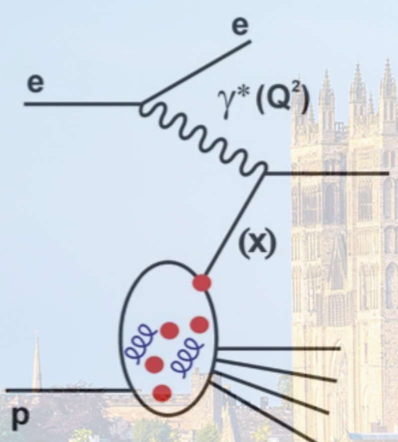
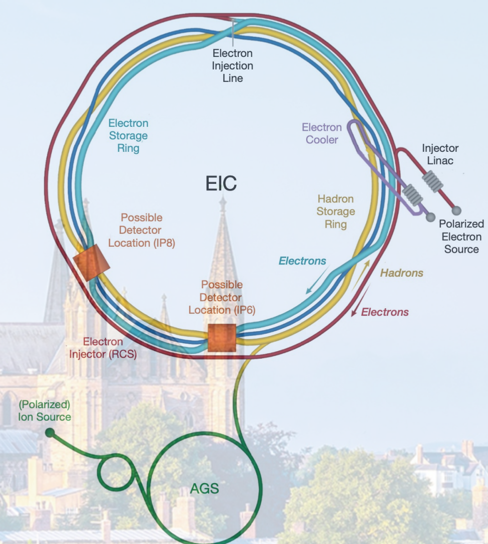
The Electron-Ion Collider: Experimental Overview

1) DIS Context
2) Overview and Machine
3) The ePIC detector
4) Kinematic reconstruction
5) Selective Physics
   → inclusive
   → diffractive
   → more …



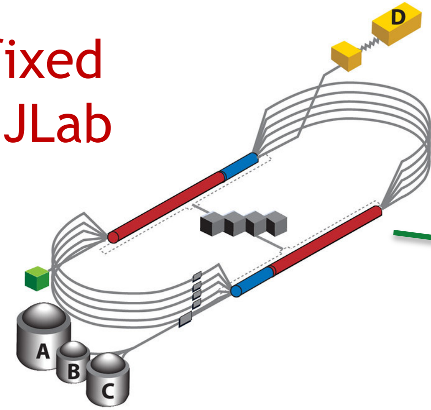
MC4EIC Workshop
(Durham)
6 June 2024

Paul Newman (Birmingham)

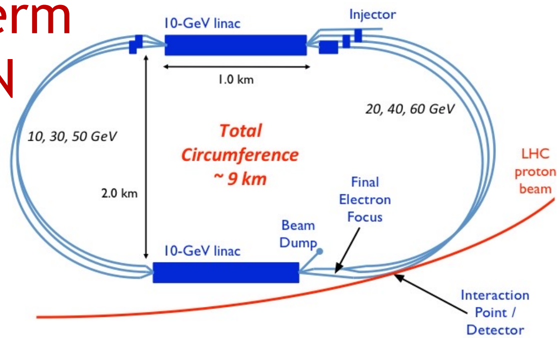


Current and Future ep Colliders

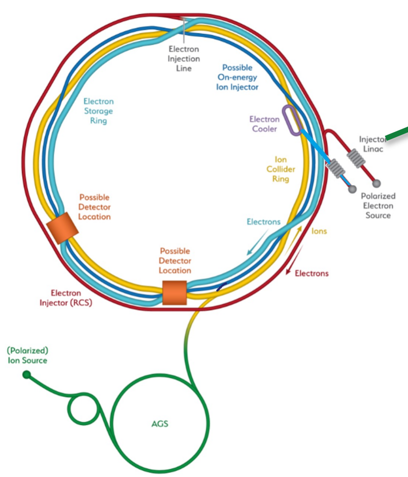
Ongoing fixed target @ JLab

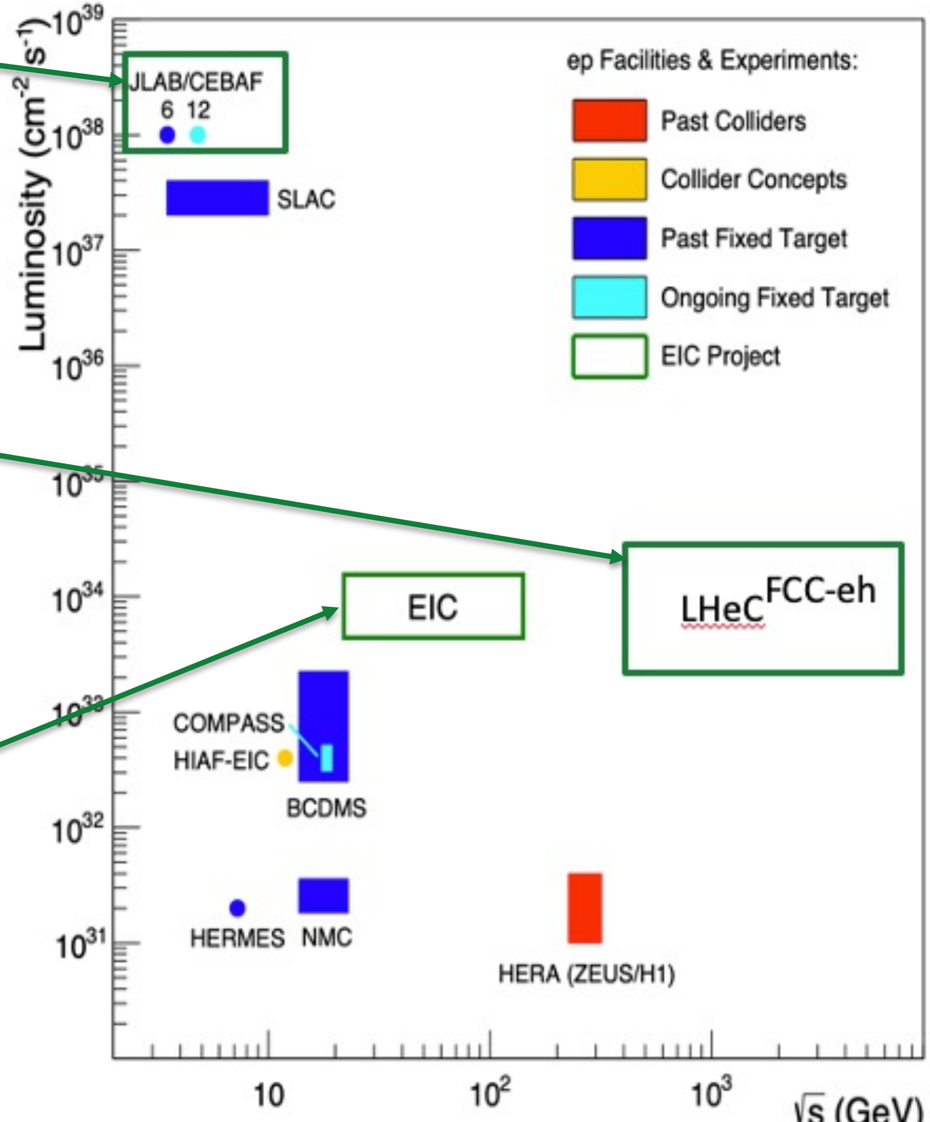


Longer-term @ CERN

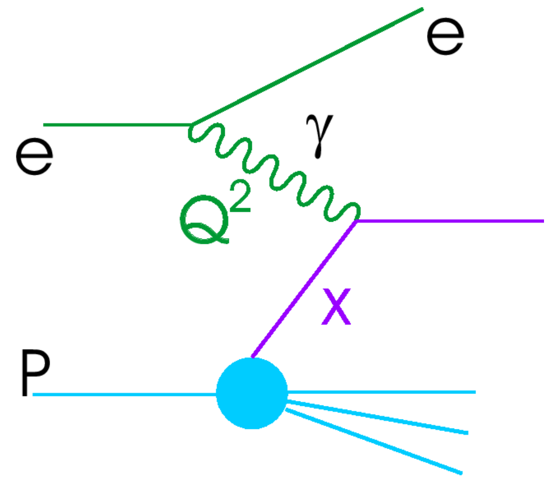


On-target for early 2030s @ BNL





Inclusive Neutral Current DIS: ep→ eX … Kinematics



$$Q^2 = -q^2 \qquad x = \frac{-q^2}{2p \cdot q}$$

x = fraction of proton momentum carried by struck quark

Q^2 = |4-momentum transfer squared| (photon virtuality)

… measures the hardness /scale of collision

… inverse of (squared) resolved dimension

$s = {Q^2}/_{xy}$ with inelasticity $y < 1$

… i.e. Maximum Q^2 and minimum x governed by CMS energy

Crude Mapping Between Physics & Facilities

Partons with decreasing x ⟶

[Kong Tu]

High x (fixed Target)
Basic Structure

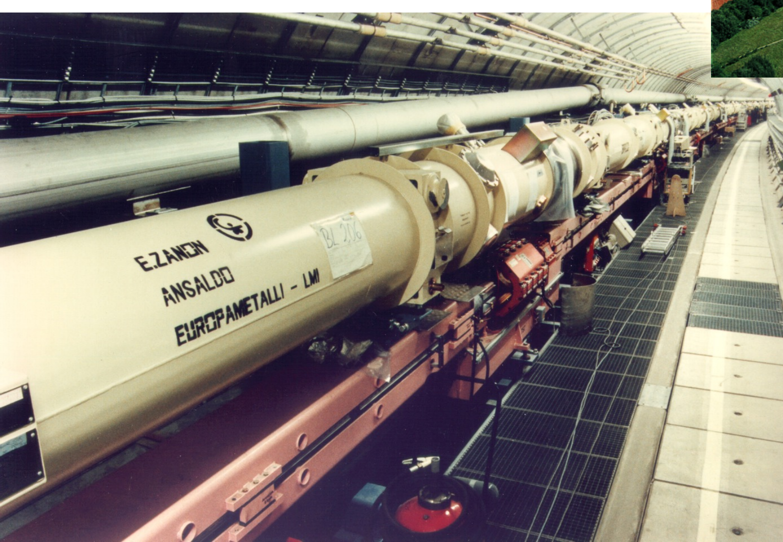
Intemediate x (EIC)
Emergent properties

Low x (HERA / LHeC)
QCD radiation
dynamics

HERA, DESY, Hamburg

$\sqrt{s_{ep}} \sim 300$ GeV

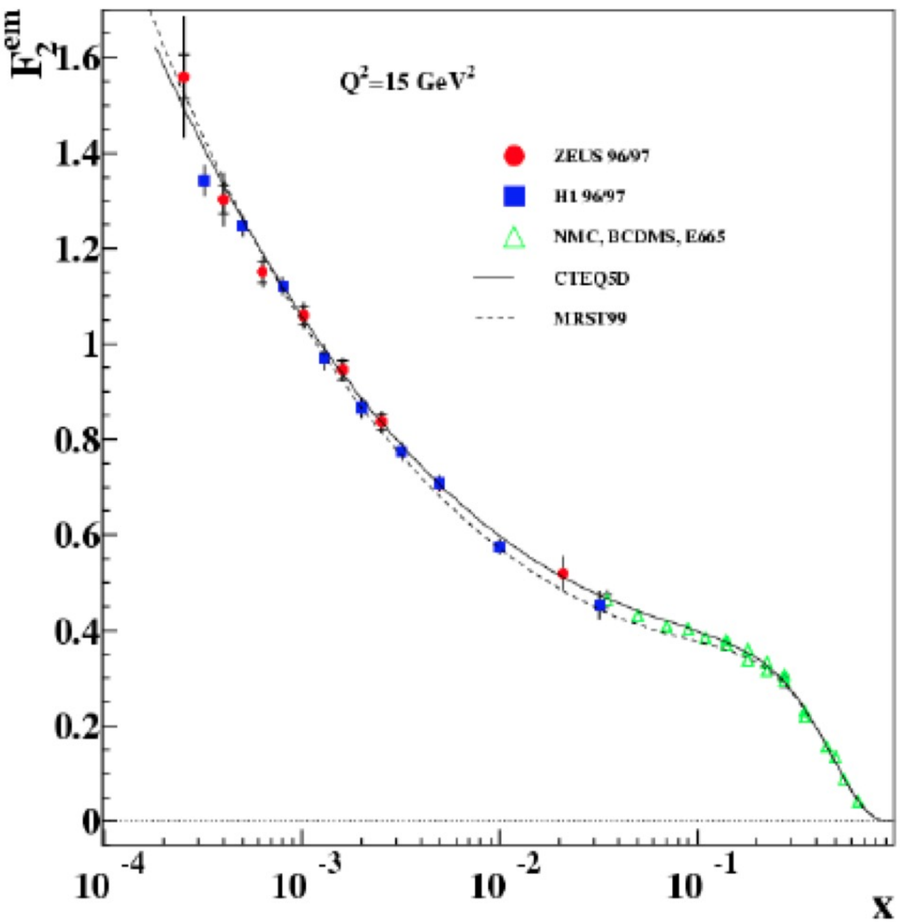
… equivalent to a 50 TeV beam on a fixed target proton

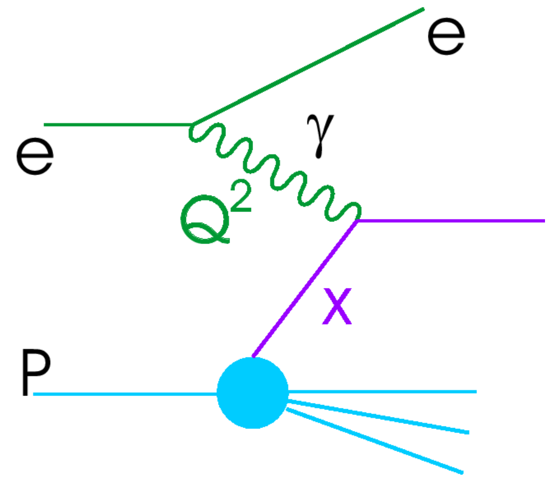


- So far still the only collider of electron and proton beams ever

→ Taught us much of what we know about proton structure
→ Only ~0.5 fb^{-1} per experiment
→ No deuteron or nuclear targets

Example Inclusive Neutral Current Data from Previous Experiments

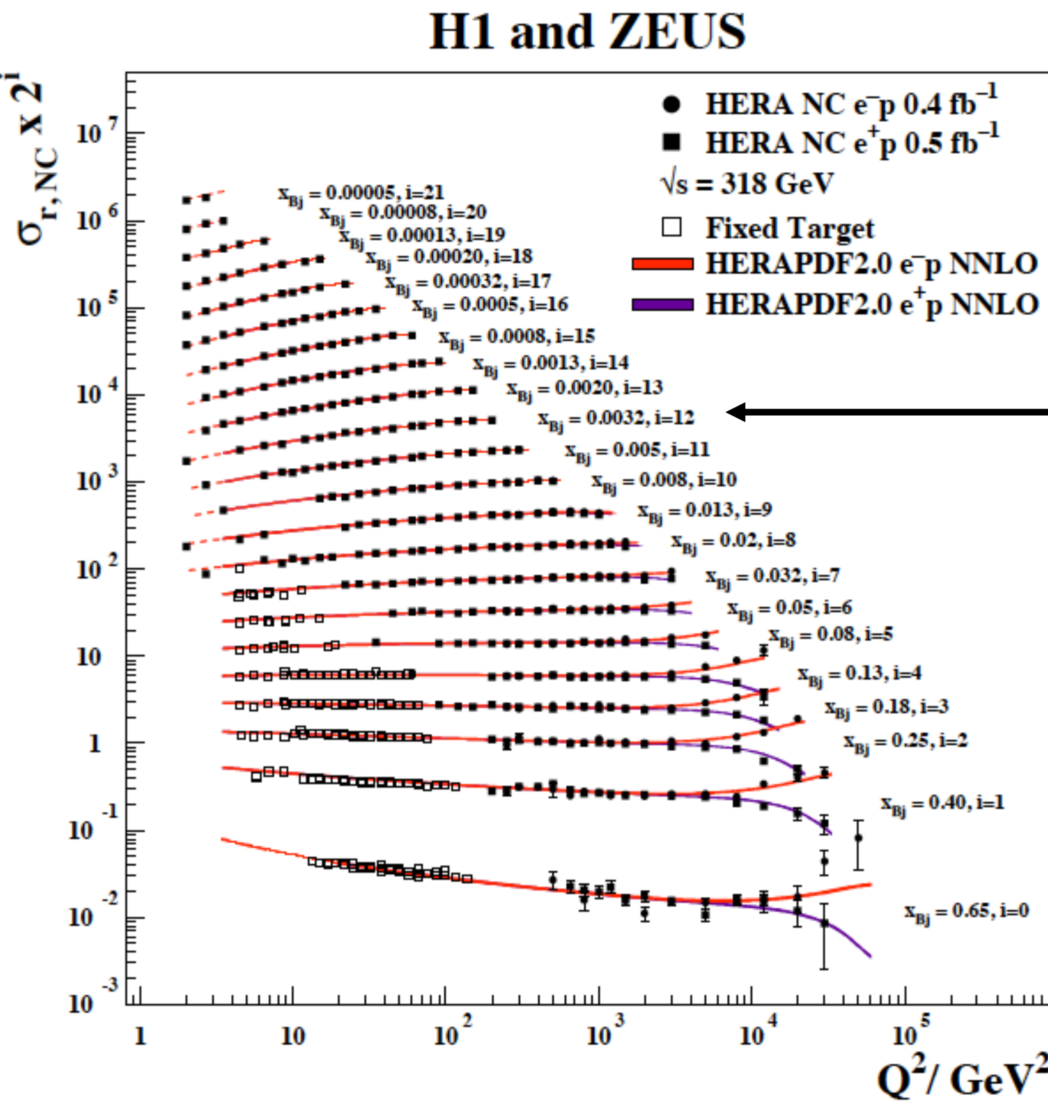




- Inclusive cross section measures (charge-squared weighted) sum of quark densities

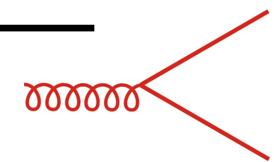
- Similar / better data at many other values of Q^2

QCD Evolution and the Gluon Density



- Q^2 dependence sensitive to gluon density via splitting function …

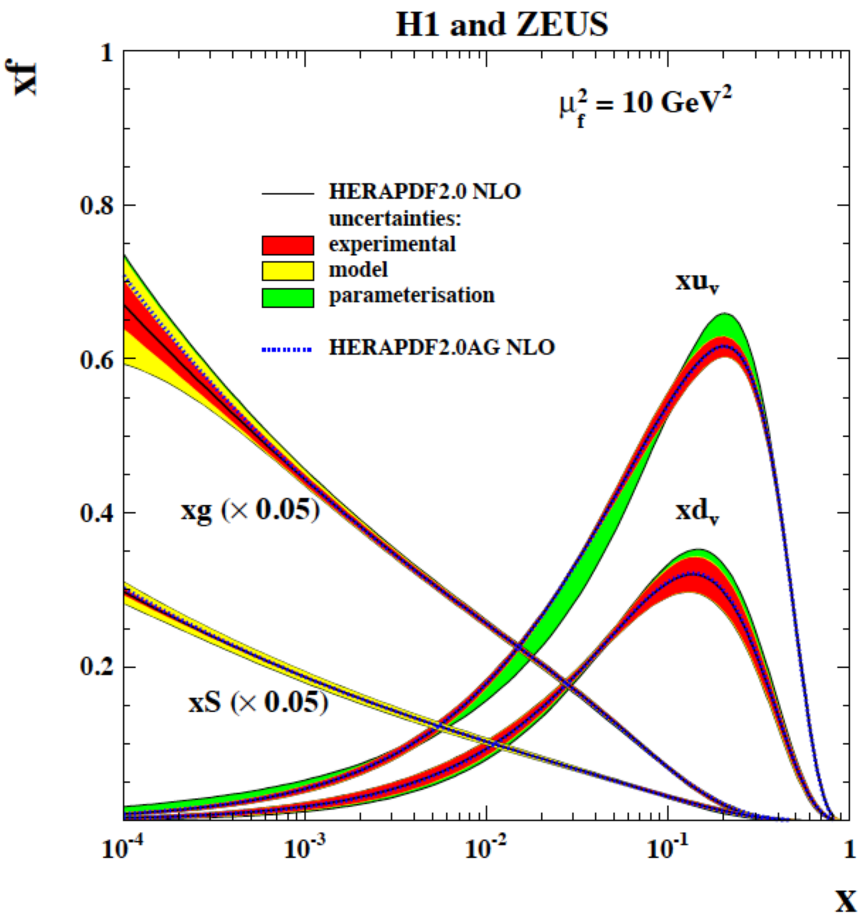
$$g \rightarrow q\bar{q}$$

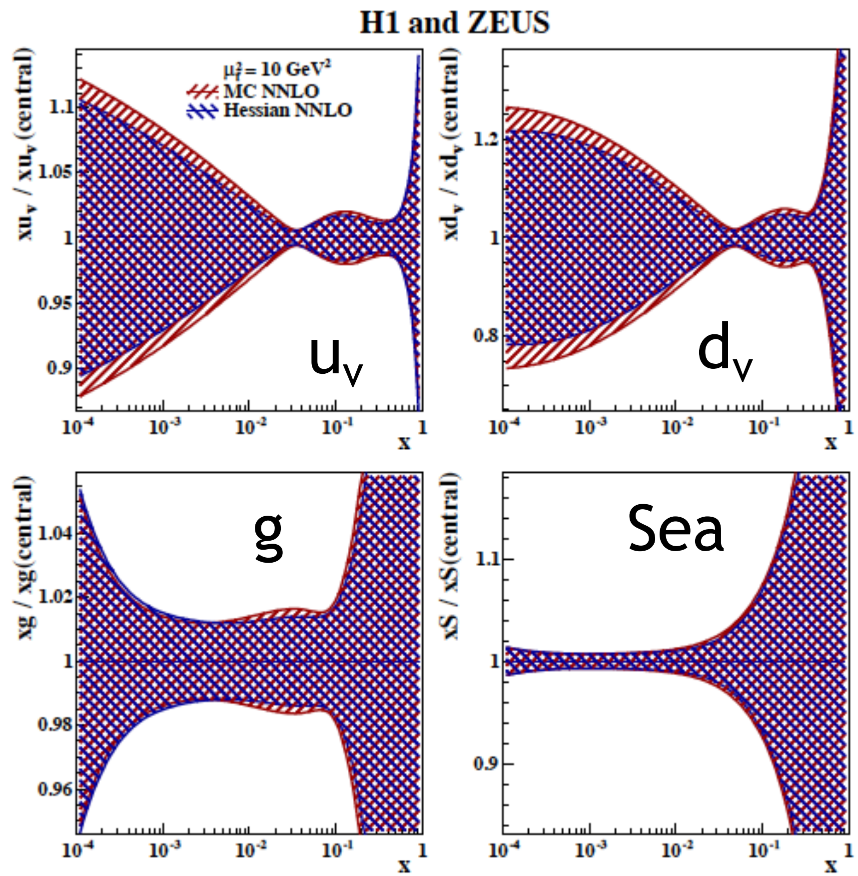


- DGLAP equations describe QCD evolution (to NNLO and approximate N^3LO accuracy)

