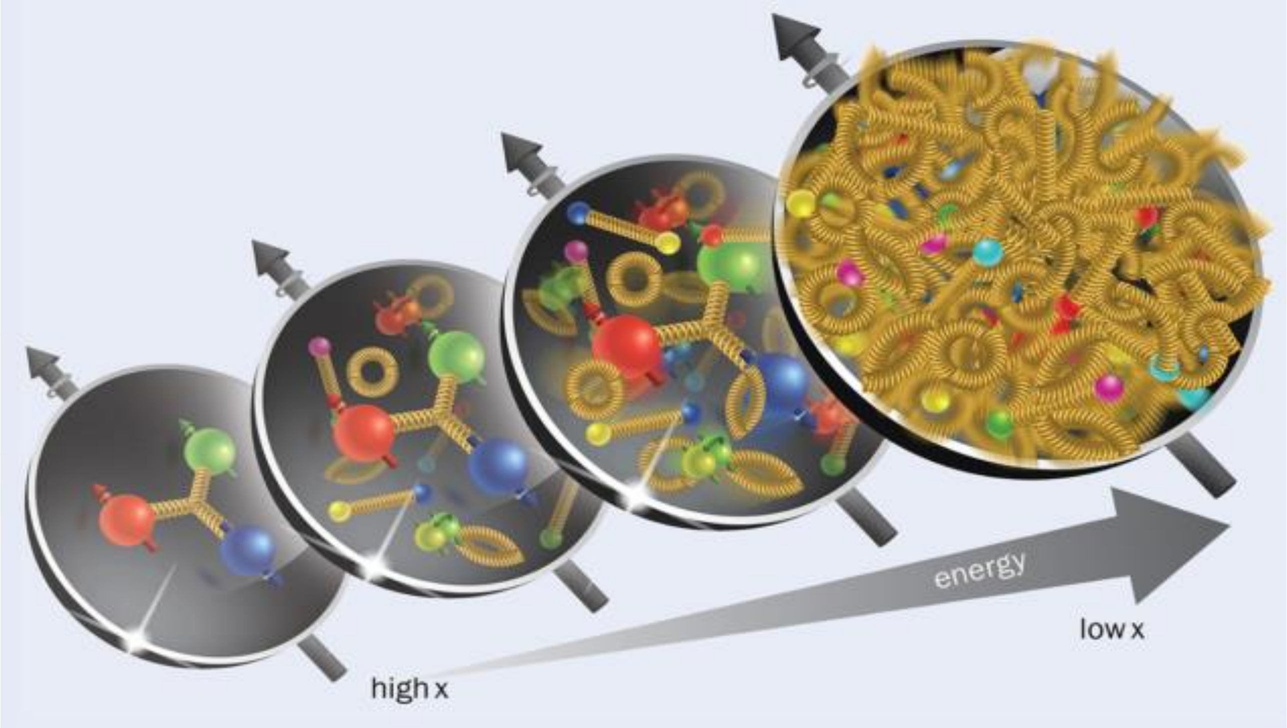
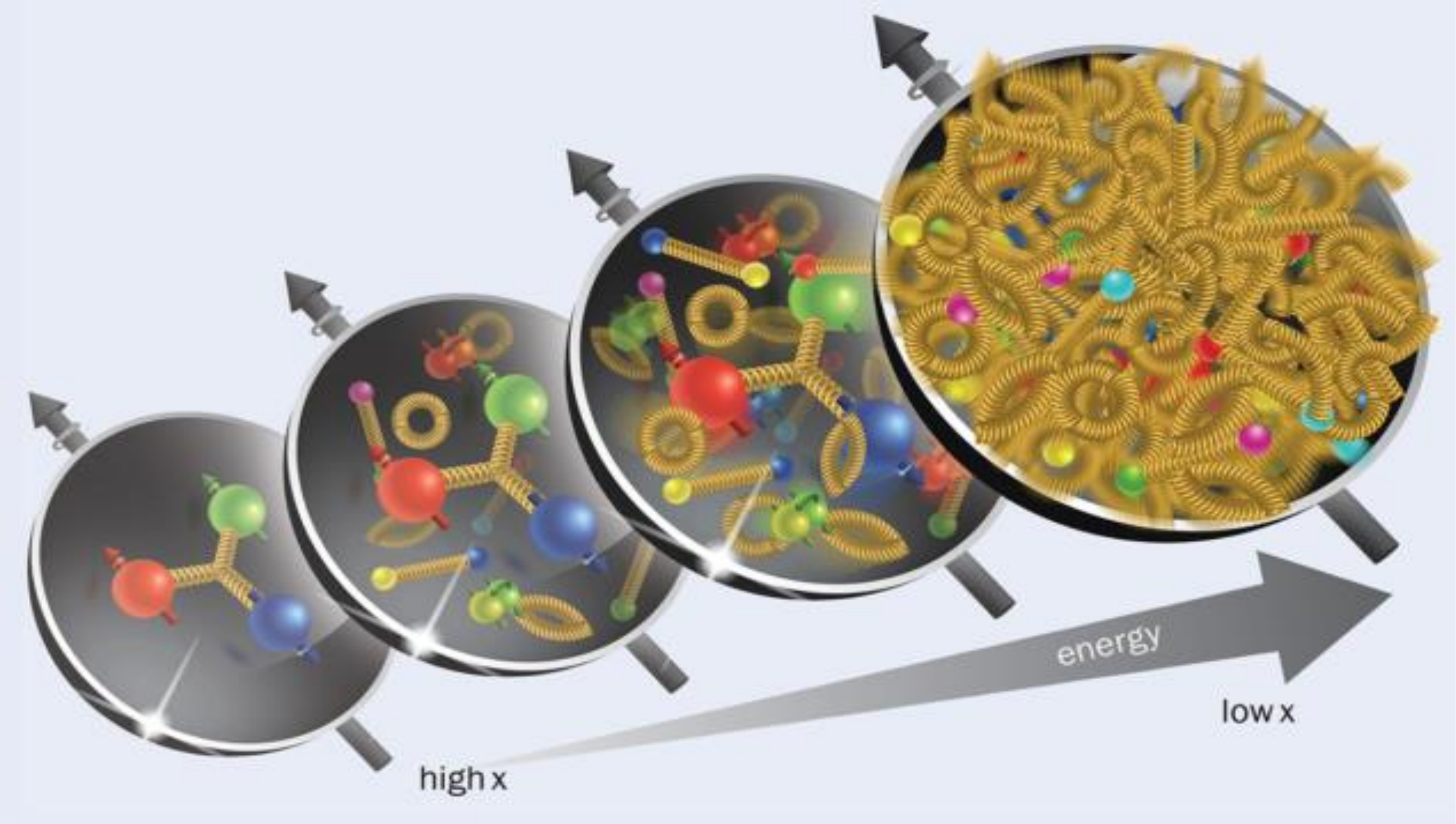
Anticipated First Results from the Electron Ion Collider



Rosi Reed
Lehigh University

Setting the Stage

- Discovery of the proton in 1917 with Rutherford Scattering
  - Neutrons as well!
- At high x, the proton seems simple
- Deep Inelastic Scattering (DIS) measurements found otherwise

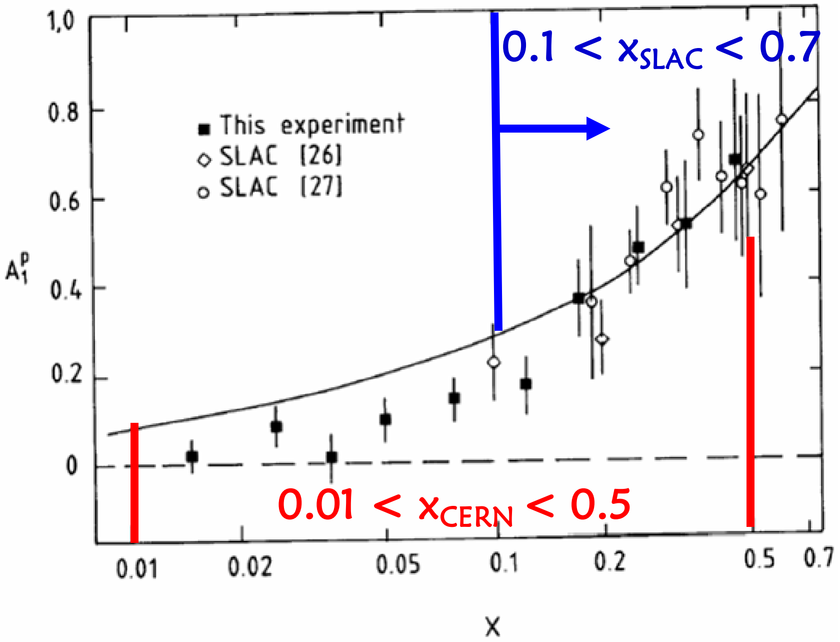


Proton Spin Crisis

- RHIC is the only polarized hadron collider in the world
  - Allows investigation of the proton spin structure! Needed to resolve proton spin crisis

SLAC: $0.10 < x < 0.7$

CERN: $0.01 < x < 0.5$



EMC (CERN), Phys.Lett.B206:364 (1988)
2760 citations!

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$

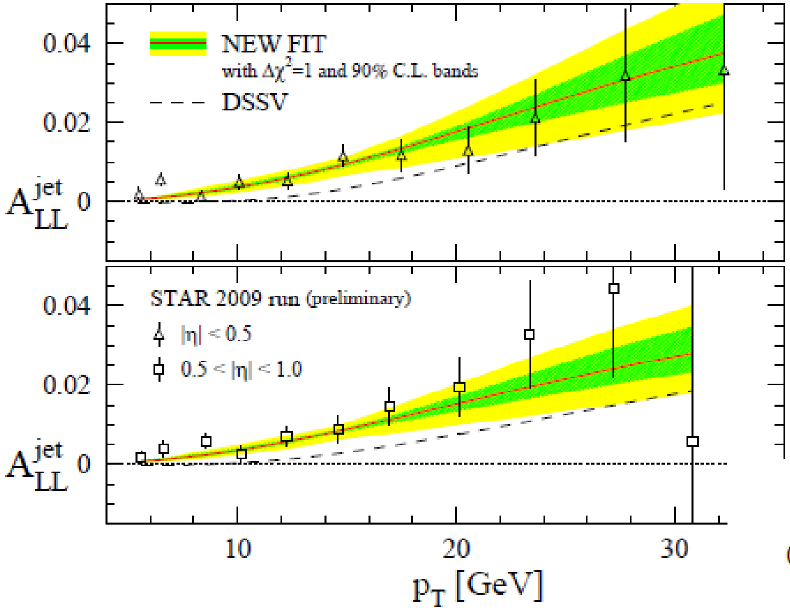
Hence $(14 \pm 9 \pm 21)$% of the proton spin is carried by the spin of the quarks. The remaining spin must be carried by gluons or orbital angular momentum

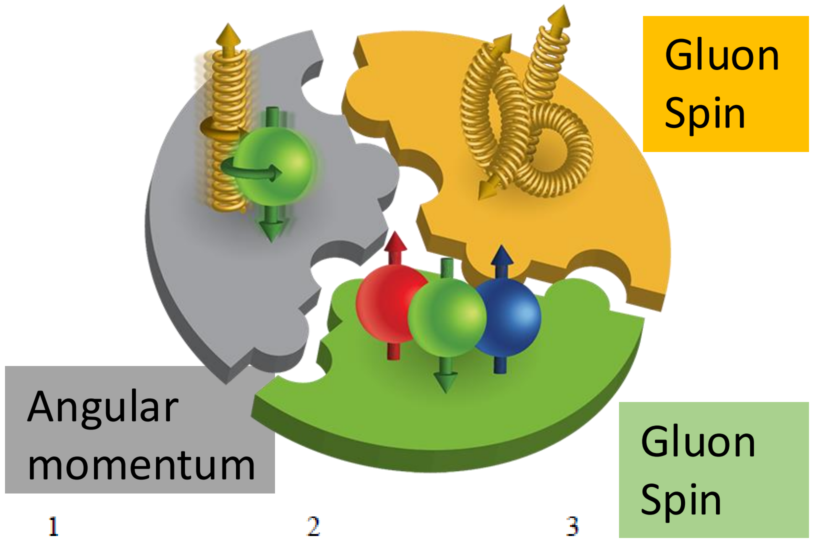
$\Delta\Sigma_{SLAC} \sim 0.6$ Quark-Parton Model expectation!

