The Electron-Ion Collider (EIC)

the next-generation US-based facility for QCD and nuclear science

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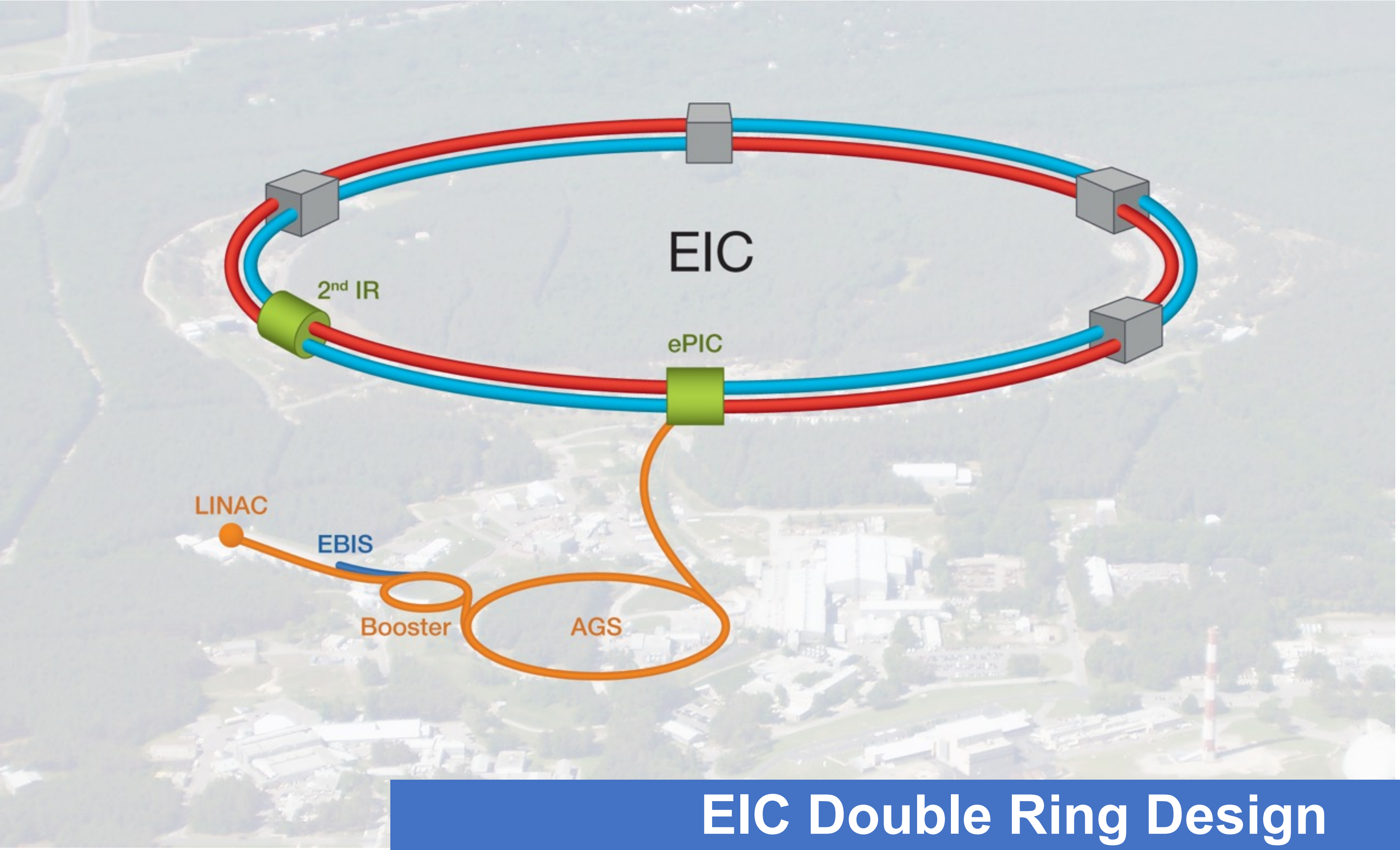
CFNS Stony Brook University

Annual Swedish Nuclear Physics and SFAIR meeting,
Uppsala, October 23-25, 2023

The Electron Ion Collider at Brookhaven National Laboratory



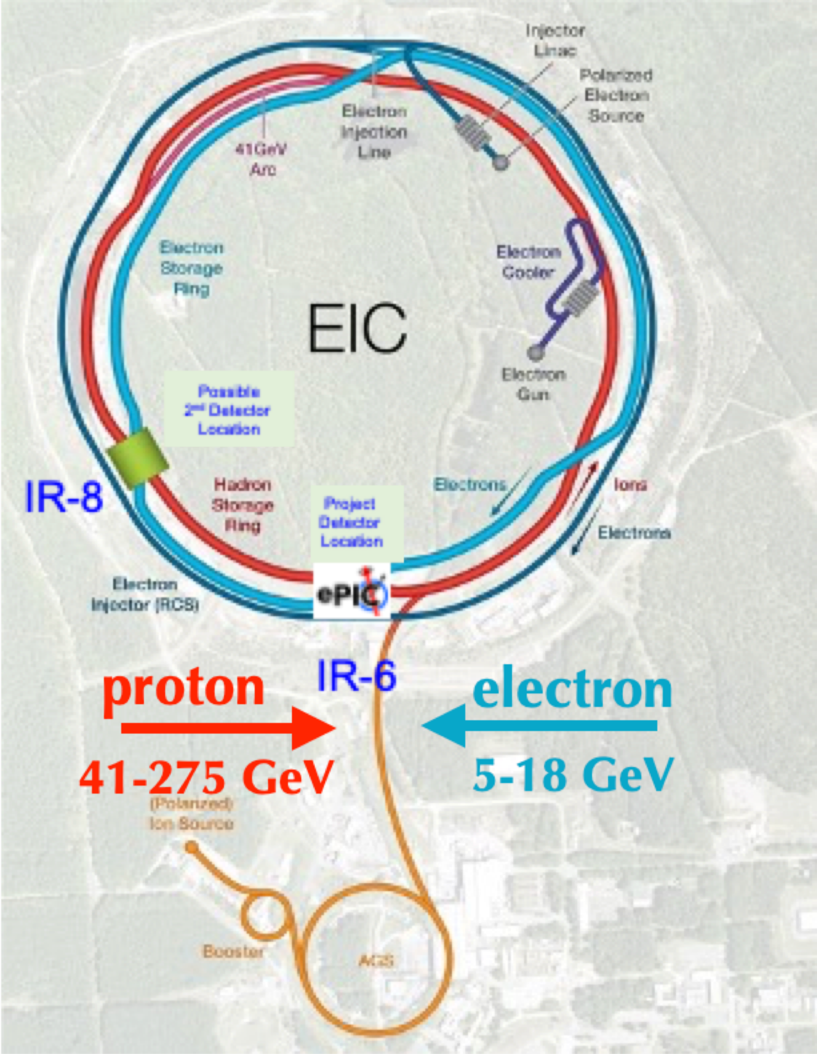
EIC Double Ring Design
Based on Existing RHIC Facility
RHIC Operations Conclude in 2025

EIC Project Requirements

Project Design Goals

- High Luminosity: L= 10^{33} – 10^{34} cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018).

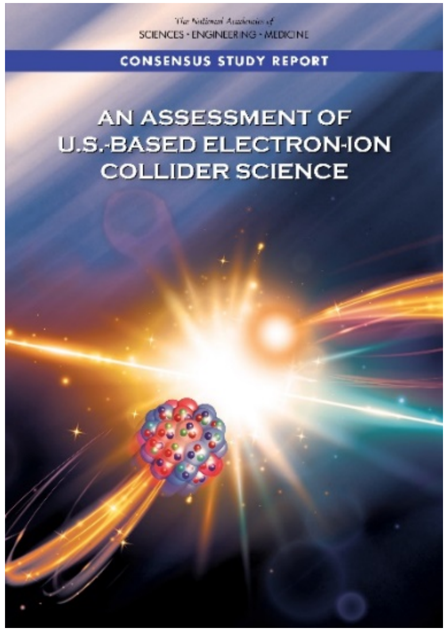


EIC – science questions

U.S. National Academy of Science Report: AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

"An EIC can uniquely address three profound questions
About nucleons—neutrons and protons—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 National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

- *Example*: the Higgs mechanism gives mass to the quarks, but the quark masses sum up to only O(1%) of the proton mass. The rest is generated by the strong interactions between then, which are described by QCD.

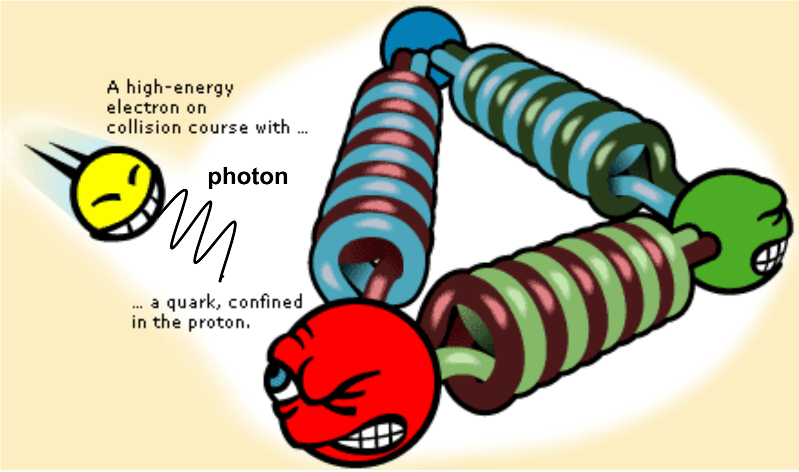
A *very* short introduction to electron scattering

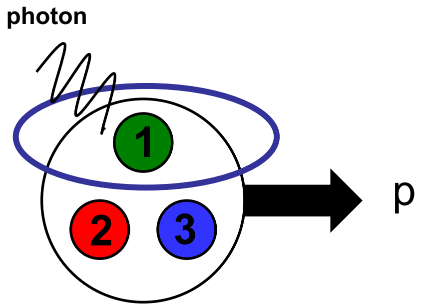
- Q^2: (four-)momentum transfer *from* the electron
  - 1/Q is the *transverse* size of the virtual photon.

- x: momentum (fraction) of the struck quark or gluon
  - 1/x is a measure of the *longitudinal* size (coherence length) of the photon in the rest frame of the target.

- t : (four-)momentum transfer *to* the target
  - t is the Fourier transform of the impact parameter b (small t corresponds to large b)
  - t and Q^2 are equivalent if no particles are produced

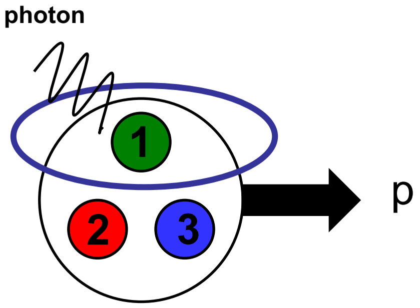
- Note that reaching a *smaller* value of x at a certain Q^2 requires a *higher* c.m. collision energy.



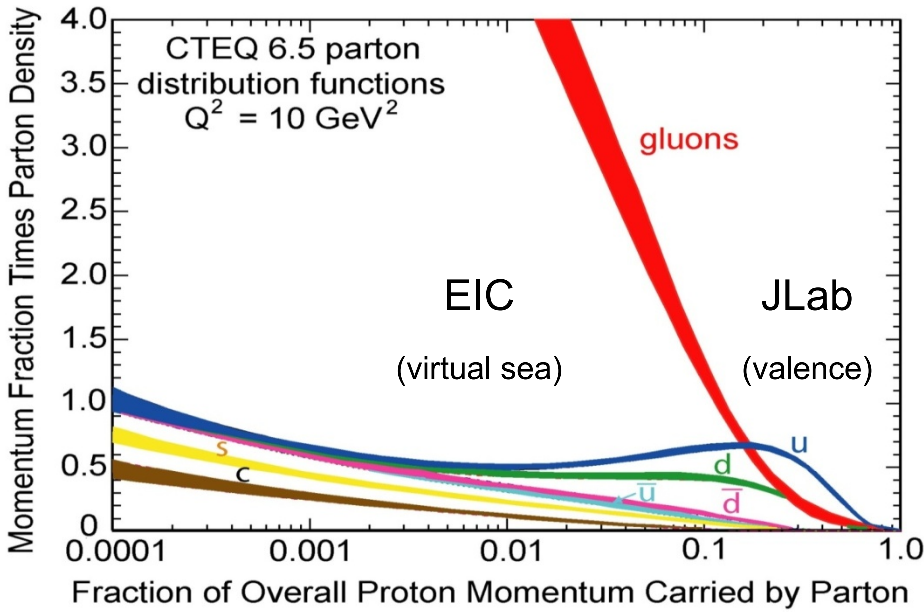


$x = p_1 / p_{proton}$

Momentum distributions of quarks and gluons

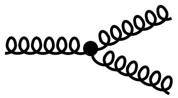


$x = p_1 / p_{proton}$



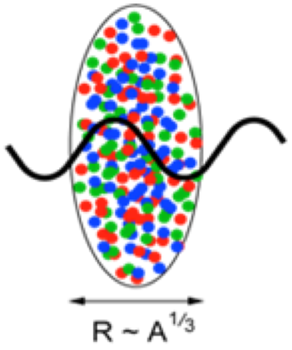
- (Deep Inelastic) Scattering of an electron off a quark or gluon tells you its momentum distribution (PDF) inside a nucleon.

