RHIC Science Program:

A Look at the Future

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Brookhaven National Laboratory
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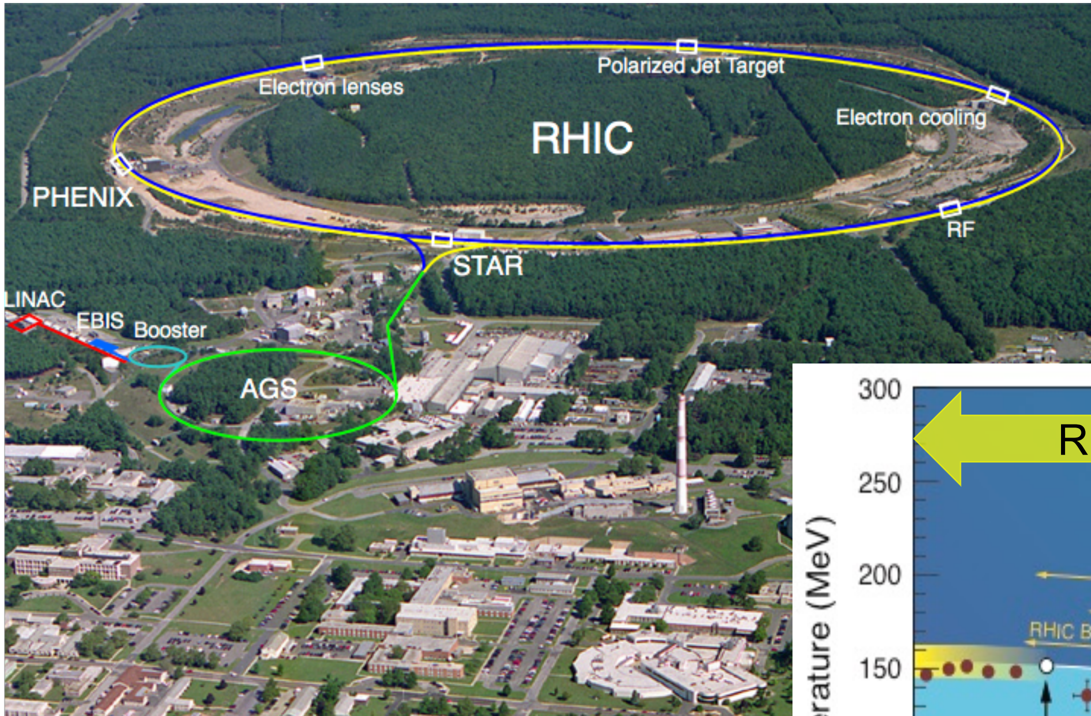
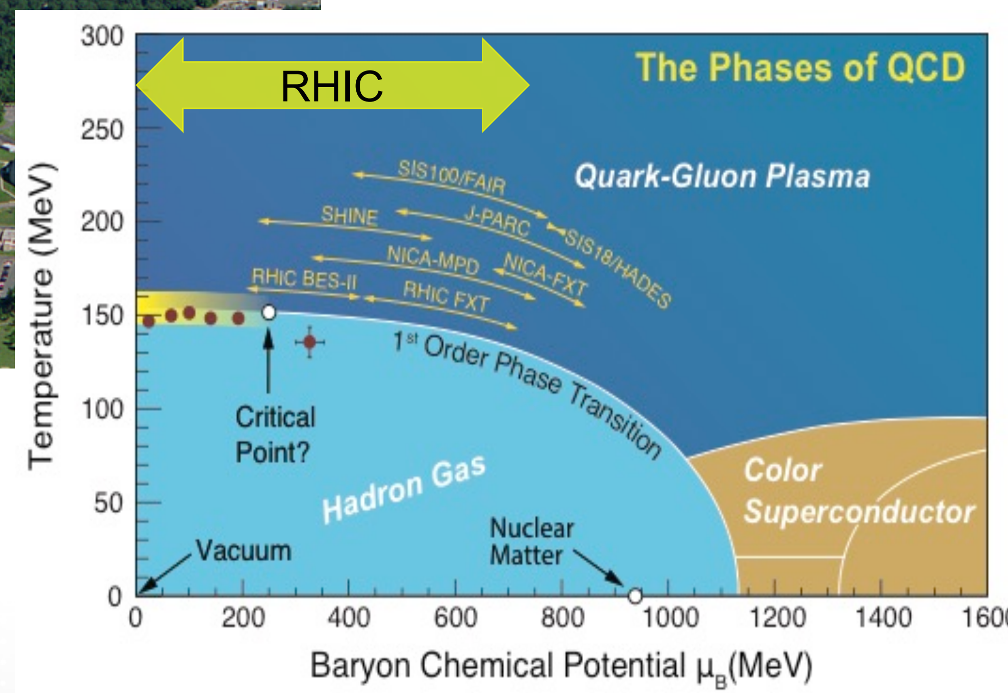
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Relativistic Heavy Ion Collider (RHIC)

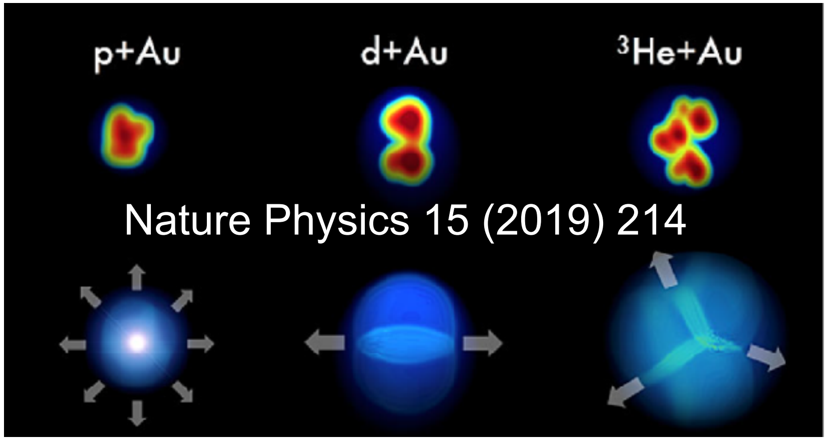


Aerial view of RHIC at Brookhaven National Laboratory



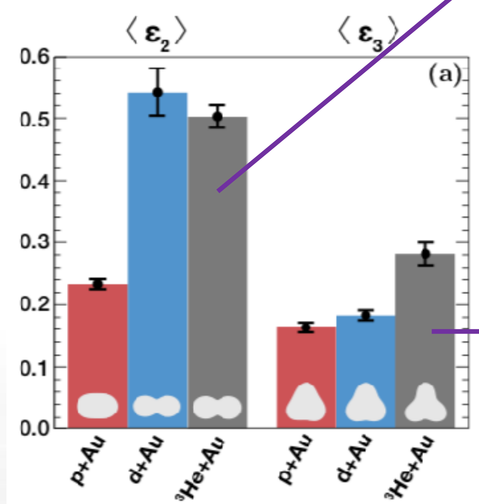
RHIC is the world's most versatile facility for the exploration of the phases of QCD matter from high temperature to high baryon density.

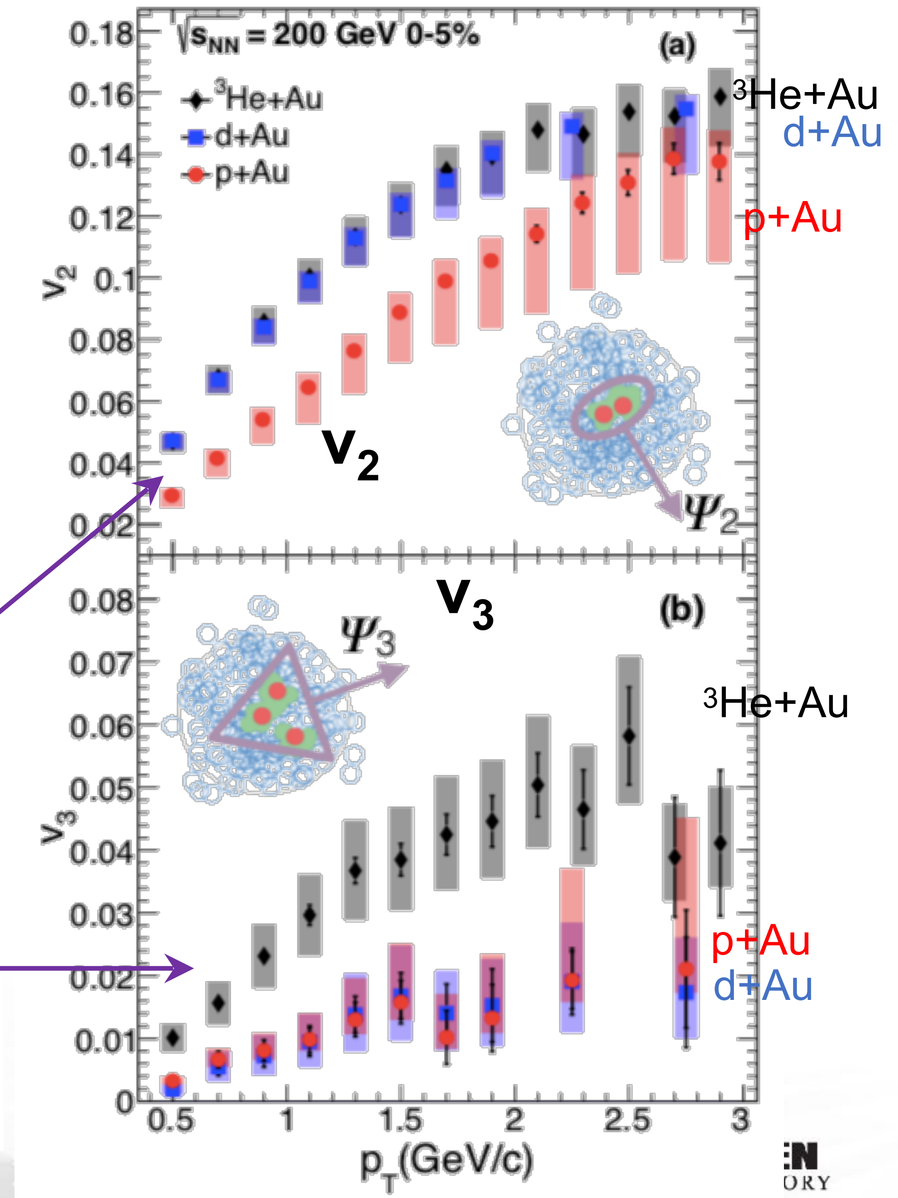
Evidence for small QGP droplets



The QGP droplets created in collisions of p+Au, d+Au, ³He+Au have characteristically different shapes resulting in different emission patterns.

The ordering of flows follows the ordering of shapes (ε_2, ε_3)

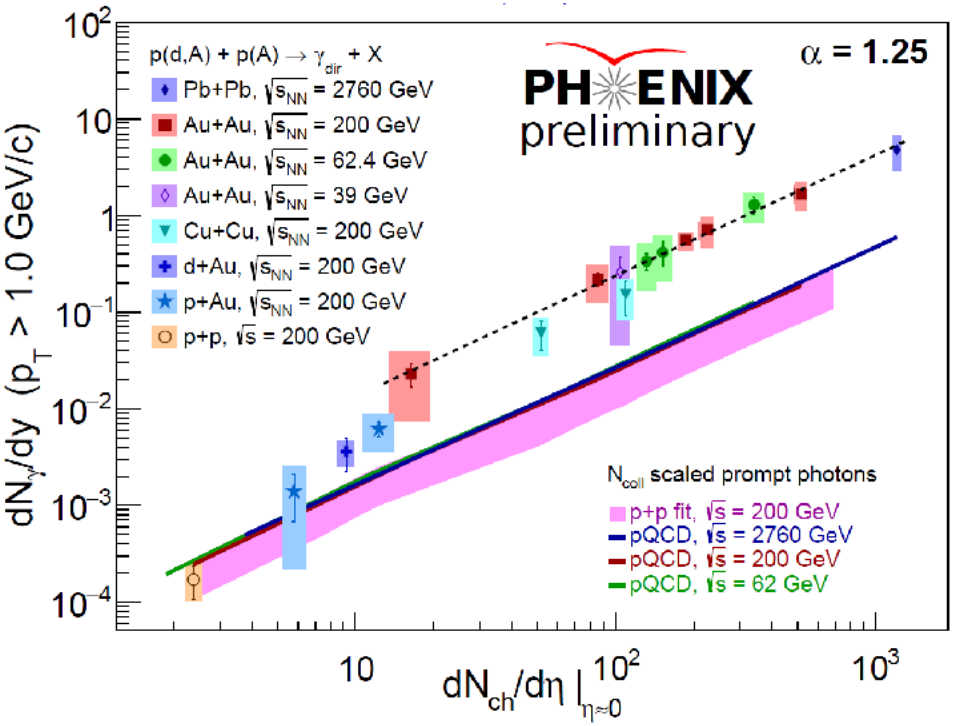


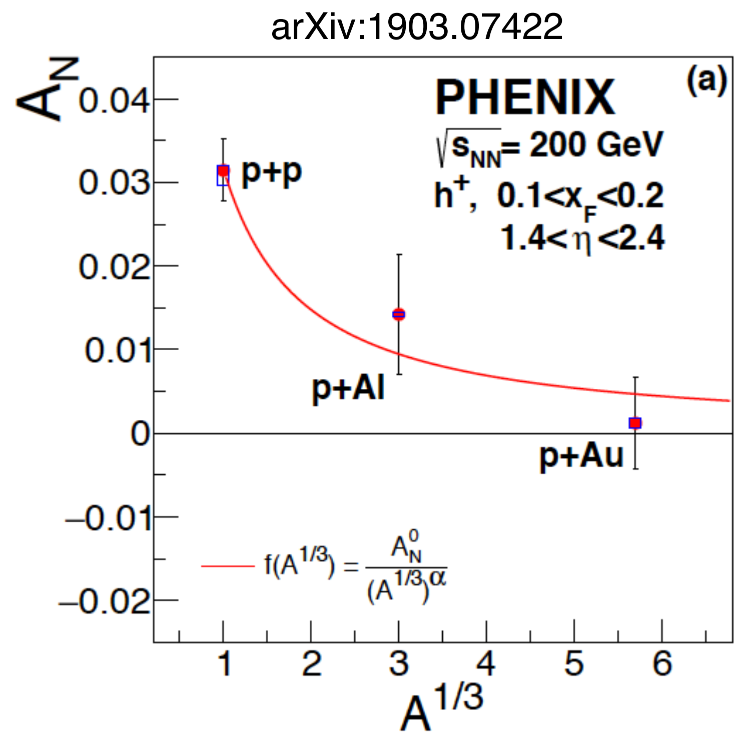


v_2(d,^{3}He+Au) > v_2(p+Au)

v_3(^{3}He+Au) > v_3(p,d+Au)

