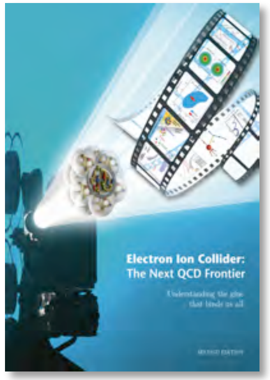
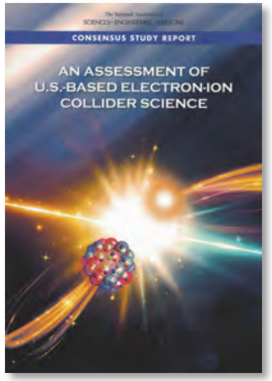
Center for Frontiers in Nuclear Science

The US Electron Ion Collider
An introduction Science and Status

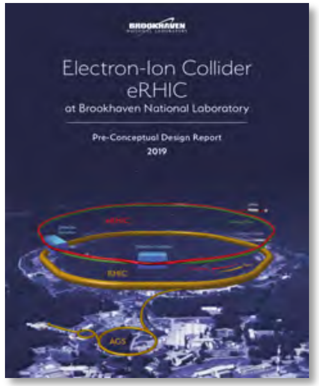
~1990's → 2015 2016 2018 2019 2019 → ~2030

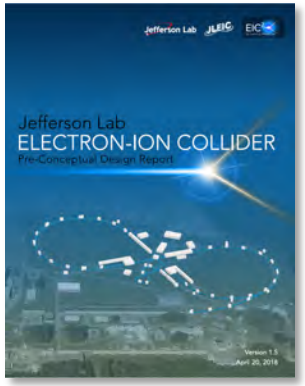


Physics of EIC



Evaluation





Realization

A Thank You!

- To the local organizing committee: Nilmani Mathur, Kajari Mazumdar, Bedanga Mohanty, **Asmita Mukherjee (chair),** M. Mustafa and V. Ravindran
- To EIC external advisors to this meeting: Christine Aidala (UMich), Guenther Dissertori (ETH), Bernd Surrow (Temple)

More importantly:

- **To all of you** who have come to this meeting driven by the physics interest.
- To those who have come long distances (Europe, US, other parts of Asia) to present aspects of EIC science and **to help build potential collaborations**

For Collaboration Building: three broad aims of this meeting

- To inform the Indian QCD & High Energy Physics community of the status and the fast progress on the US EIC

- Identify potential synergies between Indian QCD/HEP and the EIC (on many fronts):
  - Theory: partonic structure and dynamics in nucleons and nuclei, lattice QCD
  - Experiment
    - detector design and technology based on experience or/and new initiatives
    - Current activities and ongoing detector projects, near future responsibilities
  - Any other… including accelerator physics (in parallel or in future)

- *For both sides* to **learn from each other**, where we can help each other in the most impactful way and achieve *a sustained Indian involvement in the EIC activity*

This talk will cover:

A high-level introduction to open questions in QCD

Science highlights that made the case for the Electron Ion Collider

Introduction to the Electron Ion Collider

- Two concepts: @ BNL (B. Mueller) and @ Jlab (R. Ent) separate talks

The International EIC Users Group and its activities

EIC realization and the Users Group's activity

QCD: The Holy Grail of Quantum Field Theories

- QCD : "nearly perfect", fundamental quantum field theory of quarks and gluons that explains nature's strong interactions
- QCD is rich with symmetries:

$$SU(3)_C \times SU(3)_L \times SU(3)_R \times U(1)_A \times U(1)_B$$

(1) (2) (3)

(1) Gauge "color" symmetry : unbroken but confined
(2) Global "chiral" flavor symmetry: exact for massless quarks
(3) Baryon number and axial charge (massless quarks) conservation
(4) Scale invariance for massless quarks and gluon fields
(5) Discrete C, P & T symmetries

- Chiral, Axial, Scale & P&T symmetries broken by quantum effects: Most of the visible matter in the Universe emerges as a result
- Inherent in QCD are the deepest aspects of relativistic quantum field theories: (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

➔ ALL DEPEND ON NON-LINEAR DYNAMICS IN QCD

Non-linear Dynamics of QCD has Fundamental Consequences

Emergence of spin, mass & confinement, gluon fields

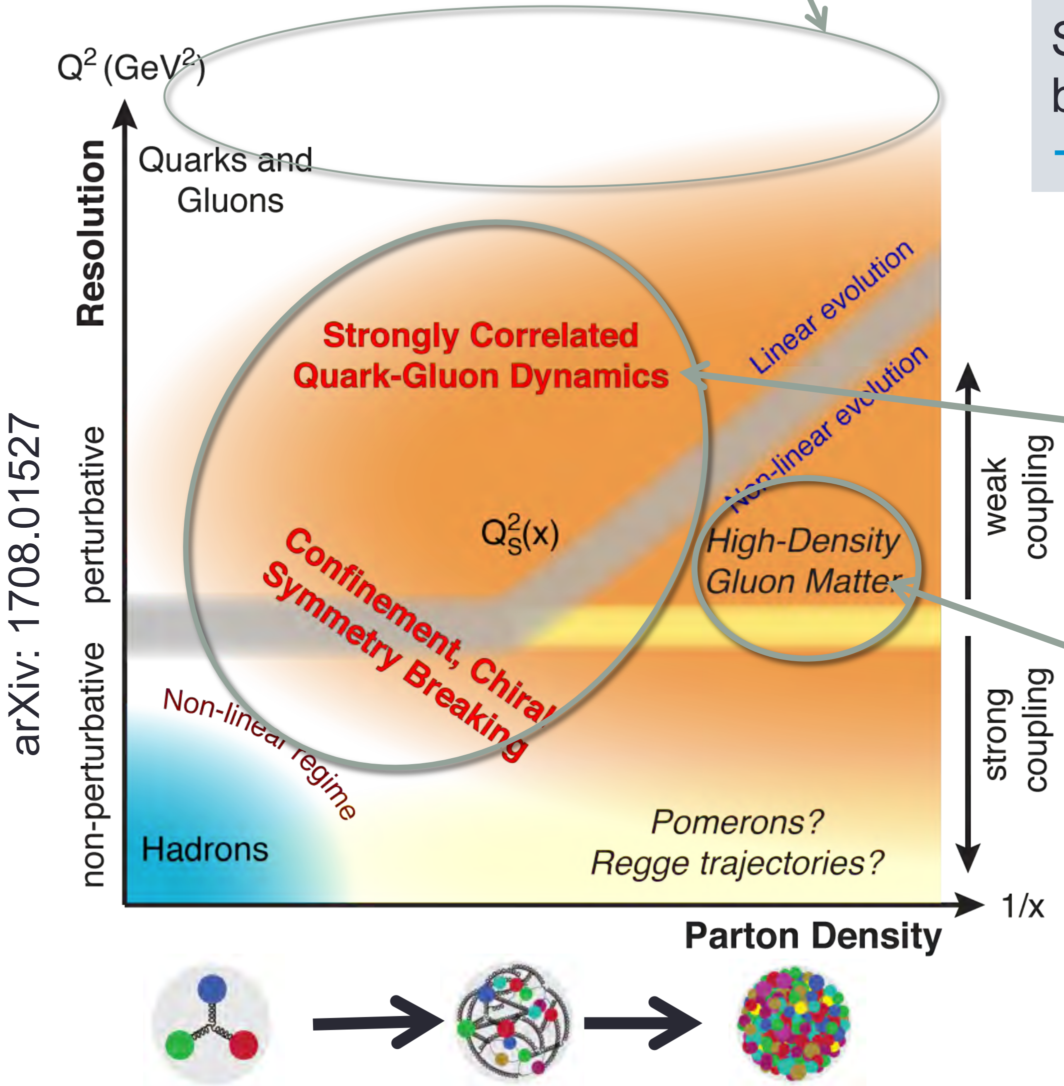
- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions -- Generalized Parton Distributions (GPDs)
- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number is tamed by existing mechanisms in QCD: Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

LHC/RHIC/CBAF & EIC are all essential for the deeper understanding of QCD

QCD Landscape to be explored by a future facility

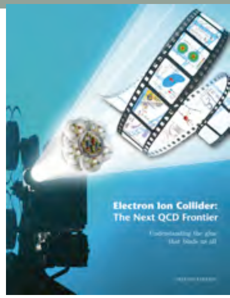
QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges



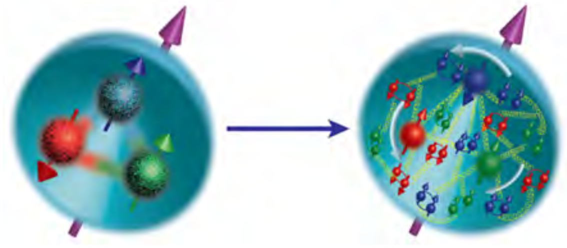
Systematically explore correlations in this region.