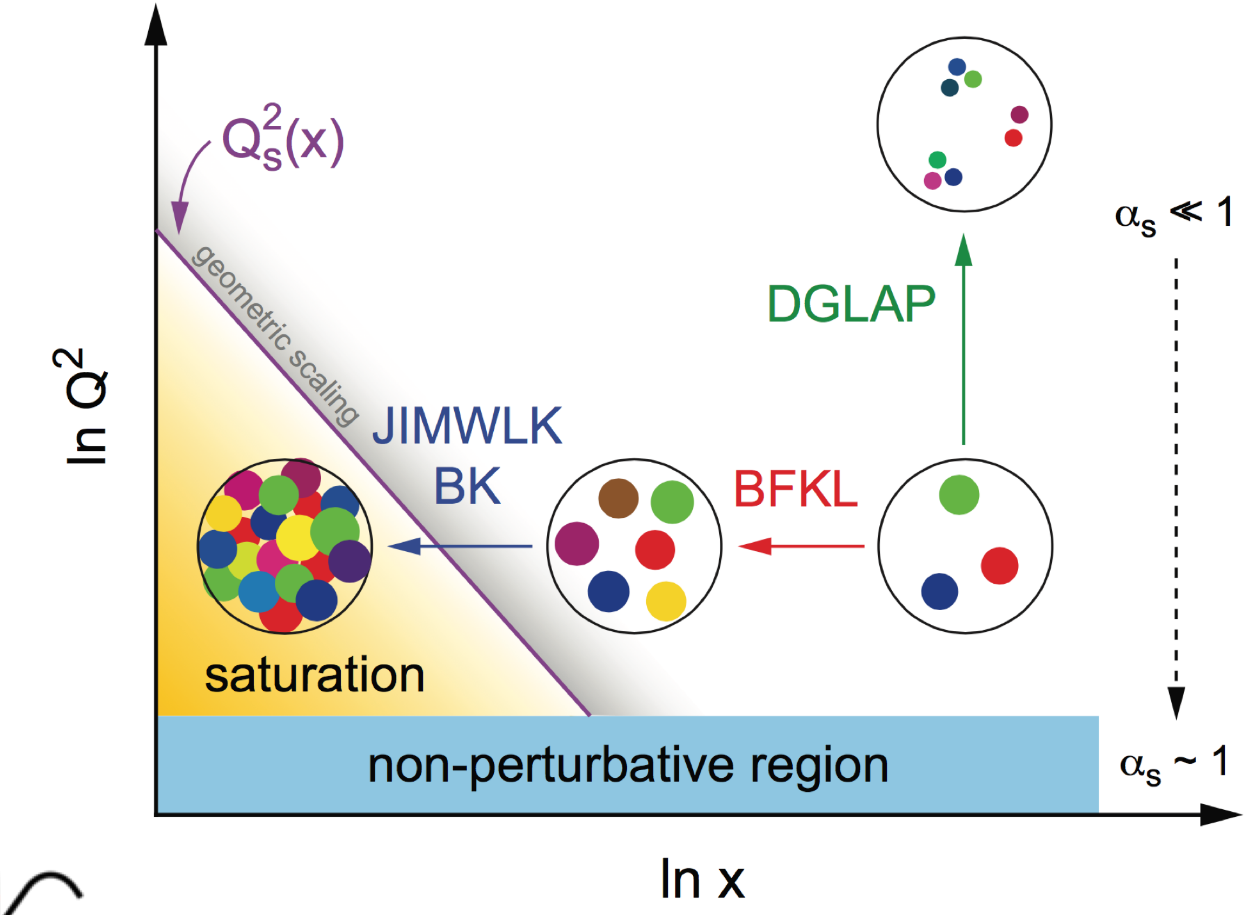
- The density of gluons at low-momentum (x) rises rapidly, since high-momentum gluons split into low-momentum ones



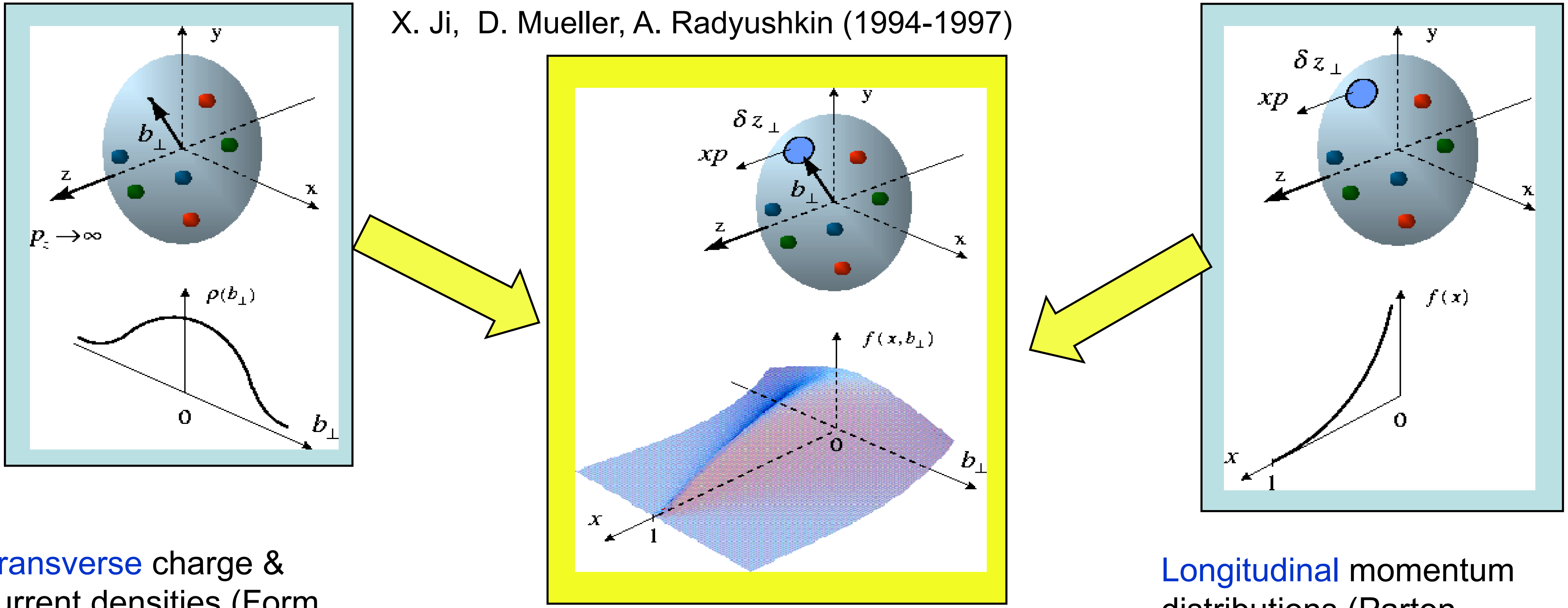
Matter at high gluon densities

- At high x and Q^2, the transverse size of the photon is small and the number of gluons is small – small cross section
- At low x and Q^2, the transverse size of the photon is large and the number of gluons is large – large cross section (black disk)
- The universal form of matter at high gluon densities is described can be described as a color glass condensate
- At low x, the coherence length of the photon is large, and it can interact with all gluons along inside its path inside a nucleus.
    - earlier onset of saturation.





3D structure (tomography) of nucleons and nuclei



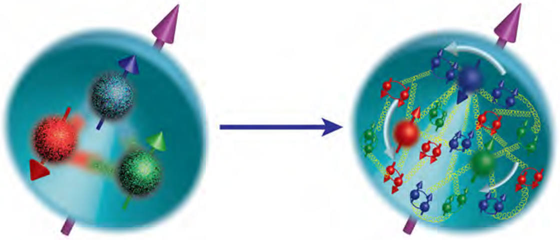
X. Ji, D. Mueller, A. Radyushkin (1994-1997)

Transverse charge & current densities (Form Factors)

Correlated quark momentum and transverse spatial distributions (Generalized Parton Distributions)

Longitudinal momentum distributions (Parton Distribution Functions)

The spin of the proton



The proton has spin ½, which reflects both the polarization of quarks and gluons, and their orbital motion.

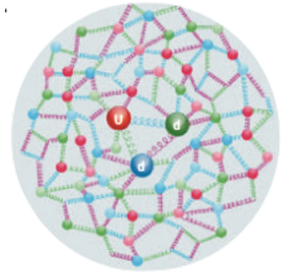
$$\tfrac{1}{2} = \underbrace{\overset{\sim 1/3}{\underset{\text{polarization}}{\frac{1}{2}\Delta\Sigma(\mu)}} + \overset{?}{\underset{\text{orbit}}{L_q(\mu)}}}_{\text{quarks}} + \underbrace{\overset{\text{small ?}}{\underset{\text{polarization}}{\Delta G(\mu)}} + \overset{?}{\underset{\text{orbit}}{L_g(\mu)}}}_{\text{gluons}}$$

What do we need to understand the origin of the proton spin?

Measure ΔG - gluon polarization

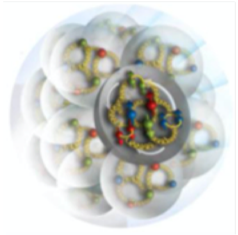
Measure 3D structure of the proton (TMD and GPDs) - orbital motion

EIC science – highlights and broader program



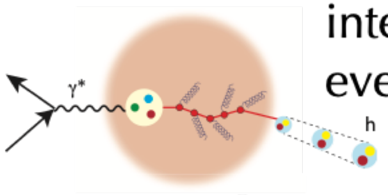
How are **partons** with their spins **distributed in space and momentum** inside the **Nucleon**, such that its **properties** emerge from their interactions?

Nucleon "femtography"



Does **gluon density saturate** at high energy, giving rise to a **universal gluonic matter** ?

Gluon saturation

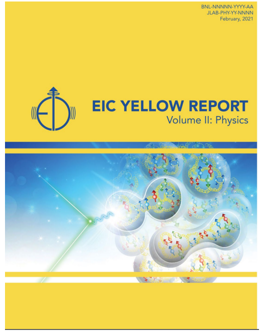


How do **colored partons propagate** and interact with **nuclear medium** such that eventually **colorless hadrons emerge** ?

Mechanisms of color confinement and nuclear binding

But EIC science is very broad!

