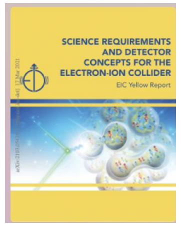
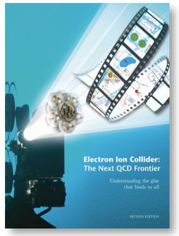
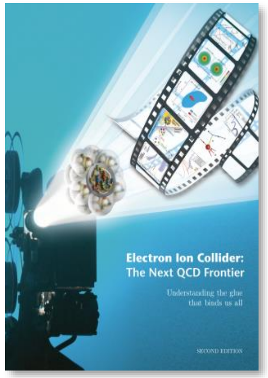
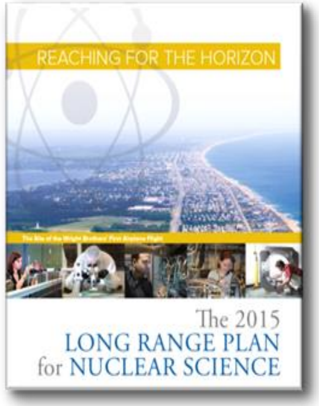



Electron Ion Collider (EIC): Student Lecture – Prague, Czech Republic

2015

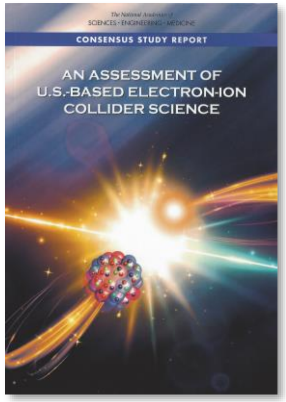


2016



Physics of EIC

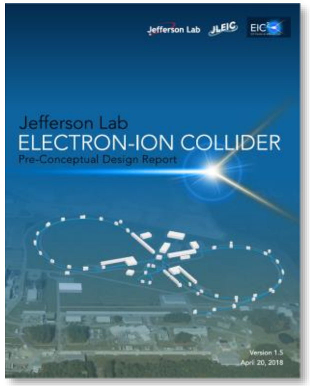
2018



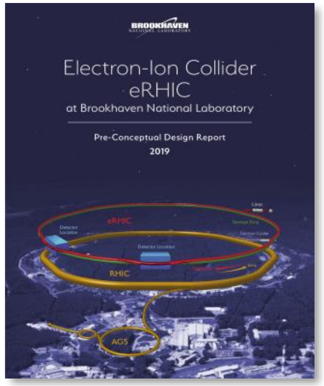
Evaluation

2019-present

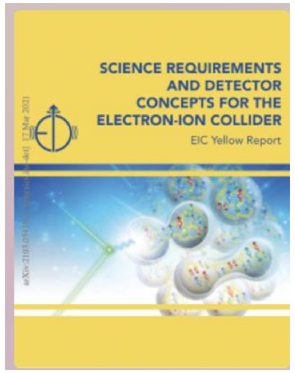
2019



machine



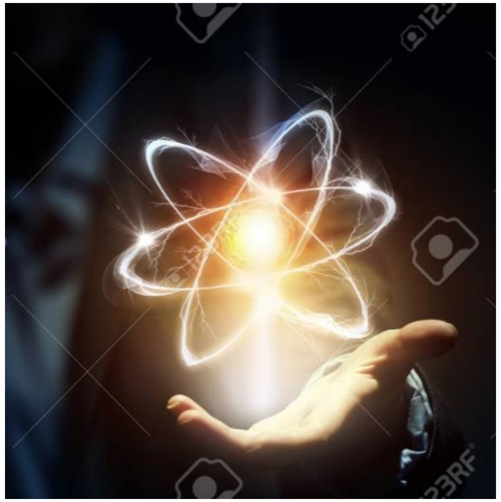
detector

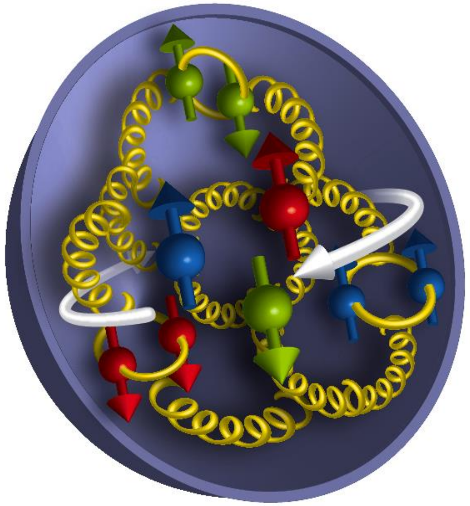


Realization

Thanks to **Abhay Deshpande for sharing his slides and for discussions**

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?

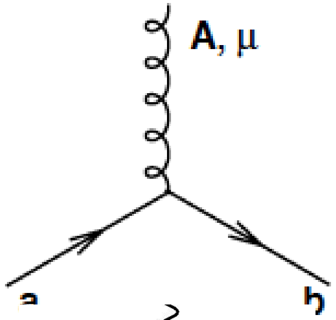
Because of the gluons

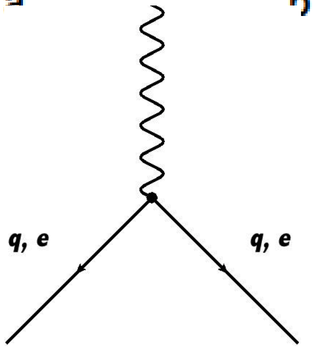
What distinguishes QCD from QED?

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

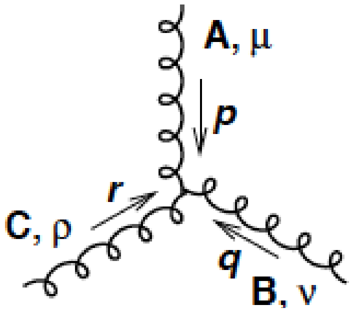
QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

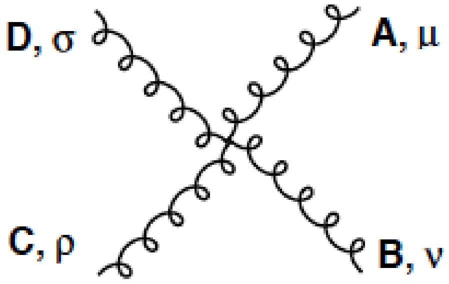
In QCD &
g → γ in QED





Only in QCD





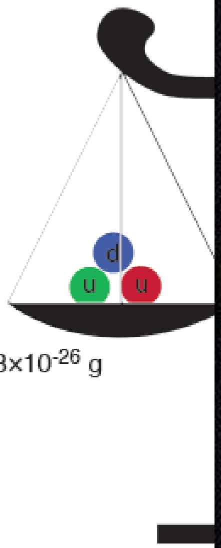
Nonlinear growth in g-g interactions…
Bring richness and complexity to QCD
Experimental guidance always needed

Proton mass puzzle

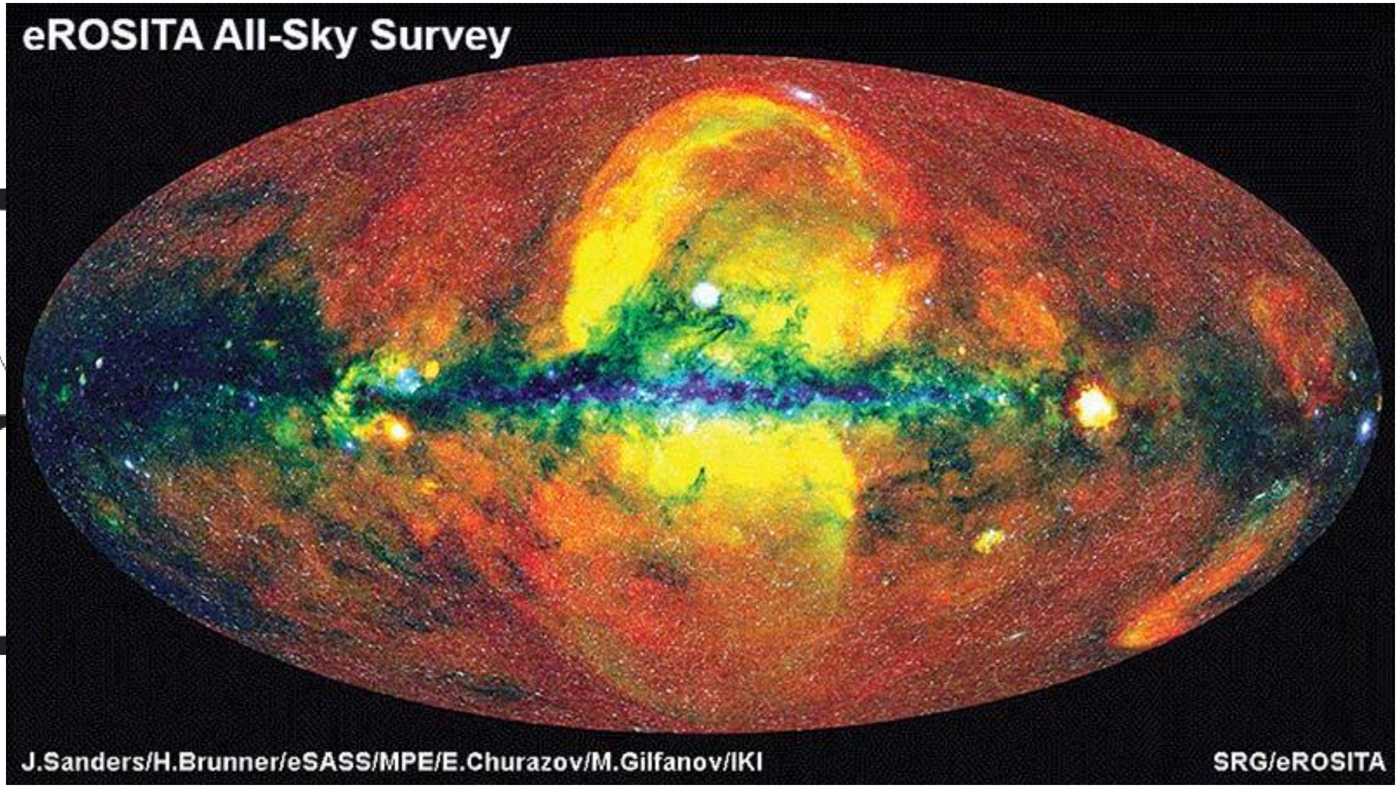
François Englert

Peter W. Higgs

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



Quarks
Mass $\approx 1.78\times10^{-26}$ g



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

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

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

➔Where does the rest of the mass come from?

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)

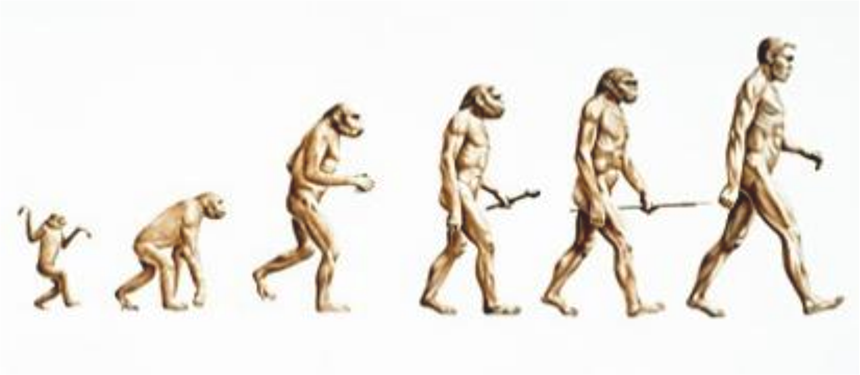
➔ Deeply connected to emergence of mass and spin of observed building blocks of nature

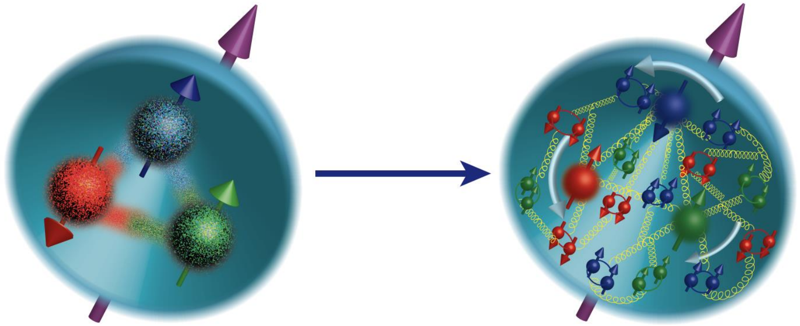
- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number: Is it tamed by existing mechanisms in QCD?
  - Is there a universal many-body structure due to ultra-dense color fields?
  - Happens **in all** hadrons and nuclei? ➔ Universal?

A-A, p-A, e-A, p-p, e/μ-p/A and e-e collisions are all essential for fully understanding of QCD

Spin "Crisis" → Spin Puzzle

Discovered by EMC experiment at CERN





25% 25%

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

? ?

Transverse motion and finite size of the proton must create the orbital motion

Connected to the mass?

Nuclear Puzzle

Discovered by EMC experiment at CERN

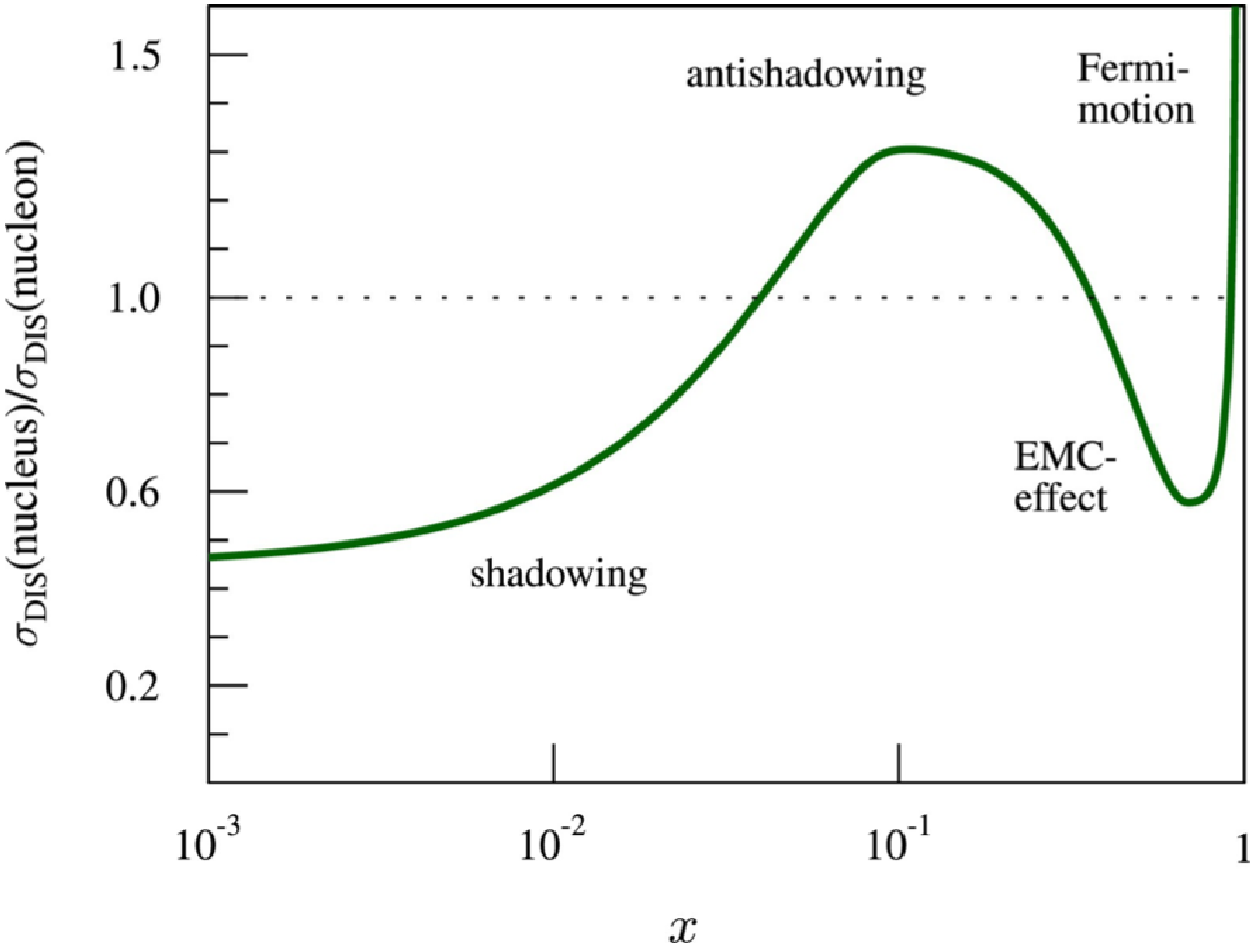
Nuclear EMC effect

Parton distributions are different in protons and nuclei

Exactly how do they get modified?