Intriguing effects in small systems





Emerging low photon enhancement in p+Au and d+Au supports QGP formation in small systems

A_N of positive hadrons in p+Au is suppressed compared with p+p

Versatility of RHIC made these unique measurements possible

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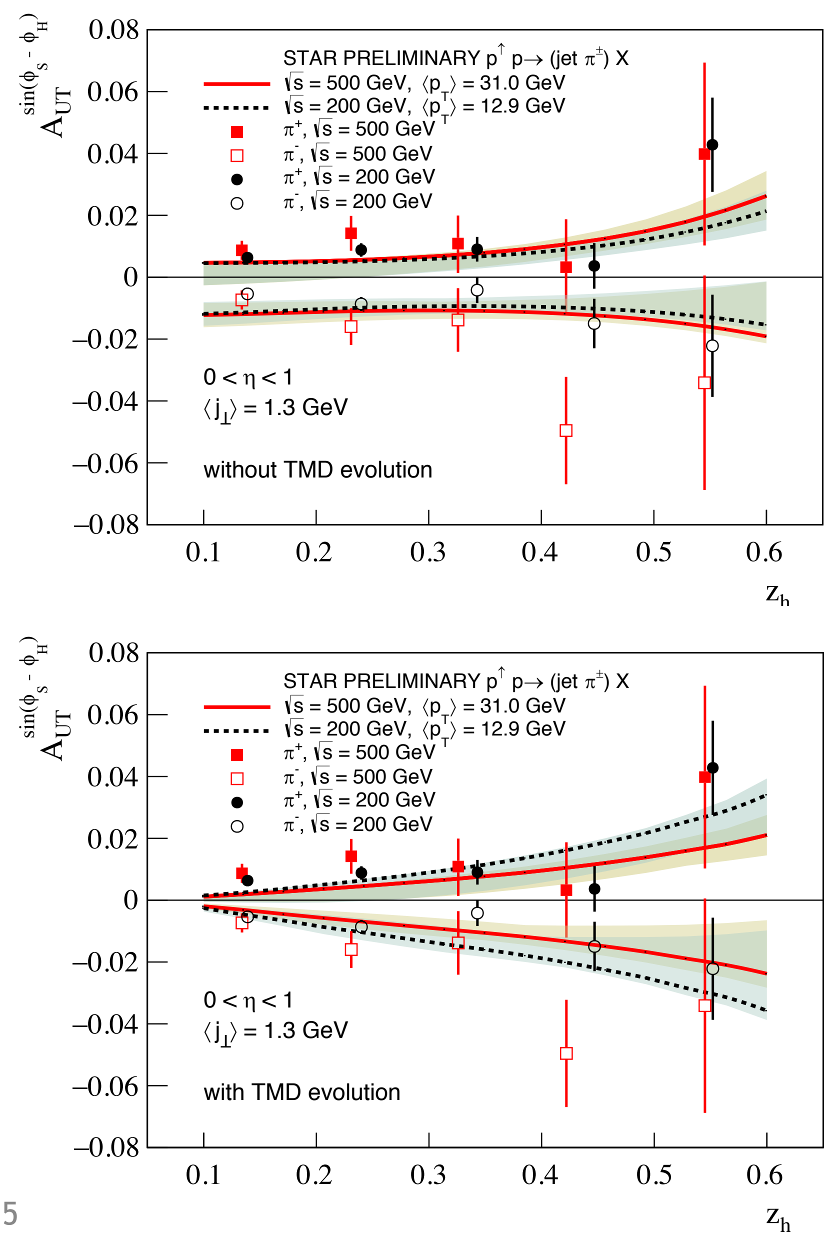
Jets: Transversity & Collins

transversity   Collins FF

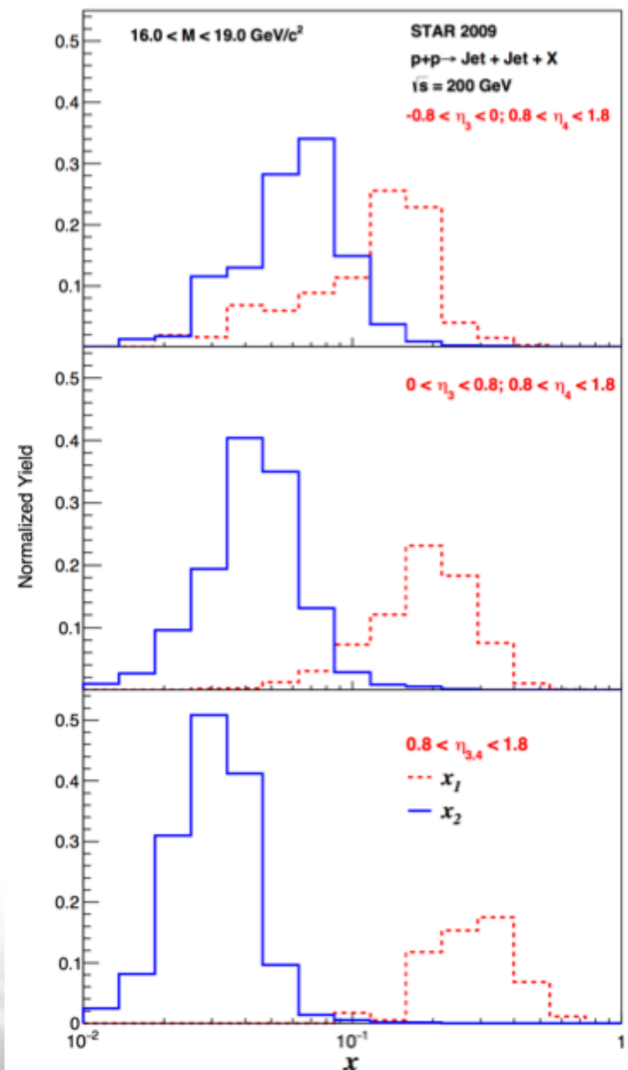
$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1,k_T)\, f_{q_2}(x_2,k_T)\,\hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u})\,\Delta D_{q_1}^{\pi^\pm}(z\, j_T)}{f_{q_1}(x_1,k_T)\, f_{q_2}(x_2,k_T)\,\hat{\sigma}_{UU}\, D_{q_1}^{\pi^\pm}(z\, j_T)}$$

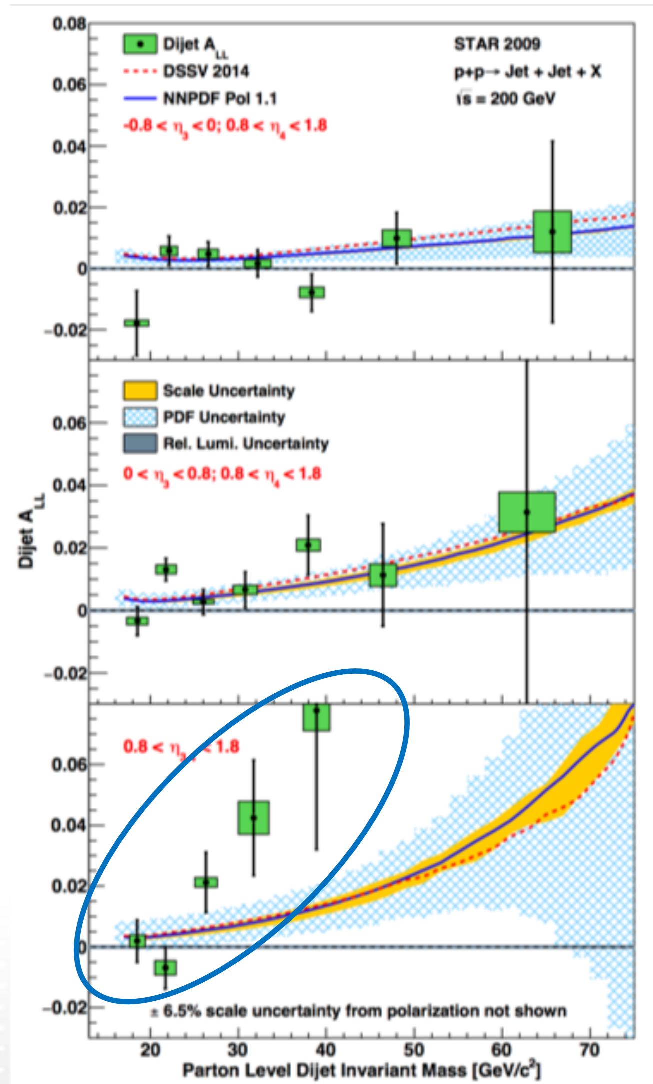
200 GeV vs. 500 GeV Comparison:

- First observation of a TMD at low x and high Q^2
  STAR 500 GeV PRD 97, 032004 (2018)
- Evolution: 200 GeV ←→ 500 GeV (factor 2.5 in Q) is modest
- Test of factorization & universality
  - compare with transversity from IFF
  - compare with SIDIS and e+e-
- Triggered a lot of theory work
  proof of factorization:
  Kang et al., arXiv:1705.08443
  asymmetry calculation:
  Kang et al., arXiv:1707.00913
  D'Alesio et al., PLB773 (2017) 300