- EIC Yellow Report:
  - Nucl.Phys.A 1026 (2022), 122447
  - arXiv:2103.05419

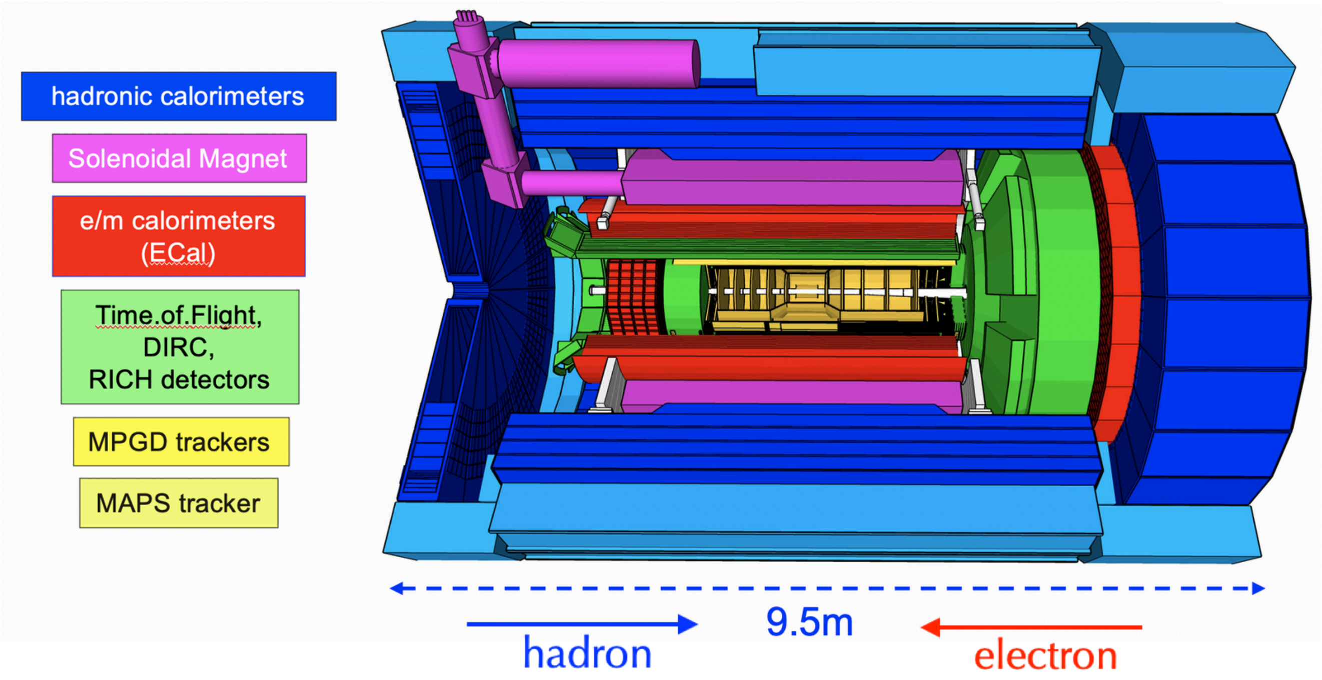


It will include

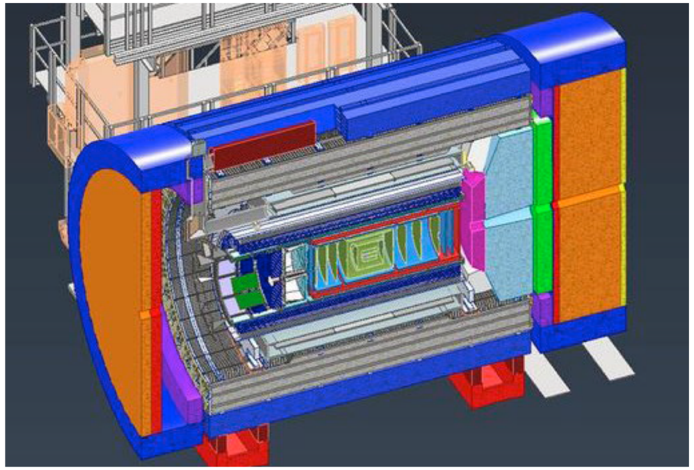
- Photoproduction and spectroscopy of exotic states (*e.g.*, XYZ)
- Structure of nuclei

and much more.

The ePIC detector and collaboration



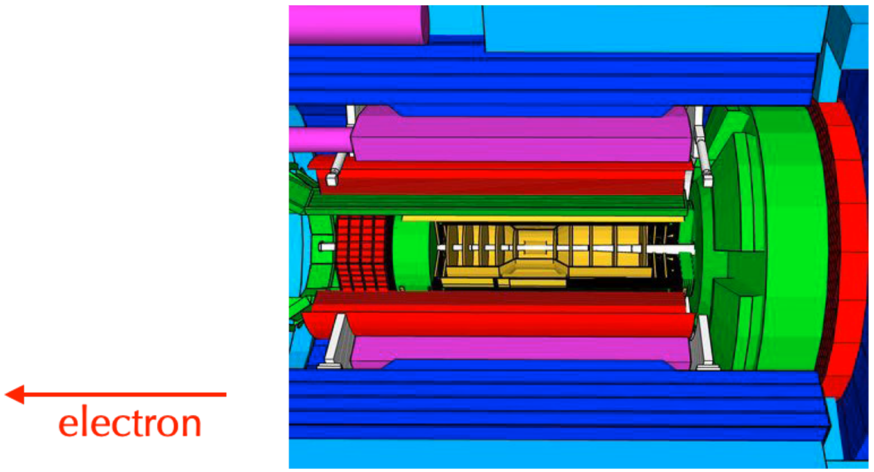
- The ePIC detector is hermetic (4π acceptance), and equipped with a full suite of subsystems for tracking, calorimetry, and particle identification to detect and identify the scattered electron and all produced particles.

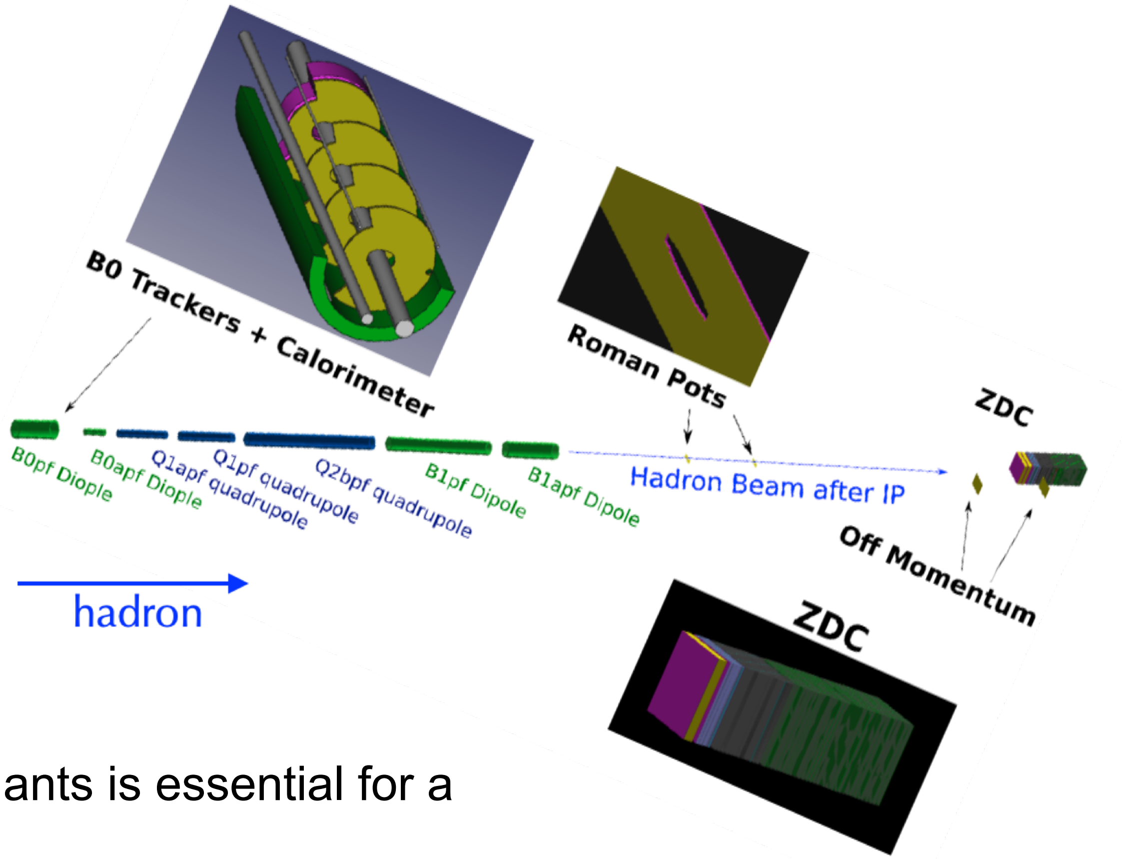


https://wiki.bnl.gov/EPIC/index.php

- The majority of the funding for the ePIC detector comes from the EIC project.
- The ePIC collaboration has now finalized subsystem selection and is currently focusing on preparations for procurement of long-lead items (CD-3A).
- New collaborators are welcome! If you have questions, please contact the spokespersons
  - John Lajoie <lajoie@iastate.edu>
  - Silvia.DallaTorre@ts.infn.it

ePIC @ IR6 is integrated with an extensive array of near-beam detectors

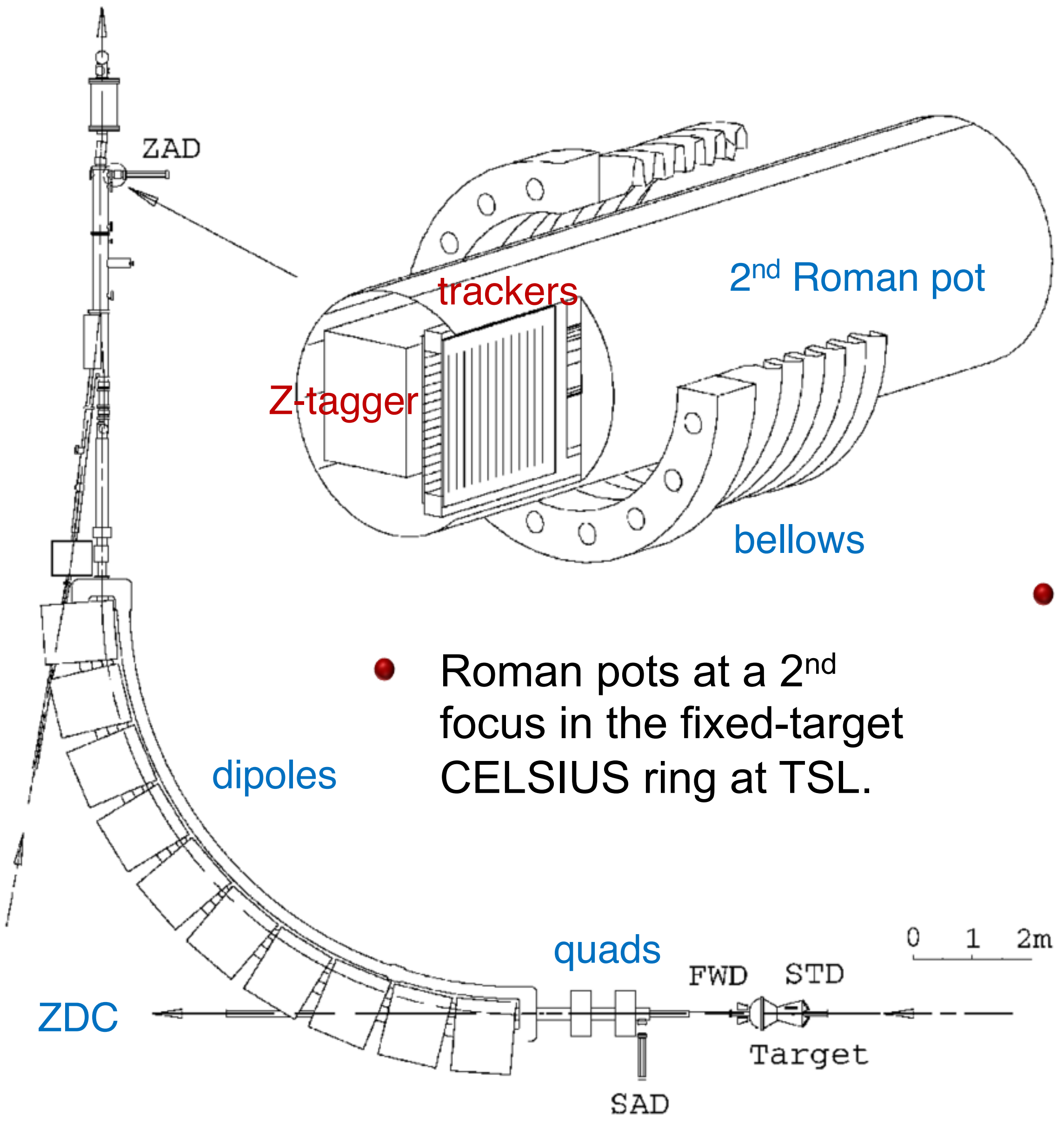




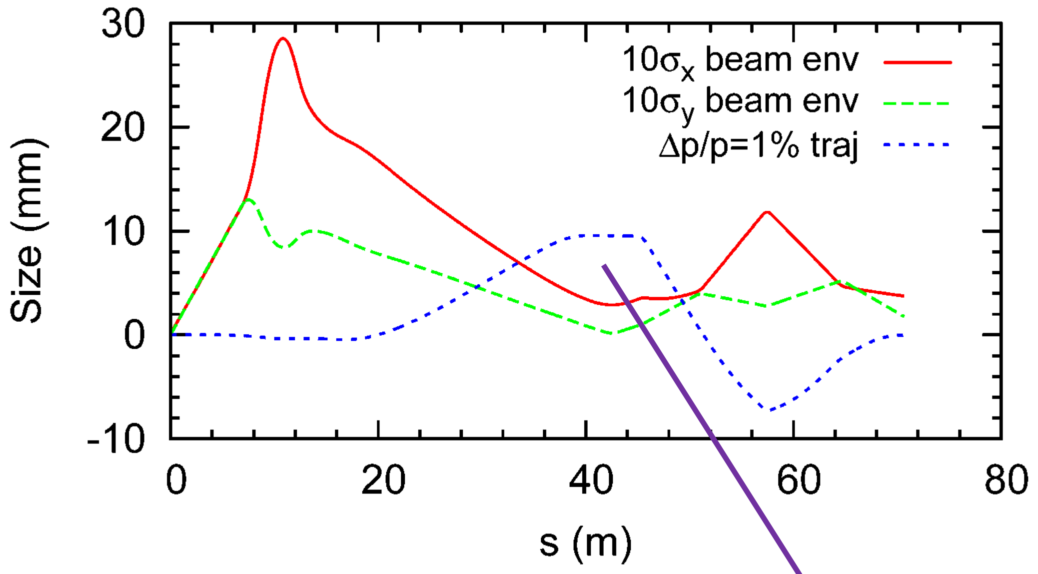
- Detection of the target (proton / ion) remnants is essential for a large part of the EIC program.

