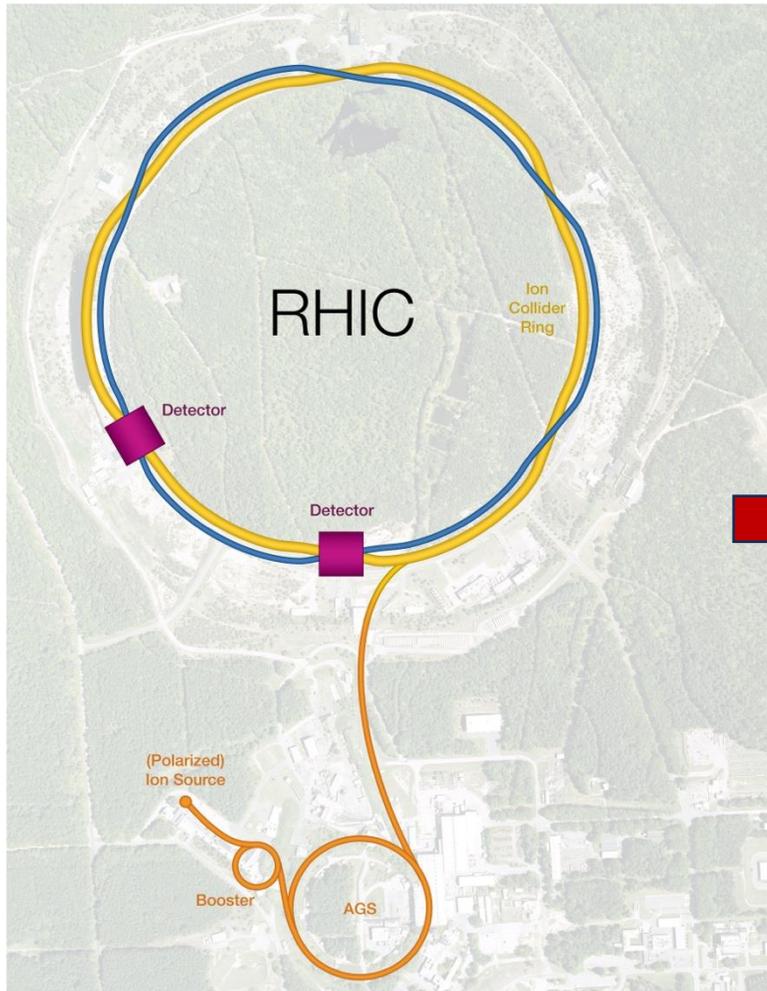




Lecture 3: Electron Ion Collider

Abhay Deshpande

Transition from RHIC to Electron Ion Collider (EIC) in 2026



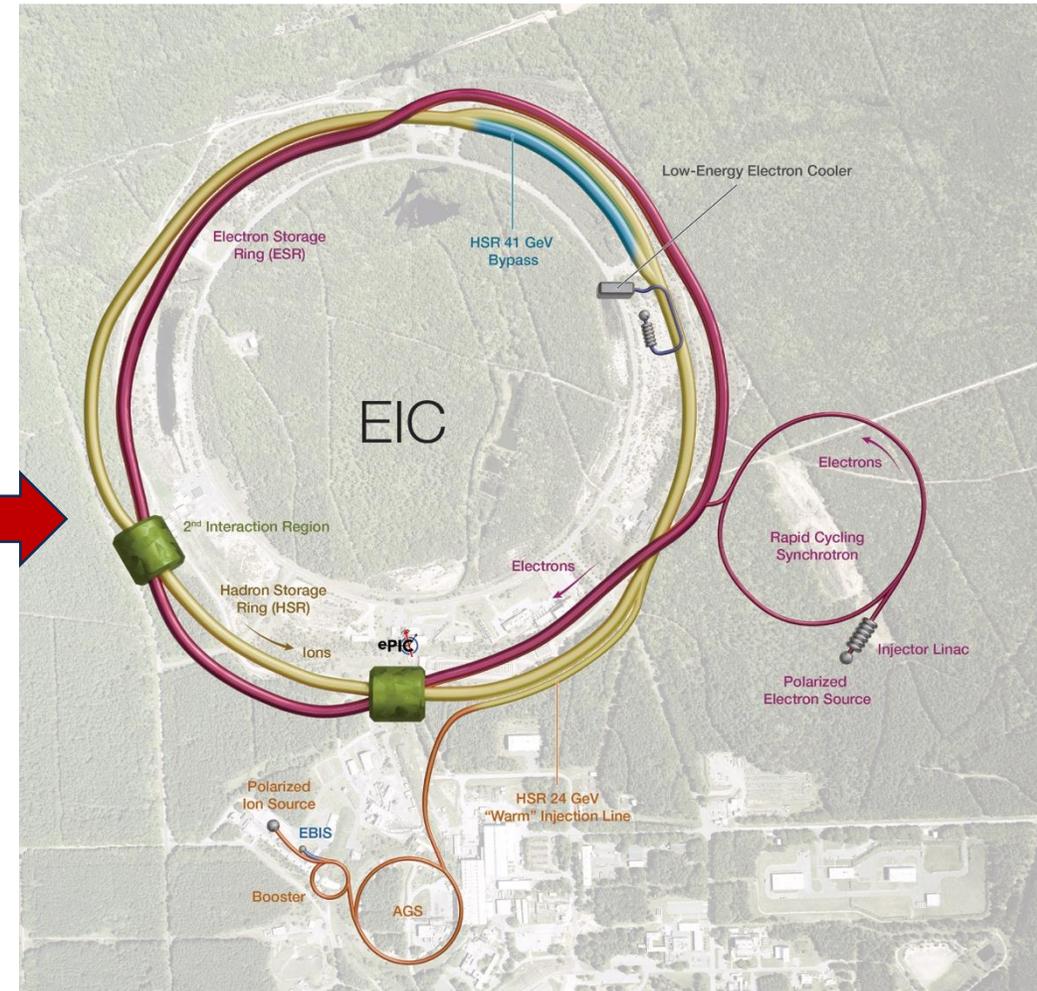
Re-Use the existing tunnel

Minimal modification to the hadron beam complex (yellow)



New electron beam facility

Build on the ~\$2B+ investment



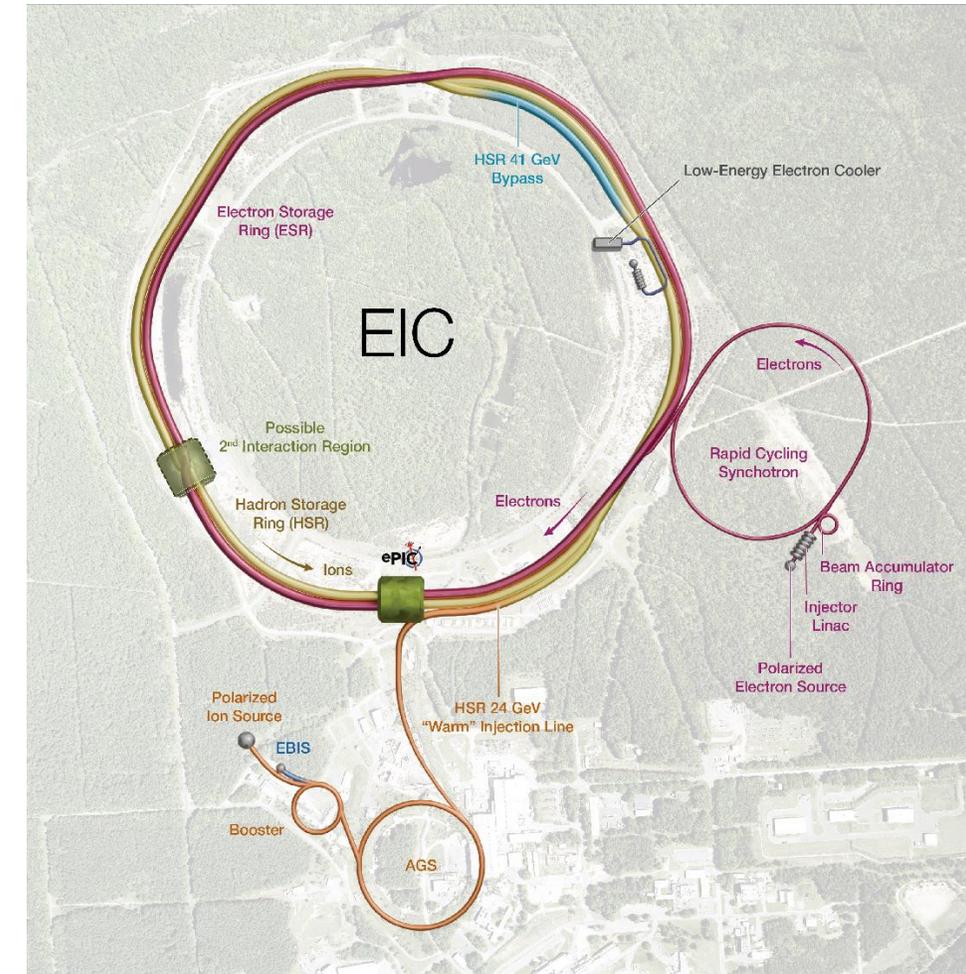
Present EIC Concept (2025)

•Ultimate EIC Performance Parameters:

- High Luminosity: $L = 10^{33} - 10^{34} \text{cm}^{-2}\text{sec}^{-1}$
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: $E_{\text{cm}} = 28 - 140 \text{ GeV}$
- Large Ion Species Range: protons – Uranium
- Large Detector Forward Acceptance and Low-Background Conditions
- Possibility to Implement a **Second Interaction Region (IR)**

Accelerator Status at a glance:

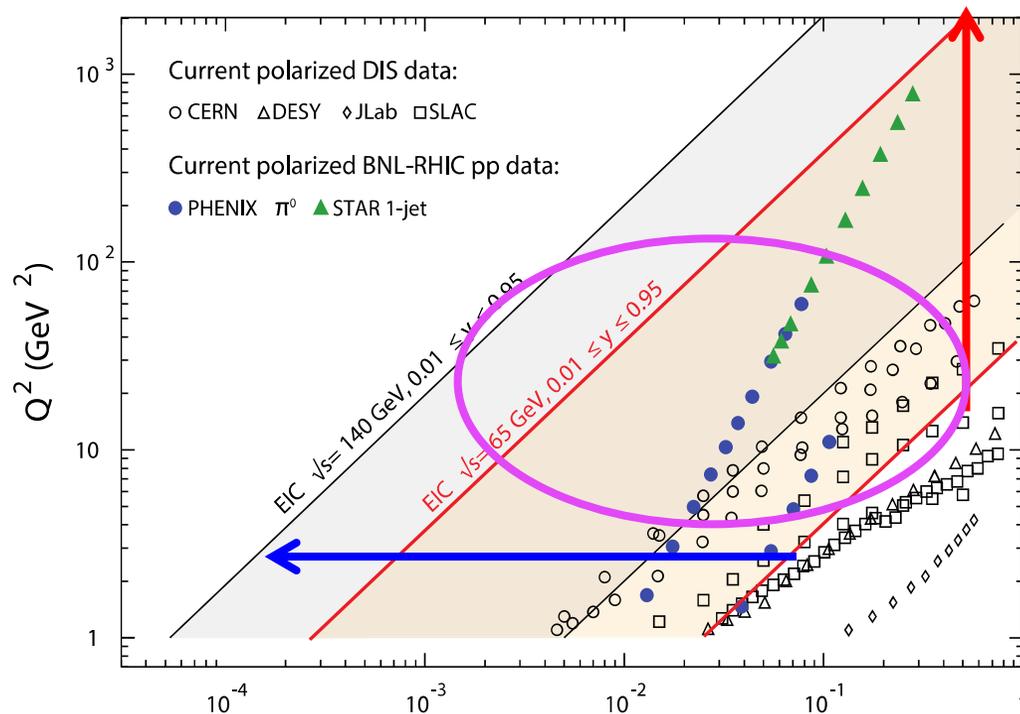
- ✓ Polarized ion/proton source
- ✓ Ion injection and initial acceleration systems – Linac (200 MeV), Booster (1.5 GeV), AGS (25 GeV)
- UPGRADE** Hadron Storage Ring (40-275 GeV) – HSR
- NEW** Electron Pre-Injector (750 MeV linac)
- NEW** Beam Accumulation Ring (750 MeV) – BAR
- NEW** Electron Rapid Cycling Synchrotron (0.75 GeV – top energy) – RCS
- NEW** Electron Storage Ring (5 GeV – 18 GeV) – ESR
- NEW** Interaction Region(s) – IR
- NEW** Hadron Cooling System



Protons: ~40 – 275 GeV
Electrons: 5 – 18 GeV

**EIC Science → what it could
provide**

EIC: Kinematic reach & properties

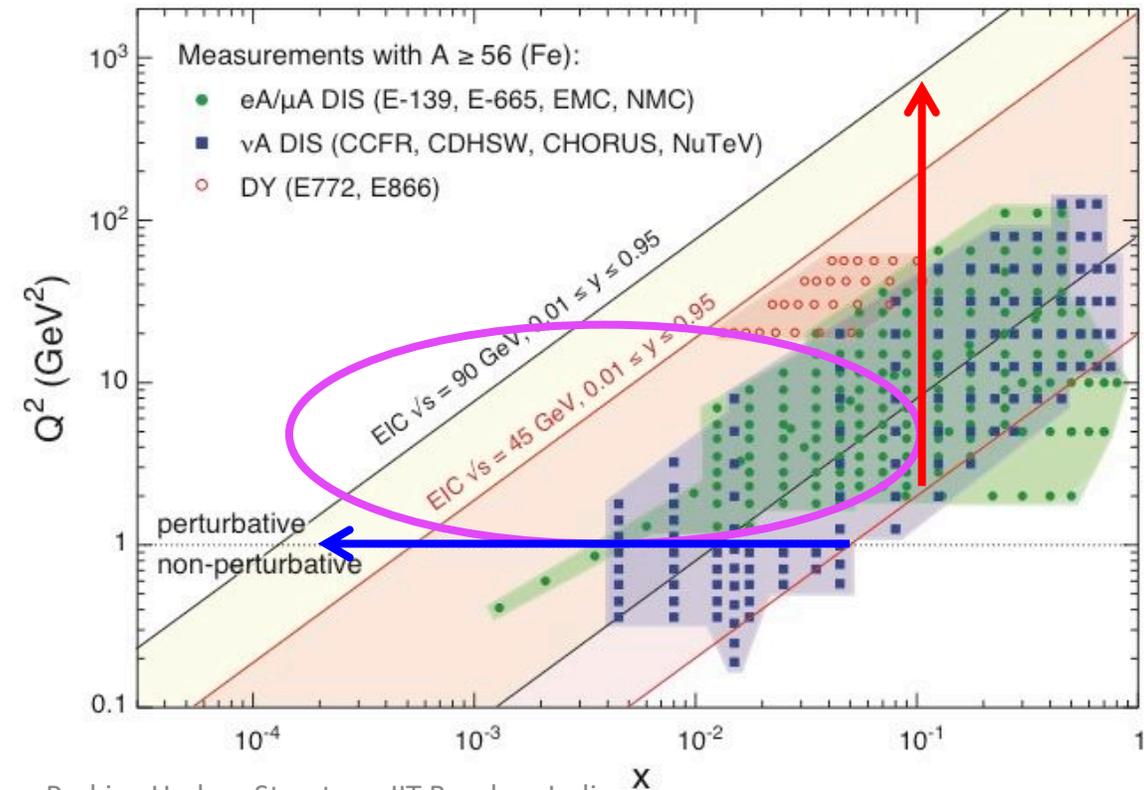


For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/³He
- ✓ 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: x

- ✓ Wide range in nuclei
- ✓ Lum. 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

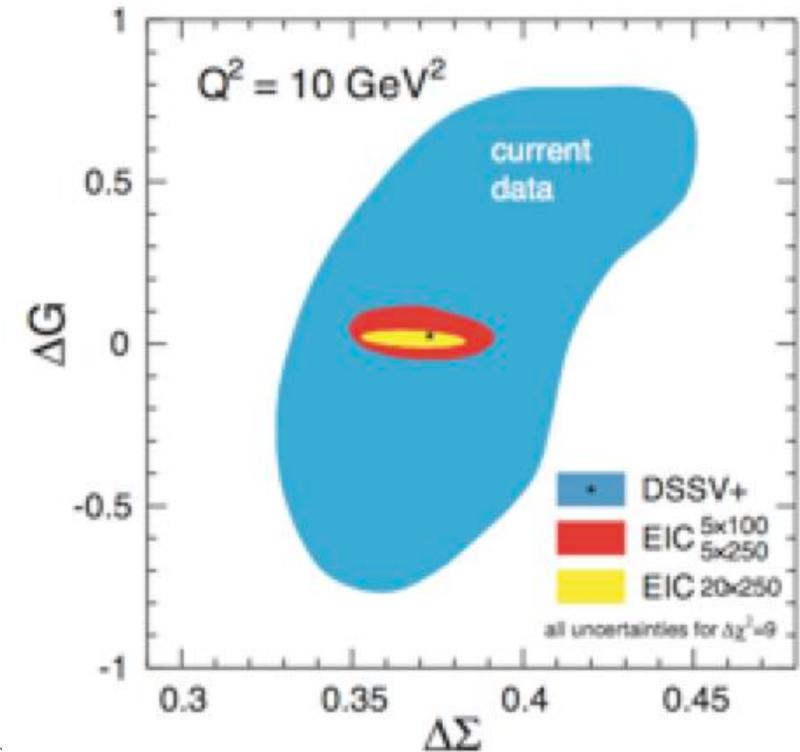
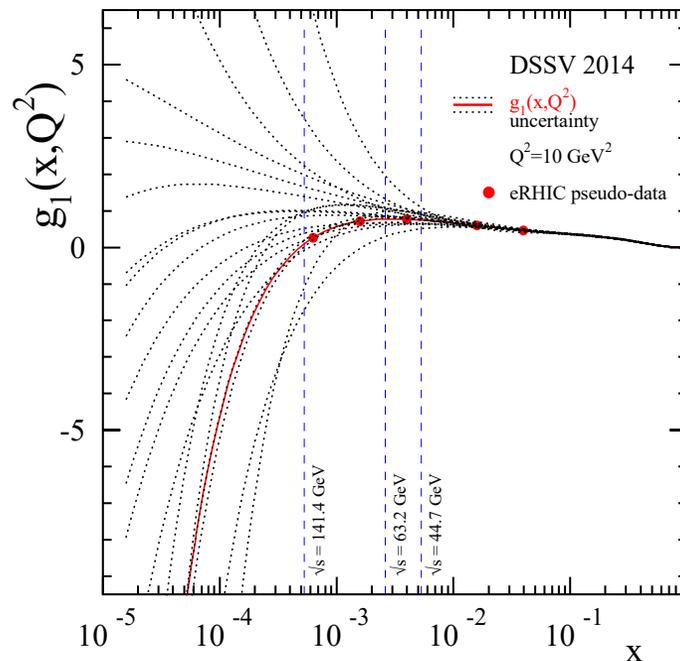
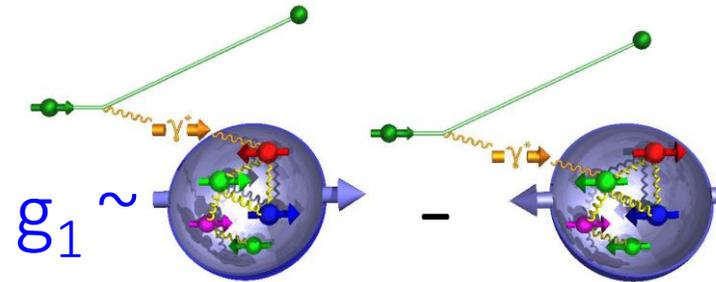
L_Q = Quark Orbital Ang. Mom

