Center for Frontiers in Nuclear Science

Science and Opportunities at the Electron Ion Collider

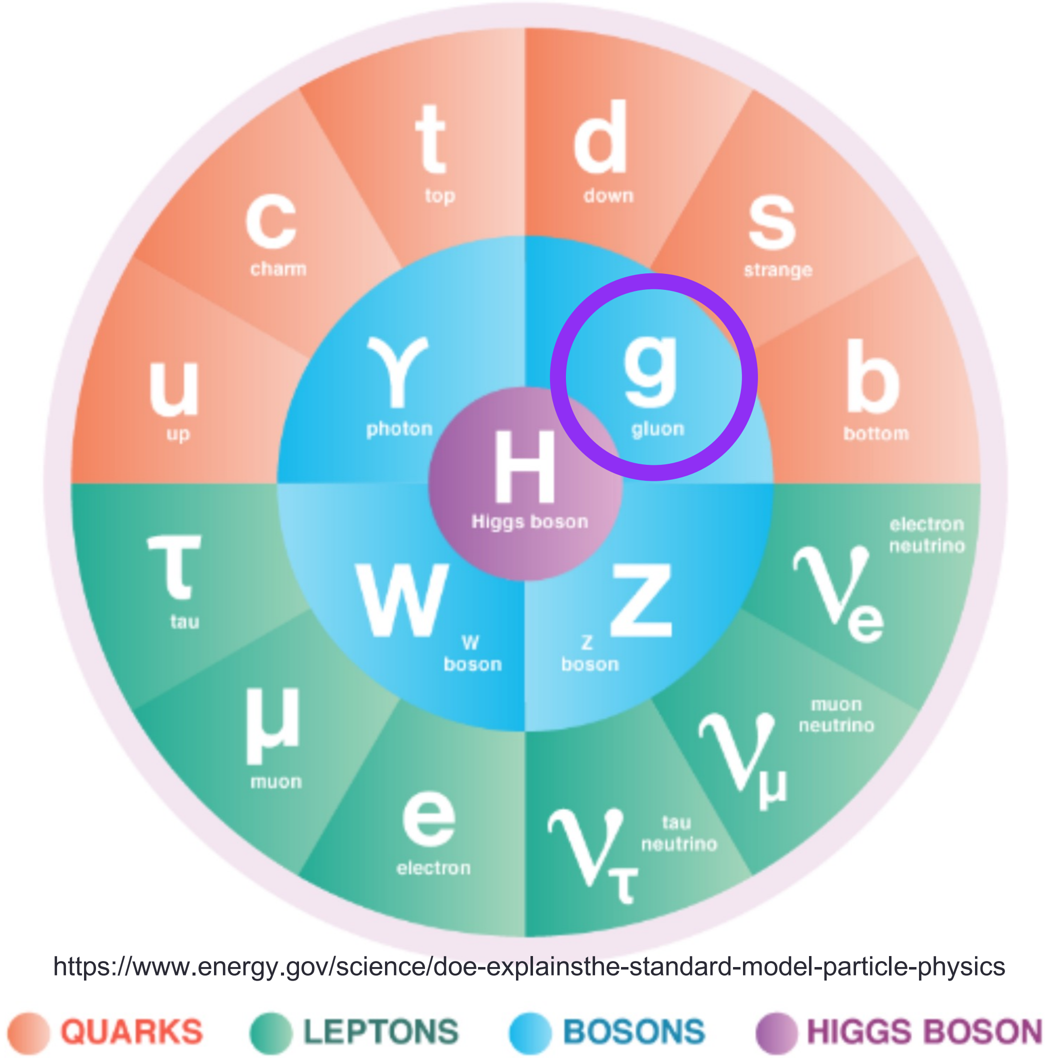
APCTP Workshop on EIC
Incheon, Seoul, Korea
November 2, 2022

Stony Brook University

Abhay Deshpande

Brookhaven National Laboratory

Standard Model of Physics: Many



https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics

- SM of Physics would not have been possible without complementary measurements of: p-p, p-pbar, e-e, and e-p scattering
  - The quest of understanding nature (SM: precision QCD+EW and Beyond SM physics) will continue with complementary probes:
  - The Electron Ion Collider & LHC – detector and luminosity upgrades in near future
  - Other future e-p, e-e and h-h
- Discussions regarding EIC and LHC being operated concurrently are being pursued in the long range planning in the US, Europe & Asia
  - Snowmass 2021, NuPECC and others

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 spontaneous symmetry breaking and anomalies).

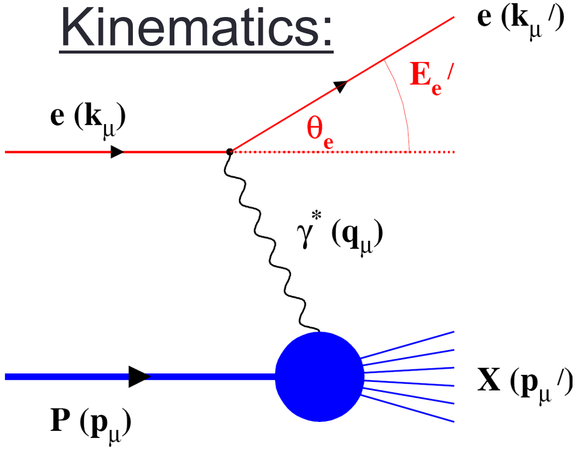
➔ **ALL DEPEND ON NON-LINEAR DYNAMICS: GLUON SELF-INTERACTIONS**

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 (and spin) of the nucleons and hence the entire visible world

How? Experimental insight and guidance needed

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^*

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

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

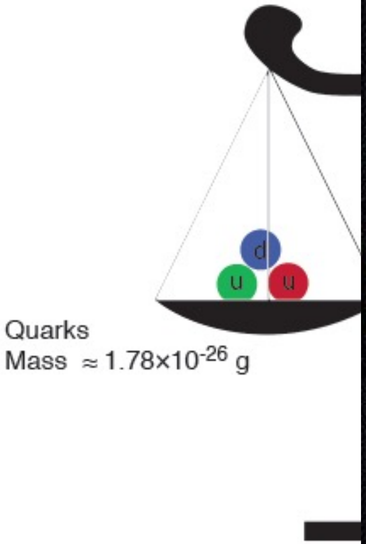
Proton mass puzzle

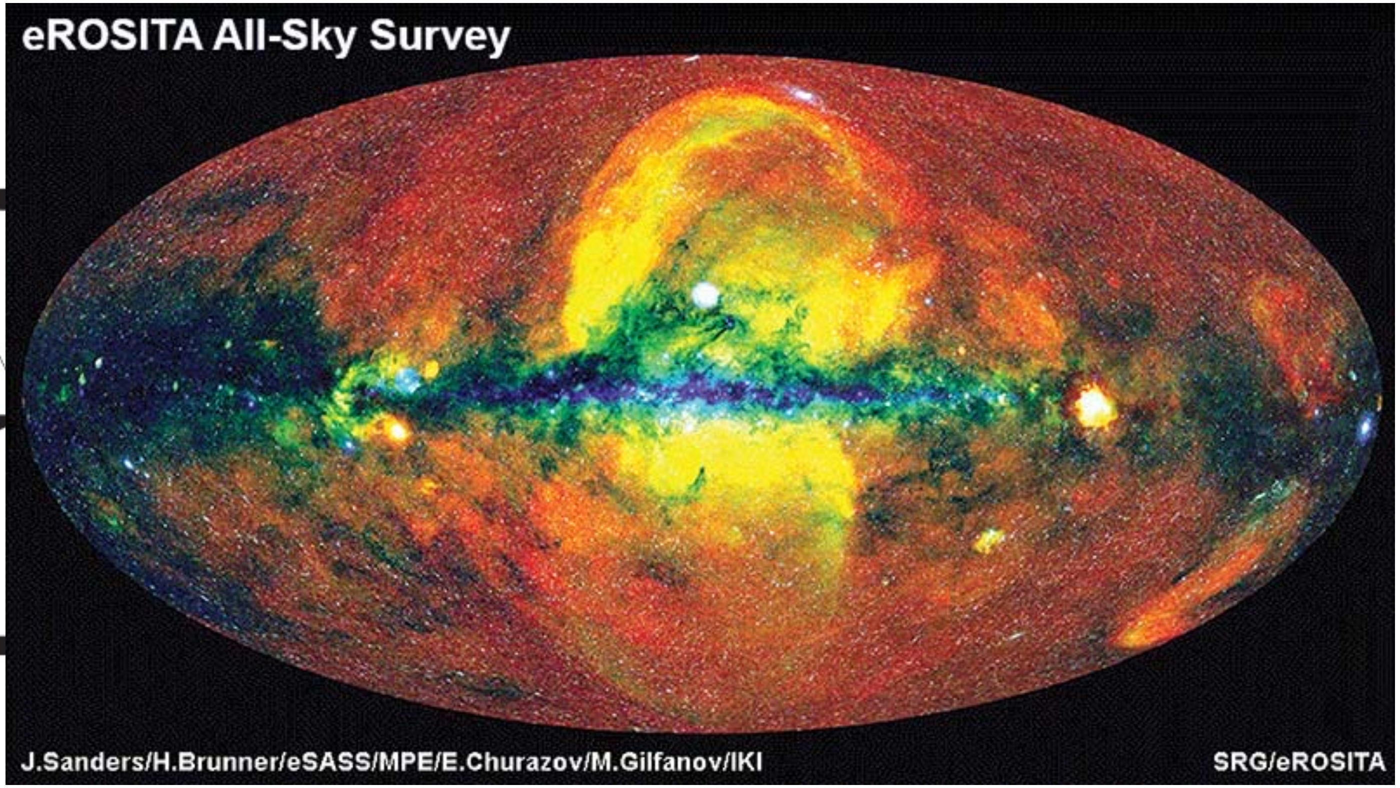
François Englert

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

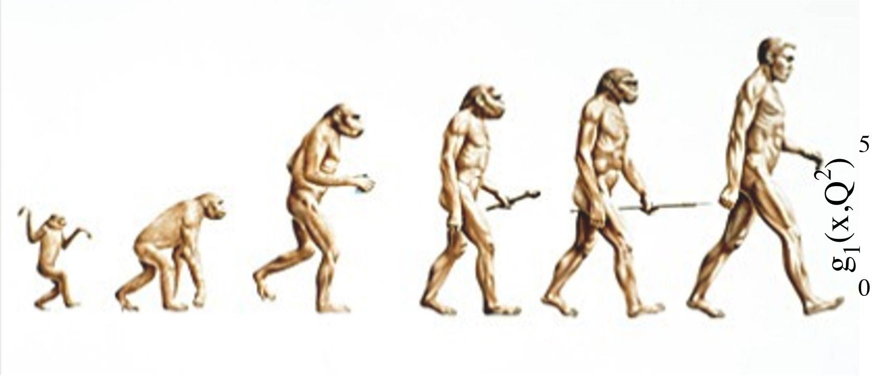
But the proton's mass is 168 x 10^{-26} grams

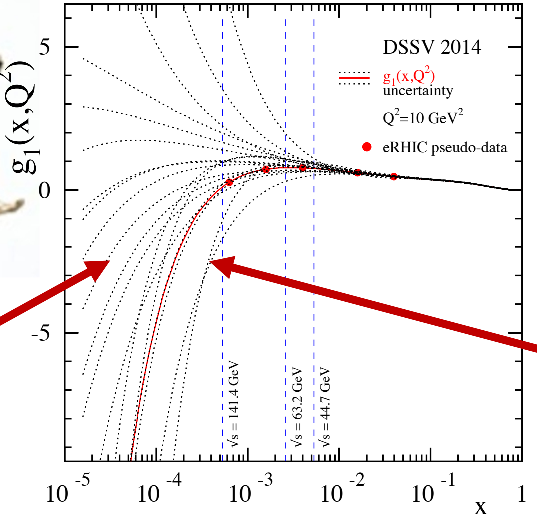
→**only 1% of the mass of the protons (neutrons)** → Hence the Universe

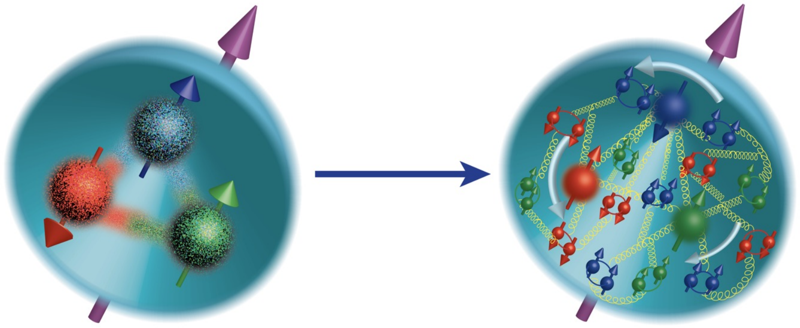
→Where does the rest of the mass come from?

Proton Spin "Crisis" → Spin Puzzle

Discovered by EMC experiment at CERN
Series of experiments since then around the world: BNL, CERN, DESY, SLAC: 30+ years







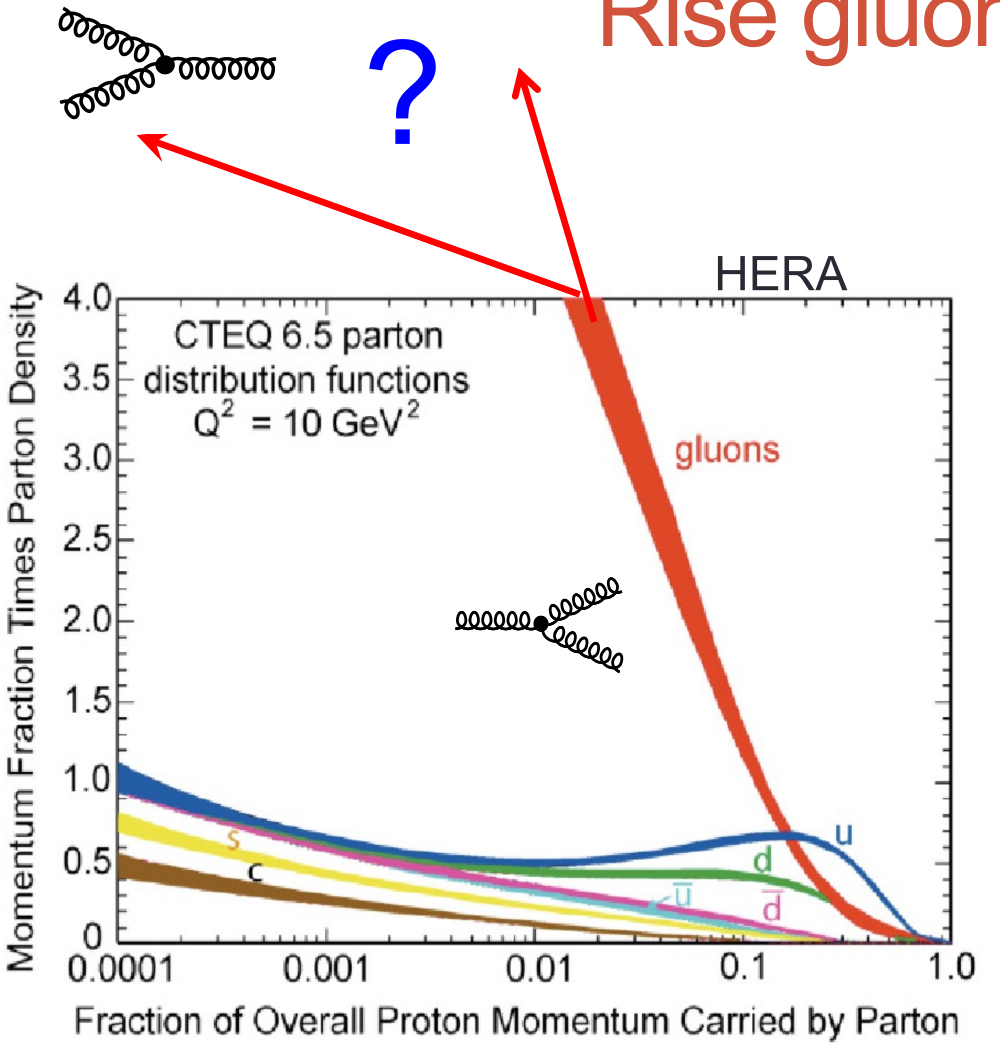
25% 25%

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

? ?

