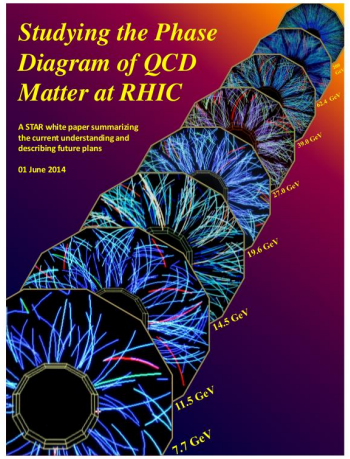
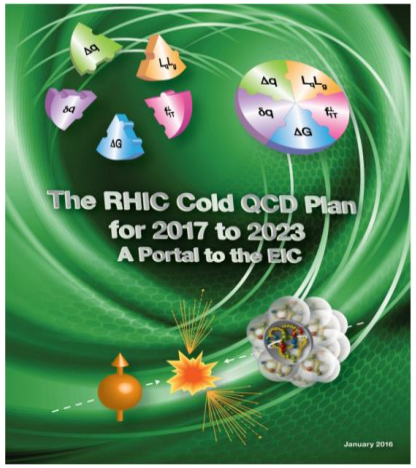
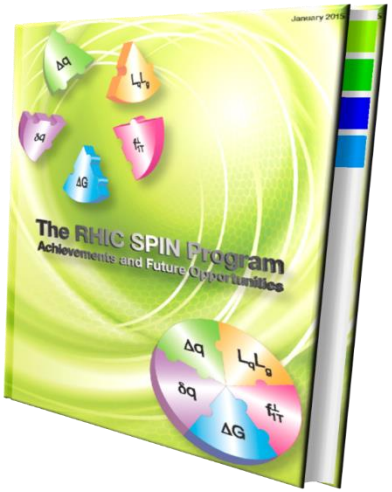
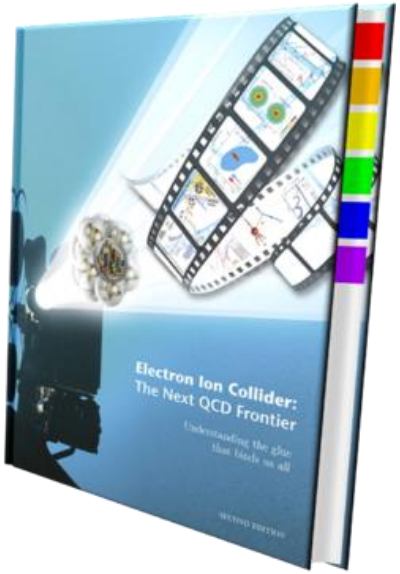
Future of heavy-ion experiments at RHIC, toward an Electron-Ion Collider

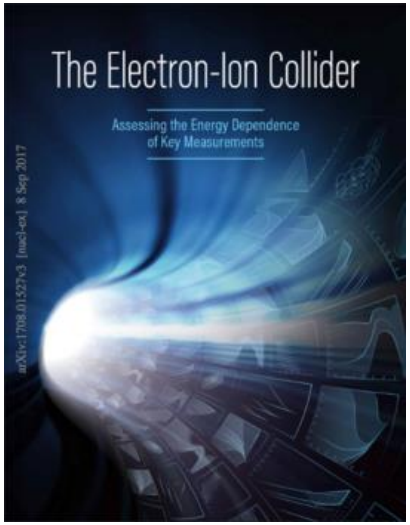
https://drupal.star.bnl.gov/STAR/system/files/BES_WPII_ver6.9_Cover.pdf









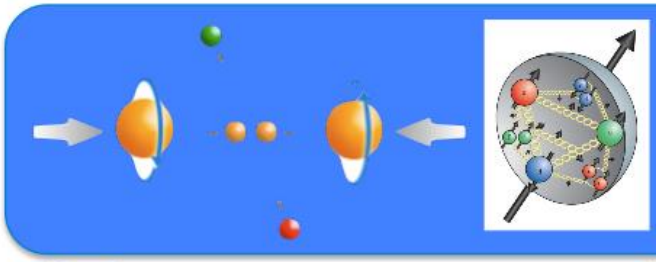


Petr Chaloupka, Czech Technical University in Prague

RHIC physics

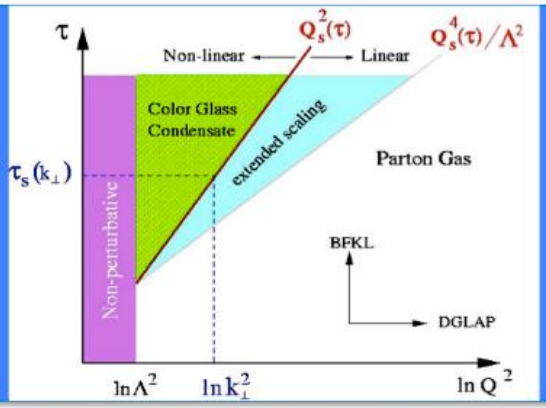
RHIC is the only dedicated heavy-ion collider in the world

- large versatility of collision species and energy ($\sqrt{s_{NN}}$ = 7-200 GeV)
- polarized proton beams ($\sqrt{s}$ up to 500 GeV)



Polarized p+p Program

- proton spin structure
- perturbative QCD



p(d)+A Program

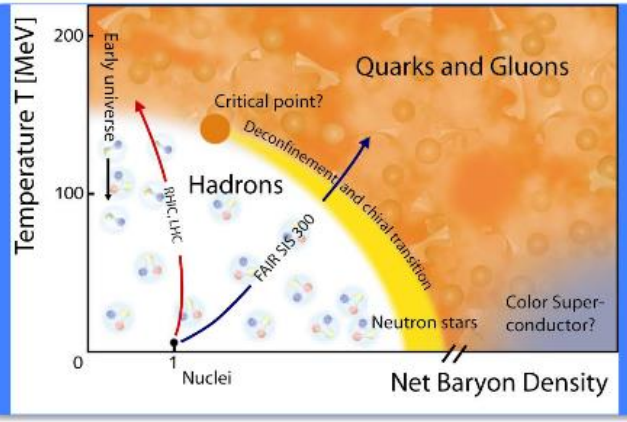
- gluon saturation, CGC
- initial conditions, CNM
- diffractive interactions

eSTAR:

Polarized

e+p / e+A

Program



A+A Top Energy

- QGP medium properties, EoS
- QCD in hot and dense medium

A+A Beam Energy Scan

- search for the critical point
- chiral symmetry restoration

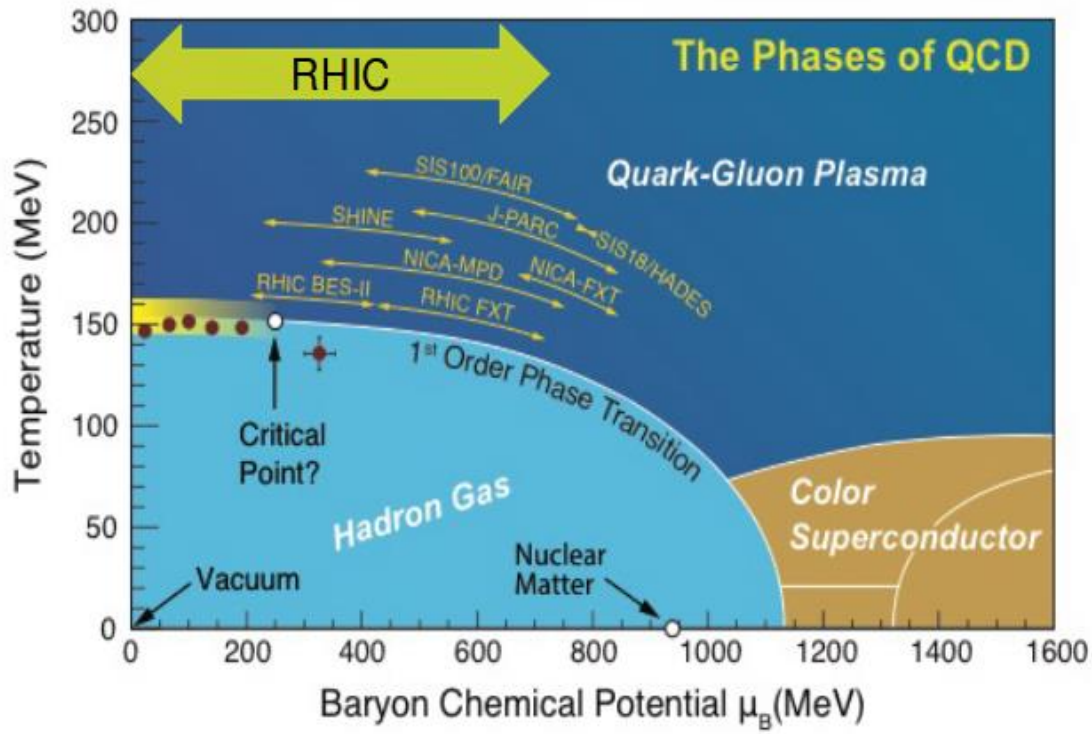
RHIC mid- and long-term plans

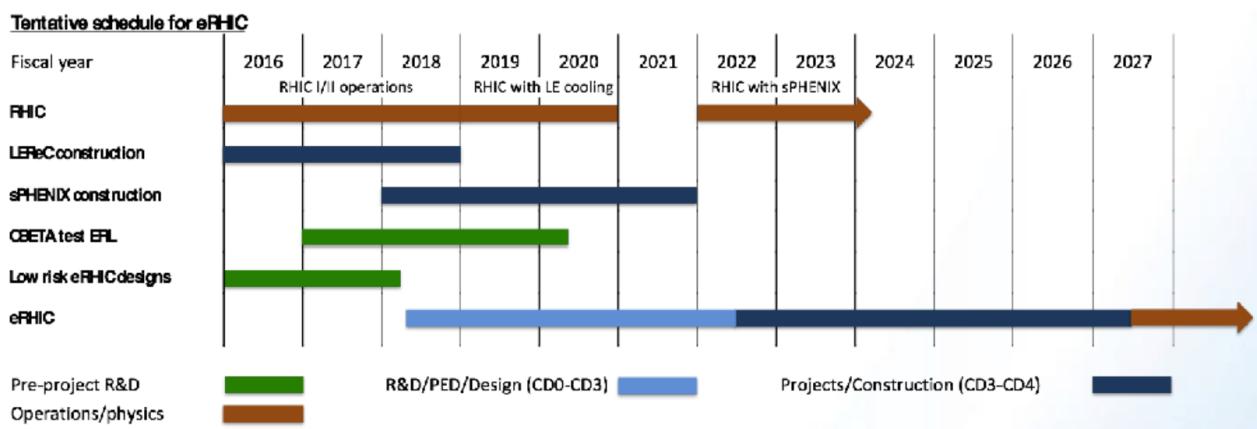
Past:

- 2010-14: Beam Energy Scan I
- 2015-16: Heavy Flavor program
- 2017: Transverse spin physics

Future plans:

- 2018: Isobar run – test of chiral symmetry
- 2019-20: Beam Energy Scan II
- 2021: sPHENIX installation
- 2022-23: High precision measurements of jet quenching and quarkonia suppression
- 2023-26: Transition to eRHIC
- 2027+: eRHIC operations





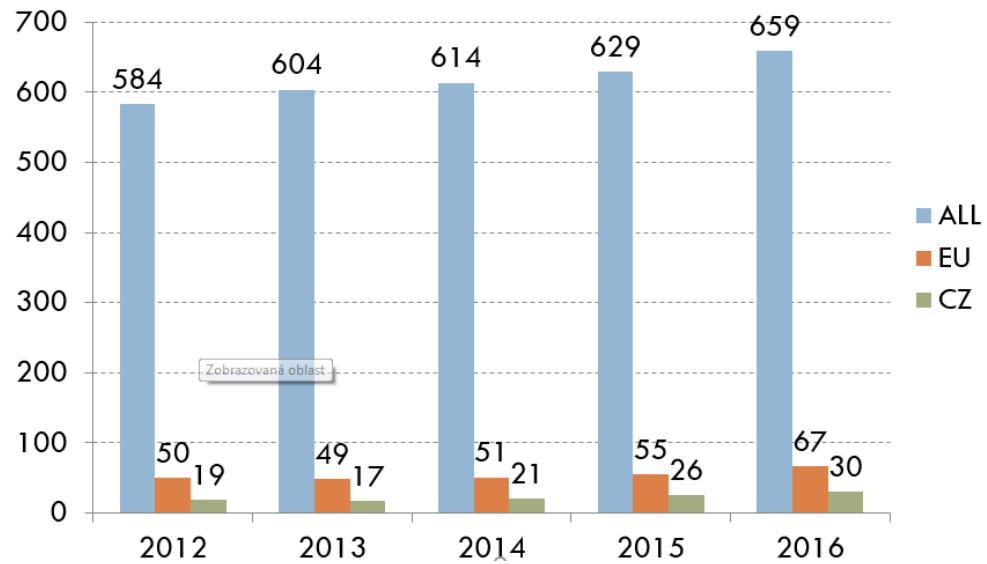
Large research infrastructure BNL-CZ

Czech proxy to Research at Brookhaven National Laboratory

- Consolidated effort of Czech Technical Uni., Charles Uni., and Nuclear Phys. Inst.
- Included in the 2016-2022 Czech Roadmap for Large Infrastructures
- supported from 2016, successful interim evaluation in 2017,
  expected funding till 2022
- additional support from MEYS: OPVVV BNL-CZ (2017-2019),
  Inter-Excellence Inter-Transfer (2018-2022)

Main goals:

- coordination and support of the Czech research institutes that conduct research at BNL
- maintenance, operation and upgrades of STAR and PHENIX detectors
- preparation of sPHENIX
- popularization of science and results related to BNL research
- support for participation of students in educational projects organized in BNL



STAR:
Czech participation grew in last five years
by a factor of 1.6
2012: 3.25% → 2016: 4.55% of STAR members

BNL-CZ support for STAR

STAR management:

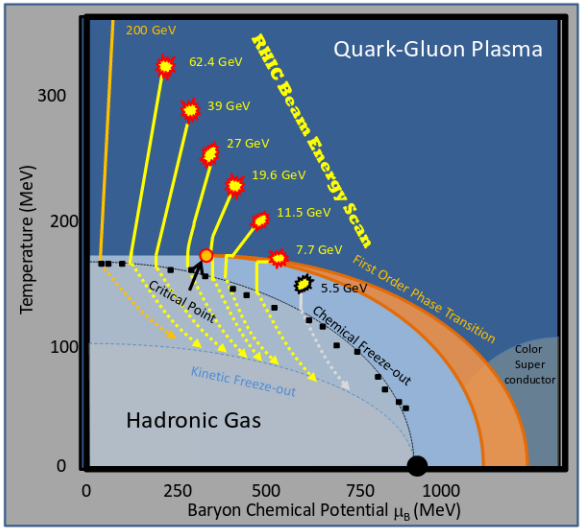
P. Chaloupka – STAR heavy flavor working group convener
D. Tlustý (now Rice Uni.) – STAR light flavor working group convener
J. Bielčíková – chair of the STAR Talks Committee
M. Šumbera – STAR Council Bylaws Committee

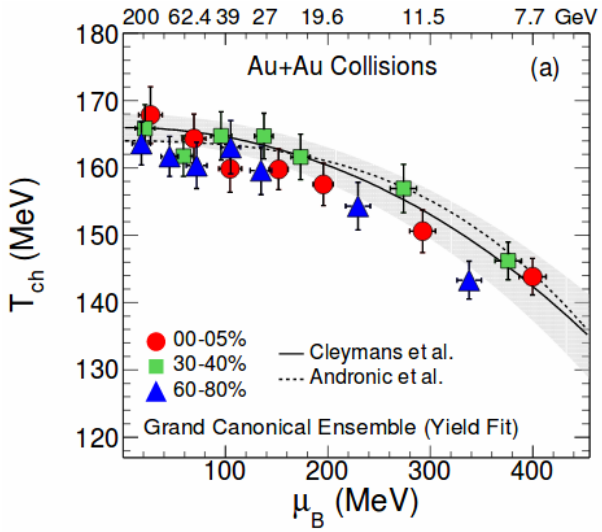
STAR operations and R&D:

Zero Degree Calorimeter (ZDC)
- on-site expert during runs, planned upgrade

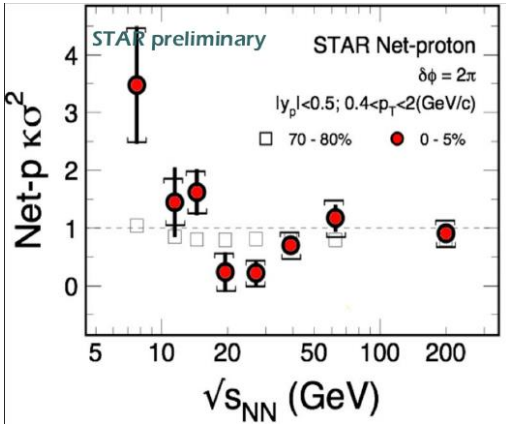
Software development and testing
- TPC calibration
- HFT vertex detector simulations
- Fast Parallel Event Reconstruction (KFparticle)

