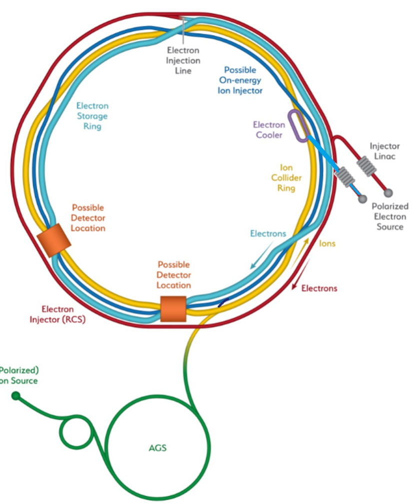
Overview of the Electron Ion Collider and its ePIC Detector

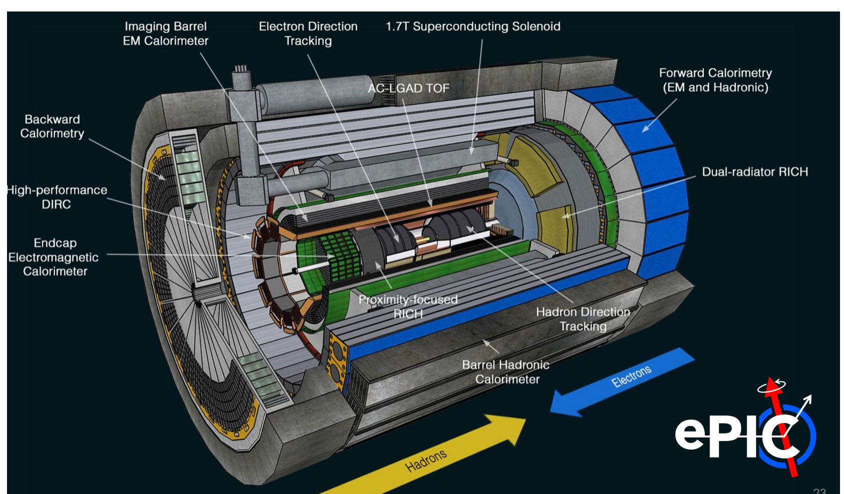
Paul Newman (Birmingham)

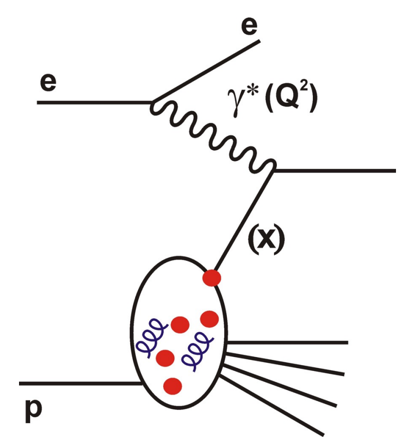
Center for Frontiers in Nuclear Science

Workshop on Extracting the Strong Coupling at the EIC and other Future Colliders

5 May 2025

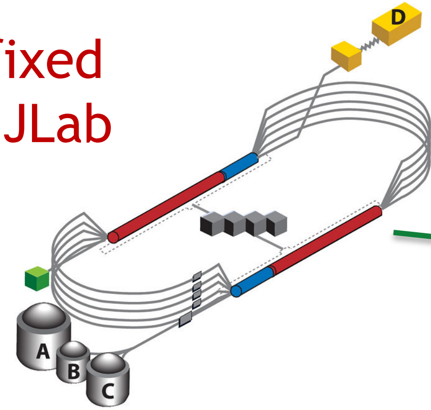




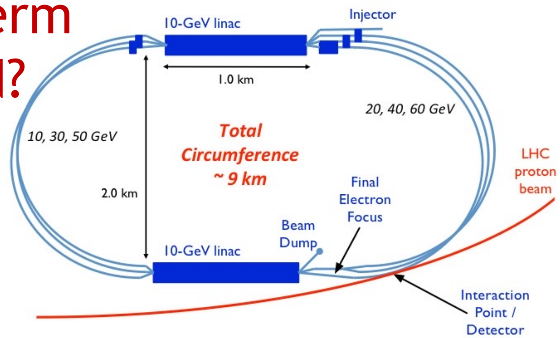


Current & Future ep Colliders

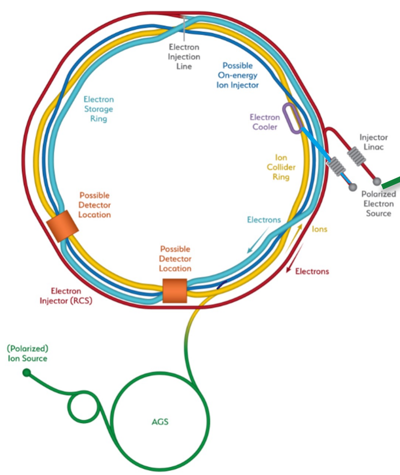
Ongoing fixed target @ JLab

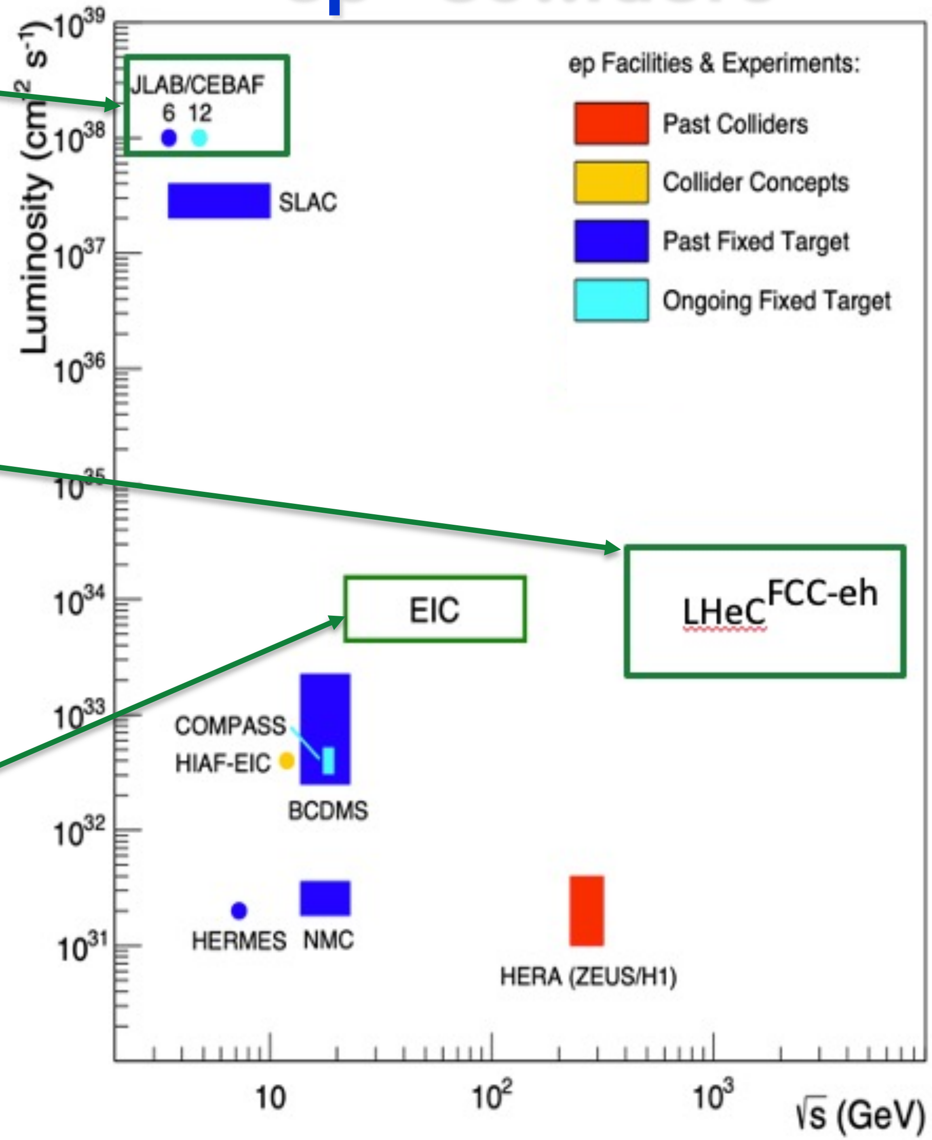


Longer-term @ CERN?