What happens in regions x < 0.001?
Not quite known, and not predictable

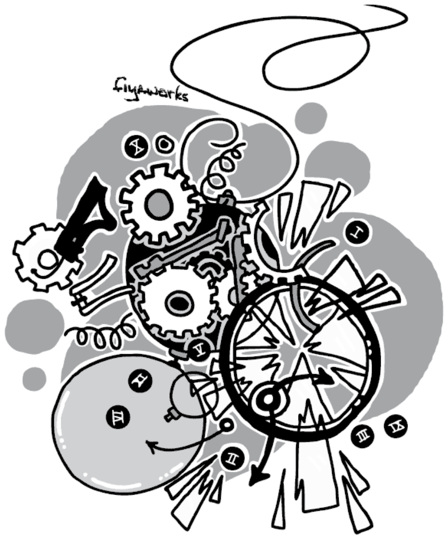
However, low-x dynamics in protons and nuclei is of great interest, need to measure experimentally



DEEP INELASTIC SCATTERING (DIS)

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

Scattering of protons on protons
is like colliding Swiss watches to find out
how they are build.



R. Feynman

We can ask : What is in there, but not how they are built or how they work!

Study of internal structure of a watermelon:

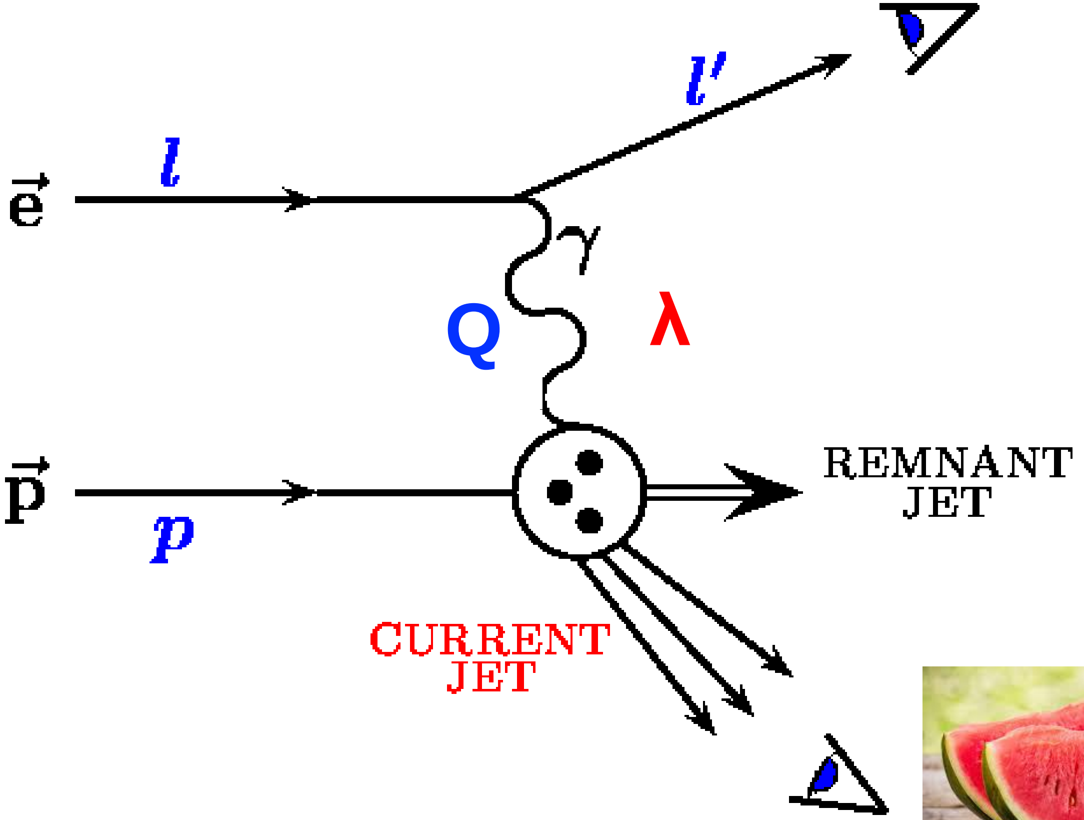
A-A (RHIC/LHC)

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

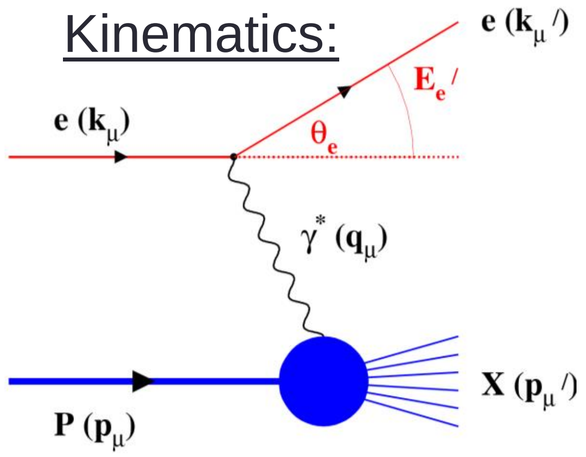
λ = wavelength

Q^2 = momentum transferred

Deep Inelastic: (λ << Proton Size)

Deep Inelastic Scattering: Precision and control

Kinematics:



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

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

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

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

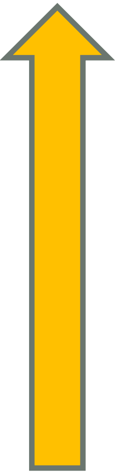
Measure of momentum fraction of struck quark

Hadron :

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

$$s = 4E_h E_e$$

High lumi & acceptance



Low 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

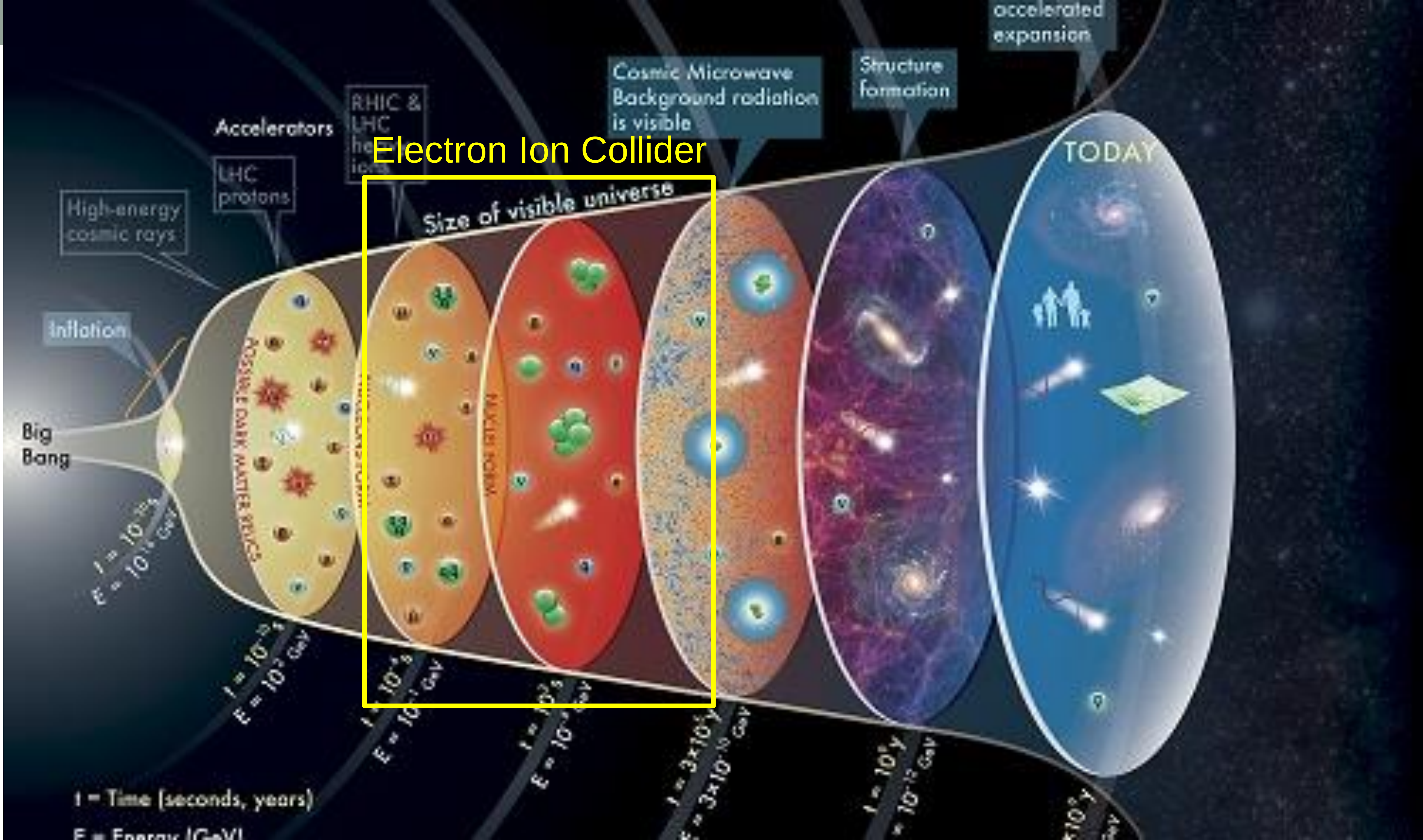
detect the scattered lepton in coincidence with identified hadrons/jets

Inclusive events:

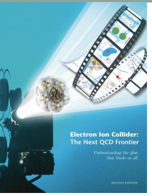
e+p/A → e'+X

detect *only the scattered lepton* in the detector

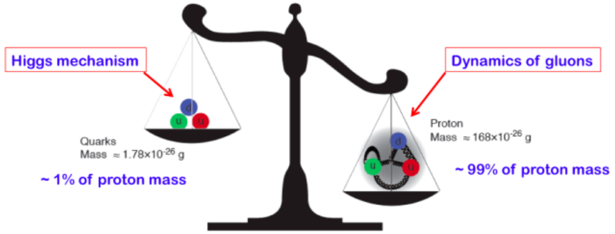
PHYSICS OF EIC



accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC &
Accelerators
Electron Ion Collider
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEI FORM
t = Time (seconds, years)

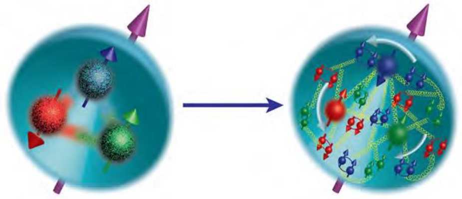


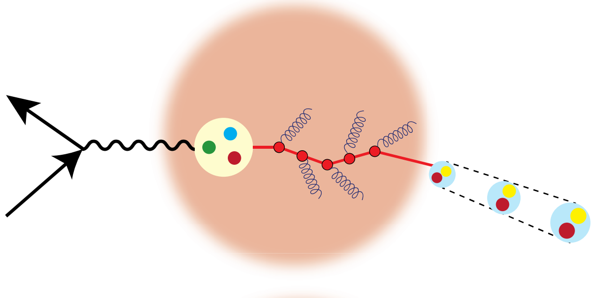
EIC Physics at-a-Glance



How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties (mass & spin) emerge from their interactions?





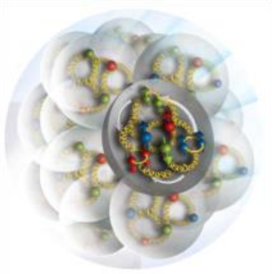
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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 quarks and gluons, their correlations, and their interactions?

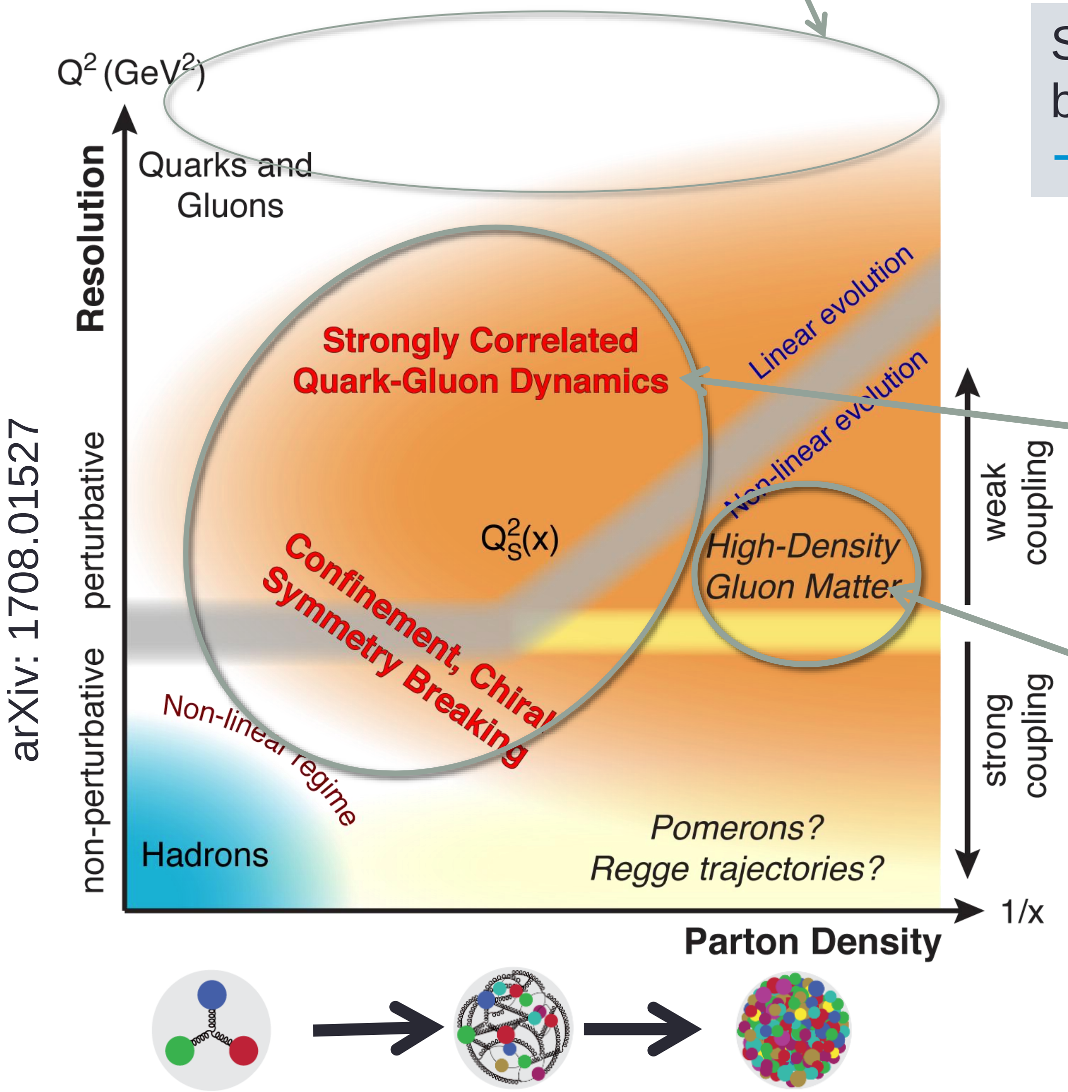
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



gluon emission ?= gluon recombination

QCD Landscape to be explored by a new future facility

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



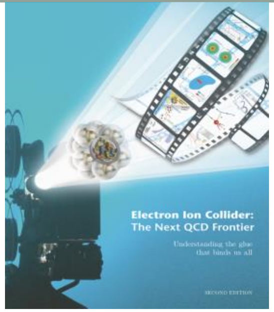
Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