Prelude - Beam Energy Scan I

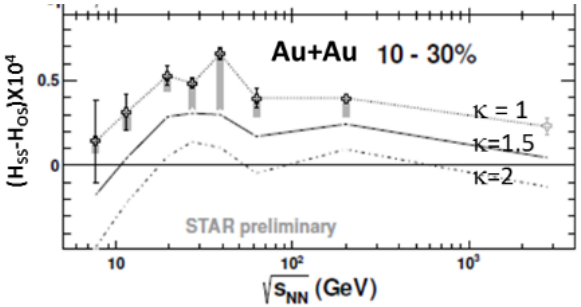




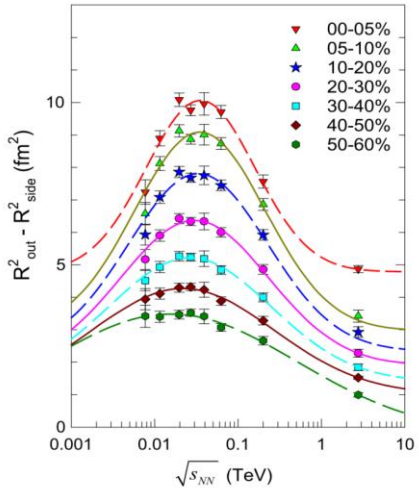
Critical point search



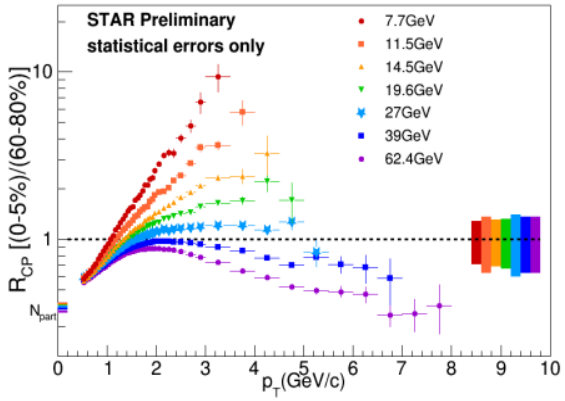
Chiral effects



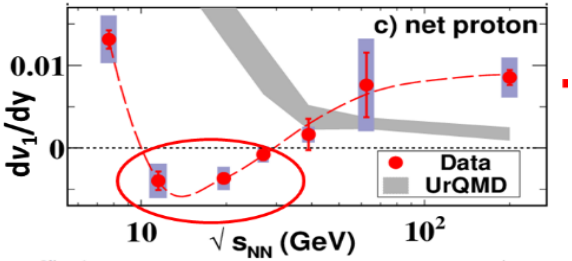
Emission duration



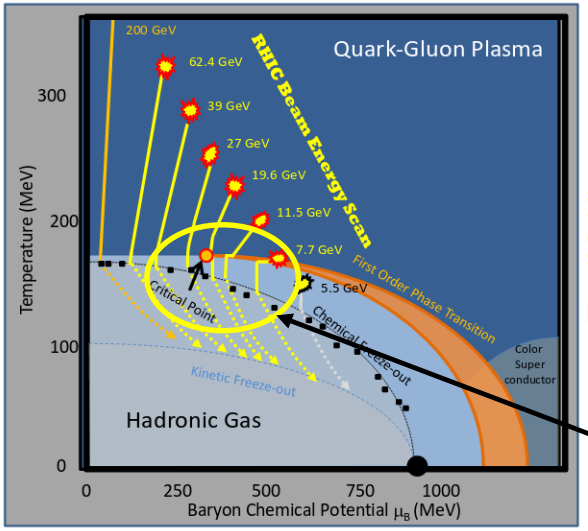
Onset of sQGP formation

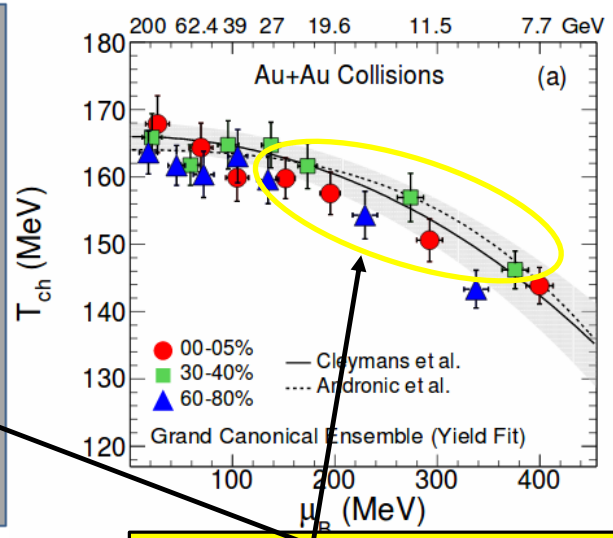


Softening of EOS



Prelude - Beam Energy Scan I





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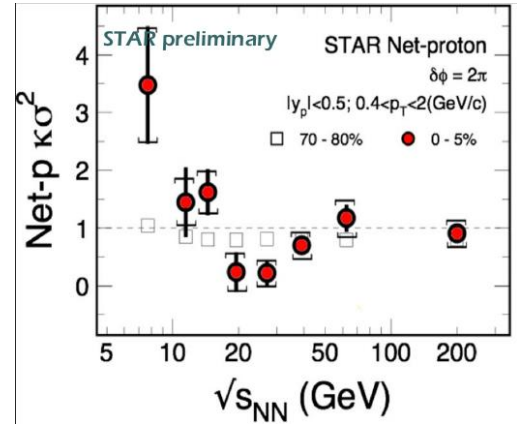
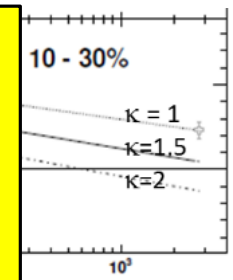
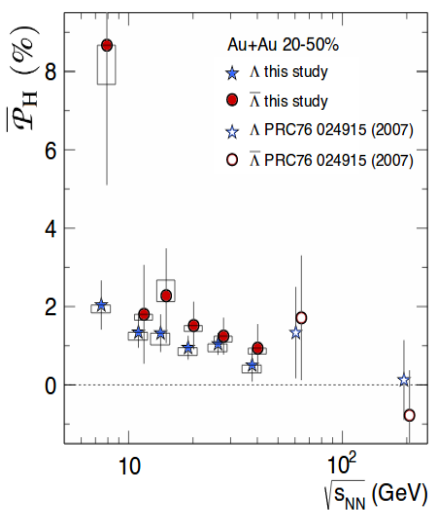


Chiral effects



- Critical point – landmark of QCD phase diagram.
- Non-monotonic behavior of multiple observables.
- Region of interest 5-30 GeV.

Global lambda polarization



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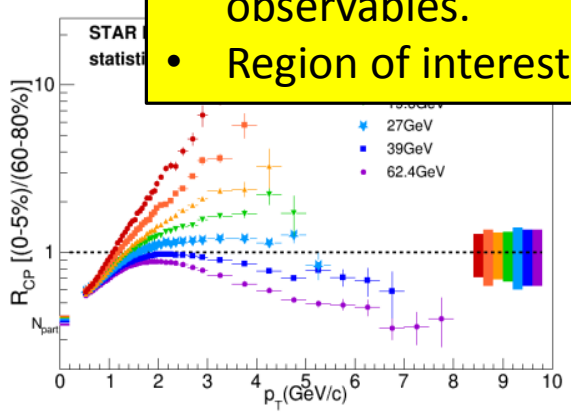
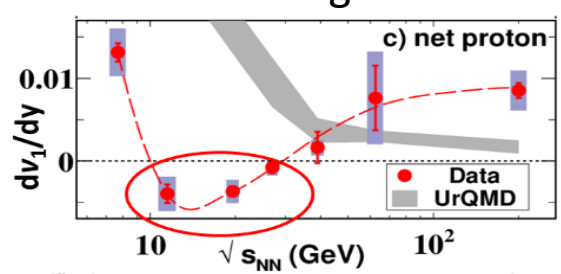


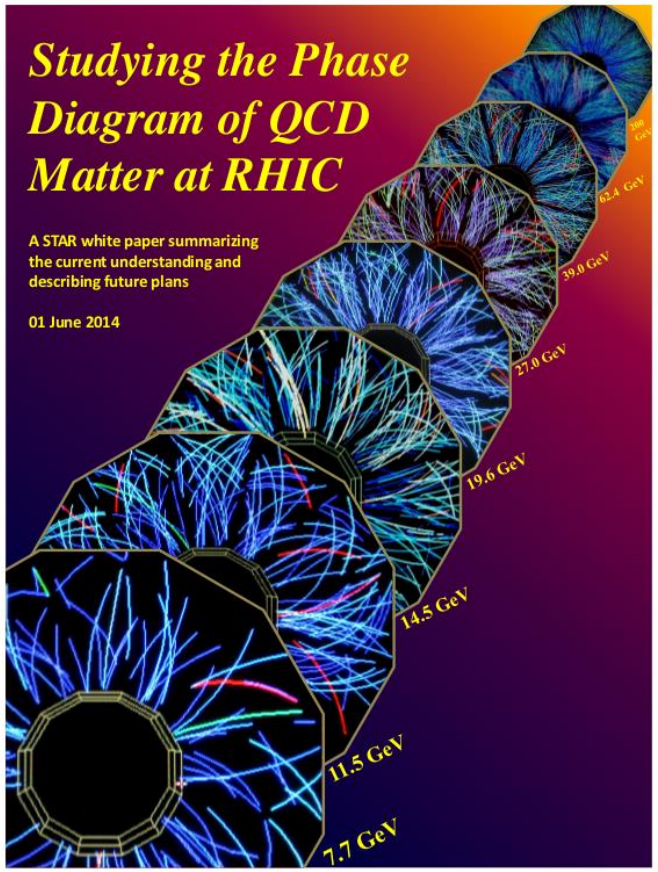
Softening of EOS



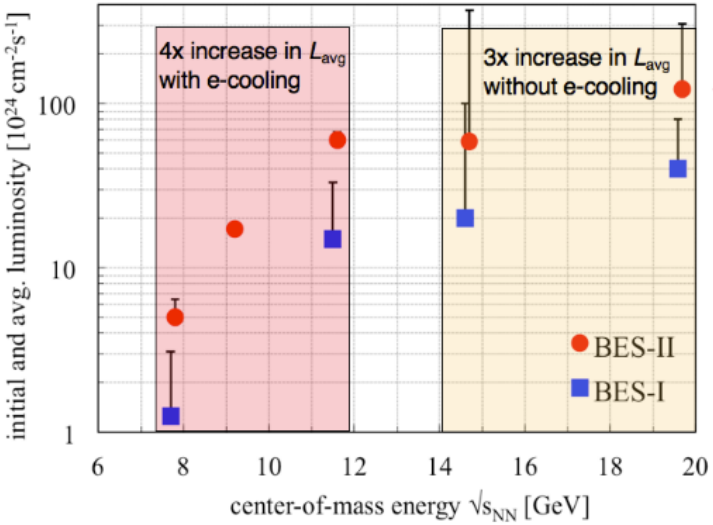
2019-20: RHIC Beam Energy scan II

Strong endorsement from NSAC long range plan:
"Trends and features in BES-I data provide compelling motivation for [...] experimental Measurements with higher statistical precision from BES-II."

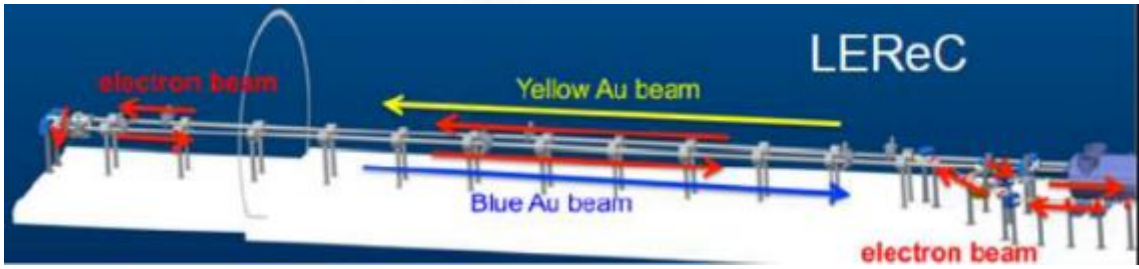
https://drupal.star.bnl.gov/STAR/system/files/BES_WPII_ver6.9_Cover.pdf



RHIC critical upgrade – e cooling
significant increase in luminosity at low energy

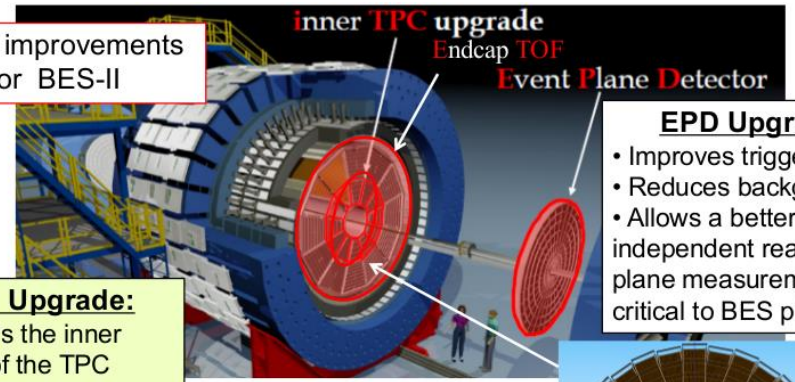


Electron cooling for the Beam Energy Scan II (BES-II) aims for a four-fold increase at the three lowest energies of the scan.
A three-fold increase at the two highest energies is possible without cooling, and has been demonstrated in 2016.



