Physics opportunities at the Electron-Ion Collider

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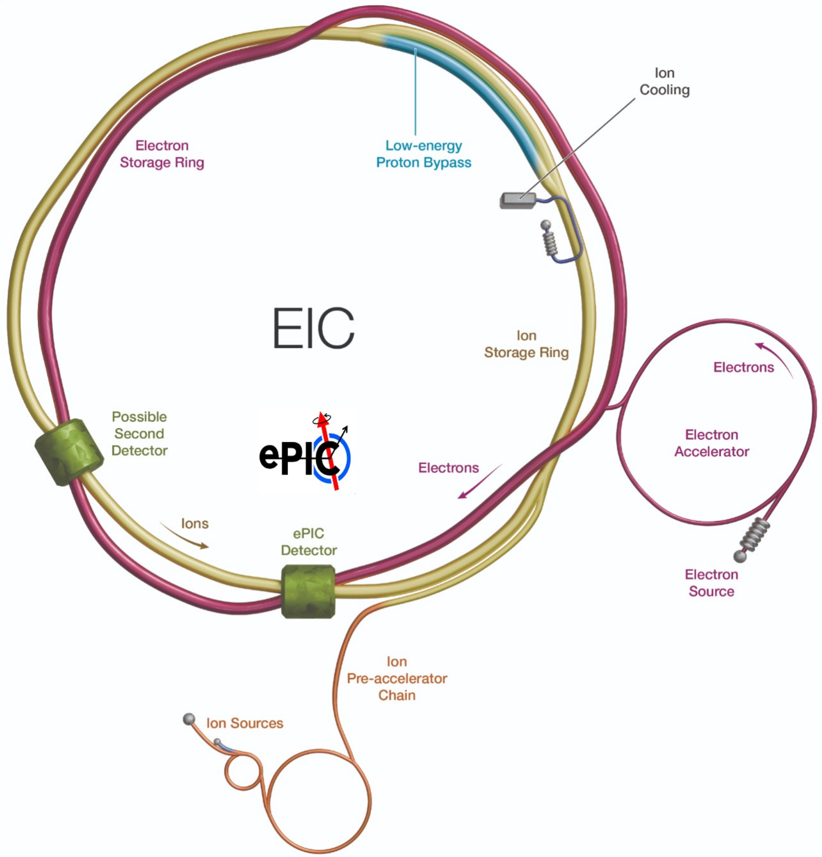


EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC, GSI, Darmstadt, Germany, July 6-10, 2026

Outline

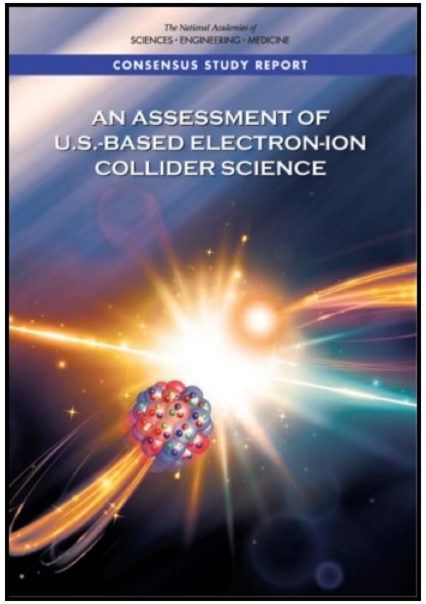
- Introduction
- The EIC and the ePIC detector
- Spin physics (selected examples)
- Heavy-ion physics (selected examples)

EIC science highlights and detector requirements

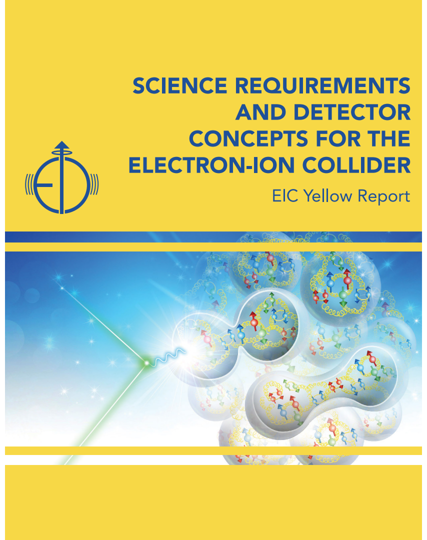
- In its assessment of U.S.-based EIC collider science by the US national academy of science (NAS) found that:

  An EIC can uniquely address three profound questions about nucleons and how they are assembled to form the nuclei of atoms:

  • How does the mass of the nucleon arise?
  • How does the spin of the nucleon arise?
  • What are the emergent properties of dense systems of gluons?



- The community yellow report added a lot of detail to the NAS assessment and formulated detector requirements.
  - The ePIC detector was developed to address them



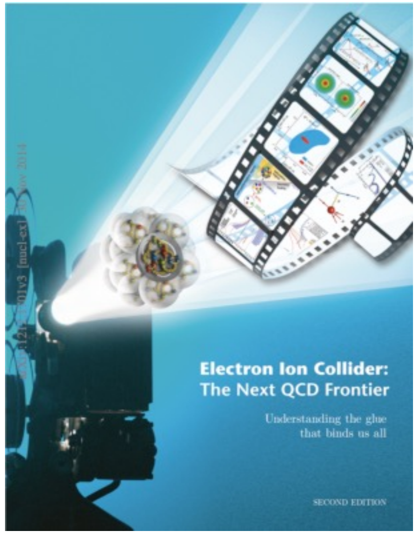
- Some of the most challenging measurements are related to the 3D structure of nucleons and nuclei.

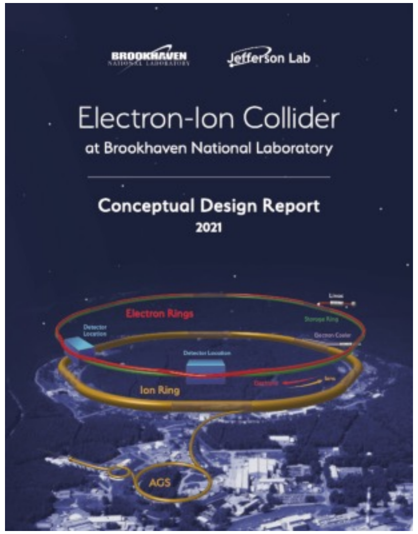
Key EIC References

- EIC White Paper: Electron-Ion Collider: The next QCD frontier
    - Eur. Phys. J. A (2016) **52**: 268
- An Assessment of U.S.-Based Electron-Ion Collider Science 2018
    - DOI: https://doi.org/10.17226/25171
- Electron Ion Collider Conceptual Design Report 2021
    - DOI: https://doi.org/10.2172/1765663
- EIC Yellow Report: Science Requirements and Detector Concepts for the Electron-Ion Collider
    - Nucl. Phys. A **1026** (2022) 122447

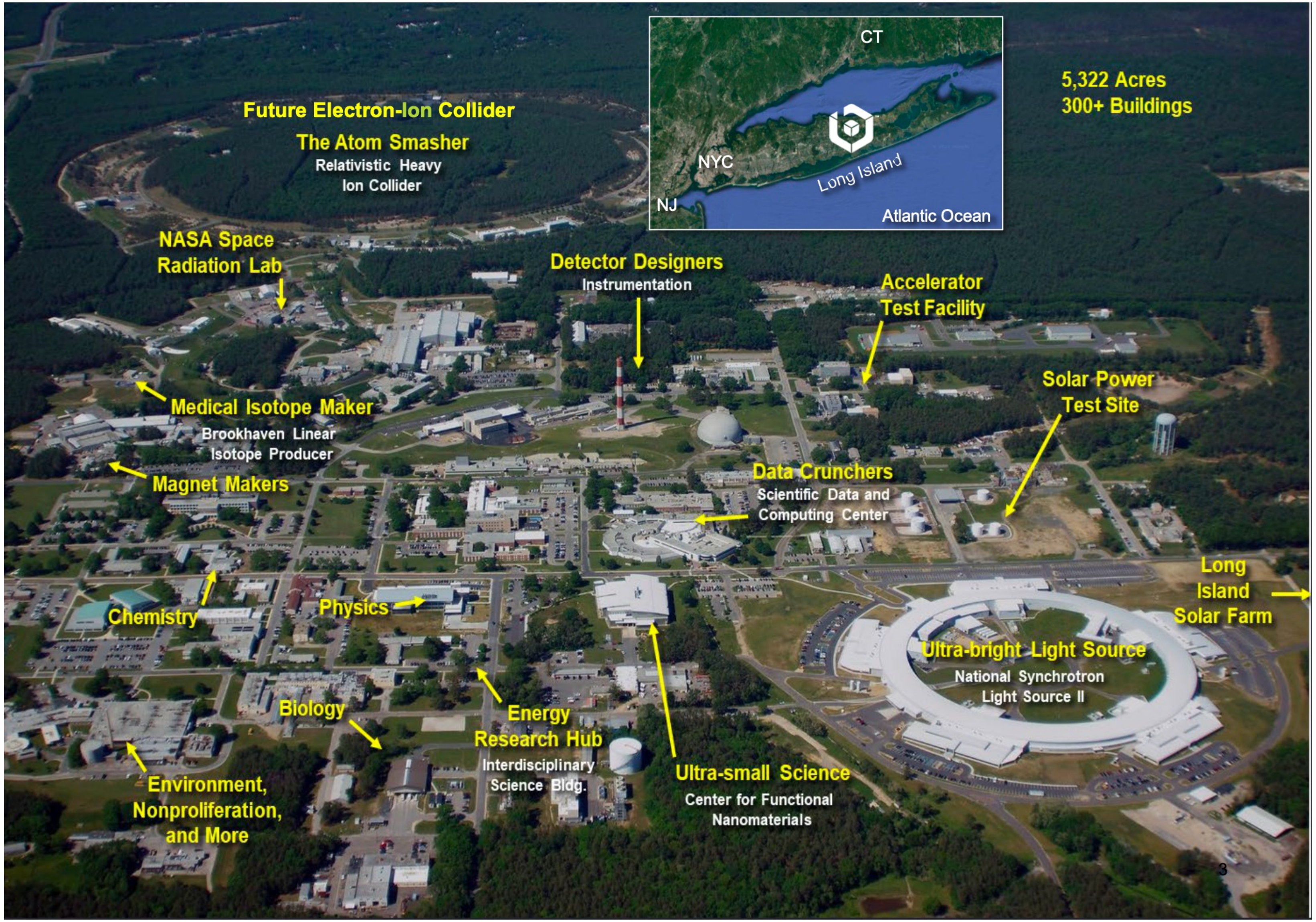
In preparation, coming soon:

- Technical Design Report (TDR)
- ePIC Early Science Report (ESR)



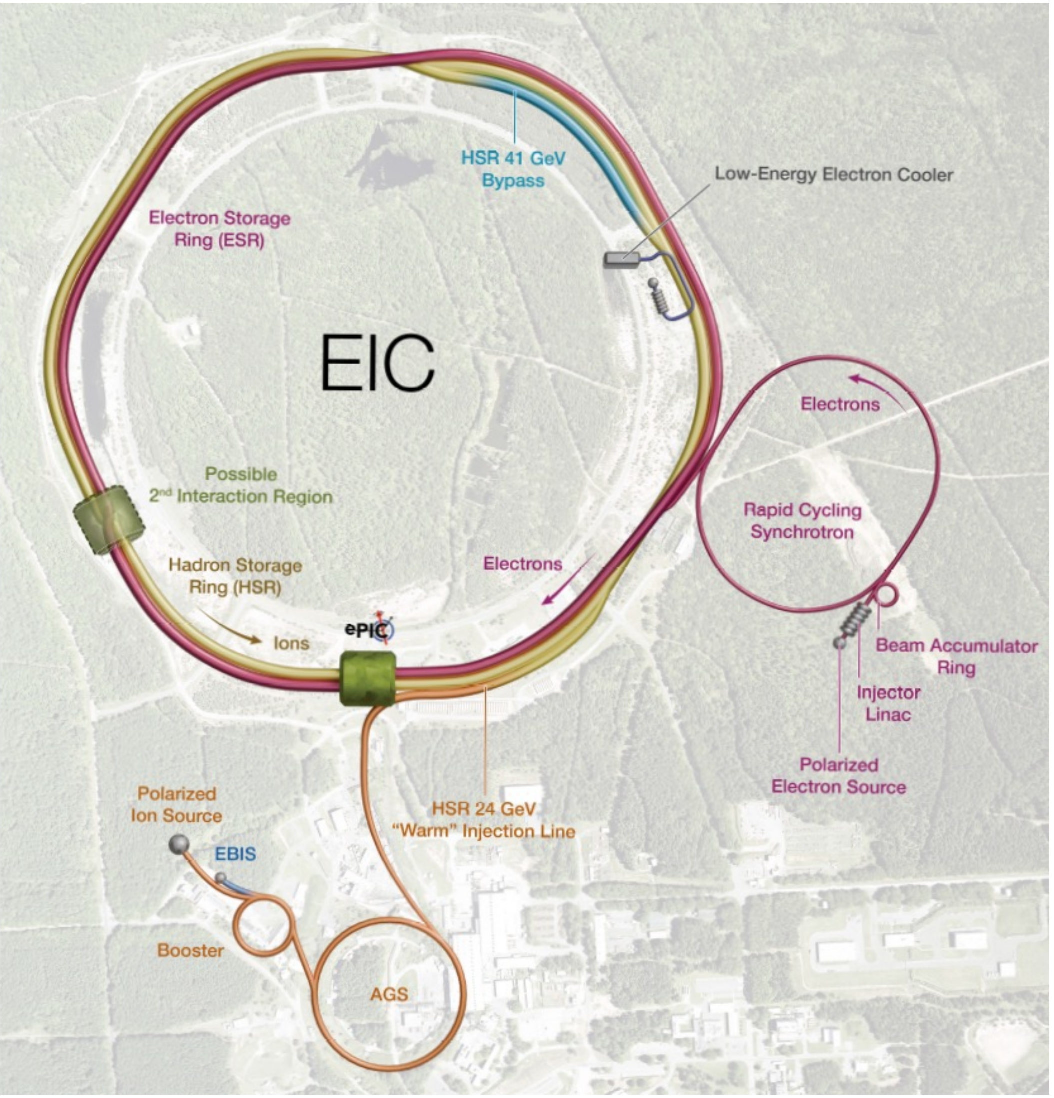


Brookhaven National Laboratory



The Electron-Ion Collider at Brookhaven National Lab

- High luminosity: $\mathcal{L} = 10^{33} - 10^{34} \frac{1}{cm^2 s}$; $10 - 100\ fb^{-1}/year$
- Polarized electron, proton, and light ion beams: 70%
  - Longitudinal and transverse target
- Center-of-mass energy: $E_{cm} = 30 - 140$ GeV
  - Electrons: initially 5 – 9 GeV (upgradable to 18 GeV)
  - Ions: $100 - \frac{Z}{A} \cdot 275$ GeV/A or 41 GeV/A using a bypass
- Full range of ion species: protons – Uranium
- Good detector acceptance and background conditions
  - Many bunch crossings per collision (not other way around)
- The EIC projects includes one detector (ePIC) and will accommodate an interaction region for a 2nd detector.
  - This staged approach is similar to that of the Tevatron at Fermilab where D0 started taking data 7 years after CDF.
- RHIC operations concluded after 25 years in February 2026. The the EIC will start construction in the RHIC tunnel.



Electron-Ion Collider User Group

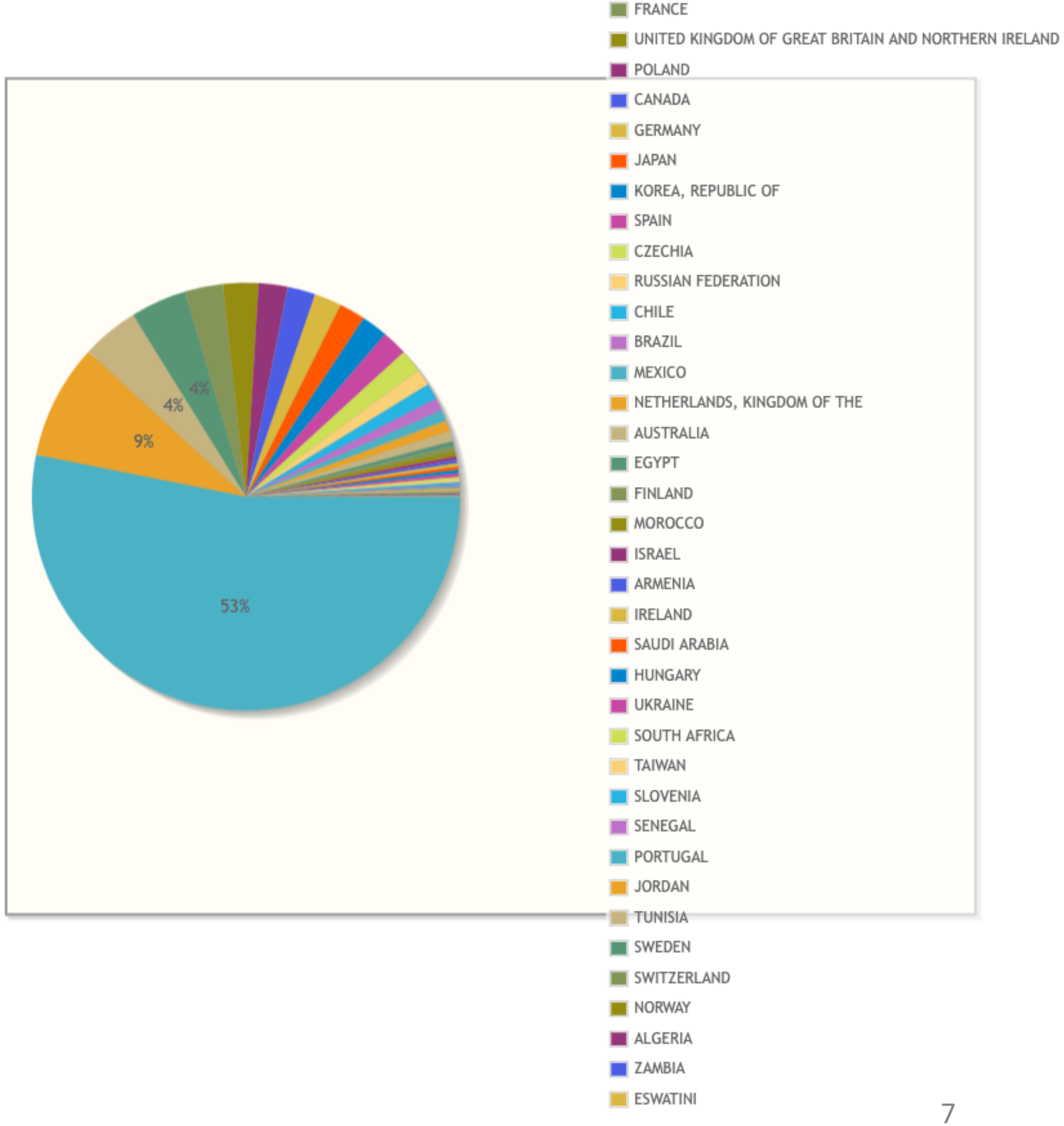
The world's most powerful microscope for studying the "glue" that binds the building blocks of visible matter.

