RHIC - Future Plans

2018 - 2025

Berndt Mueller

1st sPHENIX Workshop in China

Beijing, April 22-23, 2018

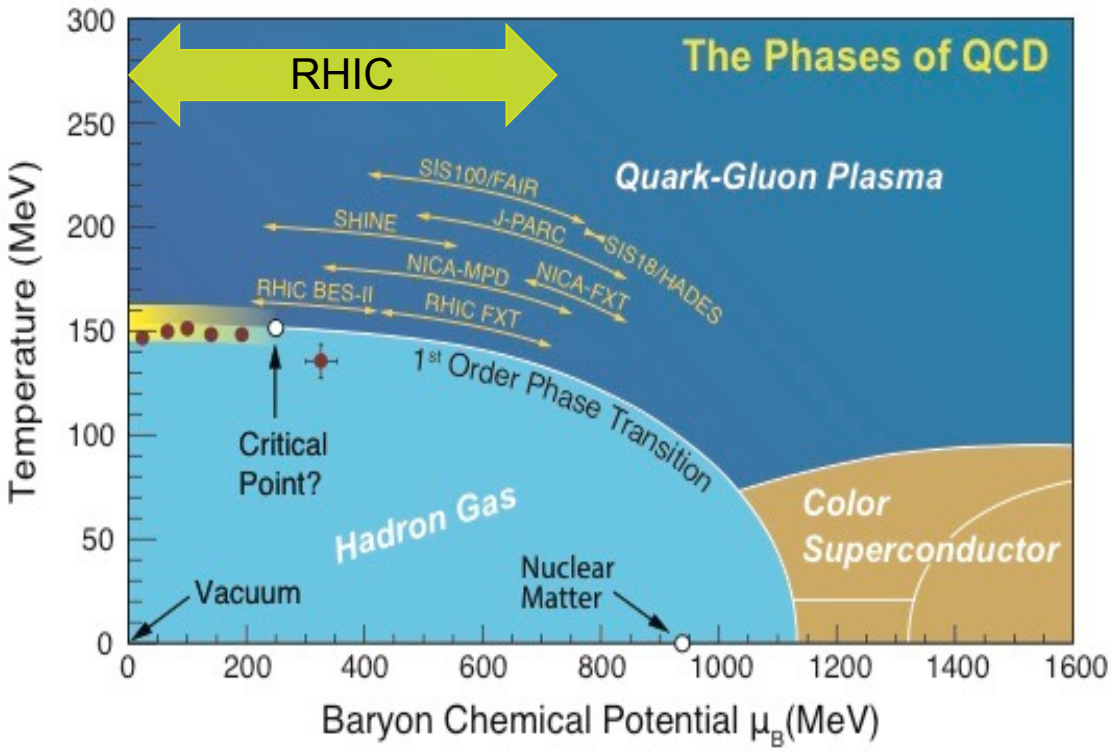
BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

RHIC: A Unique Facility

- **The world's most versatile facility for the exploration of the phases of QCD matter from high temperature to high baryon density.**
- **The world's first and only polarized proton collider and explores properties of the proton's spin.**



RHIC discoveries include:

- **The quark-gluon plasma is a "perfect liquid".**
- **Jet quenching in QCD matter.**
- **Gluons make a substantial contribution to the proton spin.**

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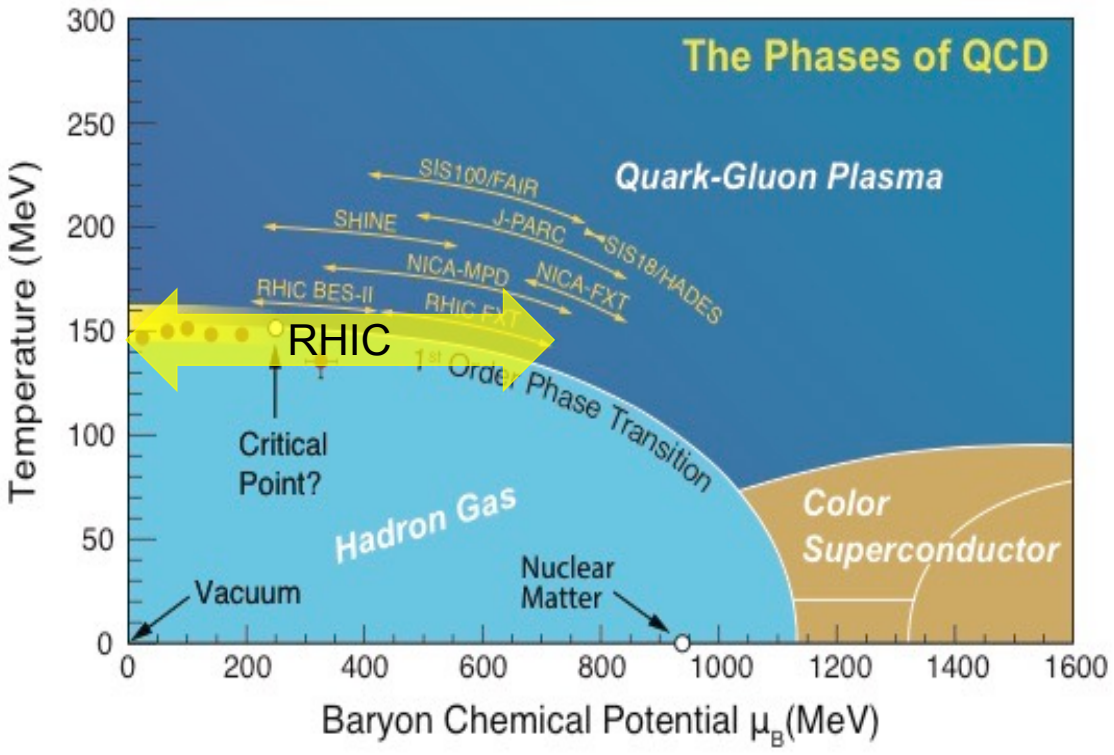
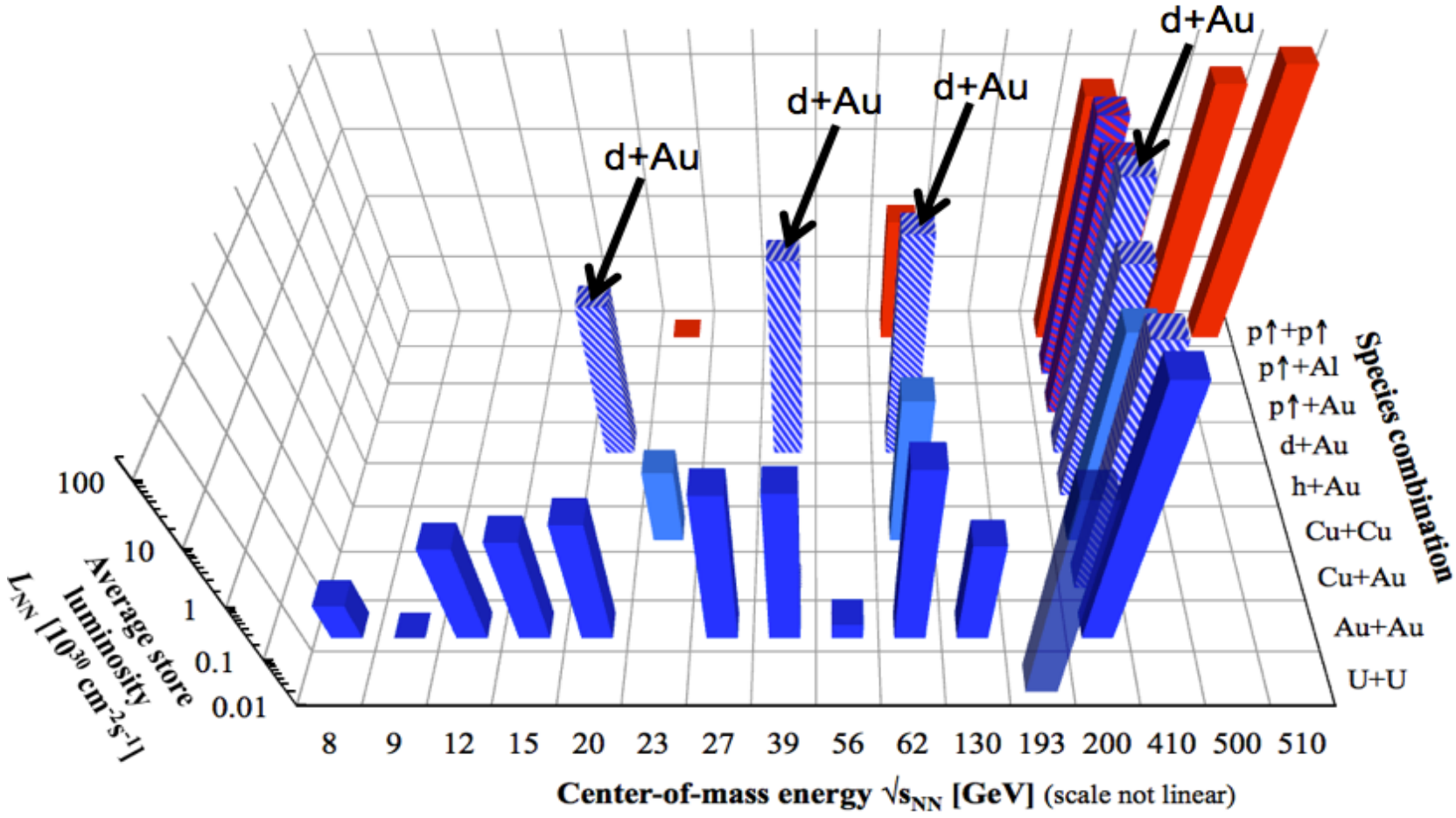


RHIC discoveries include:

- **The quark-gluon plasma is a "perfect liquid".**
- **Jet quenching in QCD matter.**
- **Gluons make a substantial contribution to the proton spin.**

RHIC Delivers Whatever it Takes



In 2016 RHIC collided deuterons with gold ions at four different energies with setup times as low as 0.8 days between energies.