- On the outgoing electron side, there are also detectors for tagging low-Q^2 electrons, as well as measuring the luminosity and polarization (not shown).

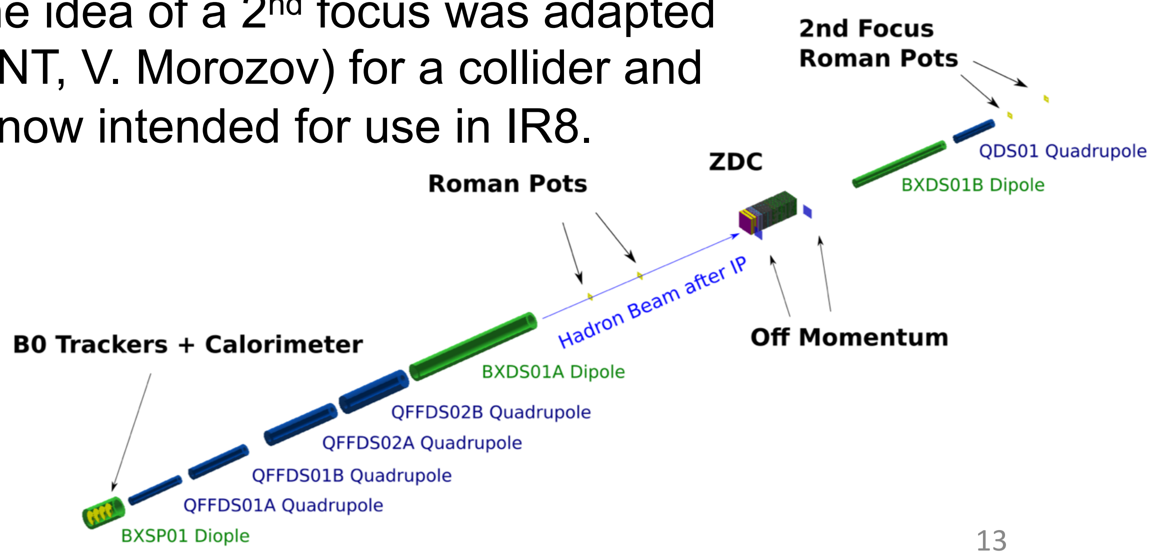
Optics for a 2nd EIC detector were inspired by the CELSIUS ring in Uppsala



- Roman pots at a 2nd focus in the fixed-target CELSIUS ring at TSL.

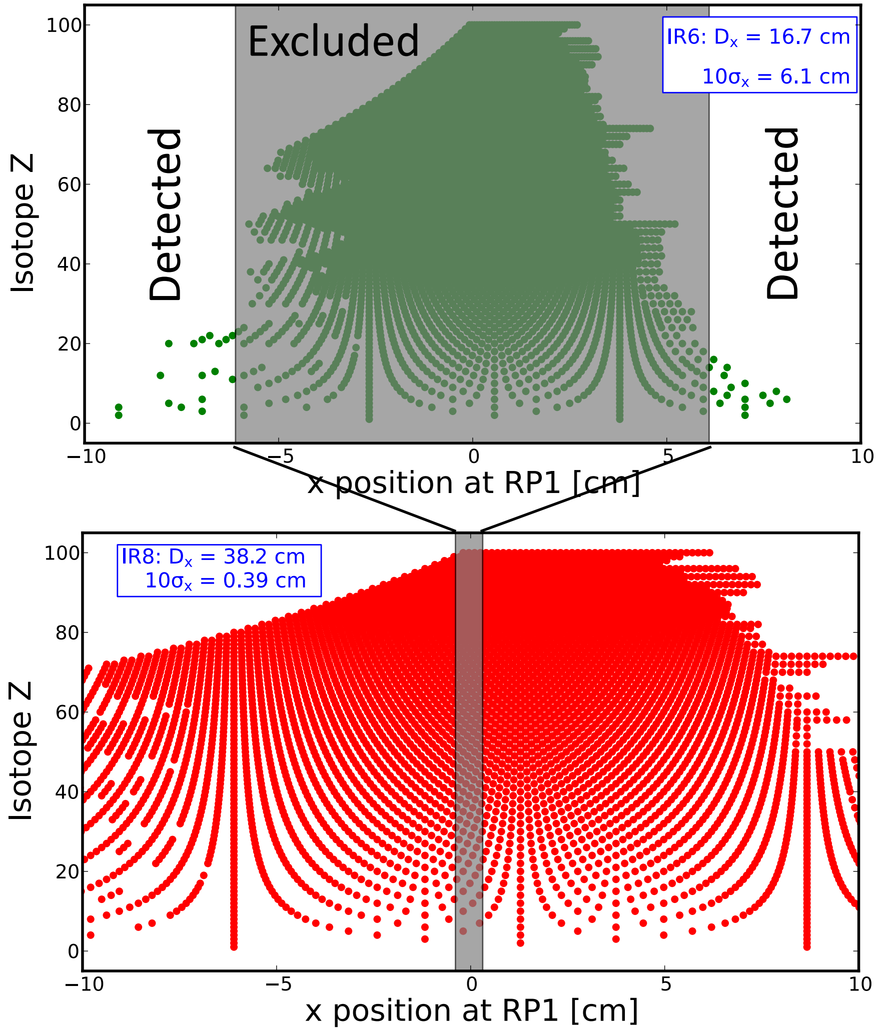


- The idea of a 2nd focus was adapted (PNT, V. Morozov) for a collider and is now intended for use in IR8.



EIC far-forward acceptance with and without a 2nd focus

Ion fragments from ^{238}U



x position ~ A/Z

Without 2nd focus:
(EPIC @IR6)

← Z' vs x_{RP}

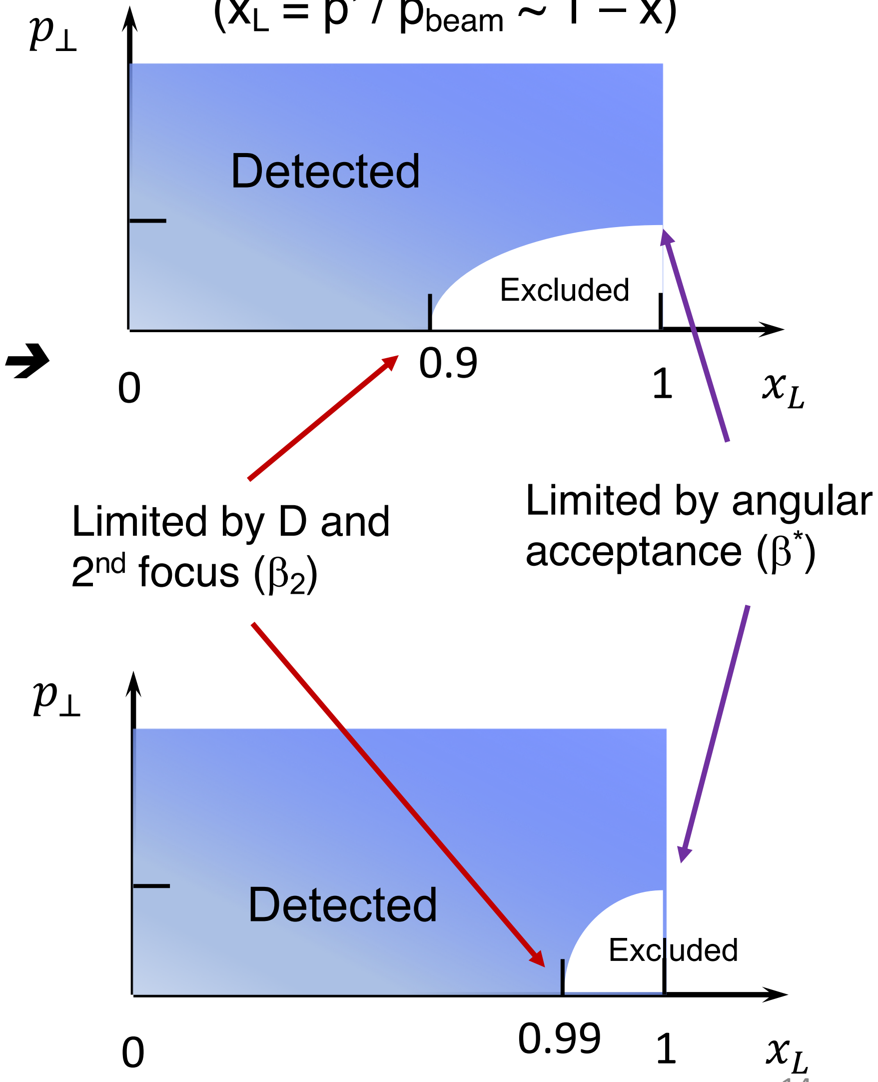
$p_\perp$ vs x_L →

With 2nd focus:
(Detector 2 @ IR8)

Order-of-magnitude improvement in forward acceptance

Exclusive protons

($x_L = p' / p_{beam} \sim 1 - x$)

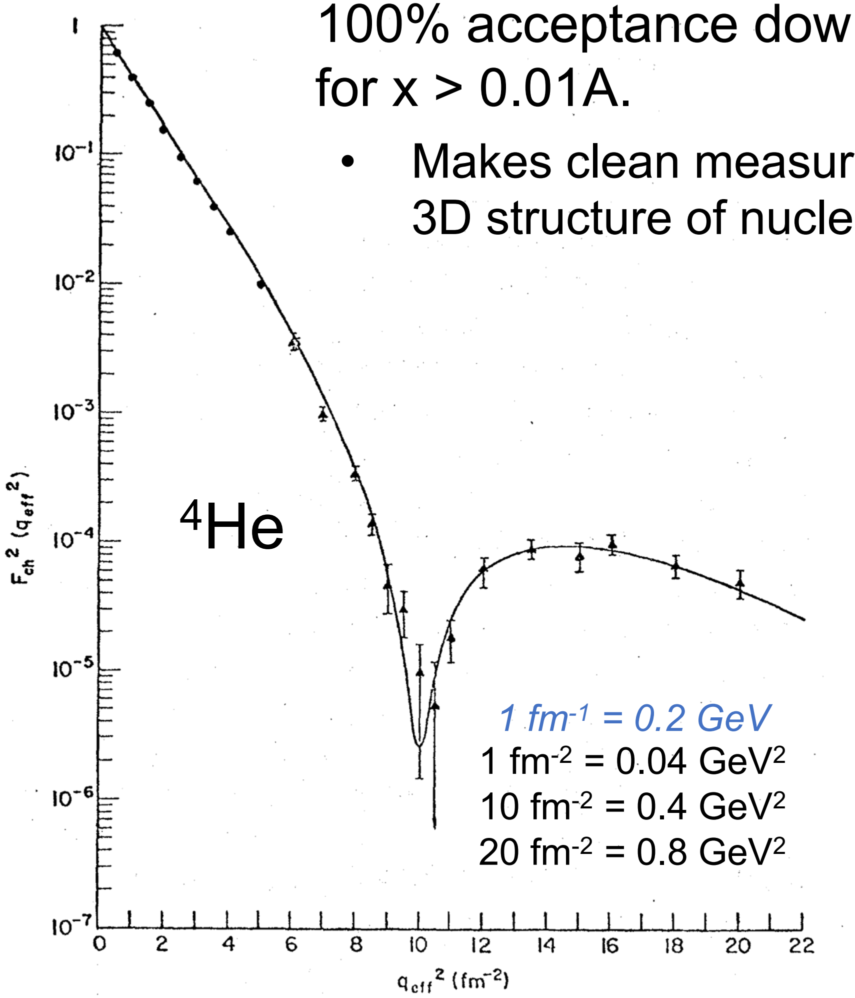


Limited by D and 2nd focus (β_2)

