Stony Brook University

Brookhaven National Laboratory

The future Electron Ion Collider
Unravelling the mysteries of the role of gluons in QCD

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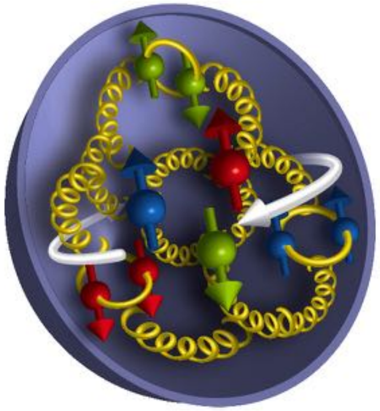
July 19, 2021

One Week Online High-End Workshop (Karyashala) on
Software Tools and Techniques used in EHEP and its Applications
July 12 - 19, 2021

SERB INDIA

ACCELERATE VIGYAN

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

WHY?

However, the internal structure of the proton is

known to only about 20-30%

~20 minutes in an hour…!

The answer lies in the difference in the forces that are at play inside the atom vs. that inside the proton…

We will try to understand why, and what needs to be done to understand the proton (& neutron…& nuclei) better

Standard Model (SM) of physics
Fundamental building blocks and the forces of nature

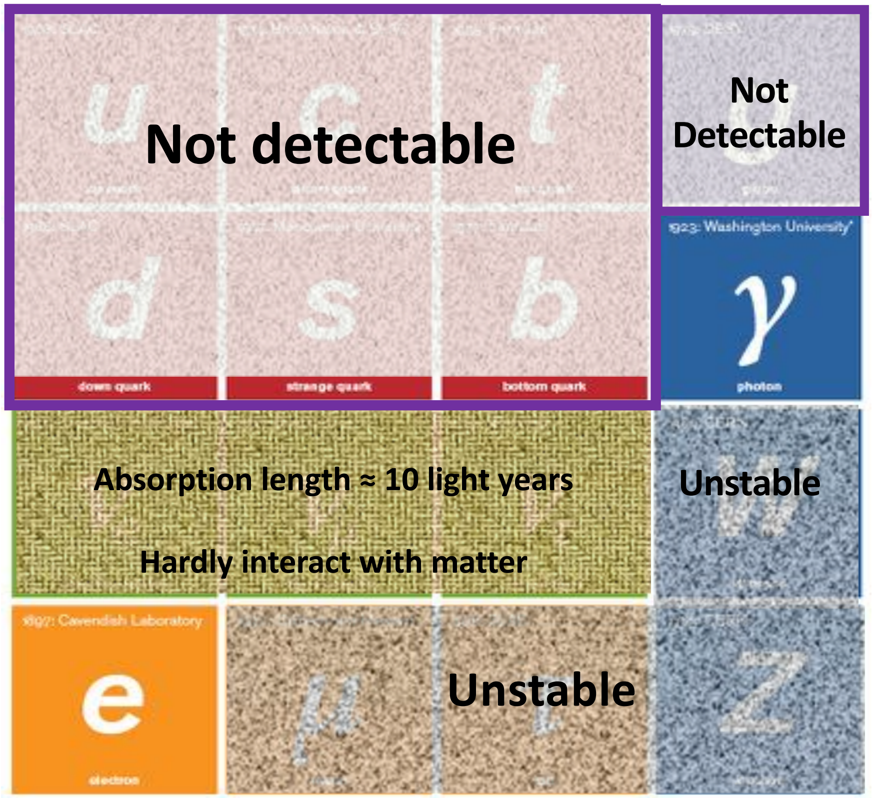
Quarks & gluons have color charge: hence interactions: quantum chromodynamics

+2/3 e

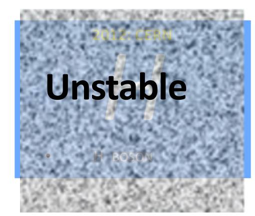
-1/3 e

0

-1 e



18 Nobel Prizes since 1950



+

2015 Gravitational waves

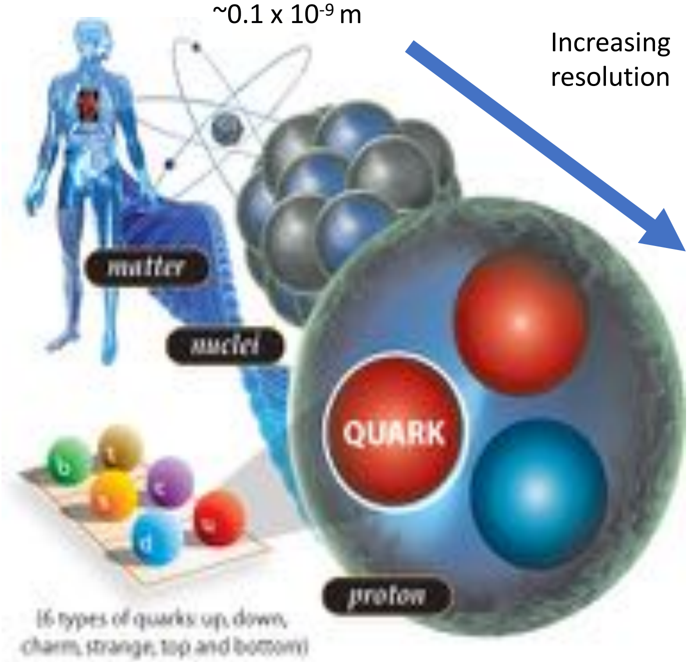
Einstein gravity

What constitutes visible matter?

ATOM

nano Scale
$\sim 0.1 \times 10^{-9}$ m

Increasing
resolution



Proton

Femto-Scale
$\sim 10^{-15}$ m

Big Question:

Can we understand
how the **visible matter** is formed from
the smallest elementary **building
blocks(quarks)**

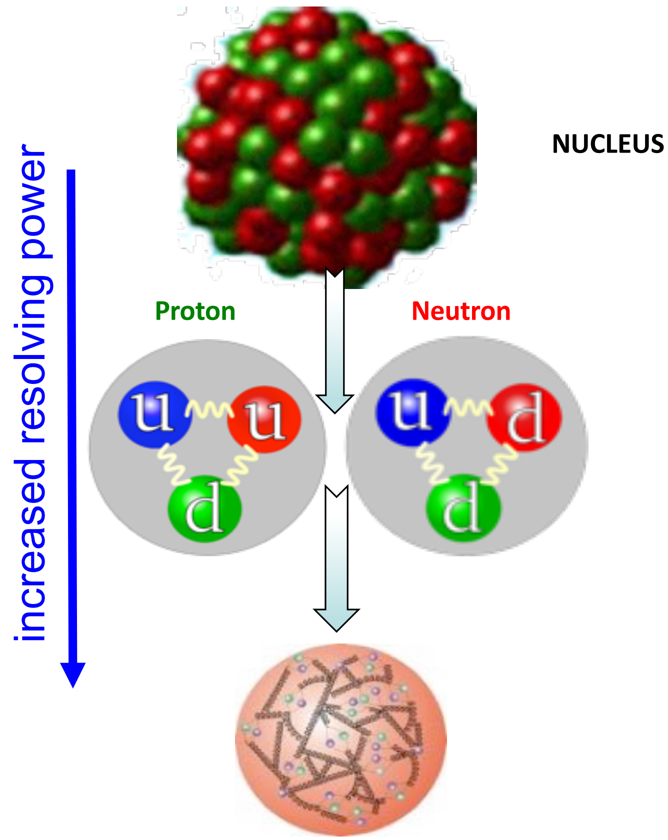
Visible matter: Protons & neutrons
Building blocks – not visible: quarks & gluons

Atomic interactions mediated by **neutral**
photons ➔ **no self interactions**

Inside the proton interactions are mediated
by the **color charged gluons ➔ self
interactions**

Study of the constituents of matter: inside the atom

Reveal more & more details



A Nucleus is made of nucleons: protons and neutrons

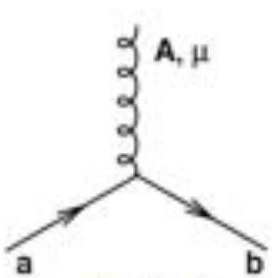
Nucleons are complex objects made of quarks bound together by self interacting gluons, carrier of Strong Force: Theory of Strong Interactions: Quantum Chromodynamics

All elementary building blocks can be characterized by their mass, spin and charge

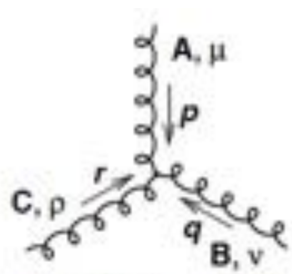
What distinguishes Quantum Chromo-Dynamics from Quantum Electro Dynamics?

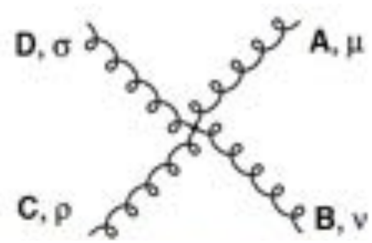
g → q + anti-quark

(gluons) g
in QCD



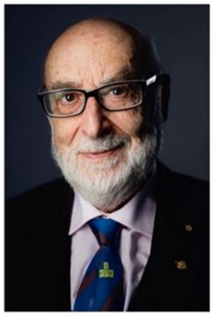
Quantum Chromodynamics





Color Charge of gluons
Enables self-interactions
g → g + g
Or
g + g → g + g

Quantum Electrodynamics



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François Englert

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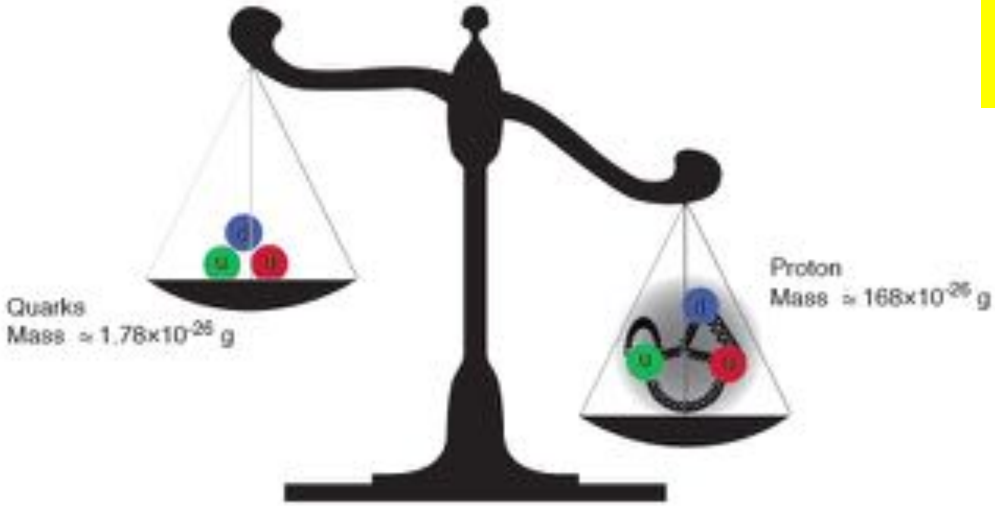
Peter W. Higgs

Nobel 2013

"Higgs Boson" that gives mass to quarks, electrons,….

Proton mass puzzle



It is like saying:

1 + 1 + 1 = 300

Mass of the 3 quarks : 1.78 x 10^{-26} grams ← This mass comes from HIGGS mechanism

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

→only 1% of the mass of the protons, neutrons from Higgs mechanism

→Where does the rest of the mass come from?

→ energy of gluon-quark interactions!

Emergent Dynamics in QCD

Without gluons,* *there would be no nucleons, no atomic nuclei… no visible world!

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons, nuclei and…. The visible world! **-- How exactly? Not known.**
- Gluons carry ~50% of the proton's momentum, a significant fraction of the **nucleon's spin**, and are responsible for the dynamics of confined partons: **-- How exactly? Not known.**
- 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. **-- How exactly? Not known?**
- Nucleon-nucleon forces emerge from quark-gluon interactions. **-- How exactly? Not known!**

Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons

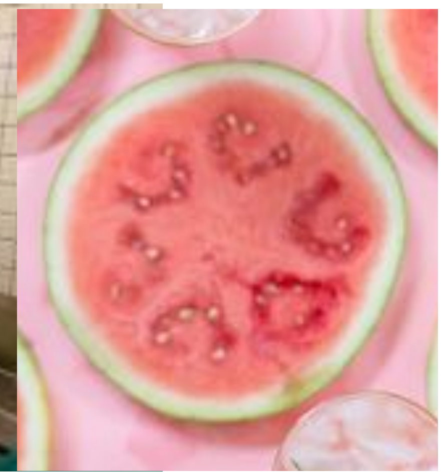
Deep Inelastic Scattering (DIS)

The best technique to understand the internal structure of protons, neutrons and the nuclei.