Transverse motion and finite size of the proton must create the orbital motion
Measure via Transverse Momentum (TMDs) and Position Distribution (GPDs

Rise gluon distribution: A novel 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.

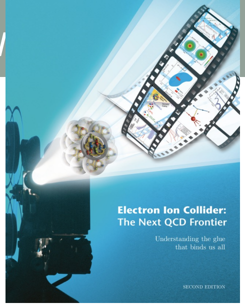
gluon emission = gluon recombination At Q_S

Observation of gluon recombination effects

→ Is there such new state of matter?

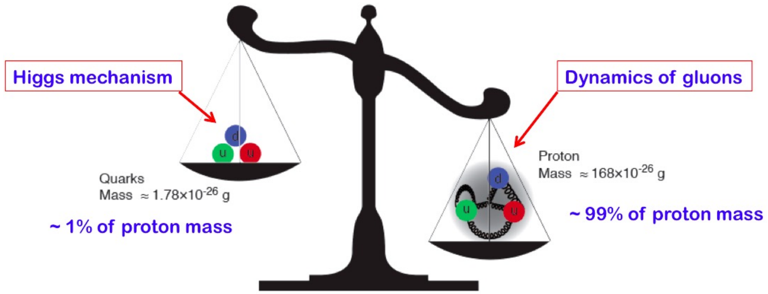
→ "Color Glass Condensate"

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

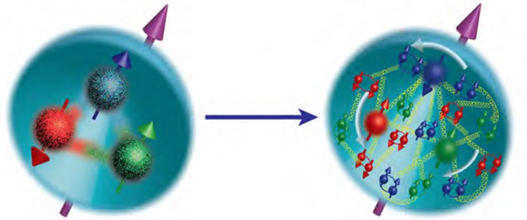


EIC Physics at-a-Glance

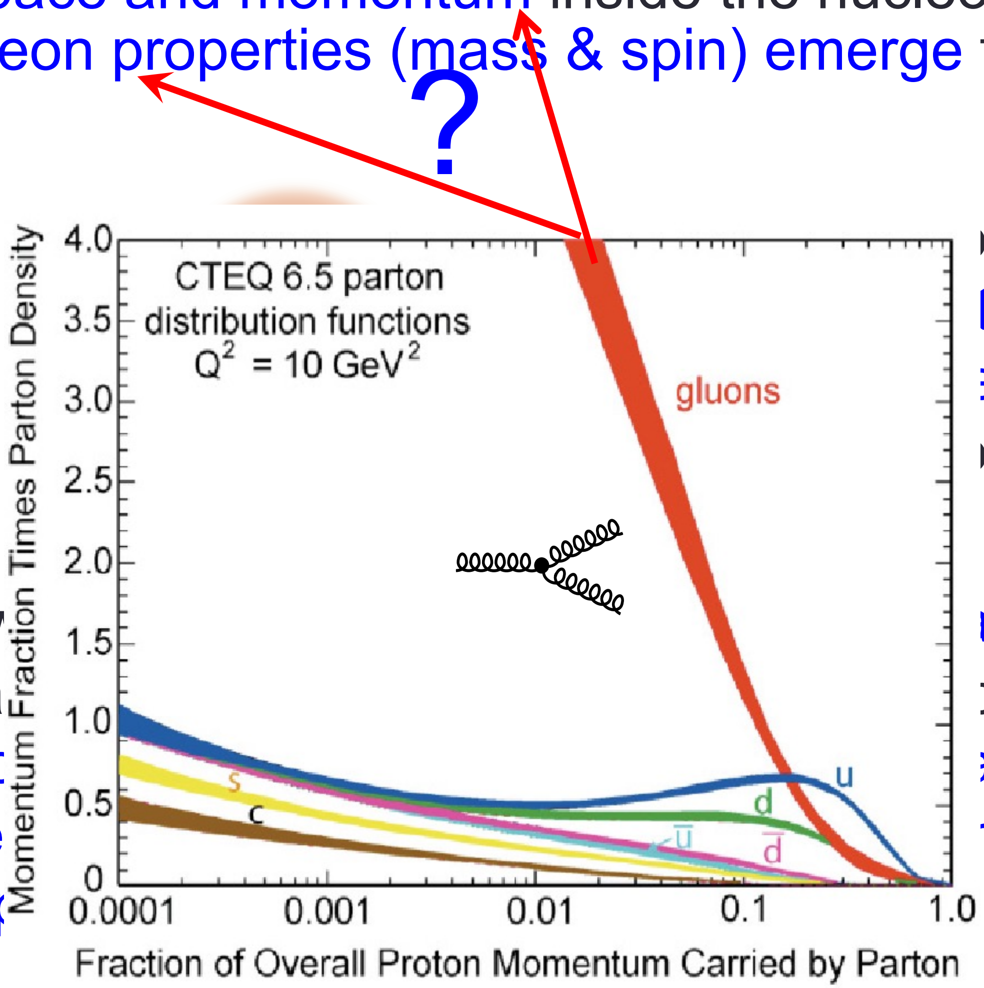
Eur. Phys. J. A 52 (2016) 9, 268 arXiv:1212.1701 (nucl-ex)



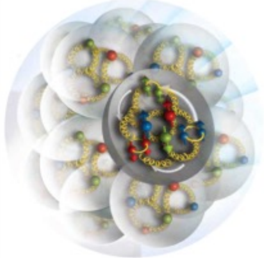
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (mass & spin) emerge from their interactions?

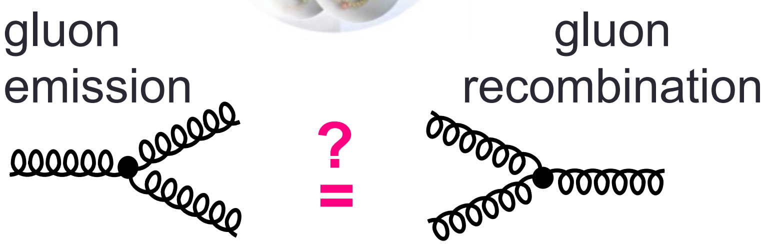


...lor-charged quarks and gluons, and colorless jets, ...th a nuclear medium? How do the confined hadronic ...erge from these quarks and gluons? How do the ...n interactions create nuclear binding?



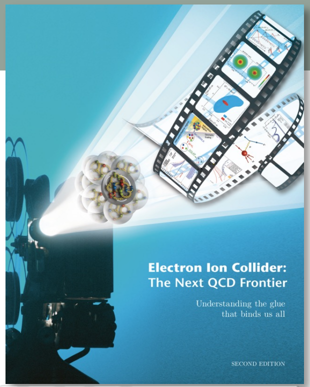
How ... qua... affect the gluc... pens to the ene... at high prop... universal

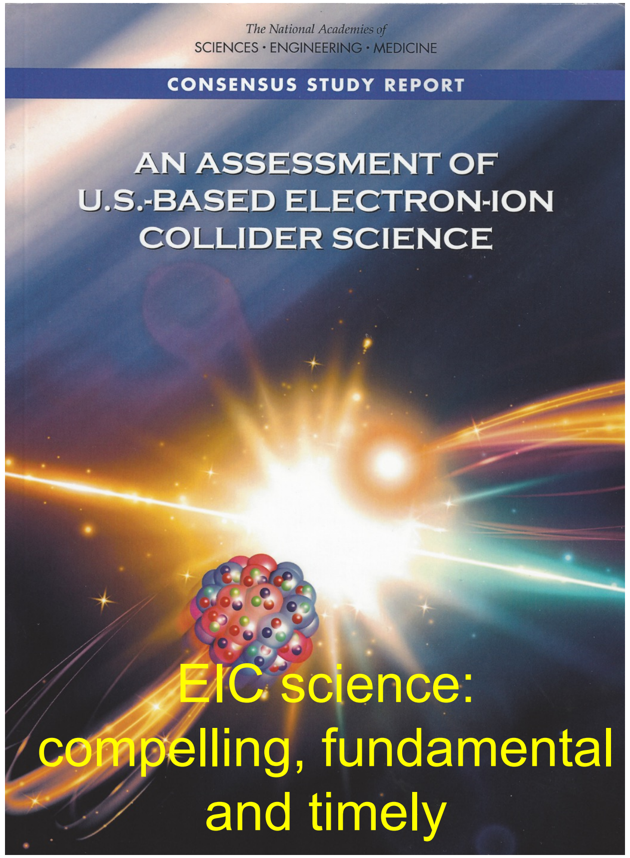




National Academy of Science, Engineering and Medicine

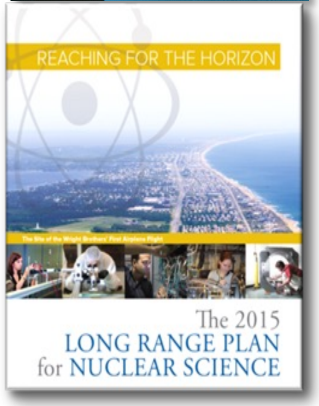
Assessment July 2018





Physics of EIC

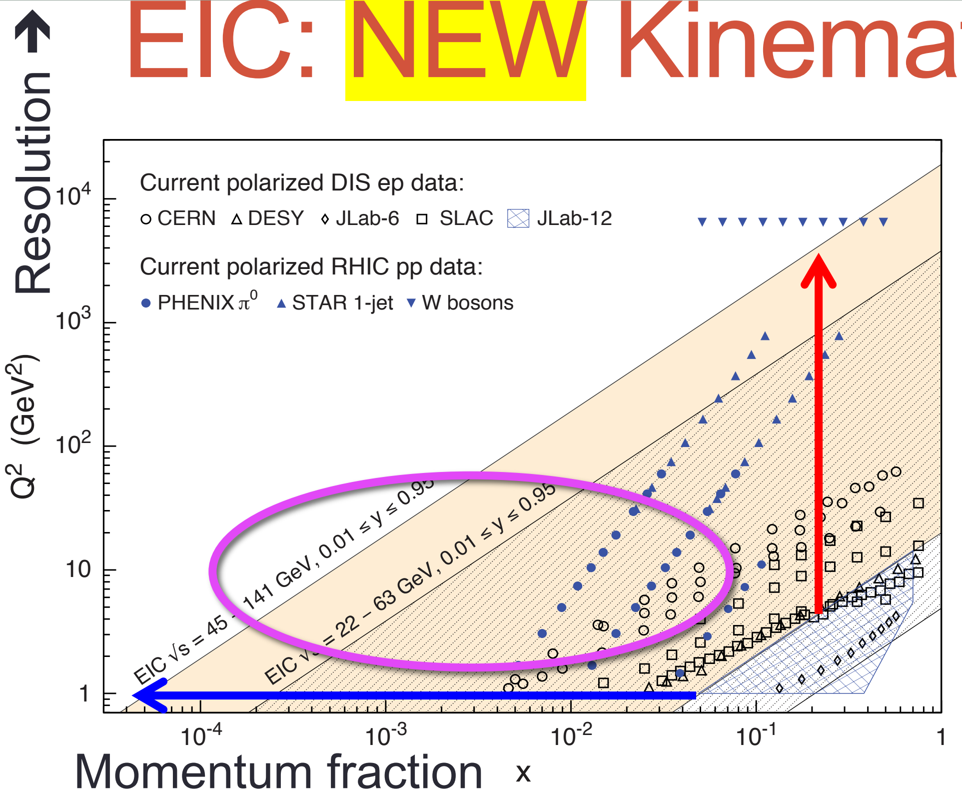
- Emergence of Spin
- Emergence of Mass
- Physics of high-density gluon fields

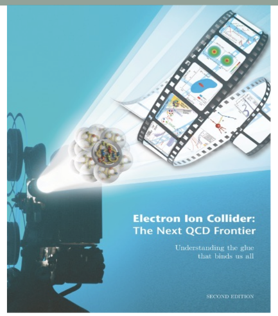


Machine Design Parameters:

- 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: NEW Kinematic reach & properties



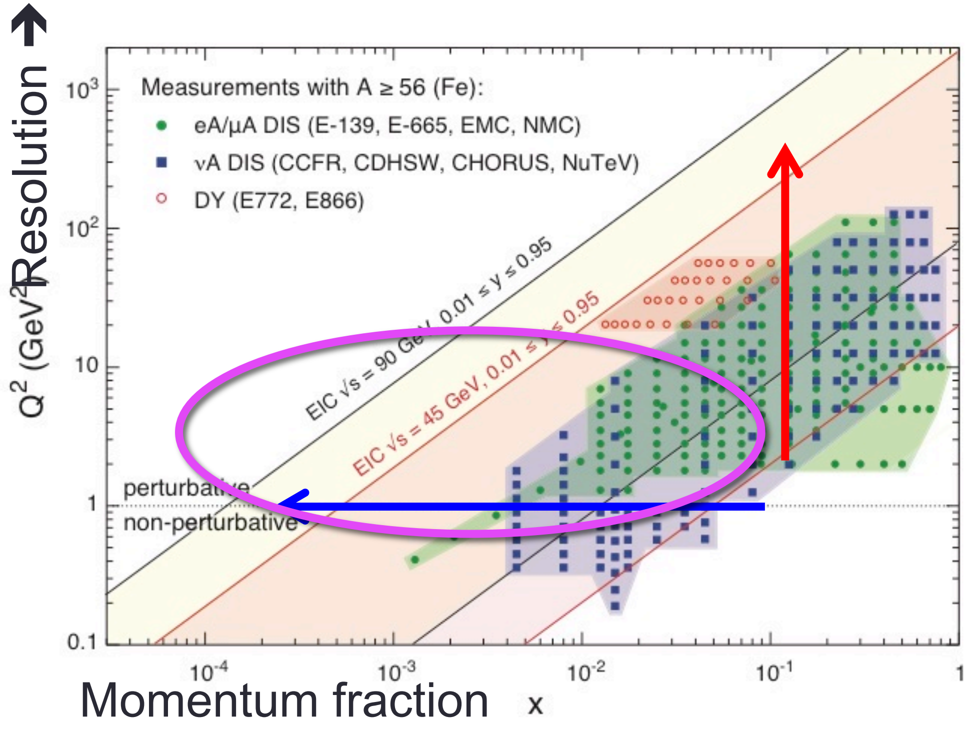


For e-N collisions at the EIC:

