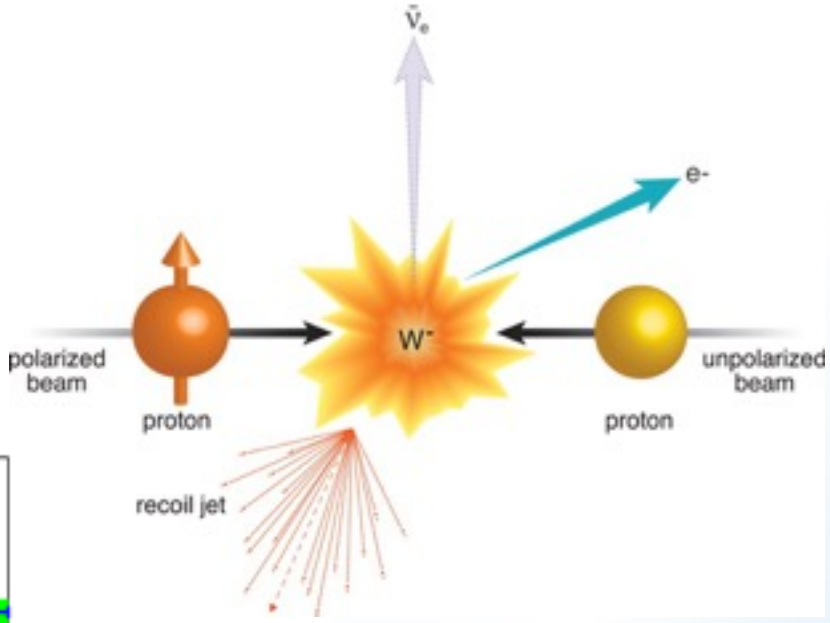


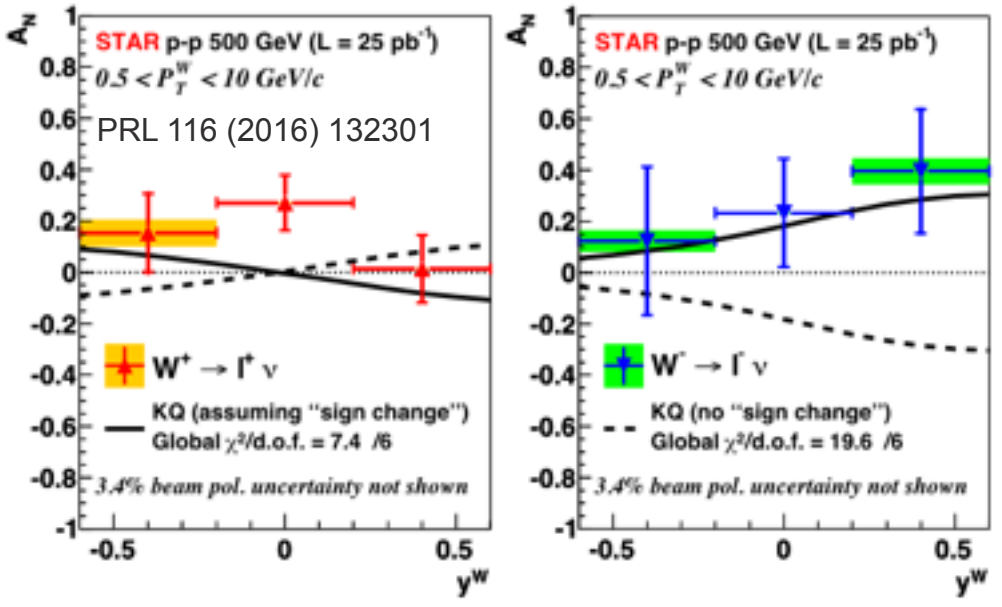
→ **Test scale evolution of transverse momentum dependent functions**
- → **Observable: compare magnitude of A_N for Drell-Yan and $W^{+/-}$**

Scale: DY: $Q^2 \sim 16$ GeV^2 $W^{+/-}$: $Q^2 \sim 6400$ GeV^2

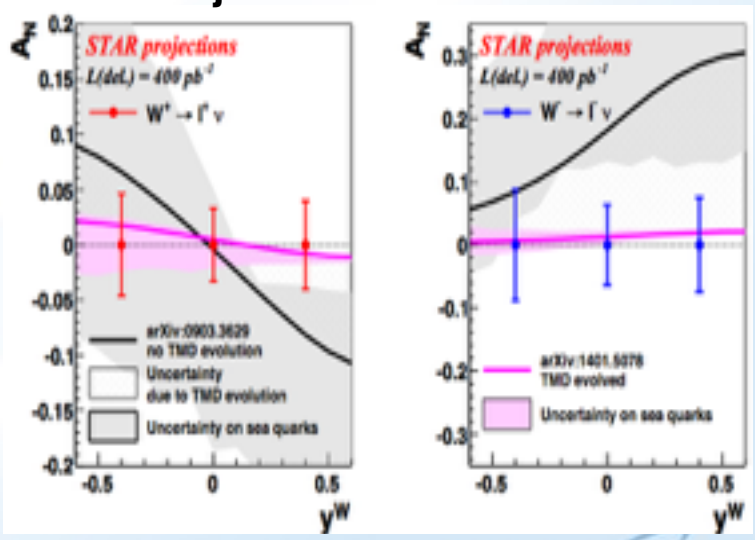
W Sivers function

Analysis of Run-15 data demonstrates viability of definitive measurement





Projections for Run-17

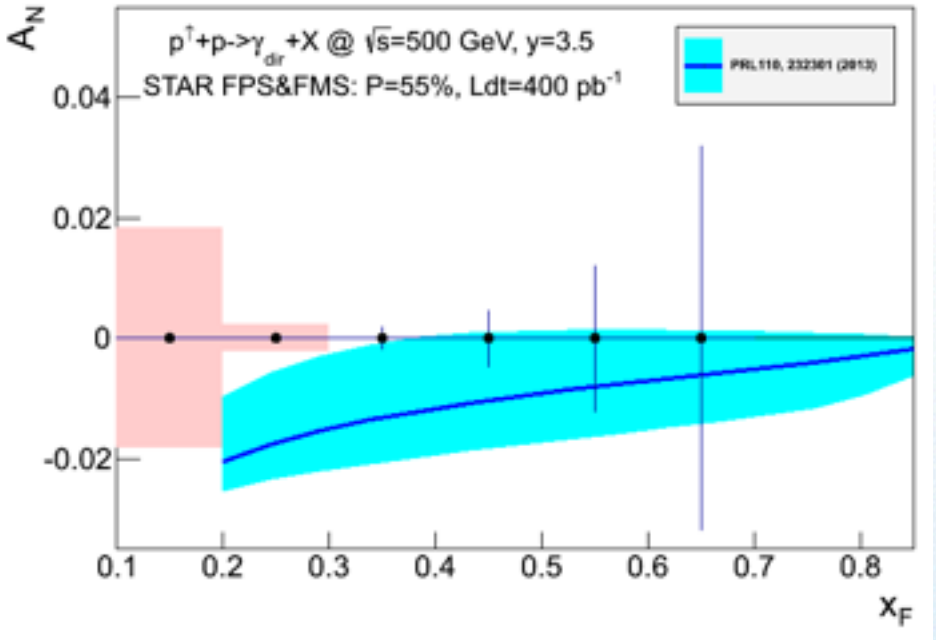


TMD scale evolution assumptions testable
Critical input into projections for EIC !

Direct photon A_N

Measurements of twist-3 observables such as direct photon A_N explore the consistency between TMD formalism and collinear Twist-3 formalism

Forward Meson Spectrometer (FMS)
+ FMS Pre-shower + Poster-Shower



Statistical and systematic uncertainties for the direct photon A_N after background subtraction compared to predictions for $\sqrt{s}$ = 500 GeV.