- EW effects give different quark sensitivities (Z-exchange separates e^+p v e^-p, W-exchange gives charged current (ep → νX)

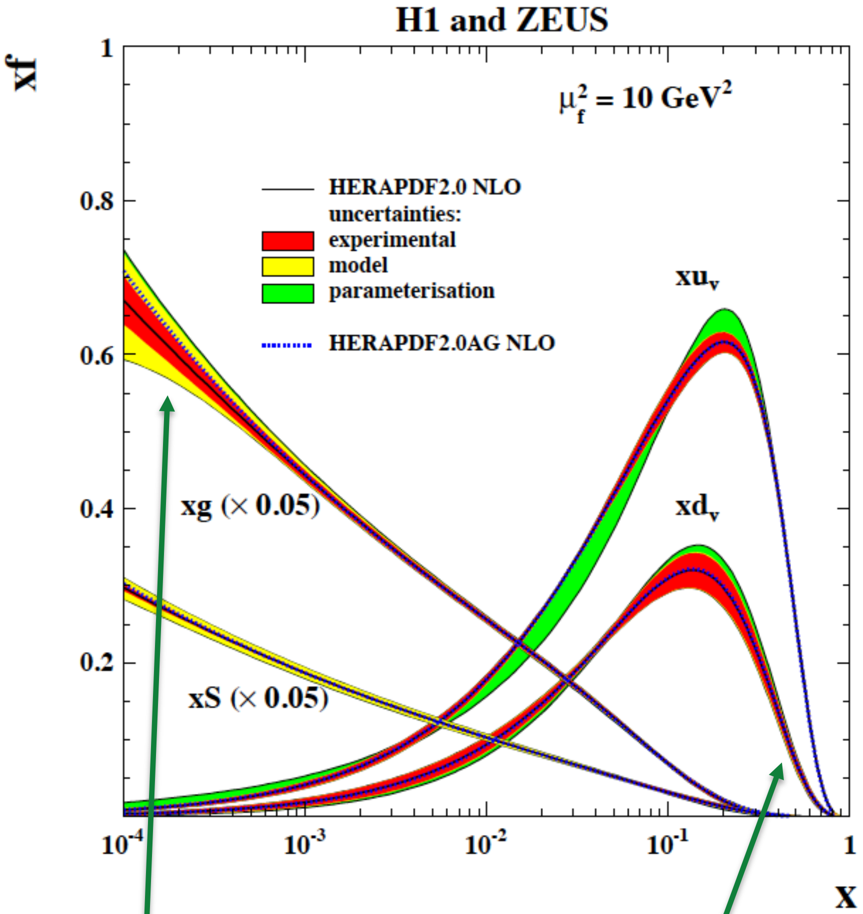
Proton PDFs from HERA only (HERAPDF2.0)

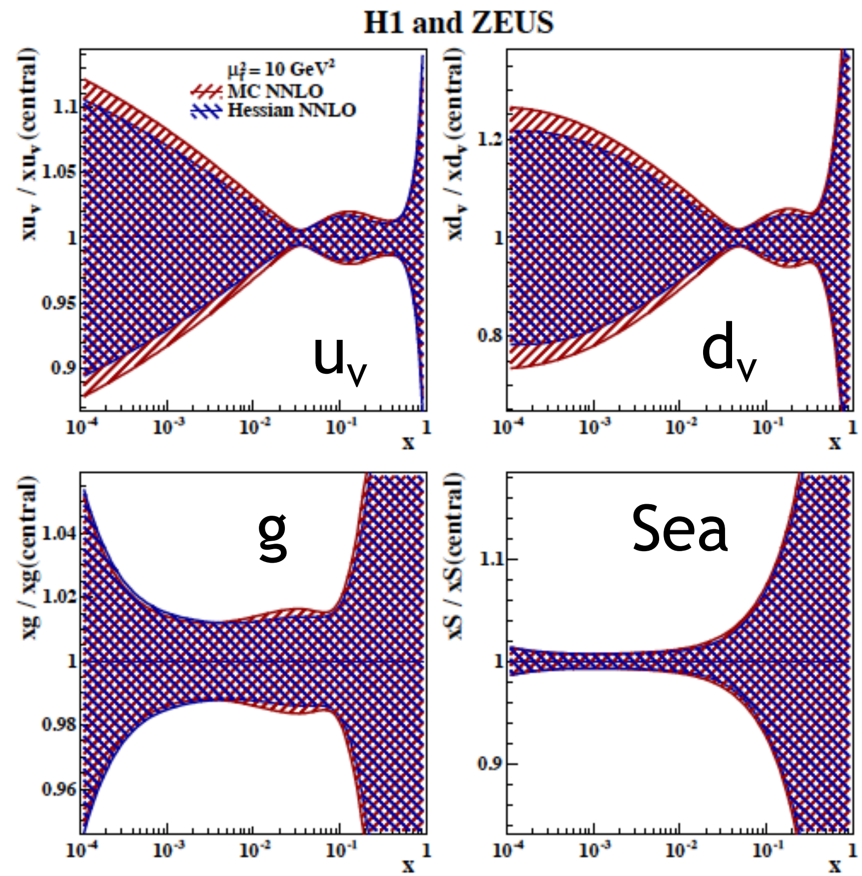




- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

Proton PDFs from HERA only (HERAPDF2.0)



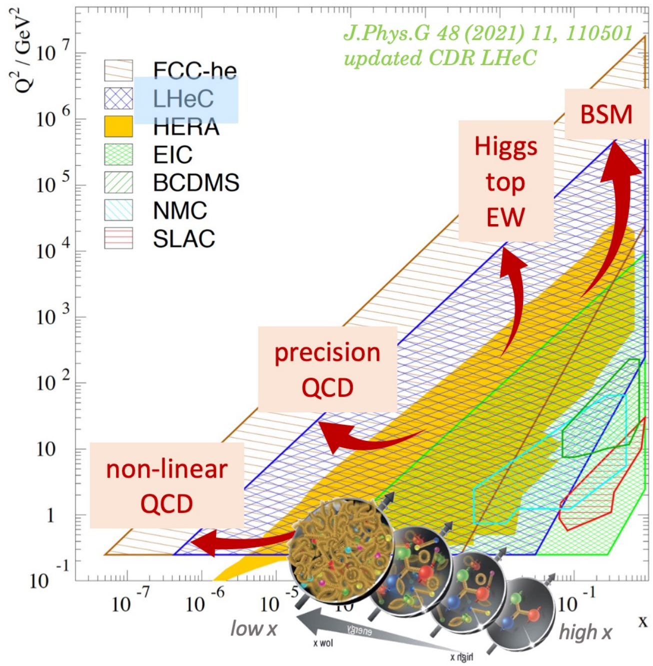


Strong interaction dragons?

Input to energy frontier discovery?

- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

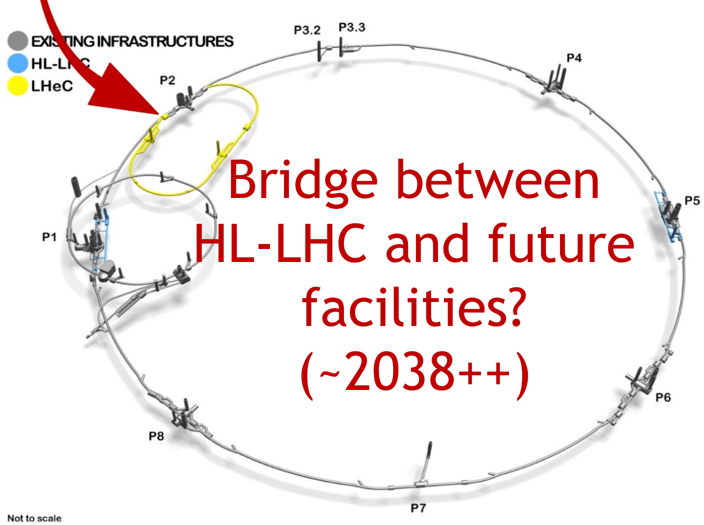
Future High Energy ep and eA Options at CERN



- Combined function of energy-frontier collider (Higgs, searches…) and DIS for QCD / structure exploration
- Extensions to lower x (10^{-6} at HL-LHC, 10^{-7} at FCC-eh)
- Ongoing studies towards Euro strategy

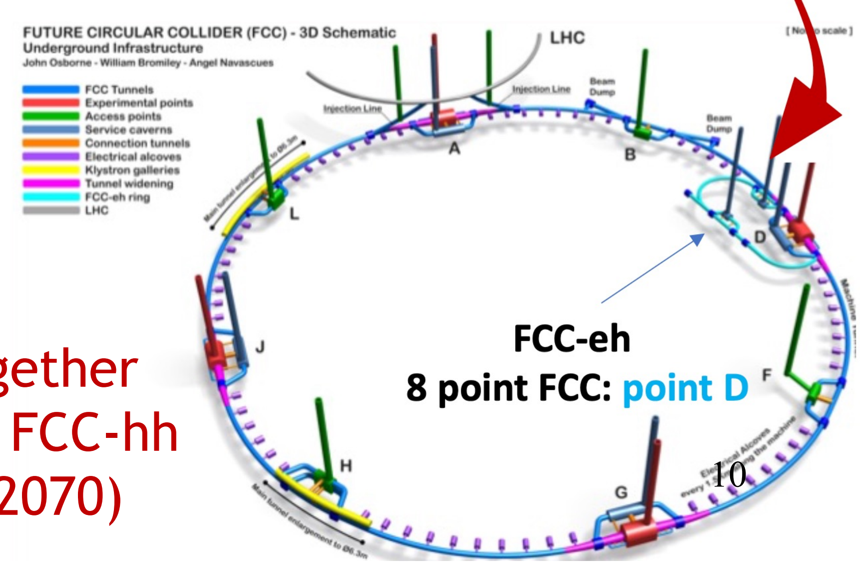
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh

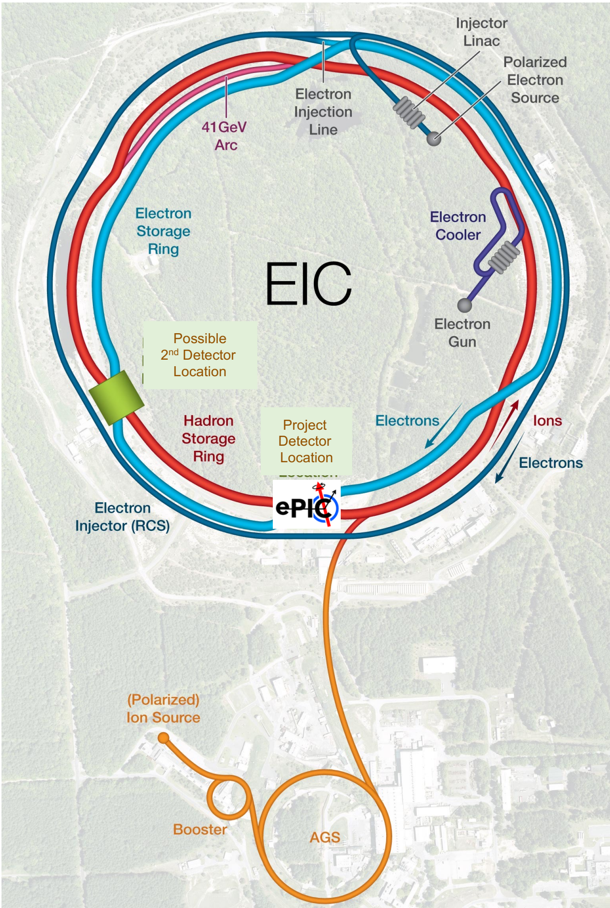


Bridge between HL-LHC and future facilities? (~2038++)

Together with FCC-hh (~2070)



The Electron-Ion Collider (BNL)

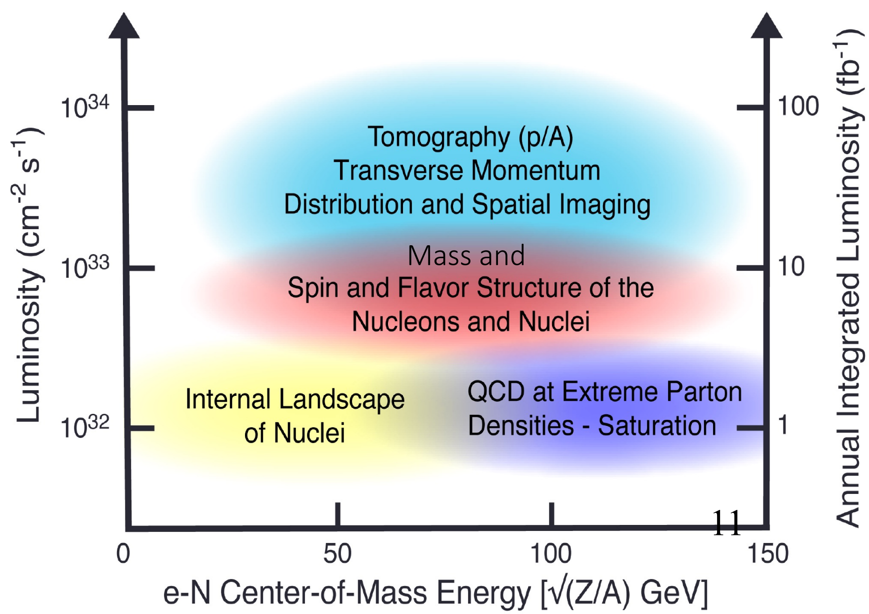


New electron ring, to collide with RHIC p, A

- Energy range **28 < $\sqrt{s}$ < 140 GeV**, accessing moderate / large x values compared with HERA

World's first …

- High lumi ep Collider **(~ 10^{34} cm^{-2} s^{-1})**
- Double-polarised DIS collider **(~70% for leptons and light hadrons)**
- eA collider **(Ions ranging from H to U)**



Specifications driven by science goals:

- 3D proton structure
- Proton mass
- Proton spin
- Dense partonic systems in nuclei

EIC Machine Design Parameters

Double Ring Design Based on Existing RHIC Facilities	
Hadron Storage Ring: 40, 100 - 275 GeV	**Electron Storage Ring: 5 - 18 GeV**
RHIC Ring and Injector Complex: p to Pb	9 MW Synchrotron Radiation
1A Beam Current	Large Beam Current - 2.5 A
10 ns bunch spacing and 1160 bunches	
Light ion beams (p, d, ^{3}He) polarized (L,T) > 70%	Polarized electron beam > 70%
Nuclear beams: d to U	**Electron Rapid Cycling Synchrotron**
Requires Strong Cooling: new concept →CEC	Spin Transparent Due to High Periodicity
One High Luminosity Interaction Region(s)	
25 mrad Crossing Angle with Crab Cavities	

Challenges from high lumi requirement include short bunch spacing and high beam currents …

→ Synchrotron load management
→ Significant crossing angle

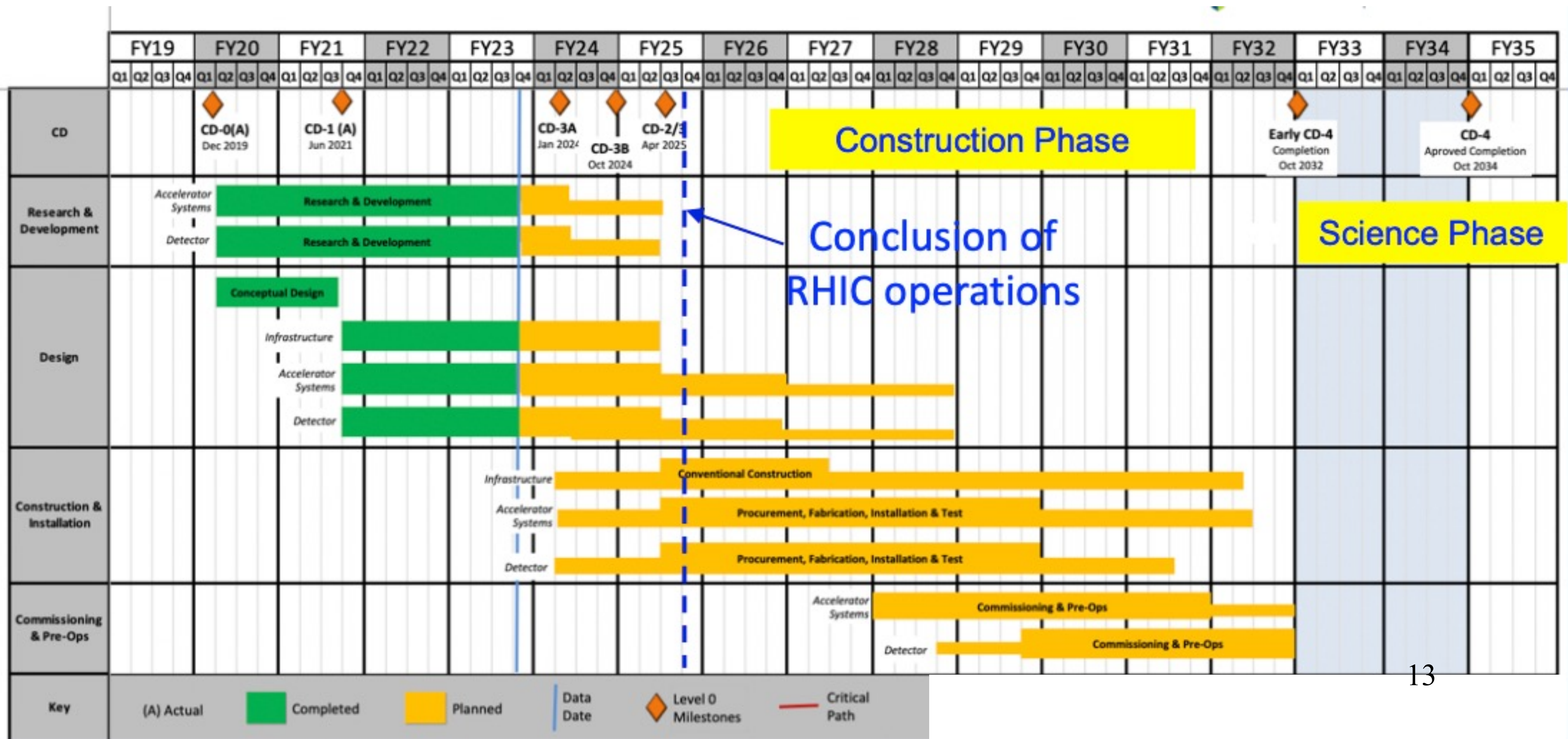
Status / Timeline

- Total cost ~$2Bn (US project funds accelerator + one detector)