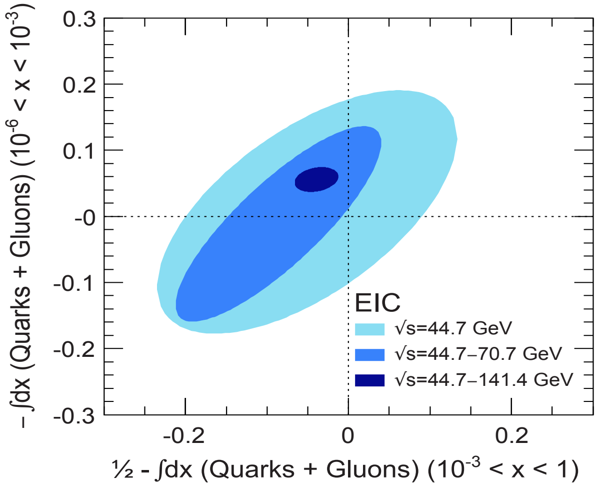
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

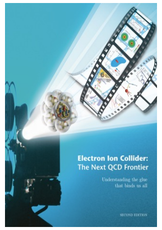
For e-A collisions at the EIC:

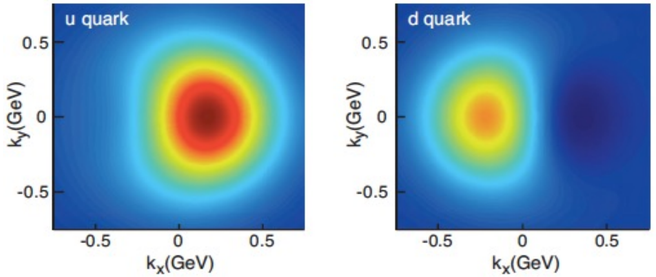
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)

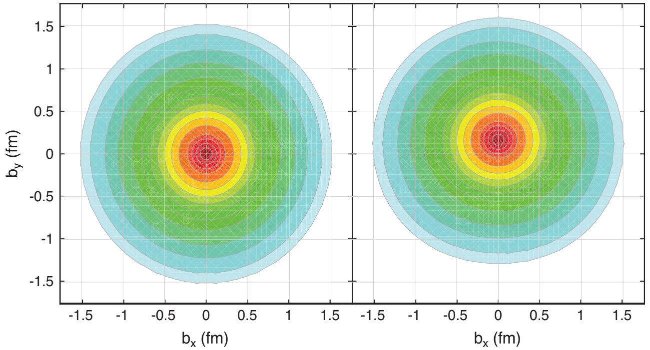


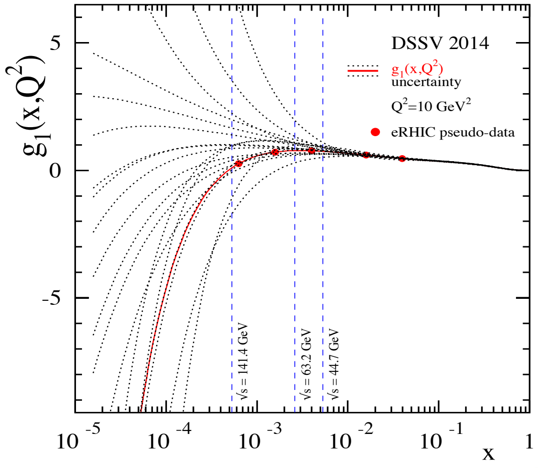
EIC science highlights

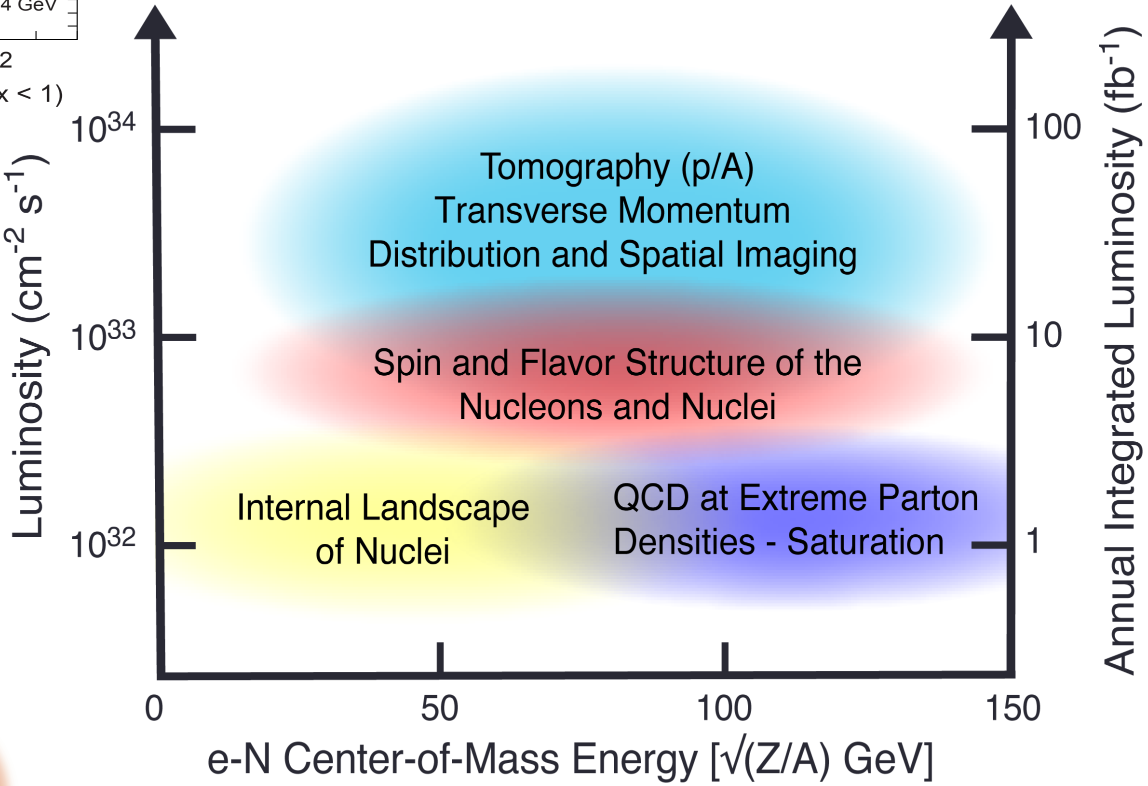


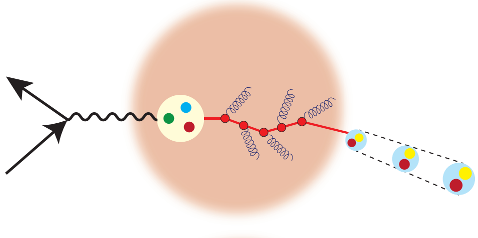


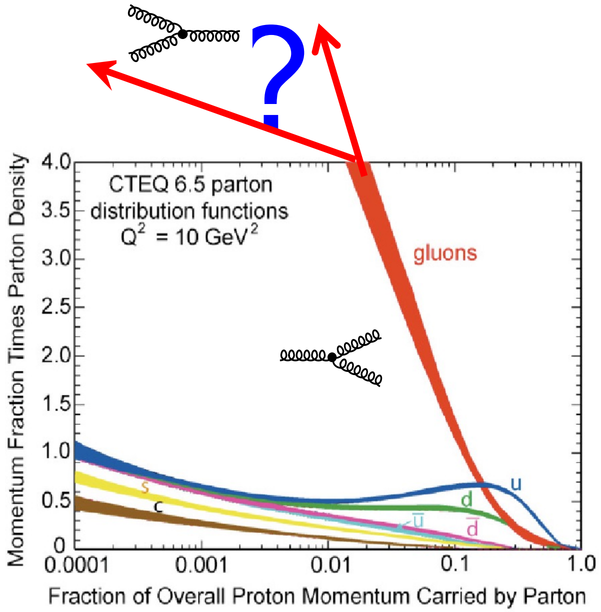




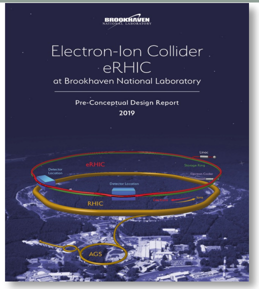




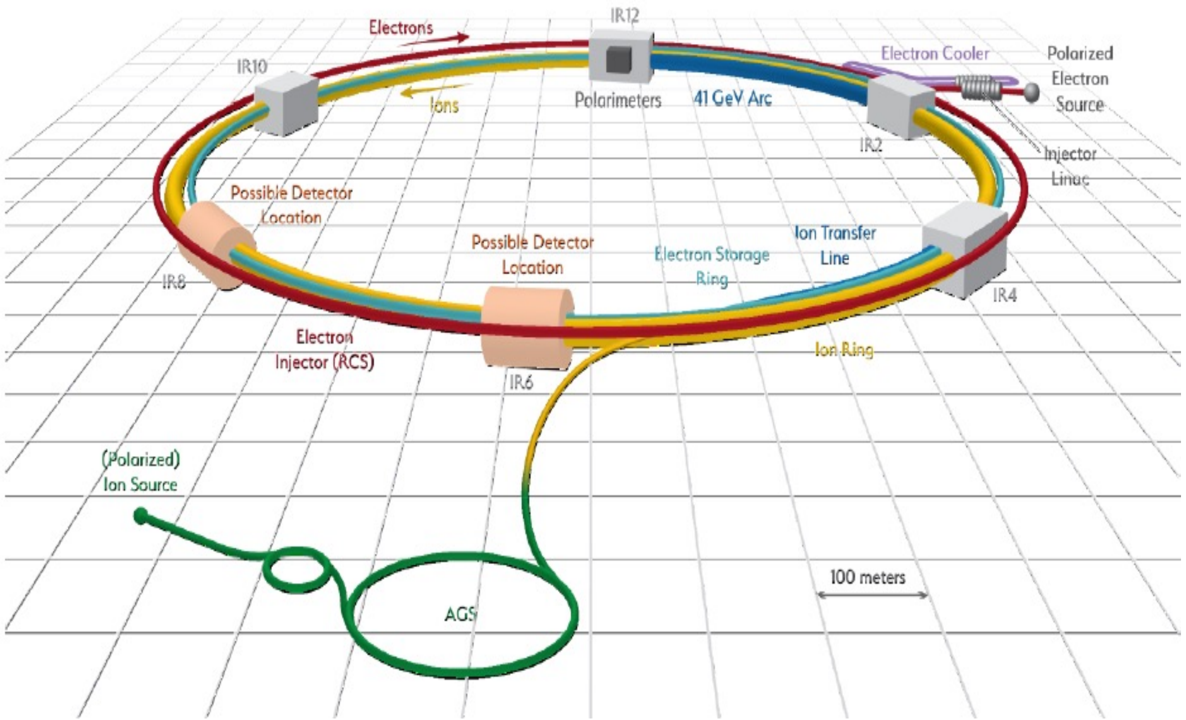




MACHINE & DETECTOR COLLABORATION



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

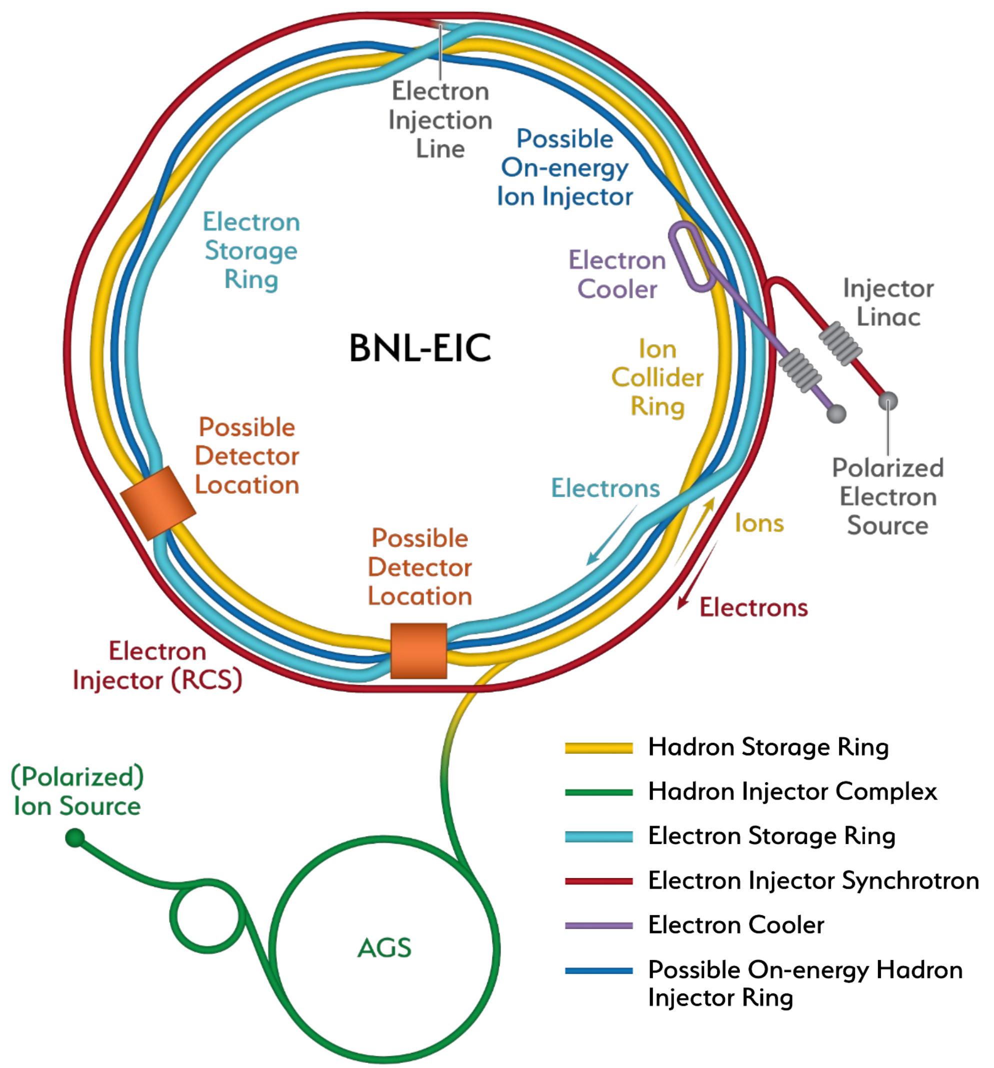
- ➢ Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- ➢ Need few modifications
- ➢ RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