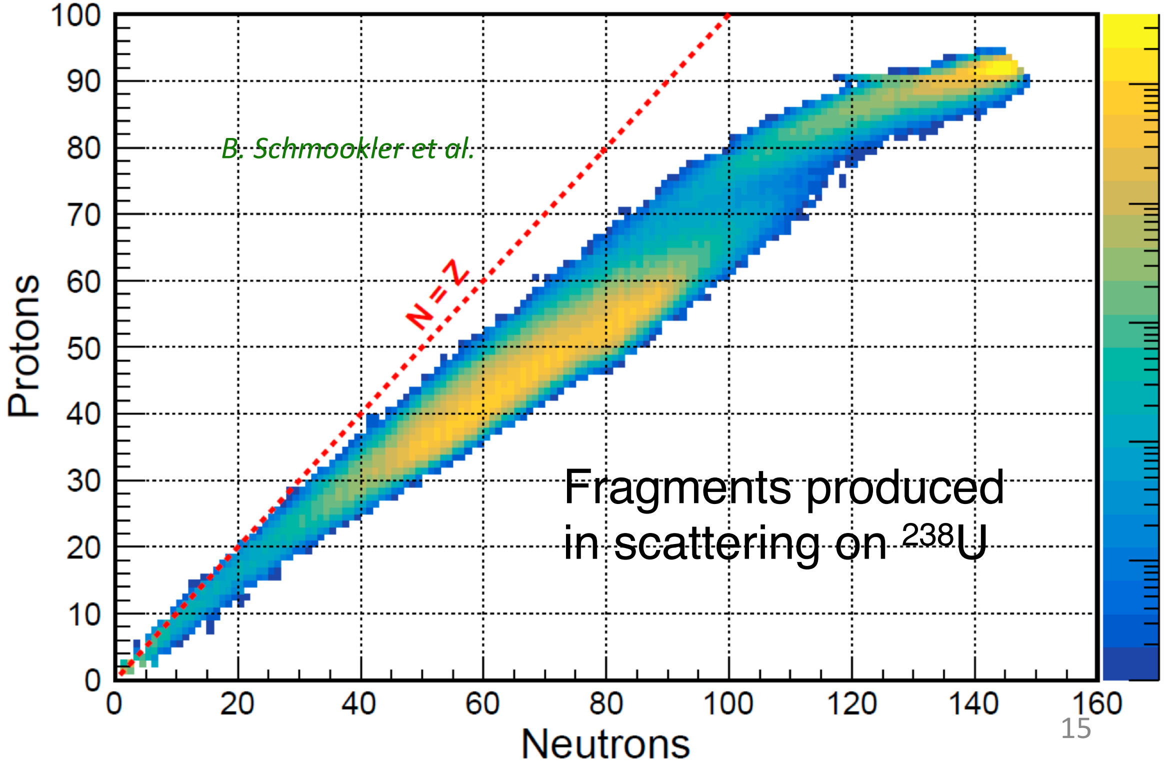
Limited by angular acceptance (β^*)

Example: exclusive coherent scattering on nuclei

- For light nuclei, the 2nd focus enables *detection* with essentially 100% acceptance down to $p_T = 0$ for $x > 0.01A$.
  - Makes clean measurements of 3D structure of nuclei possible.



- For heavier nuclei, incoherent events can be suppressed by detecting fragments (including neutrons and photons) from the breakup.



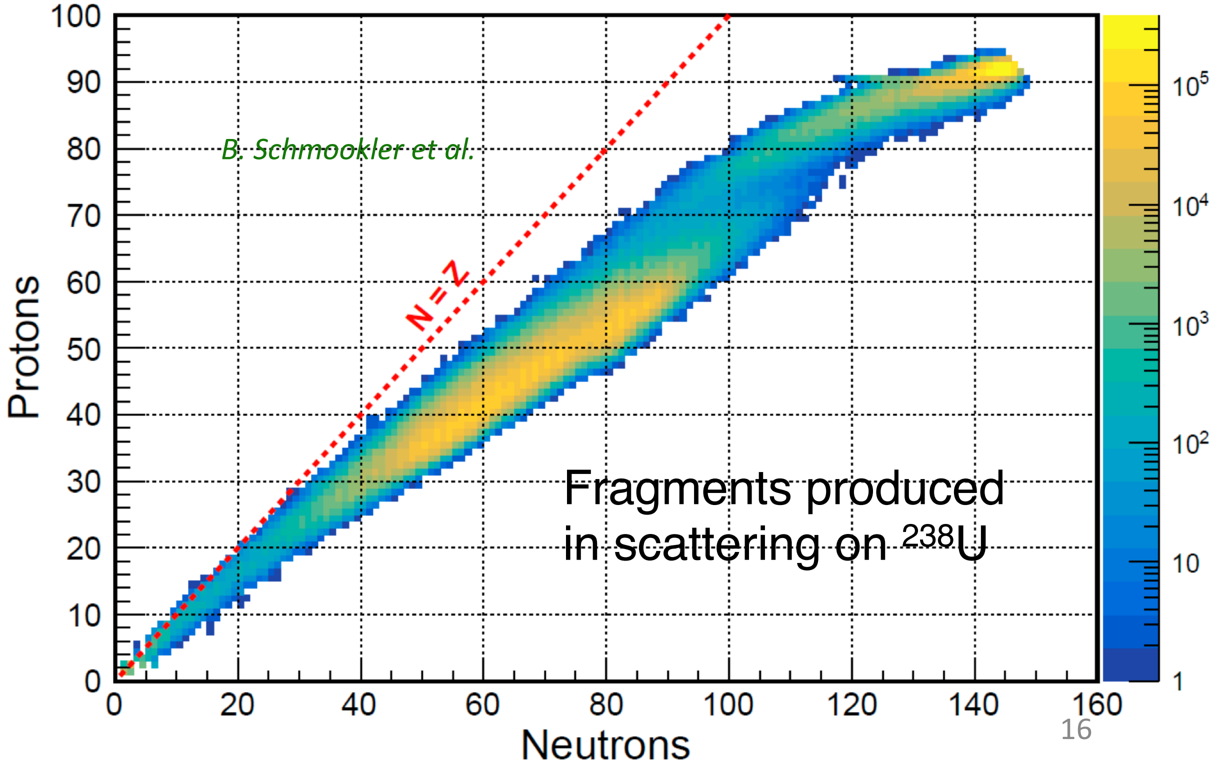
Example: tagging of heavy spectators

- Both IR6 and IR8 support tagging of spectator protons from light ions (d, He)
  - These spectators have magnetic rigidities that are very different from that of the beam ions

- A 2nd focus will allow tagging of heavy spectators
  - A-1 nuclei up to Zr-90
  - A-2, *etc*, for almost any nucleus

- Tagging of heavy spectators enables, for instance, measurements of reactions on a bound nucleon

- The produced fragments will also contain rare isotopes.
  - Gamma spectroscopy possible by measuring boosted forward-going photons in coincidence
  - Interest from the FRIB community



Motivation for a 2nd detector

- Needed to unlock the full discovery potential of the EIC
  - Cross checks of key results are essential!
  - Implies a general-purpose collider detector able to support the full EIC program

- New physics opportunities
  - Take advantage of much-improved near-beam hadron detection enabled by a **2nd focus**,
  - Impacts, for instance, exclusive / diffractive physics; greatly expands the ability to measure recoiling nuclei and fragments from nuclear breakup.
  - New ideas beyond the Yellow Report and CD0 (EW, BSM)? Your input is essential!

- Complementary design features
  - Possible to reduce combined systematics (as for H1 and ZEUS)
  - Particularly important for the EIC where high statistics mean that uncertainties for a large fraction of the envisioned measurements will be systematics limited

Aspirational goals for a 2nd EIC detector

- **MAGNETIC FIELD –** Solenoid field up to 3T (compared with 1.7 T in ePIC / Detector 1), allowing for high-resolution momentum reconstruction for charged particles.

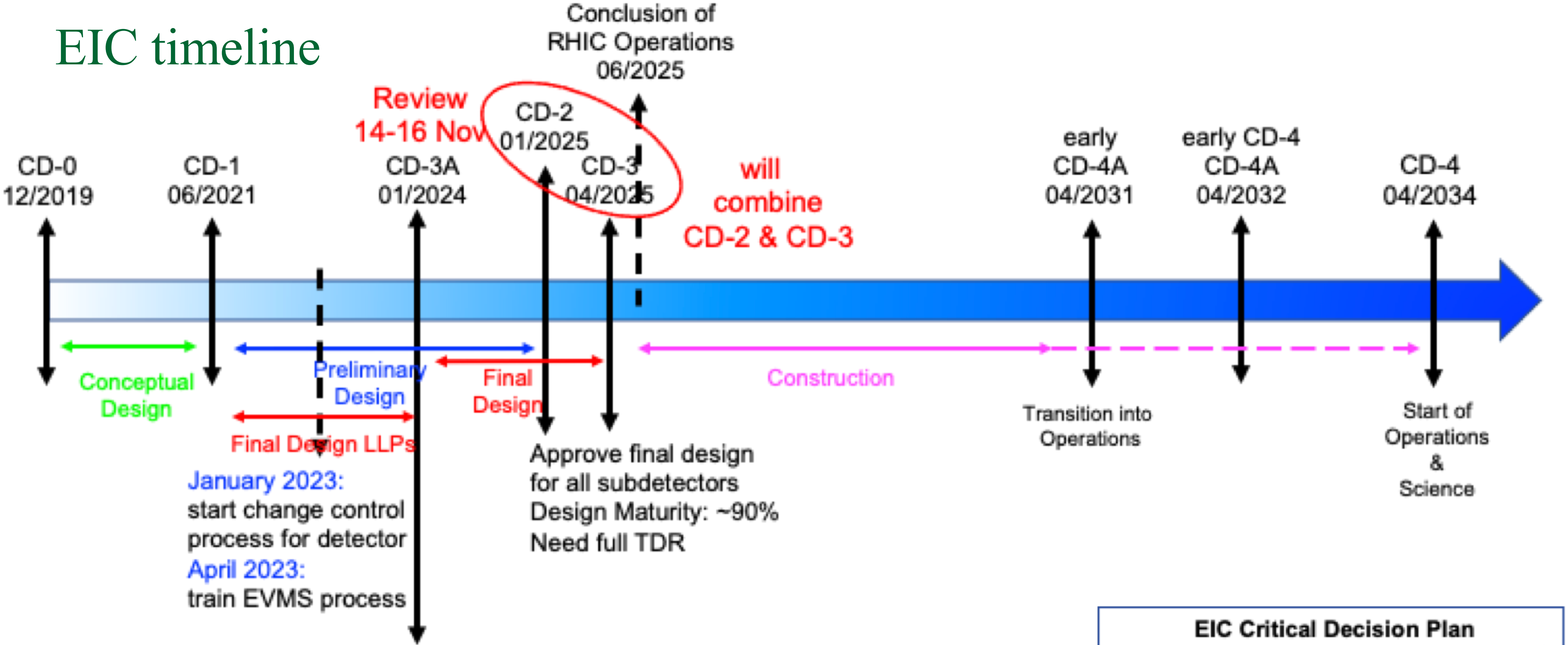
- **EXTENDED COVERAGE** for precision electromagnetic calorimetry – important for DVCS on nuclei and spectroscopy.

- **MUONS –** enhanced muon ID in the barrel and backward region.

- **BACKWARD HADRONIC CALORIMETER –** Low-x physics, reconstruction of current jets in the approach to saturation.

- **SECONDARY FOCUS –** tagging for nearly all ion fragments and extended acceptance for low-p_T/ low-x protons. Enables detection of short-lived rare isotopes.