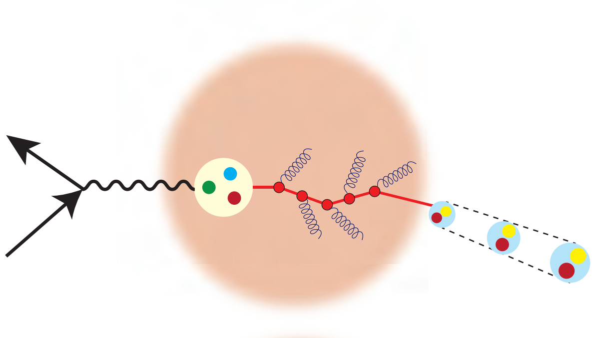
An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter



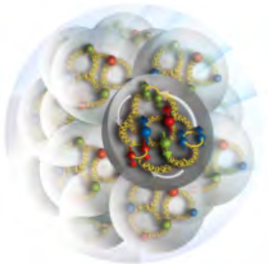
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties emerge from them and their interactions?



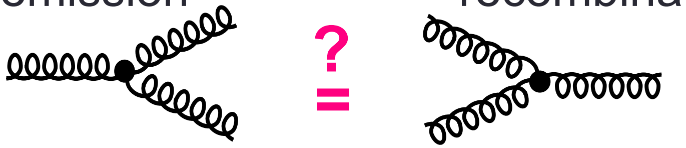


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

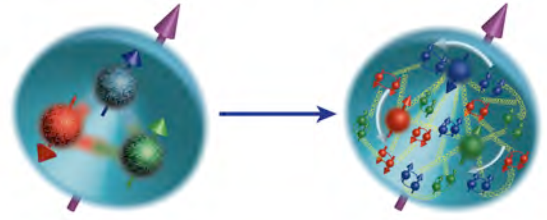


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission ?= gluon recombination



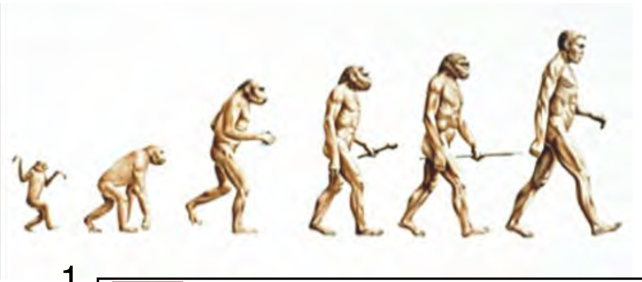
Nucleon Spin: Precision with EIC

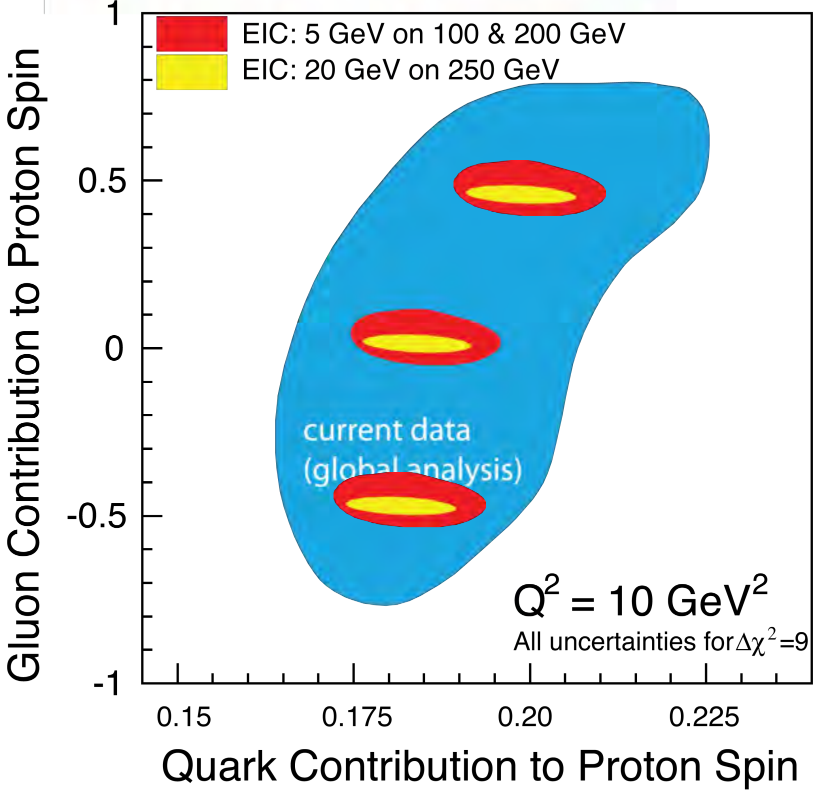


$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

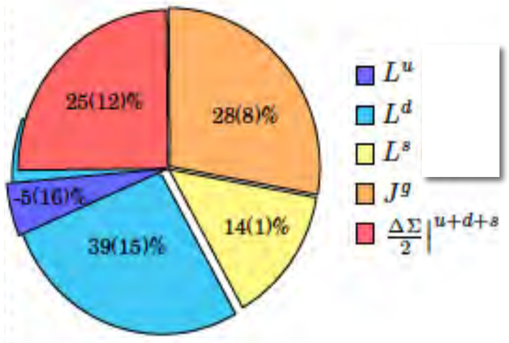
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

Precision in $\Delta\Sigma$ and Δg → A clear idea Of the magnitude of L_Q+L_G





Spin in Lattice QCD: Ab initio Calculations

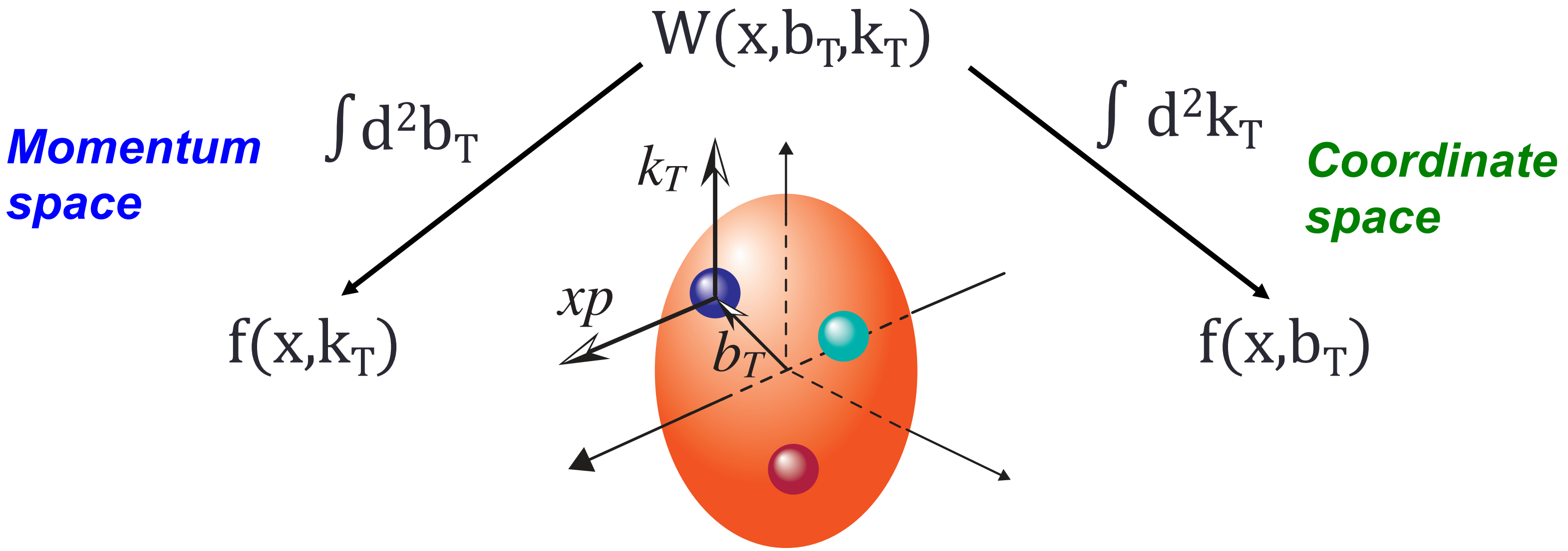


- **Gluon's spin contribution on Lattice: S_G = 0.5(0.1):** Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:** χQCD Collaboration, PRD91, 014505, 2015

3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x, b_T, k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.



