Exciting Times Ahead

2018 RHIC/AGS Annual Users Meeting

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ALD for Nuclear and Particle Physics

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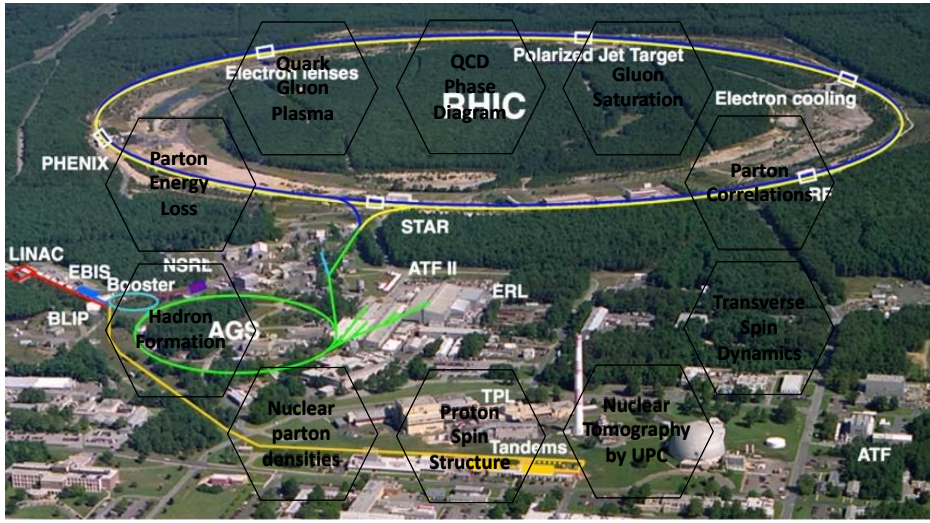
BROOKHAVEN NATIONAL LABORATORY

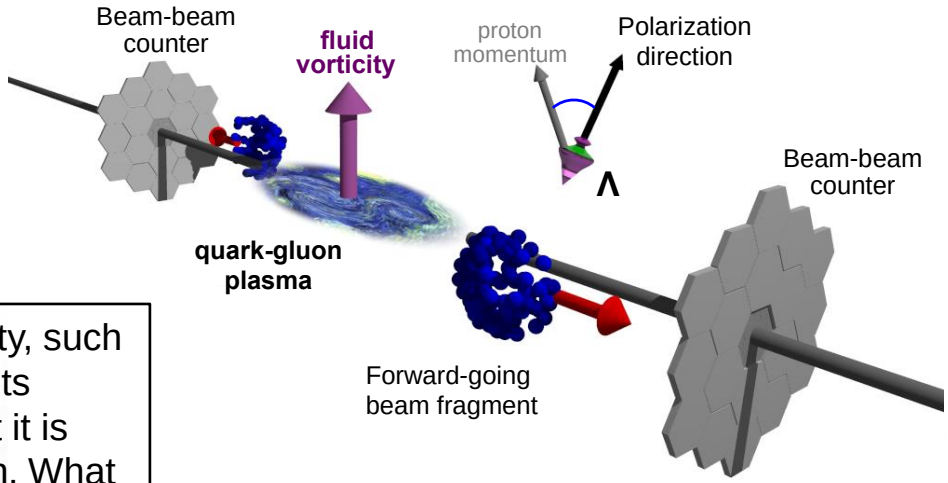
U.S. DEPARTMENT OF ENERGY

RHIC: A Unique Discovery Facility

- Unrivaled range in energy, nucleon doping, collision system choice
- Exploring the limits of ordinary matter
- Enabling very diverse science program
- Continued enhancement of collider and detector capabilities to address scientific questions with highest discovery potential
  - Low-energy electron cooling (2019)
  - STAR acceptance upgrade (2019)
  - sPHENIX detector upgrade (2023)
- Discoveries: most “perfect” (inviscid) fluid, most vortical fluid, gluon component of proton spin paving the way to an EIC
- Recent example: **QGP vorticity**

Diversity of research topics at RHIC facility





A fluid with minimal viscosity, such as the QGP, can preserve its vorticity for a long time, but it is difficult to set it into rotation. What makes the RHIC’s QGP spin?

Exploring the Phases of Nuclear Matter

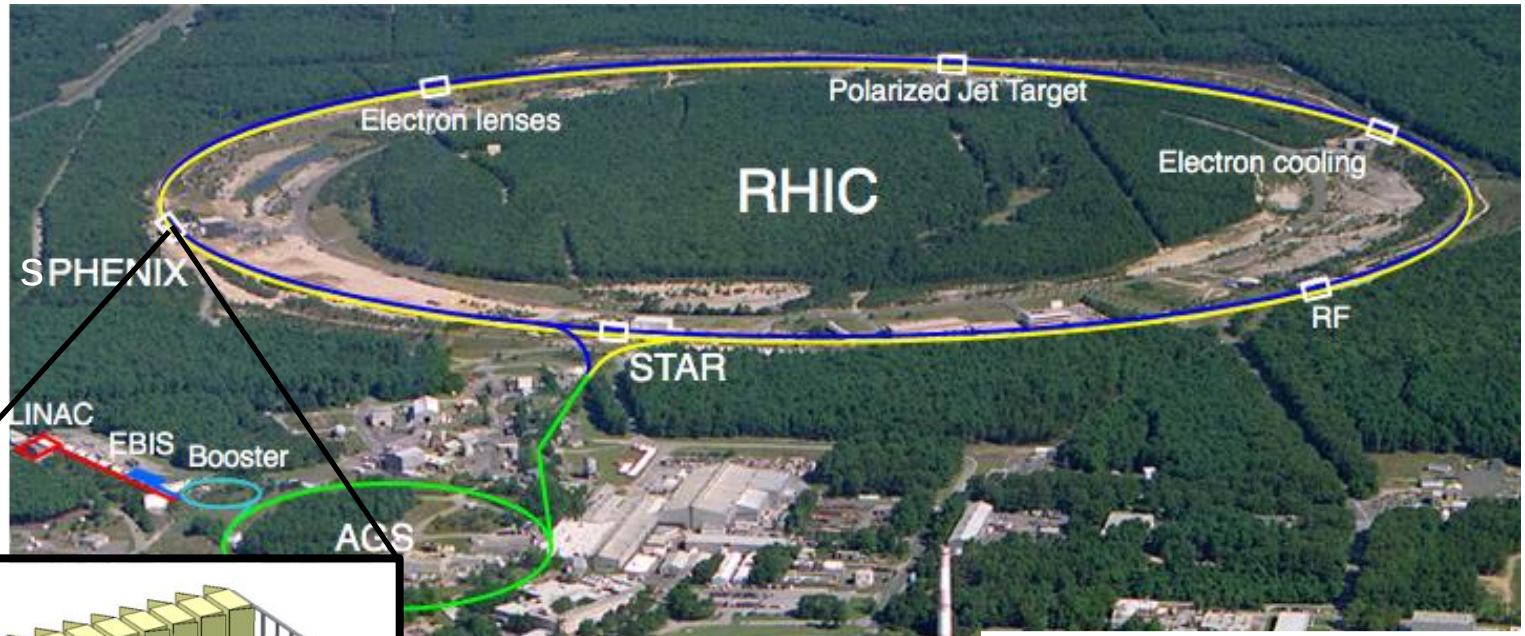
RHIC has defined a multi-year program to execute the scientific mission outlined in the 2015 Long Range Plan for Nuclear Science.

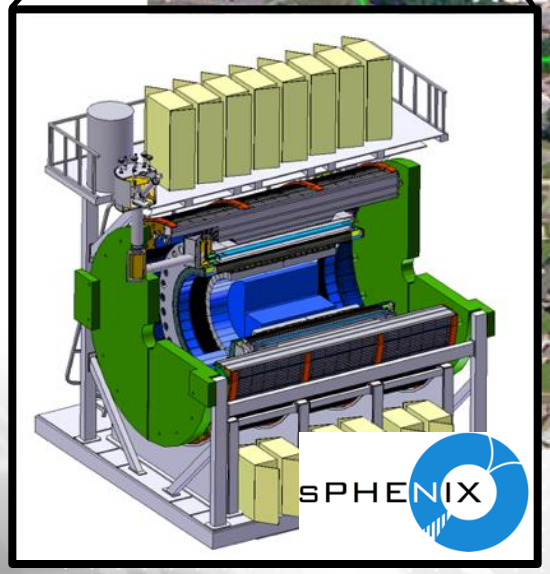
Major components of this program are:

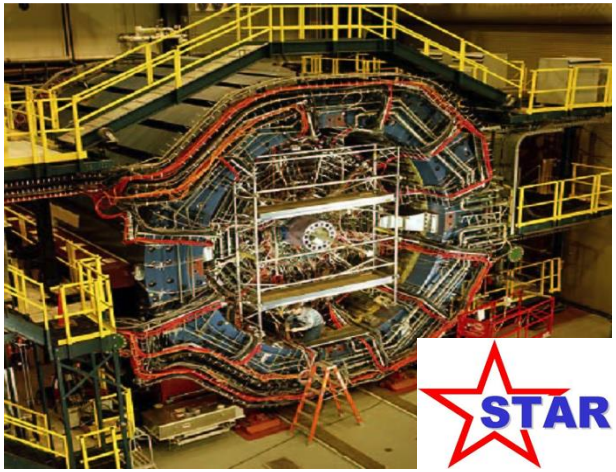
- ✓ ***Transport properties of heavy quarks in the QGP***
- ✓ ***Investigation of transverse spin dynamics in QCD***
- ***Search for chiral magnetic effect and chiral symmetry restoration (Run 18)***
- ***Search for a possible critical point in the QCD phase diagram (BES II – Runs 19-21)***
- ***Exploration of the mechanism behind the near "perfect" fluidity of the QGP discovered at RHIC (sPHENIX 2023-25)***

In 2017 RHIC discovered record breaking vorticity of the QGP by observation of global Λ polarization (top 100 discovery of 2017)

The RHIC Facility in the 2020s







Highlights of RHIC runs 2018-24

- ***Run 2018:***
  - Isobar system (^{96}Ru - ^{96}Zr) comparison run (1.2B events each)
  - 27 GeV Au+Au run, 3 GeV Au+Au fixed target run
  - Test of signatures of Chiral Magnetic Effect and measurement of vorticity
  - CeC test, (successful) fixed target prototype run

- ***Beam Energy Scan II:***
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity at lowest energies
  - Fixed target runs at $\sqrt{s_{NN}}$ = (3.0), 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for signs of critical phenomena in event-by-event fluctuations

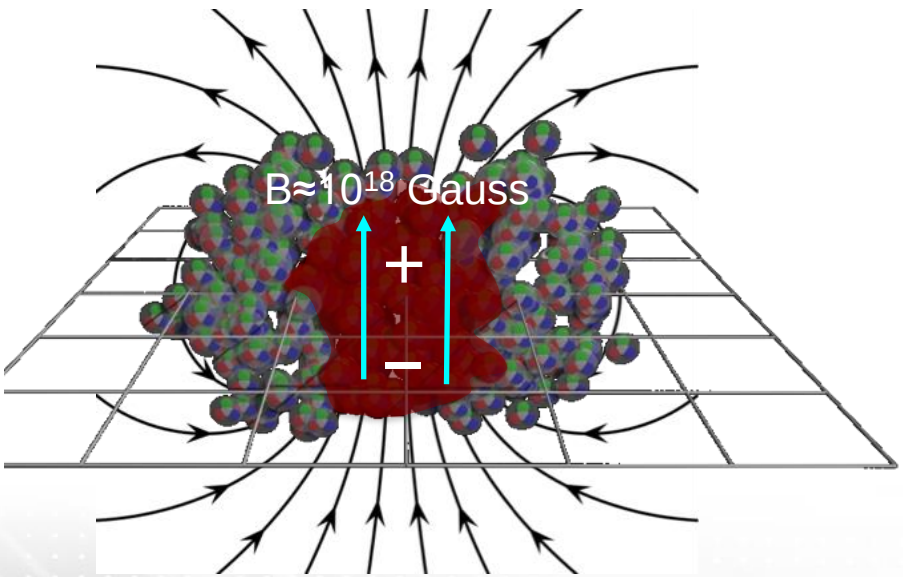
- ***Runs with sPHENIX:***
  - Full energy ($\sqrt{s_{NN}}$ = 200 GeV) Au+Au, p+p, p+Au
  - Fully resolved jets, Upsilon states, heavy quarks as QGP structure probes

