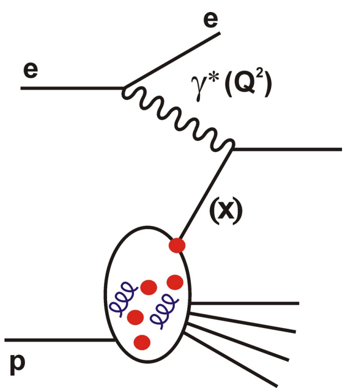
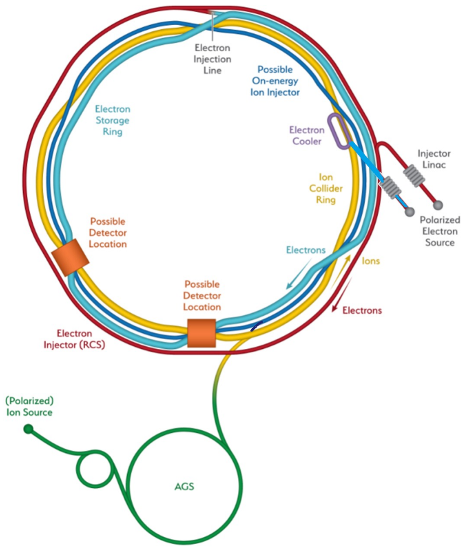
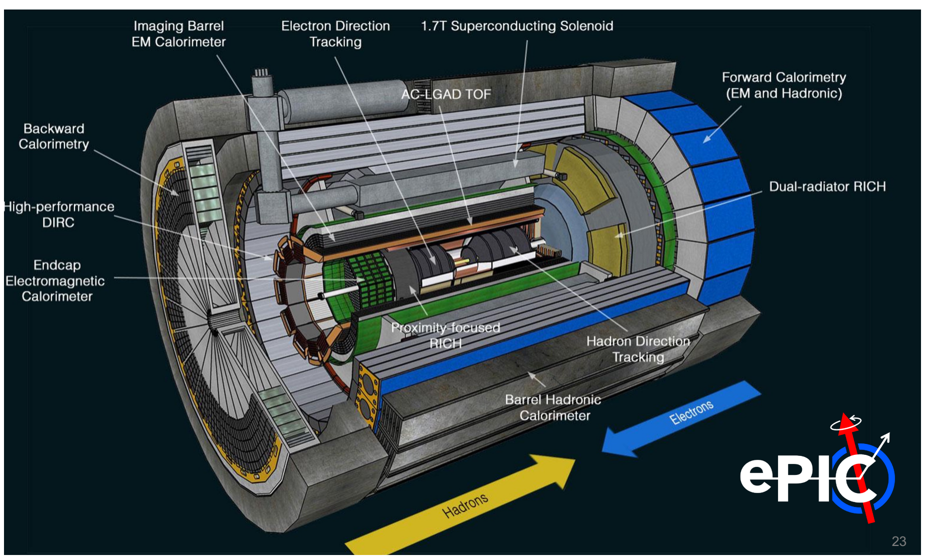
Lepton-Hadron Scattering and The Electron Ion Collider



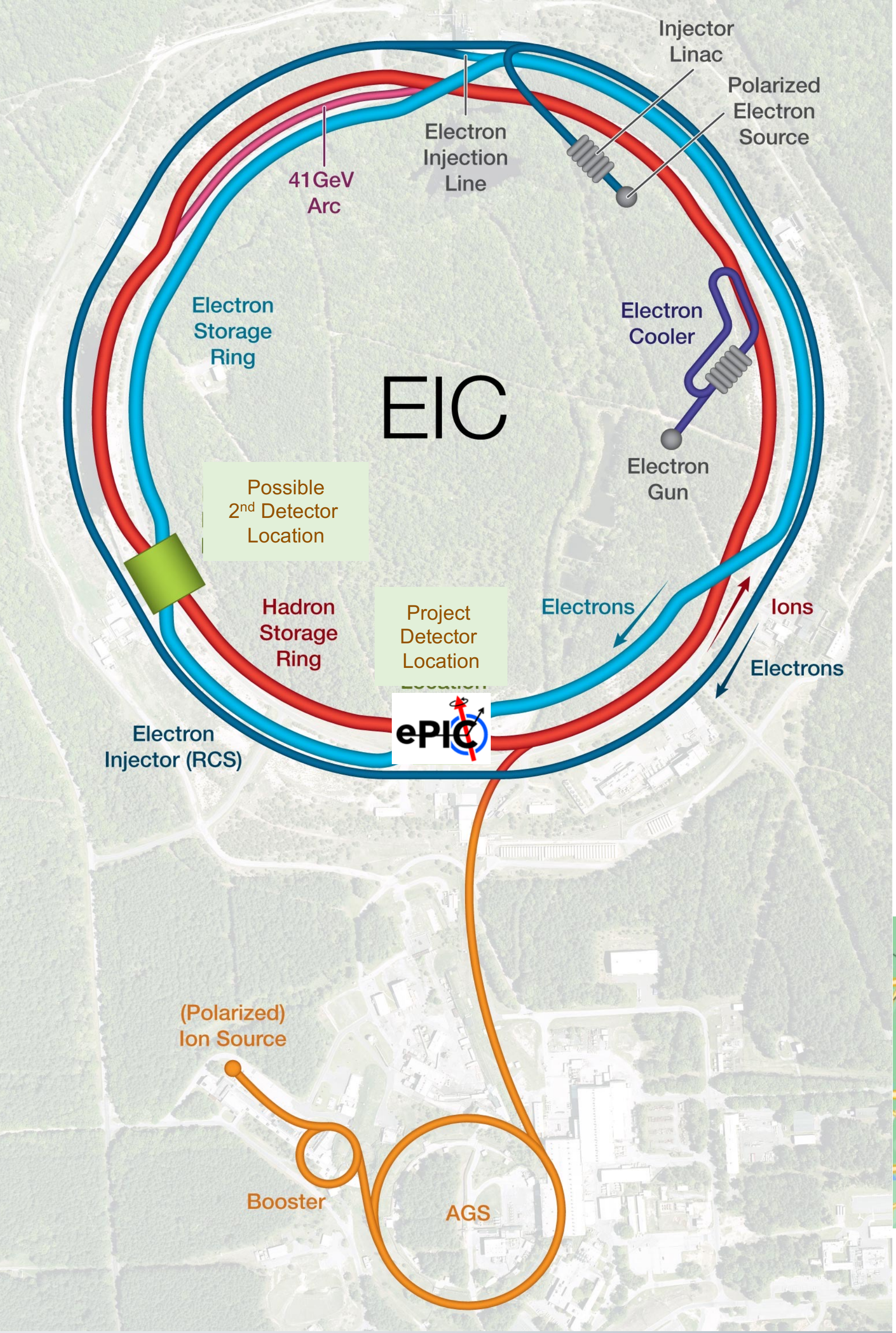
Paul Newman (Birmingham)

