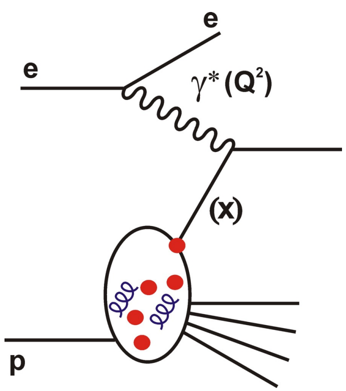
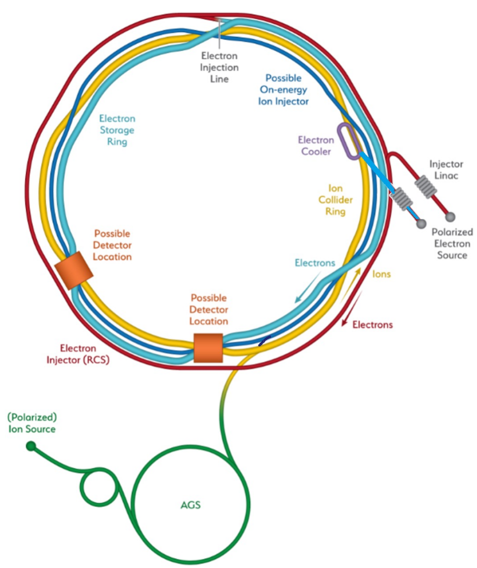
# Lepton-Hadron Scattering and The Electron Ion Collider

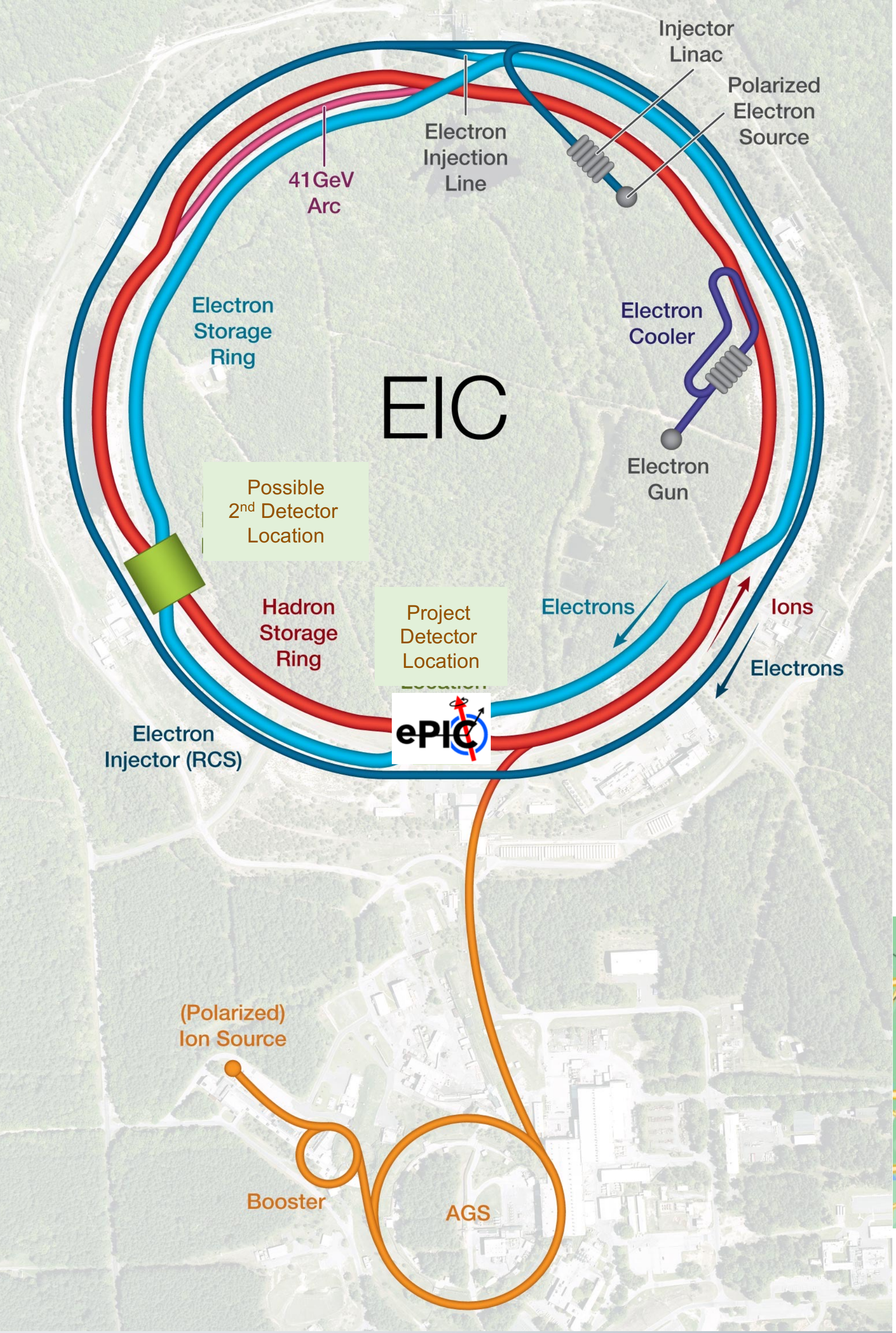



Paul Newman (Birmingham)

## Particle Physics Group Seminar
## 4 October 2023




1) DIS History and Context
2) Overview and Machine
3) The ePIC detector
4) Physics motivations and simulations
5) Timeline
6) UK and Birmingham involvement

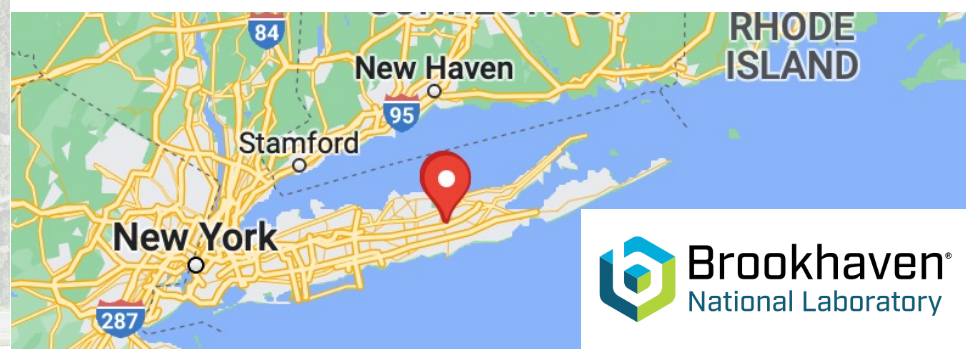



# The Electron Ion Collider

New electron storage ring at BNL accelerator complex, to collide with existing RHIC proton / ion beams

On target to be the world's next high energy* collider, starting from the early 2030s

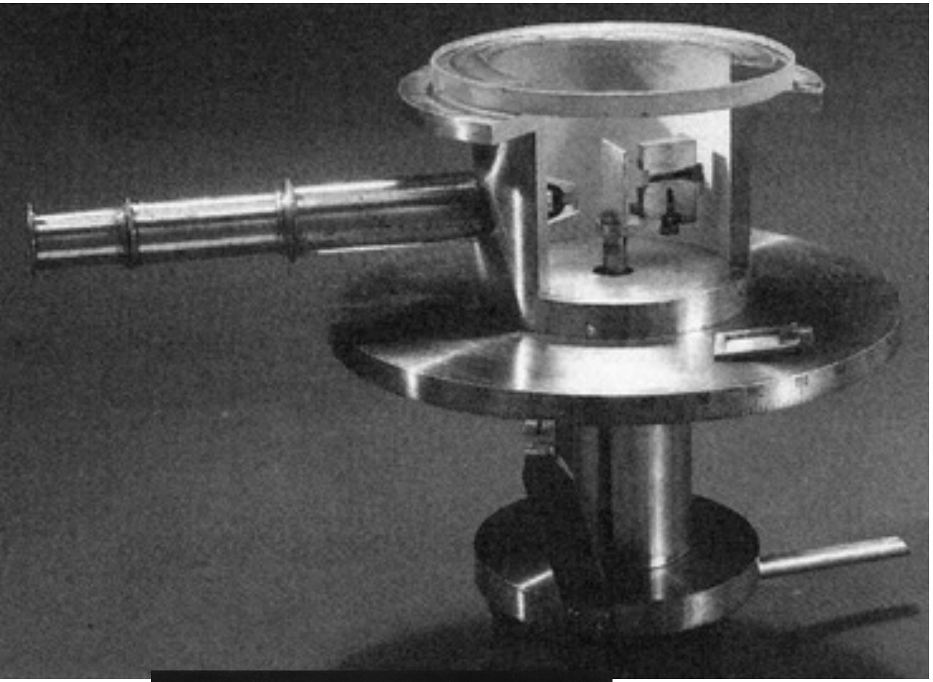
Scientific remit: continue exploration of strongly interacting matter using Deep Inelastic Scattering



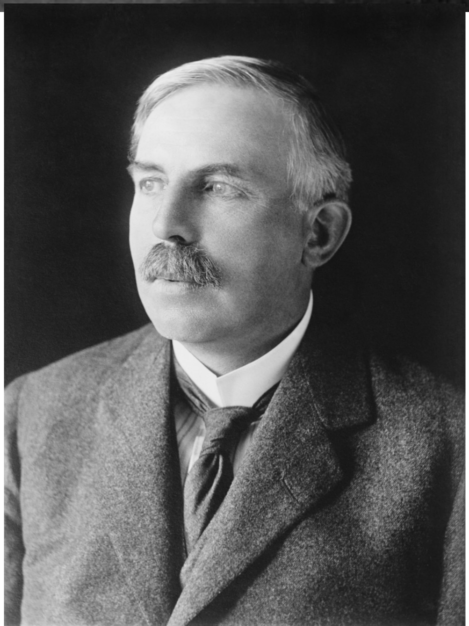



* High energy ≠ energy frontier

# Rutherford (1927, as President of Royal Society)



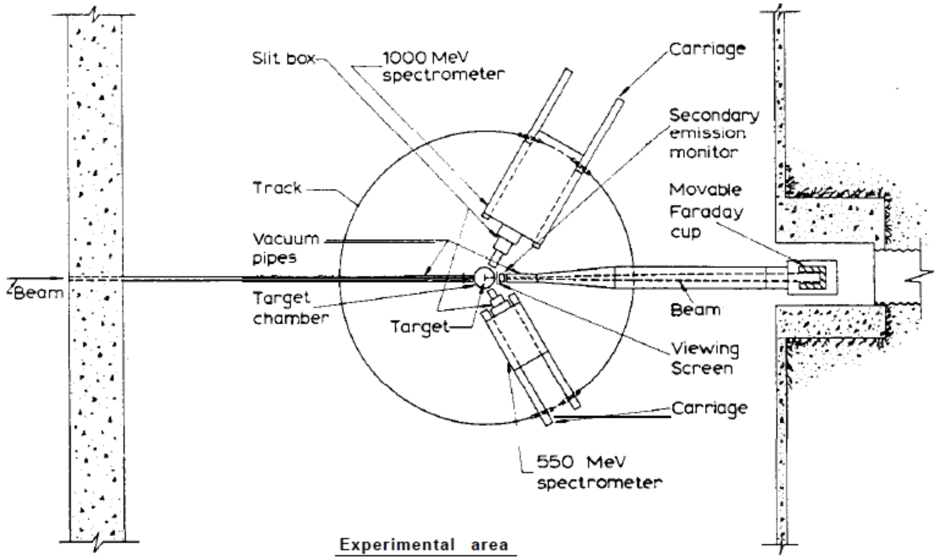
Following from the original scattering experiments ($\alpha$ particles on gold foil target) …



*"It would be of great scientific interest if it were possible to have a supply of electrons … of which the individual energy of motion is greater even than that of the alpha particle."*

# Hofstadter (Nobel Prize 1961)

## 200 MeV Electrons on a fixed target …



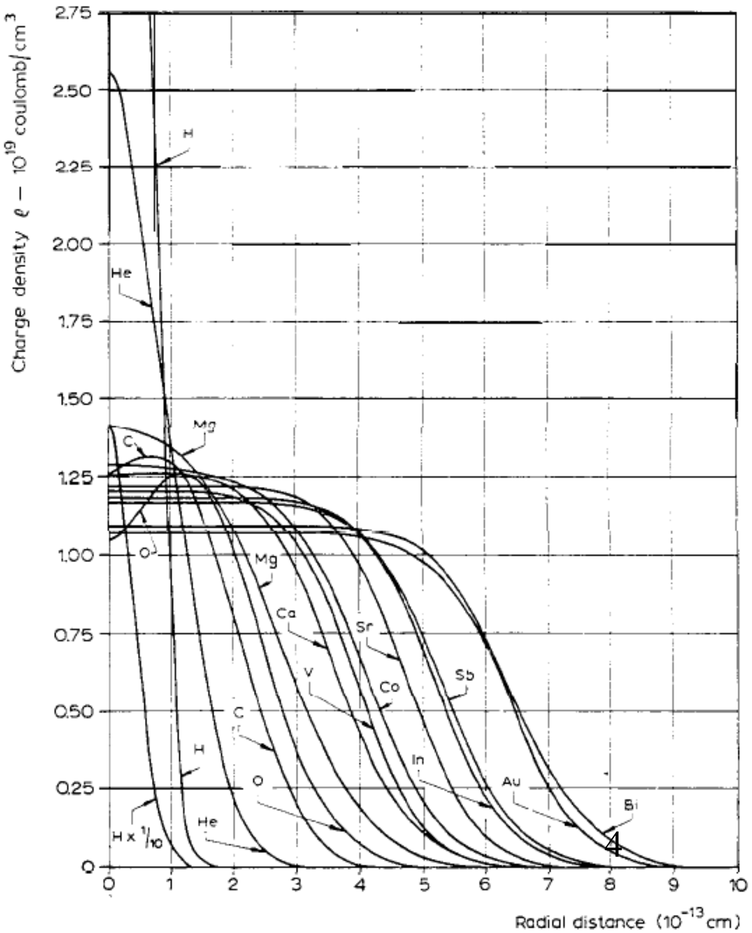


- Electron scattering reveals nuclear form factors (i.e. sizes)

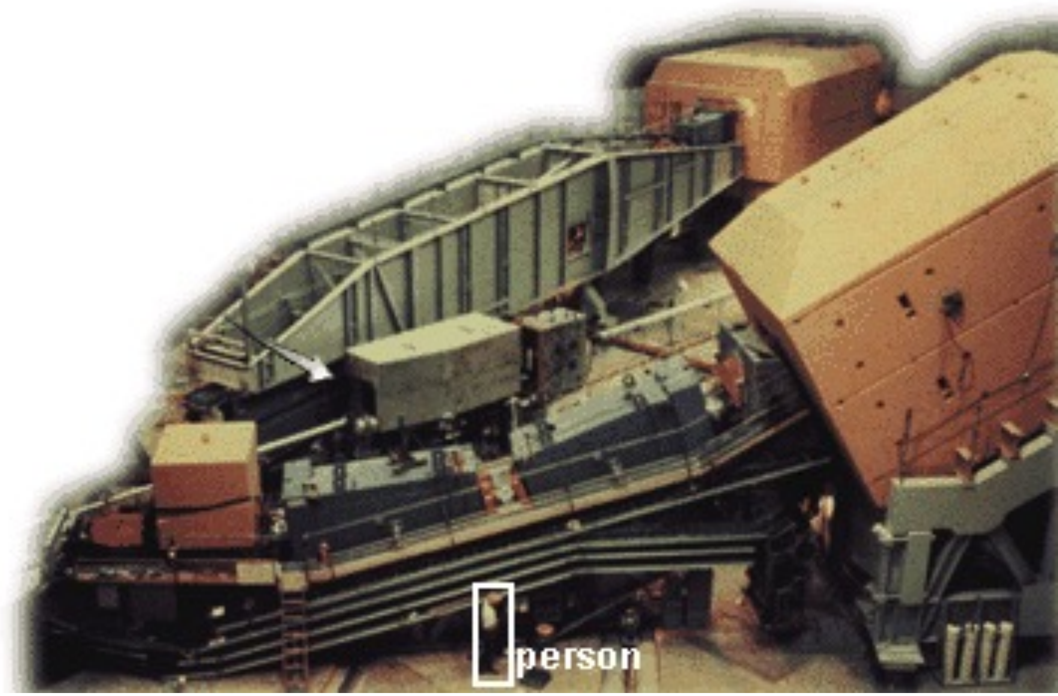
… even a hydrogen nucleus (proton) has finite size

… electric charge uniformly spread?

… "soft spheres" …



# SLAC 1969: 20 GeV electrons on protons




… observed significant scattering through wide angles (like Rutherford's alphas), implying 'point-like' scattering centres

# First Observation Of Proton Structure

Volume 23, Number 16 PHYSICAL REVIEW LETTERS 20 October 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

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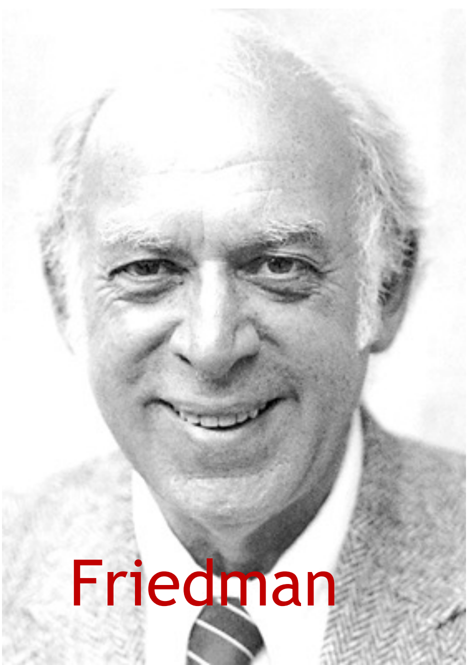
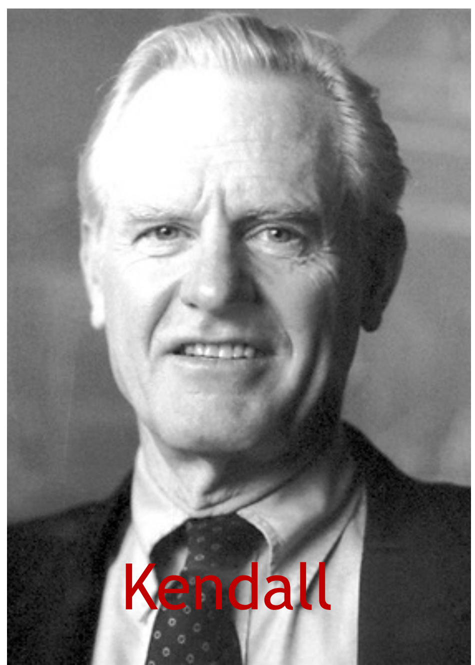
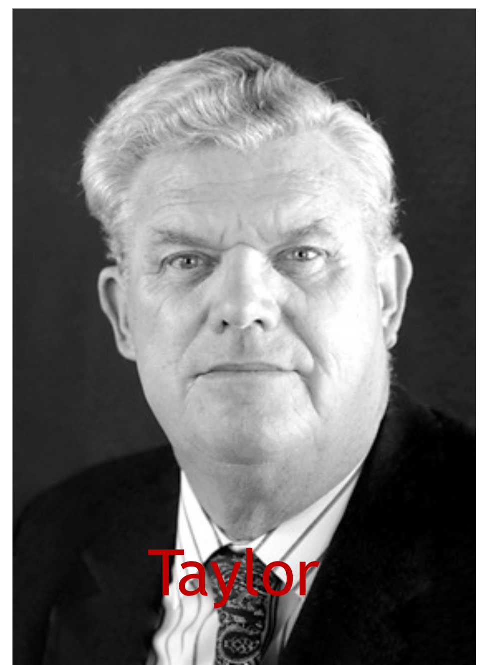
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)