On-target for early 2030s @ BNL





See arXiv:2503.18208: ‘Future Opportunities with Lepton-Hadron Colliders’

Crude Mapping Between Physics & Facilities

Partons with decreasing x →

[Kong Tu]

High x (Fixed Target/JLab)
Basic Structure

Intemediate x (EIC)
Emergent properties

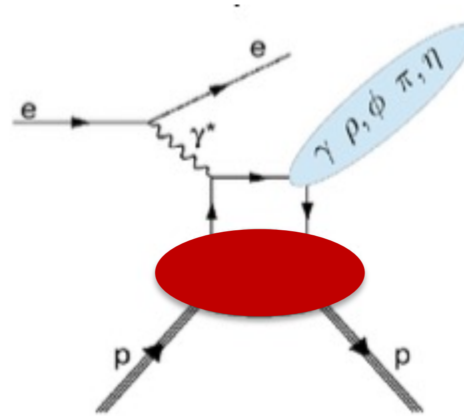
Low x (HERA / LHeC)
Non-linear dynamics

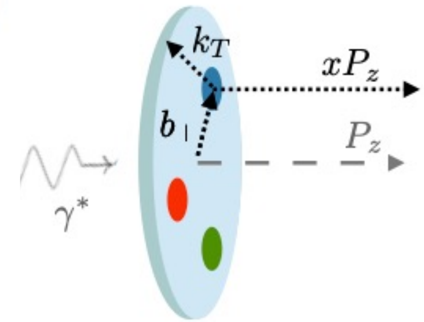
Very Low x
(LHeC,FCC-eh,
PWA) The unknown

Hadron Structure and Dynamics are much richer than longitudinal PDFs …

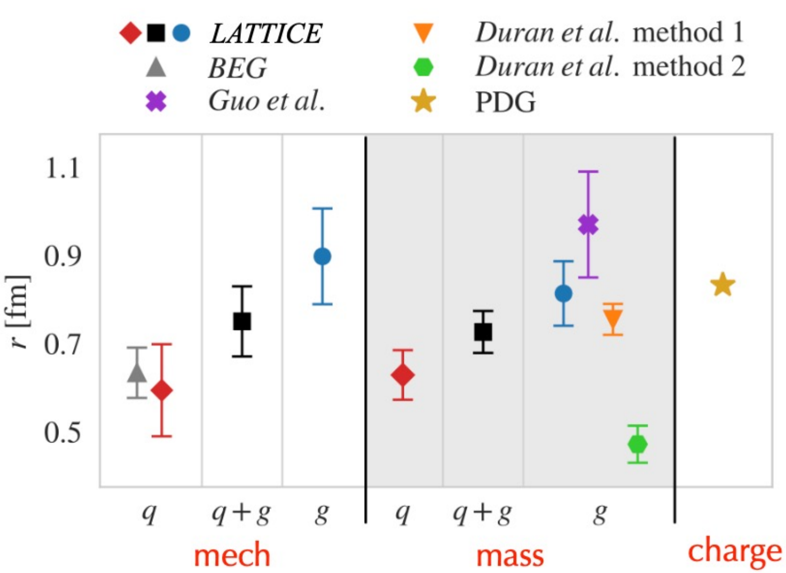
Transverse degrees of freedom, correlations in momentum and position via TMDs, GPDs through exclusive processes, SIDIS …

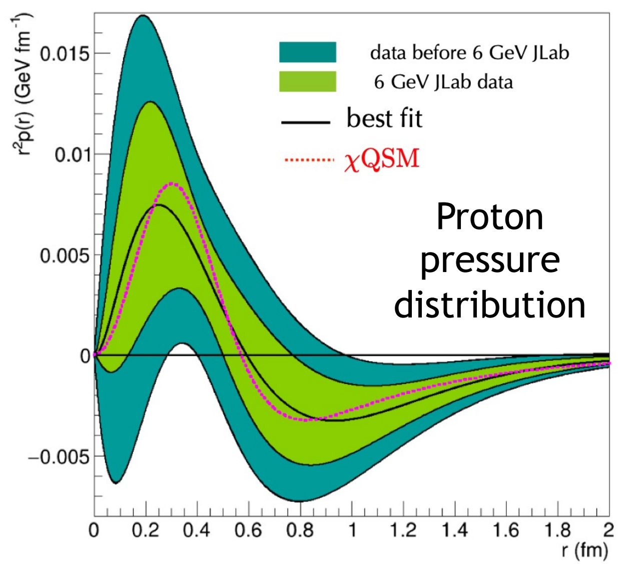
→ First glimpses of 3D structure & mechanical properties from Jlab data





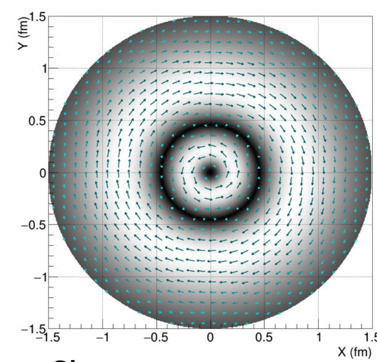
Proton size





Girod, Elouadhriri,Burkert, Nature 557 (2018) 7705

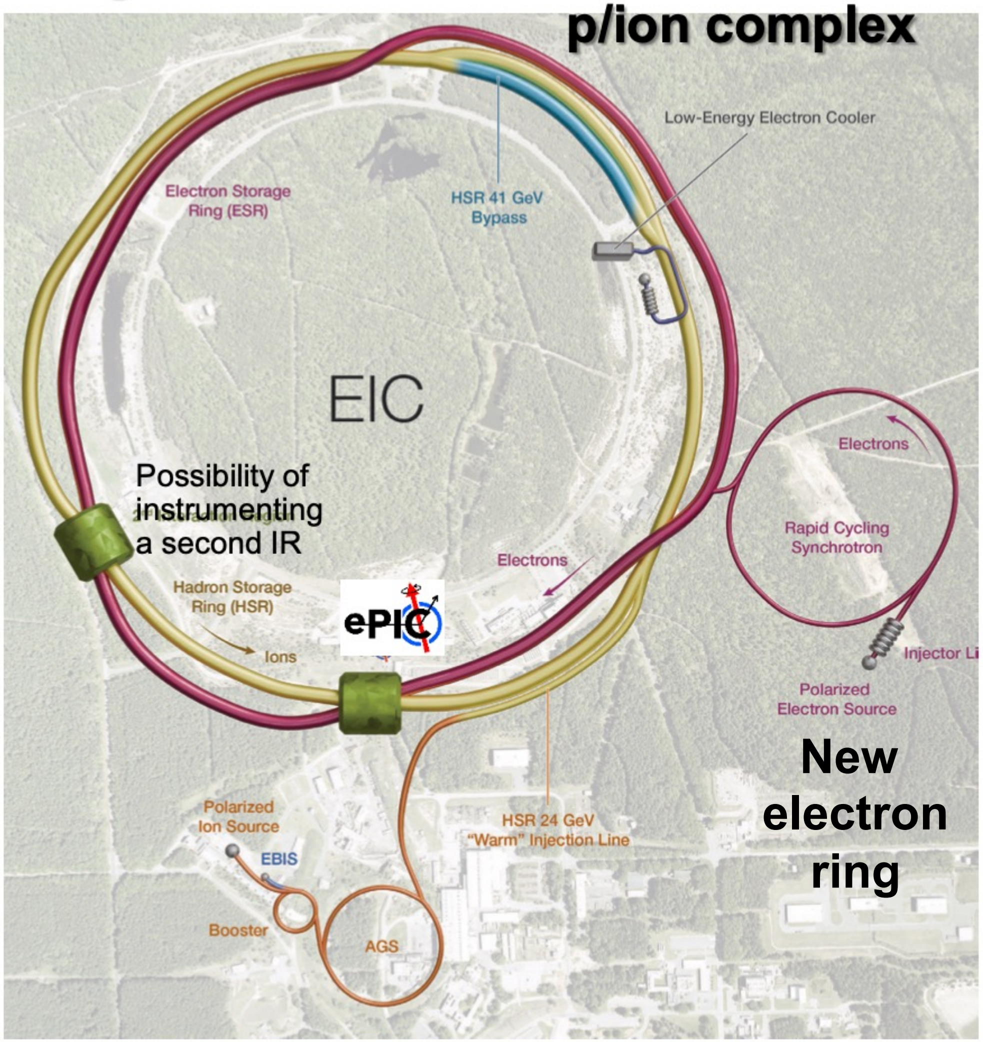
[See e.g. Barbara Pasquini, DIS'25, Cape Town]



Shear forces

The Electron-Ion Collider (BNL)

Usage of RHIC tunnel and RHIC p/ion complex



Specifications driven by science goals:

- Energy range **28 < $\sqrt{s}$ < 140 GeV**

World's first …

- High lumi ep Collider

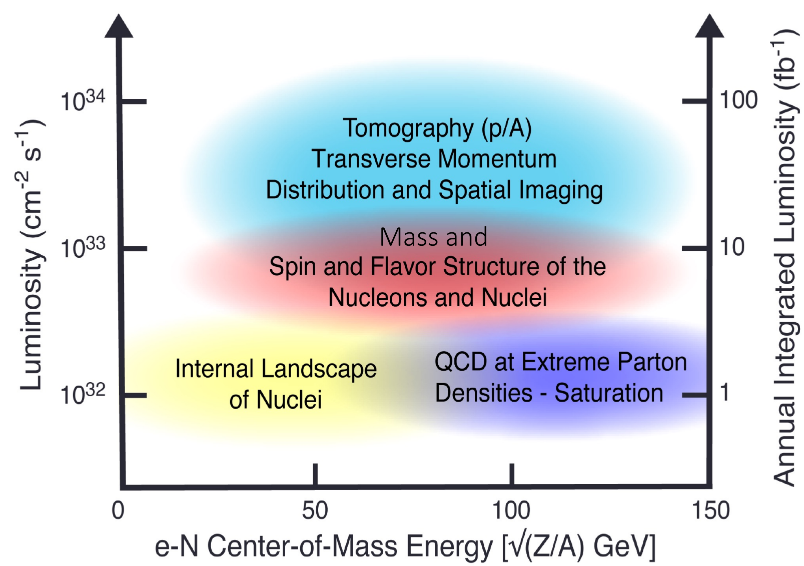
(~ 10^{33} -10^{34} cm^{-2} s^{-1})