EIC timeline



Conclusion of RHIC Operations 06/2025

Review 14-16 Nov

CD-0 12/2019

CD-1 06/2021

CD-3A 01/2024

CD-2 01/2025

CD-3 04/2025

will combine CD-2 & CD-3

early CD-4A 04/2031

early CD-4 CD-4A 04/2032

CD-4 04/2034

January 2023: start change control process for detector

April 2023: train EVMS process

Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR

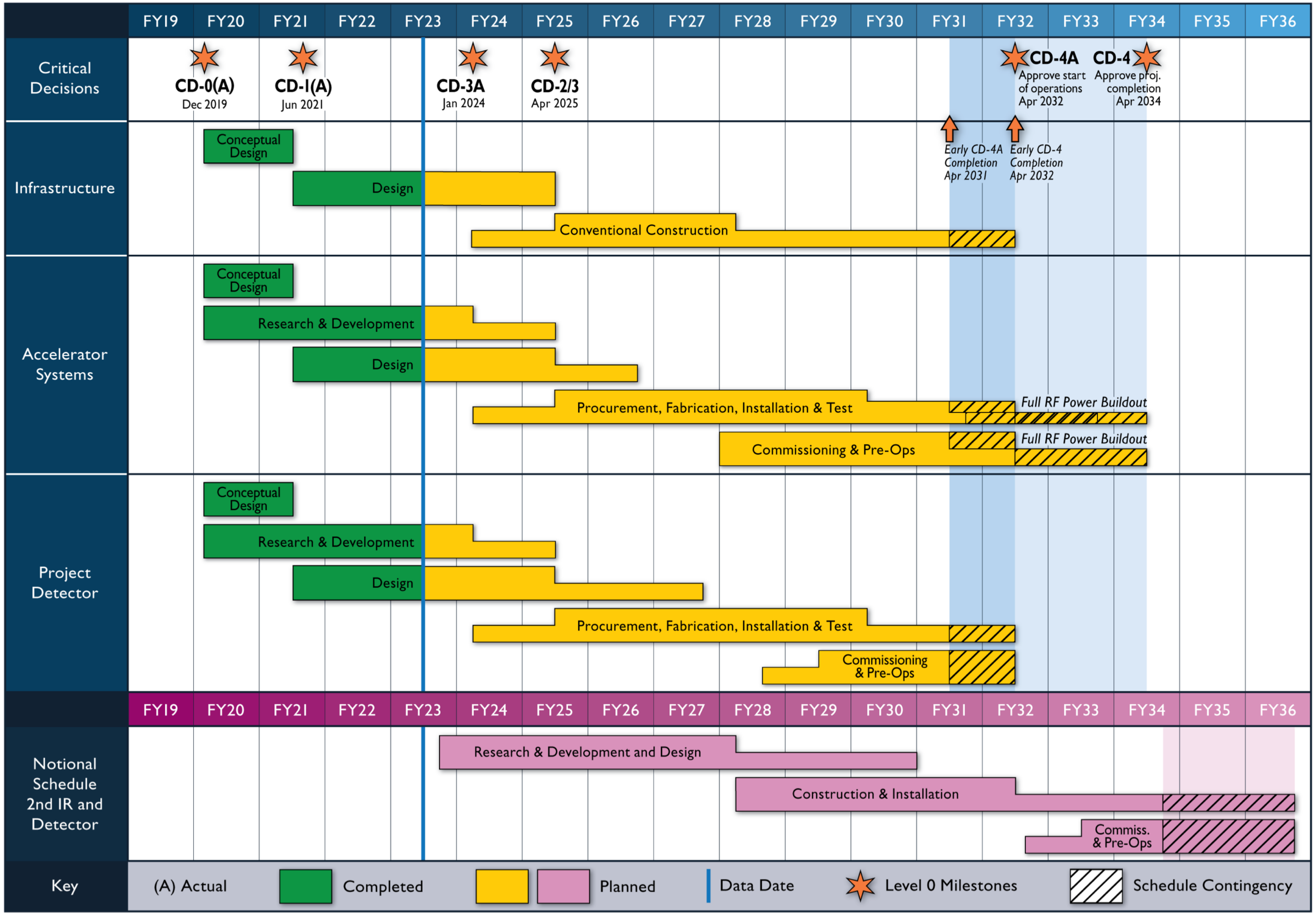
Define Baseline:
Subdetector technologies,
Scope, Cost & Schedule
→ Long Lead Procurement items ←
Design Maturity: ~90%
Plan is tracked through EVMS
& Change control process
Need TDR for LLPs

EIC Critical Decision Plan

CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3a	**January 2024**
CD-2	January 2025
CD-3	**April 2025**
CD-4a early finish	April 2031
CD-4a	April 2032
CD-4 early finish	April 2032
CD-4	**April 2034**

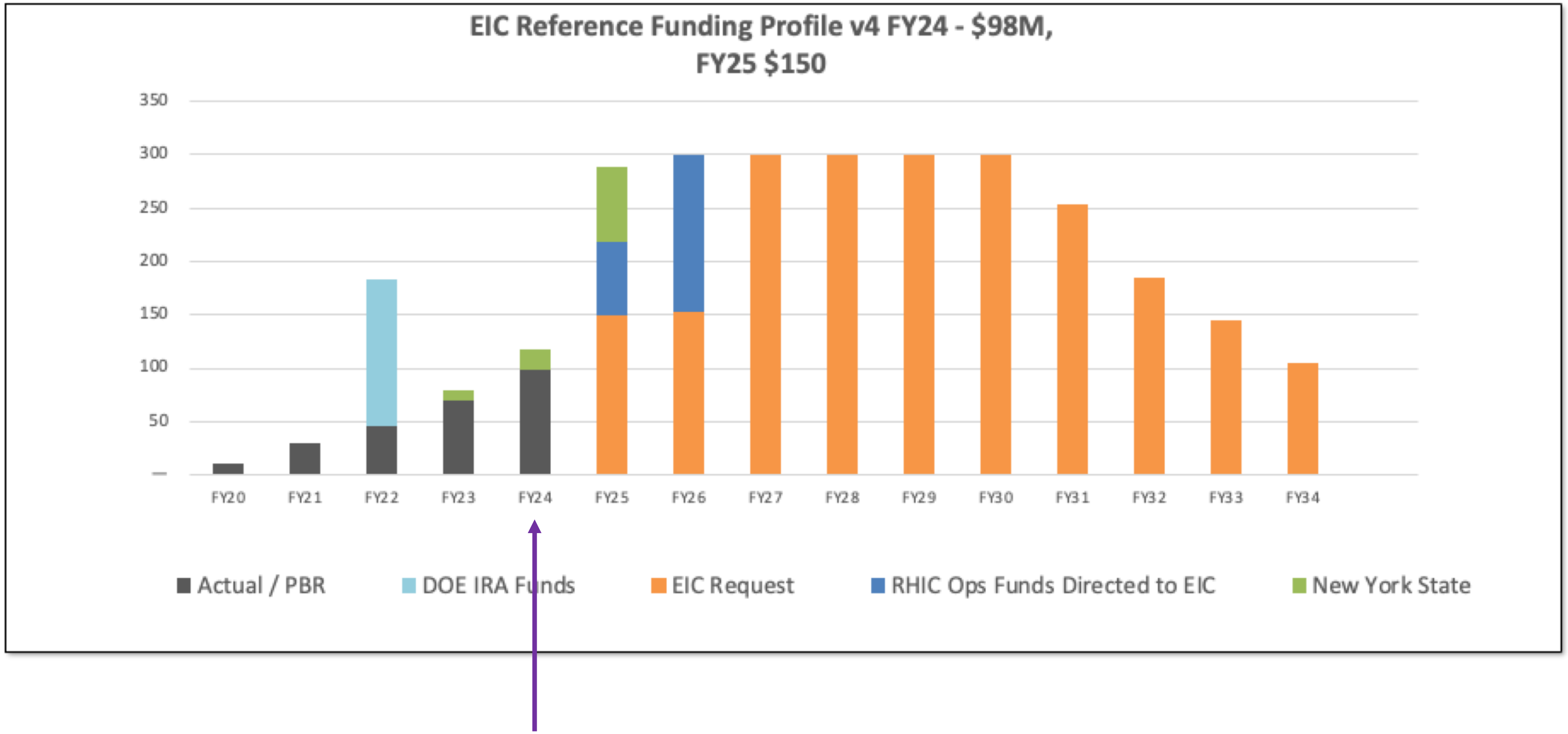
Reference schedule including a 2nd IR and Detector

Jim Yeck, EIC 2nd detector WS, May 2023



Second detector

EIC Reference Funding Profile



Today

Non-DOE Interest & In-Kind Contributions to ePIC / Detector 1

Entity	Interest and Important Facts
NSF	NSF-MSRI pre-proposal submitted by 10 US universities – aims at full scope of backward EM calorimetry (eECal). Armenia, Czech, France/IN2P3 as unfunded contributors. Invited to submit proposal. Final NSF review is ongoing.
CERN	MAPS sensor design developed by CERN/ITS-3 Group providing synergy with ALICE. Synergy of gaseous-based Cherenkov detectors and photon-sensors with ALICE & LHCb. Synergy of Forward AC-LGAD design with CMS endcap timing layer.
Armenia	Contributions, mainly labor to eECal and many EM calorimetry and particle id detectors component tests.
Canada	EIC included in 2022 Canadian Subatomic Physics Long-Range Plan; Interested in Compton Polarimetry, Barrel Electromagnetic Calorimetry and Software
China	Forward EM Calorimeter
Czech	Working with funding agency; Interested in eECal (PbWO4 crystals and glass) and Silicon
France/IRFU	Interested in MPGD/racking, electronics. Provided in-kind contributions to SC magnet design and interested to continue labor oversight during magnet construction.
France/IN2P3	International contribution to backward EM calorimetry (including in-kind design) and to readout electronics (two ASICs for AC-LGAD detectors and Calorimetry). IRFU & IN2P3 discussing together for higher-level contributions.
India	Consortium is working with Funding agency; Interested in detector software (non-project scientific contribution), contributions to DAQ/slow controls. Investigating further hardware contributions (including possible links with Si plants).
Italy/INFN	Aims at major scope of forward particle identification detector (dRICH), at (part of) the Si/MAPS tracker scope, and at photo-sensor contributions. Further investigating possible interest in EIC detector magnet scope.
Israel	B0 Detectors (Si tracking and PbWO4)
Japan	Interested in a US-Japan agreement; Aims at full scope of Zero-Degree Calorimeter in collaboration with Taiwan/Korea. Pursuit of full scope of barrel AC-LGAD detector as EIC-Asia consortium. Contribution to DAQ/streaming. Possible aerogel.
Korea	Aims at major scope for fiber-based barrel EM calorimeter, Also work packages for barrel AC-LGAD and Si-based hadronic calorimetry for ZDC.as part of EIC-Asia consortium (includes also Japan,Taiwan), Collaboration on Si tracking detector.
Poland	Actively working with ministry/funding agency; Interested in detectors along the beam line (luminosity detector, Roman Pots)
Taiwan	Pursuit of full scope of barrel AC-LGAD as part of EIC-Asia consortium. LYSO-based EM calorimeter for ZDC, Also optical readout/fiber. Possible later interest in PCBs. Computing.
UK	STFC seed funding for UK detector R&D (3M£). Interest in Si/MAPS tracker, polarimetry and detectors along the beams (Low-Q2/TimePix). Follow-up STFC/UKRI request for 5-7 years submitted early 2023 (includes accelerator part).