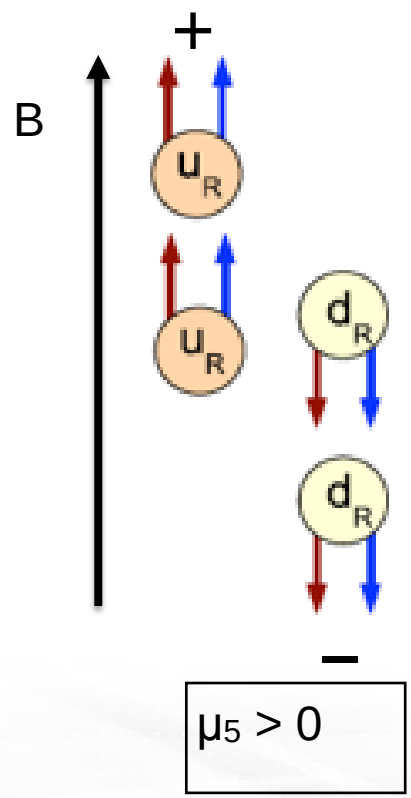
Probing Chiral Symmetry with Quantum Currents

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

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

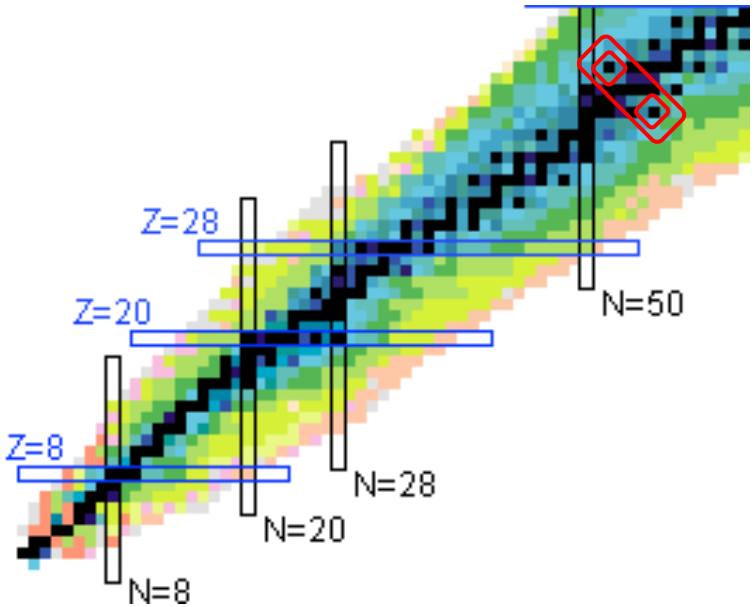
$$\langle \mu_5^2 \rangle \neq 0$$

$$\langle J J \rangle \neq 0$$

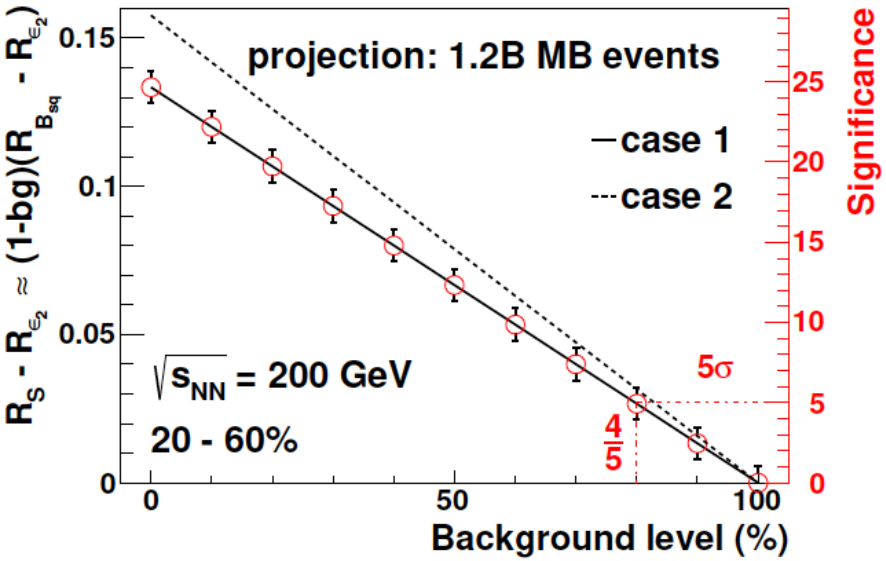
Probing Chiral Symmetry (Run-18)

Background effects unrelated to the chiral magnetic effect explain part of the observed charge separation (STAR, ALICE, CMS), but how much?

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



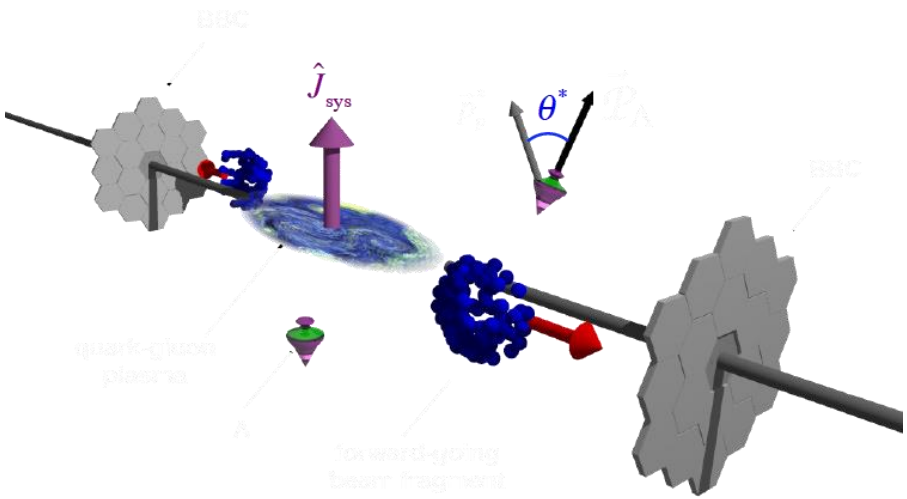
Relative difference in charge separation effects (Ru vs Zr)



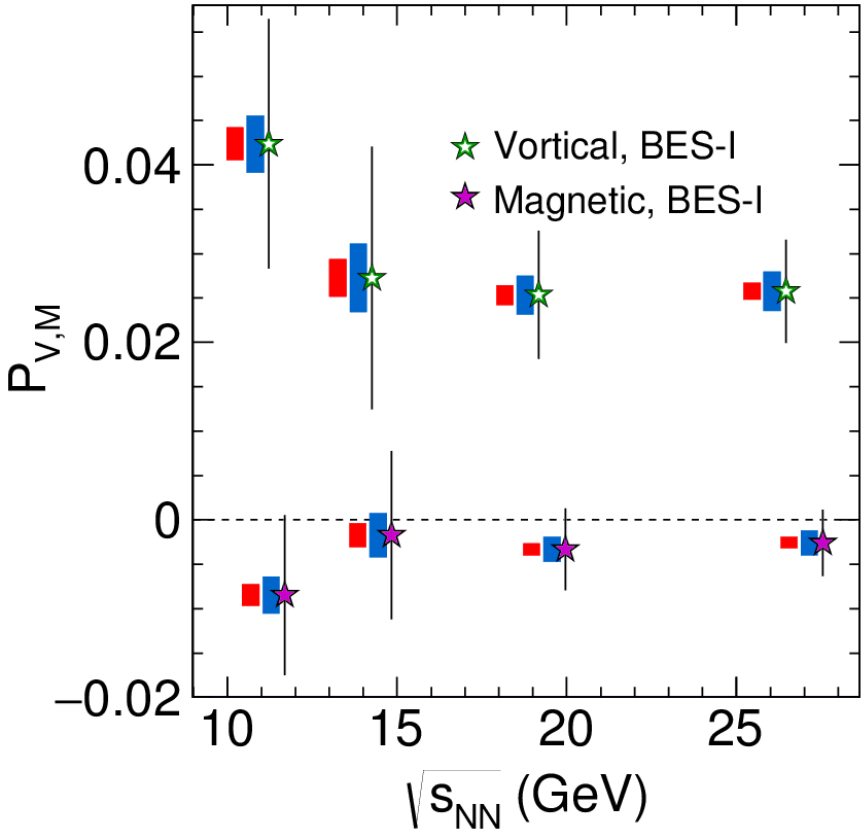
Isobar comparison will be able to detect CME contribution to the observed signal within +/- 6% (4%?) of the observed effect. The challenge will be controlling the systematic errors at that level.

Global Λ polarization (Run-18)

New tool to study QGP and relativistic quantum fluid vorticity



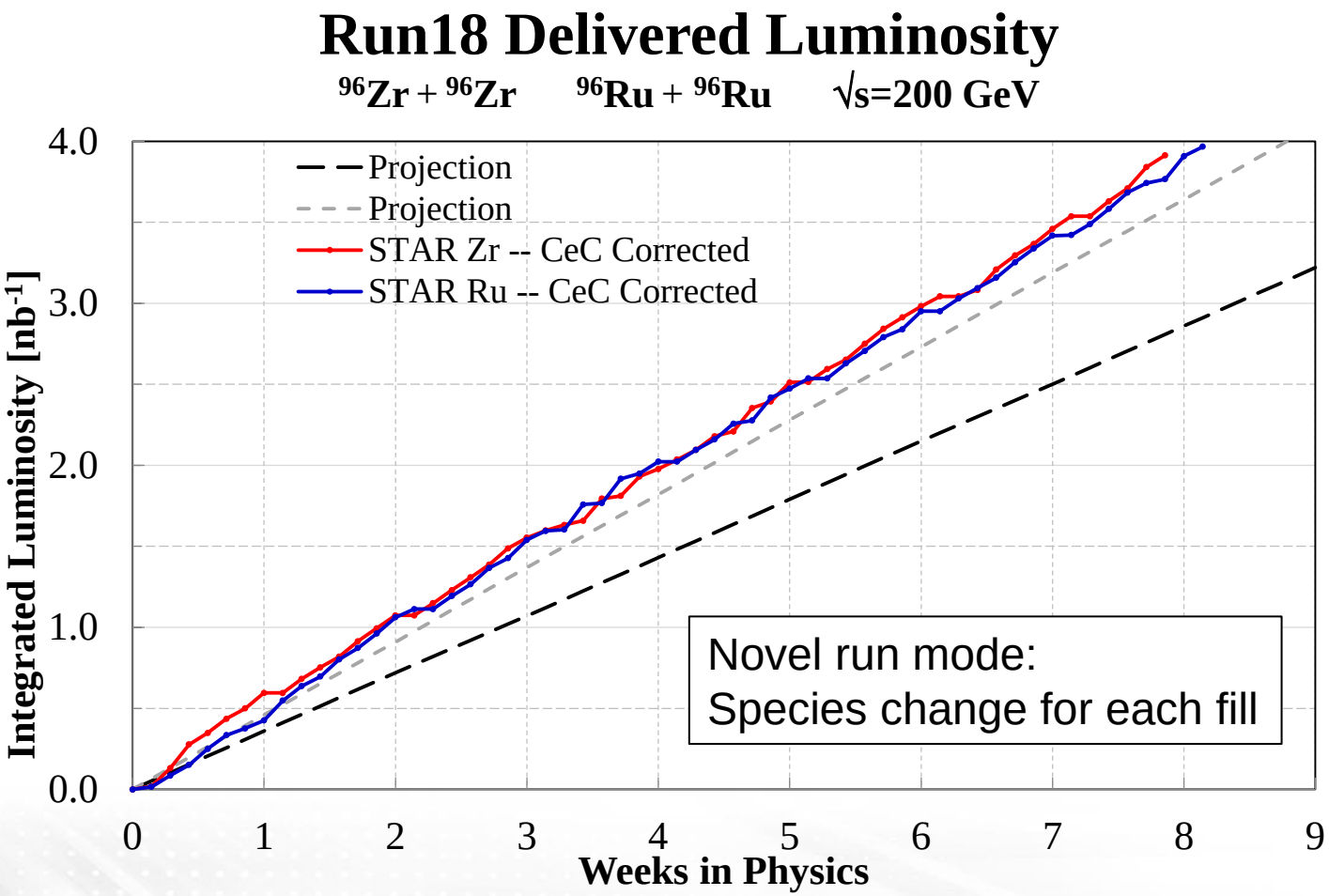
27 GeV Au+Au run will increase statistics by factor 10 & improve reaction plane resolution