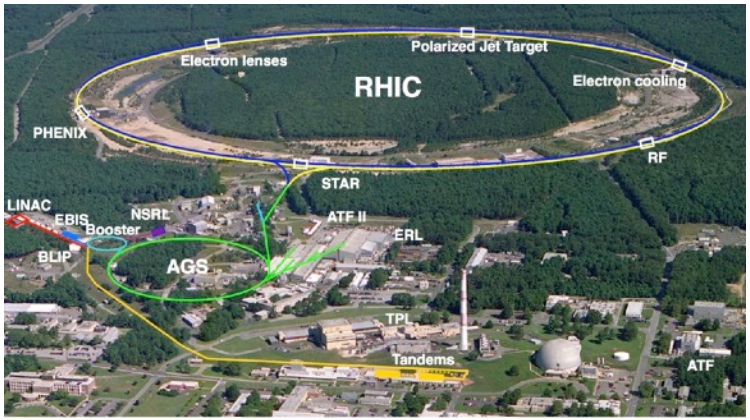
RHIC's Physics Program is Diverse

Quark Gluon Plasma

QCD Phase Diagram

Gluon Saturation

Parton Energy Loss



Parton Correlations

Hadron Formation

Transverse Spin Dynamics

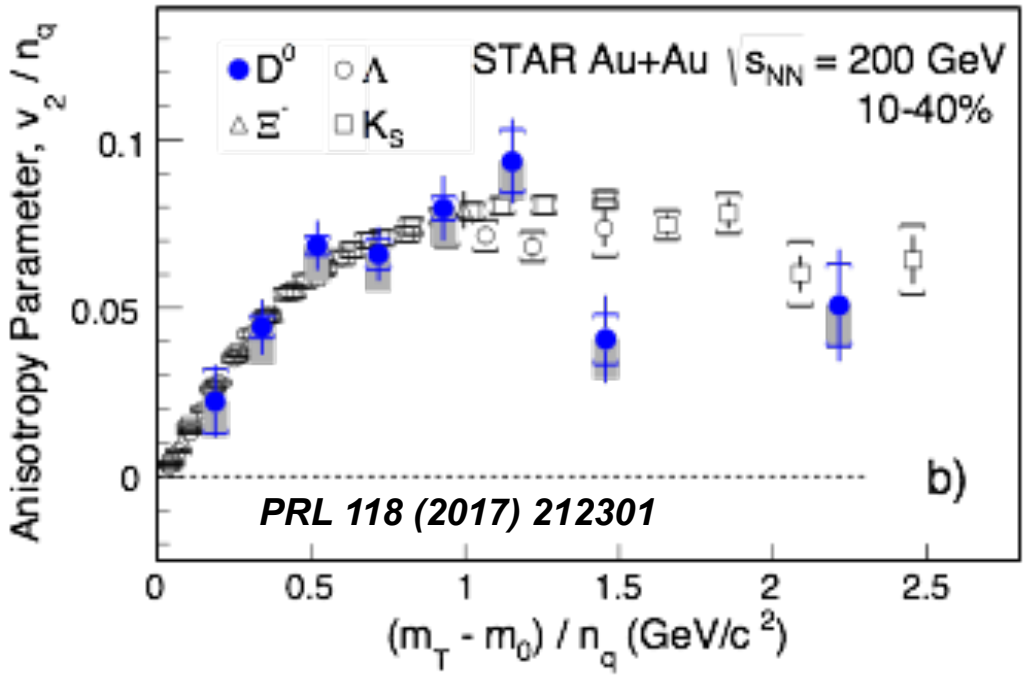
Nuclear parton densities

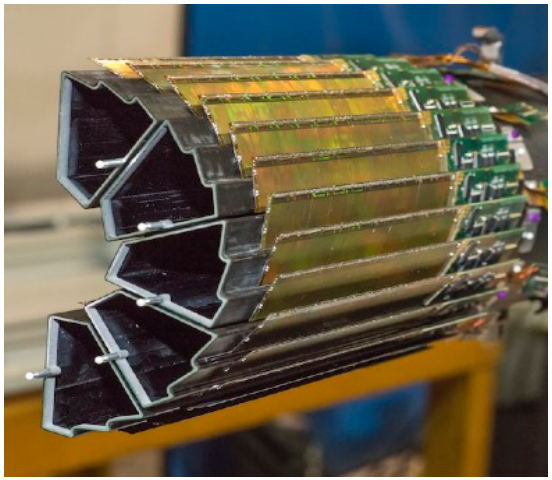
Proton Spin Structure

Nuclear Tomography by UPC

Recent RHIC Highlights I

Elliptic flow of D0 mesons (charm quarks)



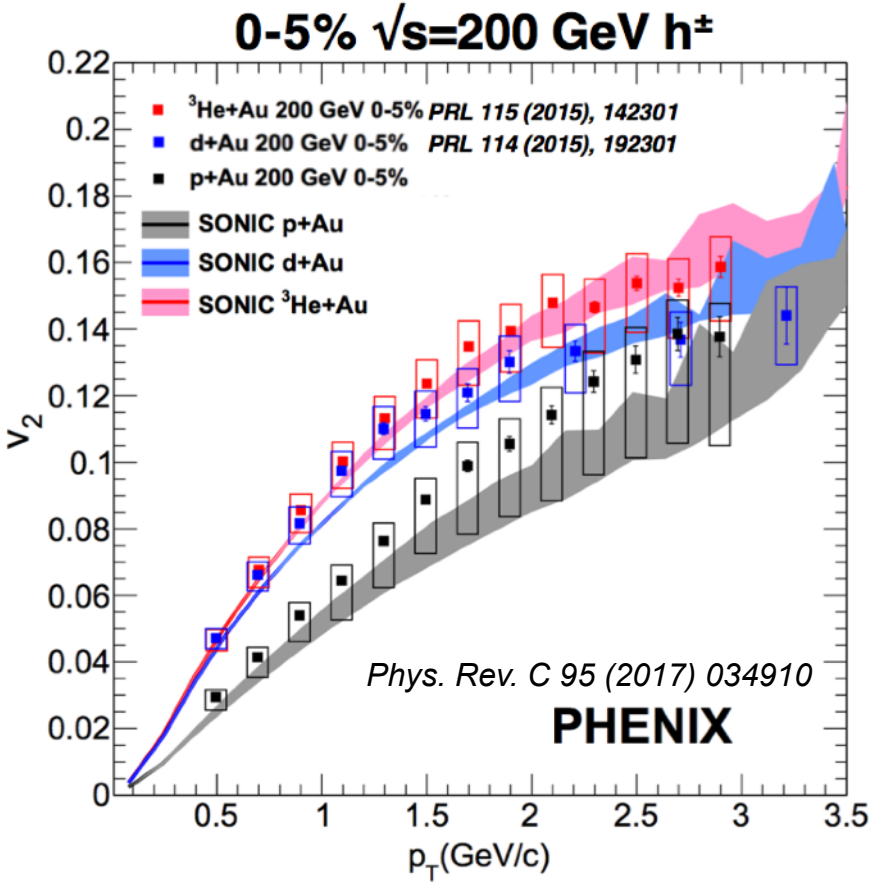


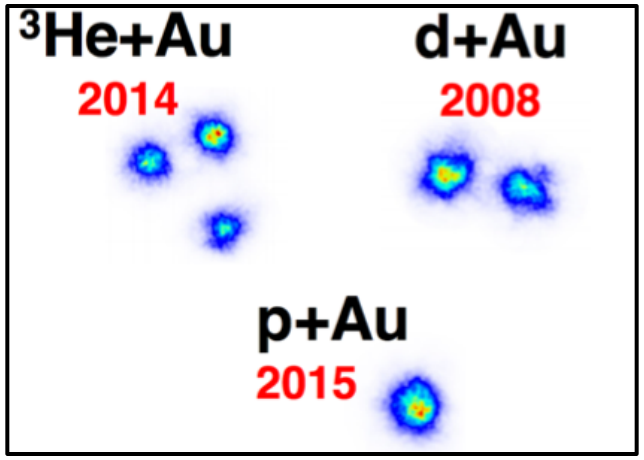
Heavy Flavor Tracker: >10-year development - first use in a collider experiment

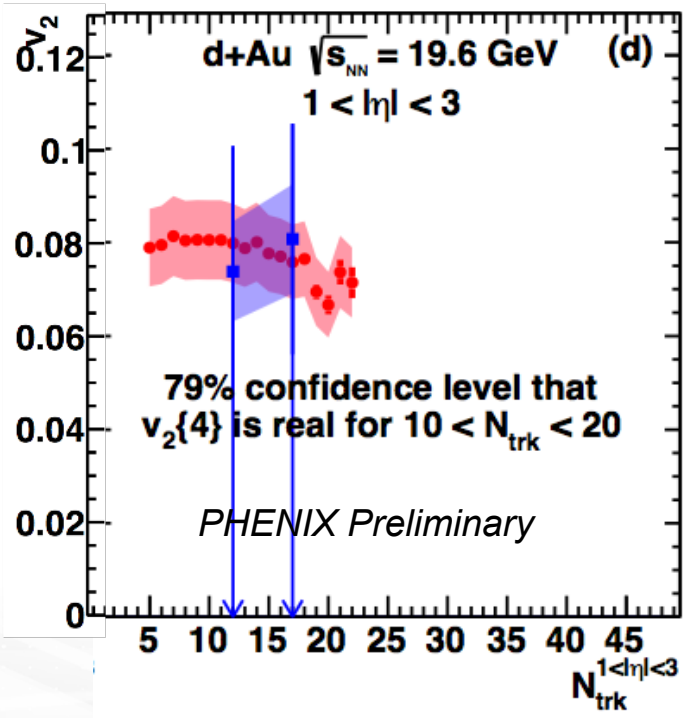
Enabling technology: High-precision low-mass Monolithic" Active Pixels

Result: Charm quarks flow just as well as lighter quarks – "Perfect liquid"

Recent RHIC Highlights II

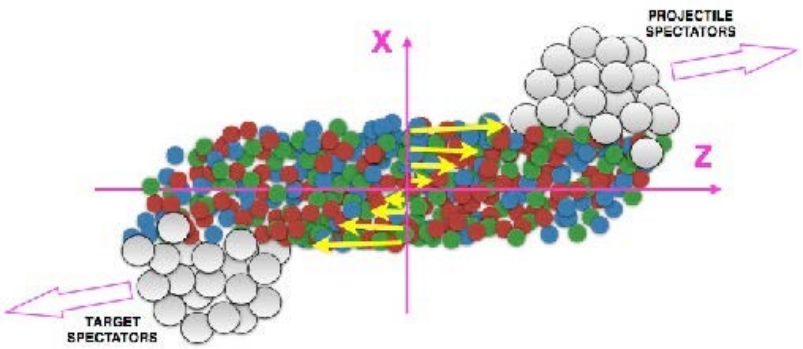






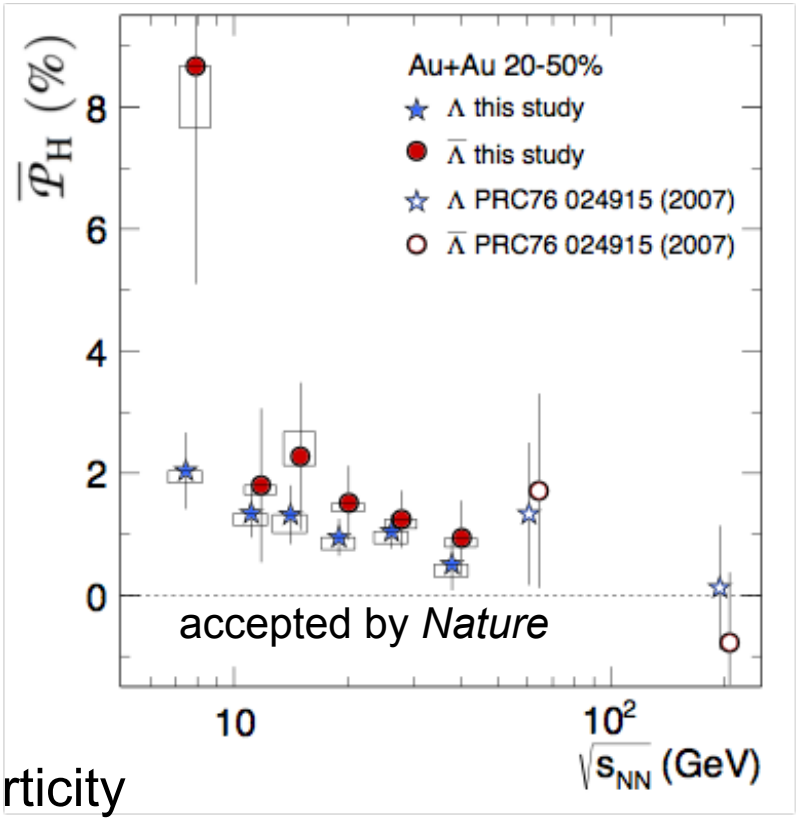
Signatures of collective flow exist even in the smallest systems and at the lowest RHIC energies

Recent RHIC Highlights III



Global collision angular momentum generates QGP vorticity

$$P_{\pm} \sim \exp\left[\pm \frac{\frac{1}{2}\hbar\omega + \mu B}{T}\right] \qquad \left(\mu_{\Lambda} = -\mu_{\bar{\Lambda}}\right)$$



Global Lambda Polarization is signal of vorticity

- Strongest signal at Beam Energy Scan (BES-II) energies

Signal is consistent with vorticity $\omega = (9 \pm 1) \times 10^{21} s^{-1}$, greater than previously observed in any system, including nuclei in high-spin states

Holds potential for measurement of late time magnetic field in BES-II

RHIC Future Plans

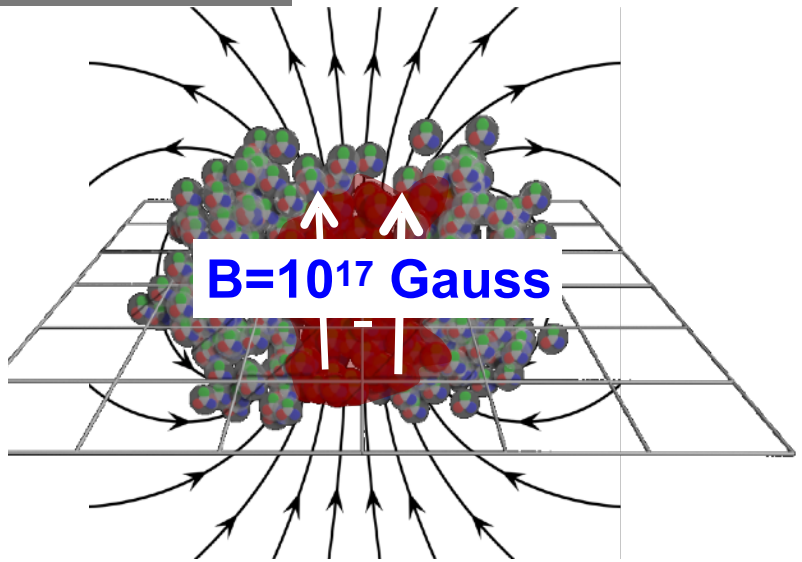
- ***Run 2018:***
  - **High statistics isobar system (^{96}Ru - ^{96}Zr) comparison run**
  - **Test of signatures of Chiral Symmetry Restoration in the QGP**
- ***Completion of the Low-Energy electron Cooling Upgrade***
- ***Installation of STAR inner TPC Upgrade***
- ***Runs 2019-20:***
  - **High statistics Au+Au beam energy scan ($\sqrt{s_{NN}}$ = 7−20 GeV)**
  - **Search for signs of critical phenomena in event-by-event fluctuations, including search for a critical point**
- ***Completion and Installation of the sPHENIX Upgrade***
- ***Runs 2022++:***
  - **Au+Au, polarized p+p, p+Au $\sqrt{s_{NN}}$ = 200 GeV**
  - **Precision measurements of fully resolved jets and Upsilon states using the new sPHENIX detector (received CD-0 in 2016**
  - **Cold QCD measurements to unambiguously separate intrinsic properties of nuclei from process dependent phenomena (EIC!)**

RHIC Run 18: Chiral Symmetry & Topology

Topology is a fundamental characteristic of QCD
Observation of topological field fluctuations requires
- (nearly) massless quarks = chiral symmetry
- superstrong magnetic fields
Heavy ion collisions provide both!