Summary of Sivers function tests

Main Run-17 measurements

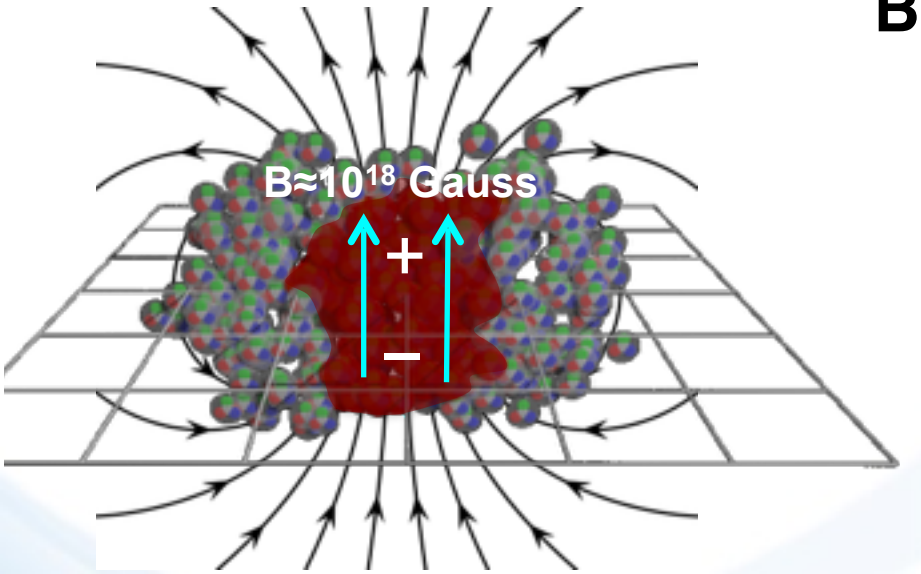
	$A_N(W^{+/-},Z^0)$	$A_N(DY)$	$A_N(\gamma)$
Sensitive to Sivers fct. sign change through TMDs	Yes	Yes	No
Sensitive to Sivers fct. sign change through Twist-3 $T_{q,F}(x,x)$	No	No	Yes
Sensitive to TMD evolution	Yes	Yes	No
Sensitive to sea quark Sivers function	Yes	Yes	No
Detector upgrade needed	No	Yes FMS post-shower	No
Biggest experimental challenge	Integrated luminosity	Background suppression Integrated luminosity	----

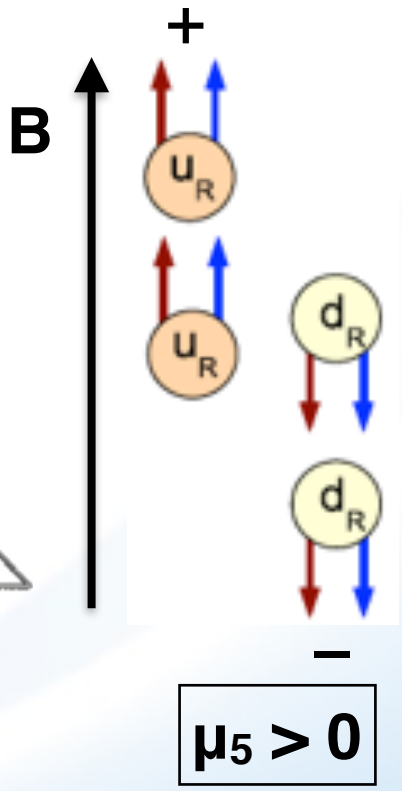
Probing Chiral Symmetry with Quantum Currents

The chiral anomaly of QCD creates fluctuating differences in the number of left and right handed quarks, characterized by a chiral chemical potential μ_5.

In a chirally symmetric QGP, this imbalance generates an electric current along the magnetic field (chiral magnetic effect).

electric charge separation





Spin

Momentum

$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5 \vec{B}$$

$$\langle \mu_5^2 \rangle \neq 0$$

$$\langle JJ \rangle \neq 0$$

$\mu_5 > 0$

Chiral Magnetic wave

Editors' Suggestion

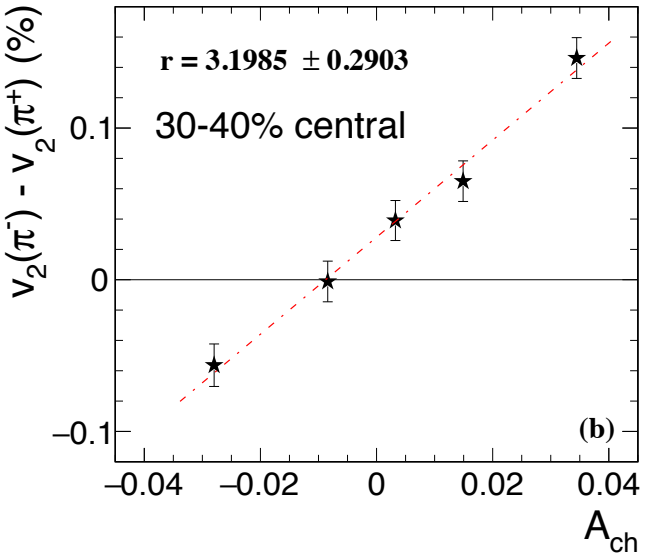
Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions

L. Adamczyk *et al.* (STAR Collaboration)

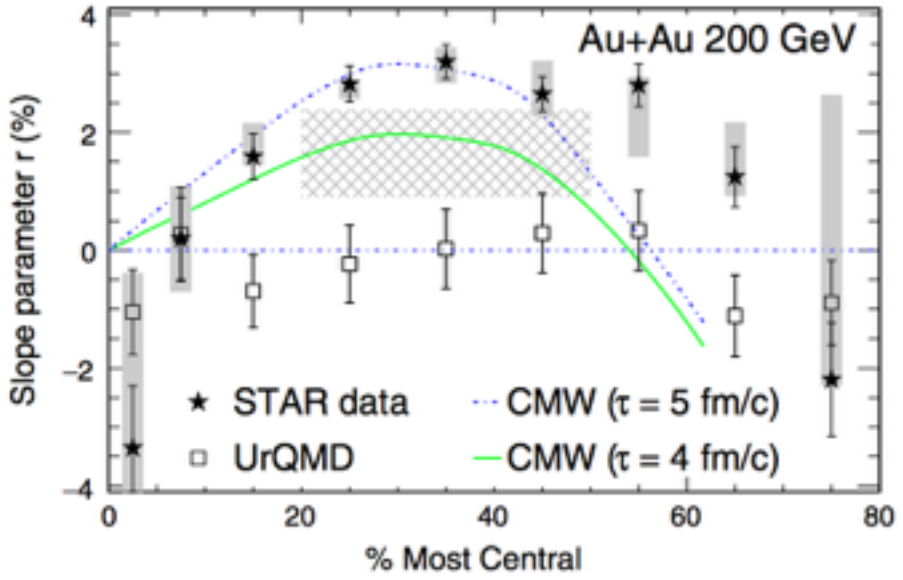
Phys. Rev. Lett. **114**, 252302 (2015) – Published 26 June 2015

A possible signature of chiral symmetry restoration, in the form of a chiral magnetic wave in the quark-gluon plasma, has been observed in heavy-ion collisions at RHIC.

Show Abstract +



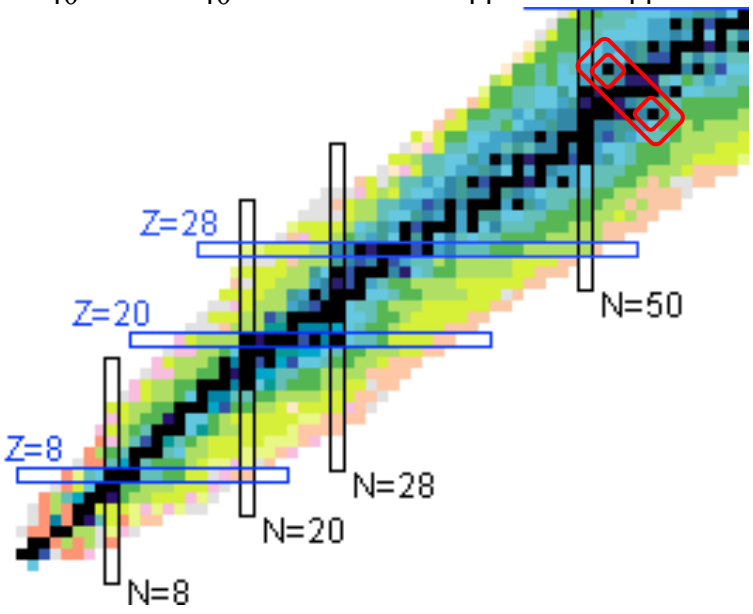
But models with magnetic field-independent flow backgrounds can also be tuned to reproduce some of the observed charge separation effects.

