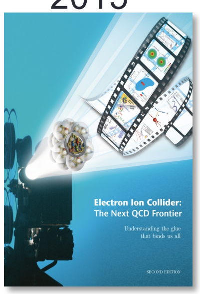
Center for Frontiers in Nuclear Science

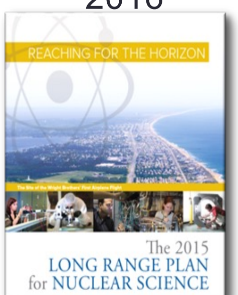
The Electron Ion Collider -- the next QCD frontier

Understanding the Glue That Binds Us All

2015

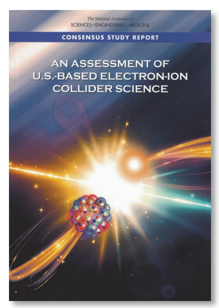


2016



Physics of EIC

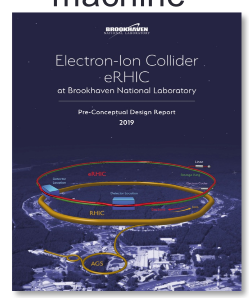
2018



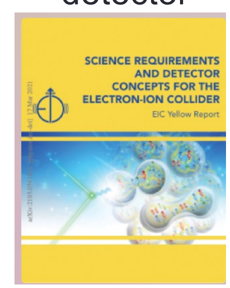
Evaluation

2019-present

machine



detector

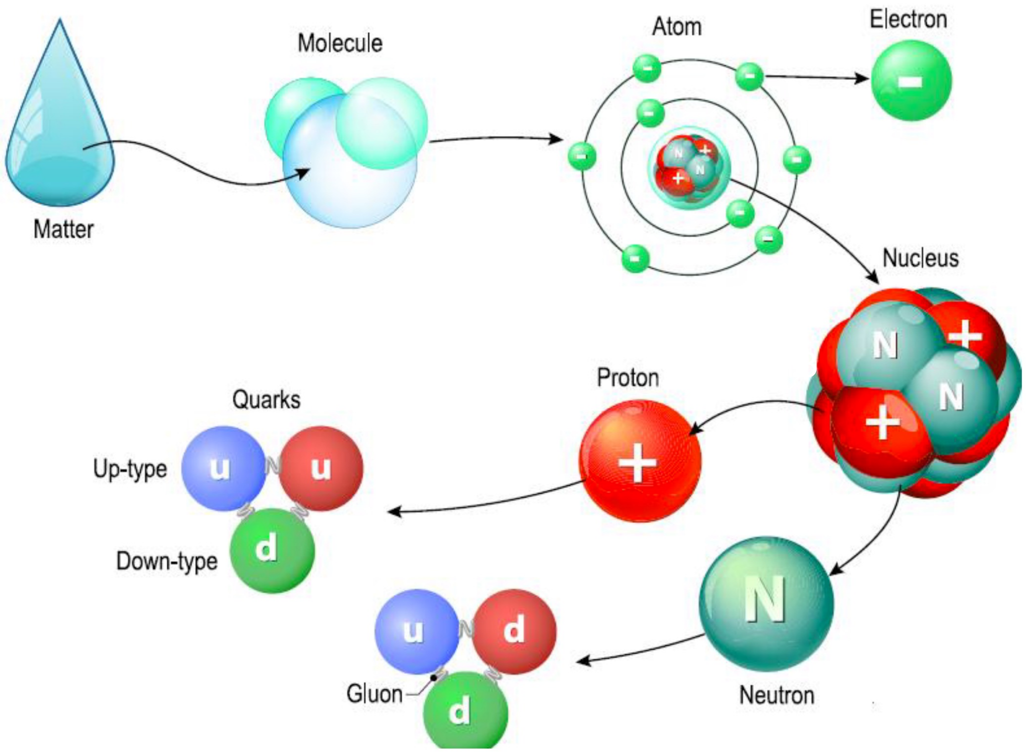


Realization

2023

Build expeditiously

Quest for the fundamental structure of matter



What's in there?

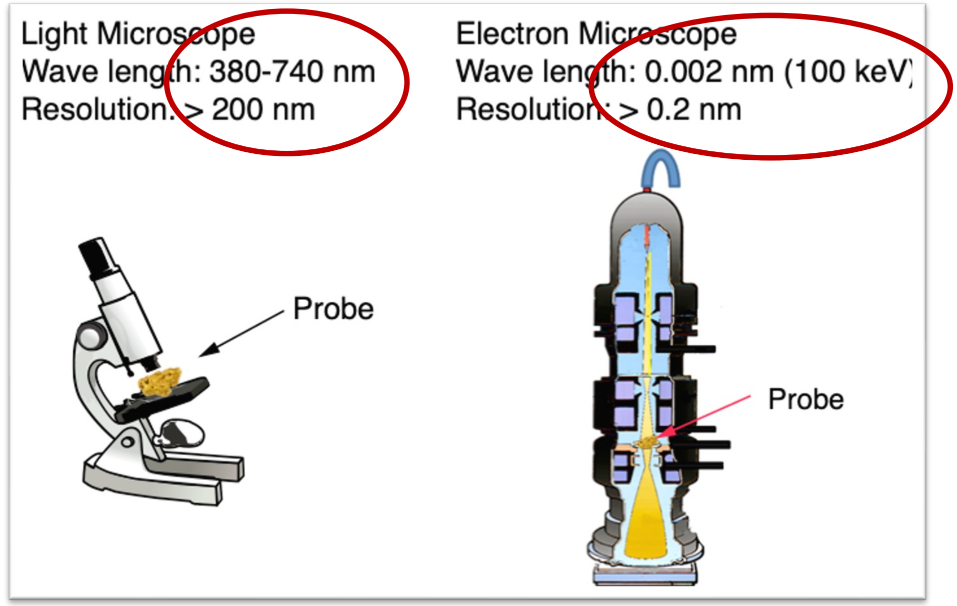
What are we made up of?

What is the "smallest"?

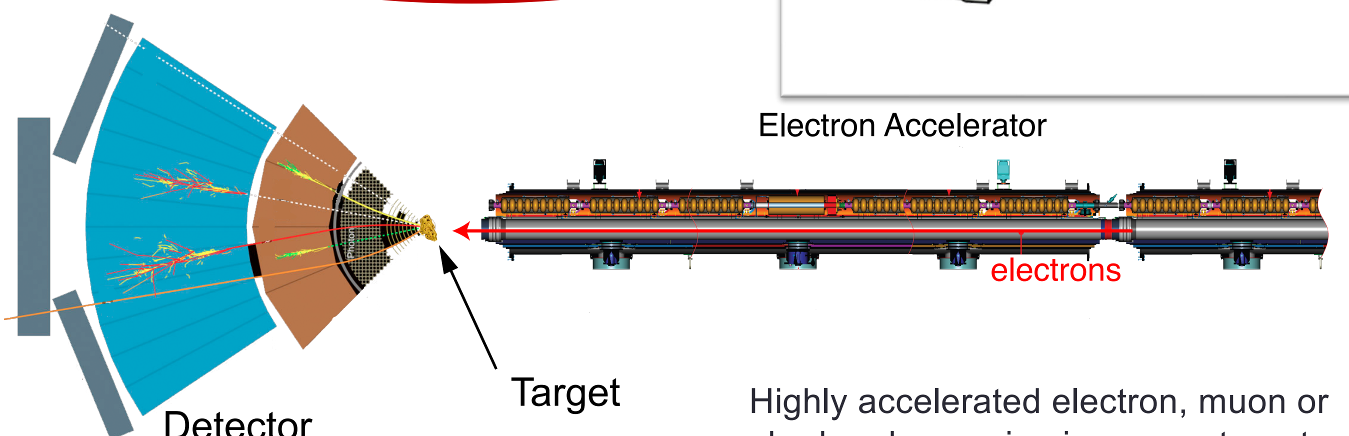
What is "fundamental" that can't be divided further?

National Academy of Sciences, Consensus Report on the US EIC

Studying smaller and smaller things…

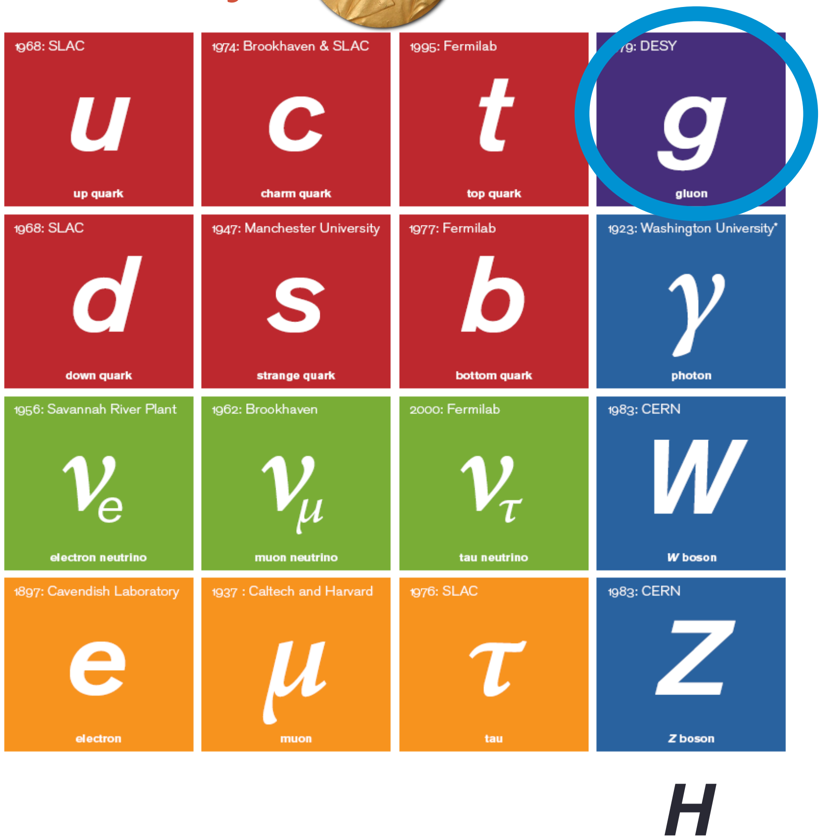


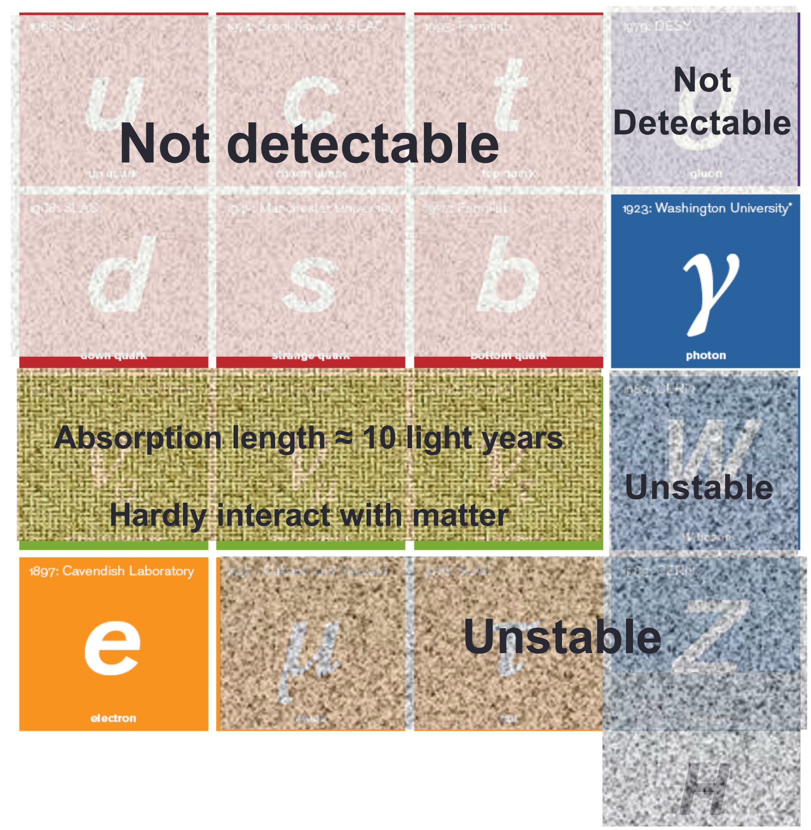
Fixed Target Particle Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm



Highly accelerated electron, muon or hadron beams impinge on a target

Many . Difficulties in understanding our universe



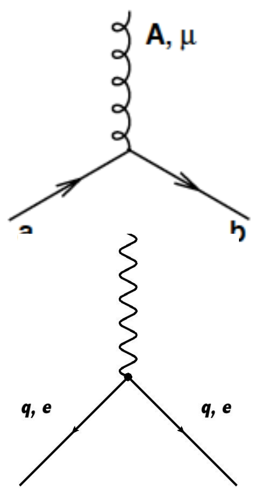


What distinguishes QCD from QED?