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

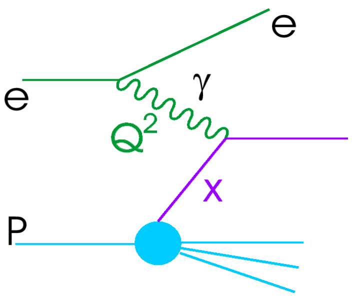
CD-0 (Mission need)	Dec 2019
CD-1 (Cost range)	June 2021
CD-3A (Start construction)	April 2024
CD-3B	Oct 2024
CD-2 (Performance baseline)	April 2025
CD-4 (Operations / completion)	2032-34

Technical Design Report: end 2025 (prelim 2024)



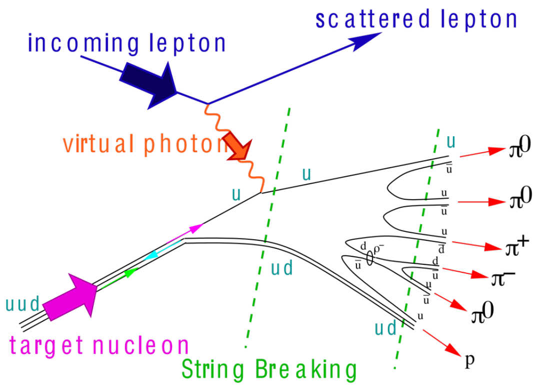
Observables / Detector Implications

Inclusive



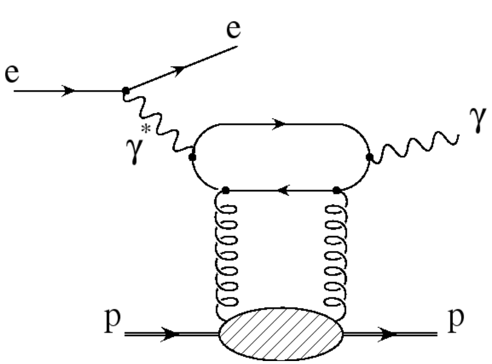
- Traditional DIS, following on from fixed target experiments and HERA → Longitudinal structure
  … high acceptance, high performance electron identification and reconstruction

Semi-Inclusive



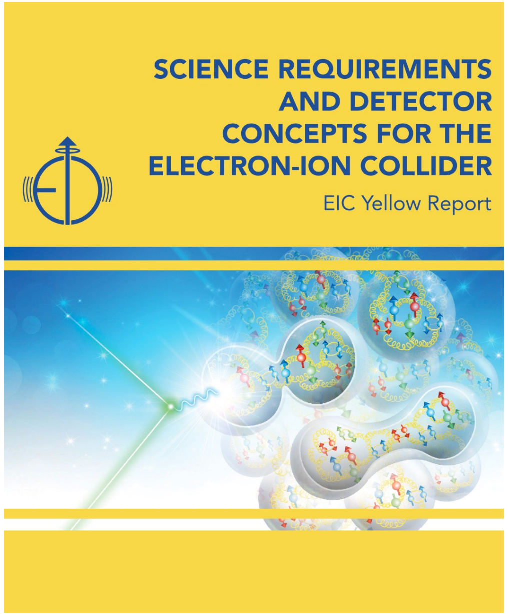
- Single particle, heavy flavour & jet spectra
  → p_T introduces transverse degrees of freedom
- Quark-flavour-identified DIS
  → Separation of u,d,s,c,b and antiquarks
  … tracking and hadronic calorimetry
  … heavy flavour identification from vertexing
  … light flavours from dedicated PID detectors

Exclusive / Diffractive



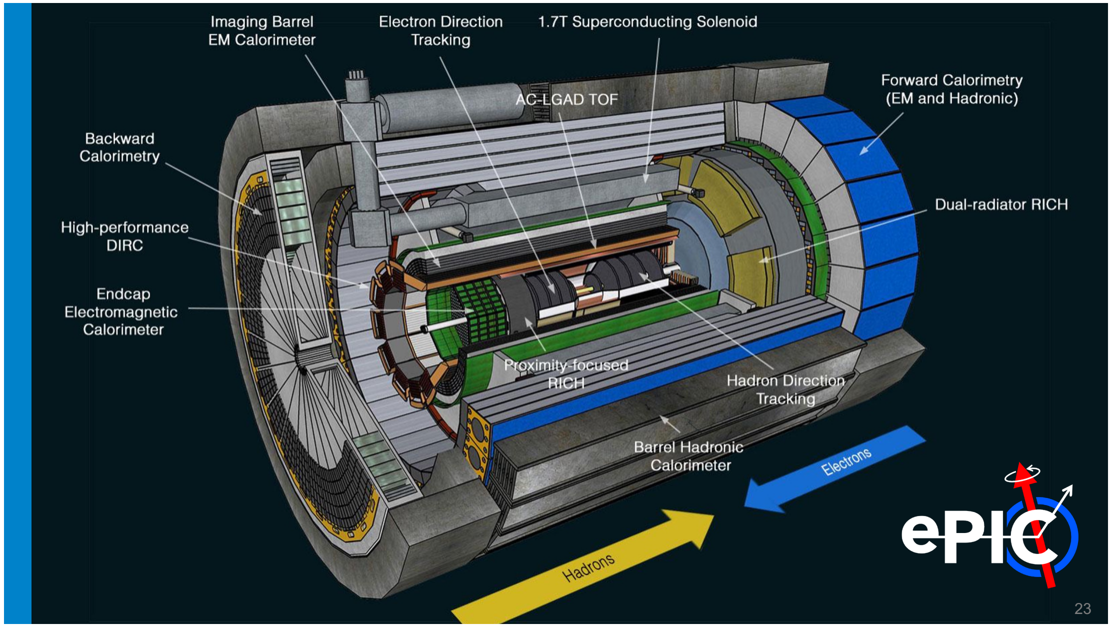
- Processes with final state 'intact' protons
  → Correlations in space or momentum between pairs of partons
  … efficient proton tagging over wide acceptance range
  … high luminosity

EIC Experiments



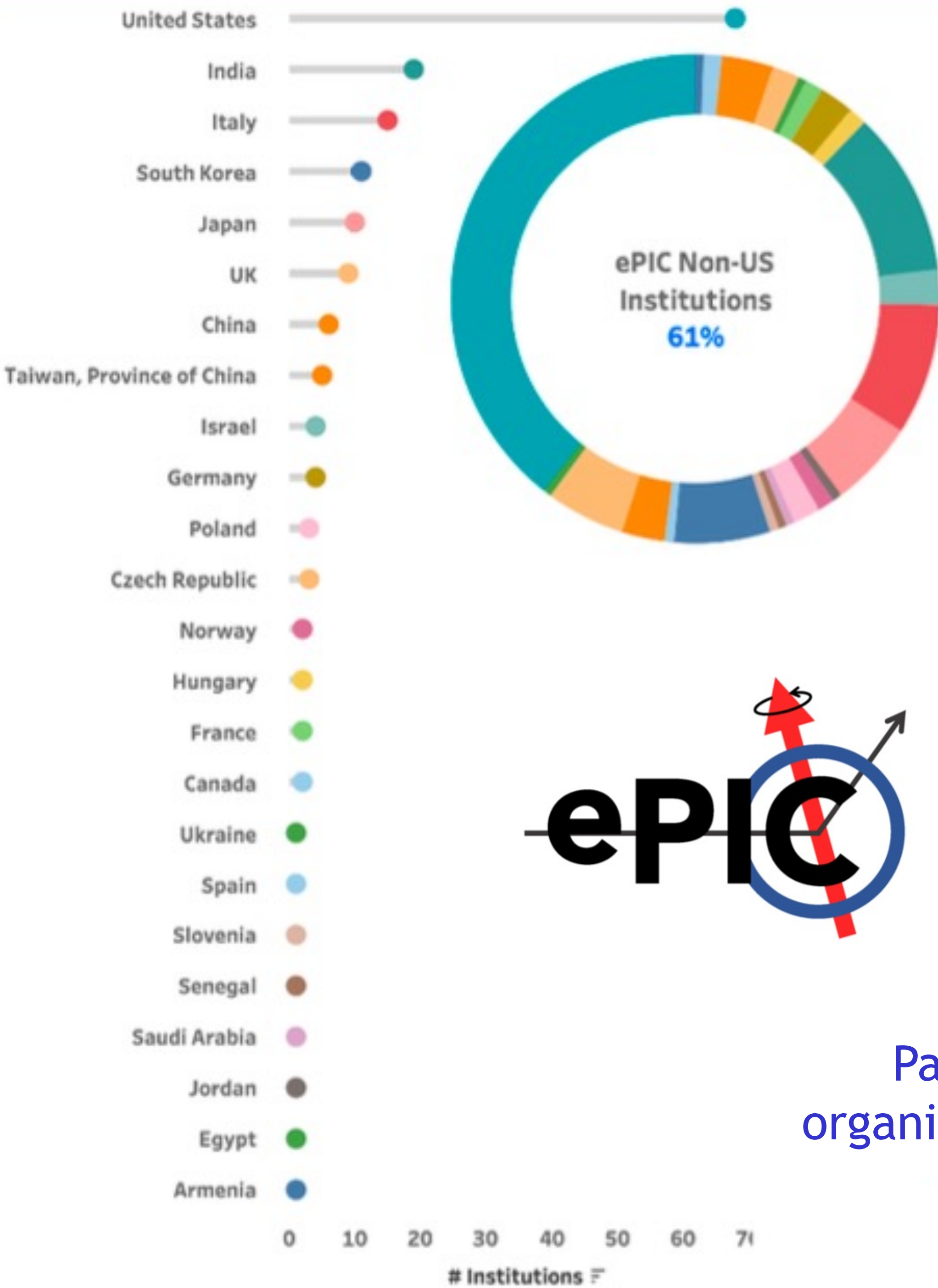
- **Yellow Report (arXiv:2103.05419):**
  … explored physics targets and corresponding detector requirements
  … defined baseline detector

- **ePIC = Project detector**
  … funded through US DoE and international partners (now including UK)



- **Second detector?**
  … an essential ingredient, but not yet funded or designed in detail
  … should bring an overlapping, but complementary physics programme

ePIC Collaboration Demographics



Over >850 participants so far, from ~173 institutes in 24 countries

Part of a wider ‘EIC User Group’ organization with around 1400 members, including theorist colleagues

A Detector for the EIC

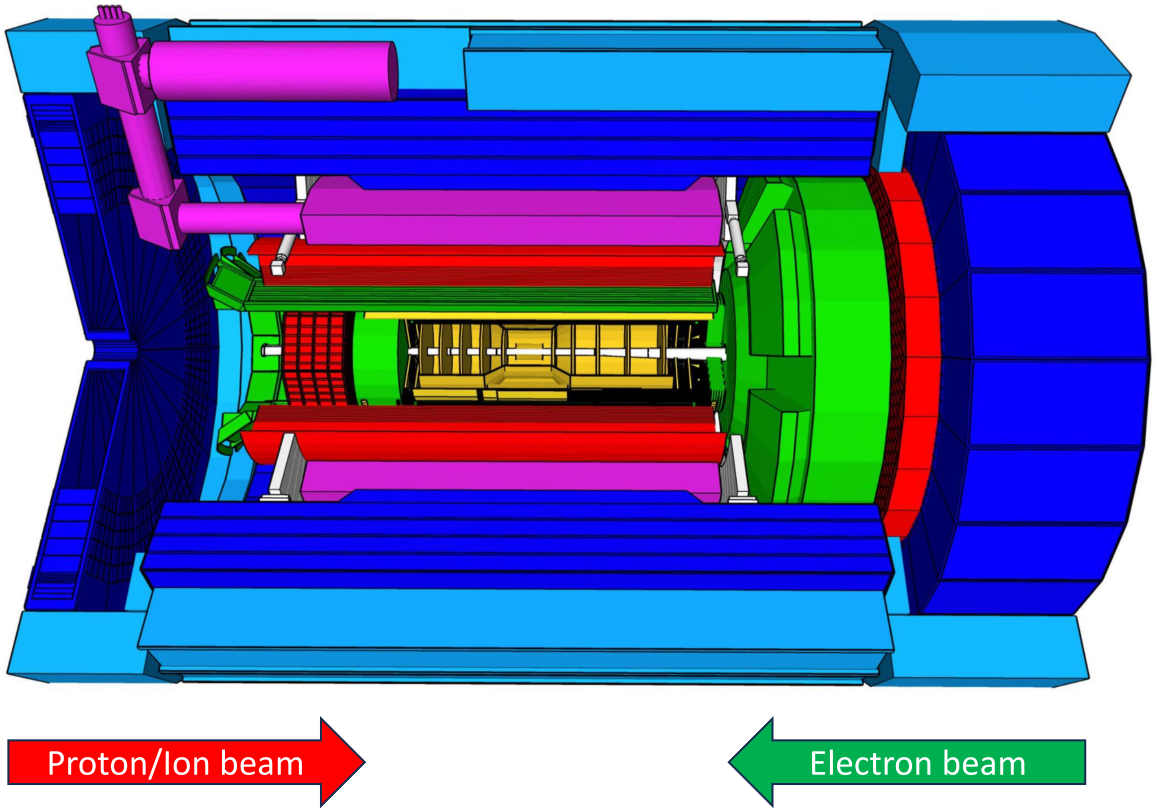
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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)



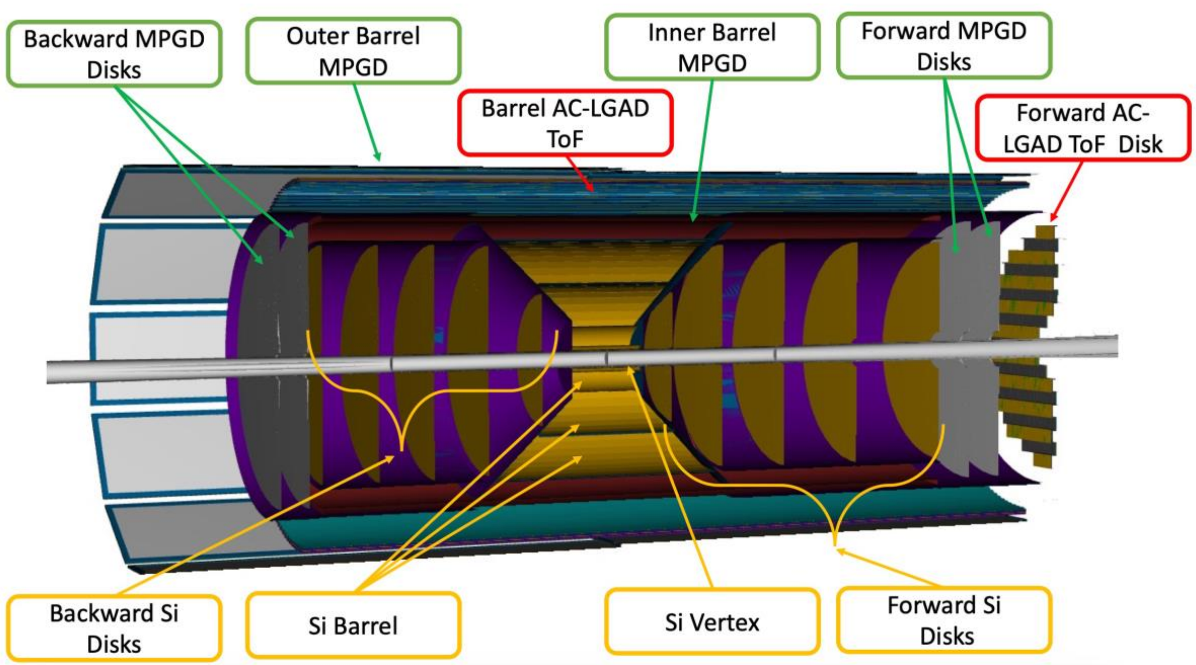
- 9m long x 5m wide
- Extensive beamline instrumentation not shown (see later)
- Continuous streaming readout with emphasis on FEB zero-suppression
- Much lower radiation fluxes than LHC widens technology options

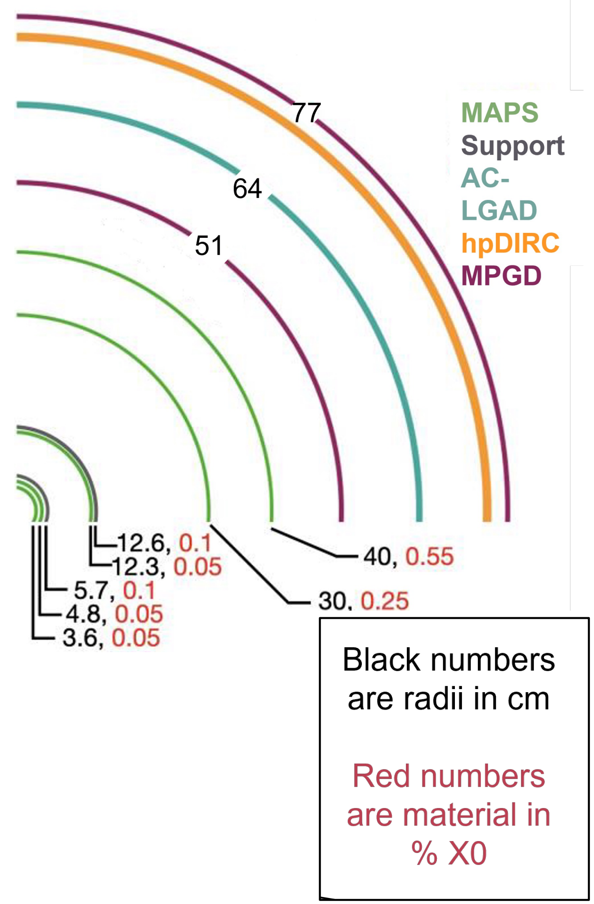
Tracking Detectors

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 8.5m² silicon)





LGAD layers provide fast timing (~20ns)

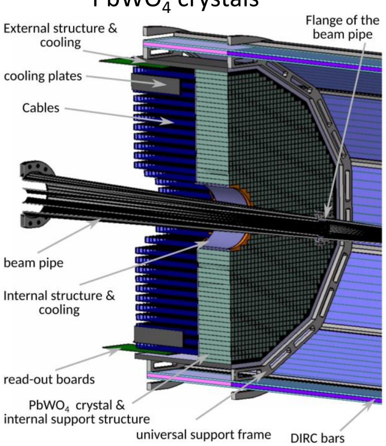
Outer gaseous detectors add additional hit points for track reconstruction

Calorimeter Overview

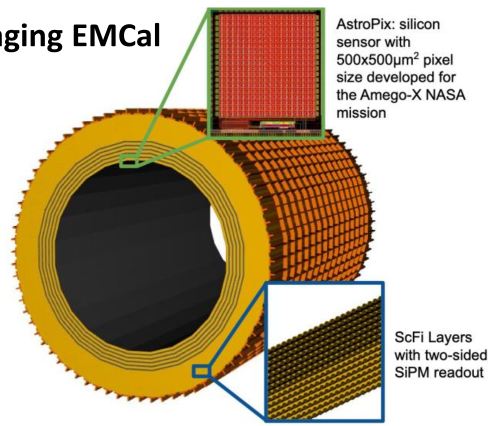
- Different technologies in barrel and end-caps, as required for varying performance targets
- New ECAL designs / technologies,
- HCAL partially recycles previous detectors
- All read out with Si PMs