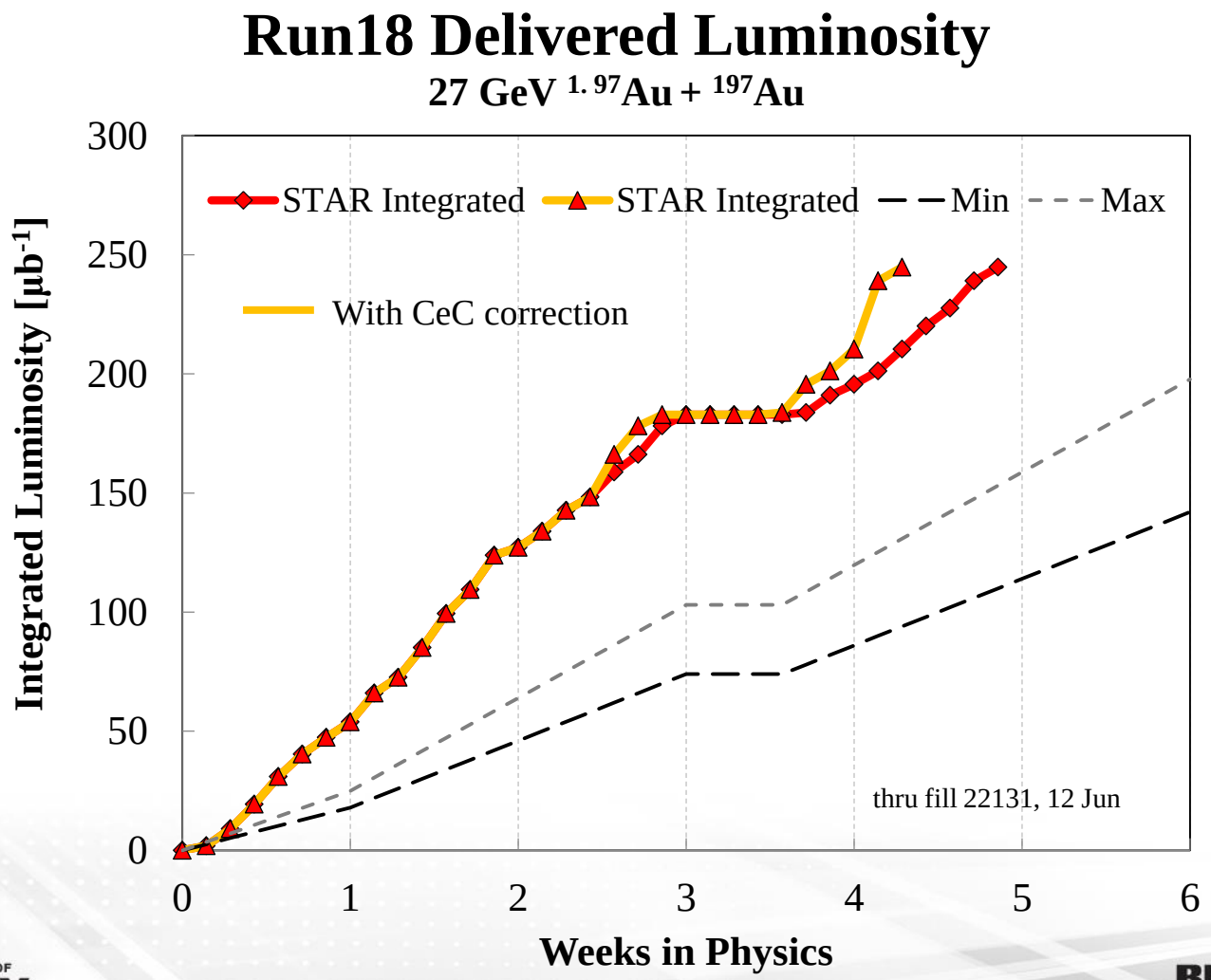
Global angular momentum transfer to hyperon polarization

Late time magnetic field would generate difference between hyperons and anti-hyperons

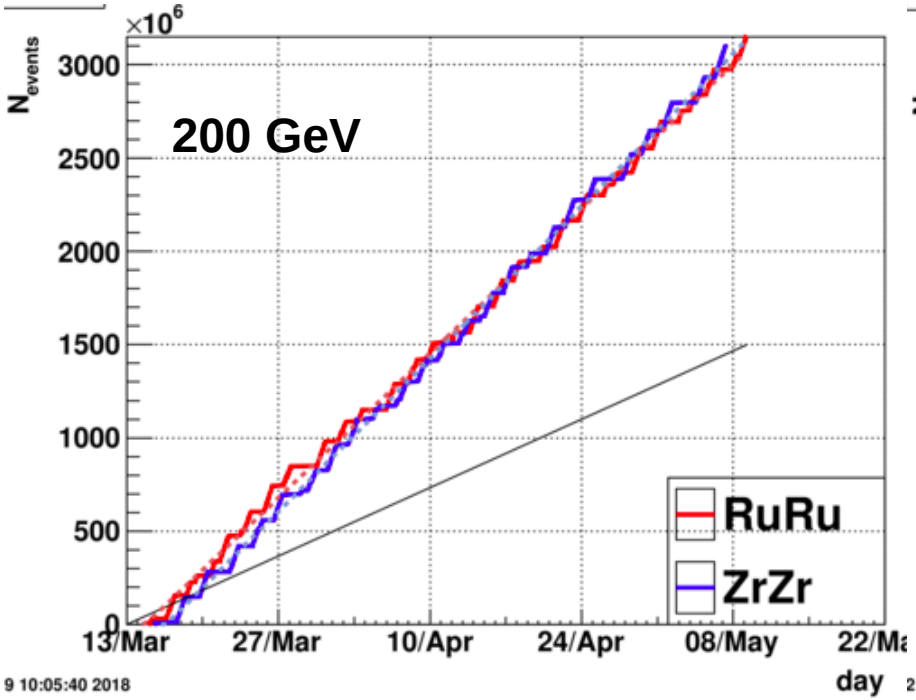
Isobar comparison run

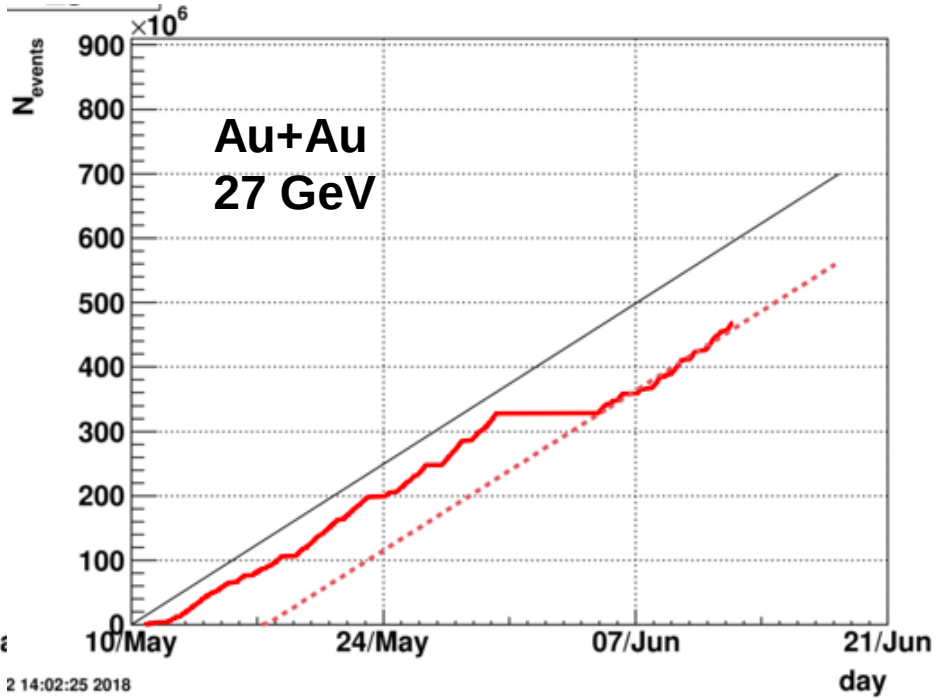


Au+Au run


Run18 Delivered Luminosity
27 GeV 1.97Au + 197Au
STAR Integrated
STAR Integrated
Min
Max
With CeC correction
thru fill 22131, 12 Jun
Integrated Luminosity [μb-1]
Weeks in Physics
0
50
100
150
200
250
300
0
1
2
3
4
5
6

STAR data taking



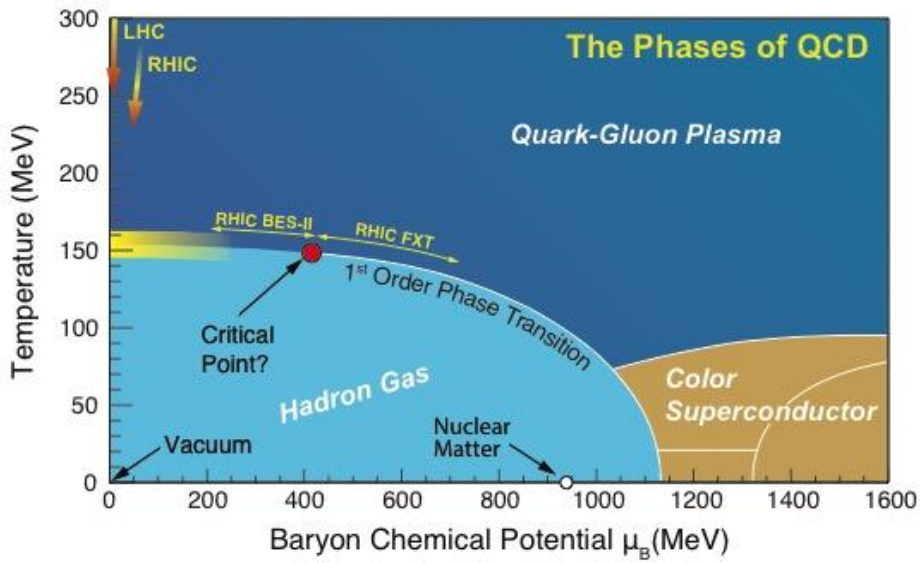


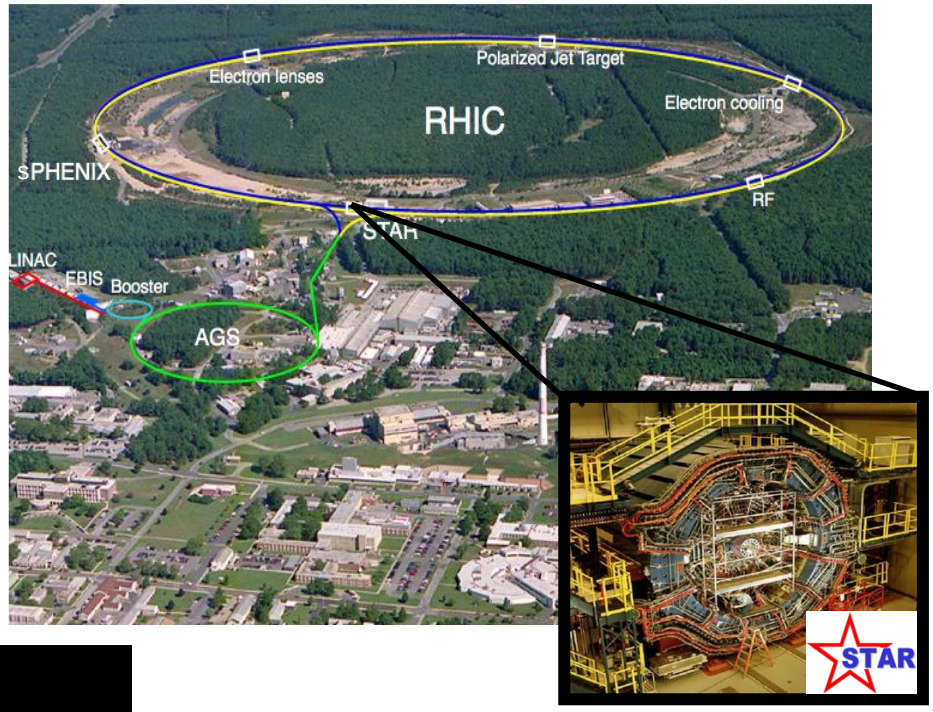
Over 3 billion events per species
= 2.5 times the 1.2 billion goal