Spin-dependent 3D momentum space images from semi-inclusive scattering → **TMDs**

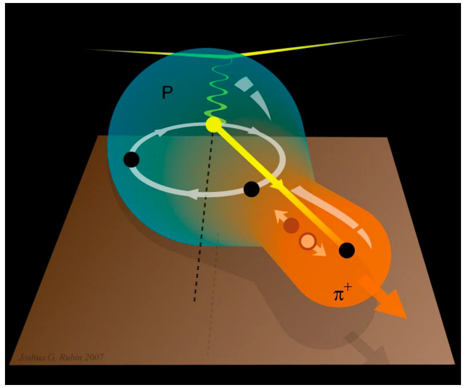
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply Virtual Compton Scattering and Deeply Virtual Vector Meson production) → **GPDs**

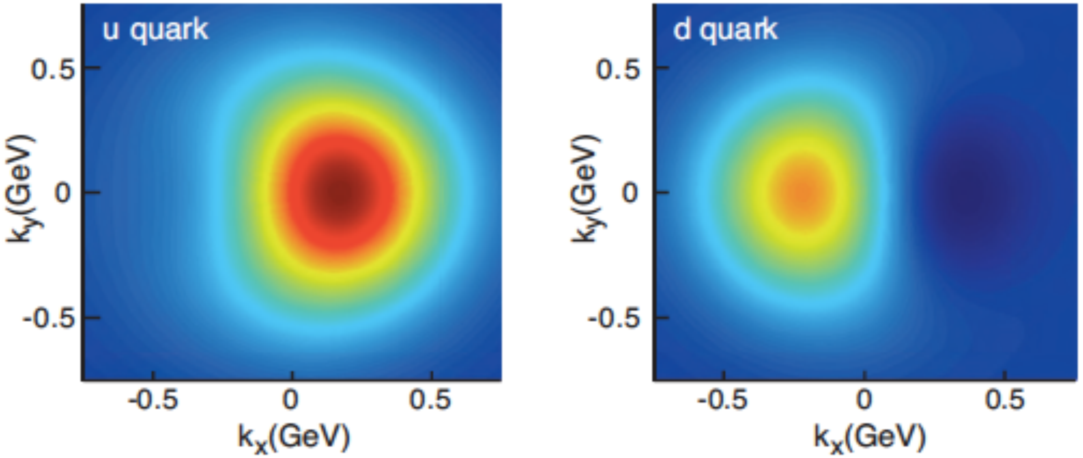
Position and momentum → Orbital motion of quarks and gluons

2+1 D partonic image of the proton with the EIC

Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions

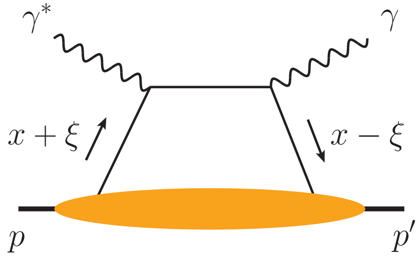


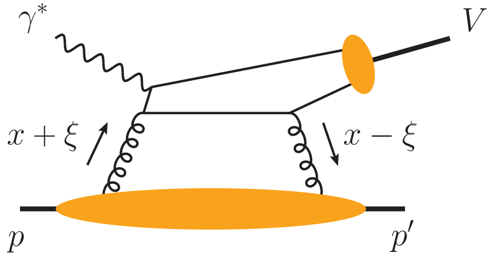


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering

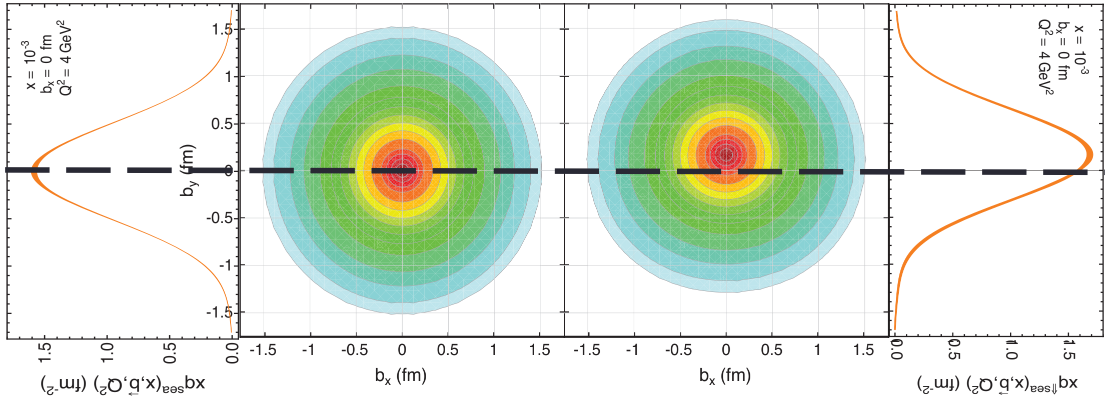
Measure all three final states

e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

sea-quarks

unpolarized polarized

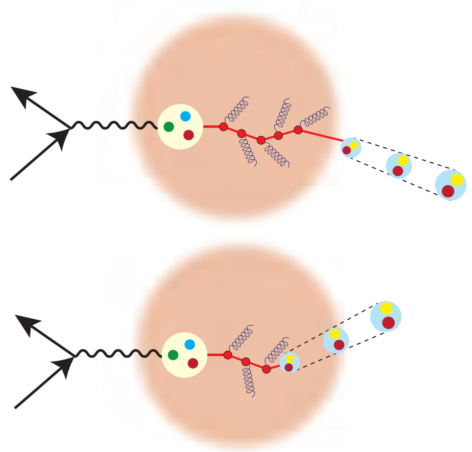


Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

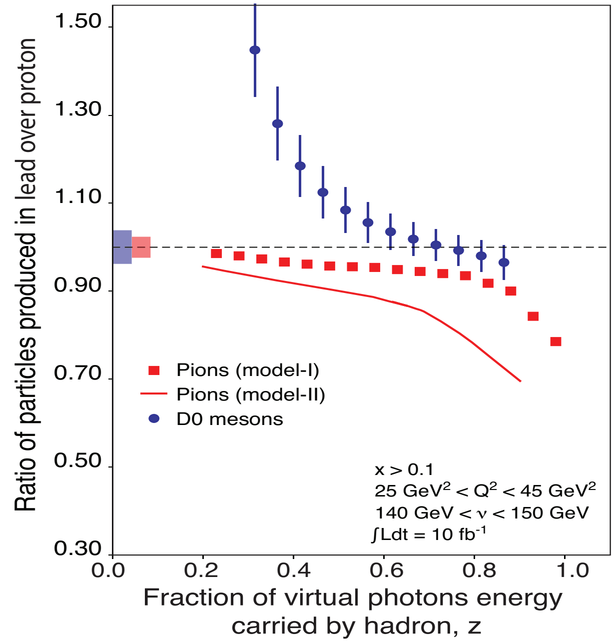
$$\nu = \frac{Q^2}{2mx}$$



Control of ν by selecting kinematics;
Also under control the nuclear size.

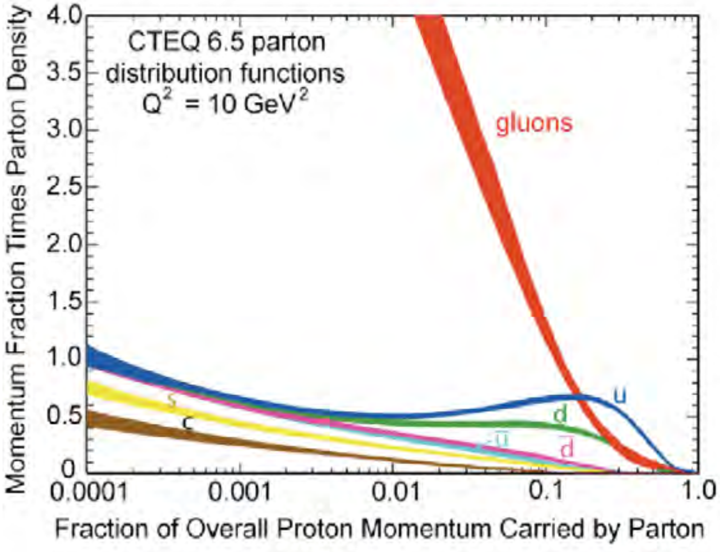
(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔ Clues to color-confinement?