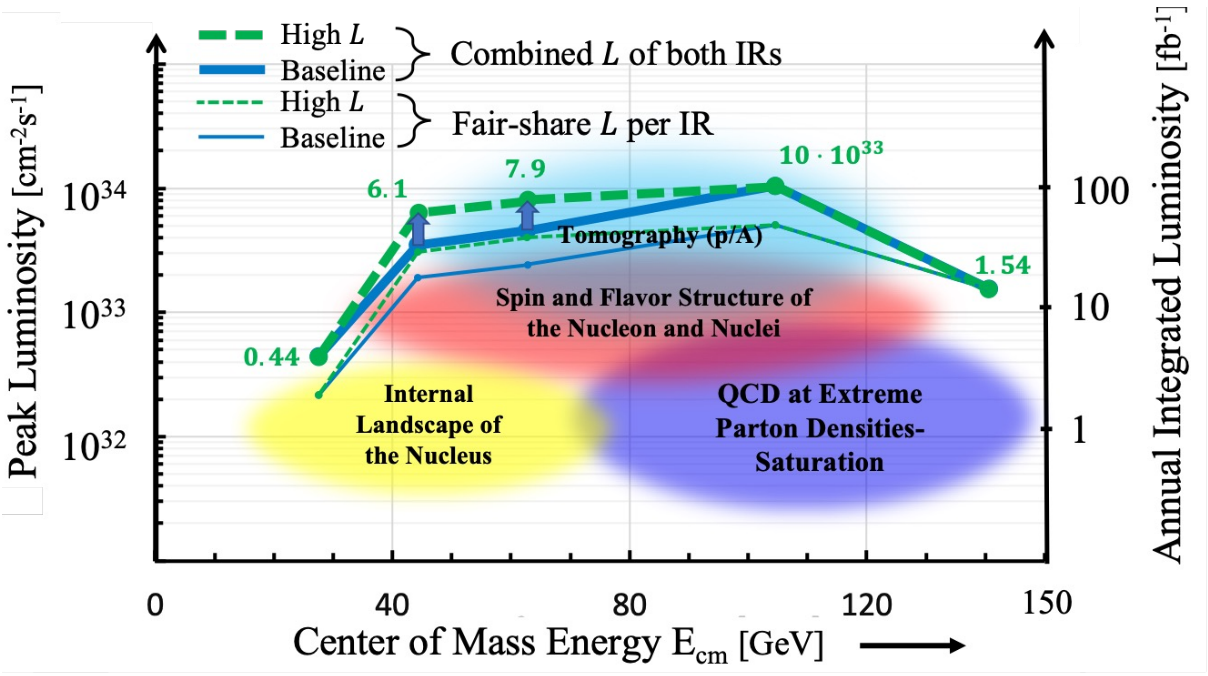
- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band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

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

EIC Accelerator Design

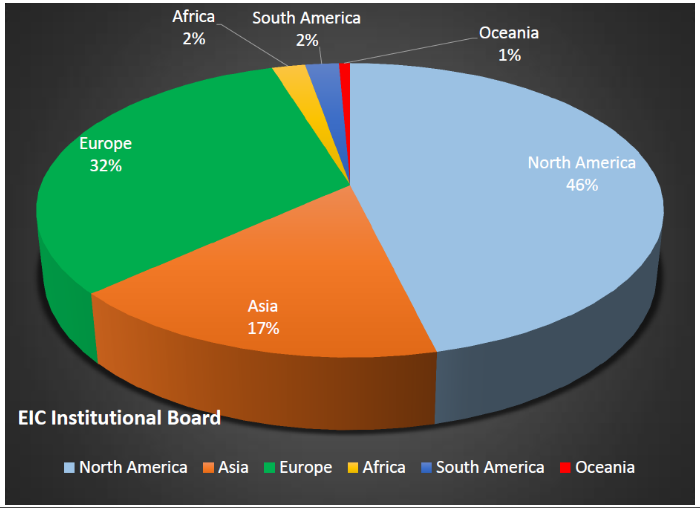


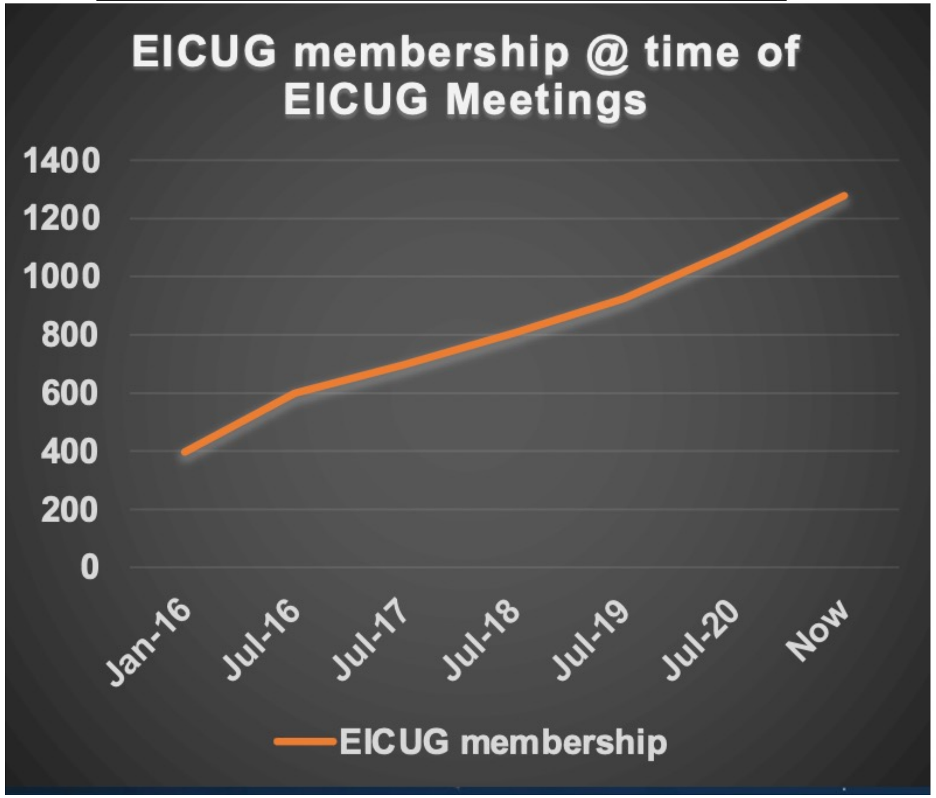
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



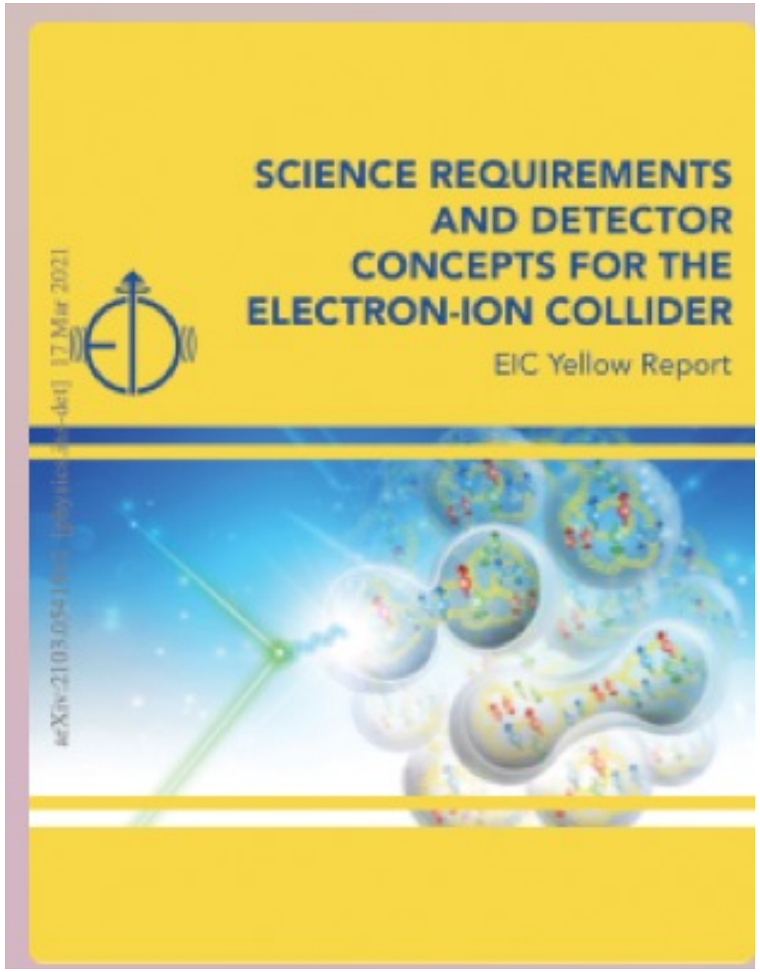
The Global EIC Users Group: EICUG.ORG

Formally established in 2016, now we have:
~1350 Ph.D. Members from ~36 countries, 266 institutions
EICUG is continuously growing
with world-wide participation



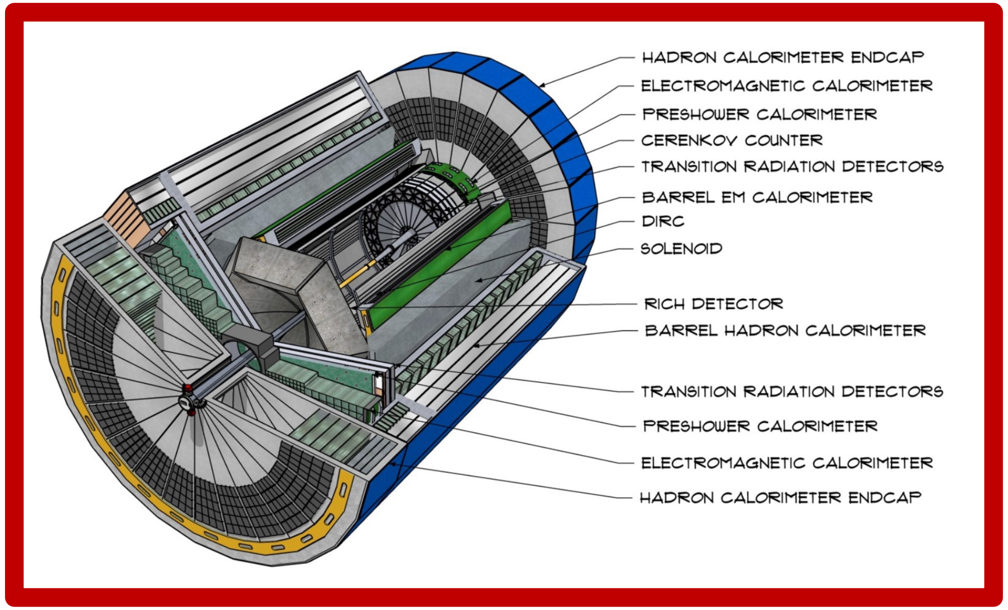


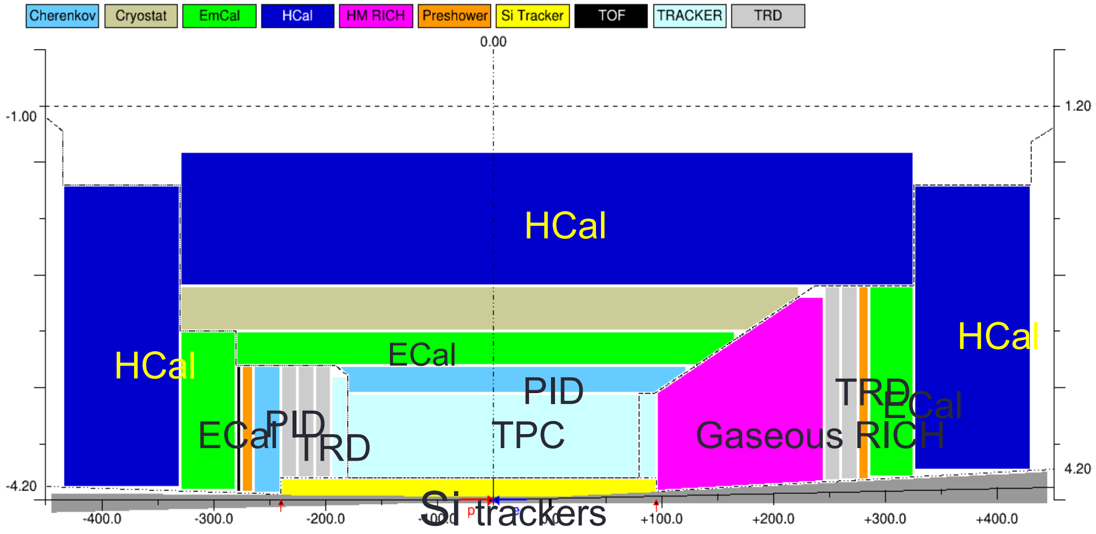
EICUG led "reference" detector design 2019-2021 "Yellow Report"