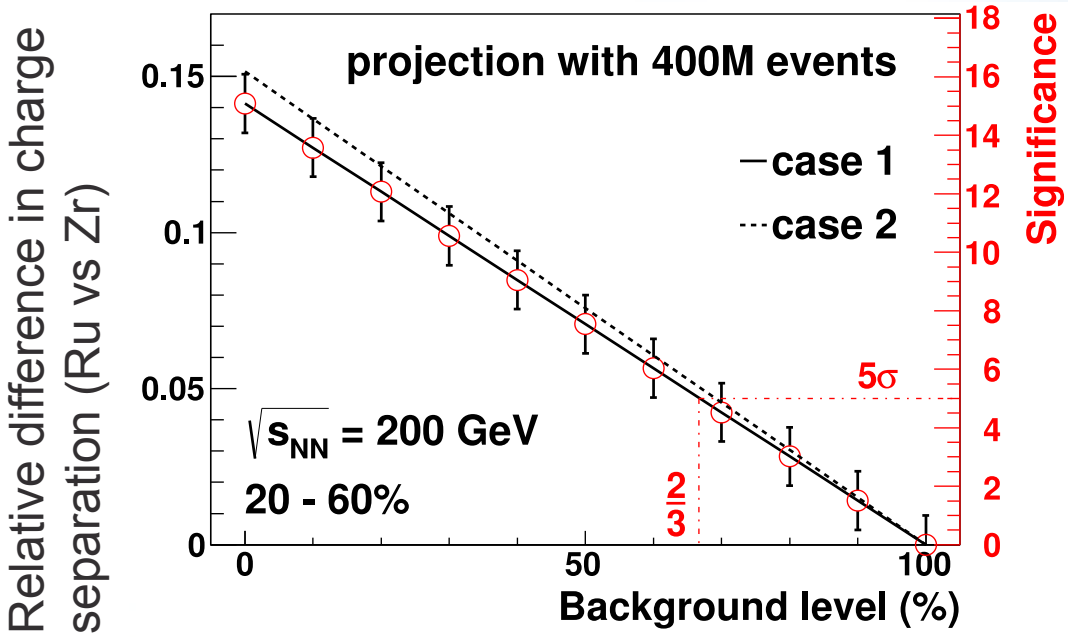


Probing Chiral Symmetry (Run-18)

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation

$^{96}_{40}Zr + {}^{96}_{40}Zr$ vs. $^{96}_{44}Ru + {}^{96}_{44}Ru$

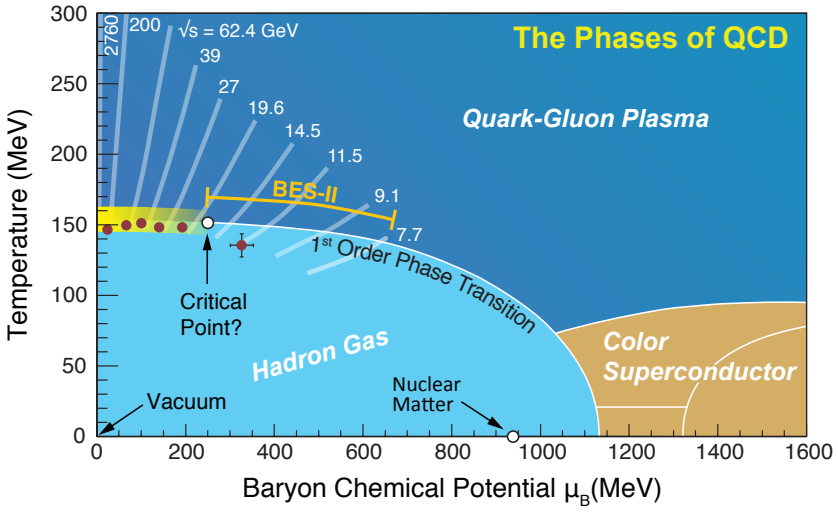




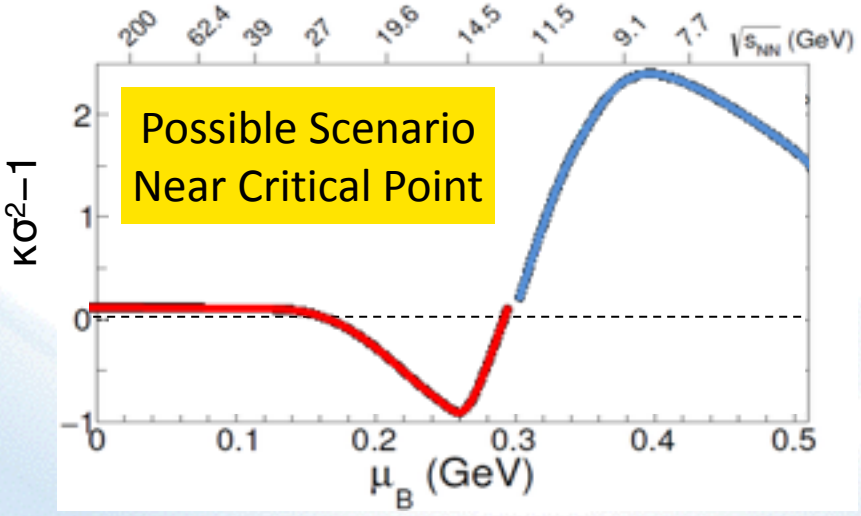
Isobar collisions will tell us what fraction of the charge separation is due to CME to within +/- 6% of the observed signal, allowing for a 5σ measurement if CME is 1/3 of the observed effect.