Energy loss by light vs. heavy quarks:



Identify π vs. D^0 (charm) mesons in e-A collisions:
Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

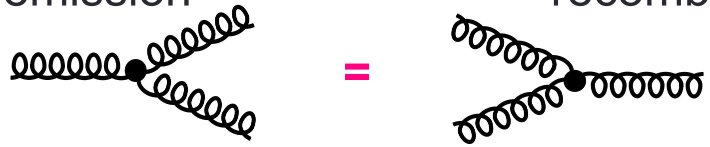
Need the collider energy of EIC and its control on parton kinematics

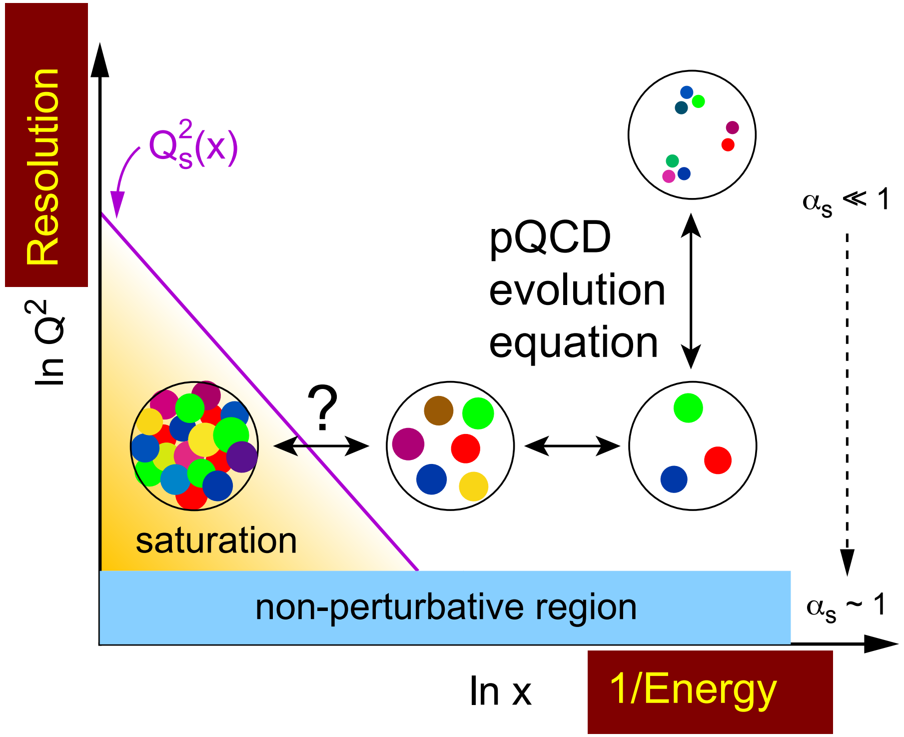


What do we learn from low-x studies?

What tames the low-x rise?

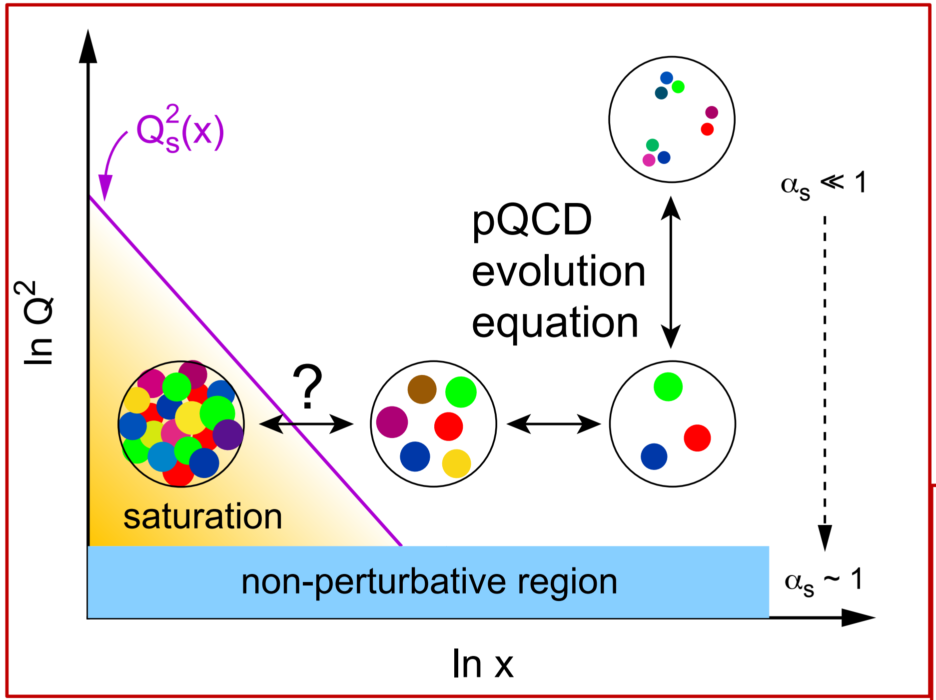
- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

