The Future of RHIC

SQM2016

Berndt Mueller

July 1, 2016

A reporter calls

"I've been poking around the idea of a story about how studying quark-gluon plasmas can help us figure out some of the big mysteries of matter – namely how gluons do their binding to give nucleons their mass and other familiar properties. I think that could make for a compelling story, so long as I can make the case that we really are learning some cool and surprising things about how matter came to be (the transition from a quark-gluon broth to hadrons) and, perhaps, why it doesn't all fall apart.

I'm particularly keen to get a grip on what we have already discovered by studying QGPs: for instance, what have we learned about how quarks and gluons are bound by watching QGPs as they cool? And what other important insights have come from studying QGP? Right now I'm struggling to pin down the key insights.

I need to understand what we're learning by creating QGPs and, say, watching them cool to study confinement in reverse – that is, what we're discovering about how gluons bind quarks, and how that might help with the missing mass problem and/or other questions, and how we plan to discover more in the future."

Daniel Cossins (New Scientist Magazine) June 27,2016

We may not have the answers to his questions, but we have some cool answers to other questions. And we have a plan to discover more in the future….

2015 Long Range Plan

RECOMMENDATION I

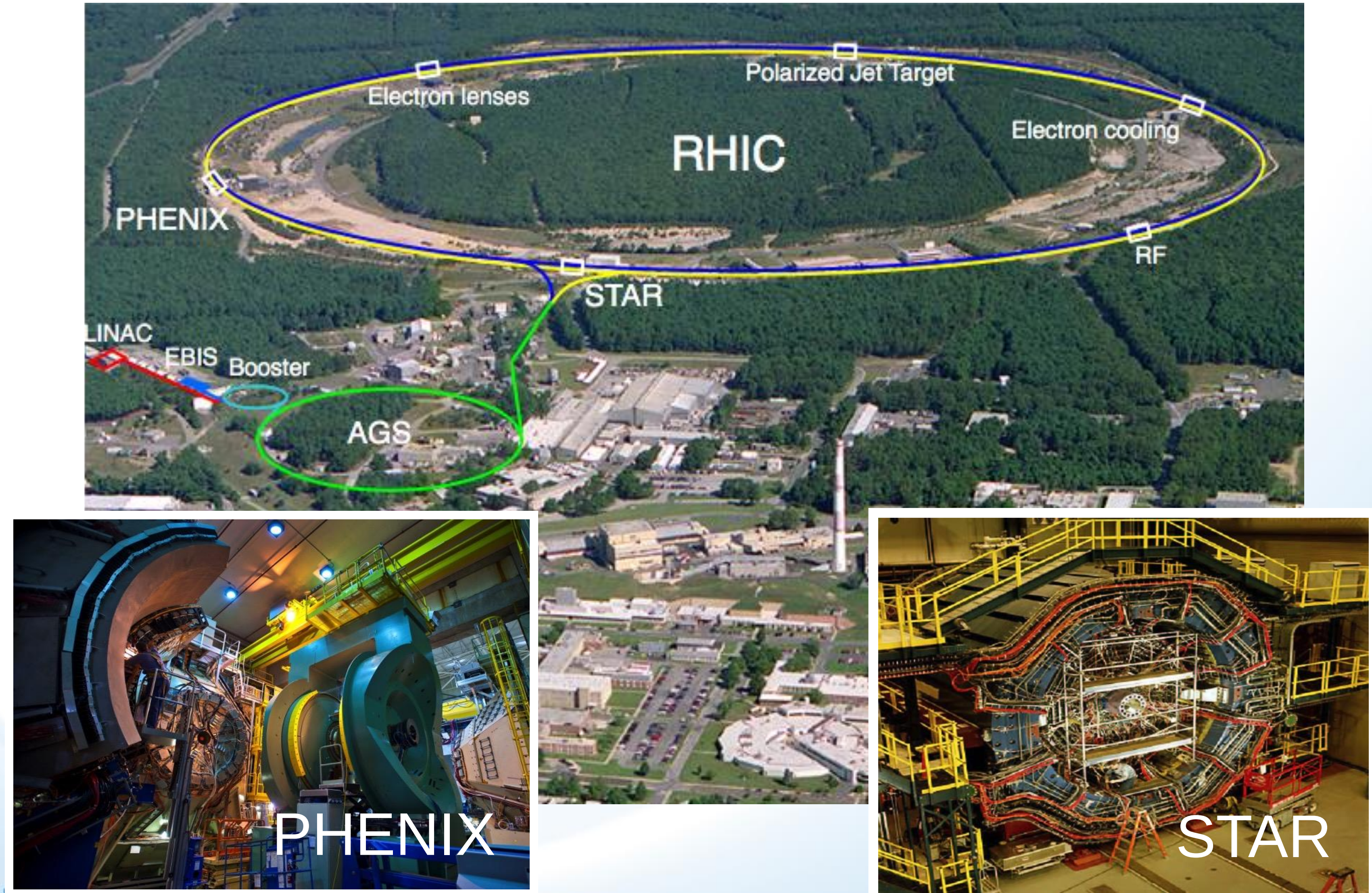
The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *Complete and run CEBAF 12 GeV upgrade*
- *Complete FRIB at MSU*
- *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.*

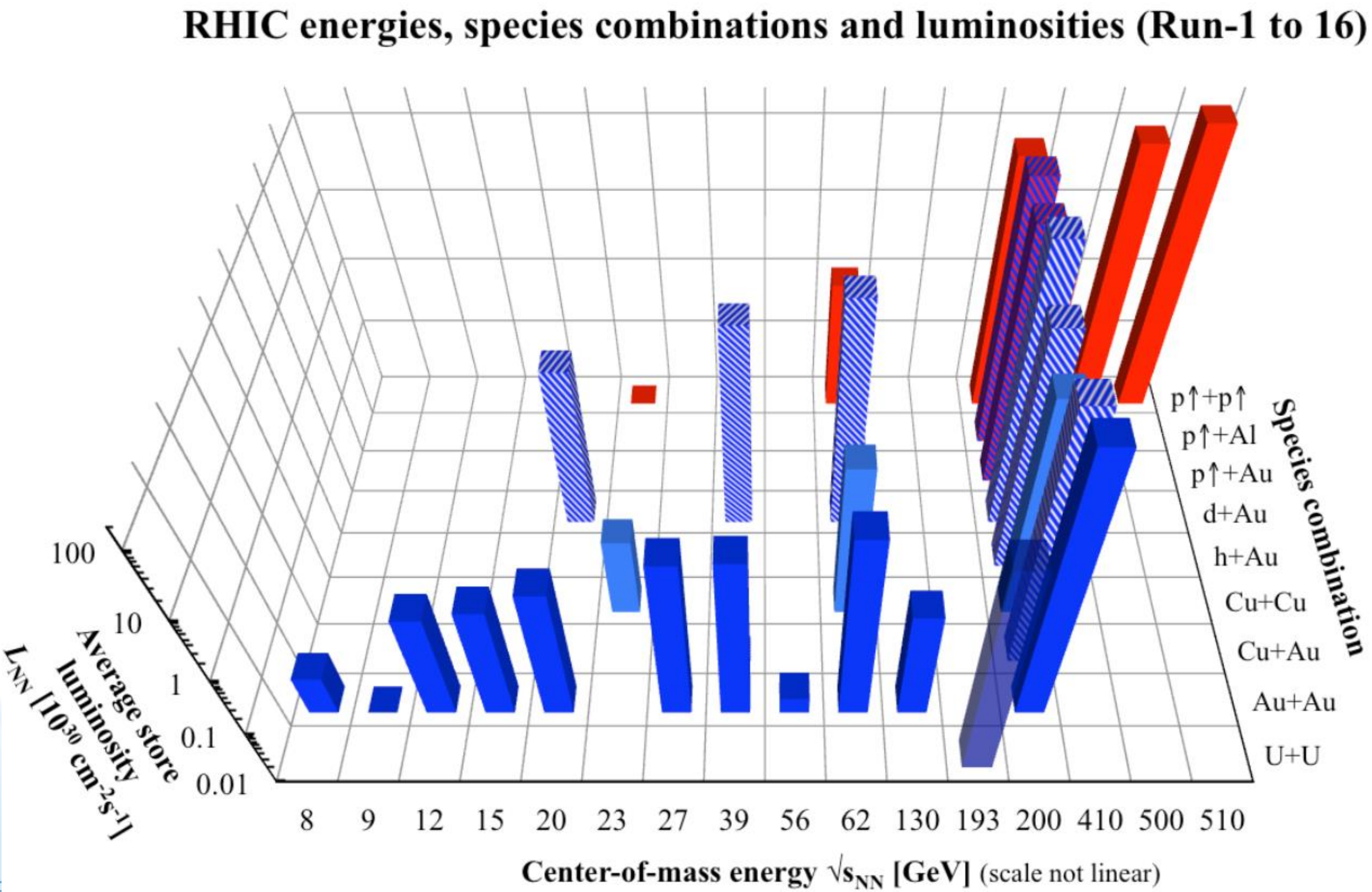
Completing the RHIC science mission

- Explore and probe the microscopic structure of the liquid QGP using energetic (or massive) probes:
  - Heavy (c and b) quarks
  - Heavy quarkonia (charmonium and Upsilon)
  - Quark and gluon jets
- Map and explore the QCD phase diagram
  - Use change of beam energy to vary (μ_B,T) location in phase diagram
- Discover predicted topological transitions in the QCD vacuum
  - Isobar system ($\Delta Z=4$) test to confirm Z^2 magnetic field dependence of parity violating fluctuations in chirally symmetric QGP
- Exploratory study of transverse spin dynamics in p+p
  - Insights will enable more reliable predictions for the EIC physics program