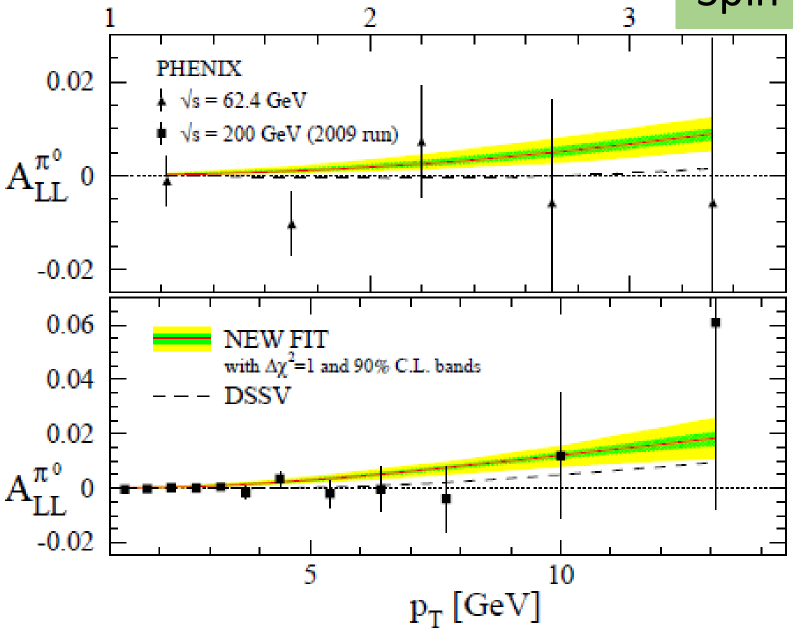
E130, Phys.Rev.Lett.51:1135 (1983)
653 citations

First evidence for nonzero gluon polarization in proton

- Suite of RHIC measurements sensitive to gluon spin, using different final-state observables
  - Neutral pions – **PHENIX**, PRD90, 012007
  - Jets – **STAR**, PRD86, 032006; PRL 115, 092002



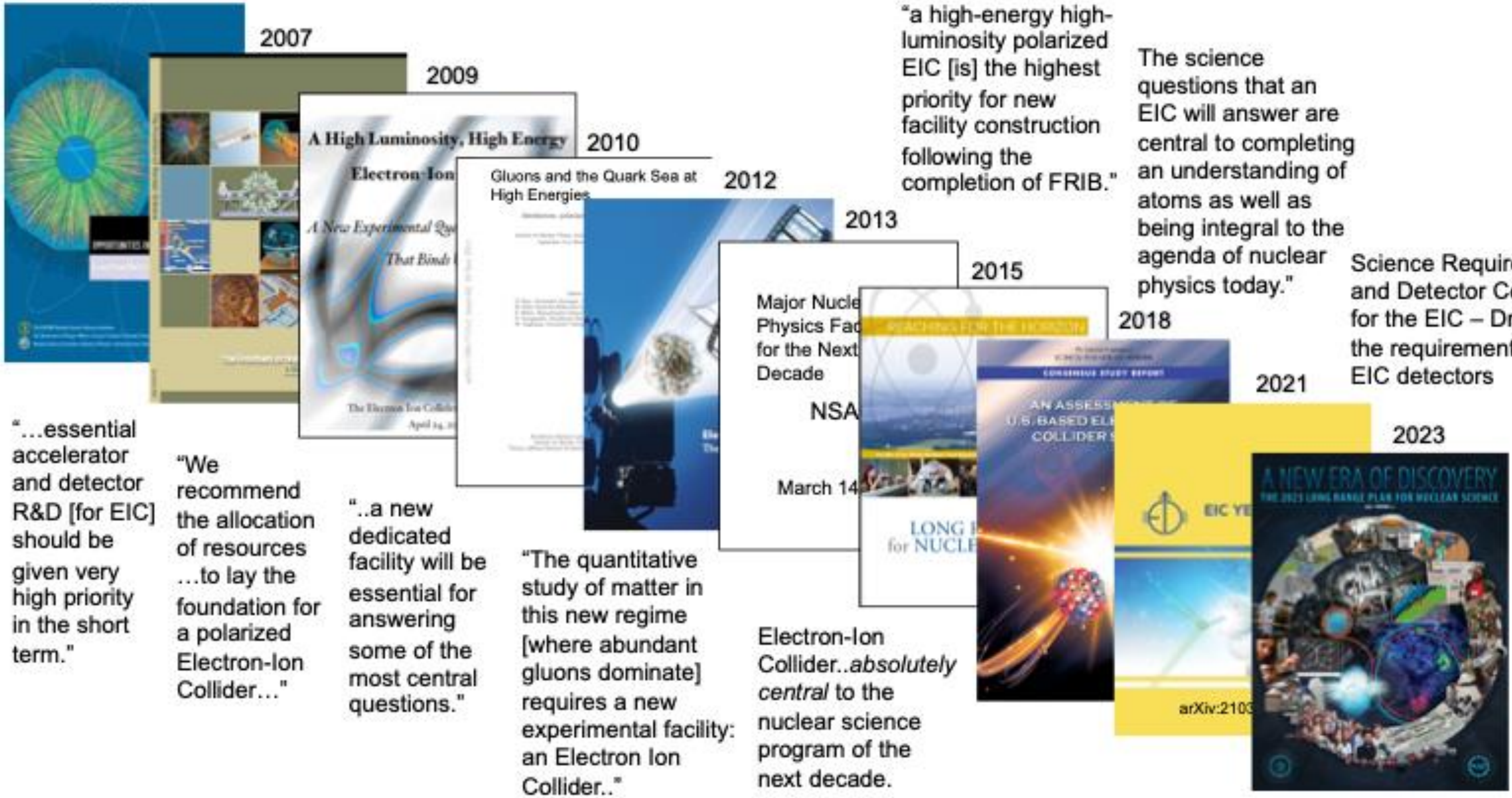




Further understanding required additional statistics and improved detectors!

Clear that the EIC is needed for full understanding

EIC Scientific Foundation



2002: "…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007: "We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009: "..a new dedicated facility will be essential for answering some of the most central questions."

2010: "The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

2013: Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

2015: "a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2018: 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."

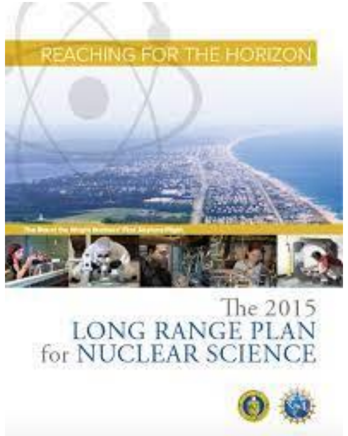
2021: Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

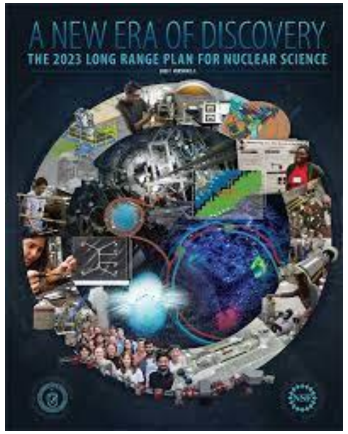
2023: We recommend the expeditious completion of the EIC as the highest priority for facility construction.

E. Aschenauer

Long Range Plan for Nuclear Physics

- LRP 2015
  - … Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a **powerful new electron ion collider (EIC)…**
  - We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction …
- LRP 2023
  - We recommend the **expeditious completion of the EIC** as the highest priority for facility construction.





EIC NAS Science Pillars

What are the different contributions from the quarks, gluons and orbital angular momentum to nucleon spin?

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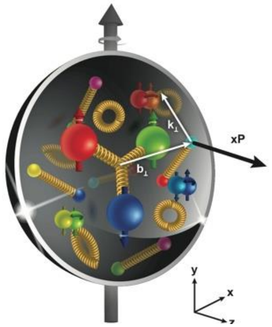
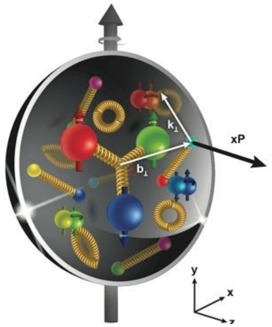


How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

EIC NAS Science Pillars



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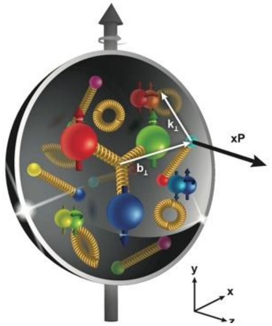