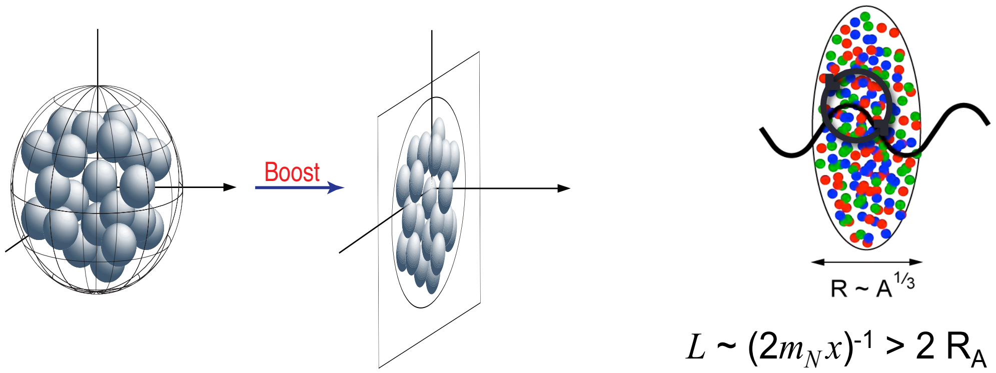




First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

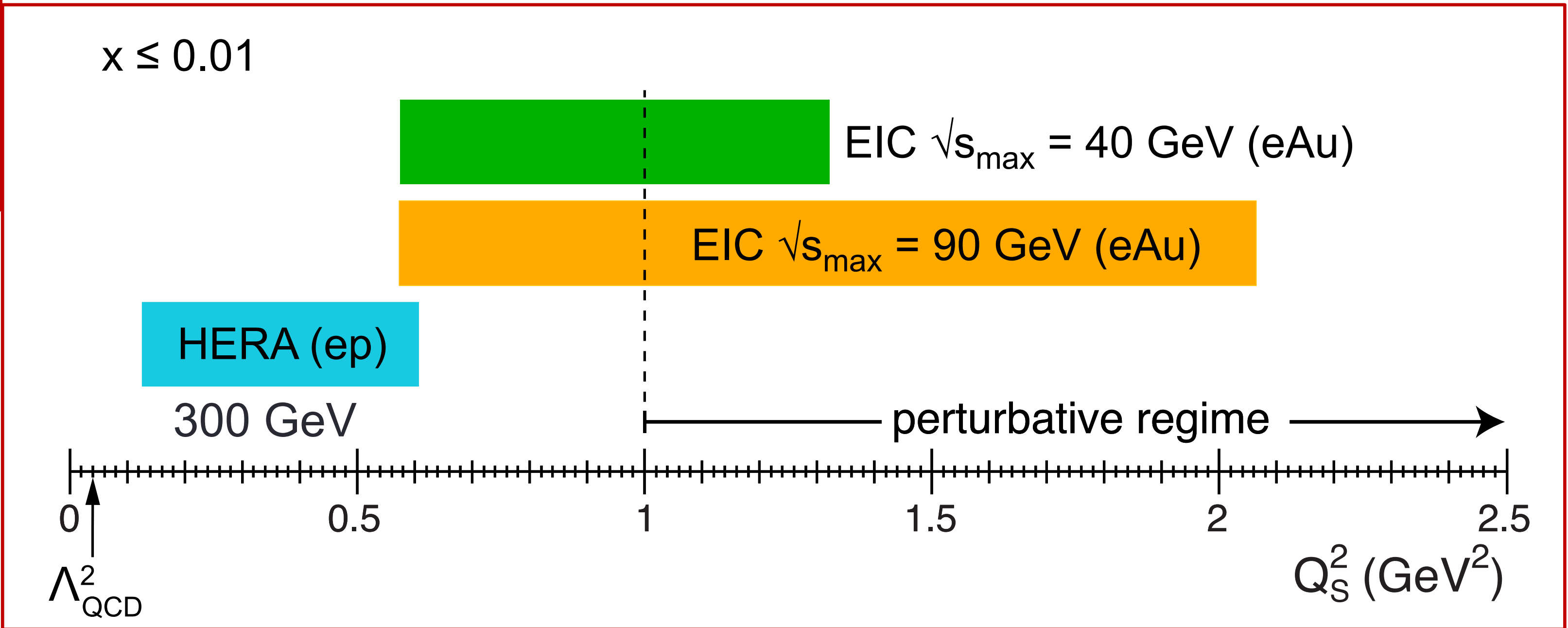
Advantage of the nucleus over proton





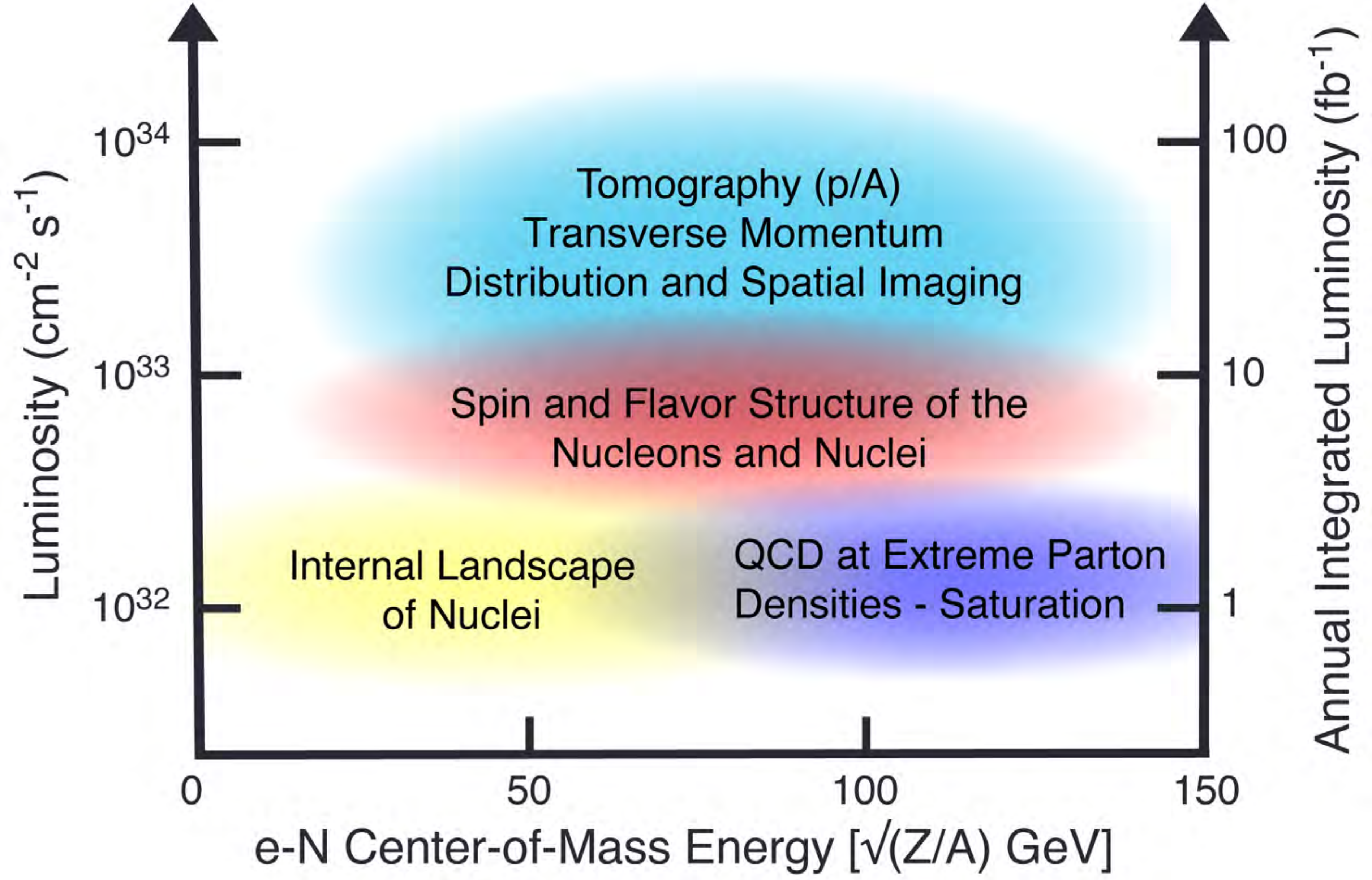
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

$L \sim (2m_N x)^{-1} > 2\, R_A \sim A^{1/3}$

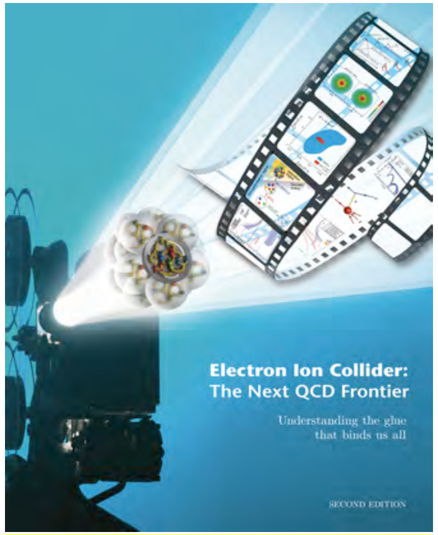


Accessible range of saturation scale $Q_s{}^2$ at the EIC with e+A collisions. arXiv:1708.01527

Summary: EIC Physics: CM vs. Luminositv vs. Intearated luminositv



The Electron Ion Collider



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:

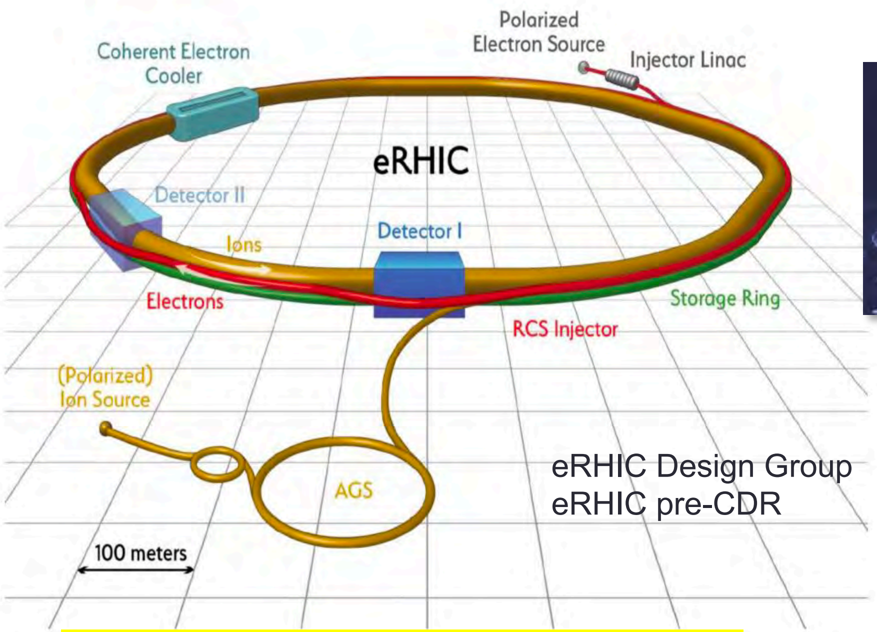
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

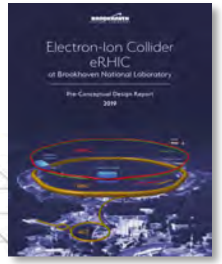
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

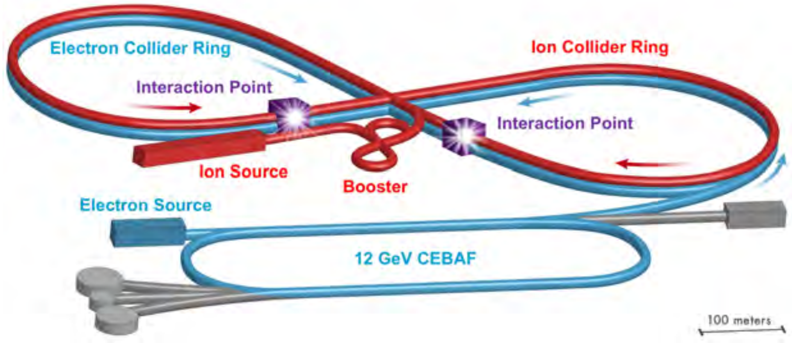
Both designs use DOE's significant investments in infrastructure