https://www.eicug.org

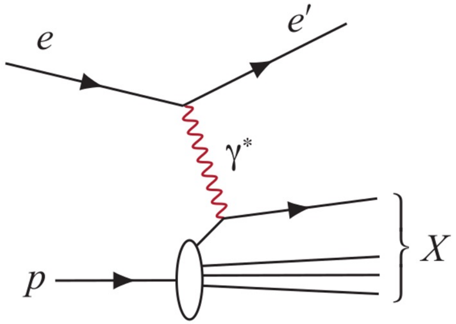
- 1556 members from 307 institutions
  - Experimental Scientists: 1031
  - Theory Scientists: 383
  - Accelerator Scientists: 125
  - Computer Scientists: 9
  - Support: 5
  - Other: 3

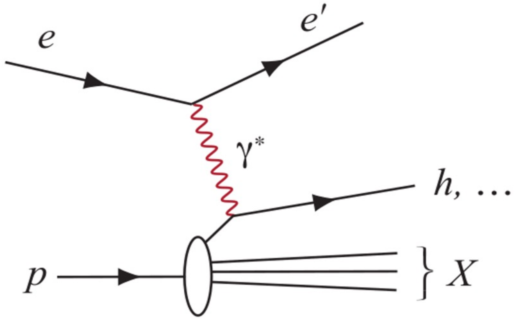
- Joining the EIC user group
  - https://www.eicug.org/content/join.html

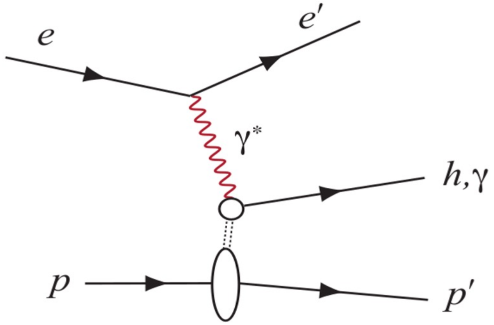
July 2025



Electron scattering







Inclusive DIS

- Information from the scattered electron.

Semi-Inclusive DIS

- The scattered electron is measured in coincidence with at least one hadron from the struck parton.

Deep Exclusive Processes

- All final-state particles are detected (*e.g*, recoil proton in coincidence with a photon or meson).

Parton Distributions in nucleons and nuclei

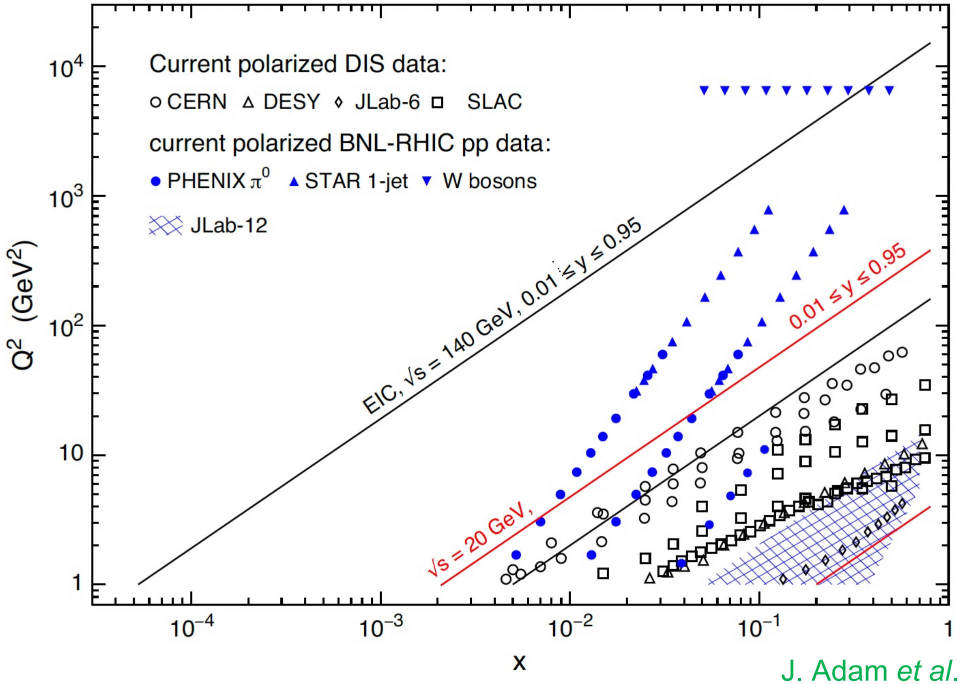
Spin and Flavor structure of nucleons and nuclei

Transverse Momentum Distributions

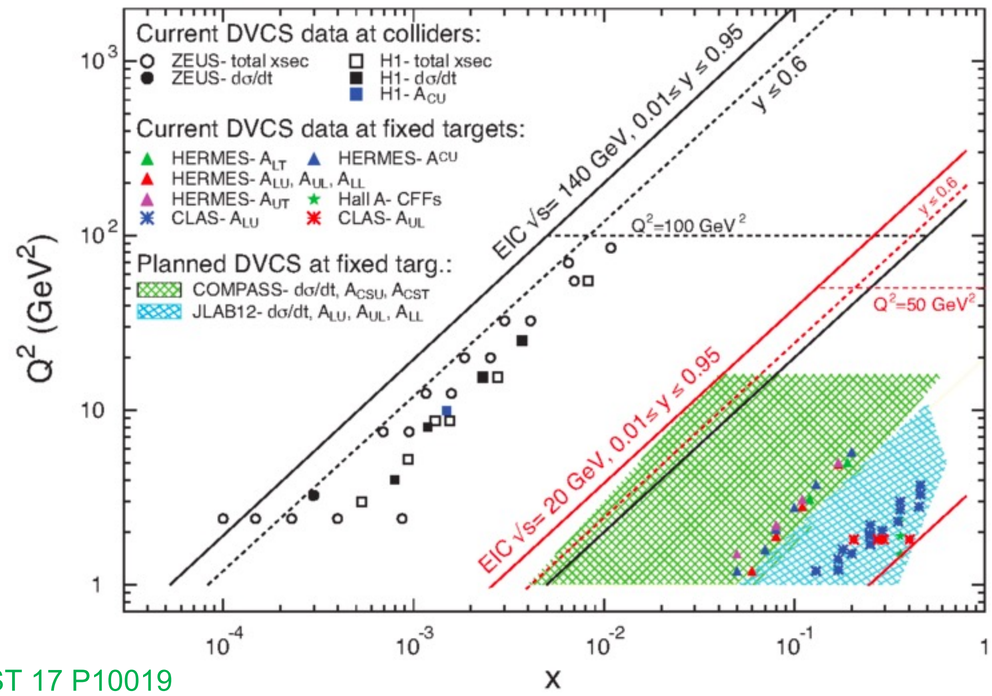
Transverse Spatial Imaging

Kinematic coverage

Polarized



DVCS
(exclusive production of a photon)