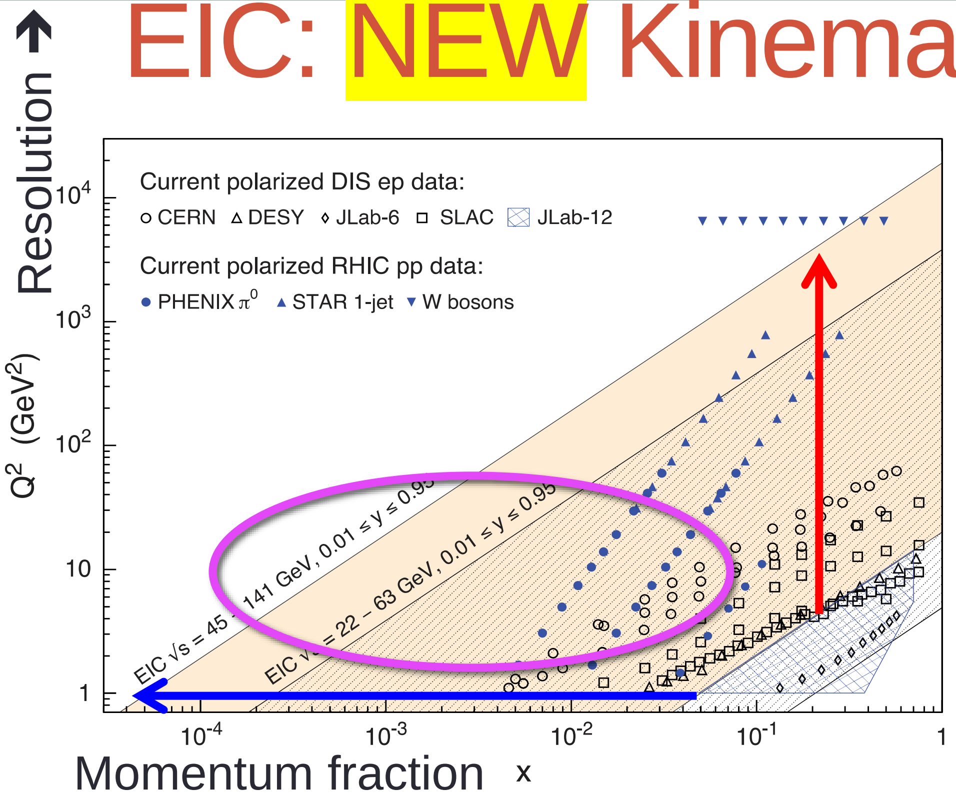
Systematically explore correlations in this region.

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

Need Precision and Control

EIC: NEW Kinematic reach & properties



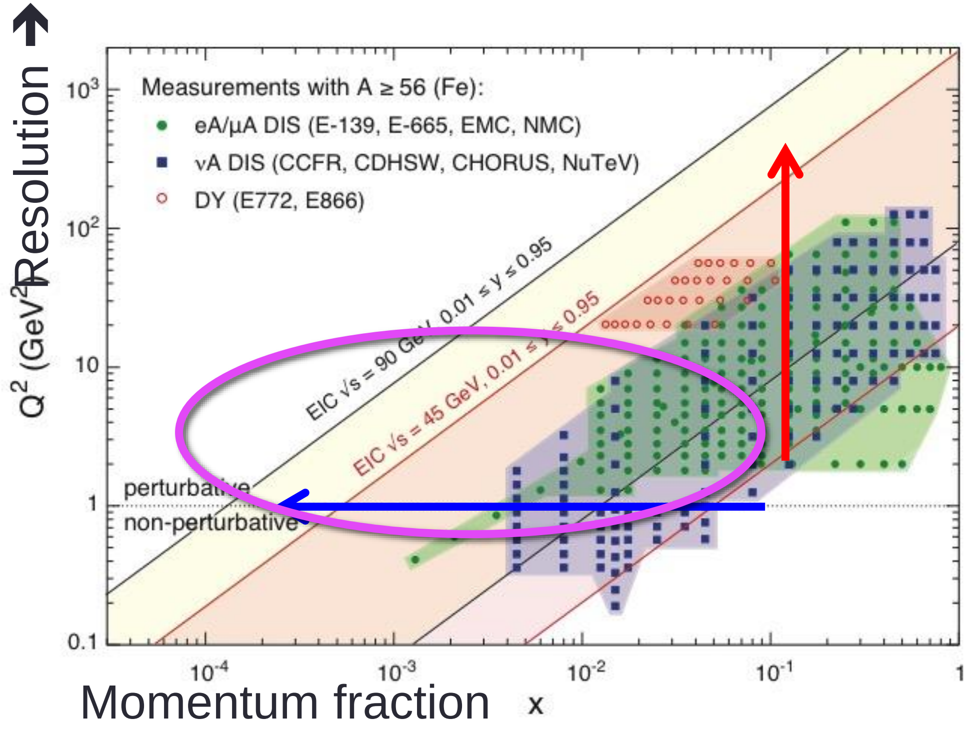


For e-N collisions at the EIC:

- ✓ 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:

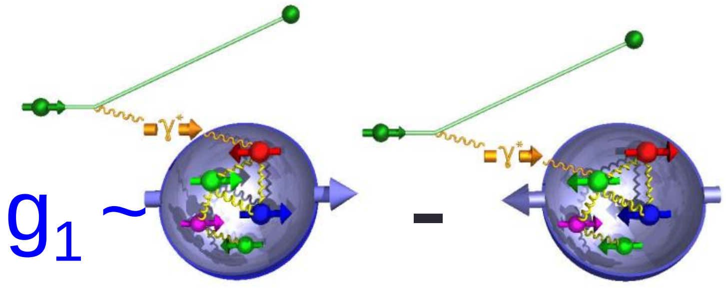
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



Nucleon Spin: Precision with EIC

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

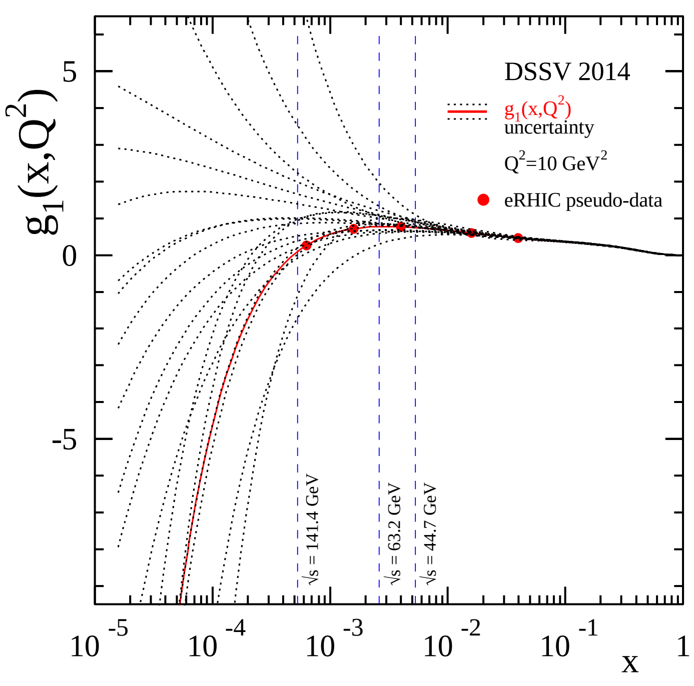
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
Δg = Gluon contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
L_G = Gluon Orbital Ang. Mom

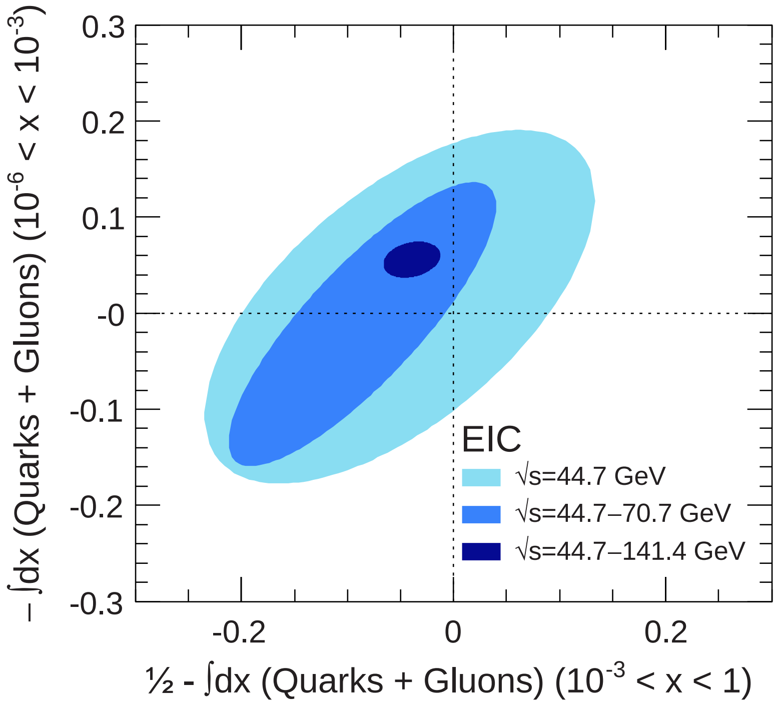


Spin structure function g_1 needs to be measured over a large range in x-Q^2

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

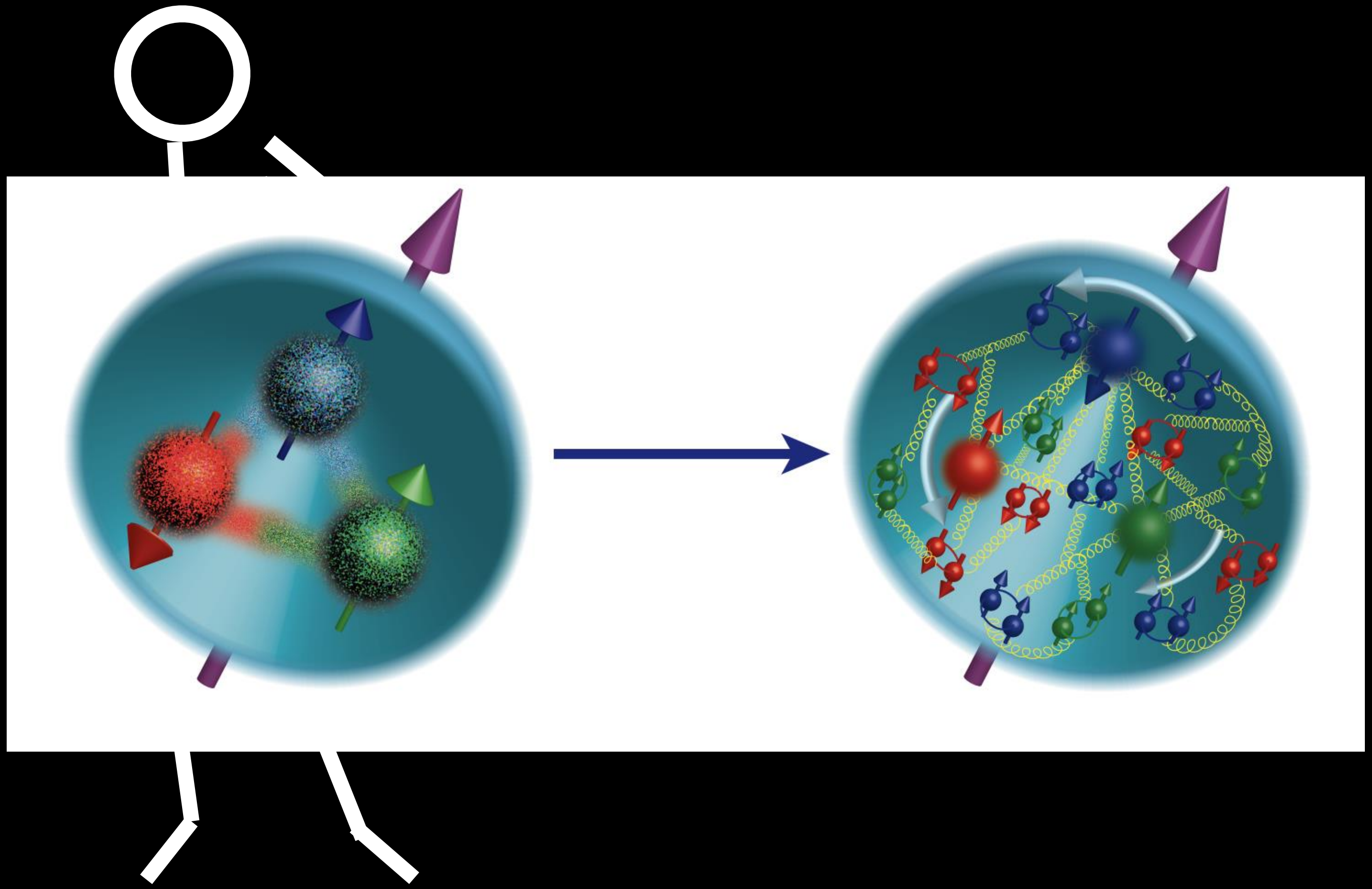
Lattice Calculations : comparison





SIDIS: strange and charm quark spin contributions

1D 3D

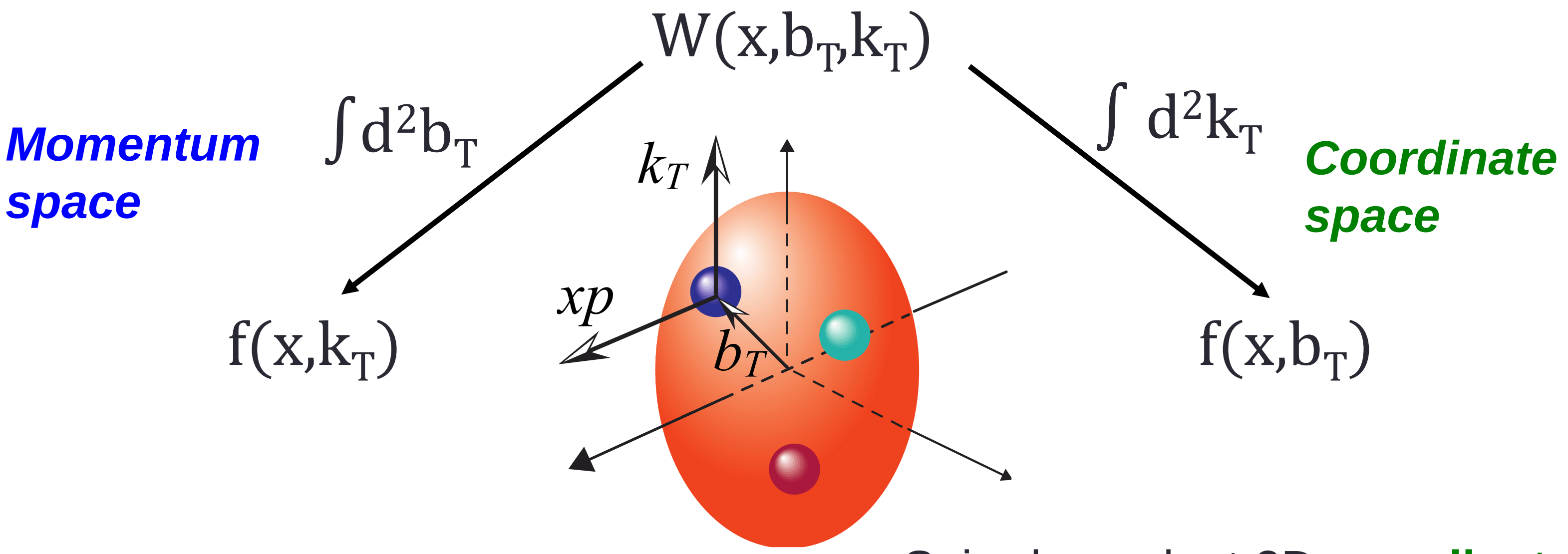


Courtesy: Alssandro Bacchetta

2+1-Dimensional Imaging Quarks and Gluons

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

offer unprecedented insight into confinement and chiral symmetry breaking.