Warwick Seminar
17 October 2024





1) DIS History and Context
2) EIC Overview and Machine
3) The ePIC detector
4) Physics motivations
5) UK involvement

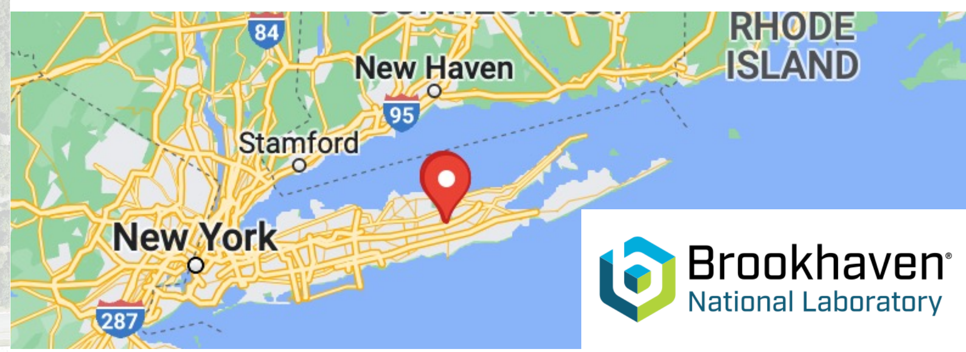


The Electron Ion Collider

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

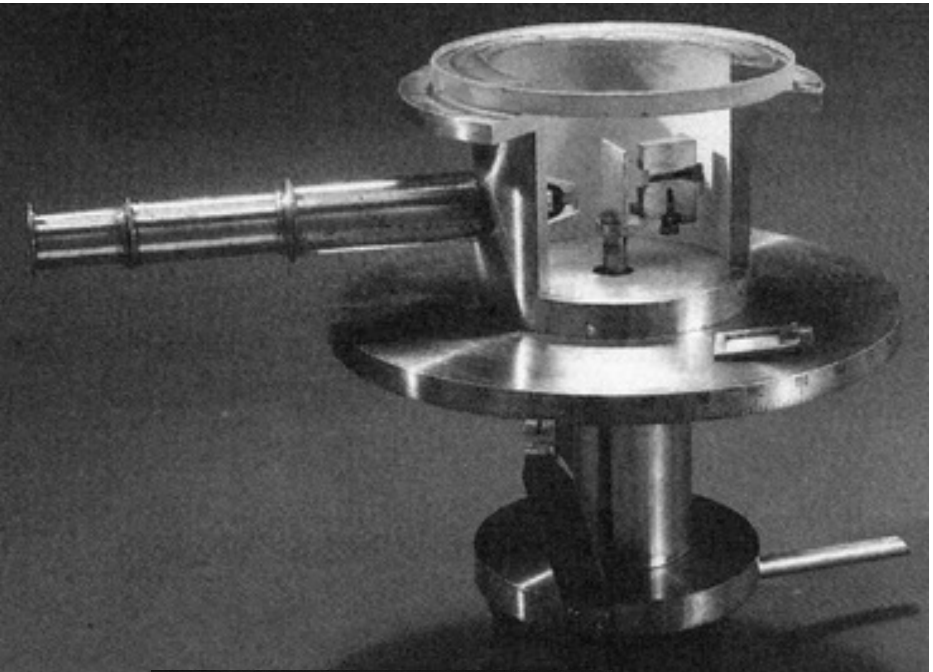
On target to be the world's next high energy* collider, starting from the early 2030s