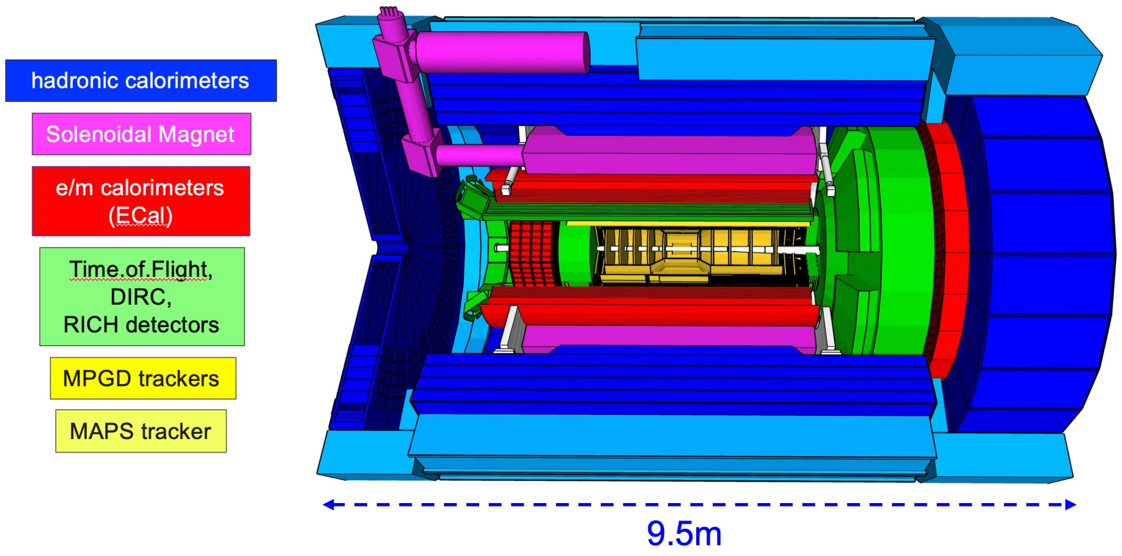
J. Adam *et al.*, 2022 JINST 17 P10019

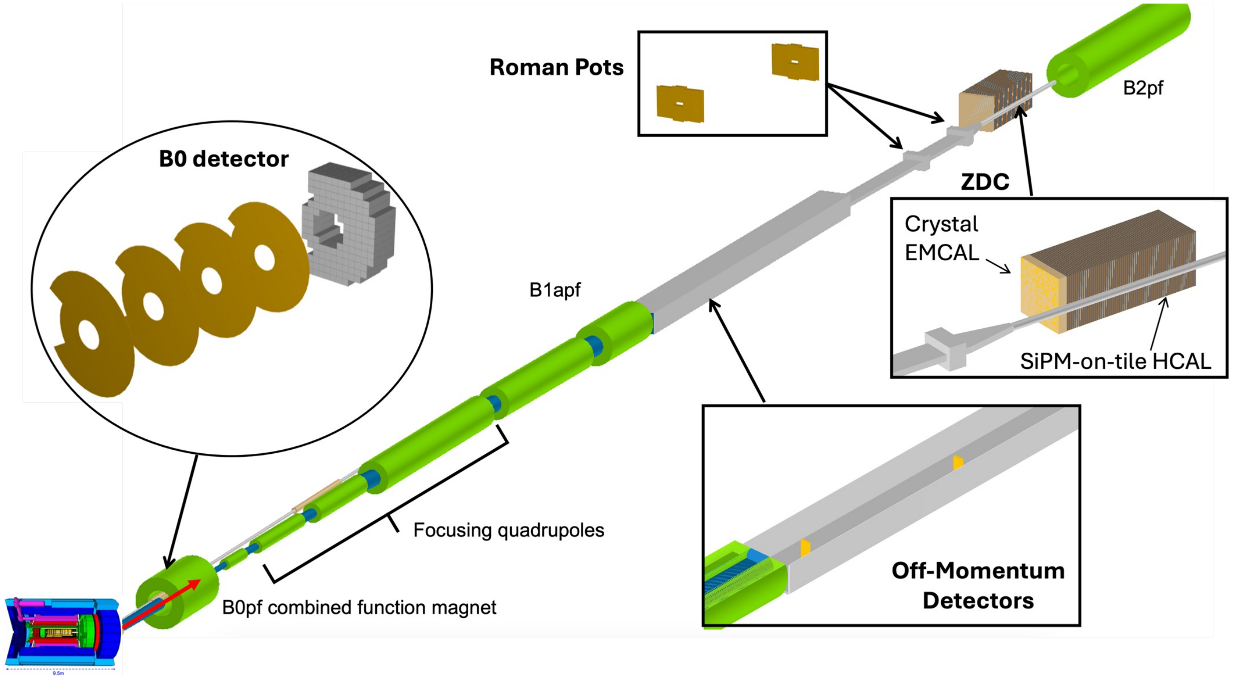
- The EIC will greatly expand the kinematic coverage for polarized measurements.

- Perhaps more surprising is that the EIC kinematic coverage will, for certain processes, also match HERA which had a higher energy (27x920).

- One important reason for this is the excellent far-forward acceptance for the recoiling proton.

The ePIC detector at IR6 of the EIC





- The central detector provides hermetic acceptance for all subsystem categories.
  - Tracking, calorimetry, particle identification (PID)
- 4π PID capabilities provide flavor sensitivity.

- Comprehensive set of forward detectors at several locations.
  - Inside B0, off-momentum, Roman Pots, ZDC
- Fully integrated with the accelerator

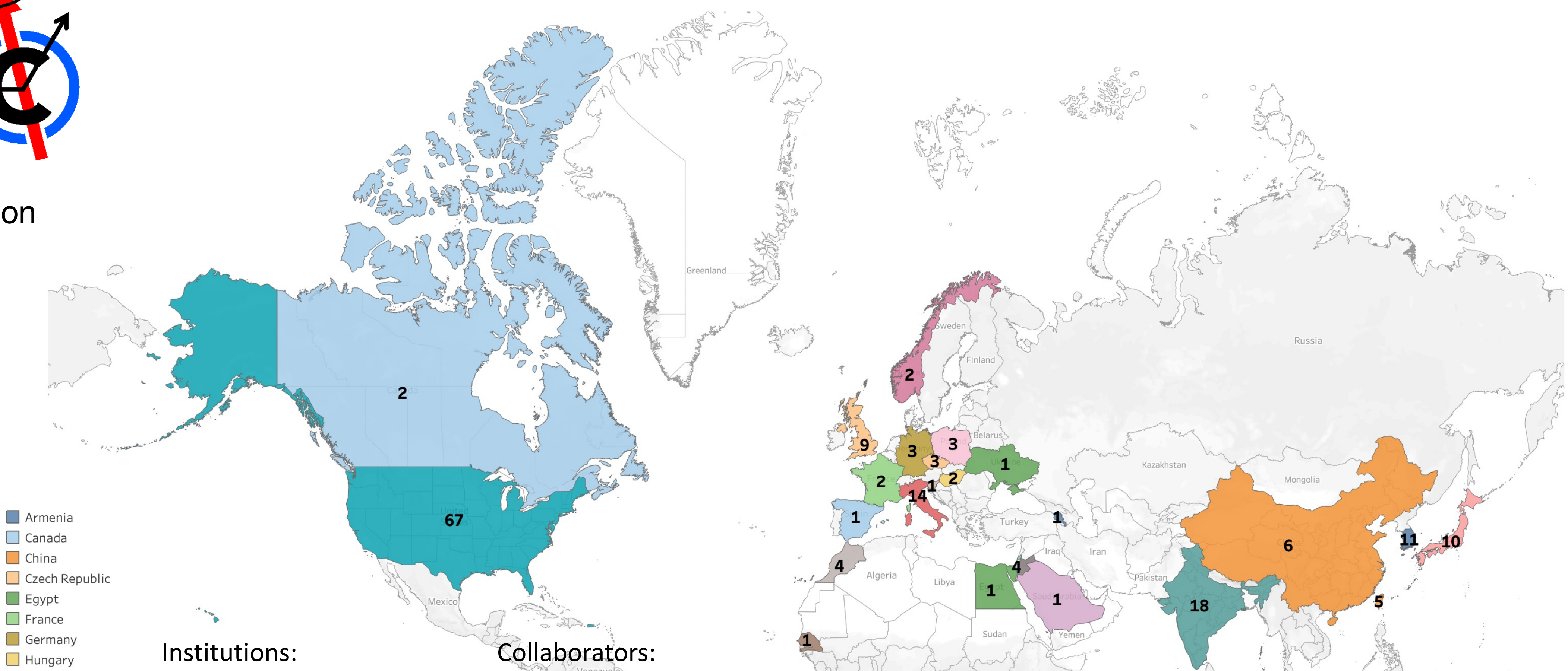
ePIC collaboration

ePIC Institutions 180

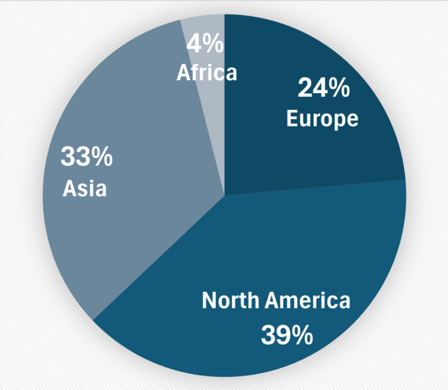
ePIC Countries 25

ePIC World Region 4

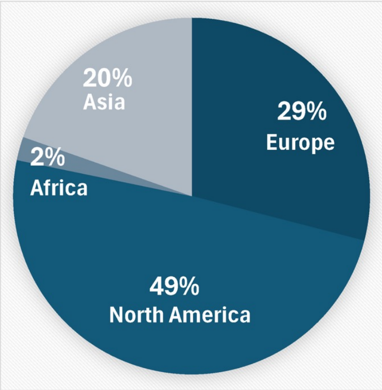
Currently:
> 1050 collaborators worldwide