Electron Endcap EMCal

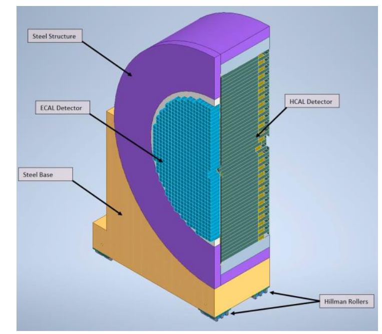
$PbWO_4$ crystals



Barrel Imaging EMCal

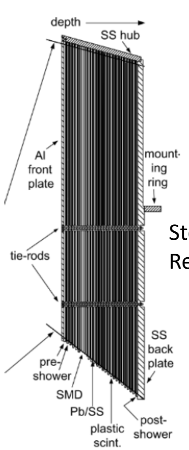


Hadron Endcap EMCal



High granularity W-powder/SciFi EMCal

Electron Endcap HCal



Steel/Scint Sandwich (10 layers)
Reuse of STAR scint. tiles

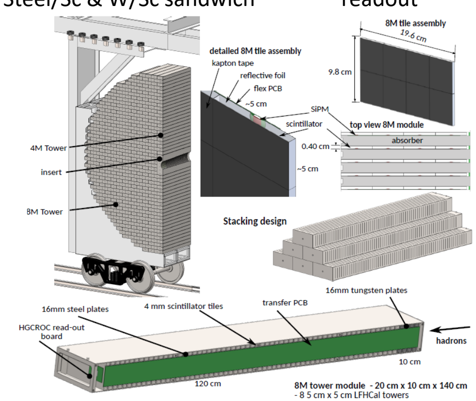
Barrel HCal

sPHENIX barrel calorimeter with new SiPMs

Hadron Endcap HCal

Longitudinally separated HCAL Steel/Sc & W/Sc sandwich

SiPM-on-tile readout

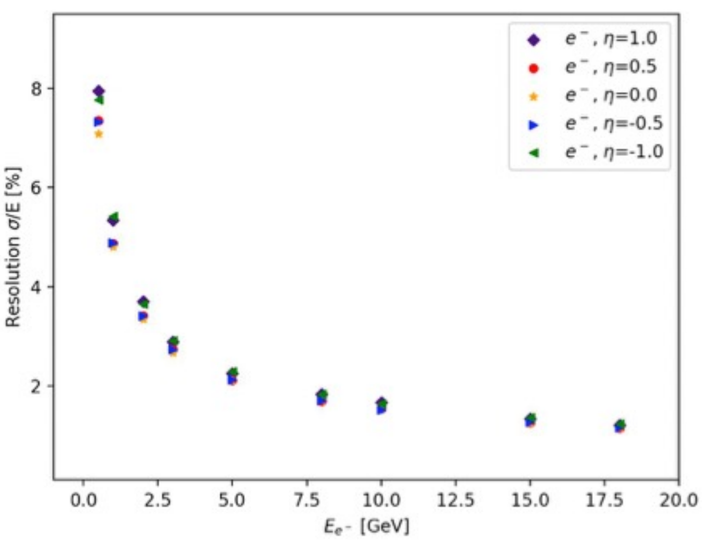


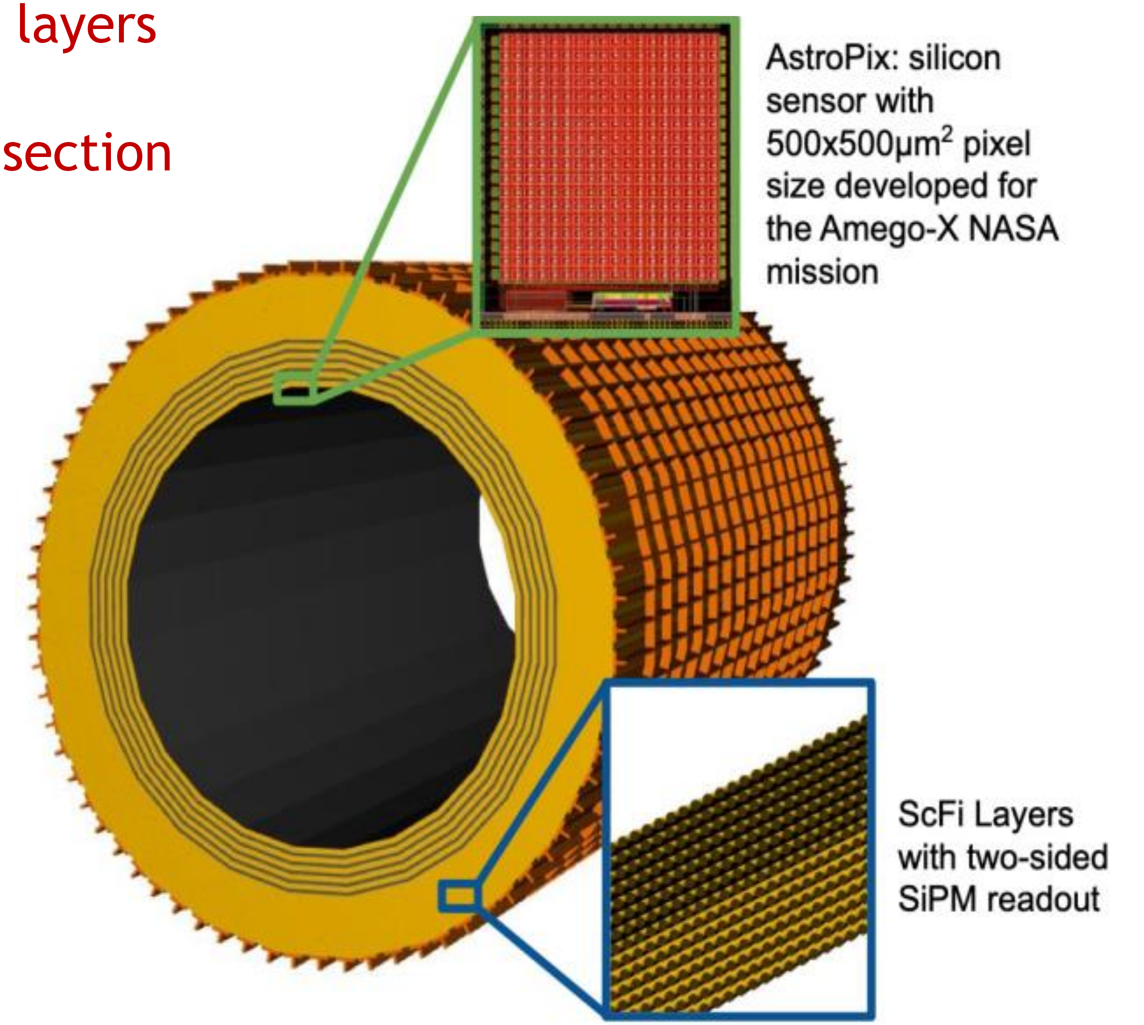
+ high granularity insert at largest η

Barrel 'Imaging ECAL'

- 4 MAPS (Astropix) layers for position resolution.
- Interleaved with 5 Pb/SciFi layers for energy resolution
- Followed by large Pb/SciFi section

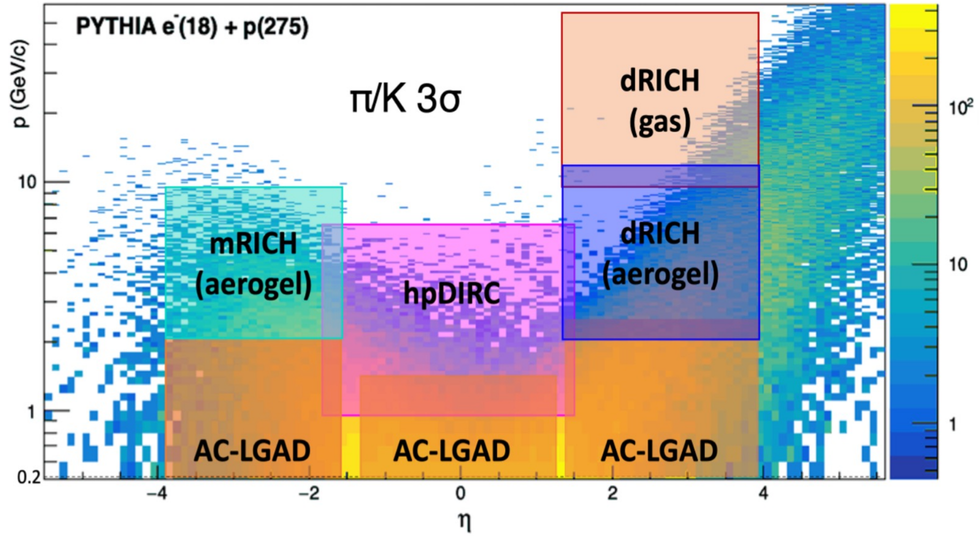
$$\frac{\sigma}{E} \sim \frac{5\%}{\sqrt{E}} + 0.5\%$$





Particle Identification

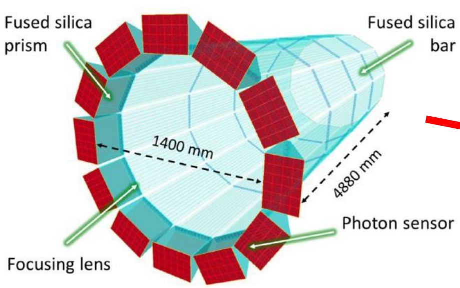
- SIDIS programme relies on π / K / p (and other PID) separation …
- Cerenkov detectors at high momentum, augmented by AC-LGADs / ToF at low momentum

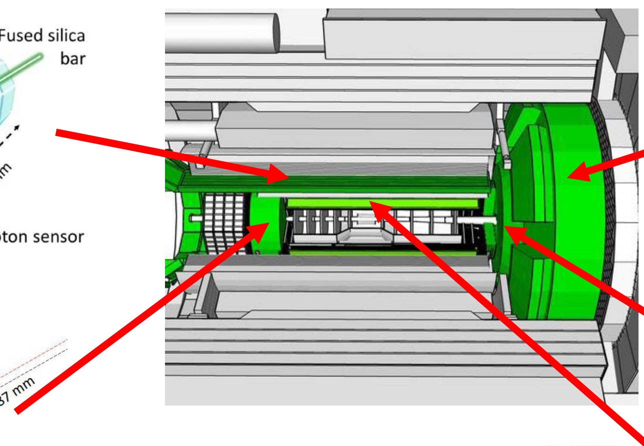


ePIC detector design – PID

High-Performance DIRC

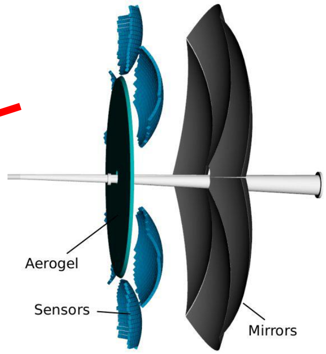
- Quartz bar radiator (reuse BaBAR bars)
- Sensors: MCP-PMTs
- π/K separation up to 6 GeV/c

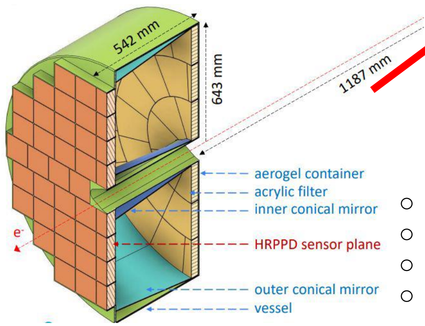




Dual-Radiator RICH (dRICH)

- C_2F_6 Gas Volume and Aerogel
- Sensors: SiPMs tiled on spheres
- π/K separation up to 50 GeV/c



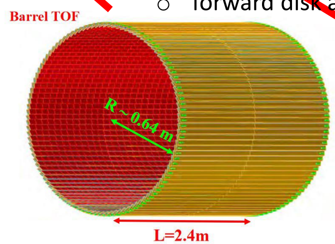


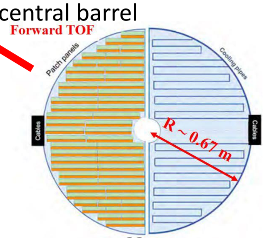
Proximity Focused (pfRICH)

- Long Proximity gap (~40 cm)
- Sensors: HRPPDs (also provides timing)
- π/K separation up to 10 GeV/c
- e/π separation up to 2.5 GeV/c

AC-LGAD TOF

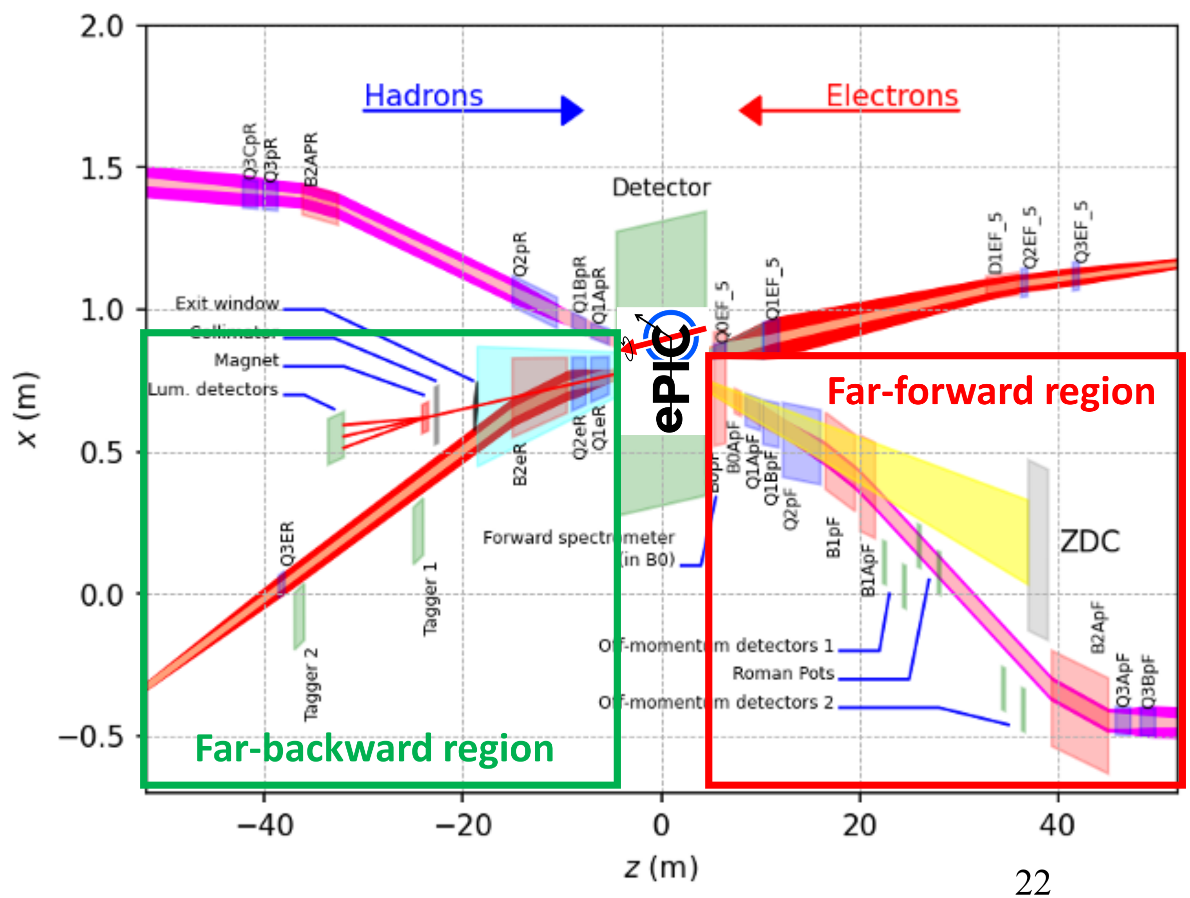
- t = ~30 psec / s = 30 µm
- Accurate space point for tracking
- forward disk and central barrel





Interaction Region / Beamline Instrumentation

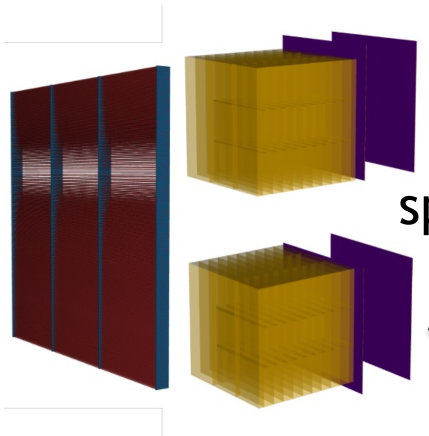
- Extensive beamline instrumentation integrated into IR design



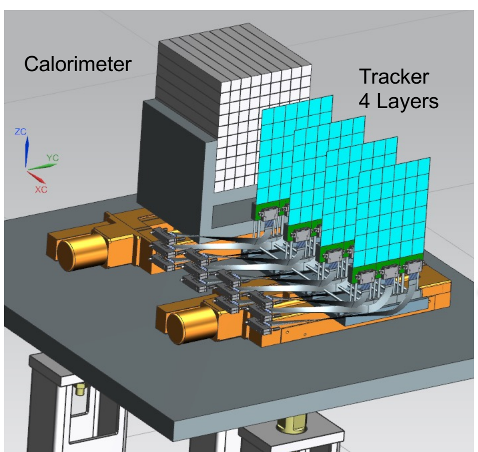
Interaction Region / Beamline Instrumentation

- Extensive beamline instrumentation integrated into IR design

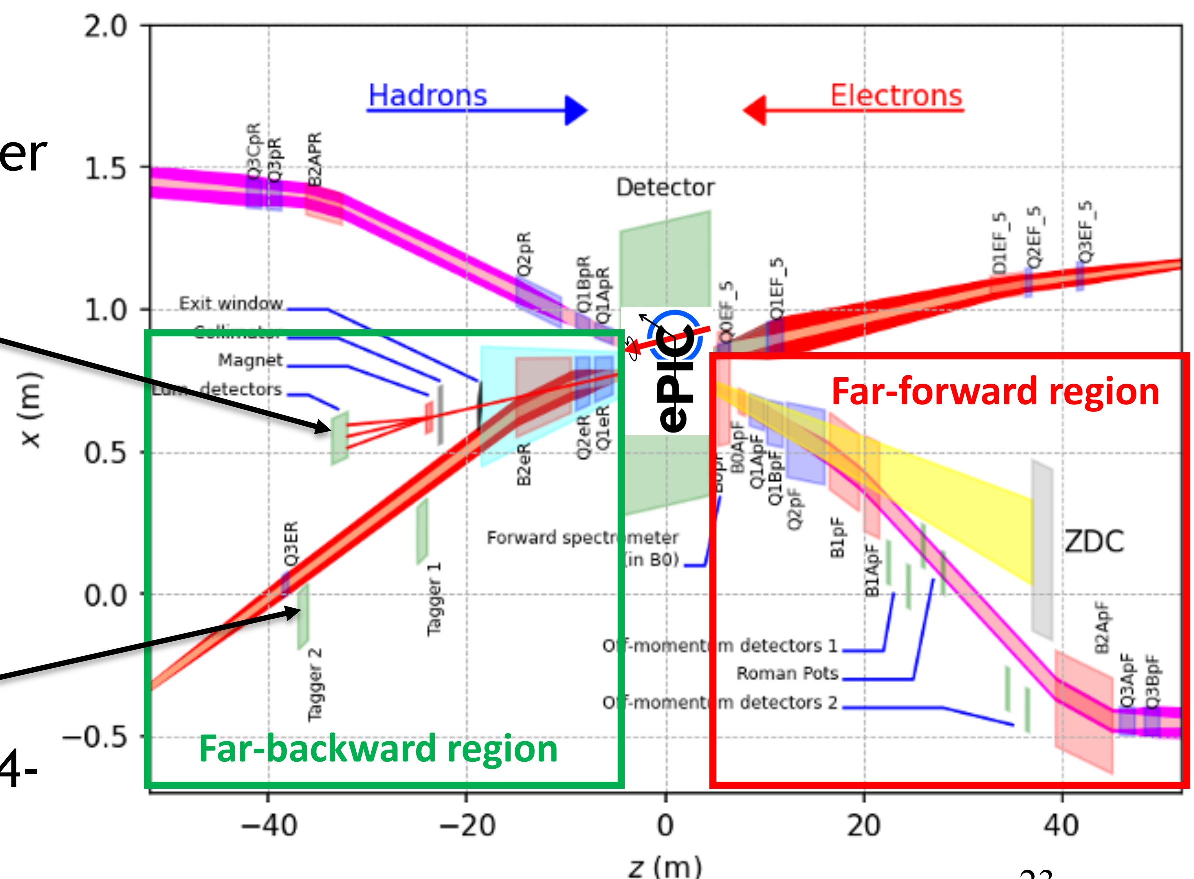
- Tagging electrons and photons in backward direction for lowest Q^2 physics studies and lumi monitoring via ep→epγ