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

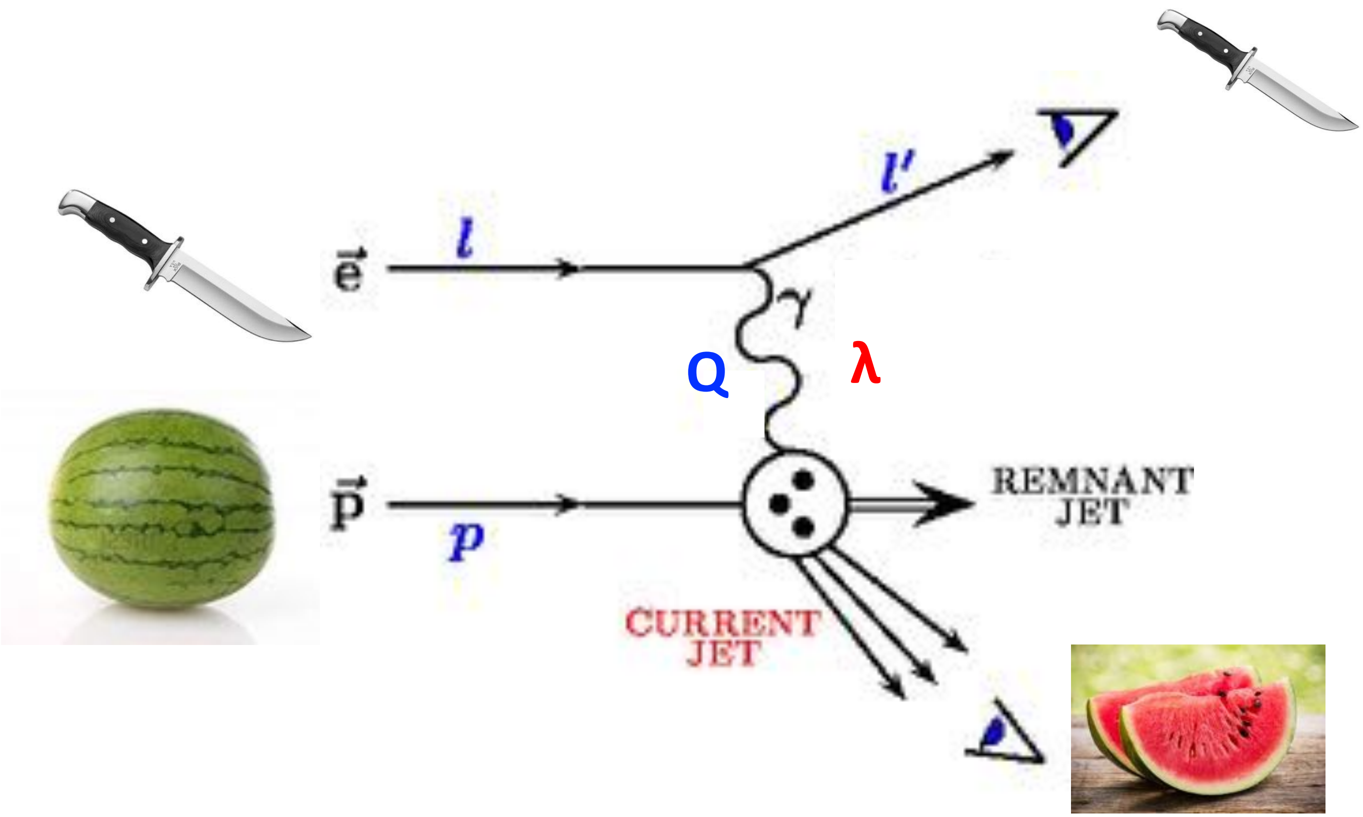
1) Violent collision of melons



2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

Deep Inelastic Scattering



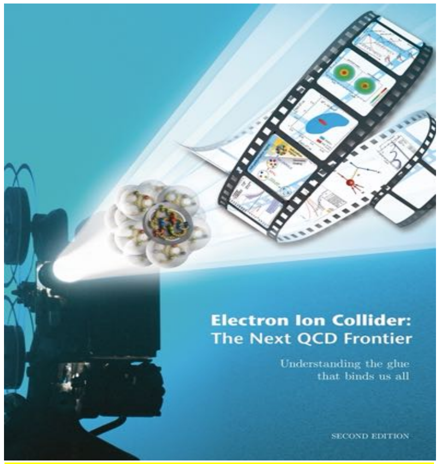
$\lambda = (h/2\pi)(1/Q^2)$

h = constant

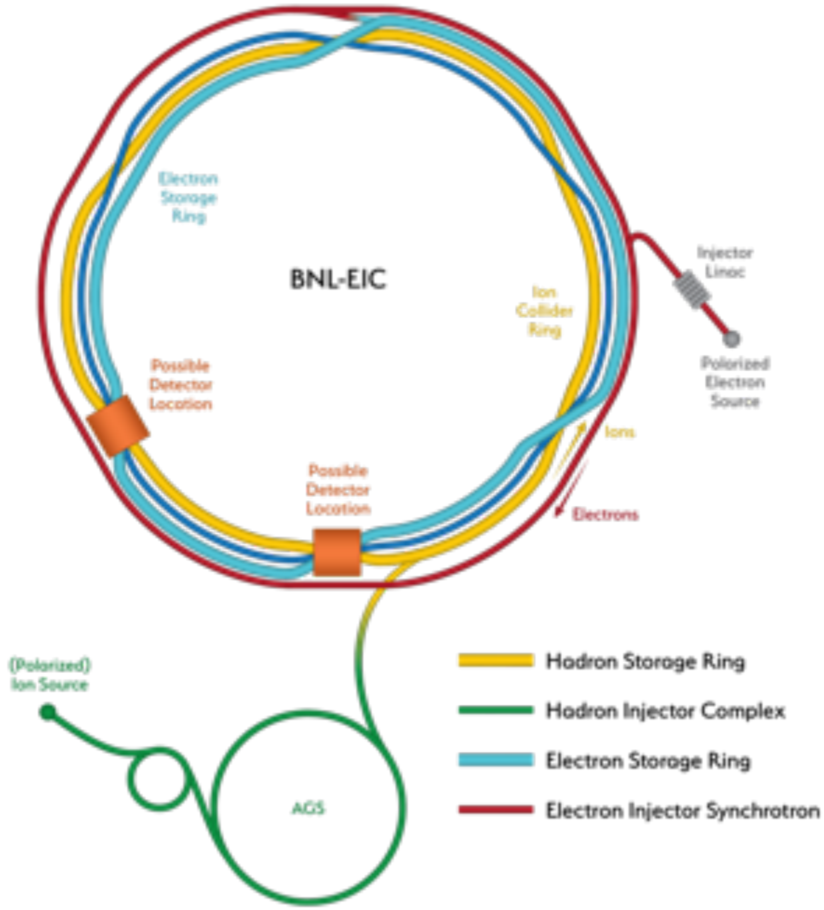
λ = wavelength

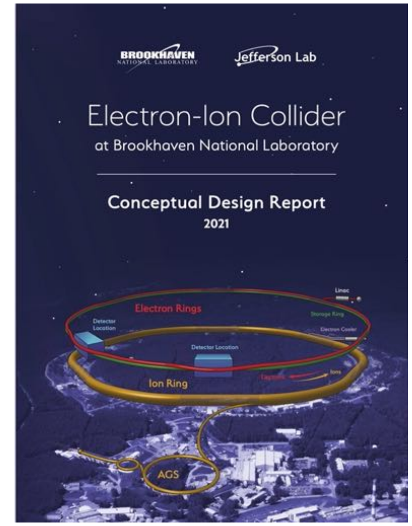
Q^2 = momentum transferred

Deep Inelastic: (**λ** << Proton Size)



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} $cm^{-2}sec^{-1}$
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same e-p
- ✓ Variable center of mass energy

The Electron Ion Collider

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

Three important quantities….

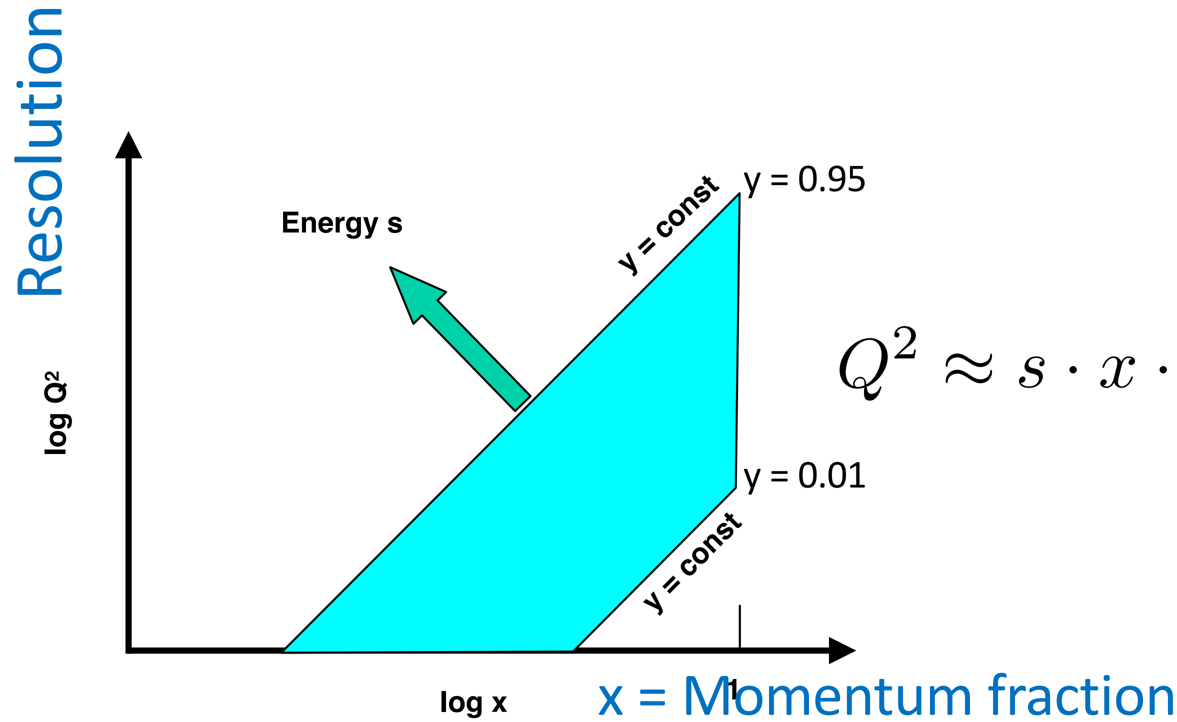
- Resolution of the probe (electron/virtual photon): ➔ Higher the Q^2, smaller the distance scales we can study (smaller the λ) ➔ **higher the Q^2, smaller the λ ➔ higher the resolution**

$$\lambda = \frac{h}{2\pi} \cdot \frac{1}{Q^2}$$

- Momentum fraction of the quark/gluon inside the proton: $x = \frac{p_{quark}}{P_{proton}}$

- S = square of the Center-of-Mass Energy $S = (\text{Center of Mass Energy})^2 = 4 \cdot E_p \cdot E_e$

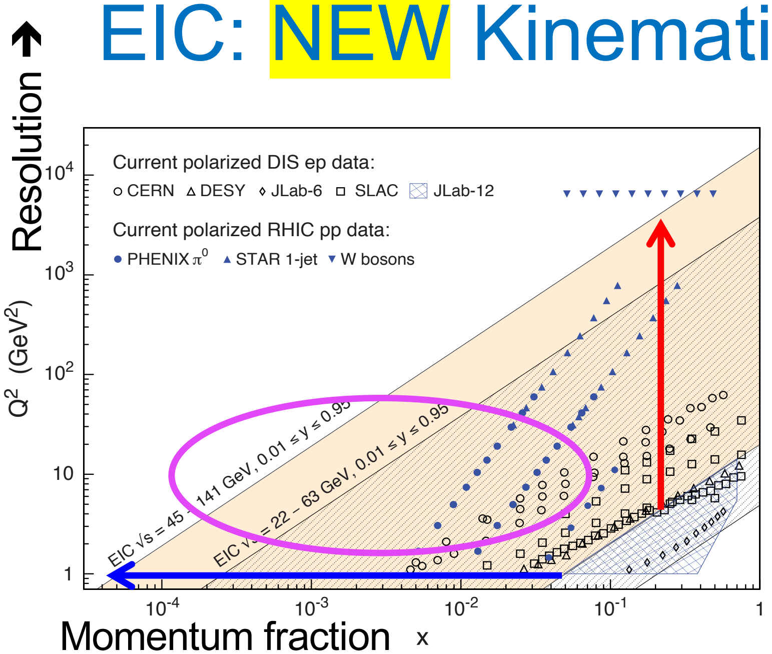
The x-Q^2 plane…



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

- Low-x reach requires large $\sqrt{s}$
- Large-Q^2 reach requires large $\sqrt{s}$
- *y* at colliders typically limited to 0.95 < y < 0.01

EIC: NEW Kinematic reach & properties

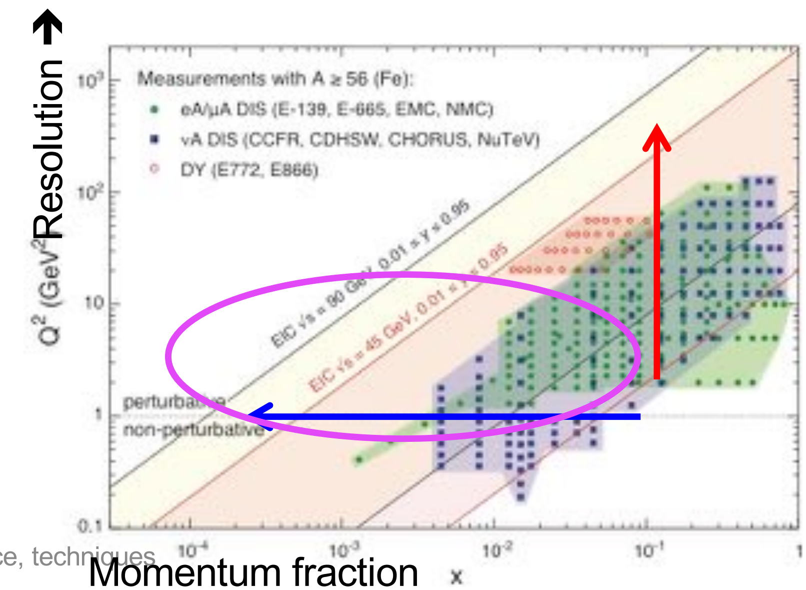


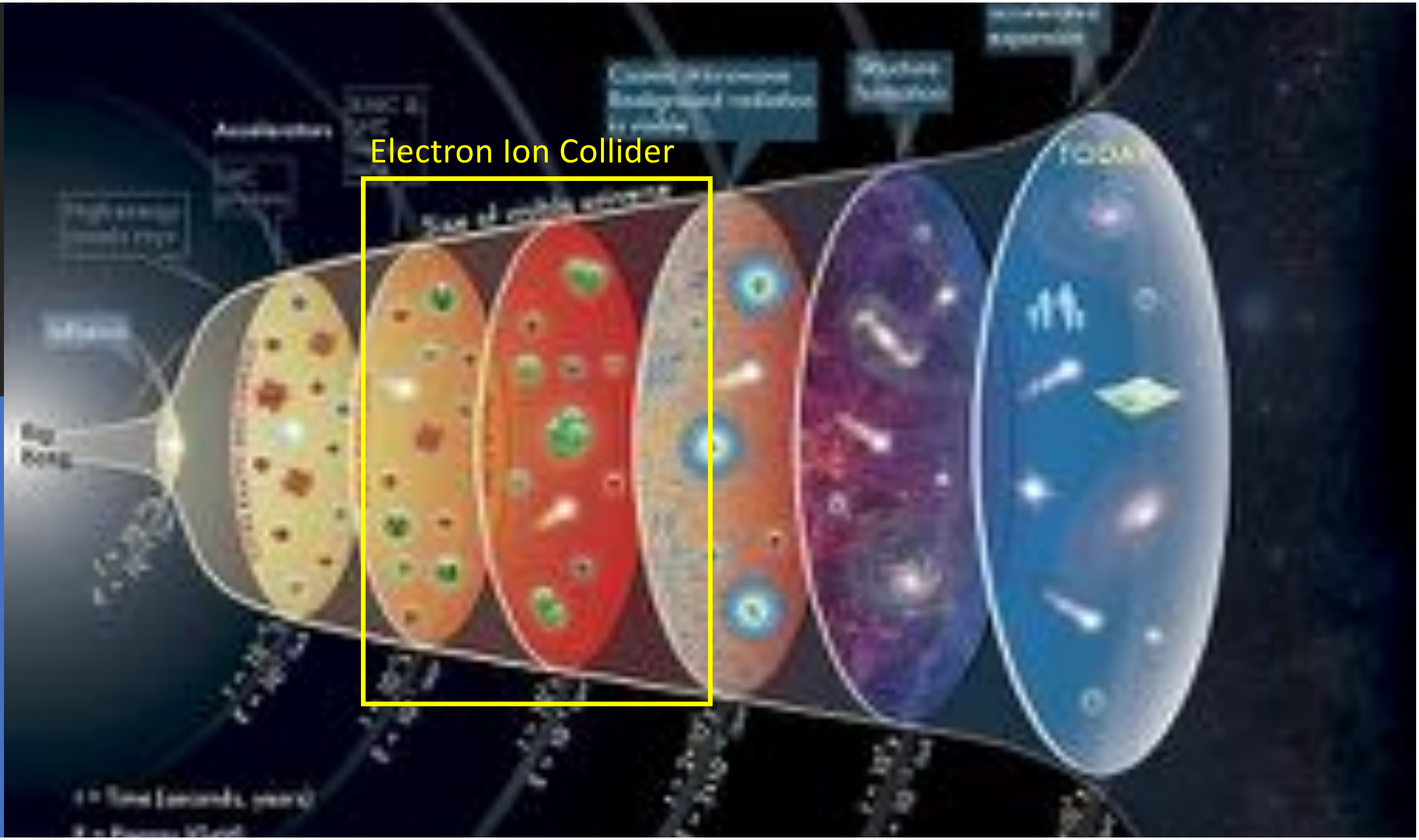
For e-N collisions at the EIC:

- ✓ 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)

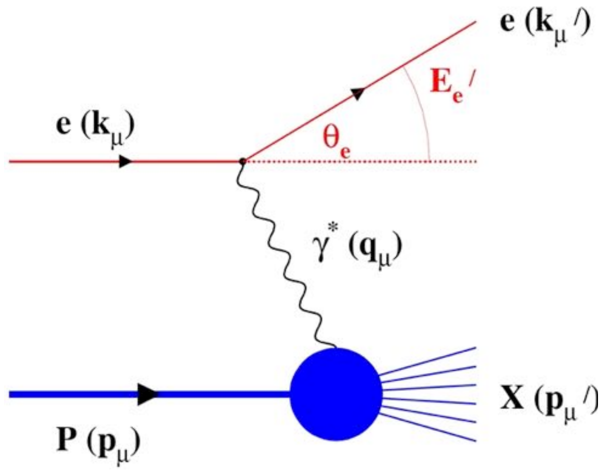




Electron Ion Collider
Accelerators
Big Bang
TODAY

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

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

Measure of resolution power

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

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

$$s = 4\,E_t\,E_e$$

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:

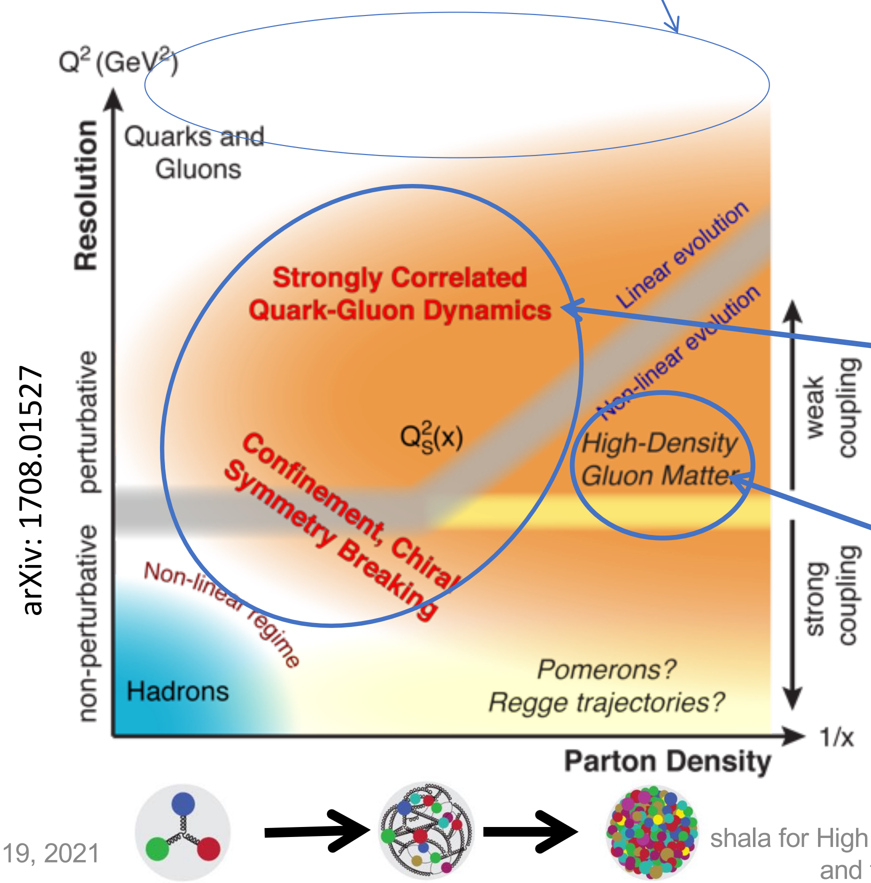
e+p/A → e'+X

detect *only the scattered lepton* in the detector

Low lumi & acceptance

QCD Landscape to be explored by a future facility

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

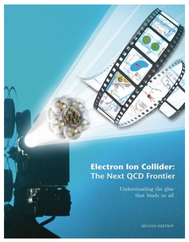


Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

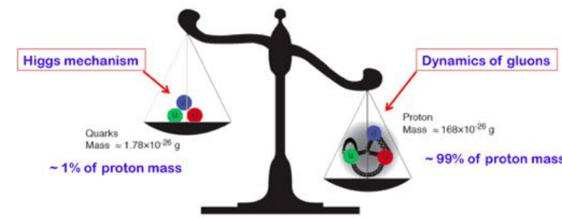
Systematically explore correlations in this region.

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

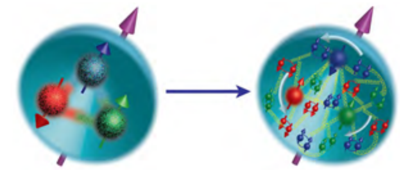
Need Precision and Control

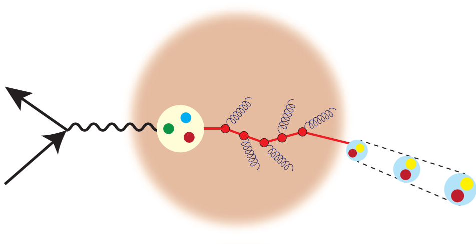


EIC Physics at-a-glance

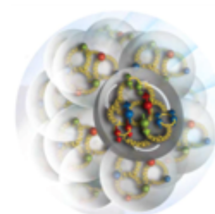


How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?

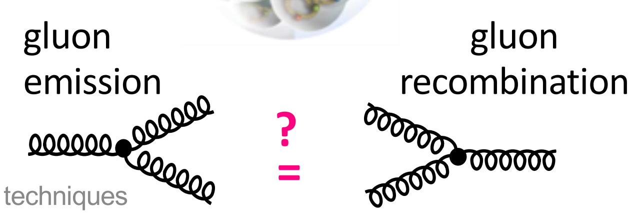


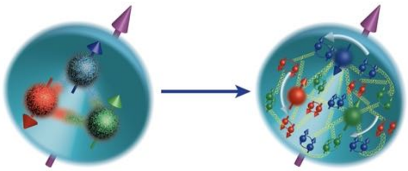


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

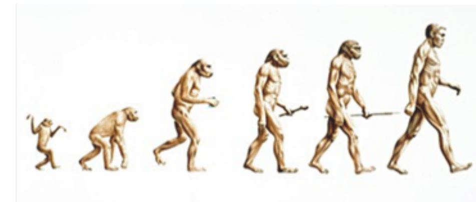


What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





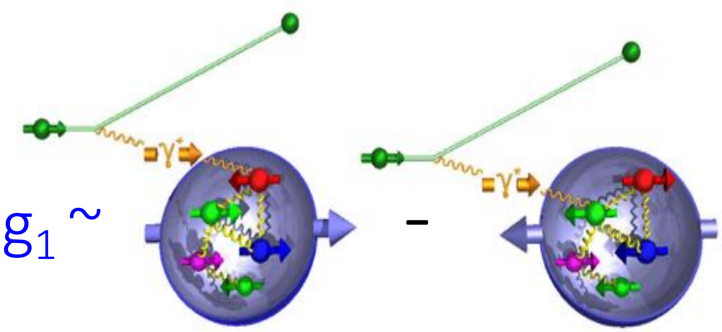
Proton Spin Crisis/puzzle

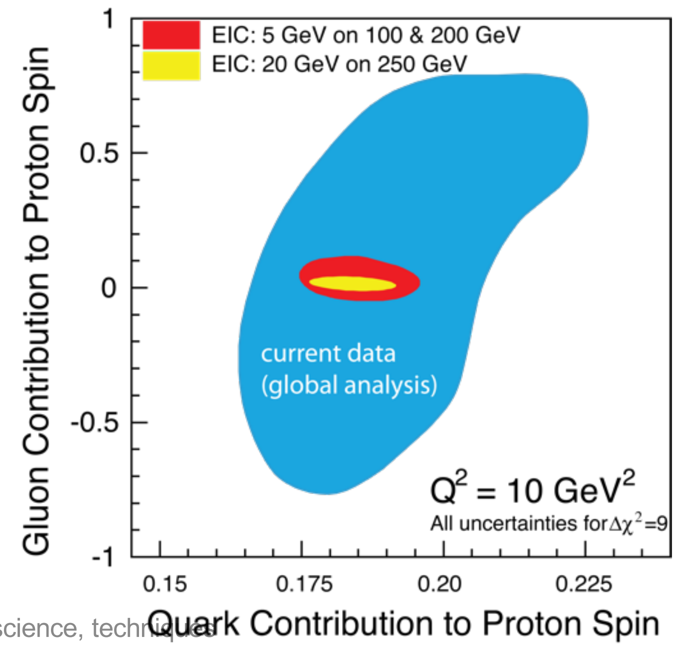


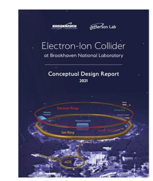
0.17 +/- 0.03 ? 0.03 +/- 0.5 ?

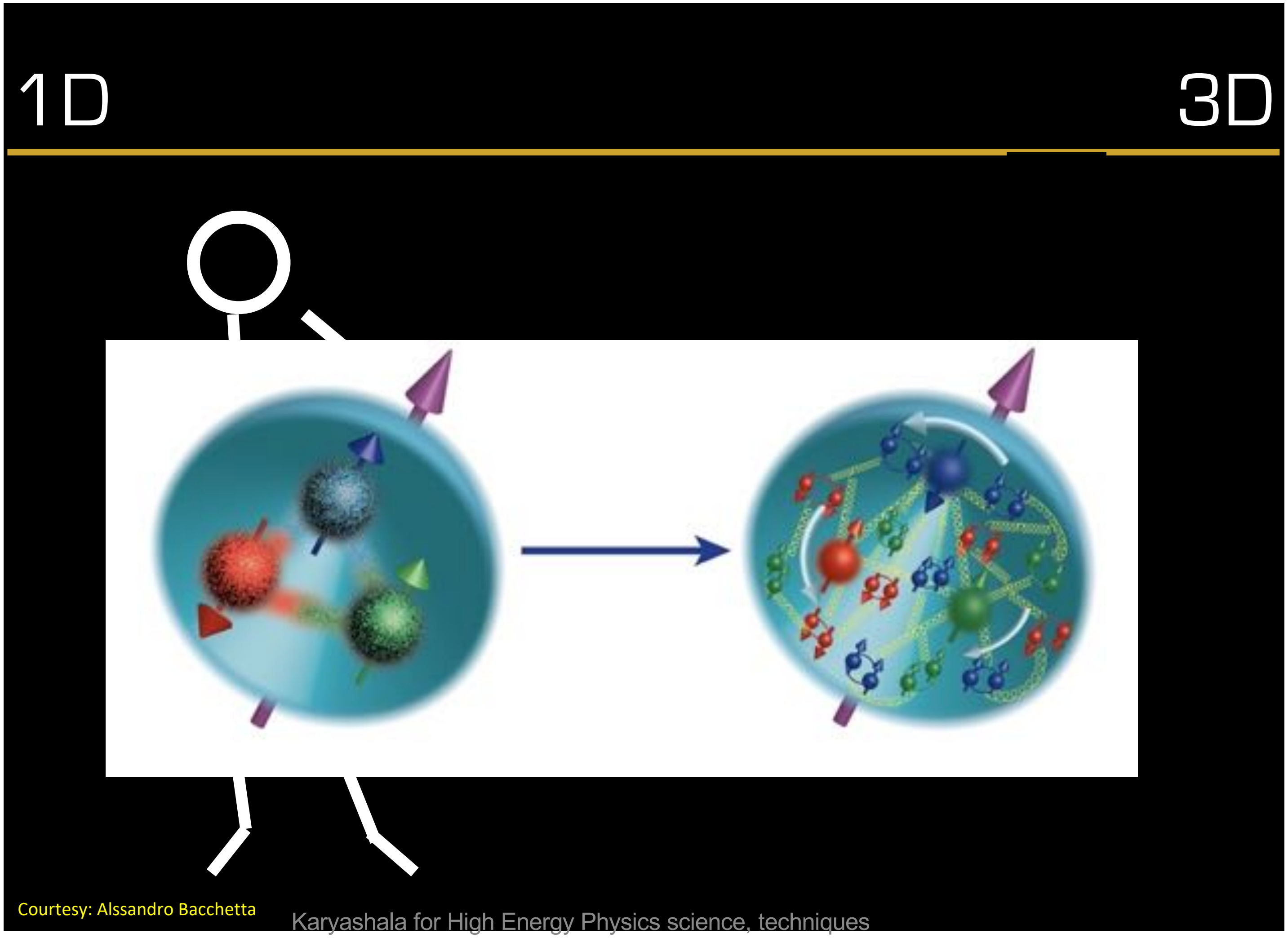
$$\frac{1}{2} = [Q_{\rm spin} + Q_{\rm ang.mom.}] + [G_{\rm spin} + G_{\rm ang.mom.}]$$

$g_1 \sim$





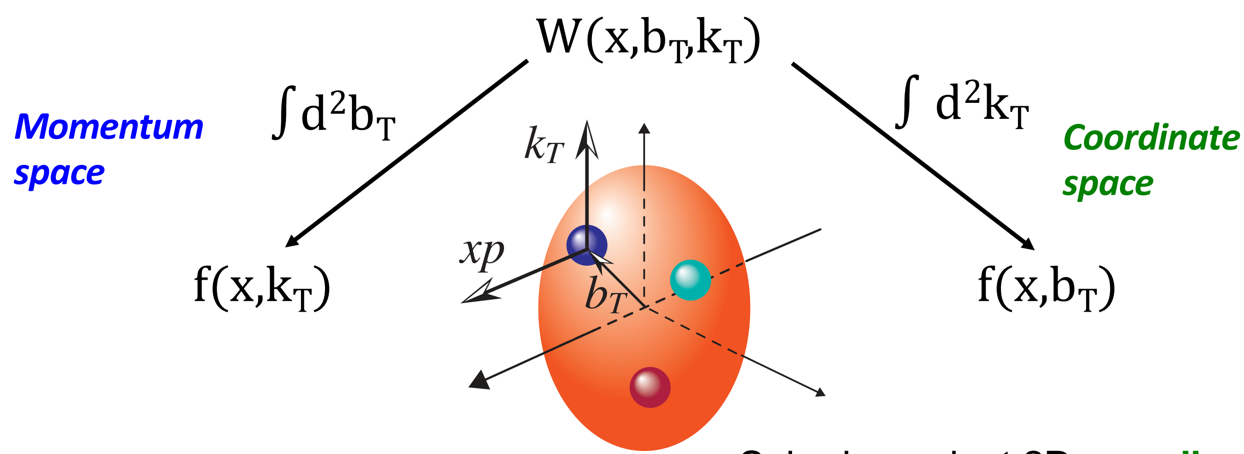



1D
3D
Courtesy: Alssandro Bacchetta

2+1-Dimensional Imaging Quarks and Gluons

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

offer unprecedented insight into confinement and chiral symmetry breaking.