- Double-polarised DIS collider

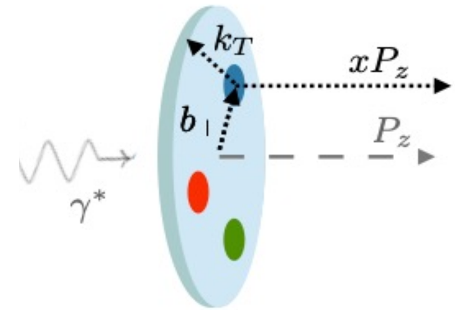
(~70% for leptons & light nuclei)

- eA collider

(Ions ranging from H to U)

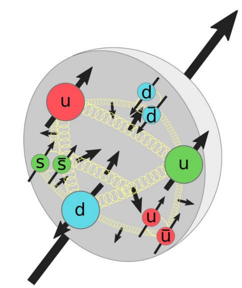


Fundamental questions for EIC



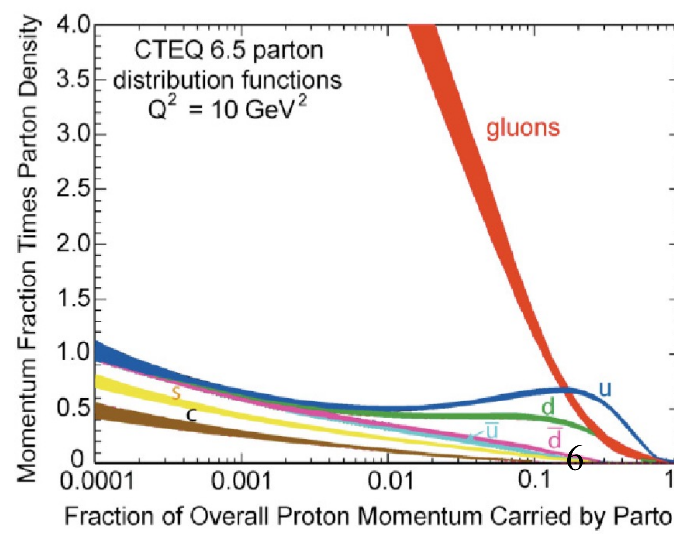
- **What do proton dynamics look like in 3D?**
  … How is proton mass generated from quark and gluon interactions?
  … How is proton spin generated?
  … What is the mechanism behind confinement?

Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100



- **How are parton properties and dynamics altered in nuclei?**
  … How do quarks and gluons interact with the nuclear medium?
  … What is the QCD-science of high density systems of gluons?
  … How is the low x growth of the gluon density tamed?

- **Revealing new features of strong interactions through precision measurements**
  … Furthering understanding QCD
  … α_s and other fundamental constants

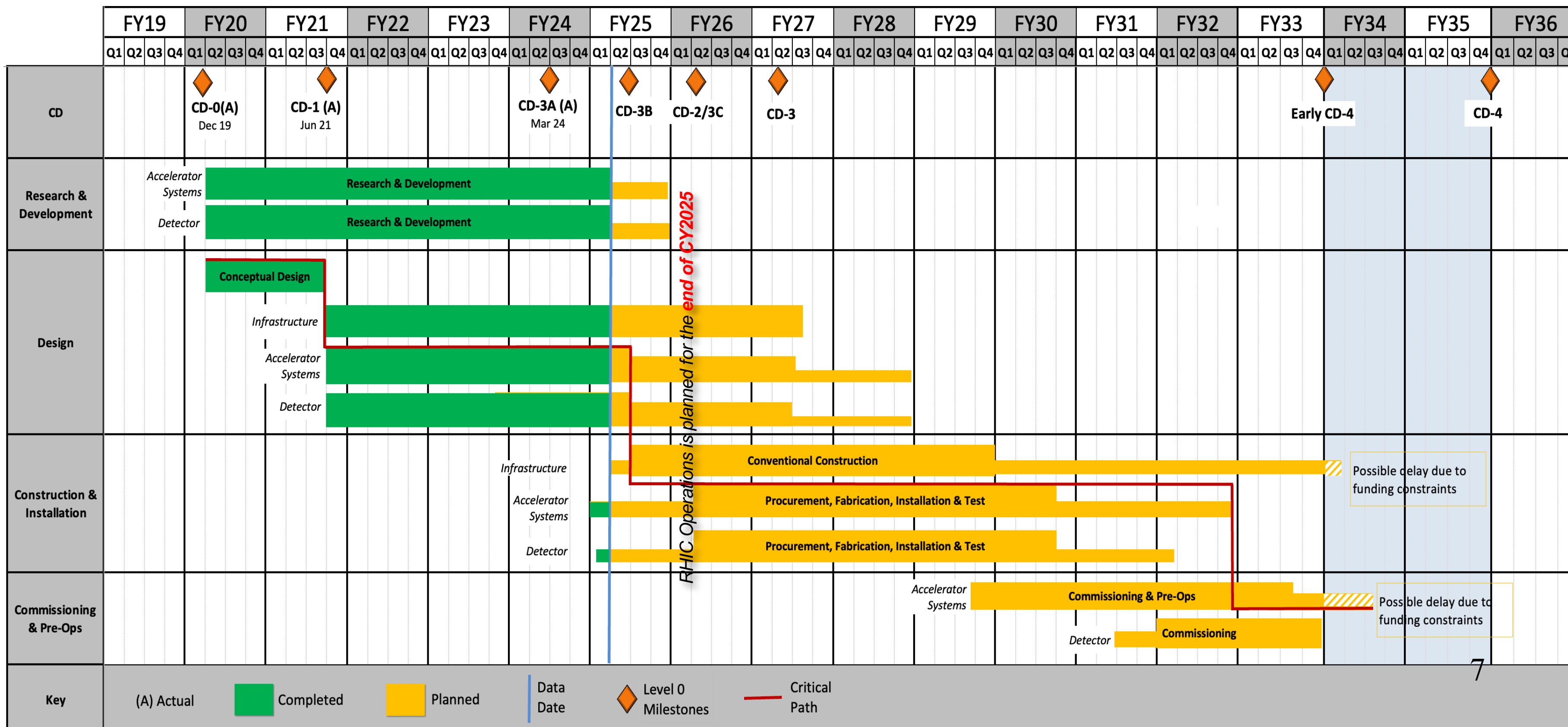


Status / Timeline

- $2.5Bn project (US DoE funds accelerator + most of one detector)

- Still several steps to go, but on target for operation early/mid 30s

CD-0 (Mission need)	Dec 2019
CD-1 (Cost range)	June 2021
CD-3A (Start construction)	April 2024
CD-3B	Under review
CD-2 (Performance baseline)	Under review
CD-4 (Operations / completion)	2034-5

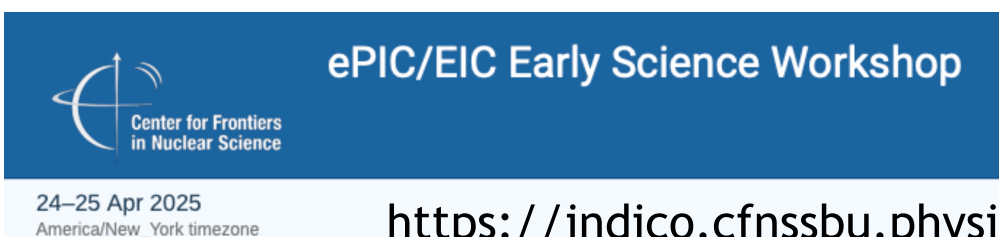


Early Running

Scenario for early running whilst finalizing full capabilities of accelerator under evaluation

	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

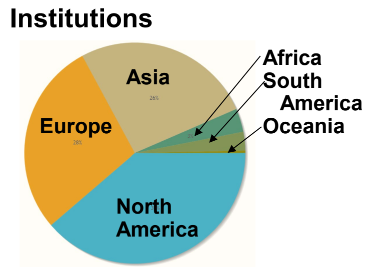
Note: the eA luminosity is per nucleon

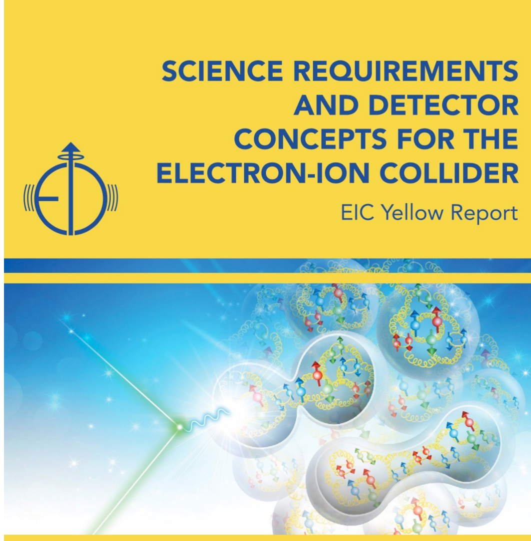


https://indico.cfnssbu.physics.sunysb.edu/event/410/

International Community

EIC User Group with >1500 members from >300 institutions including experimentalists, theorists and accelerator scientists





Nucl Phys A1026 (2022), 122447 [arXiv:2103.05419]