L_G = Gluon Orbital Ang. Mom

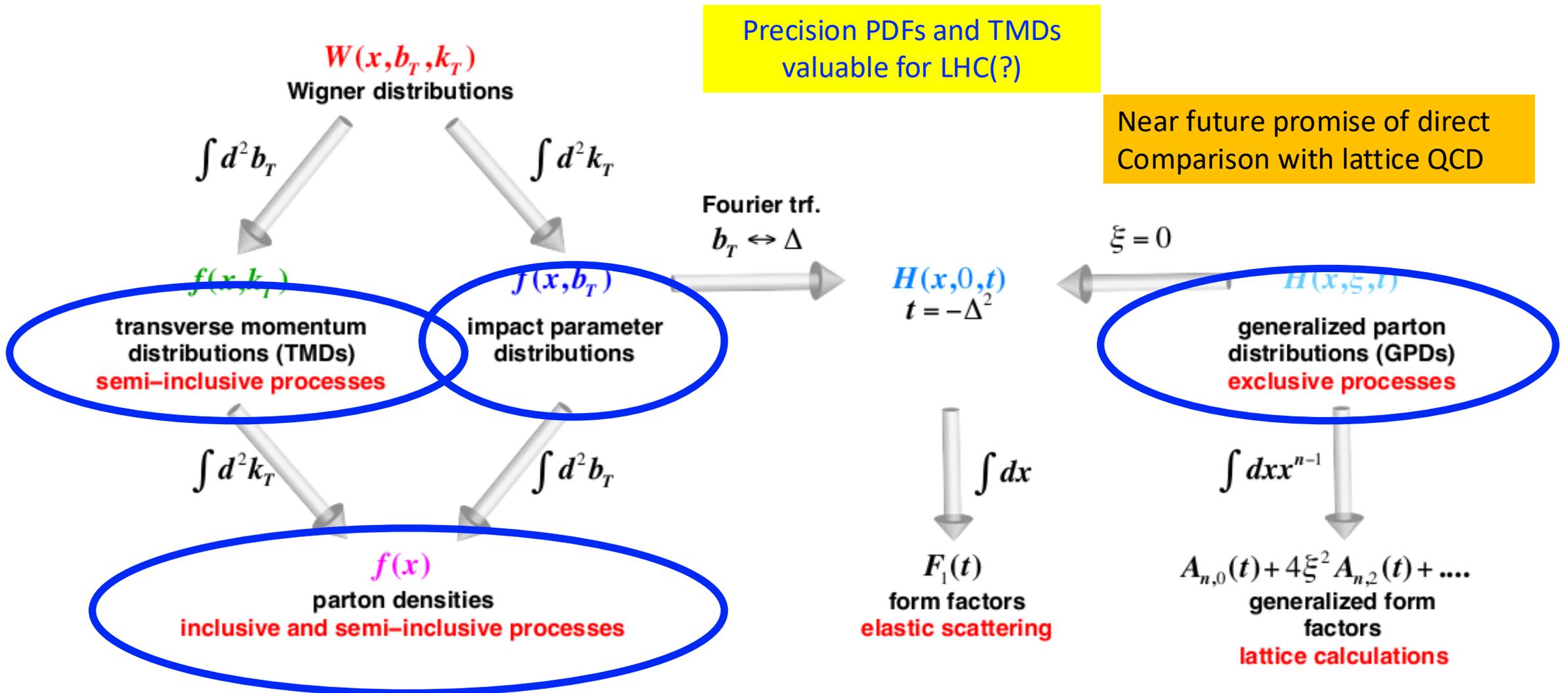
Spin structure function g_1 needs to be measured over a large range in x - Q^2

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

SIDIS: strange and charm quark spin contributions



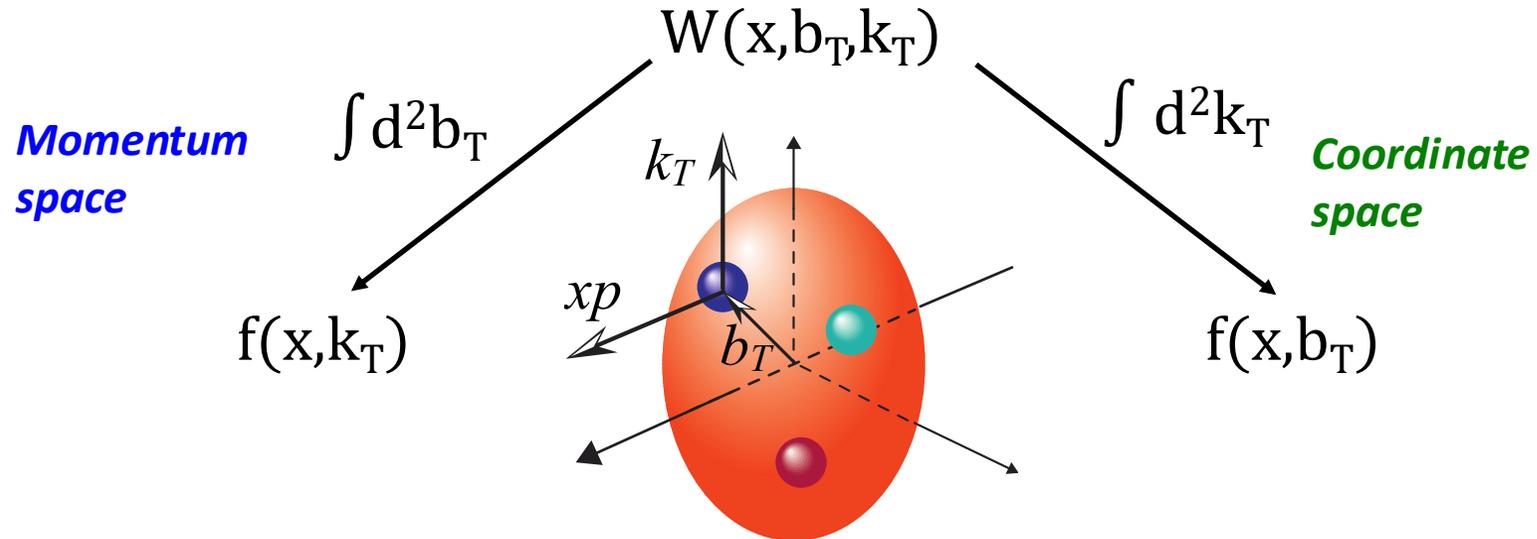
2+1D Imaging of hadrons: beyond precision PDFs



3-Dimensional Imaging Quarks and Gluons

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

offer unprecedented insight into confinement and chiral symmetry breaking.



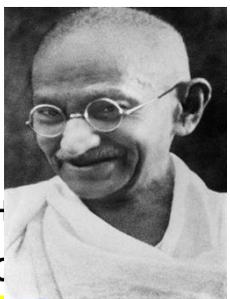
Spin-dependent 3D **momentum space** images from semi-inclusive scattering
 → **TMDs**

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

Position and momentum → Orbital motion of quarks and gluons

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

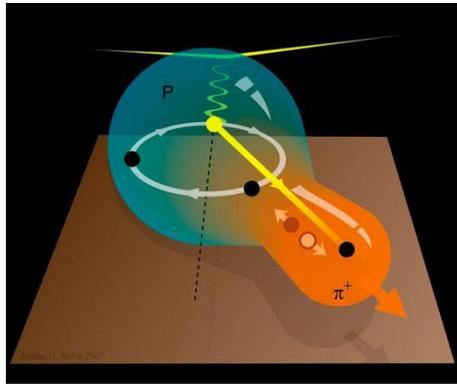
2+1 D partonic image of the proton with the EIC



Spin-dependent 3D **momentum space** images from semi-inclusive scattering (SIDS)

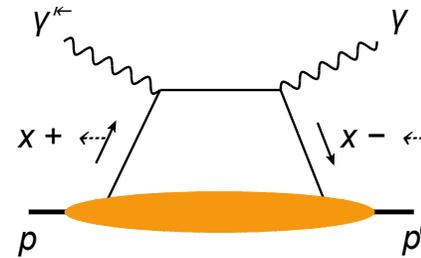
Spin-dependent 2D **coordinate space** (transverse) - (longitudinal momentum) images from exclusive scattering

Transverse Momentum Distributions



Transverse Position Distributions

Quarks Motion

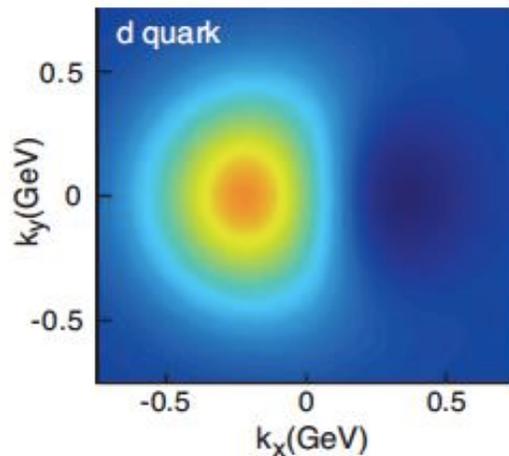
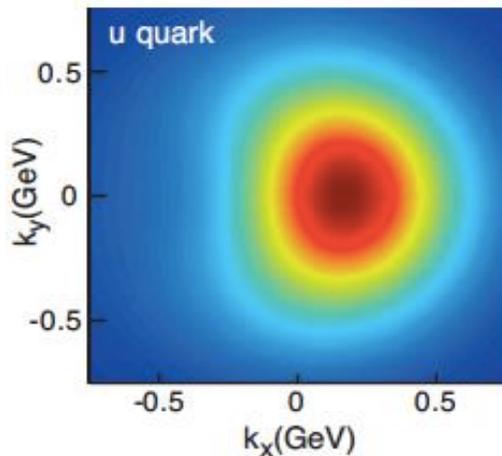


Glueons: Only @ Collider

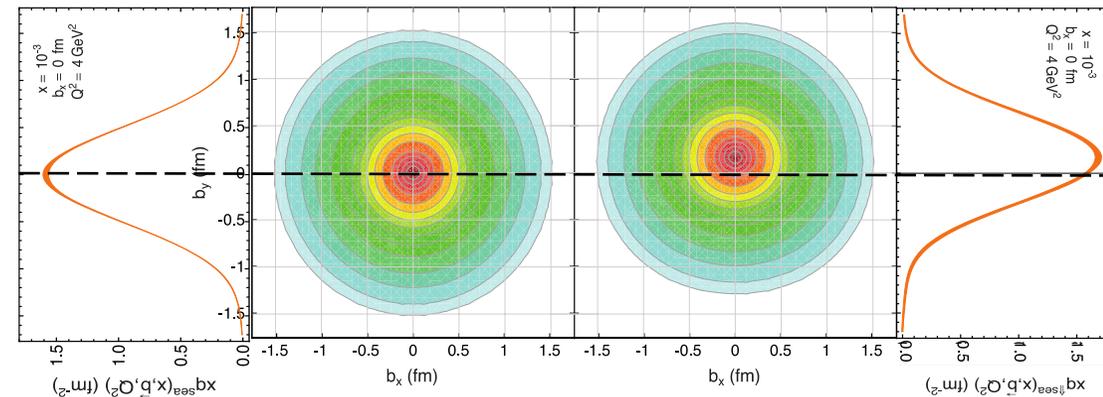
Deeply Virtual Compton Scattering
Measure all three final states
 $e + p \rightarrow e' + p' + \gamma$

Fourier transform of momentum transferred = $(p-p')$ \rightarrow Spatial distribution

Possible measurements of K (s) and D (c)



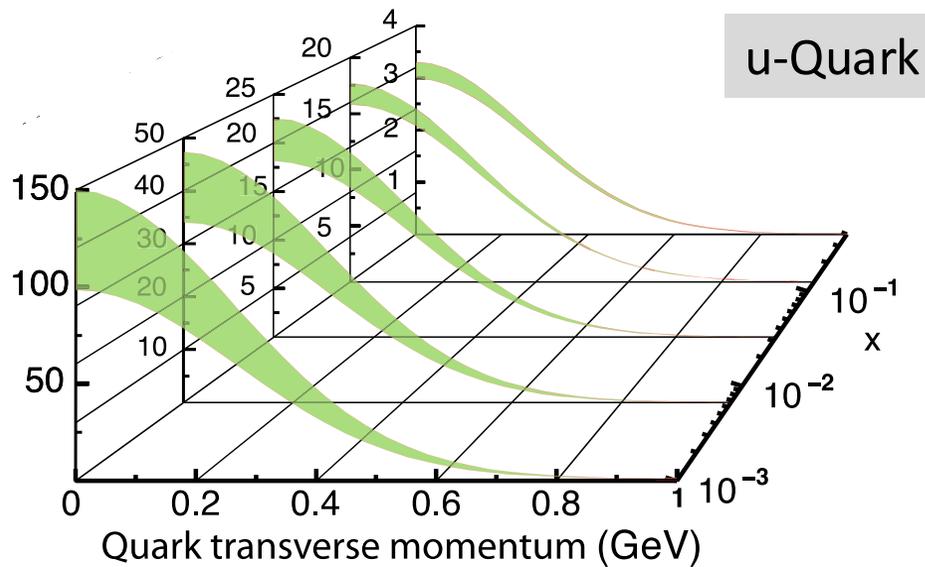
2D position distribution for sea-quarks unpolarized polarized



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

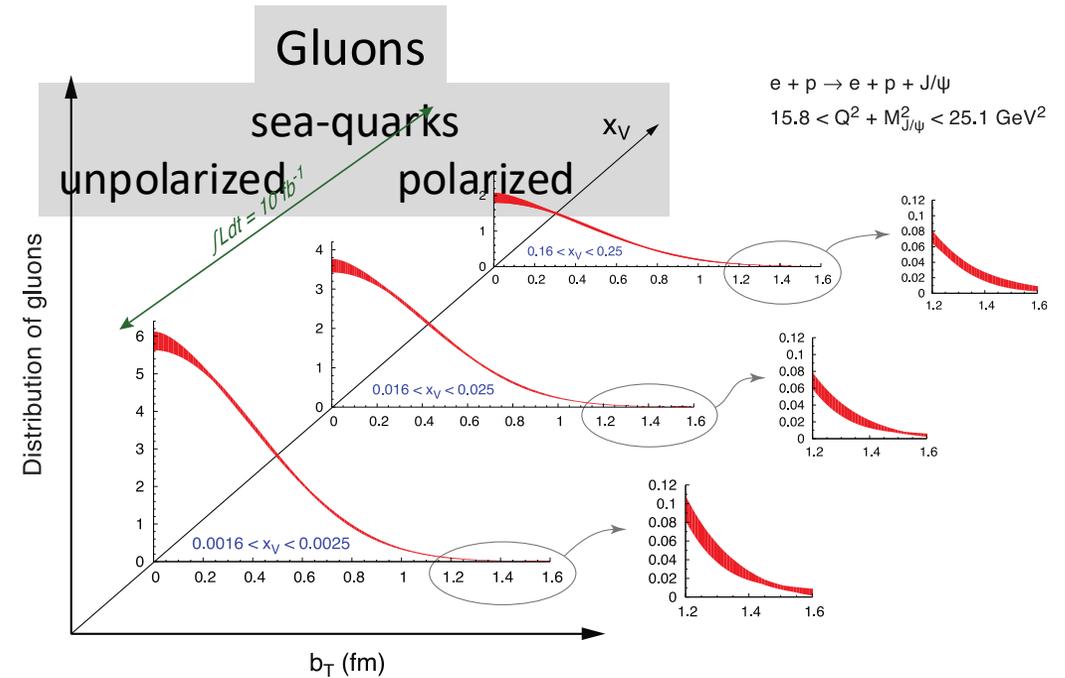
Spin-dependent 3D **momentum space** images from semi-inclusive scattering

Transverse **Momentum** Distributions



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

Transverse **Position** Distributions



“Color form factor” of proton...