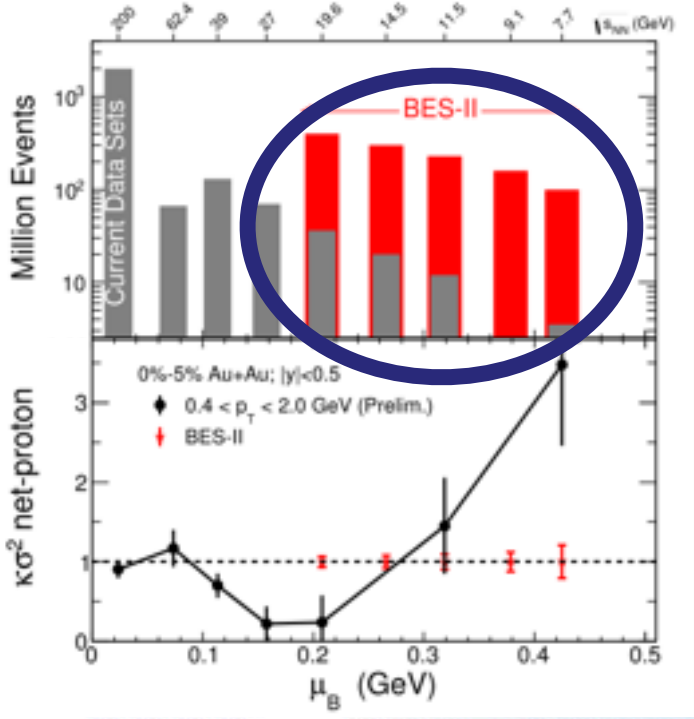
BES-2: iTPC, LEReC

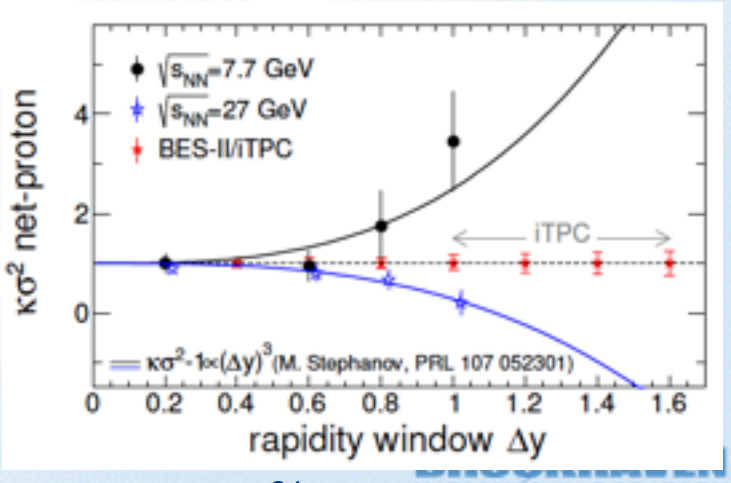
Beam Energy Scan II



Model independent structure of net baryon number kurtosis

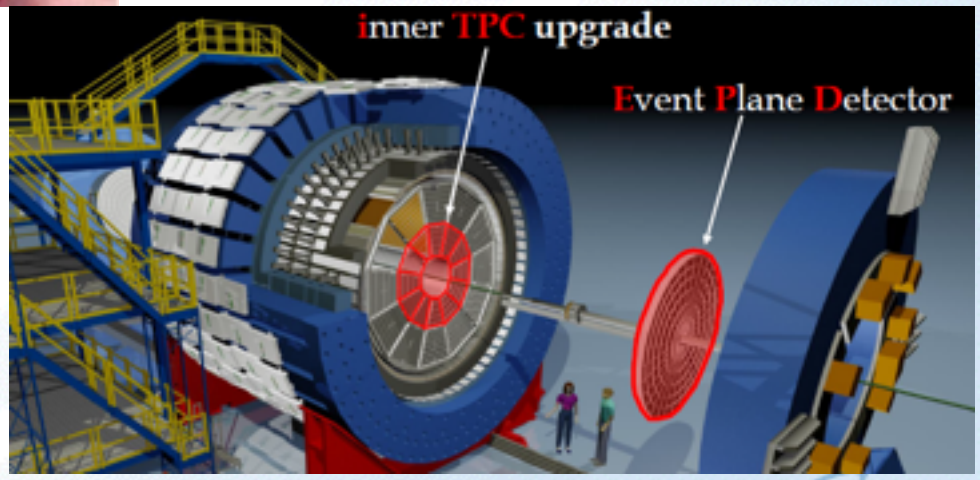






STAR Upgrades and Performance Enhancements

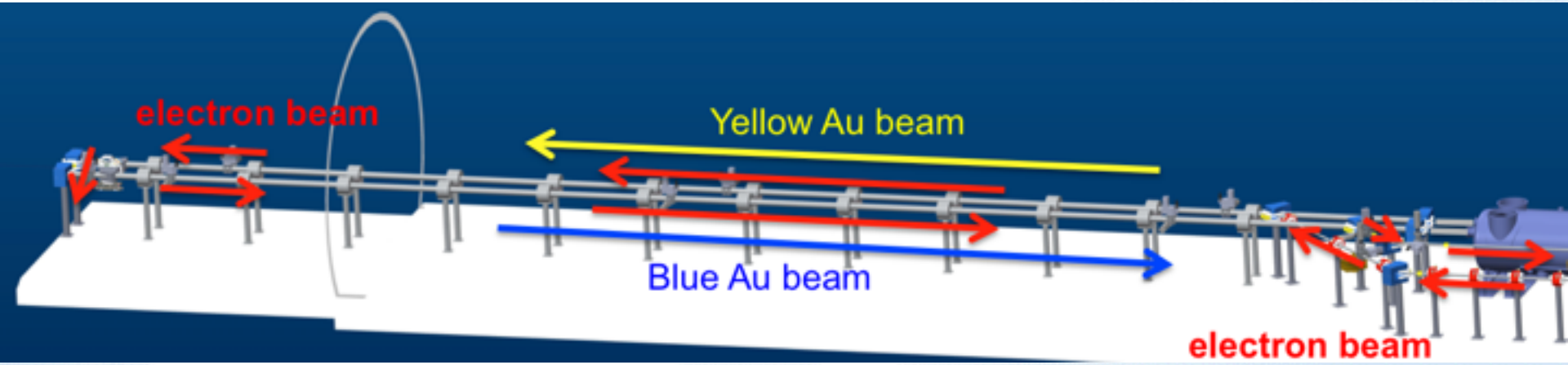
iTPC upgrade (2018)
Replace inner TPC Sectors
Extend rapidity coverage
Better particle ID
Extend low p_T coverage



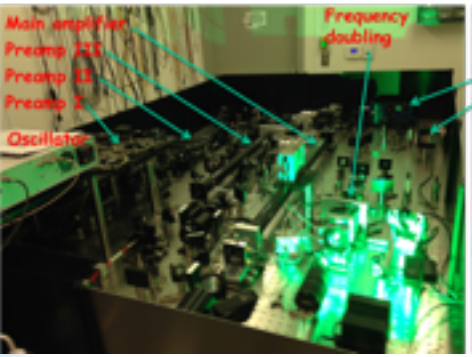
Event Plane Detector (2018)
Improved Event Plane Resolution
Centrality definition
Improved trigger
Background rejection

Low Energy e-Cooling for BES-II

- Cooling of low energy heavy ion beams (3.8–5.0 GeV/n) with bunched electron beam increases luminosity
- Enables a QCD critical point search with a high statistics Beam Energy Scan
- Use Cornell DC electron gun and existing SRF cavity for cost effectiveness
- Project on track for completion in 2018, use in low-energy RHIC runs in 2019-20