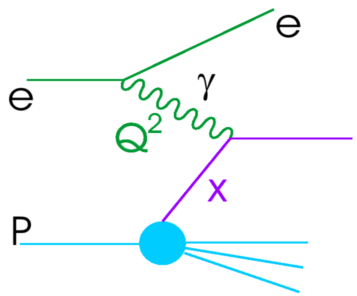
Experimental collaboration with >1000 collaborators from 177 institutions in 25 countries (48% USA)

ePIC @ Frascati, Italy, Jan '24

Joint UG + ePIC annual meeting,Jlab, July 14-18 2025 …
https://www.jlab.org/conference/eicugepic/overview

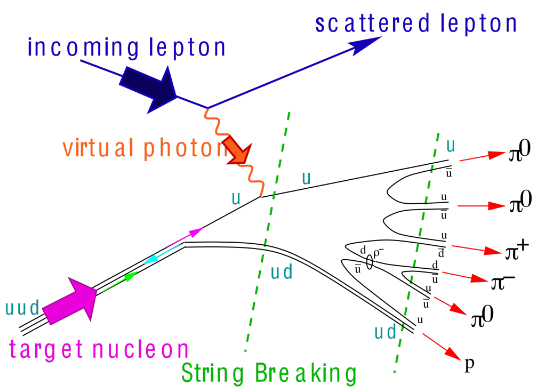
Observables / Detector Implications

Inclusive



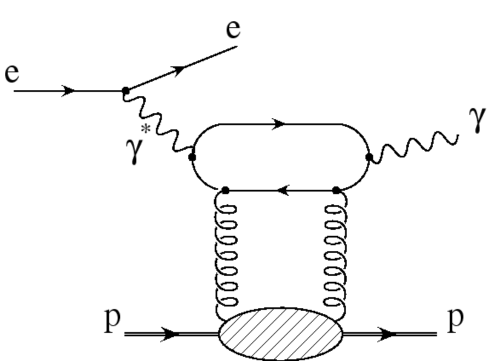
- Traditional DIS, following on from fixed target experiments and HERA → Longitudinal structure
  … high acceptance, high performance electron identification and reconstruction

Semi-Inclusive



- Single particle, heavy flavour & jet spectra
  → p_T introduces transverse degrees of freedom
- Quark-flavour-identified DIS
  → Separation of u,d,s,c,b and antiquarks
  … tracking and hadronic calorimetry
  … heavy flavour identification from vertexing
  … light flavours from dedicated PID detectors

Exclusive / Diffractive



- Processes with final state 'intact' protons
  → Correlations in space or momentum between pairs of partons
  … efficient proton tagging over wide acceptance range
  … high luminosity

A Detector For the EIC

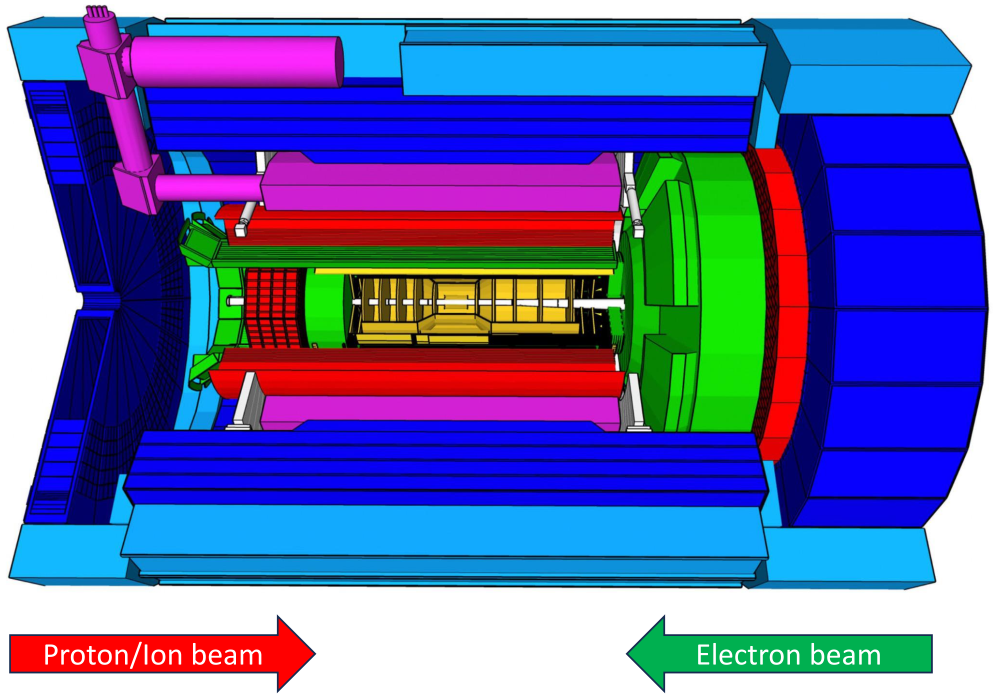
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

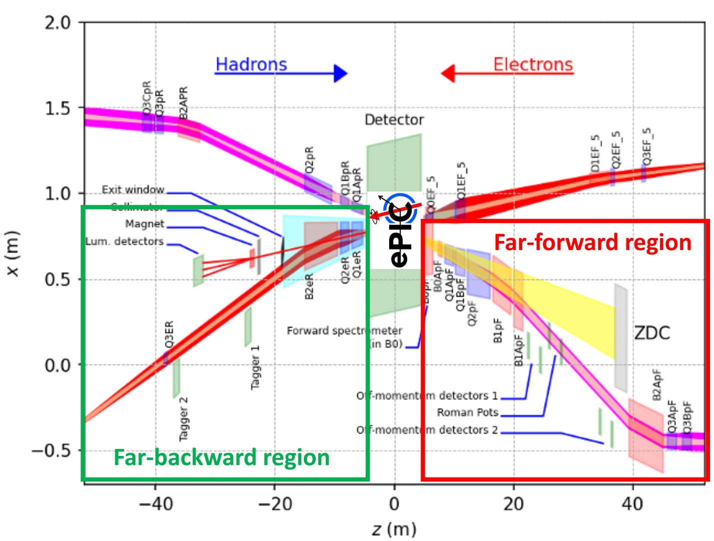
Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)





- 9m long x 5m wide
- Hermetic (central detector $-4 < \eta < 4$)
- Extensive beamline instrumentation

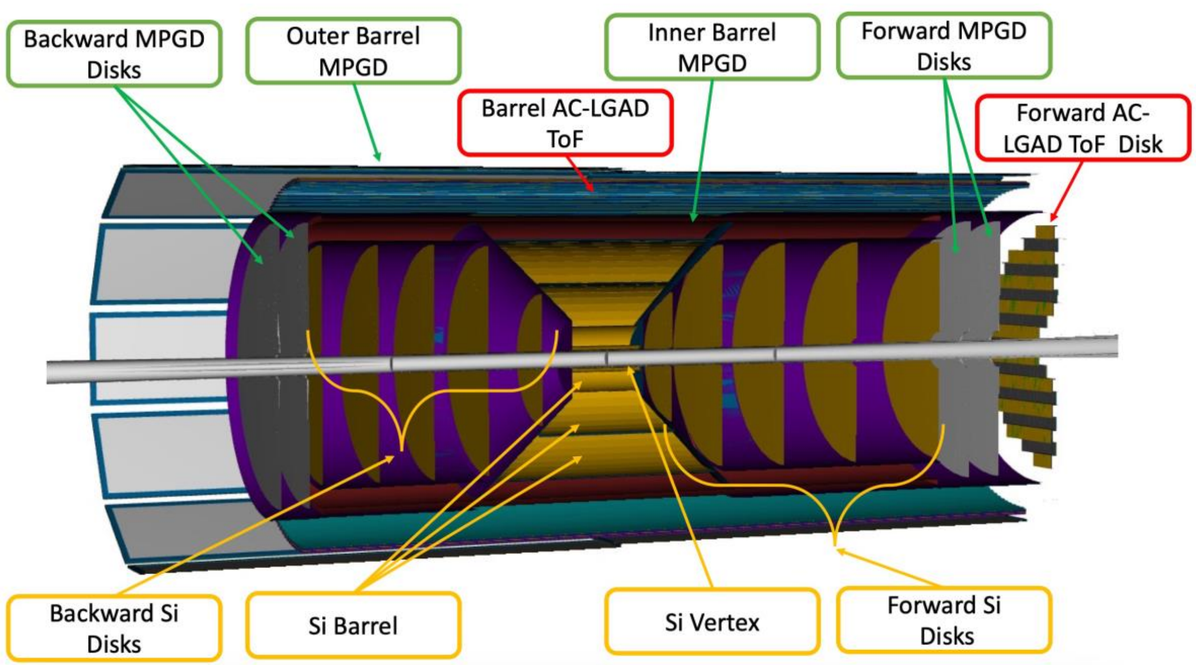
- Much lower radiation fluxes than LHC widens technology options