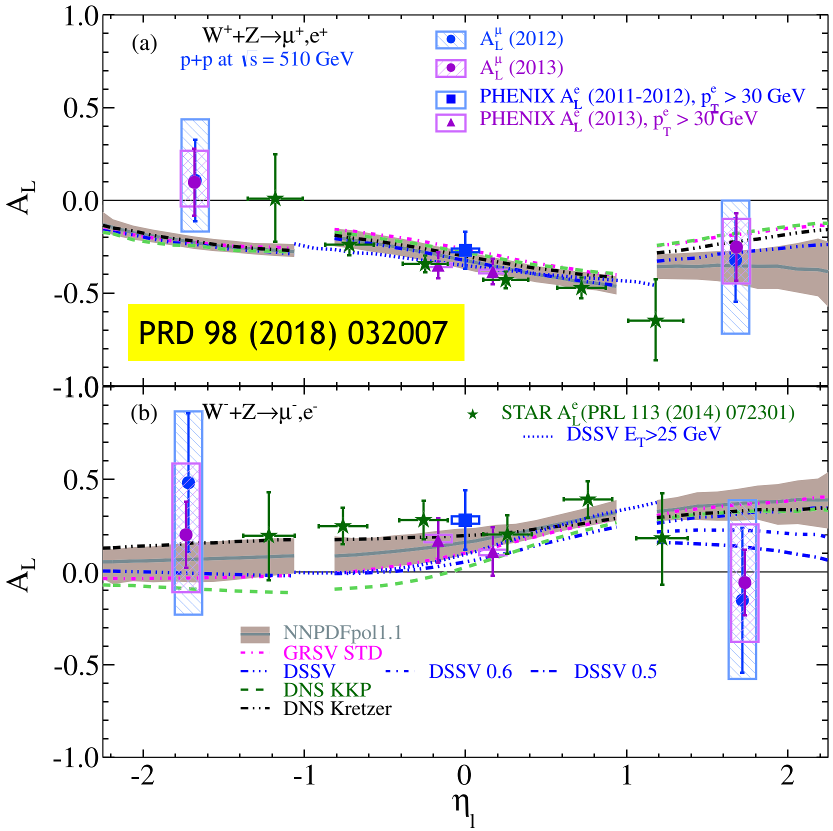
Dijet A_{LL}: Gluon polarization

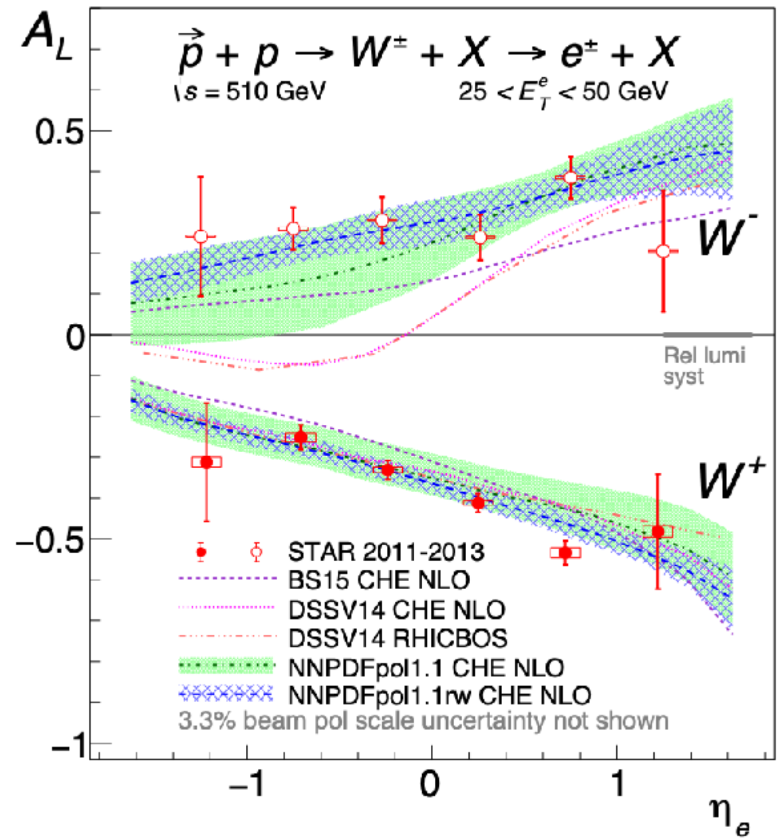




Higher degree of gluon polarization than in current fit?

RHIC Spin Results: W±



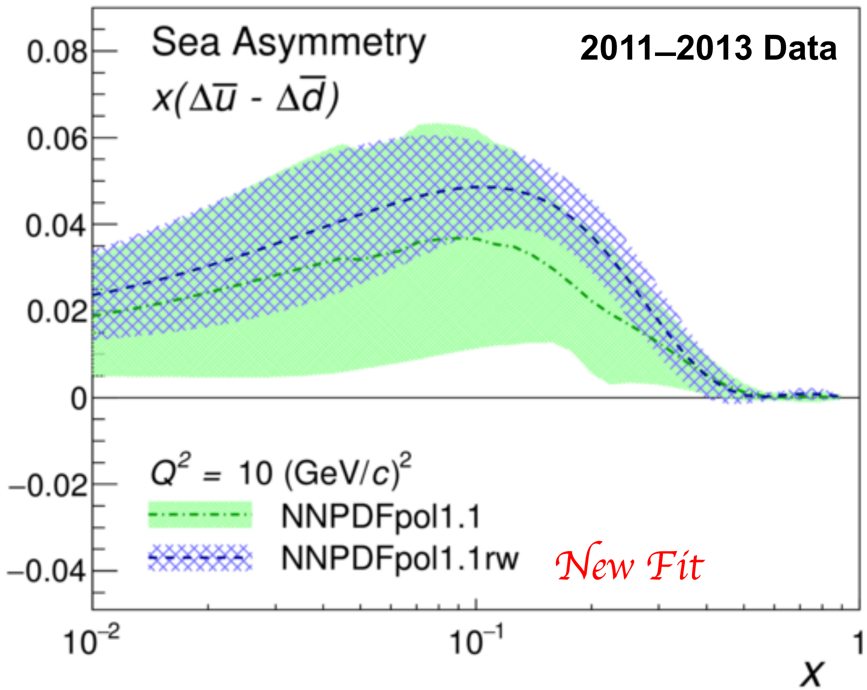


Concludes *W* A_L program

Contributes to global fit to helicity PDF

Flavor dependence of sea quark helicity

New global fit based on RHIC results extracted from W^+ and W^- A_L at 510 GeV



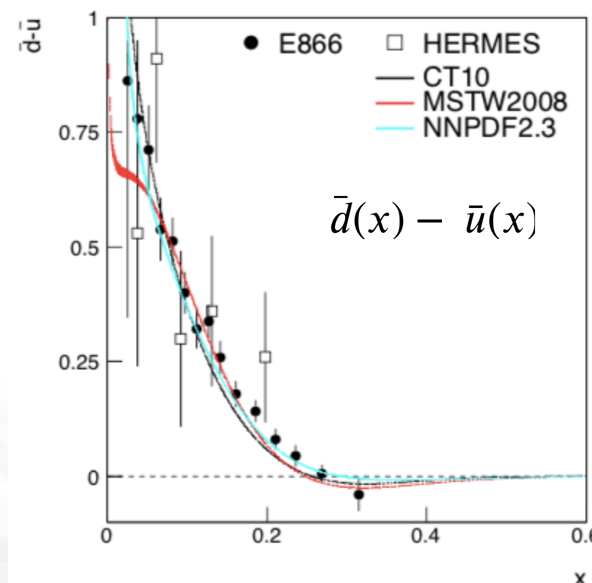
Compatible with the "statistical" model, which invokes *Pauli suppression* by the polarized valence quarks.

Result: For 0.05<x<0.25

$$\Delta\bar{u}(x,Q^2) > \Delta\bar{d}(x,Q^2)$$

Opposite sign of spin-averaged quark-sea flavor asymmetry!

$$\bar{d}(x,Q^2) > \bar{u}(x,Q^2)$$



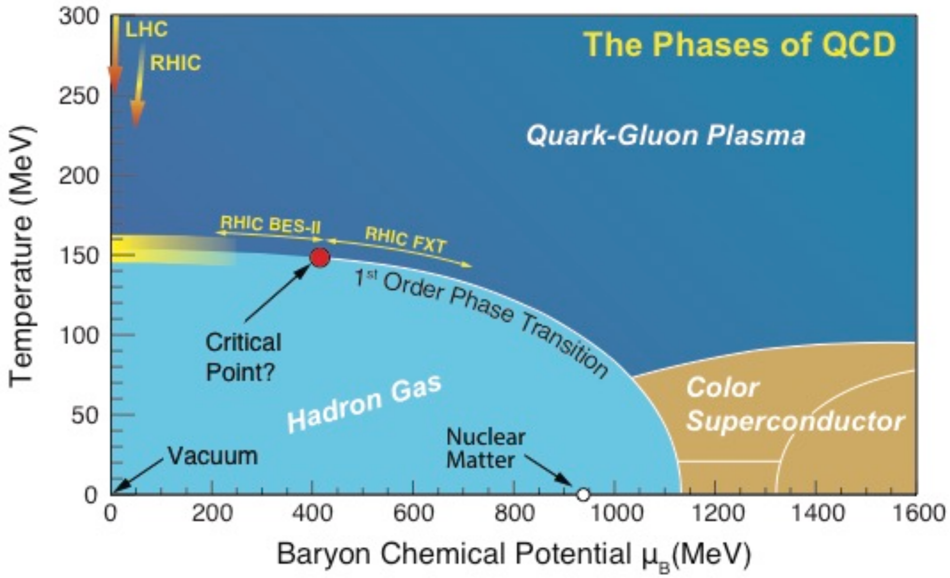
RHIC Run Plan 2019-25

- ***Beam Energy Scan II* (2019-21):**
  - 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
  - Fixed target runs at (3.0), 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for signs of critical phenomena in event-by-event fluctuations

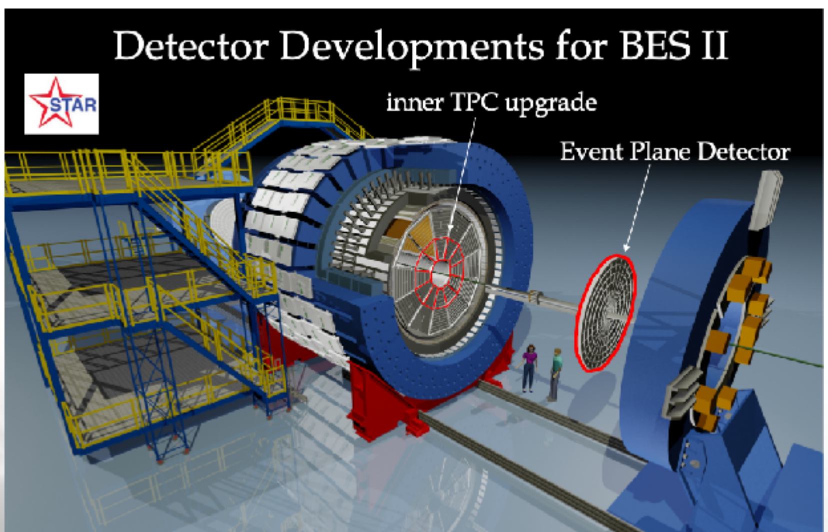
- ***Forward spin run* (2022):**
  - 500 GeV p+p (enhanced by forward upgrades of STAR)
  - Spin physics measurements complementary to EIC

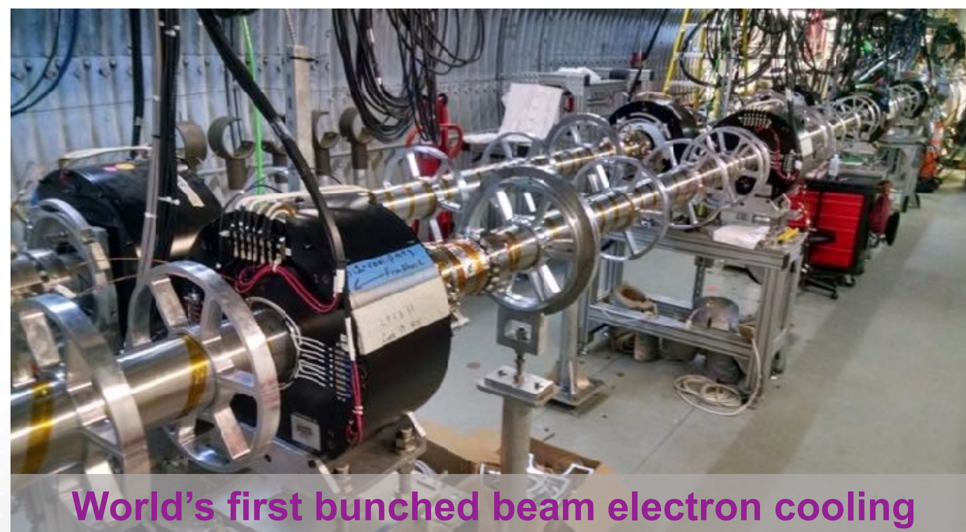
- ***Runs with sPHENIX* (2023-25):**
  - Full energy ($\sqrt{s_{NN}}$ = 200 GeV) Au+Au, p+p, p+Au
  - Precision measurements of fully resolved jets and Upsilon states

Beam Energy Scan 2019-21



Beam Energy Scan Goals:
- What is the phase boundary of ordinary nuclear matter, i.e. matter composed of baryons and mesons?
- Is there a critical point in the QCD phase diagram and, if so, where is it located?
  - 3-year run program: 12 energies
  - Run-19 already exceeding goals