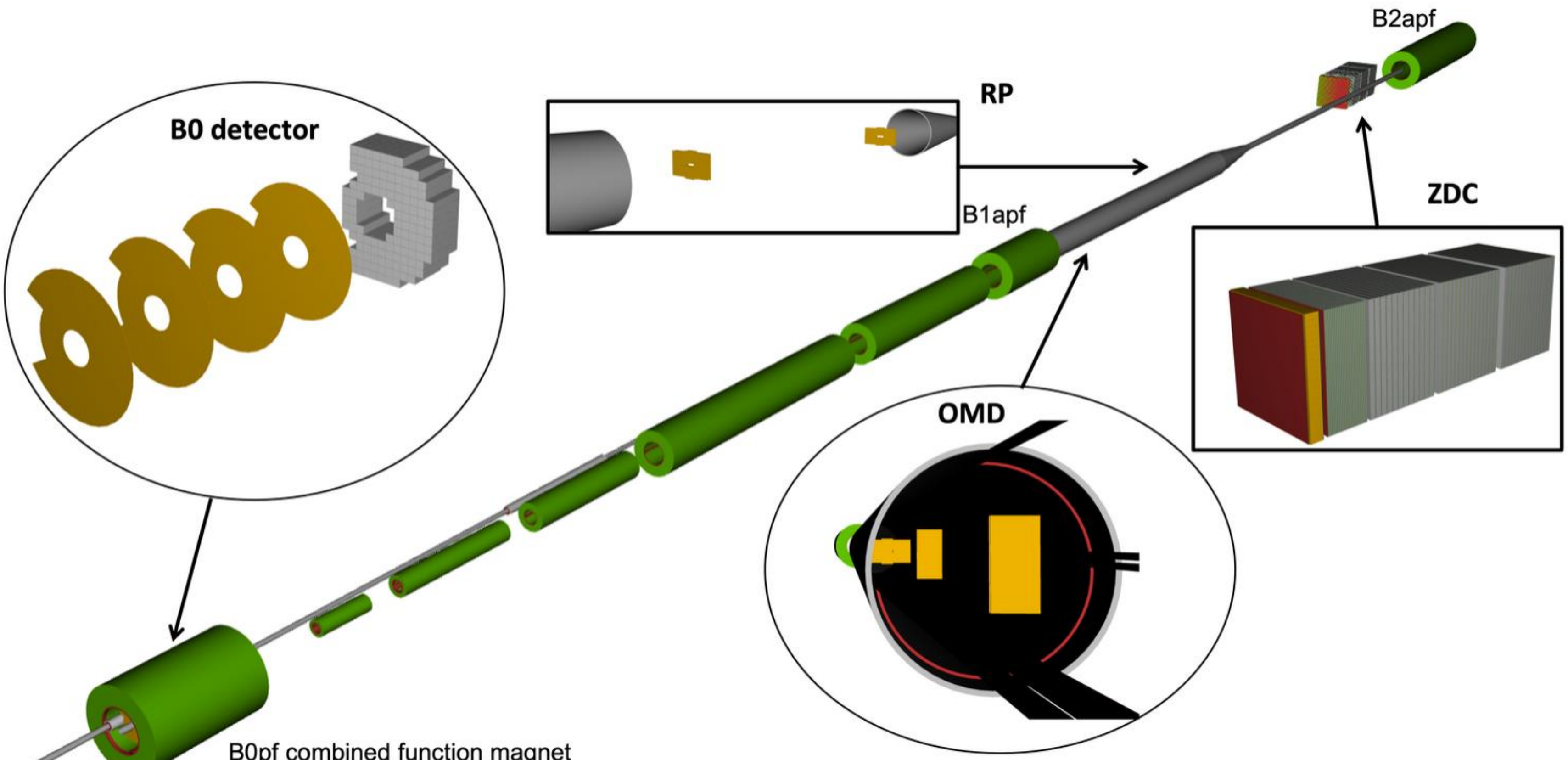
W-SciFi
Lumi Pair
spectrometer



Timepix4-
based
tracker



Far Forward Region



9/28/2023

Hermetic forward coverage outside and inside beampipe

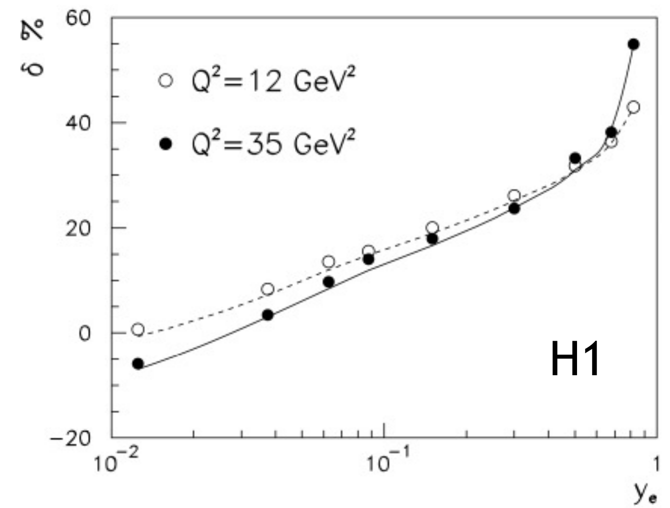
Detector	Acceptance	Particles
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5\ mrad$	Neutrons, photons
Roman Pots (2 stations)	$0^* < \theta < 5.0\ mrad$ (*10σ beam cut)	Protons, light nuclei
Off-Momentum Detectors (2 stations)	$0 < \theta < 5.0\ mrad$	Charged particles
B0 Detector	$5.5 < \theta < 20\ mrad$	Charged particles, tagged photons

Kinematic Reconstruct'n: HERA approach

- Use electron only where possible (E_e', θ_e usually very well measured)

$$y_e = 1 - \frac{E_e'}{E_e} \sin^2 \frac{\theta}{2}$$

… BUT … resolution degrades as 1/y
[E_e' large, towards the 'kinematic peak']
→ limitation on measurements at high x
(central part of EIC programme!)



… AND … initial state radiation corrections
(and uncertainties) grow as y→1 (i.e. at low x)

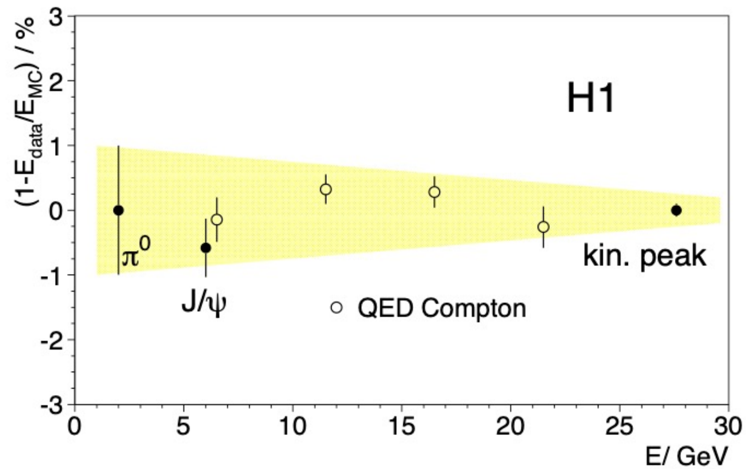
- Other methods exploiting redundancy through measurements of Hadronic Final State

1) Hadron only method (CC)
3) Double Angle methods (θ_e, θ_h)
   → insensitive to calorimeter energy resolution
4) Sigma methods (E_e', θ_e, $p_{T,h}$, $(E - p_z)_h$)
   → insensitive to forward hadronic losses & ISR

Choice depends on kinematic region and details of detector performance.

Detector Calibration

- The redundancy in NC kinematic variable reconstruction lies at the heart of the detector calibration methods used in DIS.

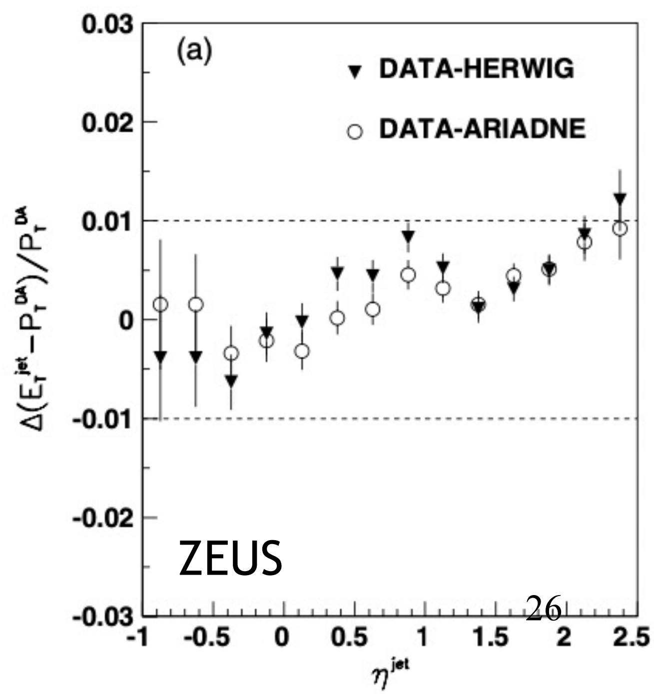


<u>Typical approach:</u>

1) Electron calibration from ‘known’ resonances / kinematic peak
2) Hadronic final state from pT and E-p_z balance relative to electron

… <0.5% on electrons and <1% on hadronic energy scale achieved at HERA.

High performance detector simulation / Monte Carlo modelling is essential for precise calibrations



Modernising Kinematic Reconstruction

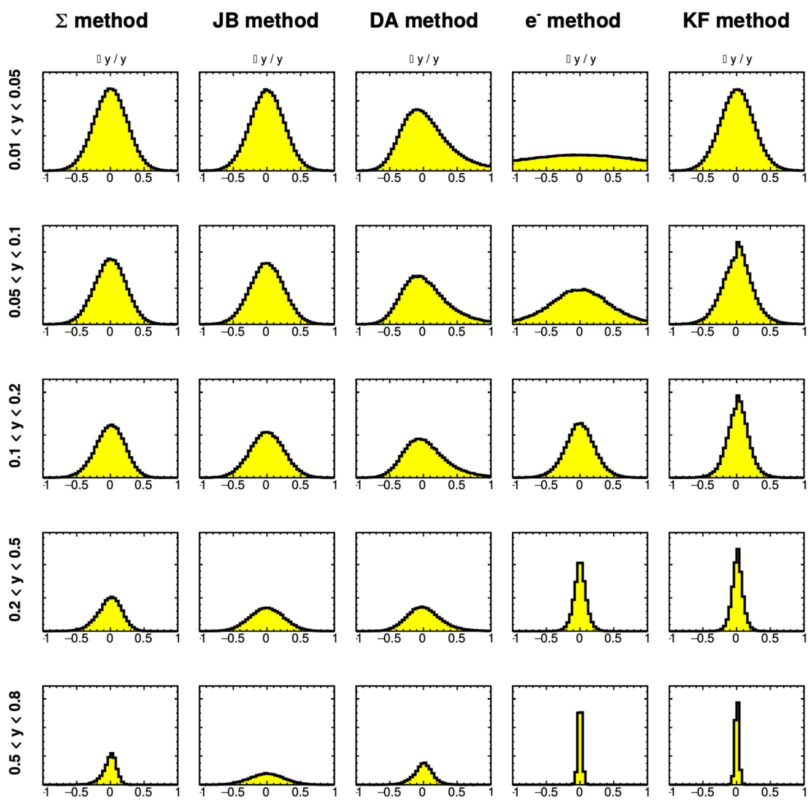
Why not use all available information from electrons and hadrons?

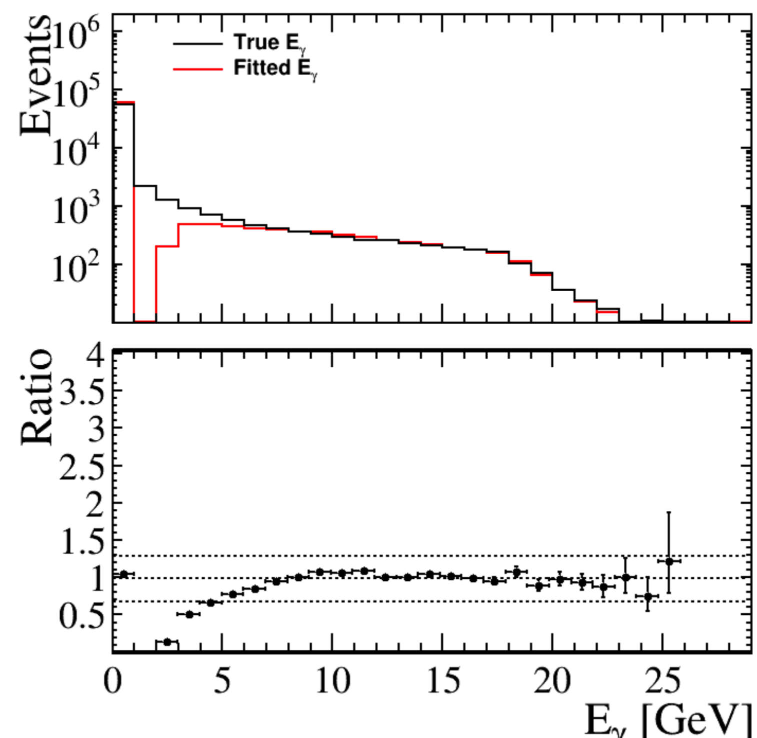
$E'_e, \theta_e, (E - p_z)_h, P_{T,h}$ always all contain useful information

1) Neural network approaches
2) Kinematic fit

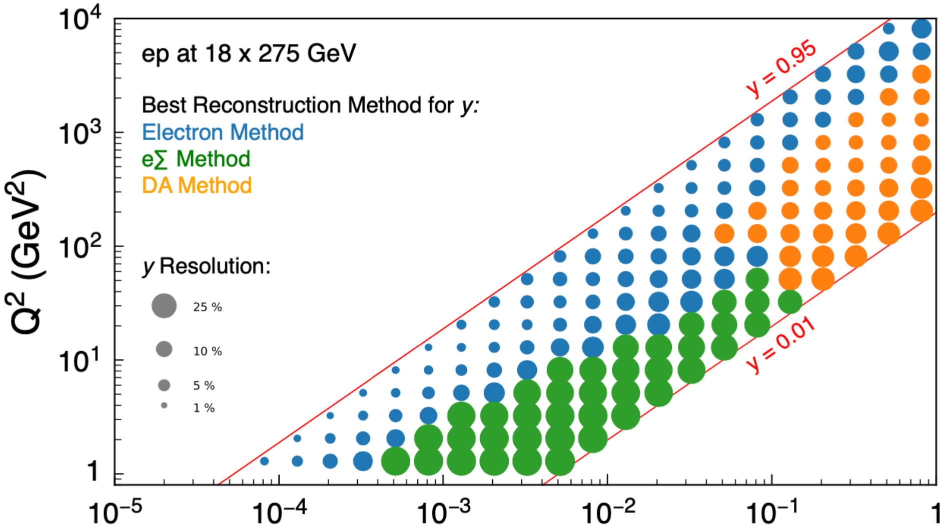
… matches best individual method everywhere and reconstructs ISR photons as a bonus (extends kinematic range, F_L …)

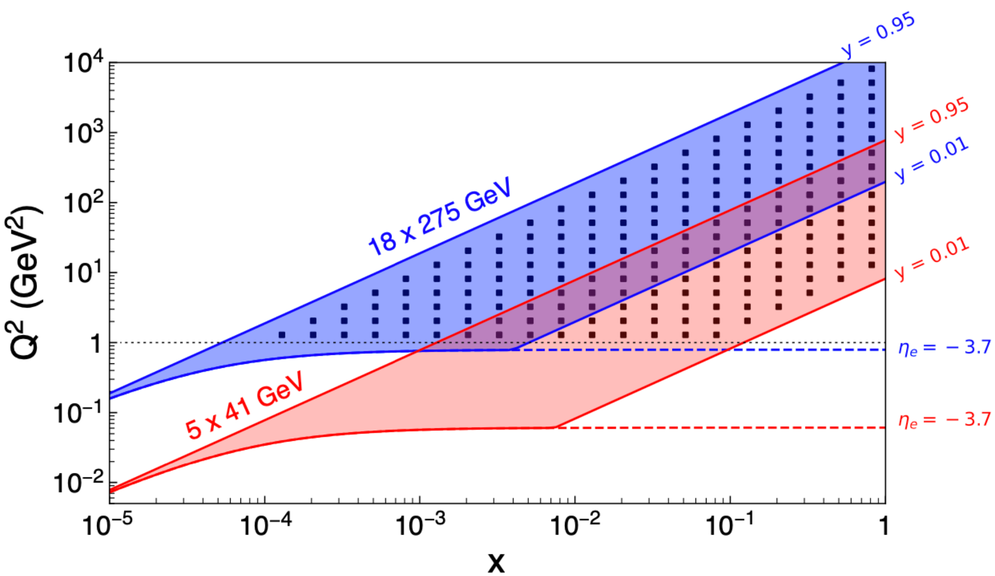
… developing in ePIC framework and benchmarking on H1 data





EIC: Performance and Measurement Strategy for Neutral Current





- Detailed simulation work to optimise resolutions throughout phase-space
→ 5 bins per decade in x and Q^2

- Pseudodata Kinematic coverage:

$Q^2 > 1$ GeV^2,

$0.01 < y \; (= \frac{Q^2}{sx}) < 0.95$,

$W^2 \; (= \frac{Q^2(1-x)}{x}) > 10$ GeV^2

- Lower y accessible in principle, but ultimately easier to rely on overlaps between data at different $\sqrt{s}$

Inclusive ePIC Pseudo-data

- Estimated luminosities corresponding to 1 year of data taking with each of 5 different beam energy configurations

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

(c.f. H1 + ZEUS @ HERA was 1fb^{-1})

- Systematic precision estimated from experience at HERA, expected EIC detector performance, and guesswork

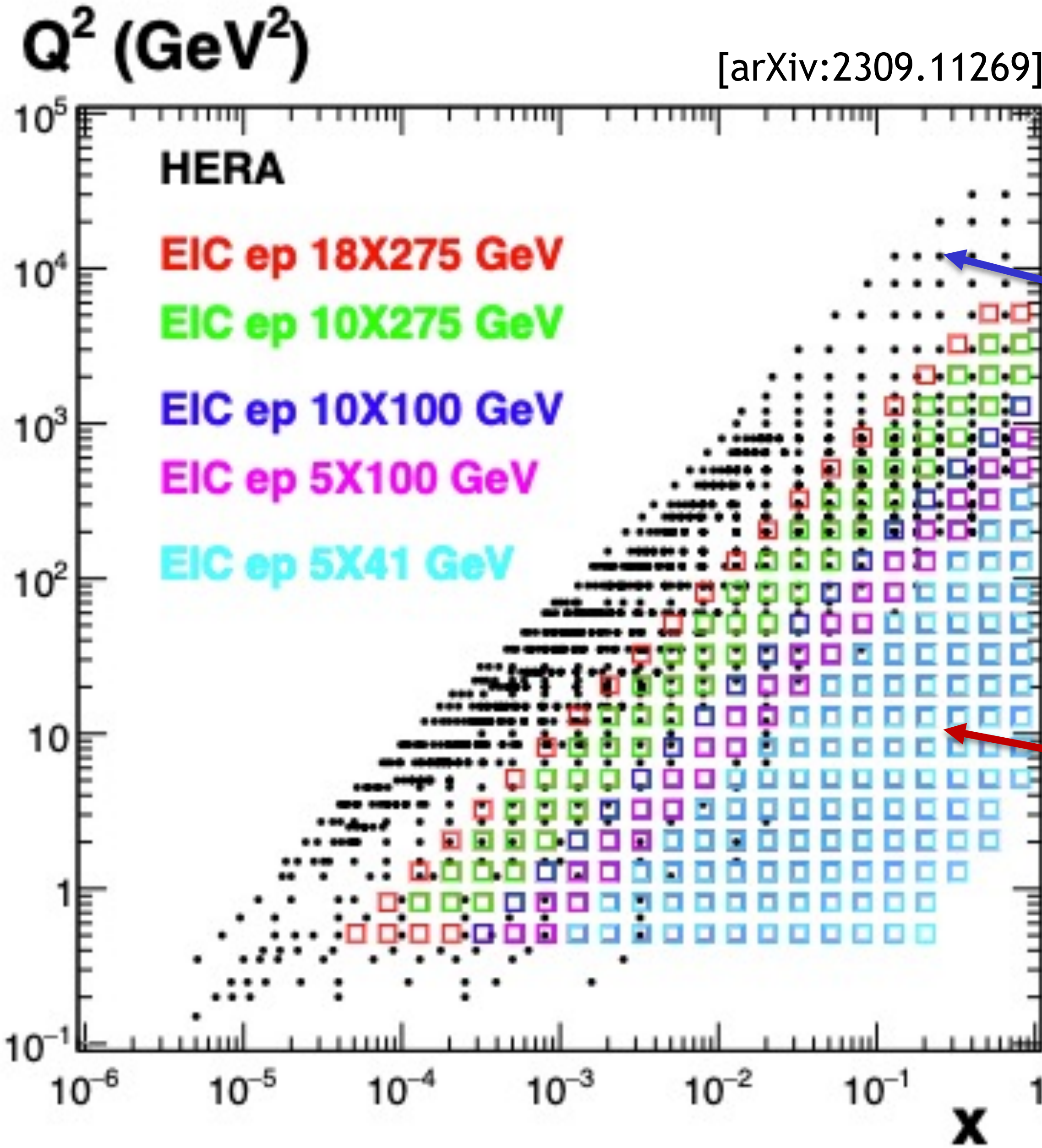
- Dominant sources at HERA were:
    - Electron energy scale (intermediate y)
    - Photoproduction background (high y)
    - Hadronic energy scale / noise (low y)