Study of internal structure of a watermelon:



A-A (RHIC)
1) Violent collision of melons

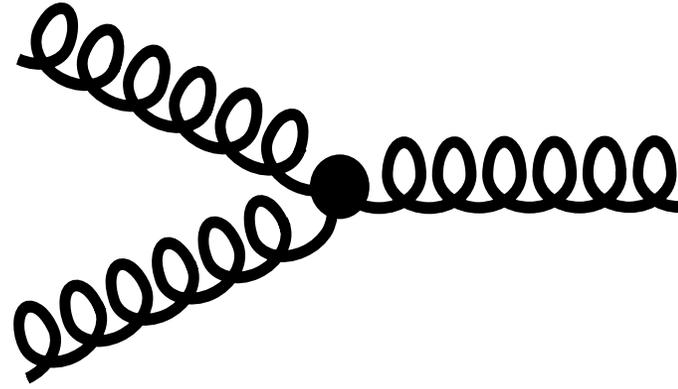


2) Cutting the watermelon with a knife
Violent DIS e-A (EIC)



3) MRI of a watermelon
Non-Violent e-A (EIC)





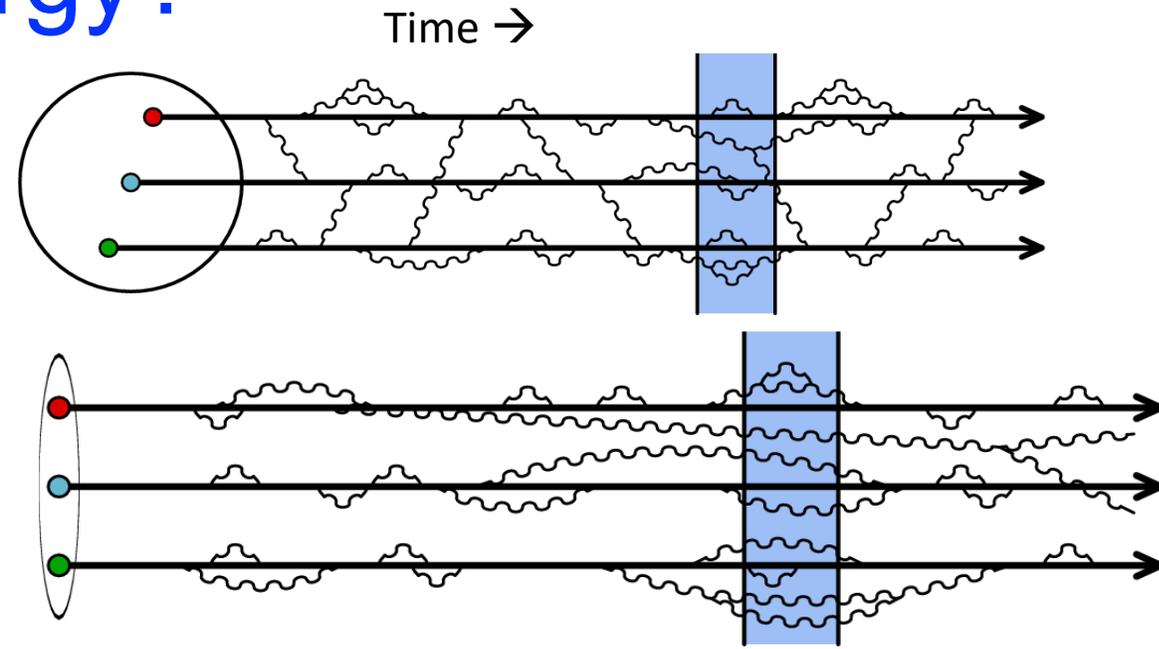
Consequence of gluon self interactions → non-linear GDLAP evolution... ?

Particularly at high energy → low-x

How does a Proton look at low and very high energy?

Low energy: High x
Regime of fixed target exp.

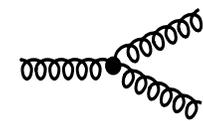
High energy: Low- x
Regime of a Collider



Cartoon of boosted proton

At high energy:

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



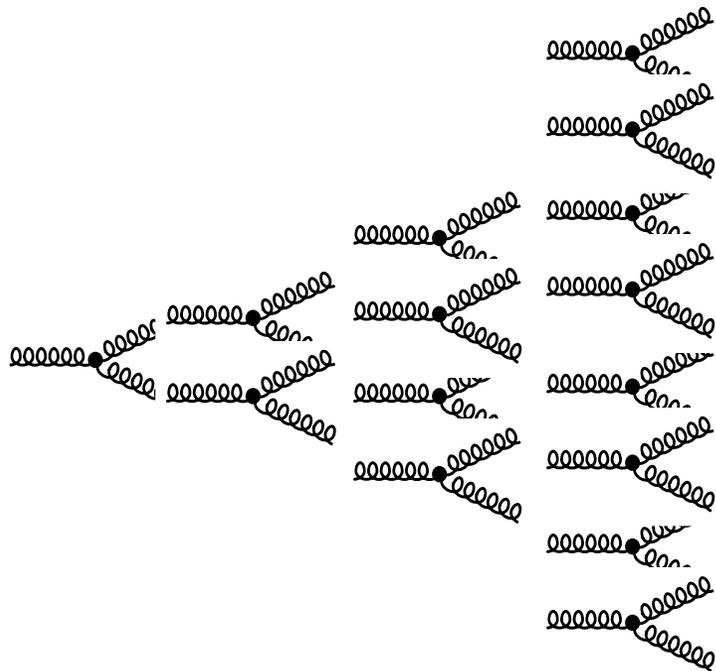
Gluon splitting

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!

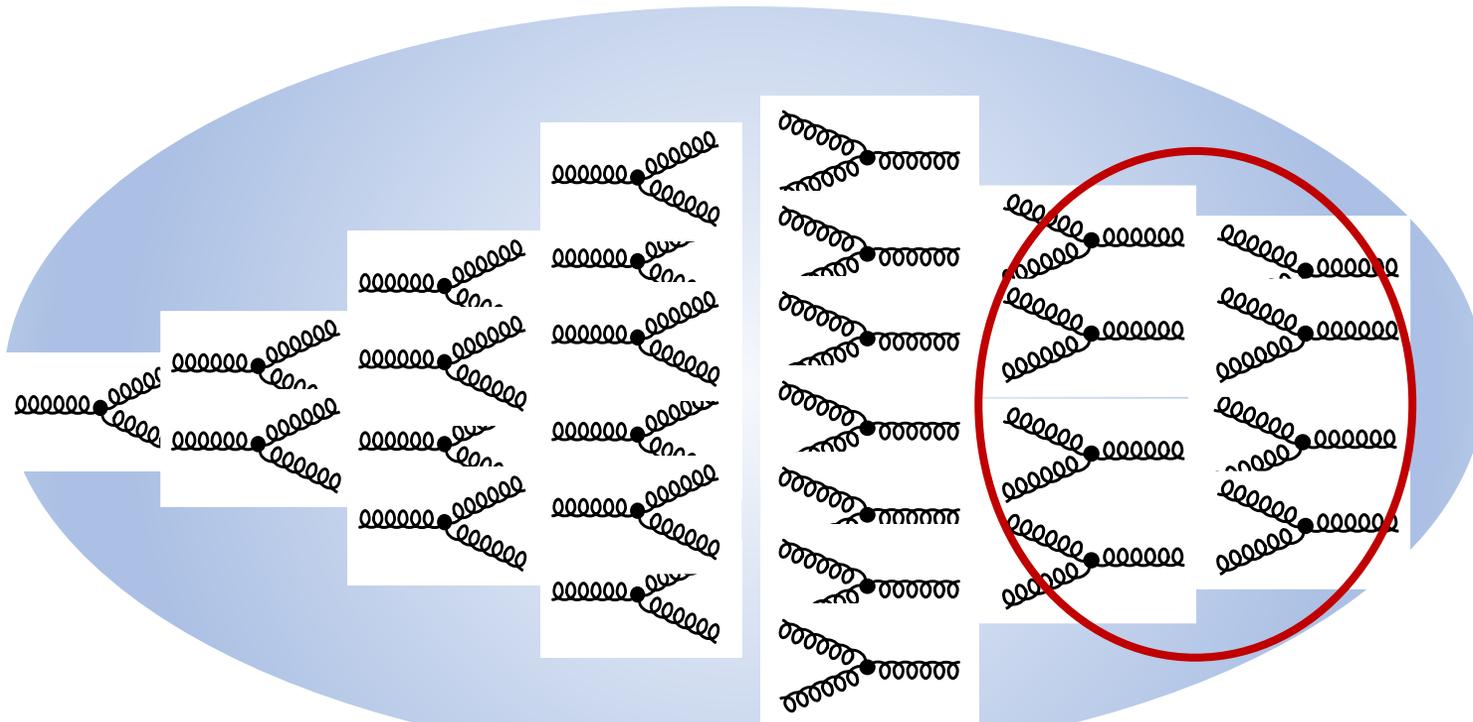


Gluon and the consequences of its interesting properties:

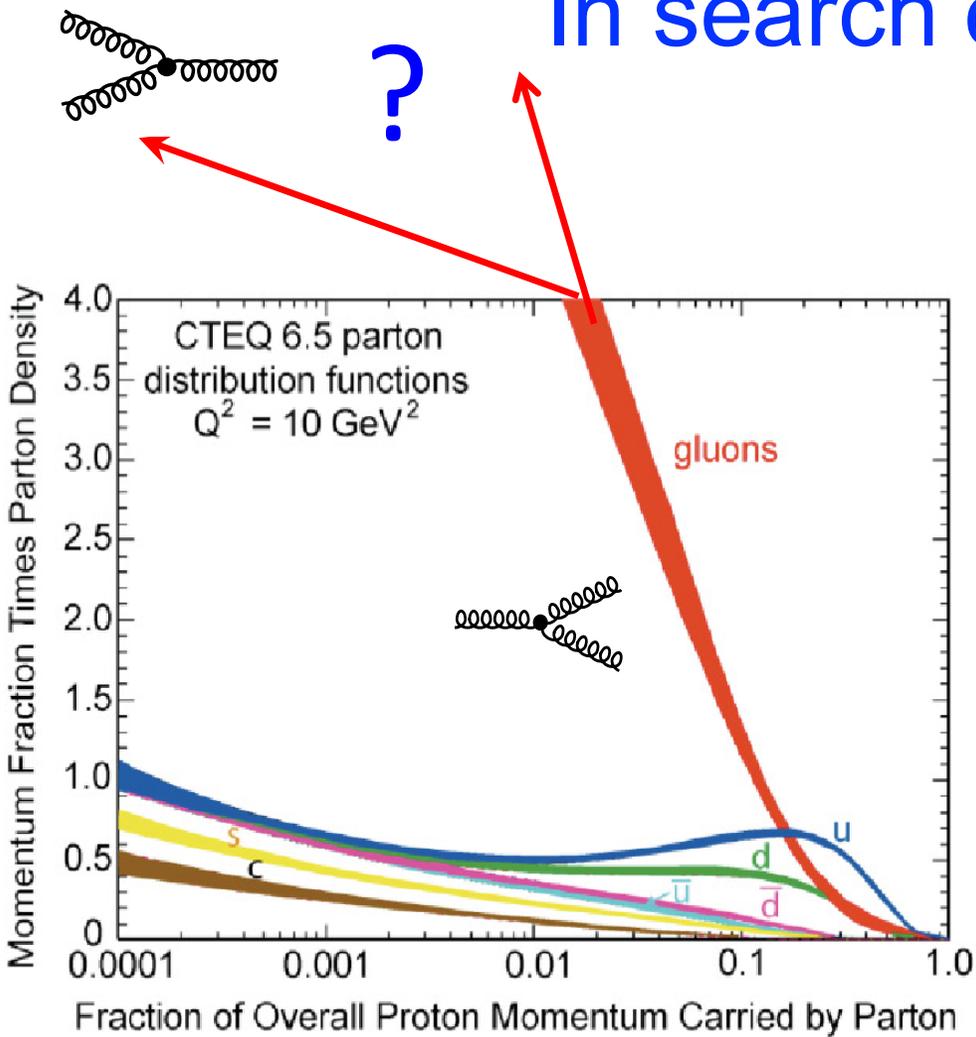
Gluons carry color charge → Can interact with other gluons!

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Nobel Prize, 2004*



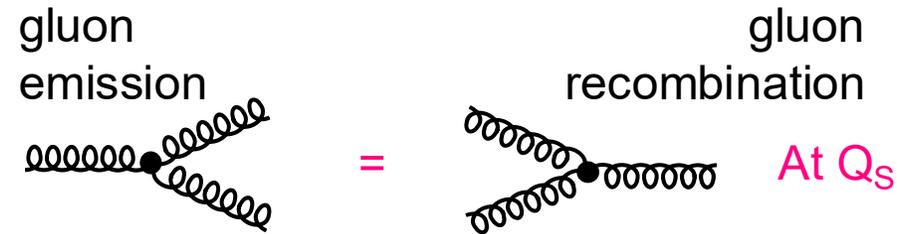
In search of a new state of matter!



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.



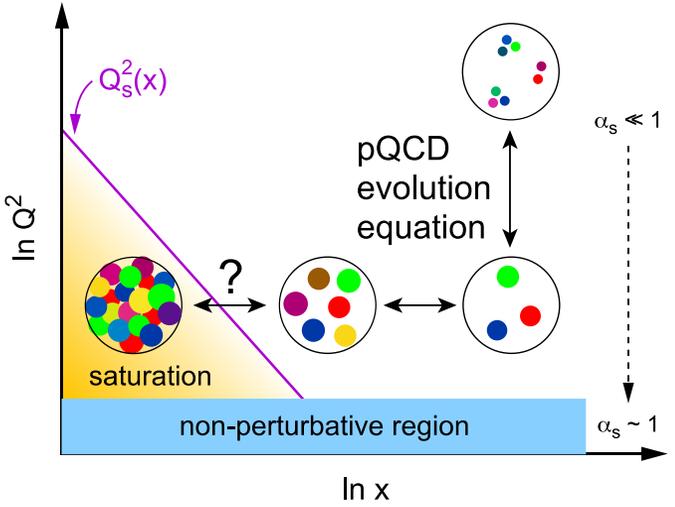
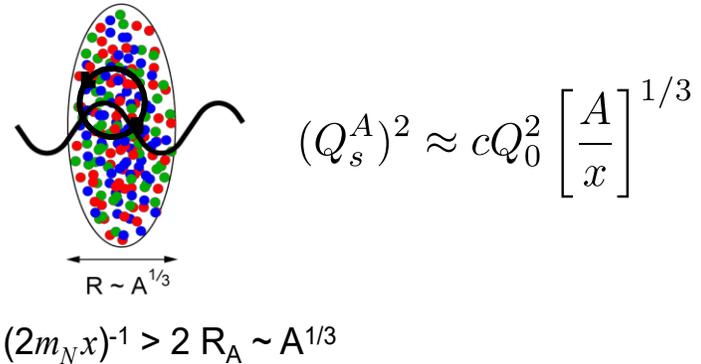
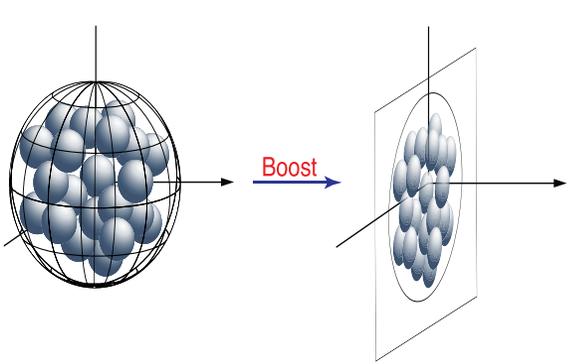
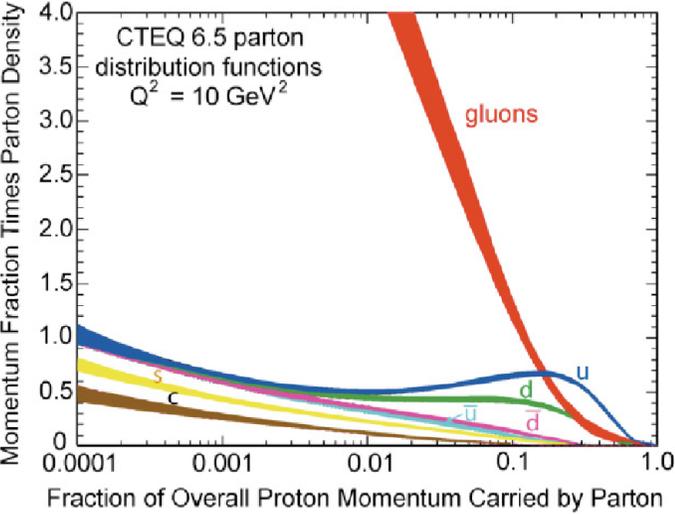
Observation of gluon recombination effects

→ Is there such new state of matter?

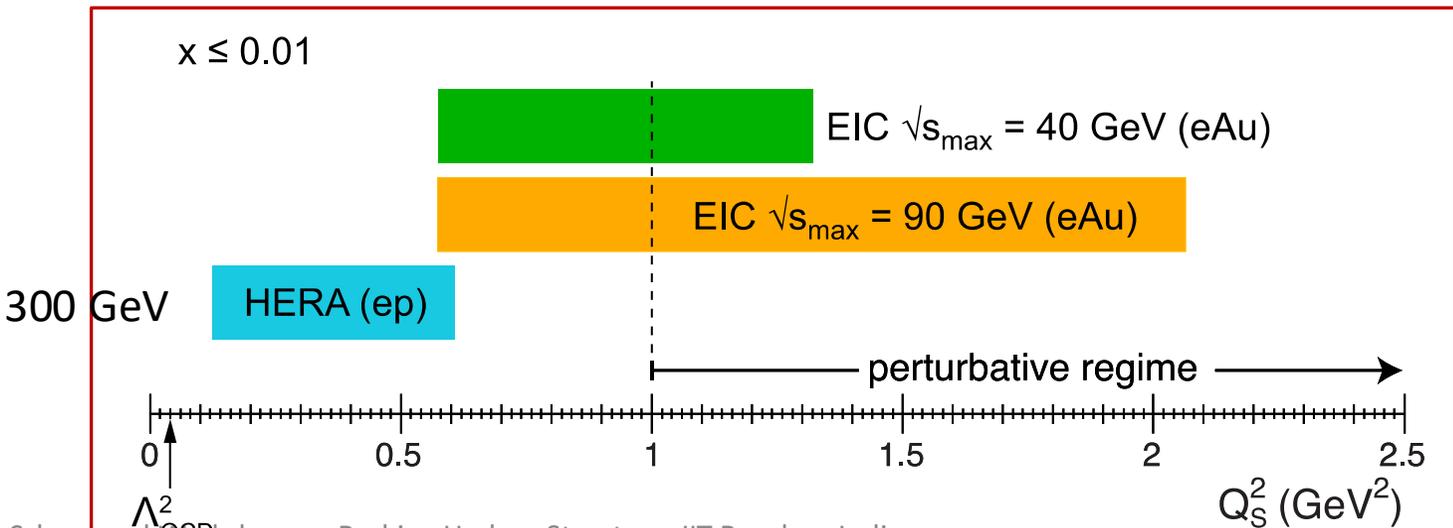
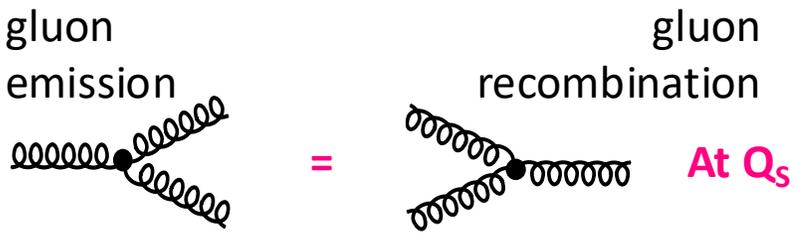
→ “Color Glass Condensate”

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

Low x physics with nuclei



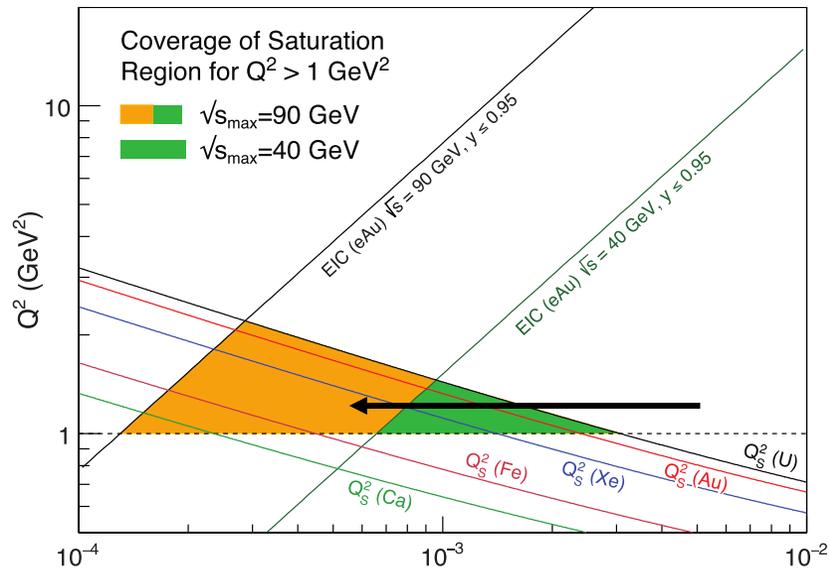
Accessible range of saturation scale Q_s^2 at the EIC with e+A collisions.
 arXiv:1708.01527



Can EIC discover a new state of matter?