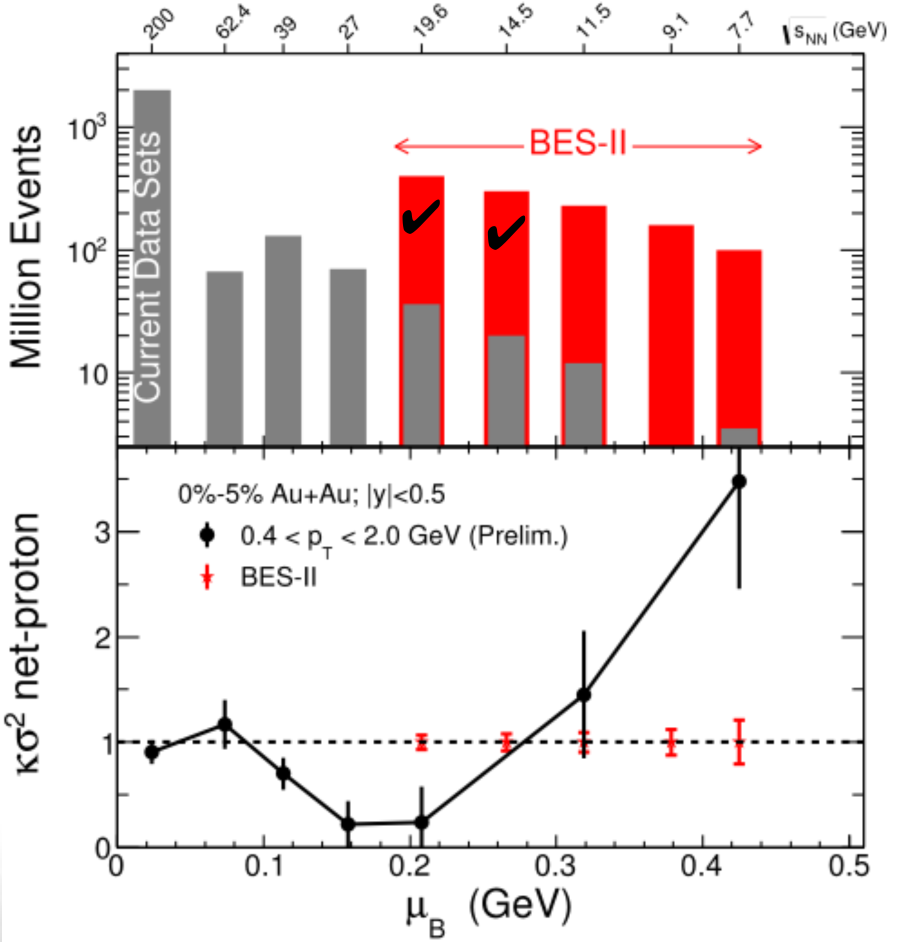


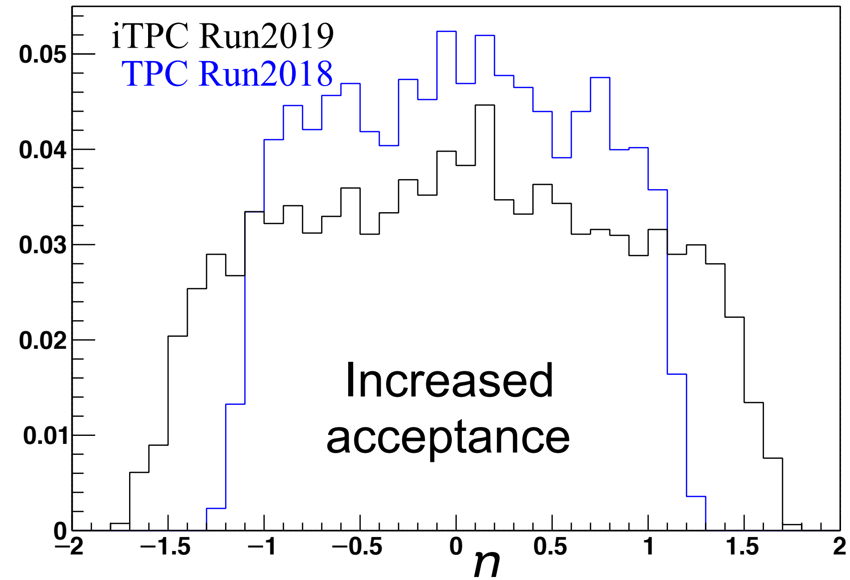


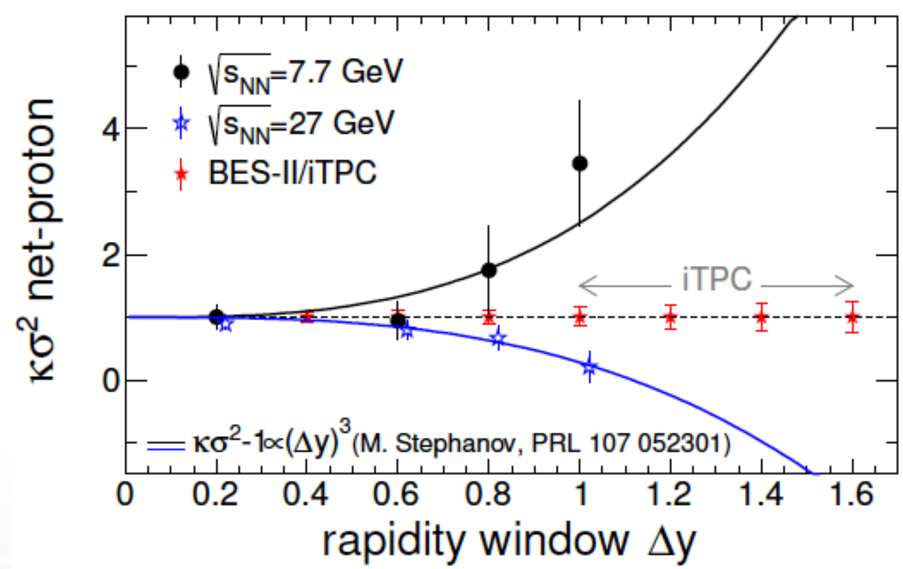
Upgrades for the BES-II

Higher statistics

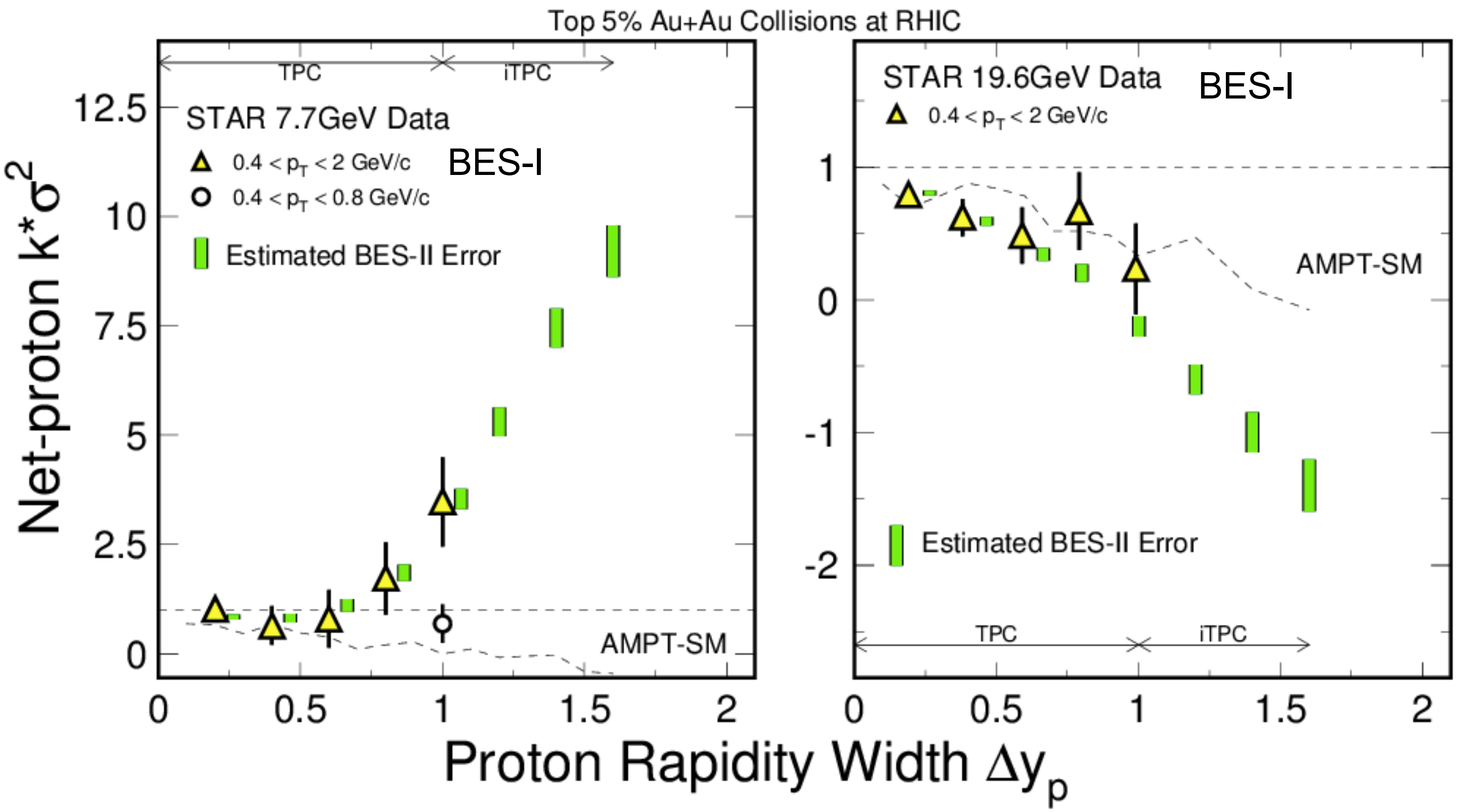
Low energy RHIC electron cooling upgrade







Increased statistics and acceptance



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

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

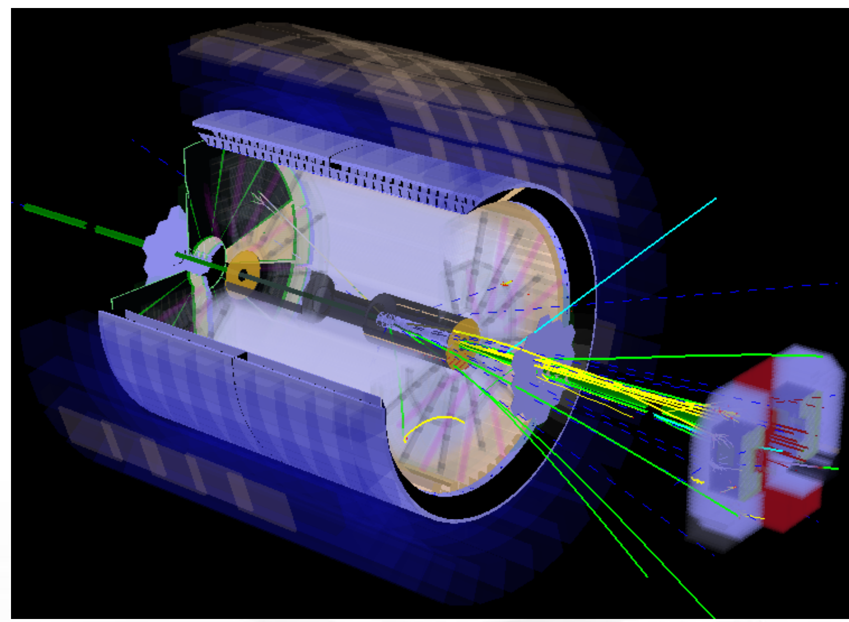
Increased luminosity reduces error bars

RHIC Program: Forward Physics

- STAR collaboration is planning to implement forward upgrades for RHIC runs beyond BES-II with significant international and non-DOE supported contributions.
- Physics program described in 2016 RHIC Cold QCD Plan - similar, but complementary to measurements planned for EIC.

Refurbished EMCal, new Hcal, STAR Pre-shower, FMS, and sTGC based tracking system, covering 2.5<η<4, forward Di tracking.

Enables polarized 500 GeV proton run in 2022, possibly continued running 2023-25.



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Cold QCD @ STAR

Mid-rapidity $-1.5<\eta<1.5$ | **Forward-rapidity $2.8<\eta<4.2$**

p+p & p+A (Mid-rapidity)

Beam:

500 GeV: p+p

200 GeV: p+p and p+A

Physics Topics:

- Improve statistical precision
  - TMD measurements (Collins, Sivers)
  - Access s & Δs through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

p+p & p+A (Forward-rapidity)

Beam:

500 GeV: p+p

200 GeV: p+p and p+A

Physics Topics:

- TMD measurements at high x transversity → tensor charge
- Improve statistical precision for Sivers through DY
- $\Delta g(x,Q2)$ at low x through Di-jets
- Gluon PDFs for nuclei
  - R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