The EIC user group at a glance

EIC Users Group Formed in 2016
EICUG.ORG

Status January 2023:

- Collaborators 1391
- Institutions 277
- Countries 37

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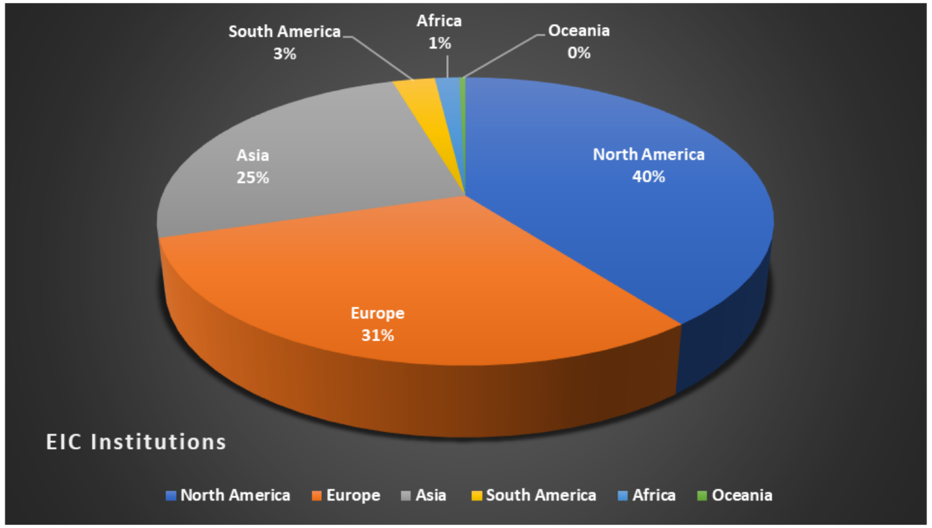
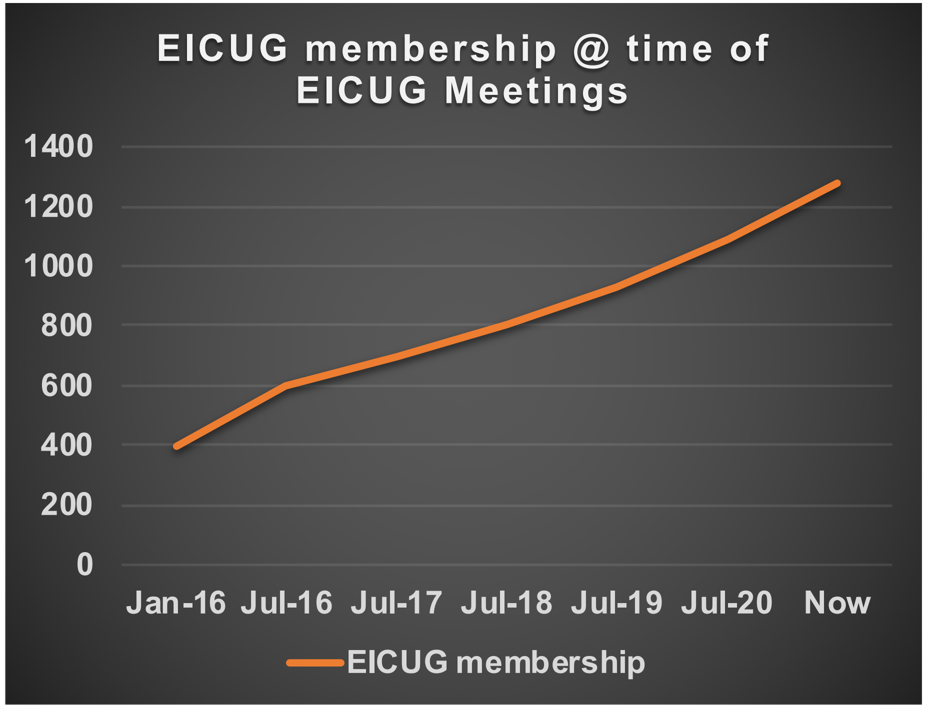
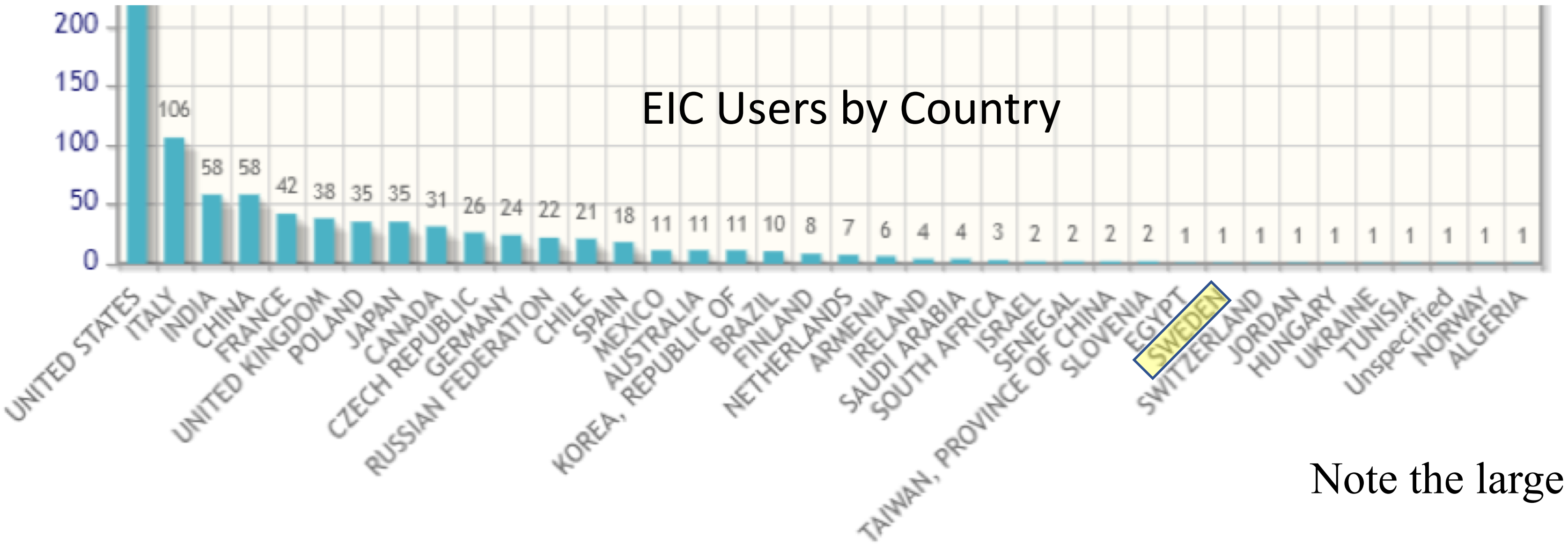
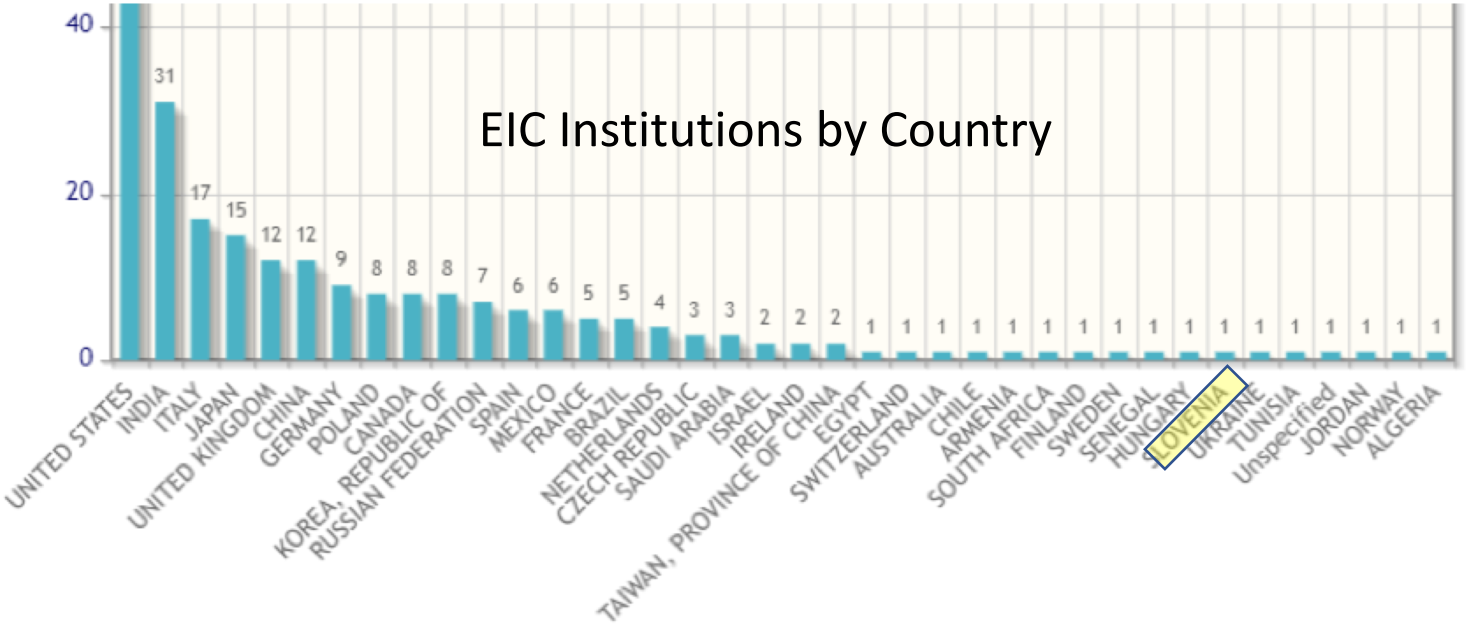




EIC users by country

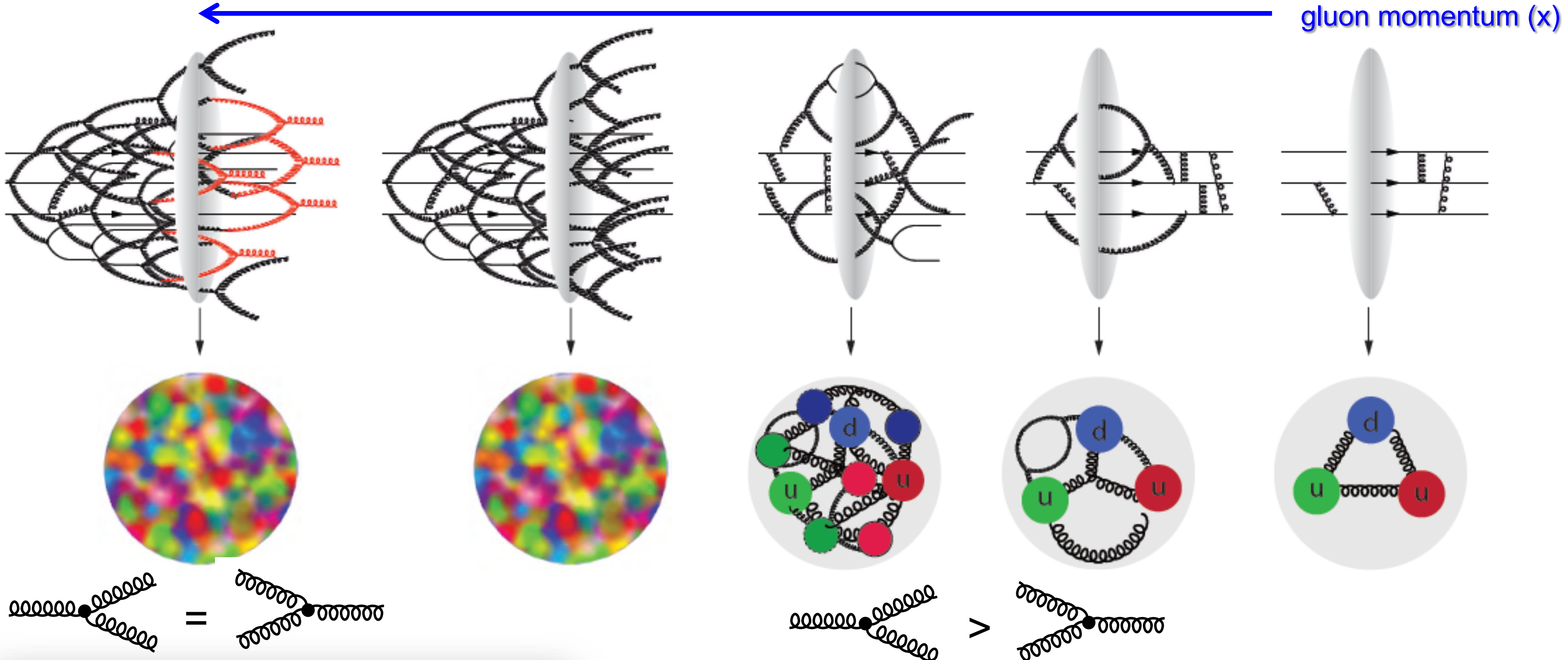


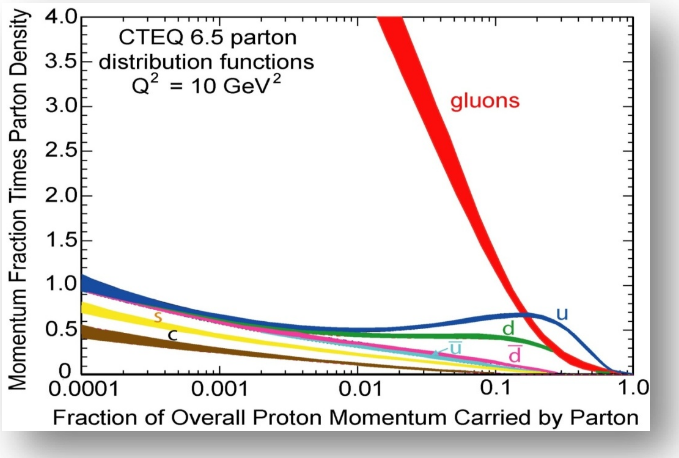
Note the large EU participation!