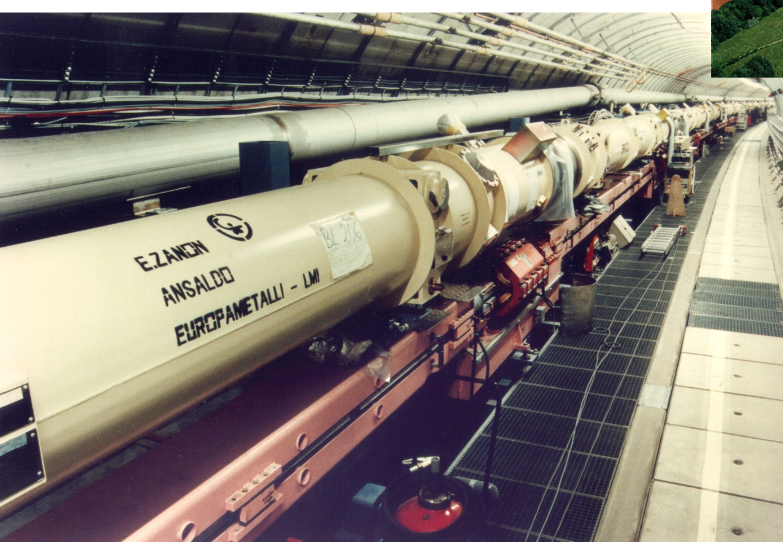




Nobel Prize 1990

# HERA, DESY, Hamburg

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

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

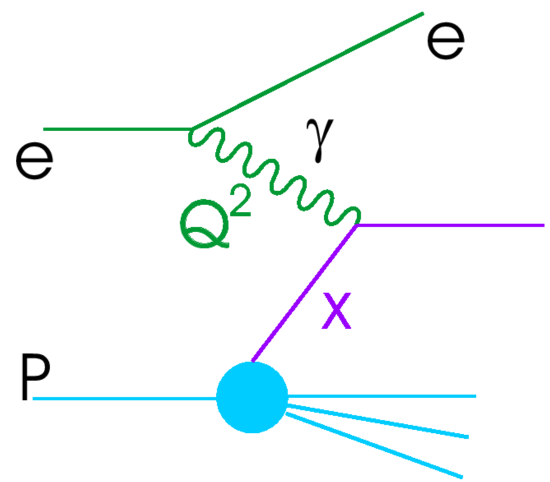

- So far still the only collider of electron and proton beams ever

→ Taught us much of what we know about proton structure

→ Only ~0.5 $fb^{-1}$ per experiment

→ No deuteron or nuclear targets

# Inclusive Neutral Current DIS: ep→ eX
# … a 2 Variable Problem




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

x = fraction of proton momentum carried by struck quark

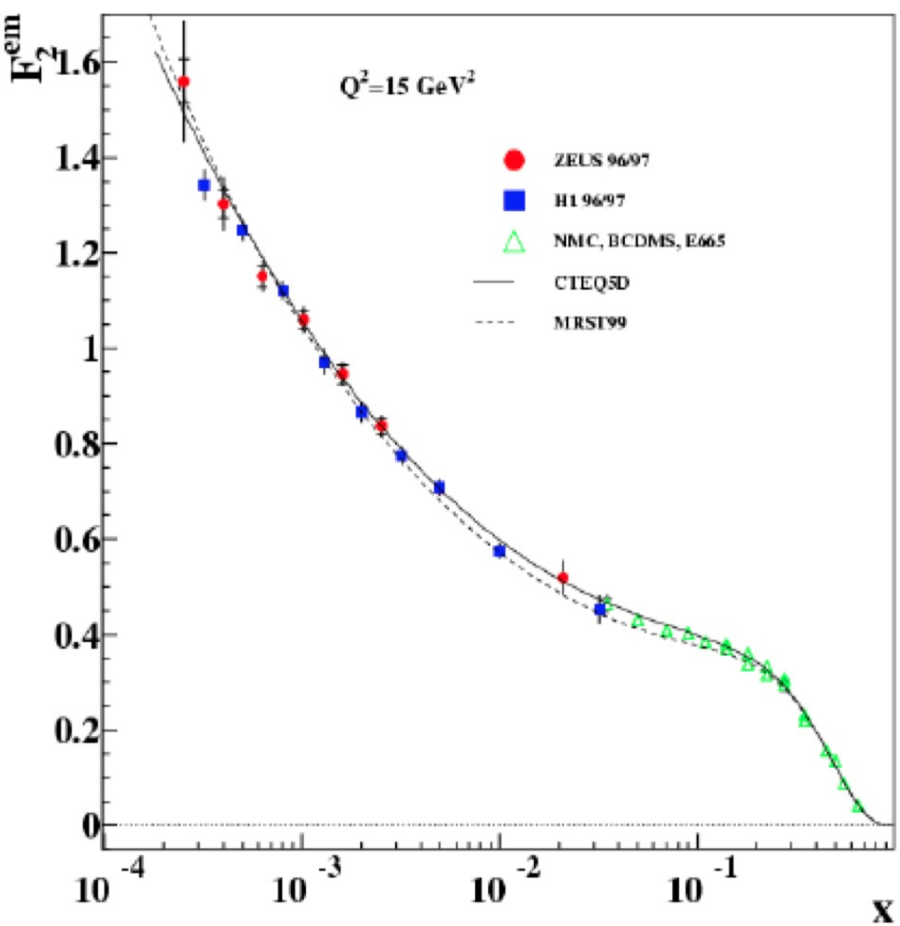
$Q^2$ = |4-momentum transfer squared| (photon virtuality)

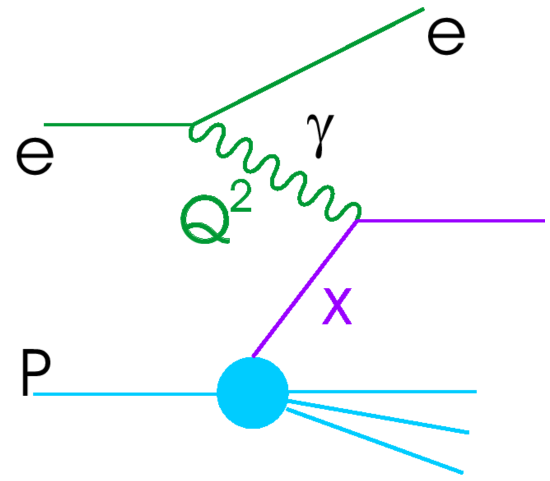
… measures the hardness /scale of collision

… inverse of (squared) resolved dimension

Note $Q^2 \leq sx$ … i.e. Maximum $Q^2$ and minimum x governed by CMS energy

# Example Inclusive Neutral Current Data from Previous Experiments

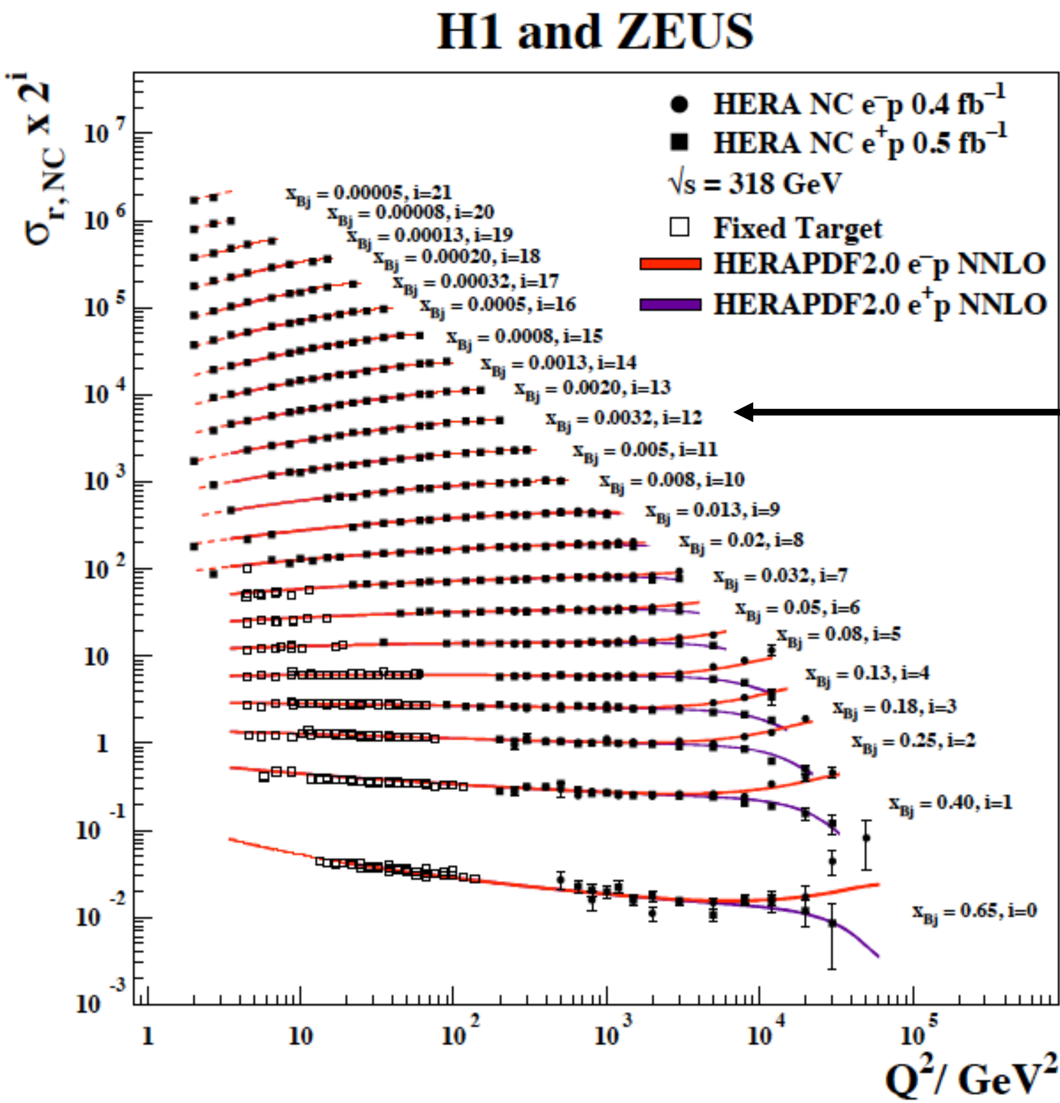



- Inclusive cross section measures (charge-squared weighted) sum of quark densities

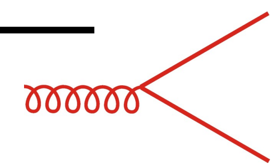
- Similar / better data at many other values of $Q^2$

# QCD Evolution and the Gluon Density




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

$$g \to q\bar{q}$$

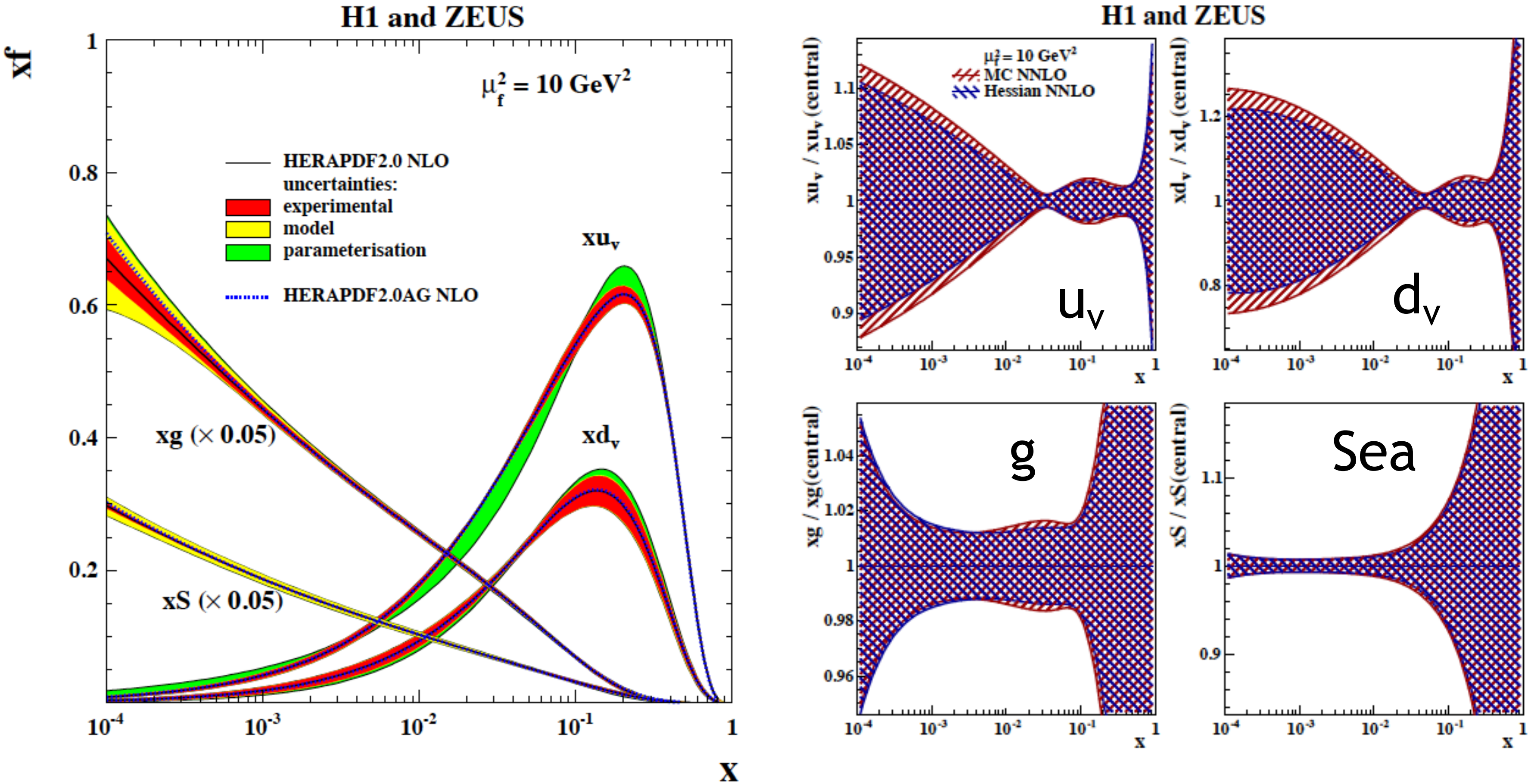


- DGLAP equations describe QCD evolution (to NNLO and approximate N³LO accuracy)

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

→ Fits to data to extract proton parton densities

# Proton PDFs from HERA only (HERAPDF2.0)




- ~2% gluon precision, 1% on sea quarks for x ~ $10^{-2}$

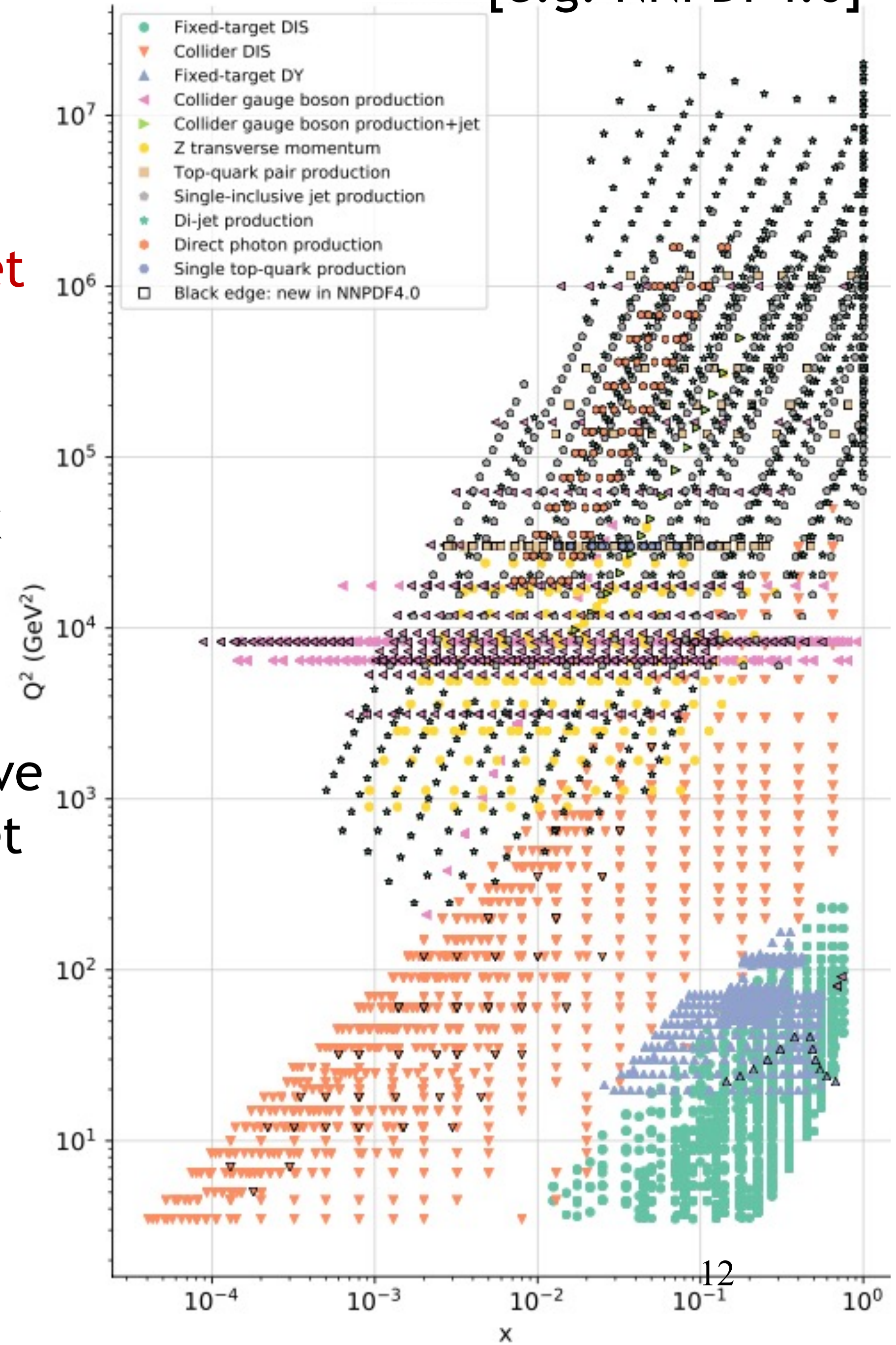
... BUT ...

- Uncertainty explodes below x=$10^{-3}$ (approach kinematic limit)
- Uncertainty explodes above x=$10^{-1}$ (limited luminosity)

# Global Fits

Global fits (NNPDF, MSHT, CT …) dominated by HERA data, but constrain high x region with fixed-target DIS and PDF-sensitive LHC observables

[e.g. NNPDF4.0]



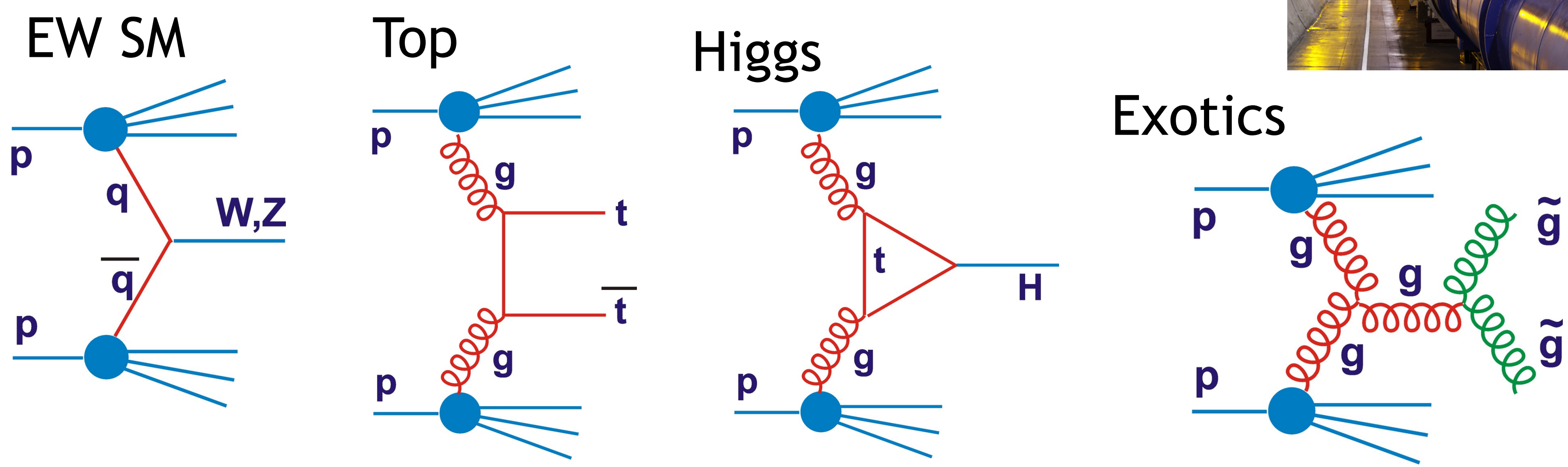

**Advantages:**

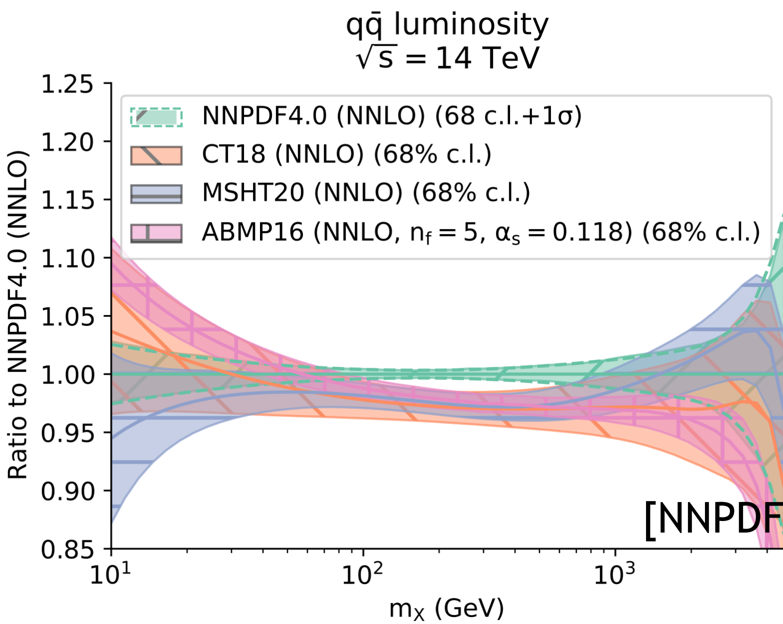
- Improved precision, especially at high x
- Exploiting all available input