902 pages
415 authors
151 institutions

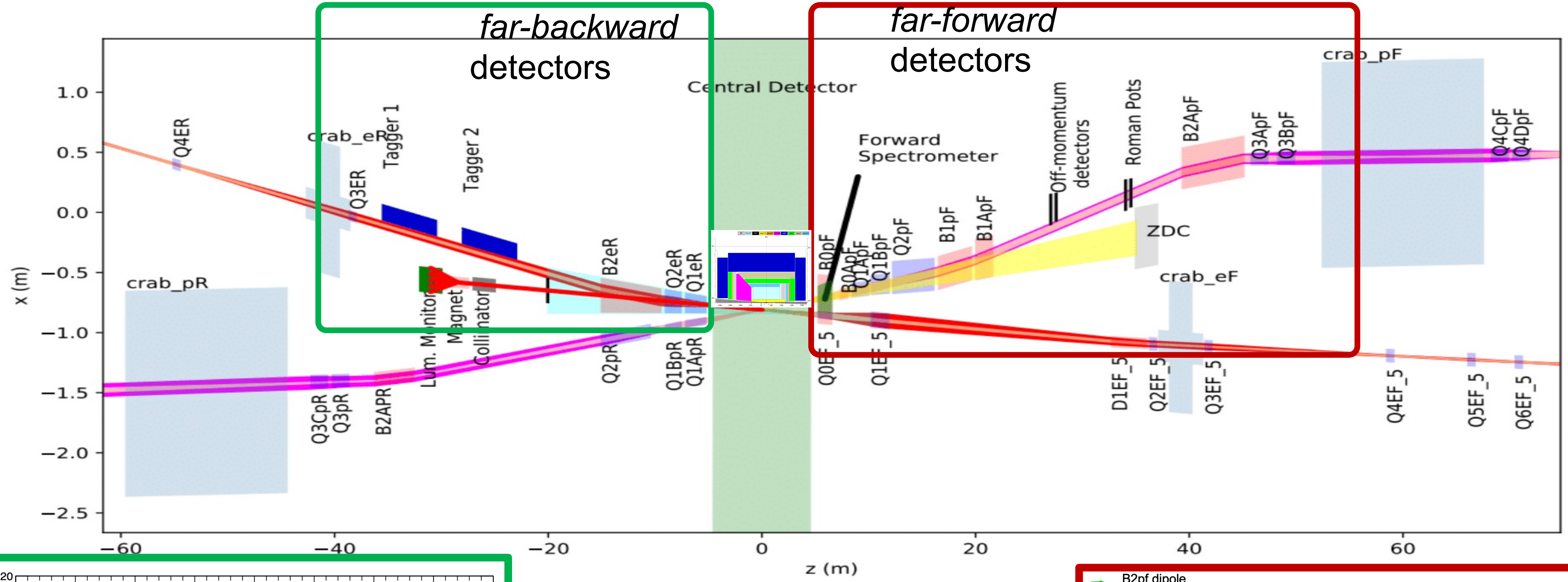
120 MB

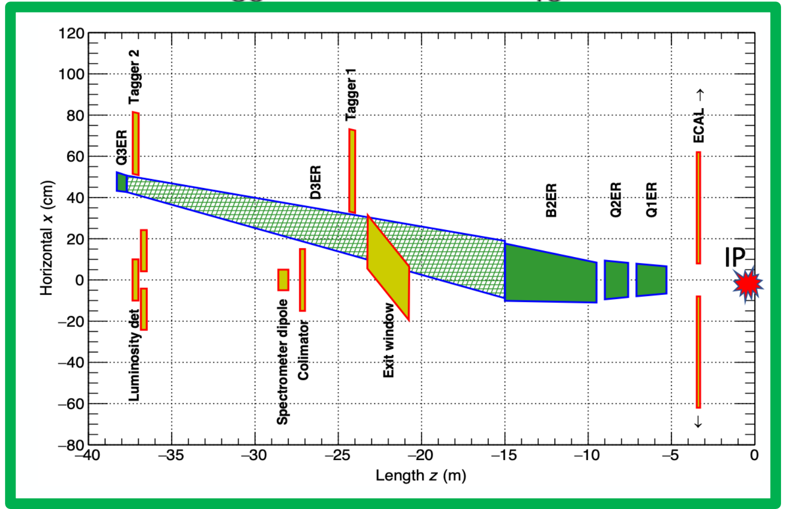




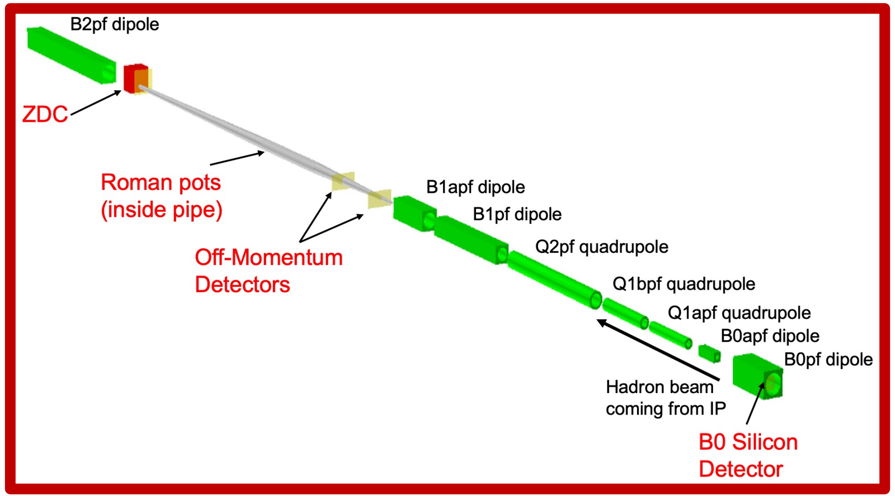
Nucl. Phys. A 1026 (2022) ; arXiv:2103.05419

Reference Detector – Backward/Forward Detectors



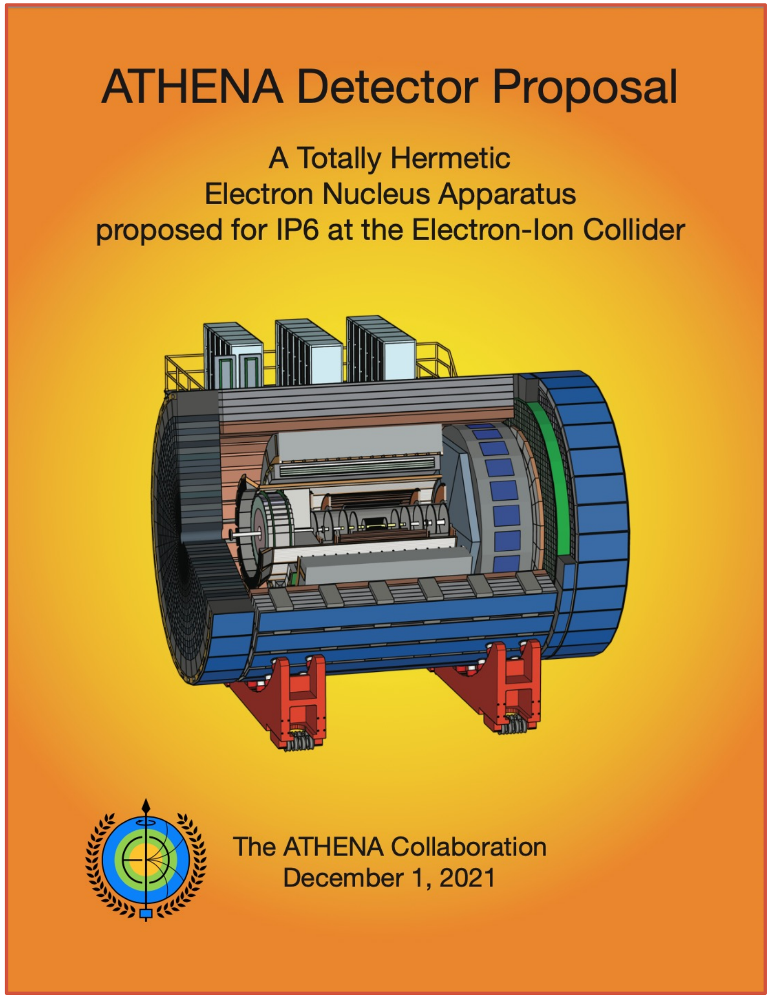


Extensive integration of forward and backward detector elements into the accelerator lattice



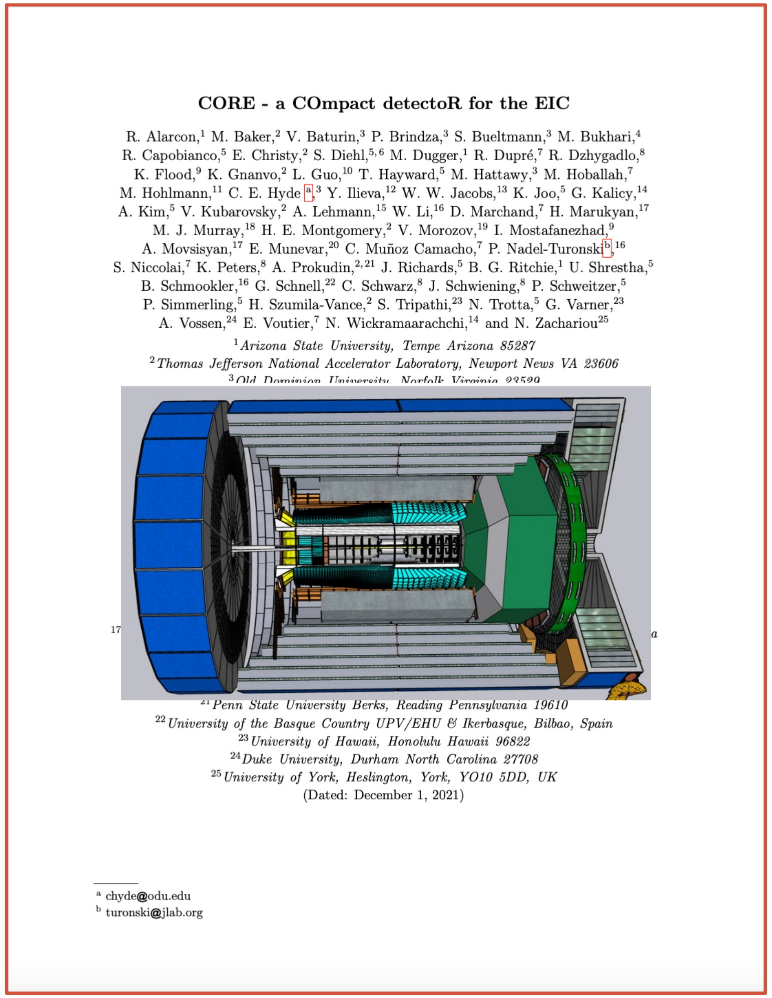
The three proposals: reviewed by an external panel

EIC Advisory Panel's recommendation on April 8, 2022


ATHENA Detector Proposal

A Totally Hermetic
Electron Nucleus Apparatus
proposed for IP6 at the Electron-Ion Collider

The ATHENA Collaboration
December 1, 2021


CORE - a COmpact detectoR for the EIC

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[24] *Duke University, Durham North Carolina 27708*
[25] *University of York, Heslington, York, YO10 5DD, UK*
(Dated: December 1, 2021)

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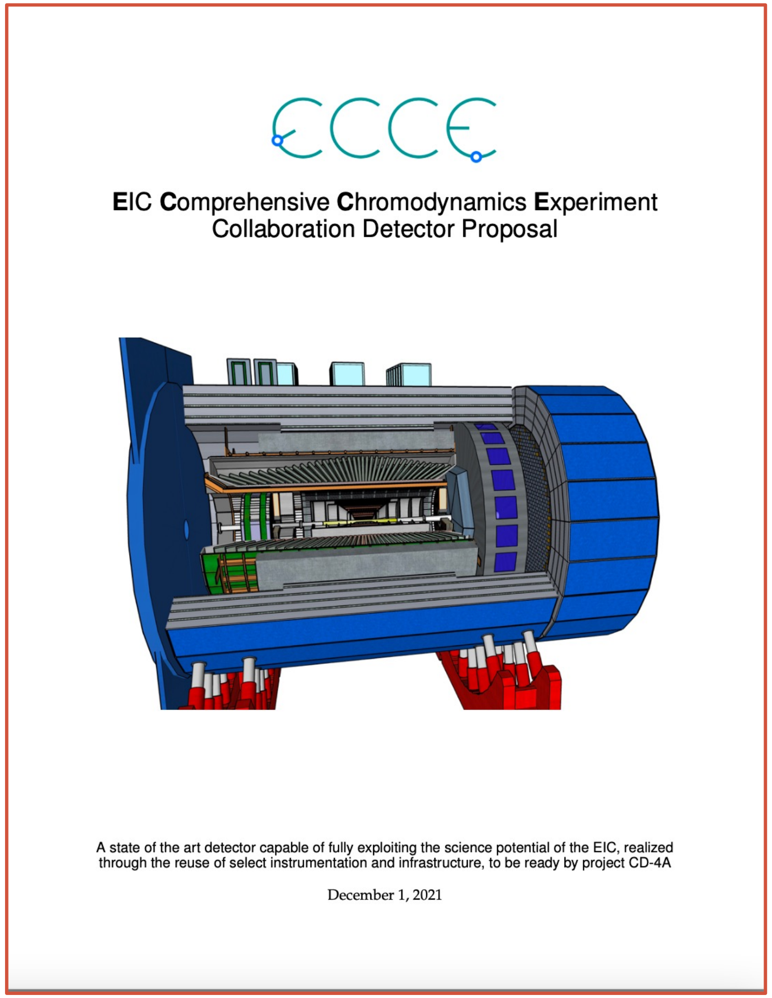
[b] turonski@jlab.org


ECCE

EIC **C**omprehensive **C**hromodynamics **E**xperiment
Collaboration Detector Proposal

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

Detector Proposal Advisory Panel

Co-Chairs: Rolf Heuer & Patty Mc Bride

All three proposals received high marks

Concluded that both ATHENA and ECCE satisfied the requirements

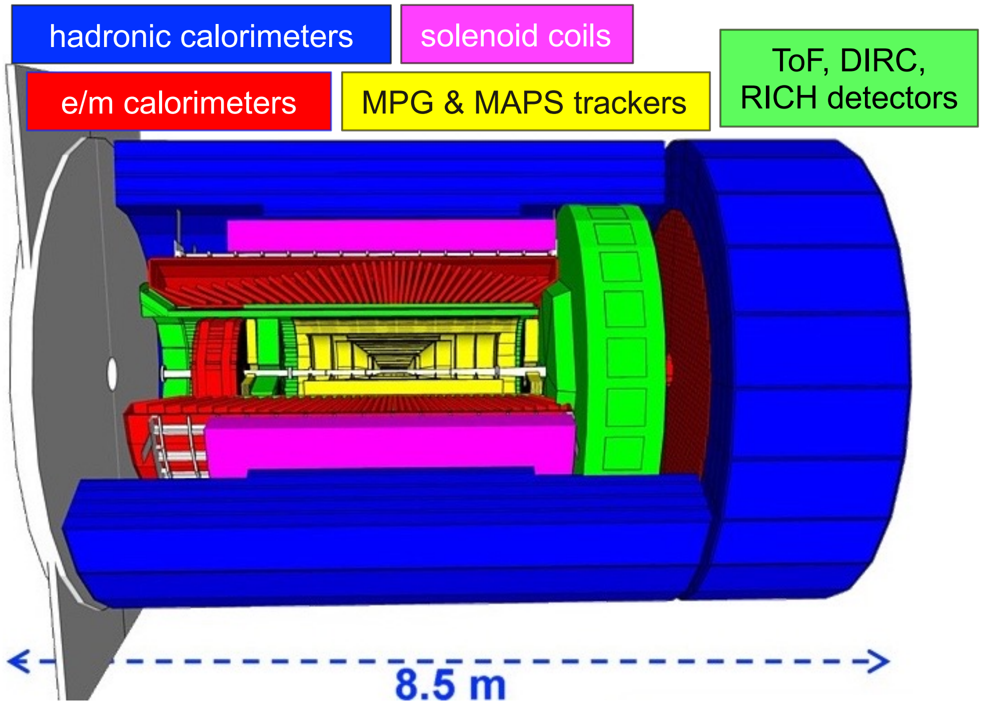
Congratulated CORE for some good ideas but too small overall