The chiral anomaly of QCD creates local fluctuations in the number of left and right handed quarks

An excess of right- or left-handed quarks will cause an electric current to flow along the magnetic field:
Chiral Magnetic Effect (CME)



When clearly established experimentally, the CME provides for an unambiguous signal of chiral symmetry restoration.

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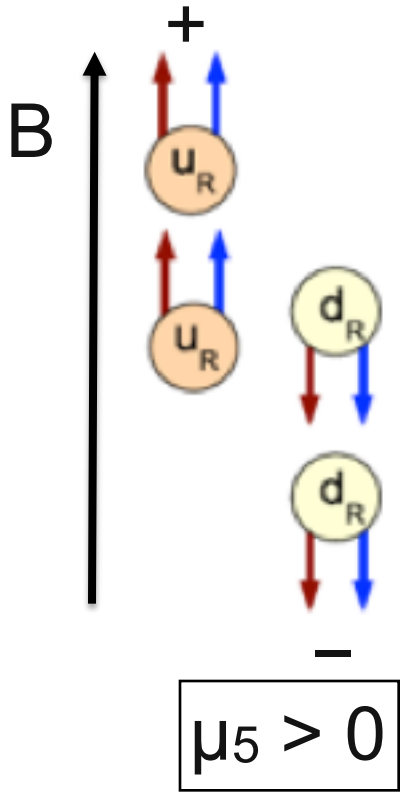


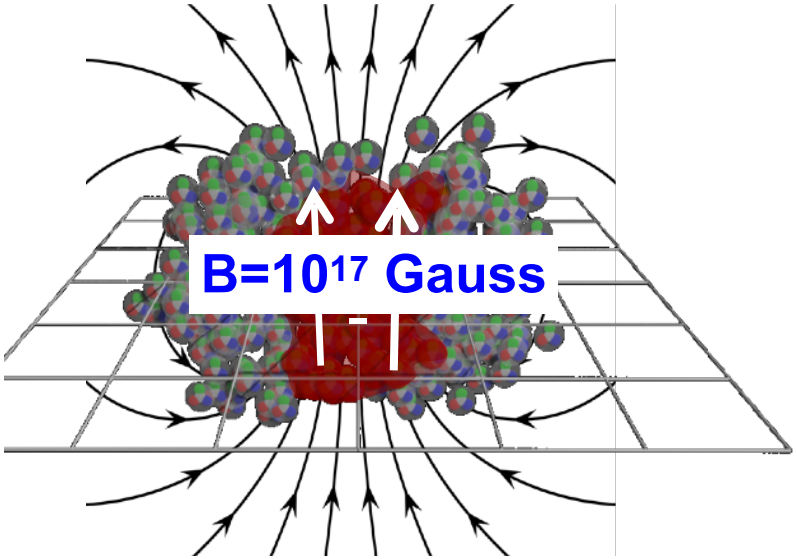
Spin

Momentum

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

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

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



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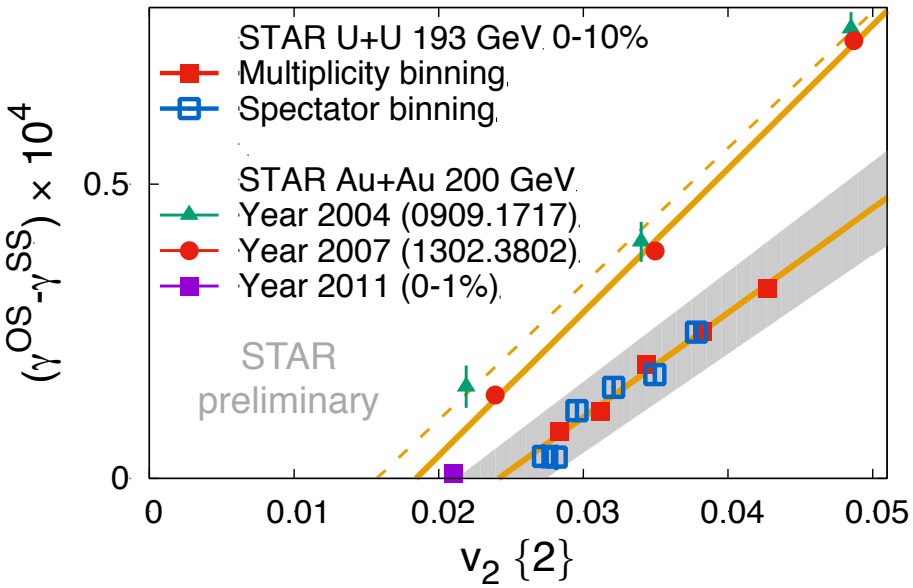
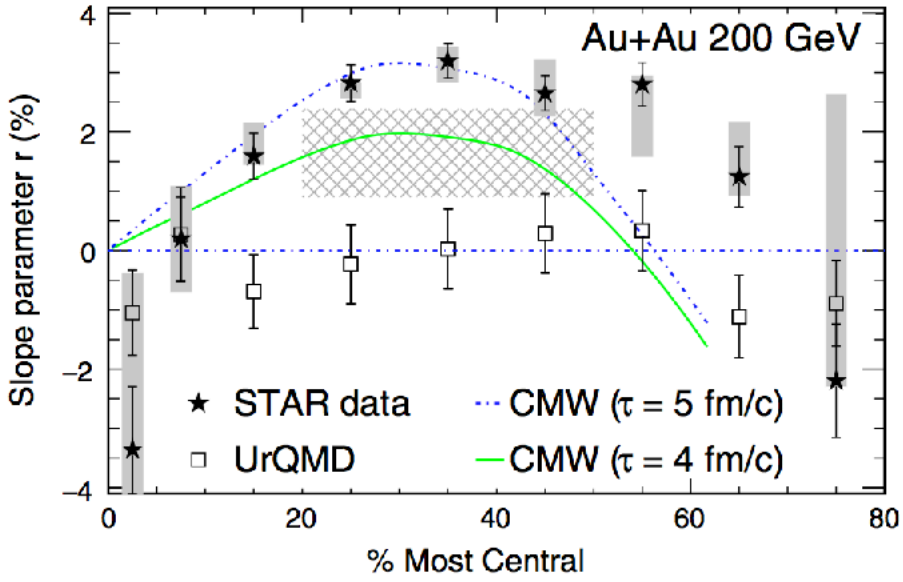
CME Phenomenology

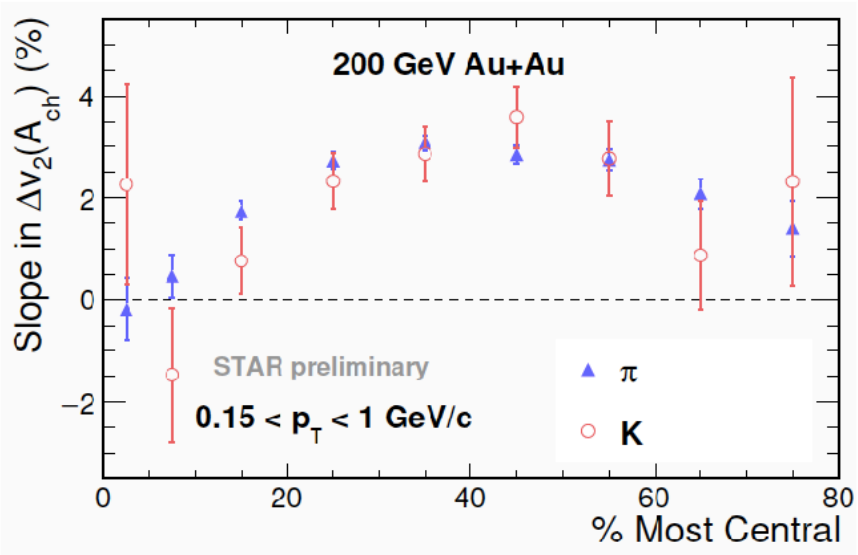
"Chiral Magnetic Wave"?

U+U and Au+Au central data:
Intercept at non-zero v_2



Measured kaon slope is positive; was predicted to be negative in one background model without CMW





CME Phenomenology

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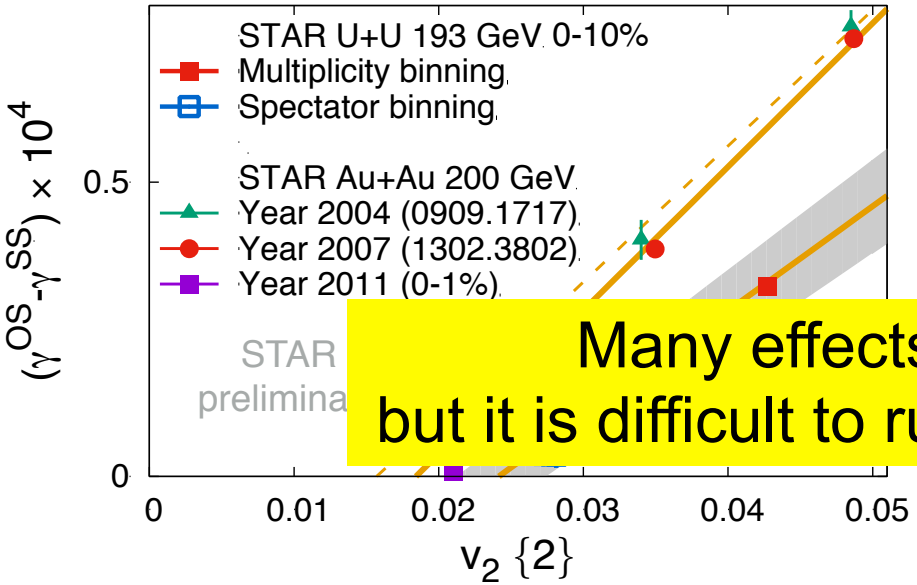
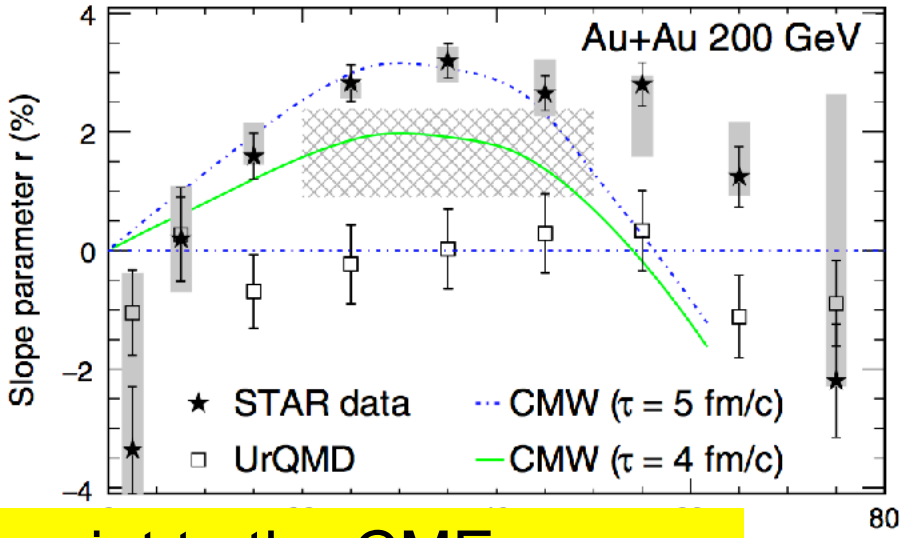
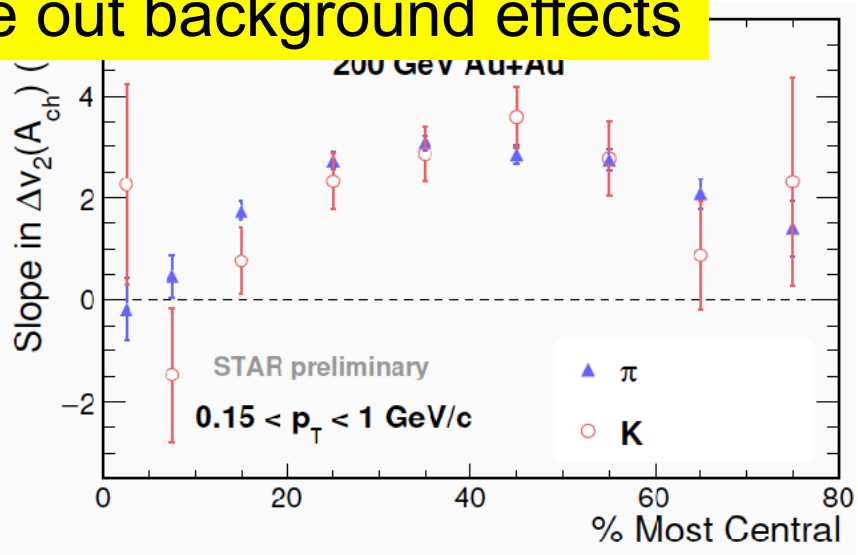