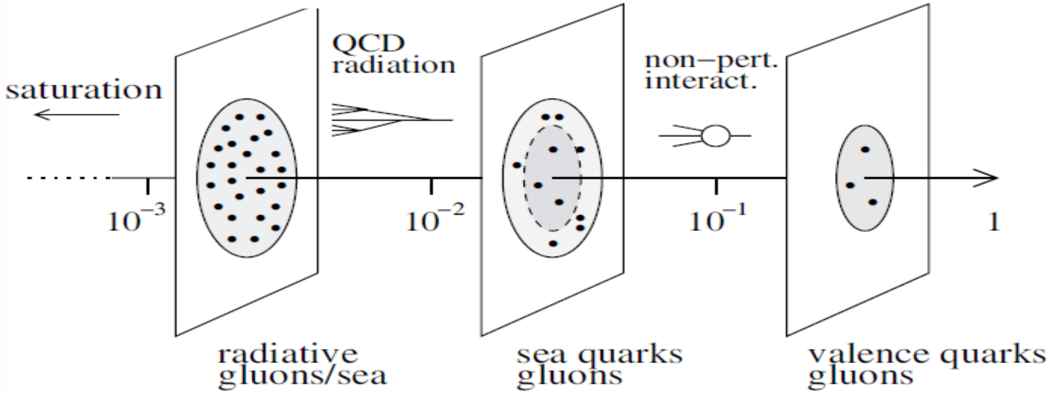


Thank you!

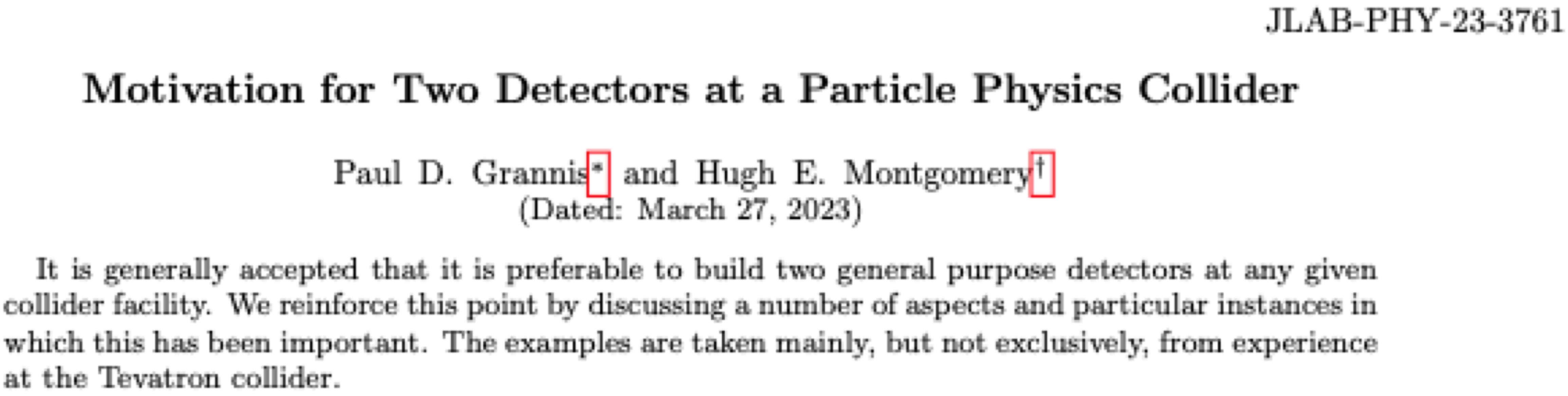
Quarks and gluons inside a moving proton







Motivation for two detectors – a HEP perspective



JLAB-PHY-23-3761

Motivation for Two Detectors at a Particle Physics Collider

Paul D. Grannis[*] and Hugh E. Montgomery[†]
(Dated: March 27, 2023)

It is generally accepted that it is preferable to build two general purpose detectors at any given collider facility. We reinforce this point by discussing a number of aspects and particular instances in which this has been important. The examples are taken mainly, but not exclusively, from experience at the Tevatron collider.

arXiv: 2303.08228v2 March 24, 2023

The paper was inspired by Mont's presentation at the first 2nd EIC detector CFNS workshop in December 2022. Mont was also JLab director 2008-2017, and has been very interested in the EIC

Three strategies for detecting forward-going particles

$$\sigma = \sqrt{\beta\epsilon + \left(D\frac{\Delta p}{p}\right)^2}$$

These are mutually supportive and ideally we want to benefit from all three

- **Drift**
  - A particle scattered at a small angle will eventually leave the beam (which could be far away).
  - When using *only* this method, the scattering angle has to be larger than the angular spread (divergence) of the beam, which is determined by the strength of the focus at the collision point (β^*).

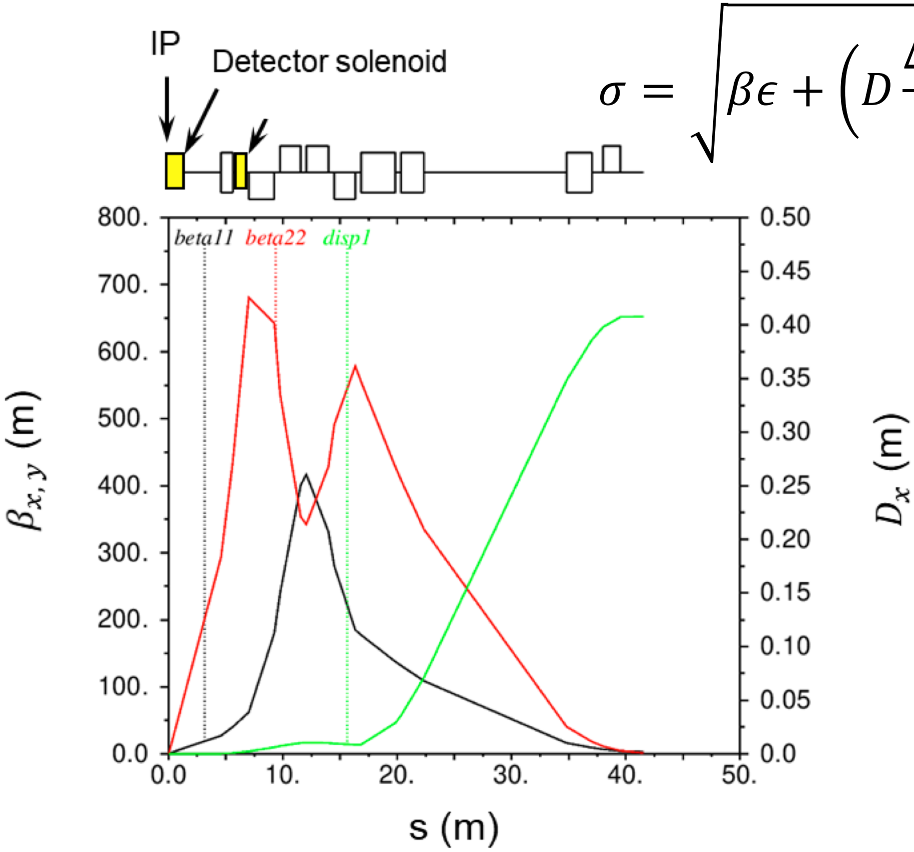
- **Dispersion** (D) translates a longitudinal momentum loss into a transverse displacement
  - dx = D dp/p , where dx is the transverse displacement at $p_T = 0$
  - With D = 0.4 m, dp/p = 0.01, and $p_T = 0$, the transverse displacement for would be **0.4 cm**

- **A 2nd focus** can reduce the (10σ) beam size at the detection point
  - Enables detectors to be placed closer to the beam – very effective in combination with dispersion
  - Without a 2nd focus (IR6): **4 cm** (high luminosity / divergence), **2 cm** (low luminosity / divergence)
  - With a 2nd focus (IR8): **0.2 cm** (high luminosity / divergence)

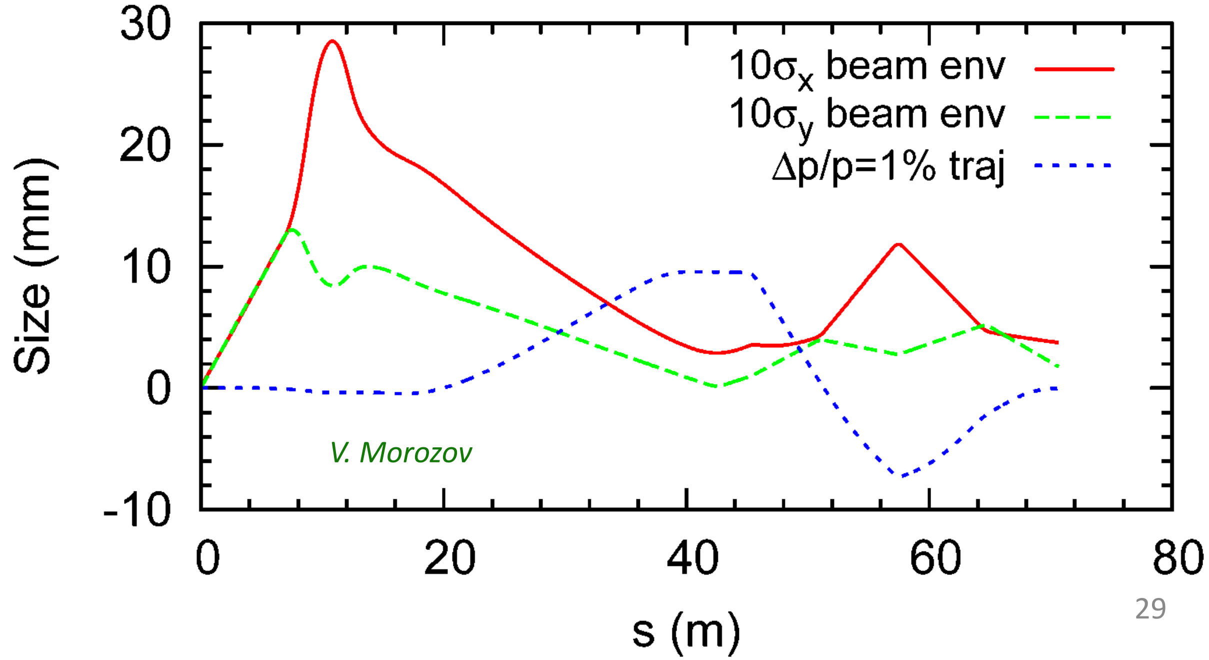
Beam optics and the actual trajectory of a $p_T = 0$ particle (blue)

- For optimal detection, the (2nd) focus has to coincide in x and y at the point of maximum dispersion (green line).
  - σ_x and σ_y should be comparable at the 2nd focus (and thus $\beta_x < \beta_y$ since $\varepsilon_x > \varepsilon_y$)

$$\sigma = \sqrt{\beta\epsilon + \left(D\,\frac{\Delta p}{p}\right)^2}$$



- A zero degree particle (blue) briefly emerges from the beam at the 2nd focus about 40 m downstream of the IP where it can be detected
  - Particles with a non-zero angle emerge earlier .
- The 2nd focus refers to the *beam*. Scattered particles have their *maximum* transverse displacement here.



Detector II/IP8 and WG charge

Renee Fatemi, EIC UG meeting, Stony Brook, July 2022

"With a clear mandate from DPAP and the EICUG to support and organize a Detector II/IP8 effort, the SC held discussions with Project, Detector I and CORE leadership. We agreed to form a dedicated working group that would address the following charge:"

1. Engage the broader community, ***including theorists, accelerator physicists and Detector I experimentalists***, to fully develop projections for the portfolio of measurements that are complementary to the Detector I physics program, including those that capitalize on the implementation of the secondary focus.
2. Work with the EICUG Steering Committee and Project to ***recruit new institutions*** and establish a diverse and vibrant 2nd Detector working group.
3. Utilize the extended design period for Detector 2 to identify groups that will focus on ***R&D for emerging technologies*** that could provide another aspect of complementarity to Detector 1.
4. Facilitate the development of a ***unified concept*** for a general-purpose detector at IR8. In particular, the 2nd detector should be complementary to the project detector at IR6 and may capitalize on the possibility of a secondary focus at IR8.

International In-Kind Contributions to the EIC Accelerator

Country	Institution	Interests	Quantity
Switzerland	CERN	Areas for collaboration FCC-EIC	
France	CEA/IRFU-Saclay	Spin rotator SC magnets	8 solenoid magnets (TBD)
	IN2P3-IJCLab	Cryo module for 197MHz cavities (injector/ERL)	
Italy INFN - Frascati		Electron Cloud Mitigation studies	1 Turn-key apparatus for SEY measurements
UK - Accelerator	Lancaster Daresbury Lab	1773MHz 5-cell cavities cryo modules	All cryomodules
UK- Detector	Oxford/Lancaster Royal Holloway Lancaster/Liverpool	LLRF synchronization & feedback Beam Position Monitors ERL modelling and design	Models All ? design studies