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

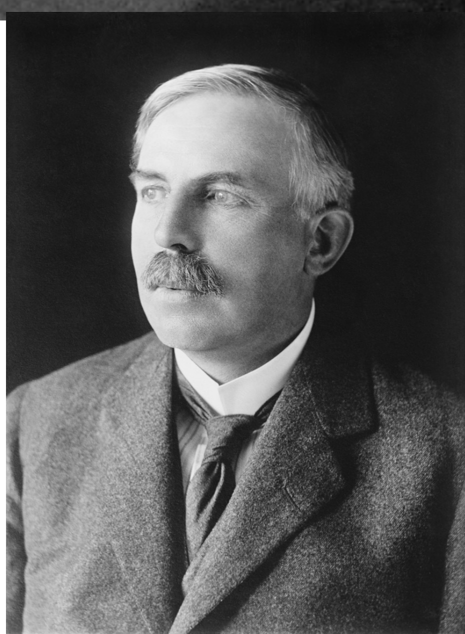


* High energy ≠ energy frontier

Rutherford (1927, as President of Royal Society)



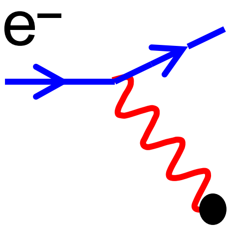
Following from the original scattering experiments (α particles on gold foil target) …



"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."

Probing the Proton with Electrons

Simple uncertainty principle arguments:

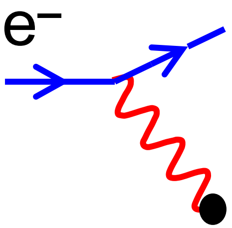


Resolved dimension: $\Delta x \sim \frac{200\text{MeV}}{E}$ fm

… need a beam energy of ~200 MeV to see proton structure (~1 fm)

Probing the Proton with Electrons

Simple uncertainty principle arguments:



Resolved dimension: $\Delta x \sim \frac{200\text{MeV}}{E}$ fm

... need a beam energy of ~200 MeV to see proton structure (~1 fm)

1950s Hoffstadter

First observation of **finite proton size** using ~200 MeV e beam

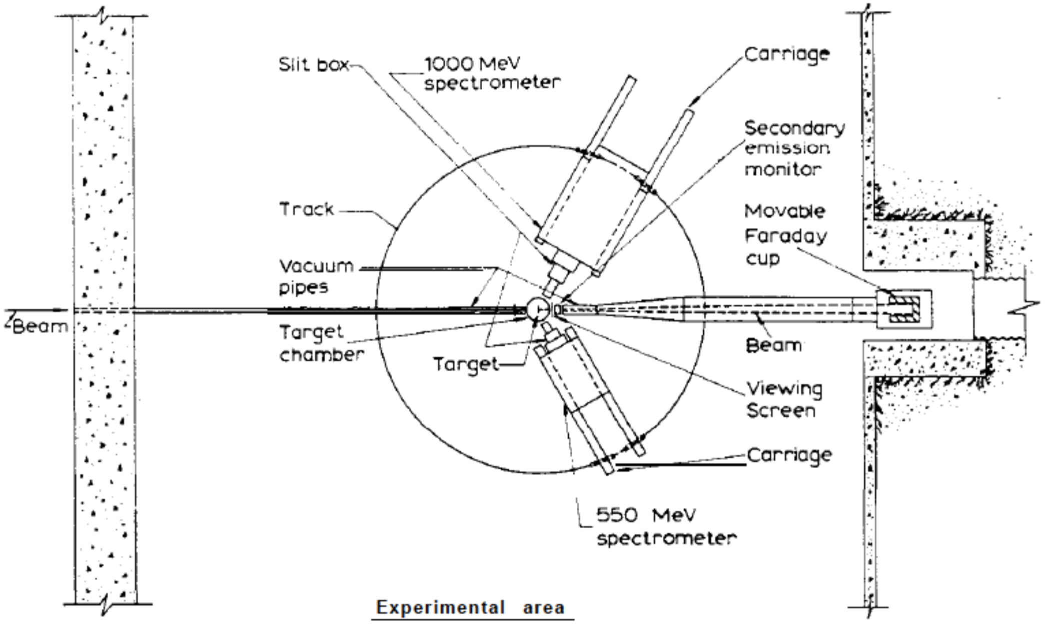
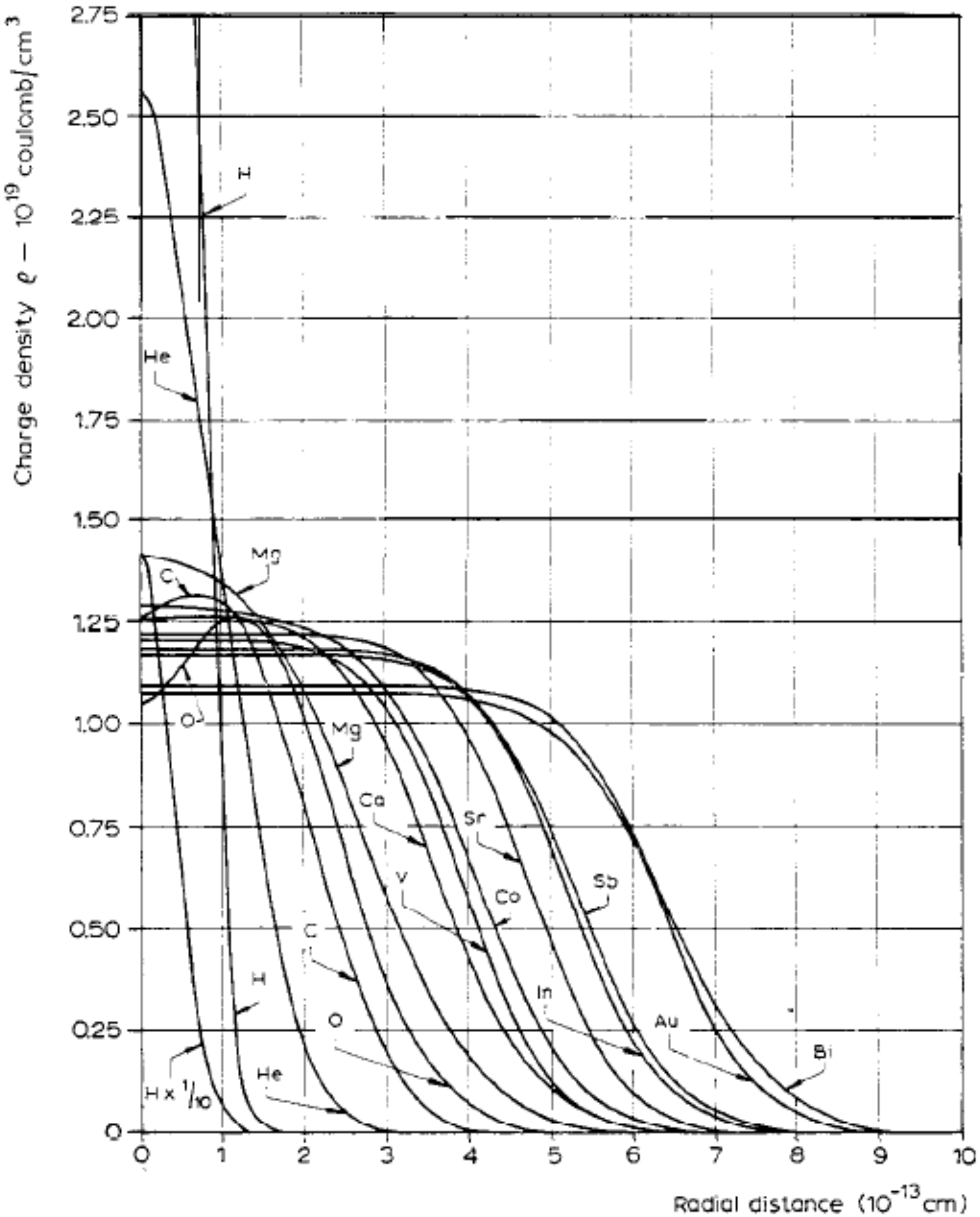