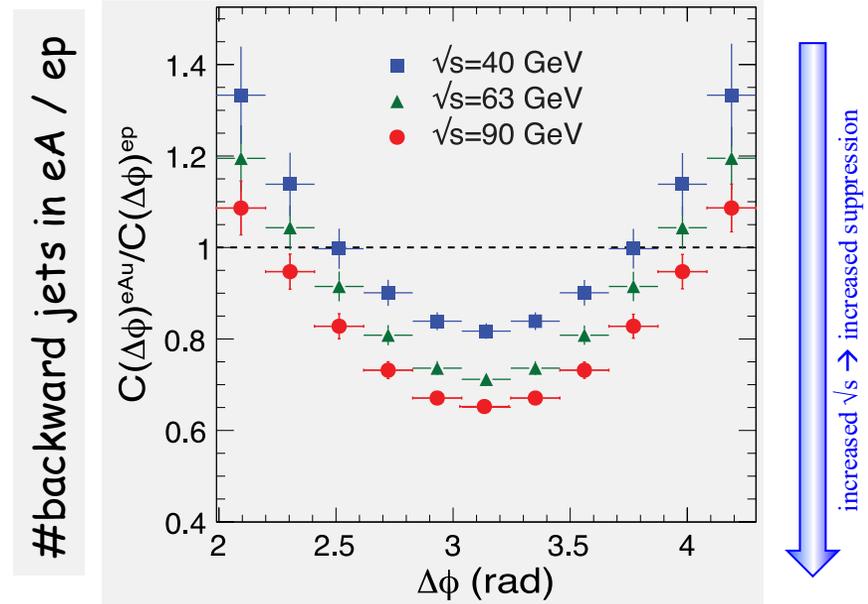
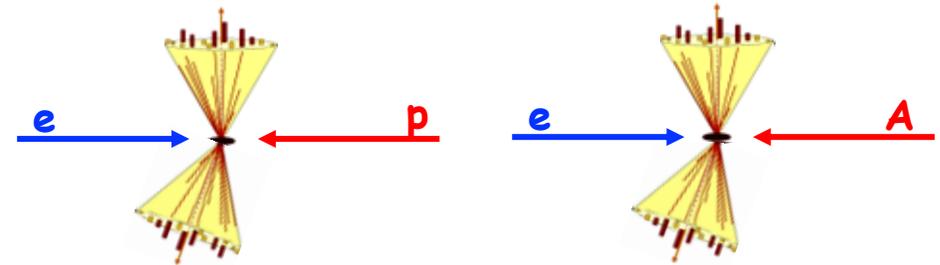
EIC provides an absolutely unique opportunity to have very high gluon densities
 → electron – lead collisions
 combined with an unambiguous observable

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

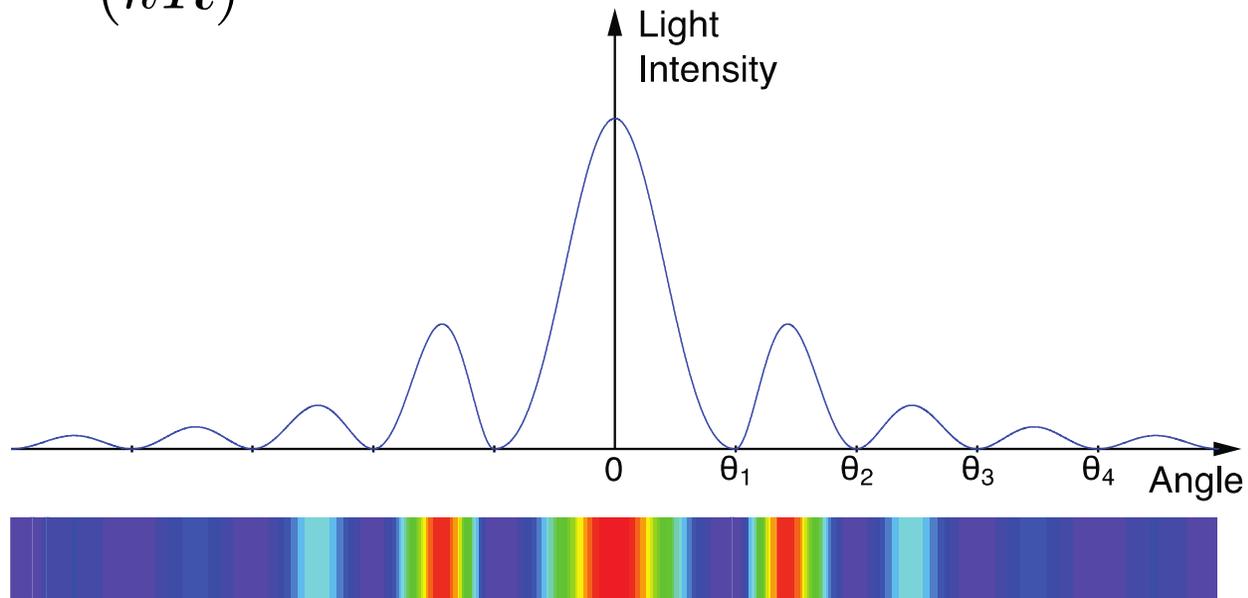


Diffraction in Optics and high energy scattering

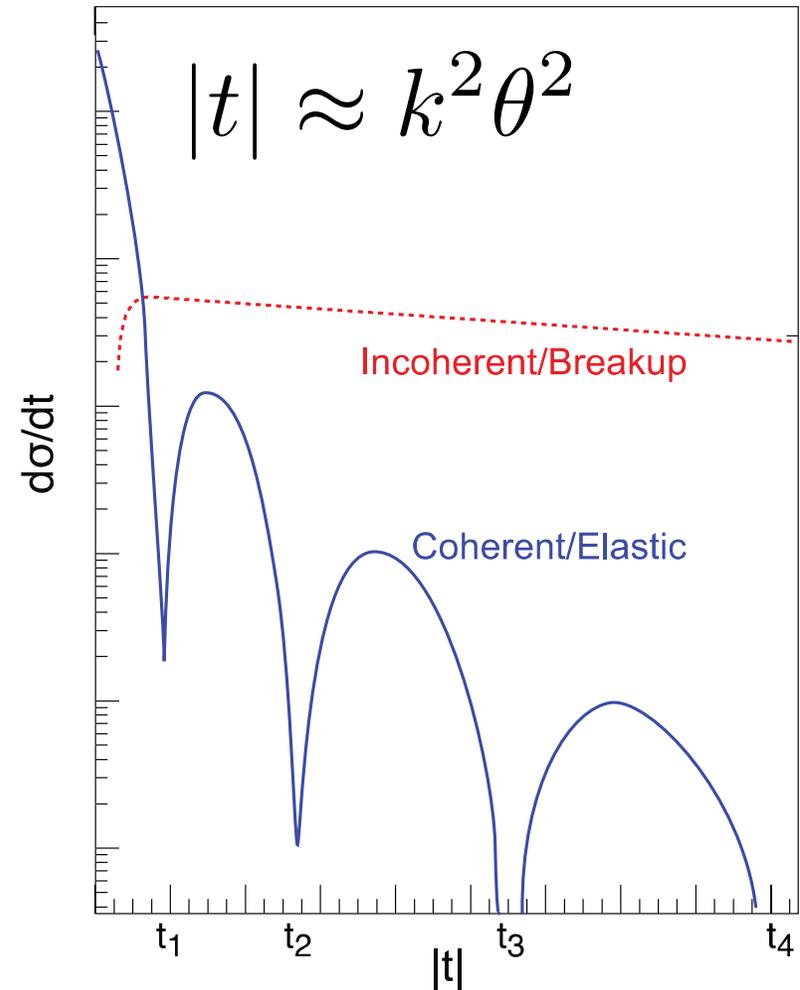
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:

$k \rightarrow$ wave number

$$\theta_i \sim \frac{1}{(kR)}$$



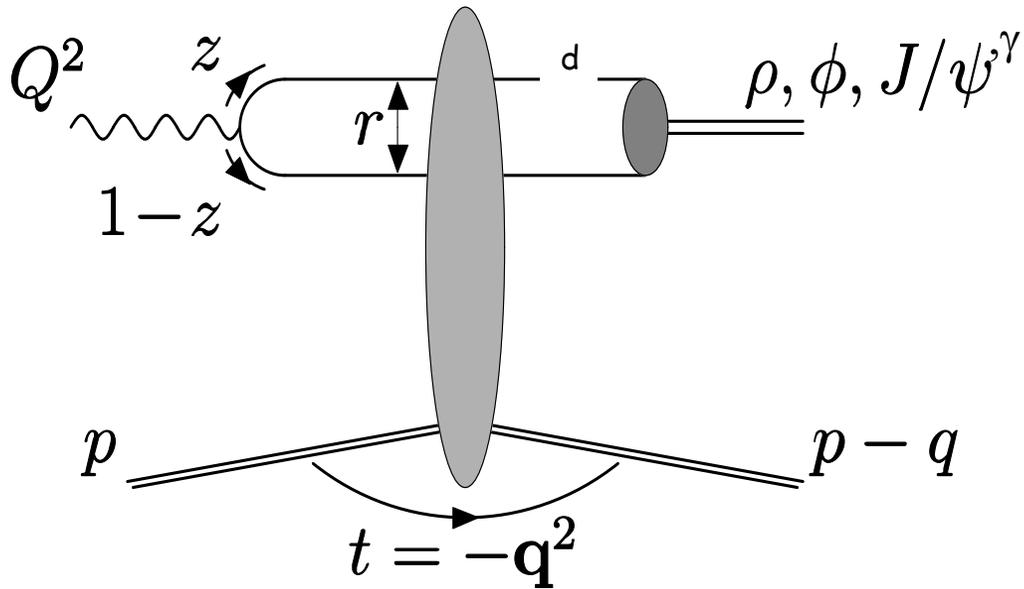
Calculation of e-A diffraction



Transverse imaging of the gluons nuclei

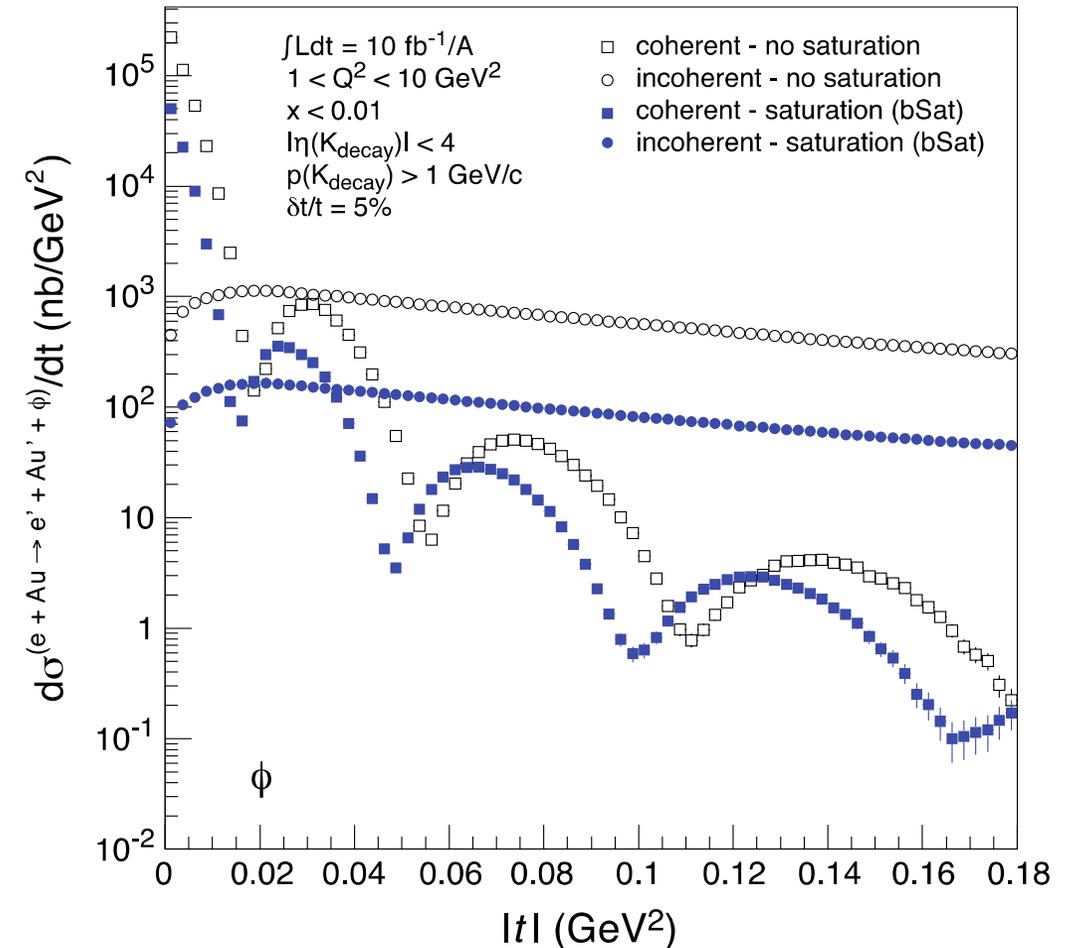
Diffraction vector meson production in **e-Au**

Diff. MC: "Sartre"

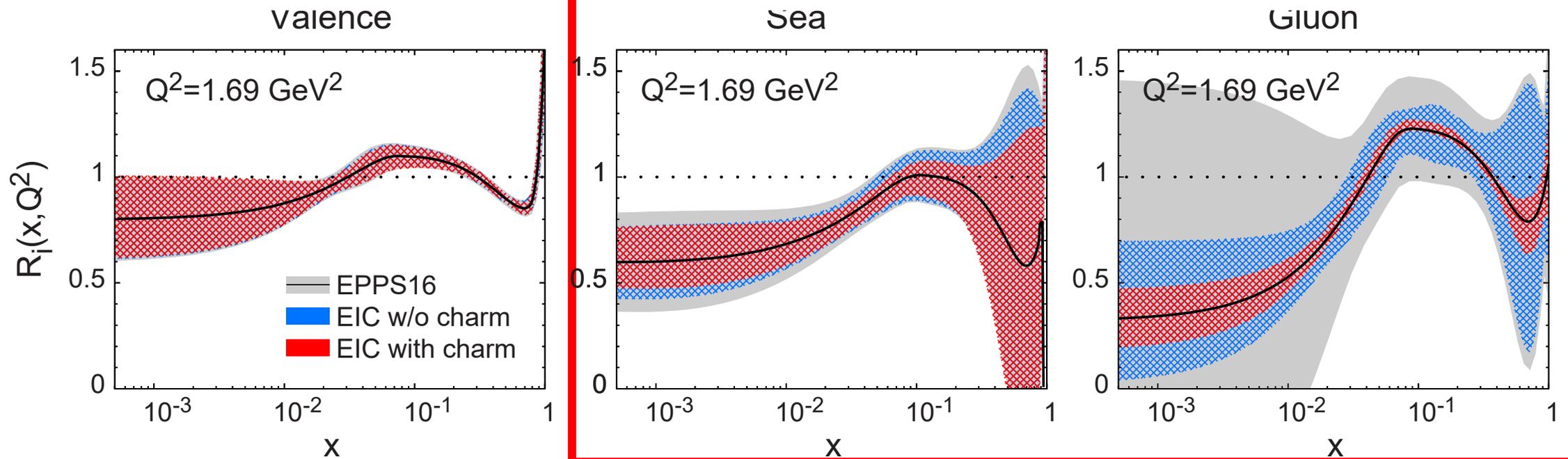


→ Does low x dynamics (Saturation) modify the transverse gluon distribution?

Experimental challenges being studied.