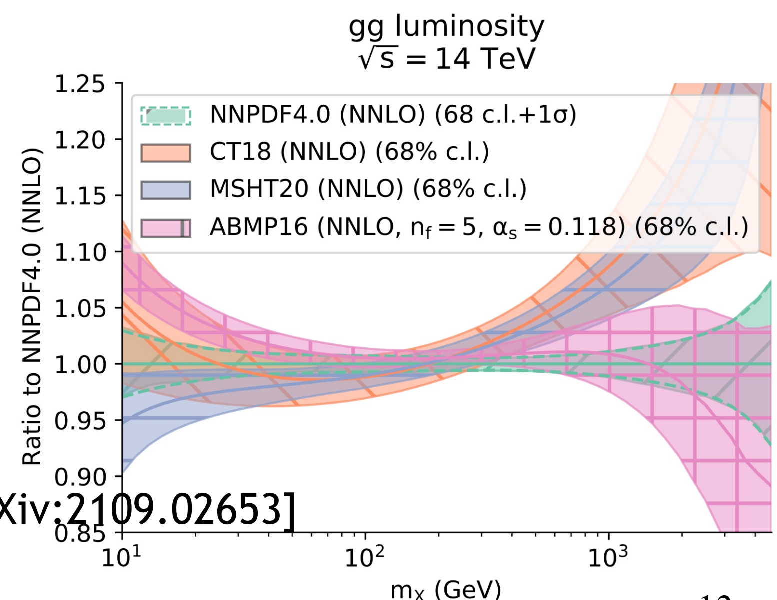
**Disadvantages:**

- Theoretical complexity (non-perturbative input for hadronisation and nuclear target corrections
- Incompatibility between some datasets (increased tolerances used to account for tensions)
- Use of high x LHC data that may contain new physics

# PDFs and LHC Parton Lumi's



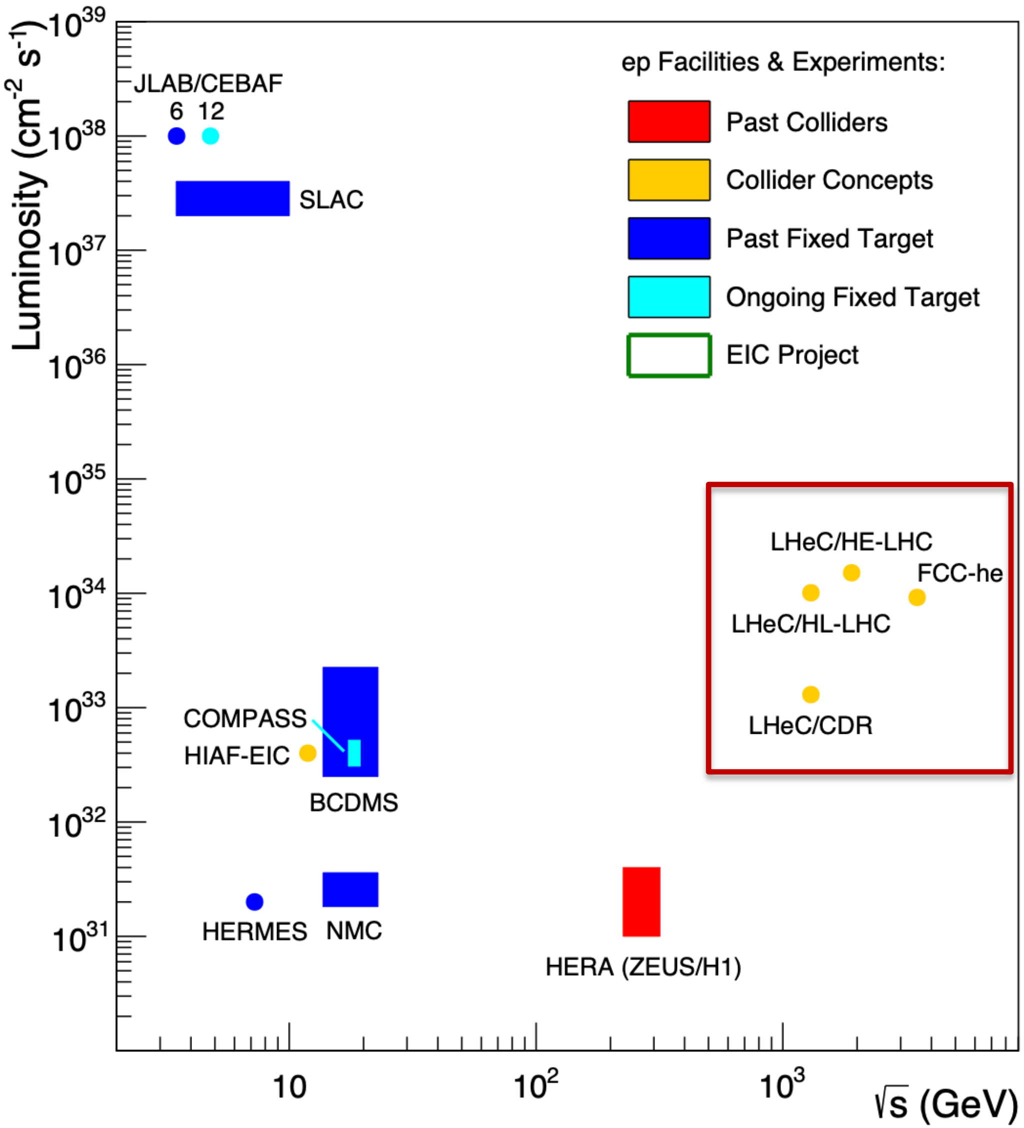




[NNPDF4.0 , arXiv:2109.02653]

Immense recent progress, but still large uncertaities near kinematic limit

# Proposed Future DIS at CERN




Future options …

LHeC

50 GeV electrons on LHC p, A beams

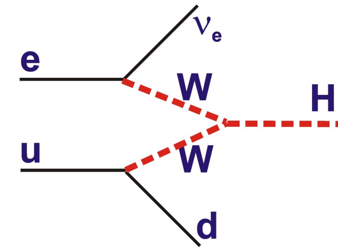
FCC-eh

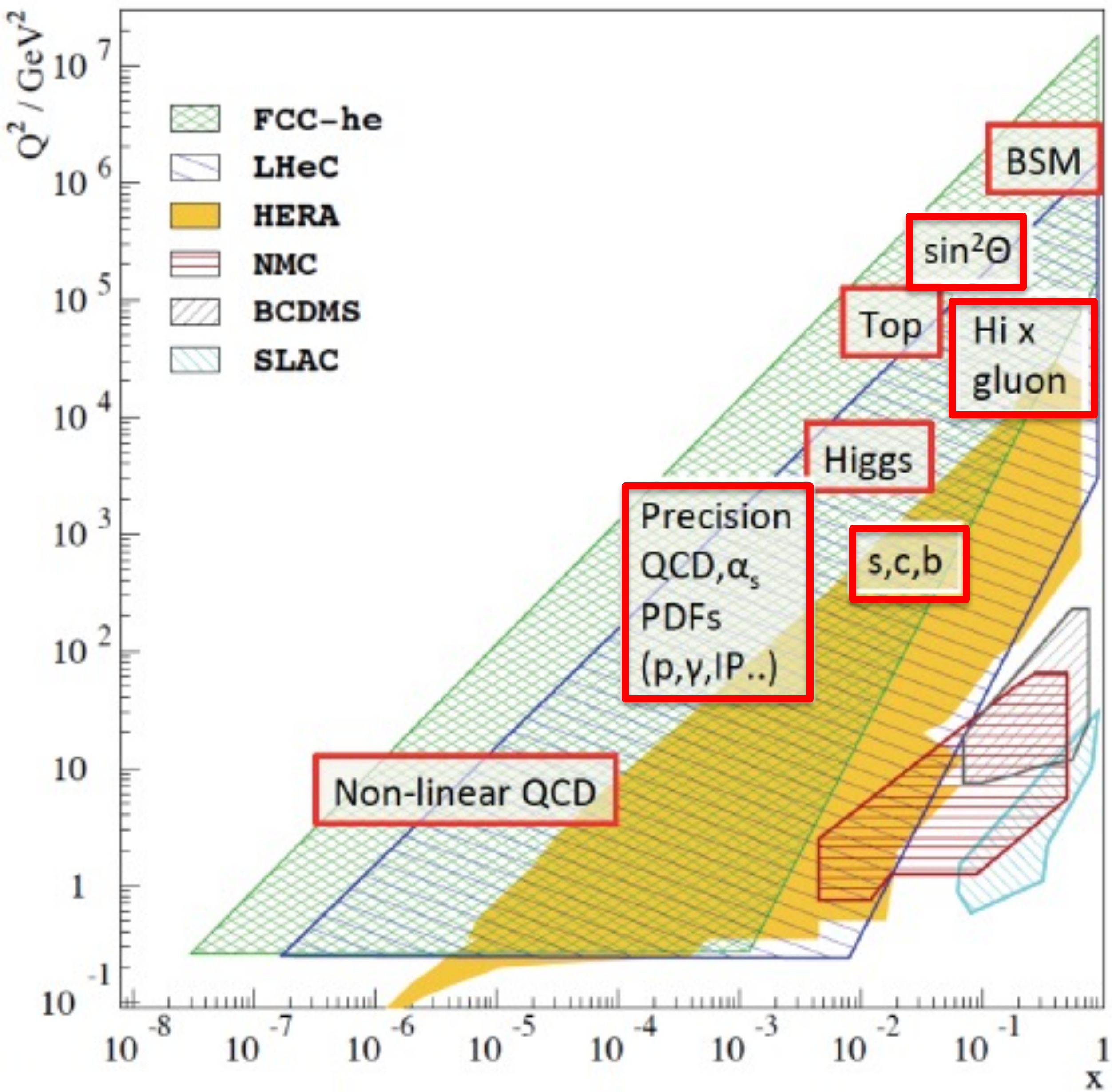
50 GeV(+) electrons on FCC hadron beams

under study with renewed mandate, working group structure and coordination (Jorgen d'Honft)

→ Kick-off meeting planned for late October

# LHeC and FCC-eh Physics




- Substantial Higgs programme

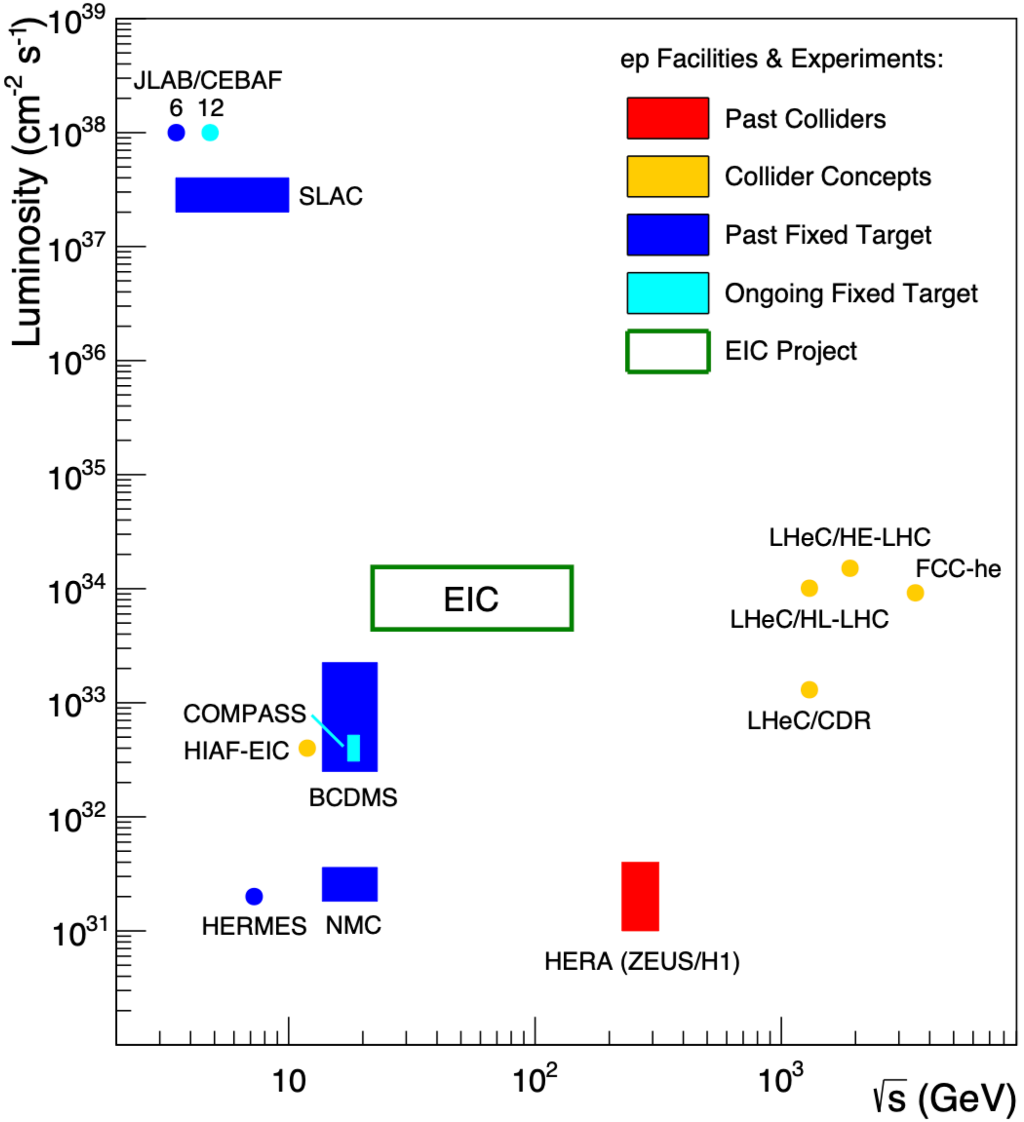
- Revolutionary proton PDF precision, improving LHC sensitivity to Higgs and new physics

- Elucidates low x dynamics in ep & eA

- 4 orders of mag. in kinematic range of nuclear structure

# The Electron-Ion Collider (BNL)

EIC will be world's first ... - High lumi ep Collider
- Polarised target collider
- eA collider

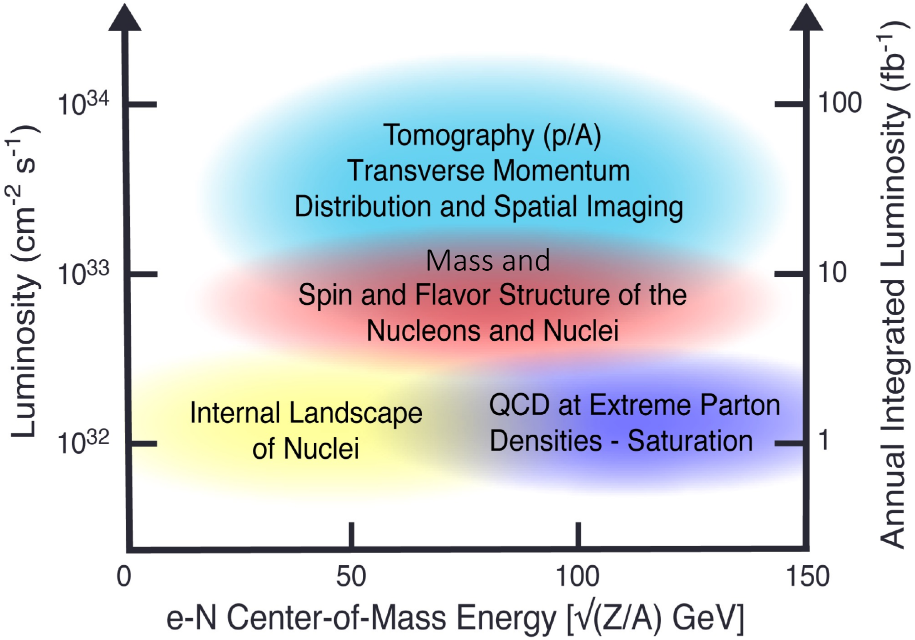



... energy range roughly $28 < \sqrt{s} < 140$ GeV, accessing moderate-to-large x values compared with HERA

... complementary physics programme to the energy frontier (cf LEP v Babar / Belle)

**Physics targets include:**
- 3D proton structure
- Proton mass
- Proton spin
- Dense partonic systems in nuclei

# The EIC Machine



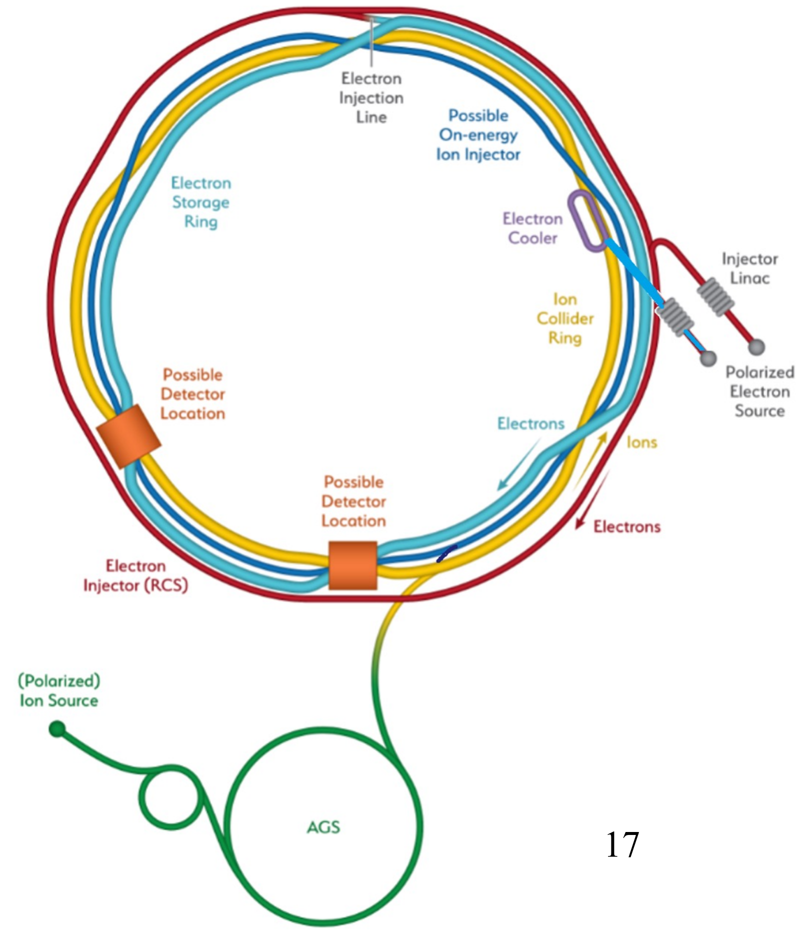

Challenges from high lumi requirement include short bunch spacing, high beam currents …