Upgrades for BES II + fixed target

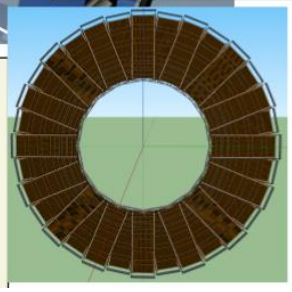
Major improvements for BES-II



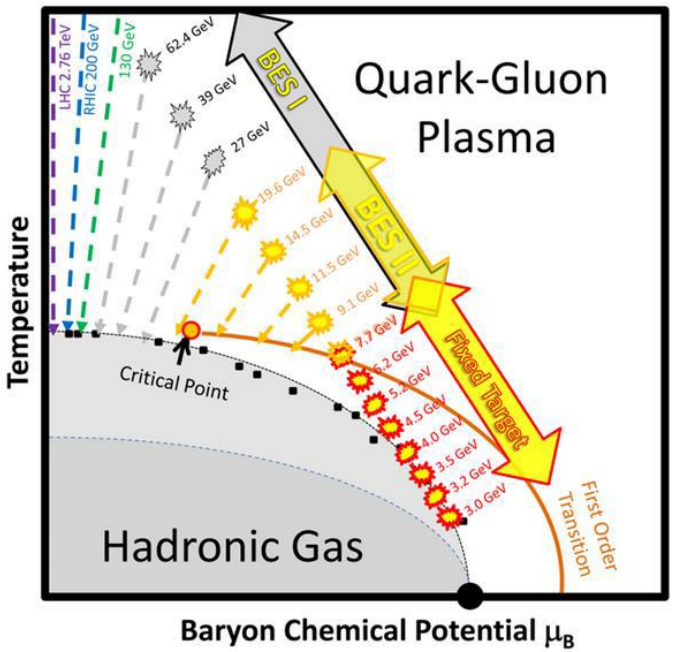
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



Upgrades for BES II + fixed target



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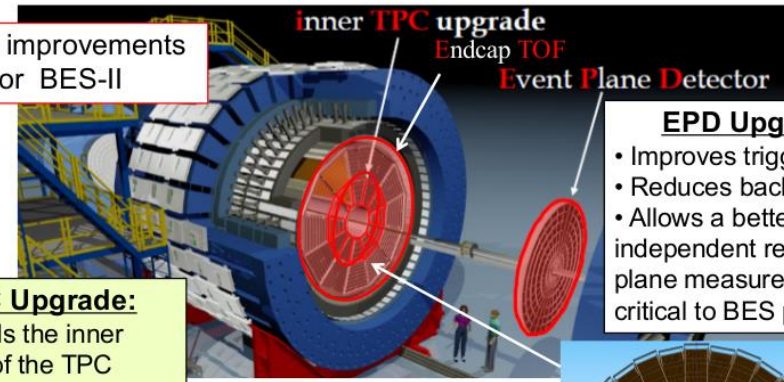

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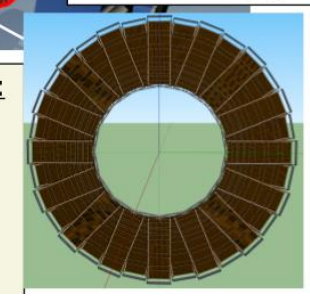
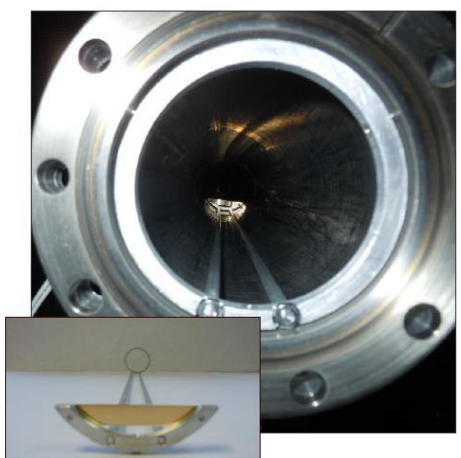
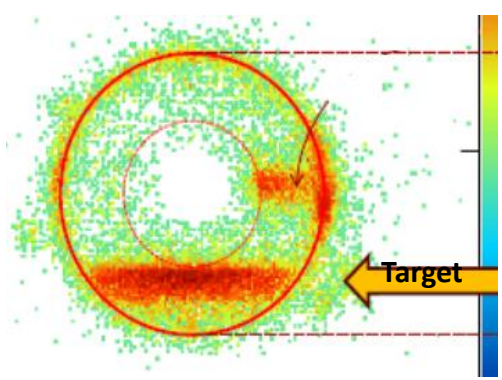
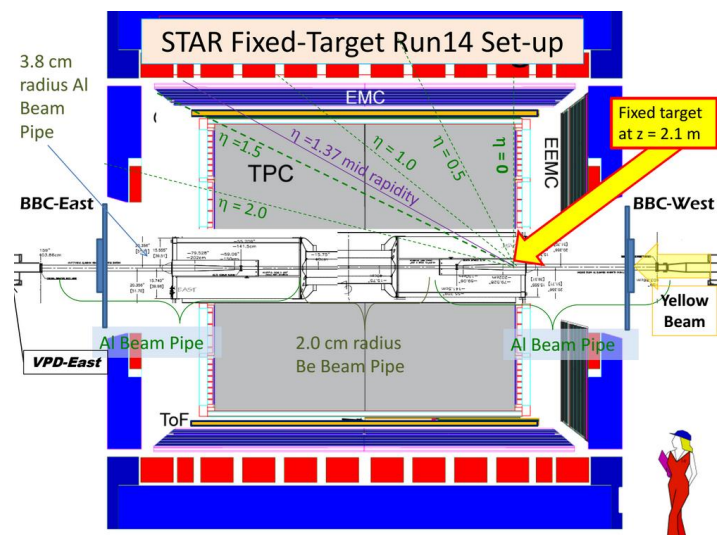
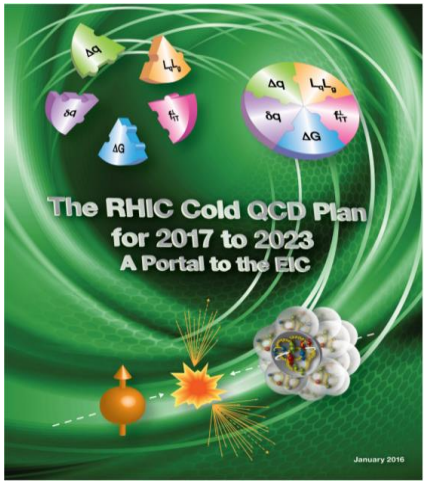






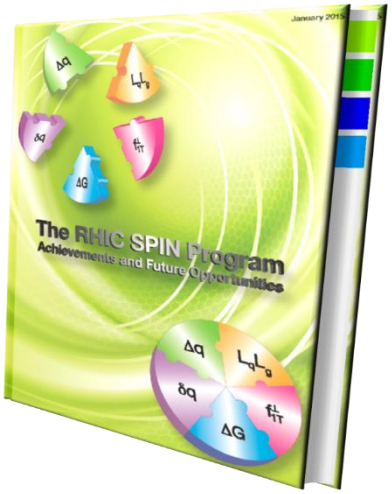


STAR at 2020+



arXiv: 1602.03922

SN0669



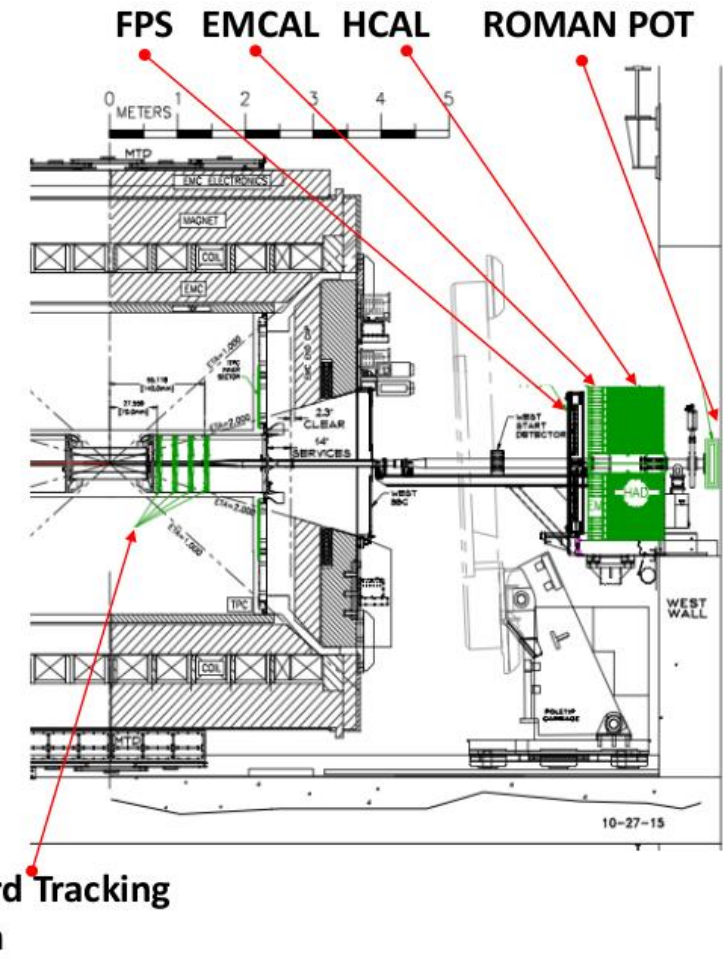
arXiv:1501.01220

Recent Endorsement from RHIC Physics Advisory Committee (PAC) :