EIC: impact on the knowledge of 1D Nuclear PDFs



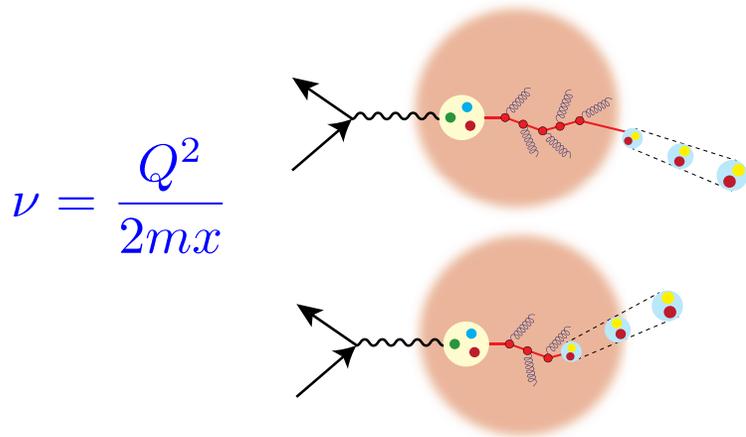
Ratio of Parton Distribution Functions of Pb over Proton:

- ❖ Without EIC, large uncertainties in **nuclear sea quarks and gluons** → With EIC **significantly reduced uncertainties**
- ❖ Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- ❖ **Does the nucleus behave like a proton at low- x ? → such color correlations relevant to the understanding of astronomical objects**

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

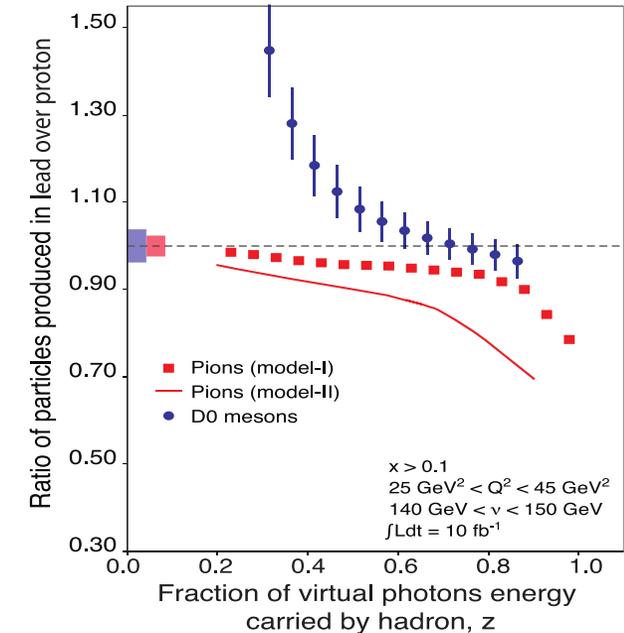
Unprecedented $\{$, the virtual photon energy range
@ EIC : precision & control



Control of $\{$ by selecting kinematics;
Also under control the nuclear size.

Study in **light** quarks
vs.
heavy quarks

Energy loss by light vs. heavy quarks:

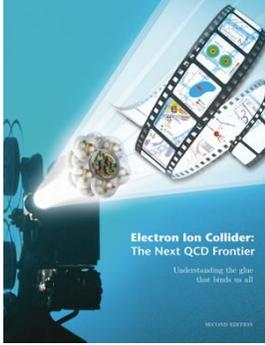


Identify π vs. D^0 (**charm**) mesons in e-A collisions:

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

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



New Studies with proton or neutron target:

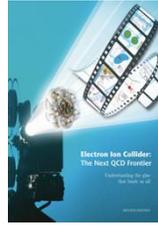
- Impact of precision measurements of unpolarized PDFs at high x/Q^2 , on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all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

Physics with nucleons and nuclear targets:

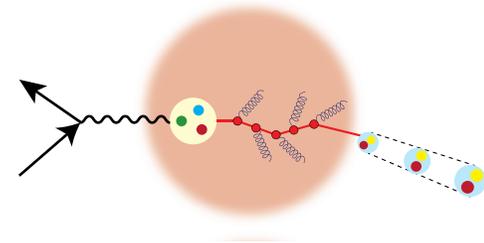
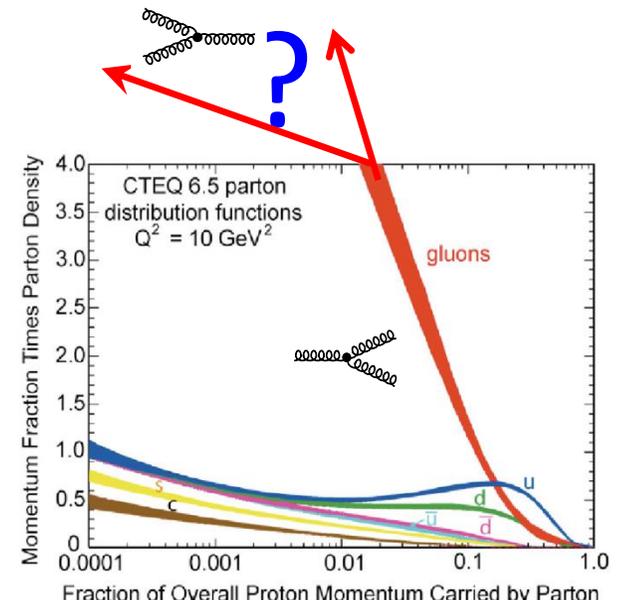
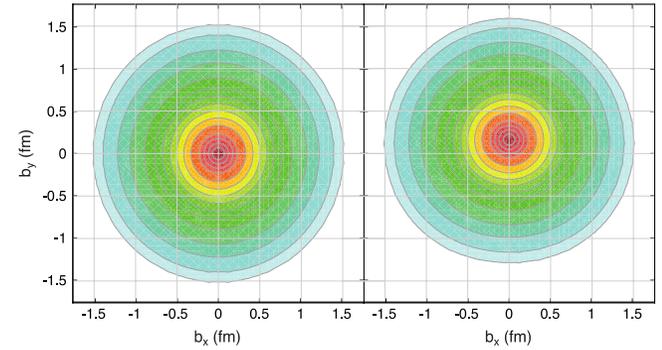
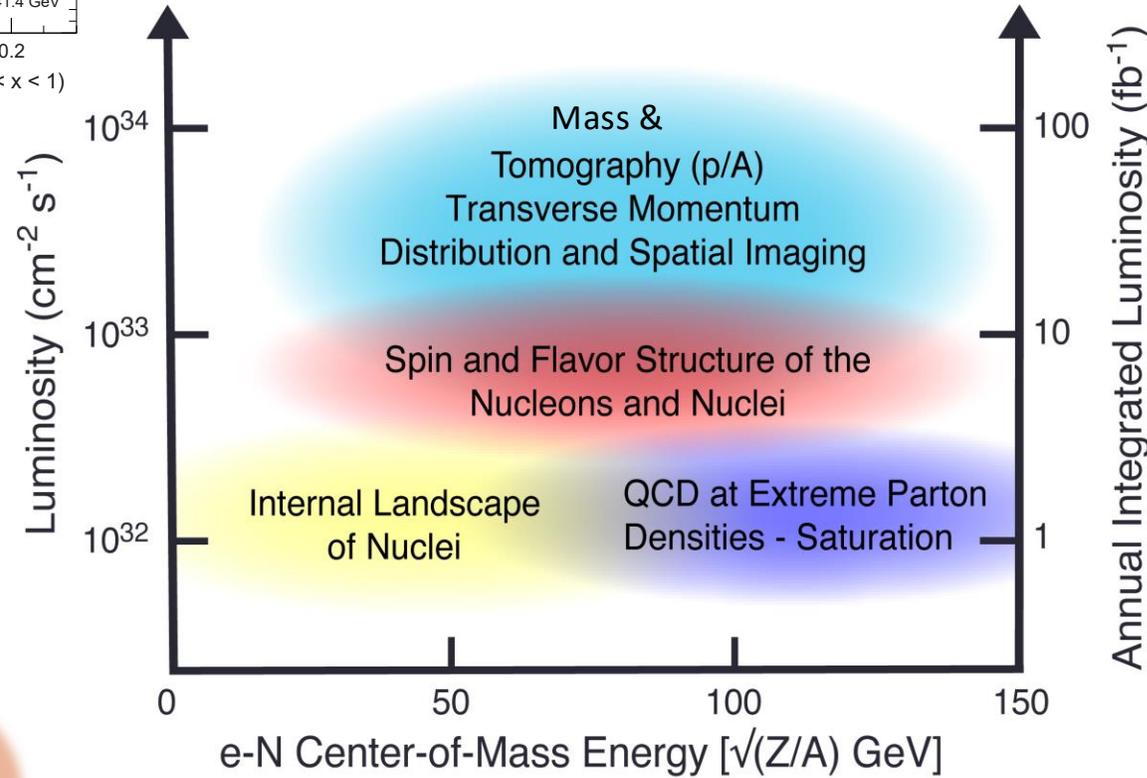
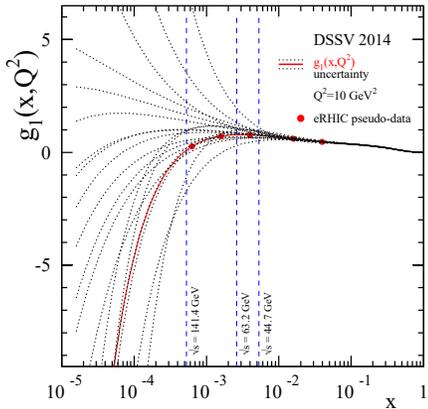
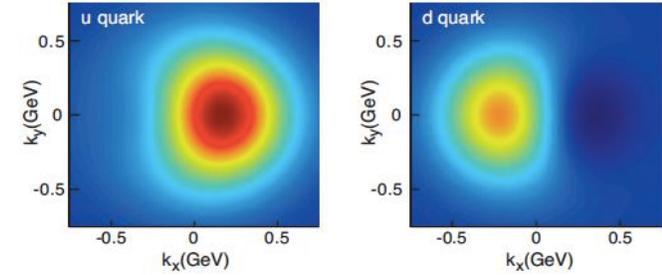
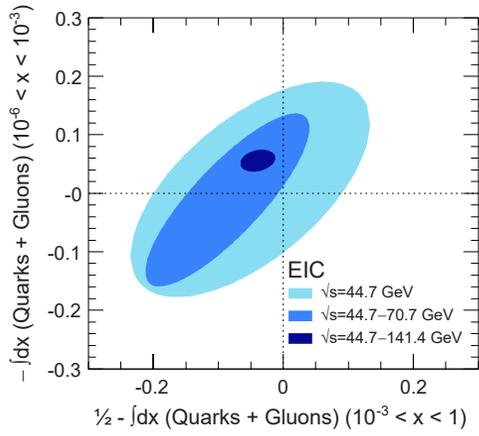
- Quark Exotica: 4,5,6 quark systems...? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
 - Internal structure of jets : novel new observables, energy variability, polarization, beam species
 - Entanglement, entropy, connections to fragmentation, 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: (Krishna Kumar, 2 lectures)

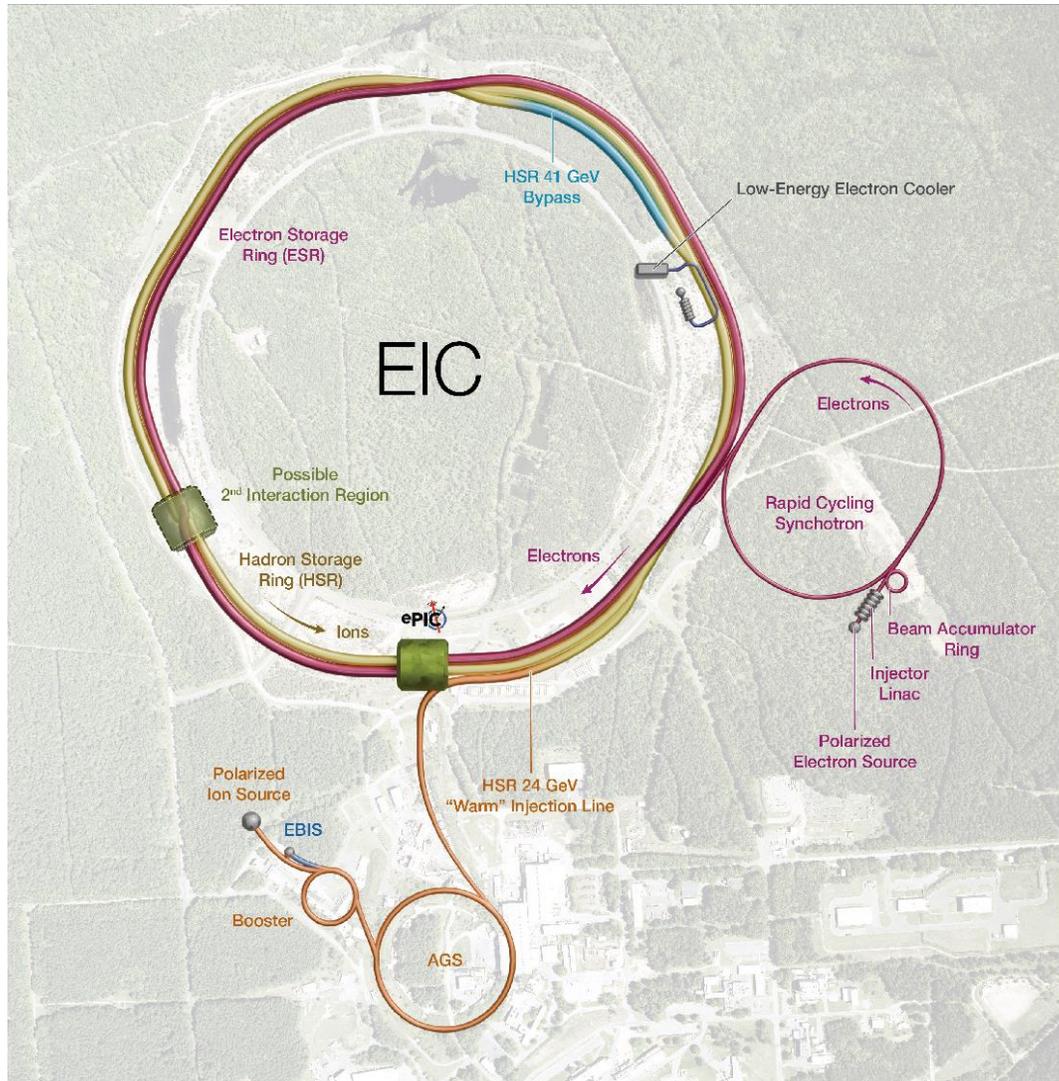
- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation