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

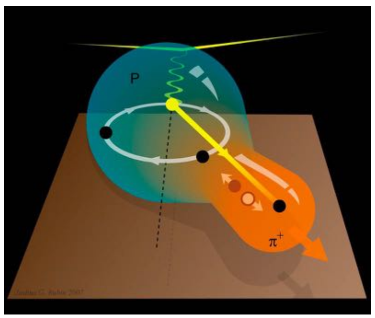
Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply virtual Compton scattering and meson production)
→ **Generalized Parton Distributions**

momentum and position distributions → Orbital motion of quarks and gluons

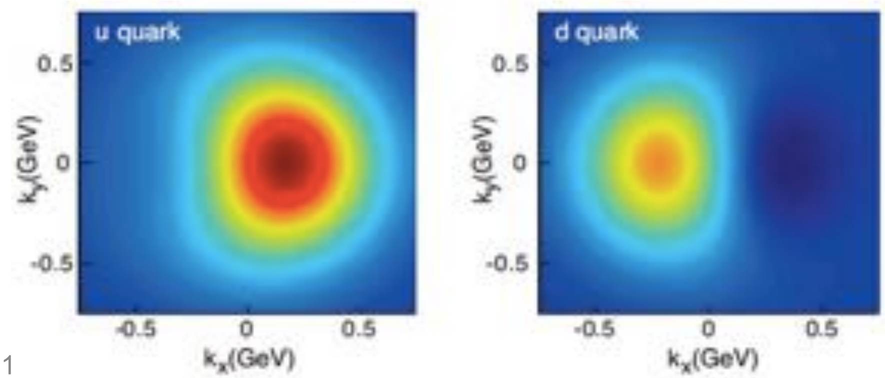
2+1 D partonic image of the proton with the EIC

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

Transverse Momentum Distributions



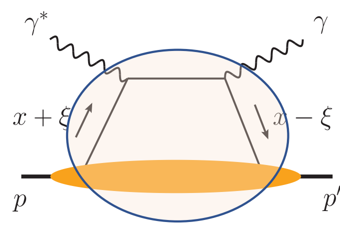
Quark's 2D momentum distribution

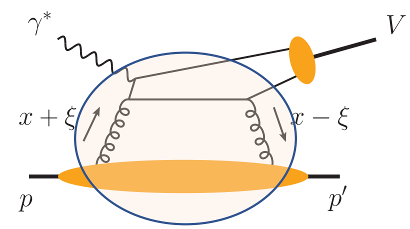


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering

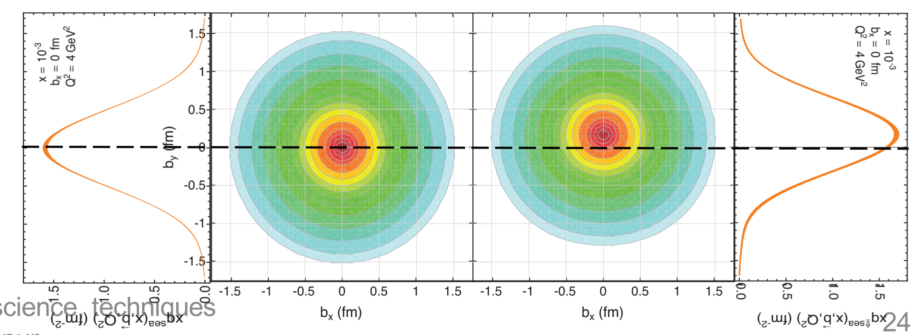
Measure all three final states

e + **p** → e'+ **p'**+ γ

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

Sea quark's 2D position distribution

unpolarized polarized



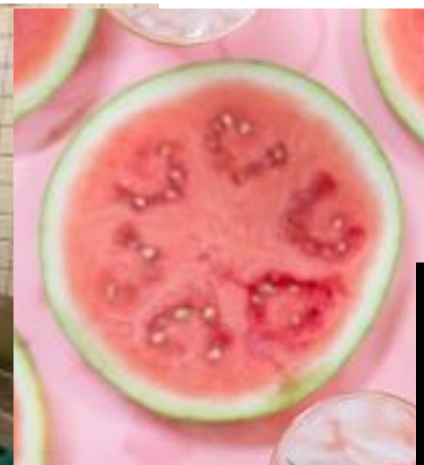
Study of internal structure of a watermelon:

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

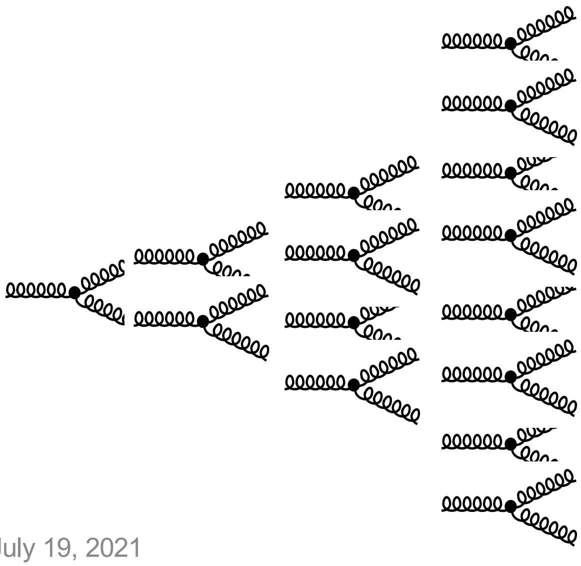
Non-Violent e-A (EIC)

Gluon 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



? Infinity?

No!

Gluon and the consequences of its interesting properties:

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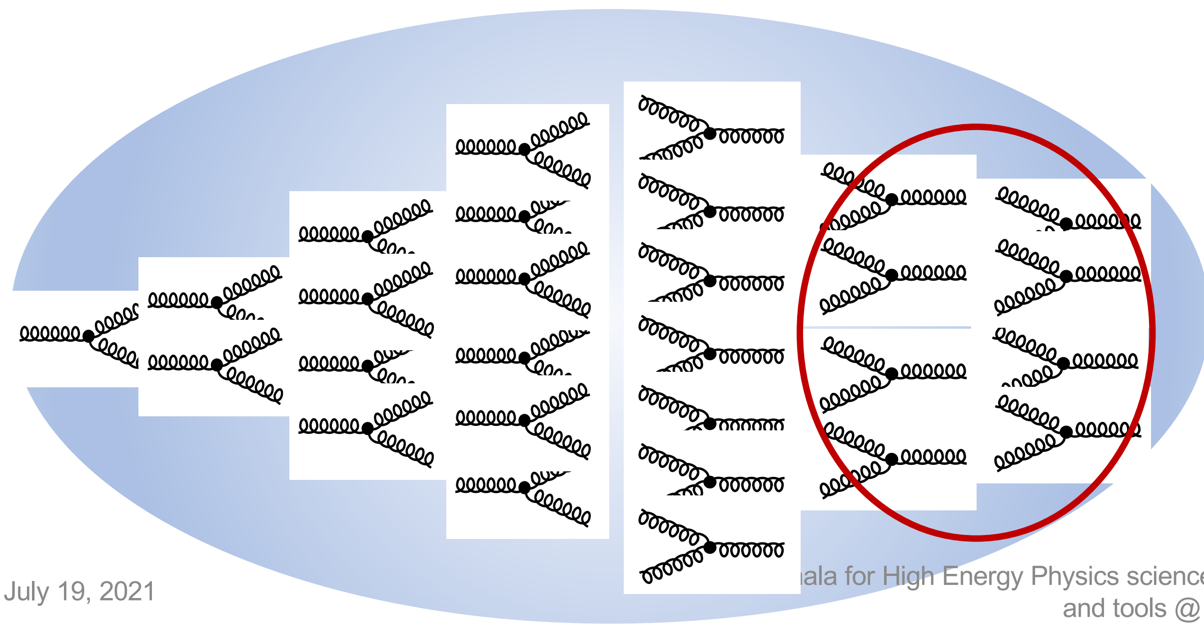
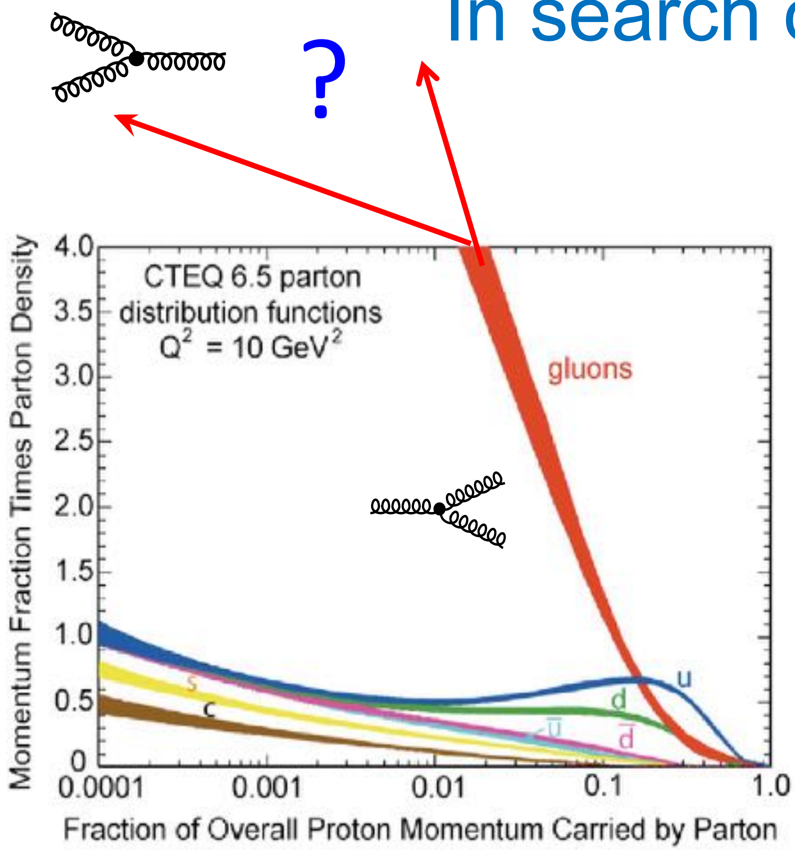


In search of a new state of matter!



Experimental evidence 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.

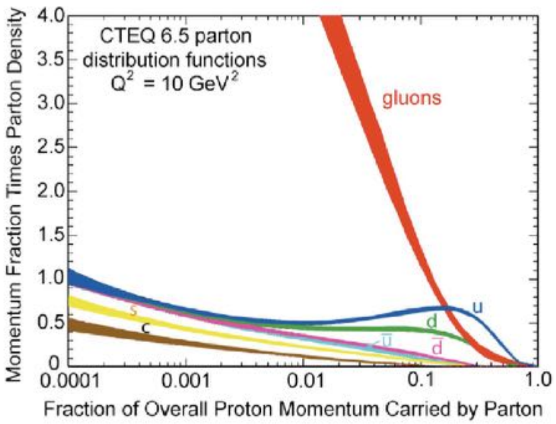
gluon emission = gluon recombination At Q_S

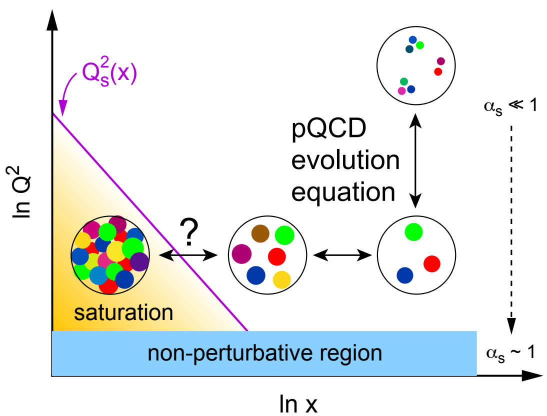
Observation of gluon recombination effects

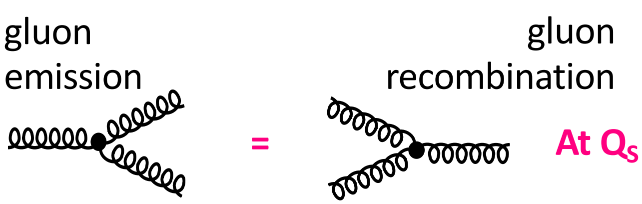
➔ Is there such new state of matter?

→ "Color Glass Condensate"

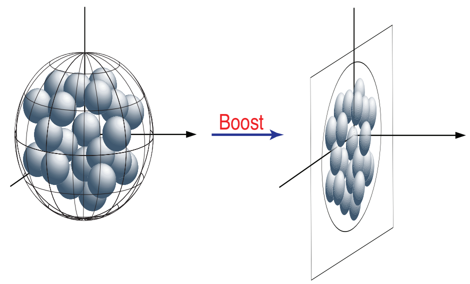
→ 50-100 times higher energy density than the core of the neutron star

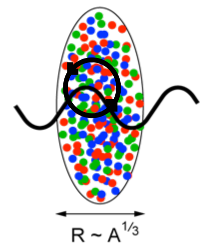






Low x physics with nuclei

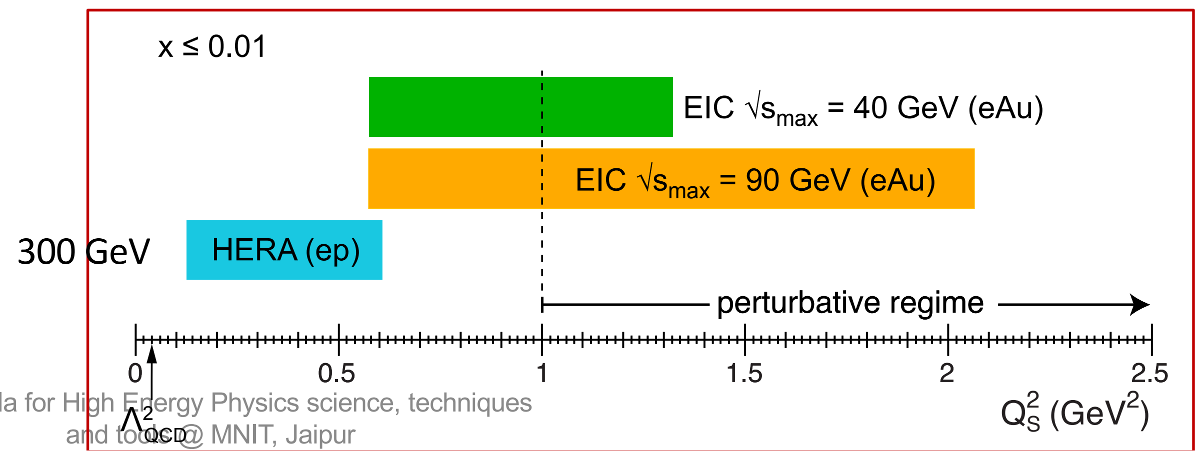




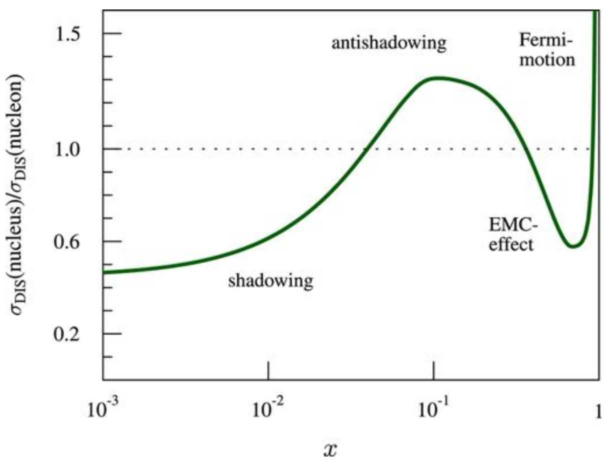
$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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