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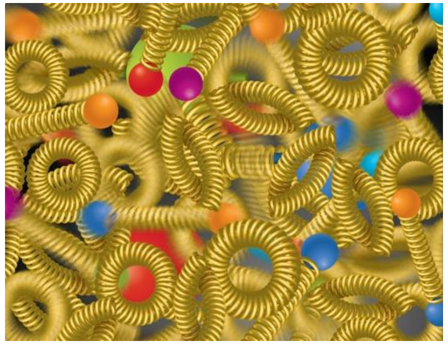
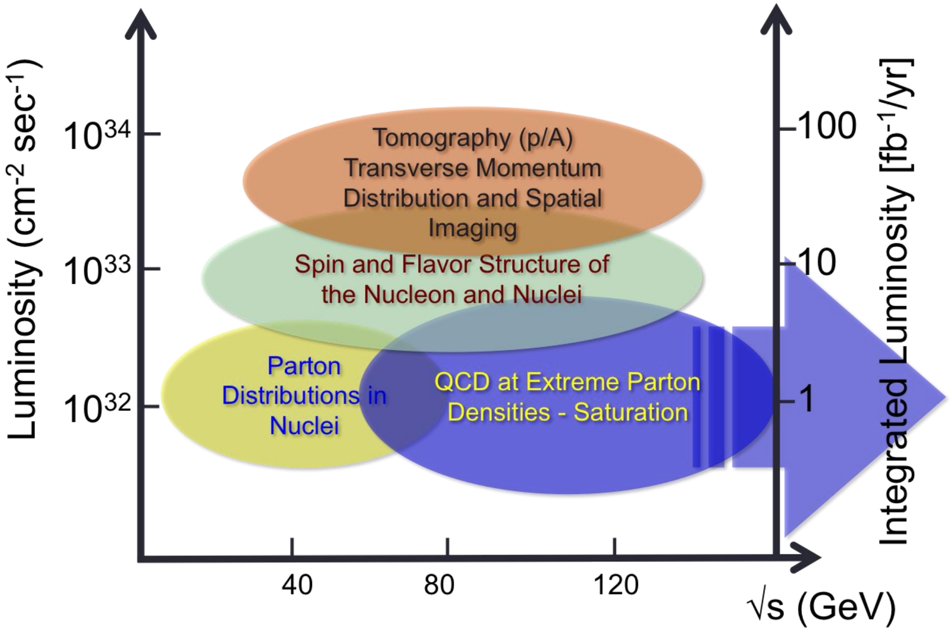
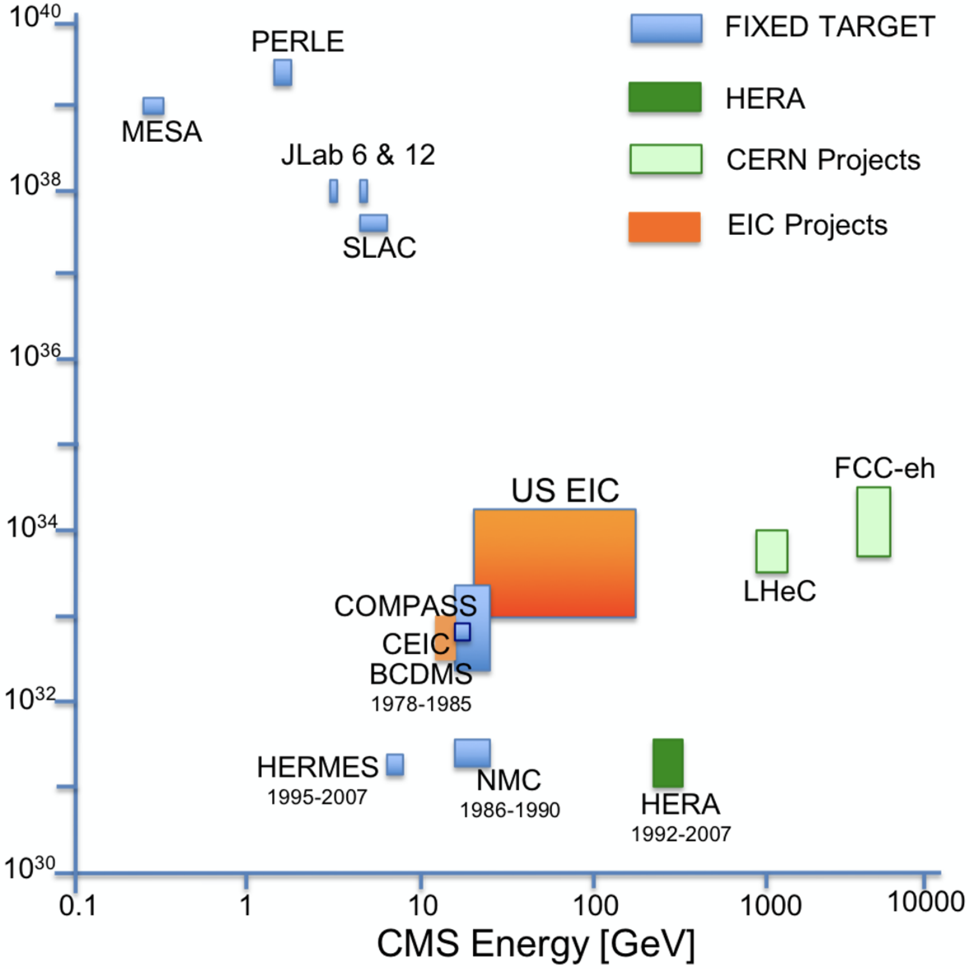


What happens to the gluon density in nuclei? Does it saturate at high energy?

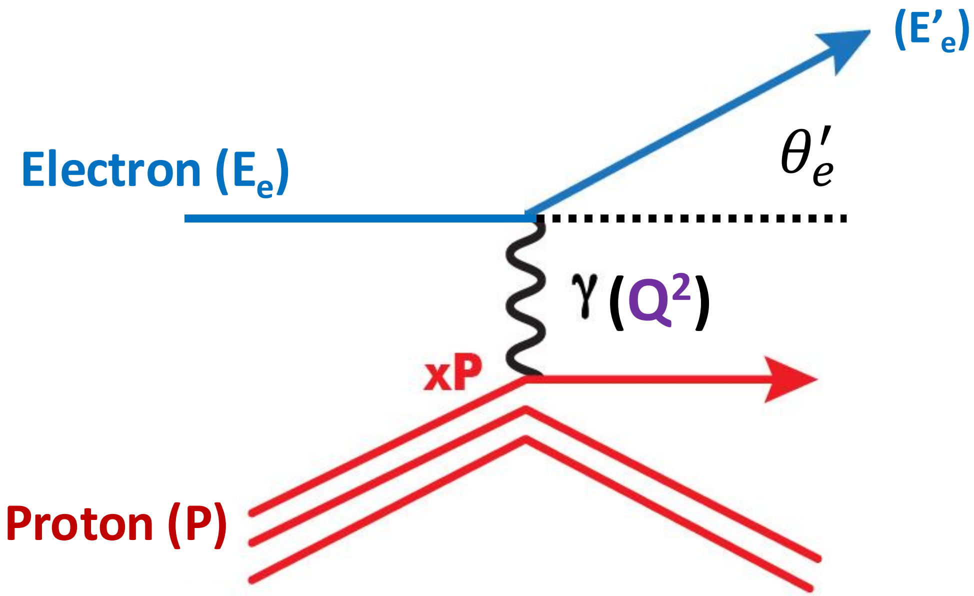
Electron Ion Collider (EIC) Requirements





- Center of mass energy: 20 – 140 GeV
  - Electrons: 5 – 18 GeV
  - Protons: 41 GeV, 100 - 275 GeV
  - Luminosity: 10^{33} - 10^{34} /cm^2/sec
- Polarization: <70% (both electron and light ion)
- Ion Species: proton - Uranium

Deep Inelastic Scattering (DIS)

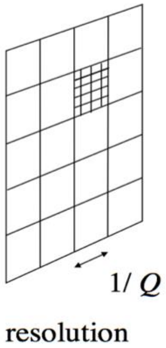


$$Q^2 = 2E_e E_e'(1 - \cos\theta_e')$$

$$x = \frac{Q^2}{2pq}$$

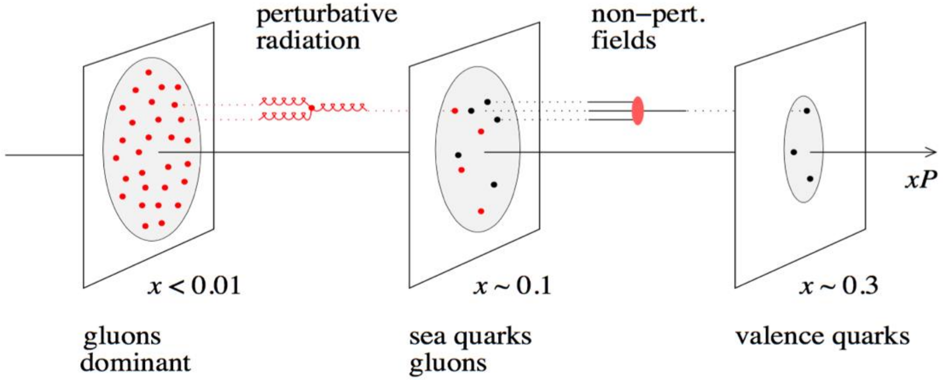
Measure of momentum fraction of struck parton

Changing Q^2 changes the resolution scale

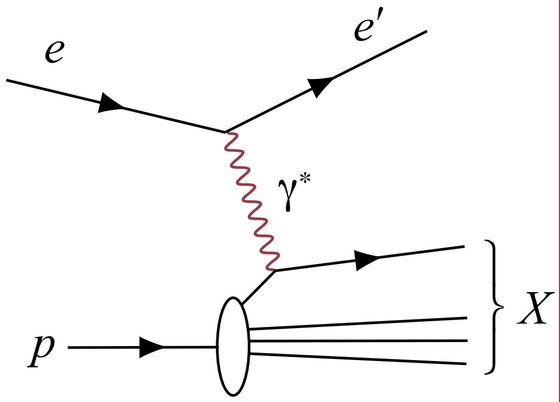


$Q^2 = 400\ \mathrm{GeV}^2$
$\Rightarrow 1/Q = 0.01$ fm

Changing x projects out different configurations where different dynamics dominate

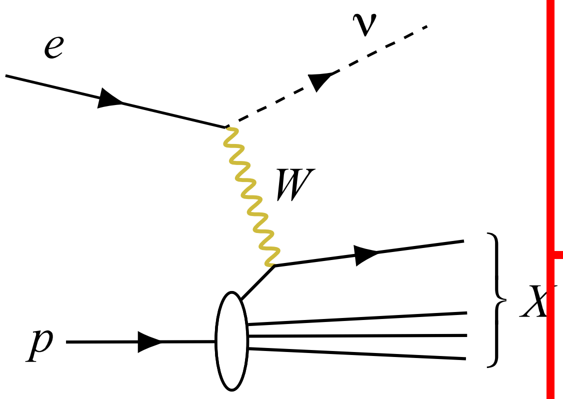


Deep Inelastic Scattering (DIS) Different Processes



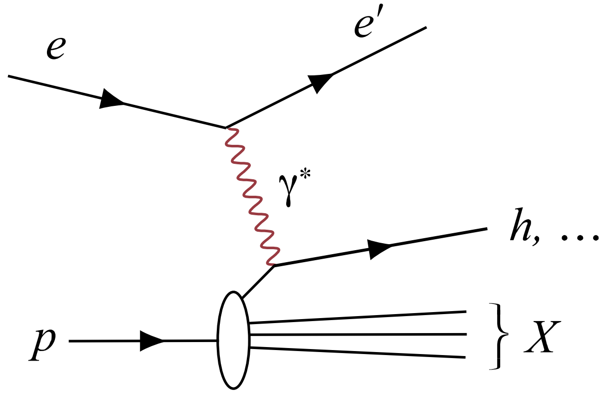
$$e + p/\mathrm{A} \longrightarrow e' + \mathrm{X}$$

Neutral-current Inclusive DIS



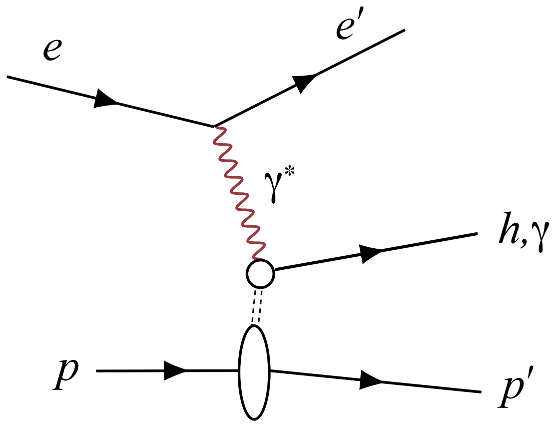
$$e + p/\mathrm{A} \longrightarrow \nu + \mathrm{X}$$