- EIC will improve in all areas → Current (conservative) assumption:

→ 1.5-2.5% point-to-point uncorrelated systematics
→ 2.5% normalisation (uncorrelated between different $\sqrt{s}$)
[Statistical uncertainties negligible by comparison]

… pseudodata on this basis (not yet a fully simulated measurement)

Inclusive EIC Pseudodata v HERA



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

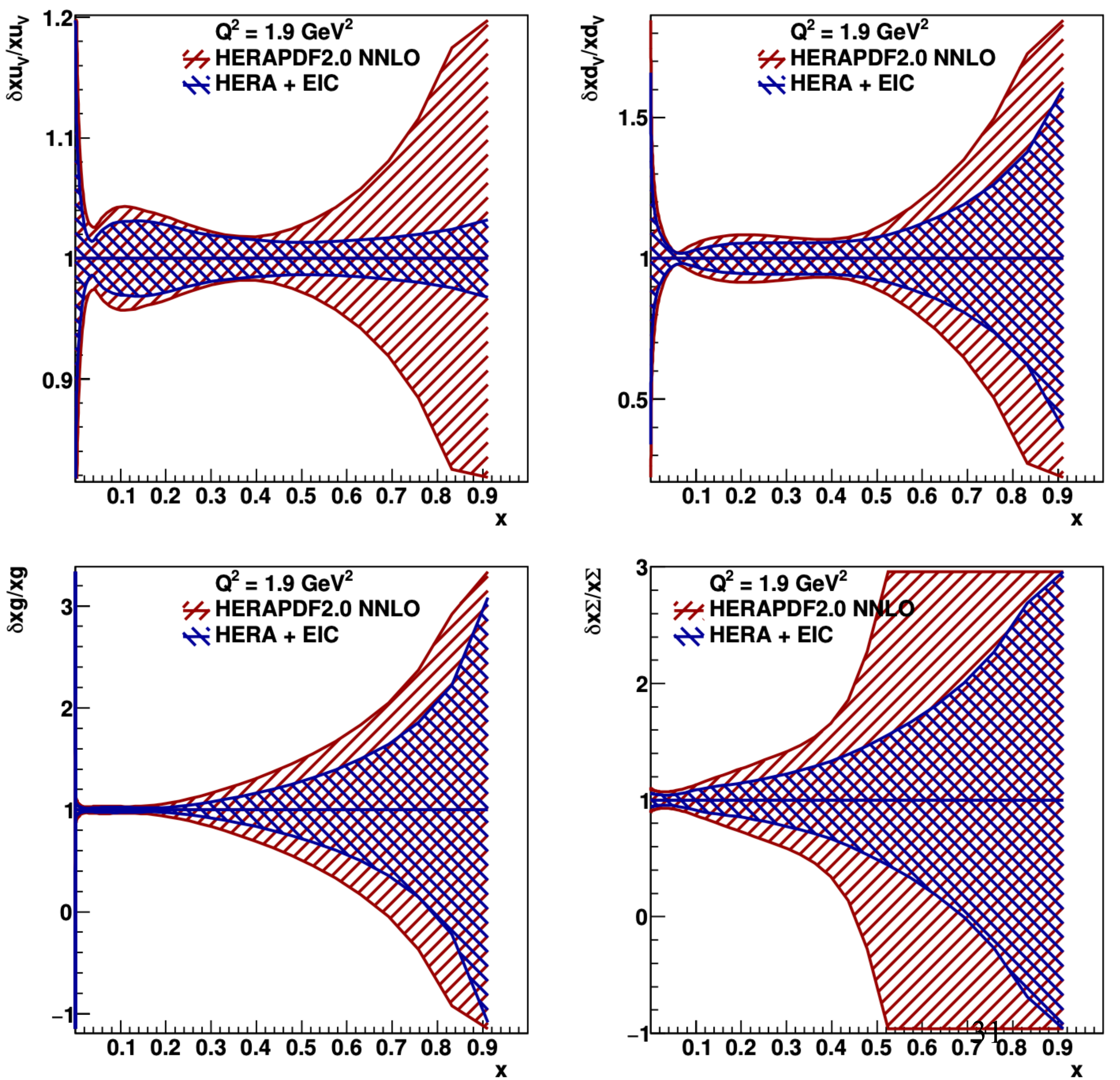
Impact of EIC/ATHENA on HERAPDF2.0

Fractional total uncertainties with / without simulated EIC data included with HERA

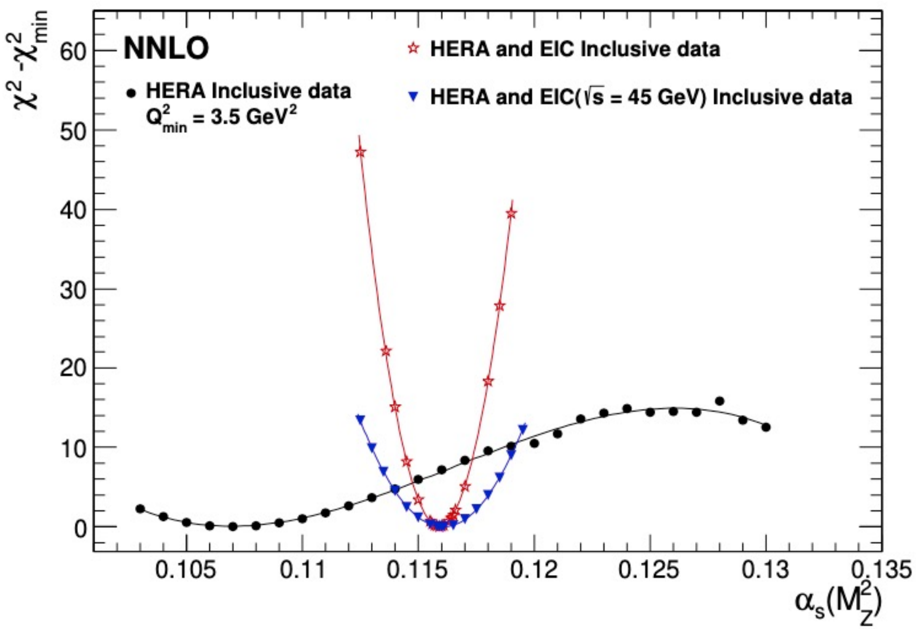
(linear x scale, $Q^2 = Q_0^2$)

… EIC will bring significant reduction in uncertainties for all parton species at large x

… most notable improvements for up quarks (charge-squared weighting)



Taking α_s as an additional free parameter



- HERA data alone (HERAPDF2.0) shows only limited sensitivity when fitting inclusive data only.

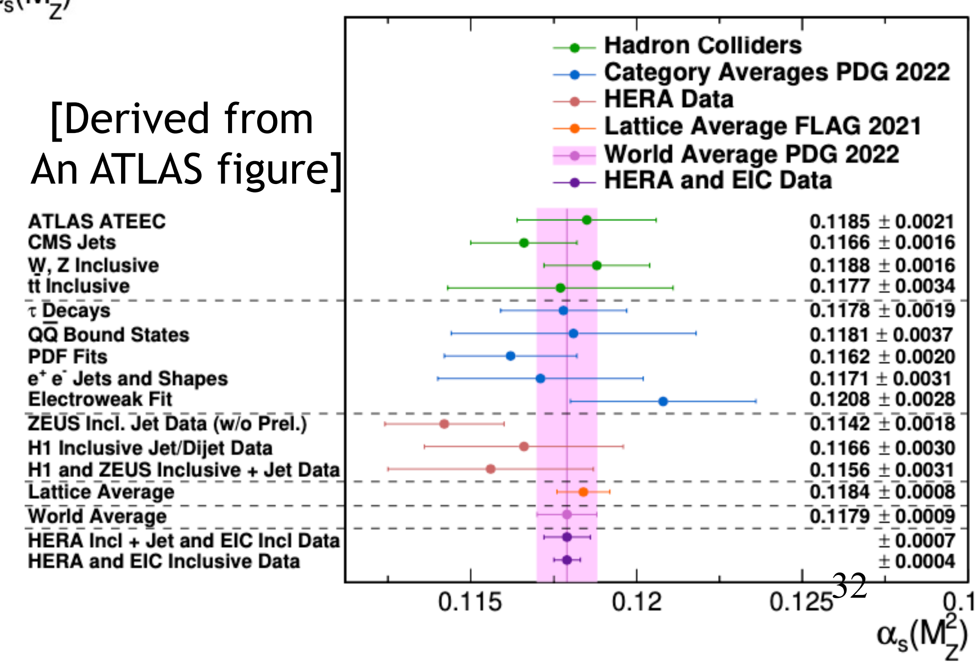
- Adding EIC simulated data has a remarkable impact

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004 \text{ (exp)}$$
$$^{+0.0002}_{-0.0001} \text{ (model + parameterisation)}$$

Adding EIC (<u>precision high x</u>) data to HERA can lead to α_s precision a factor ~2 better than current world experimental average, and than lattice QCD average

Scale uncertainties remain to be understood (ongoing work)

[Derived from An ATLAS figure]

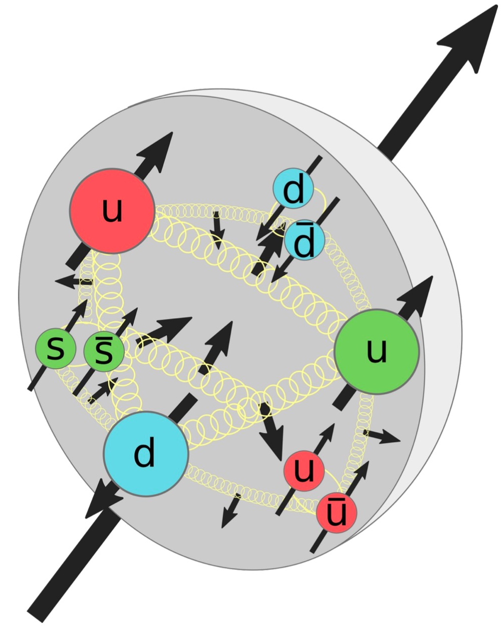


Proton Spin from Inclusive Data

- Spin ½ is much more complicated than ↑↑↓ …

- EMC 'spin crisis' (1987) … quarks only carry about 10% of the nucleon spin

- Viewed at the parton level, complicated mixture of quark, gluon and relative orbital motion, evolving with Q^2, but always = ½



Jaffe-Manohar sum rule:

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

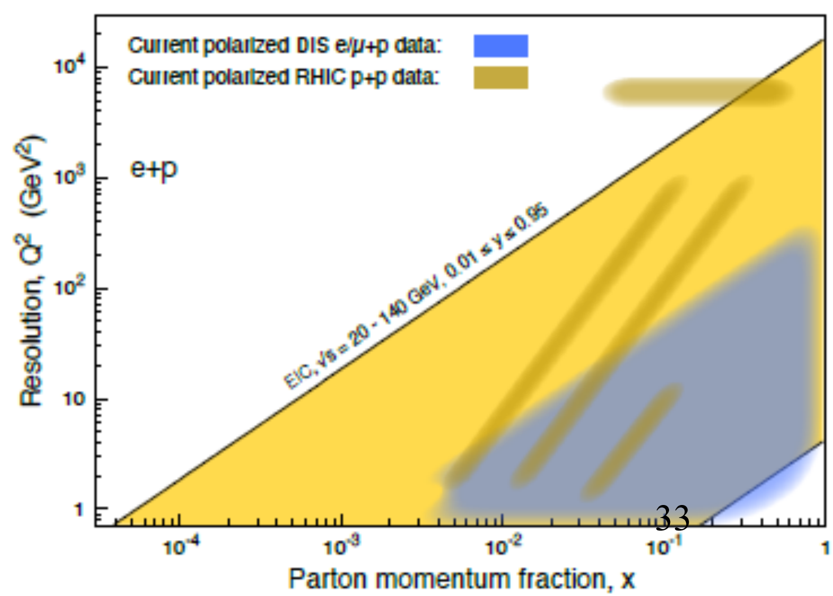
Quark helicity

Gluon helicity

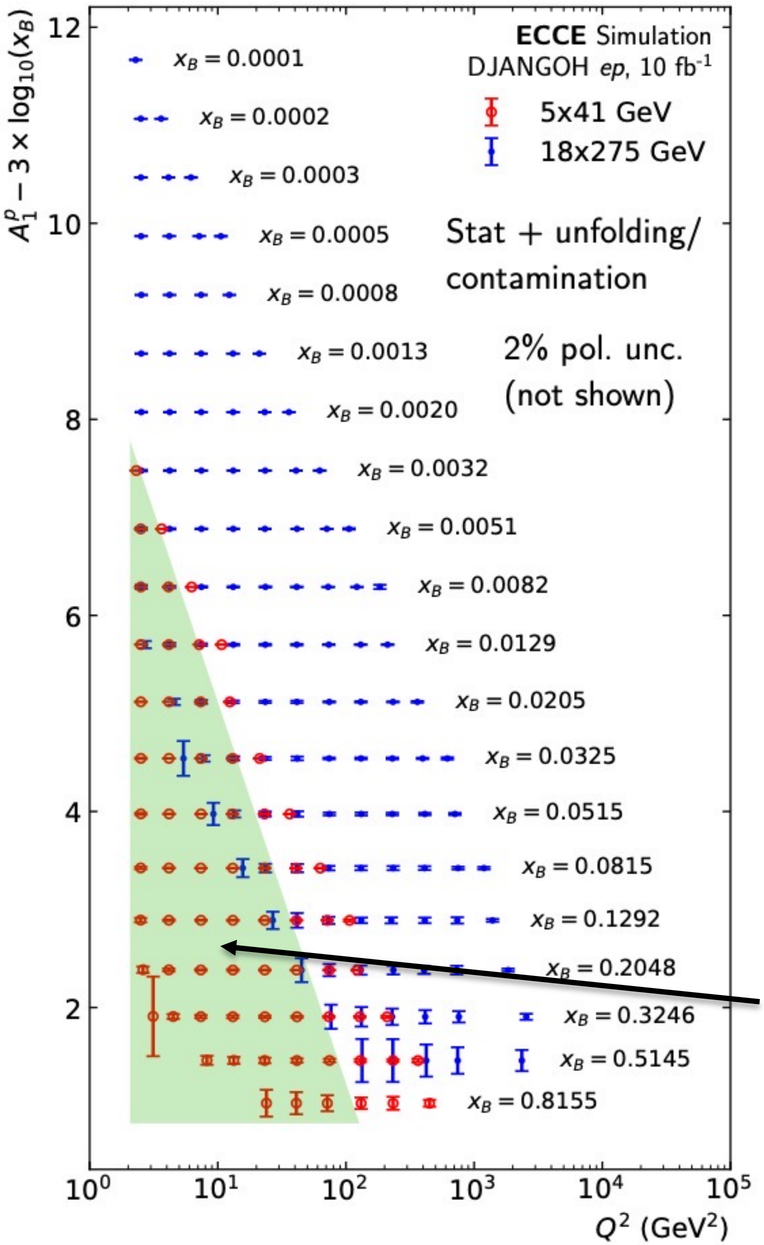
Quark canonical orbital angular momentum

Gluon canonical orbital angular momentum

- Very little known about gluon helicity contribution or importance of low x region



Spin: EIC Virtual γ Asymmetry sim'n (A_1^p)



Asymmetries between NC cross sections with different longitudinal and transverse polarisations …

$$A_{\parallel} = \frac{\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows}}{\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows}} \quad \text{and} \quad A_{\perp} = \frac{\sigma^{\rightarrow\uparrow} - \sigma^{\rightarrow\downarrow}}{\sigma^{\rightarrow\uparrow} + \sigma^{\rightarrow\downarrow}}$$

$$\rightarrow A_1(x) \approx g_1(x)/F_1(x)$$

… measure the quark and antiquark helicity distributions …

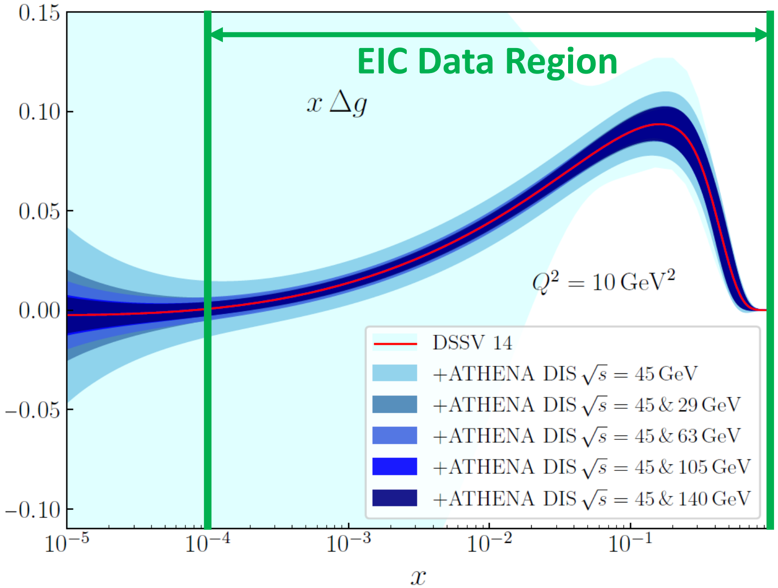
$$g_1(x) = \sum \left(\Delta q(x) + \Delta \bar{q}(x)\right)$$

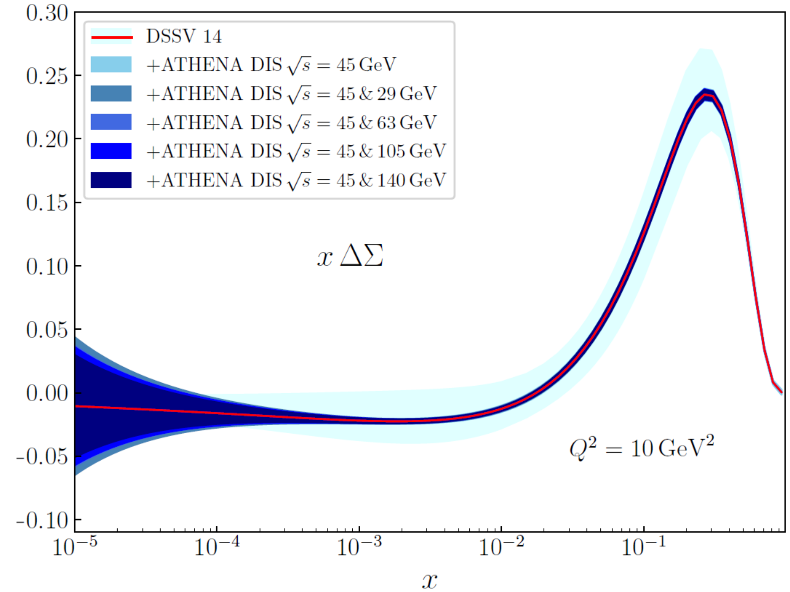
… which gives gluon sensitivity from Q^2 dependence (scaling violations)

Previously measured region (in green)

EIC measures down to x ~ 5 x 10^{-3} for 1 < Q^2 < 100 GeV^2

Impact on Helicity Distributions

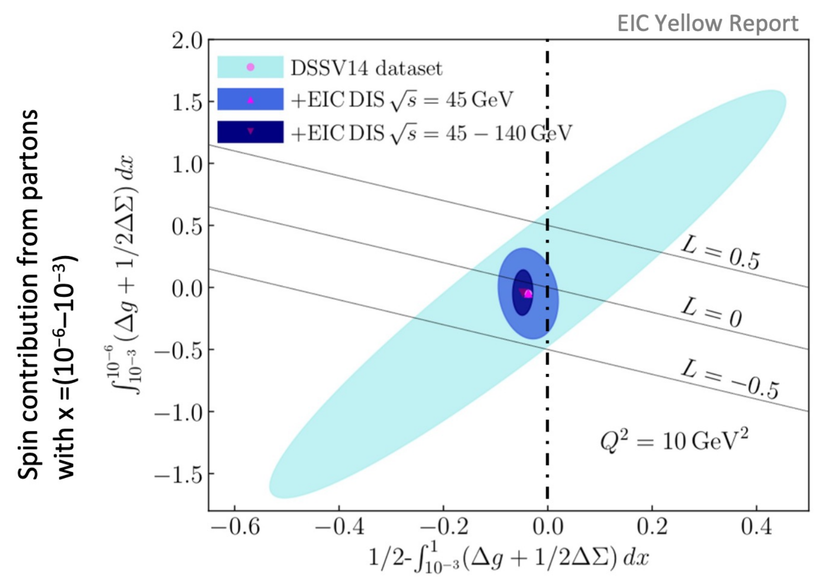




- Simulated NC data with integrated luminosity 15fb^{-1}, 70% e,p Polaris'n

- Very significant impact on polarised gluon and quark densities using only inclusive polarised ep data