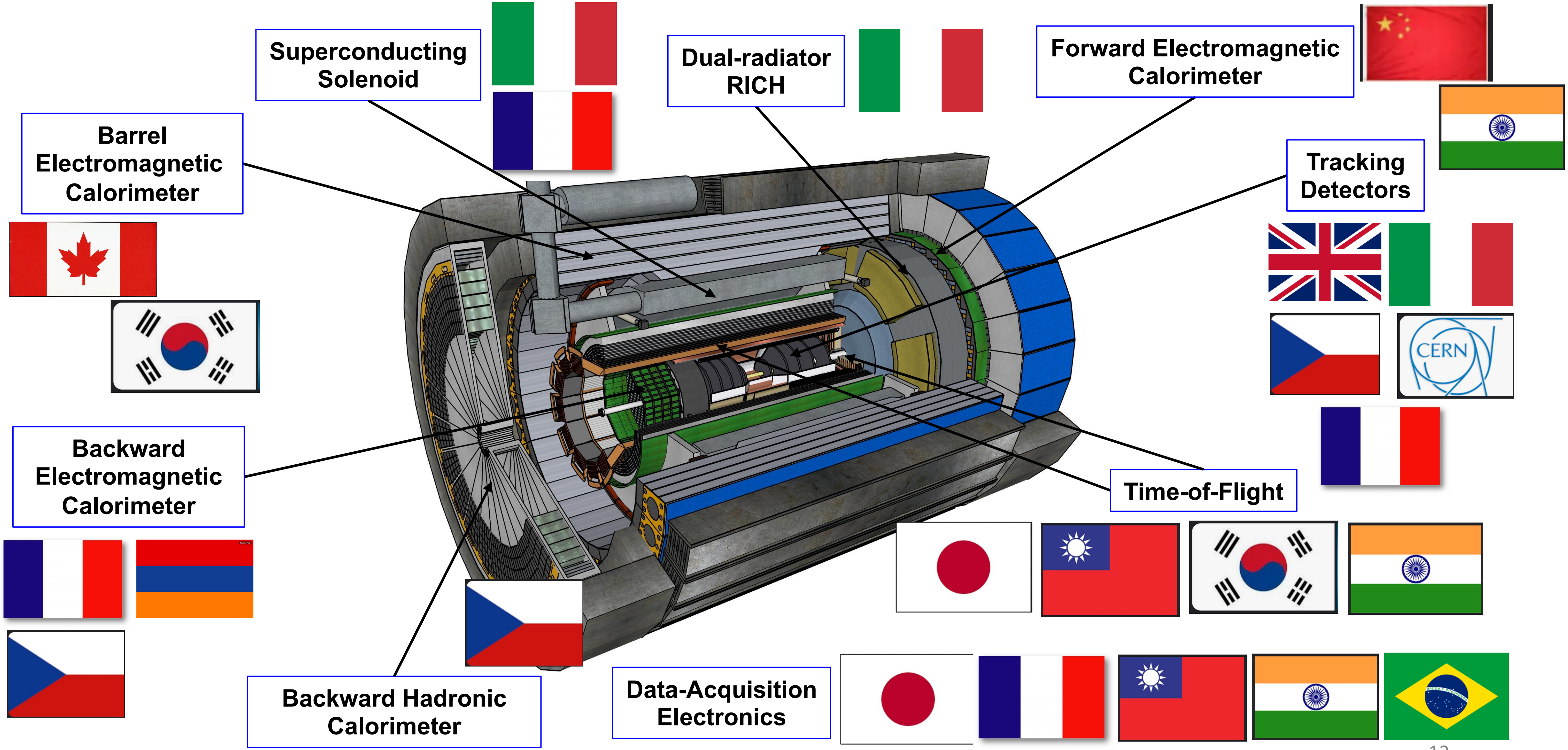
Institutions:



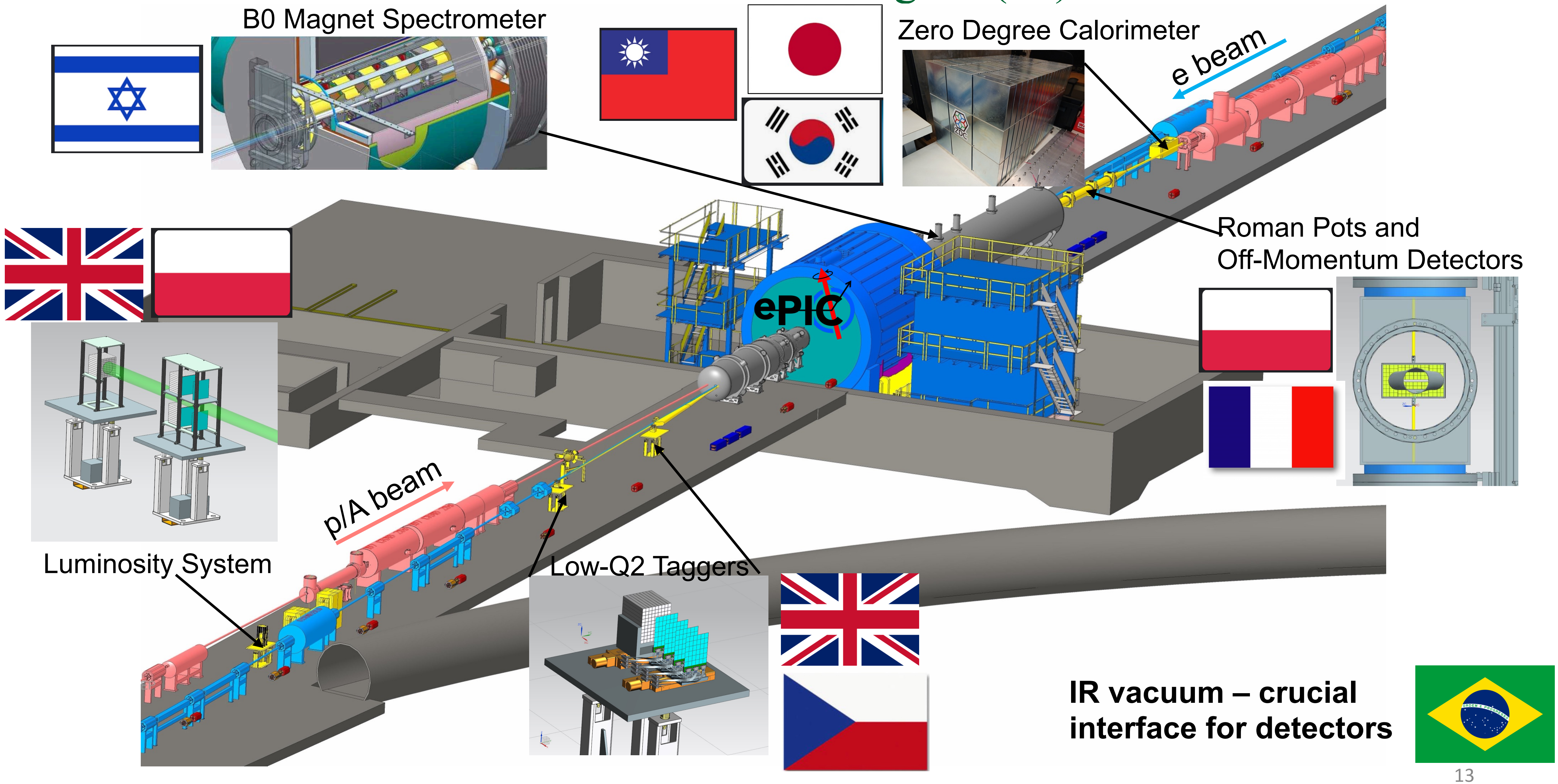
Collaborators:



International contributions to the ePIC detector

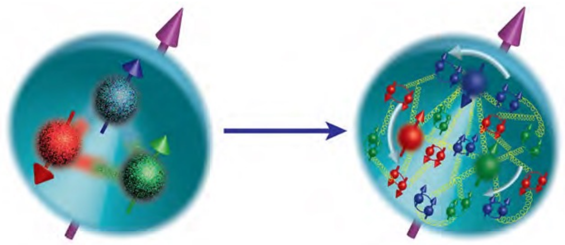


International contributions to interaction region (IR) 6



IR vacuum – crucial interface for detectors

The spin of the proton



The quark spin only contributes about 30% to the spin of proton:

$$\underbrace{\underset{\text{spin}}{\frac{1}{2}\Delta\Sigma} + \underset{\text{orbit}}{L_q}}_{\text{quarks}} + \underbrace{\underset{\text{spin}}{\Delta G} + \underset{\text{orbit}}{L_g}}_{\text{gluons}}$$

What do we need to understand the proton spin?

Measure ΔG - gluon polarization (requires longitudinal polarization)

Measure the 3D structure of the proton - orbital motion

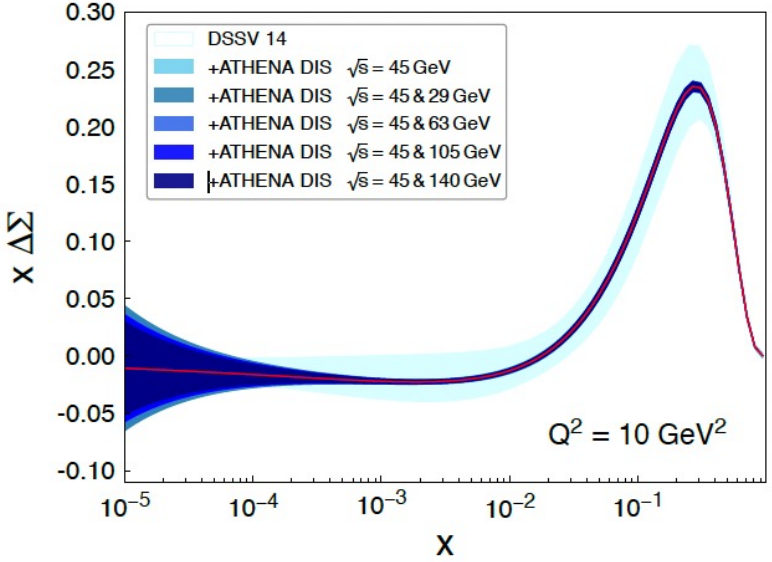
Ji sum rule

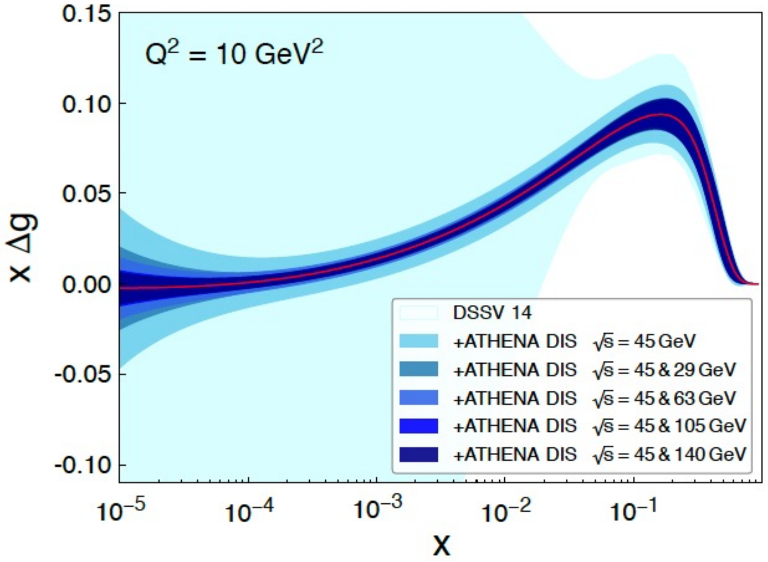
$$J = \frac{1}{2}\int_{-1}^{1} dx\, x[H(x,\xi,t) + E(x,\xi,t)]$$