→ Synchrotron load

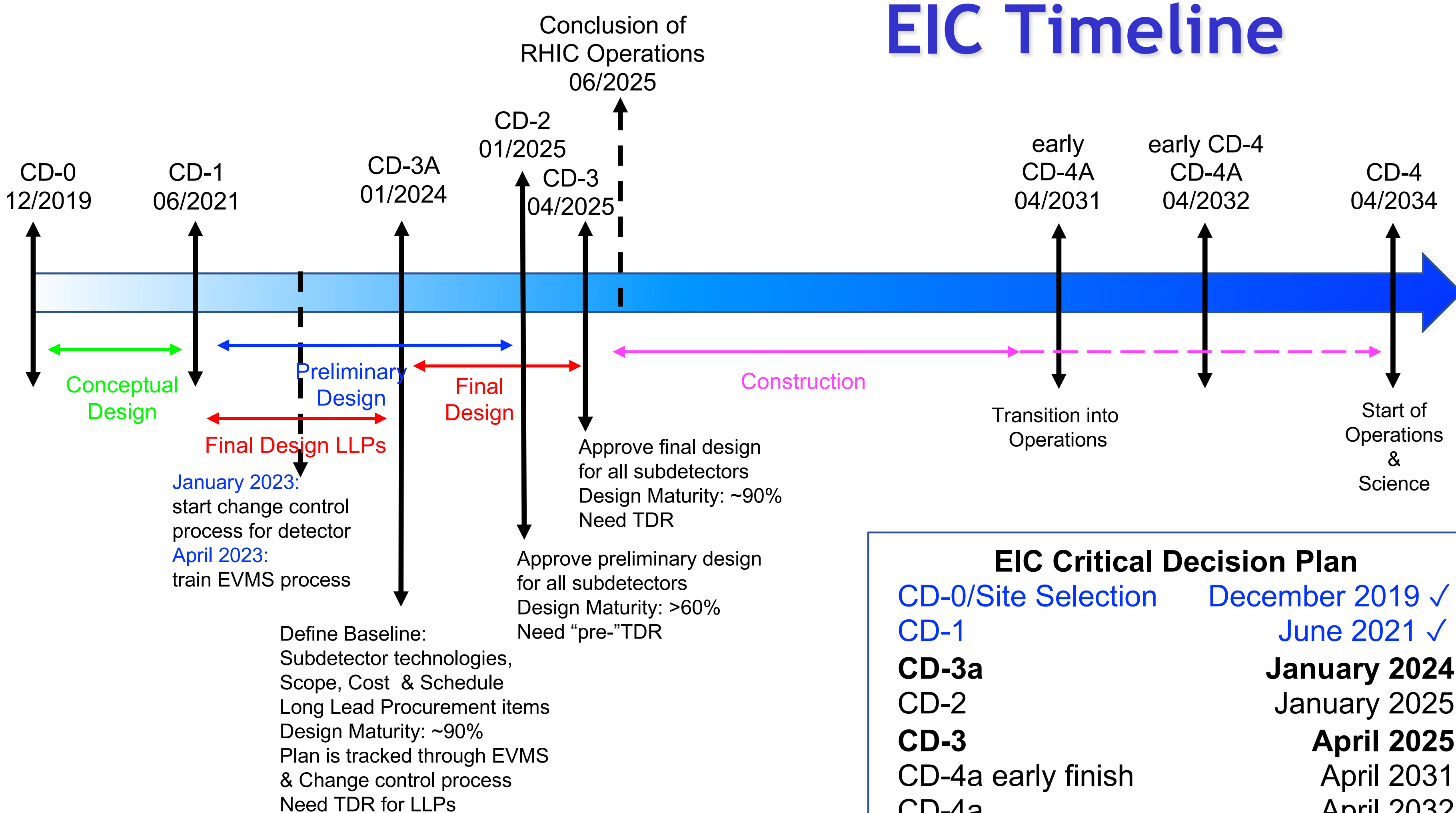
→ Crossing angle

Collider specifications driven by scientific goals

| 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 | |



# EIC Timeline



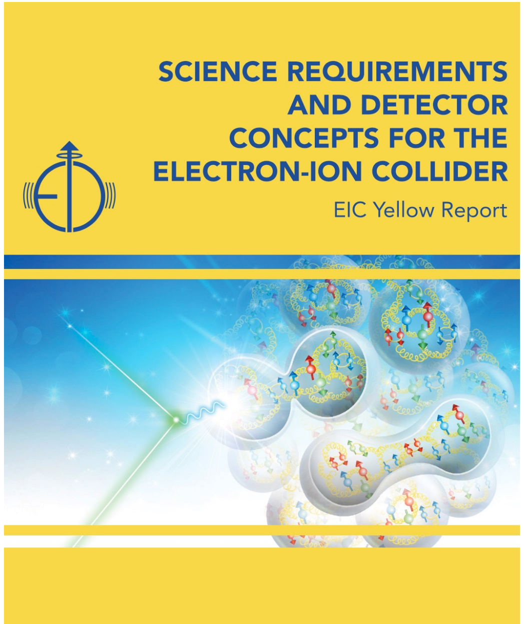

**EIC Critical Decision Plan**

| | |
|---|---|
| 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** |

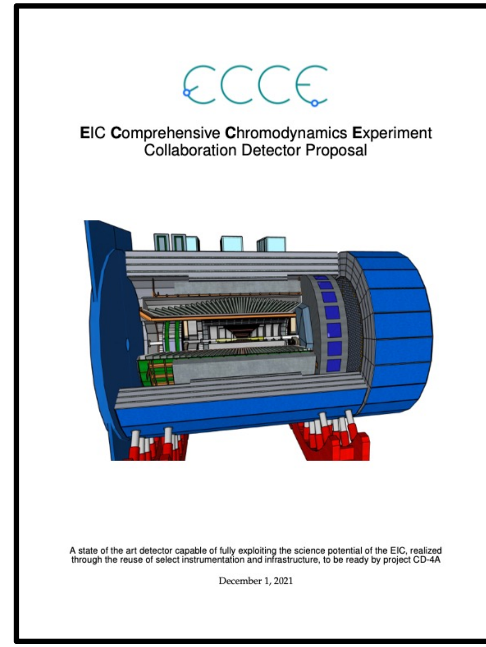
- Still several steps to go, but on target towards operation early/mid 2030s

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

# Current EIC Experimental Status








- Yellow Report (arXiv:arXiv:2103.05419) defined targets

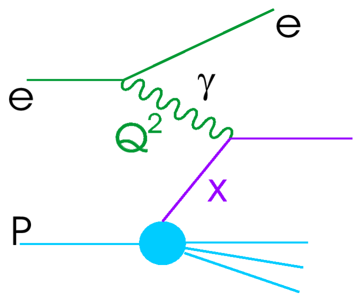
- Detector proposals then invited (ATHENA, CORE, ECCE)

- ECCE chosen as reference design. Now merged with ATHENA into 'EPIC' collaboration. Currently building detailed design and simulation framework

- Ongoing work towards a second, complementary detector.

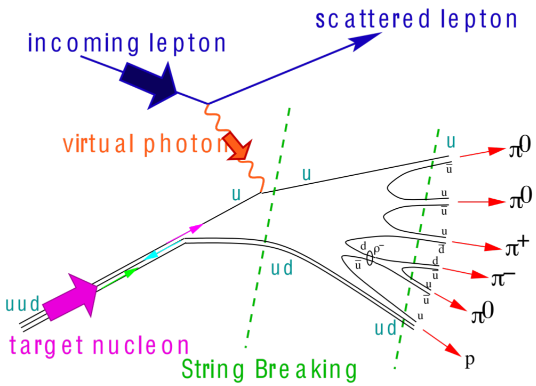
# Observables / Detector Implications

## Inclusive



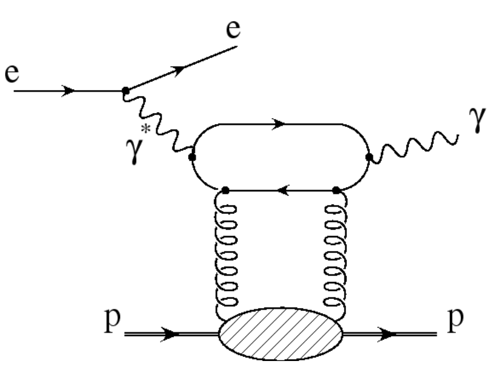

- Traditional DIS, following on from fixed target experiments and HERA → Longitudinal structure
  … high acceptance, high performance electron identification and reconstruction

## 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 flavours 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

# ePIC Detector Overview

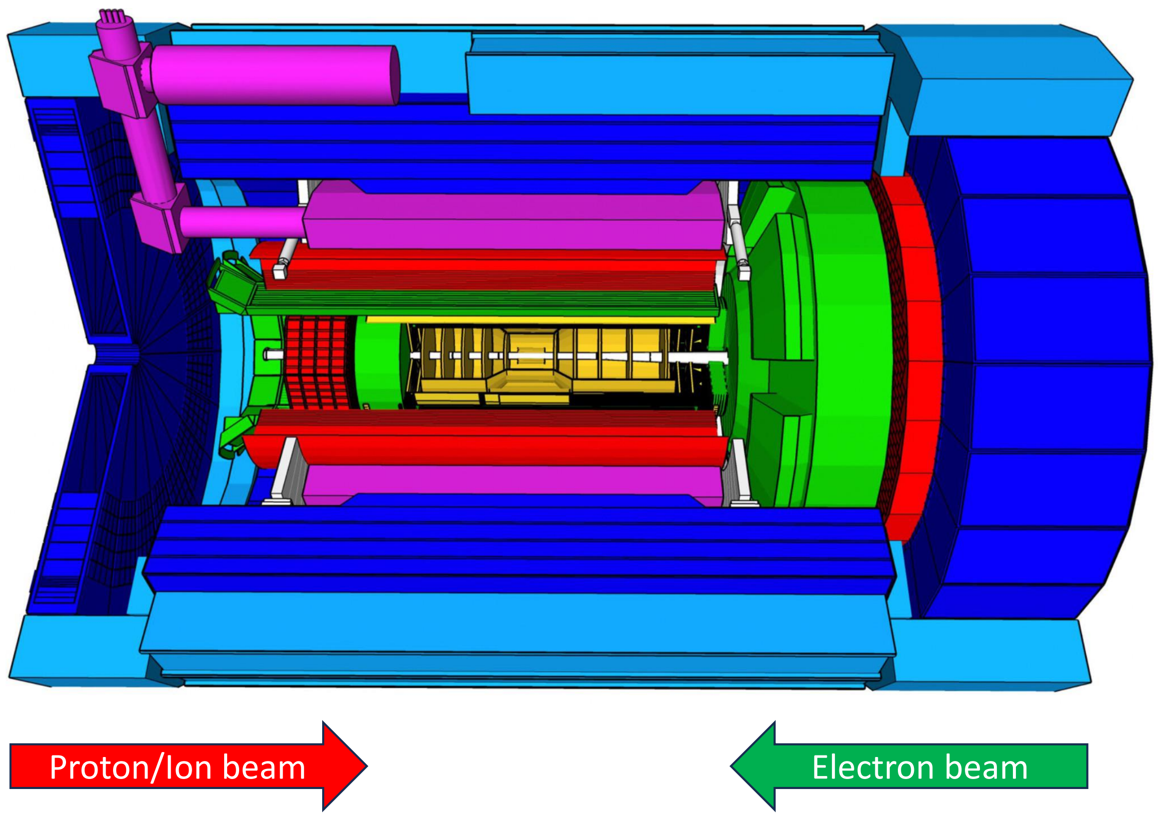
**Magnet**
- New 1.7 T SC solenoid, 2.8 m bore diameter

**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)

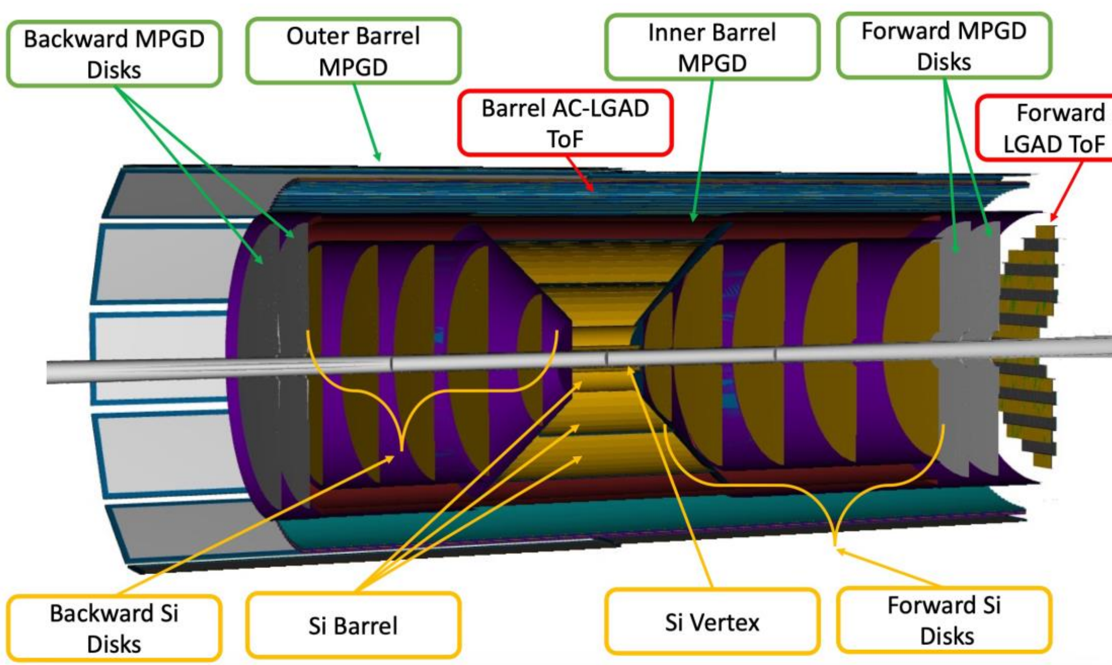


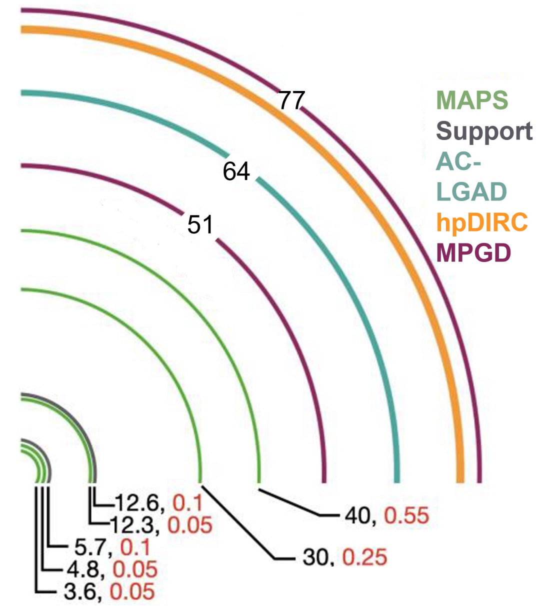

- 9m long x 5m wide
- Extensive beamline instrumentation not shown (see later)
- Continuous streaming readout with aggressive FEB zero-suppression
- Much lower radiation fluxes than LHC widens technology options

# Tracking Detectors

Primarily based on MAPS silicon detectors (65nm technology)

- Co-development with 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)



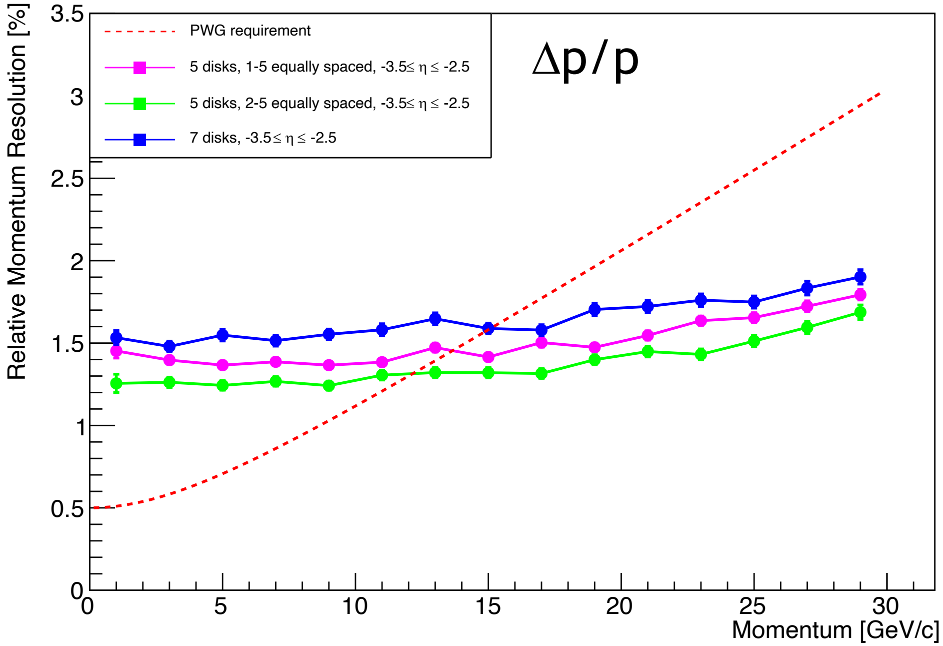

Black numbers are radii in cm

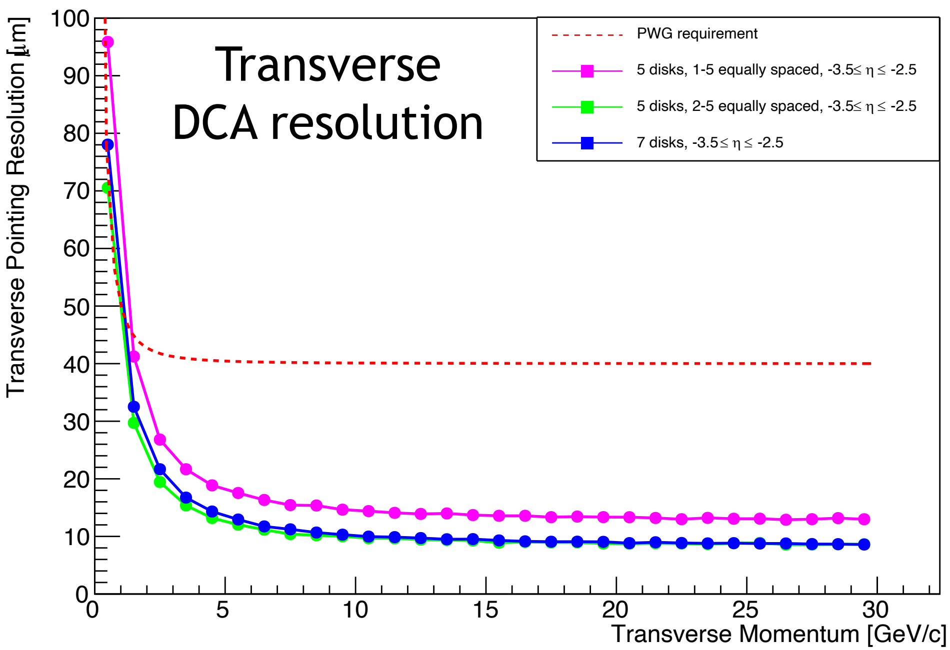
Red numbers are material in % X0

LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

# Tracking Performance & Optimisation




Birmingham group (Laura Gonella, Peter Jones, Stephen Maple) at centre of silicon detector layout and performance optimisation studies.

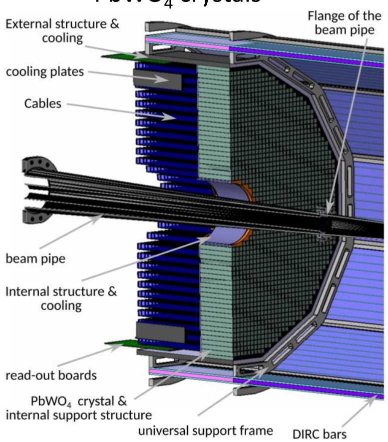
e.g. 5 disks are enough for both track and vertex reconstruction if they're in the right place!

# Calorimeter Overview

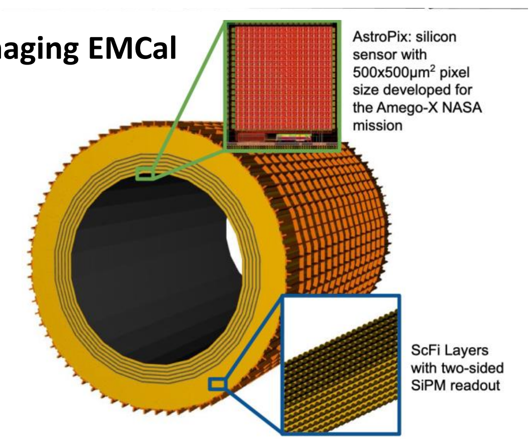
- Different technologies in barrel and end-caps, as required for performance targets
- New ECAL designs / technologies,
- HCAL partially recycles previous detectors
- All read out with Si PMs