" … importance of the proposed measurements for informing the future EIC program . In addition, the PAC was impressed by the added benefits to the heavy-ion program of the increased rapidity range provided by the proposed forward upgrades … remains so in our planning"

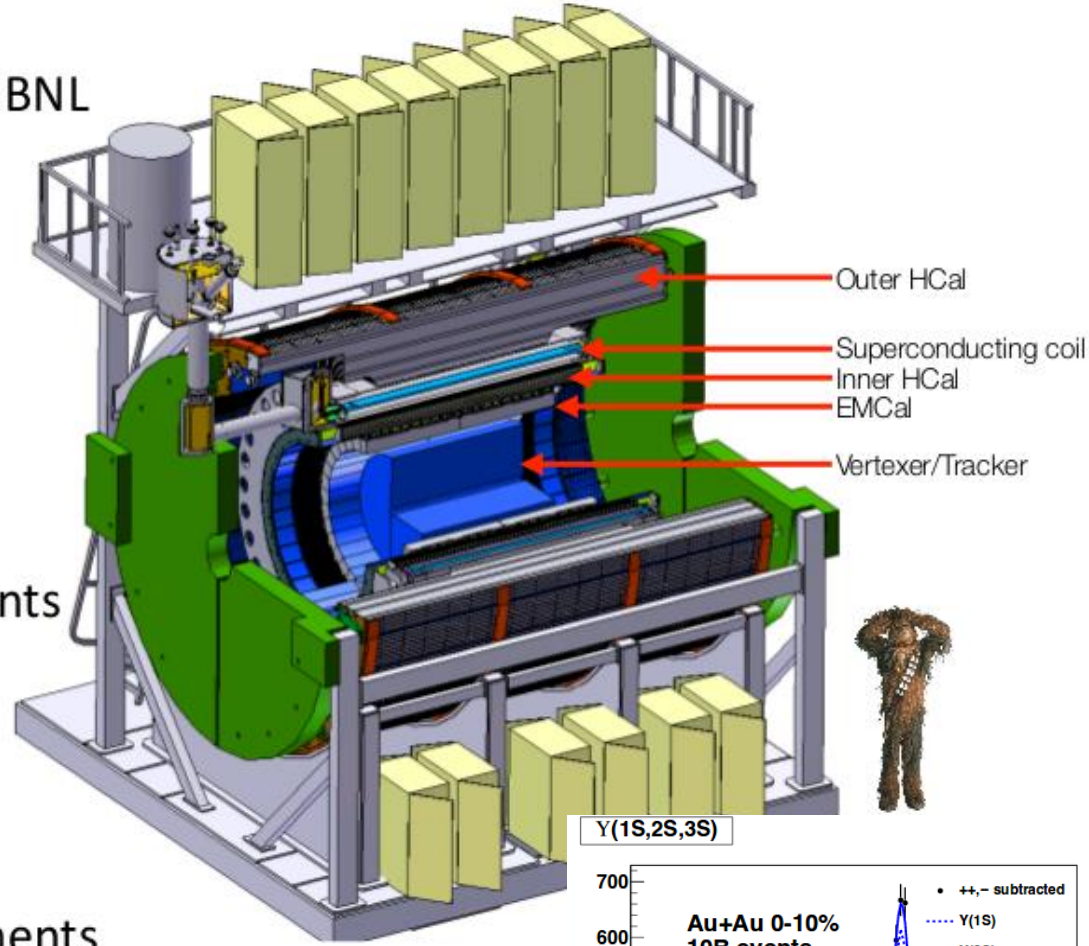
STAR upgrades for Cold matter effects

$\sqrt{s}$ (GeV)	Scientific Goals	Observable	Required Upgrade
$p^{\uparrow}p$ @ 200	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
$p^{\uparrow}Au$ @ 200	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
$p^{\uparrow}Al$ @ 200	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
$p^{\uparrow}p$ @ 510	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
$\vec{p}\vec{p}$@ 510	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal



2021+: sPHENIX

- BaBar magnet (1.5 T) already at BNL
- Hadron and EM calorimetry



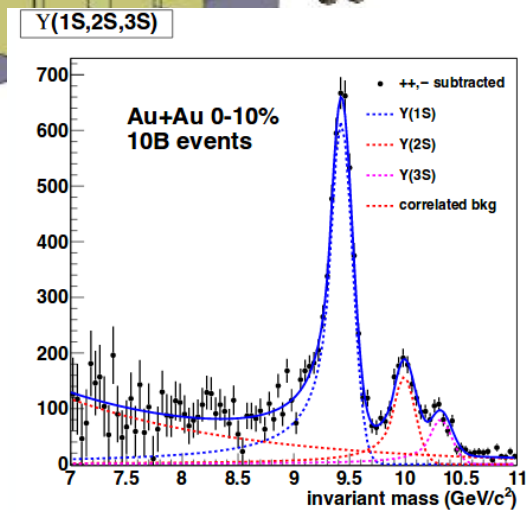
- Tracking:

Inner Tracker

1. Reuse PHENIX VTX Components
2. MAPS (ALICE ITS Upgrade)

Outer Tracker

1. New (PHENIX like) Si-components
2. Compact TPC w/GEM readout (ALICE Upgrade)



high rate, record 15kHz
large uniform acceptance for jets, photons and Upsilons

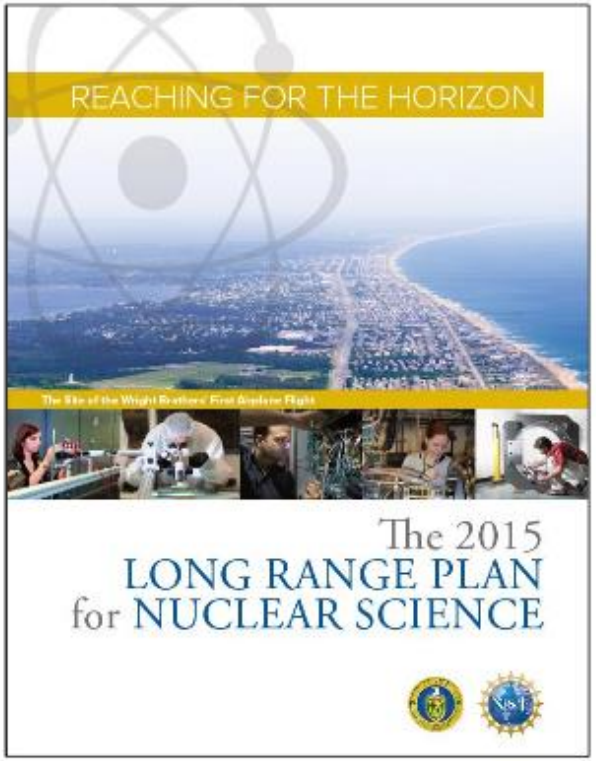
http://www.phenix.bnl.gov/phenix/WWW/publish/documents/sPHENIX_proposal_19112014.pdf

Long term plan: Electron-ion collider (EIC)

The 2015 Long Range Plan for Nuclear Science

Recommendations:

1. Capitalize on investments made to maintain U.S. leadership in nuclear science.
2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.
4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.



The FY 2018 Request supports progress in important aspects of the 2015 LRP Vision

T. Hallman, DOE

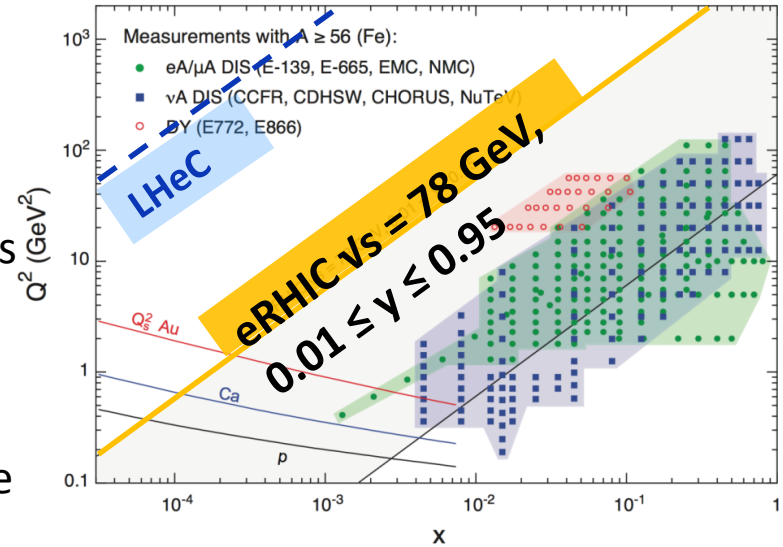
Long term plan: Electron-ion collider (EIC)

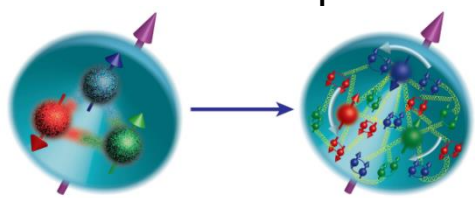
Key questions:

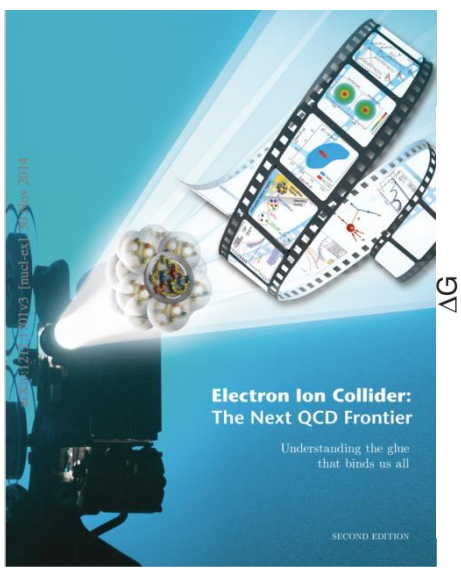
- distribution of quarks (q) and gluons (g) in space and momentum inside the nucleus
- onset of gluon saturation
- nuclear environment effects on q and g distributions and their interactions in nuclei

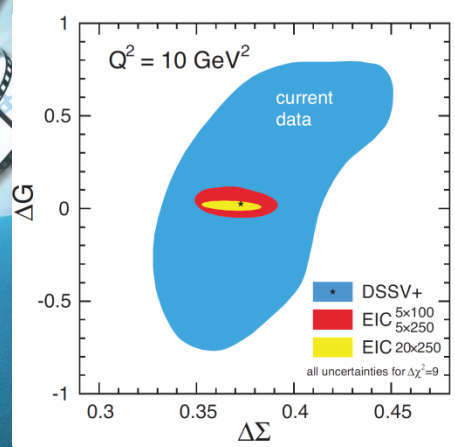
EIC precision machine

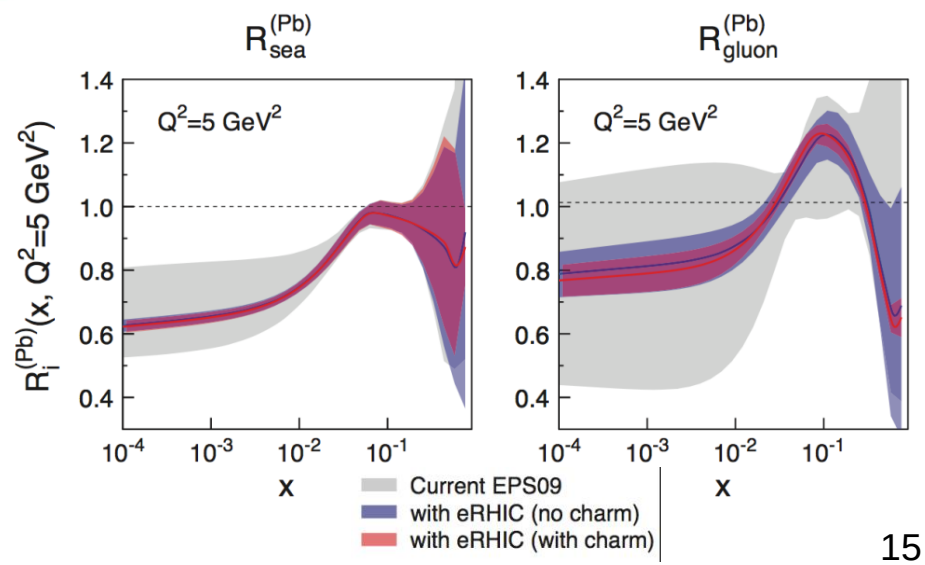
- facility at the technological forefront
- will cover kinematic domains never explored before





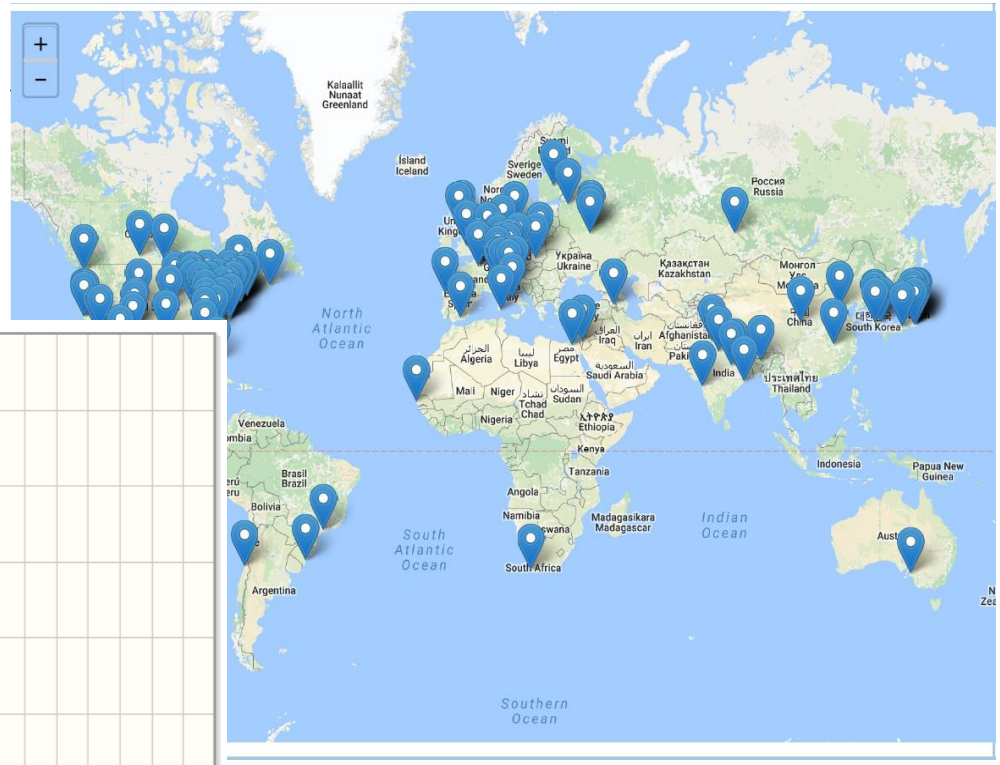


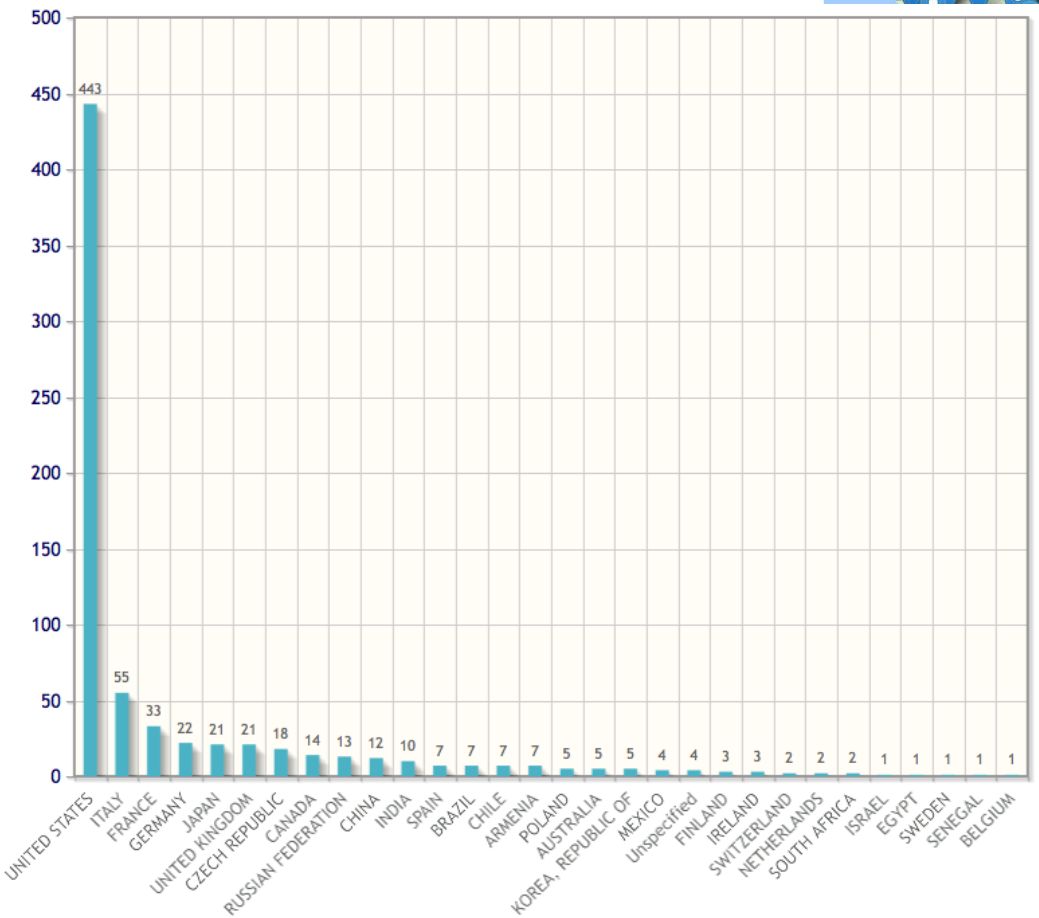




EIC Users Group

EIC is already now bringing together not only the scientific community within the U.S. but also worldwide …