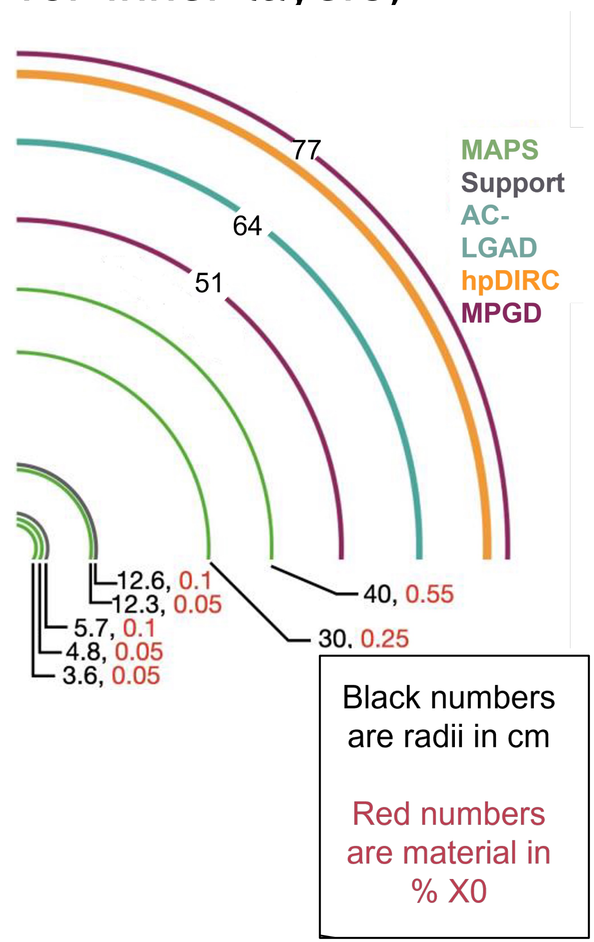
Tracking Detectors

Primarily based on MAPS silicon detectors (65nm technology)

- Leaning heavily on ALICE ITS3
- Stitched wafer-scale sensors, thinned and bent around beampipe

  → Very low material budget ($0.05X_0$ per layer for inner layers)
- 20x20μm pixels
- 5 barrel layers + 5 disks (total 8.5m^2 silicon)





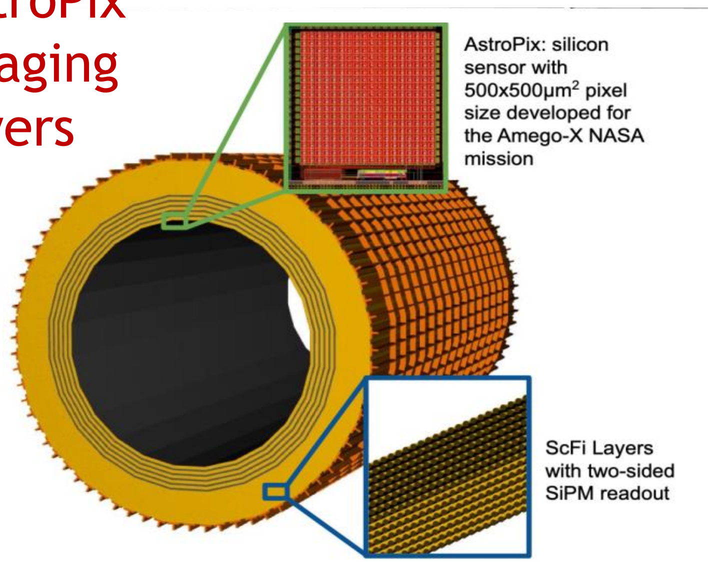
LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

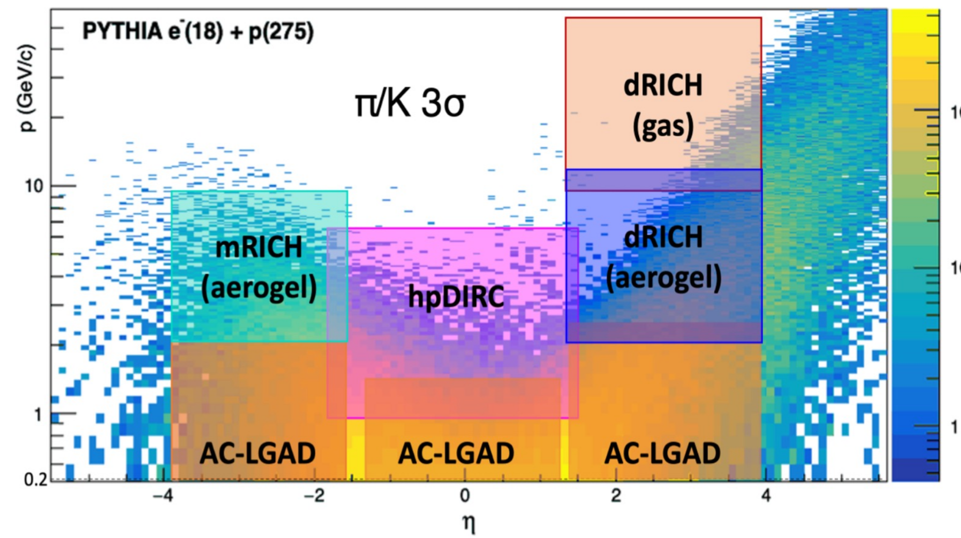
More Novel Detector Components

Imaging eCAL

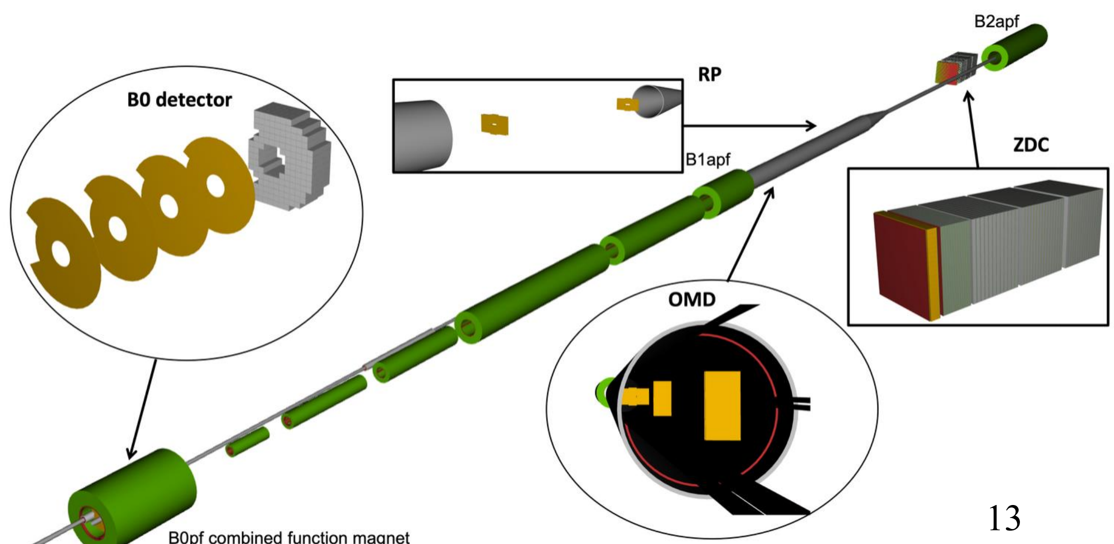
Pb/SciFi sampling + AstroPix imaging layers



Comprehensive Particle ID



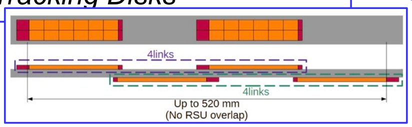
- Forward protons inside and outside beampipe ($0.45 < E_p'/E_p < 1$)
- Forward neutrons with ALICE FOCAL-like ZDC



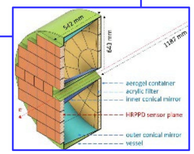
Silvia Dalla Torre, DIS’25, Cape Town

TECHNOLOGIES: WORLD FIRST AT ePIC

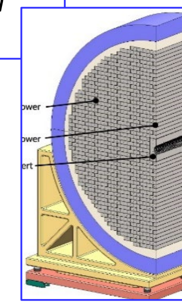
EIC Large Area Sensor (**LAS**), modification of ITS3 sensor with 5 or 6 RSU forming staves as the basic building elements *for the Outer Barrel and the Tracking Disks*

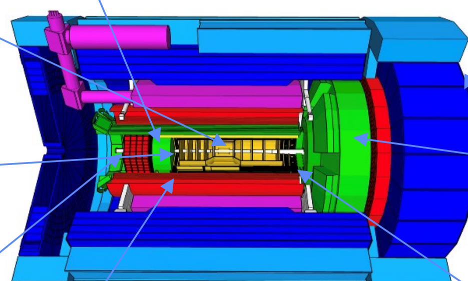


HRPPDs for Cherenkov imaging and Time-of-Flight *for pfRICH*

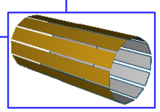


first-time **full-size CALICE-like calorimeter** in collider experiment *in the forward HCal*

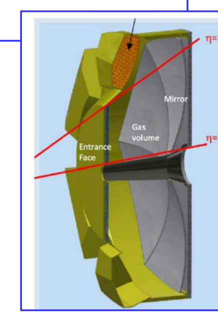




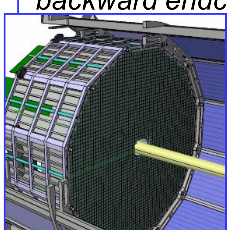
planar **double amplification (GEM & μRWELL)** modules & 2D-strip readout *for the MPGD outer trackers and disks*



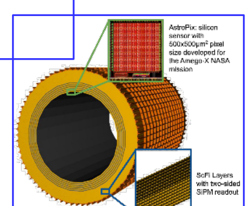
First use **of SiPMs as Photonsensors in a RICH** for the dRICH