**Many effects point to the CME,
but it is difficult to rule out background effects**



Measured kaon slope is positive;
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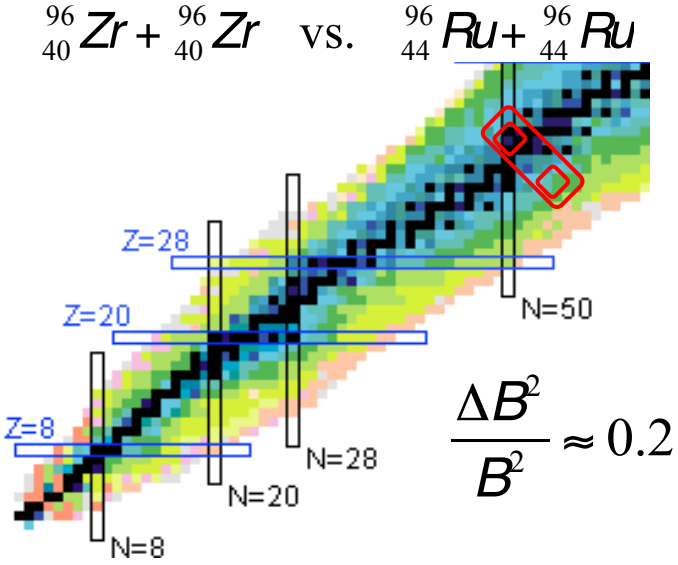
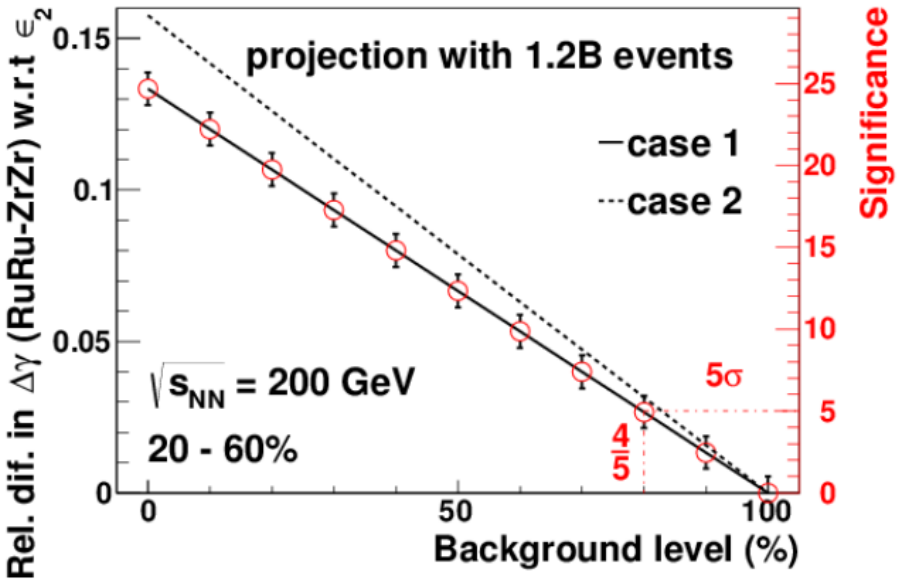
RHIC Run 18: Isobar Comparison

Various signals of fluctuating charge separation with respect to the reaction plane have been observed, but these could be caused by background effects in correlation with elliptic flow.

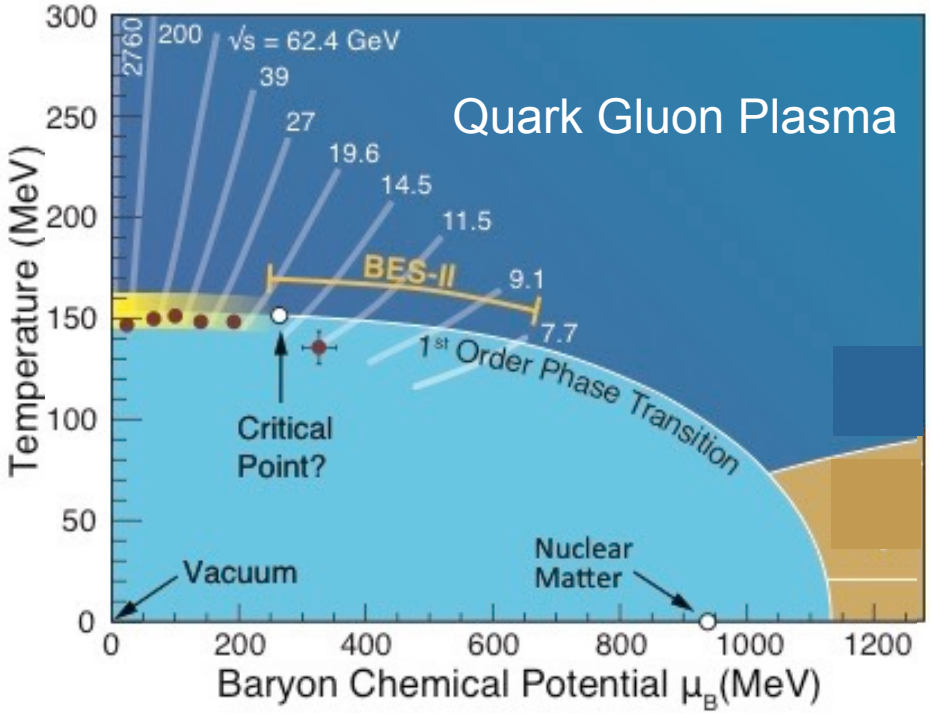




The isobar comparison run in 2018 can tell us to with +/- 6% precision what fraction of the observed charge separation is due to the CME.

BES-II: Mapping the Phases of QCD

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



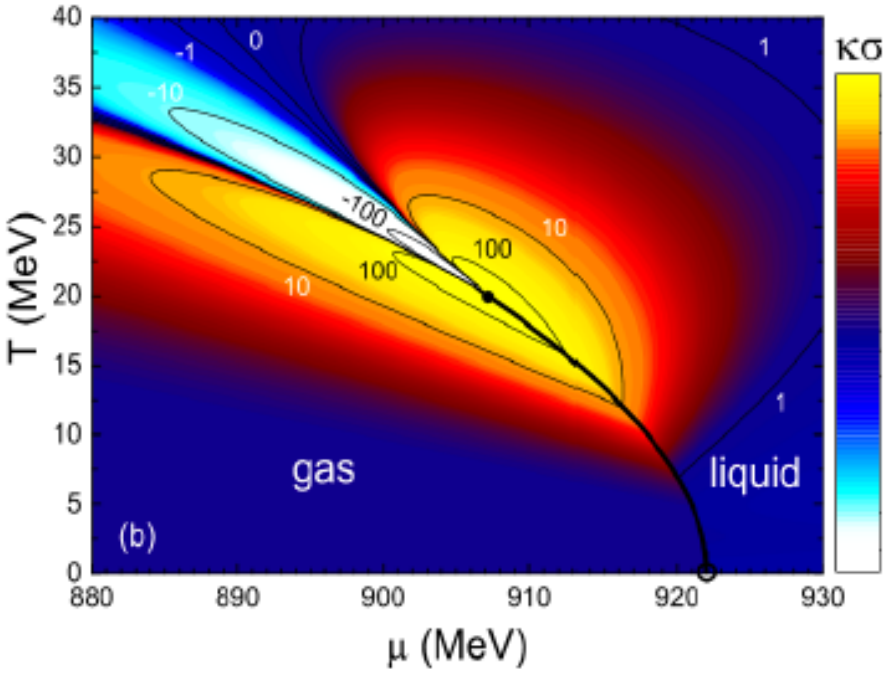
Critical Opalescence

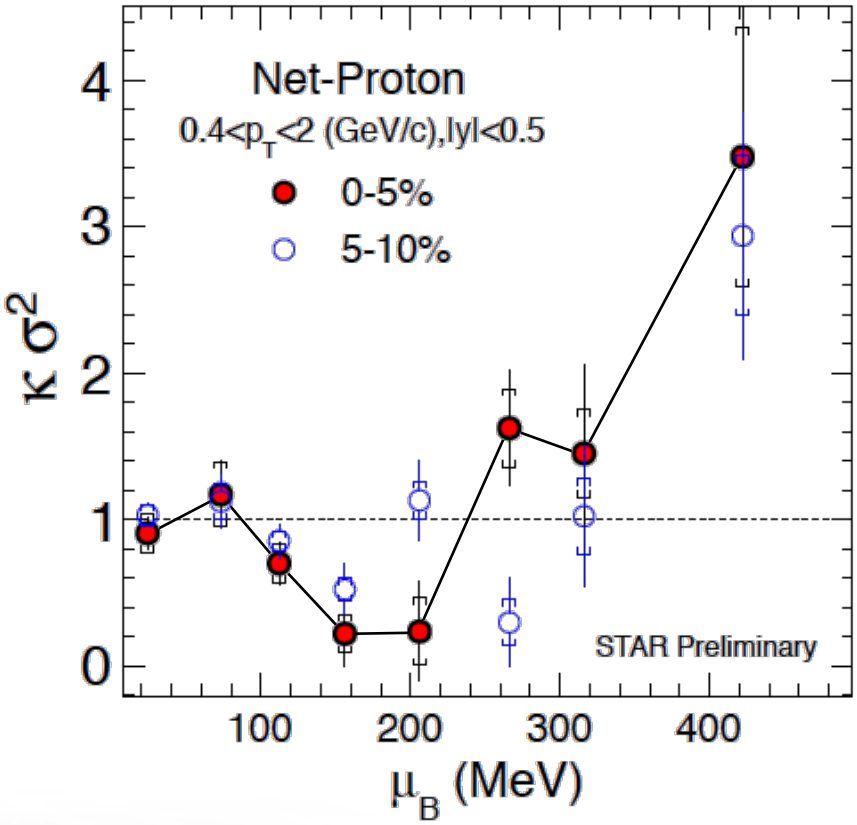
Breaking of chiral symmetry in QCD generates most of the visible mass of the universe. Is chiral symmetry restored in these collisions?

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?