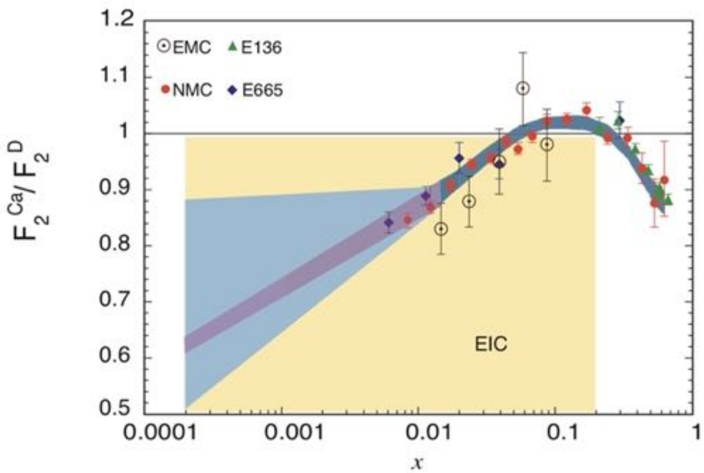
Accessible range of saturation scale $Q_s{}^2$ at the EIC with e+A collisions.
arXiv:1708.01527



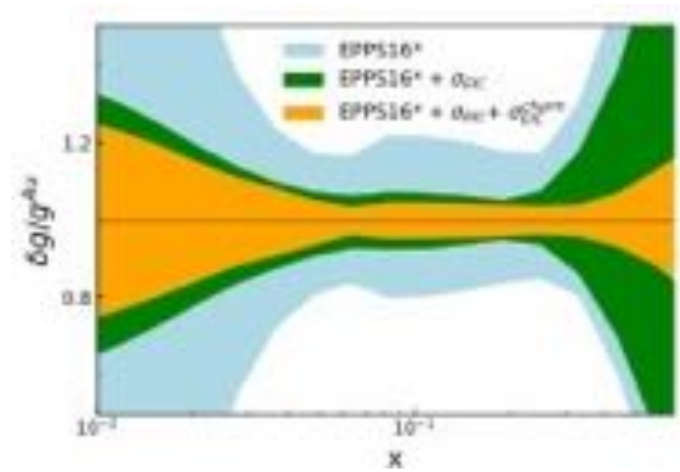
Nuclear PDFs: Different than protons & neutrons



Ratio of F_2 Structure functions of heavy vs. light nuclei



No data available at low-x where the behavior of n-PDFs might teach us a lot about q-g interactions



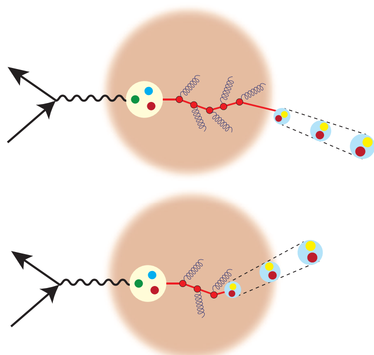
Example of improvement gluon distribution uncertainty in *Au*-nucleus from the EIC data to existing nuclear PDFs

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

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

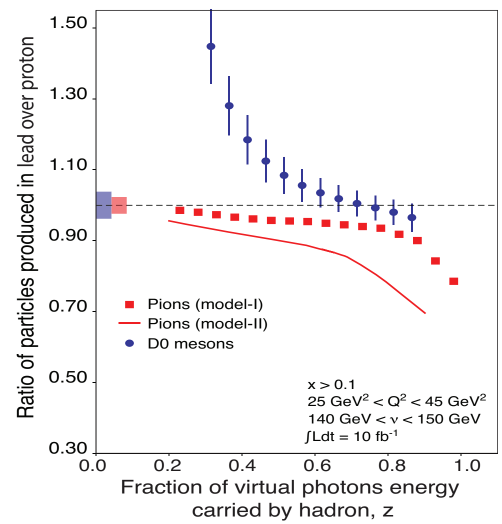


Control of ν by selecting kinematics;
Also under control the nuclear size.

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

Study in light quarks
vs.
heavy quarks

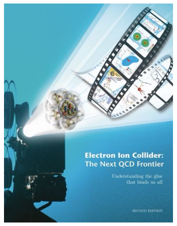
Energy loss by light vs. heavy quarks:



Identify π vs. D^0 (charm) mesons in e-A collisions:

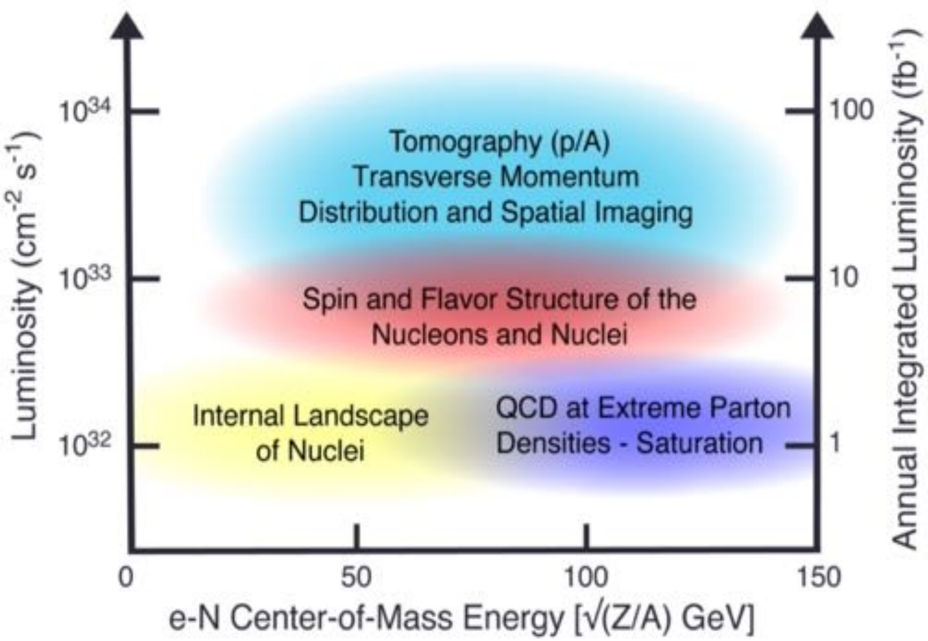
Understand energy loss of light vs. heavy quarks
traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

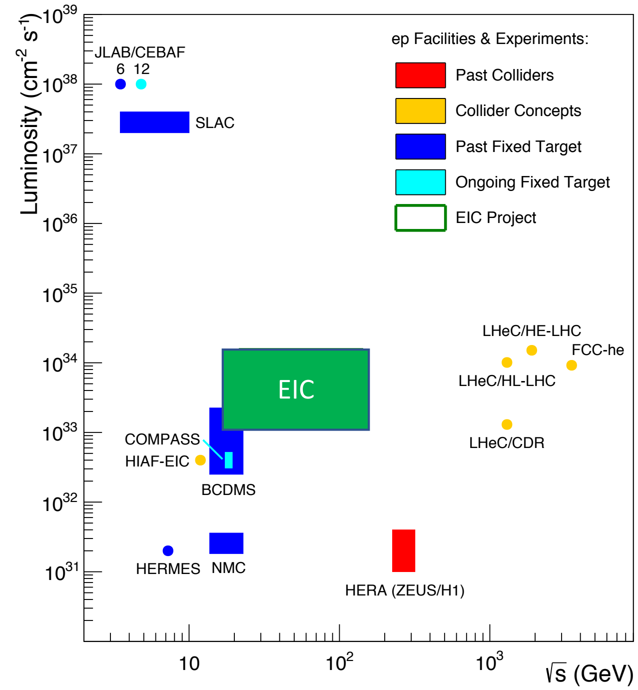
Need the collider energy of EIC and its control on parton kinematics



EIC Physics and the machine parameters

CM vs. Luminosity vs. Integrated luminosity





The US EIC with a wide range in $\sqrt{s}$, **polarized electron, proton and light nuclear beams** and luminosity makes it a unique machine in the world.

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) ➔ **Interesting to High Energy Physicists at LHC**

New Studies with proton or neutron target:

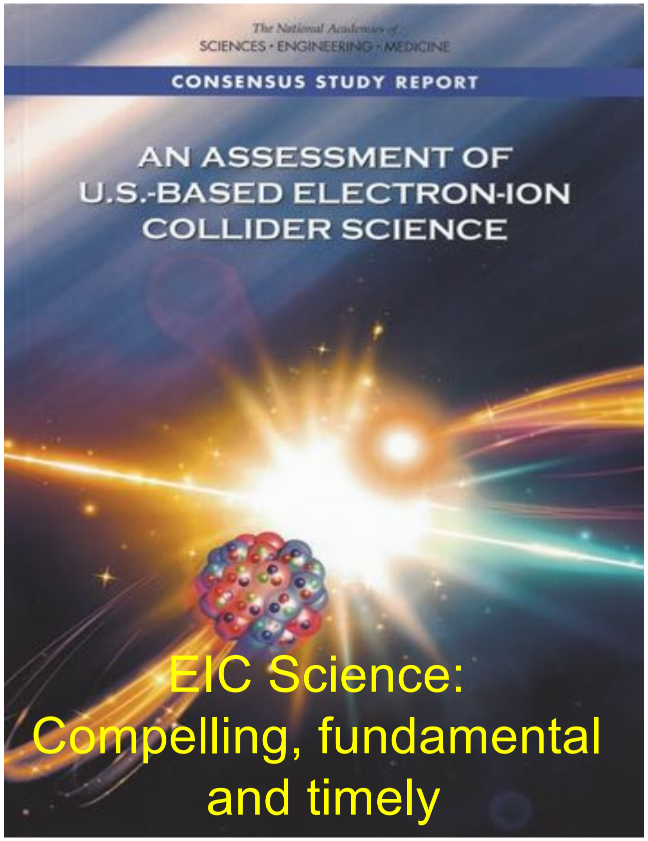
- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all or many of these?)

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:
  - Internal structure of jets : novel new observables, energy variability, polarization, beam species
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Connection to p-A, d-A, A-A at RHIC and LHC
- Polarized light nuclei in the EIC

Precision electroweak and BSM physics:

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



Consensus Study Report on the US based Electron Ion Collider
July 2018

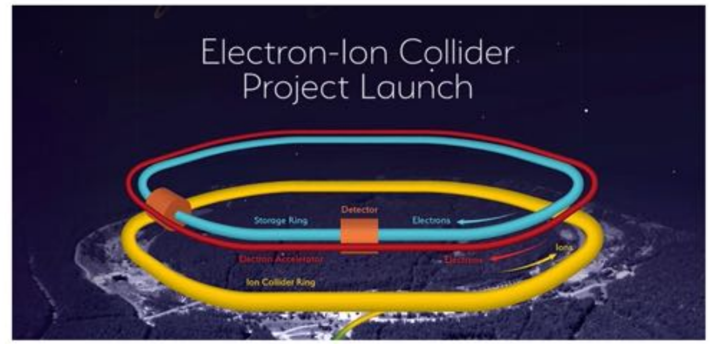
Summary:

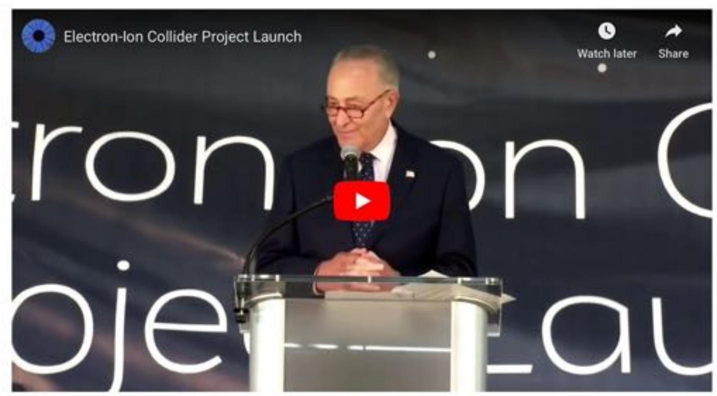
The science questions that an EIC will answer *are central* to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would *advance accelerator science and technology* in nuclear science; it would as well *benefit other fields of accelerator based science and society*, from medicine through materials science to elementary particle physics https://www.bnl.gov/newsroom/news.php?a=117399

Key Partners Mark Launch of Electron-Ion Collider Project

State-of-the-art facility and partnership among DOE, NYS, Brookhaven Lab, and Jefferson Lab will open a new frontier in nuclear physics, a field essential to our understanding of the visible universe with applications in national security, human health, and more

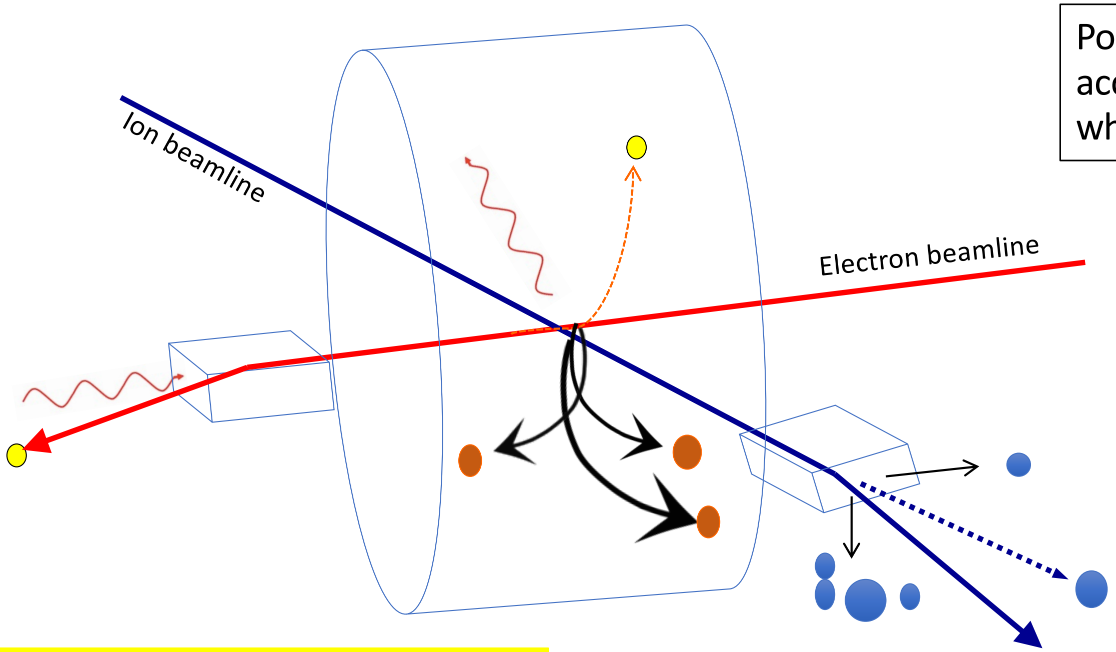
September 18, 2020





Replay of Electron-Ion Collider project launch event at Brookhaven Lab, September 18, 2020