Charged-current Inclusive DIS



$$e + p/\mathrm{A} \longrightarrow e' + h^{\pm,0} + \mathrm{X}$$

Semi-inclusive DIS



$$e + p/\mathrm{A} \longrightarrow e' + p'/A' + \gamma/h^{\pm,0}/VM$$

Exclusive DIS

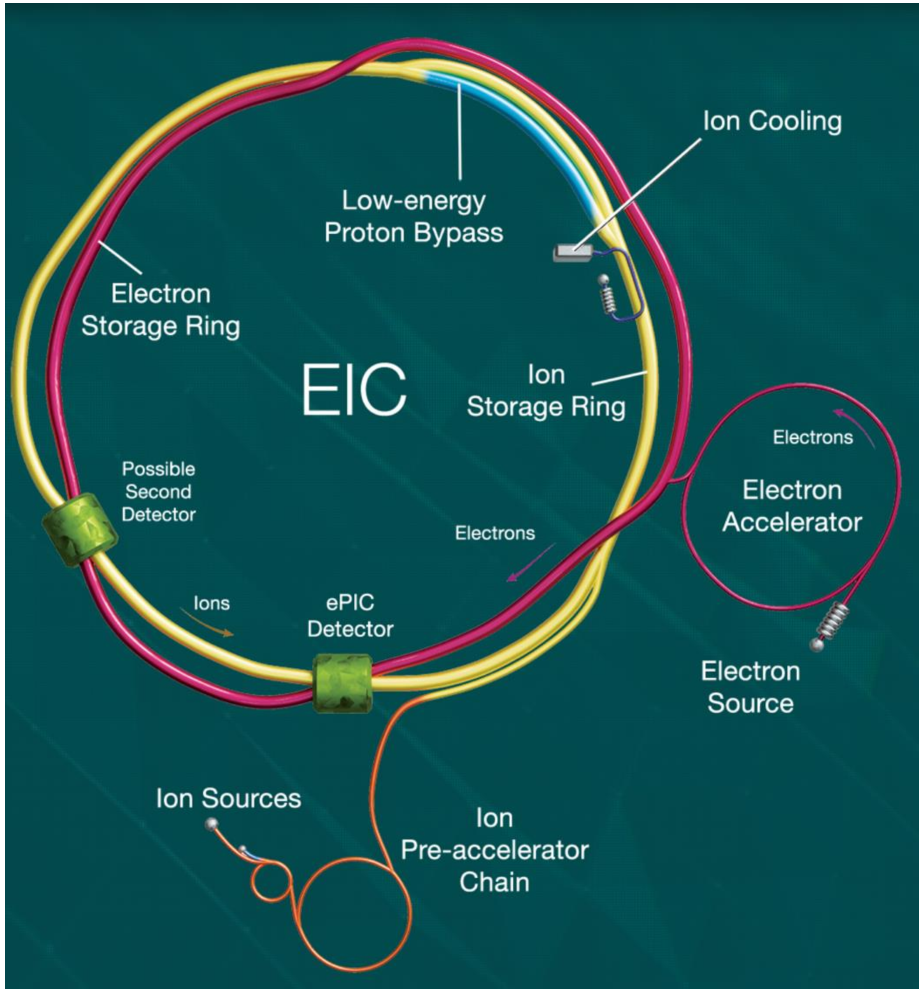
EIC Site Selection in 2020

Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

Brookhaven National Laboratory and Jefferson Lab will be host laboratories for the EIC Experimental Program. Leadership roles in the EIC project are shared.

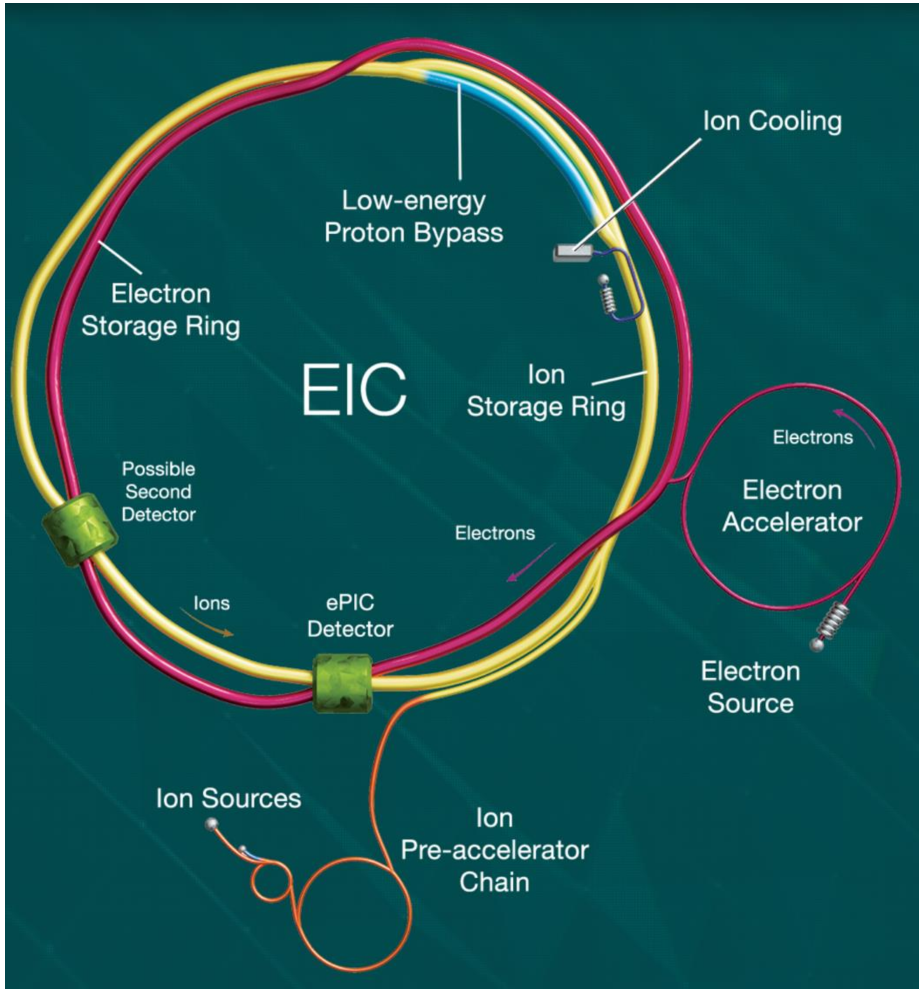


EIC Parameters

- Electrons: 5 - 18 GeV
- Protons: 41, 100 – 275 GeV
- Polarization > 70%

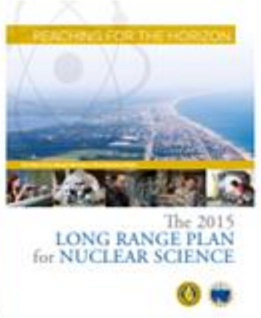
What does the EIC give us?

- A factor of 100 - 1000 higher luminosity than HERA → more statistics, higher precision!
- Both electrons and protons / light nuclei polarized → spin-dependent observables!
- Nuclear beams: d to U → heavy-nuclei provide access to novel studies in QCD!