LEReC Layout



Cooling sections

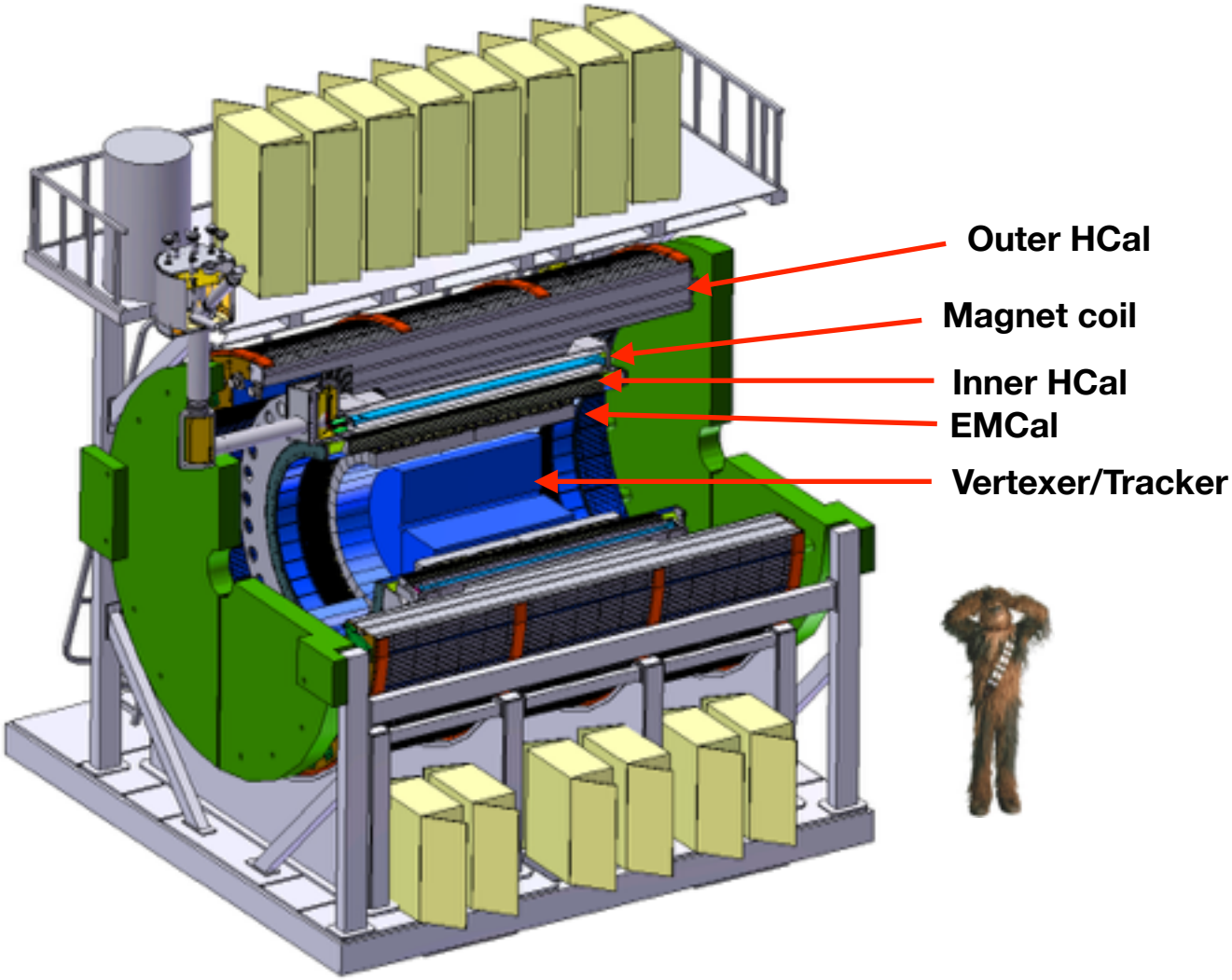
Injection Section

Laser

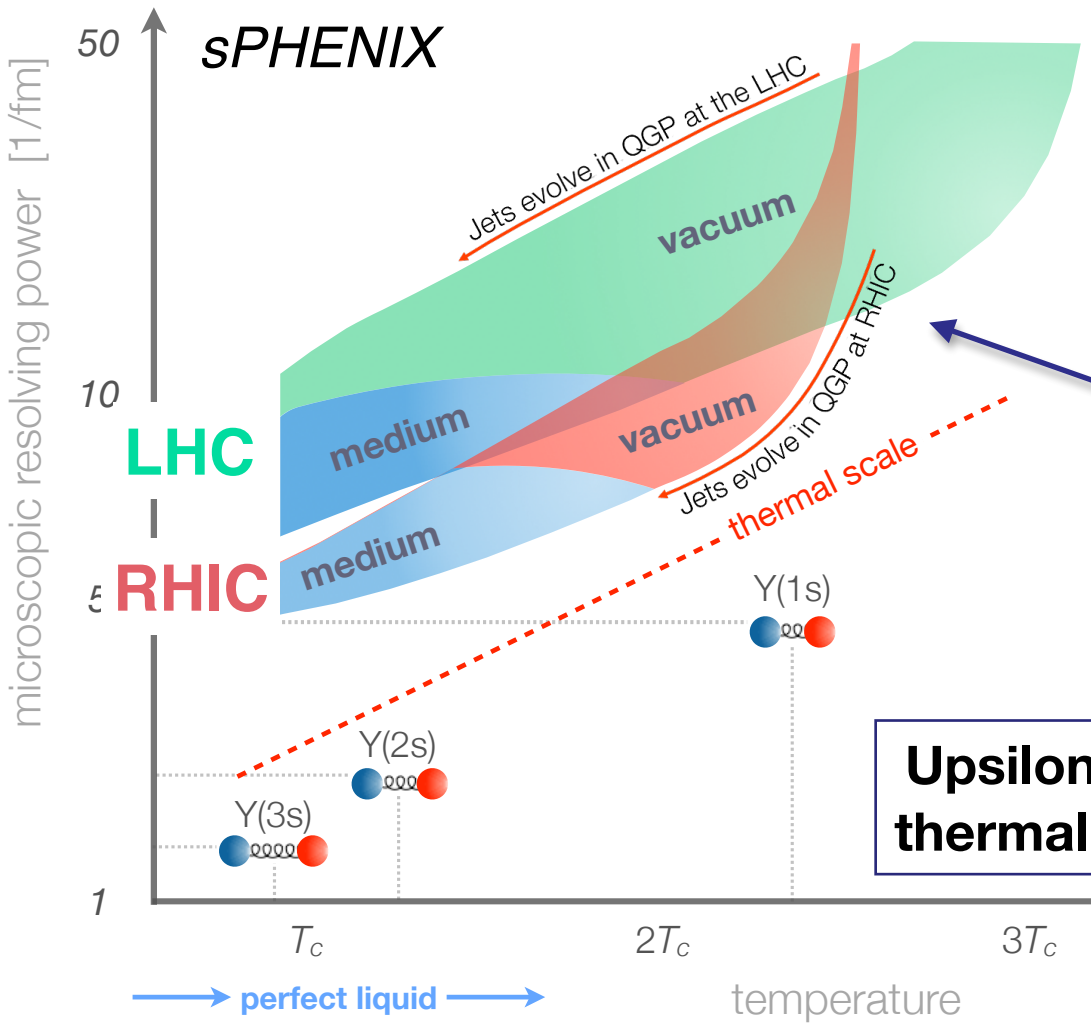
Beyond 2020
sPHENIX

sPHENIX

High-rate capable, large acceptance detector built around the former BaBar 1.5T SC solenoid, with full EM and hadronic calorimetry and precision tracking and vertexing,



Probing scales in the medium



How does the perfect fluidity of the QGP emerge from the asymptotically free theory of QCD?

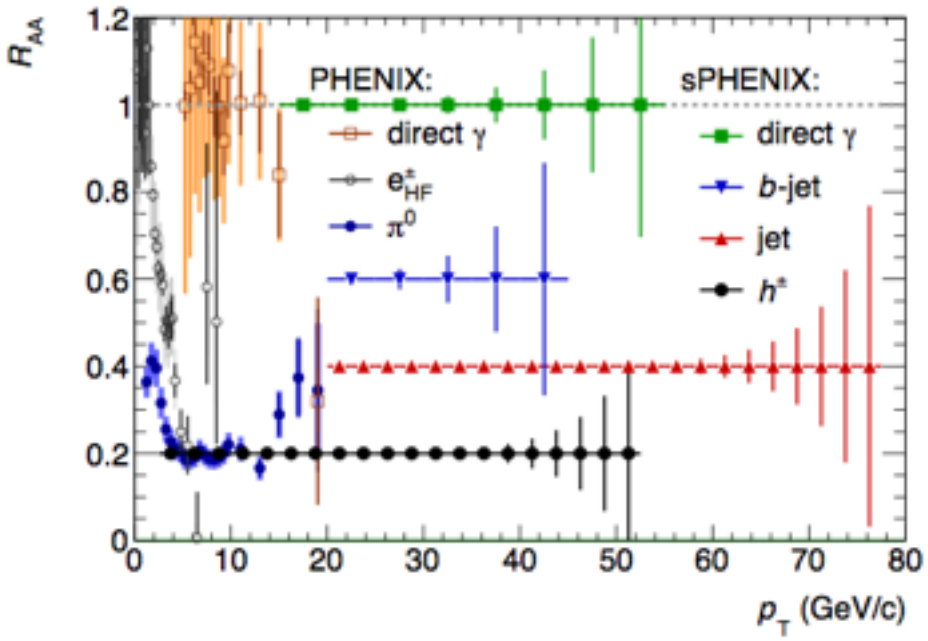
Jets probe sub-thermal length scales

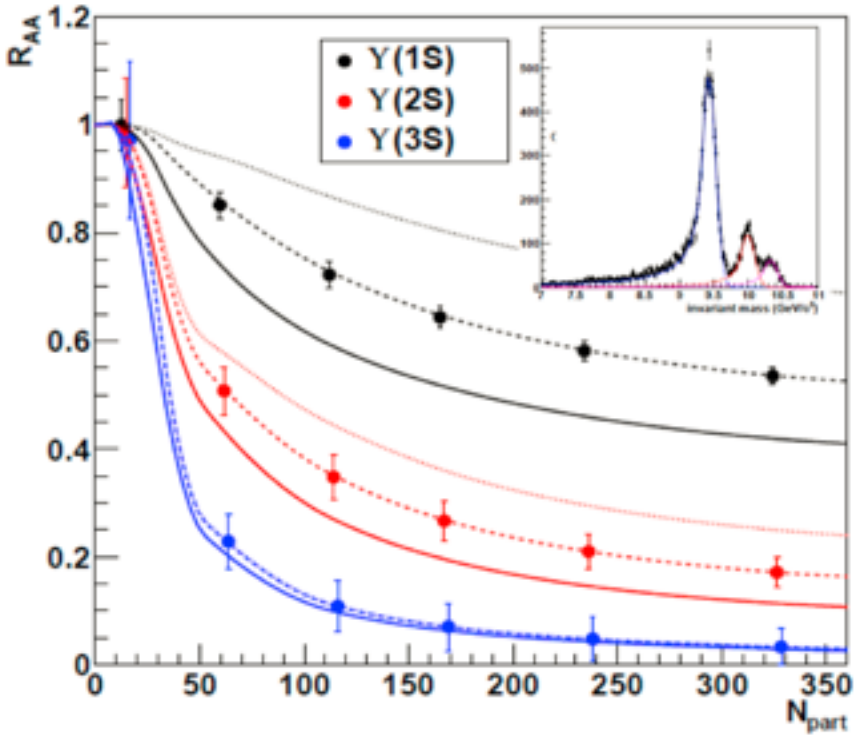
Upsilon states probe thermal length scales