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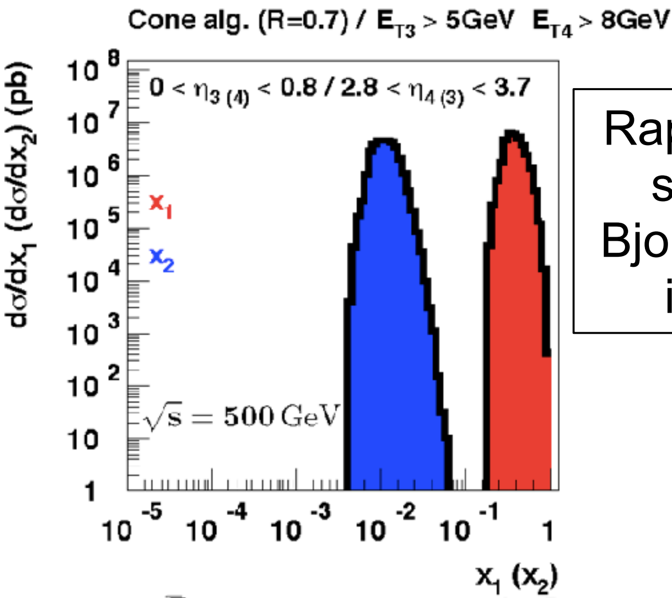
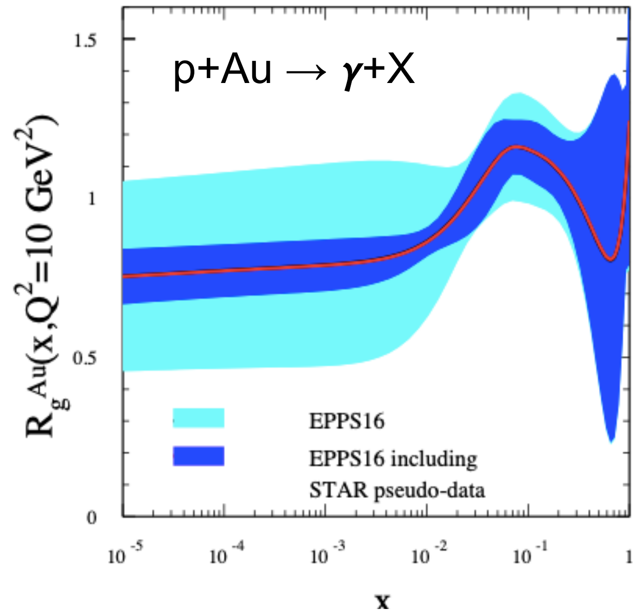
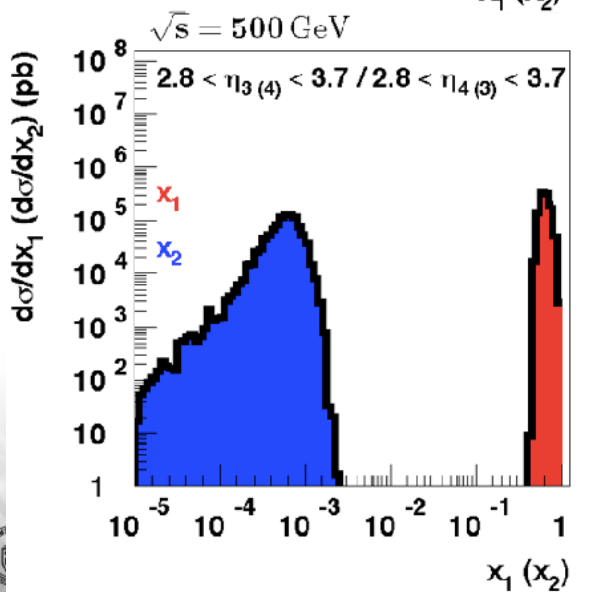
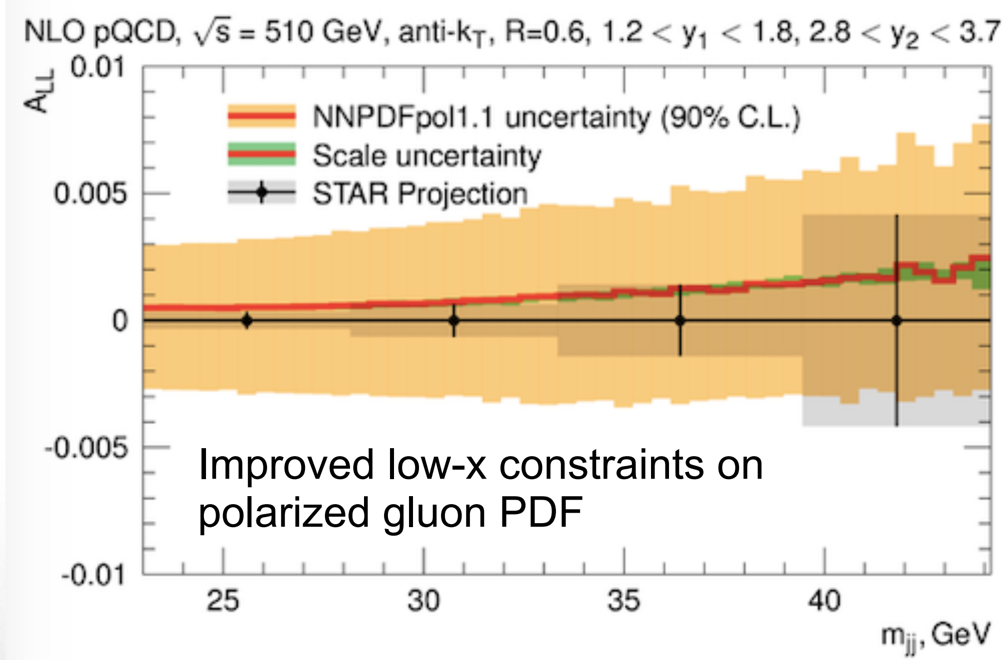
Cold QCD @ STAR



Rapidity windows select parton Bjorken-x regions in p+p, p+A

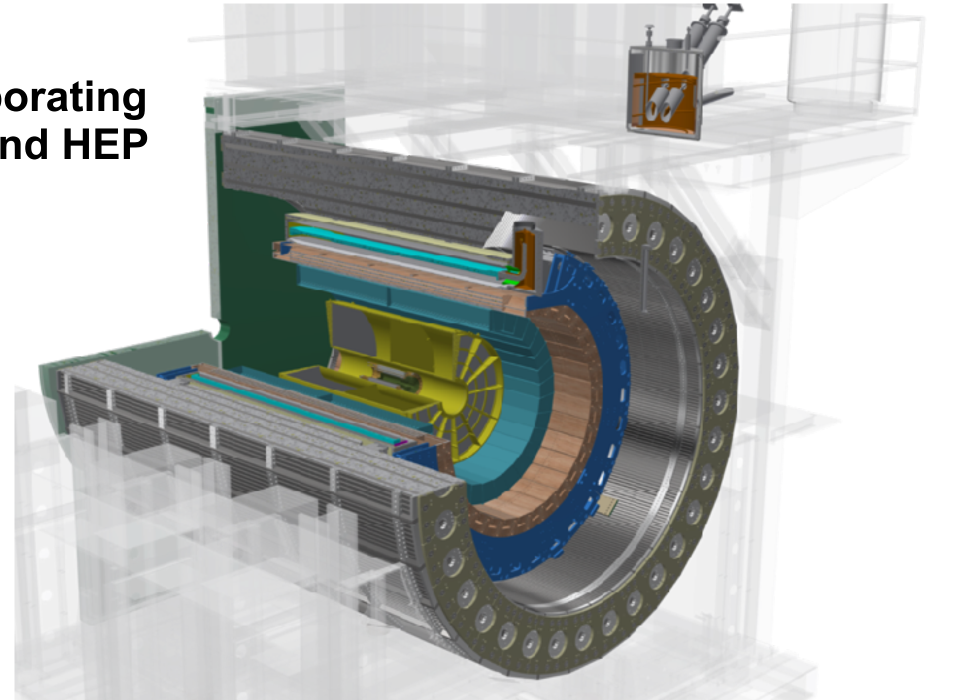




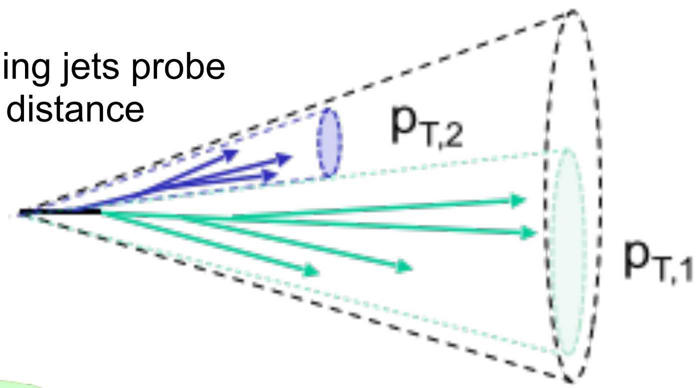


RHIC Program: sPHENIX

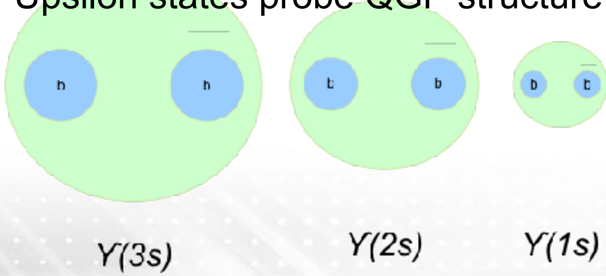
- **State-of-the-art collider detector incorporating technology developed for LHC by NP and HEP**
- **Pilot MIE for the new $50M rule**
- **Just passed PD-2/3 Review**
- **Data taking to start in 2023**



Expanding jets probe various distance scales



Upsilon states probe QGP structure

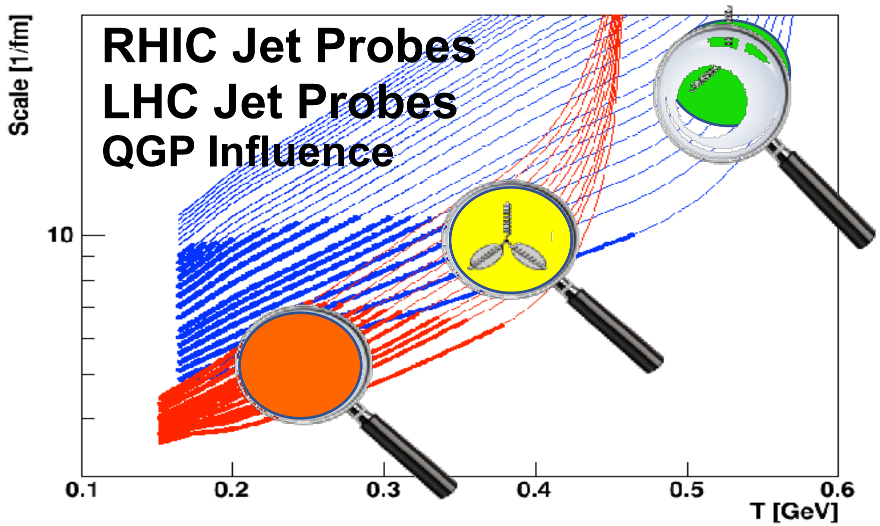


- **High energy jets probe the structure of the QGP on different length scales and determine where and how it changes from particle-like quarks and gluons to a structureless "perfect" liquid**
- **Heavy quark atoms (Upsilon) also probe the QGP structure at different scales**

sPHENIX will increase the data collection rate by a factor of 10 fully utilizing the enhanced RHIC luminosity

Jet Probes of QCD Structure

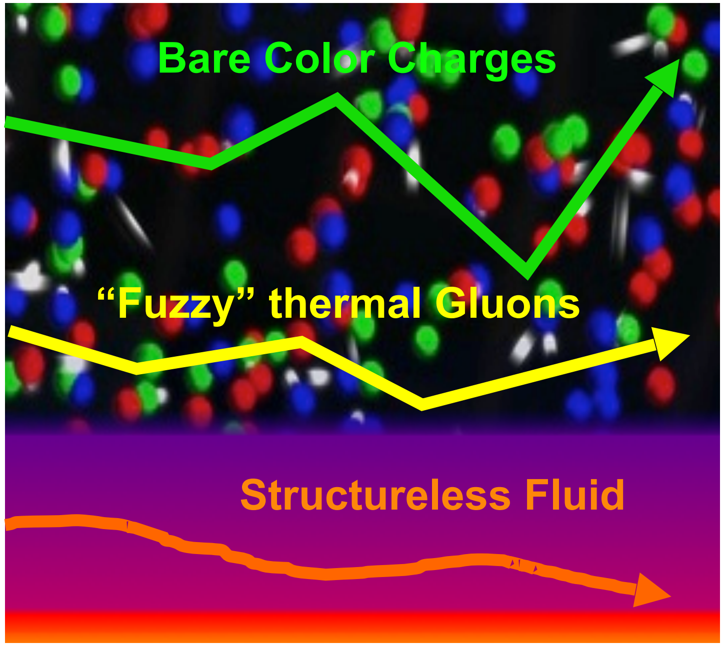
Parton virtuality evolves quickly and is sensitive to the medium at the <u>scale it probes</u>