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

Hoffstadter's Results



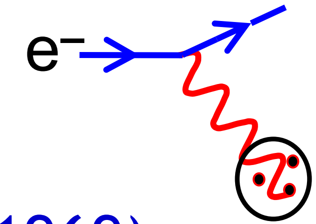
… essentially taking
a Fourier transform
of the pattern of emerging
scattered electrons
to determine spatial
distribution of the
target charge distribution

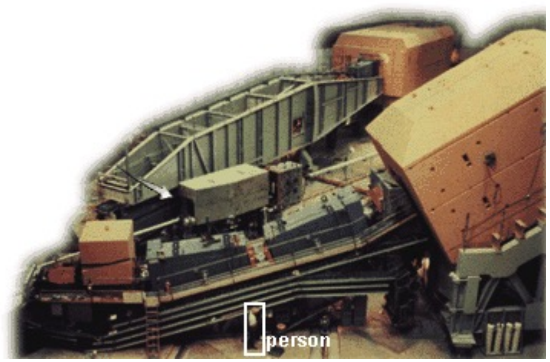
[cf Rutherford scattering]

Although suggestive,
finite spatial size does not
necessarily imply proton has
identifiable constituents

Probing the Proton with Higher Energy Electrons

… 1-2 more orders of magnitude → 0.1-0.01 fm



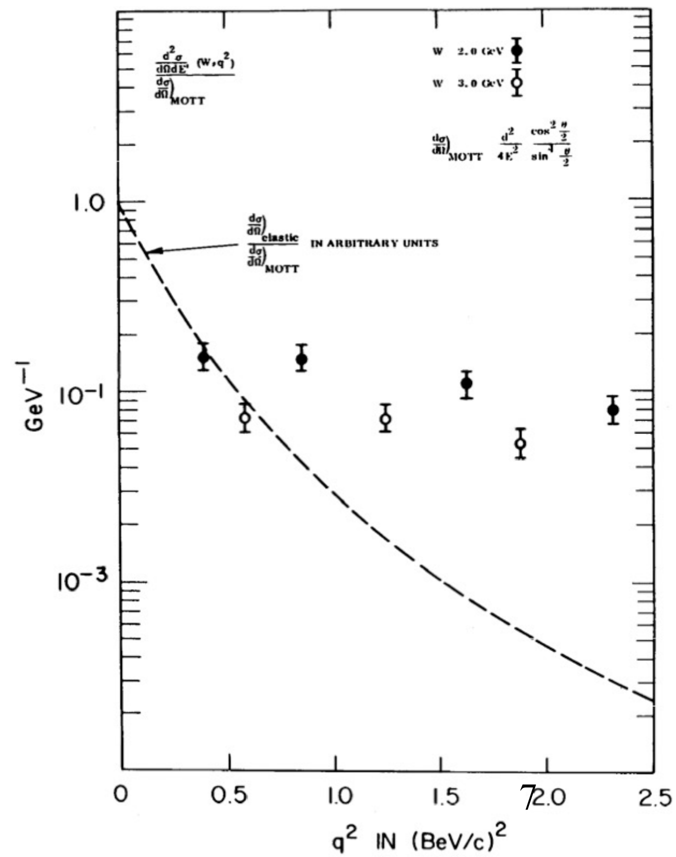


ESA experiment at SLAC (1969)