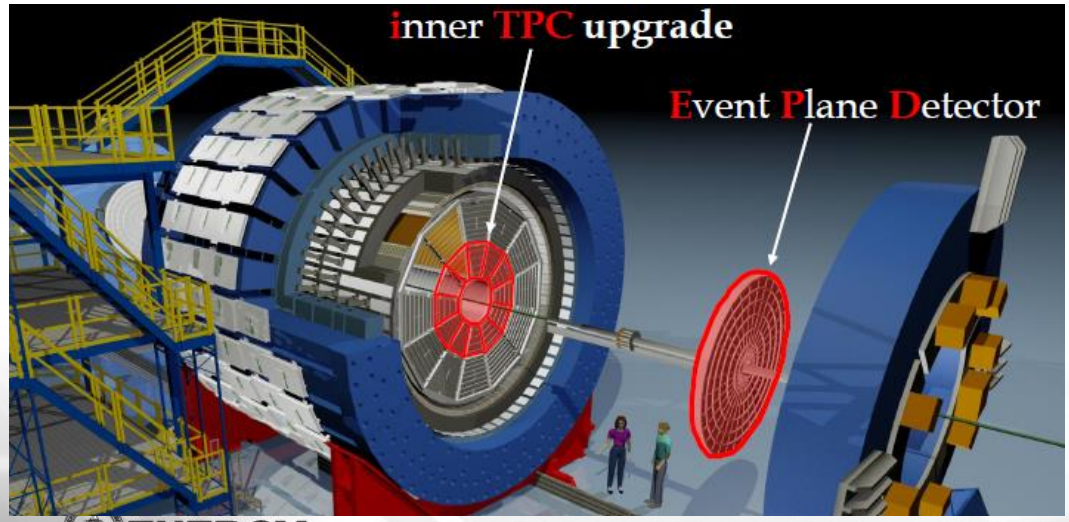
On track to 550 million
“good” Au+Au events

Run 18 is another “tremendous” success !

Beam Energy Scan II





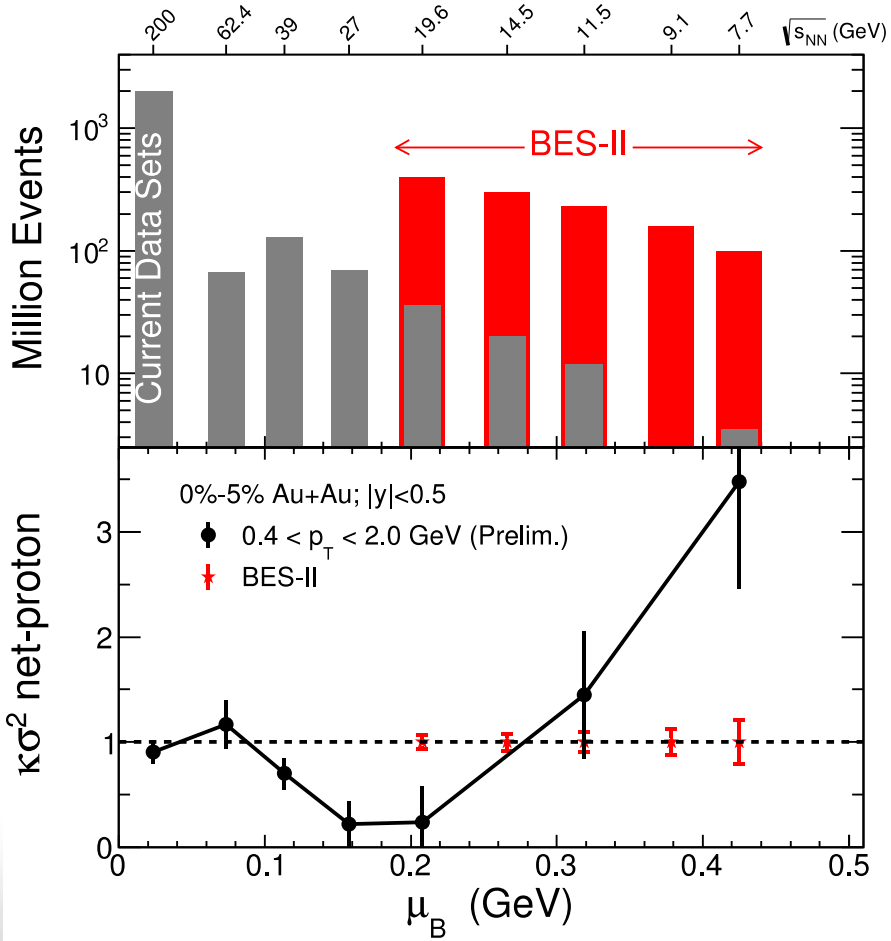


- What are the limits (the phase boundary) of ordinary nuclear matter, i.e. matter composed of baryons and mesons?
- Can the presence of a critical point in the QCD phase diagram be established experimentally?