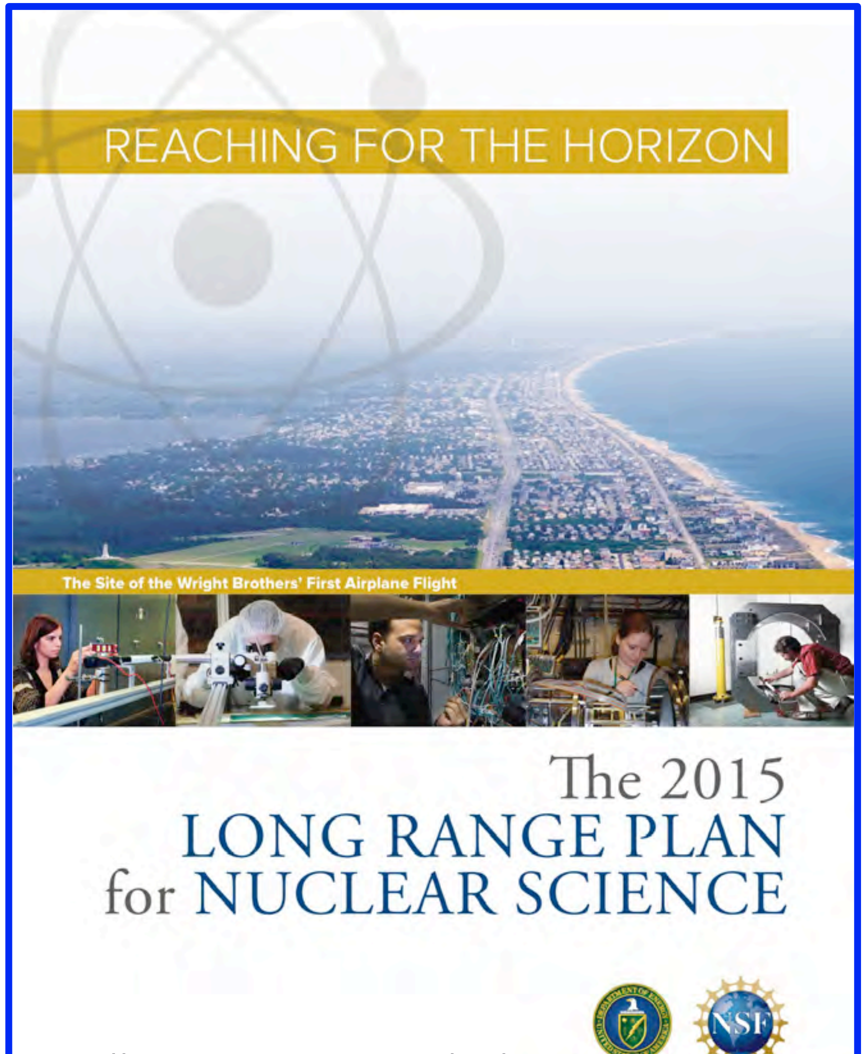
eRHIC Design Group
eRHIC pre-CDR



Berndt Mueller, BNL RHIC->EIC



Rolf Ent, Jefferson Lab, CEBAF12→ EIC



http://science.energy.gov/np/reports

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. 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), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

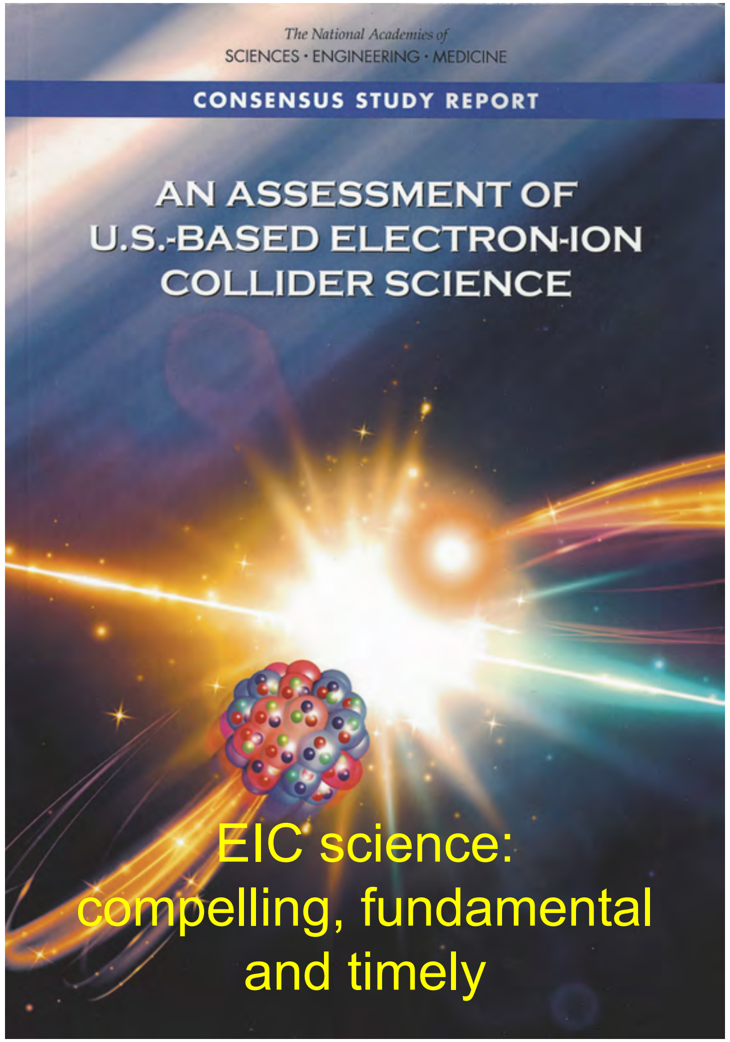
RECOMMENDATION:

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D



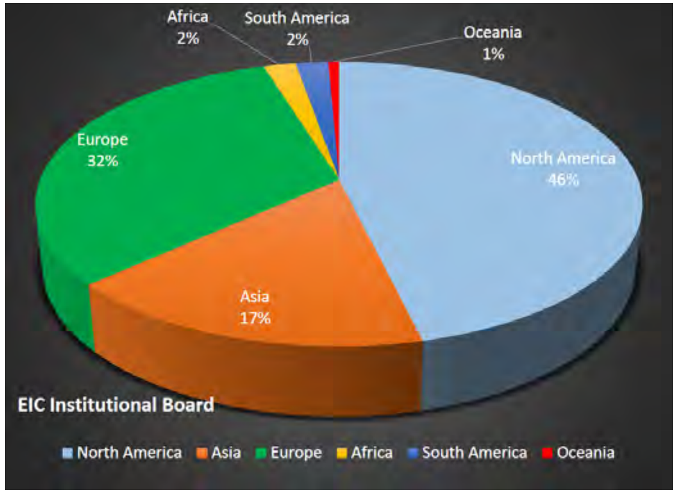
EIC science: compelling, fundamental and timely

Consensus Study Report on the US based Electron Ion Collider

Summary:

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

The EIC Users Group: EICUG.ORG



Formally established in 2016
~950 Ph.D. Members from 30 countries, 189 institutions

New:
[Center for Frontiers in Nuclear Science](#) (at Stony Brook/BNL)
[EIC²](#) at Jefferson Laboratory

EICUG Structures in place and active.
EIC UG Steering Committee, Institutional Board, Speaker's Committee

Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Warsaw (2021)**

Opportunities for YOU: Physics @ the US EIC beyond the EIC White Paper:

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs, especially at high x, for LHC
- *What role would TMDs in e-p play in W-Production at LHC?*
- *Gluon TMDs at low-x!*
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?