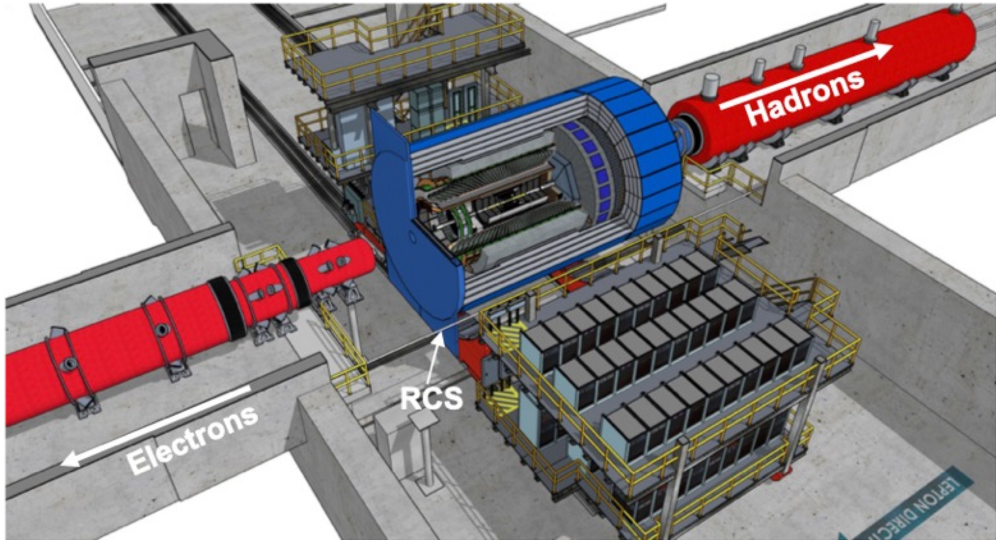
Recommended ECCE as the "reference design": lower risk and cost

- ATHENA, ECCE – collaborator overlap – neither large enough to become Detector 1
- Strongly encouraged the proto-collaborations to merge and build the **Project Detector** starting from ECCE's reference design

As of July 2022: (ATHENA + ECCE) : Electron Proton Ion Collider (**EPIC**) Detector Collaboration formed ➔ working together to realize the EIC science

Enthusiastically supported the idea of a **second detector for the 2nd IR**





EIC Management team working with the EICUG to realize EPIC

Detector requirements:

- ❑ Large rapidity (-4 < η < 4) coverage; and far beyond
  - o Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
    → Integration into IR from the beginning critical
    Many ancillary detector along the beam lines: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- ❑ High precision low mass tracking
  - o small (μ-vertex Silicon) and large radius (gas-based) tracking
- ❑ Electromagnetic and Hadronic Calorimetry
  - o equal coverage of tracking and EM-calorimetry
- ❑ High performance PID to separate e, π, K, p on track level
  - o good e/h separation critical for scattered electron ID
- ❑ Maximum scientific flexibility
  - o Streaming DAQ → integrating AI/ML
- ❑ Excellent control of systematics
  - o luminosity monitor, electron & hadron Polarimetry

E. Aschenauer & R. Ent

arXiv:2203.13199v1 [hep-ph] 24 March 2022

CONNECTION HIGH ENERGY PHYSICS AT LHC (HEP AND NP)

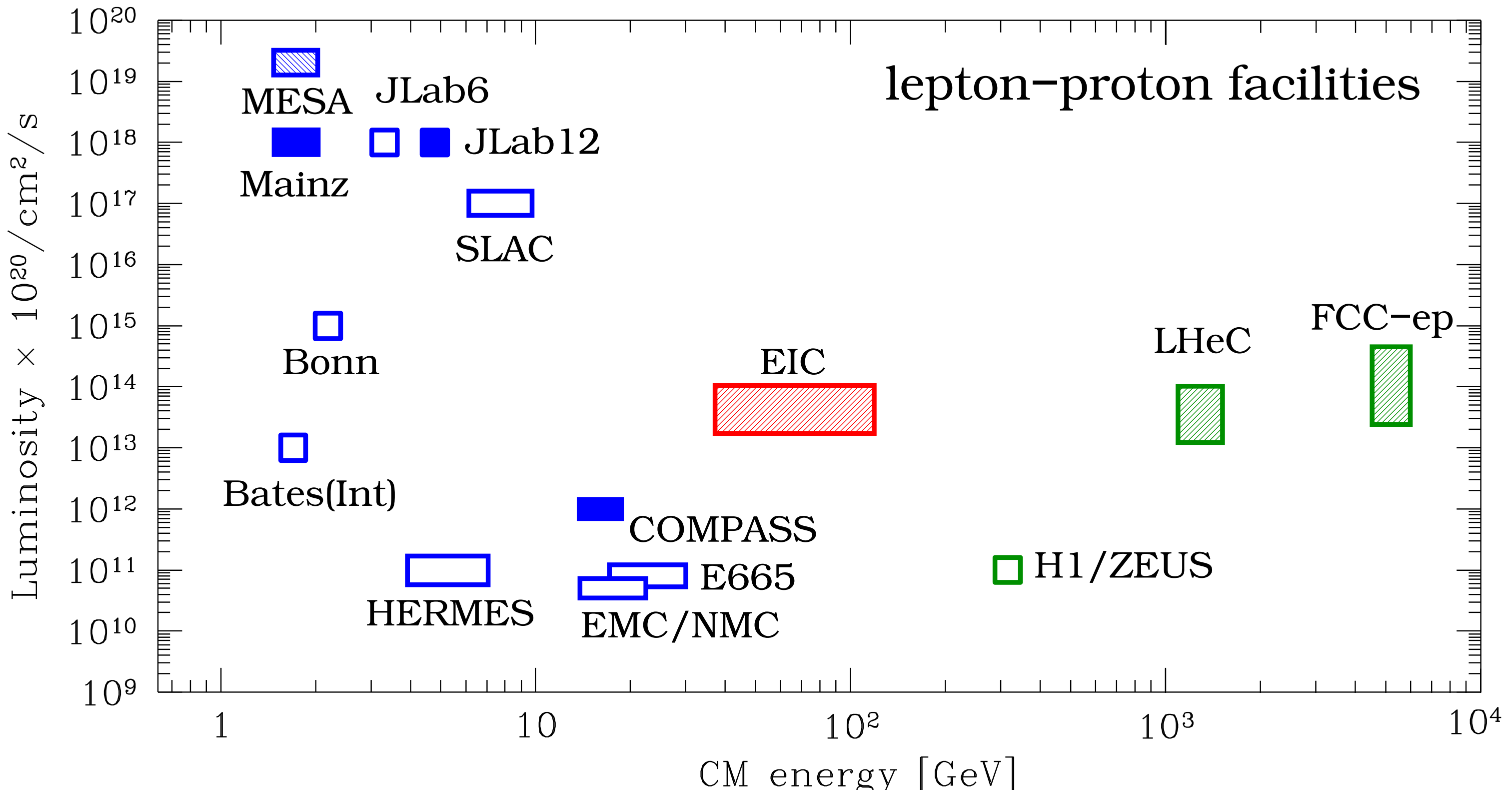
Nature does not distinguish between HEP and NP:

EIC will be useful for both!

EIC's versatility, resolving power and intensity (luminosity) open new windows of opportunity to address some of the crucial and fundamental scientific questions in particle physics. The paper summarizes the EIC physics from the perspective of the HEP community participating in Snowmass 2021

- Beyond the Standard Model Physics at the EIC
- Tomography (1,3,5 d PDFs) of Hadrons and Nuclei at the EIC
- Jets at EIC
- Heavy Flavors at EIC
- Small-x Physics at the EIC

- High luminosity wide CM range
- Polarized e, p, and ion beams
- All nuclei



Perhaps other intersections with LQCD?

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

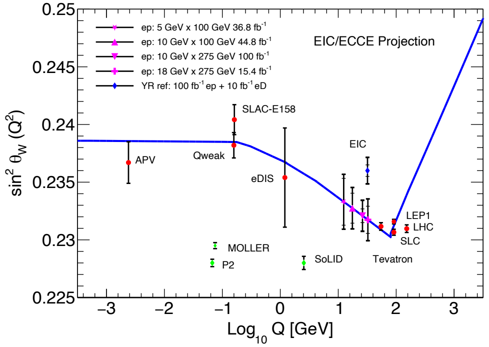
Precision electroweak and BSM physics:

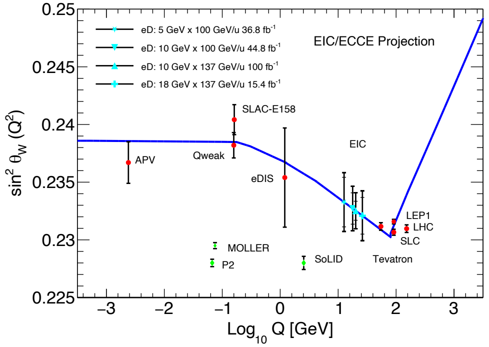
- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity

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

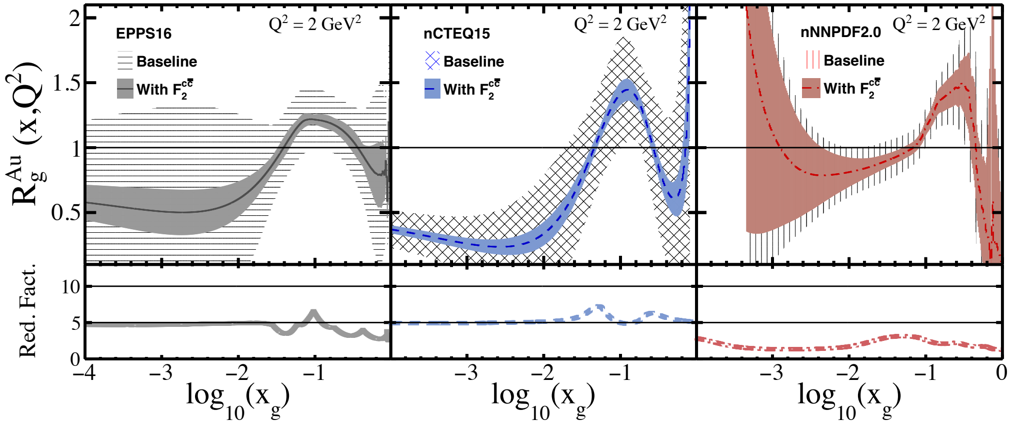
EIC for HEP & NP

Indirect search for BSM : Parity Violating Asymmetry

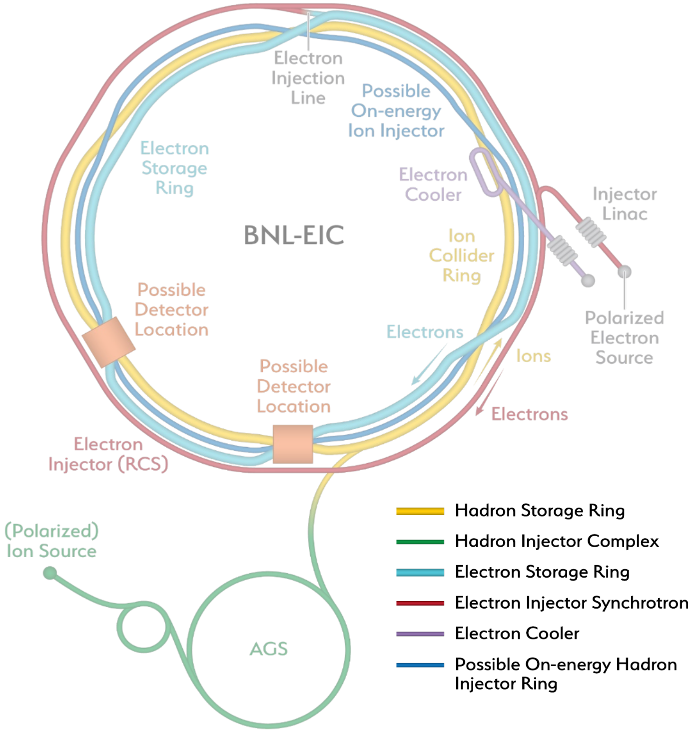


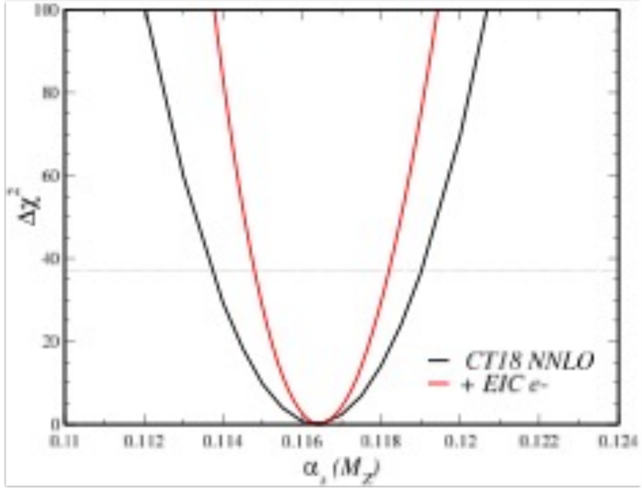


Nuclear PDF ratios with Jets @ EIC

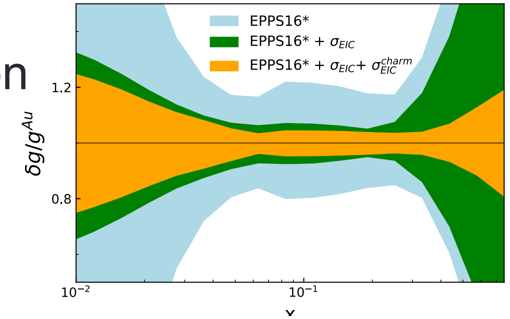


Precision PDFs ➔ α_S

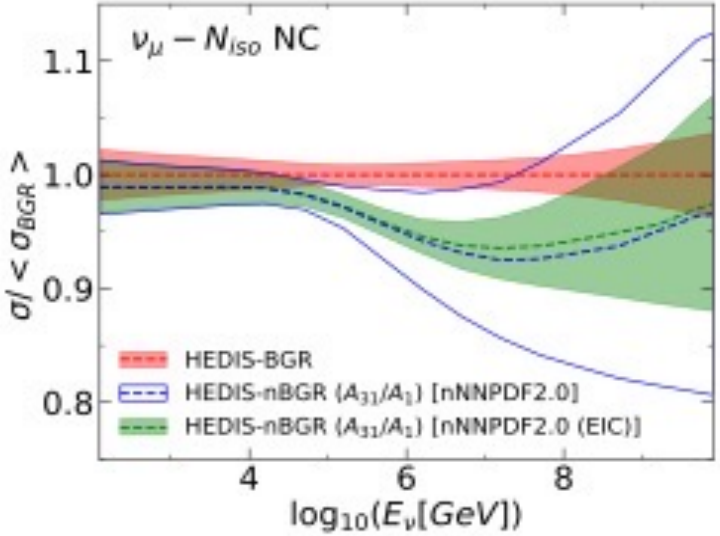




Nuclear Gluon PDFs With EIC



Nuclear corrections With EIC for neutrino-A scattering experiments



Detector technologies EIC & LHC:

Potential for overlap and collaboration:
Many EIC collaborators already part of RDXX at CERN & vice-versa.