Jets & Upsilon states

sPHENIX capabilities

Complete calorimetric jet spectroscopy



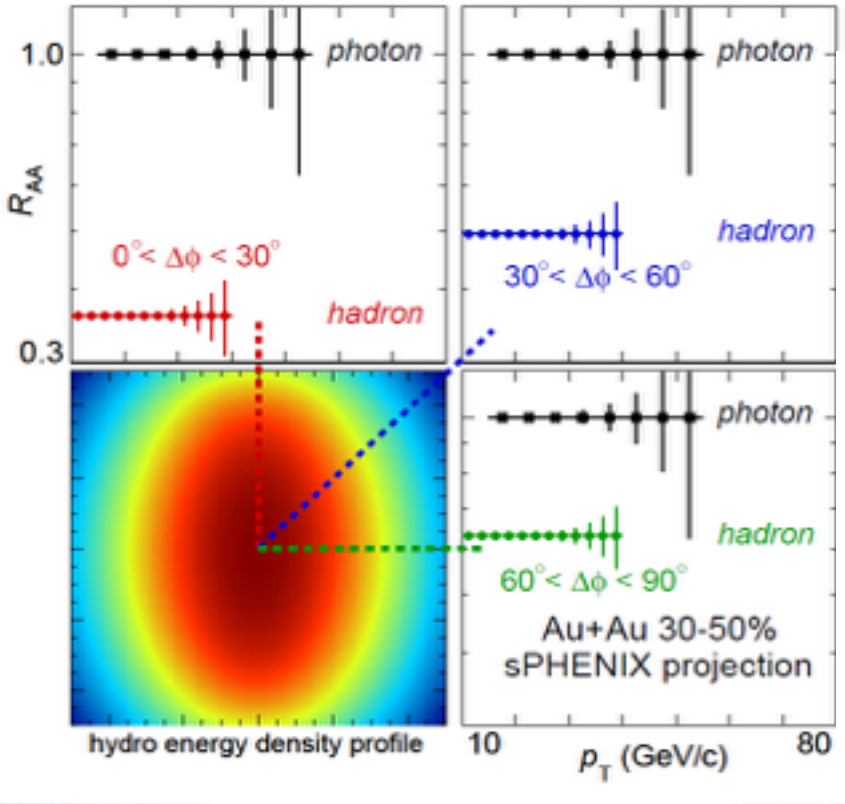


Completely resolved Upsilon spectroscopy

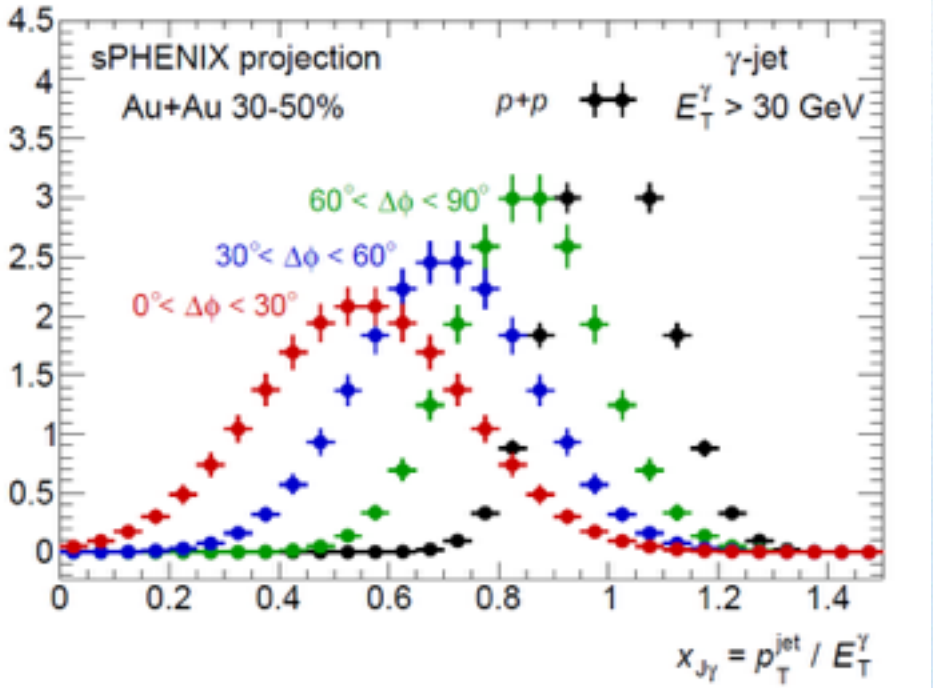
Rate enabled measurements

Example: Length dependent jet quenching

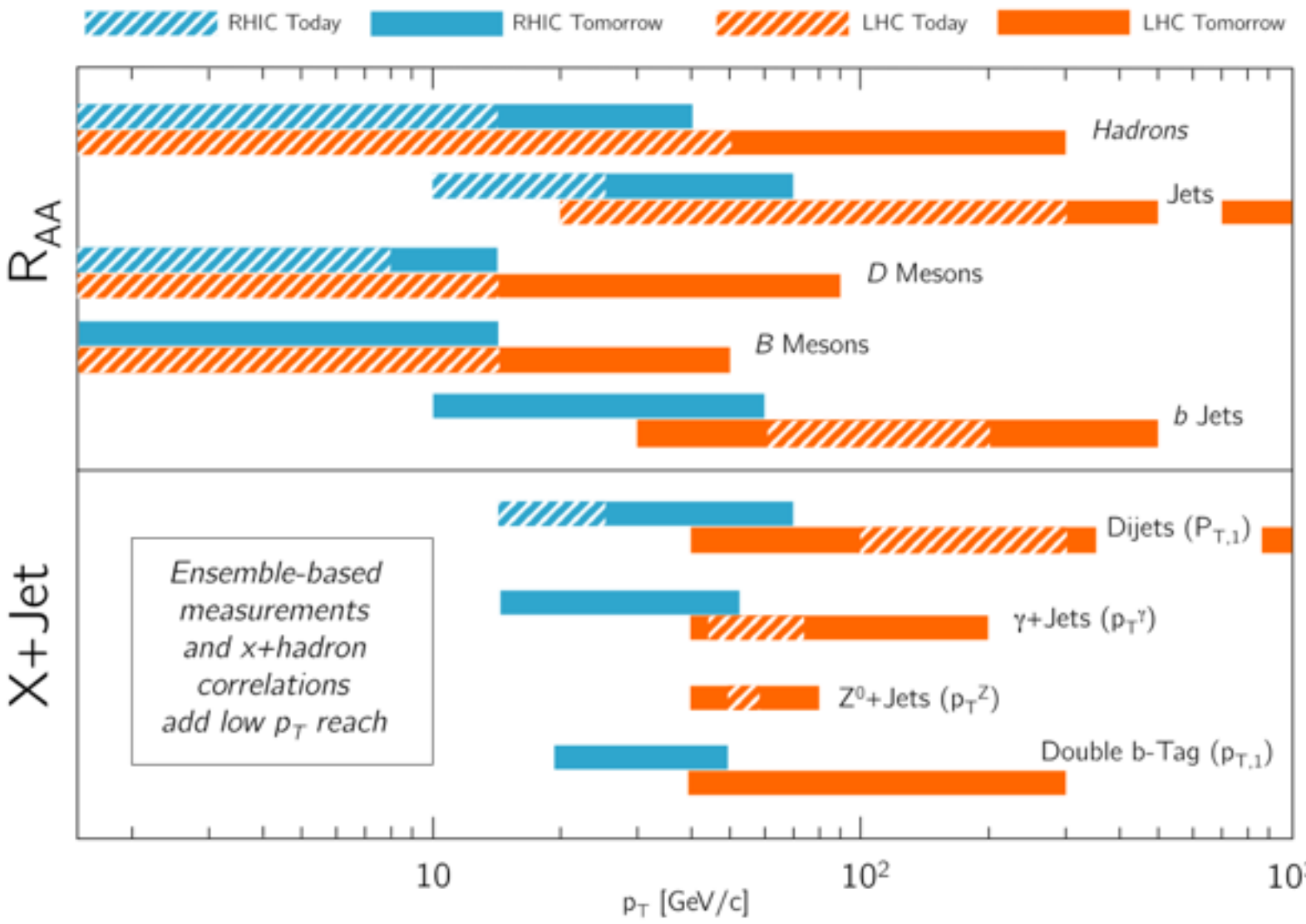
Length dependent suppression R_{AA}



Length dependent energy loss in photon tagged jet events



RHIC & LHC complementarity



Proposed run schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2017	High statistics Pol. p+p at 510 GeV	Transverse spin physics	Coherent e-cooling test II
2018	^{96}Zr+^{96}Ru at 200 GeV Au+Au at 27 GeV (?)	Establish chiral magnetic effect	Low energy e-cooling upgrade
2019-20	7.7-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR iTPC upgrade EPD upgrade CBM TOF test
2021	TBD	Contingency for BES-2 extension ?	sPHENIX installation
2022-??	200 GeV Au+Au with upgraded detectors Pol. p+p, p+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX Forward upgrades ?
mid-2020s	Transition to eRHIC	Gluon structure of p and A	Upgrade to “ePHENIX”

What RHIC will deliver

- Campaign 1 (2014-17):
  - QCD equation of state at $\mu_B \approx 0$
  - Precision measurement of $\eta/s(T \approx T_c)$
  - Measurement of heavy quark diffusion constant $D_{c/b}$
  - Measurement of nucleon/nuclear granularity at small x
  - Δg, flavor dependence of spin in the quark sea