New tools of the physics of the future…. State-of-the-art Detectors



Possible to get ~100% acceptance for the whole event

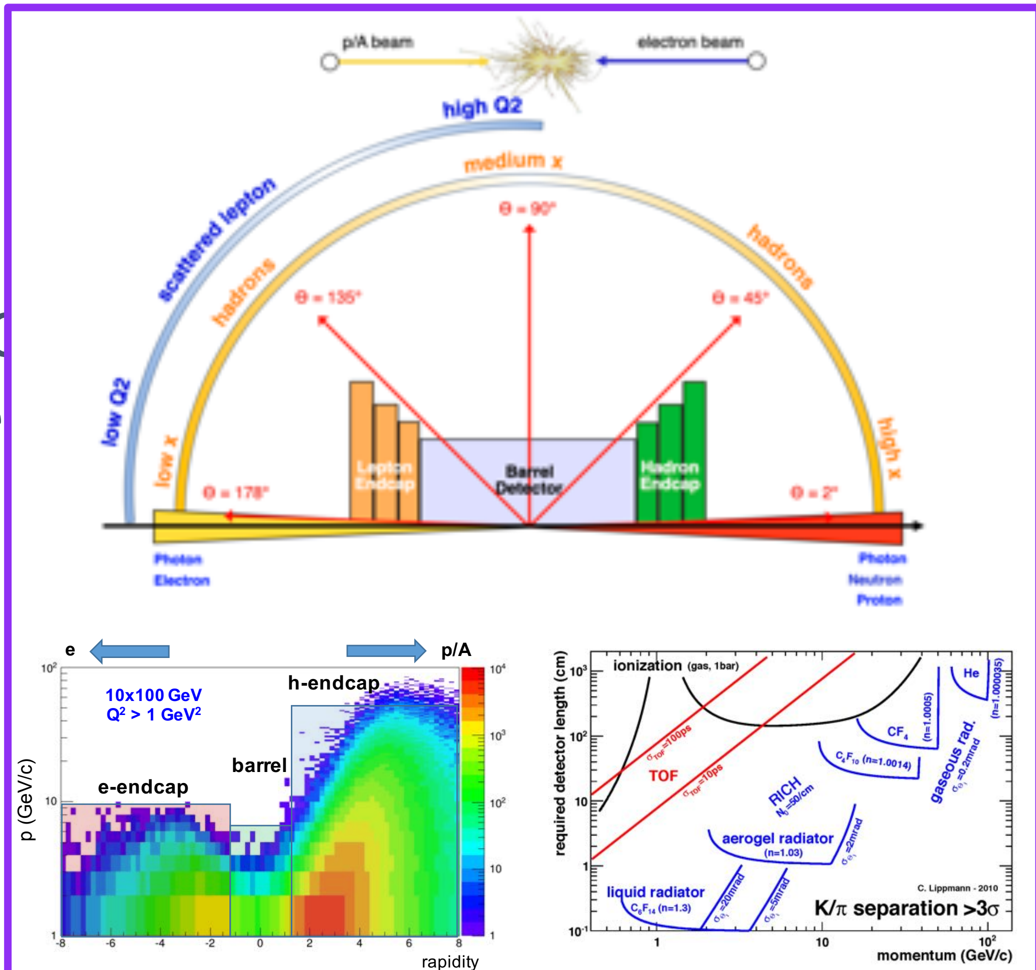
Total acceptance detector (and IR)

Crossing angles:
eRHIC: 10-22 mrad
JLEIC : 40-50 mrad

Figure Courtesey: Rik Yoshida

EI(

de



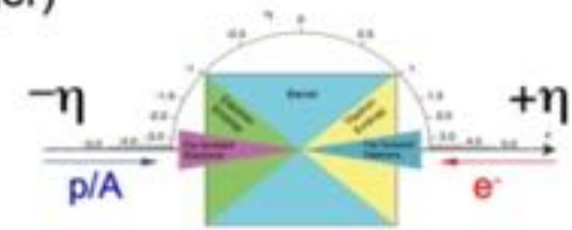
rd tracker layout

ge in tracking/calorimetry/PID for |η|<4

tion (Roman Pots, ZDC, etc)

w Q^2 tagger)

volume



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

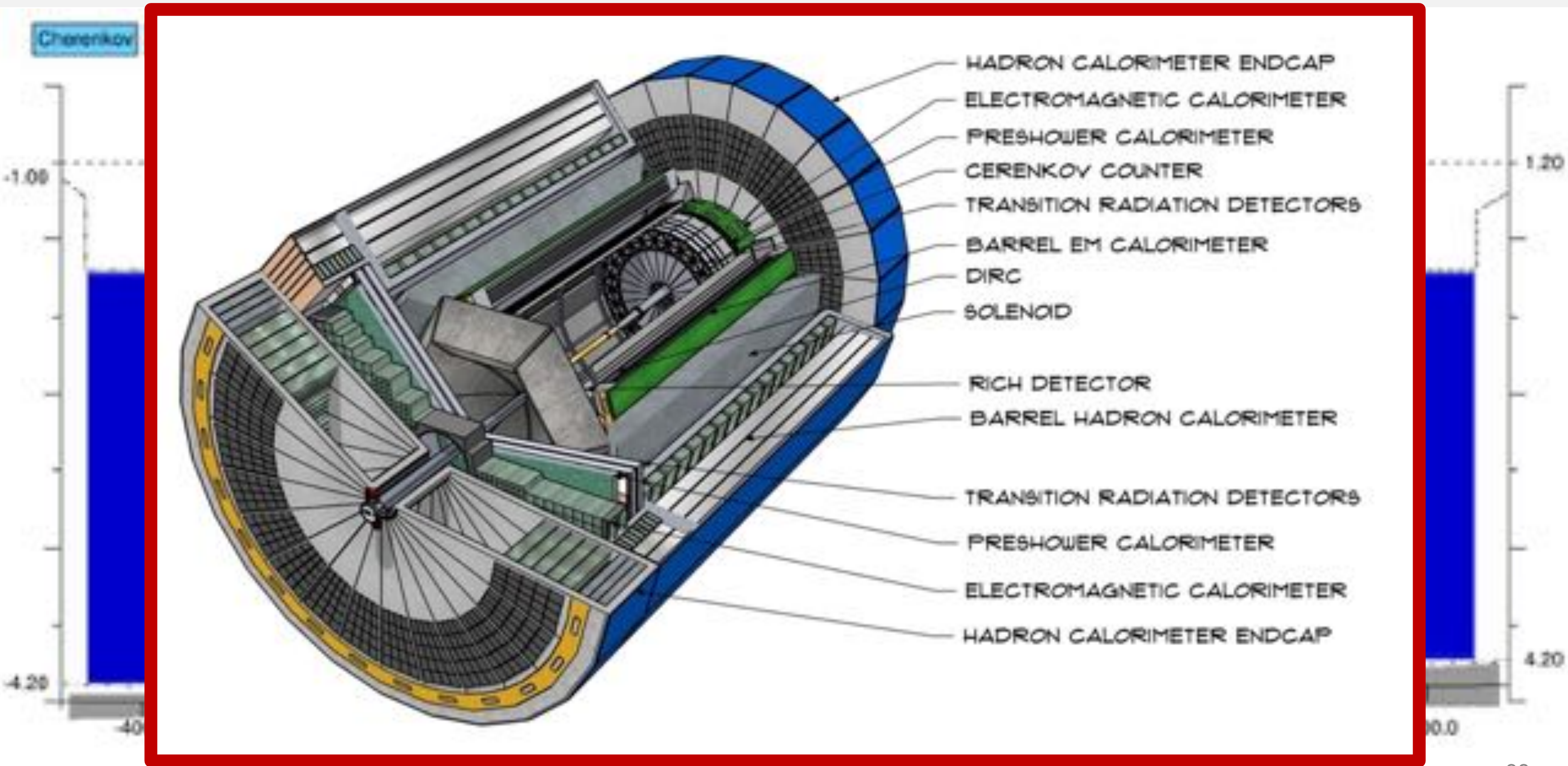
-1% level)

(<20 μm or so)

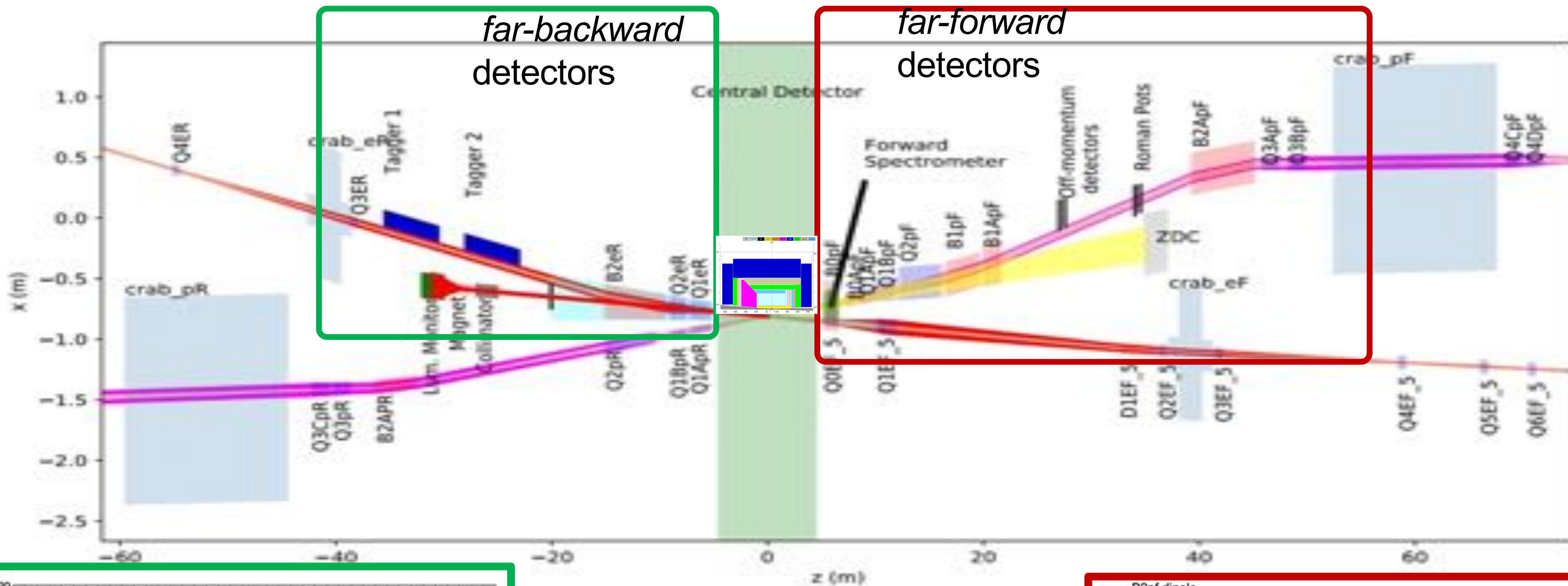
resolution

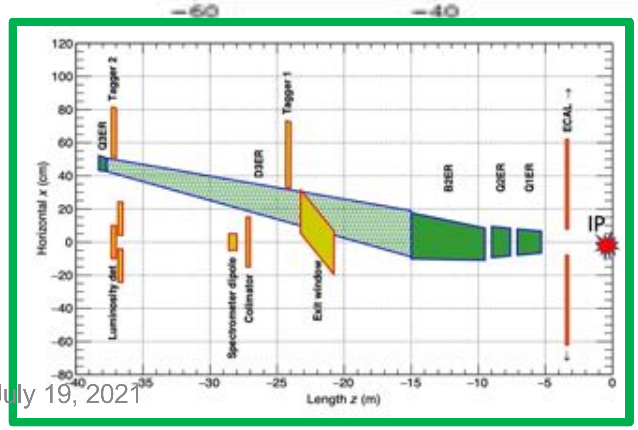
Two detectors are desired: to be decided on the funding, time-line, need for complementarity, and other things