Near future promise of direct Comparison with lattice QCD

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

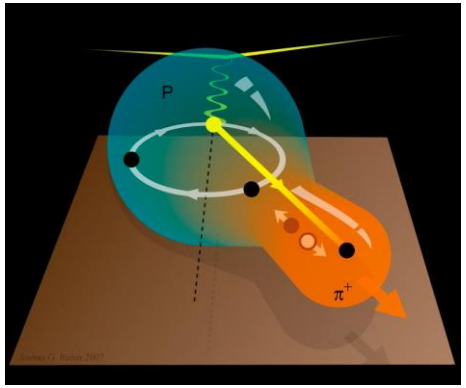
Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply virtual Compton scattering and meson production)
→ **Generalized Parton Distributions**

momentum and position distributions → Orbital motion of quarks and gluons

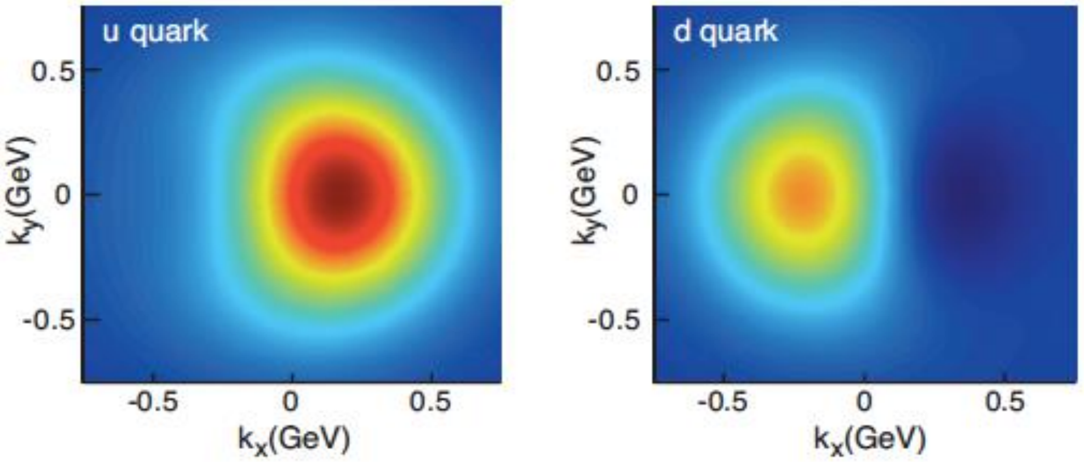
2+1 D partonic image of the proton with the EIC

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

Transverse Momentum Distributions

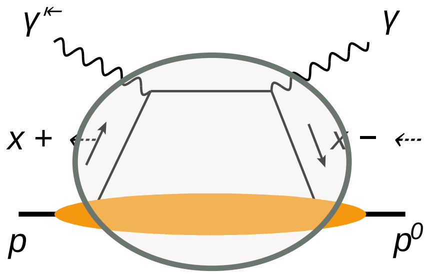


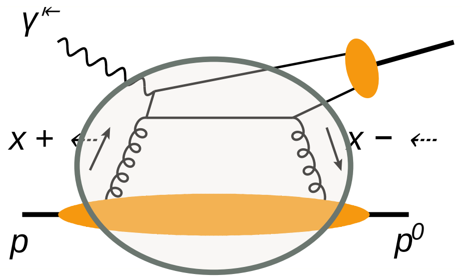
Quark's 2D momentum distribution



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

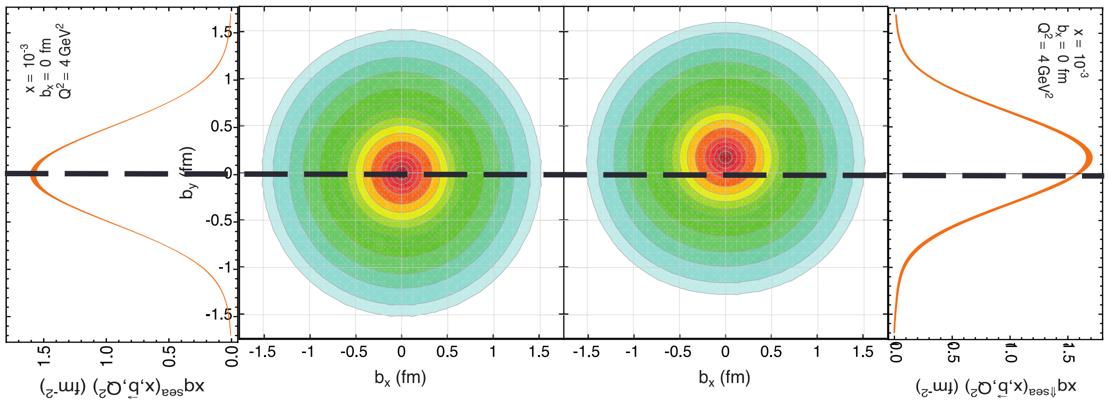
Measure all three final states

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)

CONSEQUENCE OF GLUON SELF INTERACTIONS

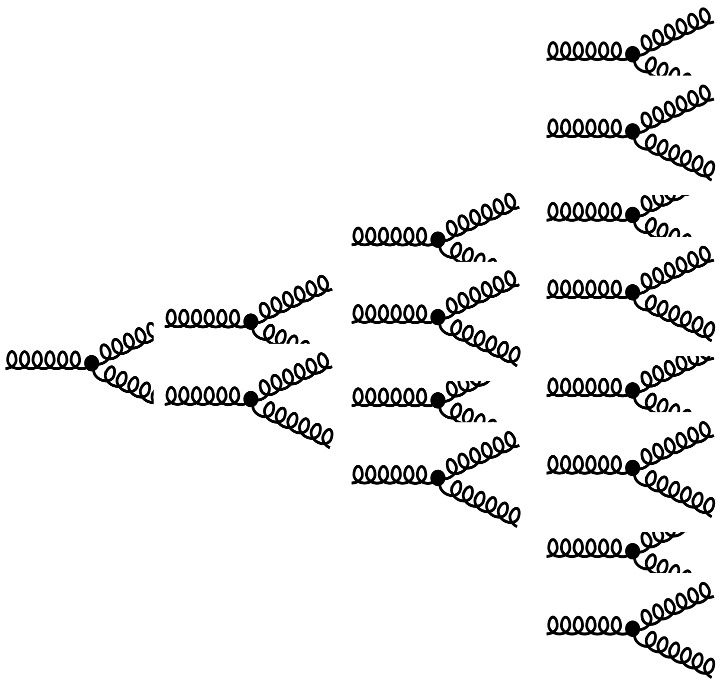
Particularly at high energy (low-x)

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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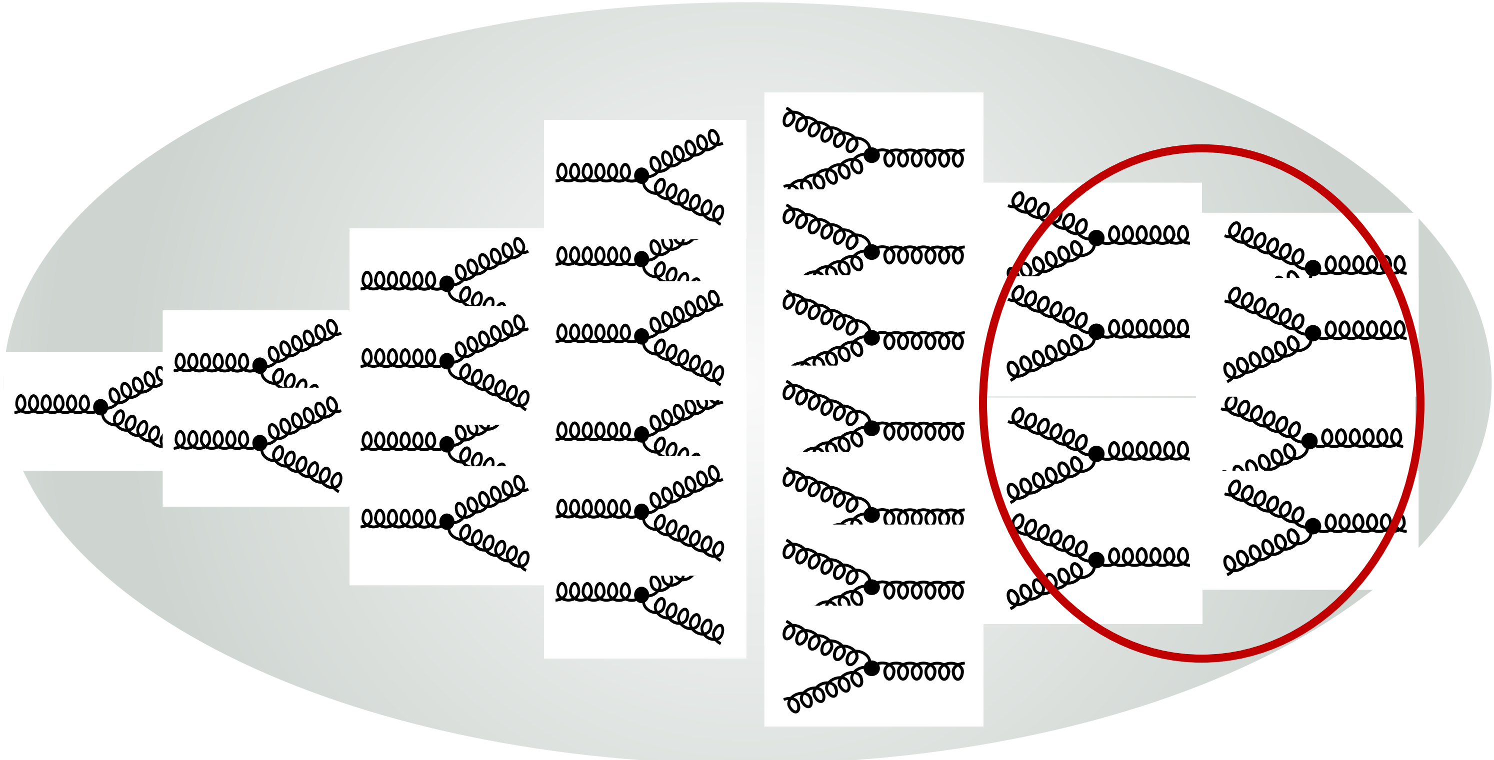
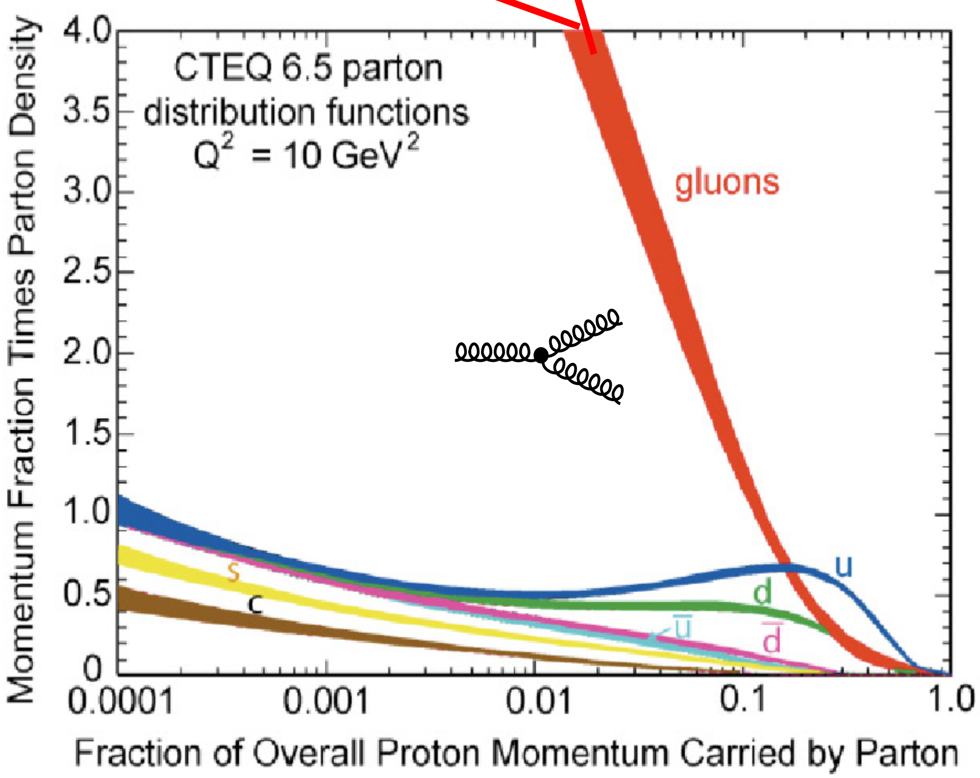


gluon emission

gluon recombination

Saturation State of Gluons reached

In search of a new state of matter!



Experimental evidence needed

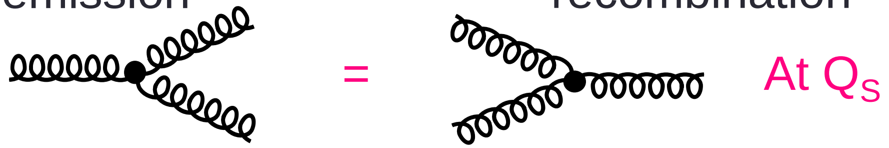
What could tame the low-x rise?

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



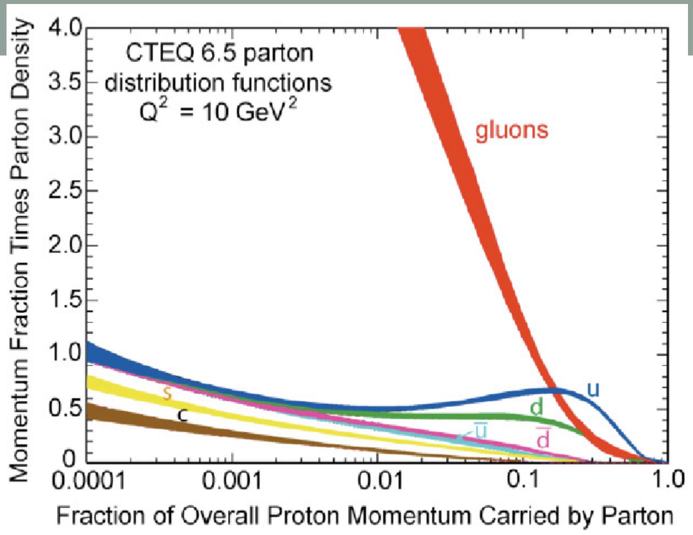
Observation of gluon recombination effects

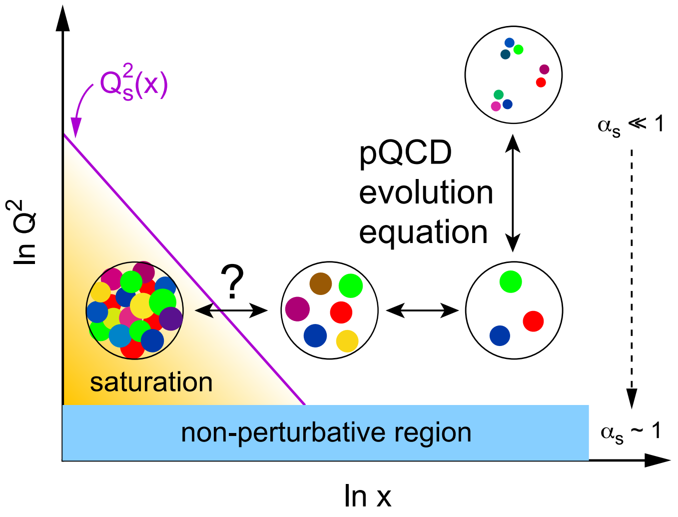
➔Is there such new state of matter?