BES-II: Critical behavior

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





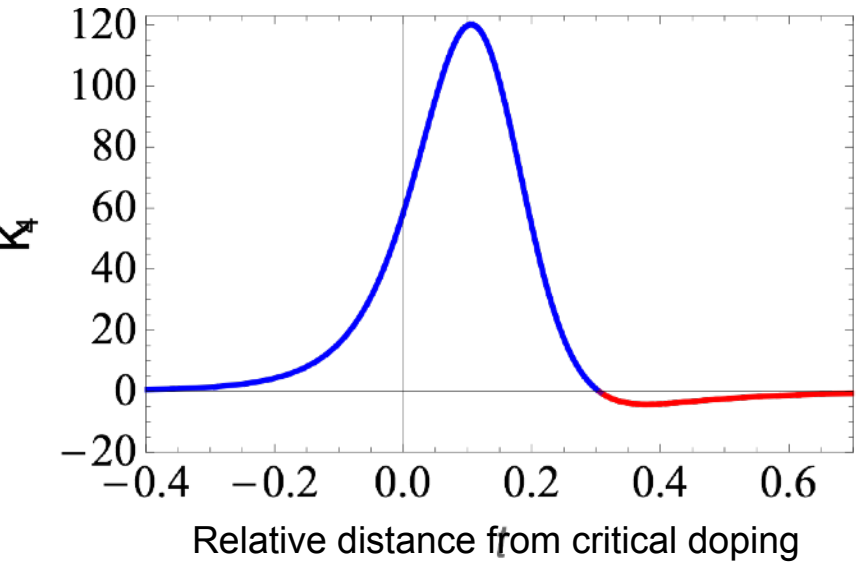
Higher moments like kurtosis*variance $\kappa\sigma^2$ change sign near the critical point

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

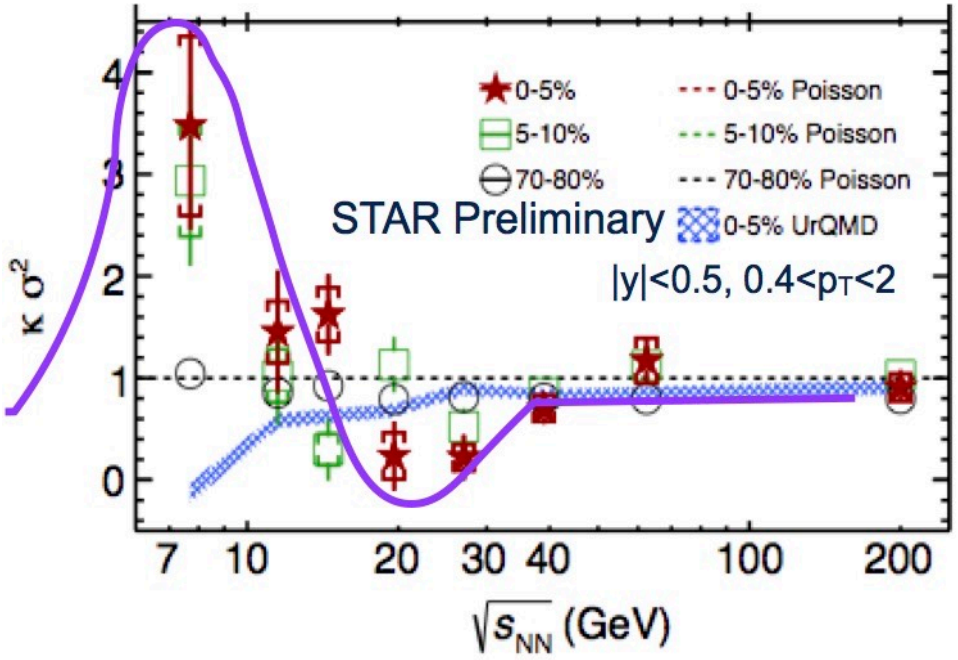
Critical signature: Net-proton kurtosis

Near a critical point, the correlation length of fluctuations diverges; kurtosis (κ−1) of the net-proton distribution changes sign

Expected behavior near critical point



Net-baryon/proton density of the QGP is controlled by the collision energy



BES I provided a tantalizing hint, but with insufficient precision

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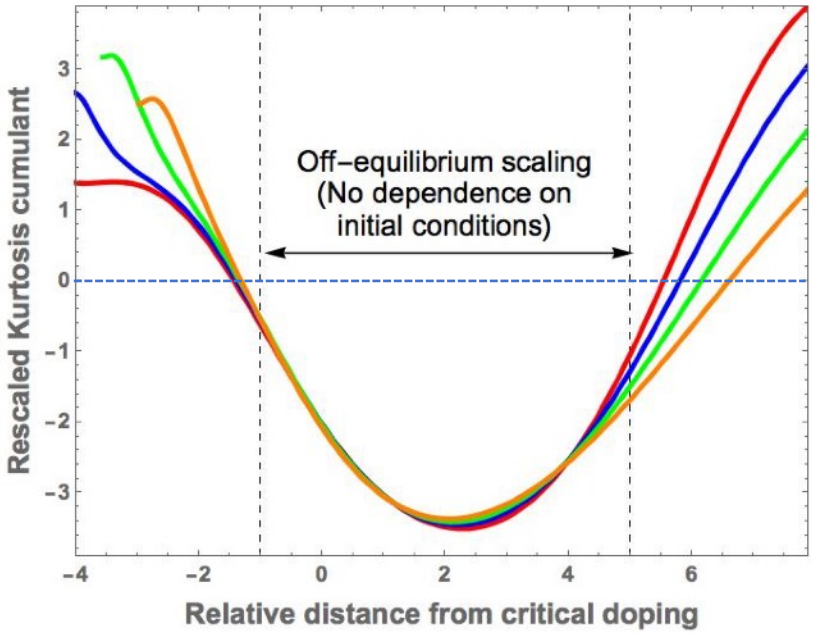
S. Mukerjee, R. Venugopalan & Yi Yin



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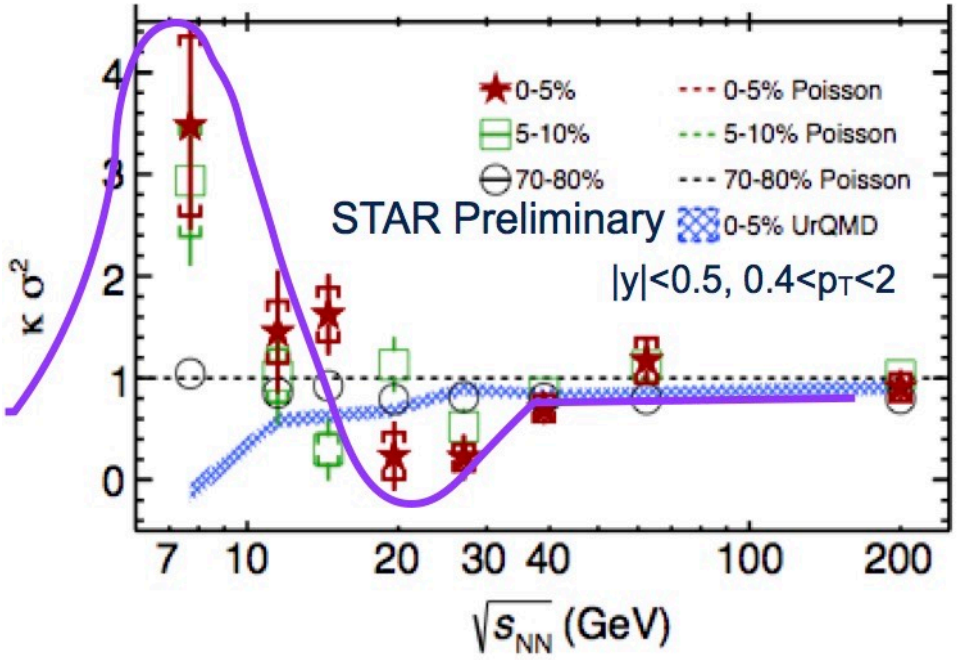

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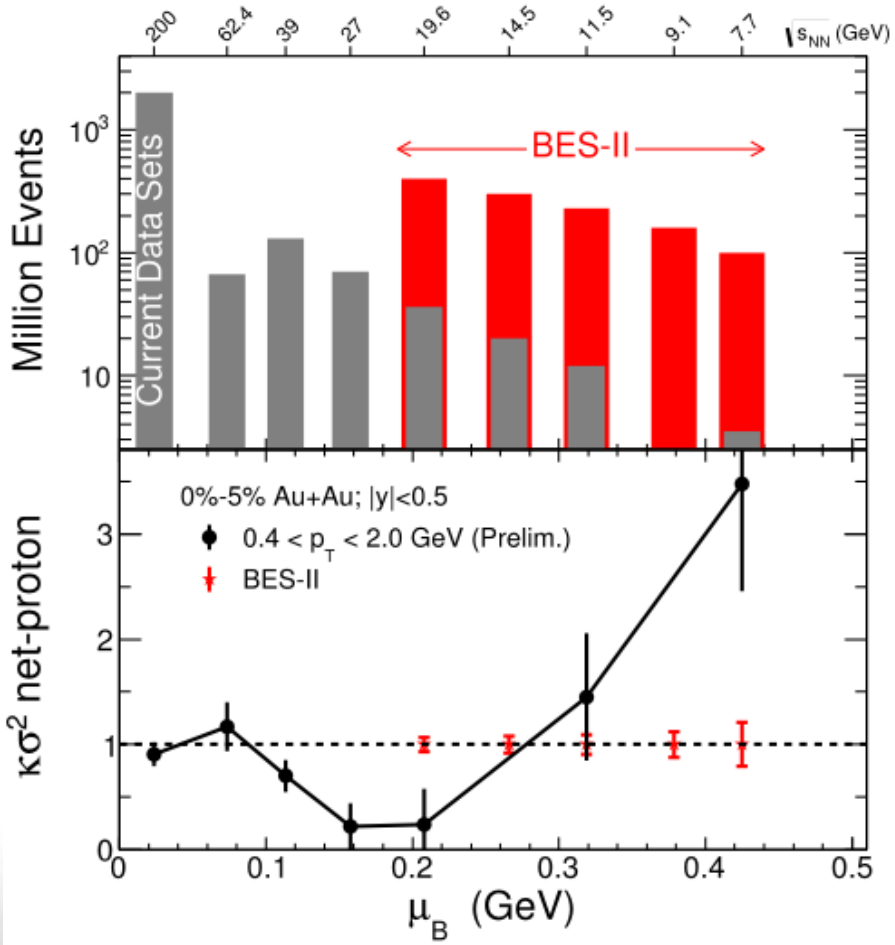
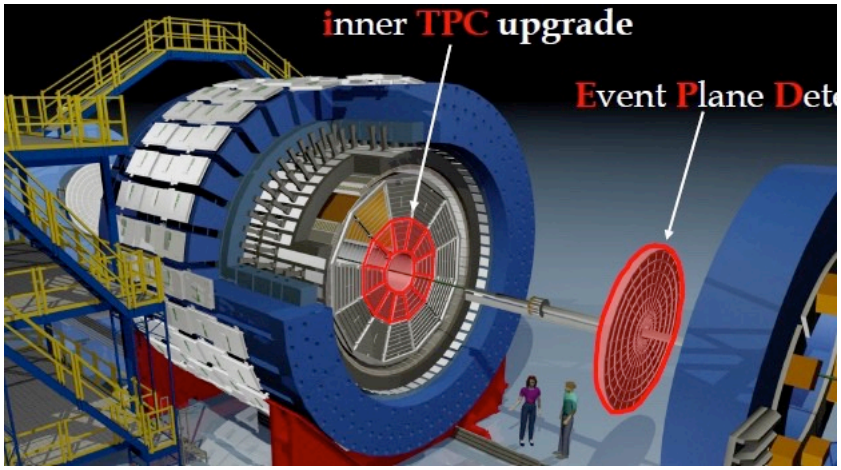
BES-II: Upgrades