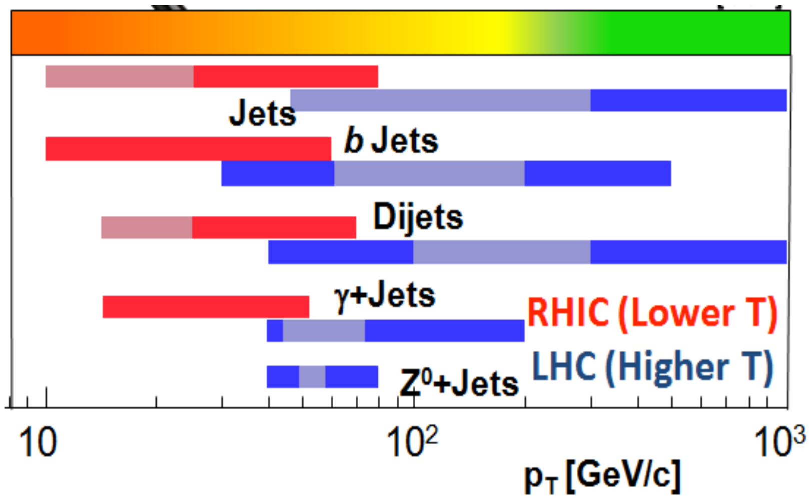


Unique critical microscope resolution range at RHIC

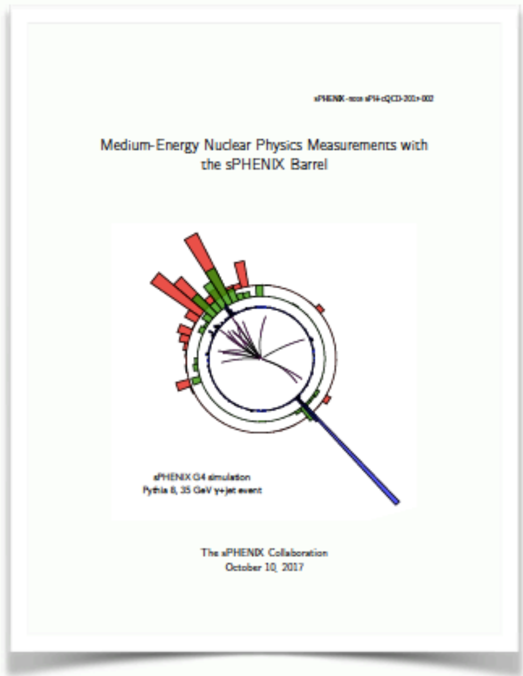
Jets are more sensitive to the QGP medium at RHIC than at LHC

Kinematic overlap between RHIC and LHC provides complementarity



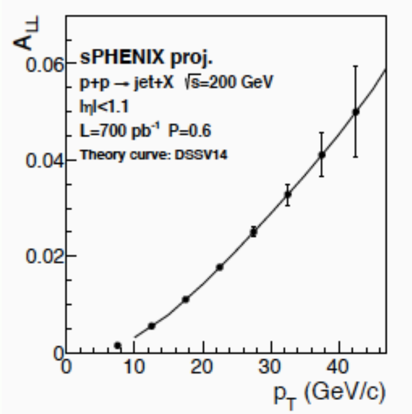


Cold QCD @ sPHENIX

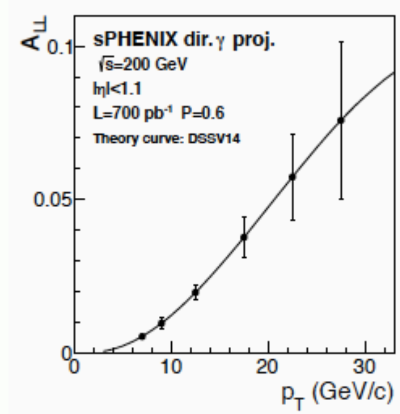


Projected capabilities for observables in longitudinally, transversely polarized collisions, nPDFs

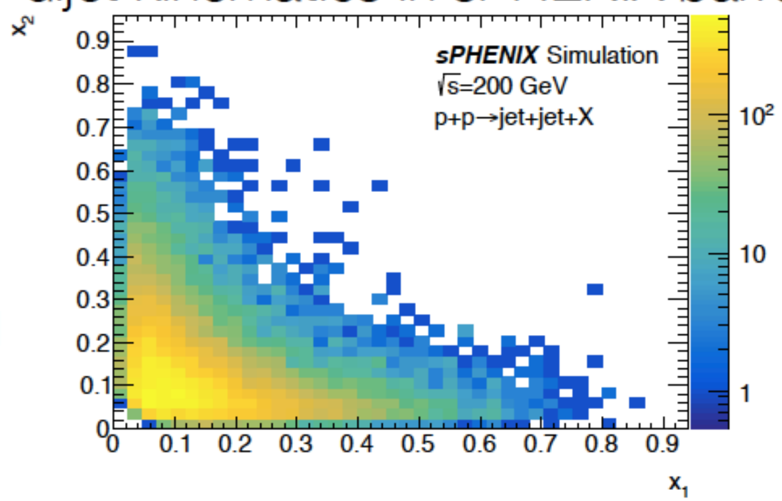
jet A_{LL}



direct γ A_{LL}

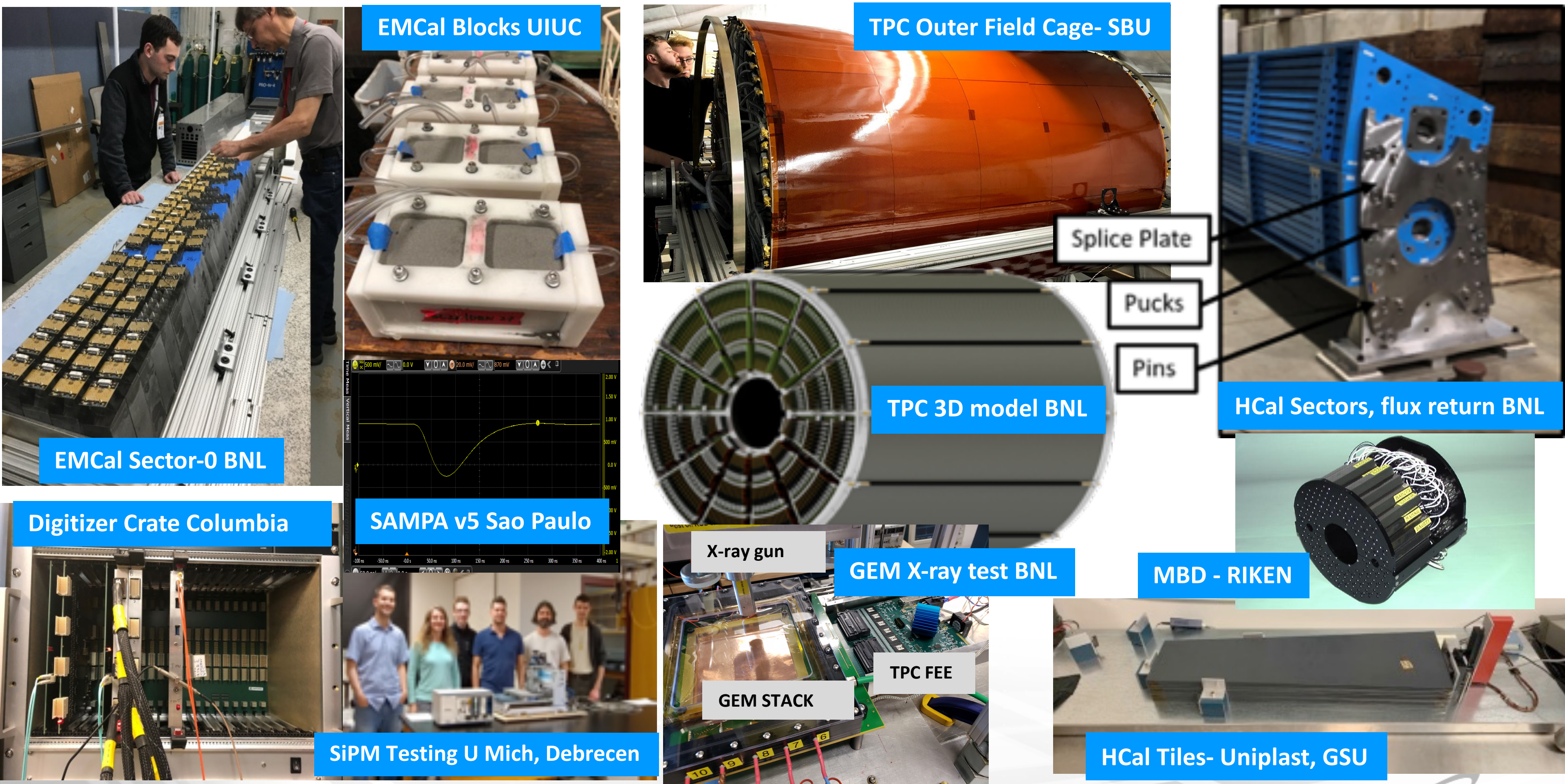


dijet kinematics in sPHENIX barrel



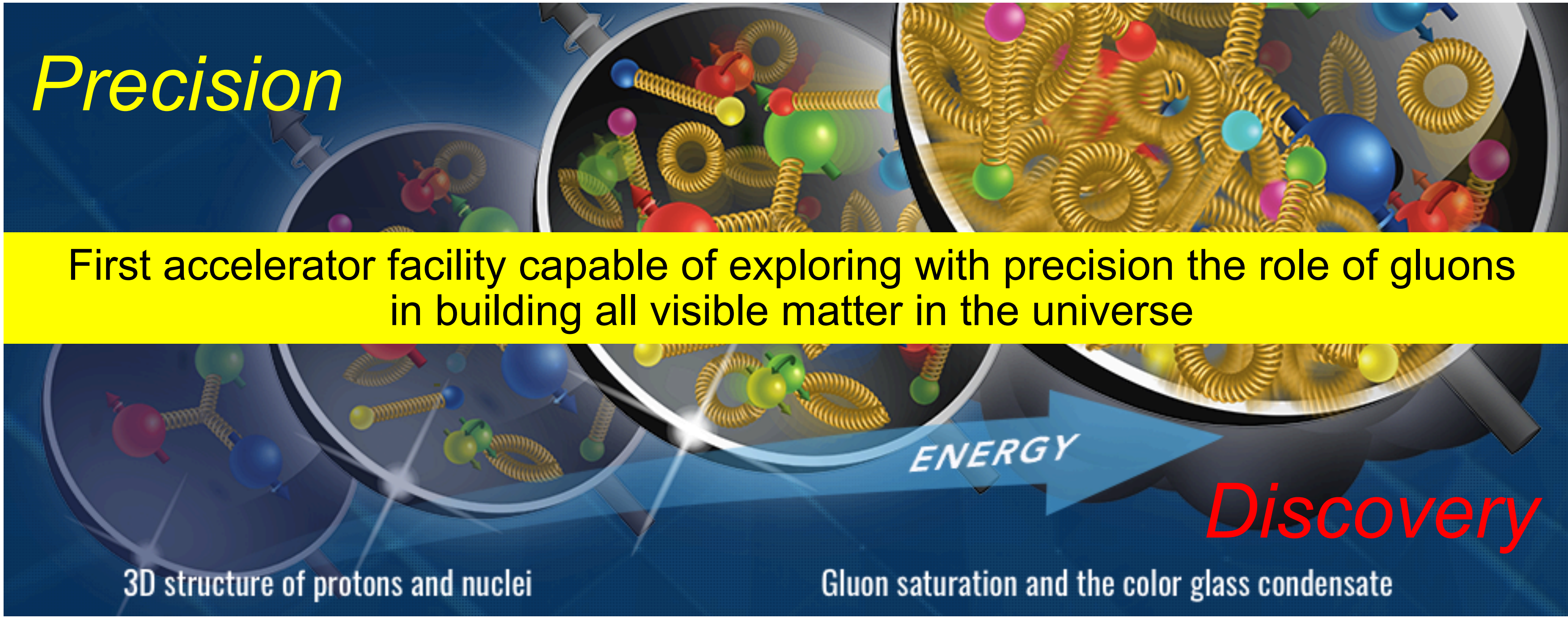
sPHENIX Hardware Progress

- Lots of progress on detector components, much of it going on at universities!
- Successful PD-2/3 review in May 2019
- Installation planned for 2022 for start of data taking in 2023



Beyond RHIC

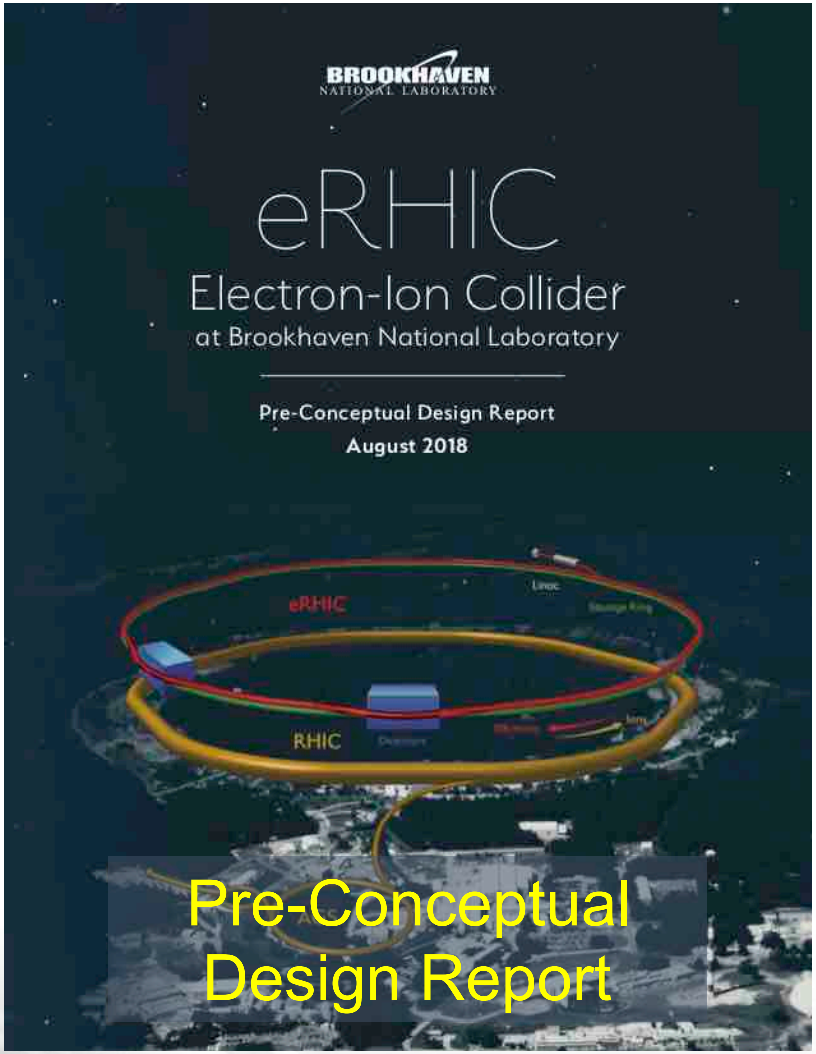
EIC: Compelling Science Case



NAS Study of the Science Case for a U.S. based EIC

In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics.