→ "Color Glass Condensate"

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

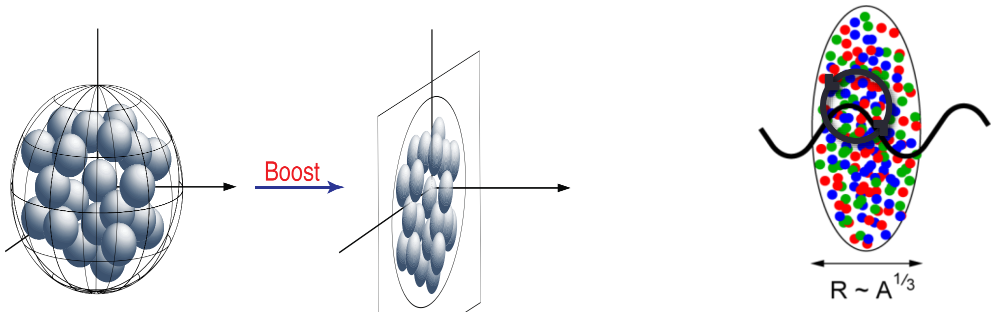
Low x physics with nuclei





gluon emission = gluon recombination

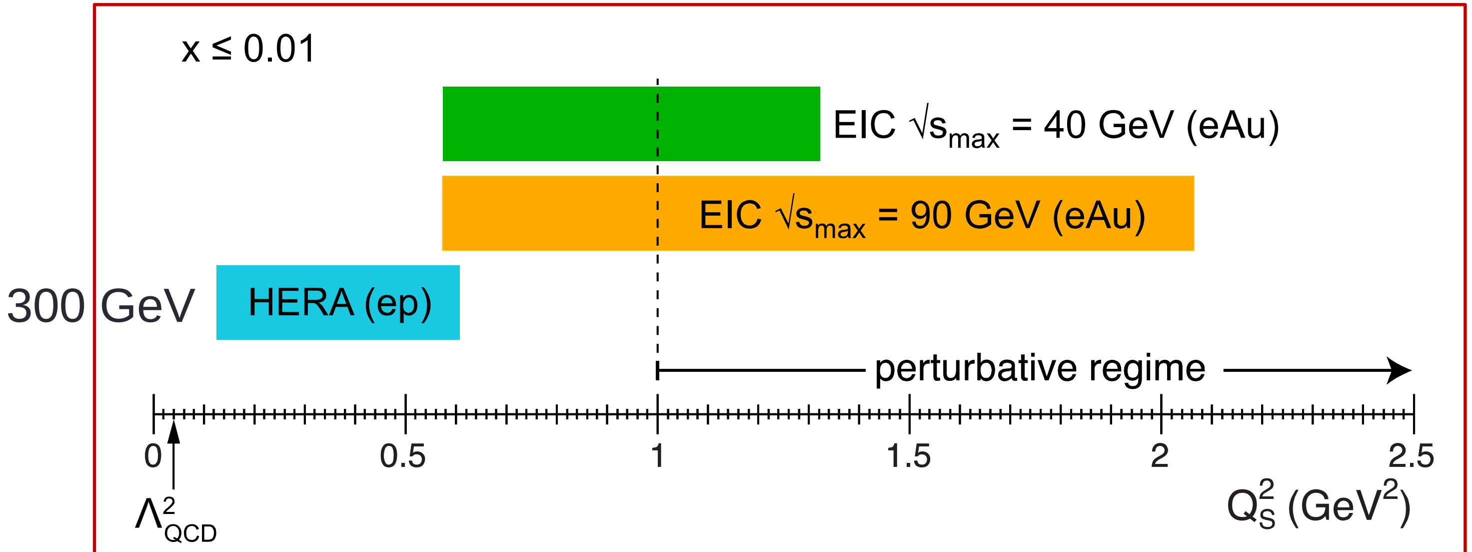
At Q_S



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

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

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

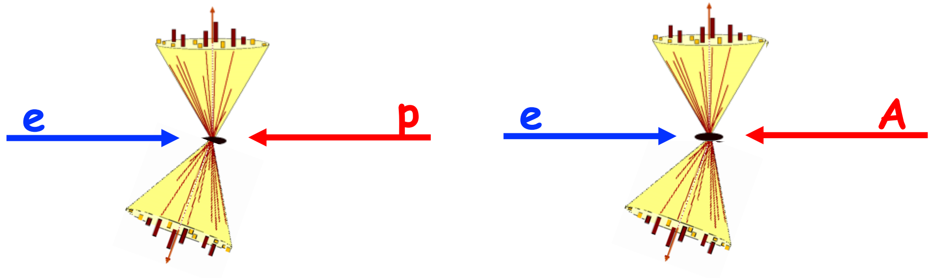


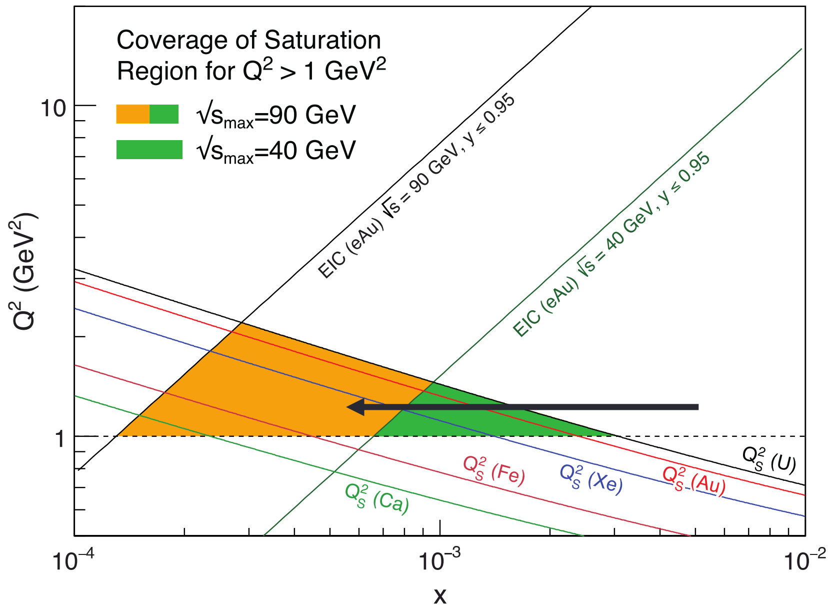
Can EIC discover a new state of matter?

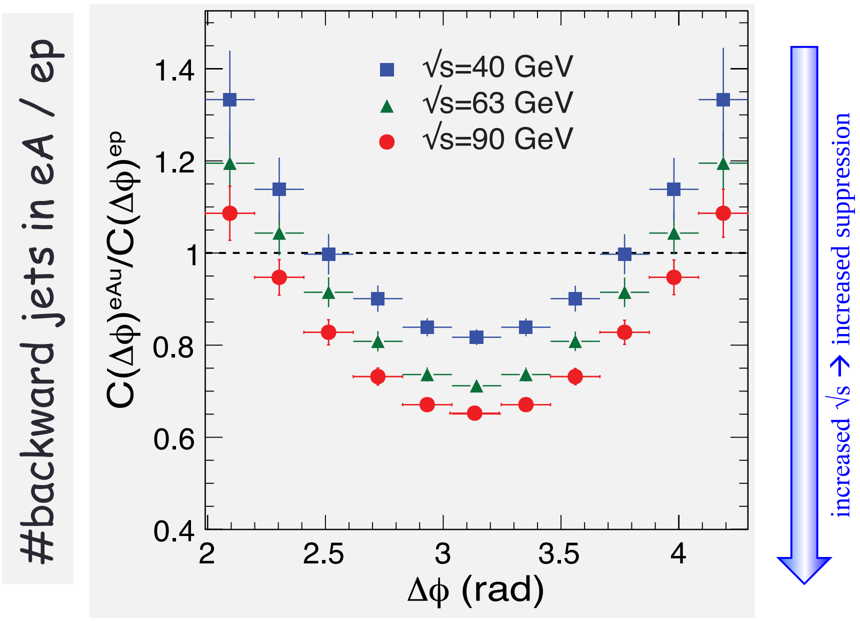
EIC provides an absolutely unique opportunity to have very high gluon densities
→ electron – lead collisions
combined with an unambiguous observable

EIC will allow 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





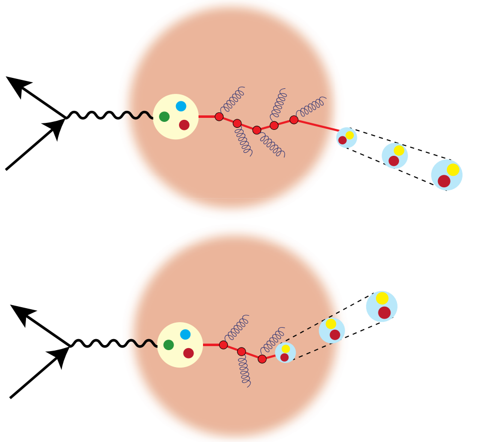


Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

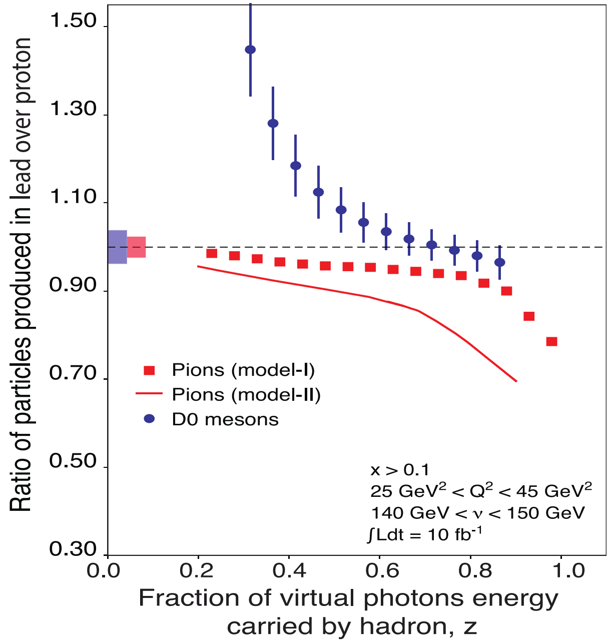
$$\nu = \frac{Q^2}{2mx}$$



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

Study in light quarks vs. heavy quarks

Energy loss by light vs. heavy quarks:



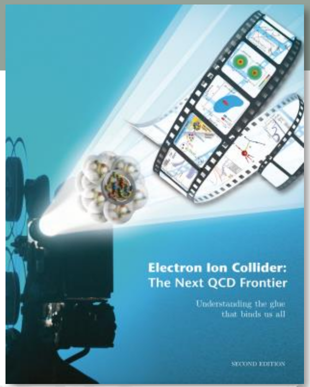
Identify π vs. D^0 **(charm)** mesons in e-A collisions:

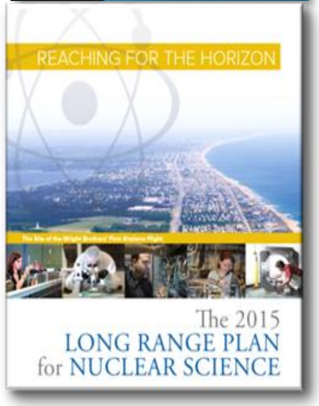
(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔ Clues to color-confinement?

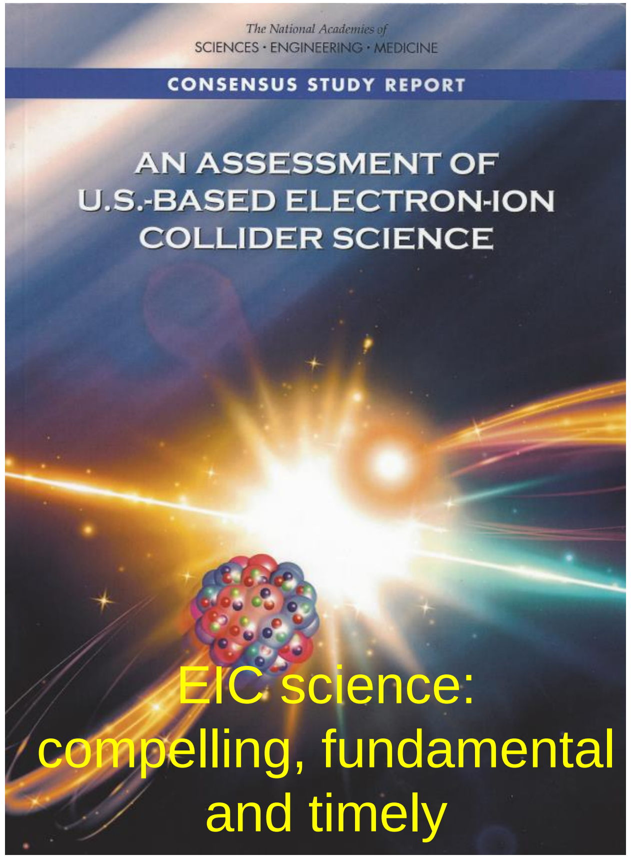
Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

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

National Academy's Assessment







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

EIC moved forward…. A major step!