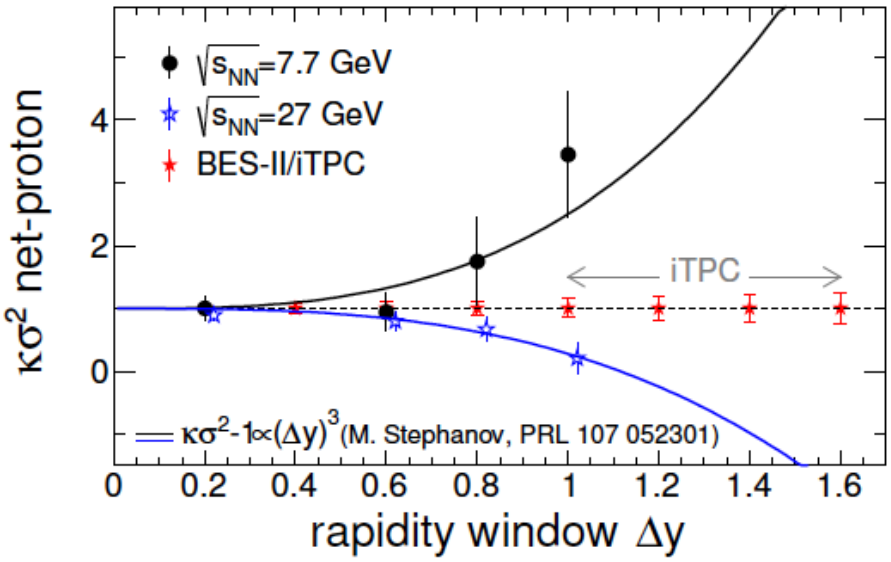
Higher statistics

Low energy RHIC electron cooling upgrade

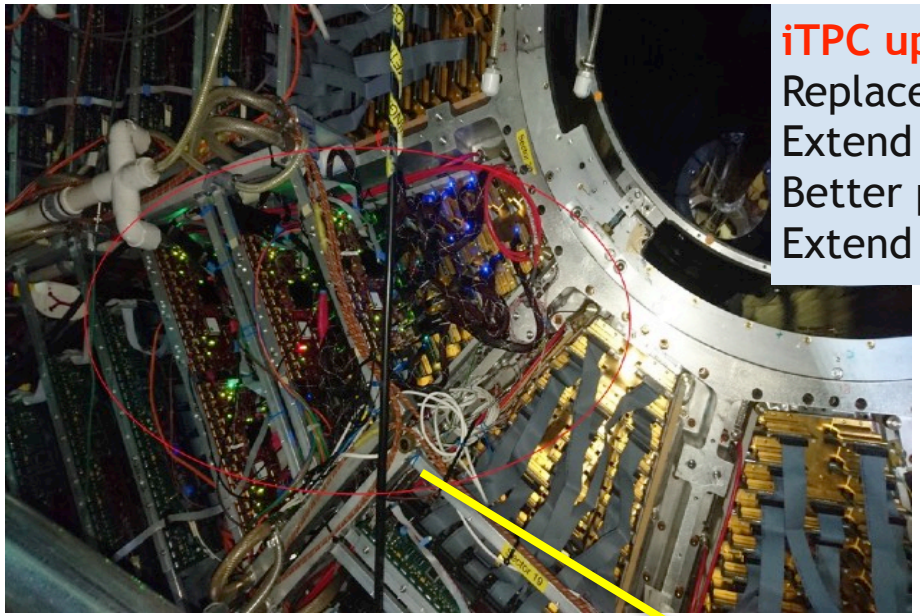


Larger acceptance

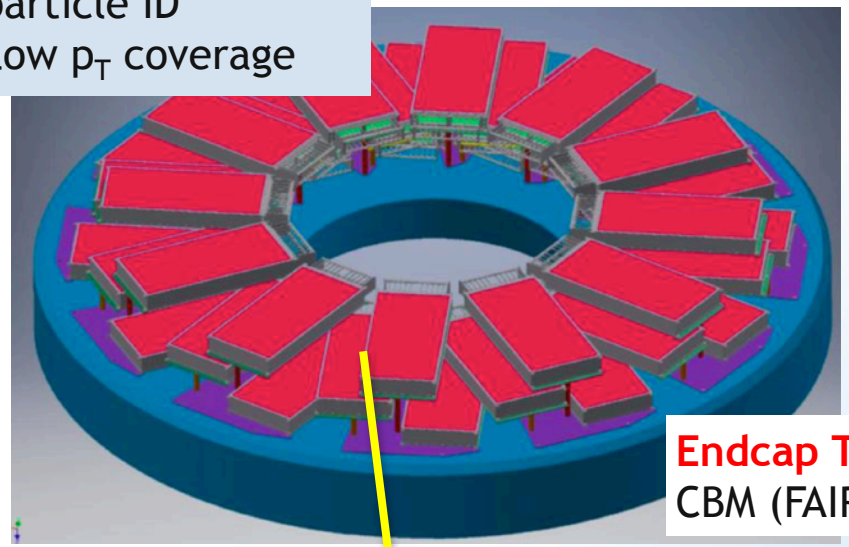




BES-II: STAR Upgrades

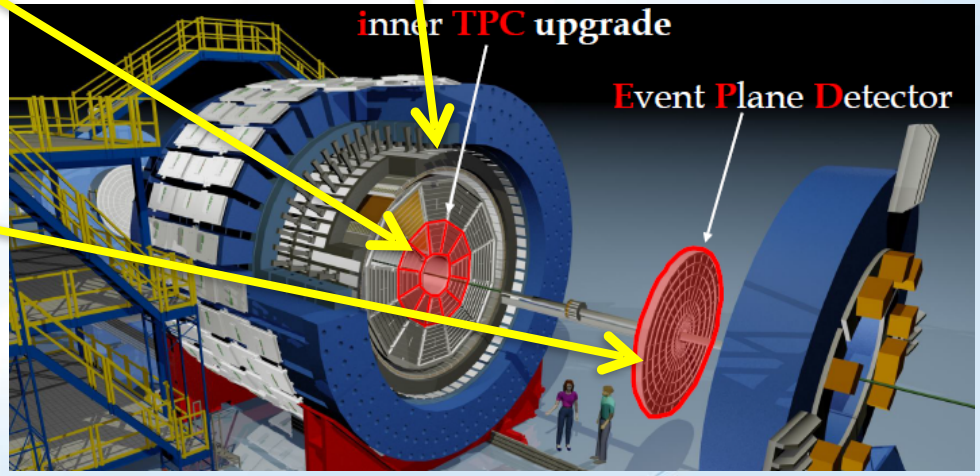


iTPC upgrade (2018)
Replace inner TPC Sectors
Extend rapidity coverage
Better particle ID
Extend low p_T coverage



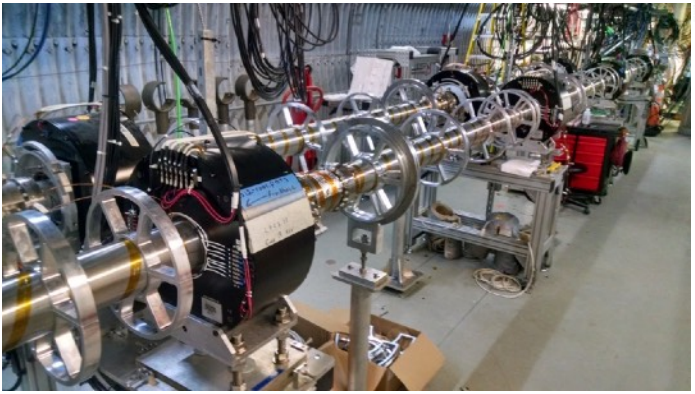
Endcap TOF
CBM (FAIR)

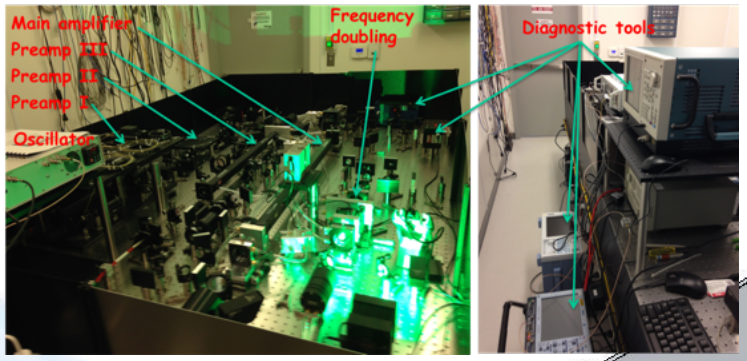
Event Plane Detector
Improved Event Plane Resolution
Centrality definition
Improved trigger