- Orbital angular momentum similarly constrained by implication



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

EIC nuclear PDFs: high parton densities

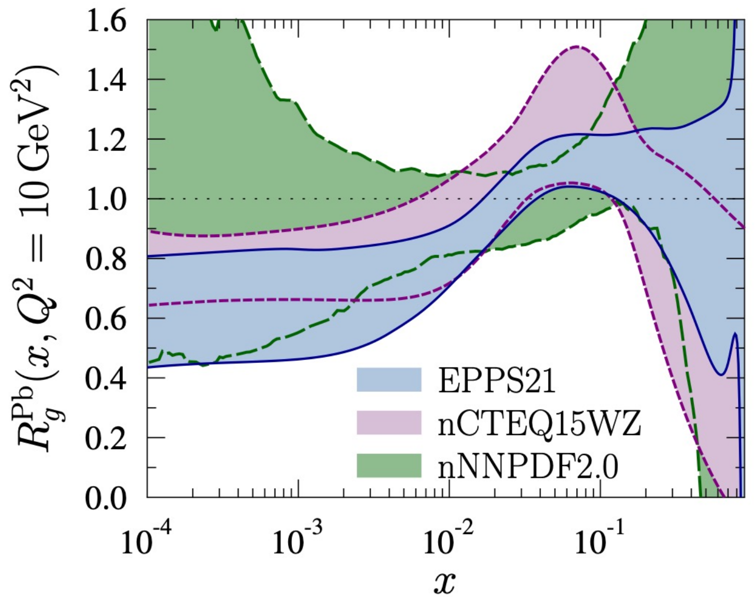
- Nuclei enhance density of partons
  ($\sim A^{1/3}$ factor at fixed x, Q^2)

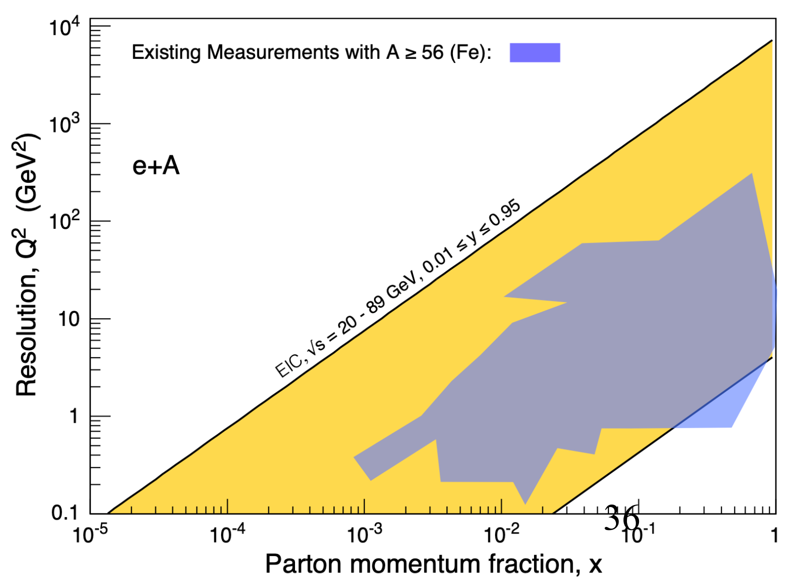
- Results usually shown in terms of nuclear modification ratios (change relative to simple scaling of (isospin-corrected) proton

$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)$$

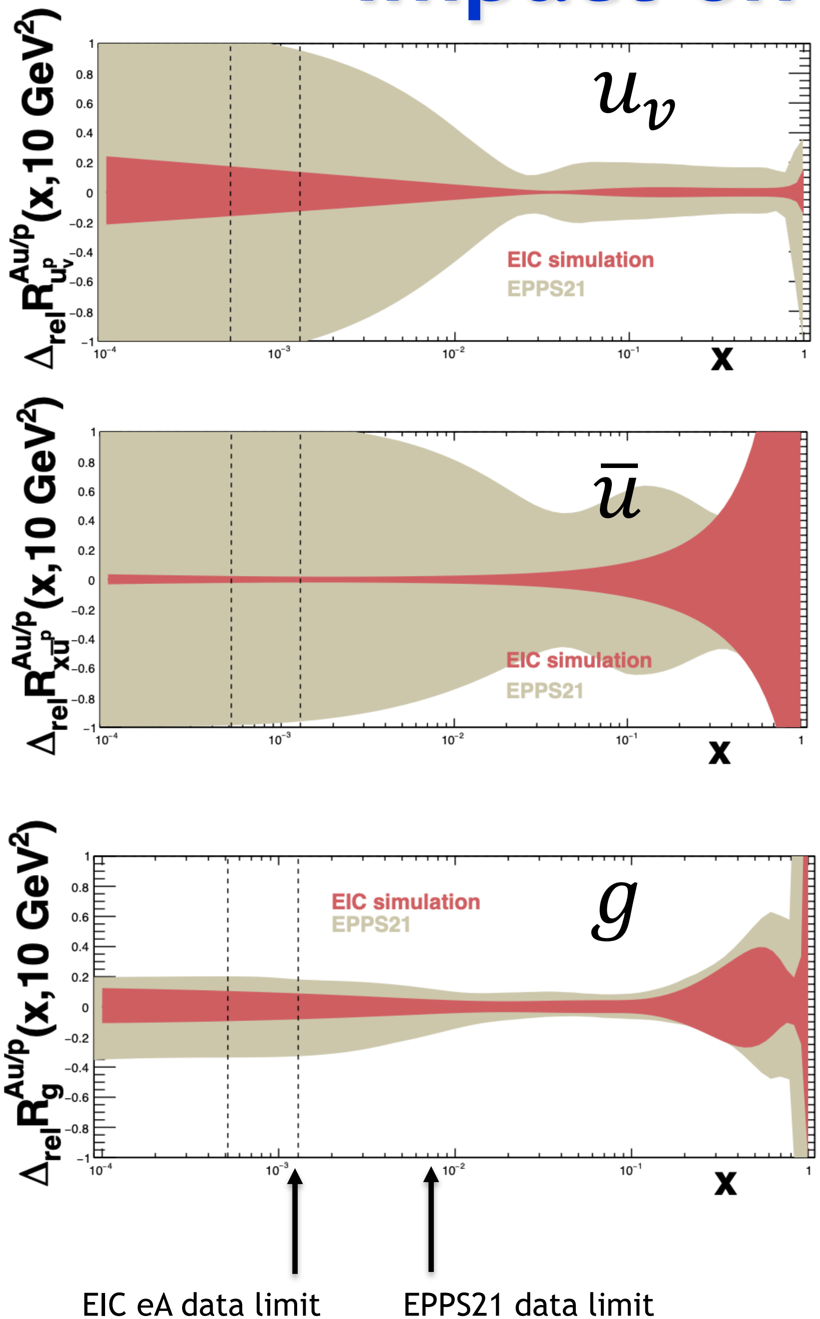
… poorly known, especially for gluon and at low x

- EIC offers large impact on eA phase space, extending into low-x region where density effects may lead to novel emergent QCD phenomena ('saturation'?)





Impact on Nuclear PDFs



- Nuclear effects in PDFs not fully understood.
- Important e.g. for initial State in QGP studies

Usually expressed in terms of nuclear modification ratio relative 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 relative to EPPS21 recent nuclear PDFs (EIC-only fit)

→ Factor ~ 2 improvement at x~0.1

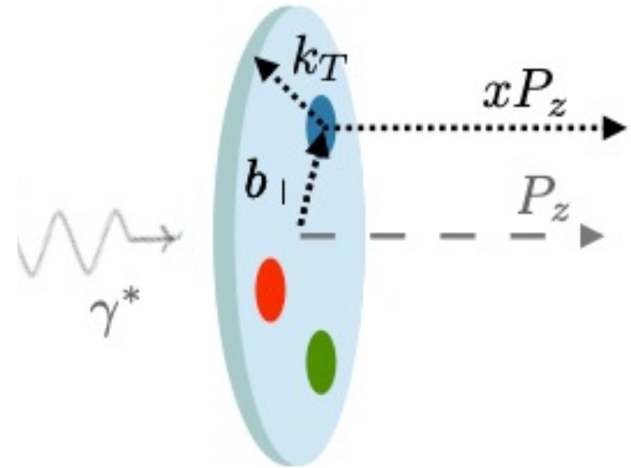
→ Very substantial improvement in newly accessed low x region

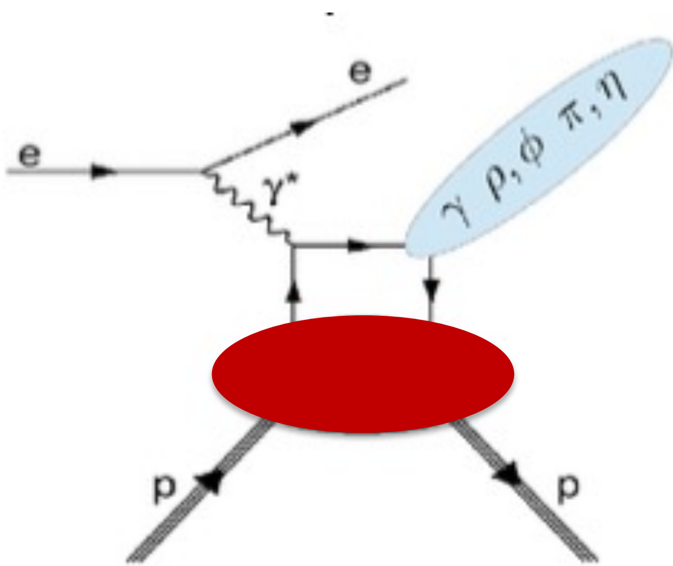
Exclusive Processes and 3D Structure

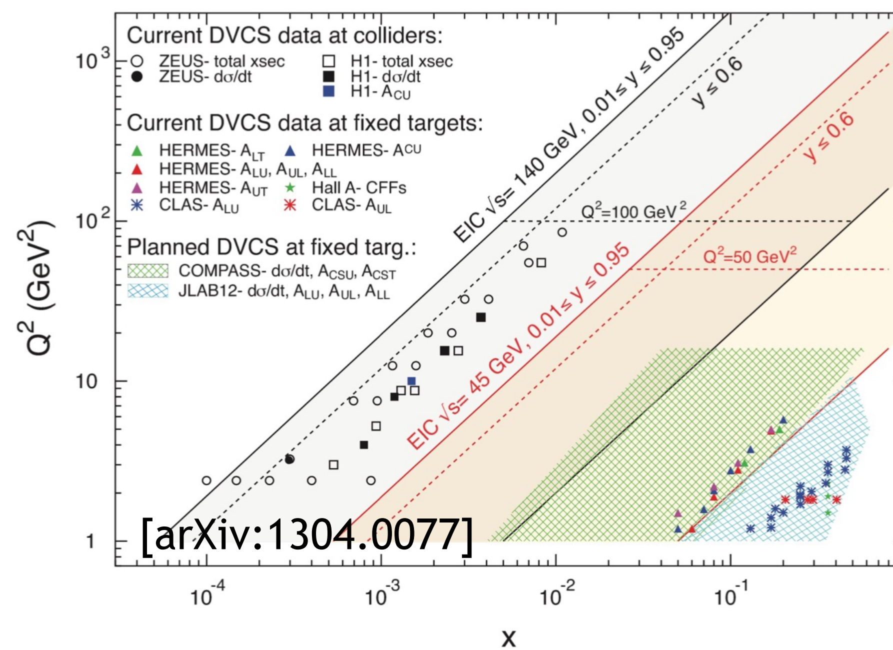
Exclusive processes, yielding intact protons, require (minimum) 2 partons exchanged

→ Sensitivity to correlations between partons in longitudinal / transverse momentum and spatial coordinates

→ access to 3D tomography





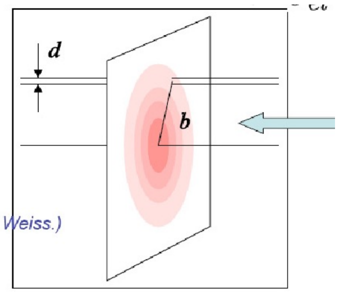


e.g. <u>Deeply Virtual Compton Scattering, ep → eγp</u>:
EIC fills gap between (high stats) fixed target & (low stats) HERA data

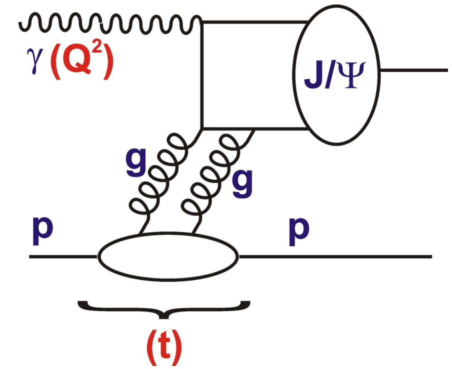
Exclusive Processes and Dense Systems

.Additional variable (Mandelstam) t is conjugate to transverse spatial distributions

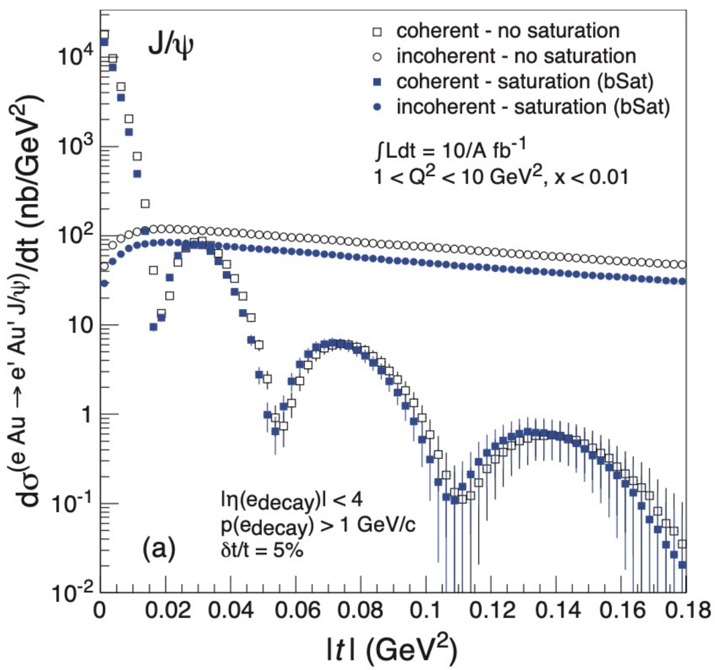
→ Large t (small b) probes small impact parameters etc.



(figure from C. Weiss.)

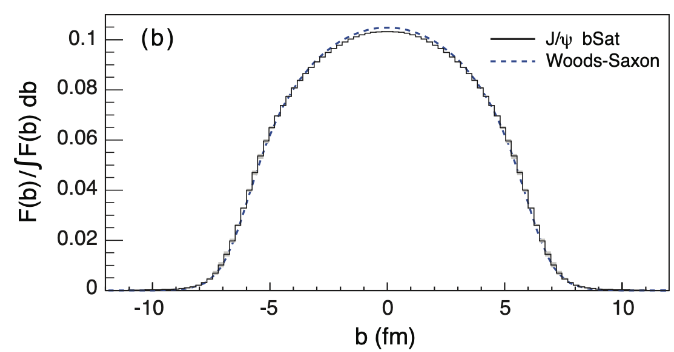


[arXiv:1211.3048]



e.g. Coherent J/Ψ production at small t in eAu measures average density profile, with dips at larger t sensitive to saturation or other novel effects in dense regions

→ Fourier transform



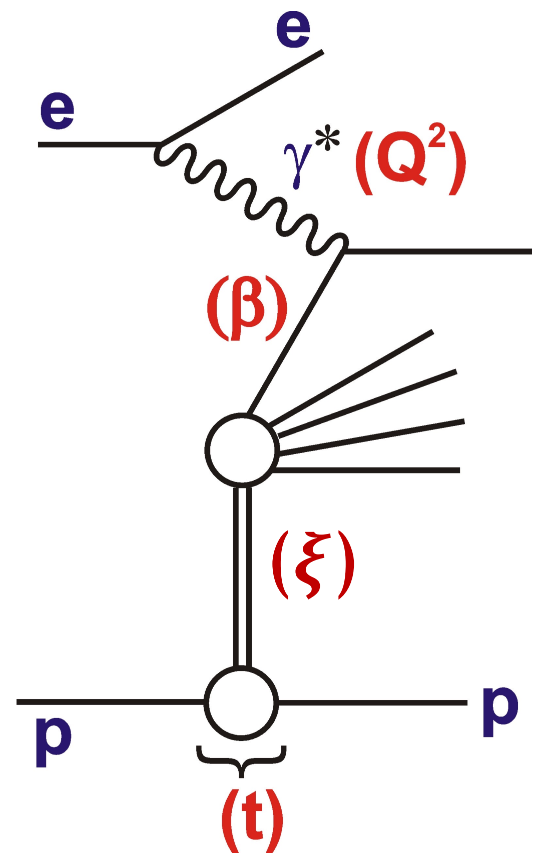
Experimental challenges from incoherent background and resolving dips

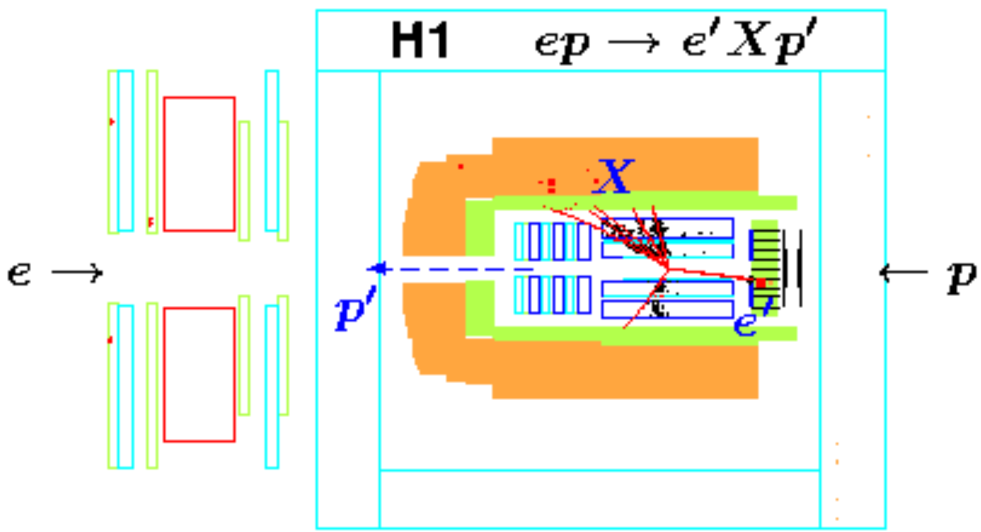
Inclusive Diffractive DIS

- DVCS / vector meson production are higher twist (Q^2 suppressed) processes

- Dominant diffractive DIS mechanism is leading twist production of multi-particle final states

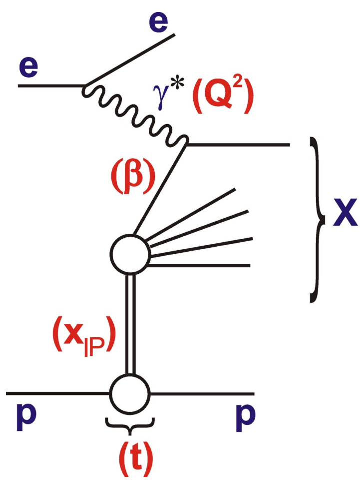
- β, Q^2 dependence interpreted in terms of partonic structure of exchange (similar to inclusive case)