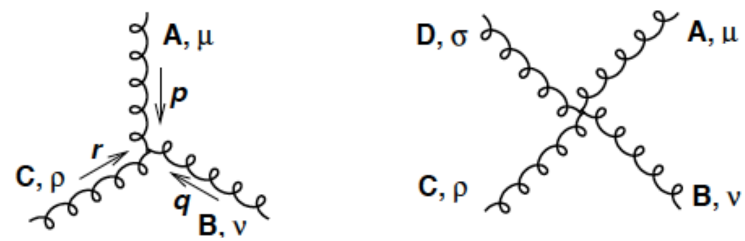
QED is mediated by photons (γ) which are charge-less (and couple to charged particles)

QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

g In QCD
and
γ in QED



Only in QCD



Nonlinear growth in g-g interactions…
Bring richness and complexity to QCD
Experimental guidance always needed

Emergent dynamics in QCD & its significance

Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. (Striking examples besides confinement are phenomena like spontaneous symmetry breaking and anomalies).

Without gluons, there would be no nucleons, no atomic nuclei…

no visible world!

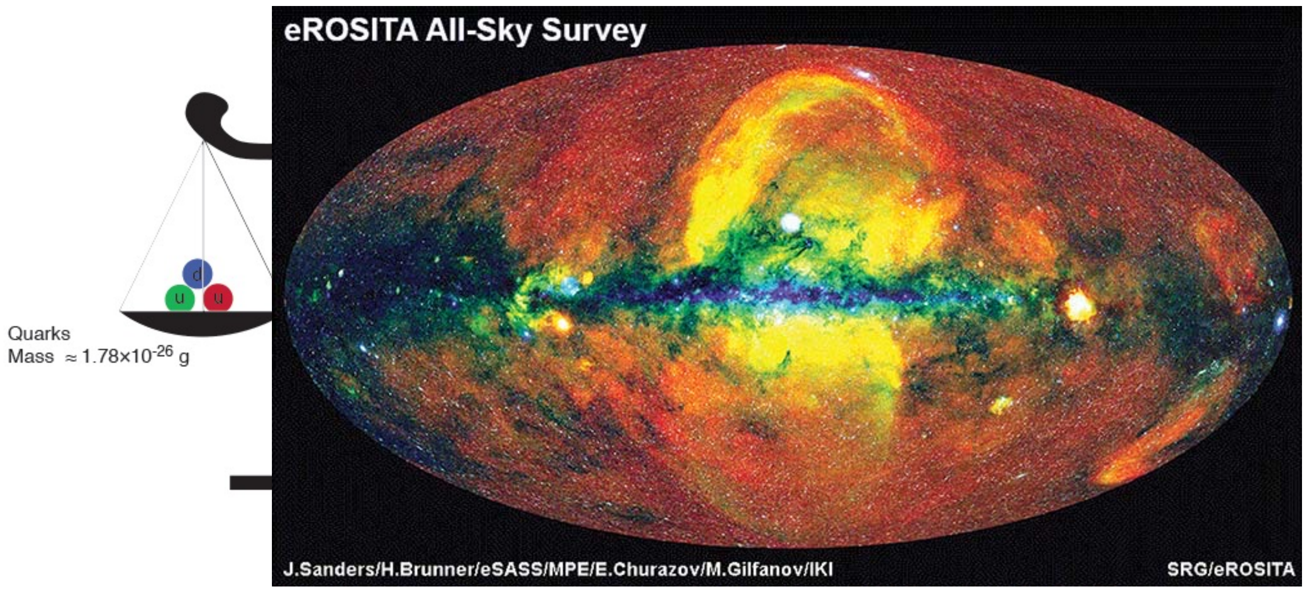
Experimental insight and guidance needed

Proton mass puzzle

François Englert

Peter W. Higgs

Nobel 2013 With Francois Englert
"Higgs Boson" that gives mass to quarks, electrons,….



Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

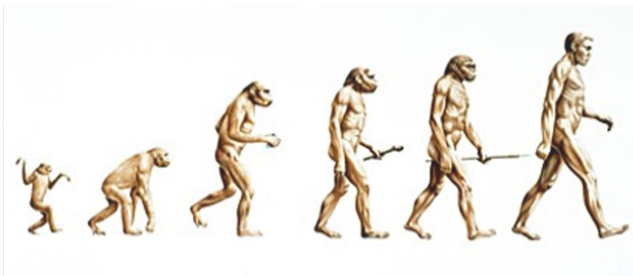
But the proton's mass is 168 x 10^{-26} grams

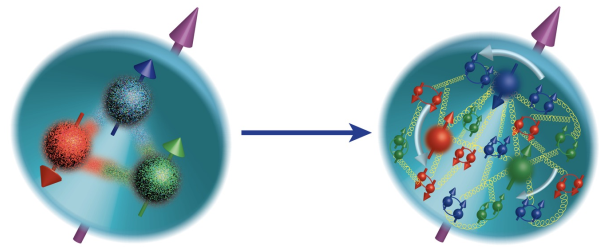
➔ **only 1% of the mass of the protons (neutrons)** ➔ Hence the Universe

➔Where does the rest of the mass come from?

Spin "Crisis" → Spin Puzzle

Discovered by EMC experiment at CERN
Confirmed by SMC, SLAC, HERMES
Gluon's contribution measured by RHIC





~25% ~25%

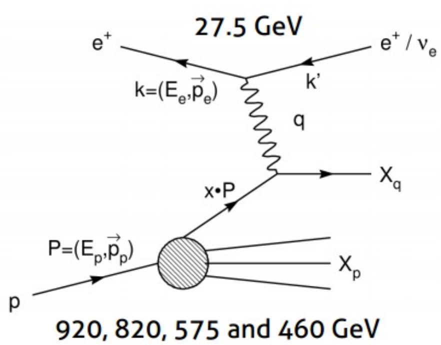
$$\frac{1}{2} = [\mathrm{Q}_{\mathrm{spin}} + \mathrm{Q}_{\mathrm{ang.mom.}}] + [\mathrm{G}_{\mathrm{spin}} + \mathrm{G}_{\mathrm{ang.mom.}}]$$

? ?

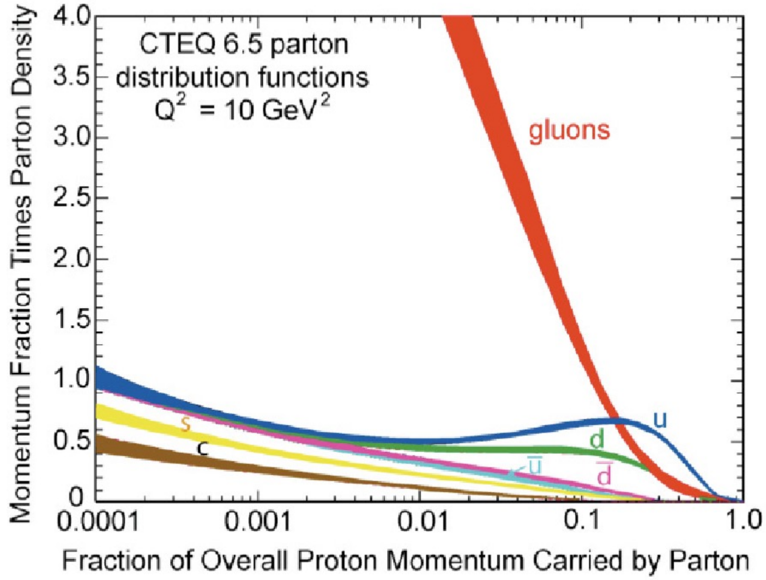
Left/right asymmetries in p-p & e-p scattering ➔ transverse motion of quarks
This, coupled with finite size of the proton must create the orbital motion (?)
Is this also connected to the mass?

Parton Distribution Functions from H1 & ZEUS : Deep Inelastic Scattering from the HERA Collider (1992-2006)

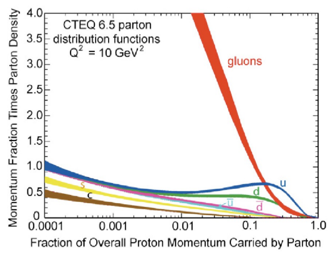
HERA — world only e±p collider



Would this growth of low-x gluon continue?

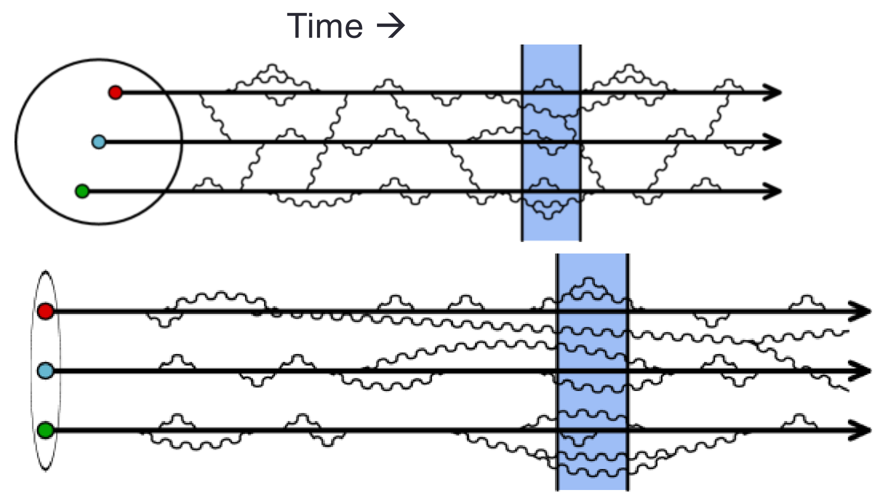


How does a Proton look at low and high energy?



Low energy: High x
Regime of fixed target exp.

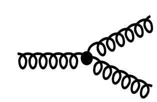
High energy: **Low- x**
Regime of a Collider



Cartoon of boosted proton

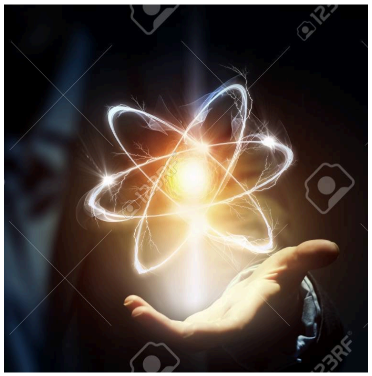
At high energy (i.e small-x):

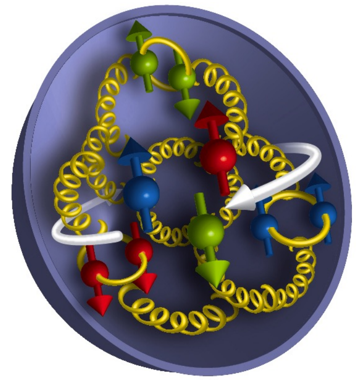
- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate smaller x gluons ➔ which in turn radiate more… a chain reaction leading to a **runaway growth?**



Gluon splitting

About 100 years after the discovery of the atom and the proton

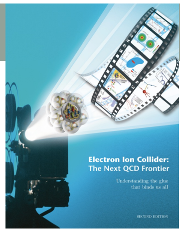




We know atomic structure so well, that we *define* “time” using electronic transitions:
Current accuracy
~1 sec in 220 Million years

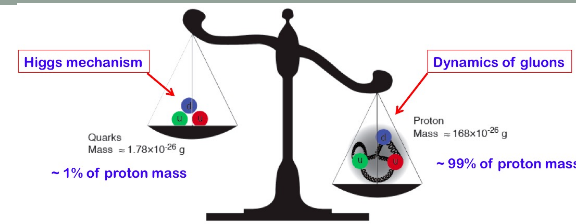
However, the internal structure of the proton is
known to only about 20-30%
~20 minutes in an hour…!