The RHIC Facility today



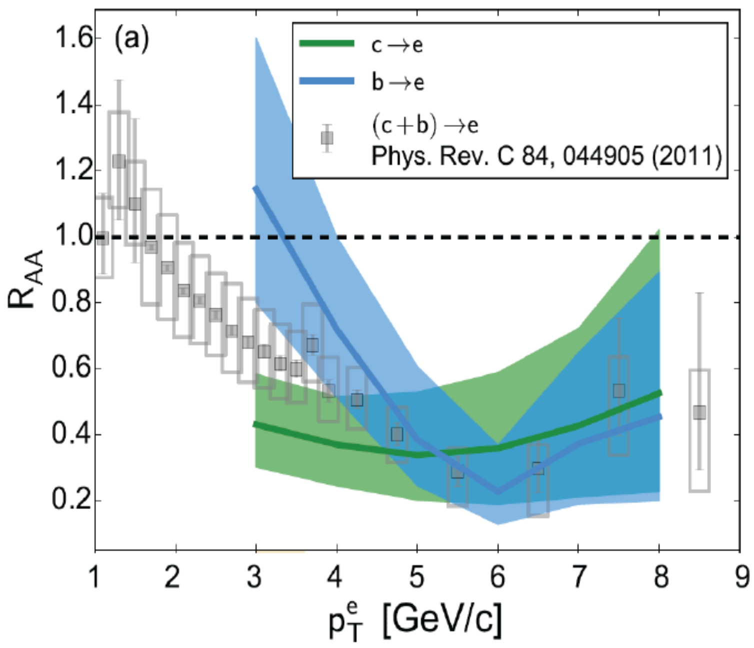
RHIC is versatile



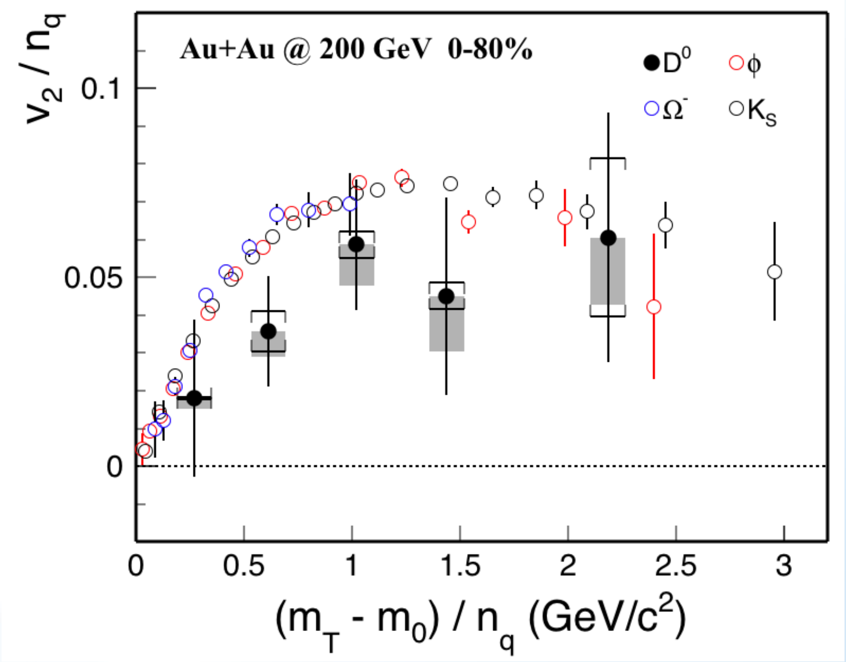
Recent Results

Heavy Quark Transport in the QGP

PHYSICAL REVIEW C 93, 034904 (2016)



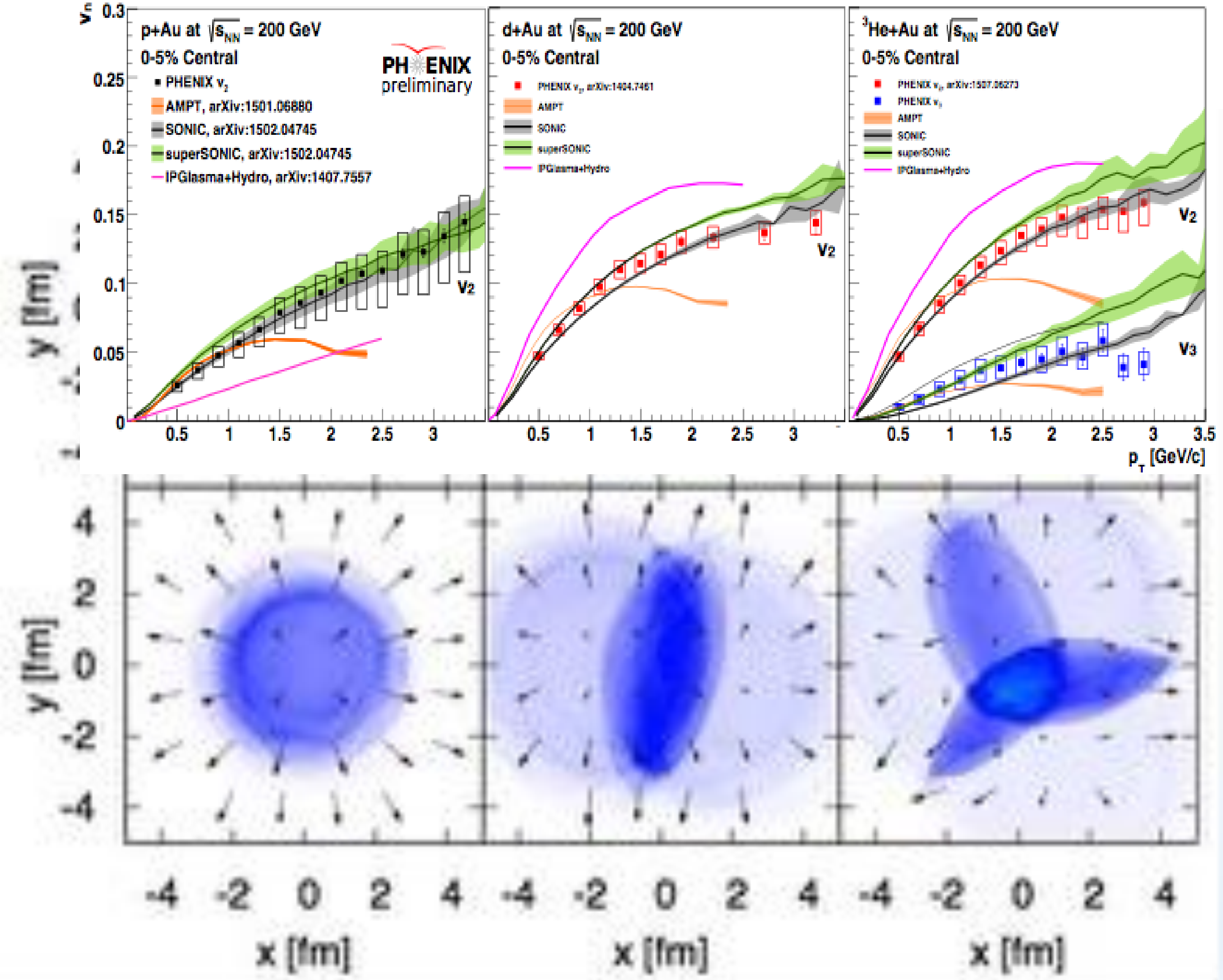
Hadrons containing c quarks show signs of collective flow



Both b and c quarks are suppressed at large p_T

Small heavy quark diffusion constant confirms strong coupling of QGP at different scale from hydrodynamics.

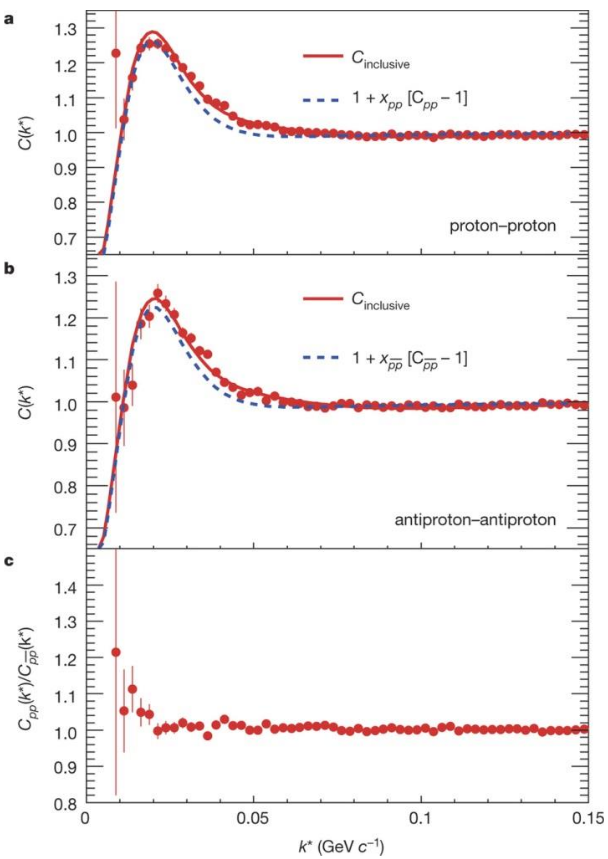
What is the smallest drop of QGP?