Conceptual DETECTOR

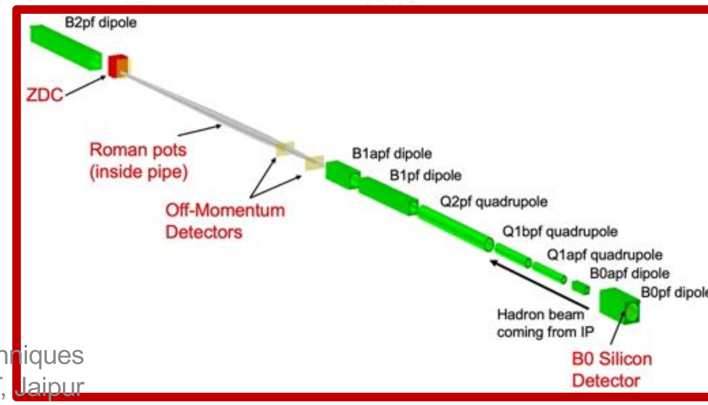


Reference Detector – Backward/Forward Detectors



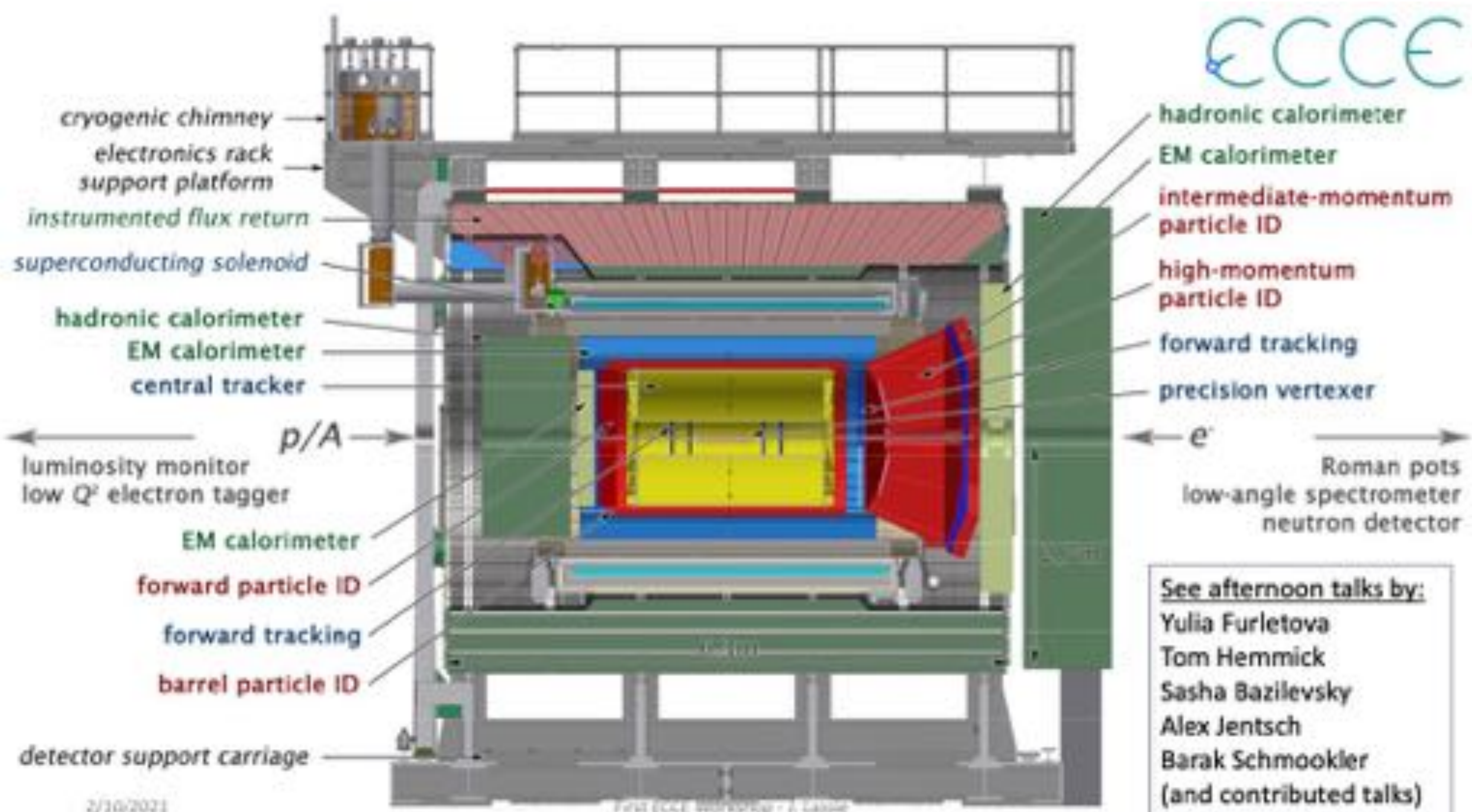


Extensive integration of forward and backward detector elements into the accelerator lattice



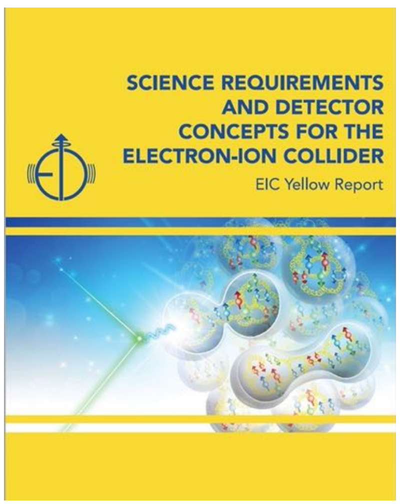
ECCE 101

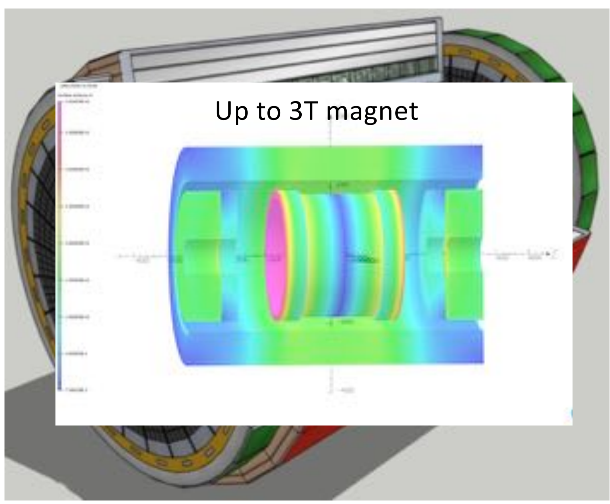
- 77 inst ... far forwar
- Based ... ginning of EIC
- ECCE ... EIC physic ("Dete
- ECCE ... ion is best se

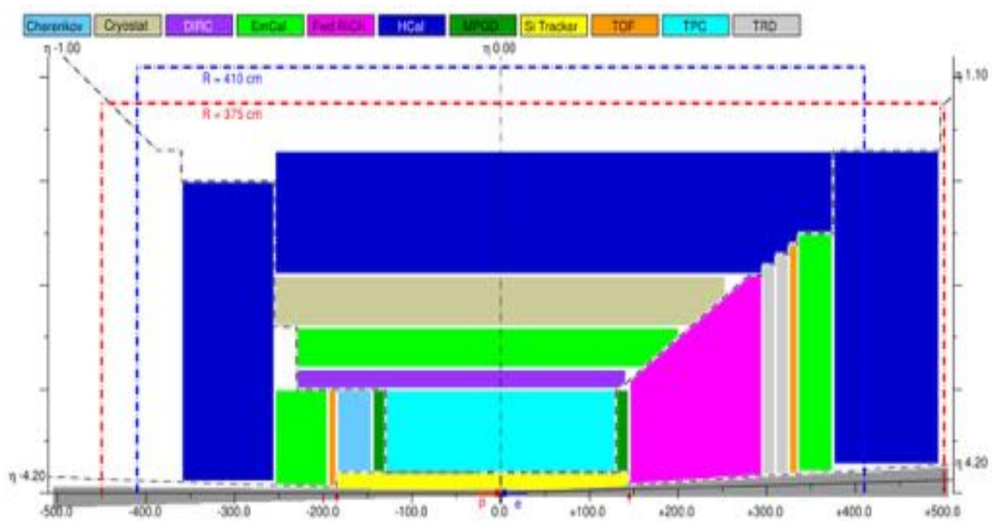


- ECCE is open to all to participate - freedom of choice to also work on other proposals

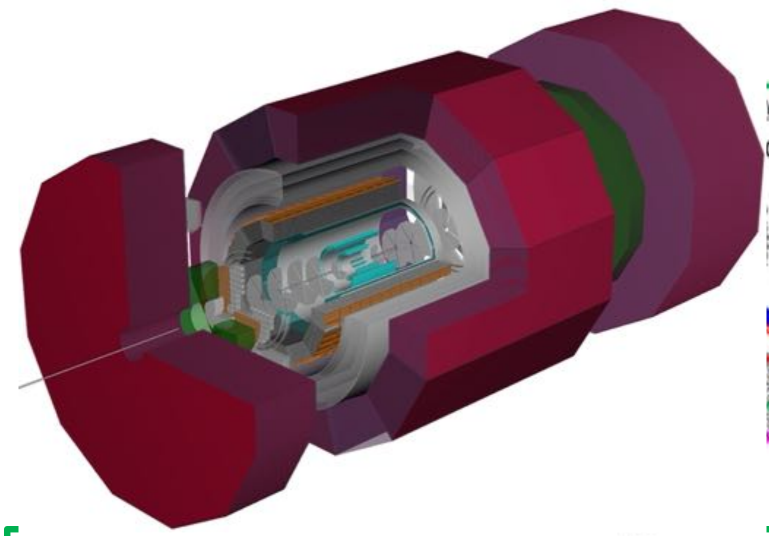
- ATHENA pre-collaboration is open to the whole EICUG community
- Web-page: https://sites.temple.edu/eicatip6
- Mailing lists: https://lists.bnl.gov/mailman/listinfo/
- Join EIC@IP6 on Slack: [link]()
- The coordination committee: Silvia Dalla Torre, Abhay Deshpande, Olga Evdokimov, Yulia Furletova , Barbara Jacak, Alexander Kiselev, Franck Sabatie, Bernd Surrow
- Institutional board, charter committee, proposal committee, Working Groups for detector and physics in place.
- **94+ institutions contributing to the effort**

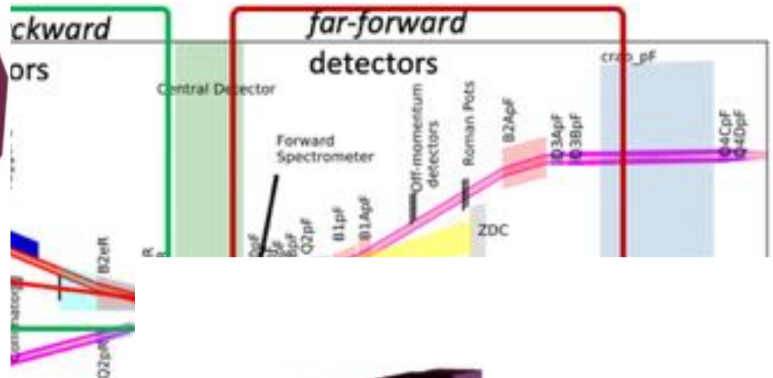


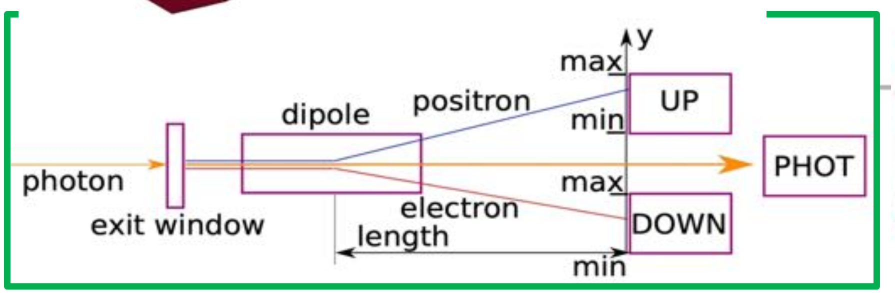




ATHENA being integrated with farword/backward detectors into a single software package for full simulations (DD4HEP)

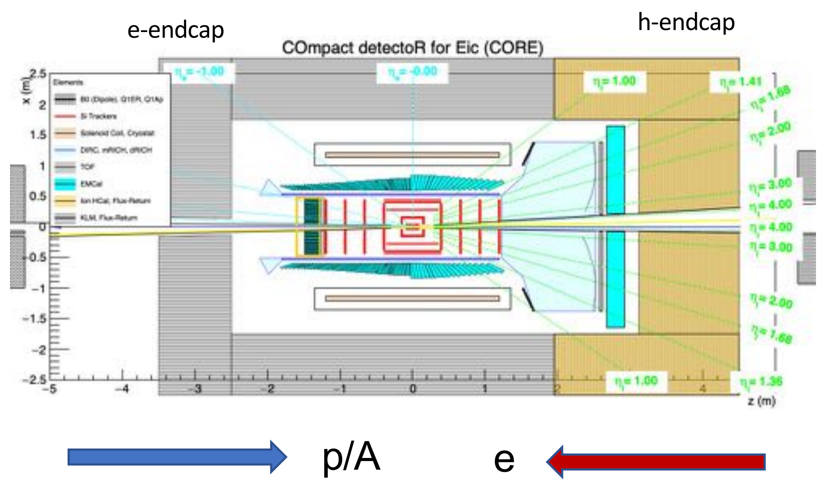






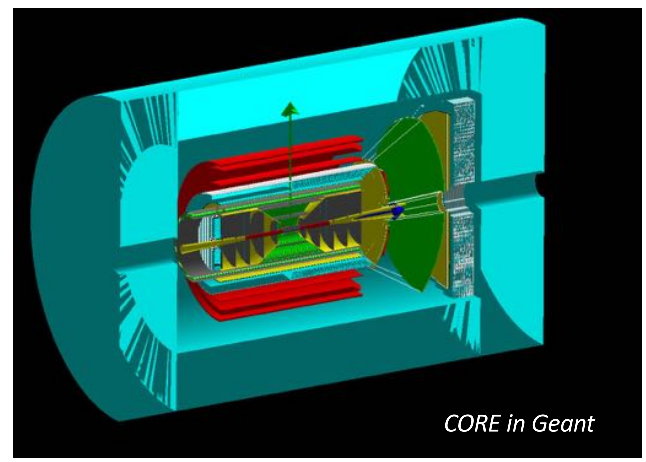
CORE: a COmpact detectoR for the EIC

- CORE is a hermetic general-purpose detector that fulfills the EIC physics requirements.
  - outlined in the Yellow Report. White Paper, etc.
- The compact size has several advantages, including.
  - higher luminosity for all c.m. energies
  - reduced cost allowing investment in critical components



Main systems

- New 2.5 T solenoid (2.5 m long, 1 m inner radius)
- Central all-Si tracker (+ GEM in h-endcap)
- PID: DIRC in barrel, dual-radiator RICH in h-endcap, LGAD TOF in e-endcap
- EMcal: PWO for $\eta < 0$ and W-Shashlyk for $\eta > 0$
- Hcal and K_L-μ (KLM) detectors integrated with the magnetic flux return of the solenoid



P. Nadel-Turonski

CORE pre-collaboration

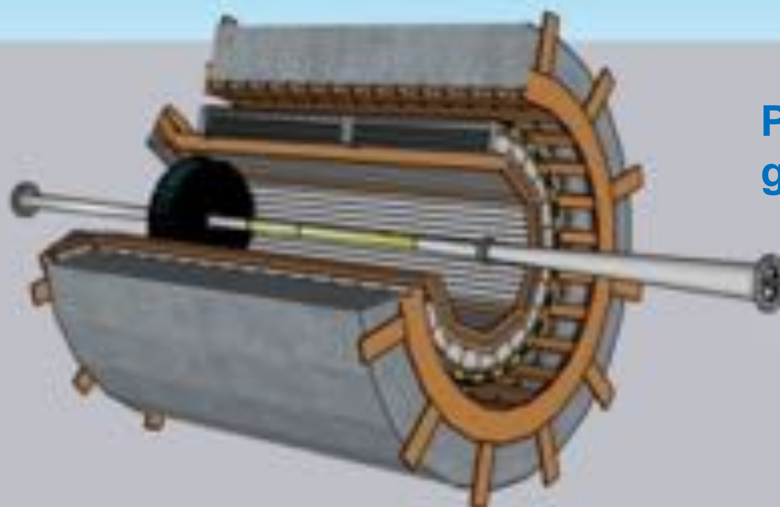
Open collaboration - all EIC enthusiasts are welcome to join!
About 20 institutions

Bi-weekly meetings

- Mondays at noon
  - Time may change due to recent conflicts with other meetings

Wiki and mailing lists

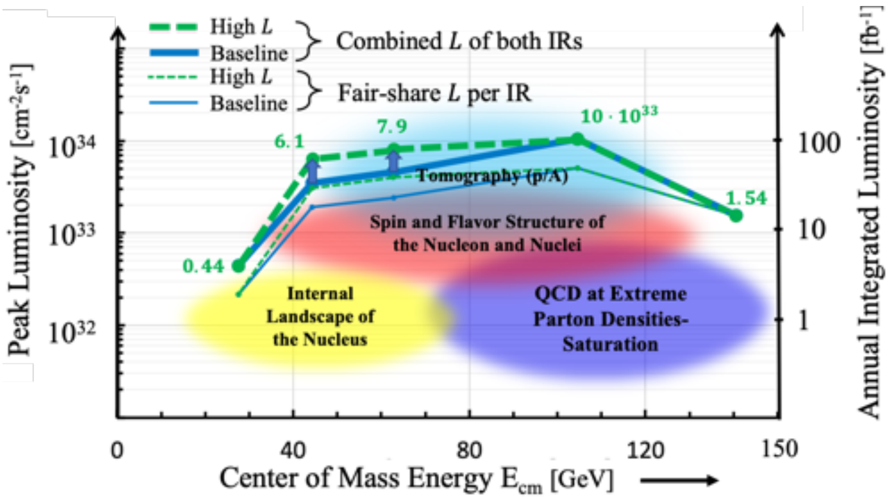
- Wiki: https://eic.jlab.org/core
- Mailing lists:
  - eic-core@jlab.org
  - eic-core-det@jlab.org
  - eic-core-phys@jlab.org



Physics working groups are forming!