WHY? Because of the gluons

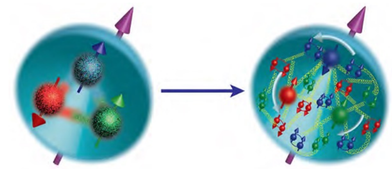


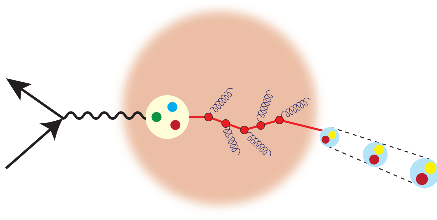
EIC Physics at-a-Glance

Eur. Phys. J. A 52 (2016) 9, 268 arXiv:1212.1701 (nucl-ex)

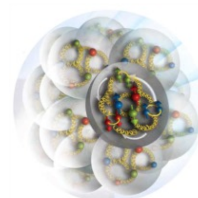


How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (mass & spin) emerge from their interactions?

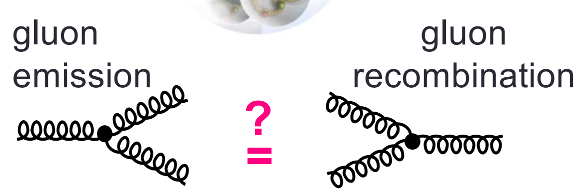




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

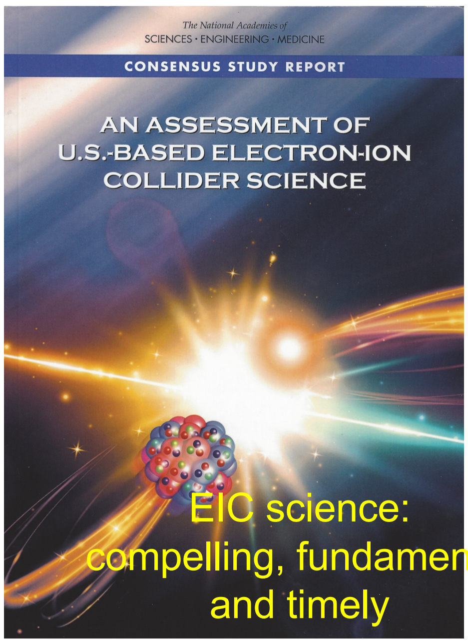


How does a dense nuclear environment affect the quark- and gluon- distributions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



National Academy of Science, Engineering and Medicine

Assessment July 2018



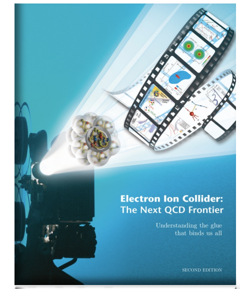
EIC science:
compelling, fundamental
and timely

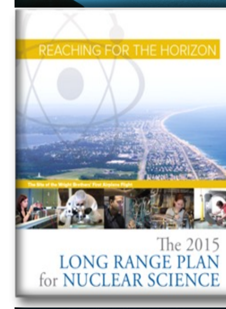
Physics of EIC

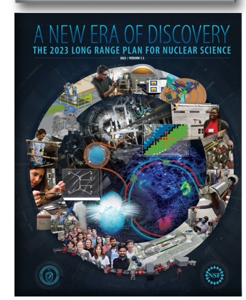
- Emergence of Spin
- Emergence of Mass
- Physics of high-density gluon fields

Machine Design Parameters:

- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice



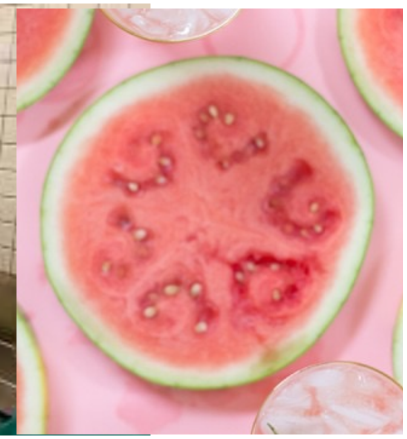




Study of internal structure of a watermelon:

A-A (RHIC/LHC)

1) Violent collision of melons

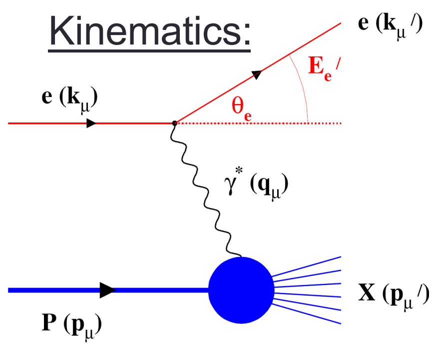


2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$ Measure of resolution power

$$Q^2 = 2E_e E'_e(1-\cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$ Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$ Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t$$ with respect to γ^*

$$s = 4\,E_h\,E_e$$

High lumi & acceptance

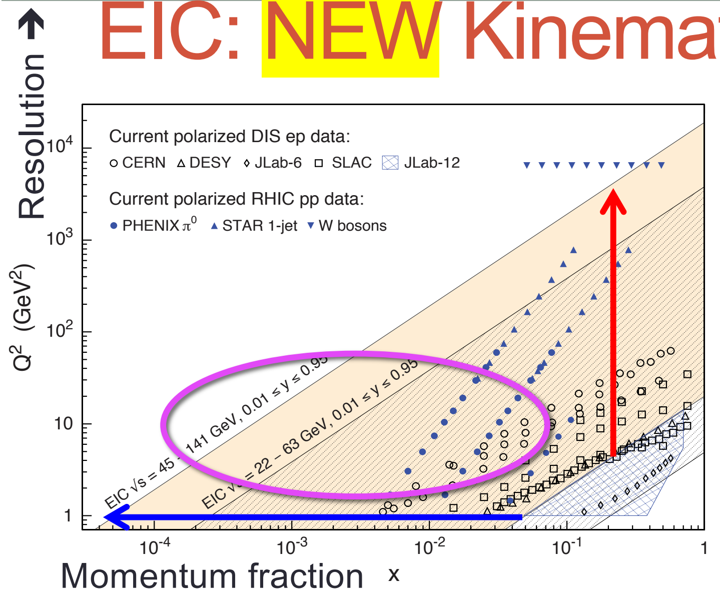
Exclusive DIS
detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:
e+p/A → e'+h(π,K,p,jet)+X
detect the scattered lepton in coincidence with identified hadrons/jets

Inclusive events:
e+p/A → e'+X
detect *only the scattered lepton* in the detector

Low lumi & acceptance

EIC: NEW Kinematic reach & properties

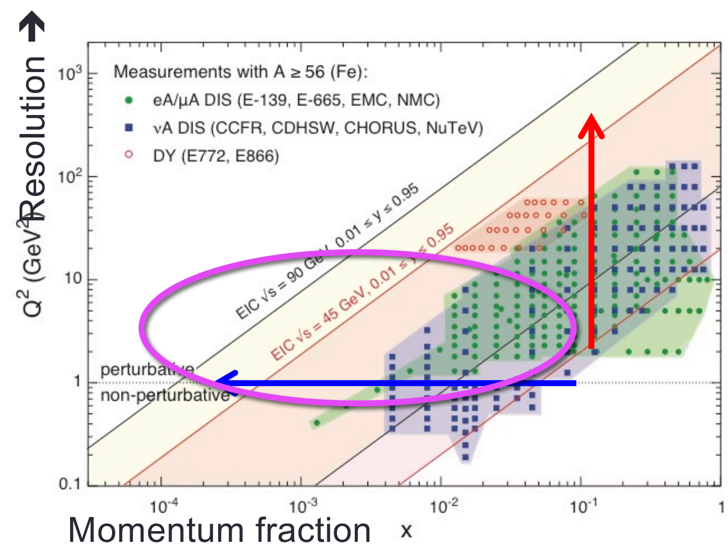


For e-N collisions at the EIC:

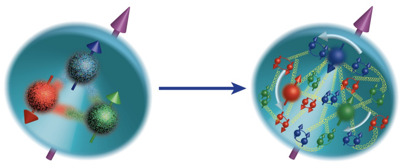
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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)



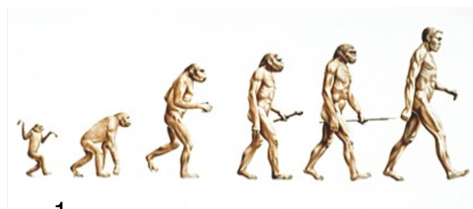
Nucleon Spin: Precision with EIC

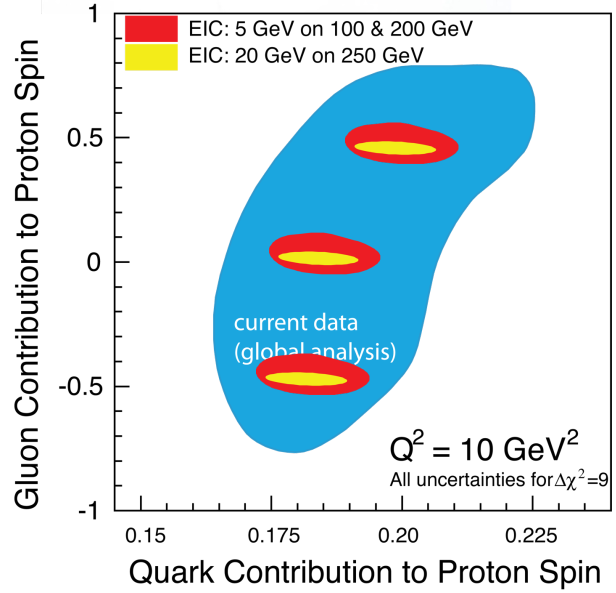


$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

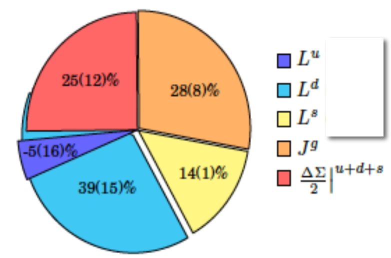
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

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





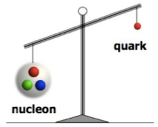
Spin in Lattice QCD:
Ab initio Calculations



- **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

SIDIS: strange and charm quark spin contributions

Mass of the Nucleon (Pion & Kaon)



"The mass is the result of the equilibrium reached through dynamical processes." **X. Ji**

" The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"
-- The 2015 Long Range Plan for Nuclear Science

Relativistic Motion ***Chiral Symmetry Breaking*** ***Quantum Fluctuations***

X. Ji, PRL 74 1071 (1995)

$$M = E_q + E_g + \chi_{m_q} + T_g$$

Quark Energy **Gluon Energy** **Quark Mass** **Trace Anomaly**

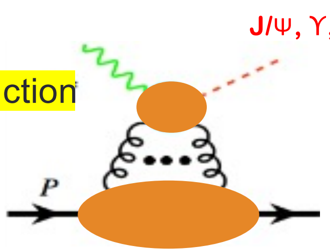
- Questions: scale-invariant? decompositions: Lorentz invariant?
- Recent interest (workshops planned) to clarify how to determine the different contributions
- **Lattice QCD providing estimates**

E_q ~30% E_g ~40% χ_{m_q} ~10% T_g ~ 25%

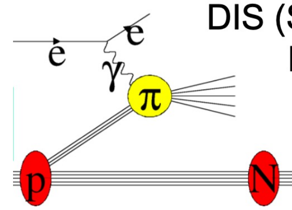
arXiv: 1710.09011

Trace anomaly:
J/Psi & Upsilon production near threshold:

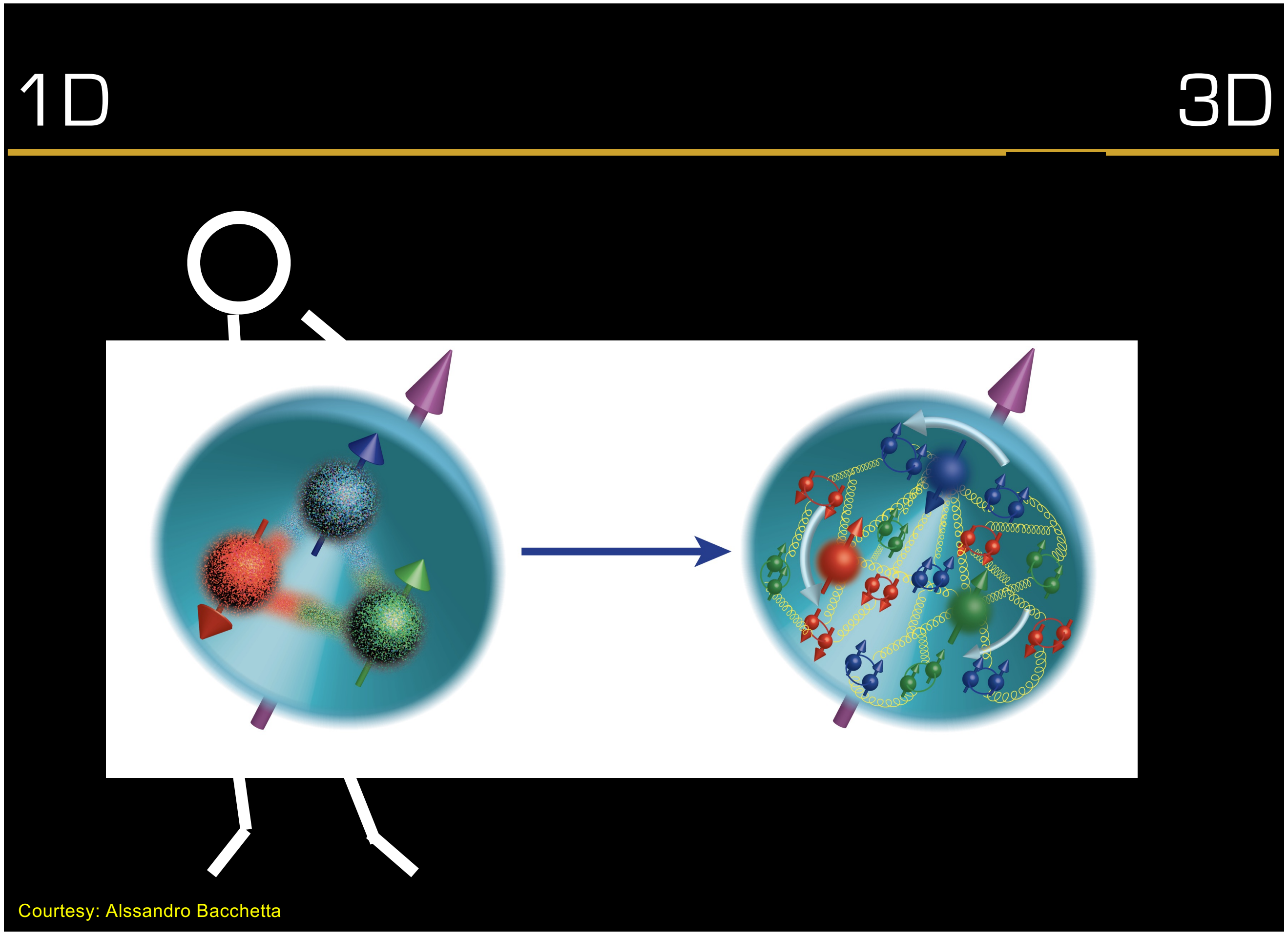
SoLID@JLab & EIC



DIS (Sullivan Process)



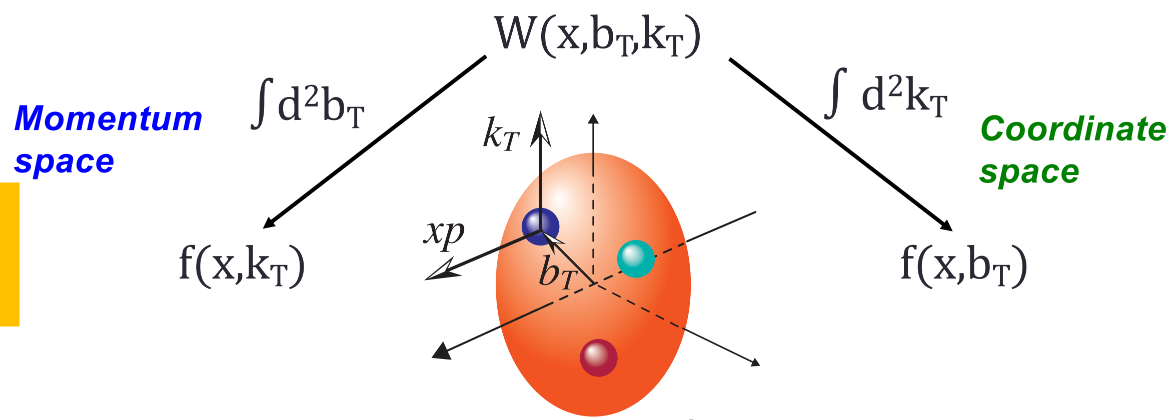
(pion/Kaon) PDFs: P. C. Barry et al. PRL 127, 232001 (2021)


1D
3D
Courtesy: Alssandro Bacchetta

2+1-Dimensional Imaging Quarks and Gluons

Wigner functions **$W(x,b_T,k_T)$**
offer unprecedented insight into confinement and chiral symmetry breaking.

Direct Comparison with lattice QCD



Spin-dependent 3D **momentum space** images from semi-inclusive scattering
→ **Transverse Momentum Distribution**

Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply virtual Compton scattering and meson production)
→ **Generalized Parton Distributions**

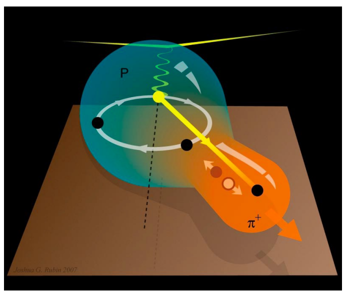
momentum and position distributions → Orbital motion of quarks and gluons

Possible direct access to gluon Wigner function through diffractive di-jet measurements at an EIC: Y. Hatta et al. PRL 16, 022301 (2016)

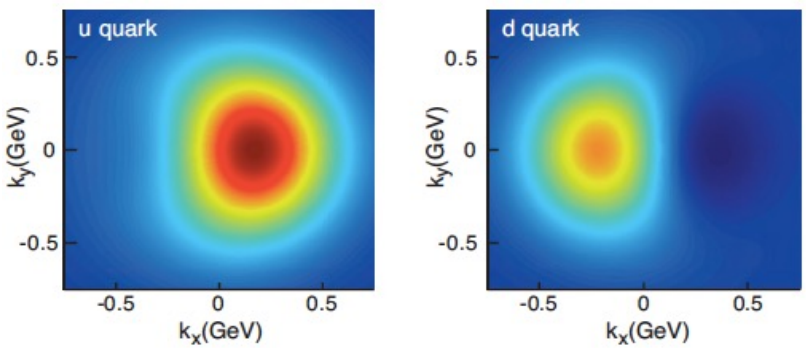
2+1 D partonic image of the proton with the EIC

Spin-dependent (2+1)D momentum space images from semi-inclusive scattering (SIDS)

Transverse Momentum Distributions

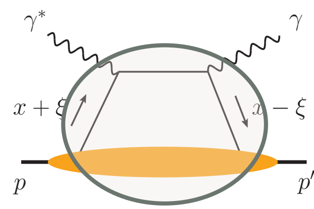


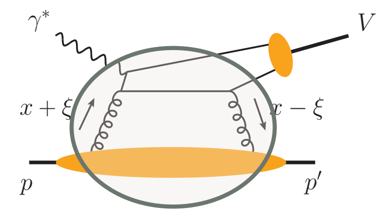
Quark's 2D momentum distribution



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

Quarks Motion



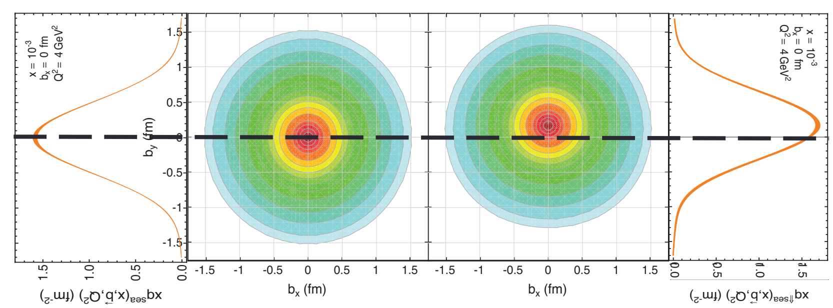


Gluons: Only @ Collider

Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

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

Sea quark's 2D position distribution
unpolarized polarized



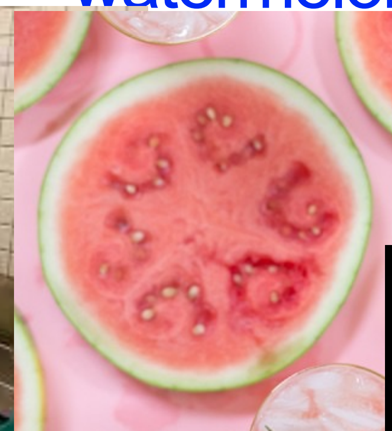
Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons

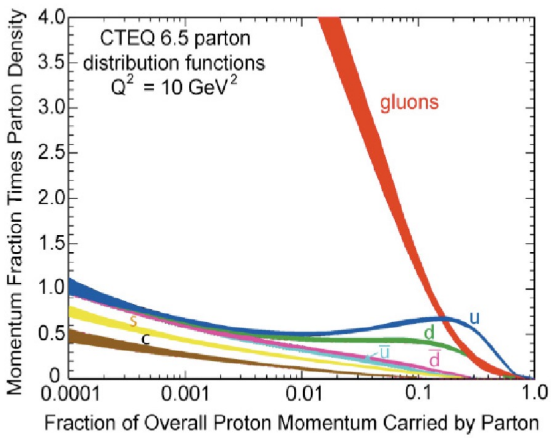
2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)



3) MRI of a watermelon

Non-Violent e-A (EIC)

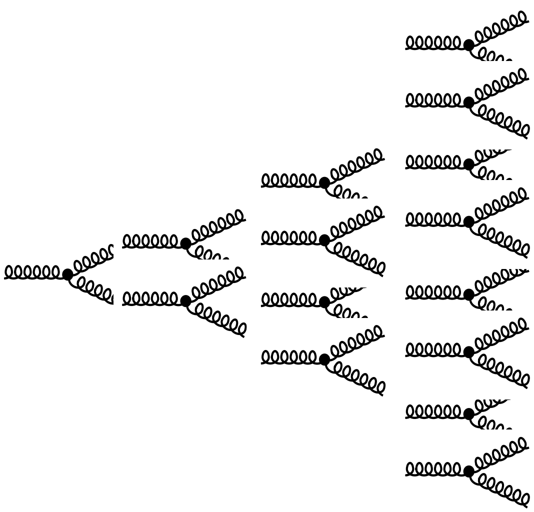


Gluon carry color… self-interactions and consequence:

Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud…."

F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004



? Infinity?

No!

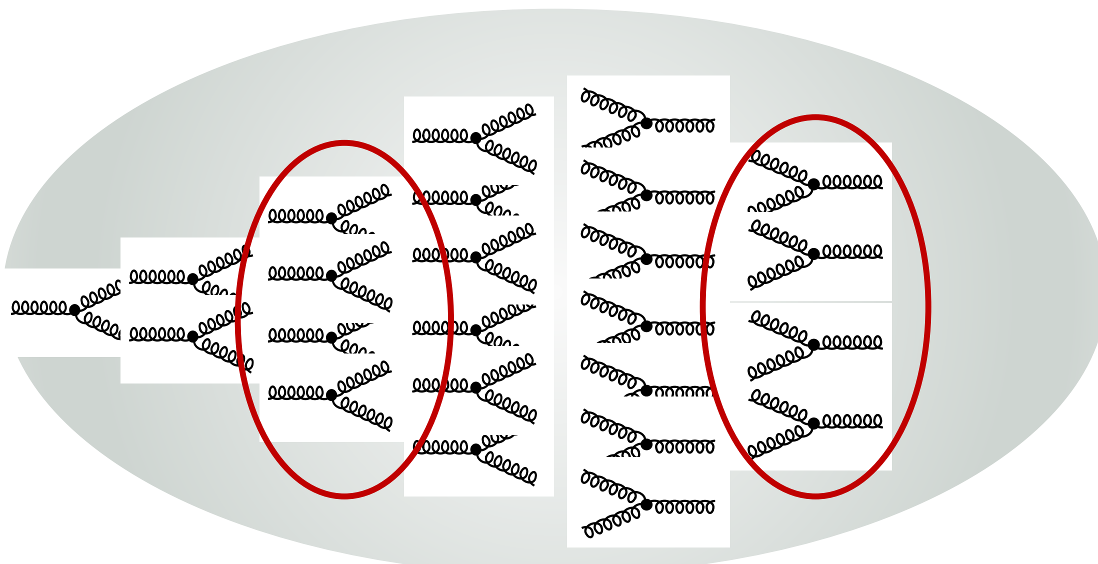
REALLY?