eRHIC Design



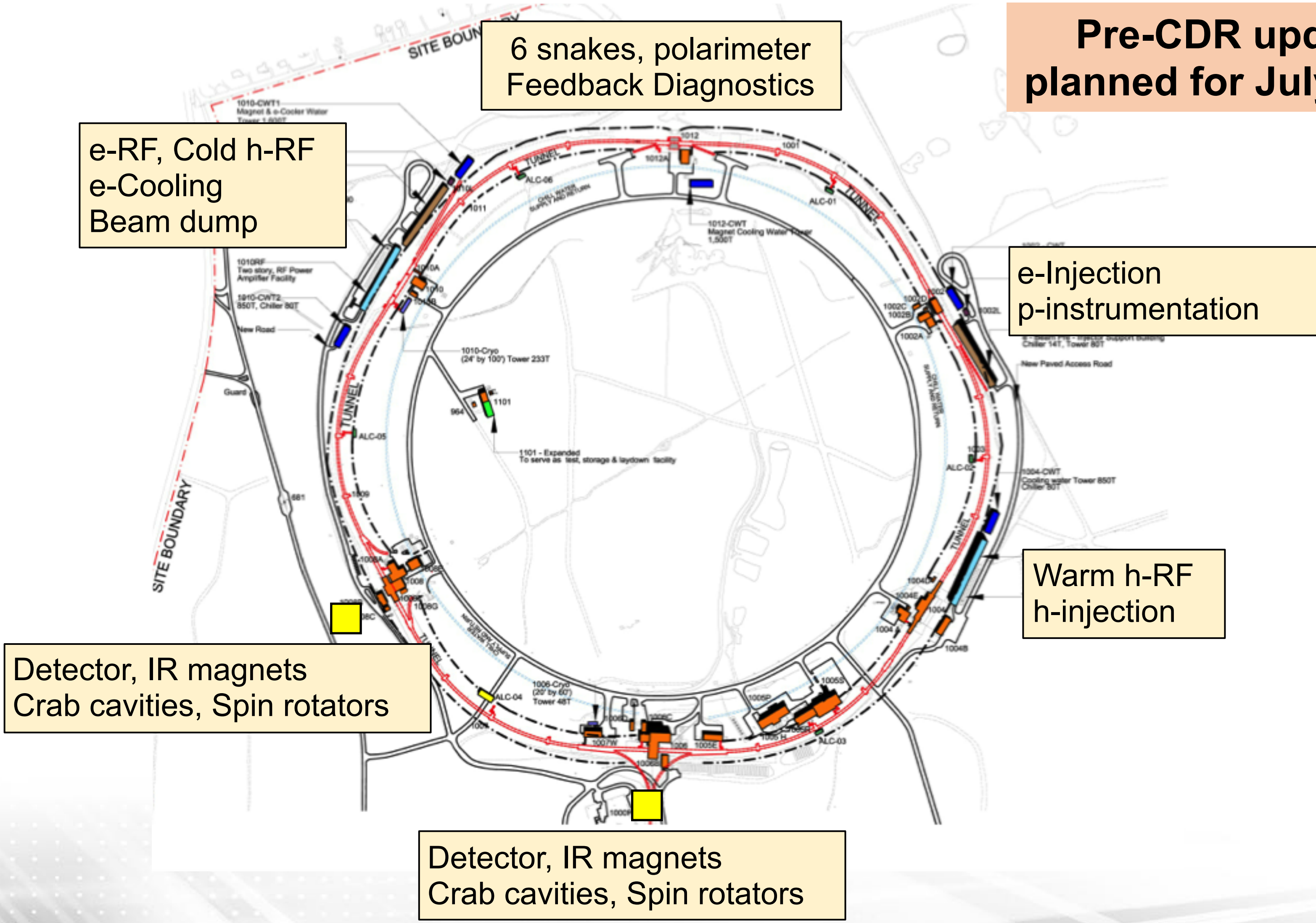
The eRHIC Team has completed a Pre-conceptual Design Report for a facility that is capable of addressing the full range of science covered in the EIC White Paper with a low-risk, cost-effective solution:

- Polarized (~70%) electrons, protons, light nuclei ($\uparrow^{3}$He, $\uparrow$d)
- Ion beams from deuterons to the heaviest stable nuclei
- CM energy range ~20–140 GeV
- Luminosity $\sim 10^{33\text{-}34}$ cm^{-2}s^{-1}
- Up to two interaction regions
- Multiple staging options

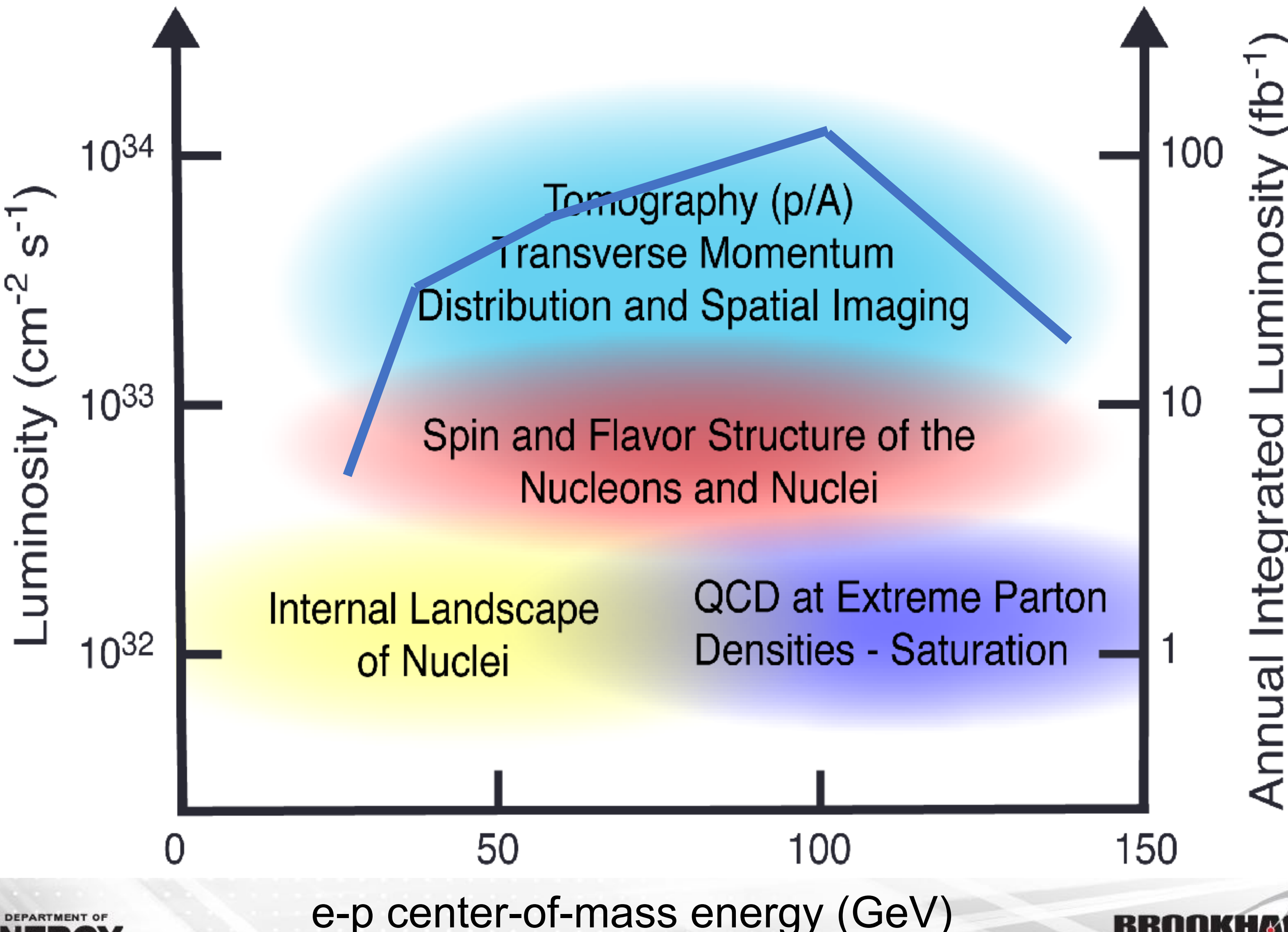
eRHIC is designed to be capable of executing the full science program outlined in the NAS Study Report.

eRHIC Layout

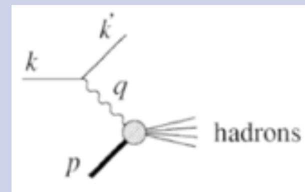
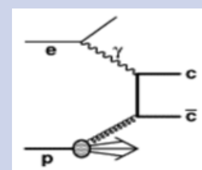
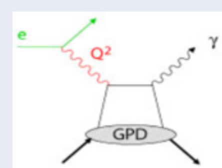
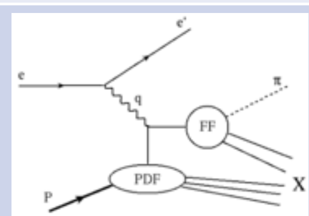
Pre-CDR update planned for July 2019



eRHIC: Luminosity versus CM Energy

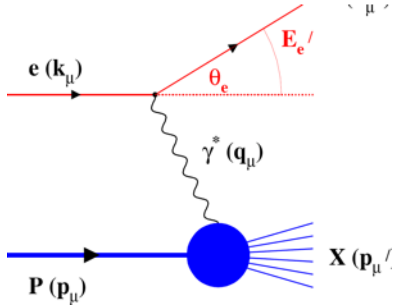


Measurements at an EIC

Physical quantity	Process	Measurement challenges
Structure functions F_2, F_L Nuclear structure functions	Inclusive scattering 	Electron identification, hadron measurement, background rejection, luminosity
Spin structure functions	Inclusive scattering	+ polarization
Gluon density	Charm, Di-jet production … 	Secondary vertex, pion/ kaon separation, hadronic jets
Generalized Parton Distributions GPDs	Deeply Virtual Compton Scattering Meson Production 	Forward proton, e, γ measurements background rejection
Transverse Momentum Distributions TMDs	Semi-inclusive Deep Inelastic Scattering 	Pion/kaon separation

EIC Experimental requirements

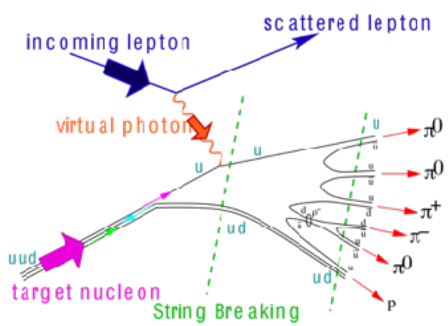
Experimental measurement categories addressing EIC physics



Inclusive DIS

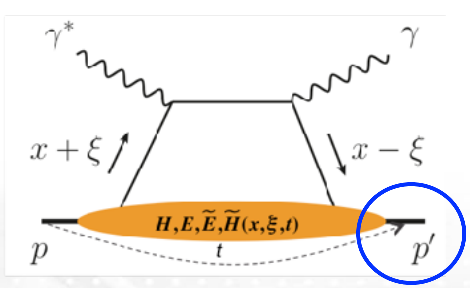
- fine multi-dimensional binning
  → x, Q^2