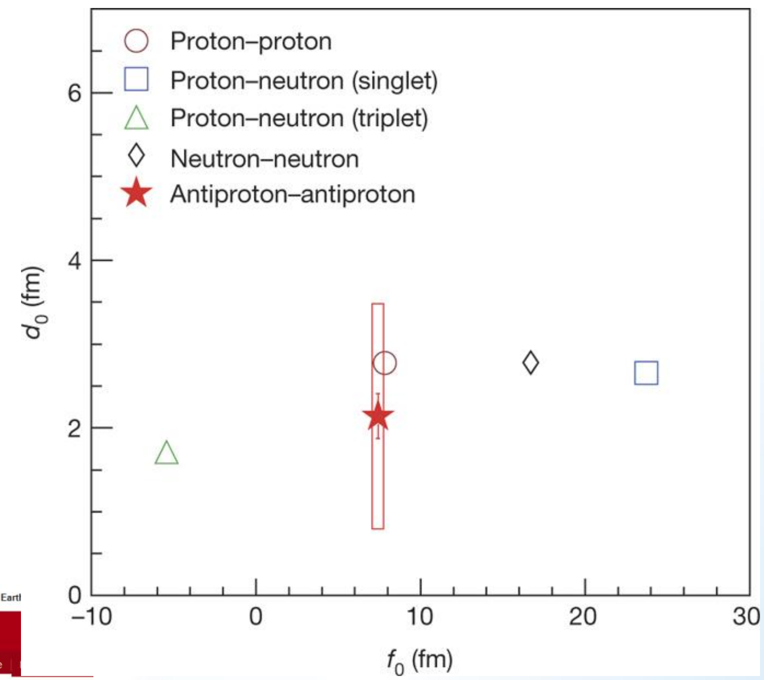
Data-Theory comparison confirms hydrodynamic collective flow

Final state

Interaction between two antiprotons



[Nature **527**, 345 (2015)]

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Science & Environment

Strong forces make antimatter stick

4 November 2015 | Science & Environment

Brookhaven Laboratory

Physicists have shed new light on one of the greatest mysteries in science: Why the Universe consists primarily of matter and not antimatter.

Antimatter is a shadowy mirror image of the ordinary matter we are familiar with.

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 corres-ponding strong interaction: the scattering length and the effective range of the interaction

RHIC 2017-23

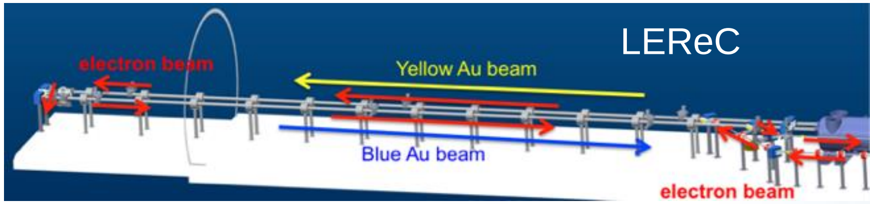
Completing the RHIC science mission

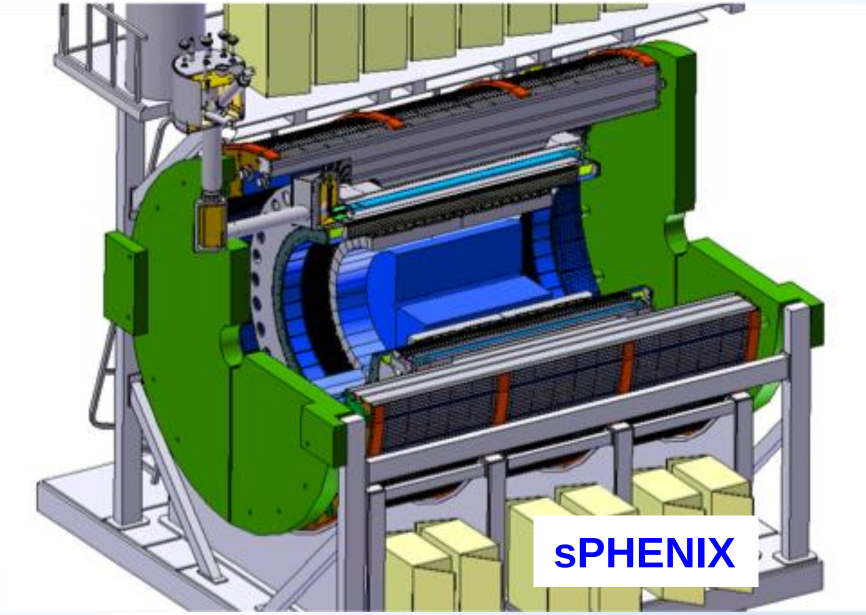
Status: RHIC-II configuration is operational

- **RHIC reaches 44 times design luminosity**

Plan:

- **2016: Completion of heavy flavor program**
- **2017: Transverse spin physics in QCD**
- **2018: Isobar system test of chiral symmetry**
- *2018: Low energy e-cooling & iTPC upgrade*
- **2019/20: High precision scan of the QCD phase diagram & search for critical point**
- *2021: Install sPHENIX*
- **2022-??: Probe structure of perfect liquid QGP with precision measurements of jet quenching and Upsilon suppression**

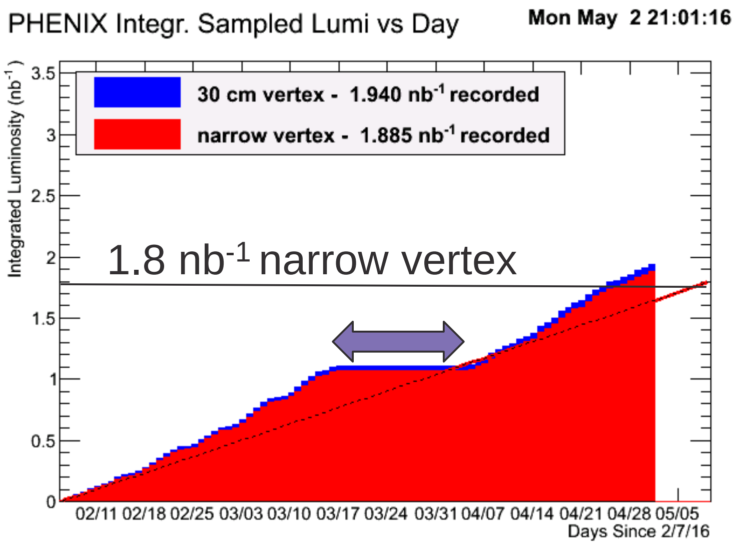




RHIC remains a unique discovery facility

Run-16

- High luminosity 200 GeV Au+Au run (11 weeks)
- Study heavy flavor flow, especially charmed baryons, parton energy loss in QGP, quarkonium studies (for NP milestone DM12)
- PHENIX exceeded its luminosity goal
- STAR reached its MB goal (2B events)
- (in spite of 19-day interruption!)



- d+Au beam energy scan (5 weeks)
- Study beam energy dependence of small system collectivity and QGP properties
- d+Au 200 GeV, 62.4 GeV, 39 GeV, 19.6 GeV completed
- Statistics goals reached or exceeded (PHENIX and STAR)

Run-17 Plan

- **High luminosity 510 GeV transverse polarized p+p run (13 weeks)**
- **Study scale evolution of the Sivers effect in W-boson production; possibly confirm sign change of the Sivers effect relative to DIS**