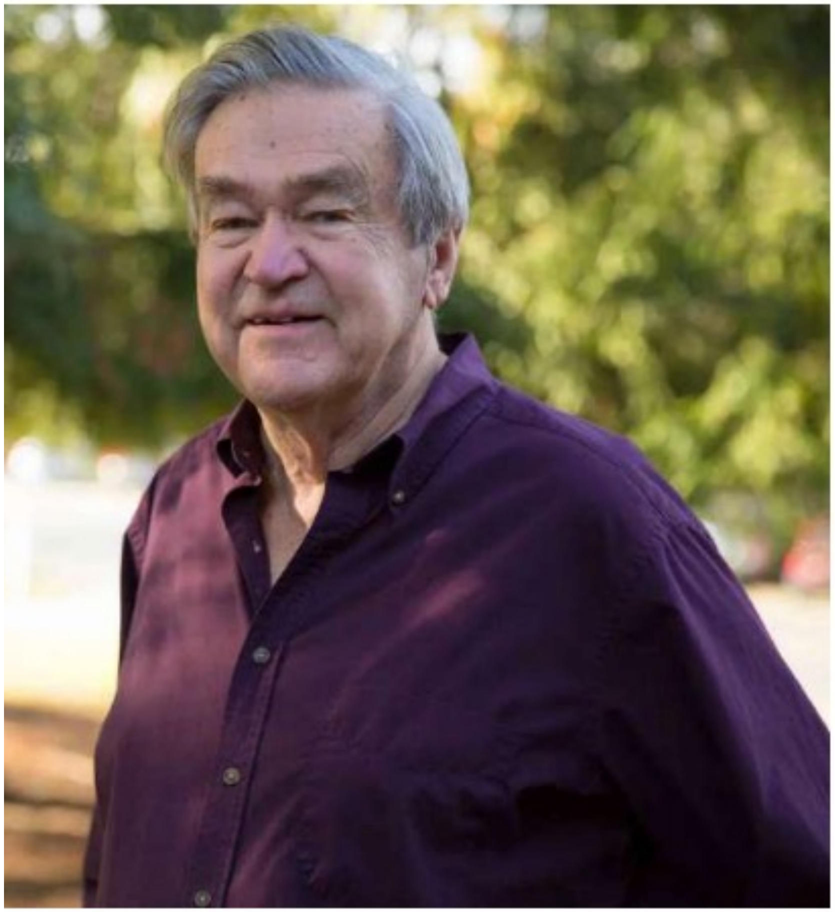
~20 GeV electrons on fixed proton target

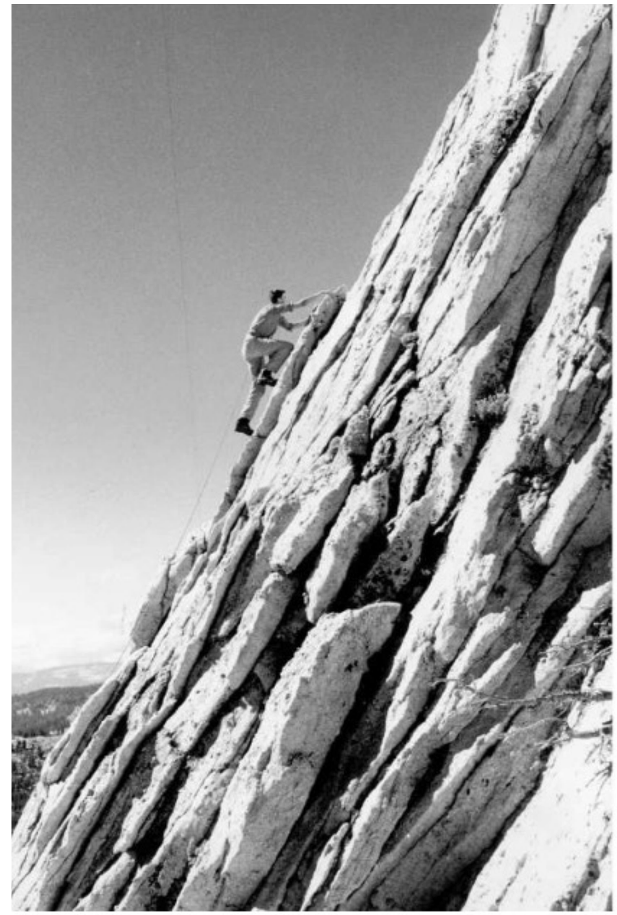
Absence of dependence of suitably expressed cross section on momentum transfer (wide-angle scattering) implies point-like constituents of target (quarks)

Bjorken Scaling



James Bjorken (22 June 1934 – 6 Aug 2024)