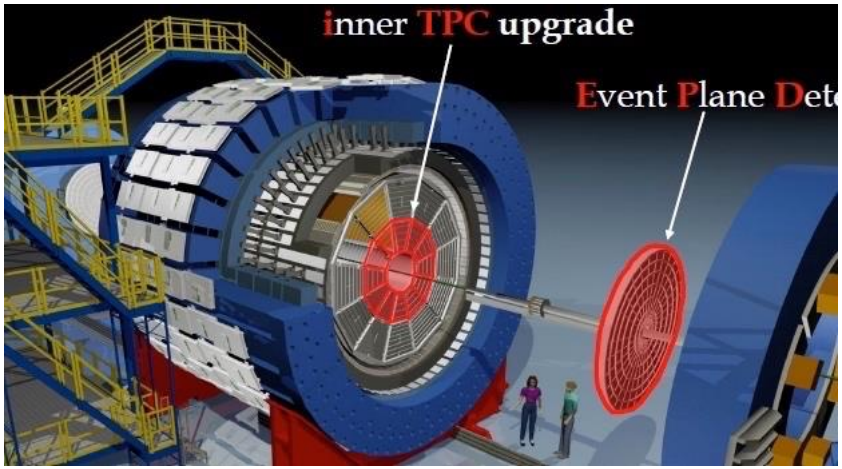
Mapping the QCD phase diagram

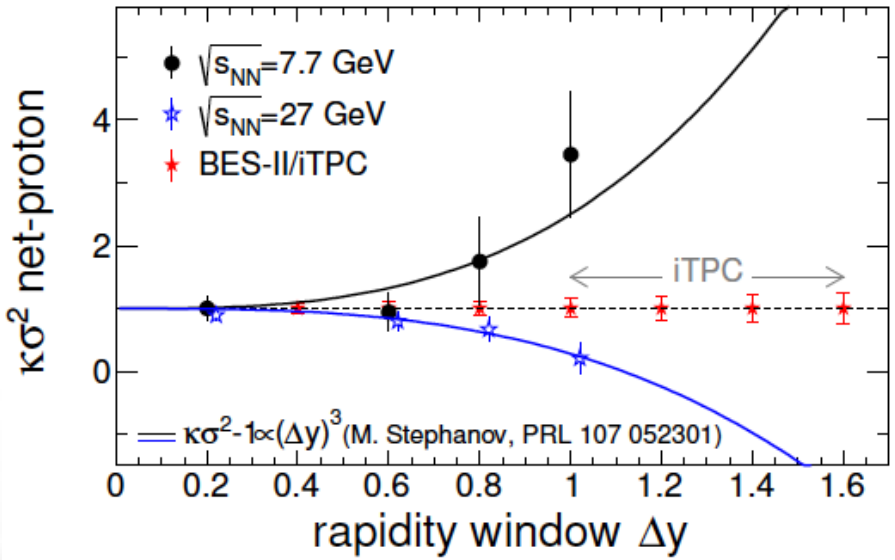
Higher statistics

Low energy RHIC electron cooling upgrade

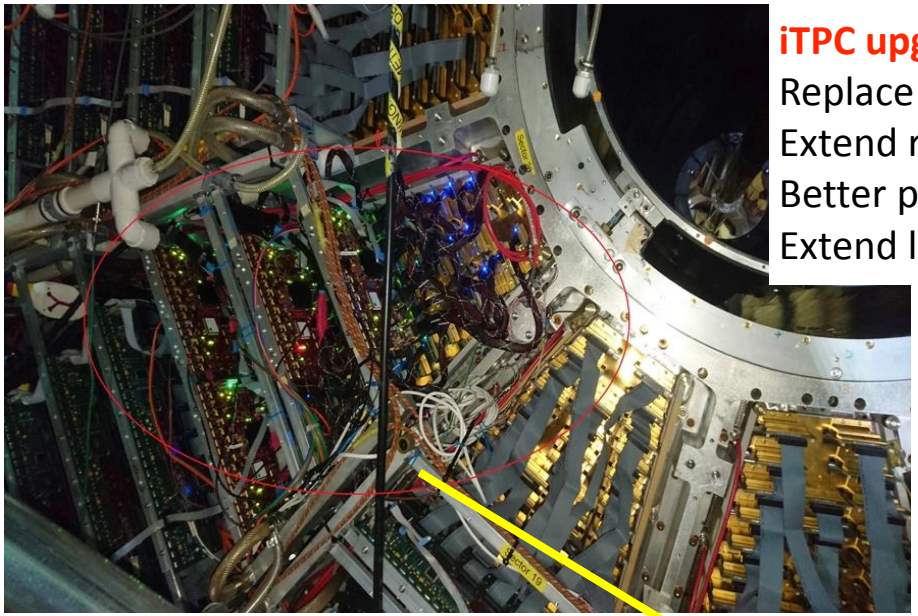


Larger acceptance

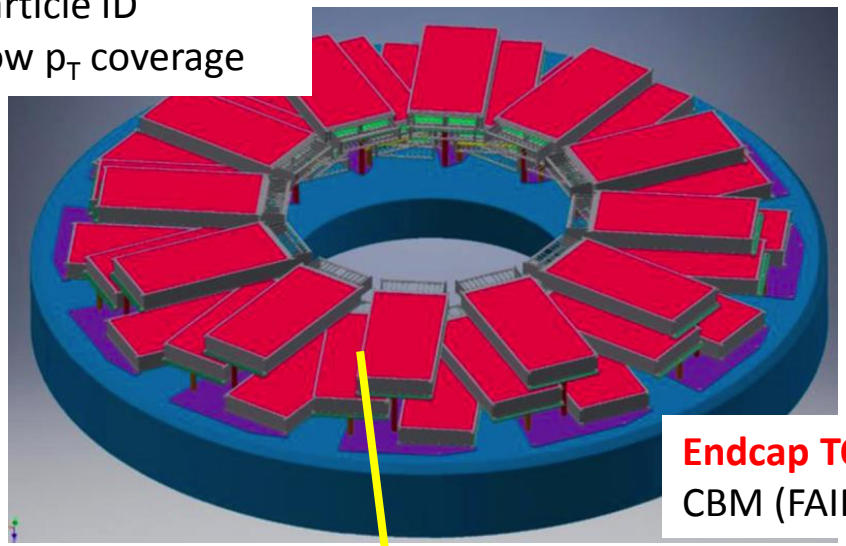




STAR Upgrades for BES-II

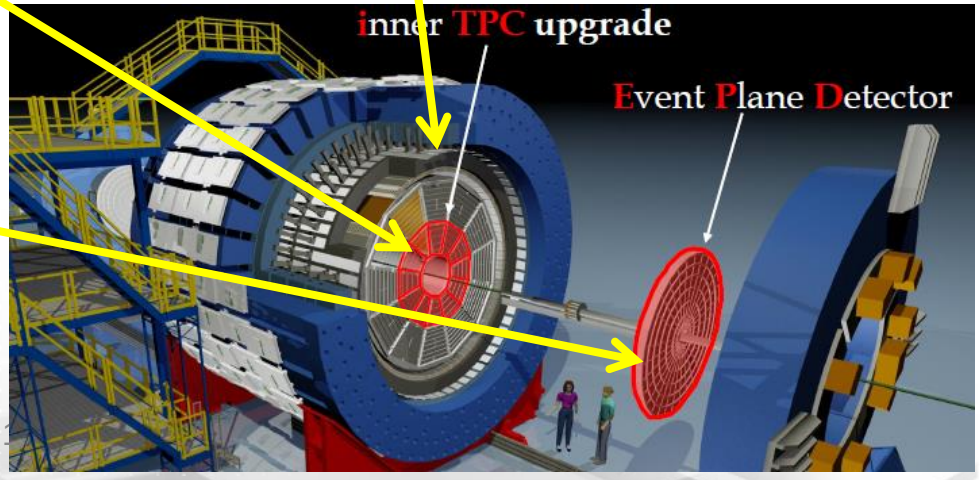


iTPC upgrade (2018)
Replace inner TPC Sectors
Extend rapidity coverage
Better particle ID
Extend low p_T coverage



Endcap TOF
CBM (FAIR)

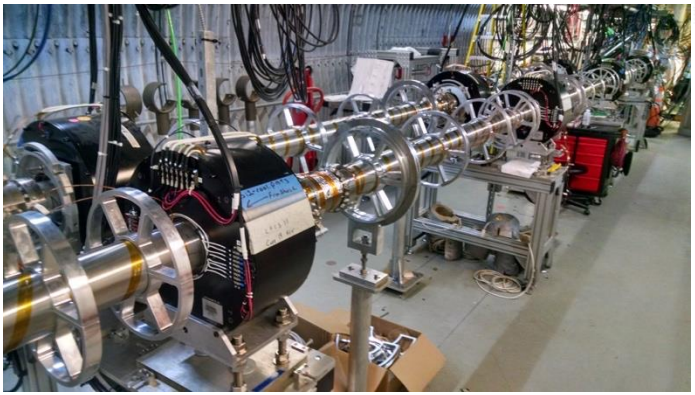
Event Plane Detector
Improved Event Plane Resolution
Centrality definition
Improved trigger

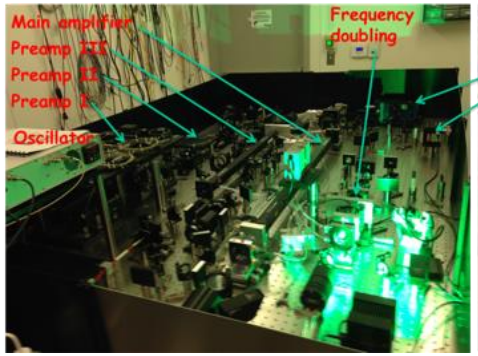


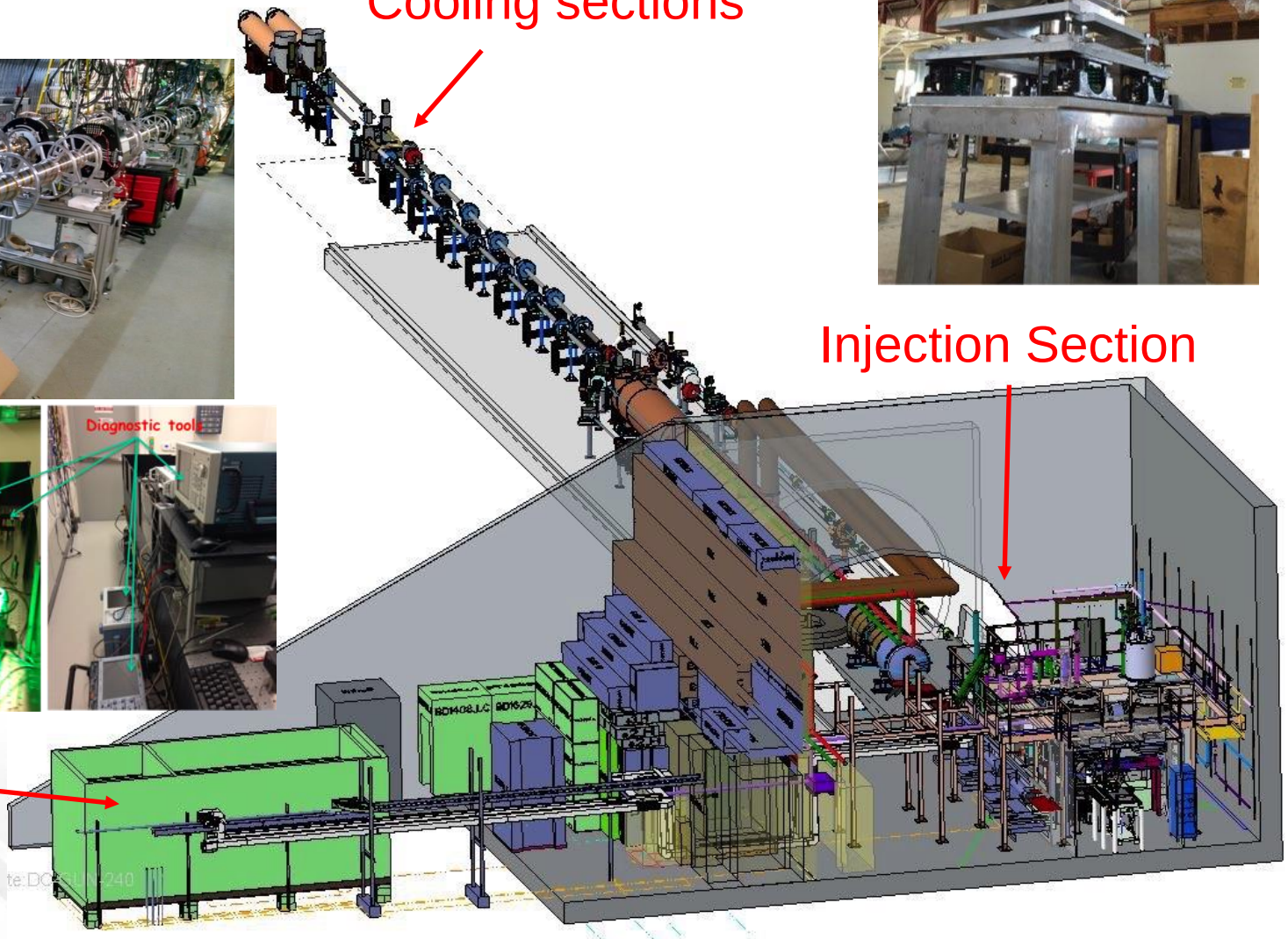
Low Energy RHIC e-Cooling

- Cooling of lowest energy heavy ion beams with bunched electron beam(never attempted before!) increases luminosity by factor 3-4
- Installation complete – commissioning w/o ion beams has started
- Requires extensive commissioning with ion beams (ca. 11 weeks in 2019/20)

LEReC Layout







Tentative BES II program

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

Run 19

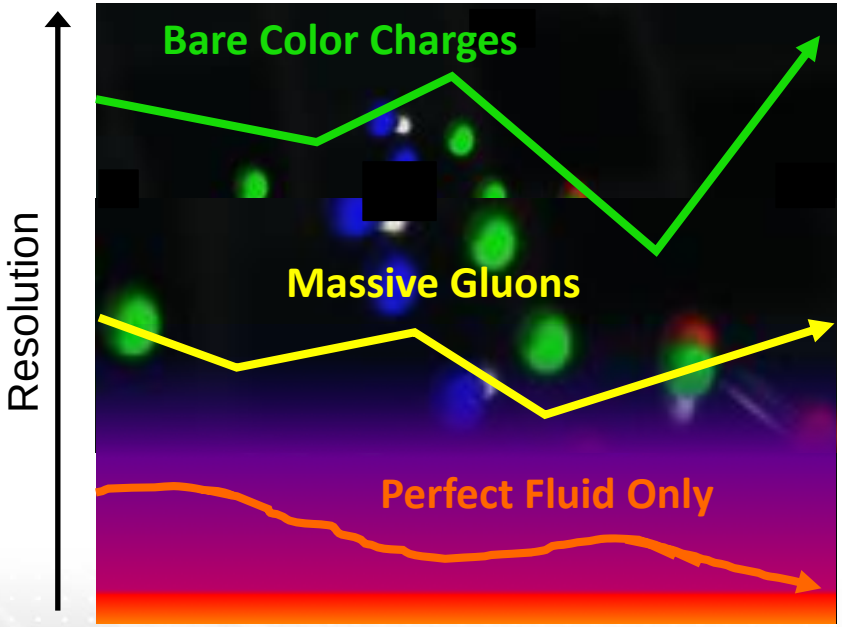
Run 20

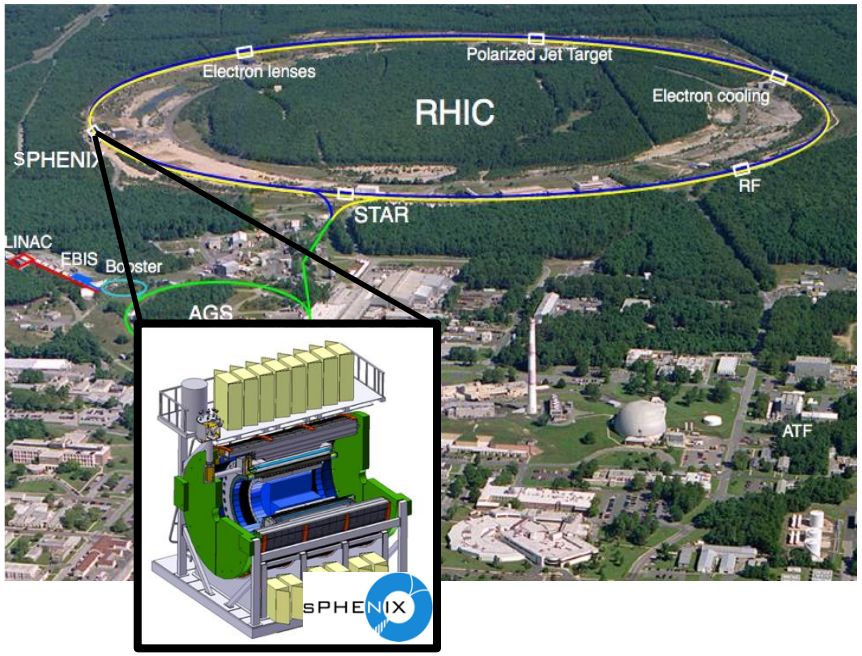
Run 21

sPHENIX

1.5 T Superconducting Magnet - Inner Silicon Tracking - Fast TPC/GEM Read-out - EM and Hadron Calorimeters

- Successful CD-1/3a Review
- Construction starts in FY 2019
- Data taking to start in 2023