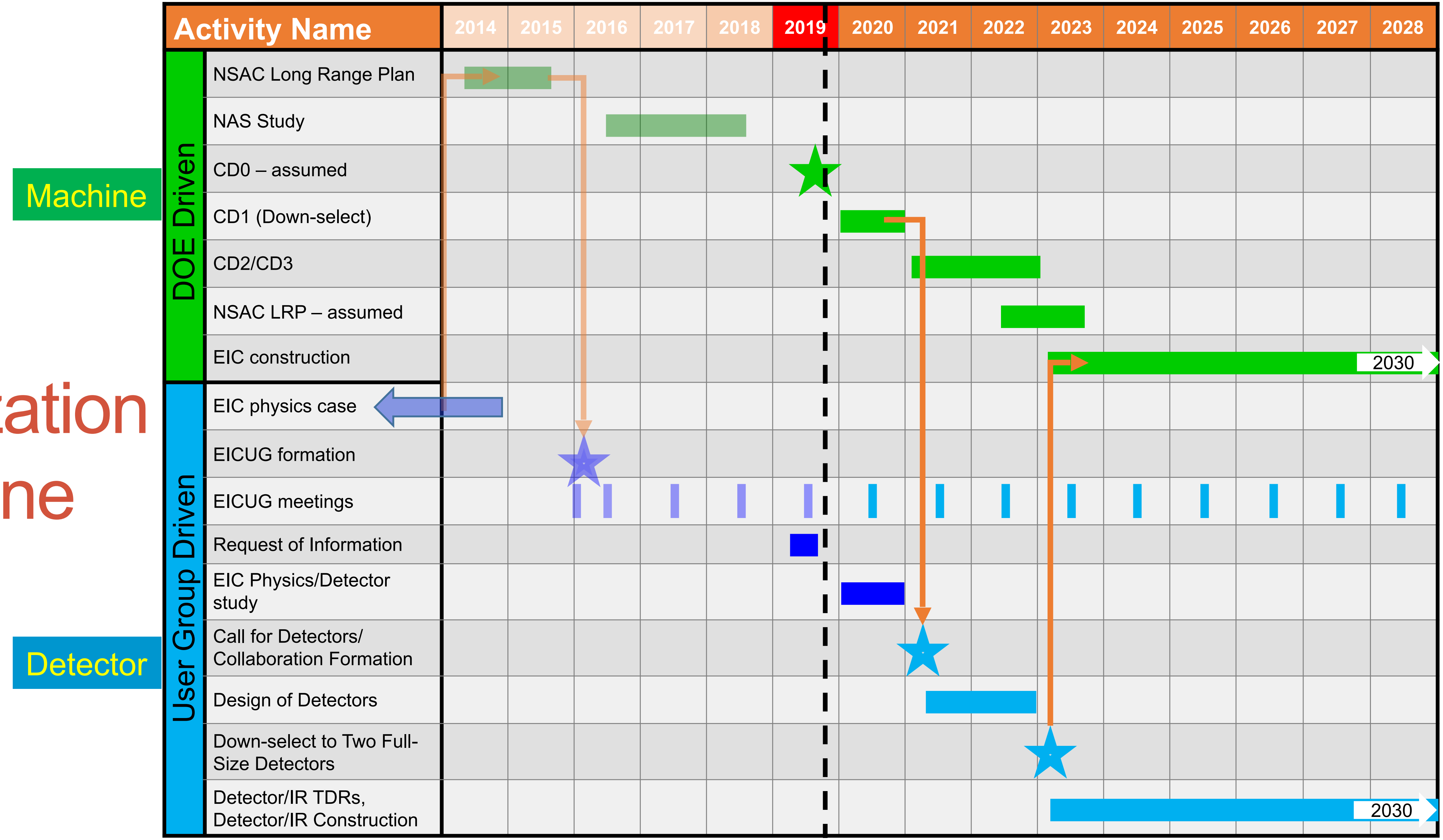
Physics with nucleons and nuclear targets:

- *Quark Exotica: 4,5,6 quark systems…?*
- Study of jets: Internal structure of jets
- *Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium: a topic interest*
- Initial state affects QGP formation!….. p-A, d-A, A-A at RHIC and LHC: many puzzles
- Polarized light nuclei in the EIC
- *Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement*

Precision electroweak and BSM physics:

- Electroweak physics and searches beyond the Standard Model

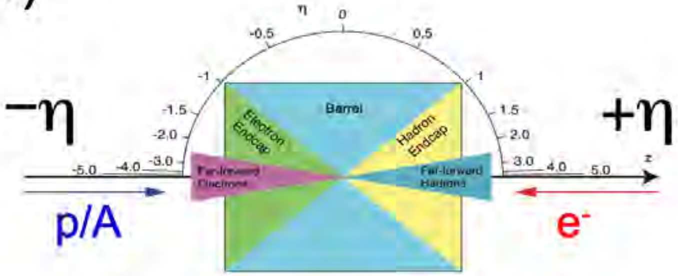
EIC realization timeline



EIC detector

More discussion in the evening

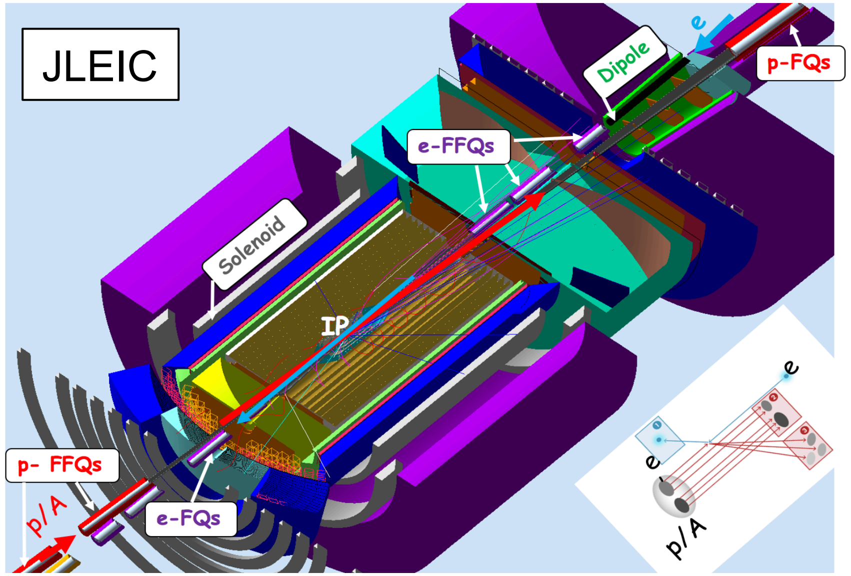
- **Key features:**
  - Vertex + central + forward/backward tracker layout
  - Central detector: hermetic coverage in tracking/calorimetry/PID for $|\eta|<4$
  - Advanced far forward instrumentation (Roman Pots, ZDC, etc)
  - Far backward instrumentation (Low Q^2 tagger)
  - Low material budget in the tracker volume
  - 1.4 – 4.0 T central solenoid field
  - Moderate momentum resolution (~1% level)
  - Moderate-to-high vertex resolution (<20 μm or so)
  - Moderate EmCal and HCal energy resolution

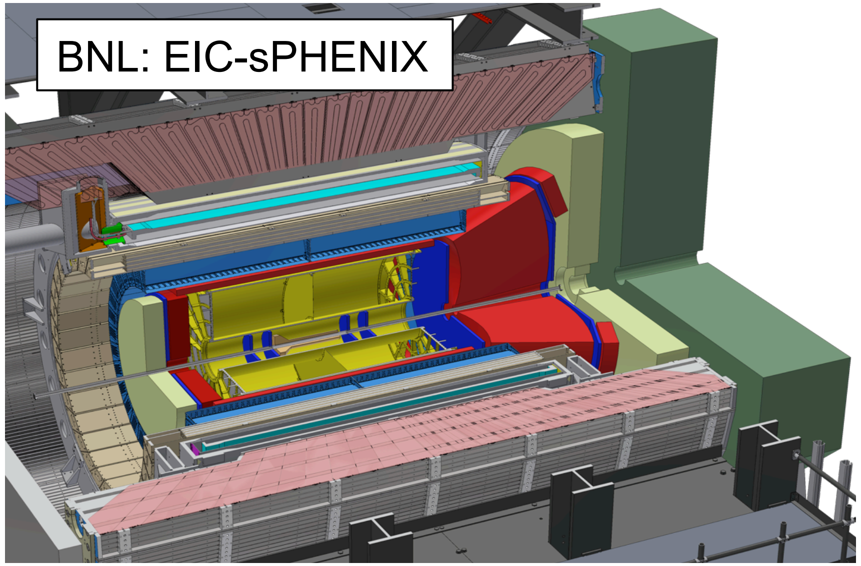


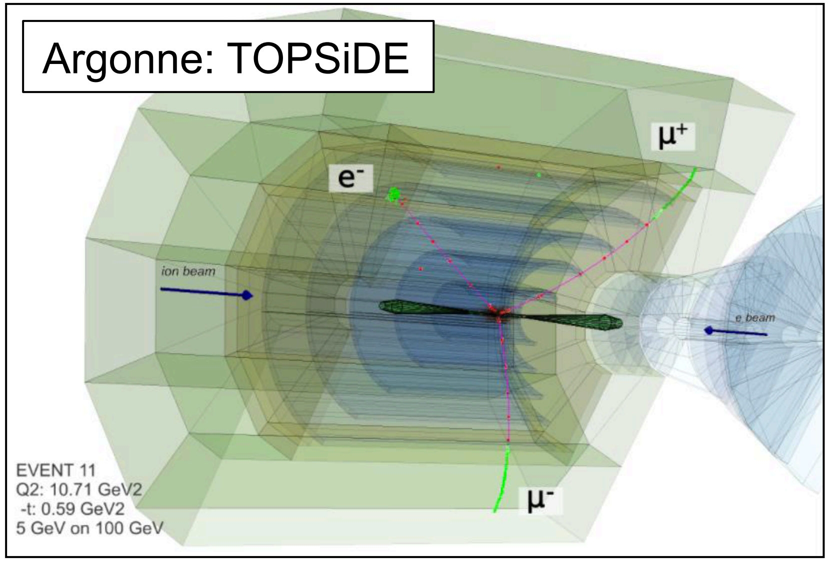
$-4<\eta<4 \sim [2^0 .. 178^0]$

Two detectors are desired: to be decided on the funding, time-line, need for complementarity, and other things