Physics at Low CM-High Lumi IR: A separate detector?

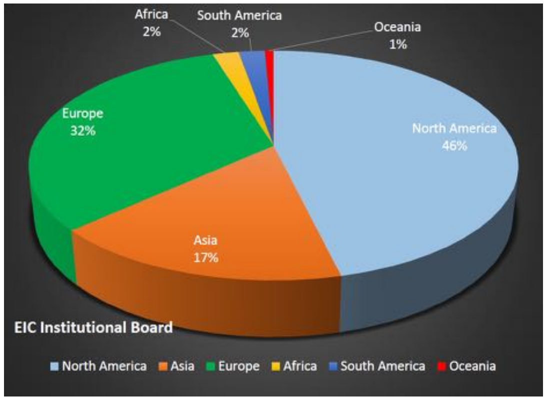
- Aim: to produce a White Paper to highlight the science at the EIC with a **high-luminosity at low-CM energy Interaction Region.**
  - DES, SIDIS, Jets, HF, Spectroscopy, various researches with light nuclei
  - Contact: Volker Burkert, Latifa Elouadrhiri, AD
- Conditions from the Call for proposal for the 2nd detector:
  - D2/IR2 complementary to D1/IR1, physics focus beyond EIC WP, and possibly modified IR2 design (compatible with IR1 and machine operations)
- Series of Center for Frontiers In Nuclear Science Workshops: 1st @ CFNS, 2nd @ ANL-CFNS, 3rd APCTP=CFNS, 4th CNF-CFNS (DC).



Recent machine development and studies
Possible to get high luminosity by only adjusting magnetic polarities of near-IR magnets

The EIC Users Group: EICUG.ORG

Formally established in 2016, now we have:
~1300 Ph.D. Members from 35 countries, 254 institutions
New members welcome



New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC^2 at Jefferson Laboratory

EICUG Structures in place and active:
EIC UG Steering Committee, Institutional Board, Speaker's Committee, Election & Nominations Committee
Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

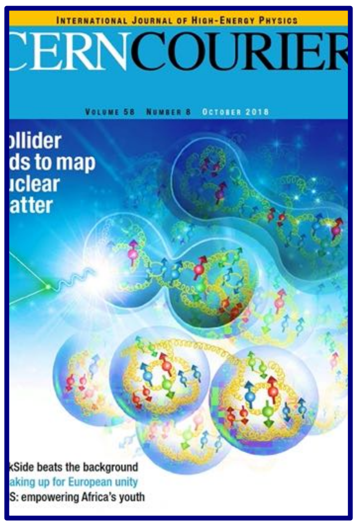
Year long workshops: Yellow Reports for detector design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016), Trieste (2017), CAU (2018), Paris (2019), FIU (2020), UCR&VUU(2021), Warsaw (2022)**

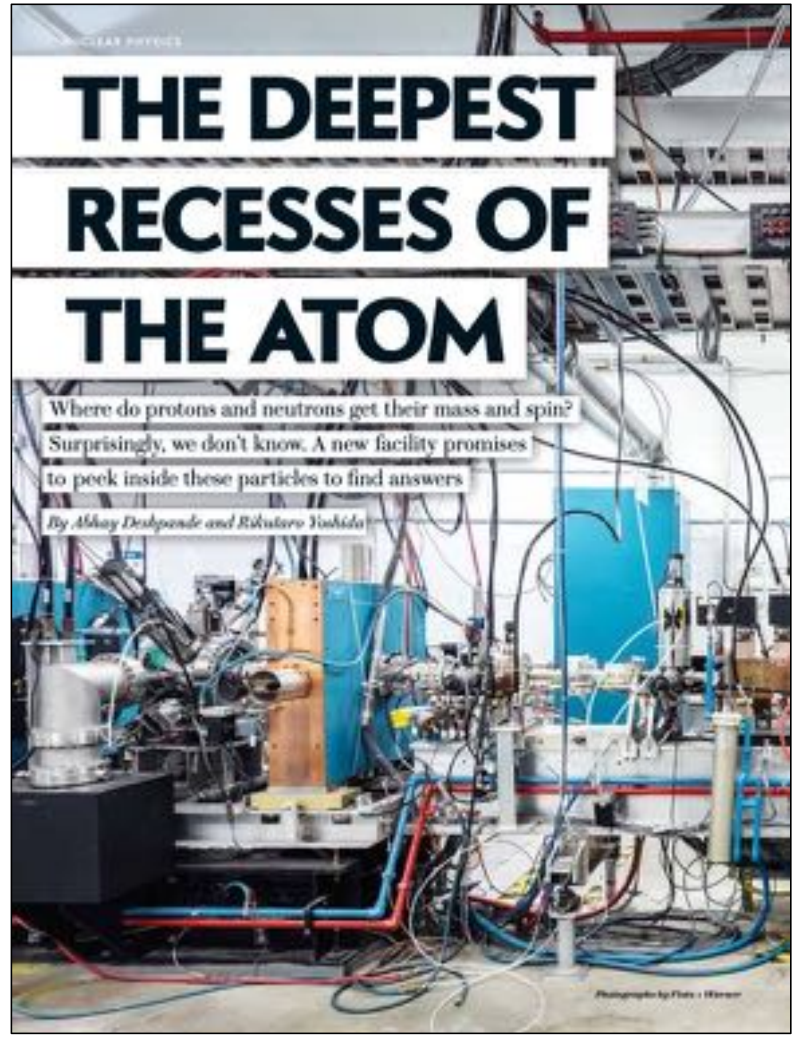

"New directions in science are launched by new tools much more often than by new concepts."
Freeman Dyson

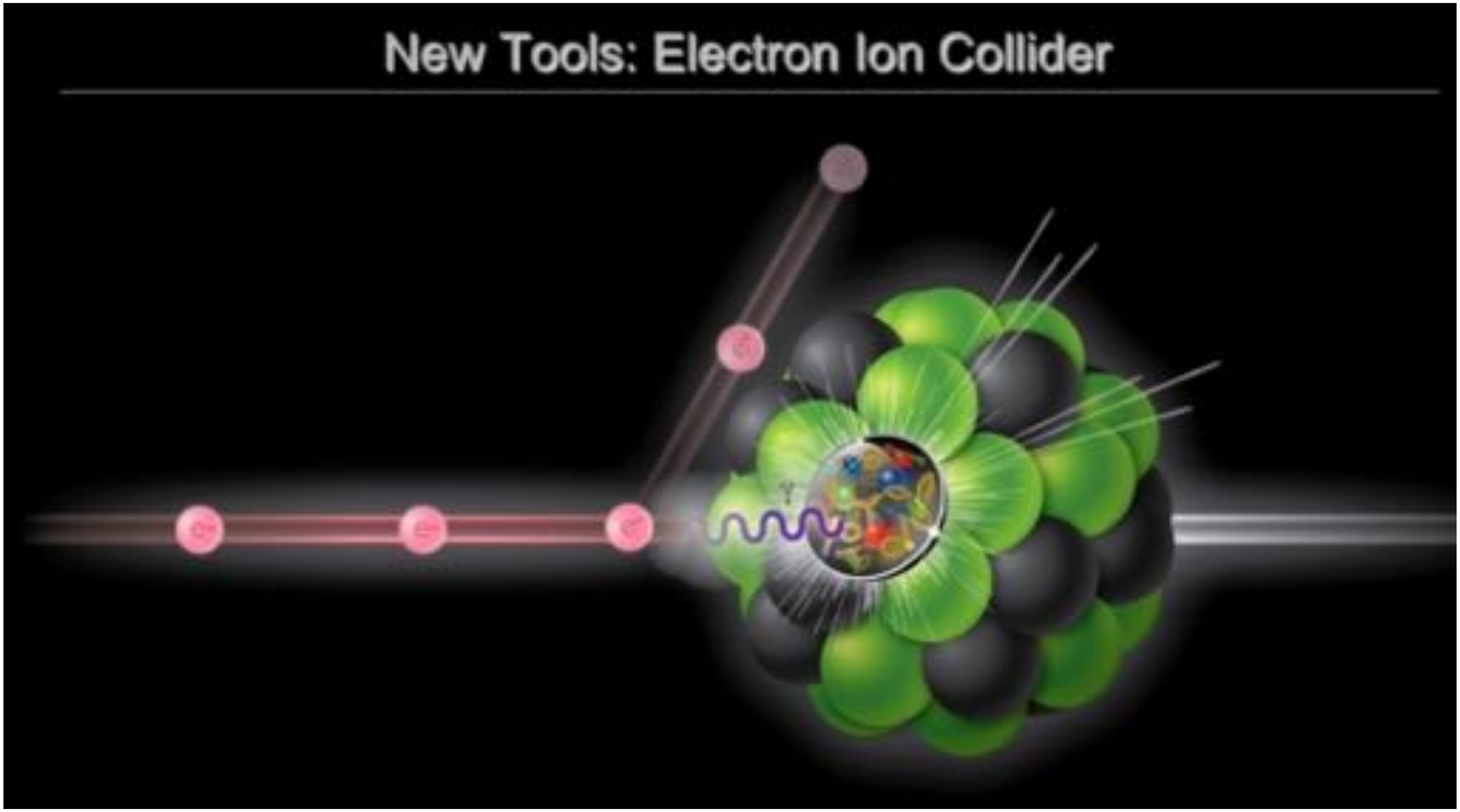
R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)

E. Aschenauer
R. Ent
October 2018



A. Deshpande
& R. Yoshida
June 2019



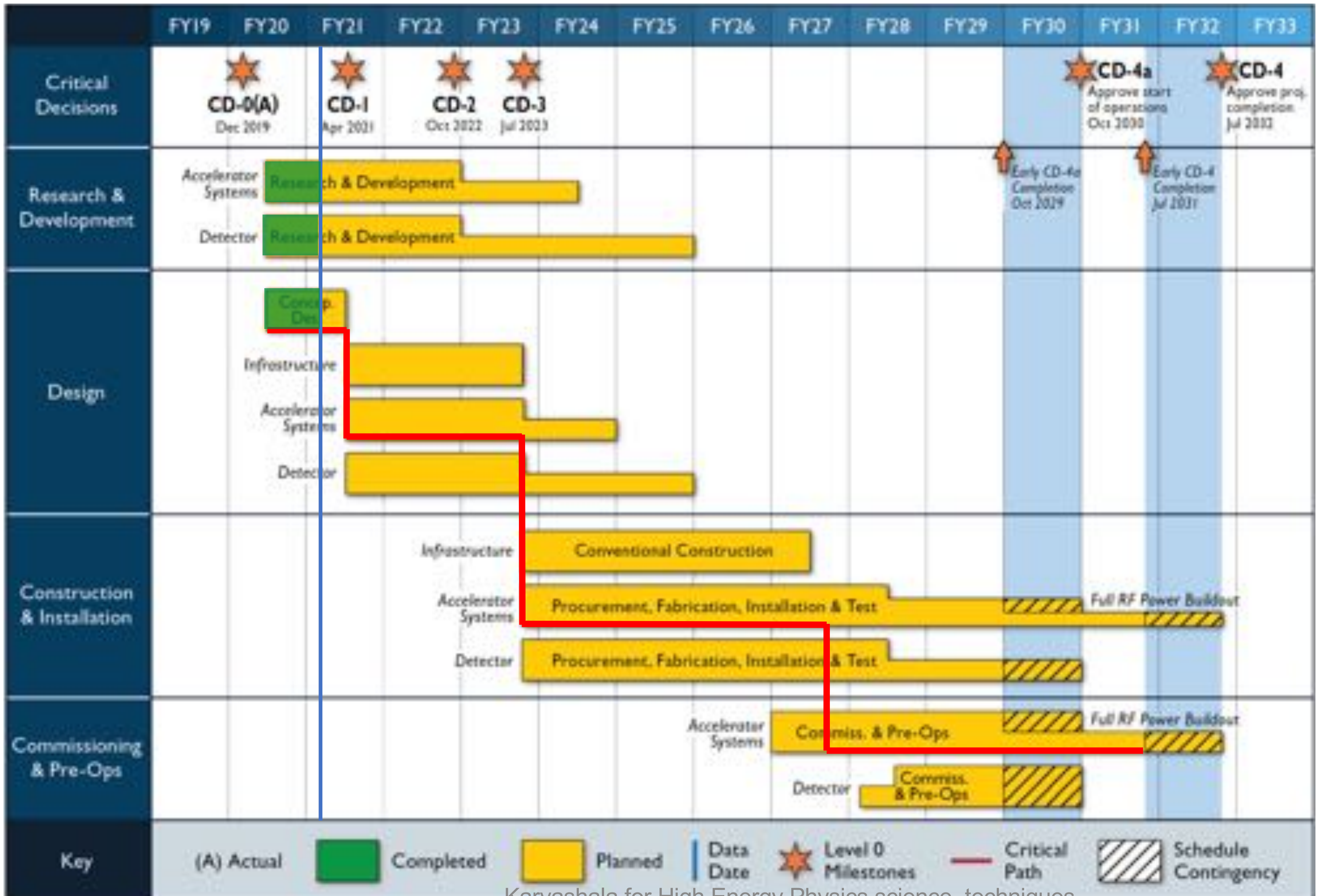

New Tools: Electron Ion Collider

Detectors Planning: Path forward

- 3 Detector pre-proposals + 1 White Paper(?))
- Due date : December 1, 2021
- Independent external committee appointed by the Lab Managements will evaluate and advise the Labs and EIC project : modifying, merging & rejection of proposal…
- *Under all circumstances: ALL Users will be accommodated*

- Current expectation Project Detector (D1) Selection : Q1FY22
- Detector Project complete Q4FY31: Ready for CD4A start of operations
- 2nd detector(?) about 2 yrs behind the 1st? Complete by CD4

Project Schedule (being finalized)



CD4A start of operations

CD4 Start of physics

Summary

- The EIC will be a unique facility to address some of the most profound unsolved problems in QCD. It will explore in great detail the precise role gluons play in QCD dynamics using polarized beams and a range of nuclei colliding with electrons.
- BNL, Jefferson Lab working as partners, supported by the US Department of Energy and the world-wide Users are well poised to realize the EIC and start exploring the EIC science early 2030's
- *Considering the age profile of the group attending this meeting in Jaipur: This machine is for YOU. We hope you make the fullest use of it by enthusiastically participating in its realization and then the promise of its Science….*