- DOE announced: January 9, 2020
  - **CD0 December 19, 2019**
  - **Site of EIC: Brookhaven National Laboratory**
- BNL and JLab realize EIC as partners
  - A formal EIC project is now setup at BNL
  - BNL+Jlab management & scientists
- **CD1 June 28, 2021**

- **CD2 Approval 3rd Quarter FY2023**
- **CD3 1st Quarter FY2024 (start construction)**
- EIC CD4A Early Finish 4thQ FY2029
- EIC CD4B 3rdQ FY 2032


SCIENCE & INNOVATION ENERGY ECONOMY SECURITY & SAFETY SAVE

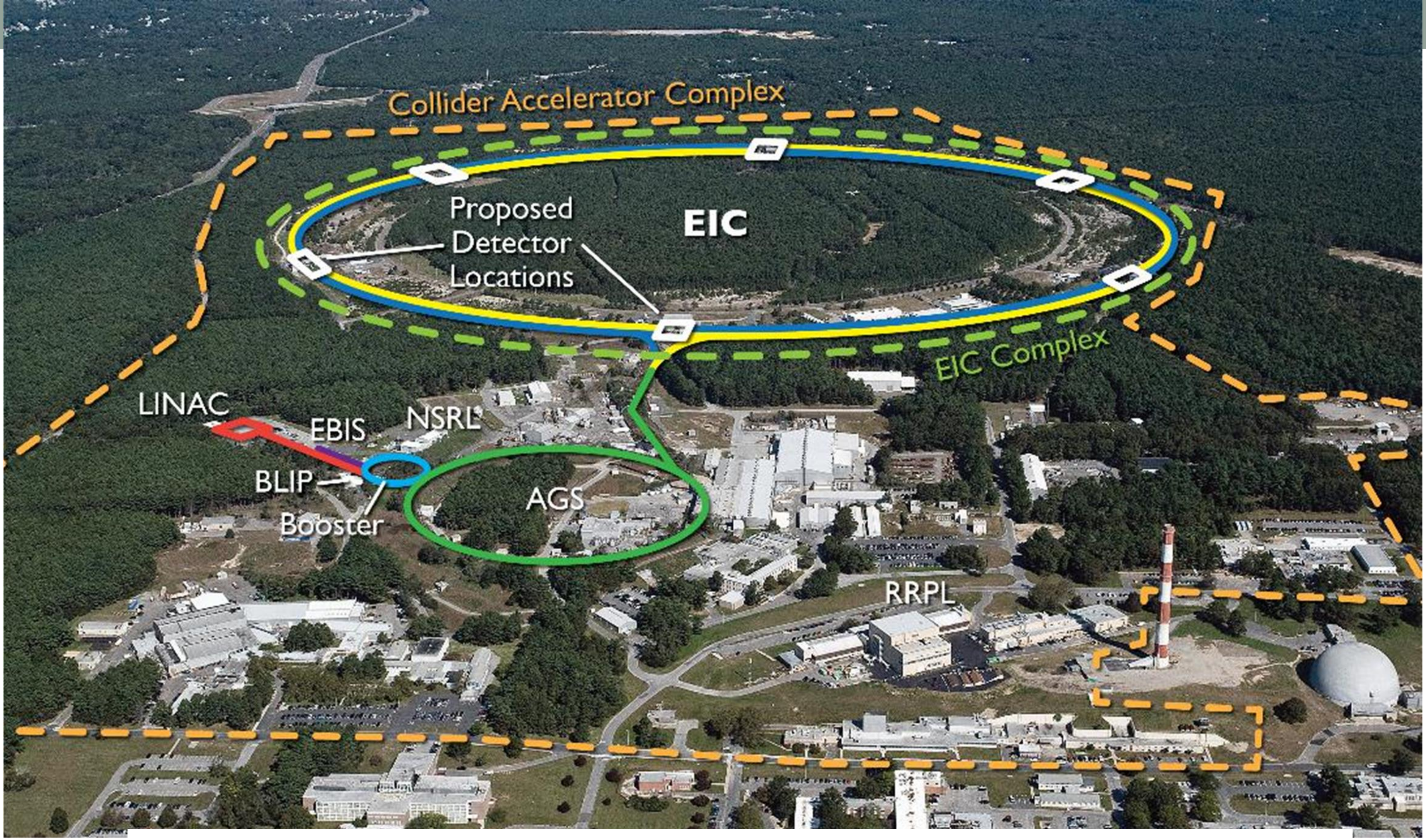
Department of Energy

U.S. Department of Energy Selects rookhaven National Laboratory to Hos Major New Nuclear Physics Facility

JANUARY 9, 2020

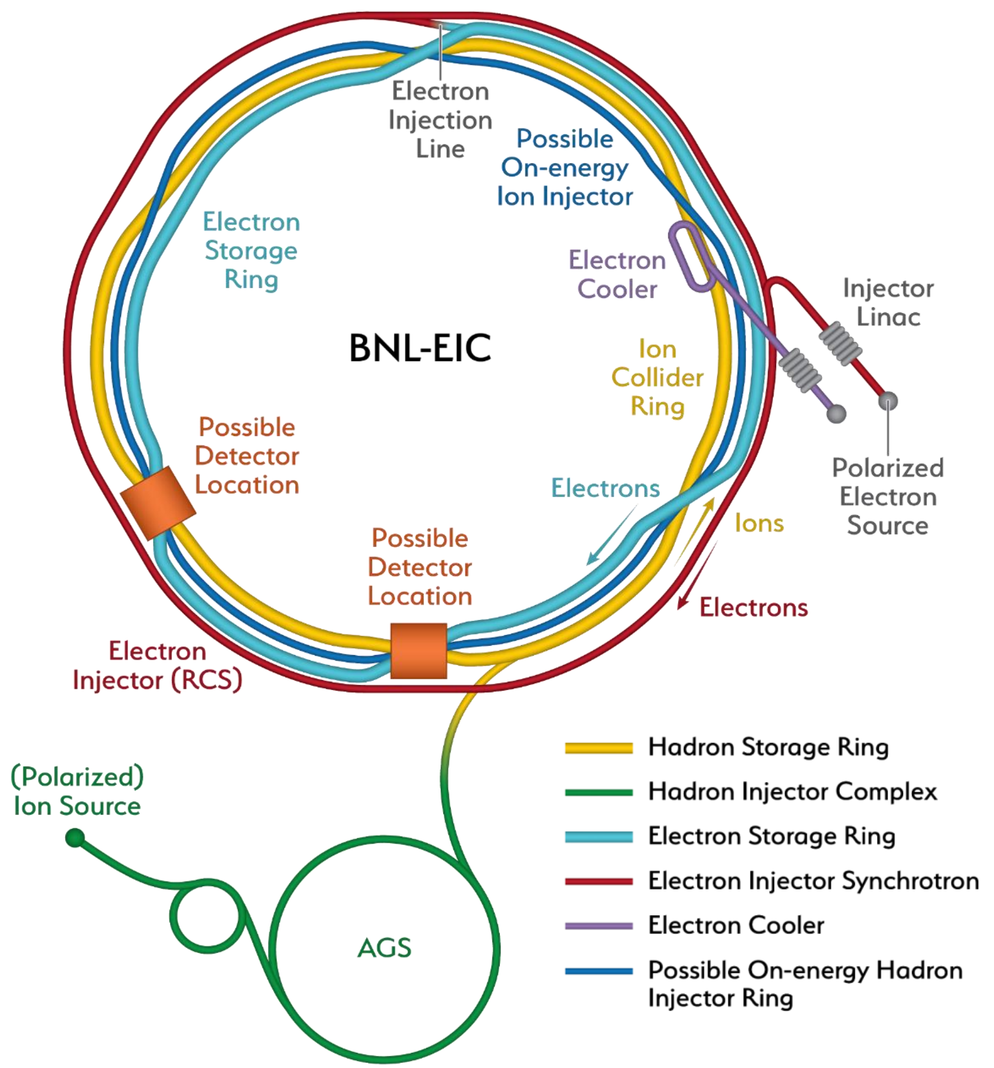
Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

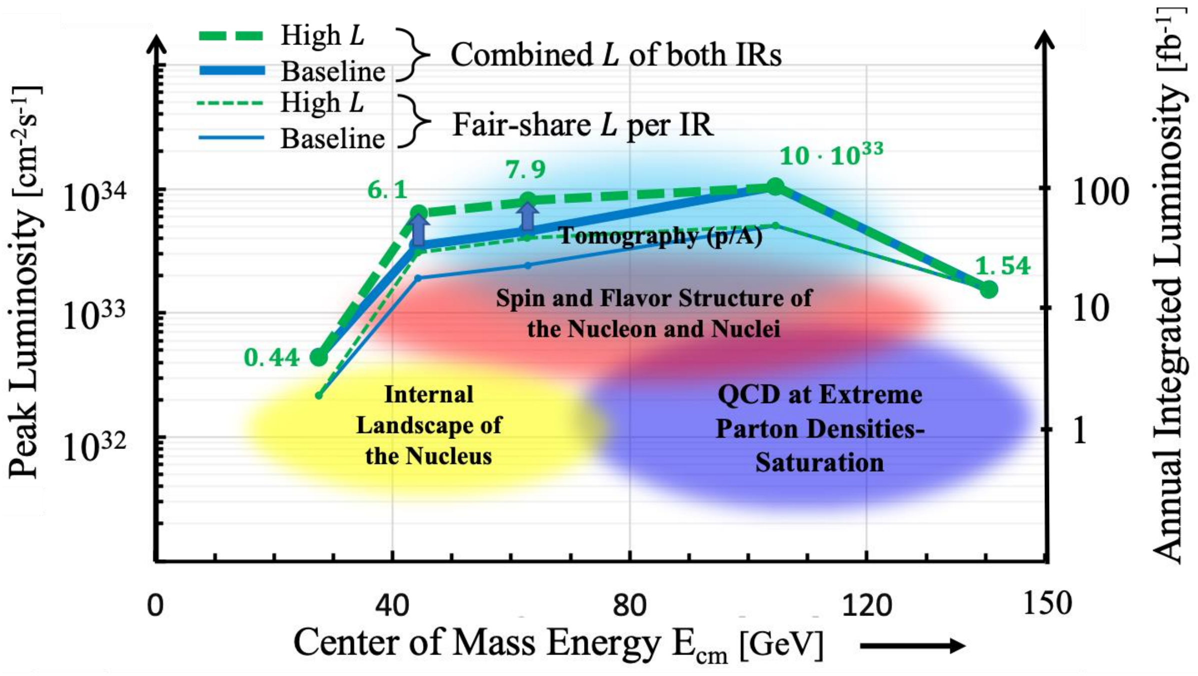


- EIC benefits from $B class investments at BNL and the highly successful RHIC program.

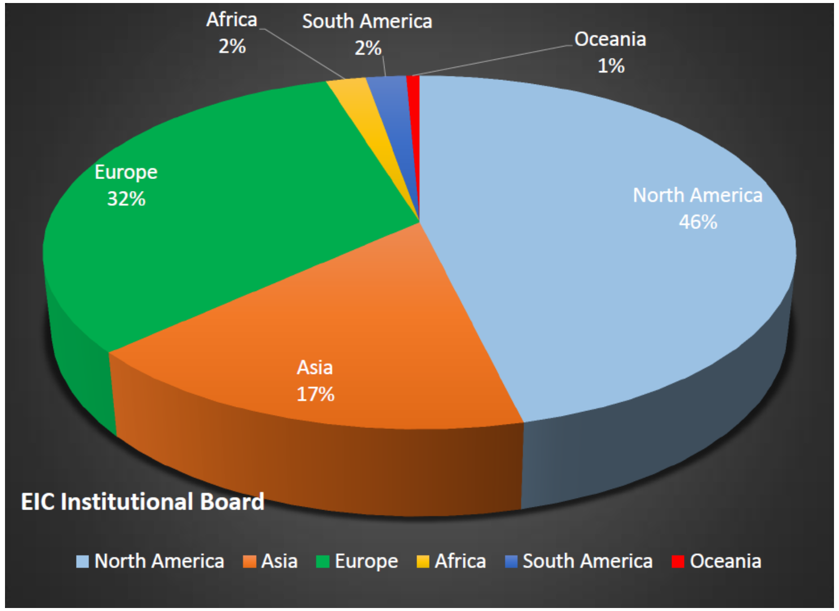
EIC Accelerator Design



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 EIC Users Group: EICUG.ORG



Formally established in 2016, now we have:
~1300 Ph.D. Members from 34 countries, 254 institutions
New members welcome

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, Election & Nominations Committee

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)**, **Remote (2021)**, **Stony Brook (2022, Hybrid)**, **Warsaw 2023**

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)

Perhaps other intersections with LQCD?

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?)

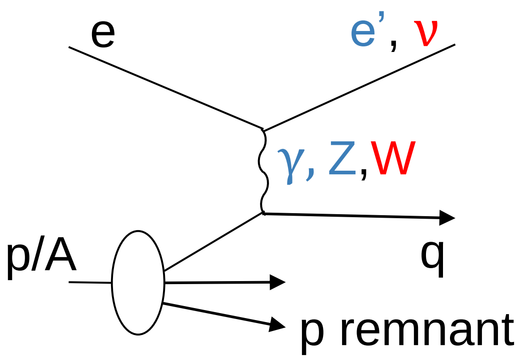
Physics with nucleons and nuclear targets:

- 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

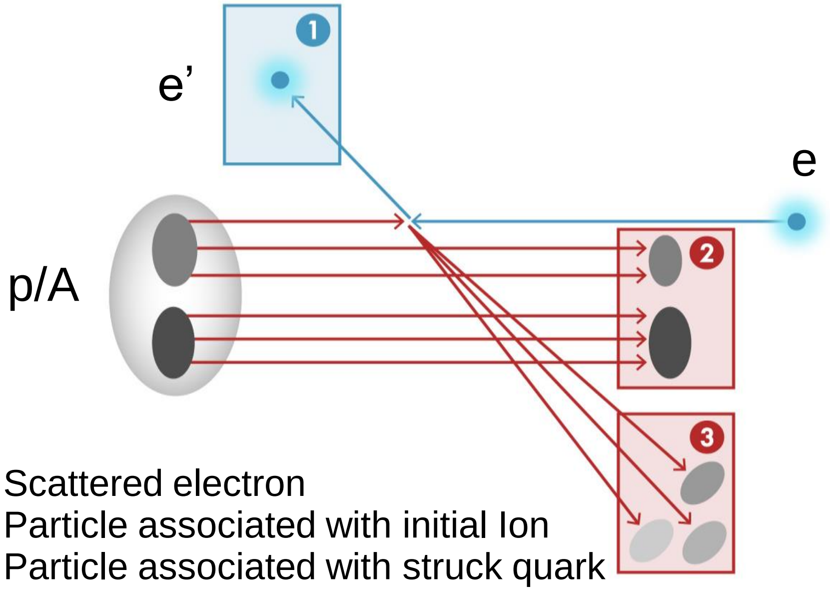
Detector Challenge of the EIC



Aim of EIC is 3D nucleon and nuclear structure beyond the longitudinal description.

This makes the requirements for the machine and detector different from all previous colliders.

"Statistics"=Luminosity × Acceptance



1. Scattered electron
2. Particle associated with initial Ion
3. Particle associated with struck quark (or associated gluon)

EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

Ion remnant is particularly challenging

- not a usual concern at colliders
- at EIC integrated from the start with a highly integrated (and complex) detector and interaction region scheme.

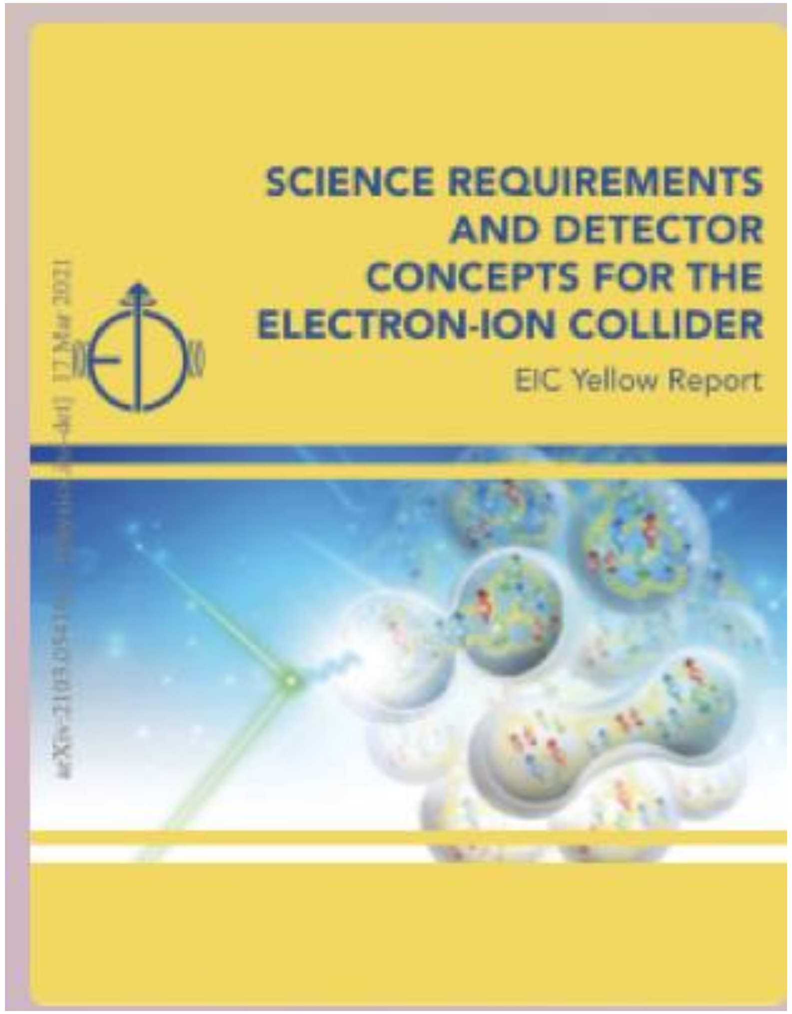
Aschenauer/Ent

December 2019 – March 2021
EICUG Yellow Report

- Led by EICUG Steering Committee, UG-wide effort towards a detailed detector design effort with a detailed document.