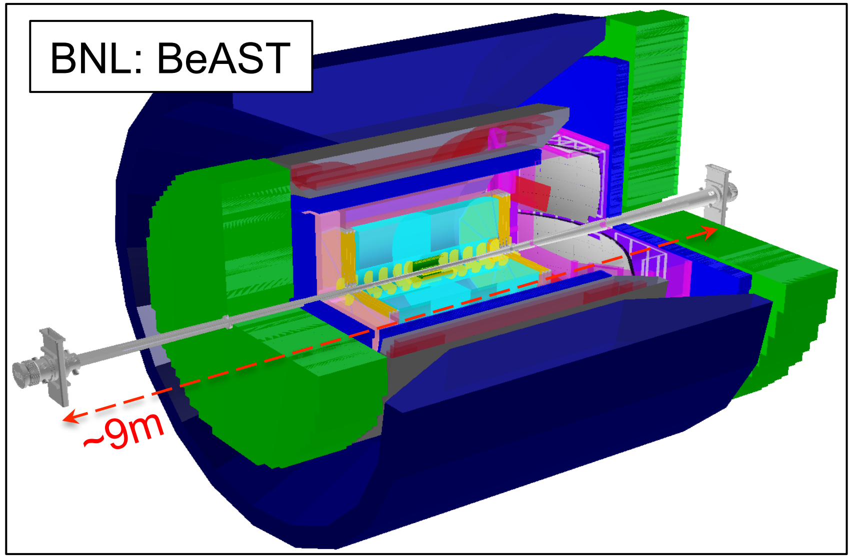
Current EIC detector concepts







Time OPtimized Silicon Detector for EIC



[Defining features]

Furletova and Kiselev

EIC detector progress/status

Ongoing studies: optimizing inclusive, semi-inclusive and exclusive DIS measurements: *Particle tracking, Electromagnetic calorimetry, hadronic calorimetry, particle identification technologies: for flavor separation/heavy-light quarks, jets, Interaction region design and integration with the EIC detector, background studies, synchrotron radiation issues near and far from the IR, beam-gas interactions….*

Additionally: *Electron and proton beam polarimetry, precision polarimetry measurements*

Various preliminary concepts for EIC detector exist, design optimization on-going

Close collaboration between *theorists, experimentalists and accelerator physicists*

Contribution from US and International Collaborators and institutions **essential**

EIC detector R&D program

- Started 2011 BNL, in association with JLab and the DOE Office of NP
- Funded by DOE through RHIC operations funds
- Program explicitly open to international participation
- Standing EIC Detector Advisory Committee consisting of internationally recognized experts in detector technology
- Typical 10-11 projects supported per FY
- 195 participants from 49 institutions (16 non-US)

Left-to-Right: Marcel Demarteau (ORNL, Chair), Carl Haber (LBNL), Peter Krizan(Ljubliana), Ian Shipsey(Oxford), Rik Van Berg (UPenn), Jerry Va'vra (SLAC) , Glenn Young (BNL)

EIC Detector R&D: types of activities

- Detector hardware related R&D
- Software development
- Detector related simulation studies
- Consortia:
  - Work on various technologies related to major detector components
  - Tracking, particle ID, calorimeter, software/simulations

- Many of the consortia are active since 2011, some of them have finished their work by achieving their stated goals
- For more information go to the EIC Detector R&D Wiki Page:

Yellow Report for EIC Physics and Detectors

For seeding future experimental collaborations

- **CERN Yellow Reports** series provides a medium for communicating CERN-related work where publication in a journal is not possible. Reports have a large impact on the future of CERN, as well as reports on new activities which do not yet have a natural platform. They includes reports on *detectors and technical papers, criteria being that the audience should be large and the duration of interest long*. We borrowed the exact same term.

- **EIC Yellow Reports** Advance the state of documented (i) physics studies (White Paper, INT program proceedings) and (ii) detector concepts (Detector and R&D Handbook) in preparation for the EIC. This will provide both the basis for development of concepts for experimental equipment best suited to the EIC science needs, including complementarity of the two detectors/interaction regions, and input towards future Technical Design Reports (TDRs) of the experimental equipment.

Yellow report strategy:

- Quantify measurements for the EIC physics (existing and new/emergent)
  - Under a **Physics Working Group** (see eicug.org for convener names etc.)
  - Address: *physics motivation → detector requirements, two vs. one detectors*
- Study detector concepts based on those physics measurements
  - Under a **Detector Working Group** (see eicug.org for convener names etc.)
  - Address: Detector concepts → technology, complementarity, experimental systematics,
  - Also address: folding in polarimetry, luminosity
  - Engage EIC detector R&D
- Study opportunities for future accelerator physics experiments
  - An **Accelerator Working Group** (see eicug.org for convener names etc.)

Yellow Report timeline 2020-2021

Workshops:

- 1st Workshop: March 19-21, 2020, Temple University, Philadelphia, PA
- 2nd Workshop: May 22-24, 2020, University of Pavia, Pavia (Italy)
- Status reports at Summer EICUG Meeting: August 3-7, 2020, FIU, Miami, FL 3rd
- 3rd Workshop: September 17-19, 2020 CUA, Washington, DC
- 4th Workshop: November 19-21, 2020, UC Berkeley, Berkeley, CA
- Optional final meeting in January 2021

Followed by:

- Period of web-based EICUG community input
- Independent review of the yellow reports
- **Release of the final report January-April 2021**

Summary and message of this talk

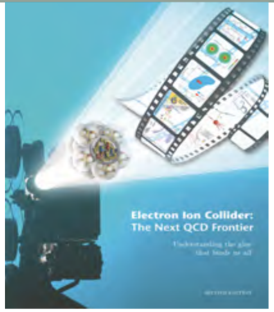
- EIC science is about *non-linear parton interactions & dynamics* in nucleons and nuclei: at the heart of which is to study the **role of gluons in QCD**
- Experimental studies employing an Electron Ion Collider with high luminosity and with polarized beams is deemed essential.

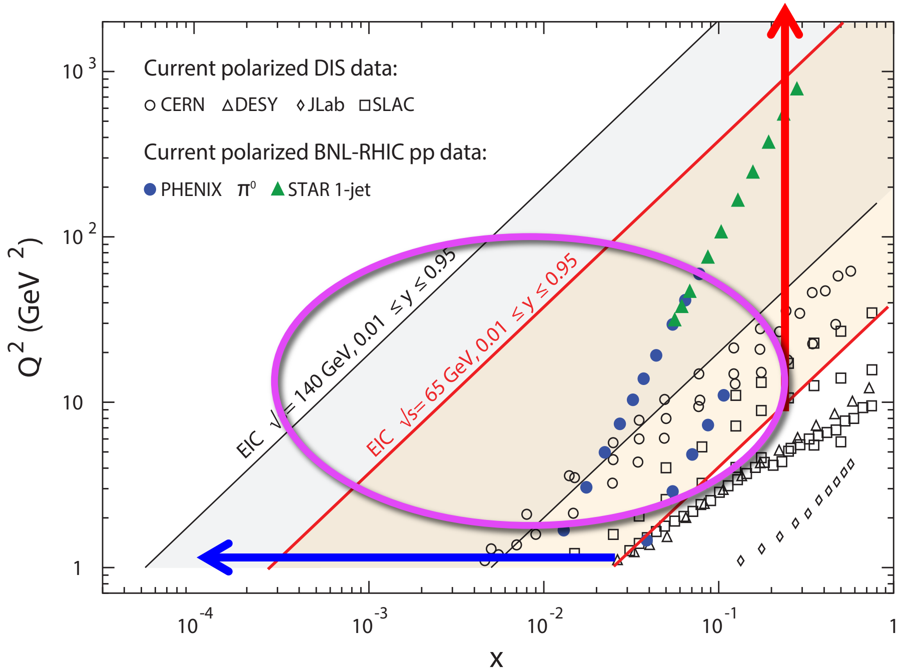
- National Academy's review and strong endorsement for the science has led to planning of EIC's realization. **Timeline for 1st collisions ~2030.**
- User Group members will eventually lead the experimental detector design and construction (through detector collaborations) **stepping up their activities.**

- Participation from the Indian (and other international) groups is opportune and essential. -- This workshop will hopefully begin the discussions.

Thank you.

EIC: Kinematic reach & properties





For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)