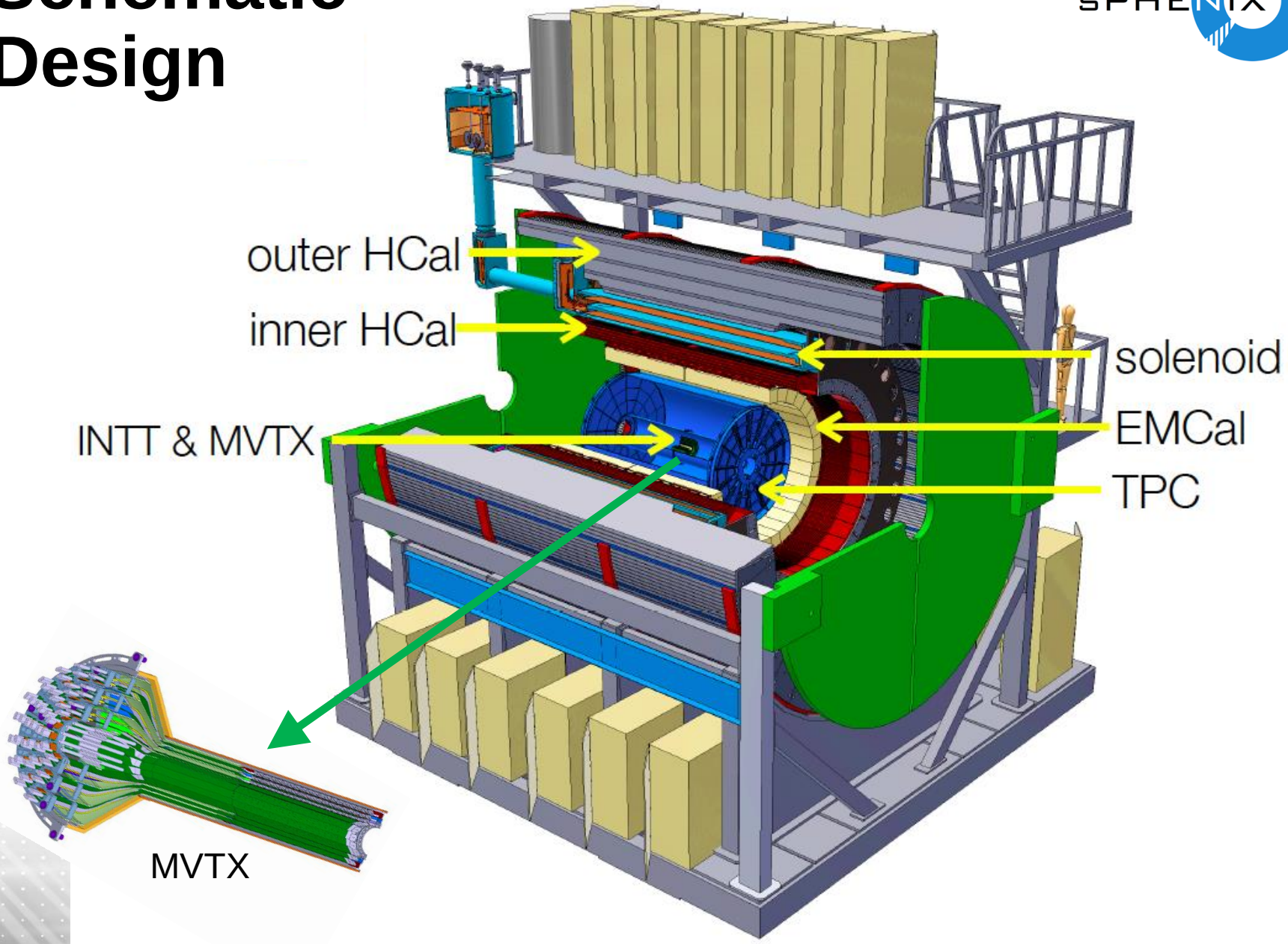


- High energy jets probe the structure of the QGP on different length scales and determine where and how it changes from particle-like quarks and gluons to a structureless “perfect” liquid
- Heavy quark atoms (Upsilon) also probe the QGP structure at different scales

sPHENIX will increase the data-taking rate by a factor 10

fully utilizing the enhanced RHIC luminosity

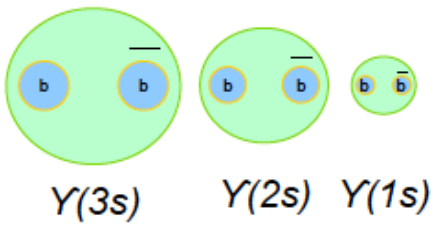
Schematic Design



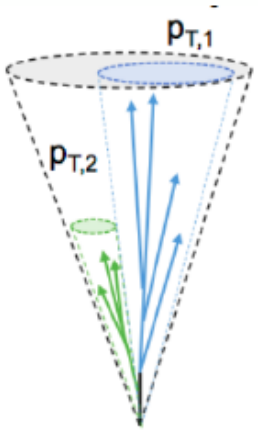
sPHENIX science pillars

Three key approaches to study QGP structure at multiple scales

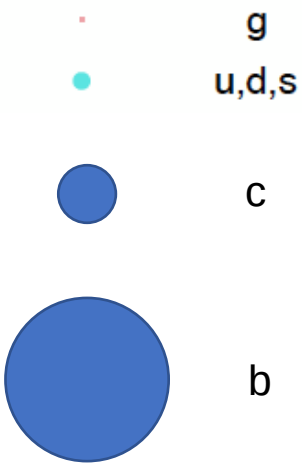
Quarkonium spectroscopy
vary size of probe



Jet structure
vary momentum/angular scale of probe



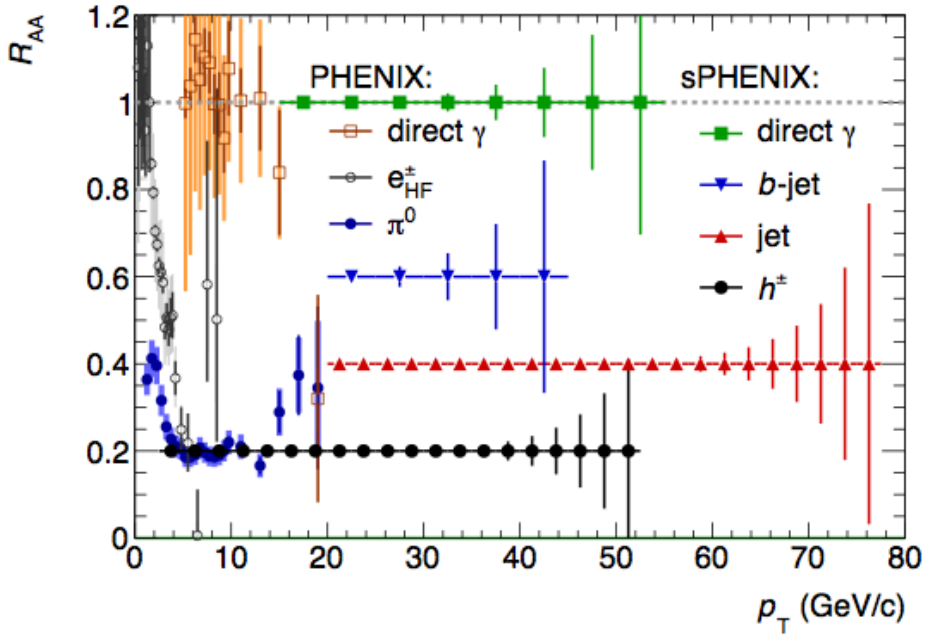
Parton energy loss
vary mass/momentum of probe

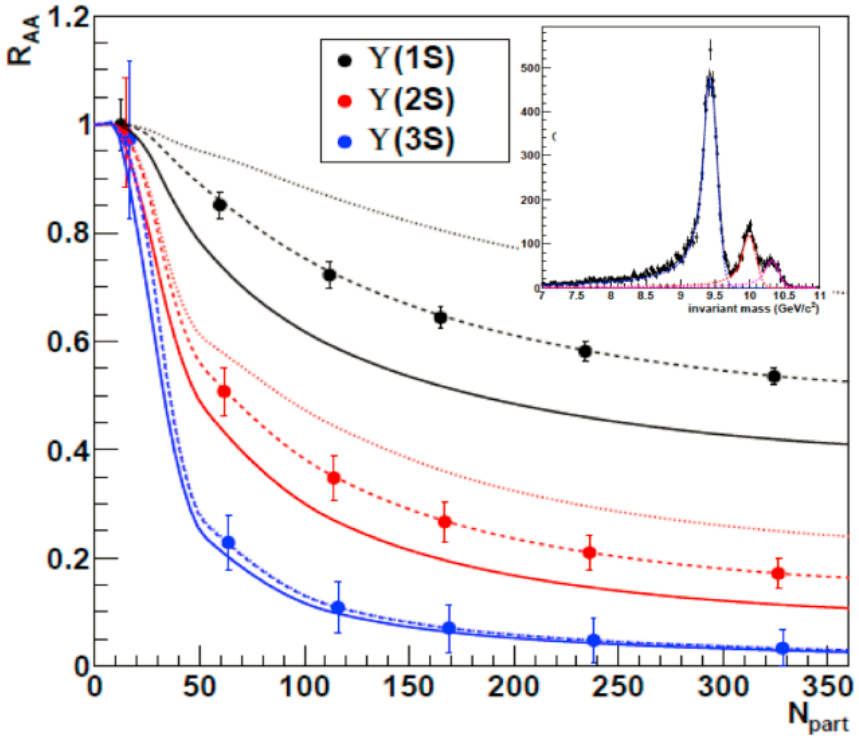


Perfomance

sPHENIX
capabilities

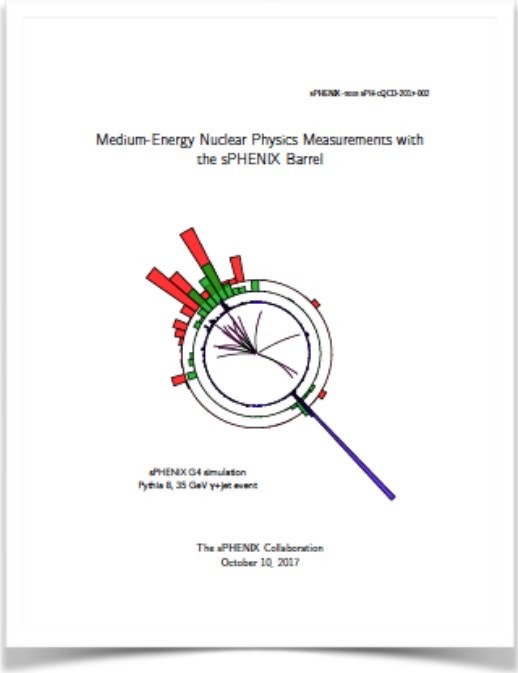
Complete calorimetric jet spectroscopy





Completely resolved Upsilon spectroscopy

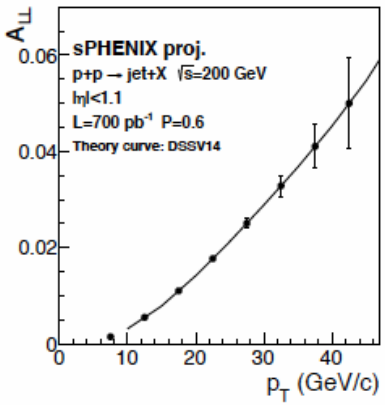
Cold QCD @ sPHENIX


Medium-Energy Nuclear Physics Measurements with the sPHENIX Barrel

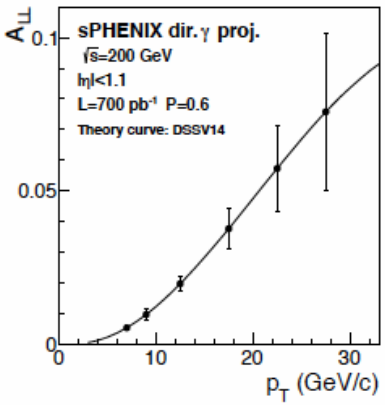
sPHENIX G4 simulation
Pythia 8, 35 GeV γ+jet event