Gluon and the consequences of its interesting properties:

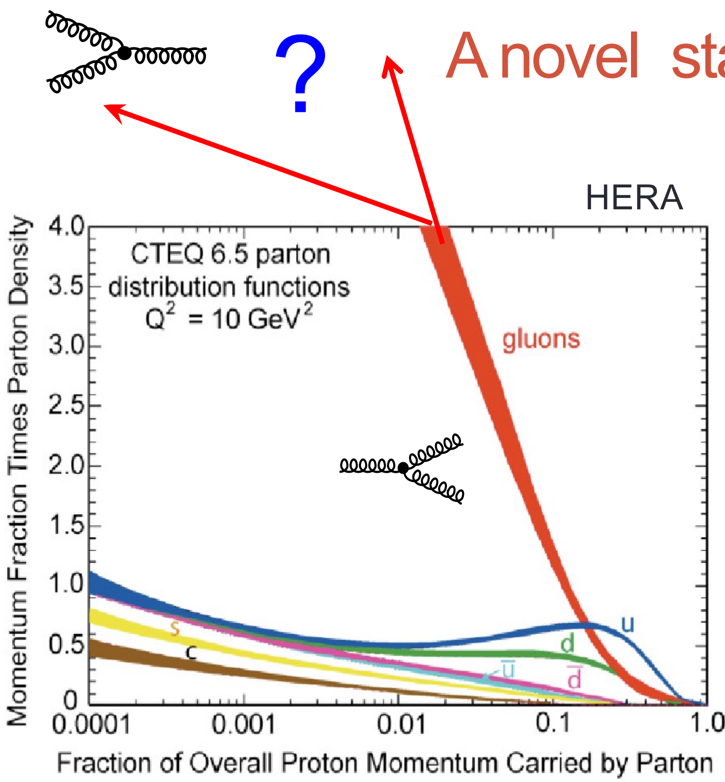
Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud…."

F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004



QCD as we know it predicts
A novel state of (~gluonic) matter at high energy



Experimental evidence for such a gluonic matter is needed

What could tame the low-x rise?
Can EIC access this region?

QCD inherently has the needed mechanism for this taming but we don't know when it gets triggered.

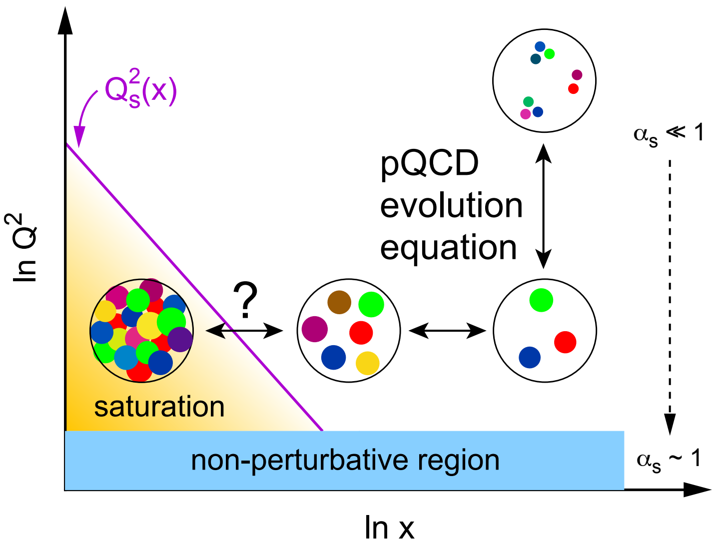
Observation of gluon recombination effects

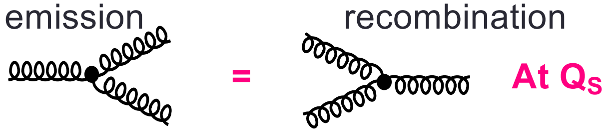
→ Is there such new state of matter?

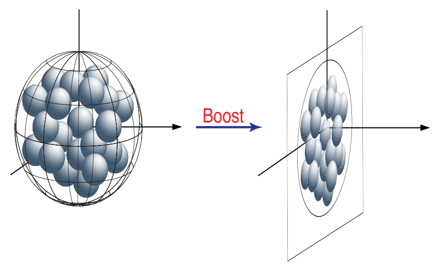
→ "Color Glass Condensate"

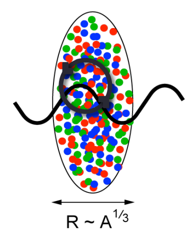
→ 50-100 times higher energy density than the core of the neutron star

Low x physics with nuclei





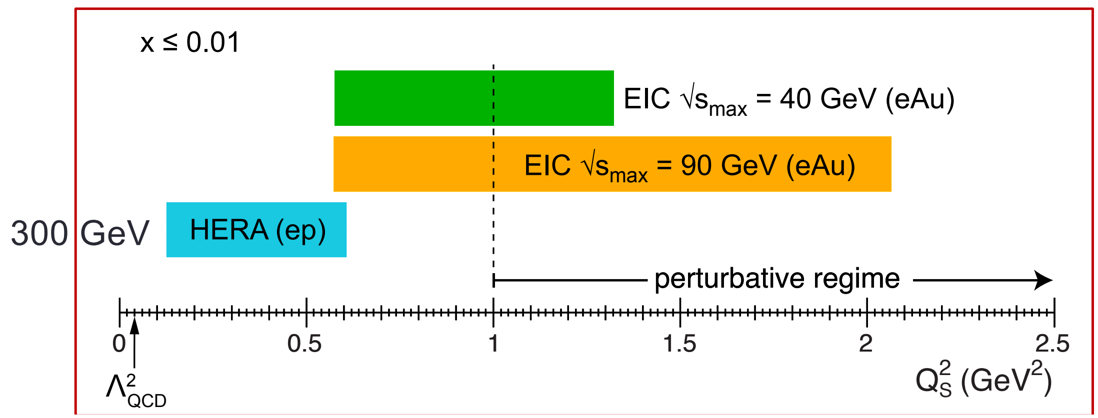




$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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

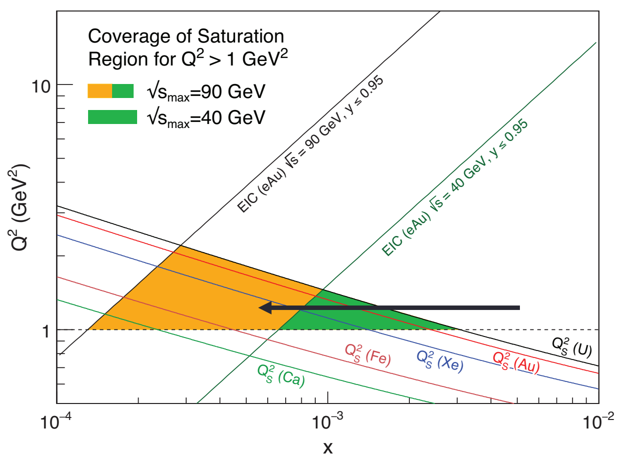
Accessible range of saturation scale $Q_s^{\ 2}$ at the EIC with e+A collisions.
arXiv:1708.01527



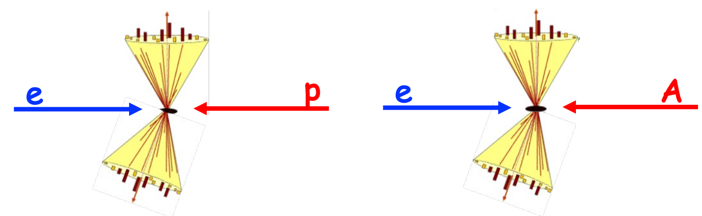
Can EIC discover a new state of matter?

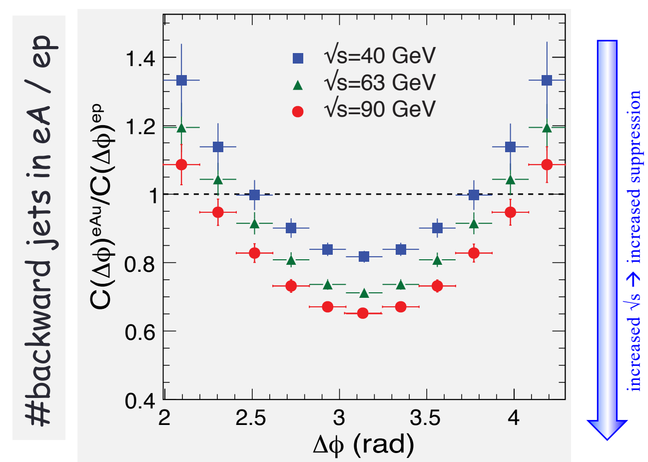
EIC provides an absolutely unique opportunity
to have very high gluon densities
→ electron – lead collisions
combined with an unambiguous observable

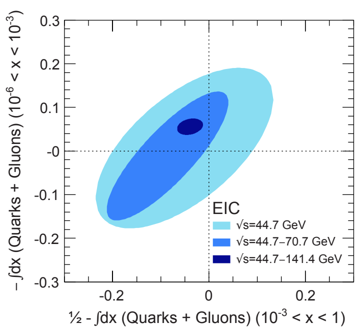
EIC will allow us to unambiguously
map the transition from a non-saturated to
saturated regime

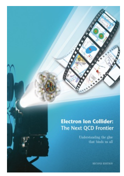


counting experiment of
Di-jets in ep and eA
Saturation:
Disappearance of backward jet in eA