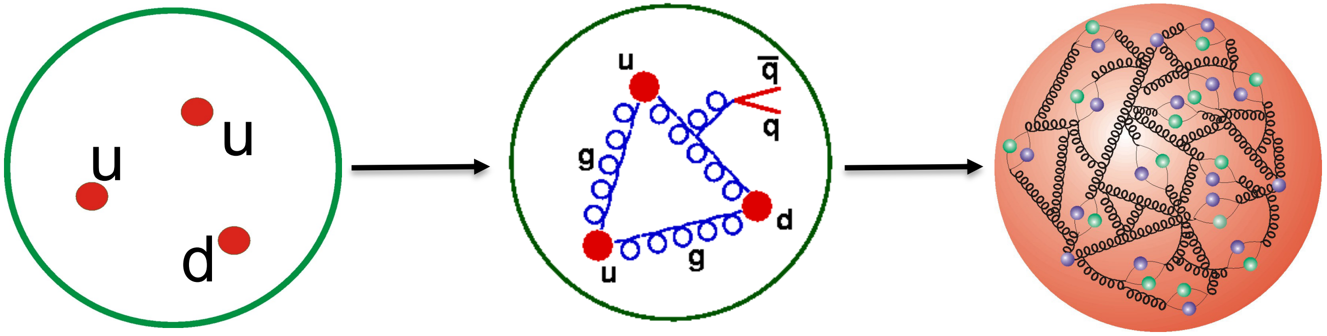


- The only ever collider of electron with proton beams: $\sqrt{s_{ep}} \sim 300$ GeV

- Equivalent to **50 TeV** electrons on fixed target

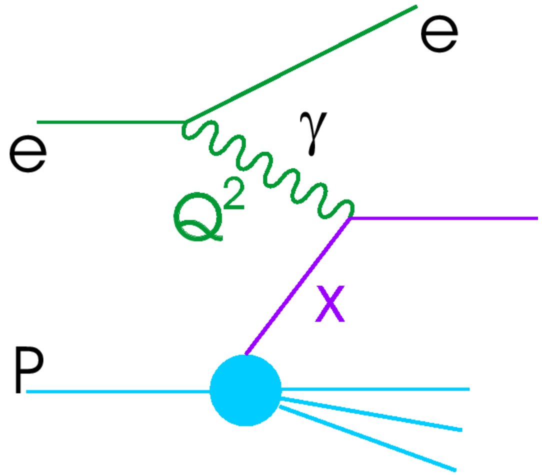
… Resolved dimension $\sim 10^{-20}$ m

→ Source of much of our knowledge of proton (longitudinal) structure, extending to partons of $x<10^{-4}$ mom^{m} fraction



BUT …
→ Only ~0.5 fb^{-1} per experiment
→ No deuterons or nuclei
→ No polarised targets

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)

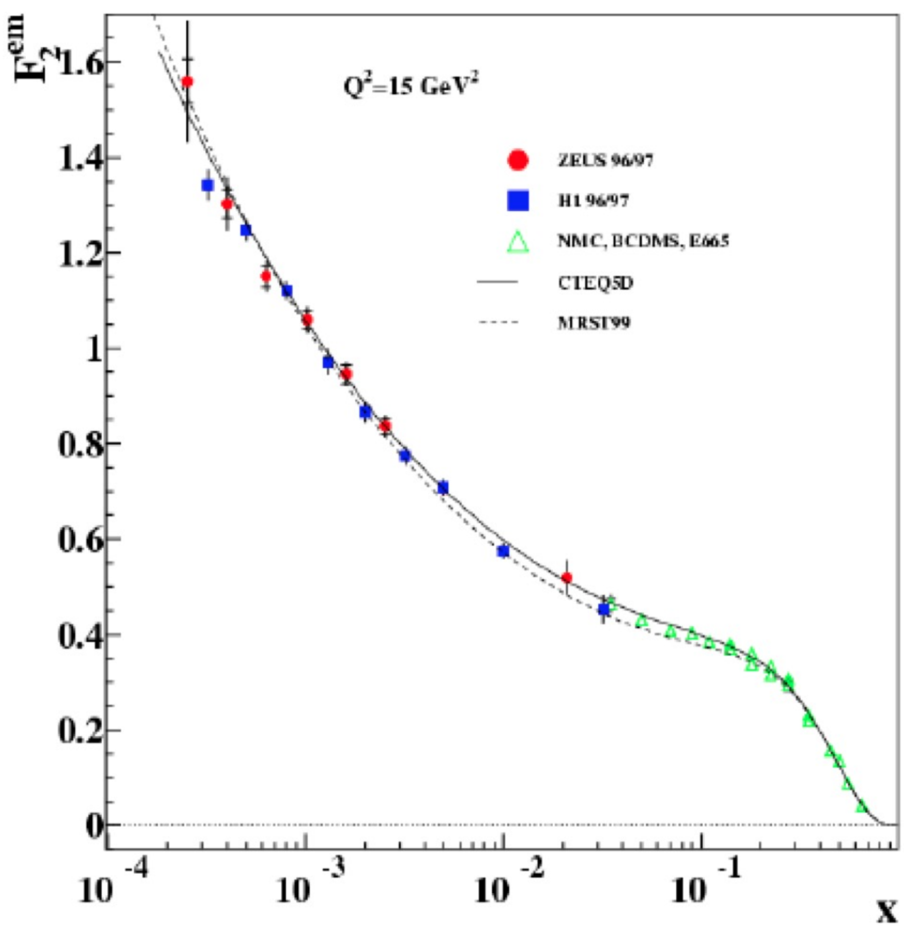
… measures the hardness /scale of collision