BES-II: LEReC Upgrade

Cooling sections

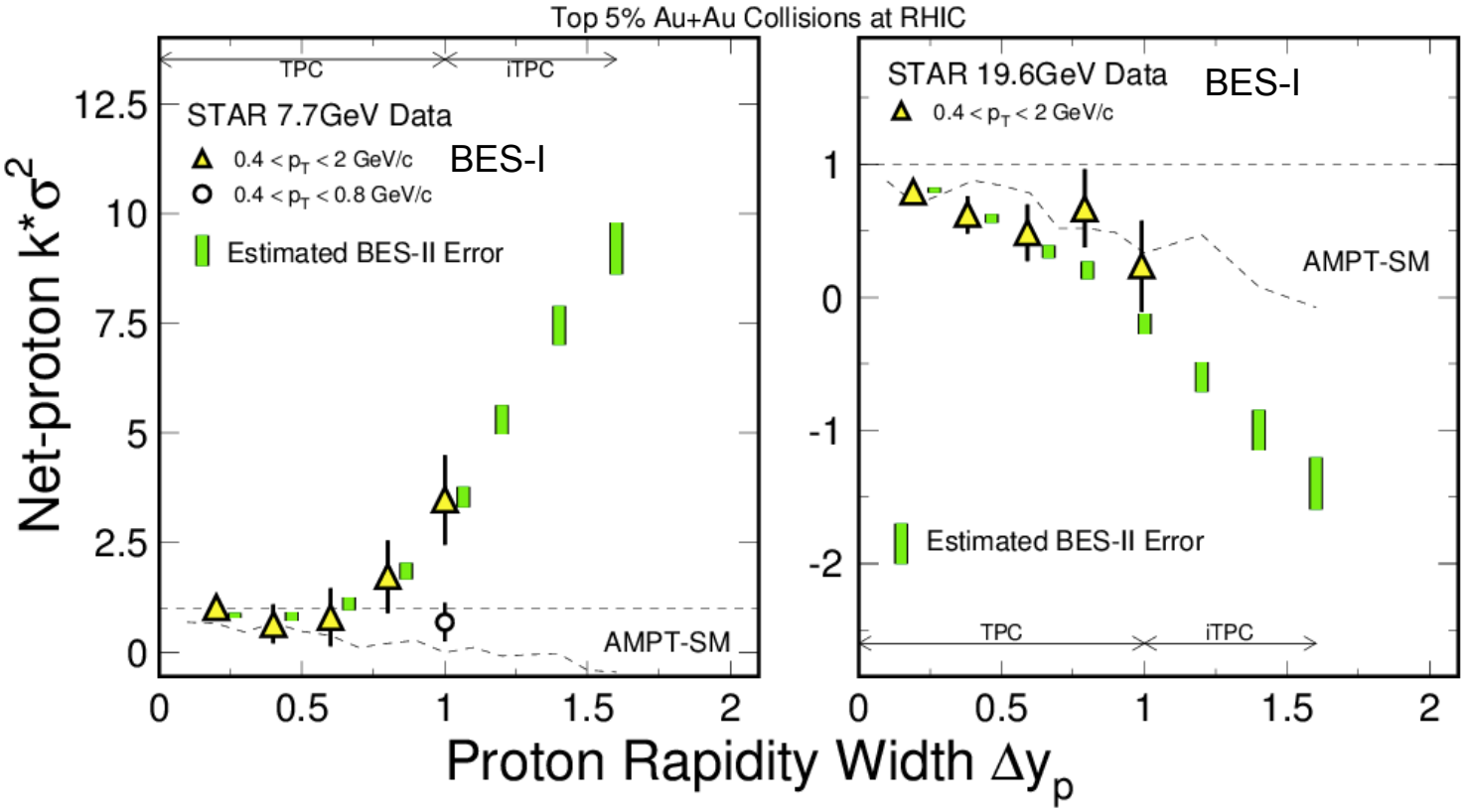




Injection Section

Laser

BES-II: Significance



Kurtosis (fourth-order fluctuations) signal grows like $(\Delta y)^3$

➔ **Detector coverage is critical for a definitive measurement**

Increased luminosity reduces error bars

Beyond BES-II: sPHENIX

State-of-the-art jet (and Upsilon & open heavy flavor) detector

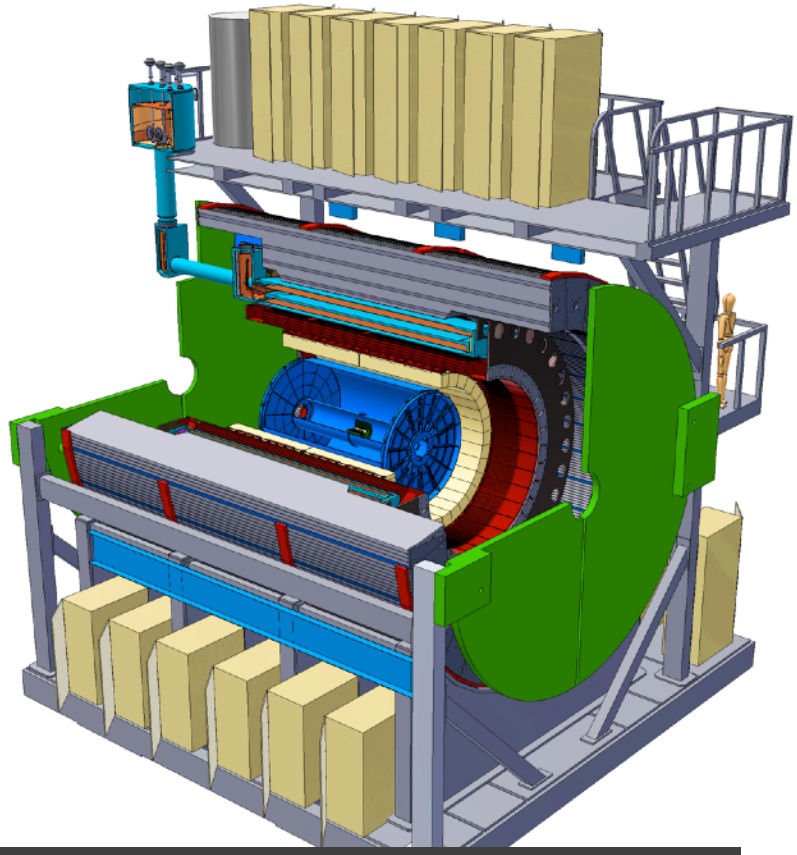
SC BaBar Solenoid 1.5 T

Coverage $|\eta| \leq 1.1$

Inner Si Tracking
Fast TPC w/GEM Read-out

Projective Electromagnetic Calorimeter

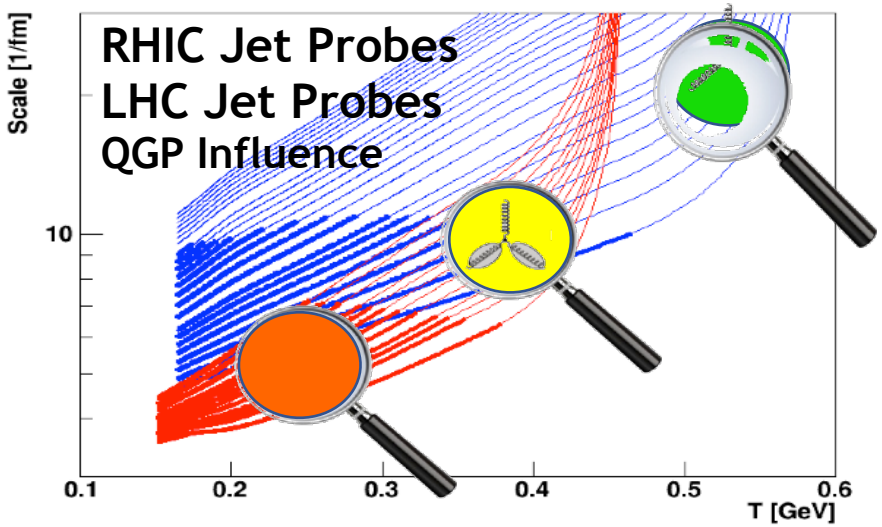
Hadronic Calorimeter



Capable of sampling 600 billion Au+Au interactions and recording 100 billion min bias events per year

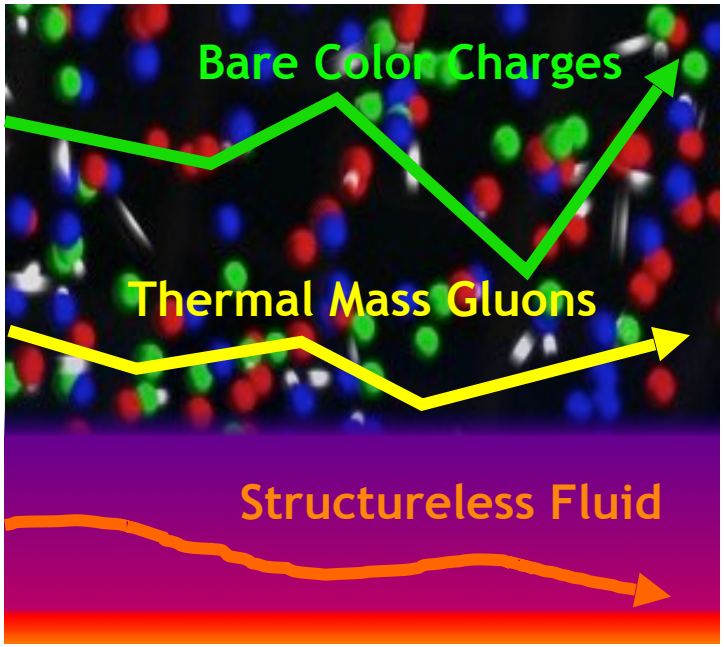
Jet Probes of QCD Structure

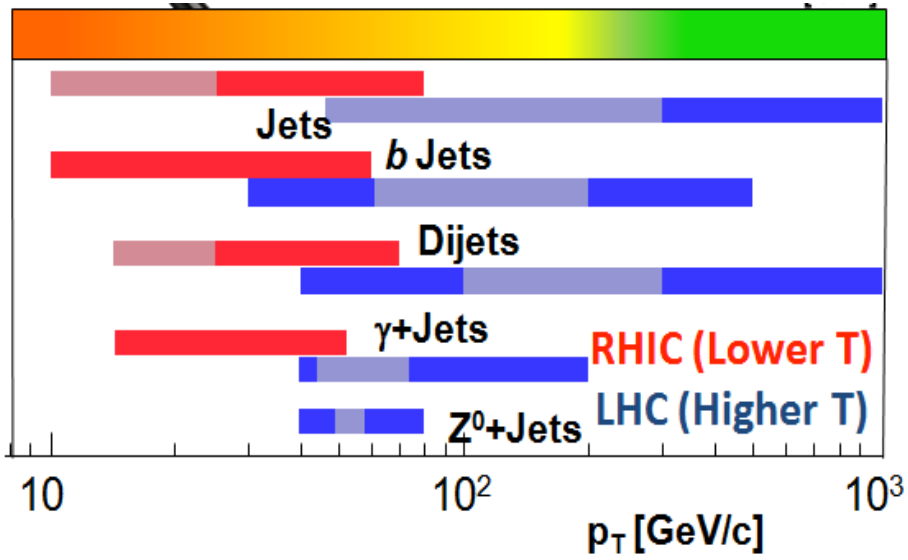
Parton virtuality evolves quickly and is sensitive to varying medium scales