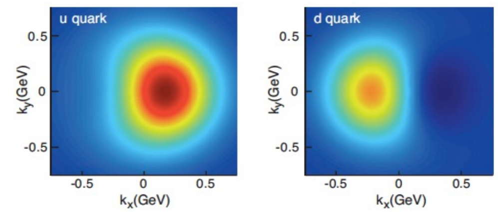


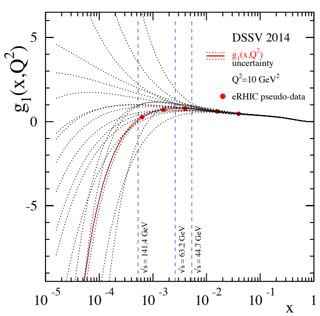


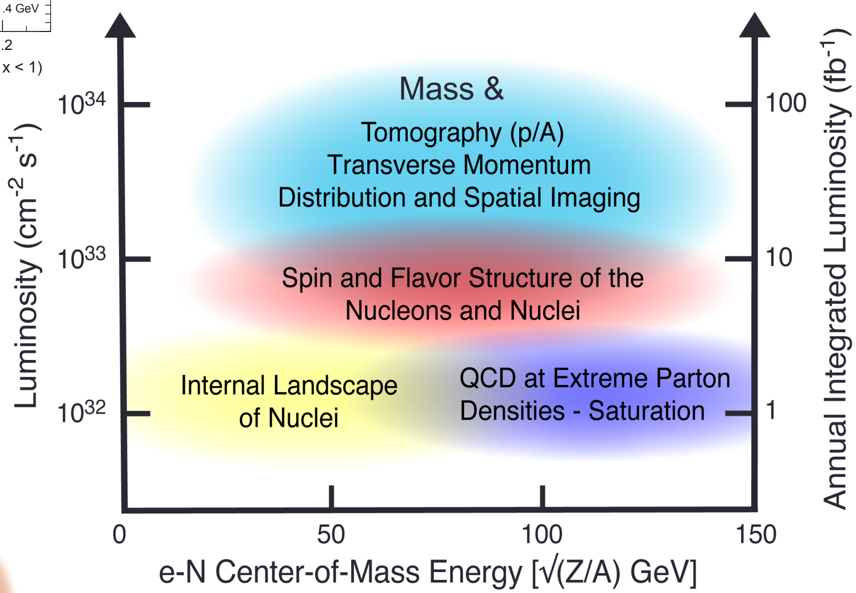


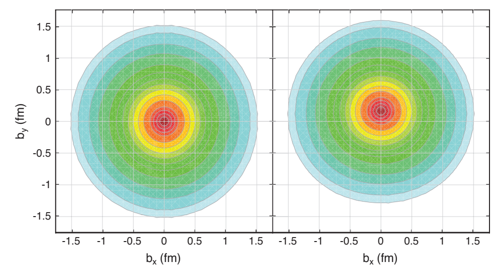


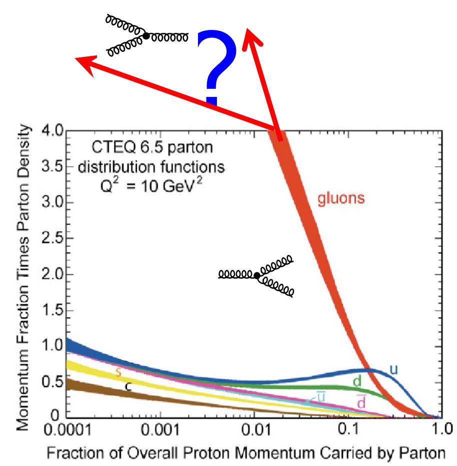
EIC science highlights

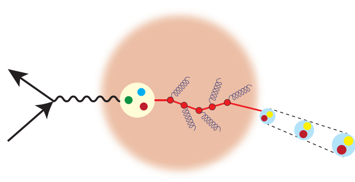












Physics @ the US EIC beyond the EIC's core science

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- Precision calculation of α_S : higher order pQCD calculations, twist 3
- Heavy quark and quarkonia (c, b quarks) studies with **100-1000 times lumi of HERA and with polarization**
- Polarized light nuclei in the EIC

Physics with nucleons and nuclear targets:

- Quark Exotica: 4,5,6 quark systems…? Much interest after recent **LHCb** led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Jets as probe of nuclear matter & Internal structure of jets : novel new observables, energy variability
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement

Precision electroweak and BSM physics:

- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity

Study of universality: e-p/A vs. p-A, d-A, A-A at RHIC and LHC

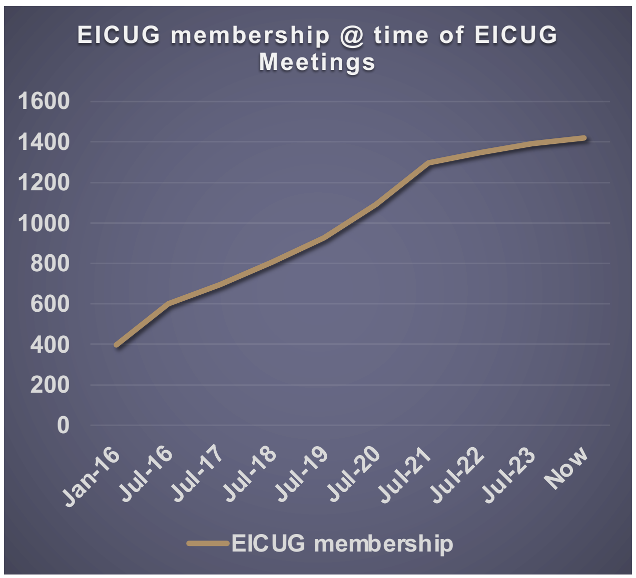
Worldwide Interest in EIC

The EIC User Group:
https://eicug.github.io/

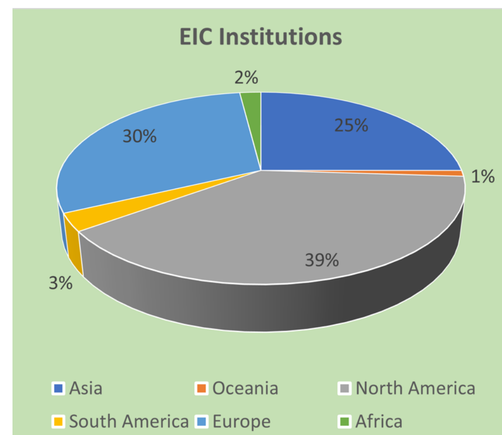
Formed 2016 –

- **1417 collaborators,**
- **37 countries,**
- **285 institutions**

as of October 02, 2023.
Strong International Participation.

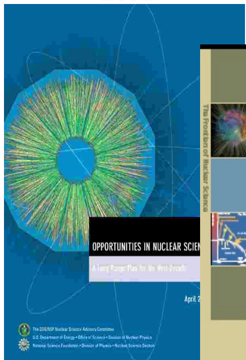


Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 FIU, Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland
2024 Lehigh U, PA



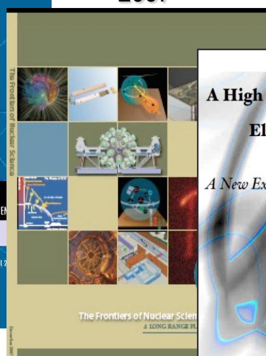
The Scientific Foundation for an EIC was Built Over Two Decades

2002



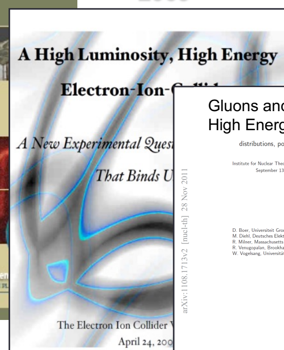
“…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term.”

2007



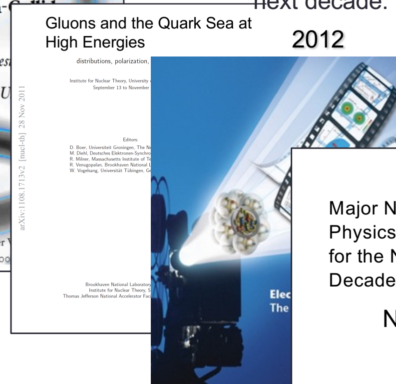
“We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…”

2009



“..a new dedicated facility will be essential for answering some of the most central questions.”

2010

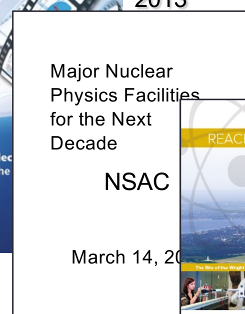


“The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider..”

2012

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

2013



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.”

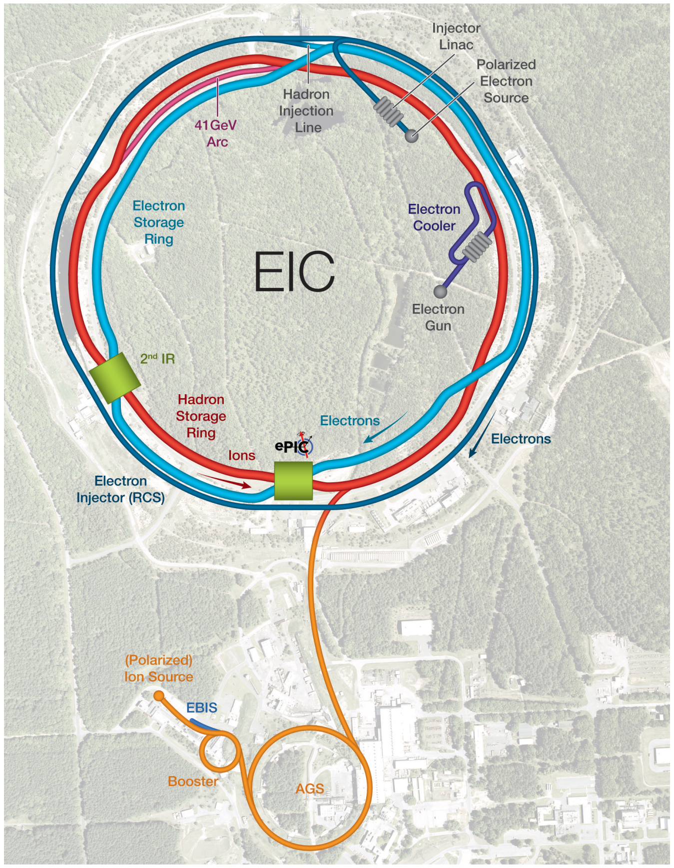
2021

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

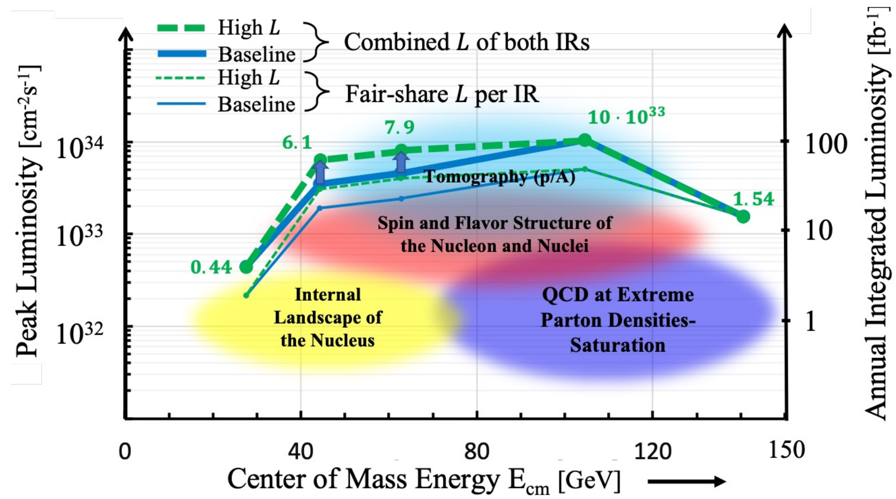
2023

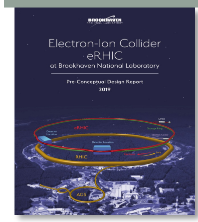
Build expeditiously

EIC Accelerator Design

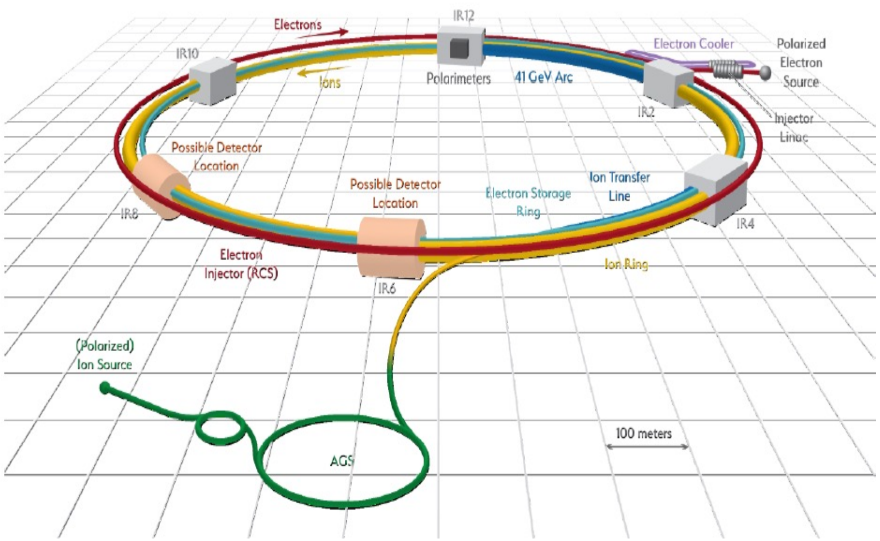


Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!