**Electron Endcap EMCal**

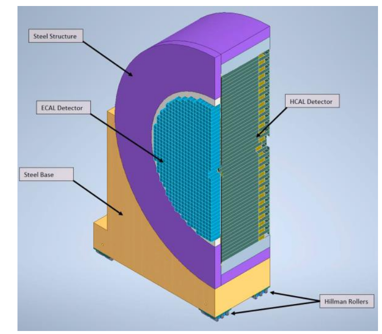
$PbWO_4$ crystals




**Barrel Imaging EMCal**

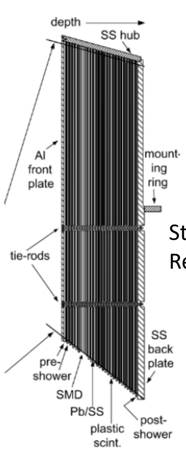



**Hadron Endcap EMCal**




High granularity W-powder/SciFi EMCal

**Electron Endcap HCal**




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

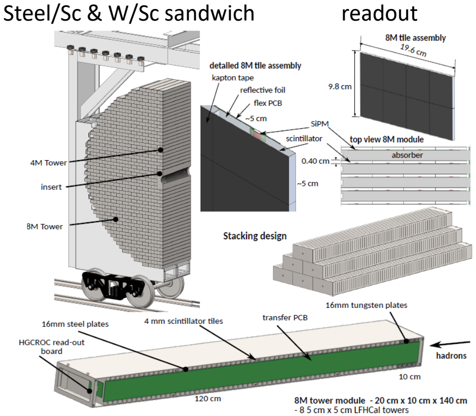
**Barrel HCal**

sPHENIX barrel calorimeter with new SiPMs

**Hadron Endcap HCal**

Longitudinally separated HCAL Steel/Sc & W/Sc sandwich

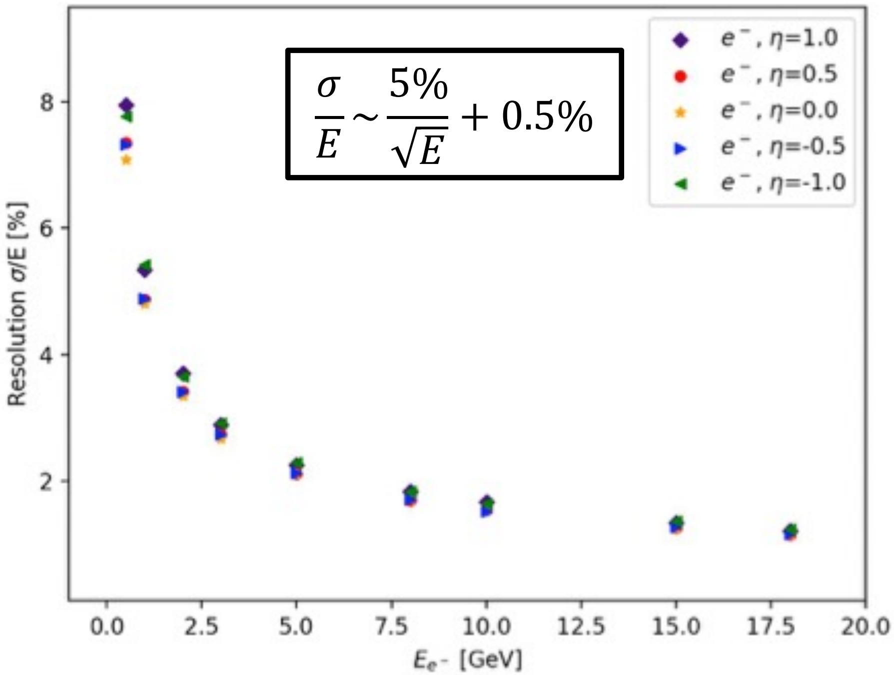
SiPM-on-tile readout

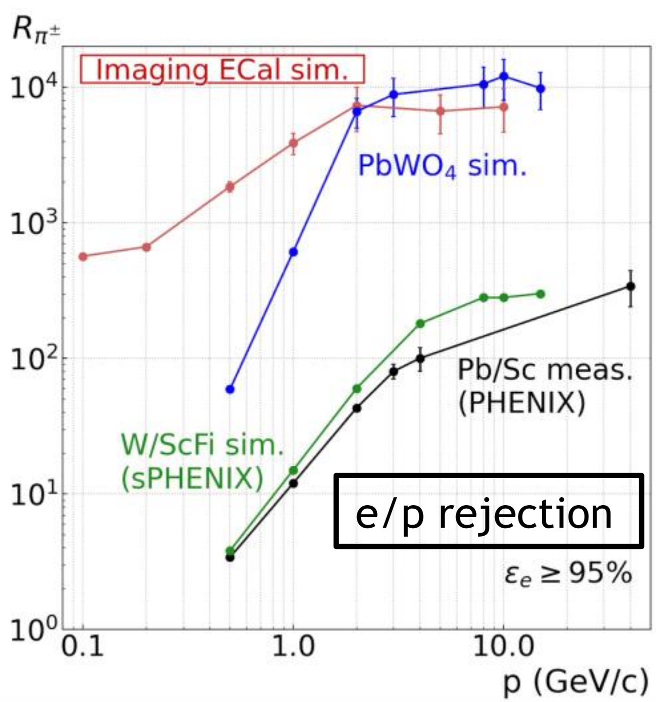


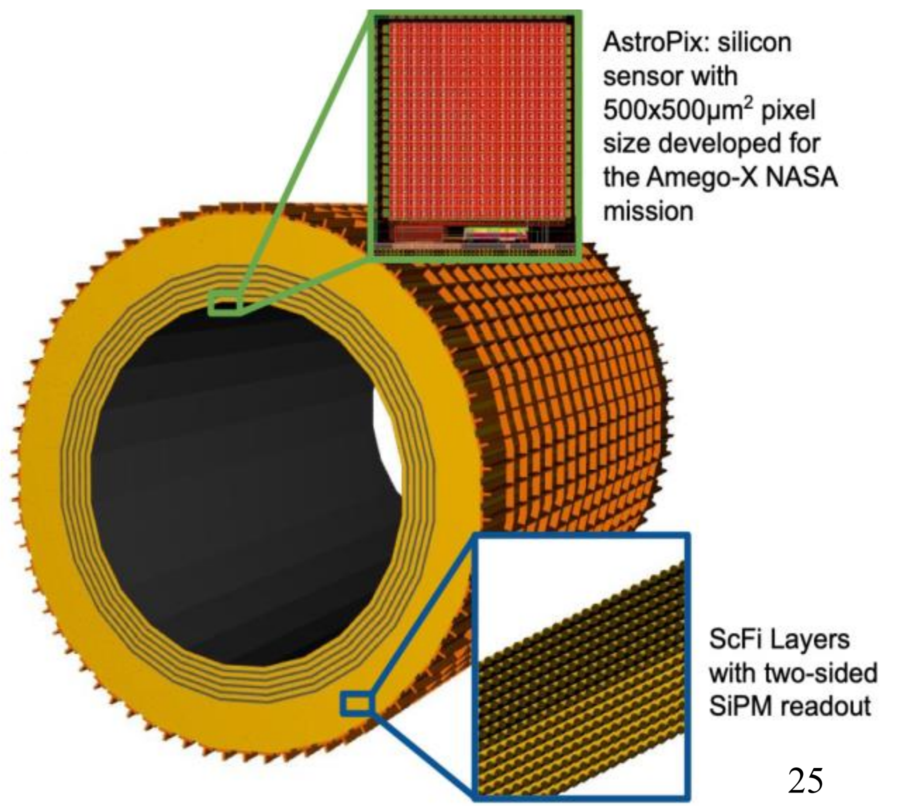

+ high granularity insert at largest $\eta$

# Barrel Imaging ECAL

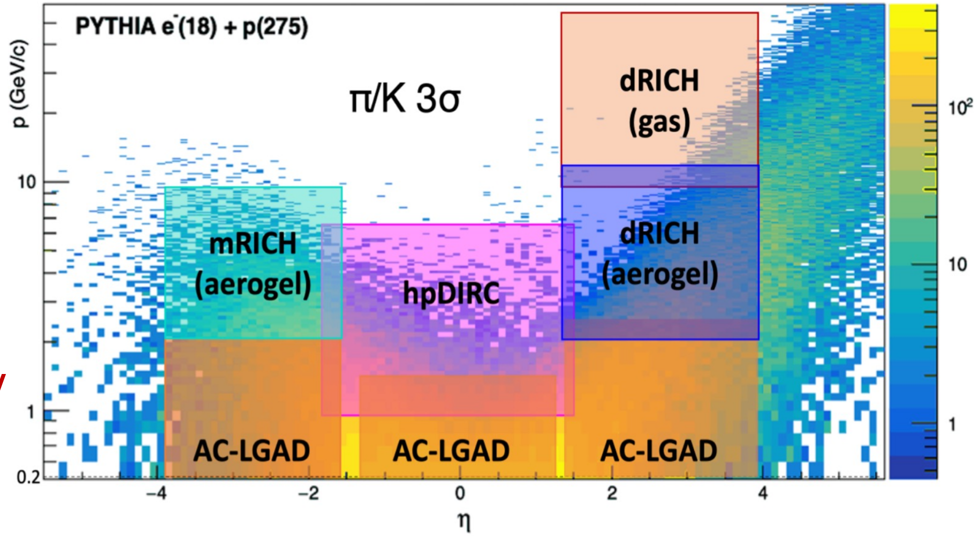
- 6 MAPS (Astropix) layers for position resolution.
- Interleaved with 5 Pb/SciFi layers For energy resolution
- Followed by large Pb/SciFi section



# Particle Identification

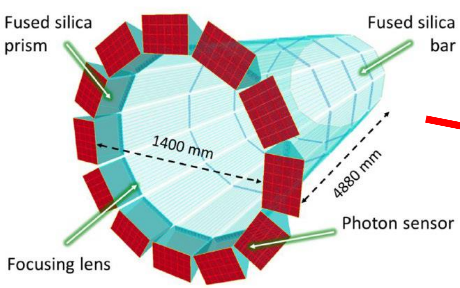


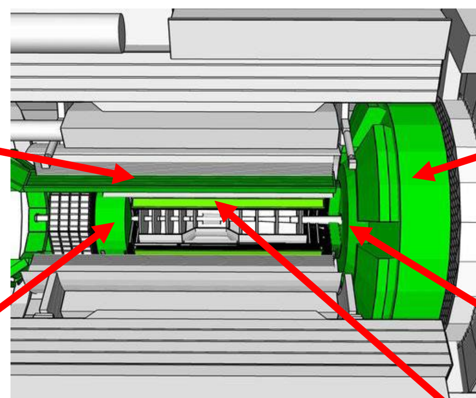

- SIDIS programme relies on π / K / p (and other PID) separation …
- Cerenkov detectors at high momentum, augmented by AC-LGADs / ToF at low momentum

## ePIC detector design – PID

**High-Performance DIRC**

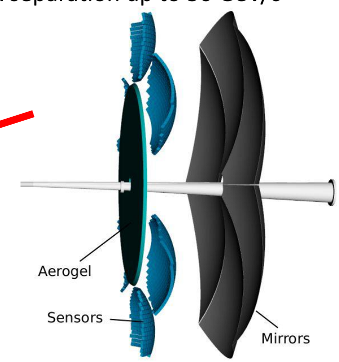
- Quartz bar radiator (reuse BaBAR bars)
- Sensors: MCP-PMTs
- π/K separation up to 6 GeV/c

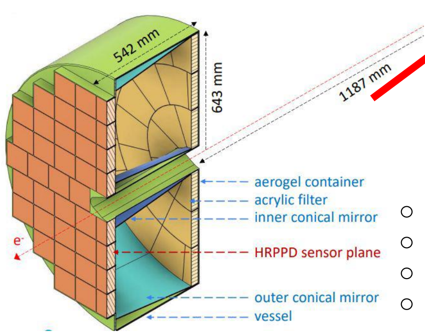


**Dual-Radiator RICH (dRICH)**

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



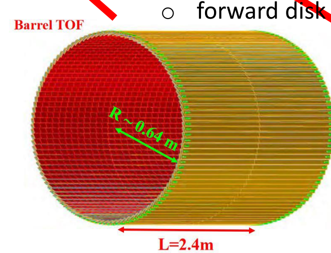



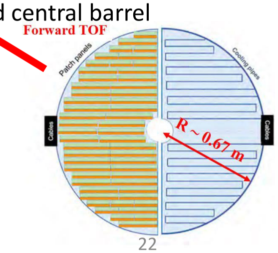

**Proximity Focused (pfRICH)**

- 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

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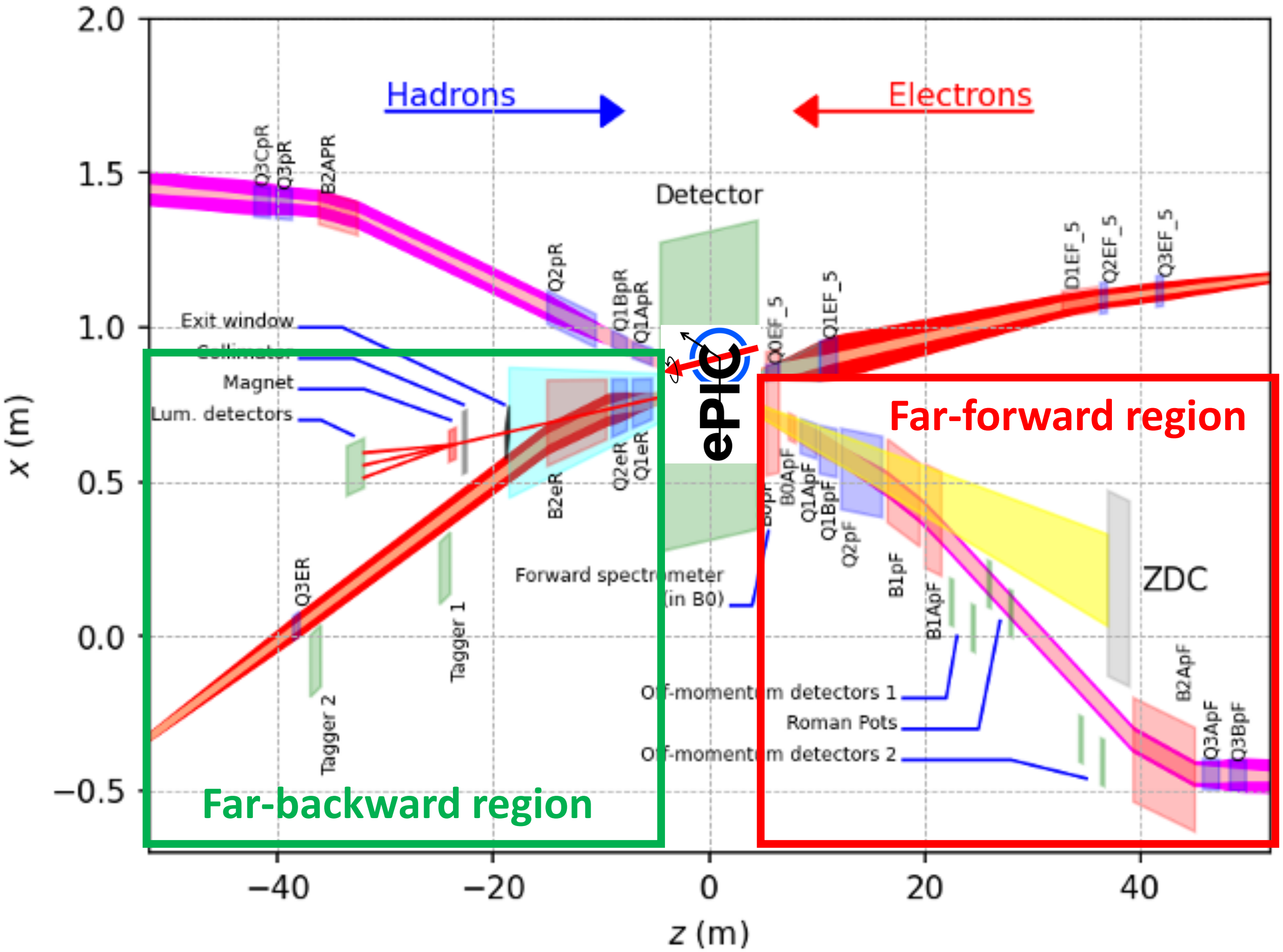
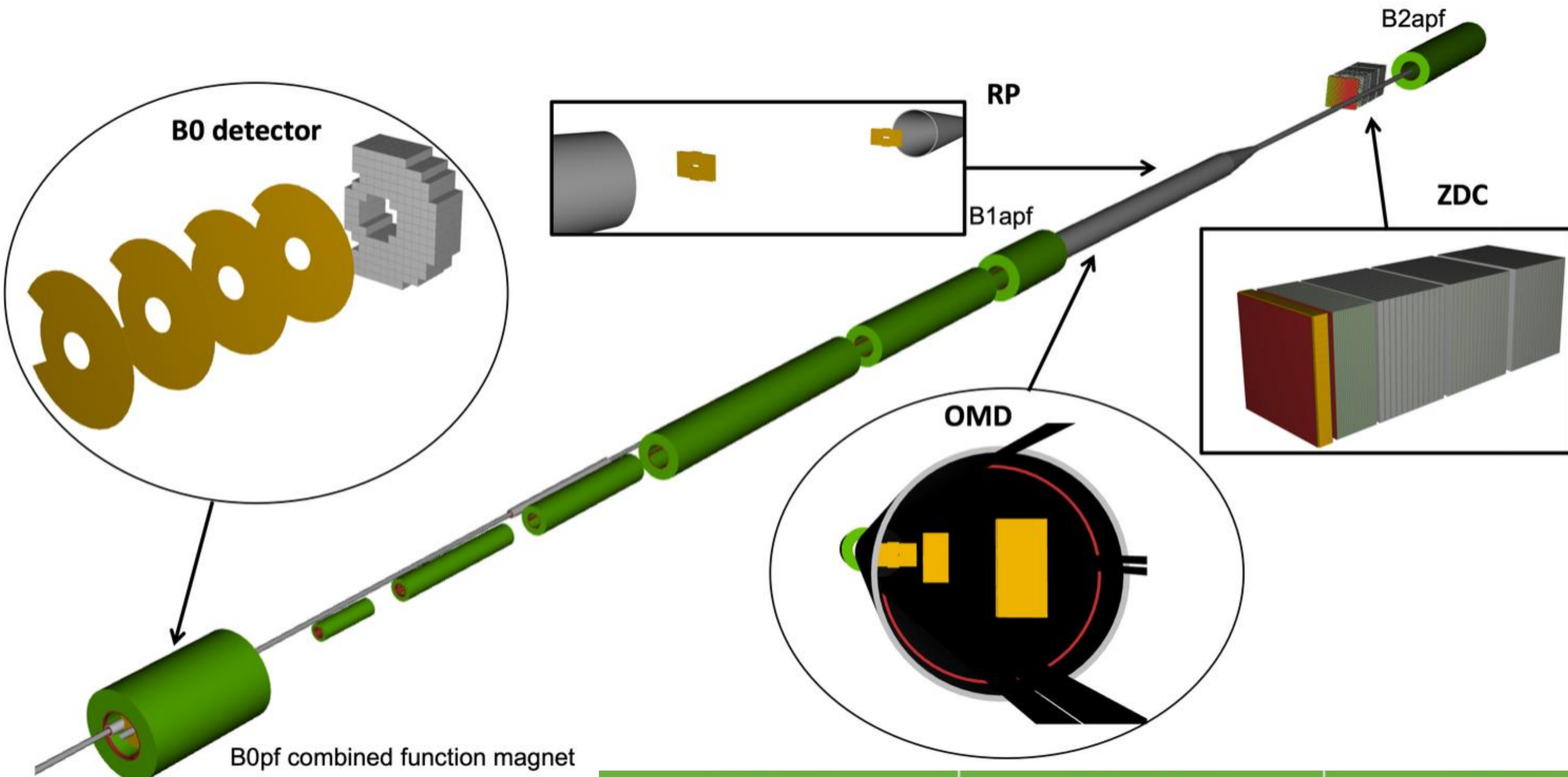
# Interaction Region / Beamline Instrumentation




- 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

# Far Forward Region



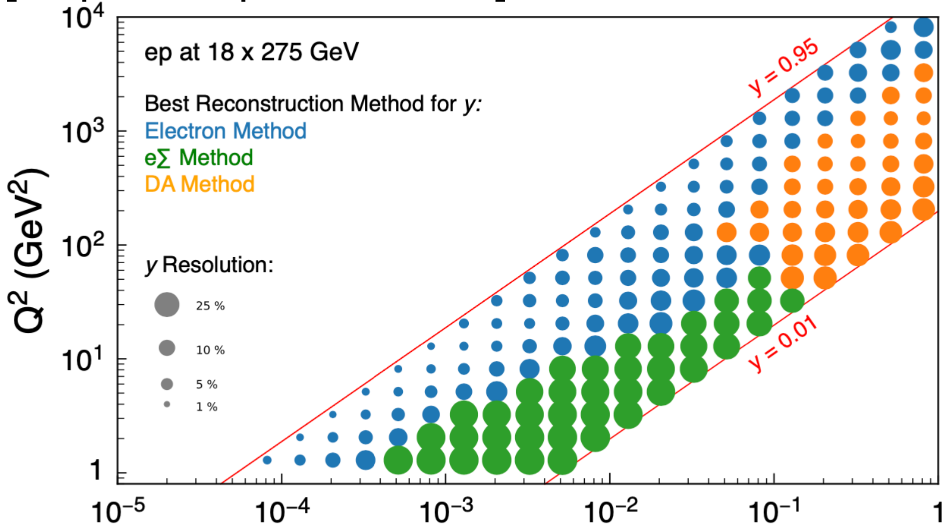


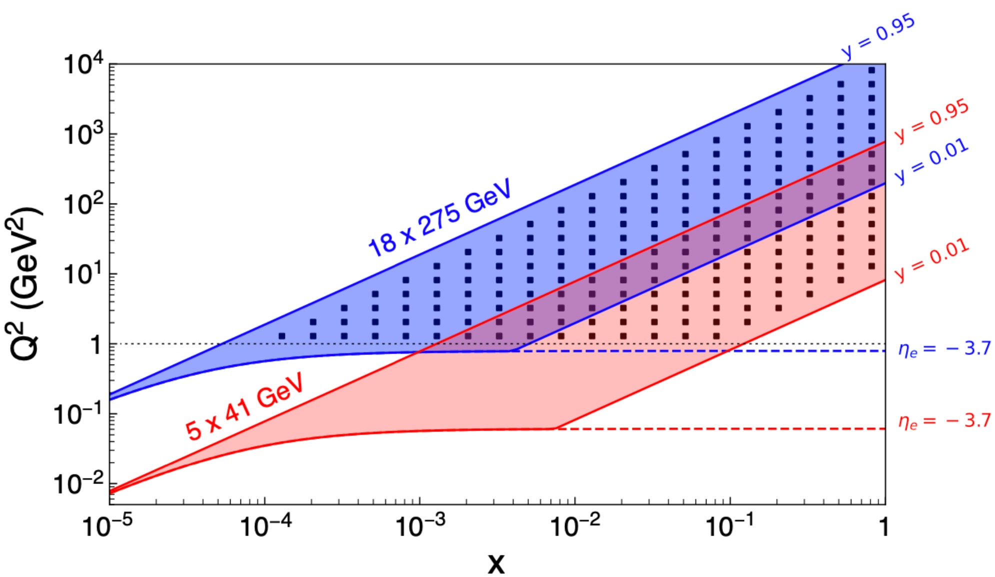

~Hermetic forward coverage except for beampipe

| 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 |

# Performance and Measurement Strategy for Neutral Current

[Stephen Maple / ATHENA]




Another Birmingham speciality …

- Choose reconstruction methods exploiting the hadronic final state as well as the electron to optimise (x, $Q^2$) resolutions throughout phase-space
→ 5 bins per decade in x and $Q^2$ are achievable for all $Q^2$ > 1 $GeV^2$

- Exploit overlaps between data at different $\sqrt{s}$ to avoid 'extreme' phase space regions

- Highest x bin centre at x=0.815

# Simulating Inclusive ePIC Measurements

- 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 $1fb^{-1}$)