→ reach to lowest x, Q^2 impacts distance of machine elements to IP



Semi-inclusive DIS

- 5-dimensional binning
  → x, Q^2, z, p_T, Φ
- to reach p_T > 1 GeV

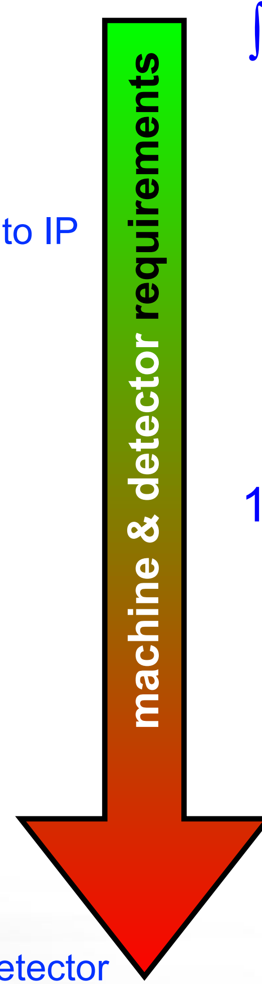


Exclusive processes

- 4-dimensional binning
  → x, Q^2, t, Θ
- proton p_t 0.2 - 1.3 GeV^2 needed

→ strong impact on IR design

→ can not be detected in main detector



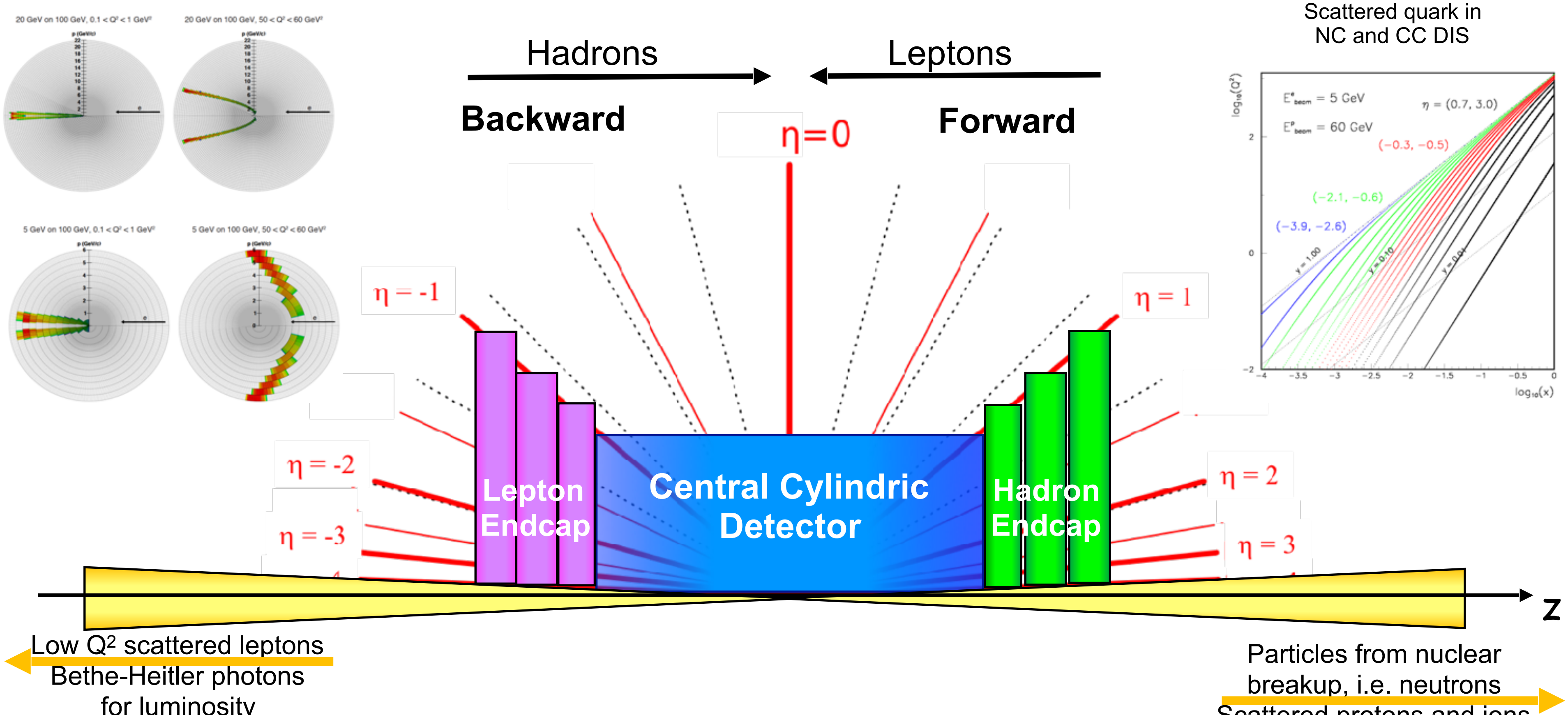
$\int Ldt$

1 fb^{-1}

10 fb^{-1}

10 - 100 fb^{-1}

EIC General Purpose Detector Sketch



EIC is a high luminosity machine 10^{33}-10^{34} $cm^{-2}s^{-1}$

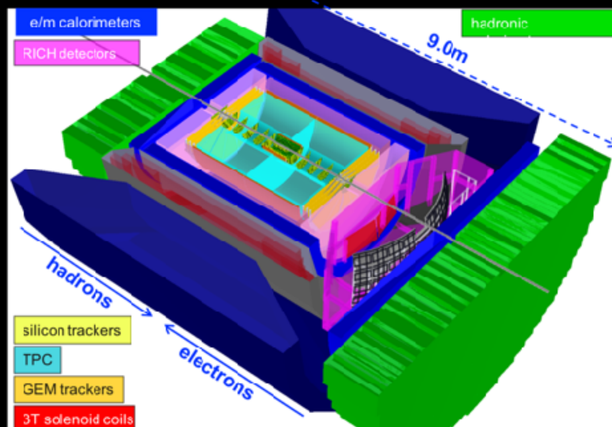
→ systematics becomes crucial

Importance of integrating **ALL** detector equipment in the collider

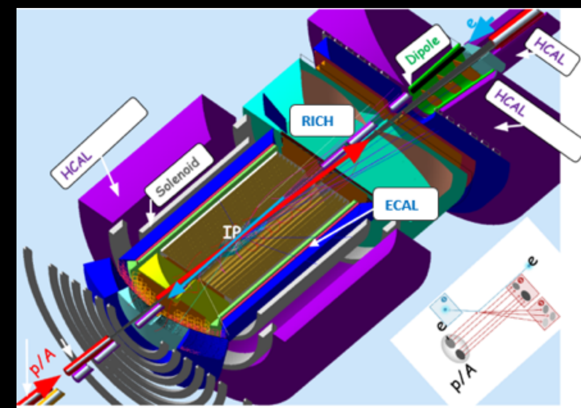
EIC Detector Concepts

eRHIC: Two interaction regions planned → Creativity has room to roam

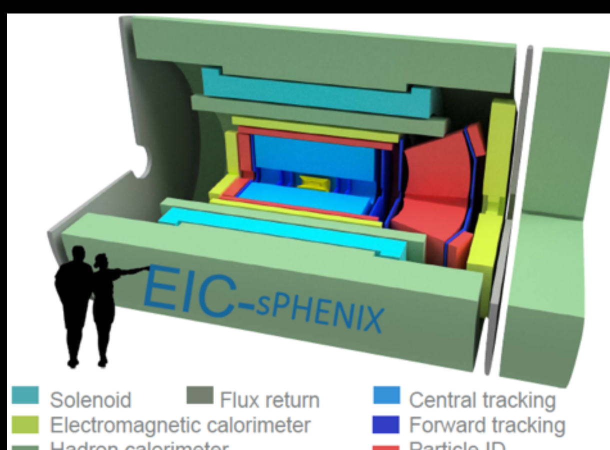
Brookhaven concept: BEAST



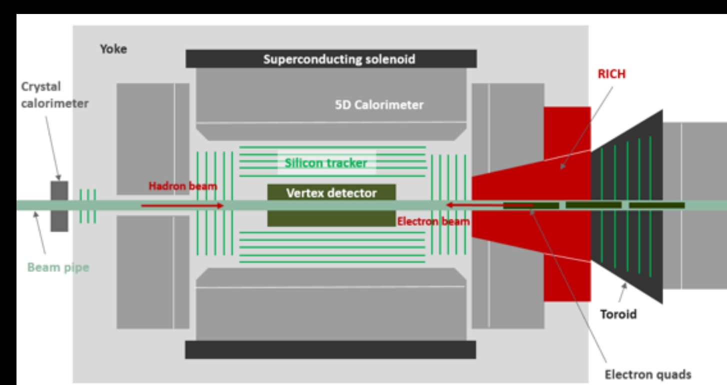
Jefferson Lab concept: JLEIC



sPHENIX → EIC



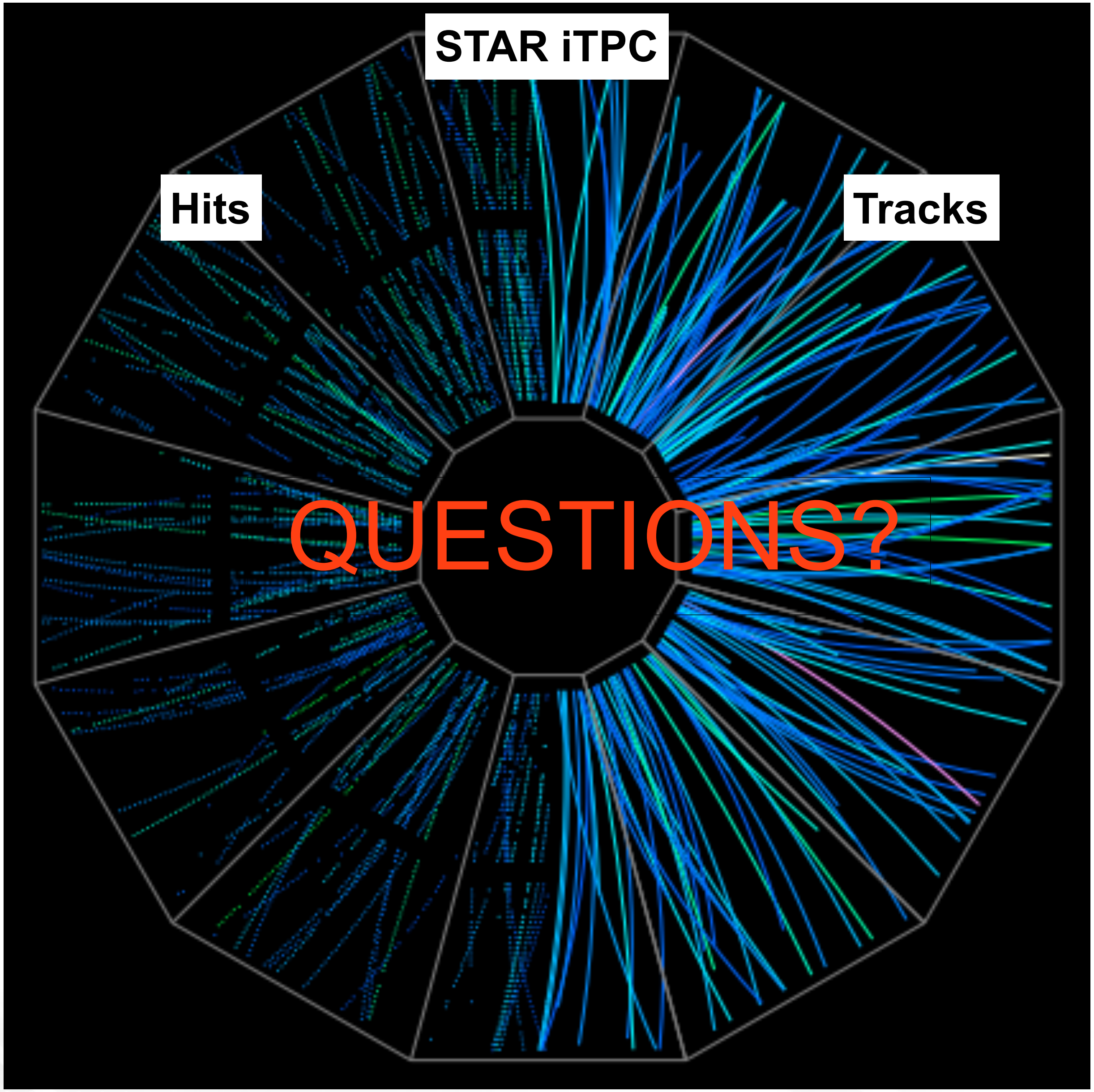
Argonne concept: TOPSiDE



Summary

- RHIC continues to produce intriguing results on QCD spin dynamics
  - Q^2 evolution of TMDs is not as strong as some theories suggested
  - Evidence for substantial gluon contribution to proton spin strengthened
- STAR iTPC and LEReC are performing well - BES II ahead of schedule
- Forward upgrades to STAR will open exciting opportunities for studies of QCD transverse spin physics at low-x prior to EIC
- sPHENIX will enable high statistics studies of hard QGP probes

- Favorable NAS Report on EIC has set the stage for *Mission Need*
- Critical Decision 0 is expected in FY 2019, first funding in FY 2020
- eRHIC pre-CDR completed in August 2018, updated version in summer 2019
- This is the time to get involved in EIC detector activities organized by the EIC Users Group



QUESTIONS?