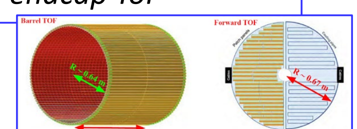
SiPM as Photonsensors in crystal calorimetry *for backward endcap ECal*



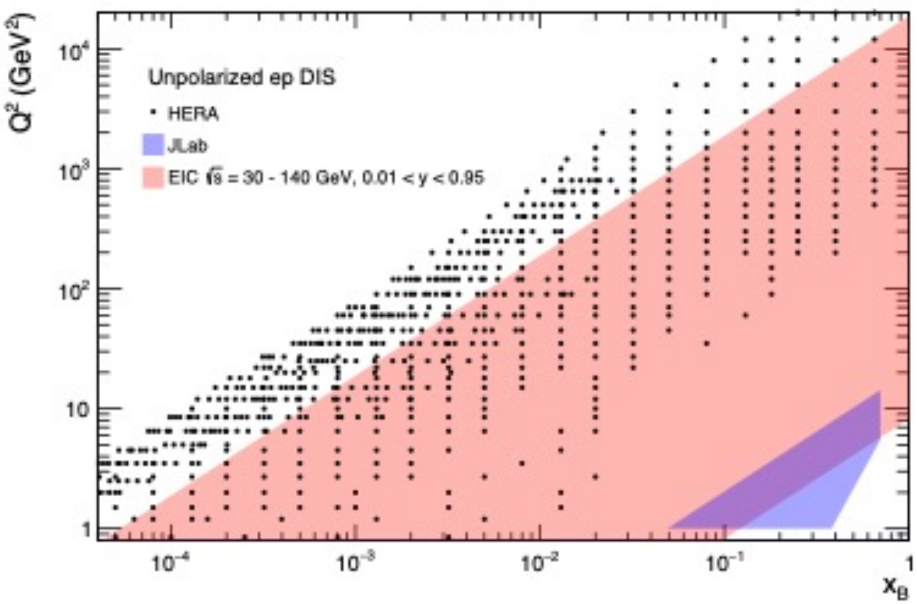
Use of **ASTROPIX in Calorimetry** *for the imaging barrel ECal*



First time use of **AC-LGAD** in a collider detector *for barrel and forward endcap ToF*



EIC Kinematic Range v Previous Data



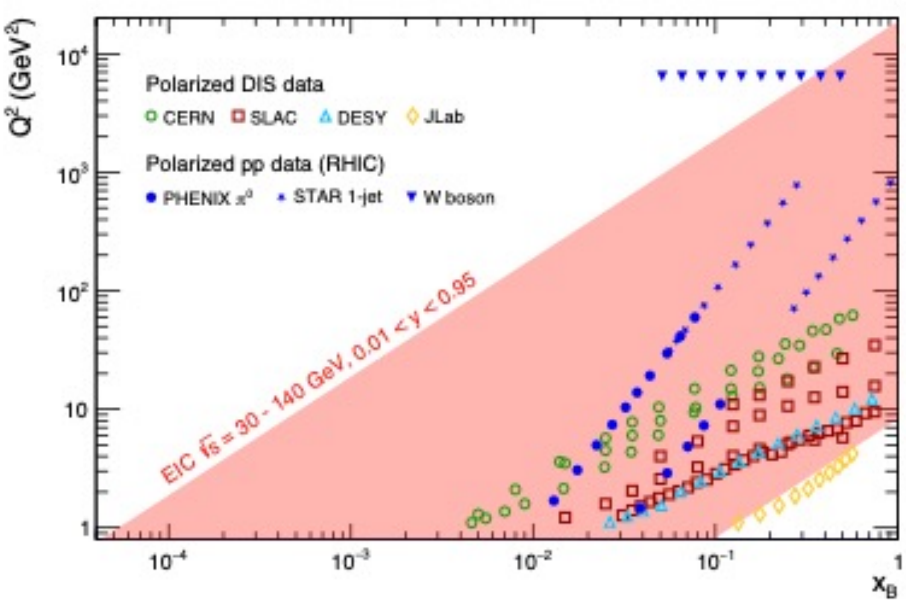
Inclusive ep DIS

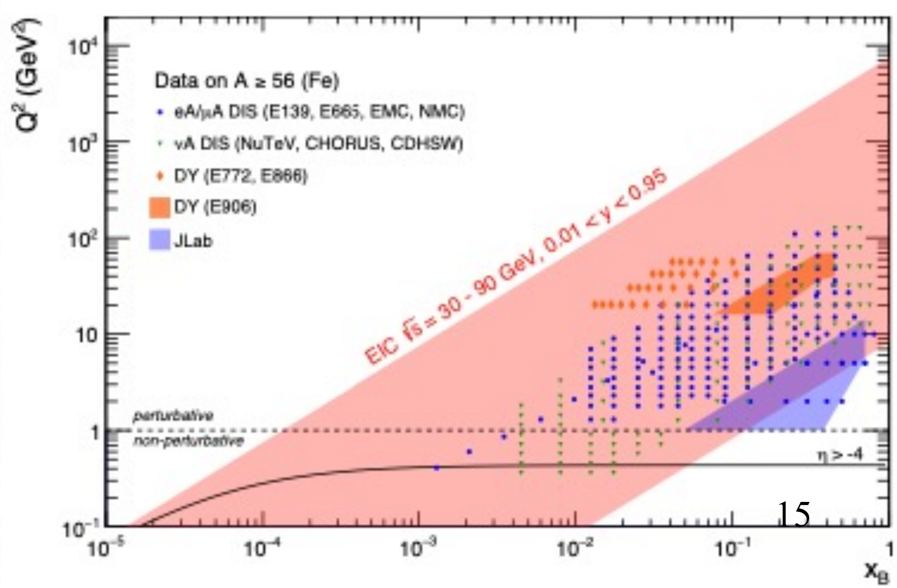
→ Closing gap and overlapping between fixed target & HERA

→ High x, moderate Q^2 precision

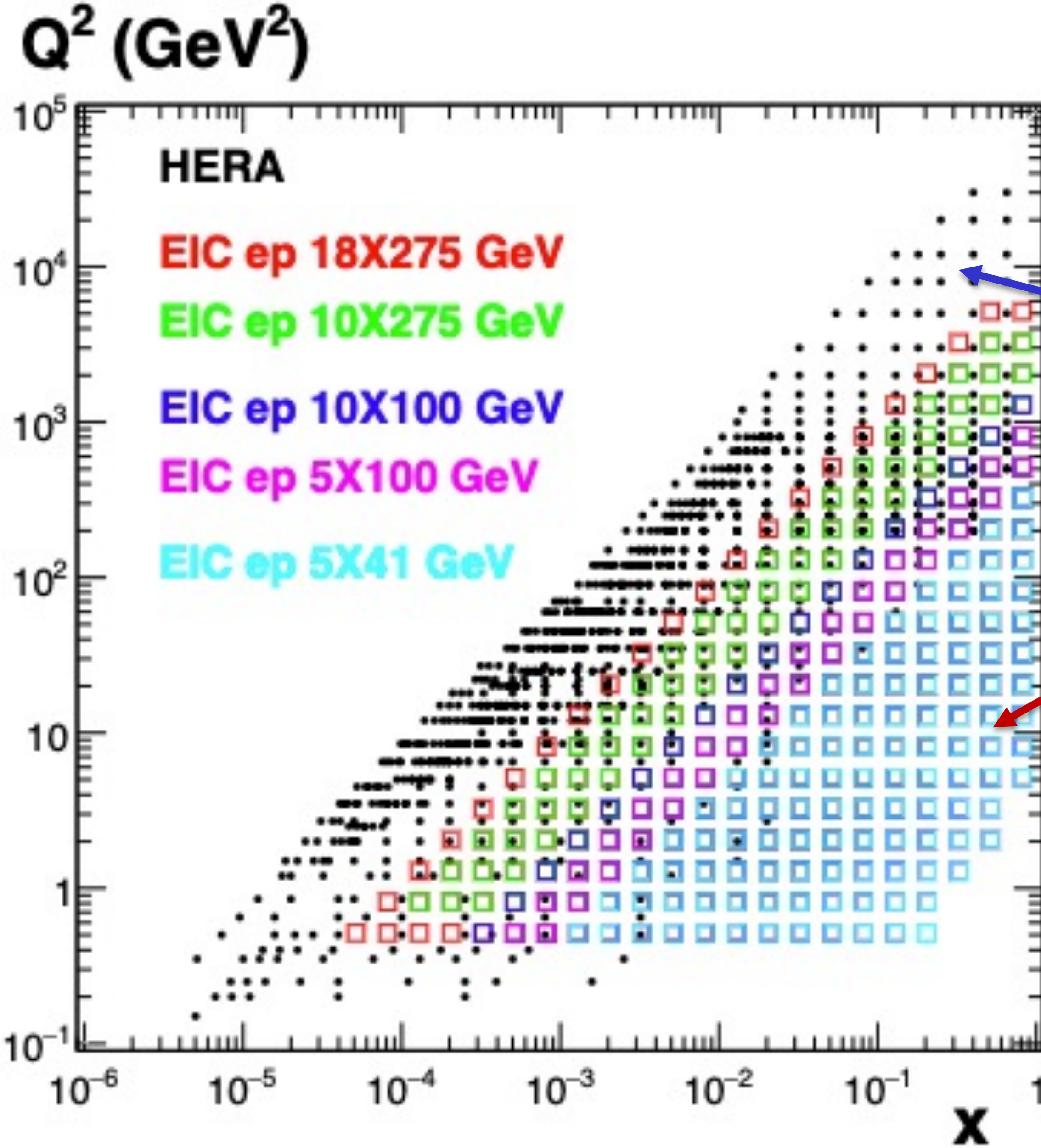
Polarised target ep & eA DIS

→ Completely unexplored regions, extending to low x





e.g. Inclusive EIC Simulated Data



HERA data have limited high x sensitivity due to $1/Q^4$ factor in cross section and kinematic x / Q^2 correlation