- **Proof of Principle test of coherent electron cooling (1 week)**

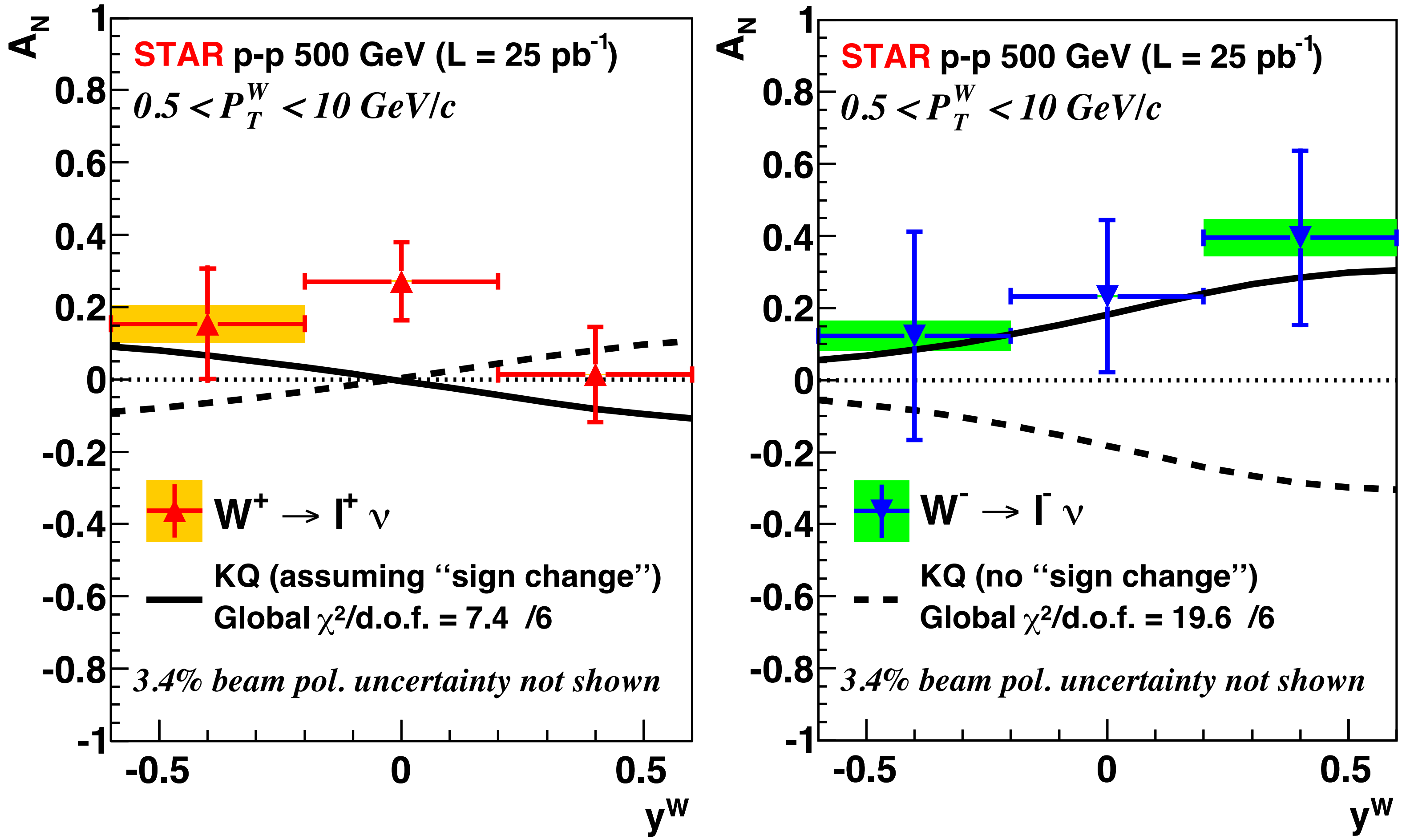
Run-18 Plan

- **Isobar system (^{96}Ru - ^{96}Zr) run (8 weeks)**
- **Critical signature of Chiral Magnetic Effect**

Strongly endorsed by 2016 RHIC PAC.

W Sivers function (Run-17)

Phys. Rev. Lett. 116 (2016) 132301



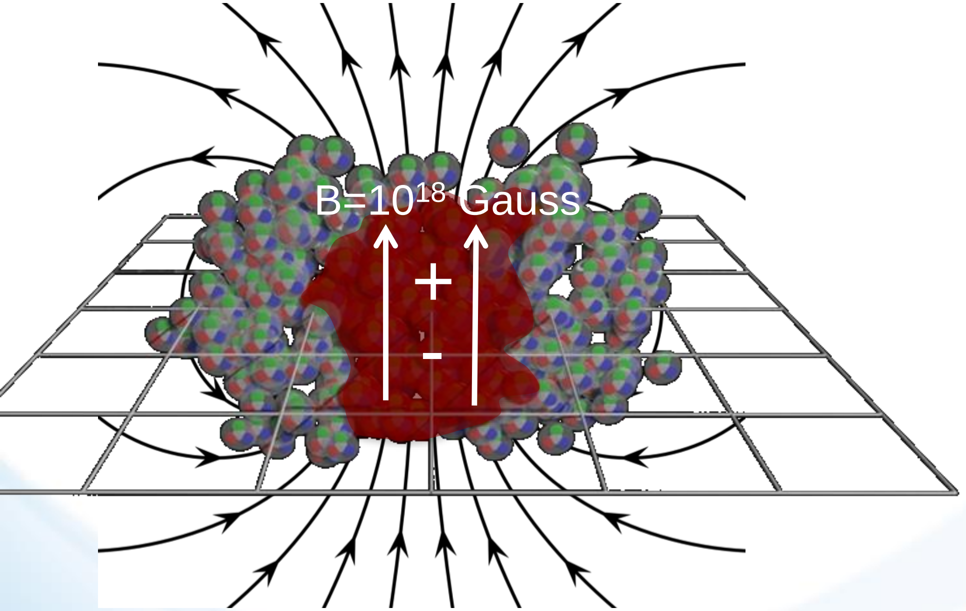
Probing Chiral Symmetry with Quantum Currents

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

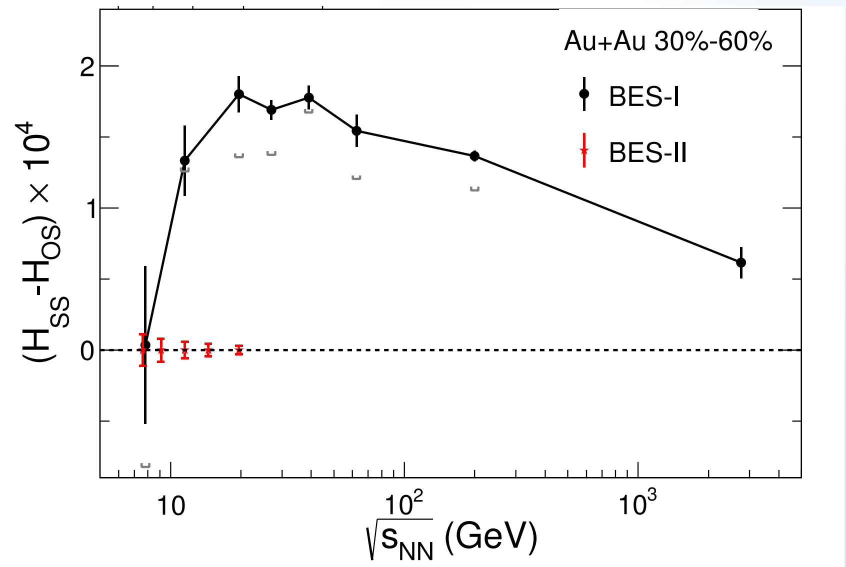
A similar mechanism in the electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

In a chirally symmetric QGP, this imbalance can create charge separation along the magnetic field (chiral magnetic effect – just discovered in CM at BNL)

charge separation



observed at all but the lowest energy

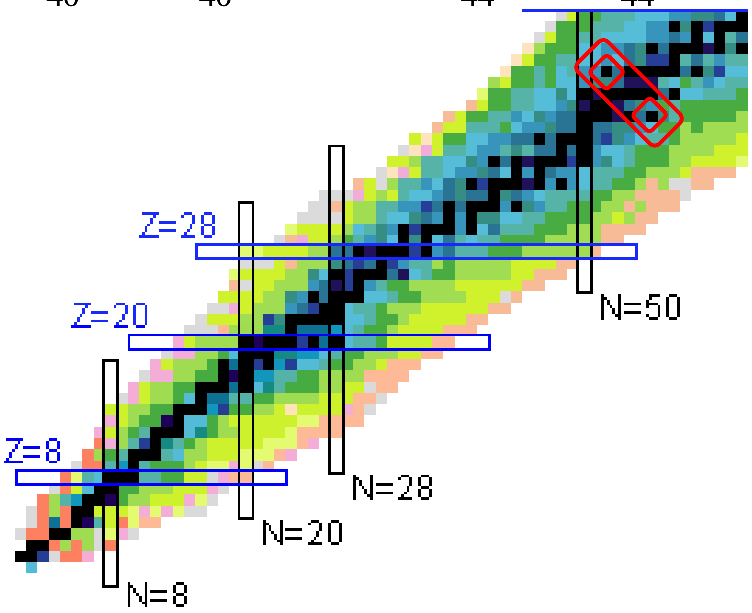


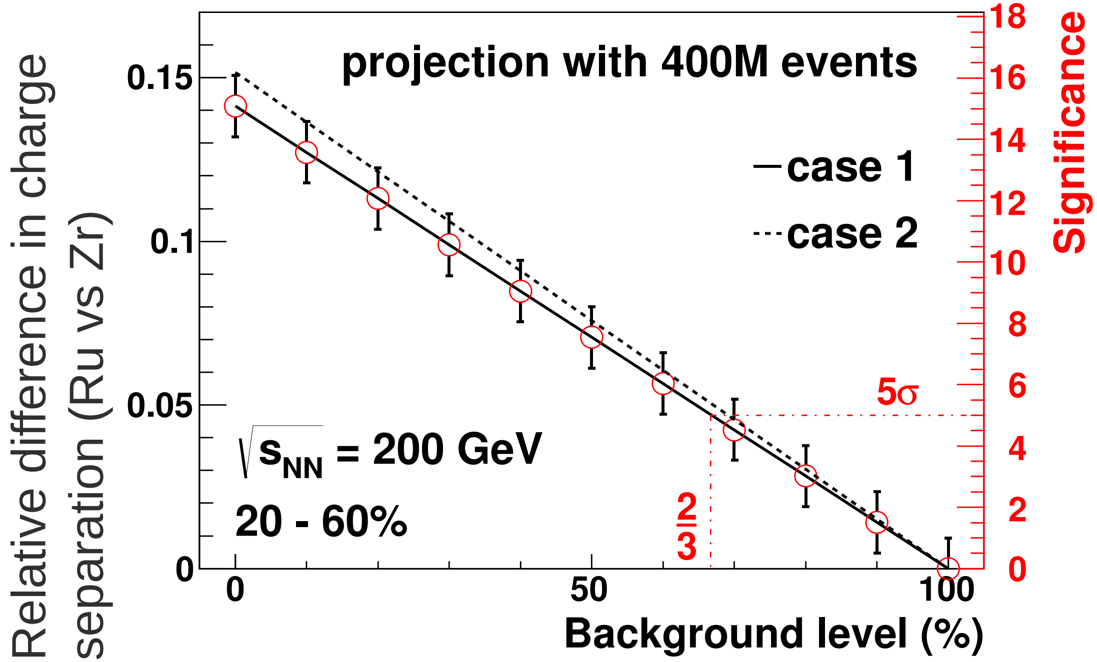
But models with magnetic field-independent flow backgrounds can also be tuned to reproduce the observed charge separation.