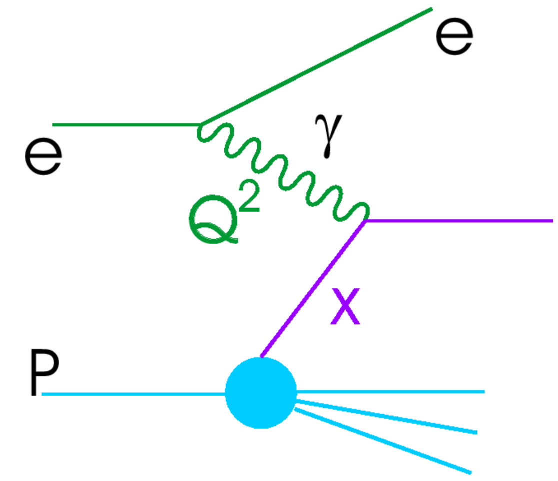
… inverse of (squared) resolved dimension

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

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

Example Inclusive Neutral Current Data from HERA / Previous Experiments

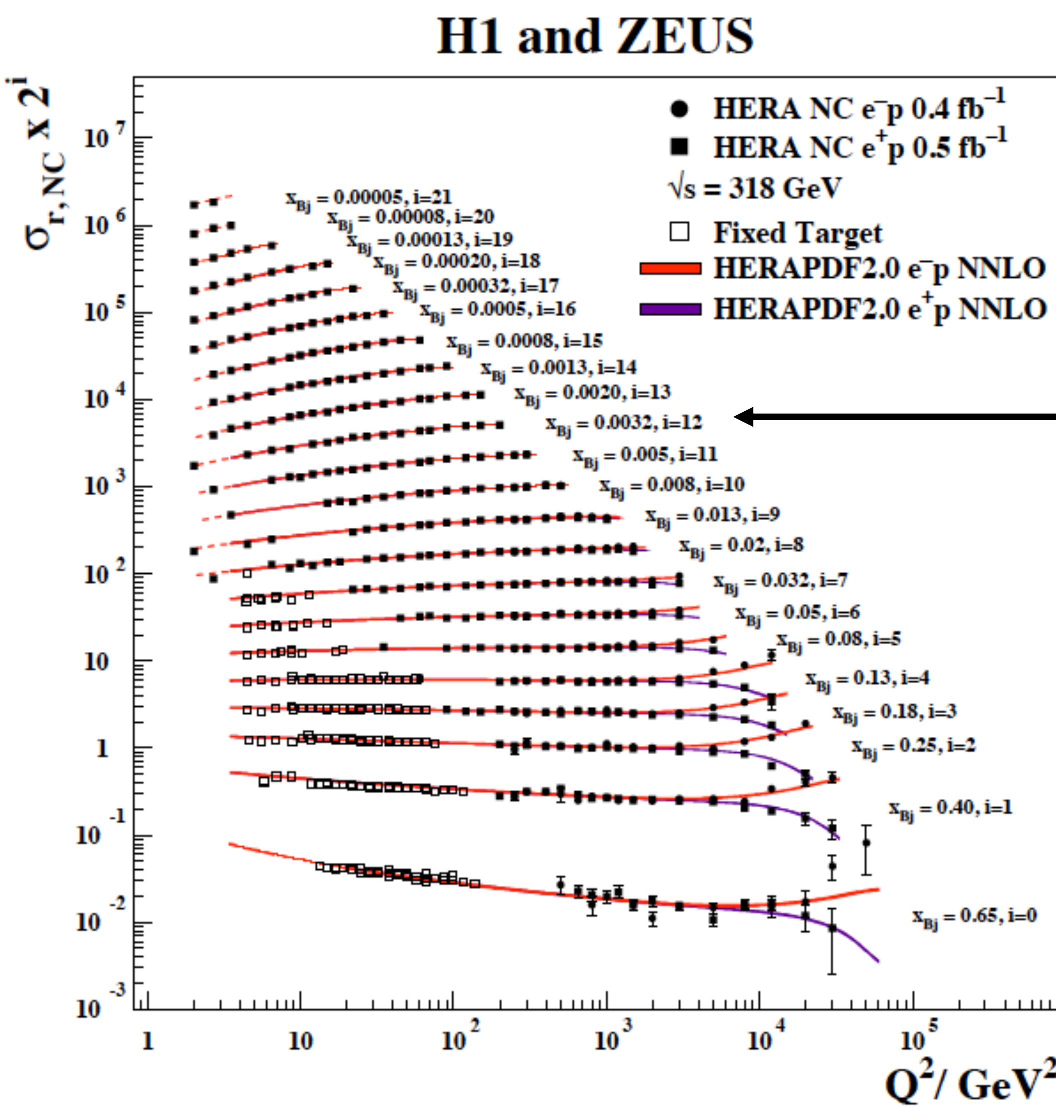




- Inclusive cross section measures (charge-squared weighted) sum of quark densities

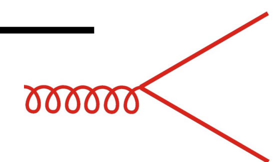
- Similar / better data at many other values of Q^2