- MAPS μVertex for primary/secondary vtx: barrel & end-caps (ALICE ITS3)
- MicroPattern Gas Detectors: large rapidity, spatial resolution ~100 μm
- Electromagnetic Calorimetry for kinematic reconstruction, precise energy measurements e, γ; e/π & π^0/γ separation. Various technologies at various locations:
  - W/SciFi w/o PMT, PbWO4, SiGlass; AstroPix & Pb/SciFi
  - High resolution Crystal Cal for e-endcap
  - Barrel EMCal 6 layers AstroPix and Pb/SciFi
- Particle Identification – extremely important for most EIC physics
  - K/pi separation over a wide range 1-20 GeV/c
  - Hadron ID: hpDIRC in Barrel, forward EndCap: duel RICH, backward Endcap: modular RICH or pF RICH, also TOF for short lever arm : LGAD, LAPPD
- Streaming Readout

EIC Science from the perspective of High Energy Physicists

arXiv:2203.13199v1 [hep-ph] 24 March 2022

Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics

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T. … Dong, … V. Guze… T.-J. H… K.S. Ku… H. … S. Mant… B. … F. Olnes… Qiu,[1]
M. Radici, S. Radhakrishnan, A. Sadofyev, J. Rojo, F. Ringer, Farid Salazar,[75,*]
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D. Wiegand,[86] C.-P. Wong,[48] K. Xie,[87] M. Zaccheddu,[2,3] Y. Zhao,[88] J. Zhang,[89] X. Zheng,[21] and P. Zurita[84]

Conclusion:

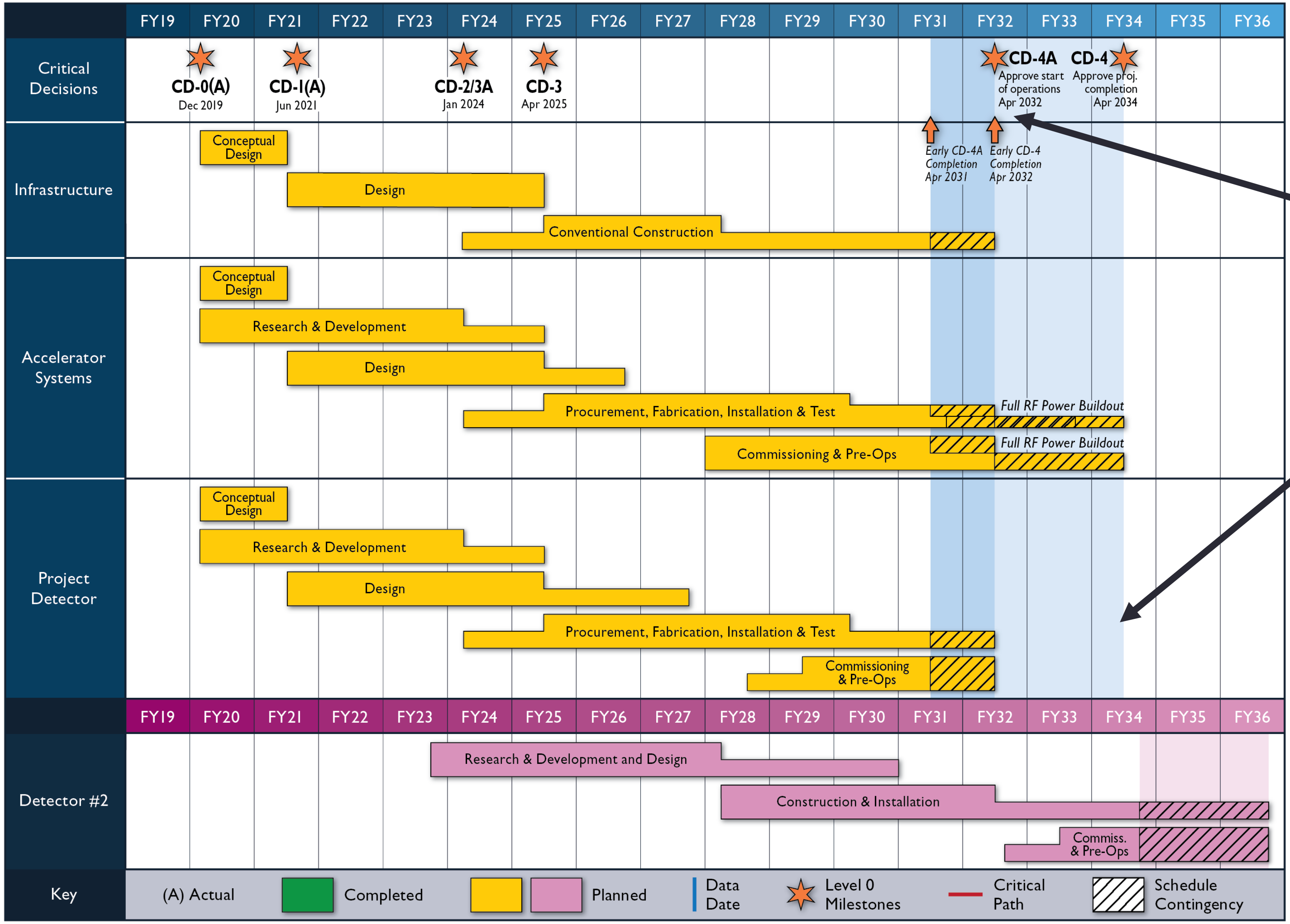
EIC will not only be of interest to nuclear physicists but would be extremely valuable to high energy physicists working at LHC and other neutrino scattering experiments

Partnerships for EIC sought and encouraged

- EIC is planned to be an international facility
  - Collaboration on EIC design and construction –mutually beneficial, advancing accelerator science and technology
- Possible contributions to the EIC accelerator could include the full range of accelerator design and hardware
  - Examples: IR magnet design and construction, luminosity monitoring, RF R&D and construction, normal conducting magnets, critical vacuum components, feedback systems, polarimetry, contributions to the 2nd IR, beam-dynamics calculations, etc.
- Detector(s) to be constructed as International collaborations & contributions from partners
  - Detailed contributions to EPIC *now under discussions* with EIC management
  - High level contacts between US DOE and international funding agencies: welcome

A. Seryi

Overall Schedule



CD4A early finish, collisions begin for machine tuning
Detector 1 needs to be ready to give feedback.

CD4 Machine delivers for physics
Detector 1 should be fully functional to start physics

2nd Detector and IR

- Current assumption realization trailing ~5 years behind Detector-1
- focus on complementary IR/physics & technologies

Summary & Outlook

- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded (predominantly) 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**. Cost of a second detector from non-DOE sources to be determined/identified
  - Experimental collaboration(s) are being formed now (in 2022)
  - An aggressive timeline : first collisions by ~2031/32; physics start by ~2033
- **High interest in having international partners both on detector and accelerator**

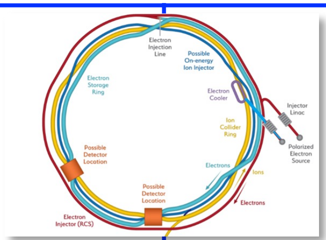
- *Early career scientists: This machine is for you! Ample opportunity for make an impact.*
- *Working with at EIC should be fully transparent to the HEP trained students*


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

Backups

Complementarity for 1st-IR & 2nd-IR

	1st IR (IP-6)	2nd IR (IP-8)
Geometry:	ring inside to outside tunnel and assembly hall are larger Tunnel: ⃠ 7m +/- 140m	ring outside to inside tunnel and assembly hall are smaller Tunnel: ⃠ 6.3m to 60m then 5.3m
Crossing Angle:	25 mrad	35 mrad secondary focus



different blind spots
different forward detectors and acceptances
different acceptance of central detector

Luminosity:

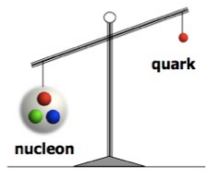
more luminosity at lower E_{CM}
optimize Doublet focusing FDD vs. FDF
→ impact of far forward p_T acceptance

Experiment:

1.5 Tesla or 3 Tesla
different subdetector technologies

ECA & RE

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

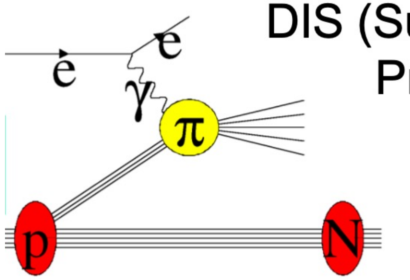
Relativistic Motion | ***Chiral Symmetry Breaking*** | ***Quantum Fluctuations***

X. Ji, PRL 74 1071 (1995)

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

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

DIS (Sullivan Process)



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

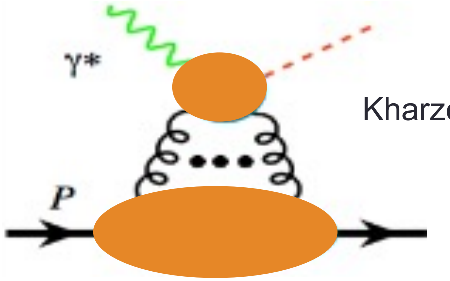
- Criticisms: not scale-invariant, decompositions: Lorentz invariant vs. rest frame
- Recent interest (workshops) planned to settle: how to determine the different contributions
- **Lattice QCD providing estimates**

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

arXiv: 1710.09011

Trace anomaly:
Upsilon production near threshold:

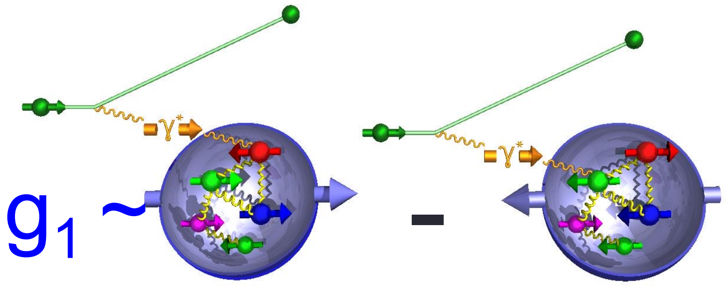
SoLID@JLab & EIC



Kharzeev et al. 1996

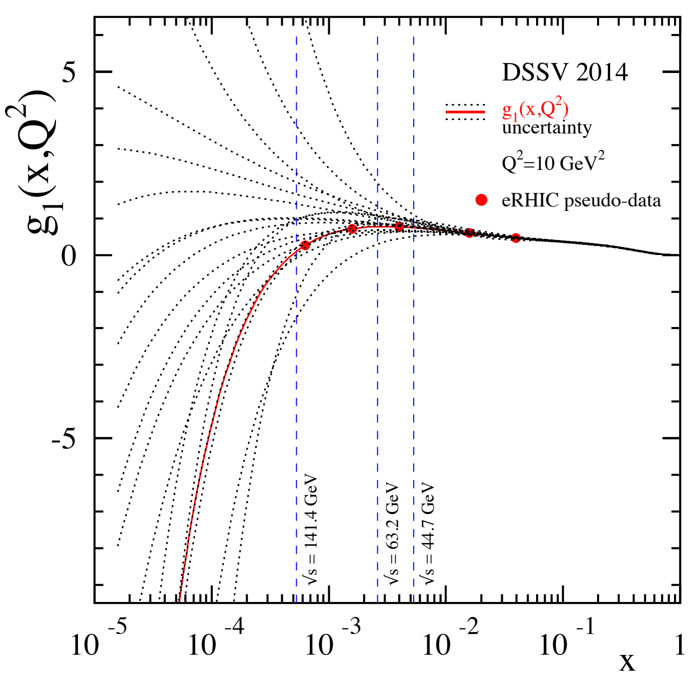
Nucleon Spin: Precision with EIC

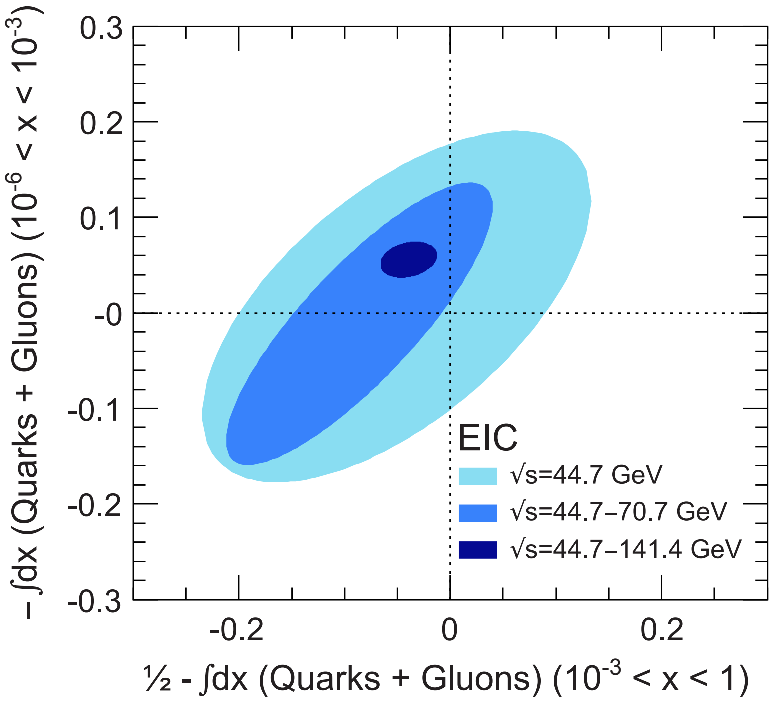
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$