Spin of the nucleon in polarized DIS

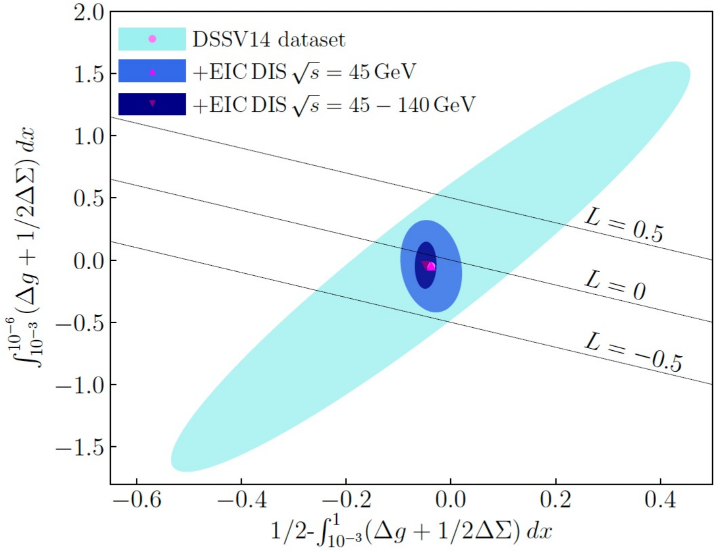
Nucleon spin: $\frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$

J. Adam *et al.*, 2022 JINST 17 P10019



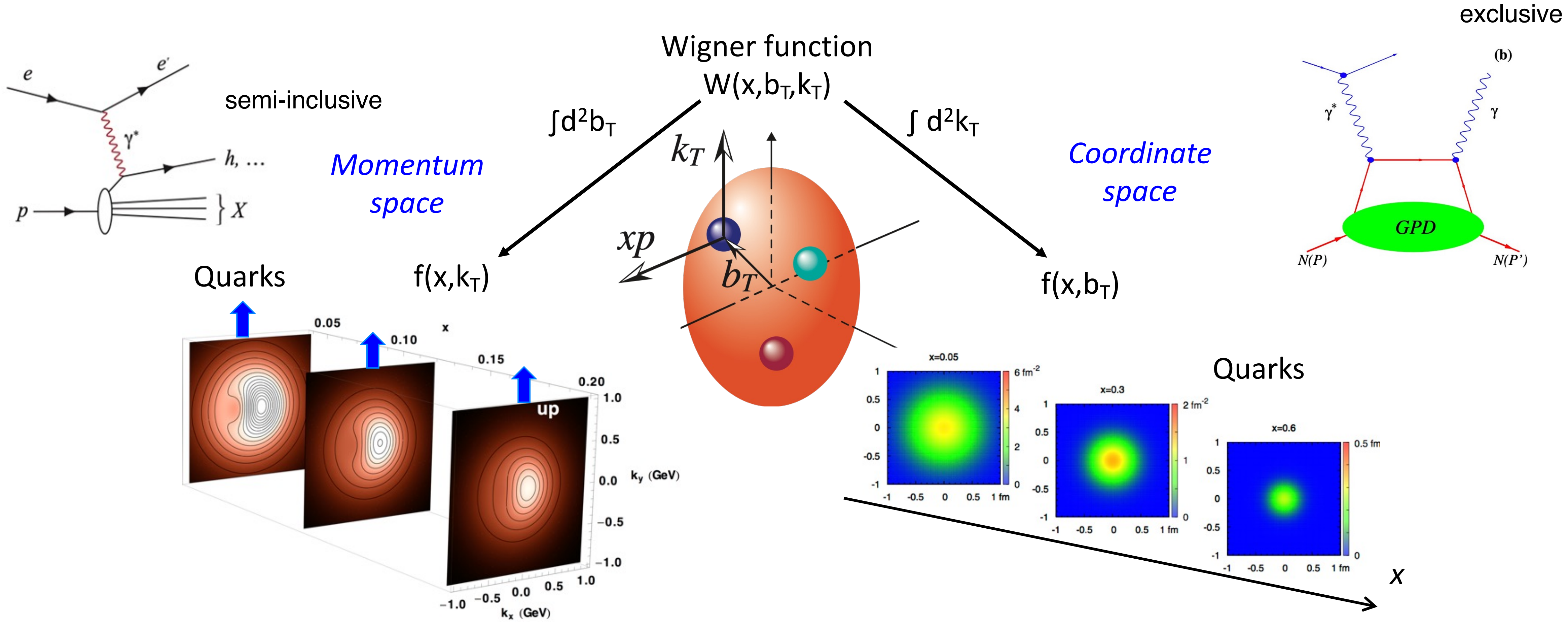


E. Aschenauer *et al.*, arXiv:2007.08300 [hep-ph] (2020)



- Constraints imposed on ΔΣ and ΔG by adding EIC pseudodata with different combination of cm energies to DSSV.
- The inclusive measurements also pose a constraint on L. But while this will be greatly improved by the EIC, measurements of OAM will still be important.

Transverse structure in momentum (k_T) and impact parameter (b) space



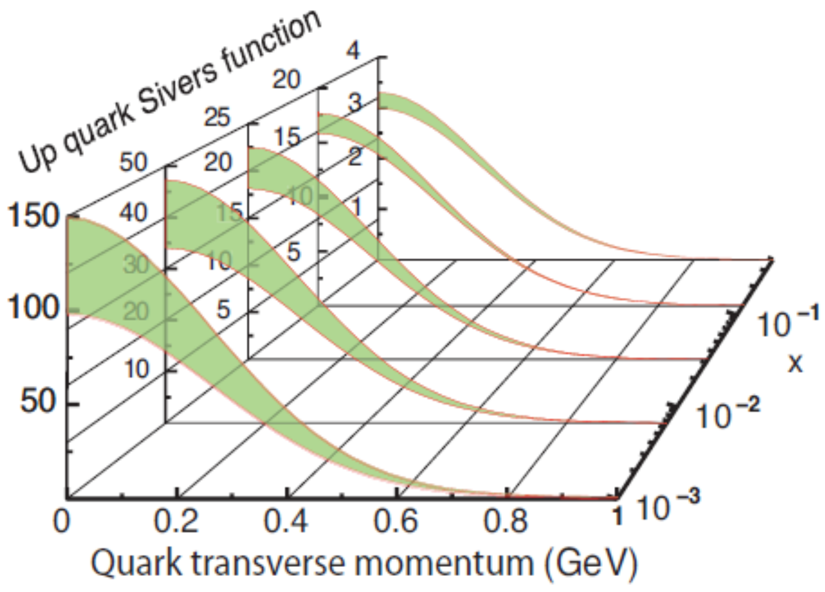
Transverse Momentum Distributions (TMDs) of partons can give insights into orbital motion.

The Ji spin sum rule for the nucleon is expressed in terms of generalized parton distributions (GPDs).