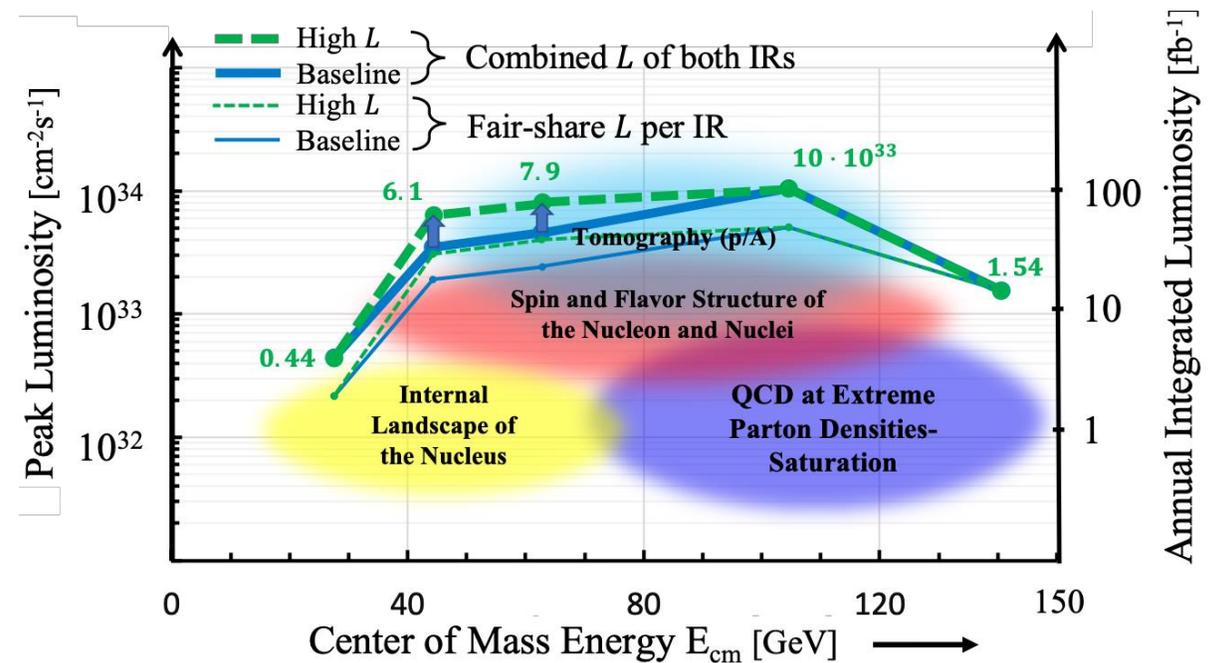
EIC science highlights

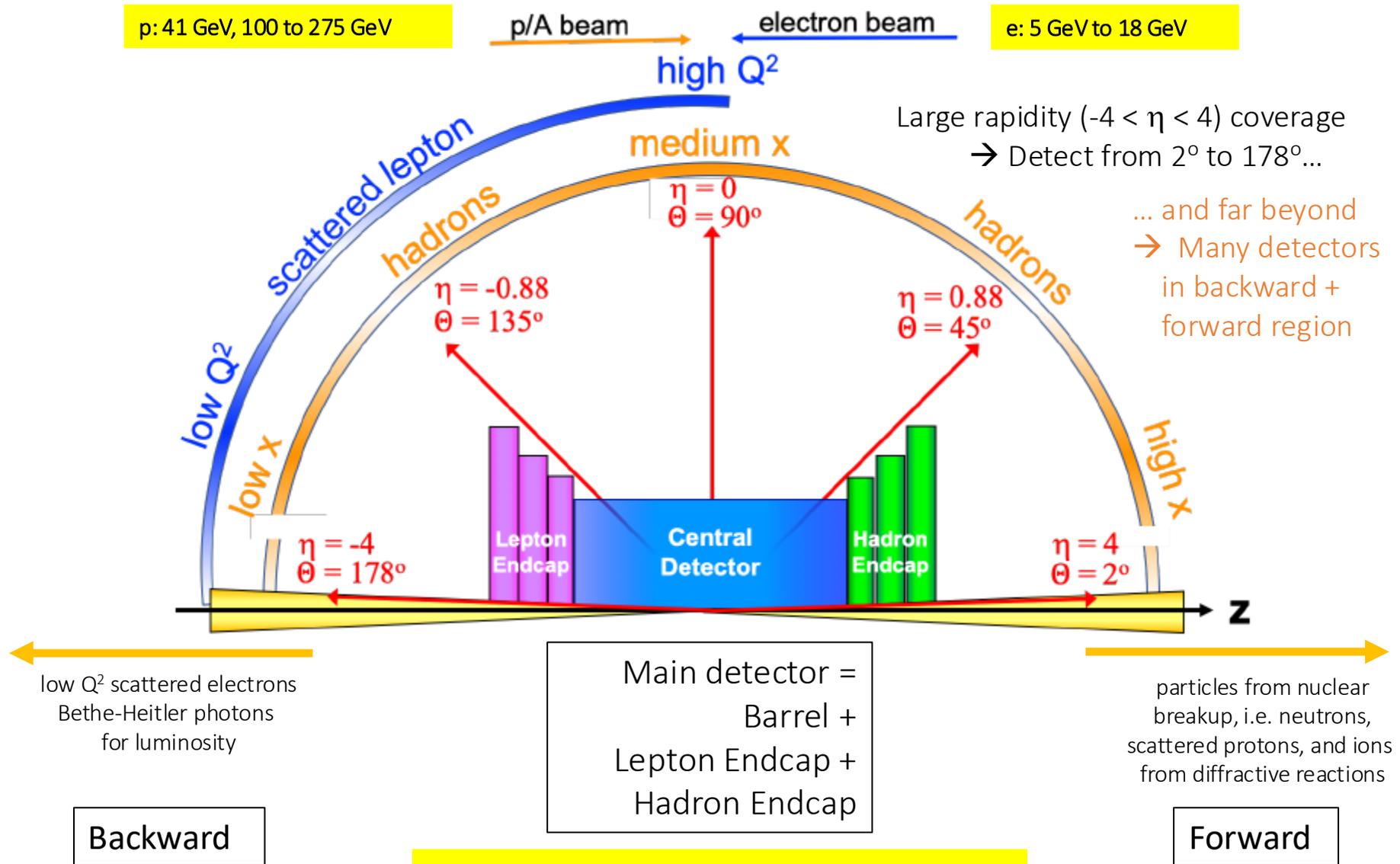


EIC Accelerator Design



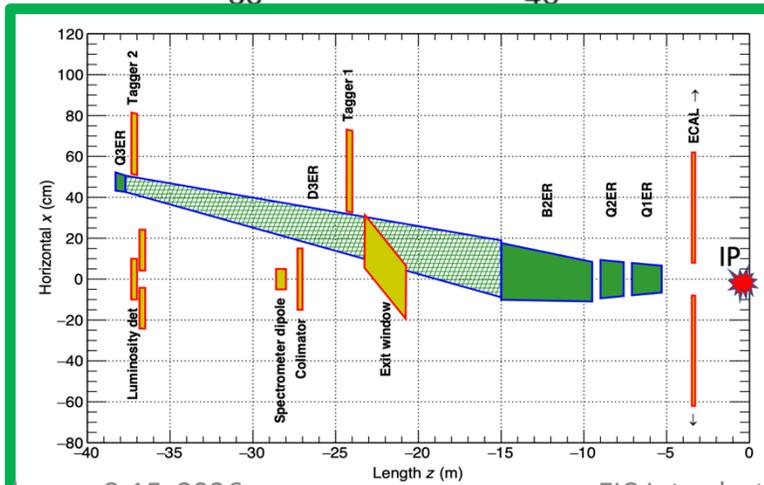
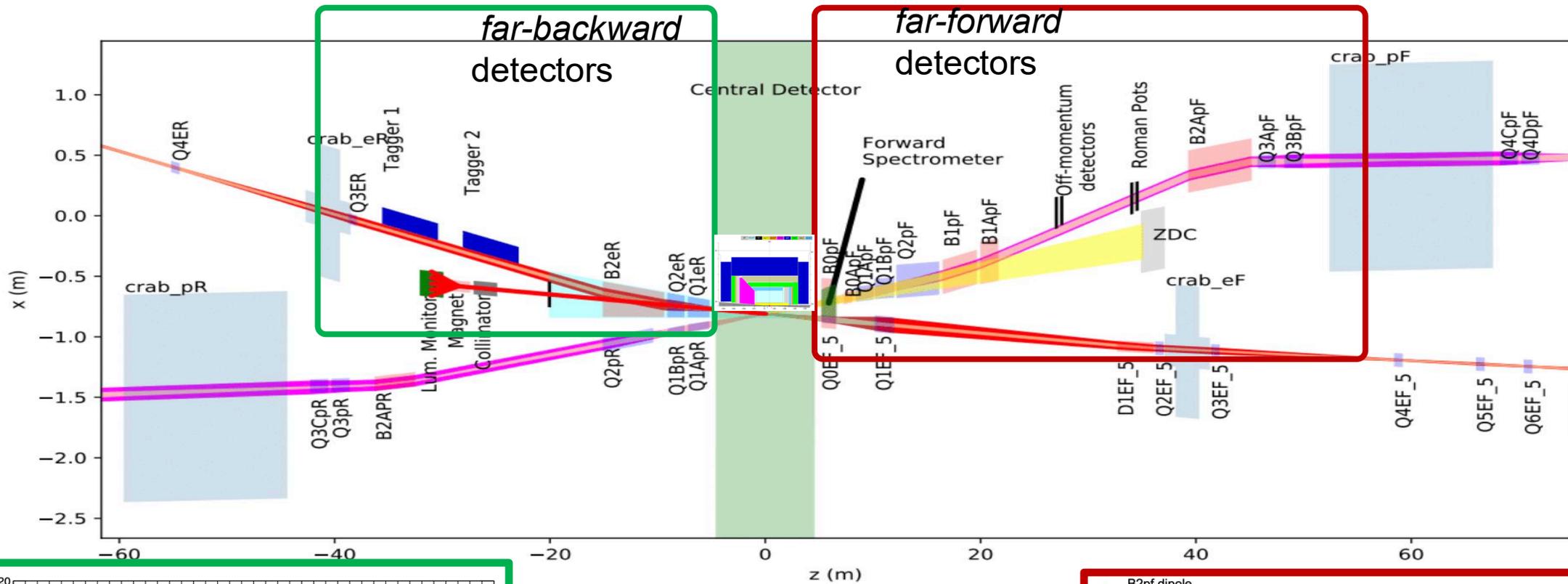
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	$10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1} / 10\text{-}100\text{fb}^{-1} / \text{year}$
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



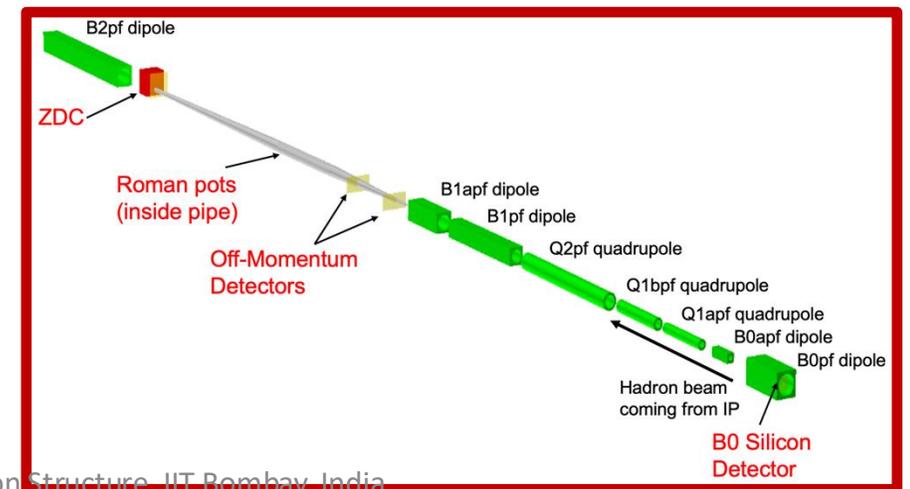


Endcaps critical because of largely asymmetric beam energies (with different beams).
 Similar large impact on IR/accelerator.

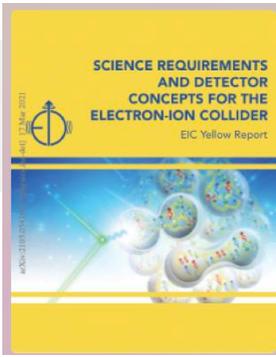
Reference Detector – Backward/Forward Detectors



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



Resulting Experimental Requirements



More and more demanding moving from **inclusive** to **fully exclusive** scattering

- **Inclusive measurements (DIS), required:**

- Precise scattered electron identification (**e.m. calorimetry, e/h PID**) and extremely fine resolution in the measurement of its angle (**tracking**) and energy (**calorimetry**)

- **Semi-inclusive measurements (SI-DIS), also required:**

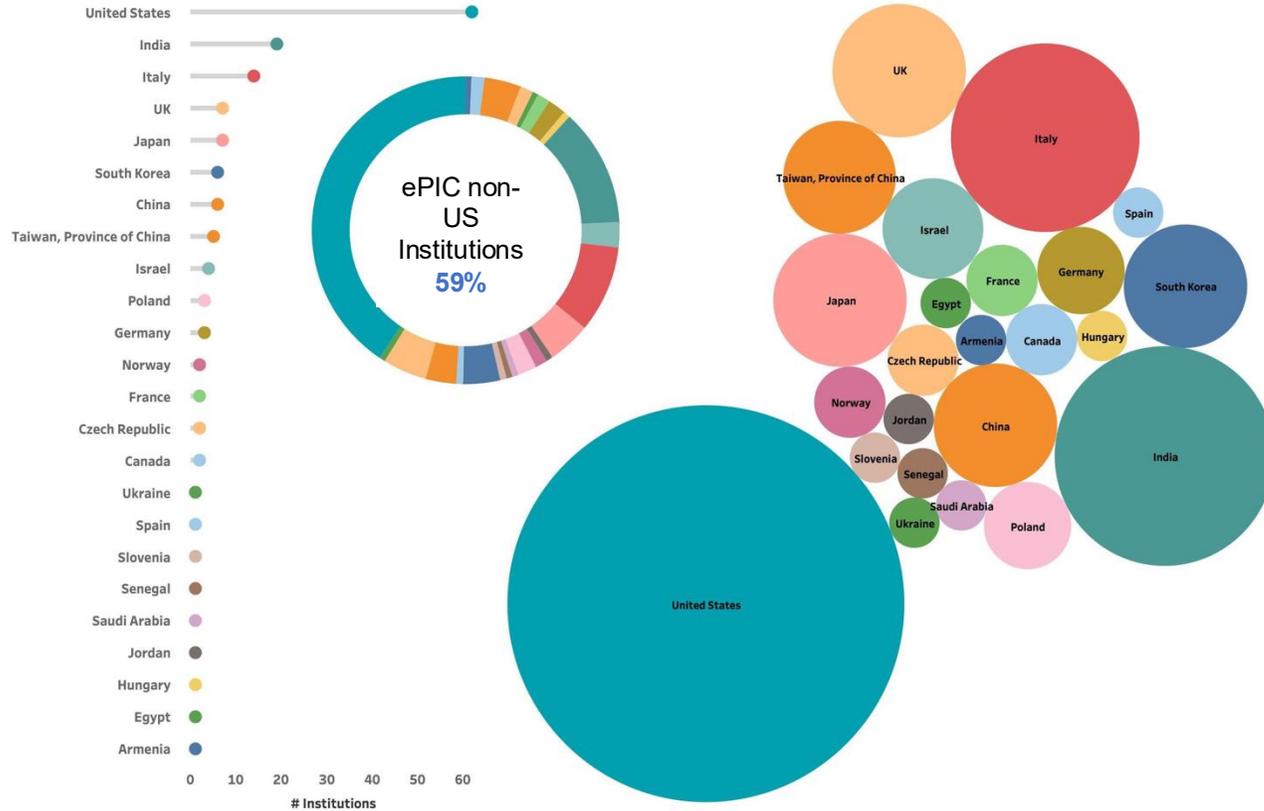
- excellent hadron identification over a wide momentum and rapidity range (**h-PID**)
- full 2π acceptance for tracking (**tracking**) and momentum analysis (**central magnet**)
- excellent vertex resolution (**low-mass vertex detector**)

- **Exclusive measurements also required:**

- Tracker with excellent space-point resolution (**high resolution vertex**) and momentum measurement (**tracking**),
- Jet energy measurements (**h calorimetry**)
- very forward detectors also to detect n and neutral decay products (**Roman pots, large acceptance zero-degree calorimetry**)

- **And luminosity control, e and A polarimeters, r-o electronics, DAQ, data handing**

The ePIC Collaboration



ePIC Spokesperson:
John Lajoie (ORNL)
ePIC Deputy Spokesperson & Interim Technical Director
Silvia Dalla Torre (INFN Trieste)

ePIC formed in 2022

ePIC is now 176 institutions.

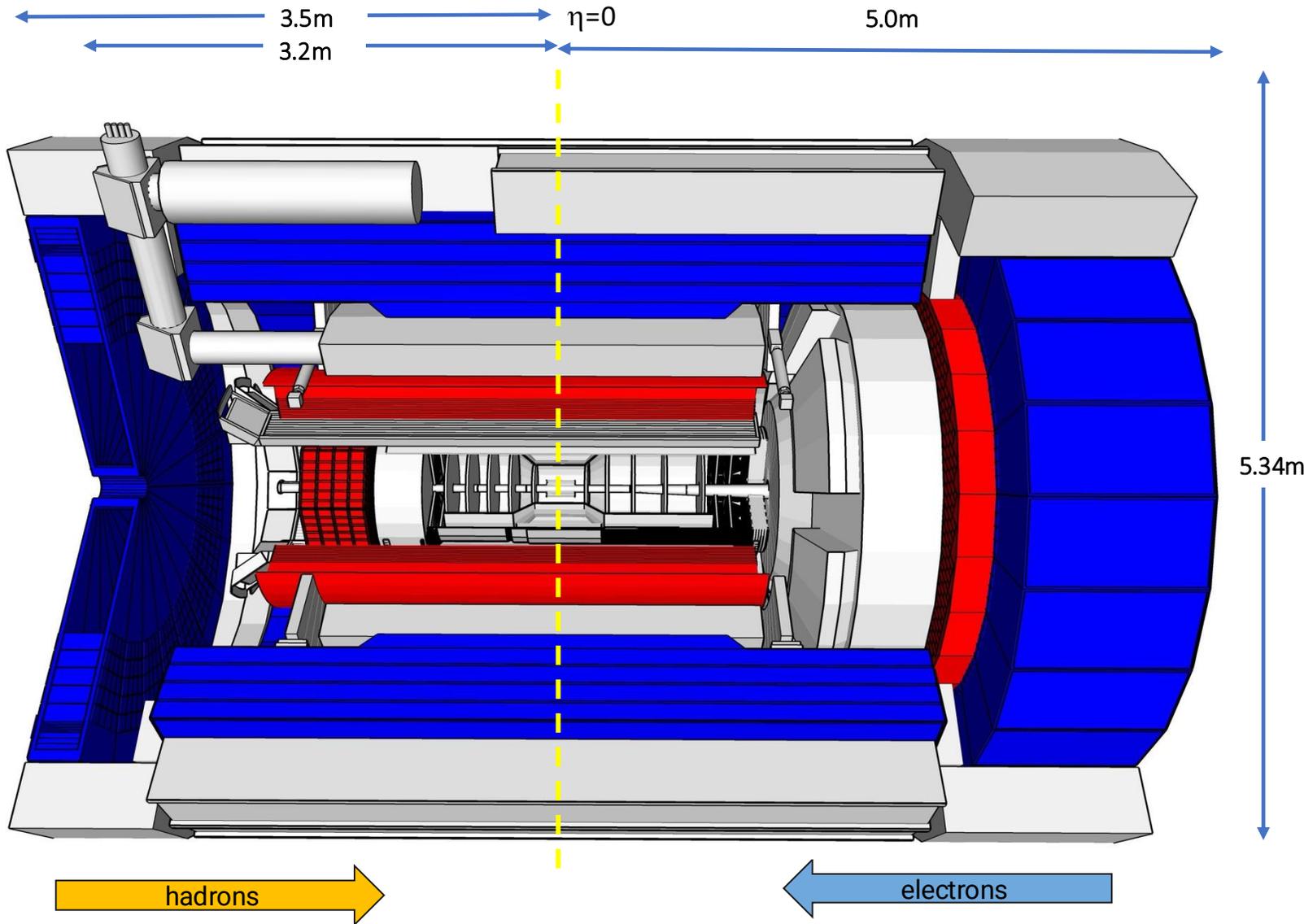
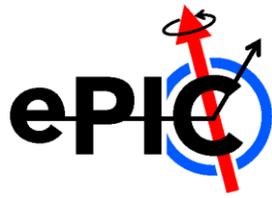
Representing 40+ countries

1000+ participants

A global pursuit for a new experiment at the EIC!



ePIC Detector Design



Tracking:

- New 1.7T solenoid
- Very thin Si MAPS Tracker
- MPGDs (μ RWELL/ μ Megas)

PID:

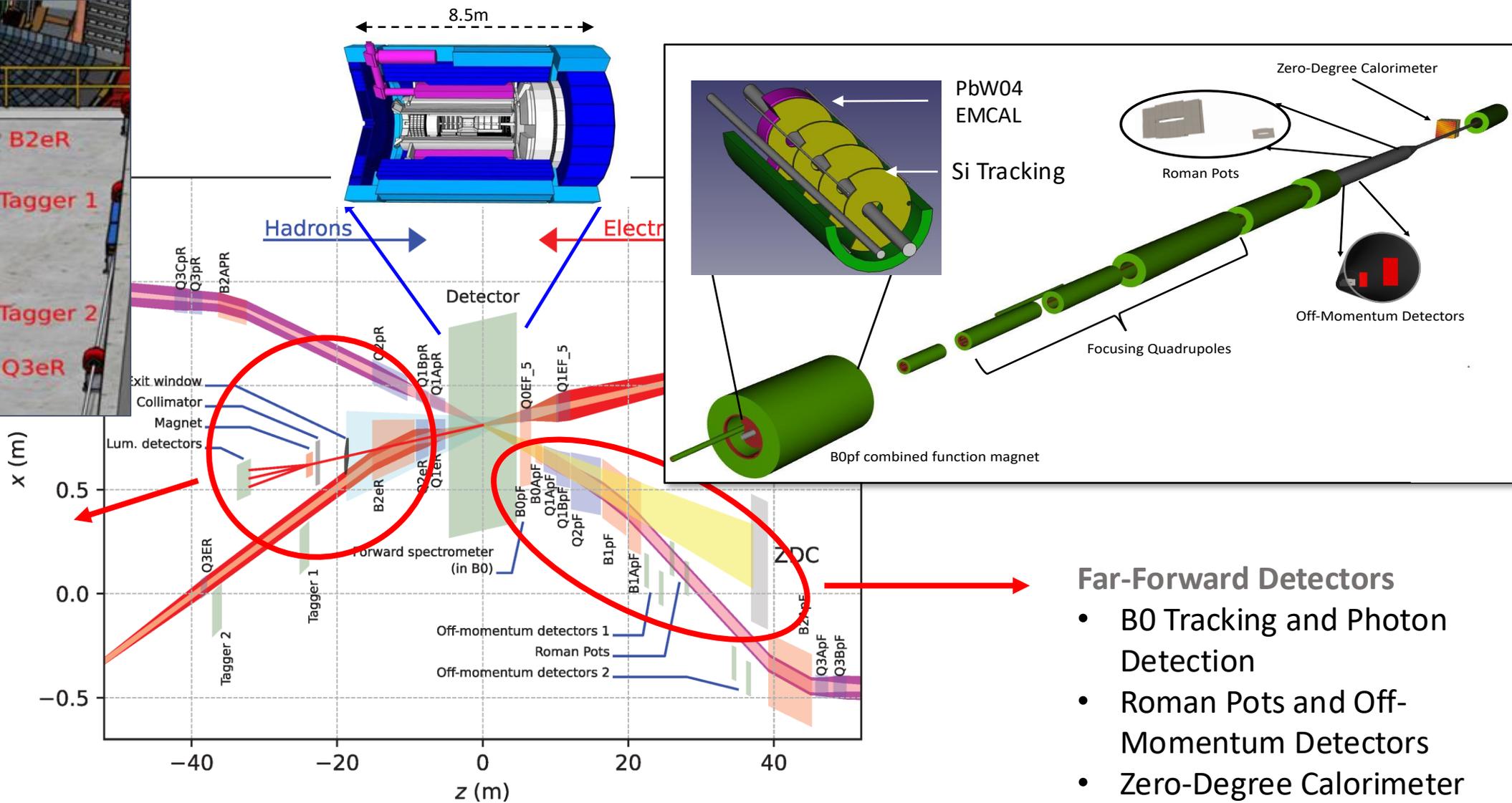
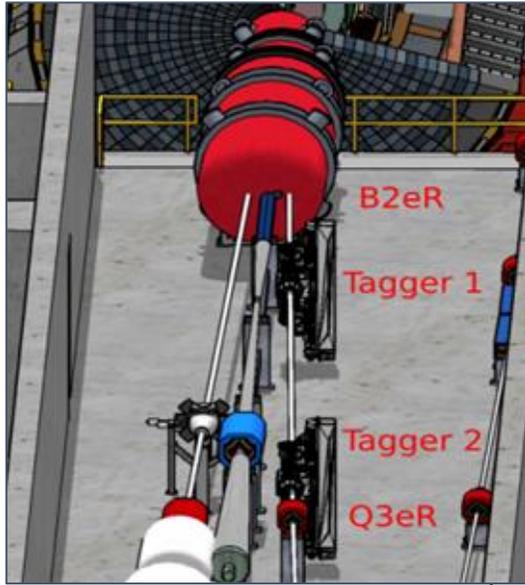
- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~ 30 ps TOF)