The US Electron Ion Collider



- ❖ Electron storage ring with frequent injection of fresh polarized electron bunches
- ❖ Hadron storage ring with strong cooling or frequent injection of hadron bunches

Hadrons up to 275 GeV

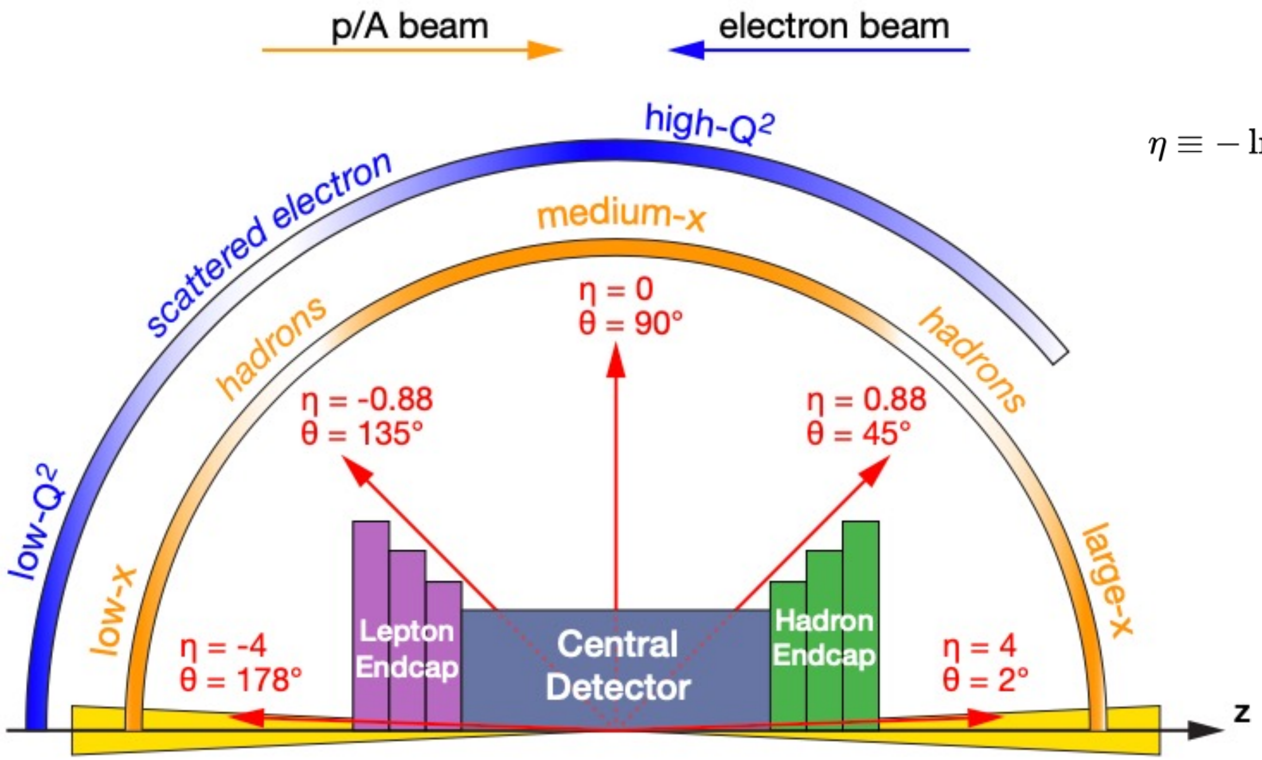
- ➢ Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- ➢ Need few modifications
- ➢ RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

Design optimized to reach 10^{34} $cm^{-2}sec^{-1}$

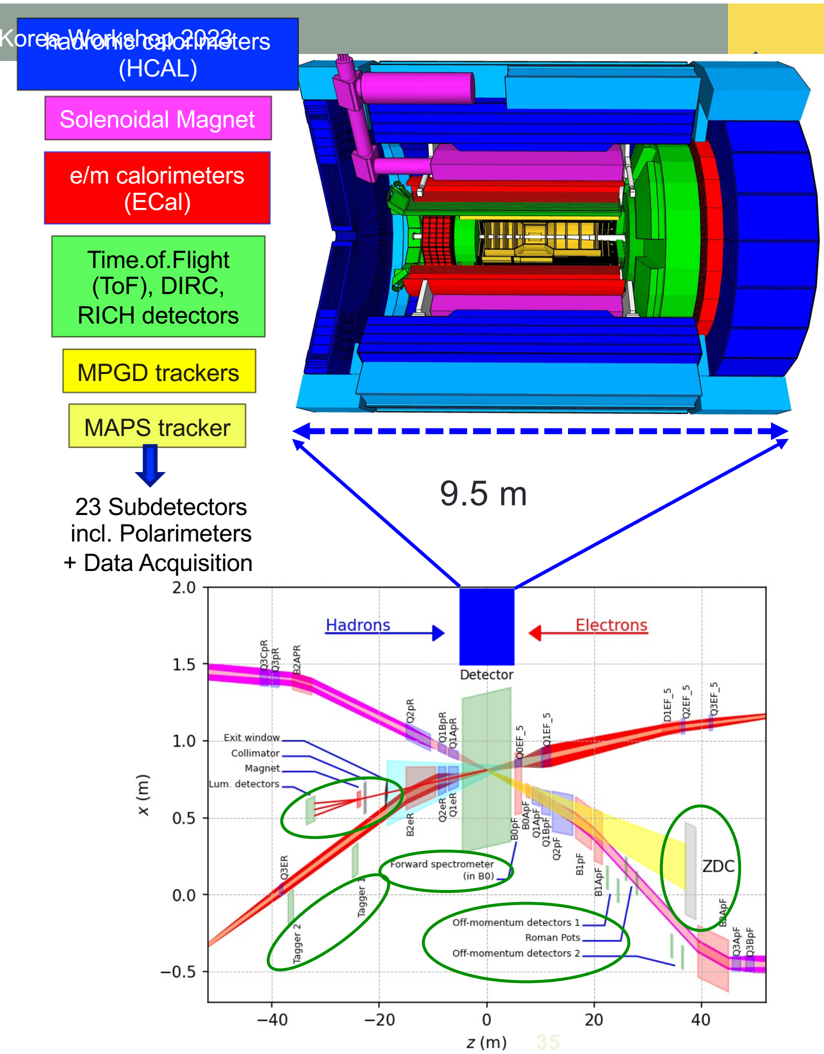
Detector polar angle / pseudo-rapidity coverage



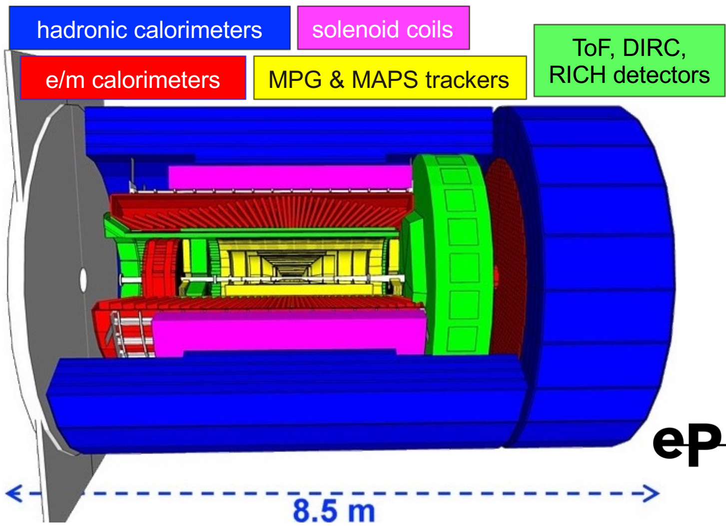
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

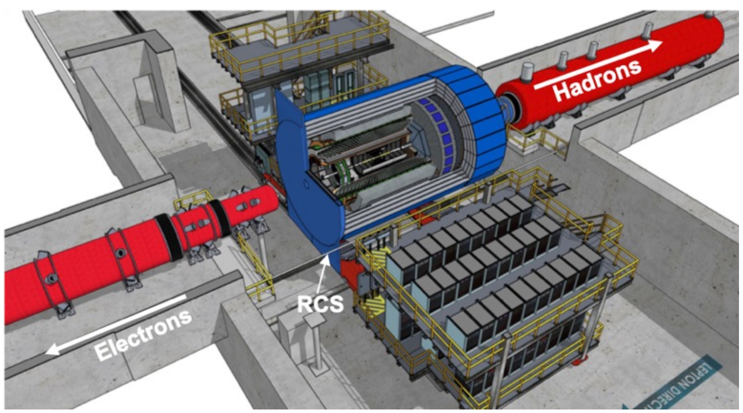
The ePIC Detector

- ❑ Asymmetric beam energies
  - ➢ requires an asymmetric detector with electron and hadron endcap
  - ➢ tracking, particle identification, EM calorimetry and hadronic calorimetry functionality in all directions
  - ➢ very compact Detector, **Integration** will be key
- ❑ Imaging science program with protons and nuclei
  - ➢ requires specialized detectors integrated in the IR over 80 m
- ❑ Momentum resolution for EIC science requires a large bore 2T magnet
- ❑ Highest scientific flexibility
  - ➢ requires Streaming Readout electronics model



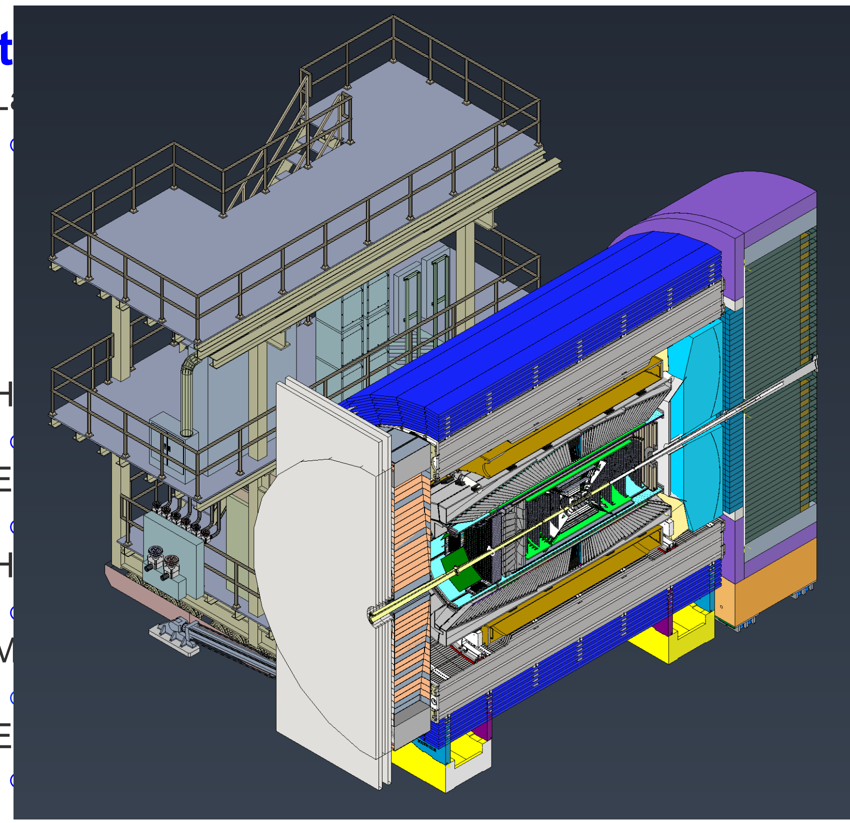
EIC Management team working with the EICUG to realize EPIC