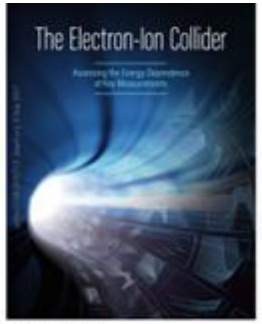


Detector 1 Design → ePIC

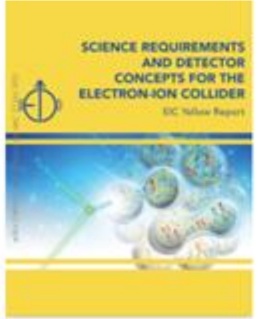
2012



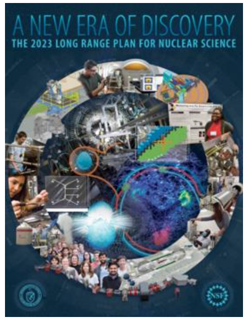
2015



2017



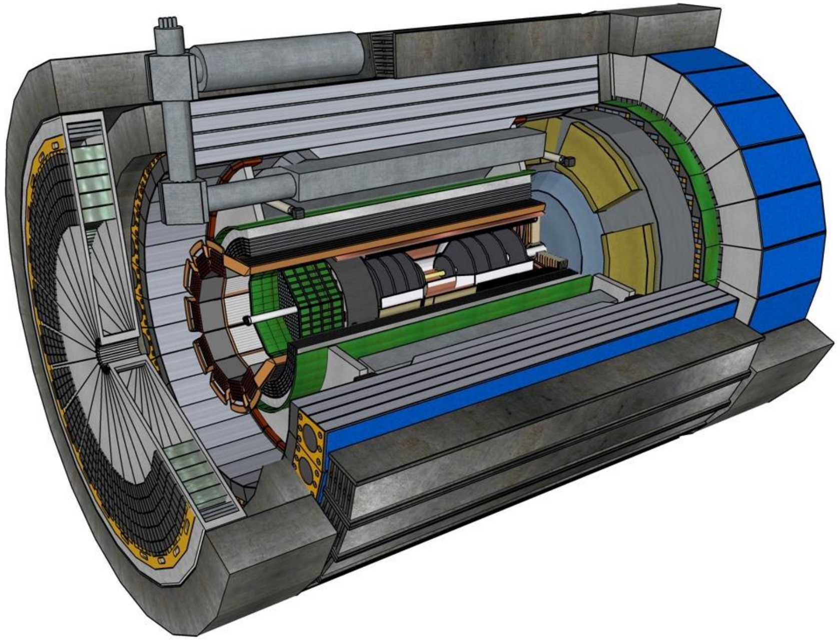
2020



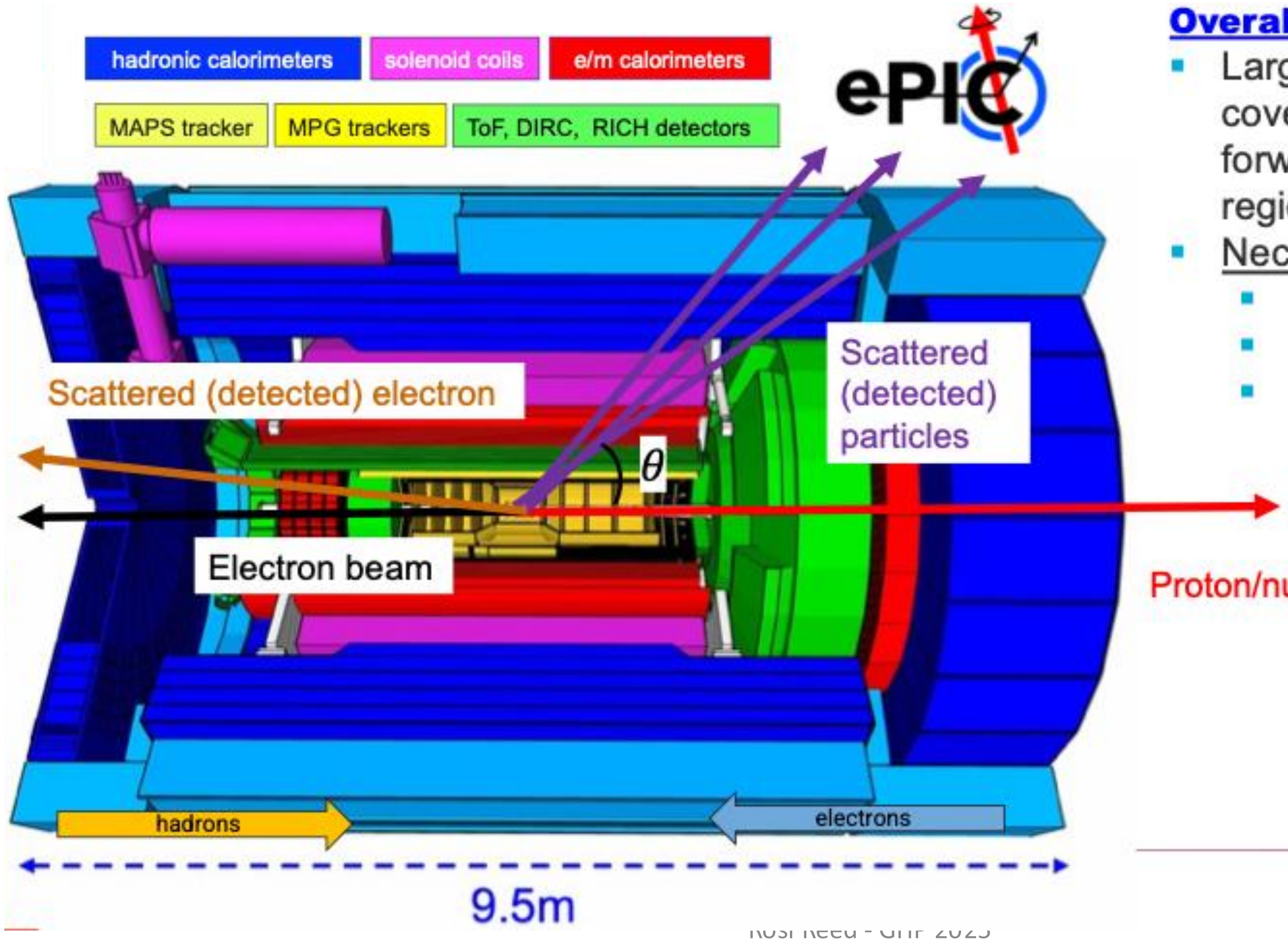
2023

Detector and machine design parameters driven by physics objectives

- Call for proposals issued jointly by BNL/JLab **March 2021** (Due Dec 2021
  - ATHENA, CORE and ECCE proposals submitted
- DPAP closeout **March 2022**
  - ECCE proposal chosen as basis for 1st EIC detector reference design
- **Spring/Summer 2022** – ATHENA and ECCE form joint leadership team
  - Joint WG's formed and consolidation process undertaken
  - Coordination with EIC project on development of technical design
- Collaboration formation process started **July 2022**
- Charter ratified & elected ePIC Leadership Team **February 2023**



ePIC Subsystems at mid-rapdity

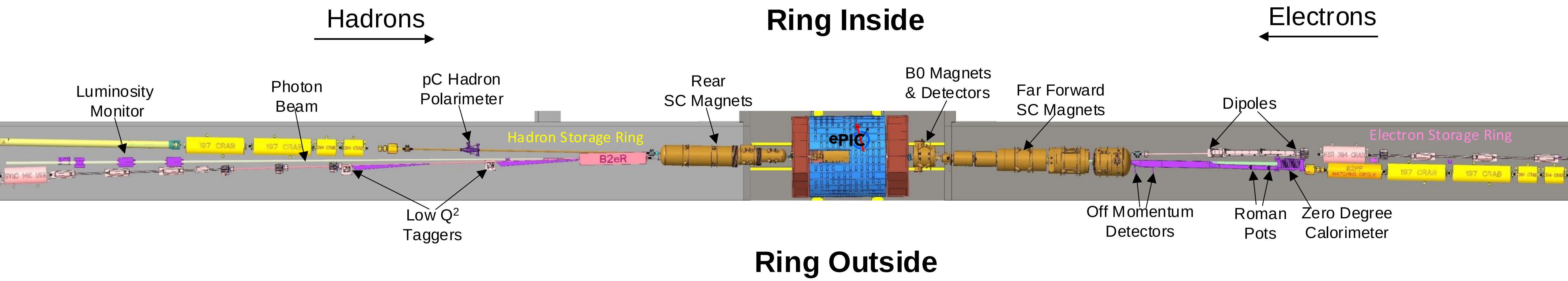


Overall detector requirements:

- Large rapidity ($-3.5 < h < 3.5$) coverage; and far beyond in far-forward/far-backward detector regions.
- Necessity for:
  - High-resolution tracking.
  - EM and hadronic calorimetry.
  - PID over a very broad momentum range.

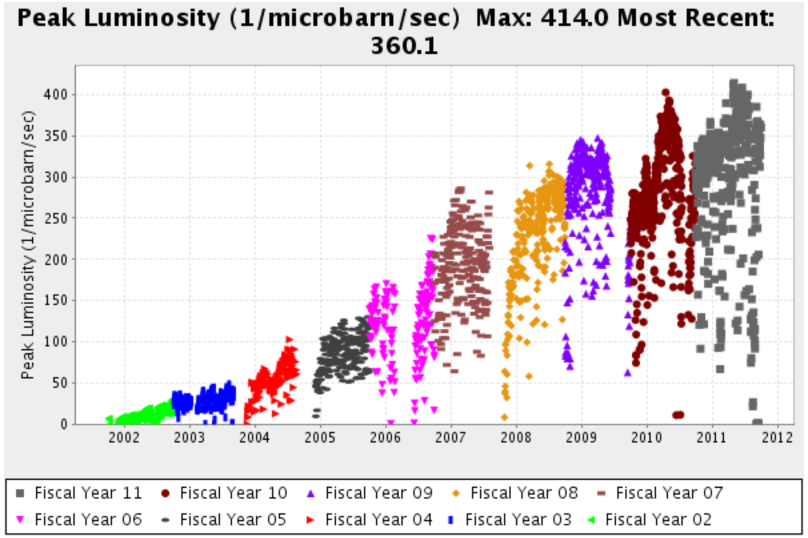
ePIC subsystems

- ePIC spans more than 80 m in order with many subsystems very near the beamline!
- After year 1 all subsystems will be available
  - Some will be in safe mode/not installed for safety for the first year of running

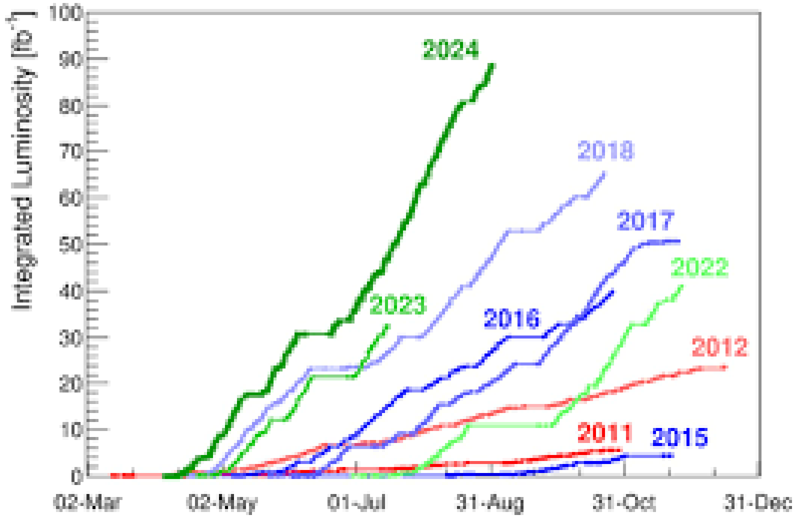


Luminosity over time

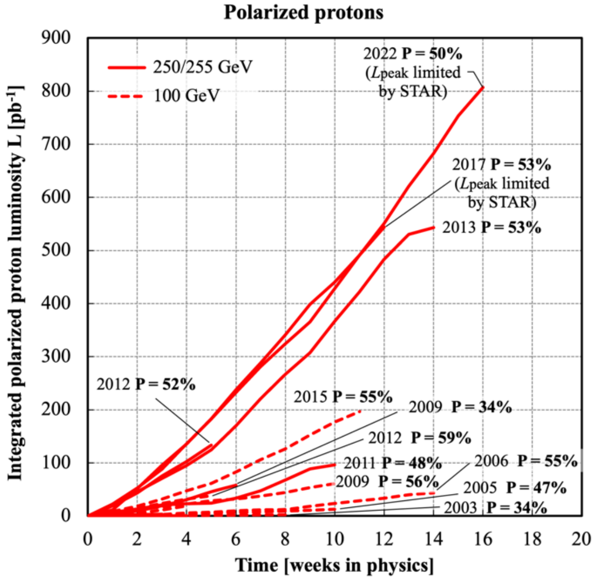
Tevatron



LHC



RHIC



For all machines, luminosity improves during the first years of the collider → We can't wait until we hit design luminosities or collision energies for our physics program!

Collider Development

- It takes time to reach design luminosities, requirements will not be reached on day one
- Prioritize the physics that can be done in the early science stage
- Important to commission the collider AND the experiment
  - Comparisons with existing measurements will be important
  - Need to also measure truly new physics
- EIC early science case is a balance between collider and detector needs and community interest
  - Allows for community input → What would you like to see on day one? Or day two?

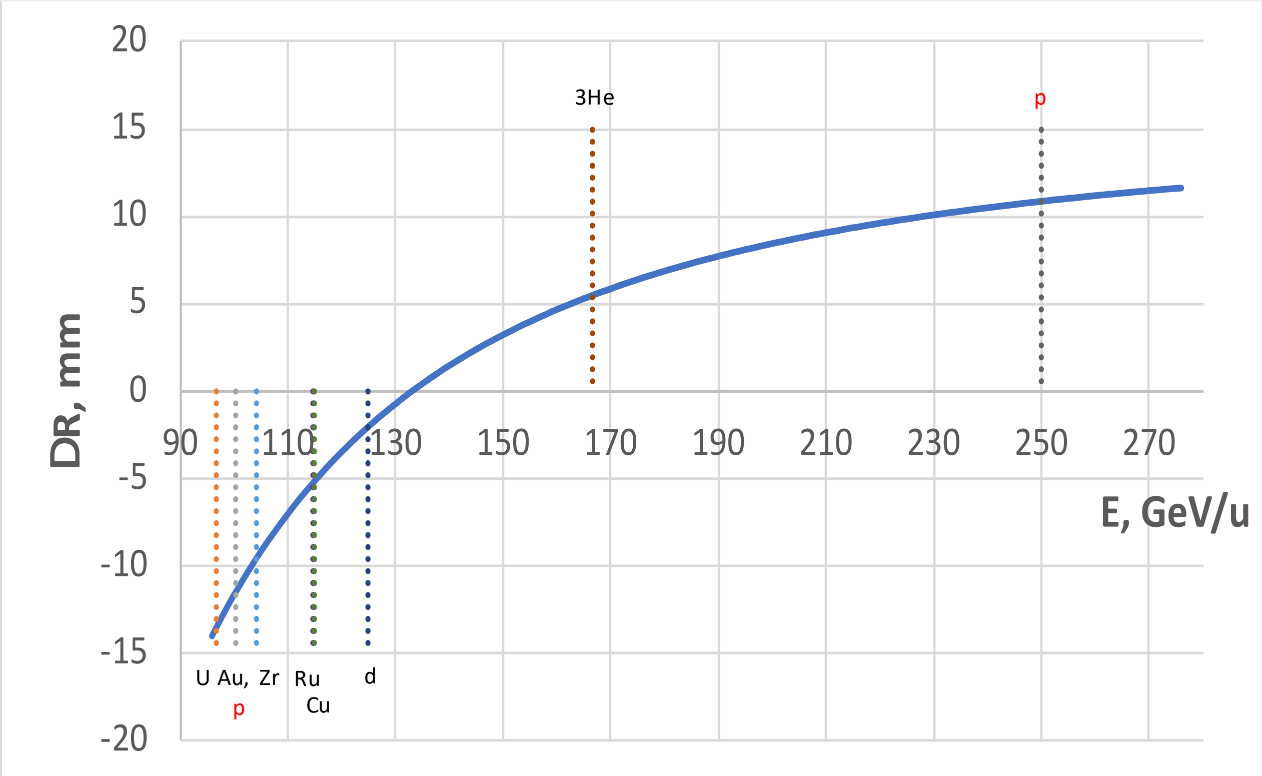
Accelerator Development
Early Science → Full Capabilities