Example projections from the EIC white paper

TMDs

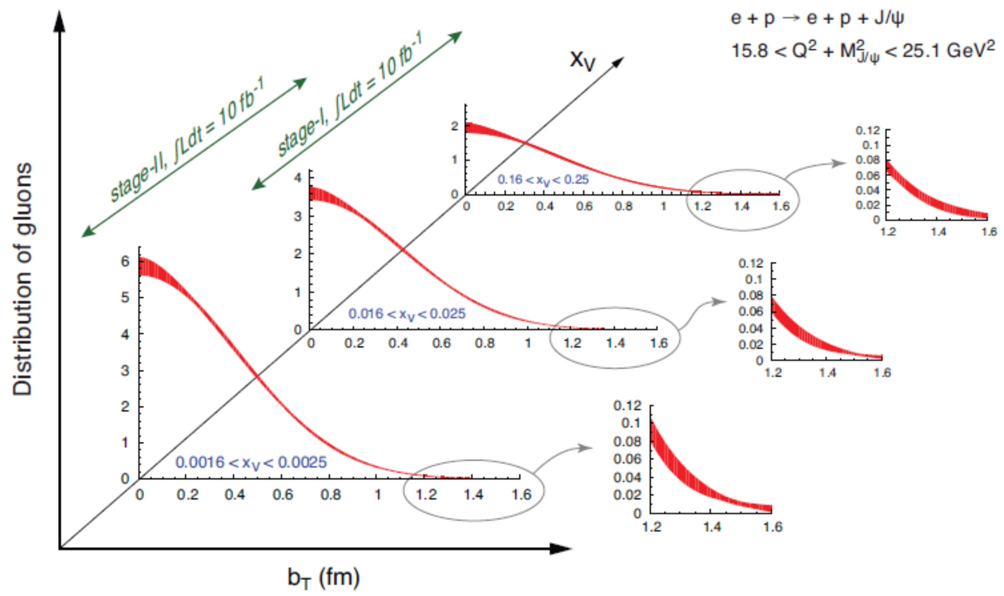
2+1 D picture in **momentum space**



Projections from the EIC white paper

GPDs

2+1 D picture in **impact-parameter space**

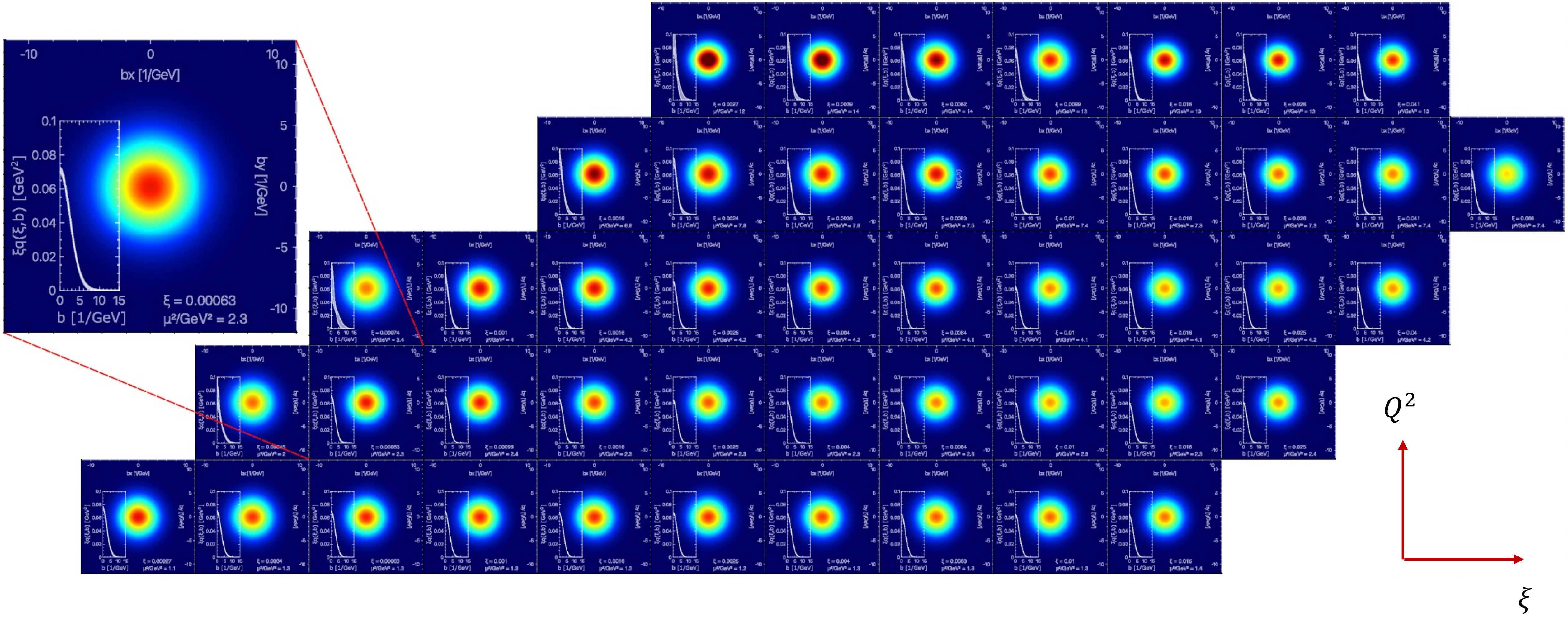


Transverse gluon distribution from J/ψ production

GPDs can also be measured for light nuclei. ^{4}He with spin 0 can be described by a single GPD.

Example: recent projections for DVCS

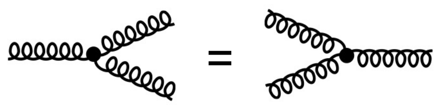
E. Aschenauer et al, Phys. Rev. D 112, 036010 (2025)



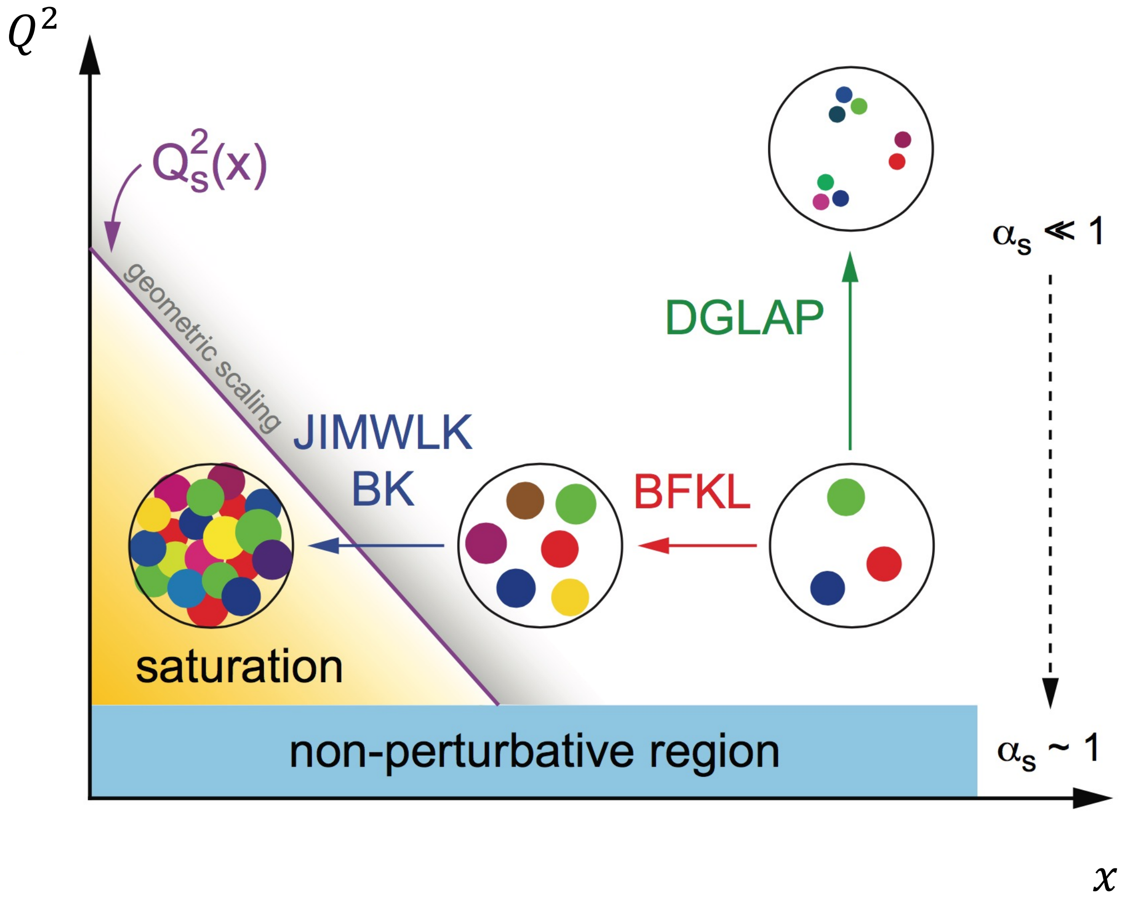
Transverse imaging of the proton in different bins of ξ and Q^2.

High gluon densities

- At low x and Q^2 we hope to see a transition to saturation, which we can interpret it as a balance between gluon splitting and recombination.



- In electron scattering both Q^2 and x are given by the electron kinematics.
  - Q^2-dependence for a single VM (*e.g.* ϕ)
  - Complementary to LHC measurements



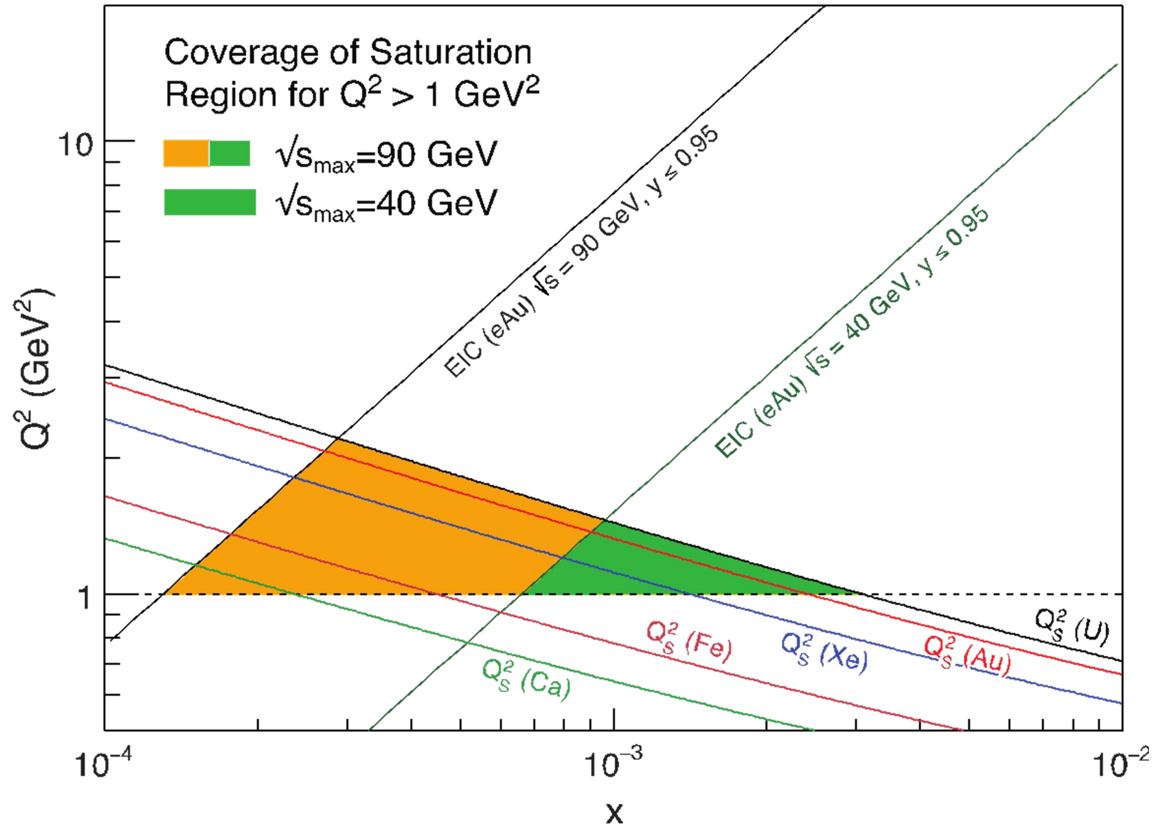
Mapping the transition to gluon saturation in nuclei