- Kick off meeting at MIT in December 2019 followed by 4 more meetings in 2020 all remote: Philadelphia, Pavia, Miami, Washington DC, Berkeley

A lot more in talks that will follow (ECCE, Diffraction, Peripheral collisions etc.)



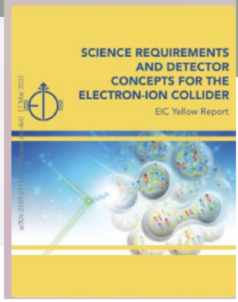
902 pages
415 authors
151 institutions

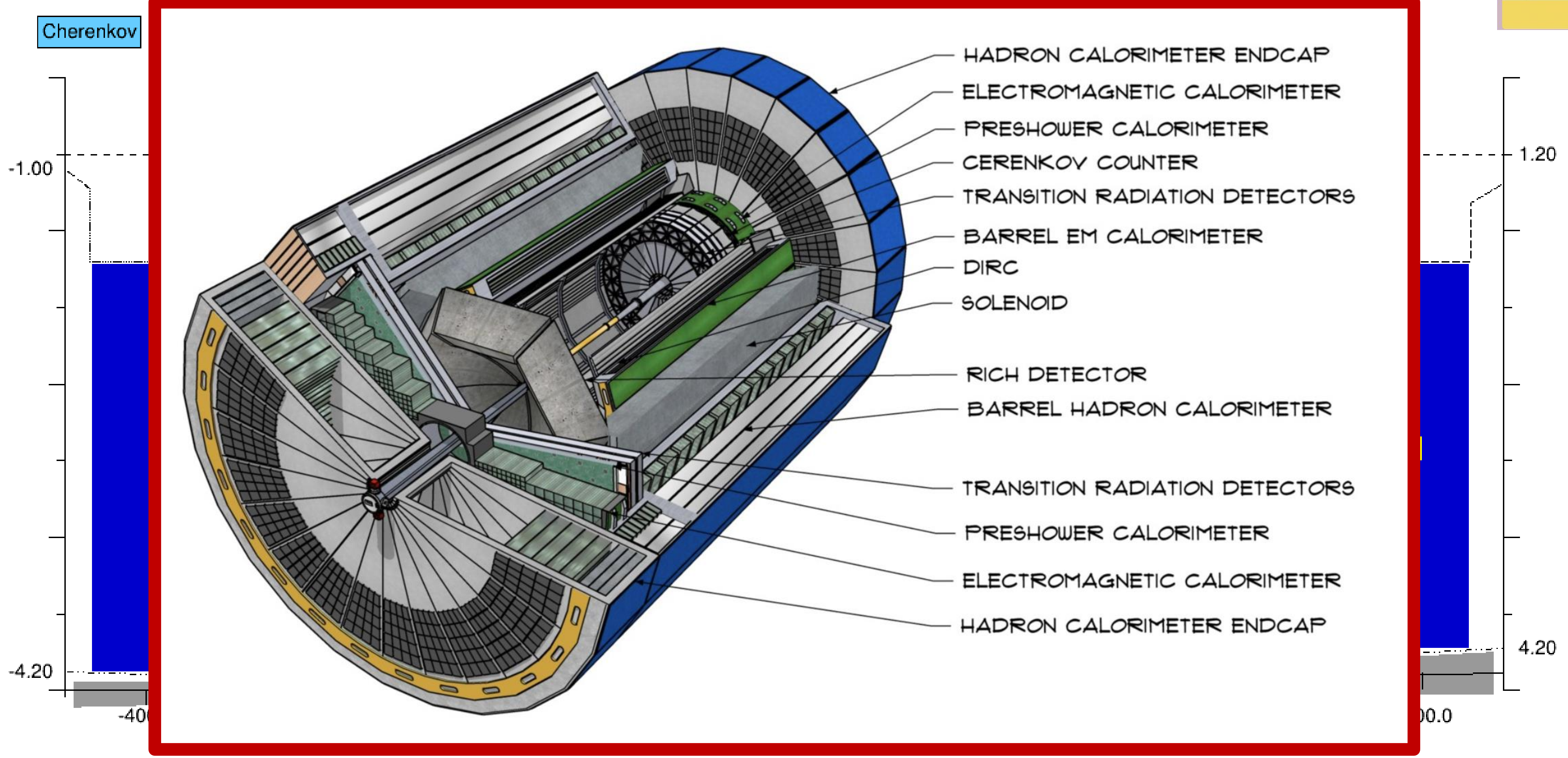
120 MB

arXiv:2103.05419

Concept DETECTOR

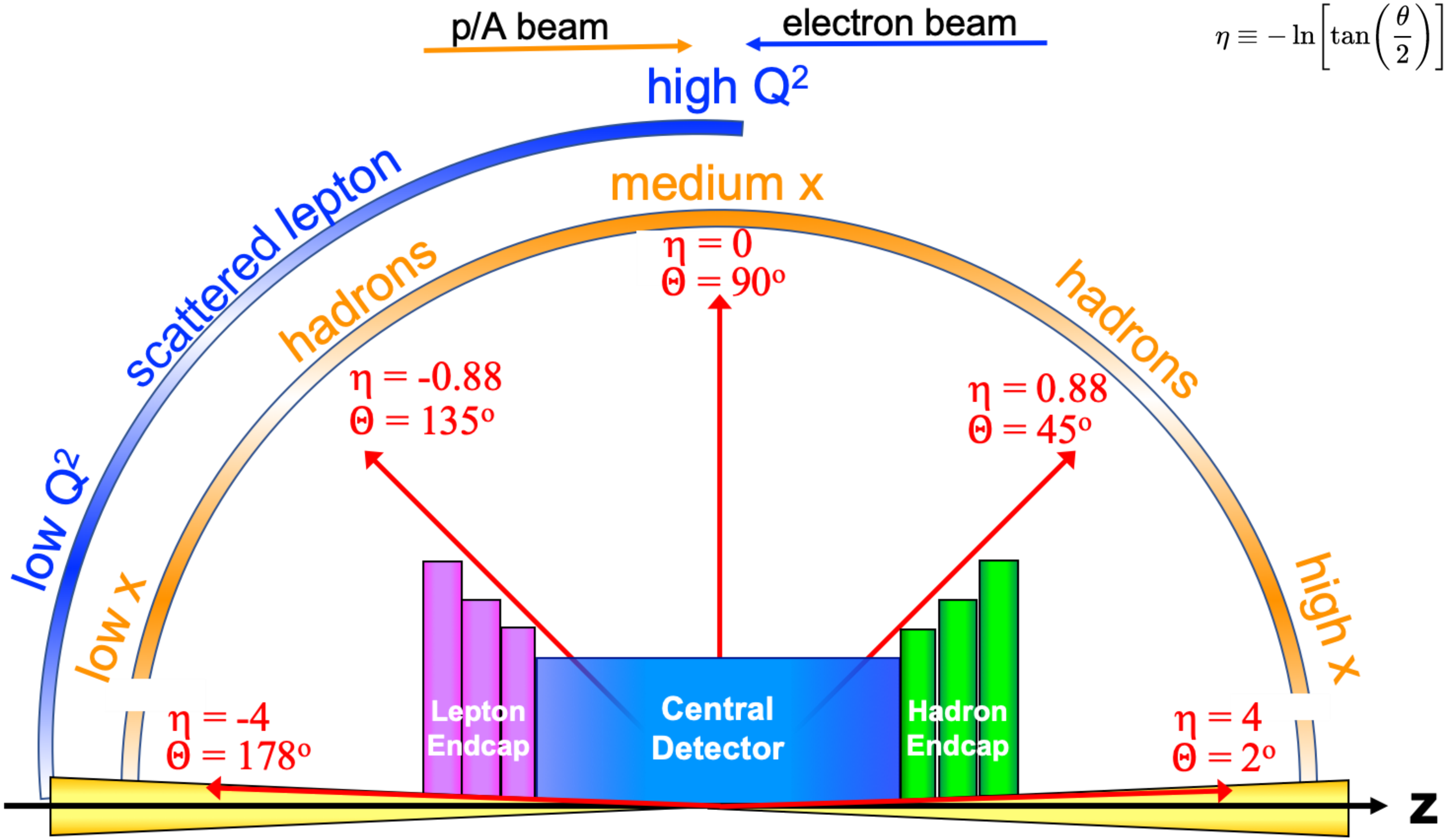
This detector concept was included in the EIC CDR prepared for the CD1 Review



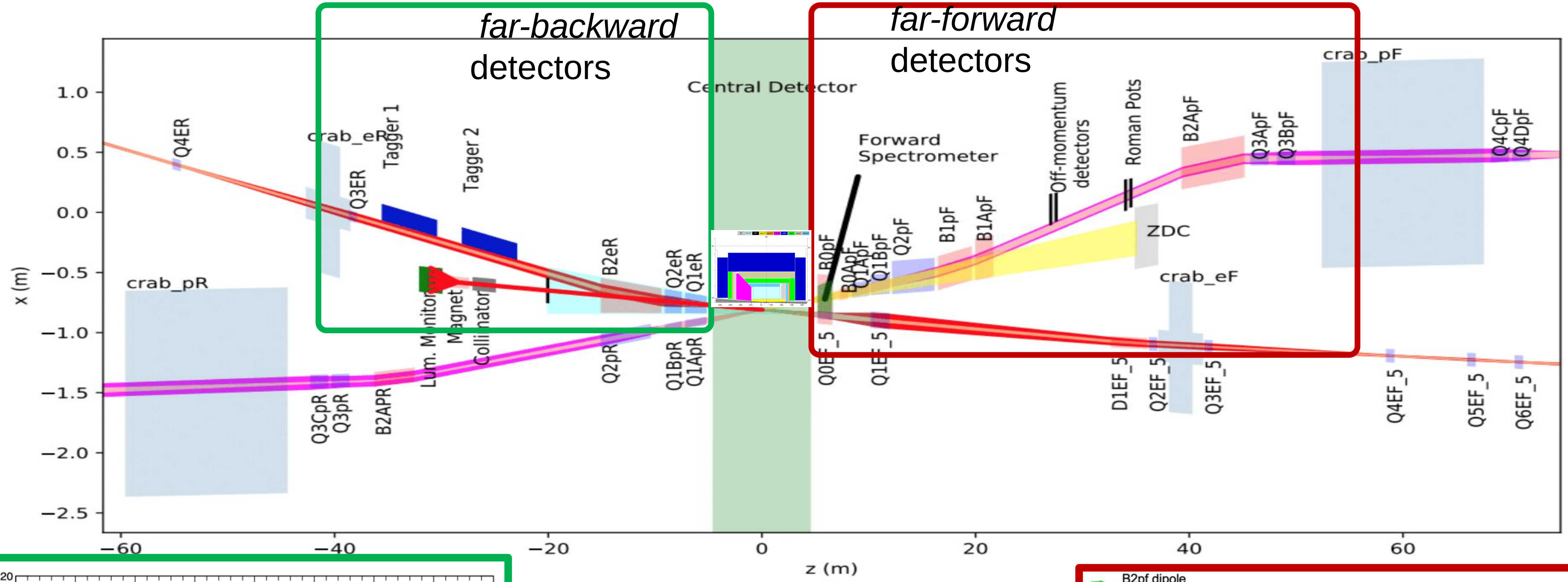


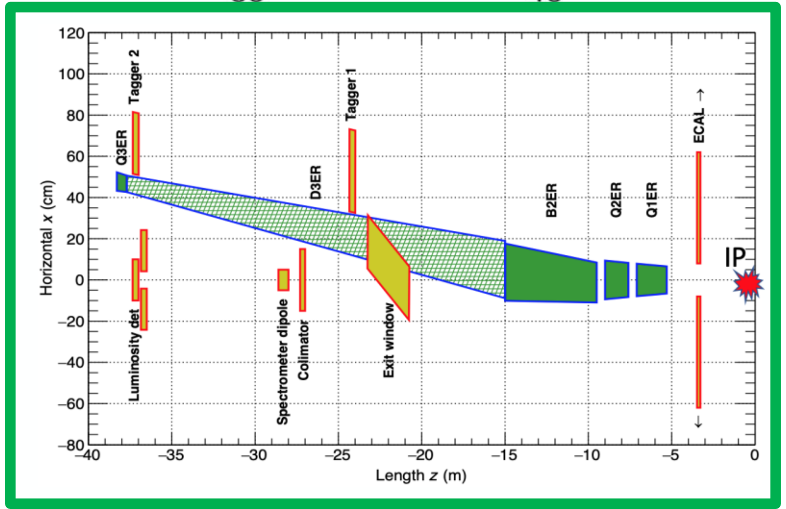
Detector polar angle / pseudo-rapidity coverage

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

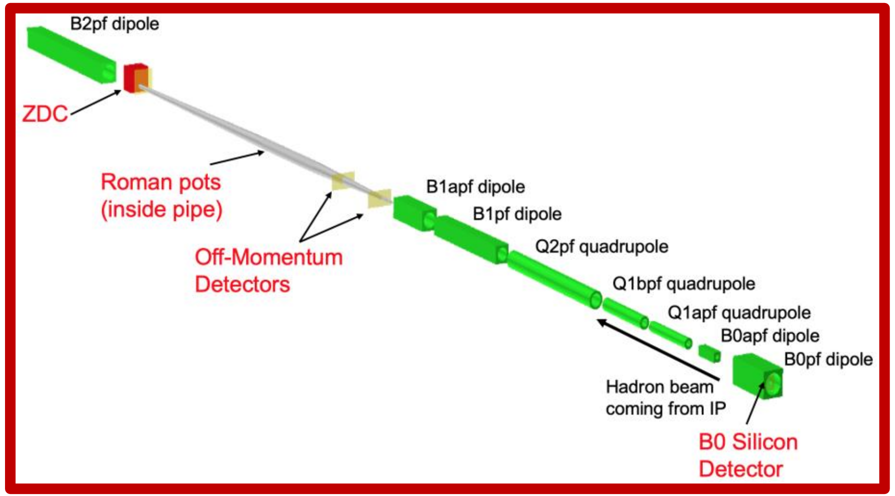


Reference Detector – Backward/Forward Detectors





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



The three proposals + White Paper: 2nd IR Physics

CFNS helped all three & the 2nd IR White Paper

EIC Advisory Panel's recommendation on April 8, 2022

ATHENA Detector Proposal

The ATHENA Collaboration
December 1, 2021

CORE - a COmpact detectoR for the EIC

R. Alarcon,[1] M. Baker,[2] V. Baturin,[3] P. Brindza,[3] S. Bueltmann,[3] M. Bukhari,[4]

(Dated: December 1, 2021)