- Expect to be systematically limited from early-on

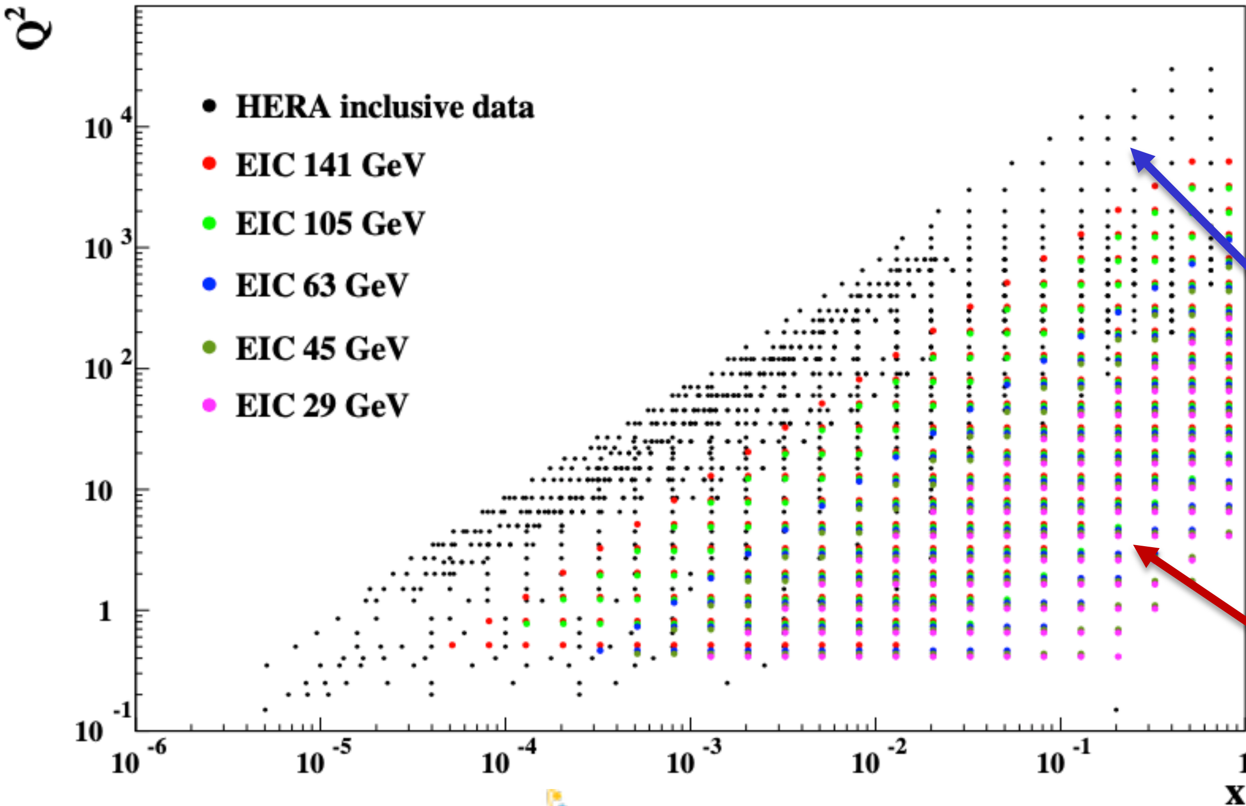
- Systematic precision estimated from experience at HERA, expected EIC detector performance, and guesswork

- 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**
**→ 2.5% normalisation (uncorrelated between different $\sqrt{s}$ )**

# Impact on Proton PDFs




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

Studies in the xFitter framework

arXiv:2309.11269

**Impact of Inclusive Electron Ion Collider Data on Collinear Parton Distributions**


Néstor Armesto[1], Thomas Cridge[2†], Francesco Giuli[3], Lucian Harland-Lang[4], Paul Newman[5], Barak Schmookler[6], Robert Thorne[4], Katarzyna Wichmann[2]

[1] *Departamento de Física de Partículas and IGFAE, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain*
[2] *Deutsches Elektronen-Synchrotron DESY, Germany*
[3] *CERN, CH-1211 Geneva, Switzerland*
[4] *Department of Physics & Astronomy, University College, London, WC1E 6BT, UK*
[5] *School of Physics & Astronomy, University of Birmingham, B15 2TT, UK*
[6] *University of California, Riverside, Department of Physics & Astronomy, CA 92521, USA*


arXiv:2307.01183

**Extraction of the strong coupling with HERA and EIC inclusive data**


Salim Cerci[1], Zuhal Seyma Demiroglu[2,3], Abhay Deshpande[2,3,4], Paul R. Newman[5], Barak Schmookler[6], Deniz Sunar Cerci[1], Katarzyna Wichmann[7]

[1] *Adiyaman University, Faculty of Arts and Sciences, Department of Physics, Turkiye*
[2] *Center for Frontiers in Nuclear Science, Stony Brook University, NY 11764, USA*
[3] *Stony Brook University, Stony Brook, NY 11794-3800, USA*
[4] *Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[5] *School of Physics and Astronomy, University of Birmingham, UK*
[6] *University of California, Riverside, Department of Physics and Astronomy, CA 92521, USA*
[7] *Deutsches Elektronen–Synchrotron DESY, Germany*

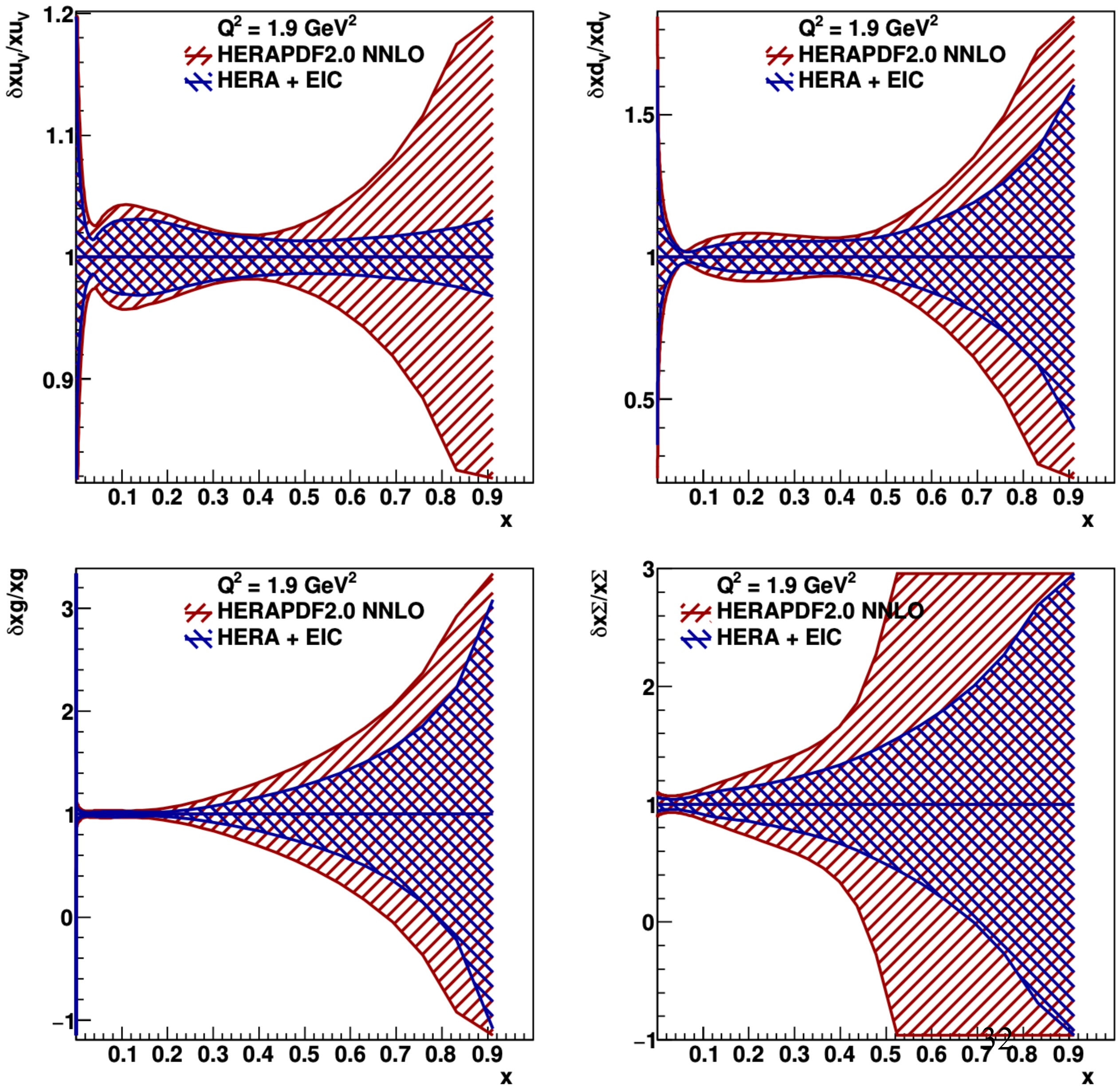
# Impact of EIC/ATHENA on HERAPDF2.0

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

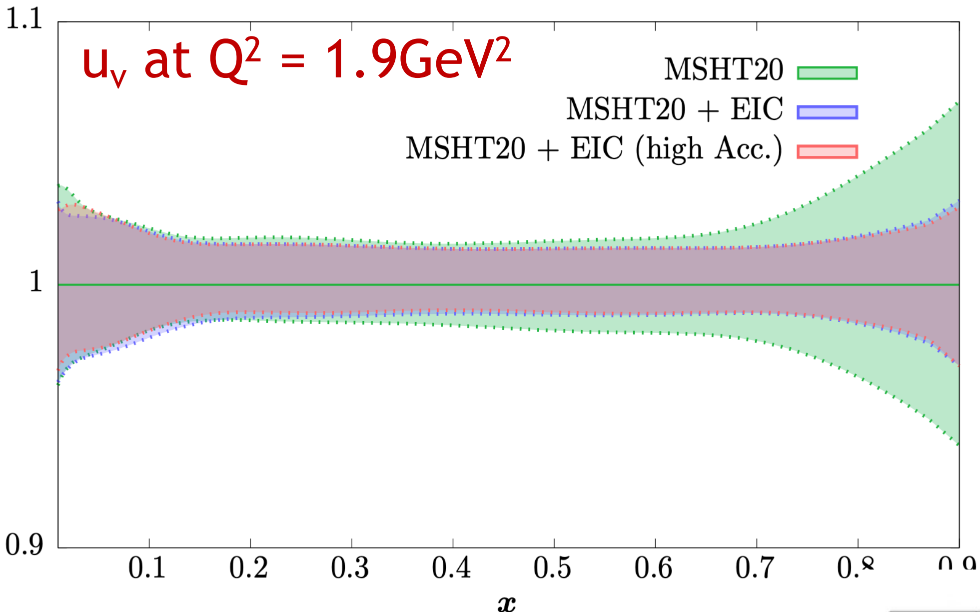
(linear x scale, $Q^2 = Q_0^2$)

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

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

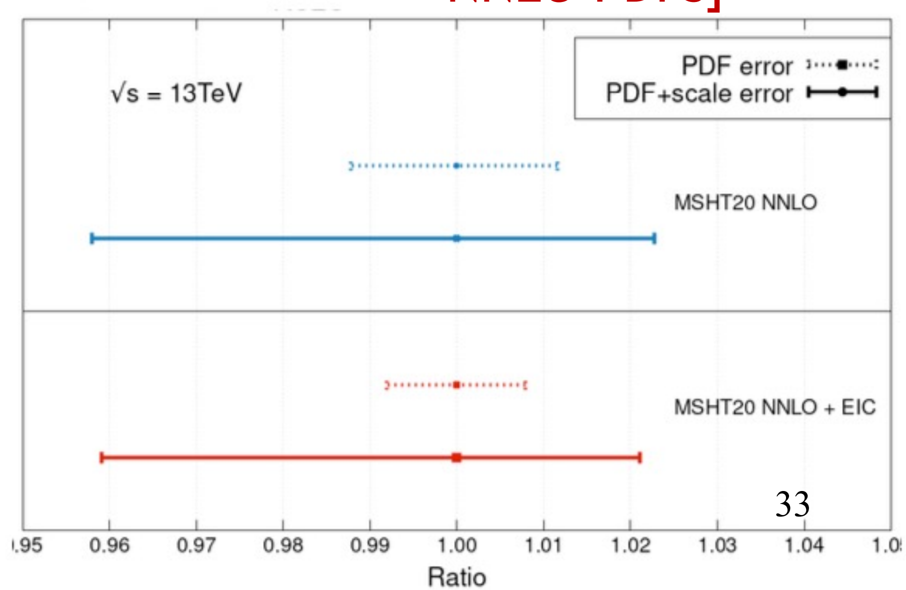


# EIC Impact relative to MSHT20 NNLO (as an example global fit)




Significant impact of EIC simulated data in up quark precision as x→1

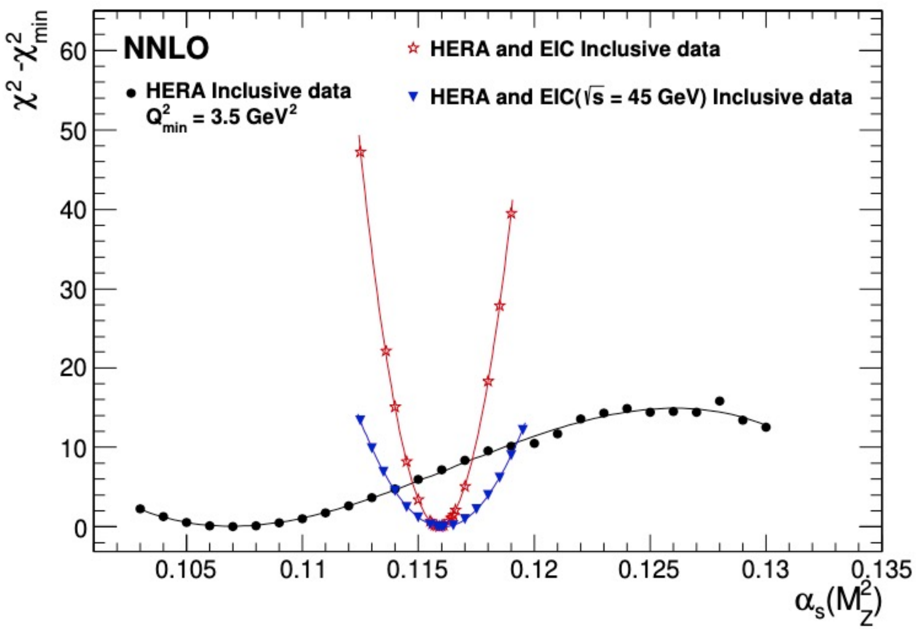
σ(gg→H) uncertainties @ LHC [N[3]LO matrix elements with NNLO PDFs]




… small, but valuable improvements in all parton species at all x, $Q^2$

… e.g. gluon improvement feeds through parton-parton luminosities to significant improvement in PDF uncertainty on gg→H at LHC

# Taking $\alpha_s$ 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

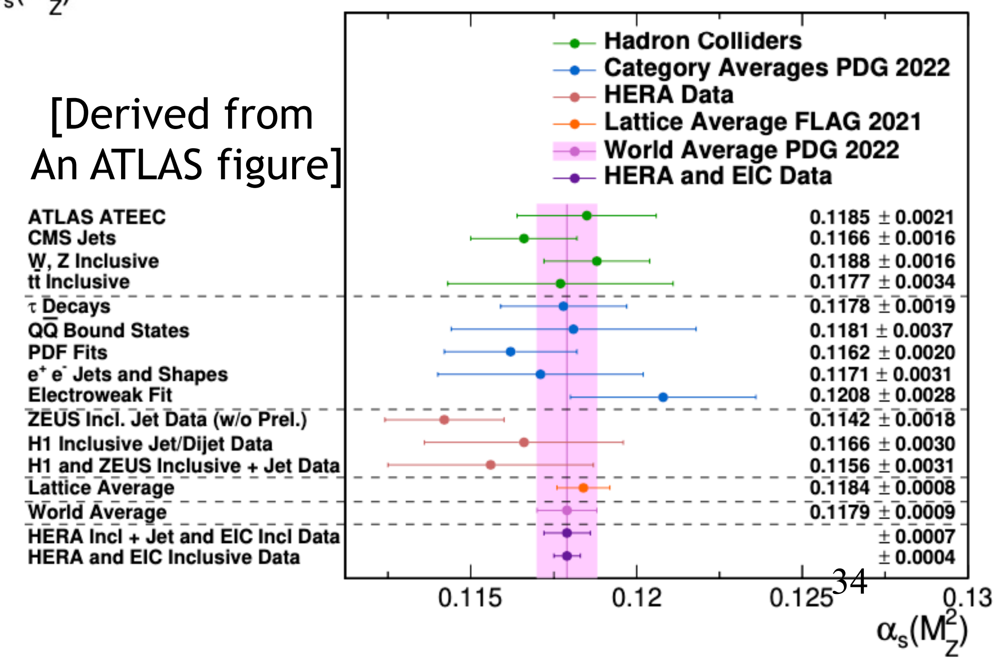
$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004 \text{ (exp)}$$

$$^{+0.0002}_{-0.0001} \text{ (model + parameterisation)}$$

Adding EIC (precision high x) data to HERA can lead to $\alpha_s$ 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]



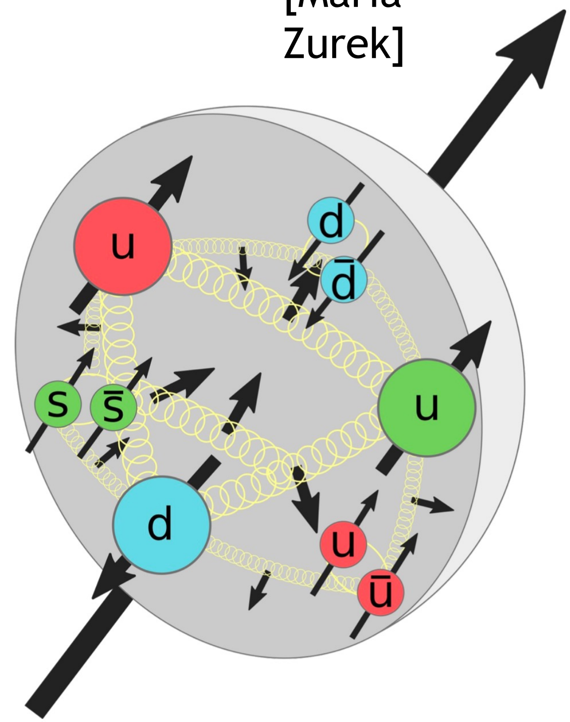
# Physics Motivation: Proton Spin

- 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

[Maria Zurek]




Jaffe-Manohar sum rule:

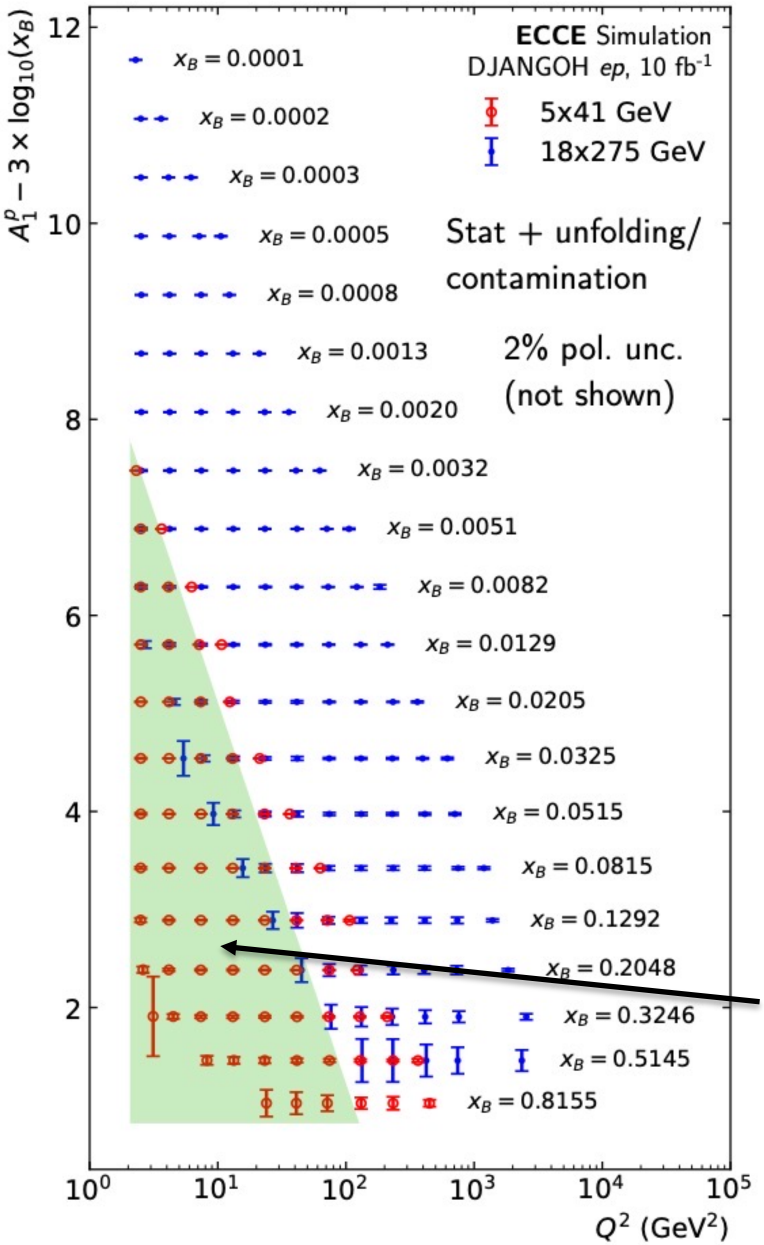
$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