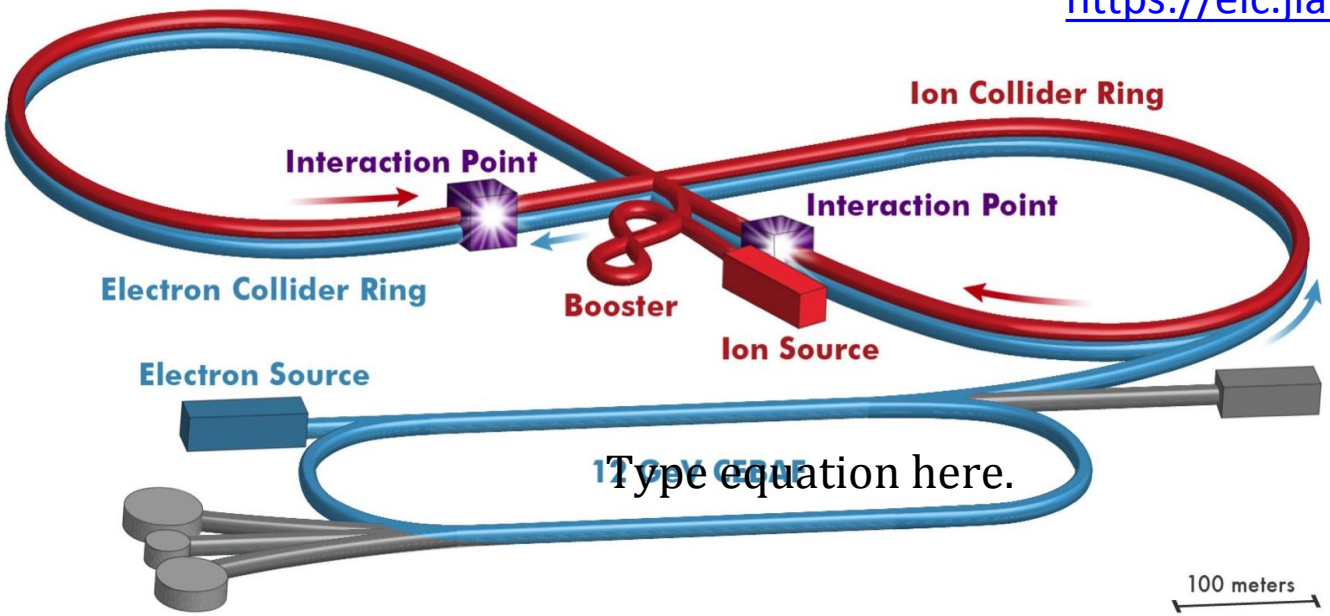
Currently (Dec. 12, 2017):
730 members
168 institutions
29 countries (**7** world regions)

Czech Republic: NPI, Czech Technical University, Charles University

http://www.eicug.org/web/

JLEIC Realization

https://eic.jlab.org/wiki



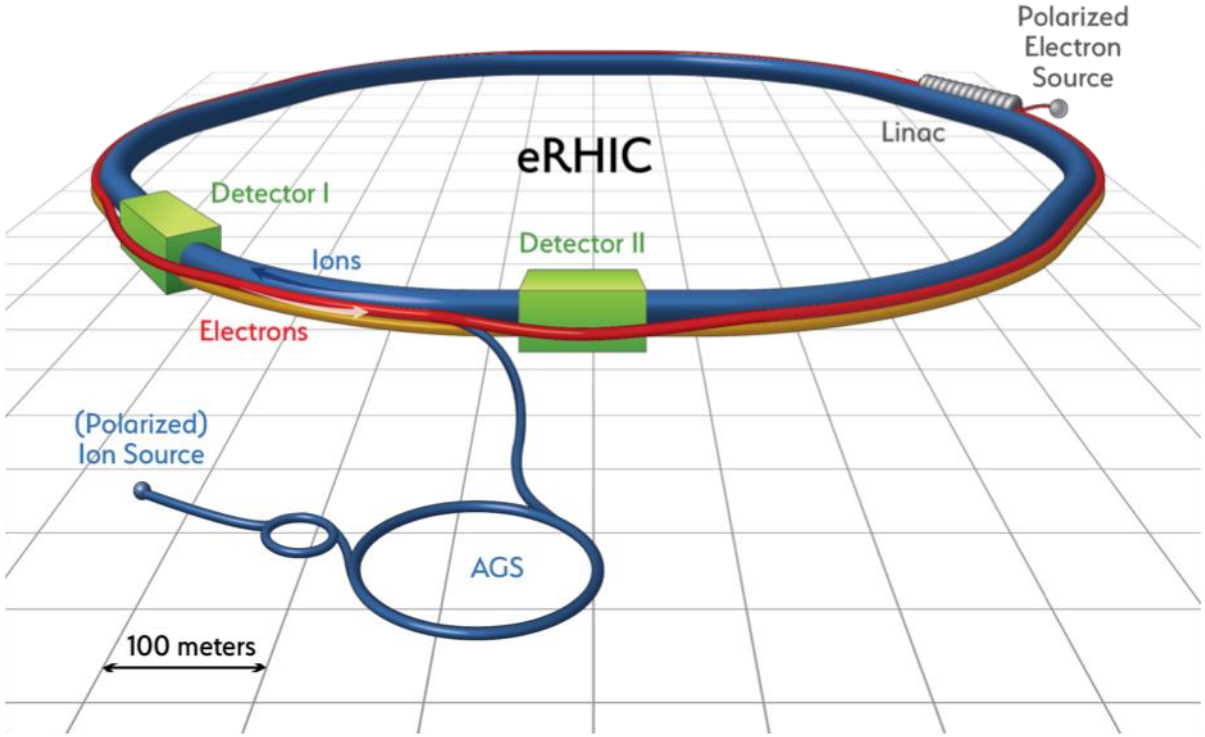
Type equation here.

- Use existing CEBAF for polarized electron injector
- Figure 8 Layout: Optimized for high ion beam polarization ➔ polarized deuterons
- Energy Range: √s : 20 to 65 - 140 GeV (magnet technology choice)
- Fully integrated detector/IR
- JLEIC achieves initial high luminosity, with technology choice determining initial and upgraded energy reach

from A. Desphande, NAS meeting, April 2017

eRHIC Realization

http://www.eicug.org/web/



- Use existing RHIC
  - Up to 275 GeV protons
  - Existing: tunnel, detector halls & hadron injector complex
- Add 18 GeV electron accelerator in the same tunnel
  - Use either high intensity Electron Storage Ring or Energy Recovery Linac
- Achieve high luminosity, high energy e-p/A collisions with full acceptance detector
- Luminosity and/or energy staging possible

from A. Desphande, NAS meeting, April 2017

Next Formal Step on the EIC Science Case is Continuing

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary
The National Academies of Sciences, Engineering, and Medicine ("National Academies") will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

"U.S.-Based Electron Ion Collider Science Assessment" is now getting underway. The Chair will be Gordon Baym. The rest of the committee, including a co-chair, will be appointed in the next couple of weeks. The first meeting is being planned for January, 2017

from T. Hallman (DOE), June 2017

NAS review of EIC Science Assessment

- NAS review charge and timeline (1)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

NAS review meetings I: February 1 - 2, 2017, Washington, DC
NAS review meetings II: April 19 - 20, 2017, Irvine, CA
NAS review meetings III: September 12 - 13, 2017, Woods Hole, MA

EICUG Input

- Questions 1: What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
  - An EIC facility will allow profound new insight into the dynamics and structure of matter emerging through fundamental interactions among quarks and gluons
  - An EIC facility is the required facility with versatile operation in terms of energy, polarization and luminosity to image quarks and gluons and explore strong color fields among quarks and gluons

http://www.eicug.org/web/sites/default/files/Charge_1_041917.pptx

EICUG response

More questions in backup

Take home message

STAR: Beam Energy Scan II program 2019-2020

STAR/sPHENIX: 2021-2023 running

Electron-Ion Collider:

- preparations ongoing
- EIC Users Group 700 scientists
- NAS review till mid 2018
- Expected construction in 2023-2026

EICUG Input

- Question 2: What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider? What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
  - Large center-of-mass energy range: Access to wide kinematic range overlapping various other experimental programs
  - Polarized electron and hadron beams: Spin structure and 3D imaging
  - Nuclear beams: Access high gluon density region
  - High luminosity: Access to rare probes / Detailed studies of 3D imaging

http://www.eicug.org/web/sites/default/files/Charge_2_061417.pptx ← EICUG response

EICUG Input

- Question 3: What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
  - Developing and building the accelerator infrastructure will contribute to leadership in accelerator technology.
  - Constructing the detectors to realize the EIC science will contribute to leadership in detector technology.
  - Developing the scope of the science program will contribute to leadership in QCD theory.
  - Bringing the expertise of an international users' group to the US will contribute to leadership and visibility as a hub of the nuclear physics community.
  - Delivering on the science program of an EIC will lead to landmark discoveries in nuclear physics.

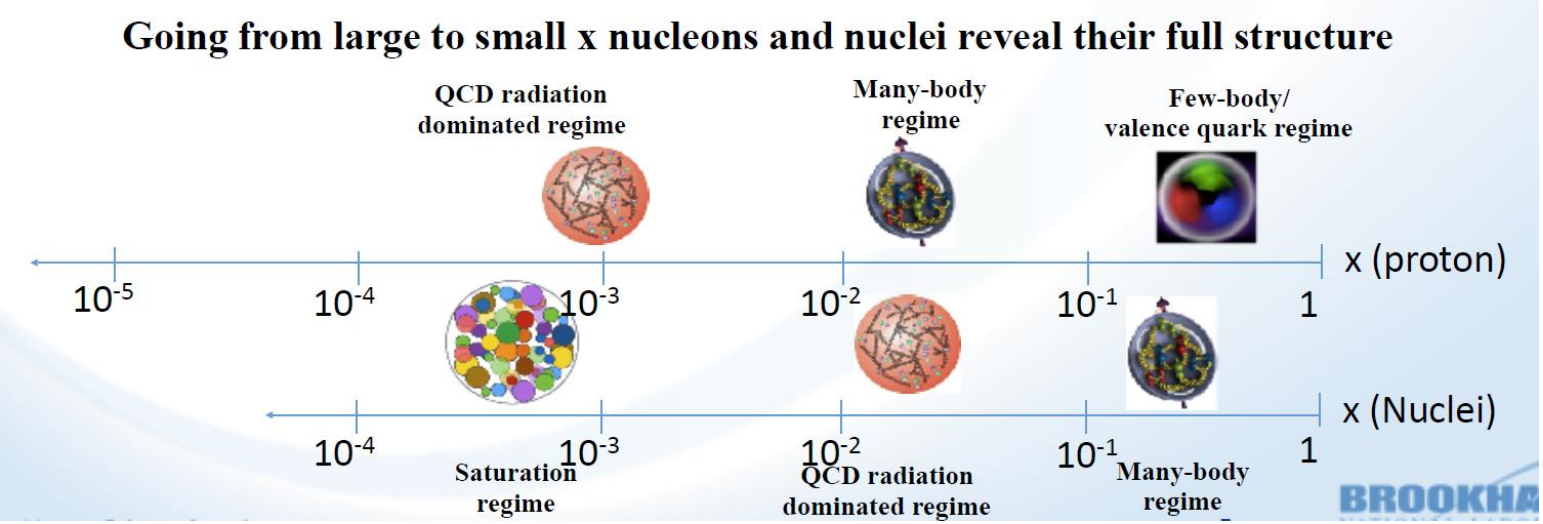
http://www.eicug.org/web/sites/default/files/Charge_3_061517.pptx ← EICUG response