  - Origin of single spin asymmetries
- Campaign 2 (2018-20):
  - QCD equation of state at $\mu_B > 0$
  - Discovery of the QCD critical point, if within range
  - Discovery of QCD anomaly driven transport in chiral QGP
- Campaign 3 (2022-??):
  - Precision measurement of q^($T \approx T_c$) and e^($T \approx T_c$)
  - Determination of length scale where the QGP becomes a liquid
  - Additional insights we can't even anticipate yet

Beyond RHIC

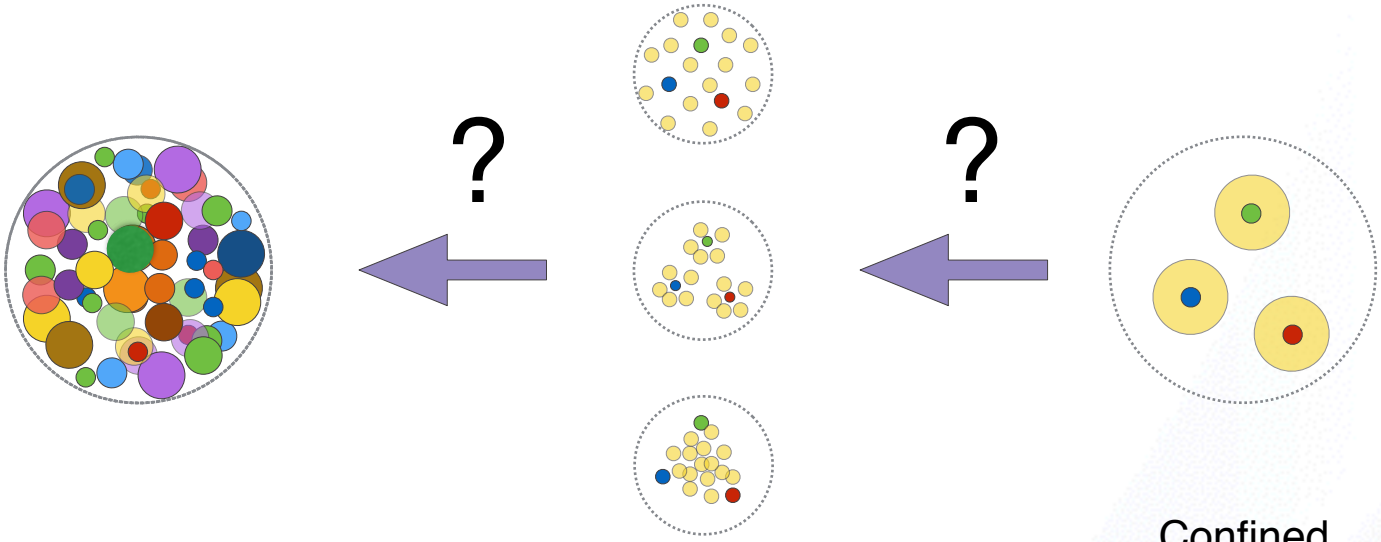
2015 NSAC Long Rang Plan

RECOMMENDATION III

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

Partons at Q^2 ~ few GeV^2



eRHIC Concept

Concept exploits the RHIC Heavy Ion collider complex with

- its superconducting magnets for up to 250 GeV proton beams
- its large accelerator tunnel and its long straight sections
- its existing Hadron injector complex

by **adding an electron accelerator** that

- makes use of superconducting LINAC technology and recirculation
- utilizes either the energy recovery concept or
- a high intensity electron storage ring
- to achieve high luminosity electron-hadron collisions

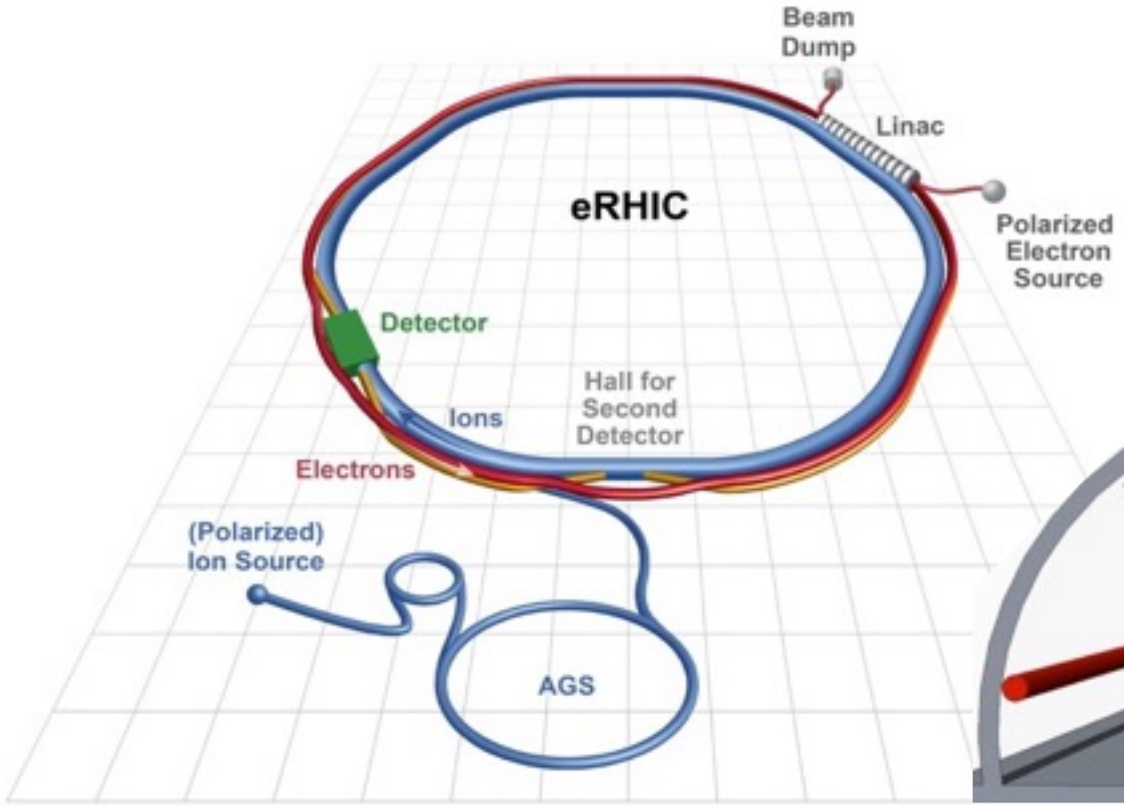
A design meeting **all** the requirements of the EIC physics program delivering luminosities of **$>10^{33} s^{-1} cm^{-2}$** over the entire range of CM energies with a maximum luminosity in excess of **$10^{34} s^{-1} cm^{-2}$** has been worked out.