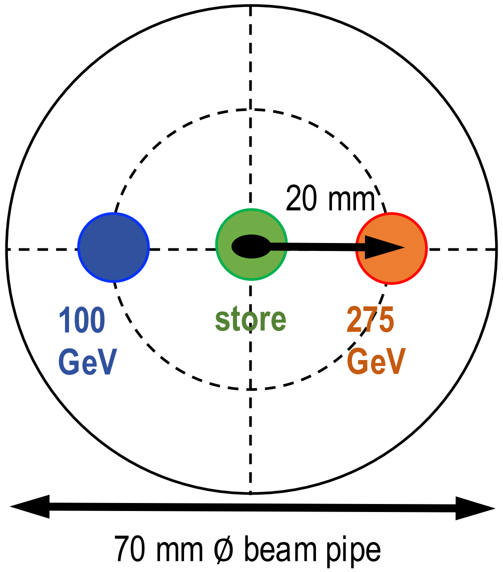
- Rapid Cycling Synchrotron (RCS)
  - 7 nC/bunch, 5 – 10 GeV polarized e- → accumulation ring + RF = 28 nC/bunch, 18 GeV electrons
- Electron Storage Ring (ESR)
  - 7 nC/bunch, 5 – 10 GeV polarized e- → more RF cavities = 28 nC/bunch, 18 GeV electrons
- Hadron Storage Ring (HSR)
  - 100 – 250 GeV polarized p, 100 GeV/u nuclear beams → Update to reach 275 GeV protons, 110 GeV/u add 41 GeV bypass to get full HSR beam energy

EIC Early Science Program

	Species	Energy	Luminosity (fb^{-1})
Year 1	e+Ru or e+Cu	10x115	1
Year 2	e+d	10x130	9
	e+p	10x130	1
Year 3	e+p	10x130	5
Year 4	e+Au	10x130	0.5
	e+p	10x250	4
Year 5	e+Au	10x100	0.4
	e+^{3}He	10x166	4

Why 130 GeV Hadrons?





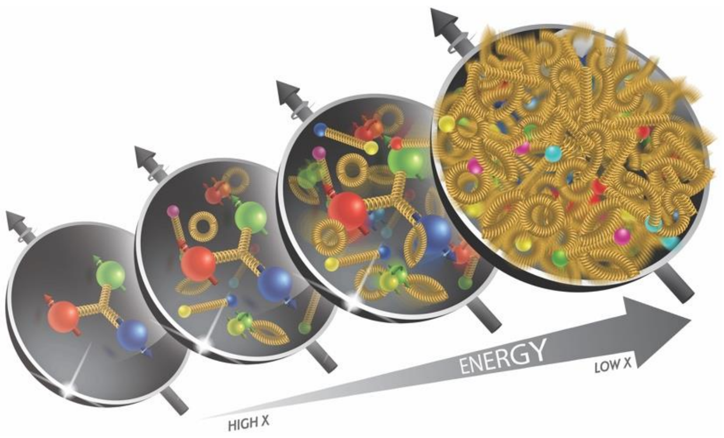
The electron revolution frequency is fixed → the hadron orbit must be adjusted with energy

- Keeps the collisions in sync

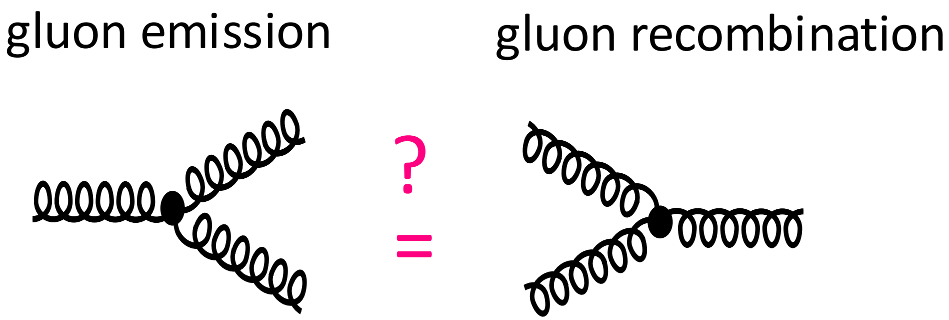
1. Start with ~130 GeV/u ('centered' hadron beam) and keeping the dipole fields under present RHIC max field (250 GeV hadrons)

Year 1 EIC Science

- Run: 10 GeV electrons on 115 GeV/u Ru or Cu
  - Commission electron polarization

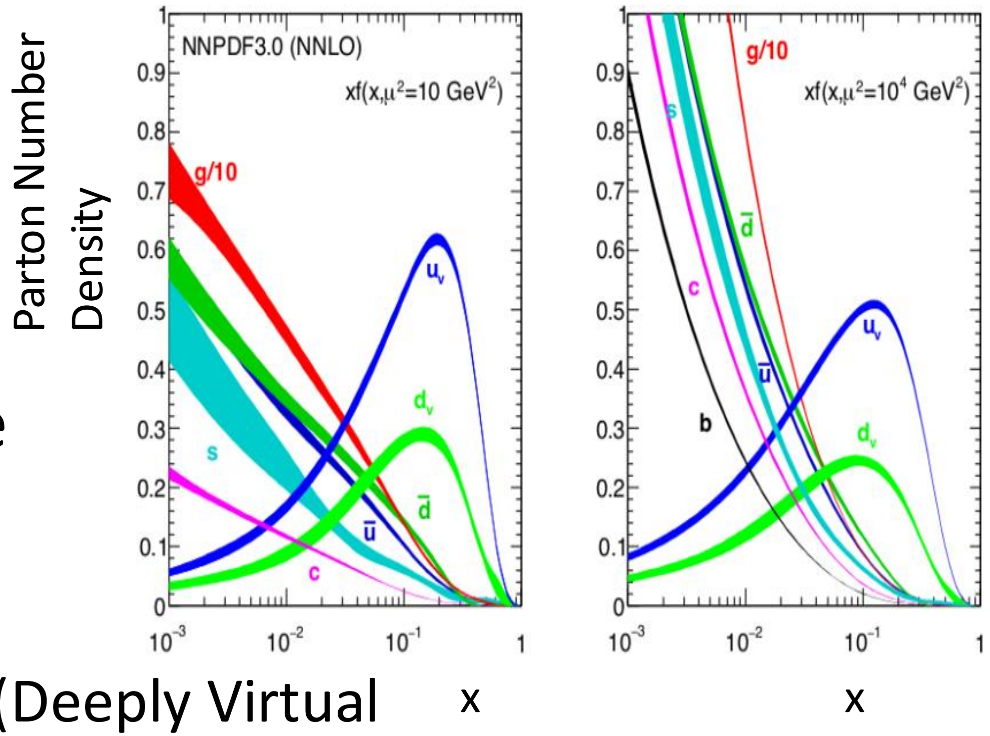


- Physics possibilities
  - DIS on proton/neutron target
  - J/ψ or ϕ production
  - Map the out nucleon and nuclei structure
    - Initial state for heavy ion physics
  - Early investigation into high gluon densities → saturation signal?
- Low luminosity, but unique data set will set the stage for the data sets that follow
  - Ru is better for saturation physics



Year 2 EIC Science

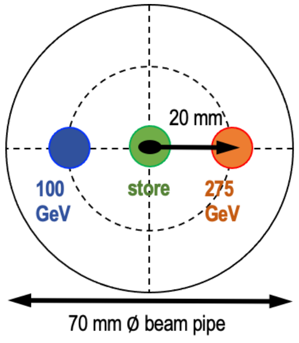
- Run: 10 GeV polarized electrons on 130 GeV/u Deuterium
  - Commission proton polarization
- Physics Possibilities:
  - Coherent/Incoherent J/ψ
  - Proton and neutron PDFs
- Run: 10 GeV electrons and 130 GeV transverse polarized protons
- Physics Possibilities
  - DVCS (Deeply Virtual Compton Scattering), DVMP (Deeply Virtual Meson Production), DEMP (Double Exclusive Meson Production)
  - Access to spin structure of nucleons and nuclei
  - Access the spatial + momentum structure of the nucleon in 3d



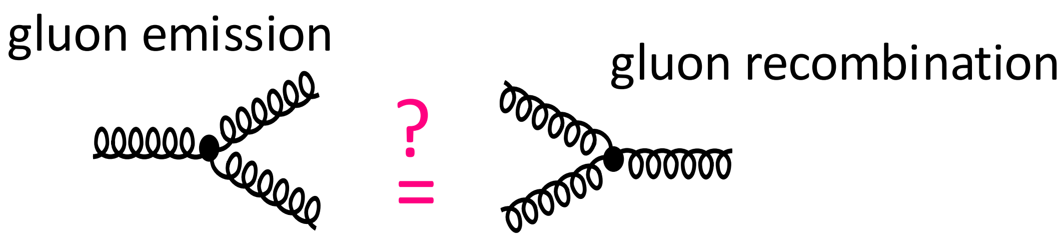
Year 3 EIC Science

- Run: 10 GeV polarized electrons on 130 GeV transverse polarized protons
  - Commission hadron spin rotators
- Run: longitudinal proton polarization
- Physics Possibilities
  - DVCS, DEMP, and DVMP measurements will become more precise
  - Transverse Momentum Distributions (TMDs) → quark/gluon spin–orbital correlations and the 3D momentum structure of the proton.
  - Measure transversity (with transversely polarized protons) and helicity (with longitudinally polarized protons)
- EIC moves to a richer spin physics campaign, this period is pivotal for gaining precision data on nucleon spin structure (through TMDs, GPDs, DVCS, etc.)
  - Lays the groundwork for the later higher-energy and higher-luminosity runs

Year 4 EIC Science



- Run: 10 GeV polarized electrons on 100 GeV Au
  - Commission hadron accelerator to operate with non-centered orbits
- Physics Possibilities:
  - High gluon densities → saturation signal



- Run: 10 GeV electrons on 250 GeV transverse and longitudinal polarized protons
- Installation of additional ESR RF and HSR PS to reach design Current and maximum Energies