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. $^{96}_{44}Ru + ^{96}_{44}Ru$



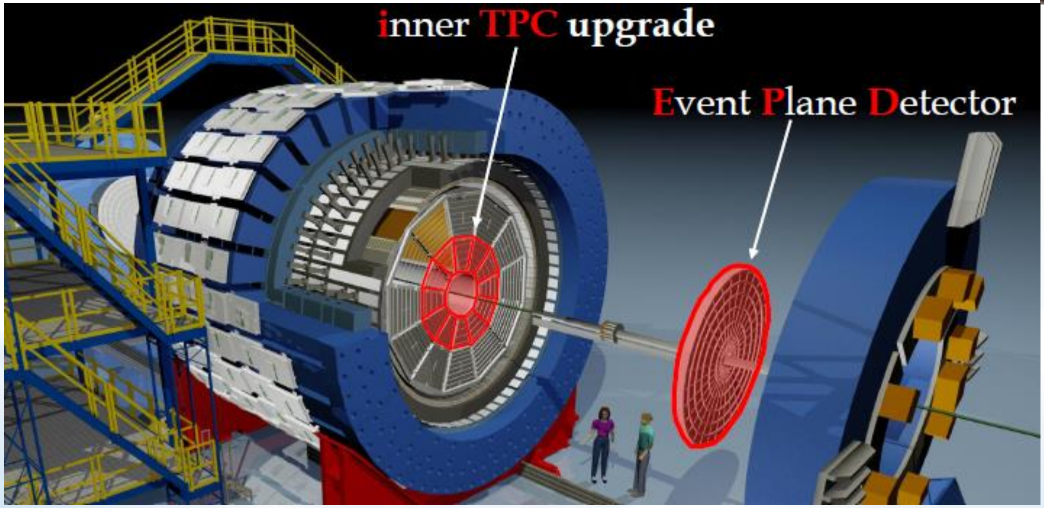


Isobar collisions will tell us what fraction of the charge separation is due to CME to within +/- 6% of the observed signal

Beam Energy Scan II

STAR Upgrades for BES II

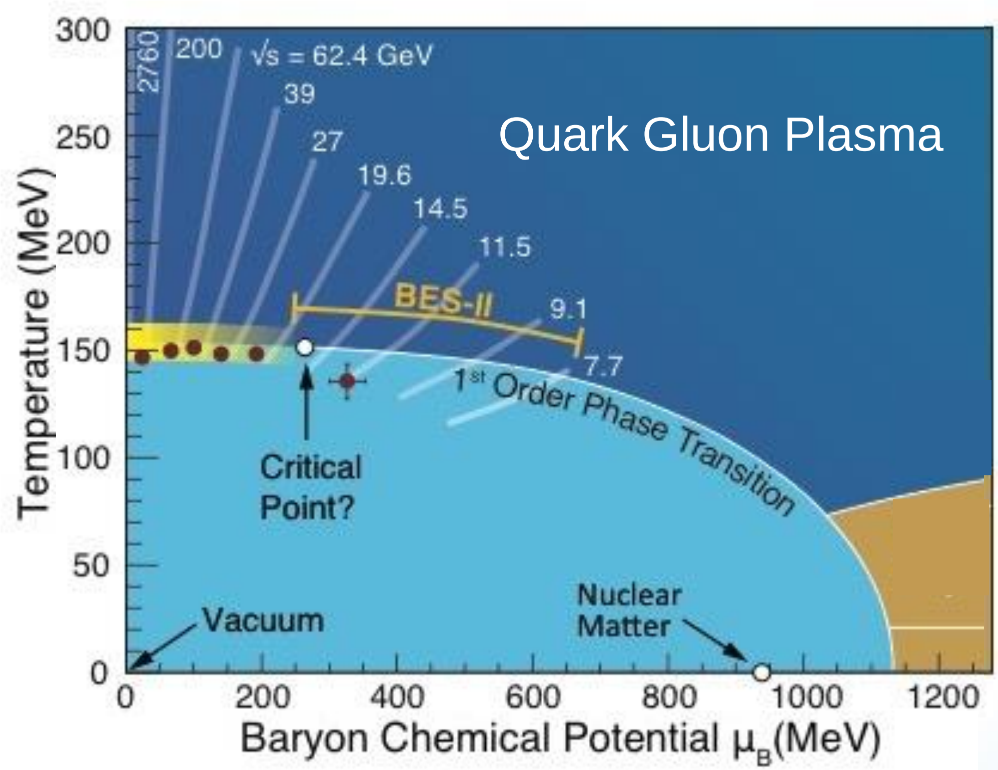
iTPC upgrade (2018)
Replace inner TPC Sectors
Extend rapidity coverage
Better particle ID
Low p_T coverage



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

Studying the Phases of QCD with RHIC

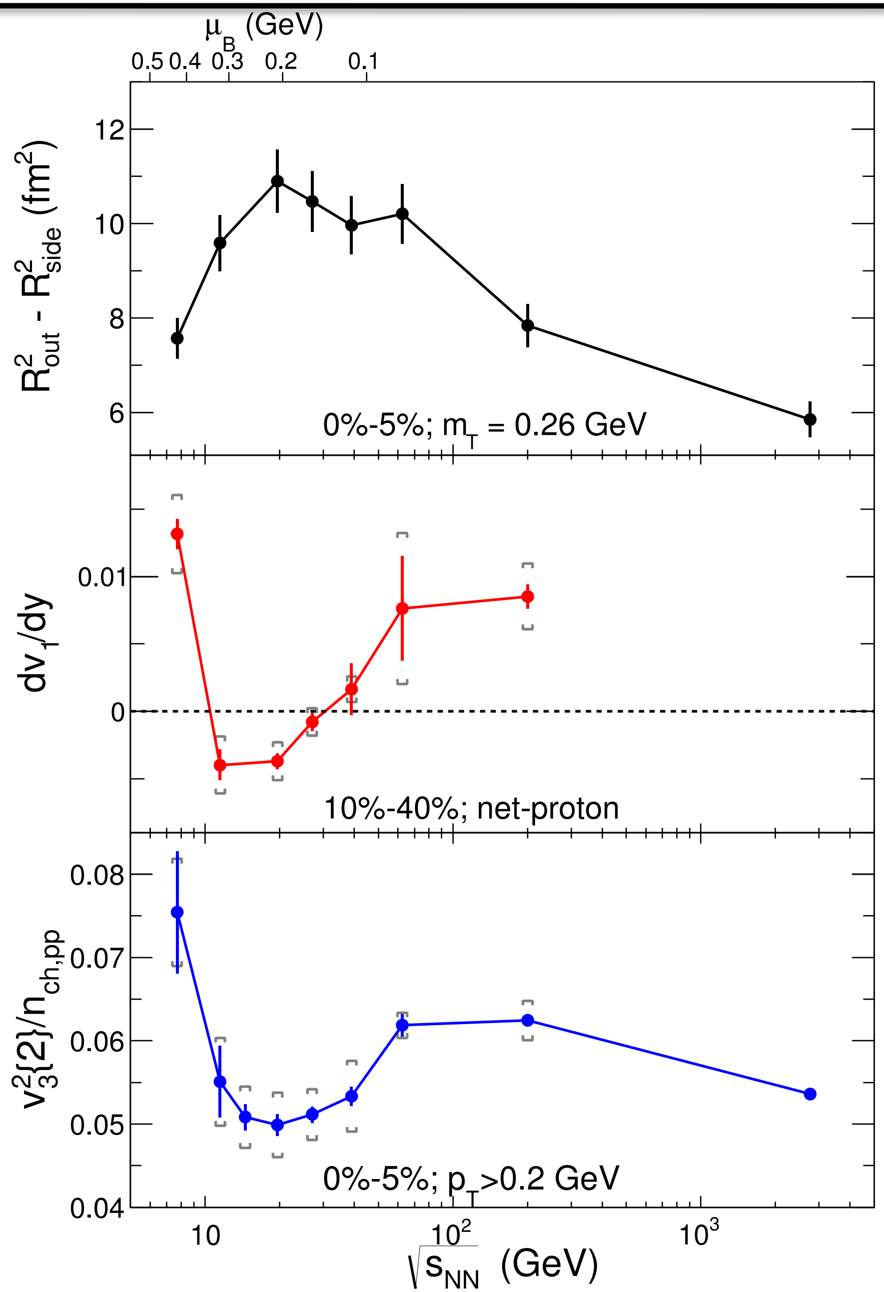
A unique RHIC capability -- a unique opportunity for U.S. science



Breaking of chiral symmetry in QCD generates most of the visible mass of the universe. Is chiral symmetry restored in these collisions?