Calorimetry:

- **Imaging** Si+PbW Barrel EMCal
- PbWO₄ EMCal in backward cal
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Overlap in technology R&D with LHC-future detectors

Far-Forward and Far-Backward Detectors



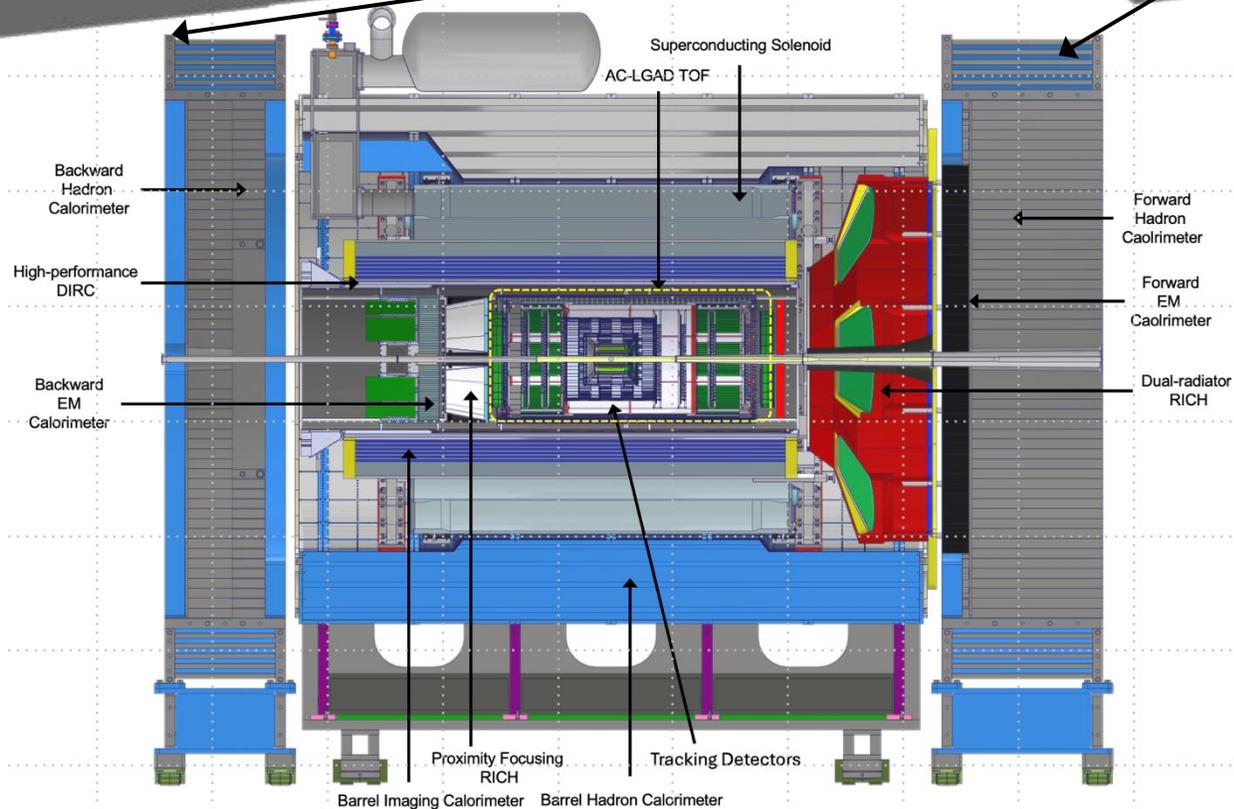
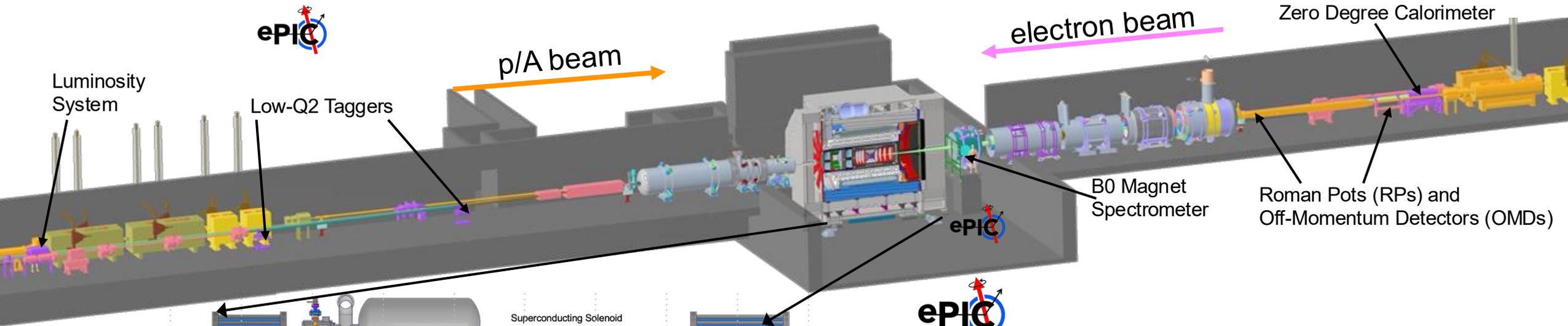
Far-Backward Detectors

- Luminosity monitor
- Low- Q^2 Tagging Detectors

Far-Forward Detectors

- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter

ePIC – The EIC State-of-the-Art General-Purpose Detector



26 subsystems over ± 40 m to measure particle momenta, energy and particle type

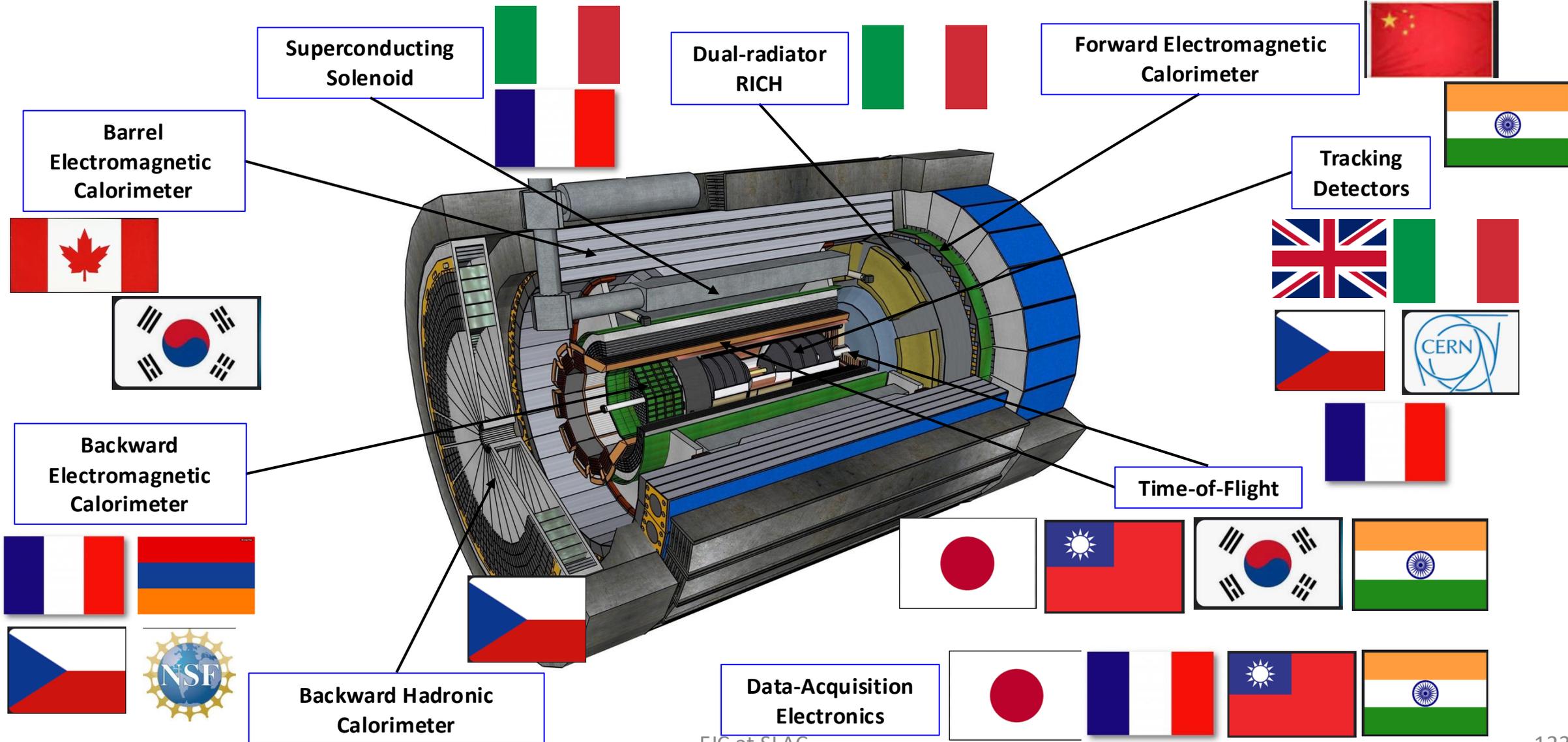
- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Multi-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxiliary detectors (Si + HCal + ECals)
- electron and hadron polarimetry

Integration, Installation and Infrastructure
Non-Beam Commissioning

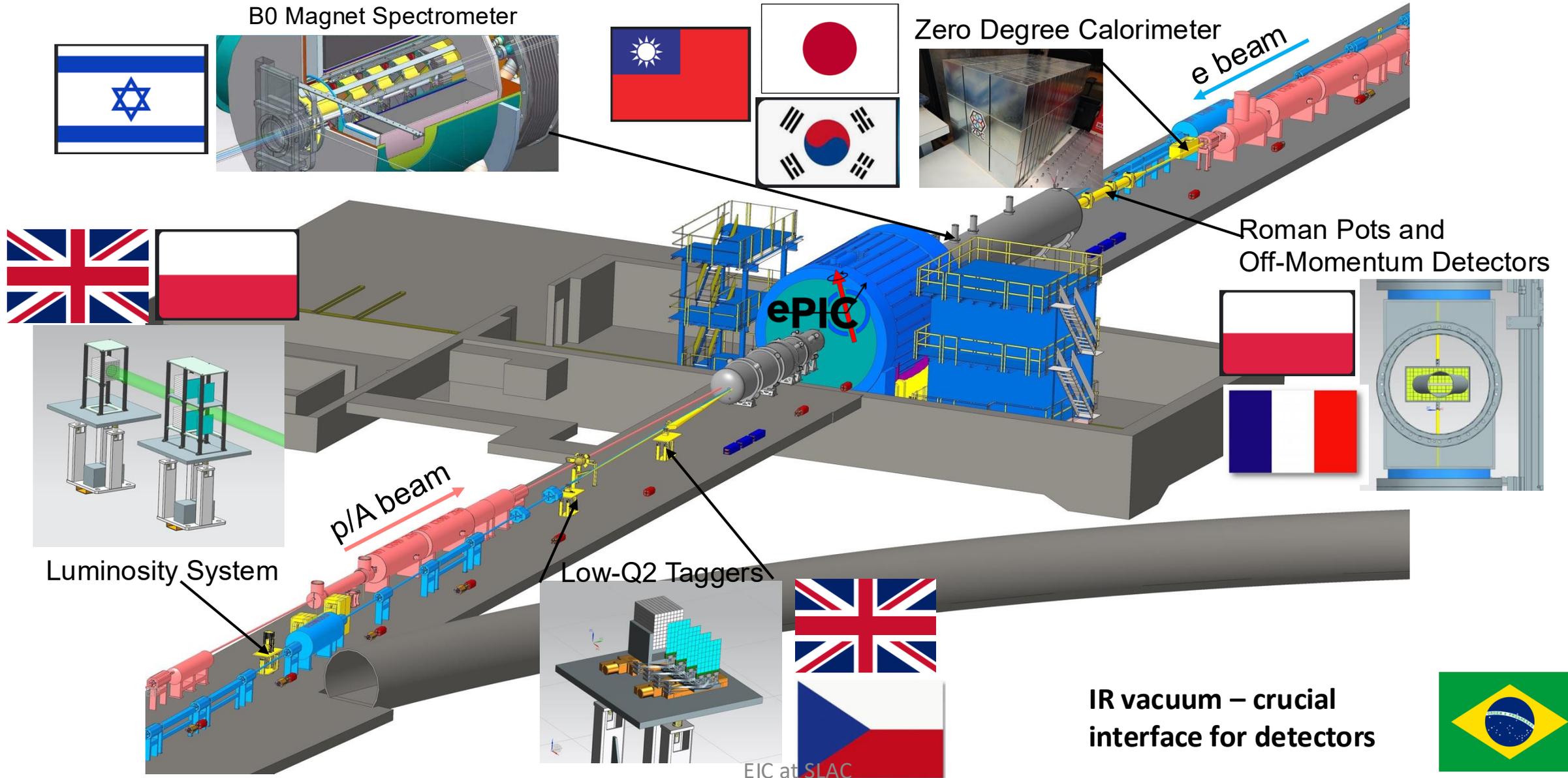
Highest scientific flexibility

- fully streaming readout electronics and data acquisition
- integration AI/ML capabilities from the start

Central Detector Non-DOE Interest & In-Kind



Far-Forward/Far-Backward Detectors Non-DOE Interest & In-kind



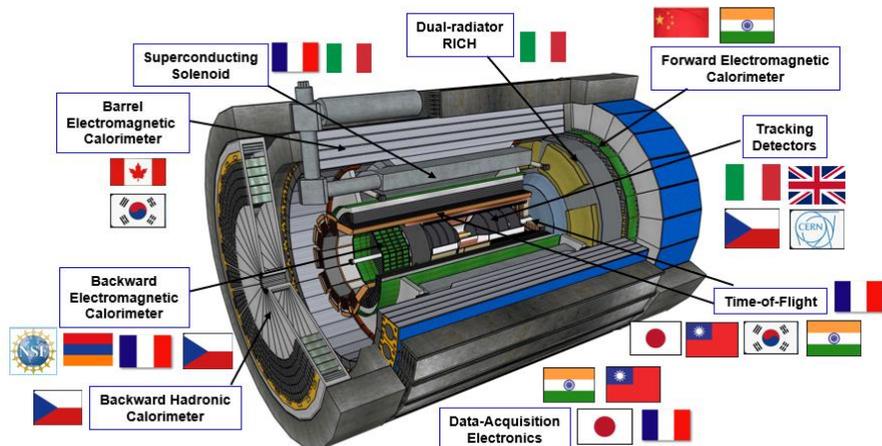
The Electron-Ion Collider

Attracting Worldwide Attention, Collaborators



The EIC design and construction has many scientific and technical challenges, creating opportunities for worldwide collaborators to become part of this exciting endeavor.

- **EIC U.S. Partners** (performing work and/or providing materials)
 - Brookhaven and Jefferson Lab among eight, total, national laboratories
 - 22 universities
- **EIC Collaborators** (developing experiments, contributing expertise)
 - EIC User Group: 1,558 members and increasing
 - 907 institutions worldwide representing 41 countries
 - 80+ U.S. universities



Department of Energy Lab Partners



The Scientific Foundation for an EIC was Built Over Two Decades

2002
 OPPORTUNITIES IN NUCLEAR SCIENCE
 Long Range Plan for the Next Decade
 April 2002

2007
 The Frontiers of Nuclear Science
 A LONG RANGE PLAN
 April 2007

2009
 A High Luminosity, High Energy
 Electron-Ion Collider
 A New Experimental Quest
 That Binds Us
 The Electron Ion Collider
 April 24, 2009

2010
 Gluons and the Quark Sea at High Energies
 distributions, polarization
 Institute for Nuclear Theory, University
 September 13 to November
 Editors:
 D. Boer, Universität Göttingen, The M.
 M. Diehl, Deutsches Elektronen-Synchrotron
 DESY, Zeuthen, Institut für Physik
 R. Venugopalan, Brookhaven National
 W. Vogelsang, Universität Tübingen.