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

- Can be resolved in full with EIC inclusive, semi-inclusive and exclusive data

- e.g. - Current ‘front-line’ … gluon contribution at ‘small’ x from inclusive data …

# 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 …

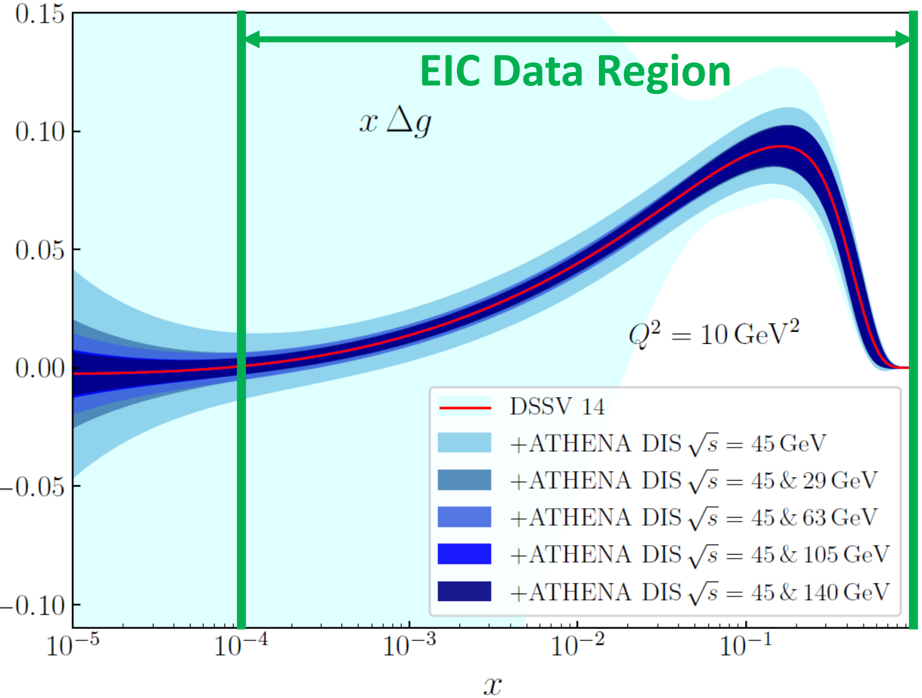
$$g_1(x) = \sum \left(\Delta q(x) + \Delta \bar{q}(x)\right)$$

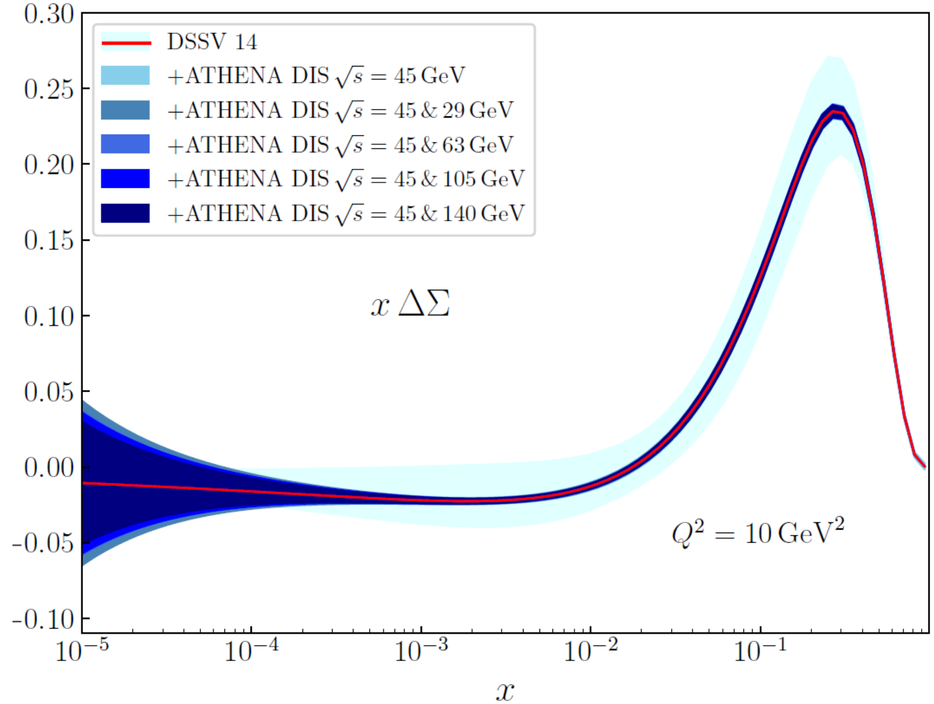
… which gives gluon sensitivity from $Q^2$ dependence (scaling violations)

Previously measured region (in green)

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

# Impact on Helicity Distributions (Study in DSSV framework)




Study based on simulated NC data with integrated luminosity $15\mathrm{fb}^{-1}$, and 70% e,p polarization

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

# EIC and nuclear PDFs

- Nuclei are dense systems of partons, leading to complex binding effects and possibly to novel emergent QCD phenomena at low-x (‘saturation’?) where gluon grows

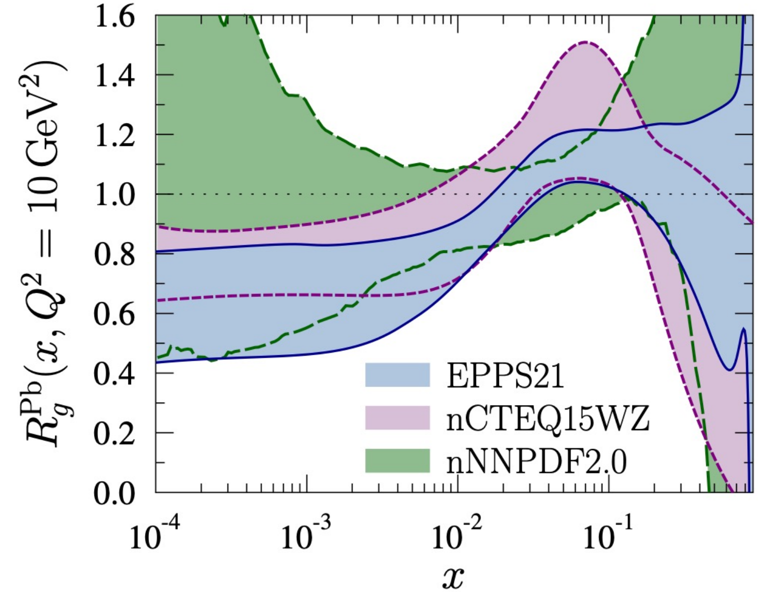
- Needed for quark gluon plasma physics (initial state of heavy ion collisions)

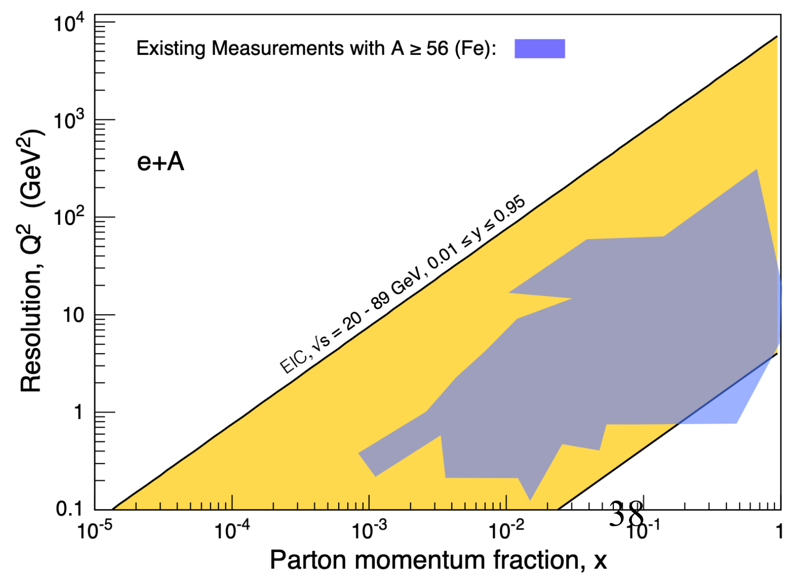
- Results usually shown in terms of nuclear modification ratios (change relative to simple scaling of (isospin-corrected) proton

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

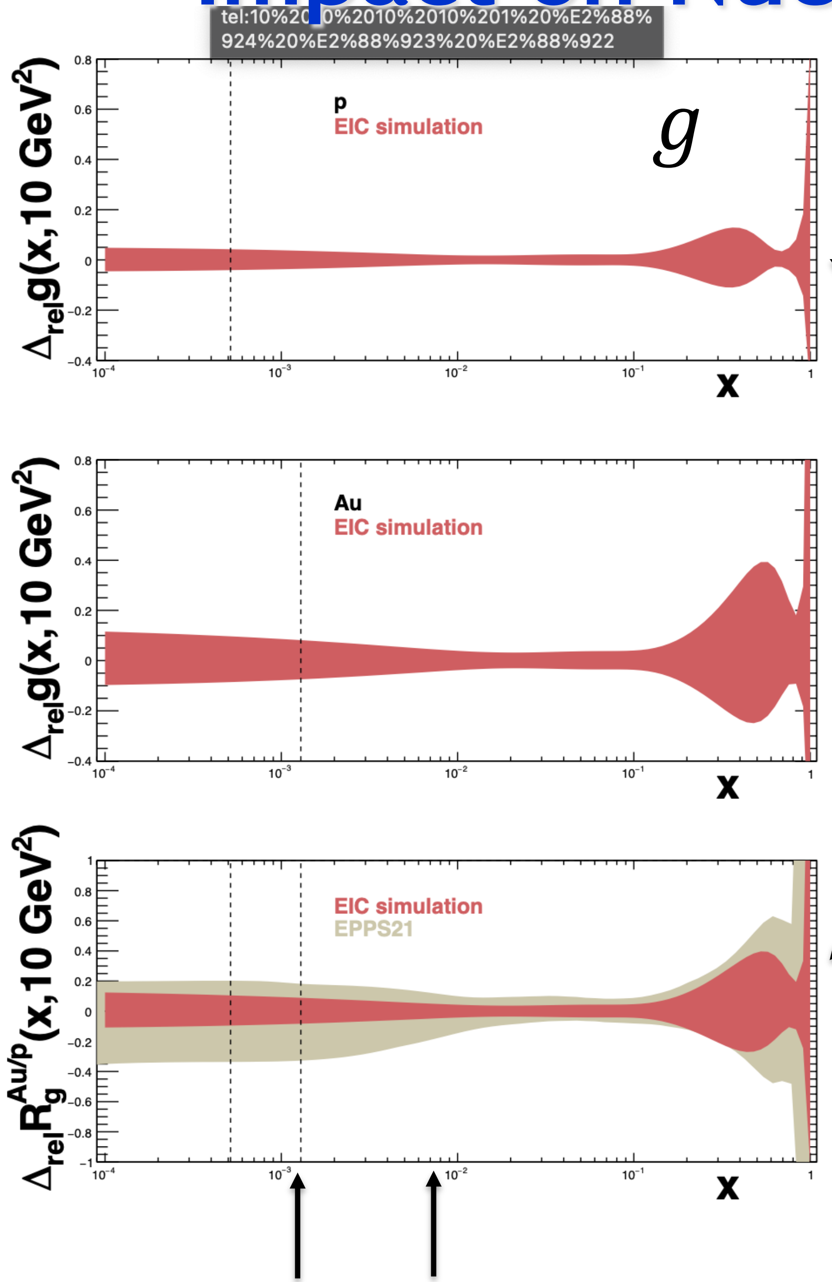
… very poorly known, especially for gluon and at low x

- EIC will have revolutionary impact on eA phase space



# Impact on Nuclear PDFs: Gluon




EIC eA data limit

EPPS21 data limit

Studies in xFitter framework to assess sensitivity of EIC relative to EPPS21

Projected uncertainty on gluon density of proton from EIC-only fit

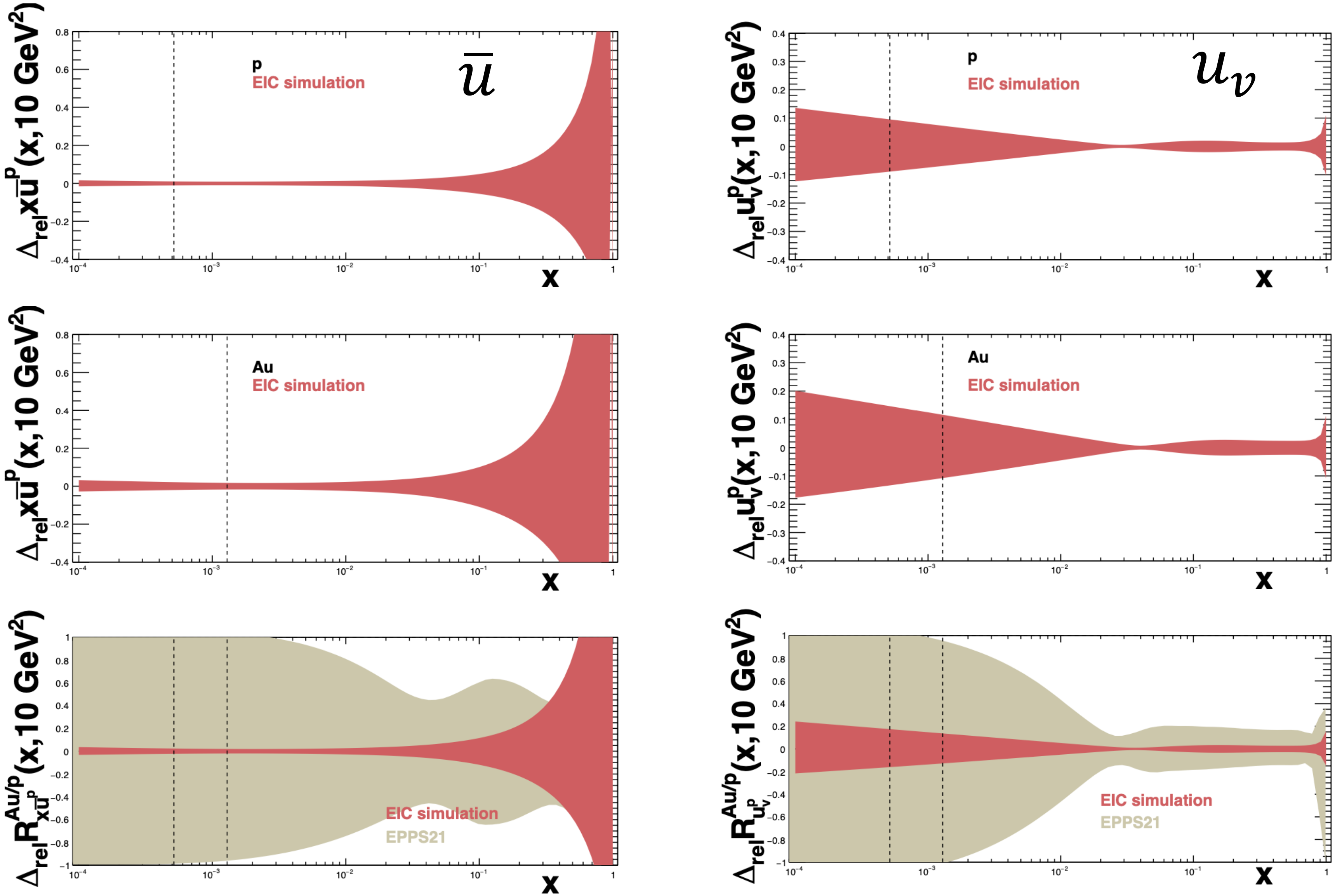
Projected uncertainty on gluon density of (gold) nucleus from EIC-only fit → ~10%

Projected uncertainty on nuclear modification ratio, EIC-only compared with EPPS'16

→ Factor ~ 2 improvement at x~0.1

→ Very substantial improvement in newly accessed low x region

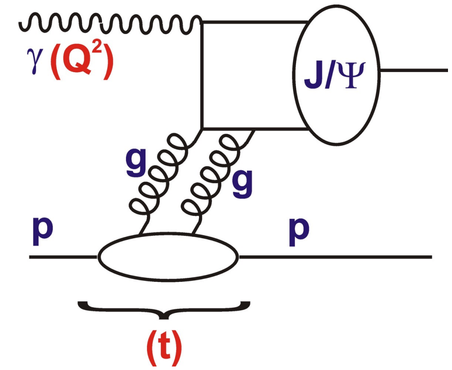
# Impact on Nuclear PDFs: quarks



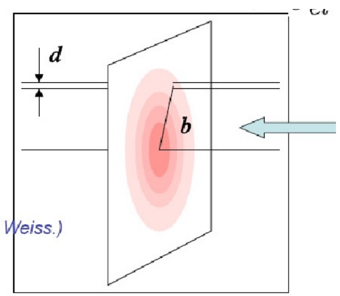

Similarly compelling improvements at low x in particular

# Physics Motivation: Exclusive Processes

Intact protons require (minimum) 2 partons exchanged.

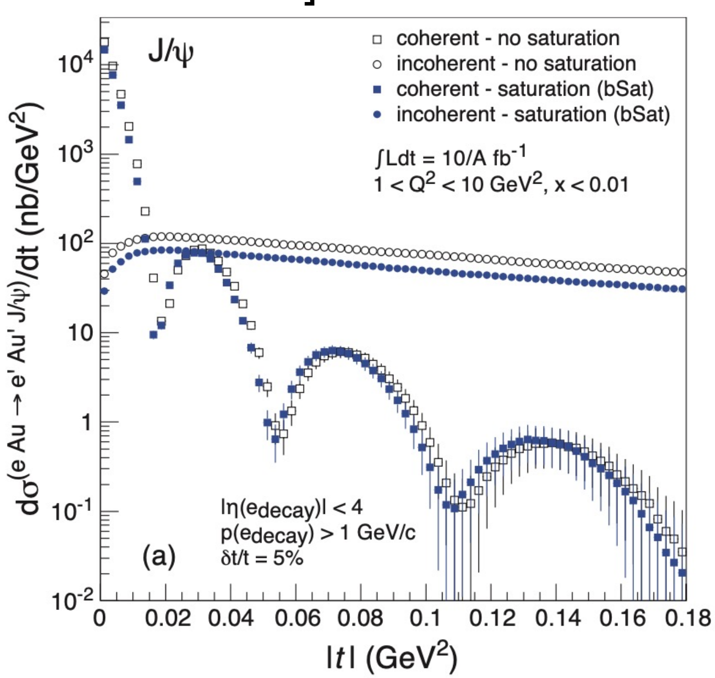



1) Additional variable (Mandelstam) t is conjugate to transverse spatial distributions
   → Large t (small b) probes small impact parameters etc.



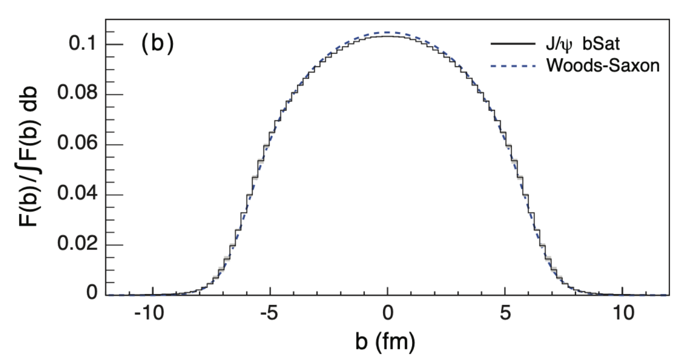

(figure from C. Weiss.)

[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

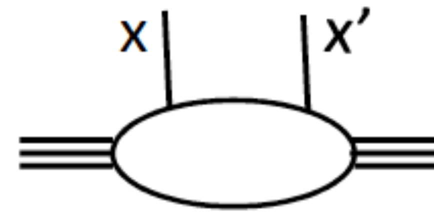





Experimental challenges from incoherent background and resolving dips

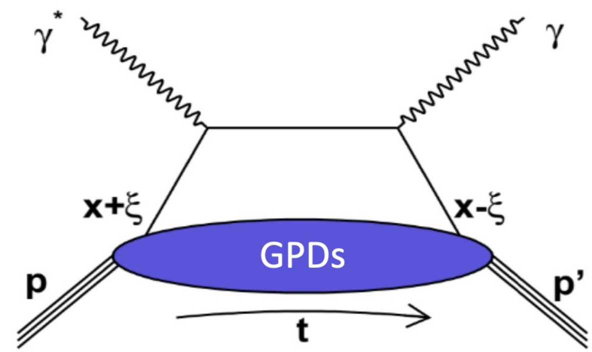
# Physics Motivation: Exclusive Processes

Intact protons require (minimum) 2 partons exchanged.