At low density, the phase transition between QGP and hadrons is smooth. Is there a 1st order transition and a critical point at higher density?

Critical Behavior: Anomalies in the Pressure?



Maximum in lifetime?

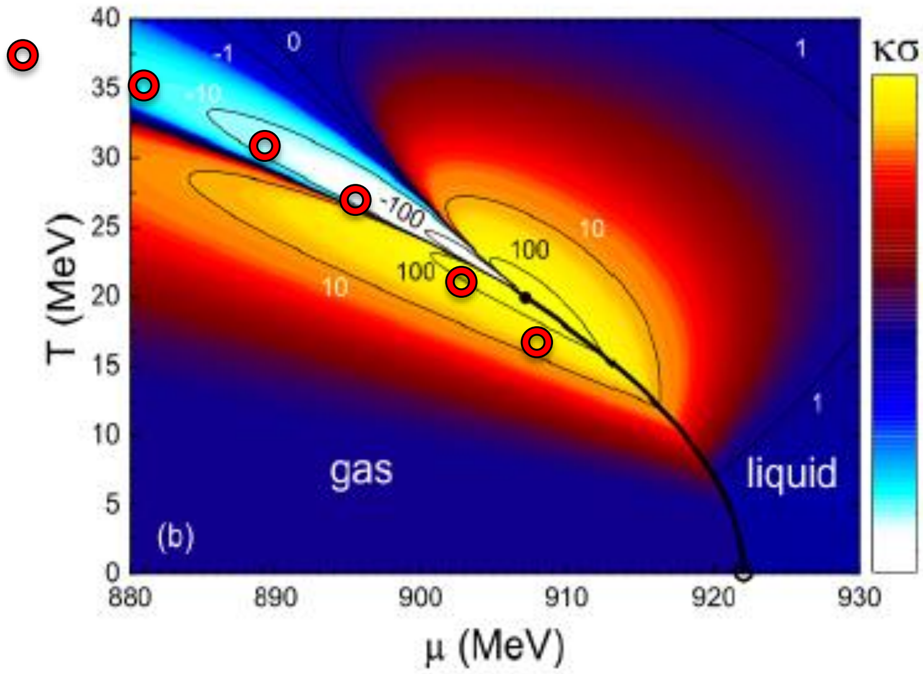
Minimum in pressure?

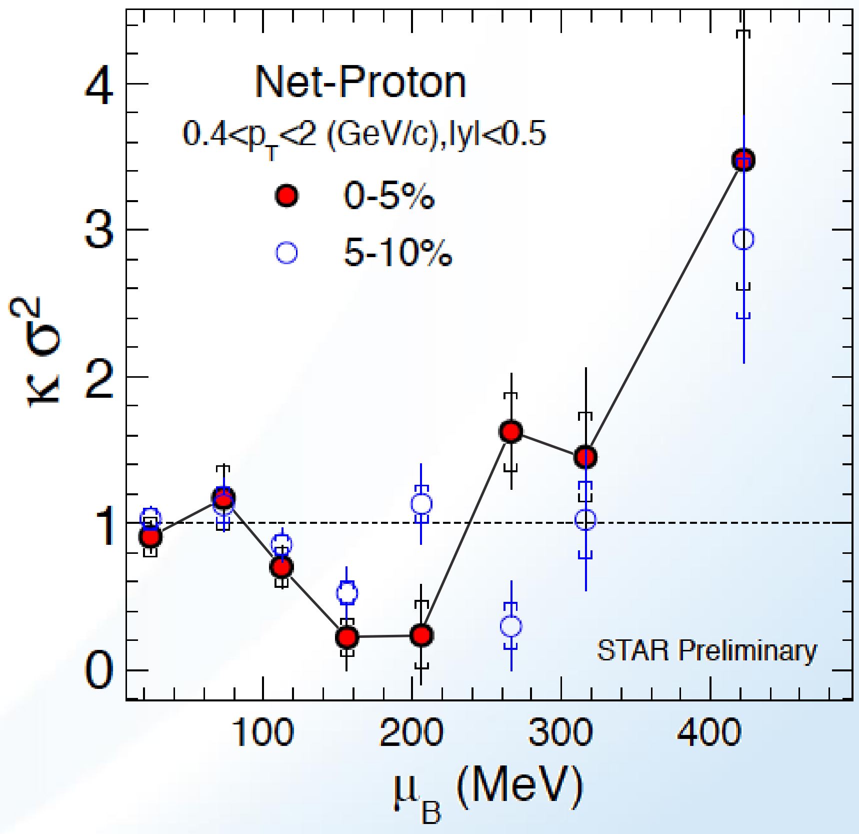
Region of interest $\sqrt{s_{NN}} \lesssim 20$ GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear crossing times, etc.

Requires concerted modeling effort: the work of the BESTheory topical collaboration is essential

Critical behavior

The moments of the distributions of conserved charges are related to susceptibilities and are sensitive to critical fluctuations





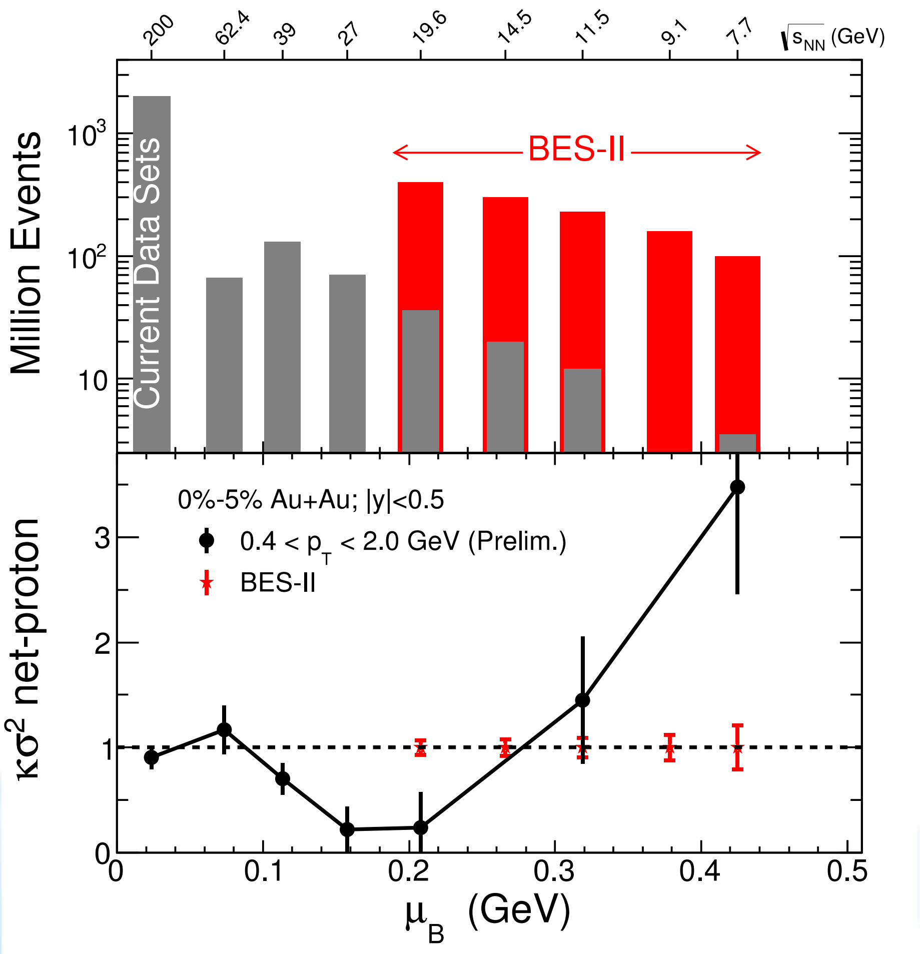
Higher moments like kurtosis*variance $\kappa\sigma^2$ change sign near the critical point

Non-monotonic trend observed in BES-I with limited statistical precision!