2011
 arXiv:1108.1713v2 [hep-ph] 28 Nov 2011

2012
 Major Nuclear
 Physics Facilities for
 the Next Decade
 NSAC
 March 14, 2012

2013
 REACHING FOR THE HORIZONS
 THE 2013 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2015
 AN ASSESSMENT OF
 U.S.-BASED ELECTRON
 COLLIDER SCIENCE
 CONSENSUS STUDY REPORT
 The National Academies of
 SCIENCES • ENGINEERING • MEDICINE

2018
 EIC YELLOW REPORT
 Volume 1
 arXiv:2103.05419

2021
 A NEW ERA OF DISCOVERY
 THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE
 (EIC Yellow Report II)

2023
 Build expeditiously

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

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

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

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

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

“a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB.”

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.”

Summary & Outlook

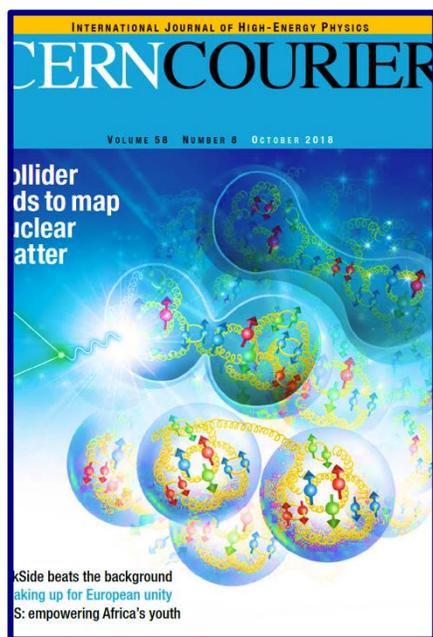
- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the DOE will be built in this decade and operate in 2030's.
 - Will address some of the most profound question yet unanswered in the Standard Model of Strong Interactions (and beyond)
- Up to two hermetic full acceptance detectors under consideration, currently **EIC project has funds for 1 detector**, **cost of a second detector from non-DOE sources**
 - **Experimental collaboration formed: ePIC)**
 - EIC project assumes **an aggressive timeline : engineering collisions around 2033/4, 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.**

Welcome to the EIC family....



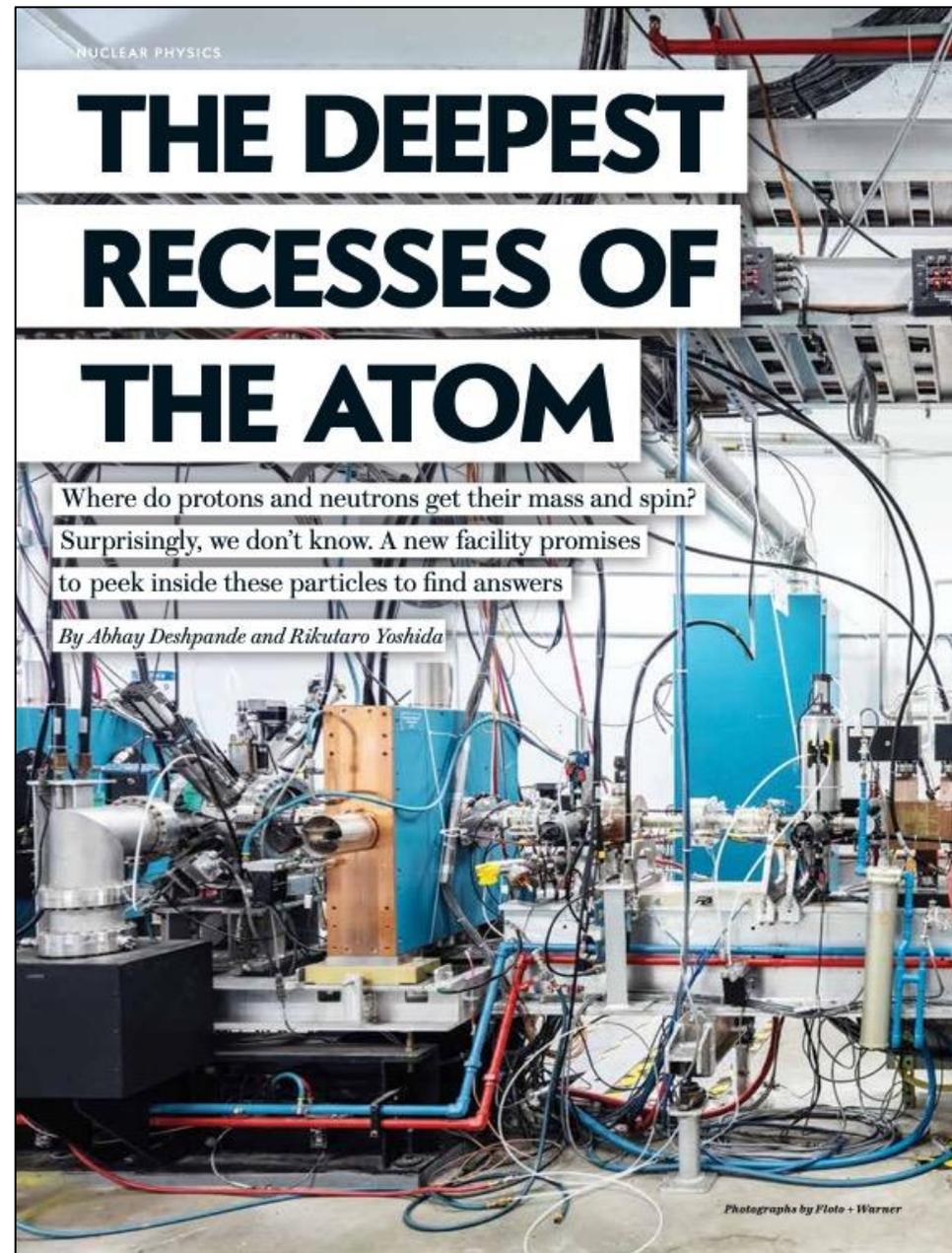
R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)

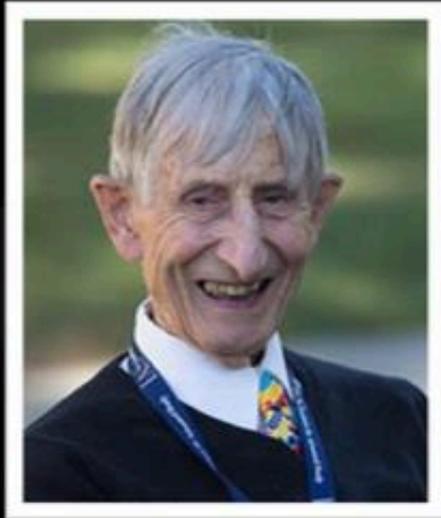
Translated into multiple languages



E. Aschenauer
R. Ent
October 2018

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





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

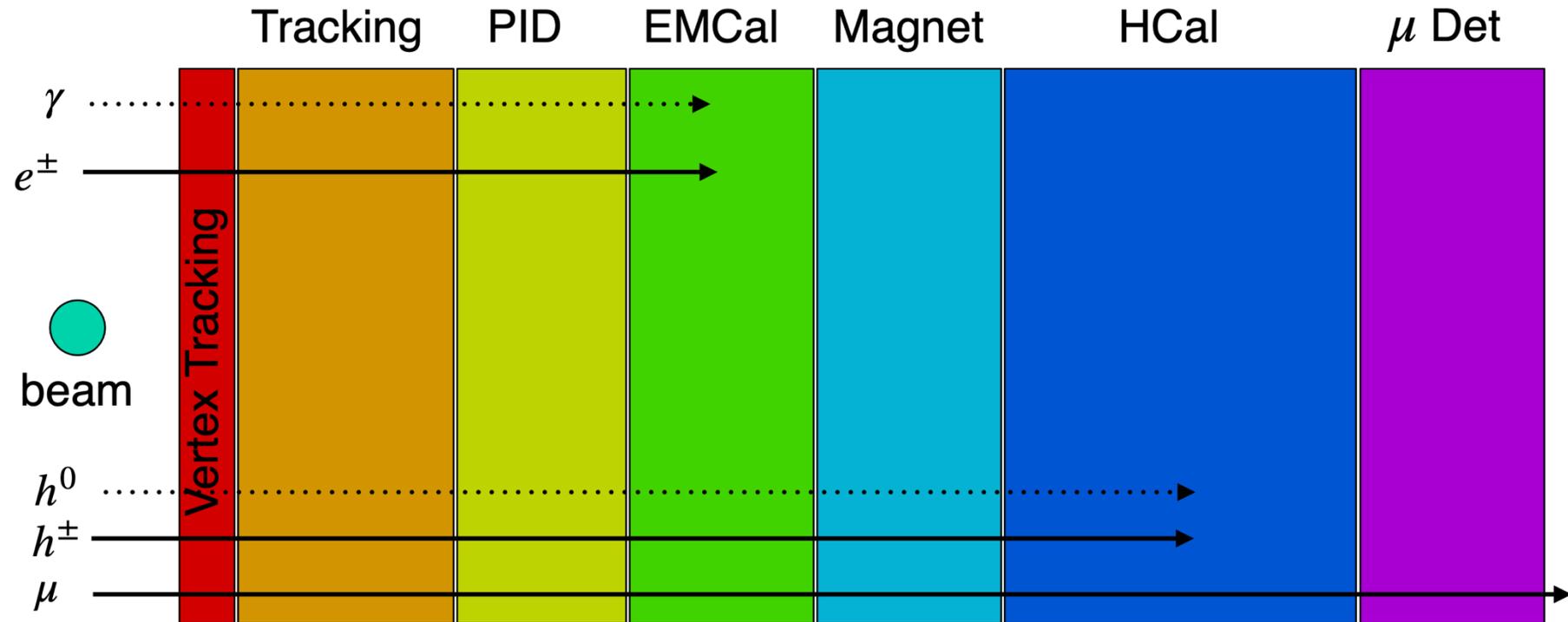
Freeman Dyson

December 2019 – March 2021 EICUG Yellow Report

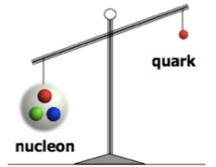
- Led by EICUG Steering Committee, with R. Ent & T. Ullrich as point people for the effort, initiated a UG-wide effort towards a detailed detector design effort with a detailed document.
- Kick off meeting at MIT in December 2019 followed by 4 more meetings in 2020 all remote: Philadelphia, Pavia, Miami, Washington DC, Berkeley



Bringing it All Together



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*

X. Ji, PRL 74 1071 (1995)

$$M = E_q + E_g + \chi m_q + T_g$$

Relativistic Motion
Chiral Symmetry Breaking
Quantum Fluctuations

Quark Energy

Gluon Energy

Quark Mass

Trace Anomaly

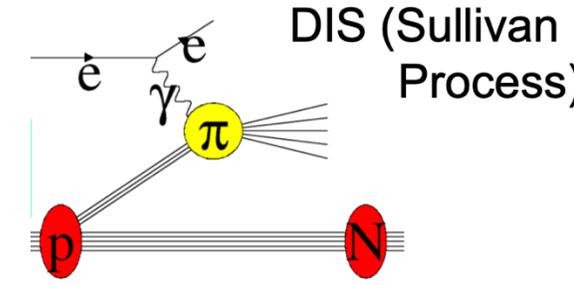
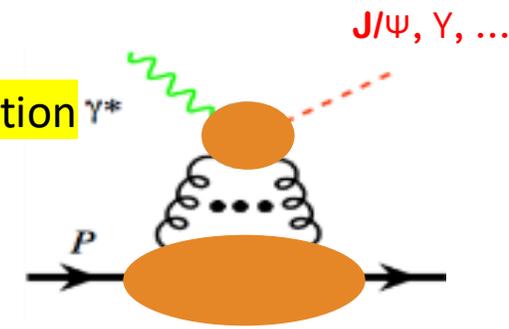
- Criticisms: not scale-invariant, decompositions: Lorentz invariant vs. rest frame
- Recent interest (workshops planned) to clarify how to determine the different contributions
- **Lattice QCD providing estimates**

$$E_q \sim 30\% \quad E_g \sim 40\% \quad \chi m_q \sim 10\% \quad T_g \sim 25\%$$

arXiv: 1710.09011

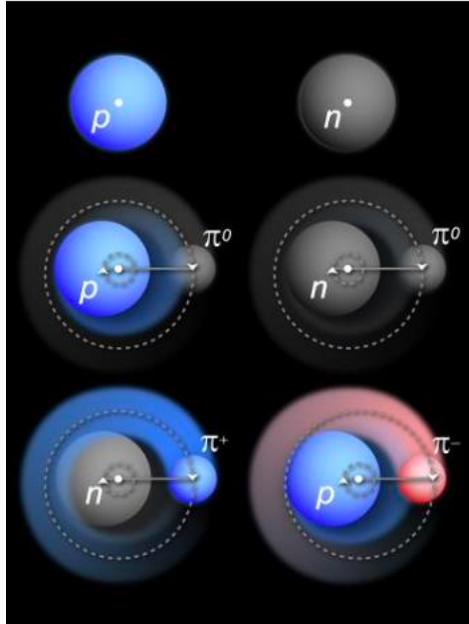
Trace anomaly:
 J/Psi & Upsilon production near threshold:

SoLID@JLab & EIC



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

Pion/Kaon mass & PDFs



Relativistic Motion

Chiral Symmetry Breaking

Quantum Fluctuations

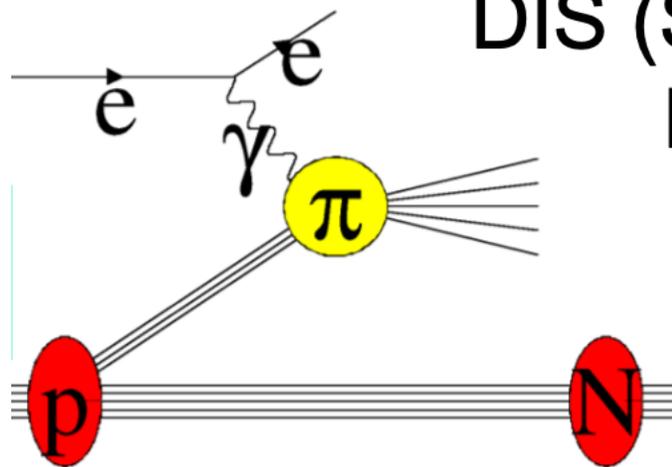
$$M = E_q + E_g + \chi m_q + T_g$$

Quark Energy

Gluon Energy

Quark Mass

Trace Anomaly

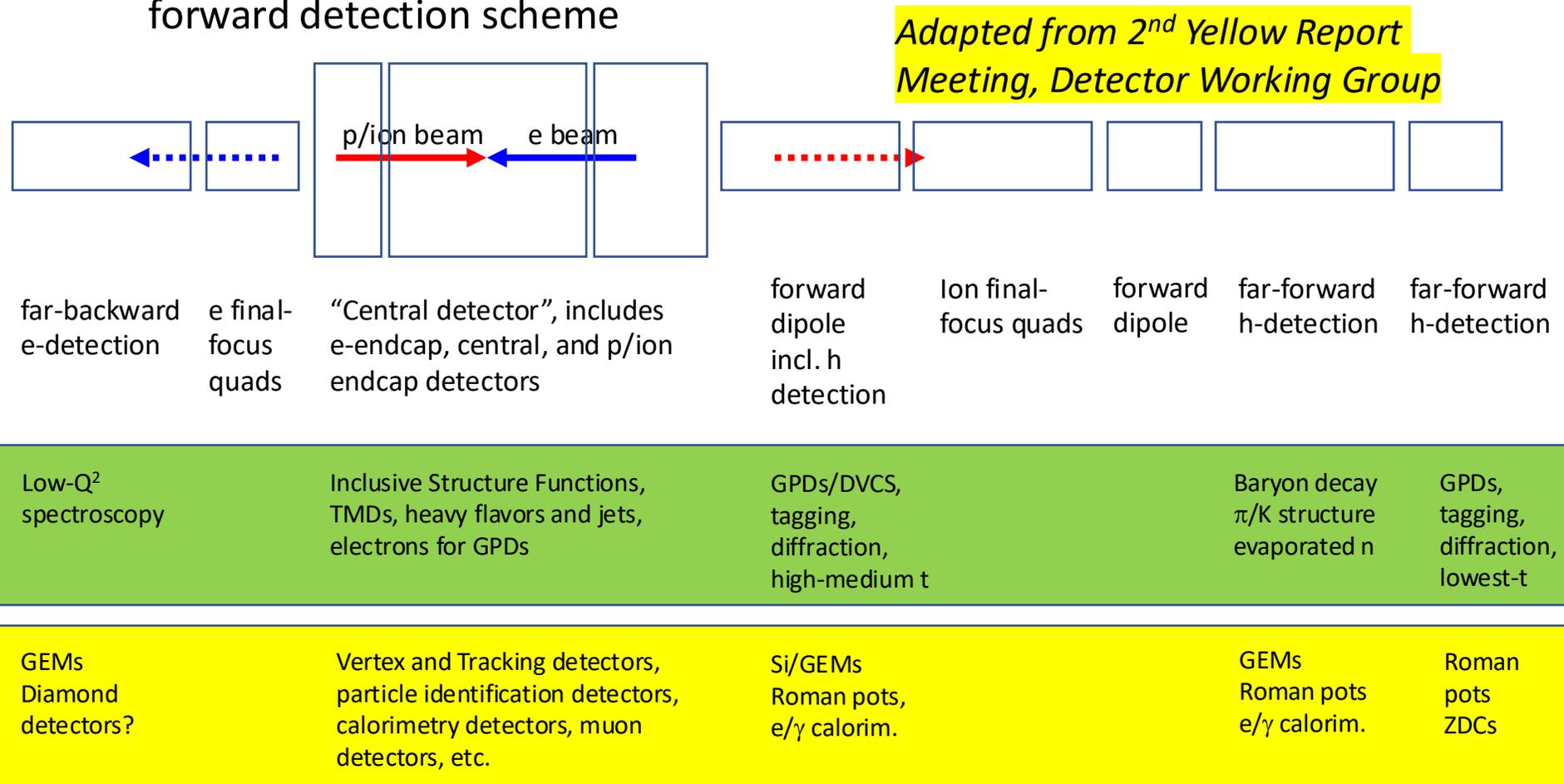


DIS (Sullivan Process)
For PDF studies

- How different are these terms in 2-quark systems? Light vs. heavy quarks?
- What can we learn from Sullivan Process about their structure?
- Hints for learning about origin of emergent mass?

Cartoon/Model of the Extended Detector and IR

- ❑ EIC physics covers the entire region (backward, central, forward)
- ❑ Many EIC science processes rely on excellent and fully integrated forward detection scheme



physics examples

detector examples