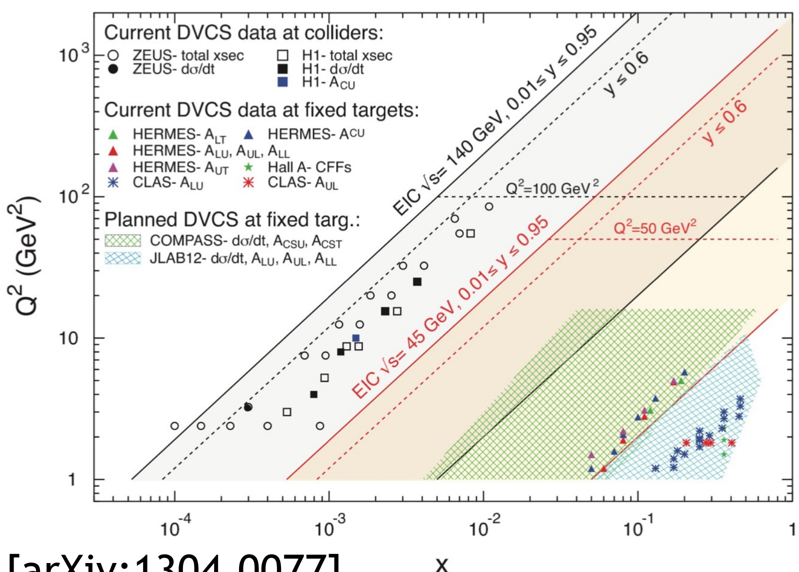



1) Sensitivity to correlations between partons in longitudinal / transverse momentum and spatial coordinates

→ Full 3 dimensional tomography




Deeply Virtual Compton Scattering ($\gamma^* p \rightarrow \gamma$|
is a key process, encoding 3D information
Generalised Parton Densities (GPDs)




[arXiv:1304.0077]

- EIC fills gap between (high statistics) fixed target data and (low statistics) HERA data

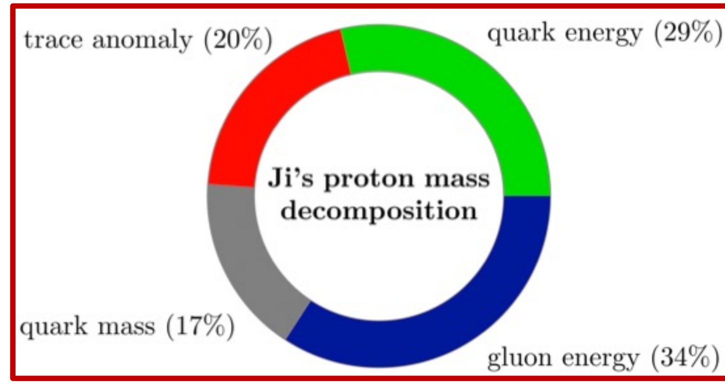
- Requires multiple polarisation states and very large luminosities to map observables onto basic structure

# Physics Motivation: Proton Mass

- Constituent quark masses contribute ~1% of the proton mass

- Remainder is `emergent' → generated by (QCD) dynamics of multi-body strongly interacting system

- Decomposition along similar lines to spin:




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

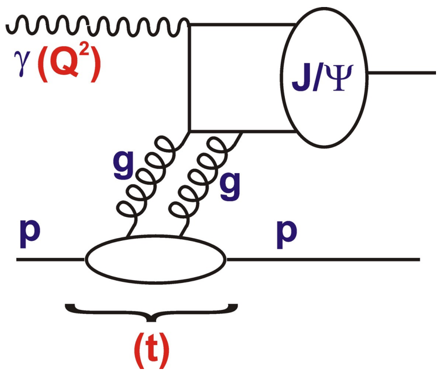
Valence and sea quark masses (including heavy quarks)

Quark and gluon 'KE' from confinement and relative motion

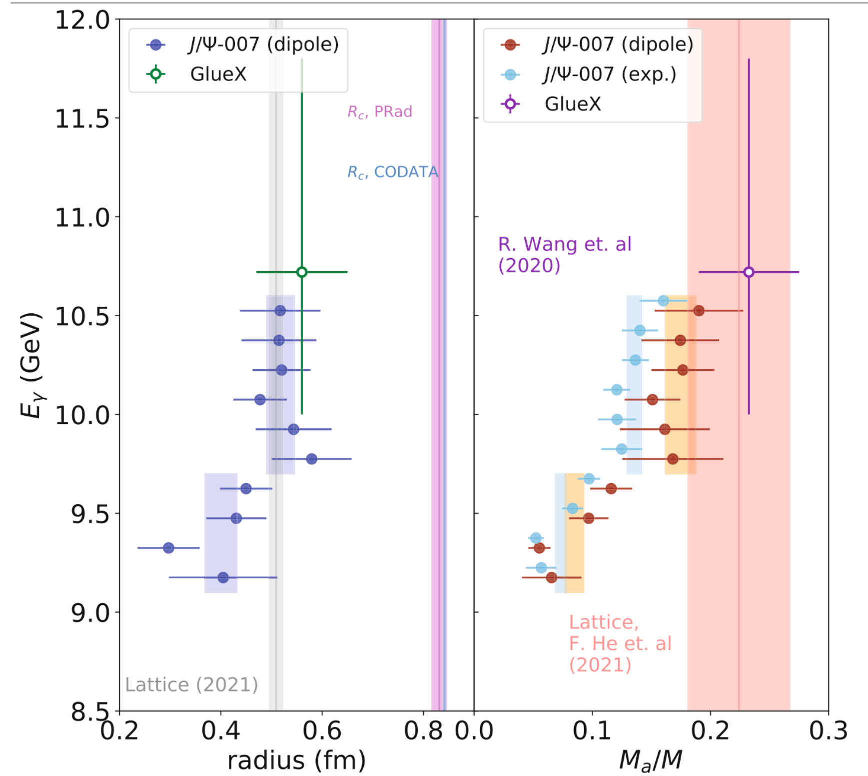
QCD trace anomaly (purely quantum effect - chiral condensates)

- Relations to experimental observables still being understood.
- Recent progress, eg with gravitational form factors of the proton

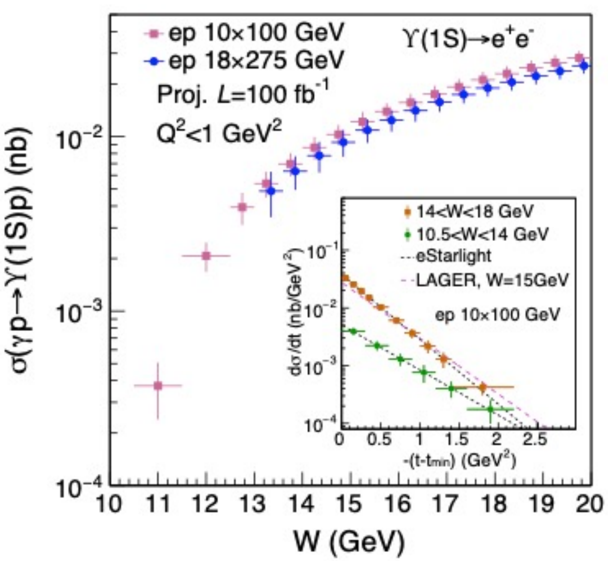
# Proton Mass & Exclusive Vector Mesons

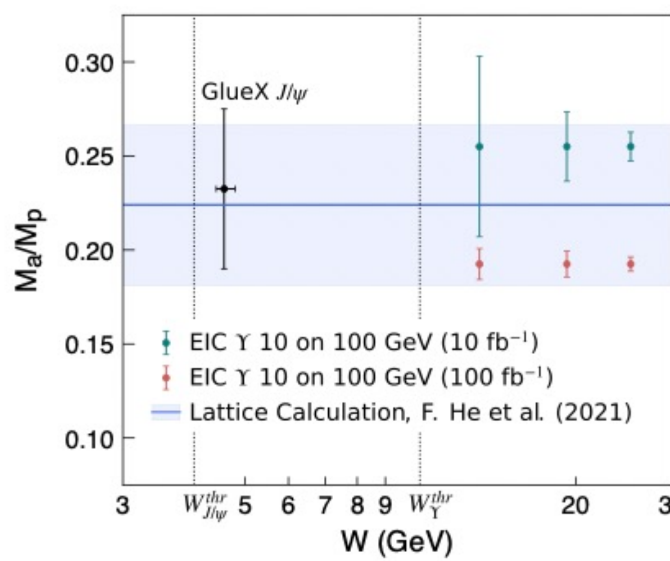



- Recent Jlab data on t dependences of J/Ψ production near threshold → Gravitational form factors




- Gluon radius smaller than charge radius
- Interpreted in terms of trace anomaly




Simulated EIC measurement extends the study to Υ with much improved precision

# ePIC Collaboration Demographics


Over 500 participants so far, from ~160 institutes in 24 countries

UK physicists deeply involved through Yellow Report, Collaboration formation and now ePIC stages, including significant leadership roles.

UK is the fourth largest contributor to ePIC

Birmingham (particle & nuclear physics) largest UK group by some distance.

Part of a wider ‘EIC User Group’ organization with around 1400 members

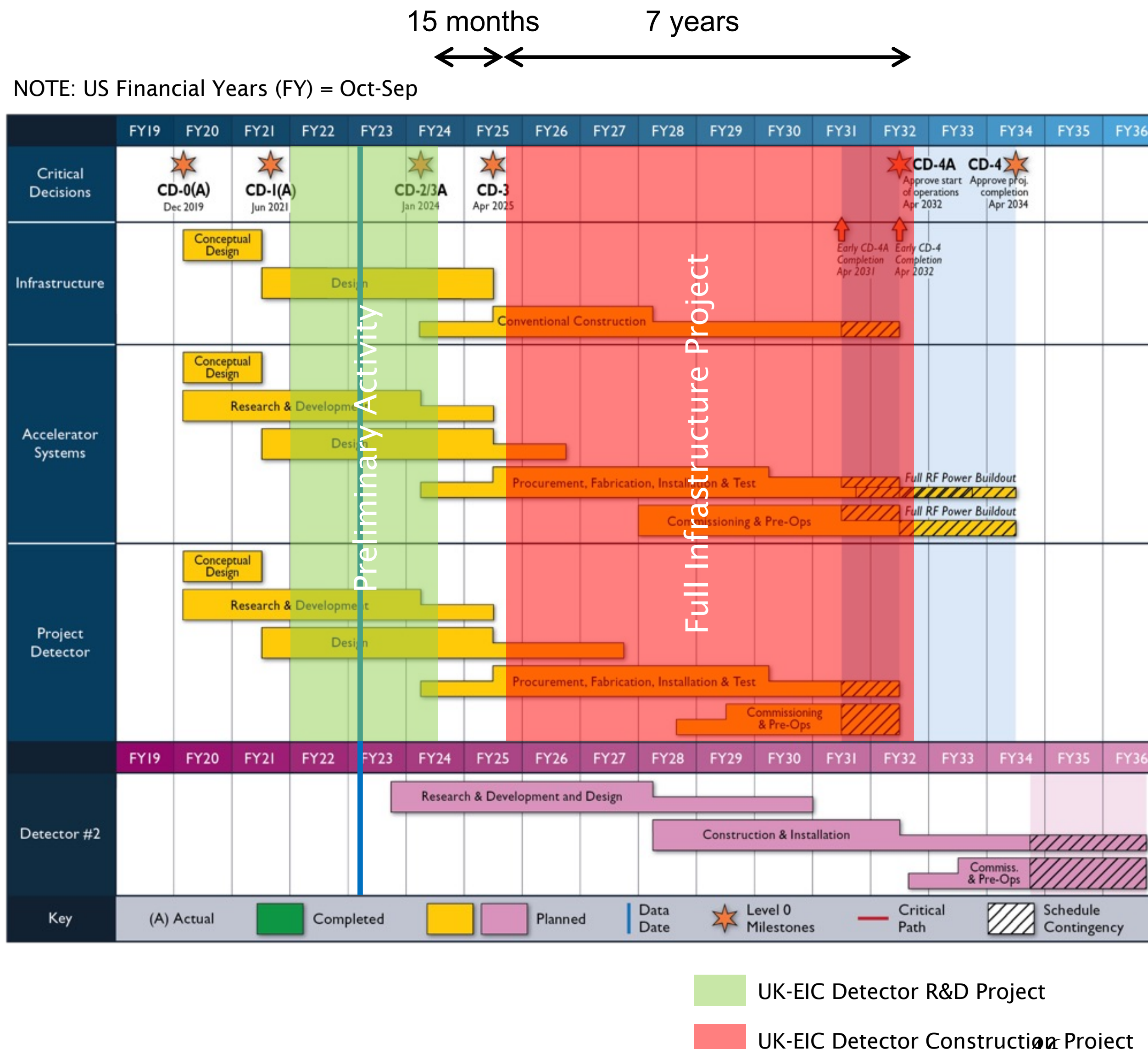
# The UK Involvement

- Initial Birmingham funding obtained for BILPA silicon detector R&D through US DoE.

- More recently UKRI Infrastructure Fund (co-PI Peter Jones)

- ‘Preliminary’ or ‘Scoping’ activity: £3M covering October 2021 – 2024

- Full proposal: 2025-2032 under current review



# The UK Project in more detail

WP1: MAPS → 65nm CMOS (wafer scale) stitched sensors, co-developed with ALICE-ITS3, to be deployed in central tracker
→ Construction of 2 barrel layers, corresponding to around 1/3 of silicon tracker (WP lead = Laura Gonella, also involving James Glover, Li Long, Eve Tse …)

WP2: Timepix → Application of pixel sensors for beamline electron tagger for luminosity and physics at $Q^2 \to 0$

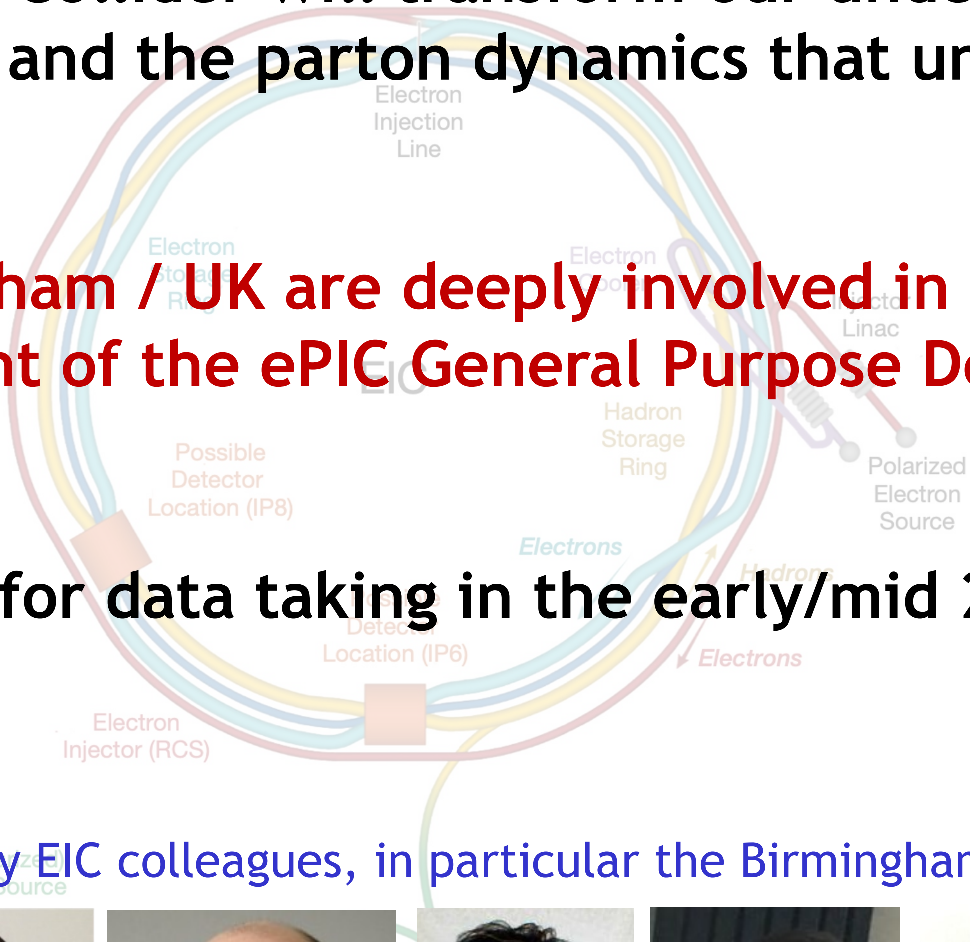
WP3: Lumi Monitoring → Novel pair-spectrometer, beamline $\gamma \to ee$ counting

WP4: Accelerator → Primarily SRF systems for Energy Recovery cooler.
→ Also crab-cavity LLRF synchronisation, beam position monitoring, Energy Recovery modelling and design

University of Birmingham
Brunel University London
University of Glasgow
Lancaster University
Science & Technology Facilities Council Daresbury Laboratory
Rutherford Appleton Laboratory
ASTeC
University of Liverpool
University of Oxford
University of York
The Cockcroft Institute of Accelerator Science and Technology
JAI John Adams Institute for Accelerator Science

# Summary

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




**Birmingham / UK are deeply involved in the development of the ePIC General Purpose Detector**

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

[with thanks to many EIC colleagues, in particular the Birmingham team]

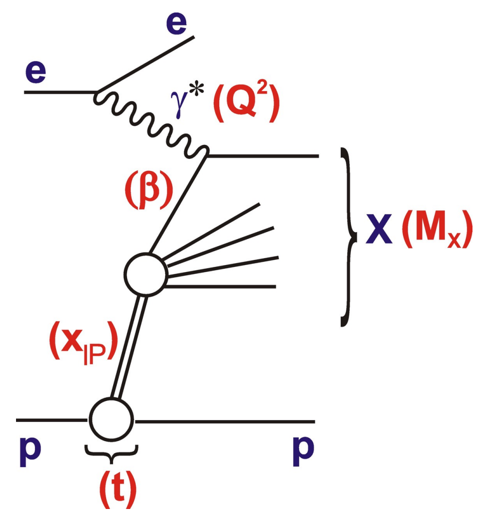


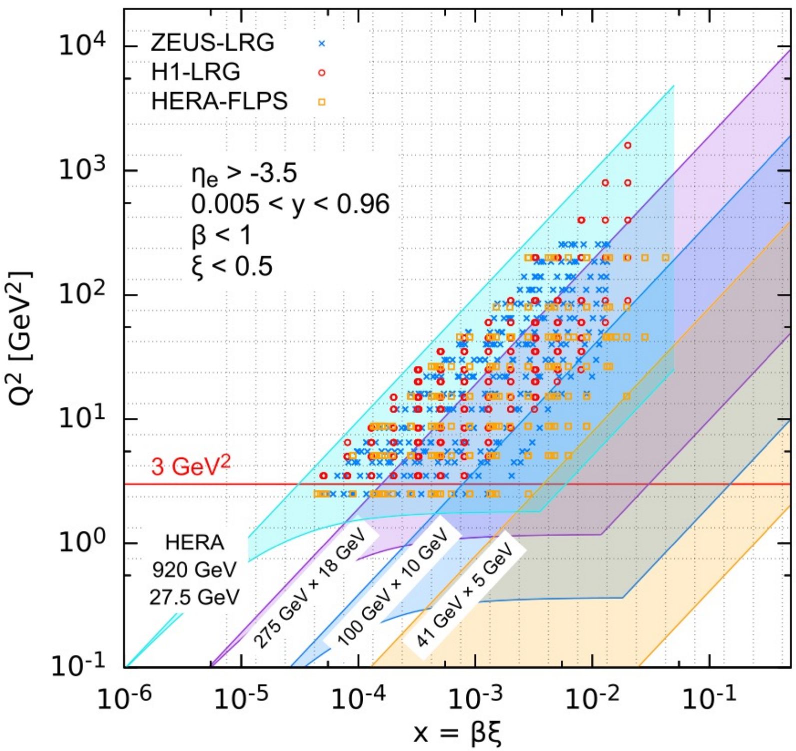



# Inclusive Diffraction from Protons

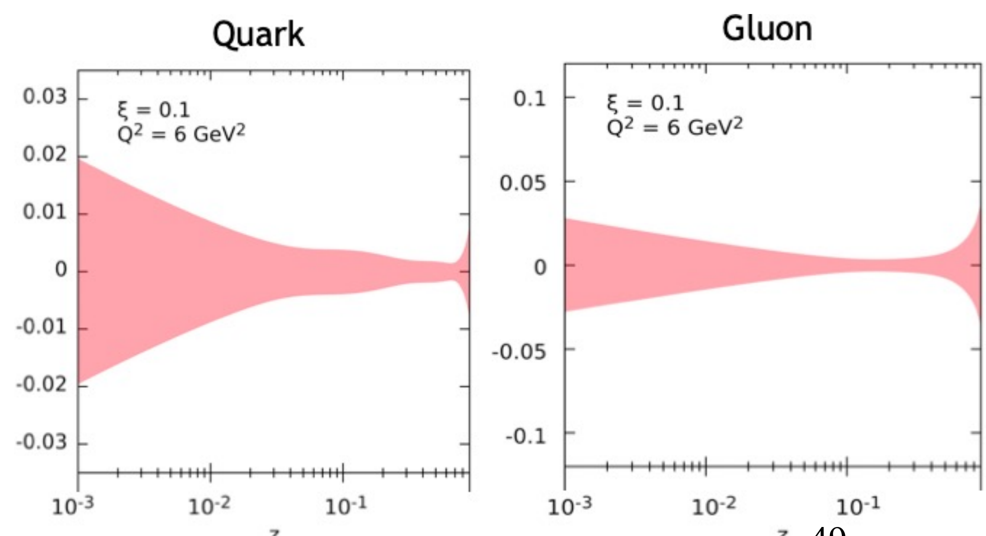
- Partonic structure of vacuum exchange (or 'pomeron') encoded in 'Diffractive Parton Densities'

- Planned EIC Roman pots provide excellent coverage at large x, moderate $Q^2$, complementing HERA and addressing lack of fixed-target data




… New level of precision …






[Ongoing studies]