The sPHENIX Collaboration
October 10, 2017

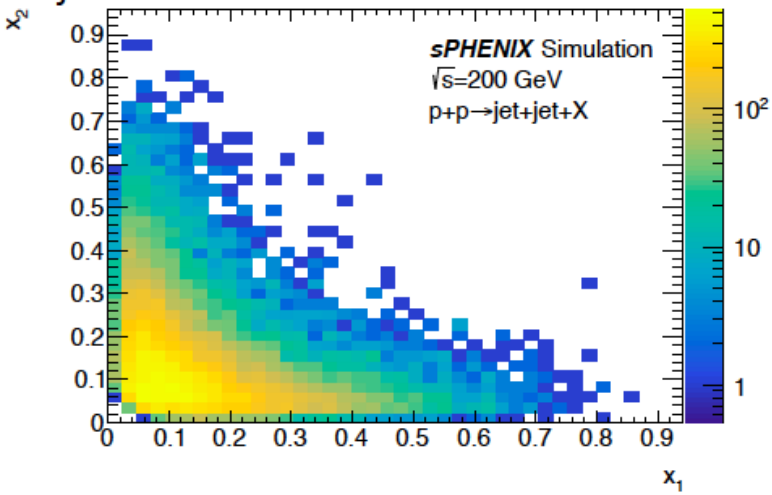
jet A_{LL}



direct γ A_{LL}

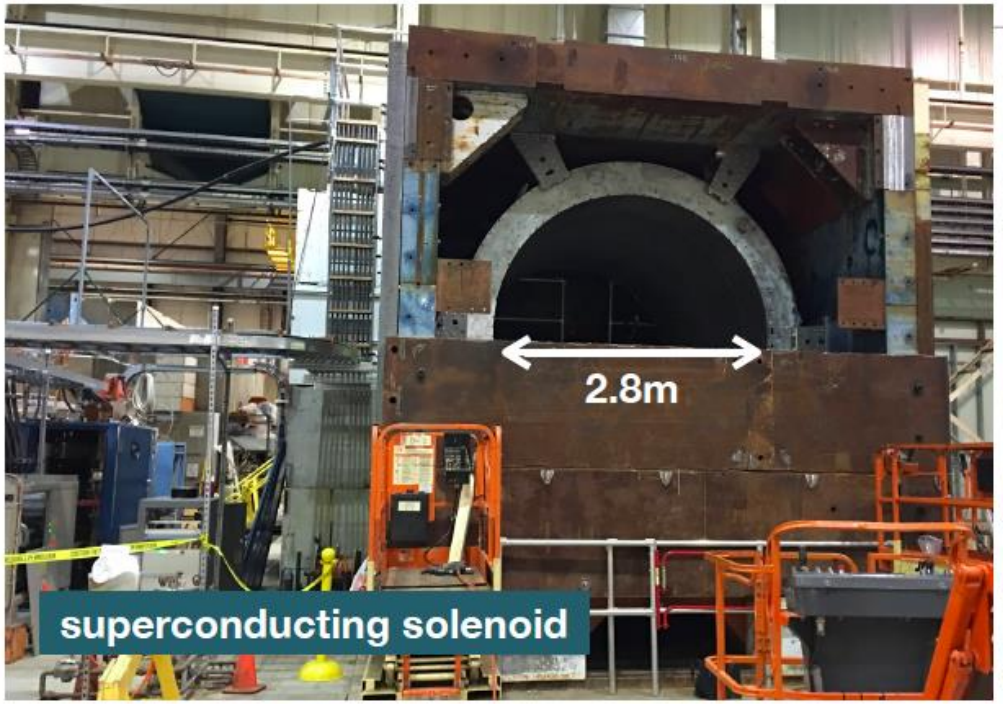


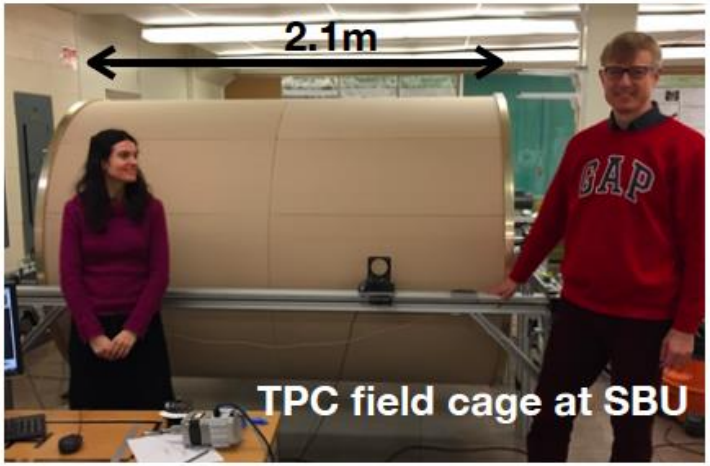
dijet kinematics in sPHENIX barrel

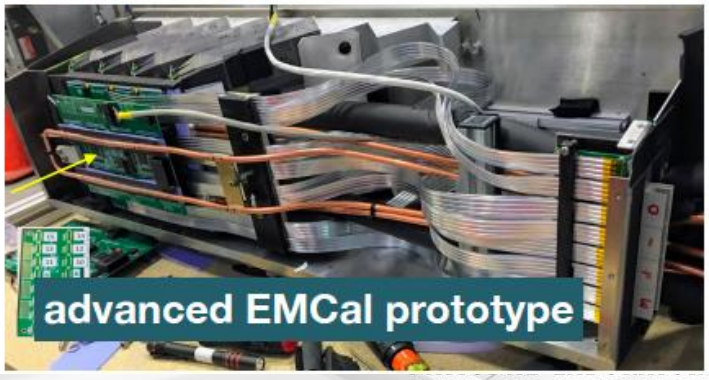


Projected capabilities for observables in longitudinally, transversely polarized collisions, nPDFs

sPHENIX Progress







- Magnet successfully tested to full current
- Contract awarded for full order of oHCal steel
- Full chain tests of calorimeter stack, MVTX telescope, INTT telescope, readout electronics
- TPC prototype to see test beam next week

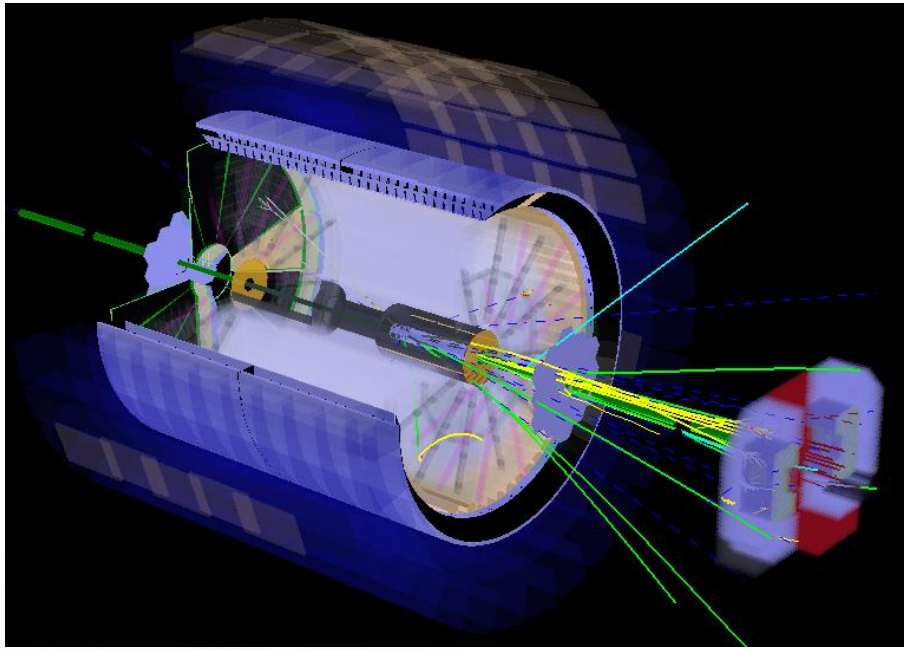
STAR Opportunities beyond BES

- STAR collaboration has proposed modest forward upgrades for RHIC runs beyond BES-II with significant Chinese contributions.
- Physics program described in 2016 RHIC Cold QCD Plan
- Endorsements from 2017 & 2018 PAC.

Possible stand-alone p+p run after the BES-II followed by running in parallel to sPHENIX.

Refurbished EMCal, new Hcal, STAR Pre-shower, FMS, and sTGC based tracking system, covering $2.5<\eta<4$.

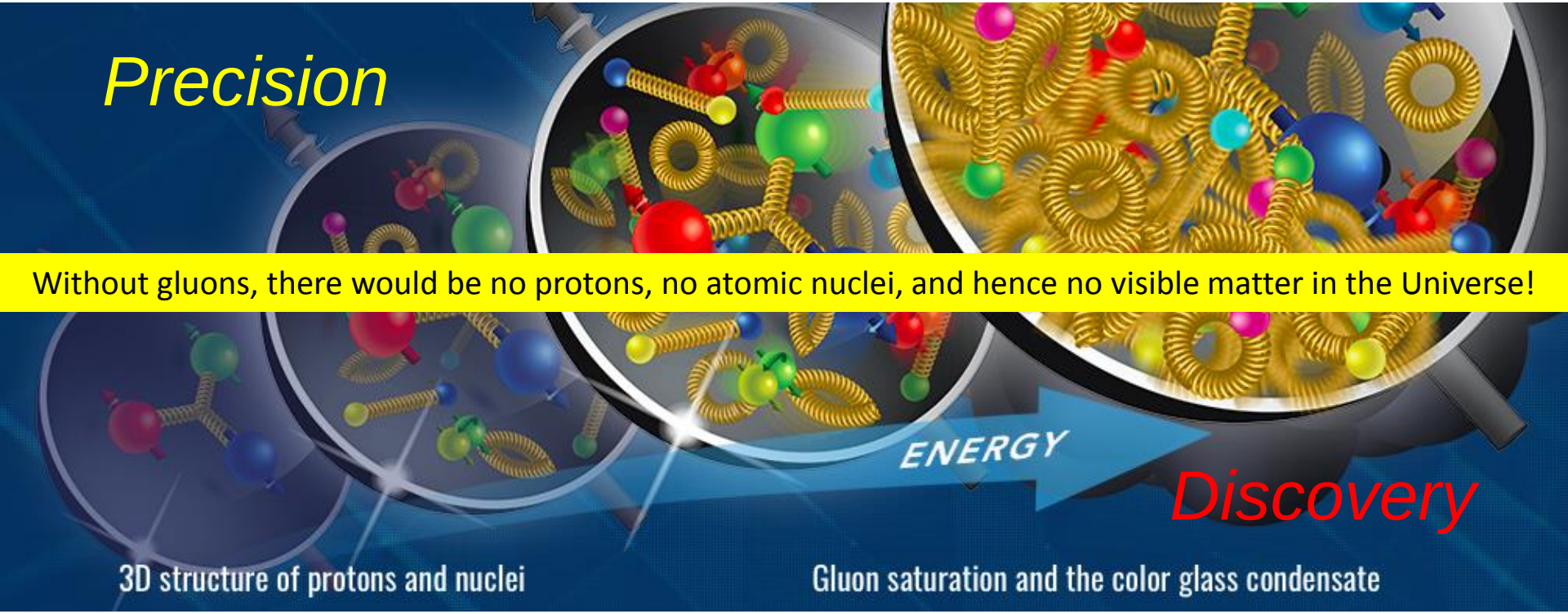
Yes/no decision needed in 2018.