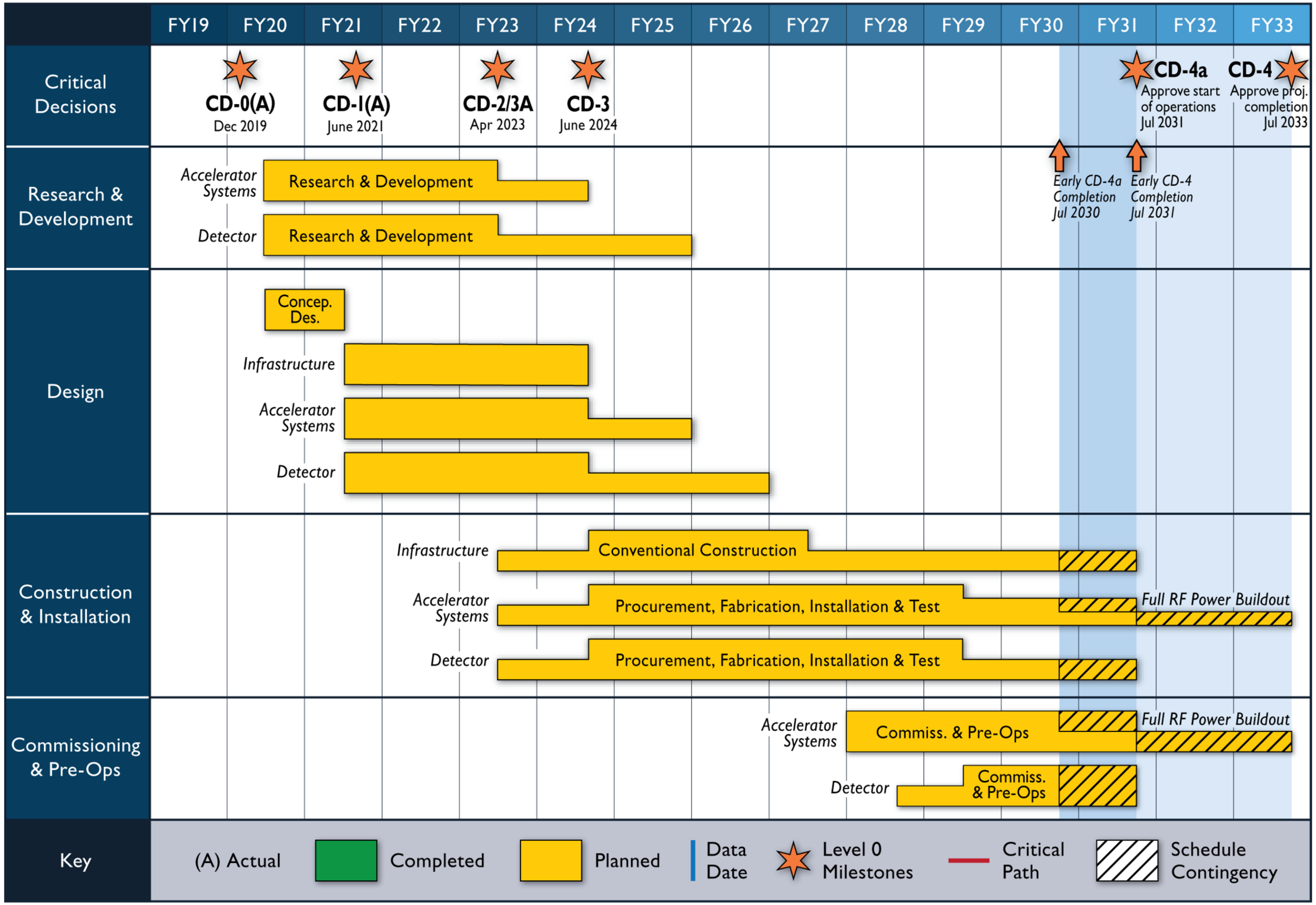
[a] chyde@odu.edu
[b] turonski@jlab.org

A state of the art detector capable of fully exploiting the science potential of the EIC, realized through the reuse of select instrumentation and infrastructure, to be ready by project CD-4A

December 1, 2021

- The panel finds that ECCE and ATHENA fulfill all requirements for a Detector 1.
  - ECCE has several advantages, in particular reduced risk and cost, and qualifies best for Detector 1.
  - CORE presented a more conceptual design and given the tight timeline for CD2/3a would generate a schedule risk for the EIC Project as Detector 1.
- The panel supports the case for a second EIC detector.
  - DOE resources to start a Detector 2 project will most likely be delayed for several years, or the resources would have to found from other sources. There is significant international participation in the proto-collaborations, however, the panel found the overall resources were insufficient to proceed with a second detector effort at this time.
- The EIC's project planning for Detector 1 should incorporate a period for integrating new collaborators and re-optimizing experiment conceptual design in advance of CD-2.

Reference Schedule



Detector 1 needs to be ready by CD4A to help with initial collider operations. This is the 1st (left) CD4A blue band (uncertainty)

Detector 2 ideally should be ready by CD4 (about 2 yrs later, the 2nd blue band on right)

J. Yeck, EICUG Meeting

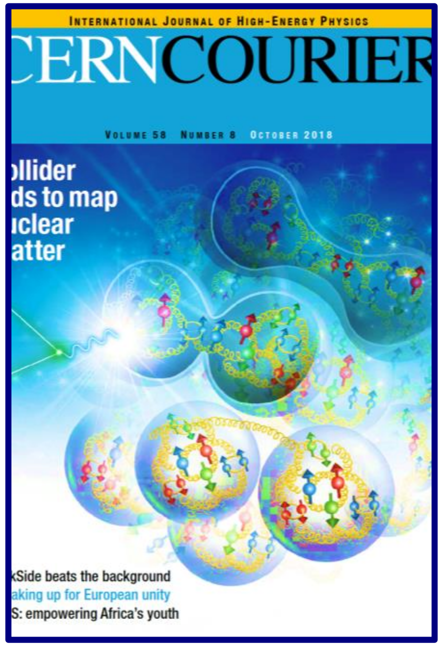

"New directions in science are launched by new tools much more often than by new concepts."
Freeman Dyson

Summary & Outlook

- 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 some of the most profound question yet unanswered in the Standard Model of Strong Interactions (and beyond)
- Up to two hermetic full acceptance detectors under consideration, currently **EIC project has funds for 1 detector**, cost of a second detector from non-DOE sources
  - Experimental collaboration(s) to be formed by late 2022/early 2023
  - EIC project assumes **an aggressive timeline : engineering collisions around 2031, physics collisions within 2-years of that.**
- **High interest in having international partners both on detector and accelerator**

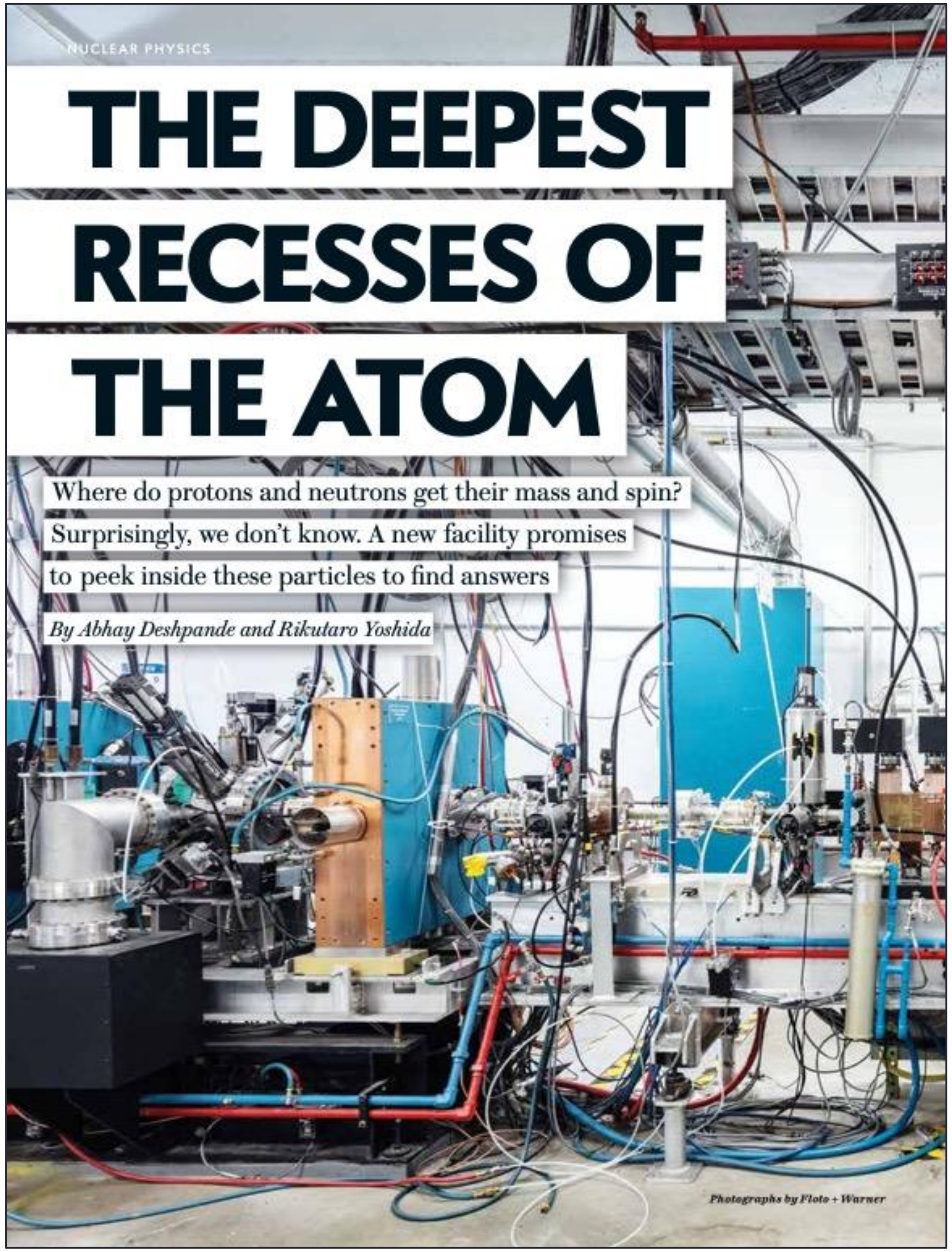
- For all early career scientists, graduate and undergraduate students: This machine is for you! Ample opportunity to contribute to machine, detector & physics of a new project.

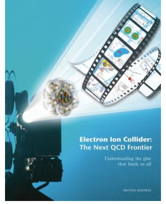
R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
Translated into multiple languages



E. Aschenauer
R. Ent
October 2018

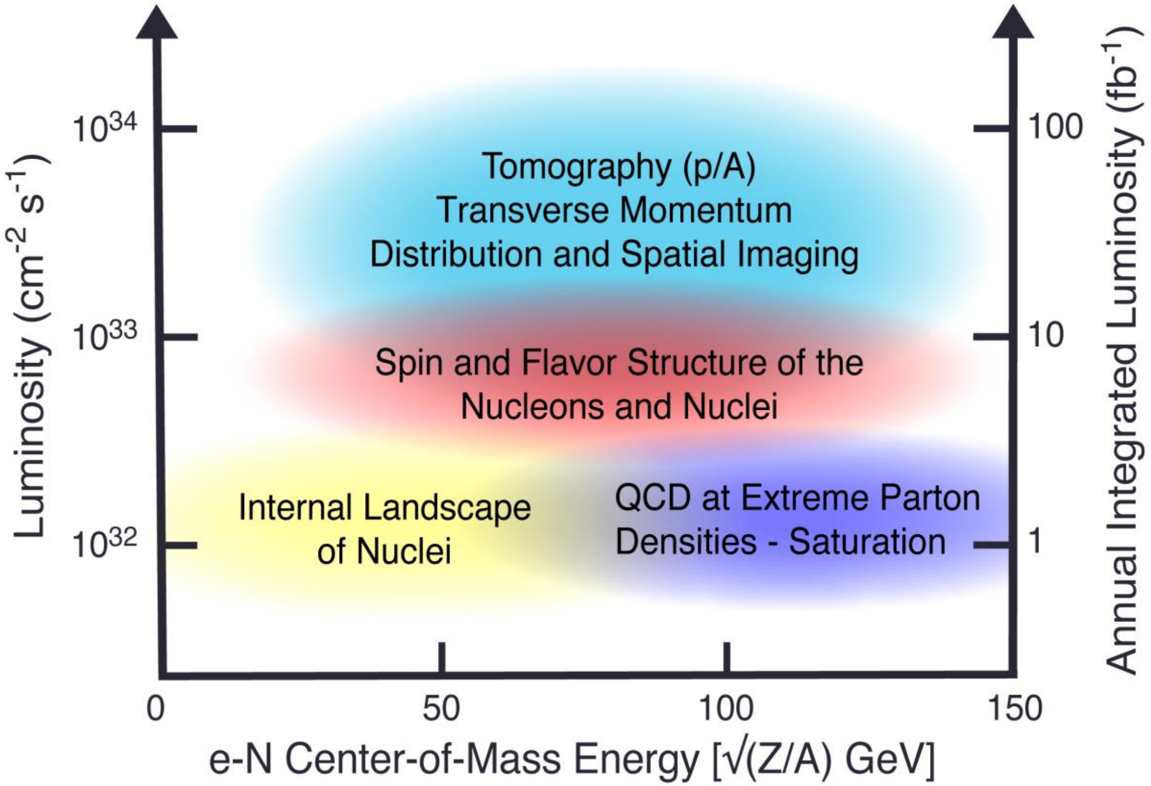
A. Deshpande
& R. Yoshida
June 2019
Translated in to multiple languages

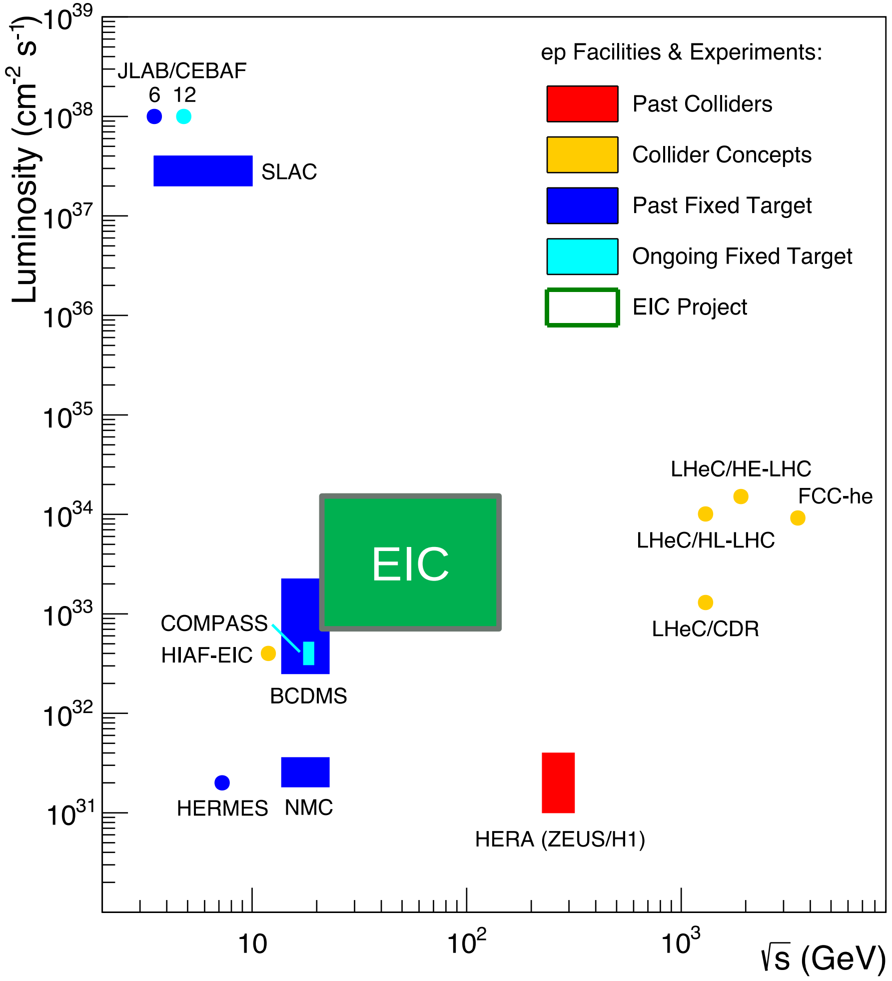




EIC Physics and the machine parameters

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.