EIC data fills in large x, modest Q^2 region with high precision

Estimated annual lumi

e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

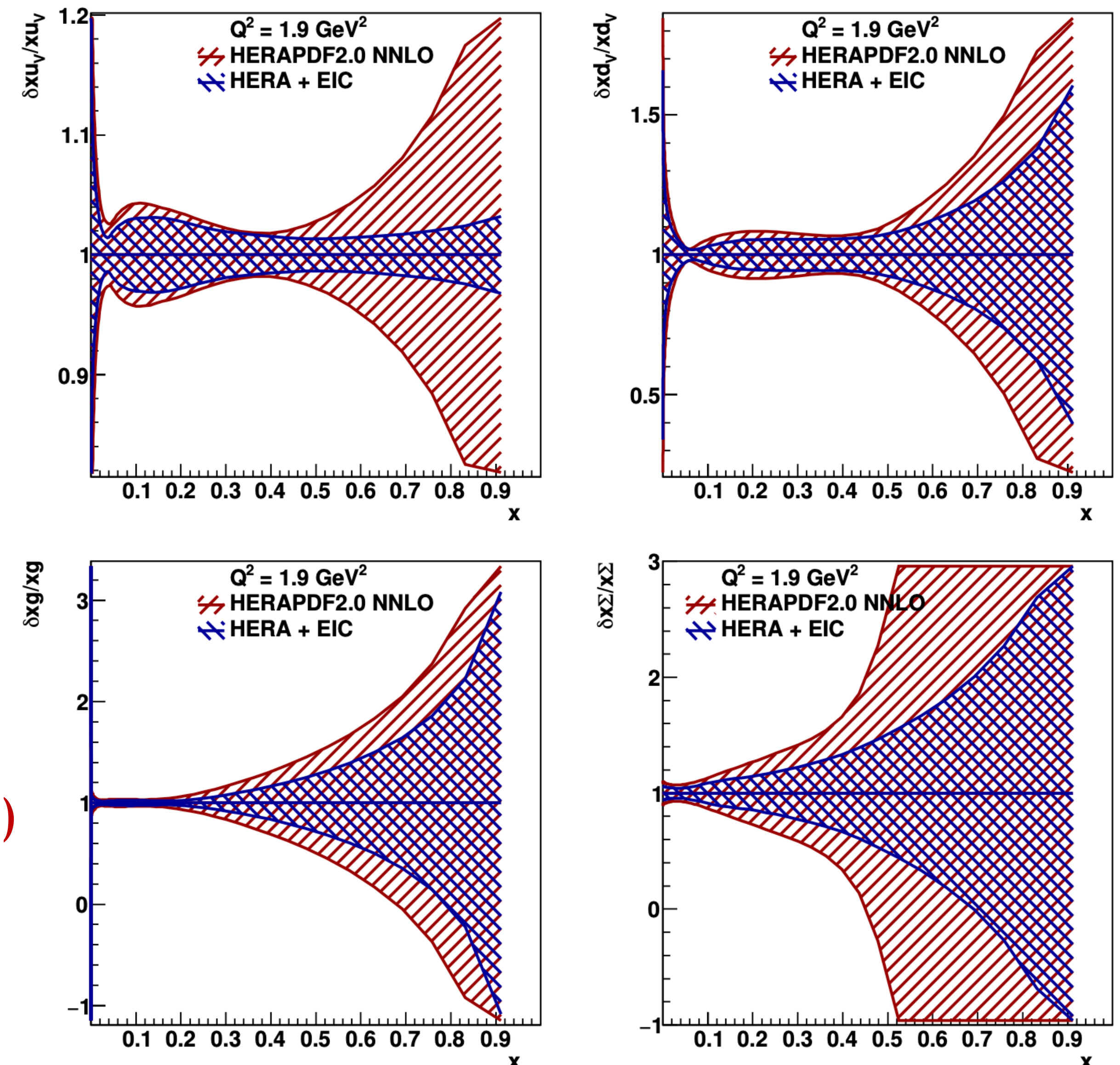
EIC Impact on Proton Parton Densities

Fractional total uncertainties with / without simulated EIC data added to HERA (lin-x scale)

… EIC brings reduction in large x uncertainties relative to HERA for all parton species

Up quarks improve relative to global fits including LHC (not shown)

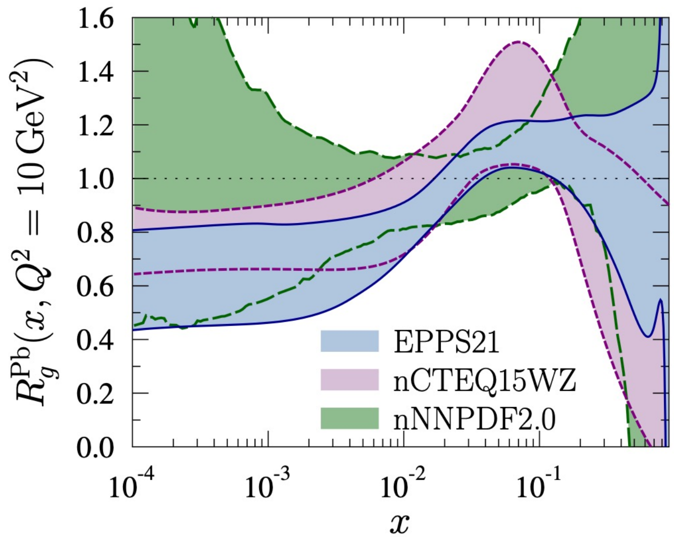
Precision high x data also yield world-leading strong coupling precision



EIC Impact on Nuclear Parton Densities

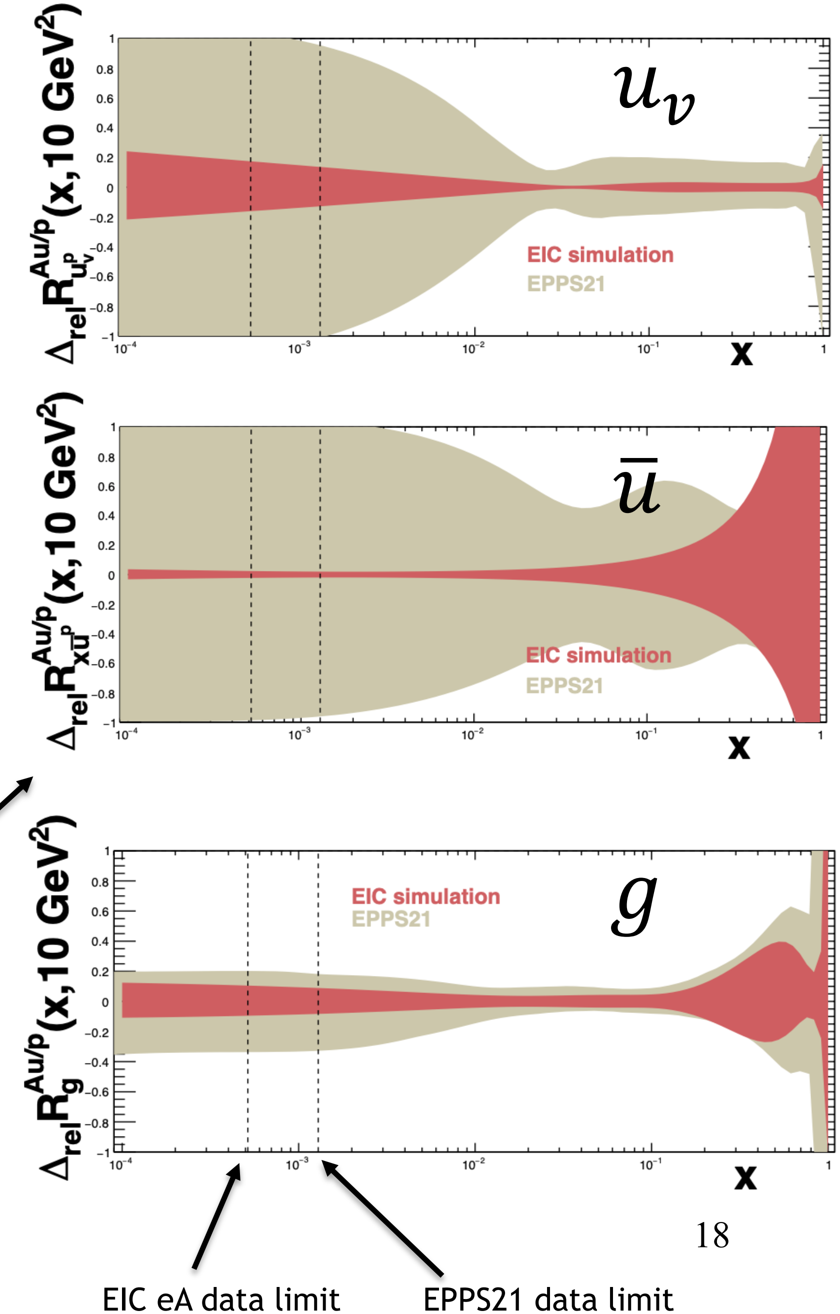
Parton nuclear modification ratio rel to scaled isospin-adjusted nucleons:

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$



Sensitivity of EIC-alone relative to EPPS21 global fits (include LHC pA)

→ Factor ~ 2 improvement at x~0.1
→ Very substantial improvement in newly accessed low x region

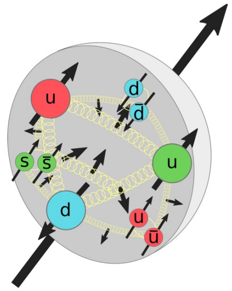


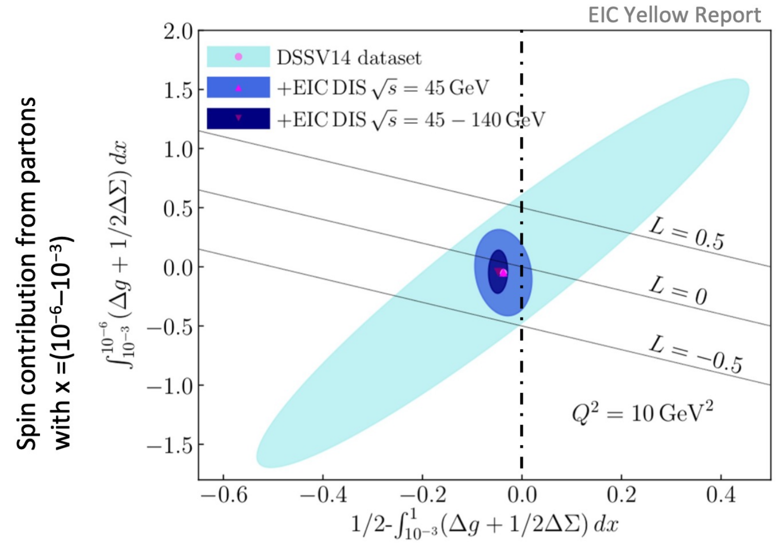
Proton Spin

Jaffe-Manohar sum rule:

$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

Quark helicity — Gluon helicity — Quark canonical orbital angular momentum — Gluon canonical orbital angular momentum

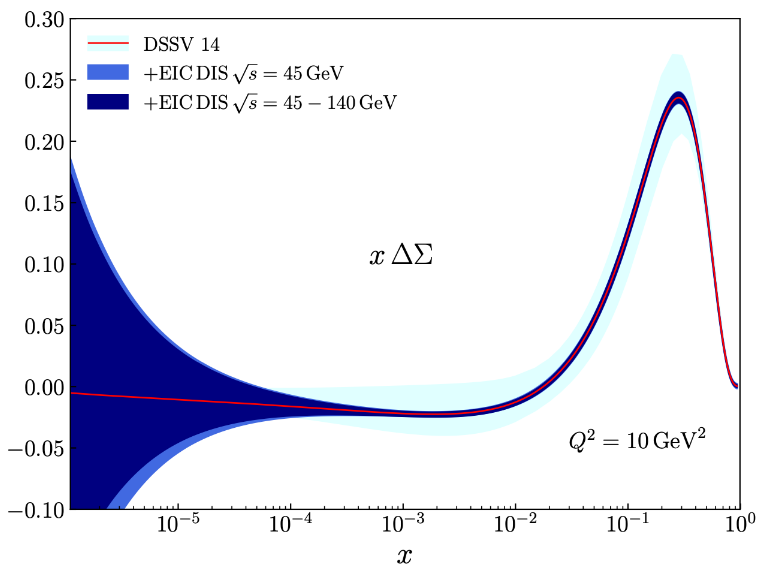


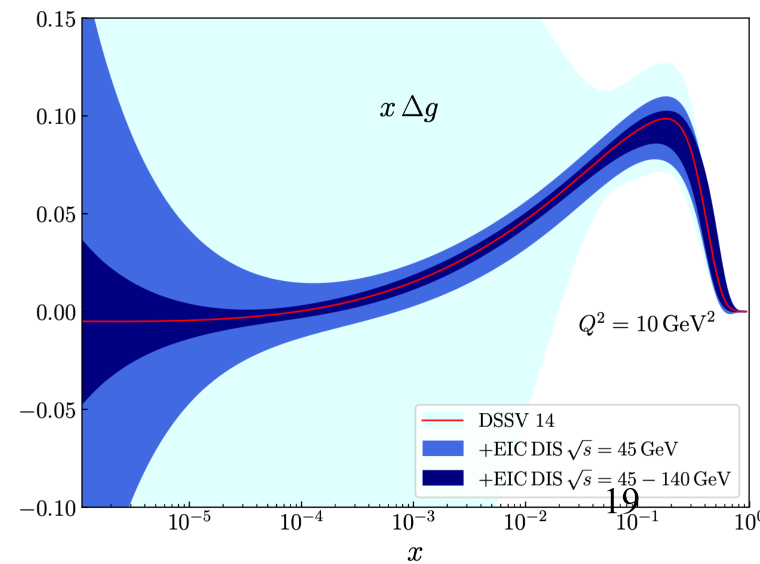


- Very little known about gluon helicity contribution & low x region

Room left for potential OAM contributions to the proton spin from partons with x > 0.001

- Simulated EIC inclusive data show very significant impact on polarised gluon and quark densities → orbital angular momentum constrained by implication … Full decomposition.

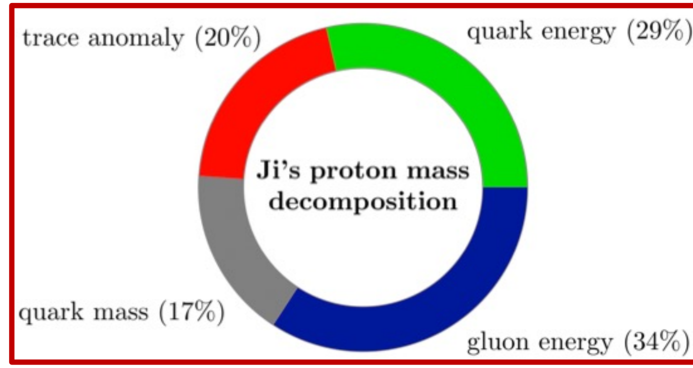




Proton Mass

- Decomposition along similar lines to spin:

$$m_p = m_m + m_q + m_g + m_a$$



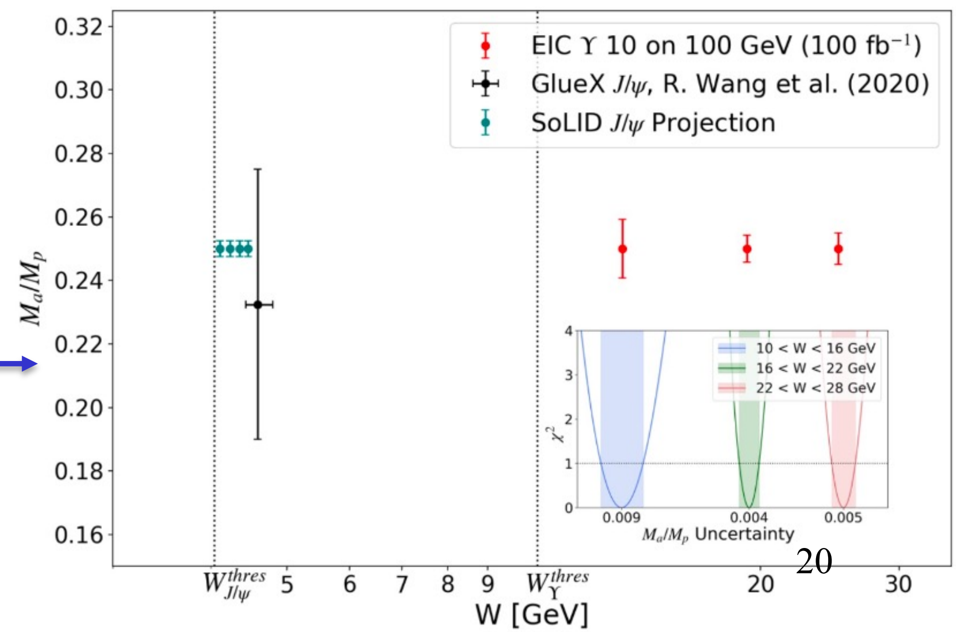
Valence and sea quark masses (including heavy quarks)

Quark & gluon 'KE' & 'PE': confinement and relative motion

QCD trace anomaly (purely quantum effect - chiral condensates)

- Relations to experimental observables being understood

- eg gluon contribution to trace anomaly from J/Ψ (Jlab, also J/Ψ-007) to Υ (EIC) near threshold



Summary

The Electron Ion Collider will transform our understanding of nucleons, nuclei and the parton dynamics that underlie them

α_s measurements will be a significant component of its programme

On target for data taking in the early/mid 2030s