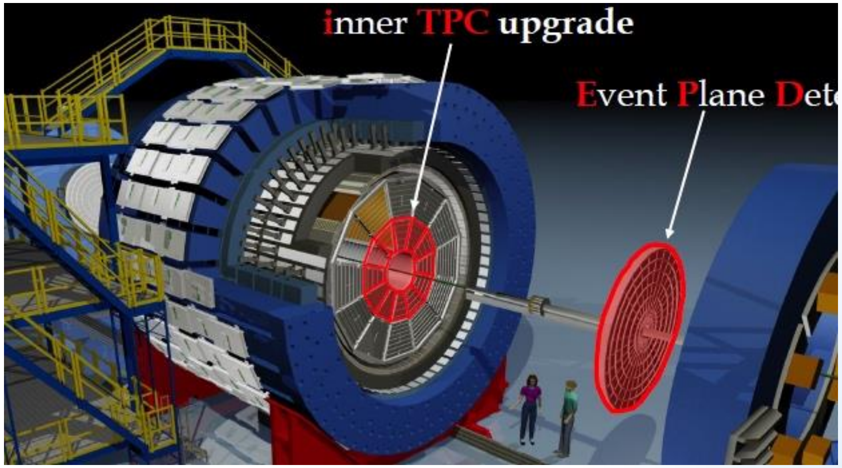
Mapping the QCD phase diagram in BES-II

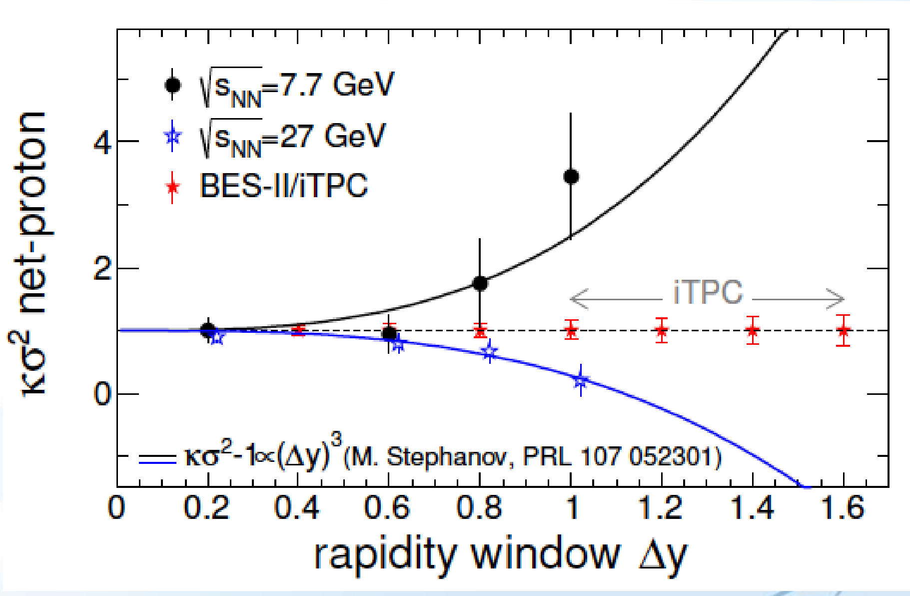
Higher statistics

Low energy RHIC electron cooling upgrade



Larger acceptance





sPHENIX

The overarching scientific question:

How do asymptotically free quarks and gluons
create the near-perfect liquidity of the QGP?

or

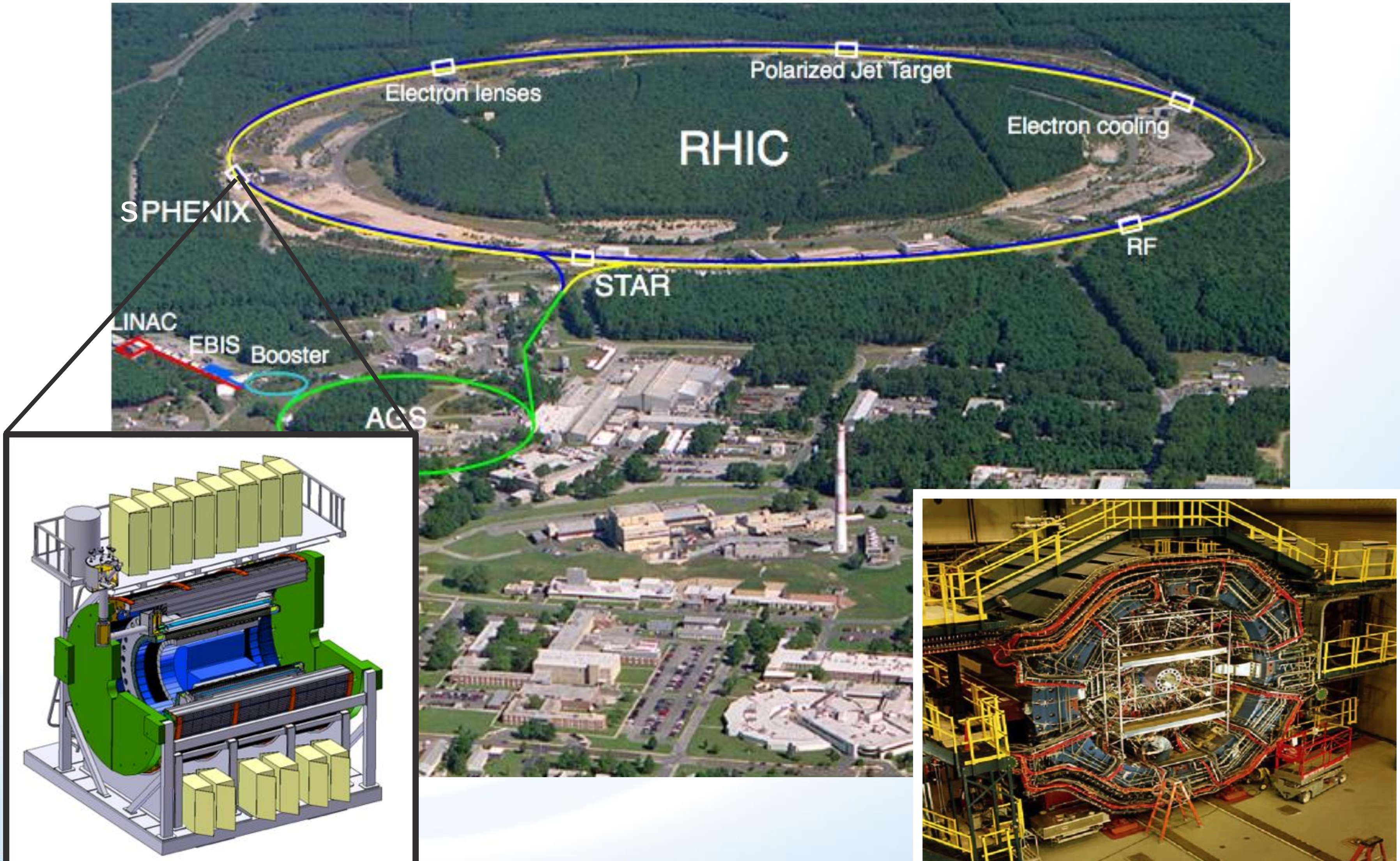
What degrees of freedom
not manifest in the QCD Lagrangian
produce the near-perfect liquidity of the QGP?

The (experimental) answer:

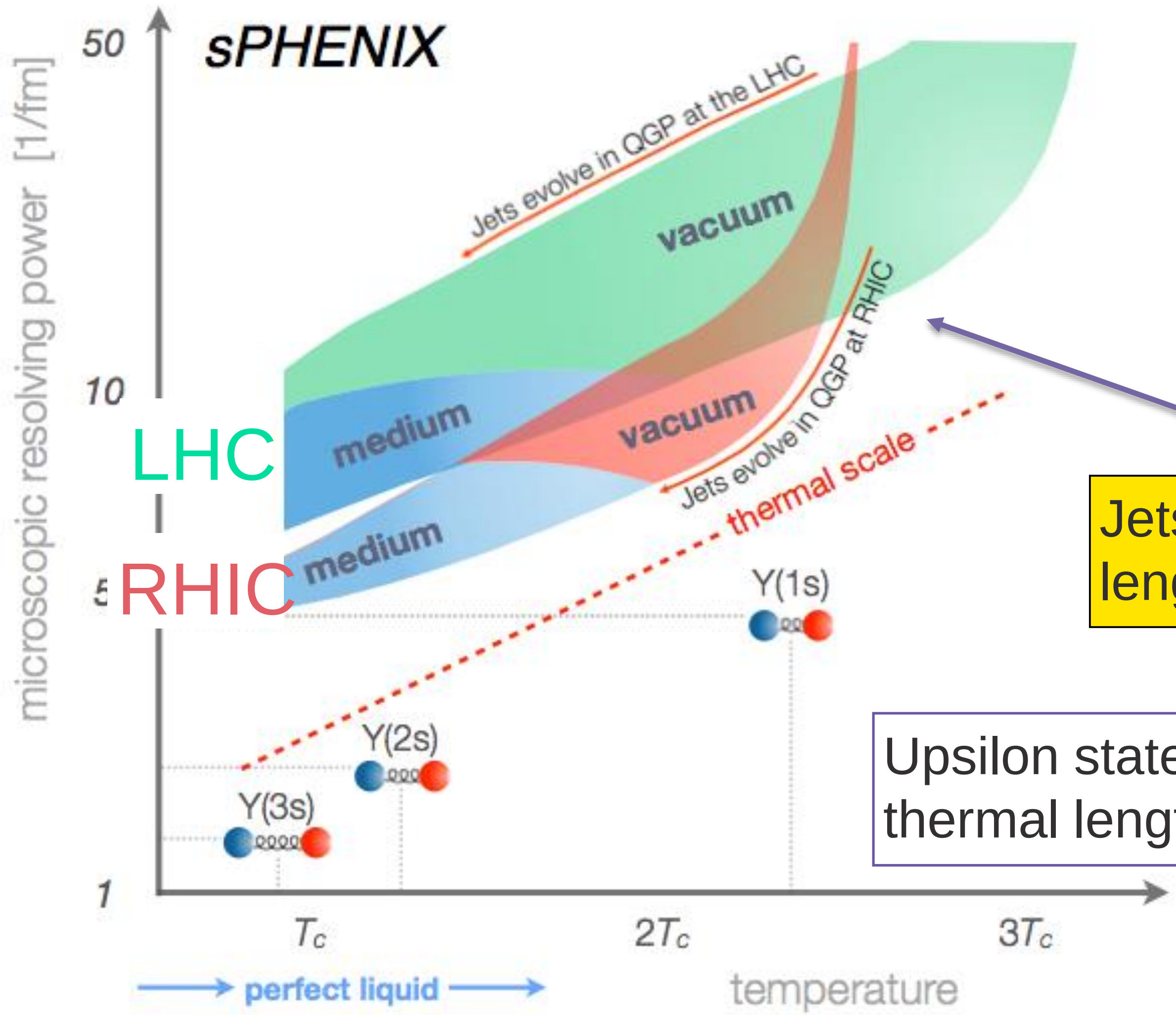
Deploy probes with a resolution that reaches well
below the thermal ~ 1 fm scale of the bulk:

Jets & b-quark (Upsilon) states

The RHIC Facility in 2022



Probing scales in the medium



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

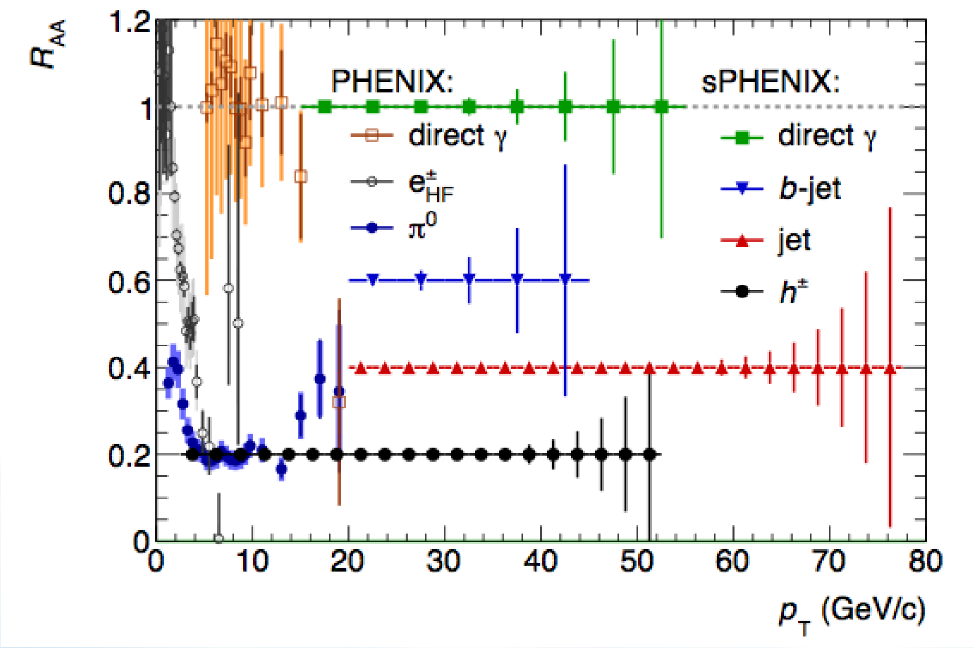
Jets probe sub-thermal length scales

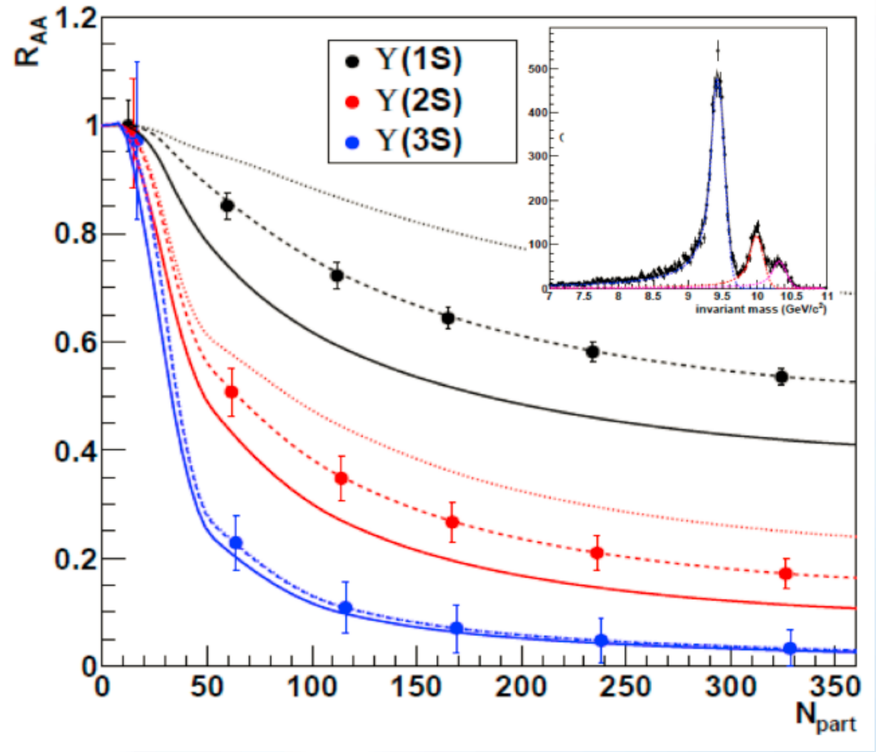
Upsilon states probe thermal length scales

Jets & Upsilon states

sPHENIX capabilities

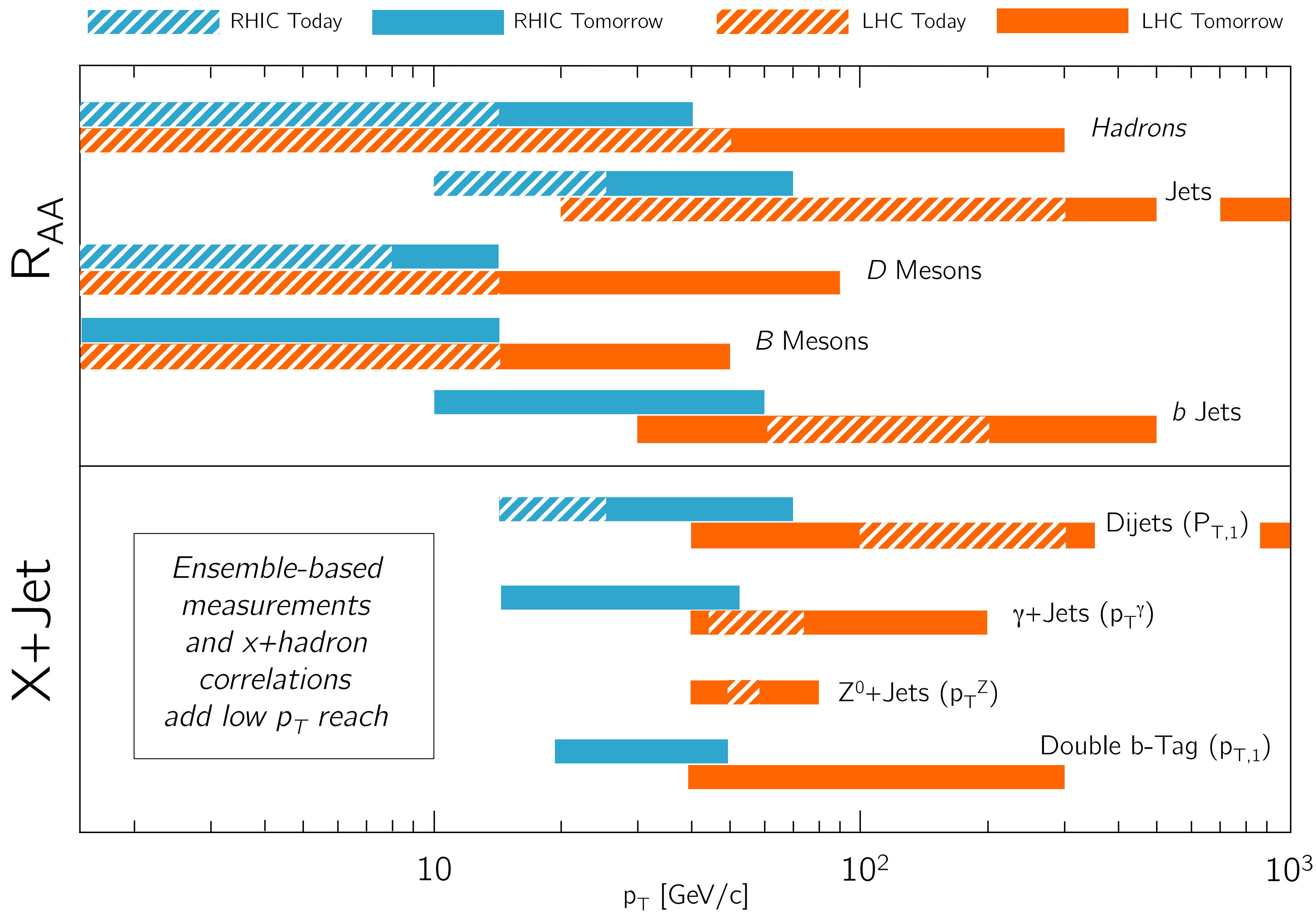
Complete calorimetric jet spectroscopy





Completely resolved Upsilon spectroscopy

RHIC & LHC complementarity



The Future of RHIC is Bright !

I hope you will be part of it.