- Compared with the LHC the maximum energy of the EIC is modest.
- It is, however, reasonable for studying shadowing and the transition to saturation in nuclei, where the saturation scale depends on A.

$$Q_s^2 \sim A^{1/3}/x^{0.3}$$

- The EIC offers many channels and observables for assessing the signatures of saturation, *e.g.*,
  - di-hadron (jet) production
  - coherent diffraction
  - etc

EIC Yellow Report, arXiv:2103.05419



Coherent nuclear processes

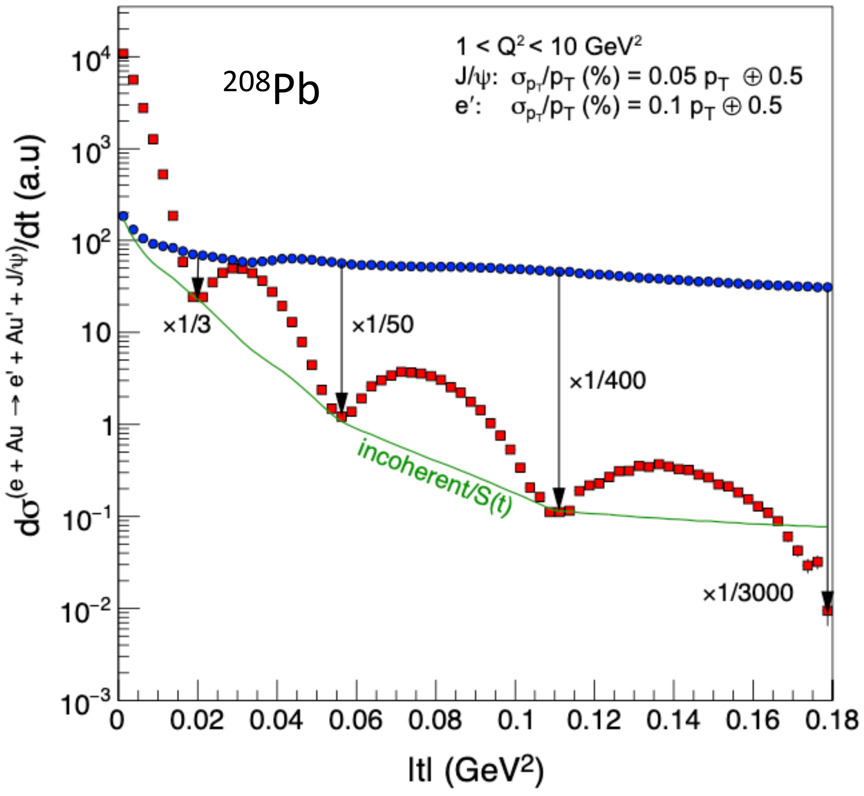
Light ions

- Access to 3D structure (GPDs)
  - Exclusive reactions like DVCS, DVMP
  - Combines spin and nuclei
- Recoiling ion is *detected* in Roman pots
  - ePIC can detect ^{3}He over a significant range in t.

Medium- and heavy ions

- Coherent diffraction (right)
  - Spacing of minima is reduced at larger A
- Incoherent events are selected by vetoing of breakup
  - Detection of neutrons, protons, and photons
  - With a 2nd detector also light ions and nuclear fragments

EIC Yellow Report, arXiv:2103.05419



Electron-Ion Collider Detector II

Slide by the EIC UG 2nd detector WG presented to the SCAC in May 2026.

Major facilities need at least two detectors to maximize the science.

Independent confirmation of results and discoveries, reduction of systematic uncertainties.

A 2nd EIC detector will allow for enhanced capabilities in several sectors.

A novel far-forward detection system utilizing a second focus will significantly expand the opportunities for nuclear measurements and for the 3D structure of nucleons and nuclei. Improved muon identification is another example of complementarity with the 1st detector.

A 2nd detector is essential to fully leverage the investment made in the EIC

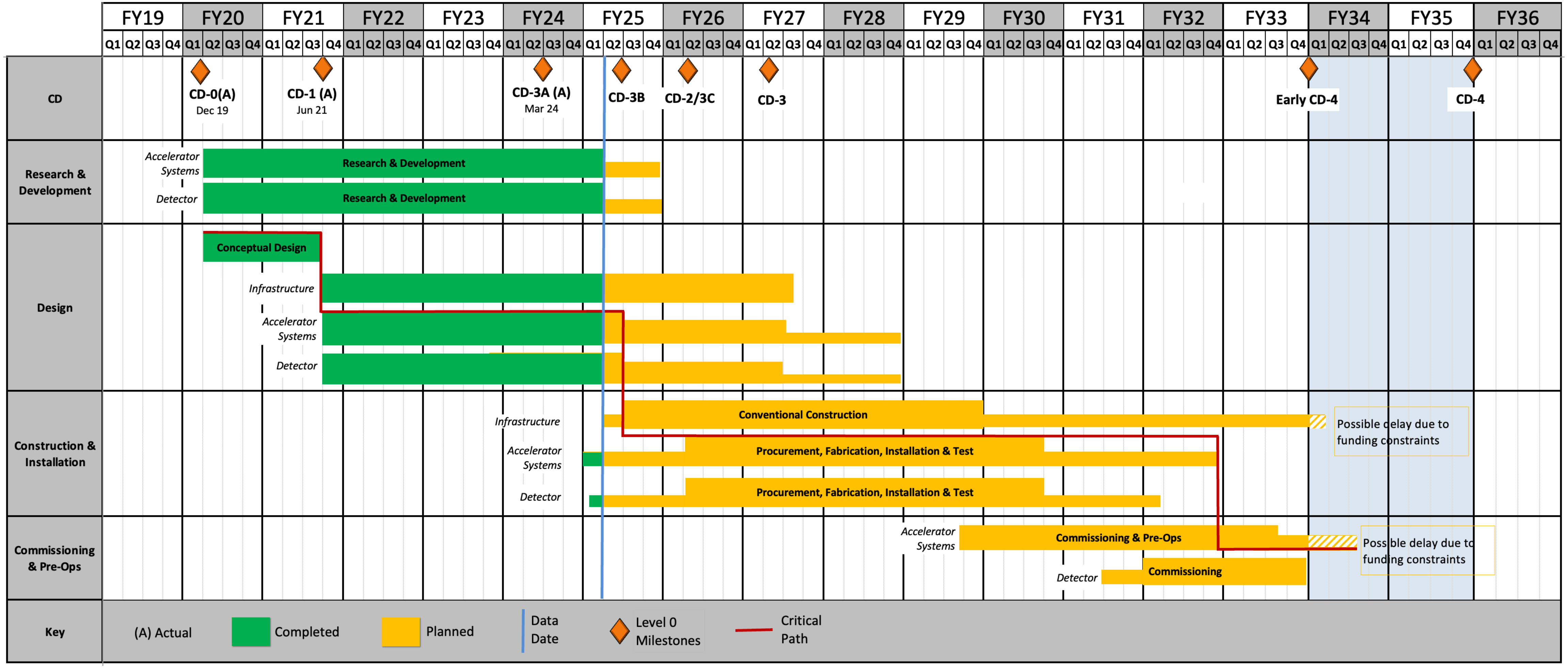
A slightly longer timeline will also make it possible to take full advantage of AI in all aspects of the project, which would be naturally synergistic with the Genesis mission. Completing the 2nd detector after early running would not significantly affect its overall contribution to EIC science (note that the D0 detector at the Tevatron came 7 years after CDF).

Significant progress has been made on the implementation

Includes an optimized beam optics that could be used in IR8 or IR12.

More details on Thursday!

EIC project schedule



Early science – tentative running conditions

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

- The current plan is to start data taking as soon as possible with running conditions that will will initially be less demanding for the accelerator. Capabilities will be added in parallel, and performance will improve over time.
  - If a 2nd detector is added it would be after completion of early running.
  - The early science report will soon be released with updated running conditions and more details.

Thank you!