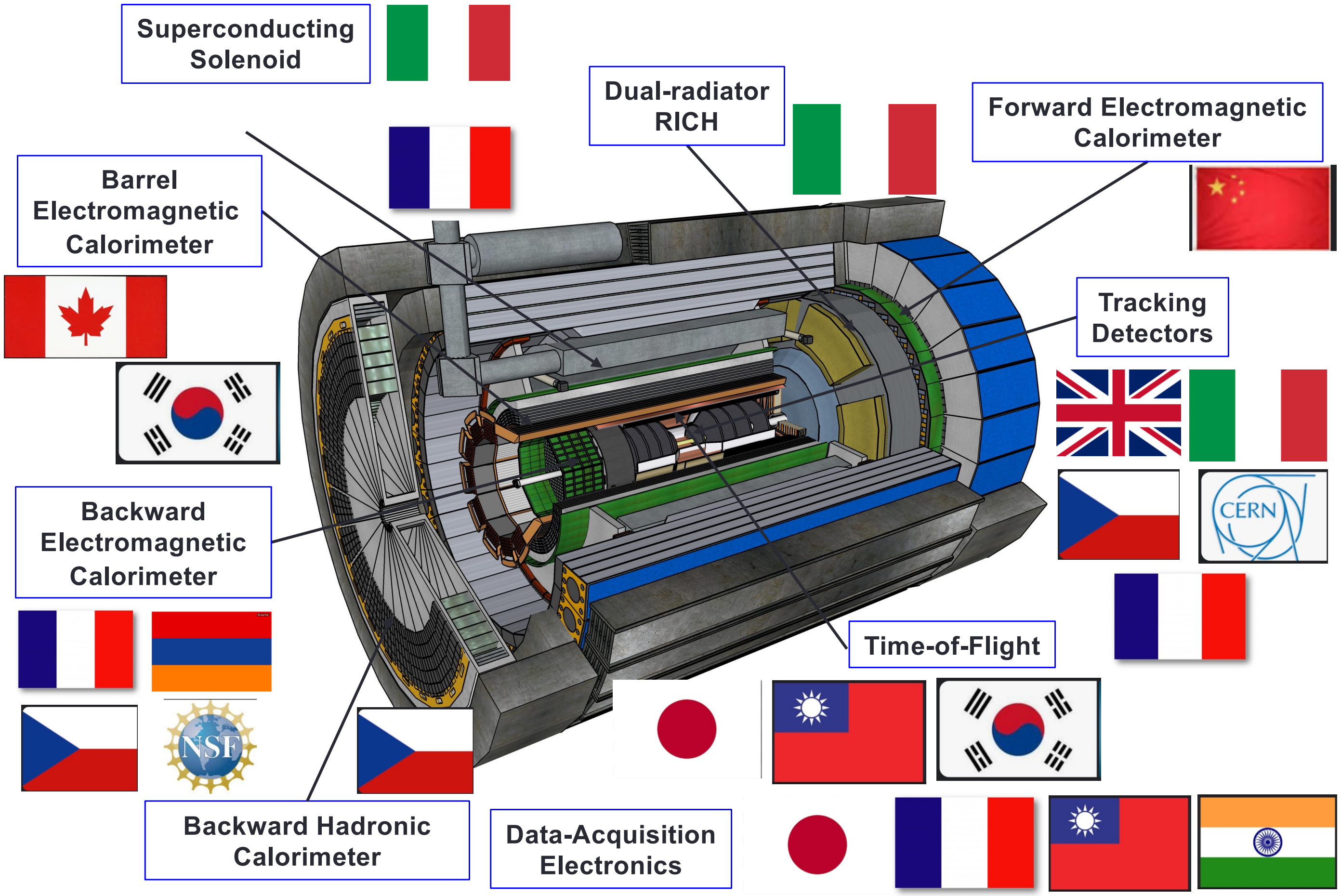


Det

- L … from
- H … d) tracking
- E
- H … vel … D
- M
- E



Central Detector Non-DOE Interest & In-Kind



Detector Non-DOE Interest & In-Kind

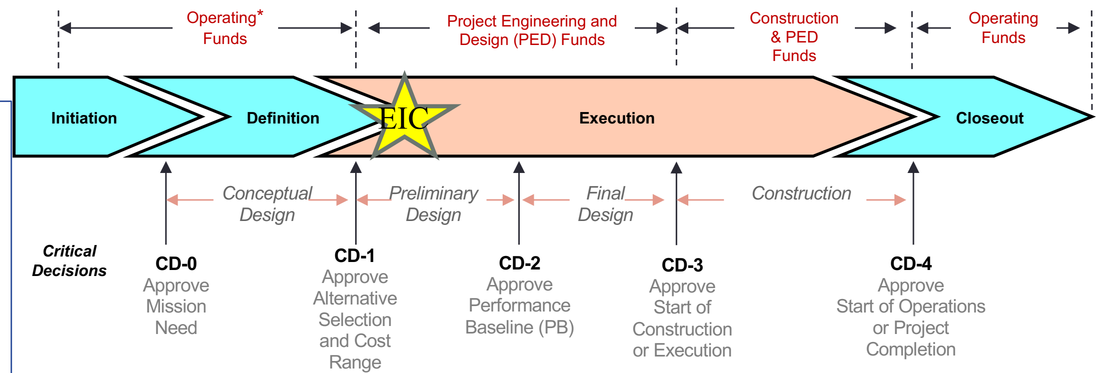
Entity	Interest and Important Facts
NSF	NSF-MSRI pre-proposal submitted by 10 US universities – aims at full scope of backward EM calorimetry (eECal). Armenia, Czech, France/IN2P3 as unfunded contributors. Invited to submit proposal. Final NSF review is ongoing.
CERN	MAPS sensor design developed by CERN/ITS-3 Group providing synergy with ALICE. Synergy of gaseous-based Cherenkov
Italy/INFN	Aims at major scope of forward particle identification detector (dRICH), at (part of) the Si/MAPS tracker scope, and at photo-sensor contributions. Further investigating possible interest in EIC detector magnet scope.
Israel	B0 Detectors (Si tracking and PbWO4)
Japan	Interested in a US-Japan agreement; Aims at full scope of Zero-Degree Calorimeter in collaboration with Taiwan/Korea. Pursuit of full scope of barrel AC-LGAD detector as EIC-Asia consortium. Contribution to DAQ/streaming. Possible aerogel
Korea	Aims at major scope for fiber-based barrel EM calorimeter, Also work packages for barrel AC-LGAD and Si-based hadronic calorimetry for ZDC.as part of EIC-Asia consortium (includes also Japan,Taiwan), Collaboration on Si tracking detector.
Poland	Actively working with ministry/funding agency; Interested in detectors along the beam line (luminosity detector, Roman Pots)
Taiwan	Pursuit of full scope of barrel AC-LGAD as part of EIC-Asia consortium. LYSO-based EM calorimeter for ZDC, Also optical readout/fiber. Possible later interest in PCBs. Computing.
UK	STFC seed funding for UK detector R&D (3M£). Interest in Si/MAPS tracker, polarimetry and detectors along the beams (Low-Q2/TimePix). Follow-up STFC/UKRI request for 5-7 years submitted early 2023 (includes accelerator part).

Aims at major scope for fiber-based barrel EM calorimeter; work packages for barrel AC-LGAD and Si-based hadronic calorimetry for ZDC. As part of EIC-Asia consortium (includes also Japan, Taiwan), Collaboration on Si tracking detector.

Timeline:

EIC Critical Decision Plan

CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	**January 2024**
CD-2/3	**April 2025**
CD-4A	October 2032
CD-4	**October 2034**



CD-3A Review: (November: RECOMMENDED to PROCEED)

Define Baseline:

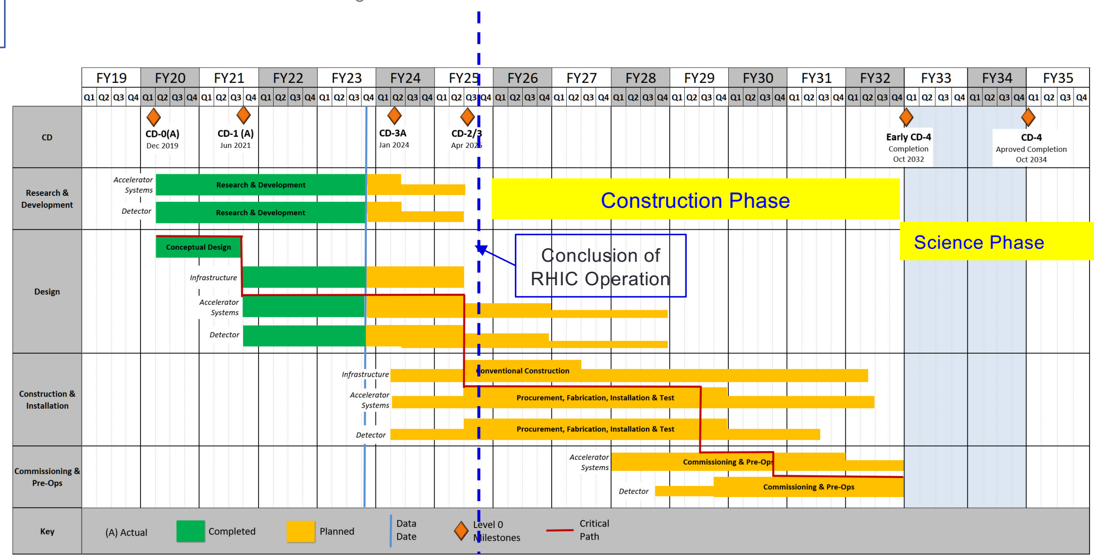
technologies, Scope, Cost & Schedule

Long Lead Procurement (LLP) items

Design Maturity: ~90%

Plan is tracked through EVMS & Change control process

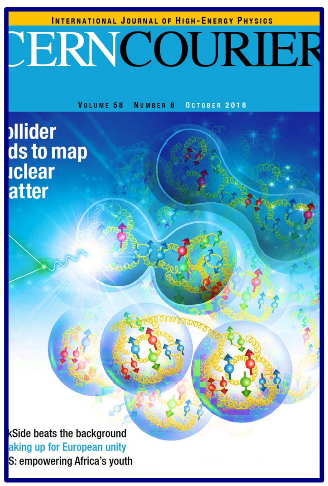
Start of construction for LLPs



Summary & Outlook : Korea is important to us!

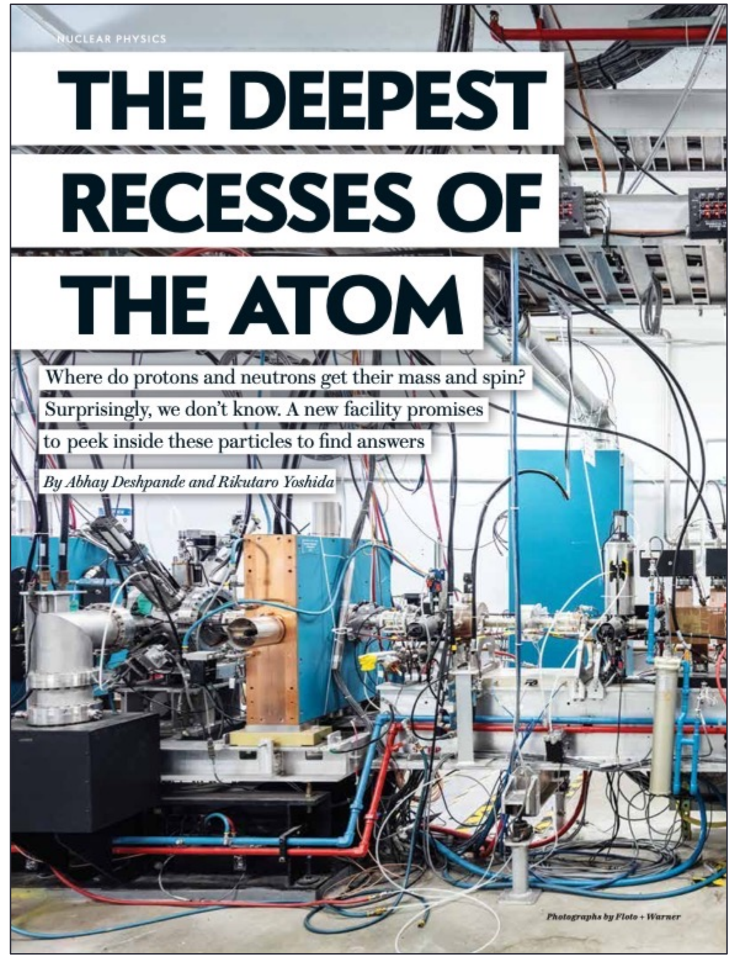
- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the DOE will be built in this decade and operate in 2030's.
  - Will address the most profound unanswered questions in QCD
- Up to two hermetic (full acceptance(?) and complementary) detectors under consideration, although **EIC project has funds for 1 detector**.
  - Experimental collaboration EPIC formed
  - An aggressive timeline : first collisions by ~2031/32; physics start by ~2033/34
  - **High interest in having international partners both on detector and accelerator**
  - A second detector a few years later
- *For all early career scientists, graduate and undergraduate students: This machine is for you! Ample opportunity to contribute to machine, detector & physics of the EIC.*

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
Translated into multiple languages



E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
Translated in to multiple languages




"New directions in science are launched by new tools much more often than by new concepts."
Freeman Dyson