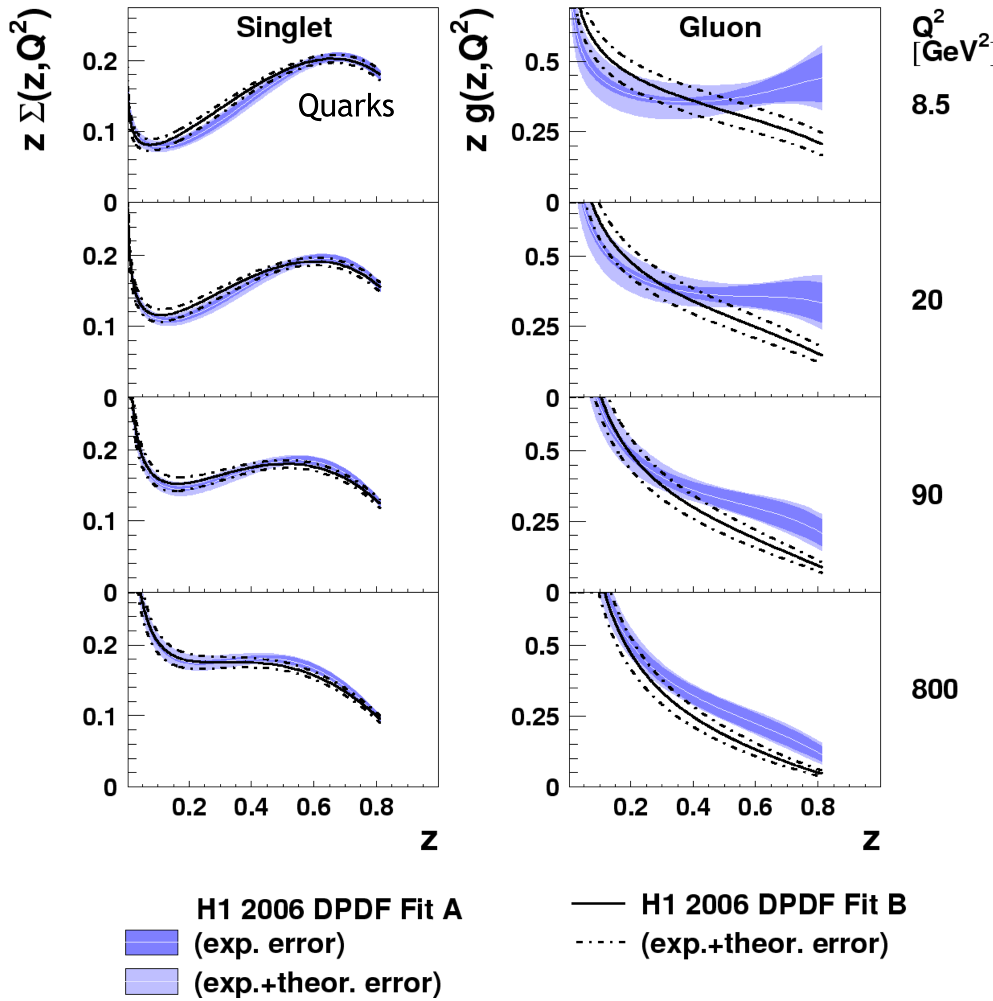




<u>HERA conclusion:</u>
DIS from universal(ish) soft colourless target … sometimes referred to as a `pomeron'

HERA Pomeron Parton Densities



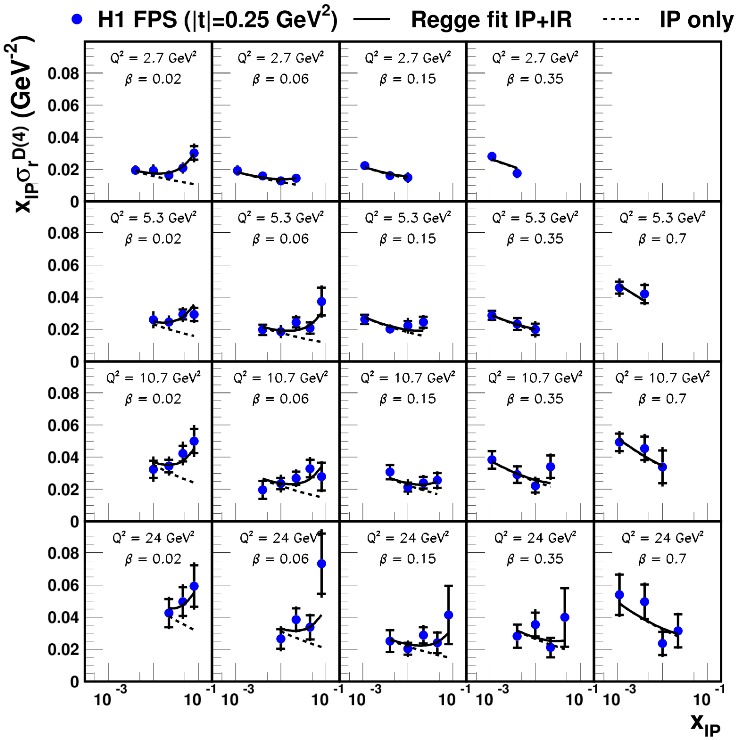


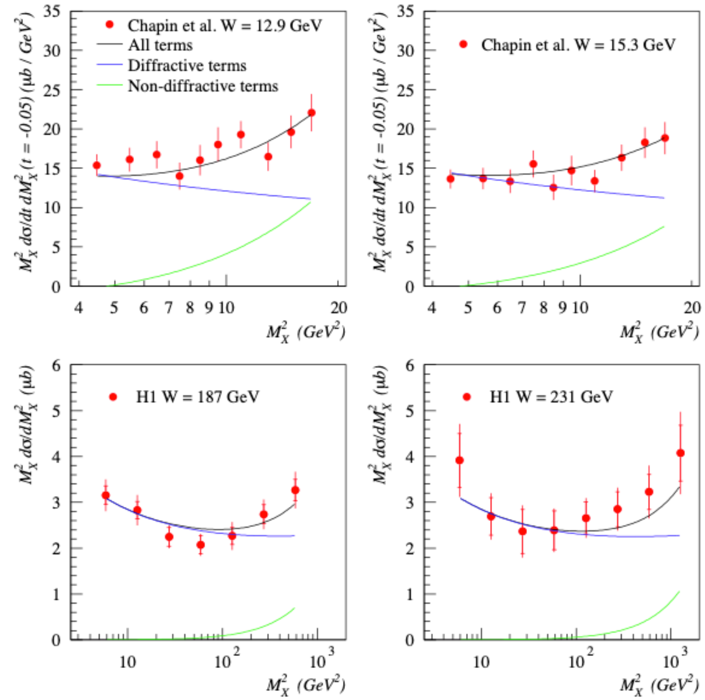
… extracted from DGLAP fits to inclusive (& jet) diffractive DIS data, similarly to inclusive DIS

… dominated by gluon density extending to large momentum fractions, z

… describe diffractive final state data remarkably well.

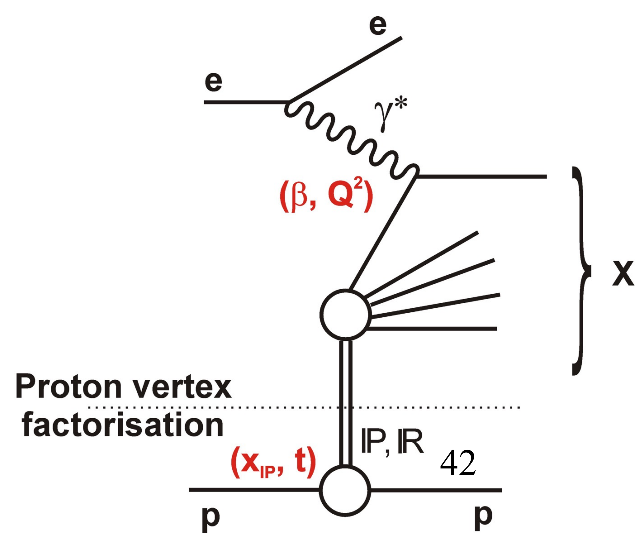
Diffractive data from HERA: beyond IP



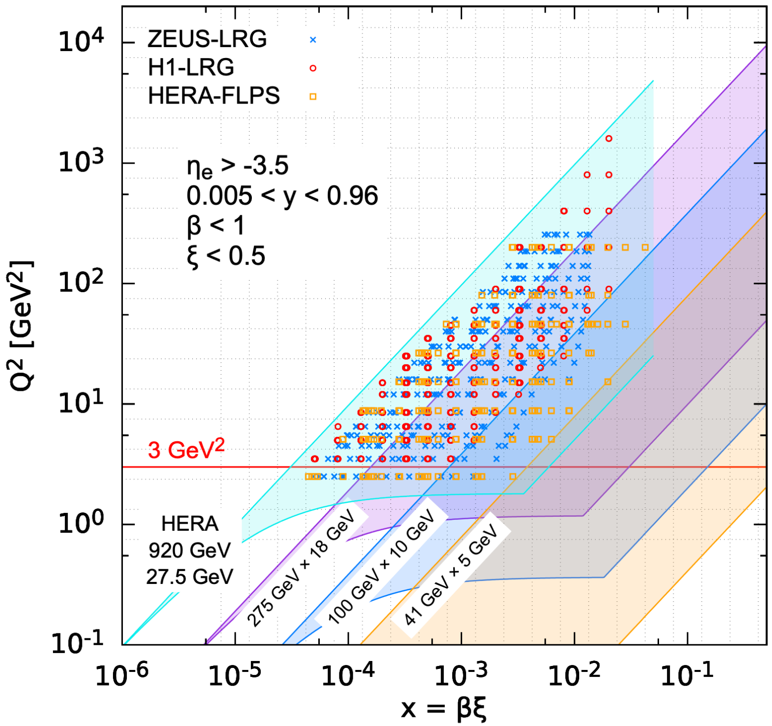


Generally decomposed into two components:
- Leading ‘Pomeron’ (IP) at low ξ
- Sub-leading ‘Reggeon’ or ‘Meson’ (IR) at largest ξ

Sub-leading term poorly constrained
- Isoscalar? – Isovector?
- Combination of multiple exchanges?



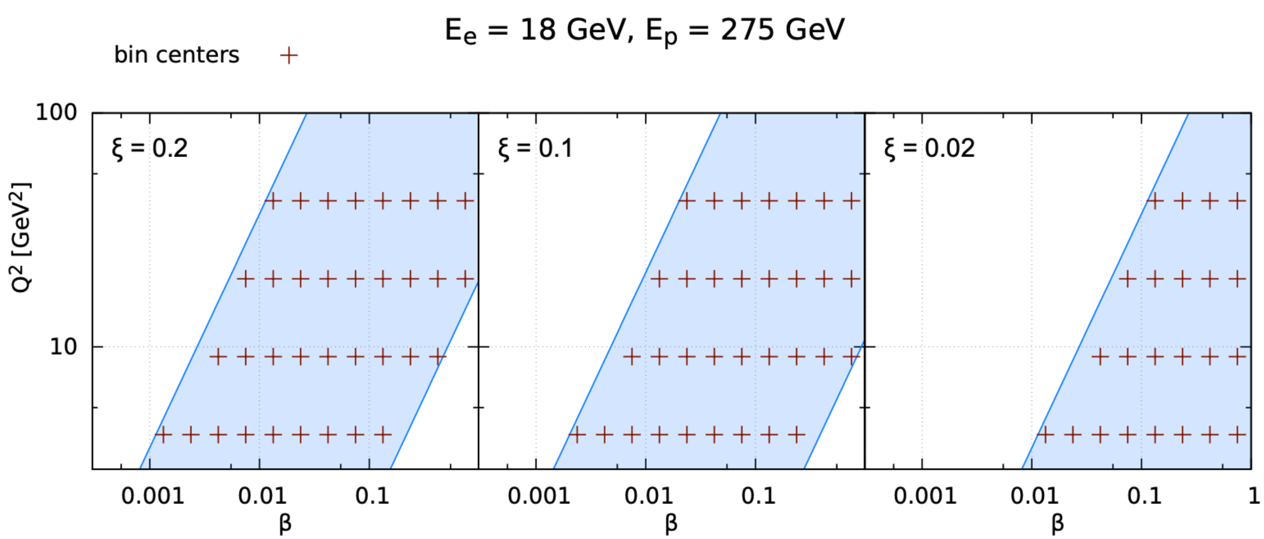
Diffractive DIS Phase Space at EIC



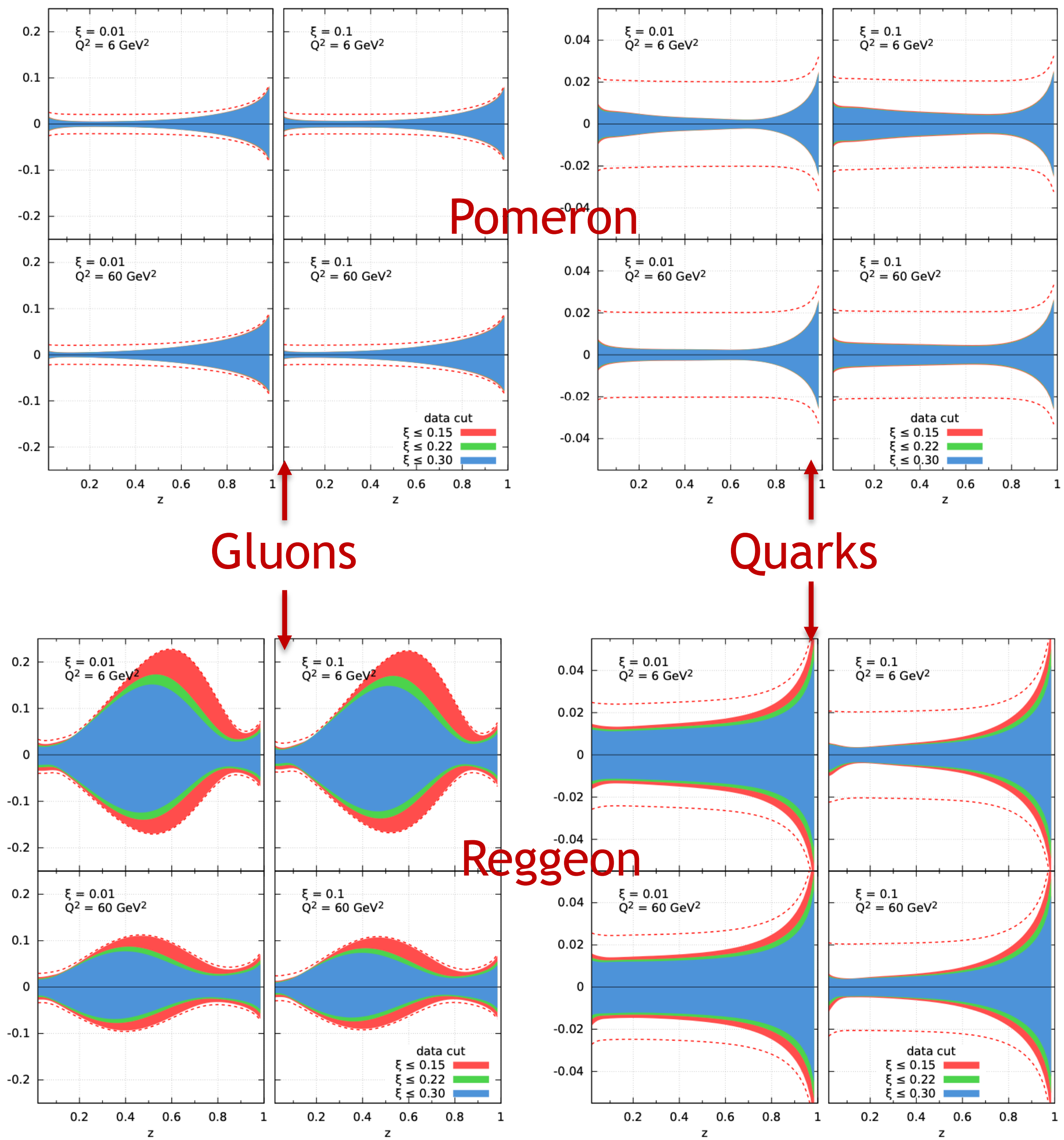
In the absence of fixed target diffractive DIS data, EIC fills in the currently unknown high x (=βξ), low Q^2 region

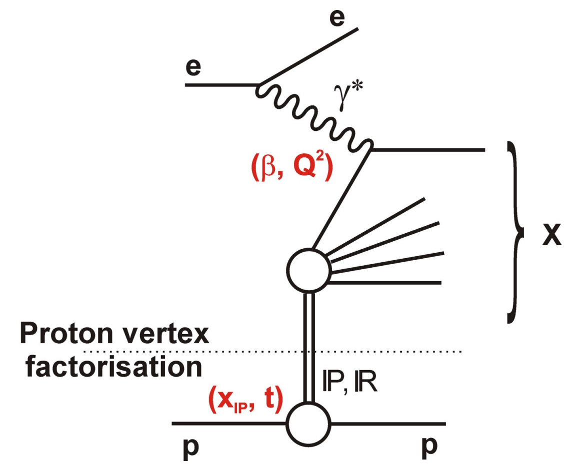
EIC complementarity to HERA:
→ constrains the DPDFs at large z
→ constrains sub-leading Reggeon (IR)

Pseudodate produced to assess EIC impact (example at highest $\sqrt{s}$)



Diffractive PDFs from EIC



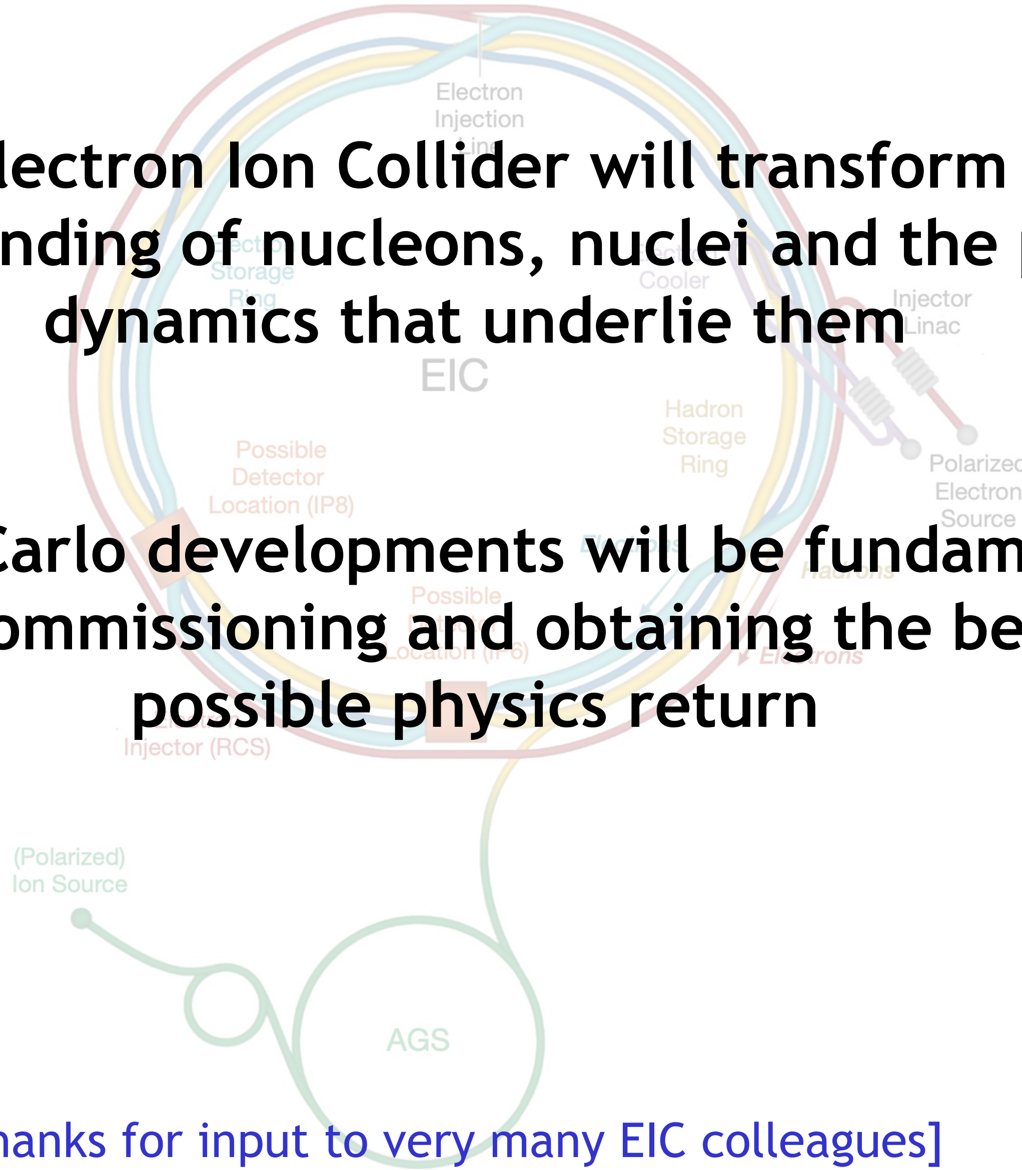


Relative precision from 1 year at highest $\sqrt{s}$ …

- New level of precision for pomeron.
- Reggeon precision similar to HERA pomeron
- Mostly dominated by normalis^n uncert’y (lumi)

Further gains by adding lower $\sqrt{s}$ data, especially for Reggeon

Summary



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

Monte Carlo developments will be fundamental to commissioning and obtaining the best possible physics return

[with thanks for input to very many EIC colleagues]