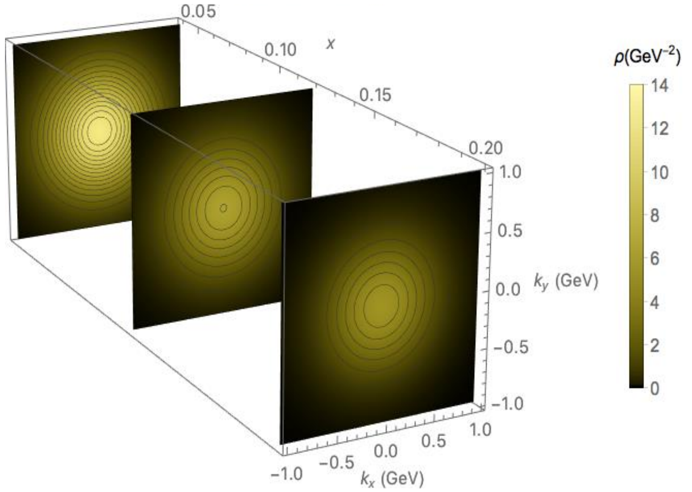
Year 5 EIC Science

- Run: 10 GeV polarized electrons on 100 GeV Au
- Run: 10 GeV electrons on 166 GeV transverse and longitudinal polarized ^{3}He
- Physics Possibilities:
  - Since nuclear spin is essentially carried by the neutron → probe the neutron spin.
  - Longitudinal Spin Structure (g_1 and g_2 functions) → how quarks' spins are aligned along the nucleon's spin direction, quark-gluon correlations and higher twist effects
  - Transverse Spin Structure (transversity h_1) → how quark spins are oriented transversely relative to the nucleon's momentum.
- Installation of additional ESR RF and HSR PS to reach design Current and maximum Energies

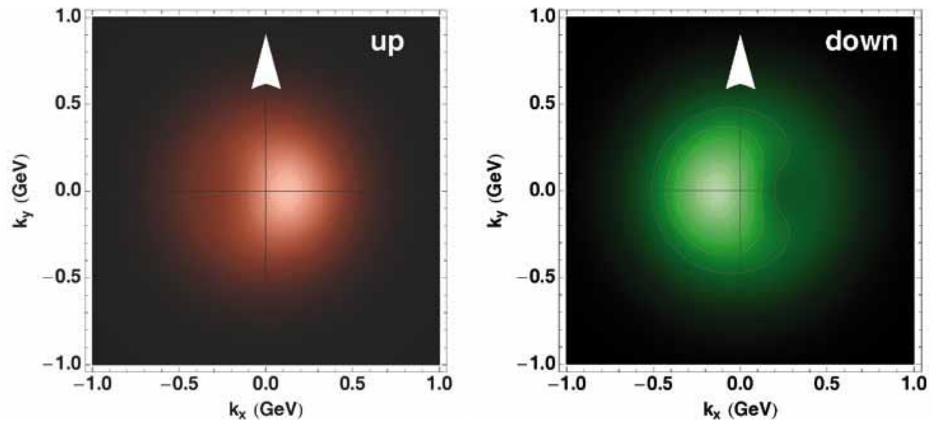
Beyond Year 5

- Run: 18 GeV polarized electrons on 275 GeV/u polarized (longitudinal & transverse) proton beams
- Commission ESR & HSR at max. energy and beam currents
- Operate HSR with 41 GeV bypass → Run: 5 GeV polarized electrons on 41 GeV transverse polarized proton beams

Unpolarized nucleon



Transversely polarized nucleon



Fully EIC Program! Exclusive processes to examine QCD at Extreme Parton densities and spatial imaging are especially statistics hungry

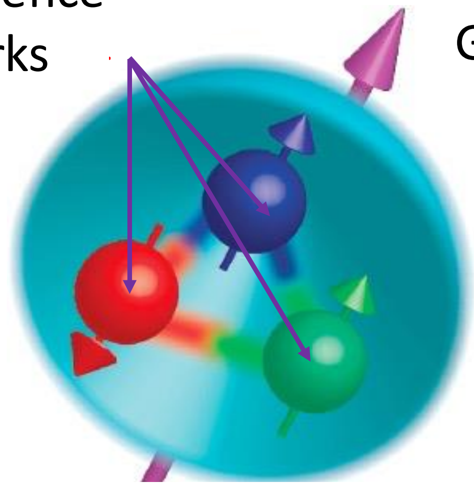
Outlook to the Future

- The EIC program will start with moderate-energy collisions and a focus on commissioning
  - Verify detector performance, validate calibration procedures
- Early on the measurements of light nuclei and partially polarized protons will establish crucial benchmarks (such as inclusive structure functions, J/ψ production, and early indications of gluon saturation)
- By Year 3, high-precision polarized electron–proton scattering with both transverse and longitudinal polarization → nucleon's spin structure and 3D momentum distributions
- The beams of heavier nuclei (Au) at higher energies allow direct exploration of dense gluon fields and possible saturation effects in large nuclei
- Currently developing a suite of observables to maximize the impact of our early science program
  - Demonstrate a rich and full physics program will exist a decade after RHIC has ended

Back-Up

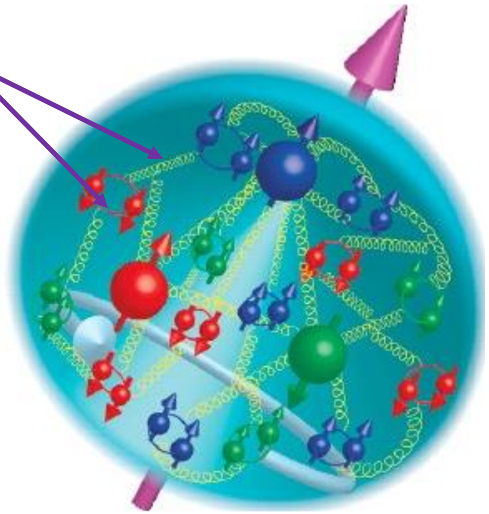
Properties of the Proton

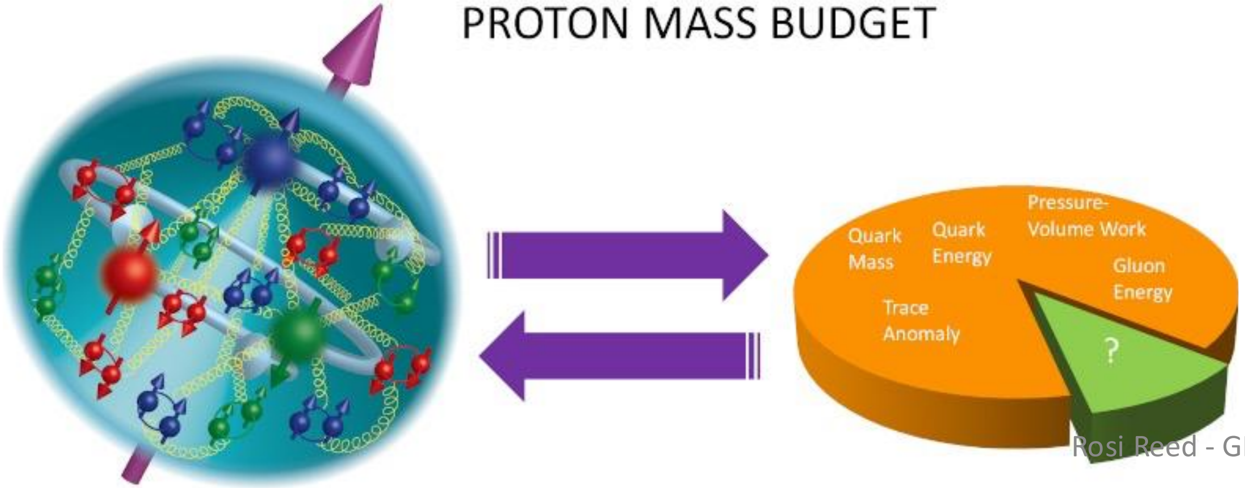
3 Valence Quarks



Sea Quarks and Gluons

Increase Energy





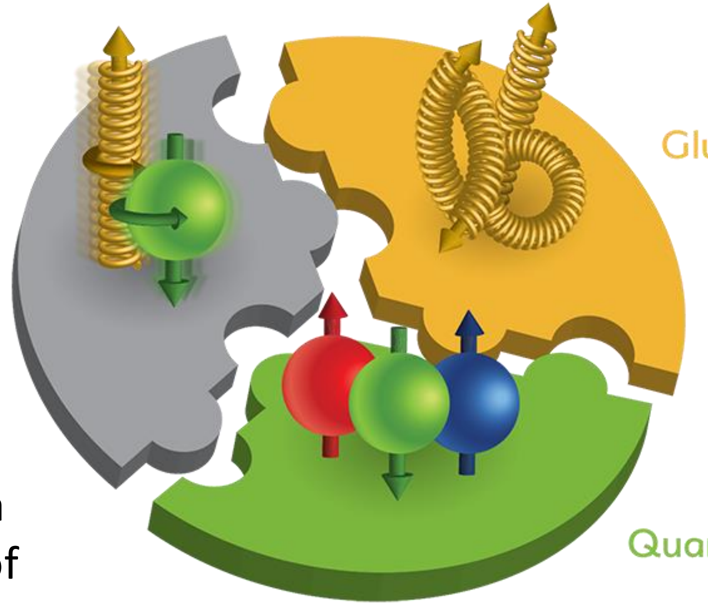
Mass is driven by a complicated sum of various QCD interactions!

quarks gluons

Proton spin: $\frac{1}{2} = \frac{1}{2}\Sigma_q \Delta q + \Delta G + L_{q,g}$

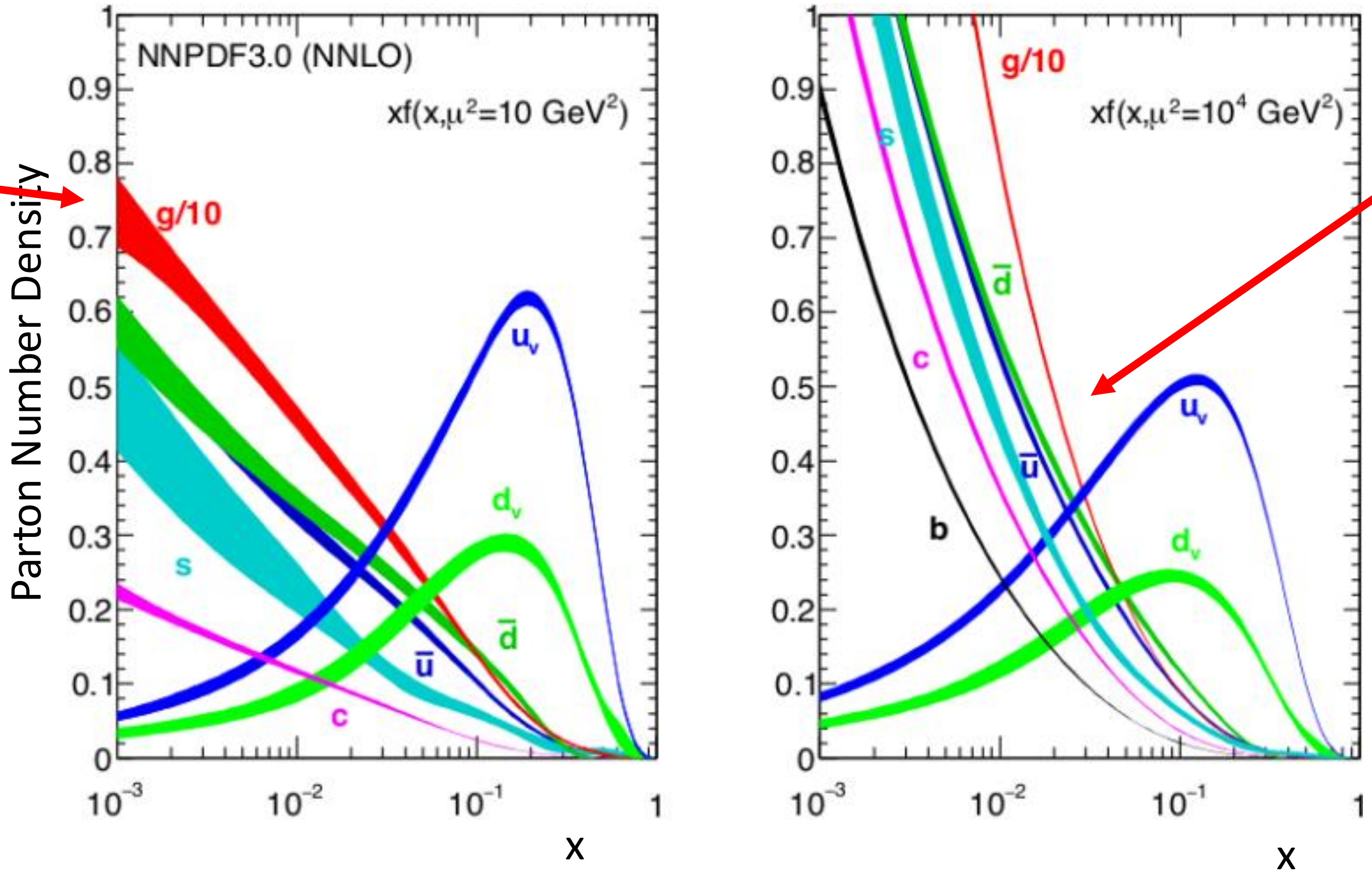
Orbital angular momentum

Only 20-30% comes from the quarks!