$\Delta\Sigma/2$ = 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

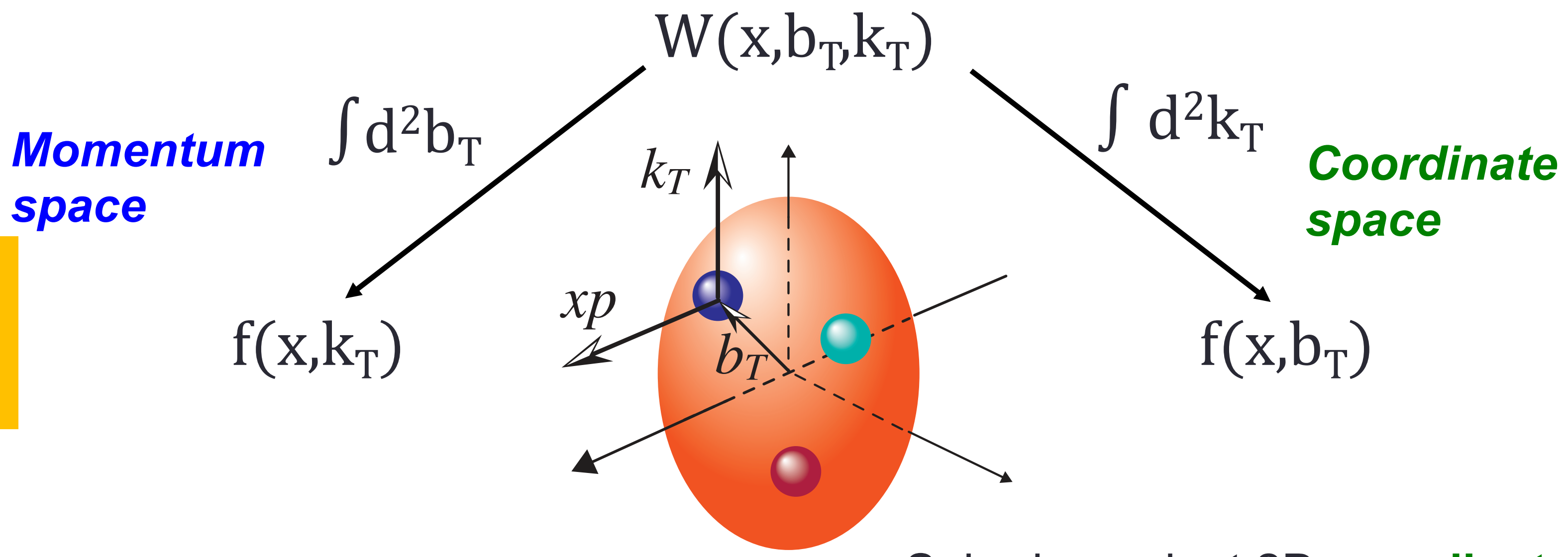
Lattice Calculations : comparison

SIDIS: strange and charm quark spin contributions

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**

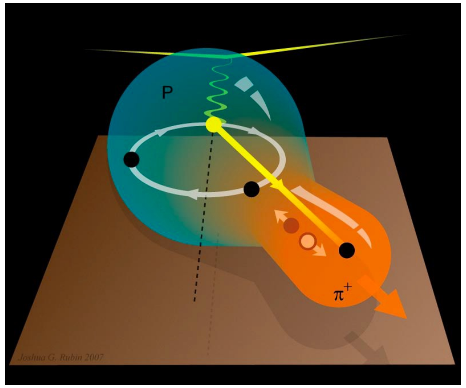
Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply virtual Compton scattering and meson production)
→ **Generalized Parton Distributions**

momentum and position distributions → Orbital motion of quarks and gluons

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

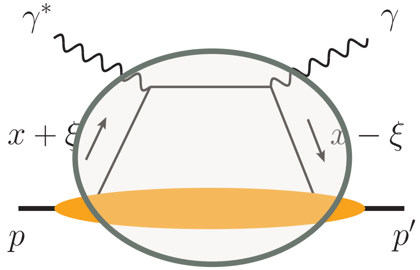
Spin-dependent (2+1)D momentum space images from semi-inclusive scattering (SIDS)

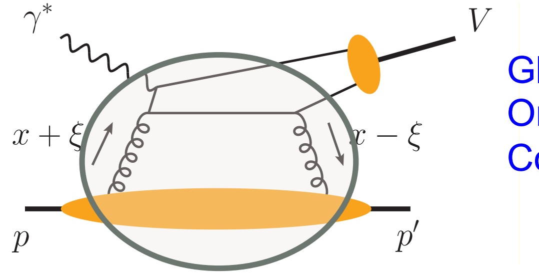
Transverse Momentum Distributions



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

Quarks Motion



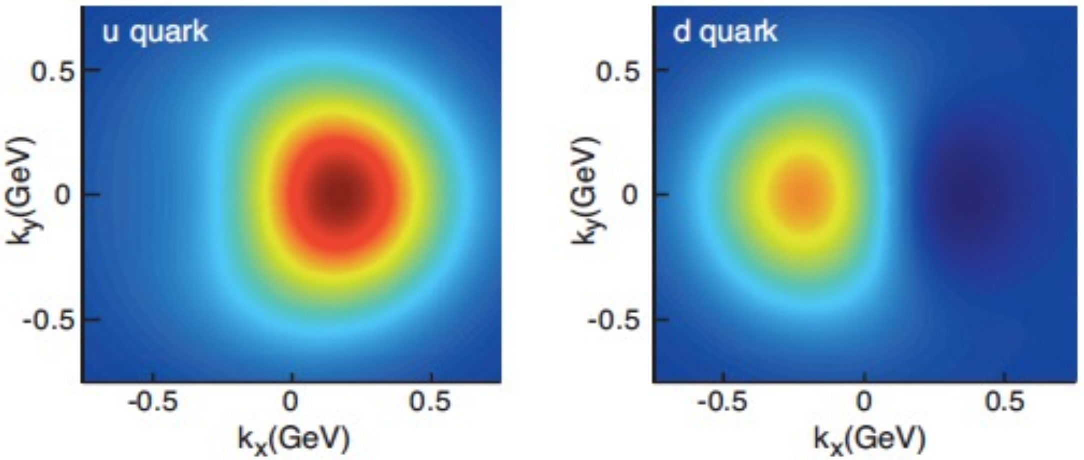


Gluons: Only @ Collider

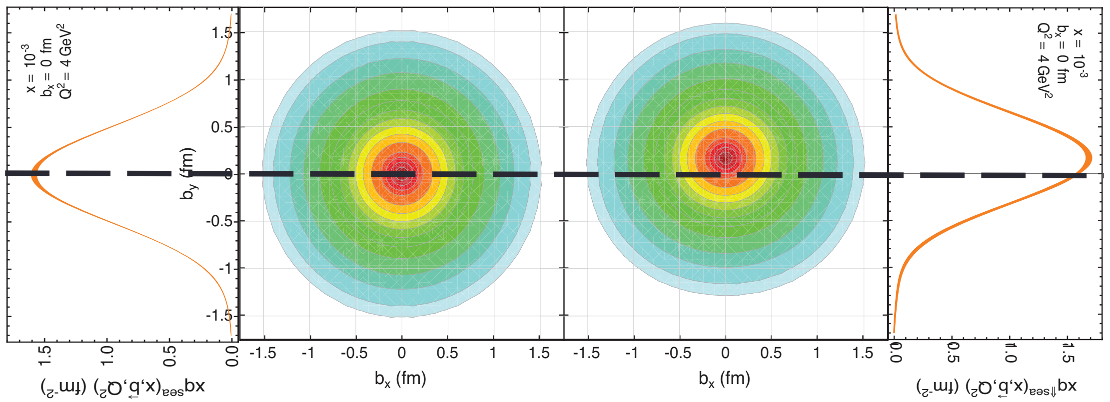
Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

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

Quark's 2D momentum distribution



Sea quark's 2D position distribution
unpolarized polarized

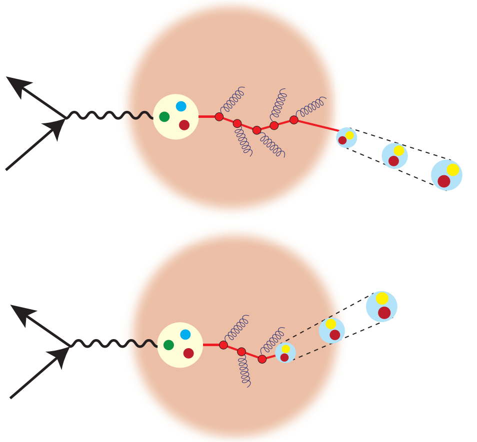


Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

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

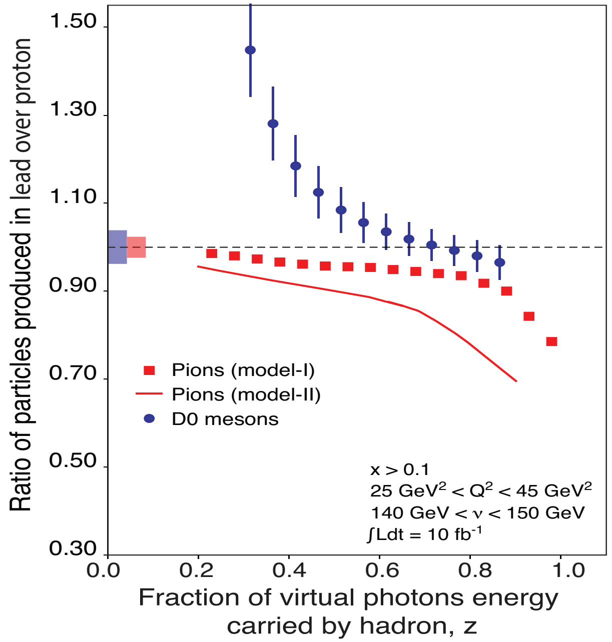


Control of ν by selecting kinematics;
Also under control the nuclear size.

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

Study in light quarks
vs.
heavy quarks

Energy loss by light vs. heavy quarks:

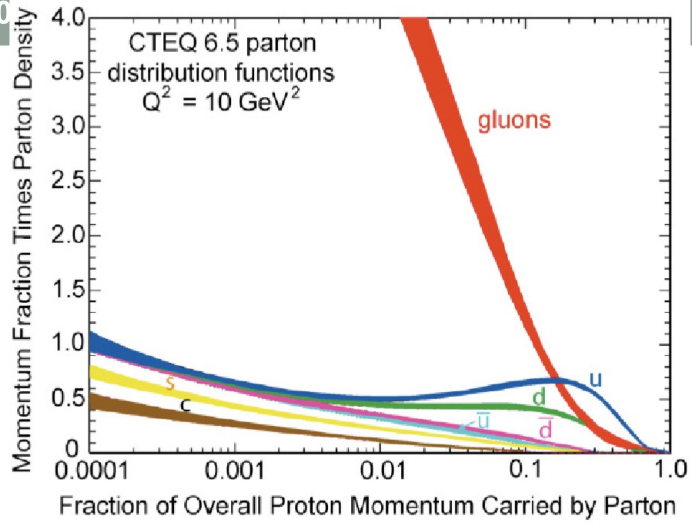


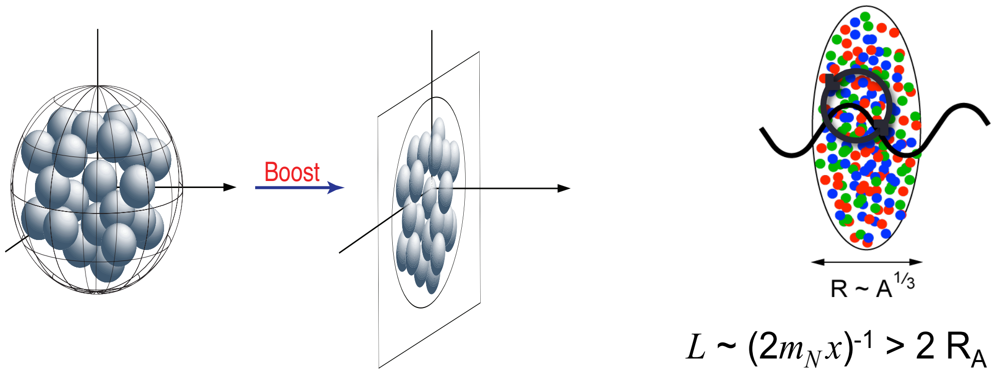
Identify π vs. D^0 (charm) mesons in e-A collisions:

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

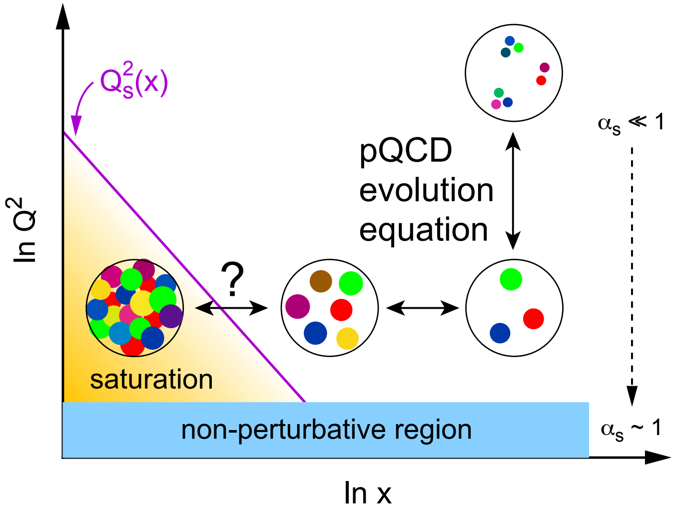
Low x physics with nuclei



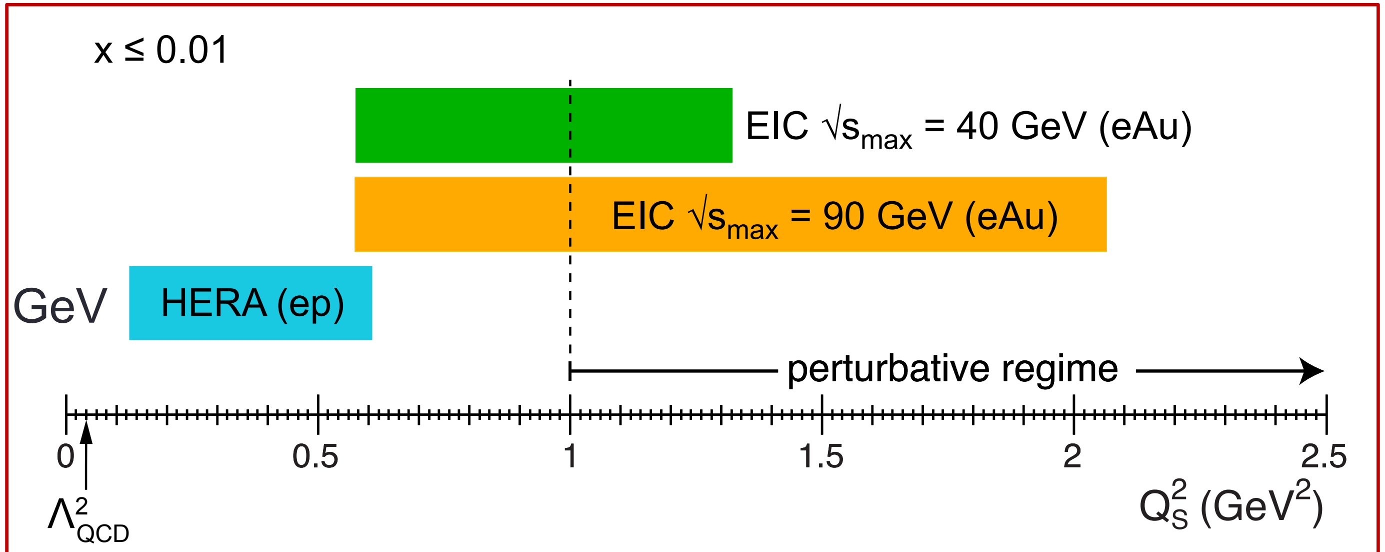


$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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



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



gluon emission = gluon recombination

At Q_S