Unique critical microscope resolution range at RHIC

Kinematic overlap between RHIC and LHC provides complementarity

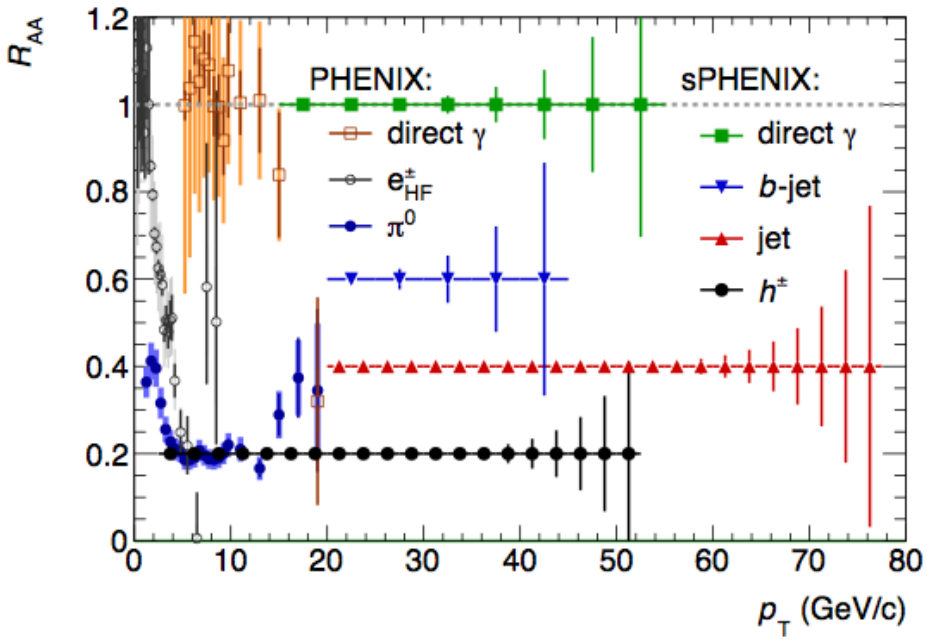


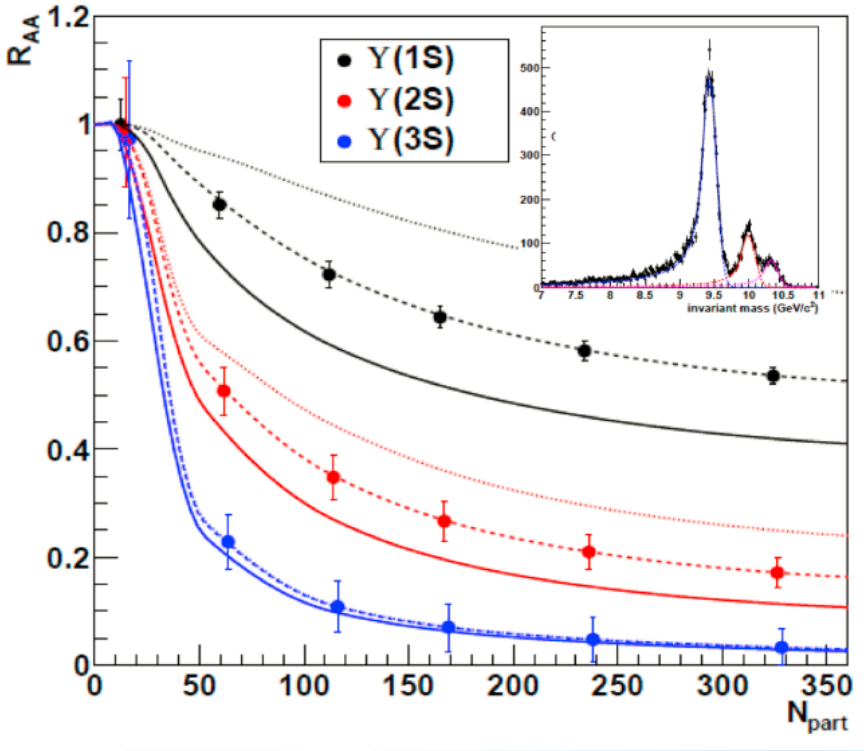


sPHENIX: Jets & Υ states

sPHENIX Capabilities

Complete calorimetric jet spectroscopy



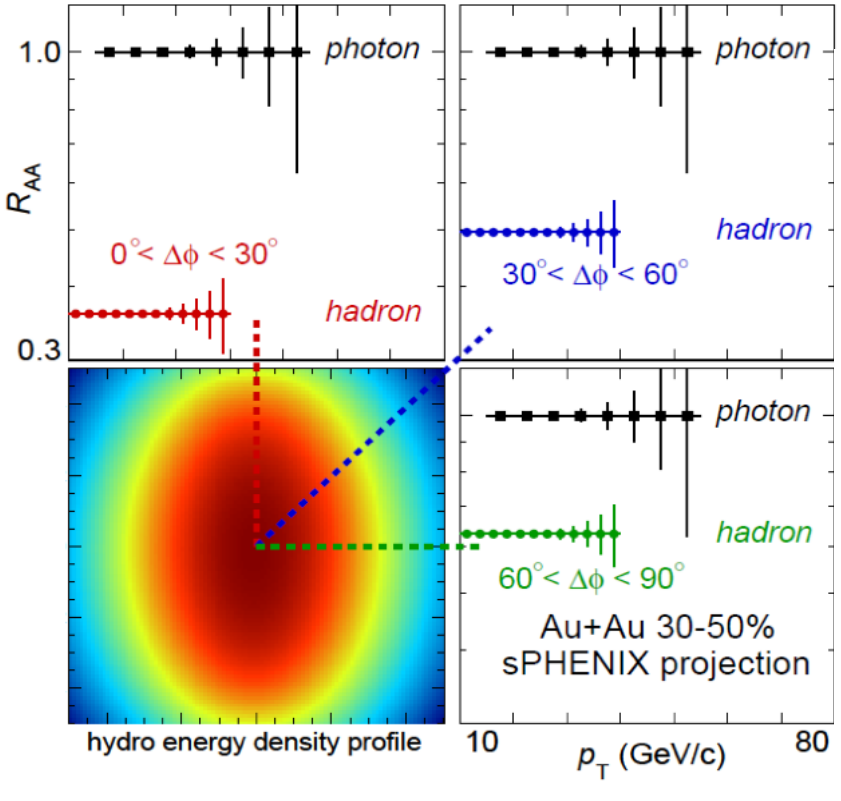


Completely resolved Upsilon spectroscopy

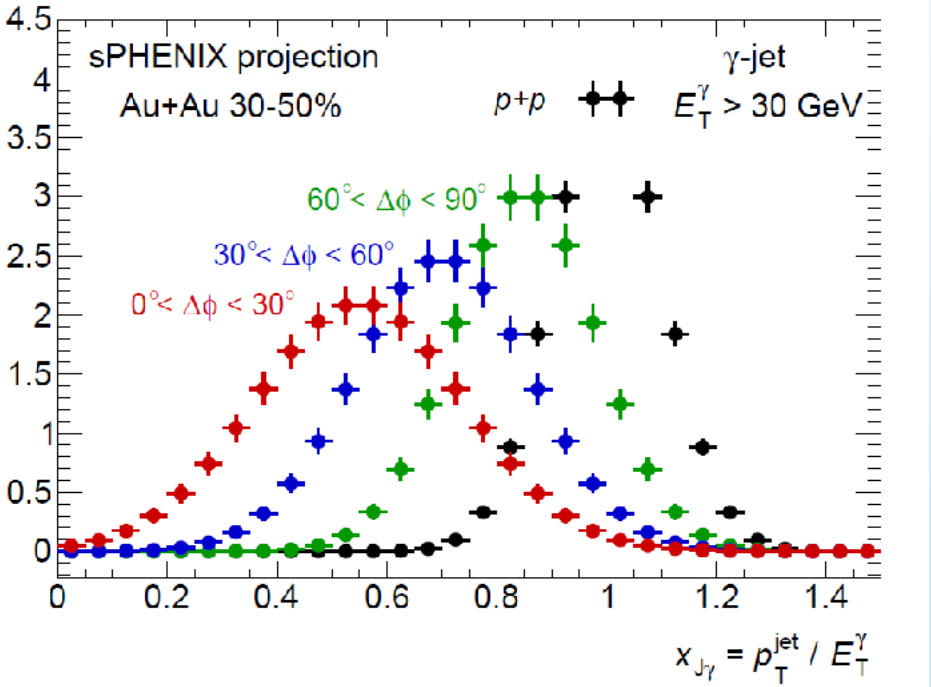
sPHENIX: Rate enabled measurements

Example: Length dependent jet quenching

Length dependent suppression R_{AA}



Length dependent energy loss in photon tagged jet events



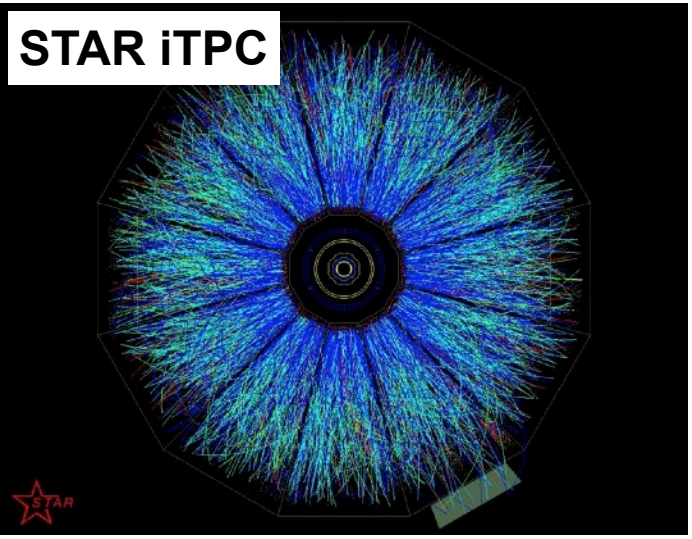
RHIC notional run plan

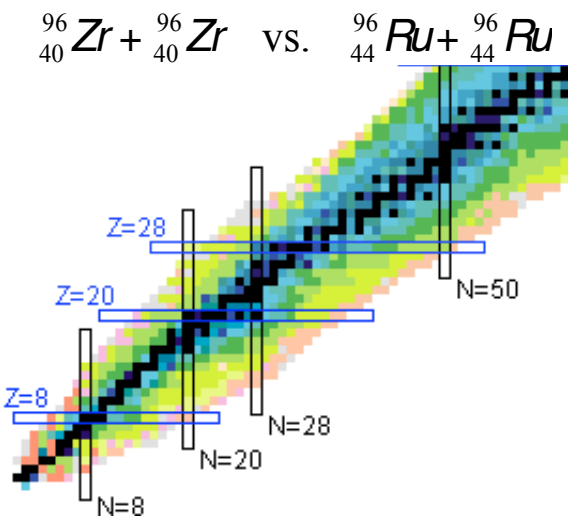
Year	Species	Goals
2019	Au+Au	High Statistics Beam Energy Scan: Search for QCD Critical Point Collider mode: $\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6 GeV Fixed target: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
2020	Au+Au	High Statistics Beam Energy Scan: Search for QCD Critical Point Collider mode: $\sqrt{s_{NN}}$ = 7.7, 9.1 GeV
2021	Au+Au p+p/Au	Completion of high statistics beam energy scan (?) Forward measurements in p+p and p+Au (?)
2022	No run	sPHENIX installation
2023	Au+Au	sPHENIX Commissioning Single jet, di-jet, photon-tagged jet, b-tagged jet spectra Di-jet asymmetry, Upsilon spectra
2024	p+p p+Au	Reference data for modification of jets, di-jets, b-tagged jets Jet A_{LL} Reference data for cold nuclear matter effects
2025	Au+Au	Direct photon measurement Study of flavor dependence of jet observables Modification of jet fragmentation functions, jet splitting functions, other complex jet observables

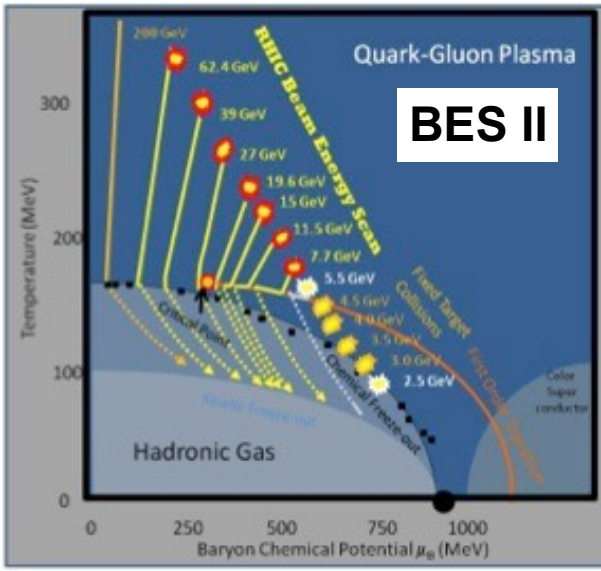
"What RHIC Will Deliver"

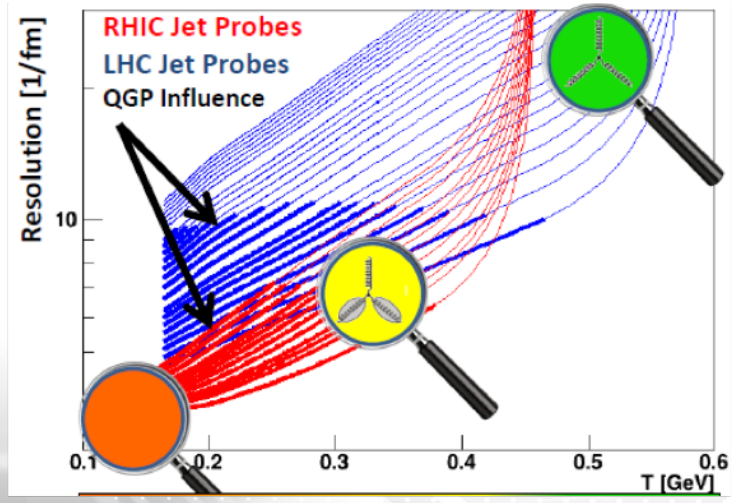
- **Campaign 1 (2014-17):**
  - ✓ QCD equation of state at $\mu_B \approx 0$
  - ✓ Precision measurement of $\eta/s(T \approx T_c)$
  - ✓ Measurement of heavy quark diffusion constant $D_{c/b}$
  - ✓ Measurement of x-dependence of nuclear granularity
  - ✓ Origin of single spin asymmetries
  - ✓ ΔG, flavor dependence of spin in the quark sea
  - ✓ QGP vorticity [not anticipated in 2015]
- **Campaign 2 (2018-21):**
  - ➢ Chiral symmetry restoration via CME
  - ➢ QCD equation of state at $\mu_B > 0$
  - ➢ Discovery of the QCD critical point, if within the accessible range
- **Campaign 3 (2023+):**
  - Precision measurement of q^($T \approx T_c$) and e^($T \approx T_c$)
  - Determine length scale where the QGP becomes a liquid
  - Cold QCD measurements critical to EIC physics

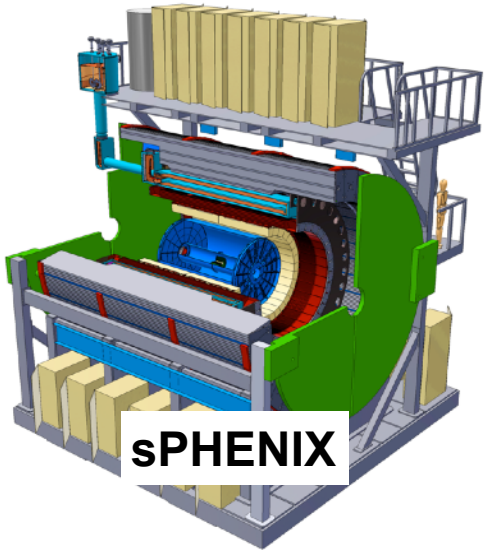
The RICH Opportunities of RHIC

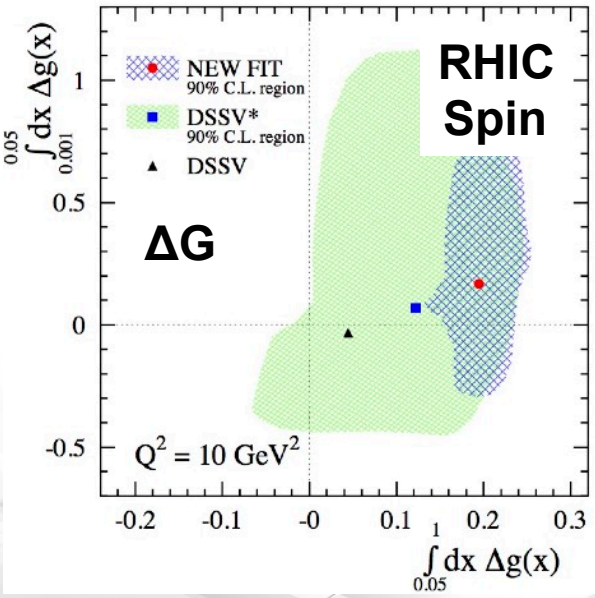












Backup slides

sPHENIX $\sqrt{s_{NN}}$ = 200 GeV notional run plan

Year	Species	Goals
2023	Au+Au	Commissioning Single jet, di-jet, photon-tagged jet, b-tagged jet spectra D-jet asymmetry IUpsilon spectra
2024	p+p p+Au	Reference data for modification of jets, di-jets, b-tagged jets Jet A_{LL} Reference data for cold nuclear matter effects
2025	Au+Au	Direct photon measurement Study of flavor dependence of jet observables Modification of jet fragmentation functions, jet splitting functions, other complex jet observables
2026	p+p	High statistics data for Upsilon modifications High statistics data for jet A_{LL}
2027	Au+Au	High statistics data for b-tagged jets and photon-tagged jets High statistics data for jet fragmentation functions, jet splitting functions, other complex jet observables High statistics data for high p_T direct photons High statistics data for Upsilon modifications, including Υ(3S) Collective flow of b-quarks (B hadron elliptic flow)

STAR Opportunities beyond BES

- STAR collaboration is considering modest forward upgrades for RHIC runs beyond BES-II with significant Chinese contributions.
- Physics program described in 2016 RHIC Cold QCD Plan
- Strong endorsement from 2017 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 $2.5<\eta<4$.

Estimated cost: ~$5M.