Quarks and Gluons Structure and Motion

Where does this saturate?

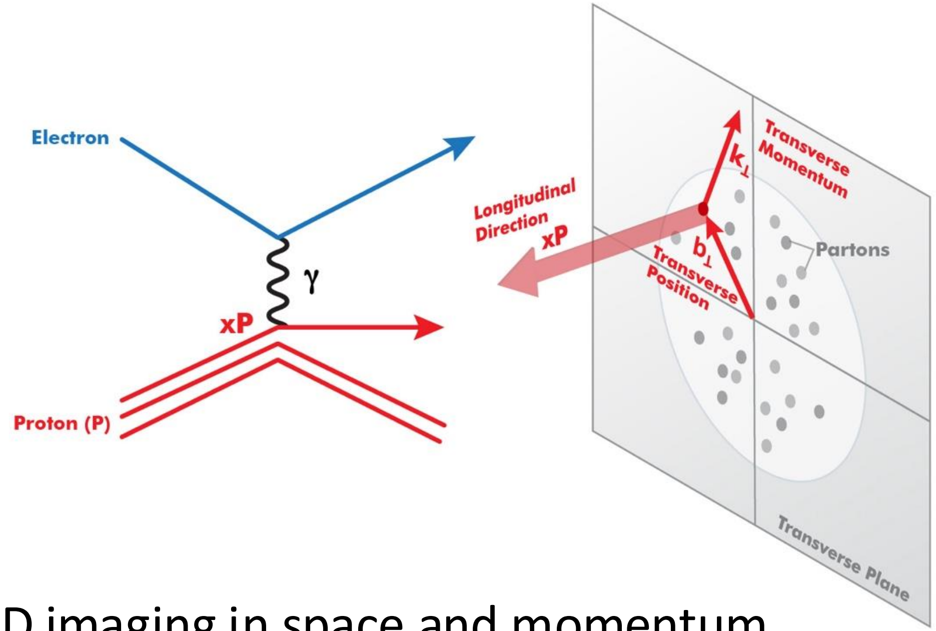


What do these distributions look like for protons in a nucleus?

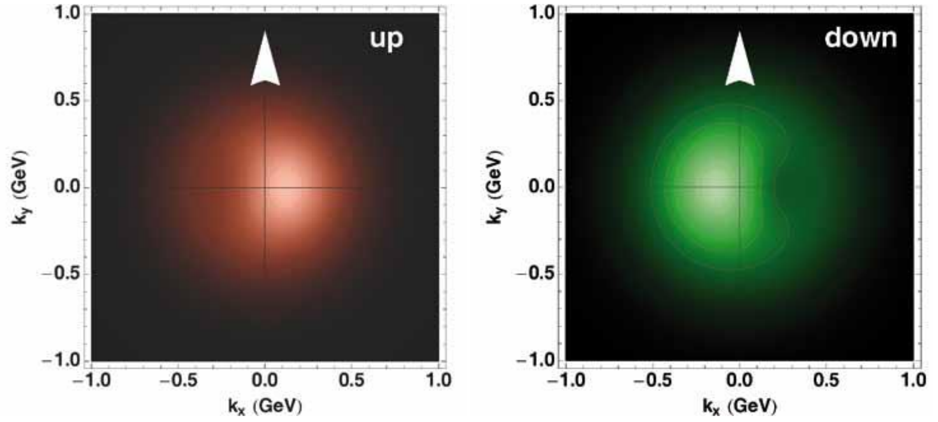
Fraction of Proton Momentum Carried by Parton

3D Imaging in Space and Momentum

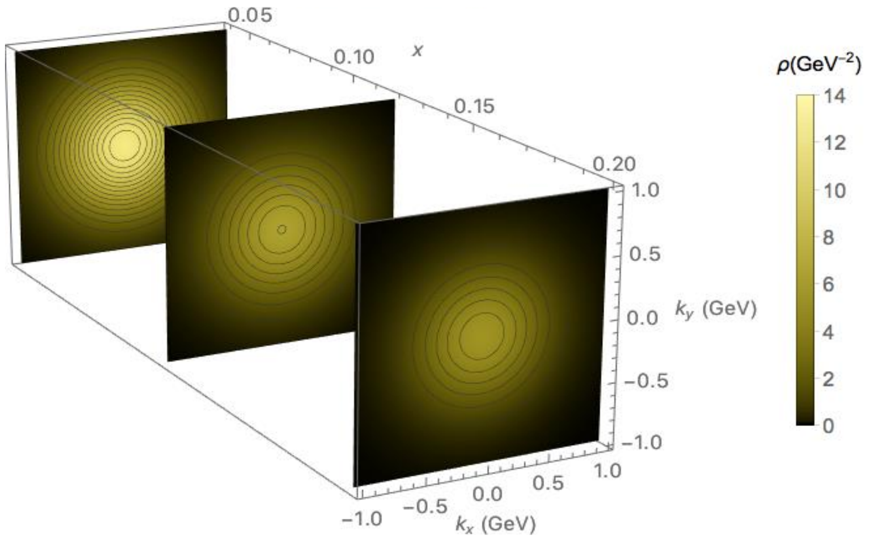
RHIC is the only polarized hadron collider in the world → EIC polarization capabilities



Transversely polarized nucleon



Unpolarized nucleon

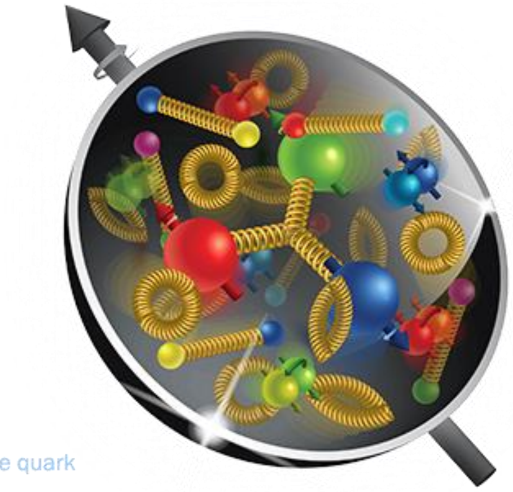


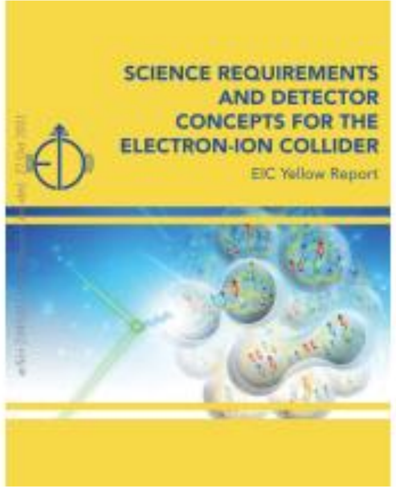
3D imaging in space and momentum

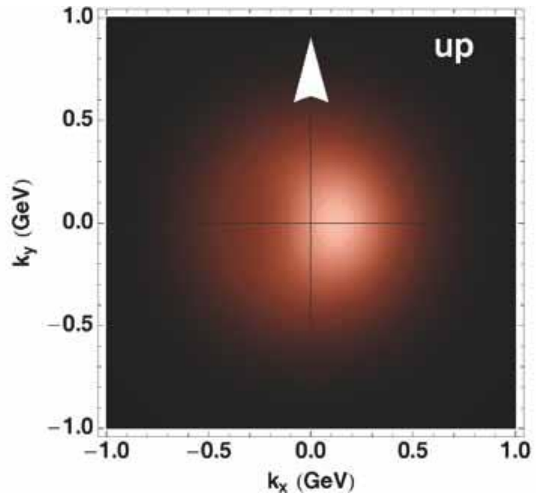
longitudinal structure (PDF)
+ transverse position Information (GPDs)
+ transverse momentum information (TMDs)

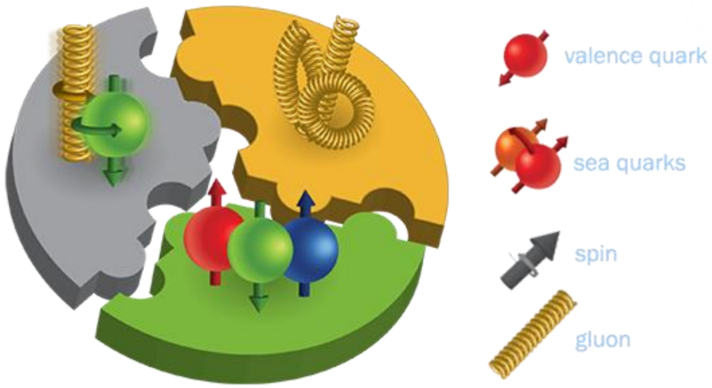
Translation to Physics

- Detector requirements stated in the Yellow Report are what is required to measure the key observables needed to answer the fundamental questions
  - 3D structure of protons and nuclei (space and momentum)
  - Gluon saturation and the color glass condensate
  - Solving the mystery of proton spin
  - Quark and gluon confinement









Conclusions

- RHIC is a versatile collider in both energy and species (and the only polarized hadron collider in the world)
  - A QCD laboratory workhorse
  - Finishing the RHIC science mission with the new built sPHENIX detector and upgraded STAR detector is key
    - High statistics data from last RHIC runs
    - Personpower to calibrate and analyze data to be recorded and that which is already on tape!
    - Preserving this data for future analysis
- The EIC will be a new QCD laboratory designed to elucidate:
  - Origin of Nucleon Mass & Spin, Confinement, Nucleon / Nuclear Femtography, Dense Gluon States, BSM physics
- The EIC science goals are a natural extension of QCD studies at JLab and RHIC, and there is complementarity between the future programs at the EIC and JLab
- The ePIC Detector is maturing into a detailed technical design to pursue the EIC science program
  - EIC detectors are an enormous undertaking that will require participation and expertise from both the RHIC and JLab communities, as well as key international contributions!
  - Next ePIC Collaboration meeting is Jan 9 – 13, 2024: https://indico.bnl.gov/event/20473/