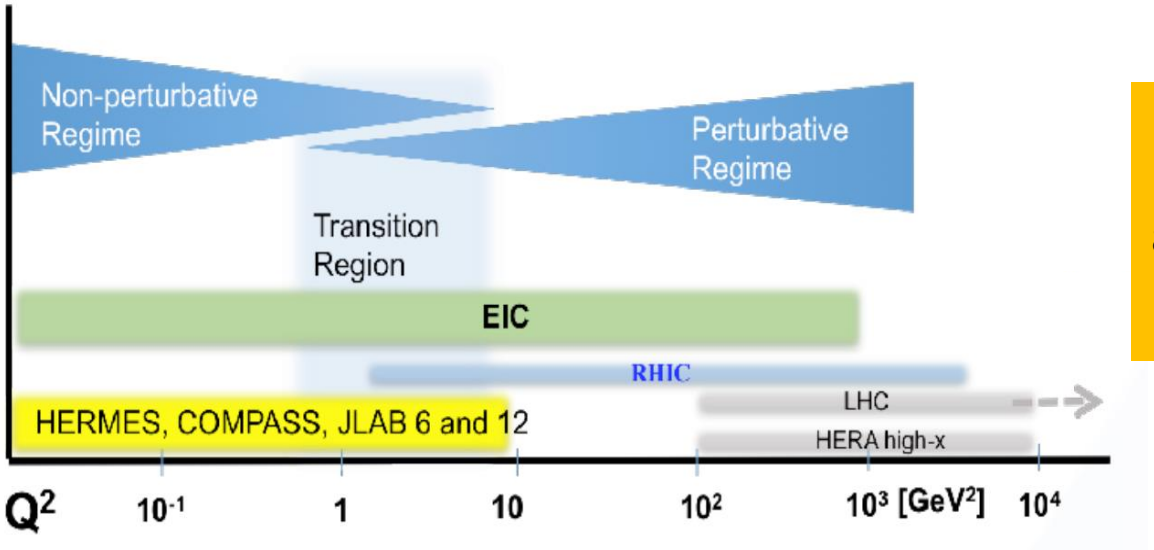
EICUG Input

- Question 4: What are the benefits to other fields of science and to society of establishing such a facility in the United States?
  - Education and Training: Individuals going to other sectors benefitting society / Relevance for Medical Science / Ambassadorship of Nuclear Scientists
  - Technology - Accelerator, detector, data science and data management: Benefits to society outside of academic research and other fields of academic research
  - Science: Scientific advances driven by the EIC will benefit other fields in science
  - Economic impact: Increase in overall economic output based on economic studies at BNL and JLab

http://www.eicug.org/web/sites/default/files/Charge_4_061417.pptx ← EICUG response

Importance of large x-Q^2 coverage





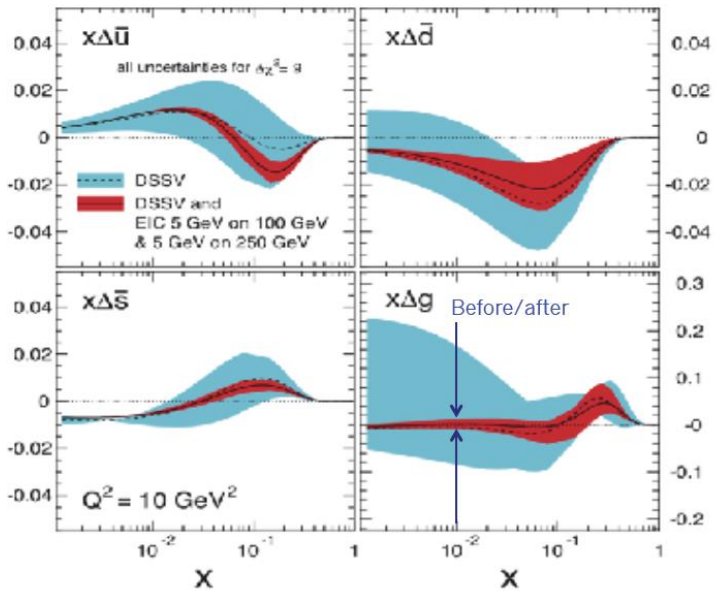
EIC coverage:
non-perturbative, transition and perturbative regimes

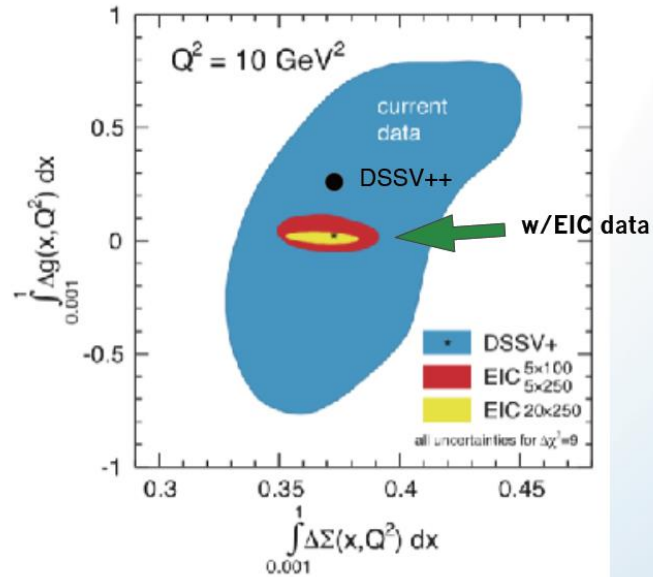
Q^2 up to ≈1000 GeV^2 (0.01 fm)

Solving the spin puzzle

The EIC – the decisive measurement (in the 1st year of running**):**

(Utilizing the wide Q^2, x range accessible at the EIC)



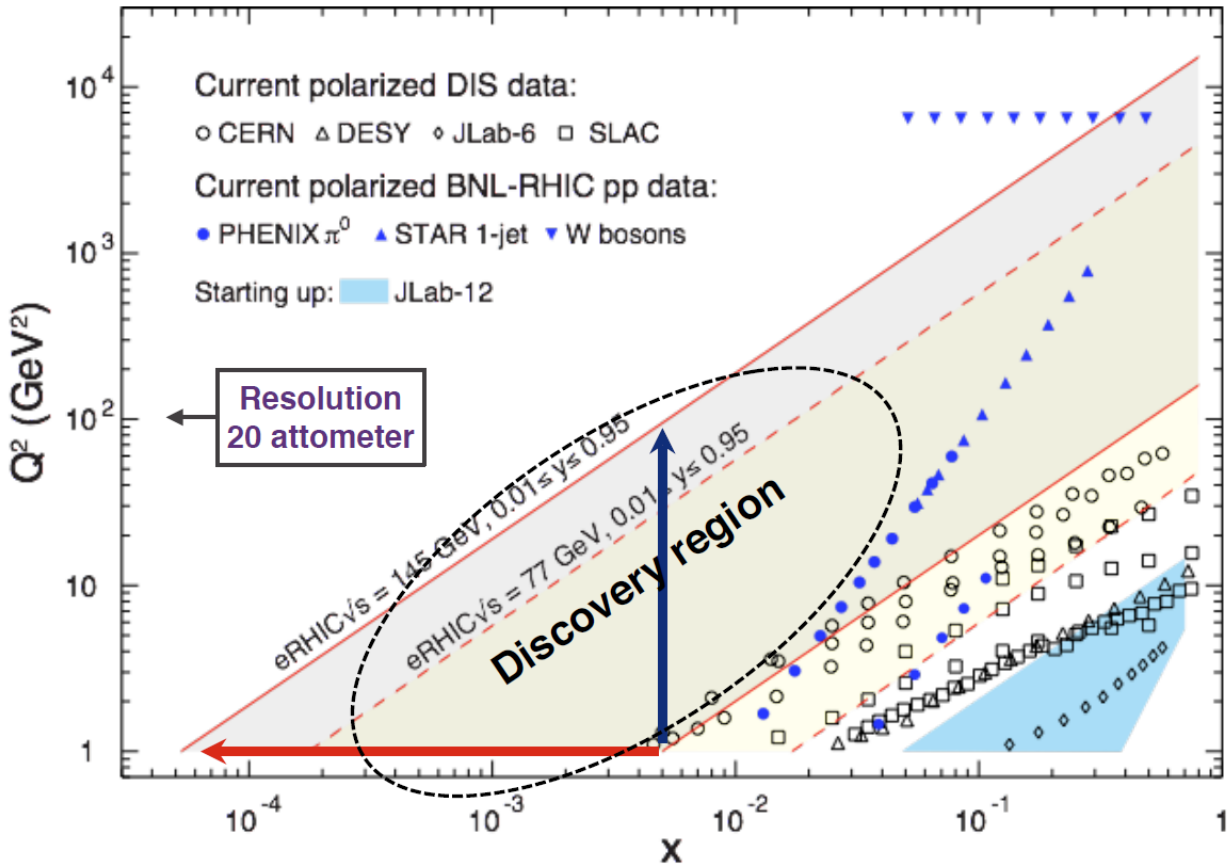


No other machine in the world can perform this measurement!

Solution to the proton spin puzzle:

- ***Precision measurement of ΔG – extends to smaller x regime***
- ***Orbital angular momentum – motion transverse to proton's momentum***

Requirements: √s and Polarization



polarized
ep*, μ*p*, *pp

$$Q^2 \approx s \cdot x \cdot y$$

- ✳ Need to reach low-x where gluons dominate (ΔG, ΔΣ range!)
- ✳ Flexible energies (see also structure functions later)
- ✳ Need sufficient lever arm in Q^2 at **fixed** x (evolution along Q^2 or x)
- ✳ Electrons and protons/light nuclei (p, ^{3}He, d) highly polarized (70%)