Current Run Plan 2018-25

Year	STAR	sPHENIX
2018	28 (15+13) cryo-weeks ^{96}Zr / ^{96}Ru at 200 GeV Au+Au at 27 GeV, 3.0 GeV (FXT)	CD-1/3A
2019	28 (24+4) cryo-weeks Au+Au at 14.5, 19.6 GeV Au+Au at 3.9, 4.5, 7.7 GeV (FXT)	Construction
2020	20 cryo-weeks Au+Au at 9.1, 7.7 (or 11.5) GeV Au+Au at 3.2, 3.5, 5.2, 6.2 GeV (FXT)	Construction
2021	20 cryo-weeks Au+Au at 7.7 (and 11.5) GeV TBD	Construction
2022	No run	Installation
2023	TBD	20 cryo-weeks Au+Au at 200 GeV
2024	TBD	24 cryo-weeks p+p, p+Au at 200 GeV
2025	TBD	24 cryo-weeks Au+Au at 200 GeV

EIC Science Pillars



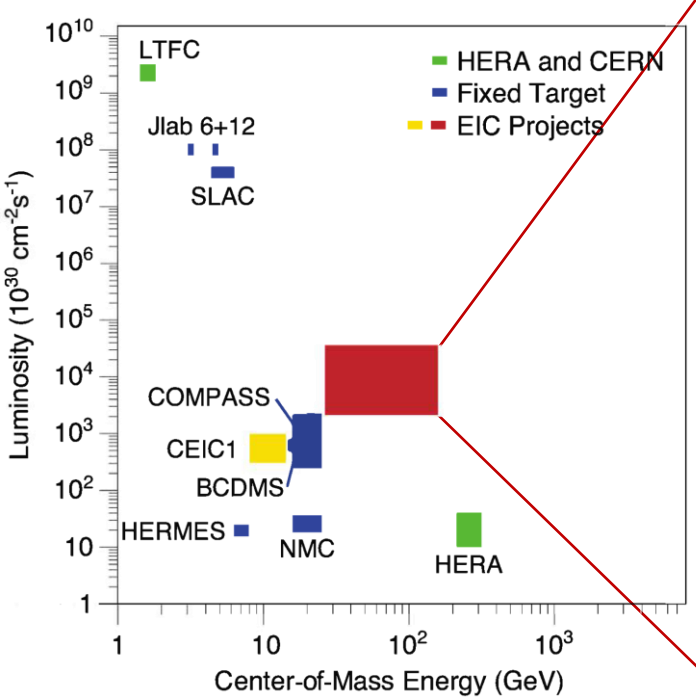
Without gluons, there would be no protons, no atomic nuclei, and hence no visible matter in the Universe!

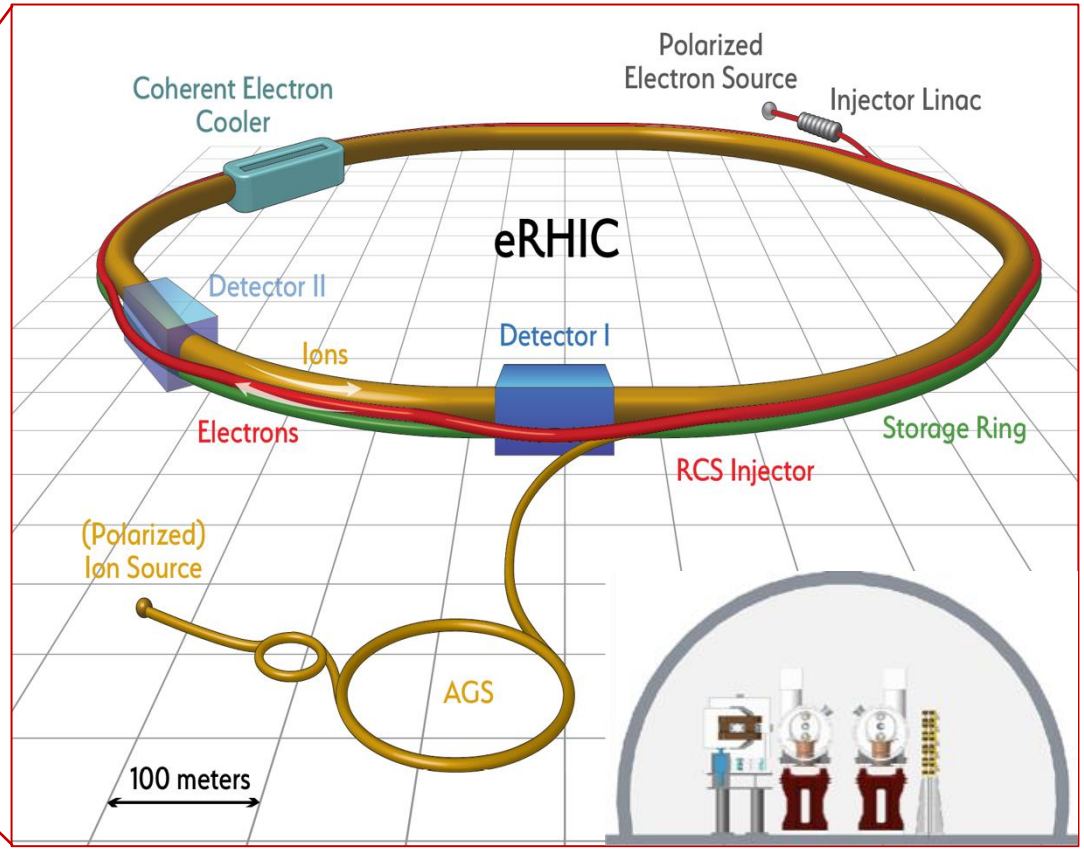
The EIC will collide high-energy electrons with high-energy protons or heavier atomic nuclei to produce "freeze-frame" snapshots of their inner structure, creating precise first-ever tomographic images of the "ocean" of gluons within. These images will tell us how gluons and quarks bind each other to form the particles that lie at the core of all atoms.

New experiments and advances in theory suggest that protons, neutrons, and nuclei appear as dense "walls" of gluons when probed at high energy, creating what are conjectured the strongest fields in nature. Discovering and studying this new form of matter, the "color glass condensate," will give us additional insight into why matter in this sub-atomic realm is stable.

… and much, much more! (see EIC White Paper)

eRHIC: The EIC at BNL

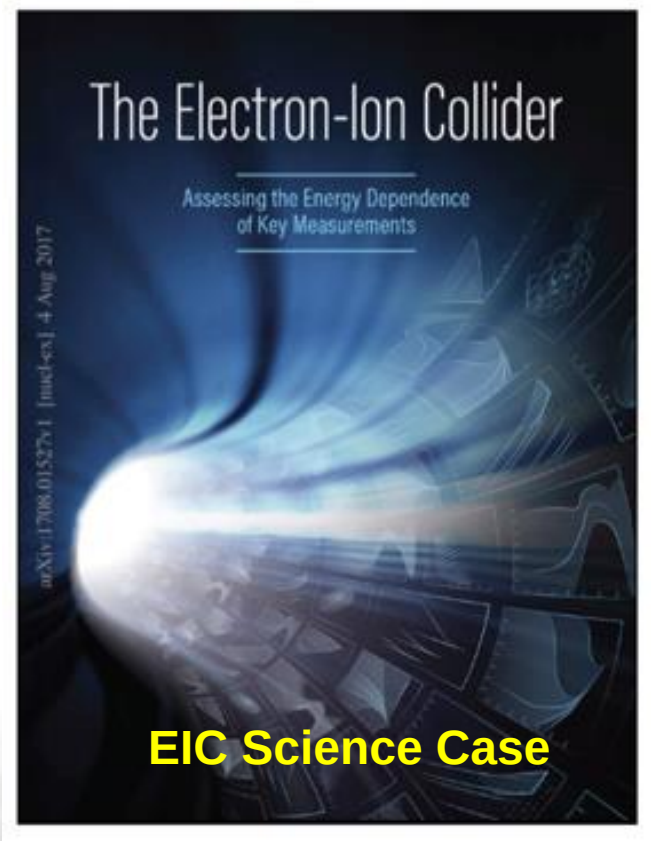


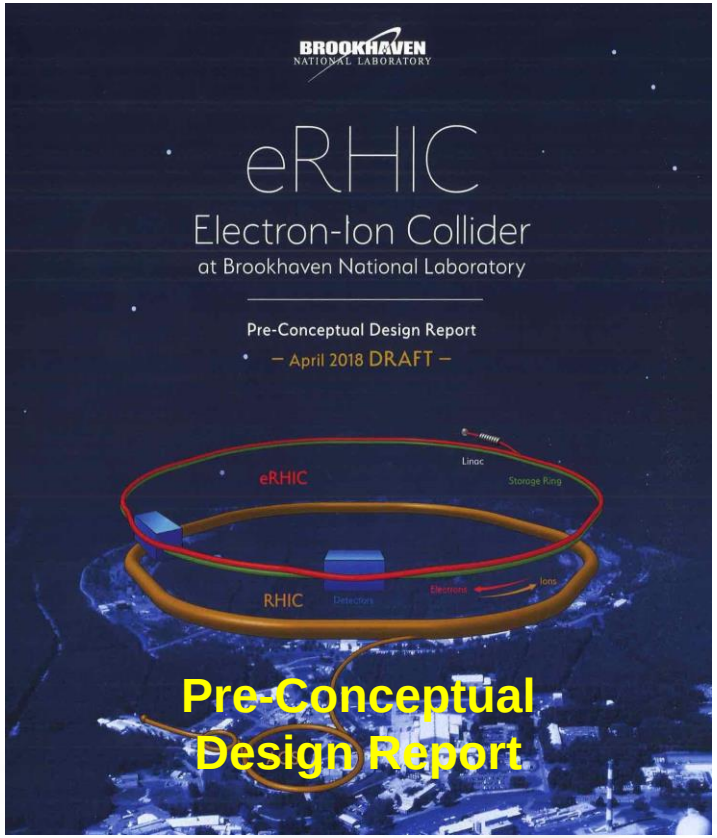


The eRHIC concept is economical, because it re-uses the large DOE investment in RHIC.

eRHIC Planning

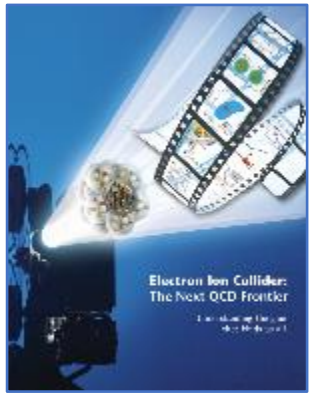
- Formation of a dedicated eRHIC Design Team
- Creation of SBU/BNL Center for Frontiers of Nuclear Physics
- Completion of a Pre-Conceptual Design Report (end of June 2018)

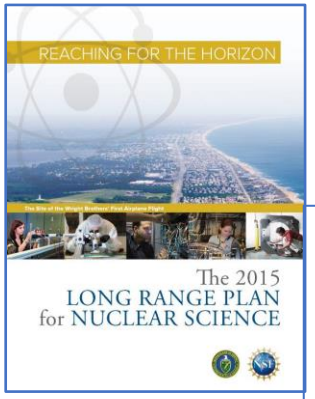




Timeline (Past & notional future)

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018





Review by US National Academy of Sciences

LRP RECOMMENDATION

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

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31
Critical Decisions		CD-0 Approve Mission Need Dec 2018		CD-1 Approve Selection and Cost Range Dec 2020		CD-2 Approve Selection Performance Baseline Dec 2021		CD-3 Approve Start of Construction Dec 2023					CD-4 Approve Project Completion Dec 2029	

Beam Energy Scan

sPHENIX

eRHIC

There are, indeed,

Exciting Times Ahead!