However, this design is based on novel technologies that require a long term R&D program and demonstration of feasibility before a commitment can be made to build a large and costly facility based on this approach.

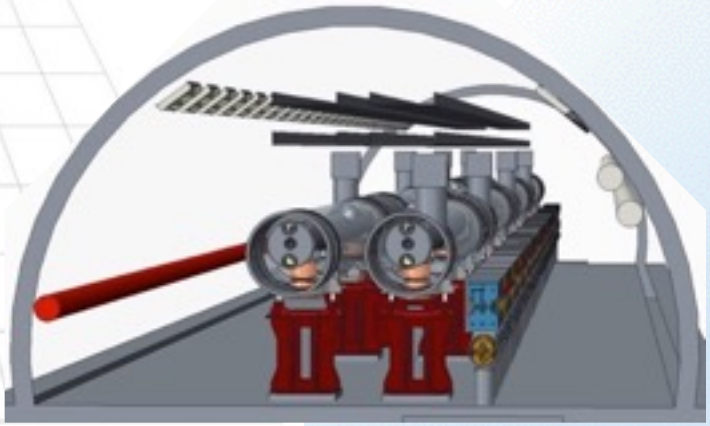
BNL EIC Design: eRHIC

eRHIC ERL + FFAG ring design @ 10^{33}–10^{34}/cm^{2}s

~20 GeV e^- + 255 GeV p or 100 GeV/u Au.



Day-1 Detector



eRHIC Strategy

⇒ Design eRHIC start version towards lower luminosity 10^{32}–10^{33} $s^{-1}cm^{-2}$ that enables a compelling initial science program

This lower boundary condition makes a **storage ring** based collider an interesting alternative to a **multi-pass ERL** based concept.

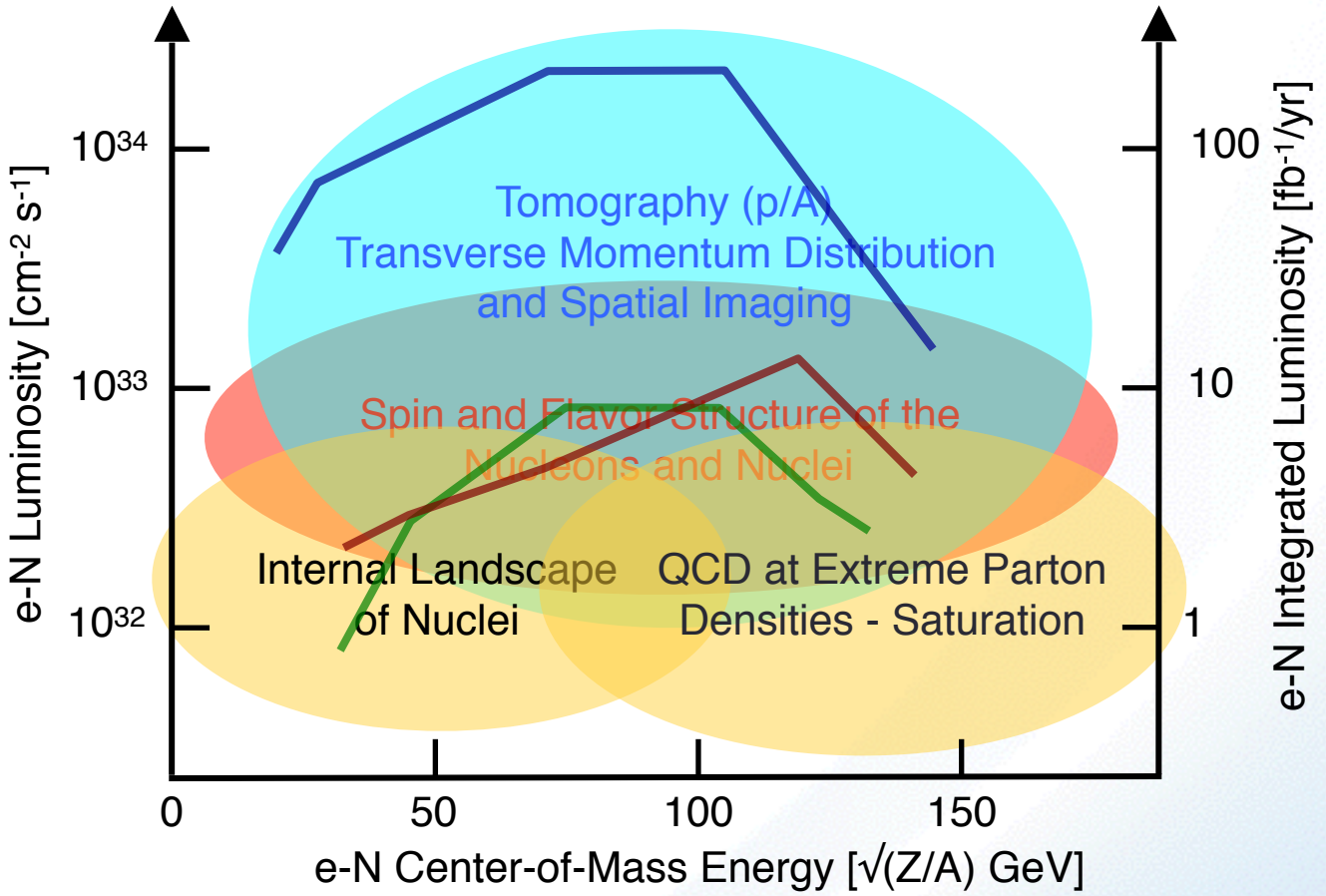
➔ **Strategy towards eRHIC Design:**

- Study in parallel multi-turn ERL and storage ring based collider designs
- Compare the two options in terms of performance, residual risk and cost, and feasibility of high luminosity upgrade
- Select a final conceptual design for the eRHIC start version in the near future

Key Elements of the ongoing long term R&D program are:

- High-rate electron cooling to achieve the small emittance hadron beam needed for ultra-high luminosity
- High average current polarized electron gun to provide the required substantial (~50 mA) CW electron beam
- Multi-pass superconducting energy recovery LINAC
- A significant cost saver in this concept is the FFAG-based recirculation scheme, which is a large extrapolation of existing FFAG accelerators

Physics vs. Luminosity & Energy



ERL-Ring design

w/o cooling of protons
P_{synch} ~ 2.5 MW

Ring-Ring design, 330 bunches

w/o cooling of protons
P_{synch} ~ 10 MW

eRHIC Luminosity Upgrade

Summary

- **RHIC is planning a unique forefront science program with continued discovery potential as laid out in NSAC LRP:**
  - **Quantify the transport properties of the QGP *near* T_c using heavy quarks as probes**
  - **Measure gluon and sea quark contributions to proton spin and explore transverse momentum-spin dynamics of QCD**
  - **High statistics map of the QCD phase diagram, including search for a possible critical point**
  - **Probe internal structure of the *most liquid* QGP using fully reconstructed jets and resolved Upsilon states as probes**
- **Important machine and detector upgrades underway for BES II (LEReC, iTPC, EPD)**
- **Major detector upgrade underway (sPHENIX)**
- **Transition from RHIC to eRHIC in mid-2020s**