QCD Evolution and the Gluon Density



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

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

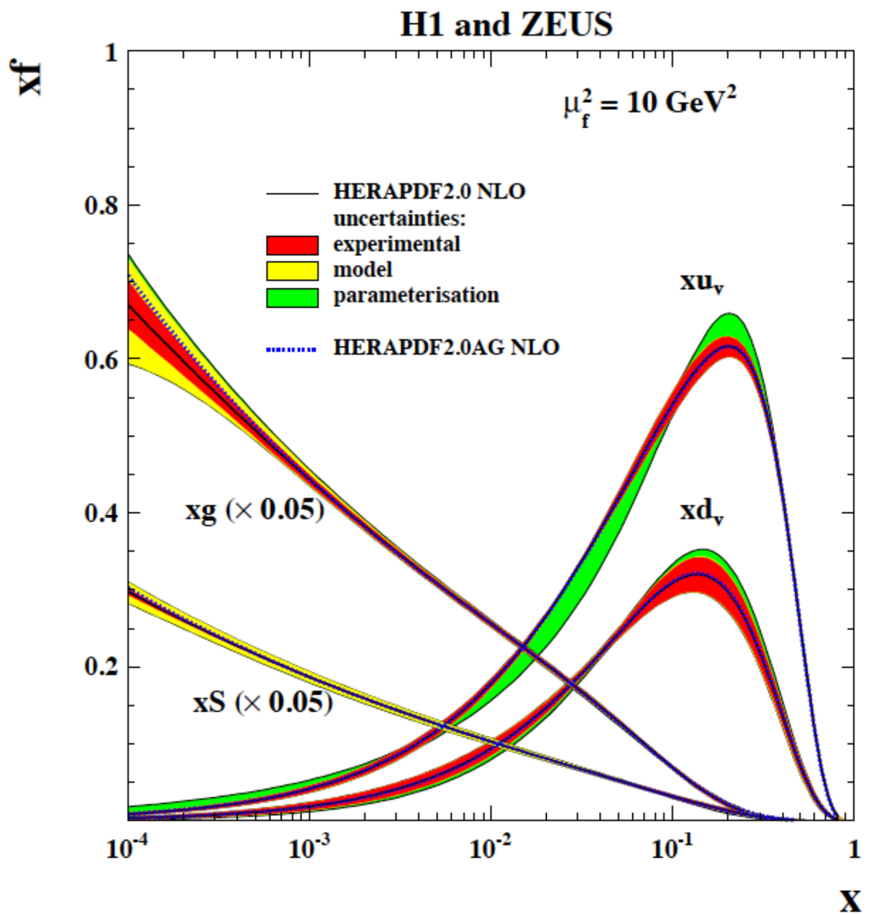


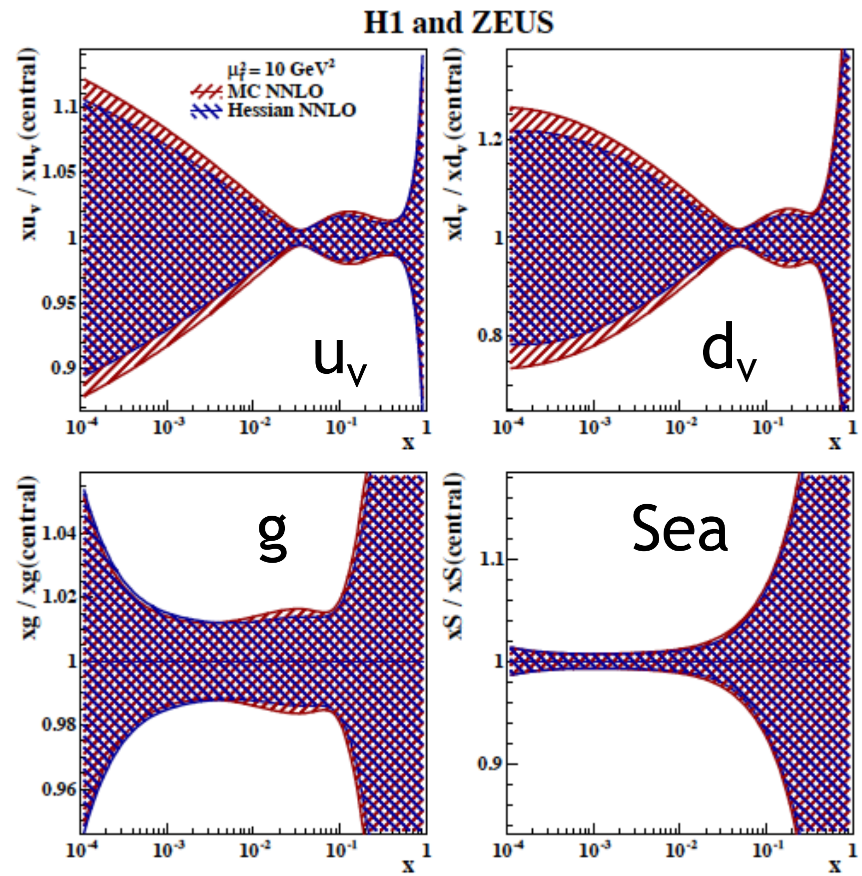
- DGLAP equations describe QCD evolution (to NNLO and approximate N^3LO accuracy)

- EW effects give different quark sensitivities (Z-exchange separates e^+p v e^-p, W-exchange gives charged current ($ep \to \nu X$)

→ Fits to data to extract proton parton densities

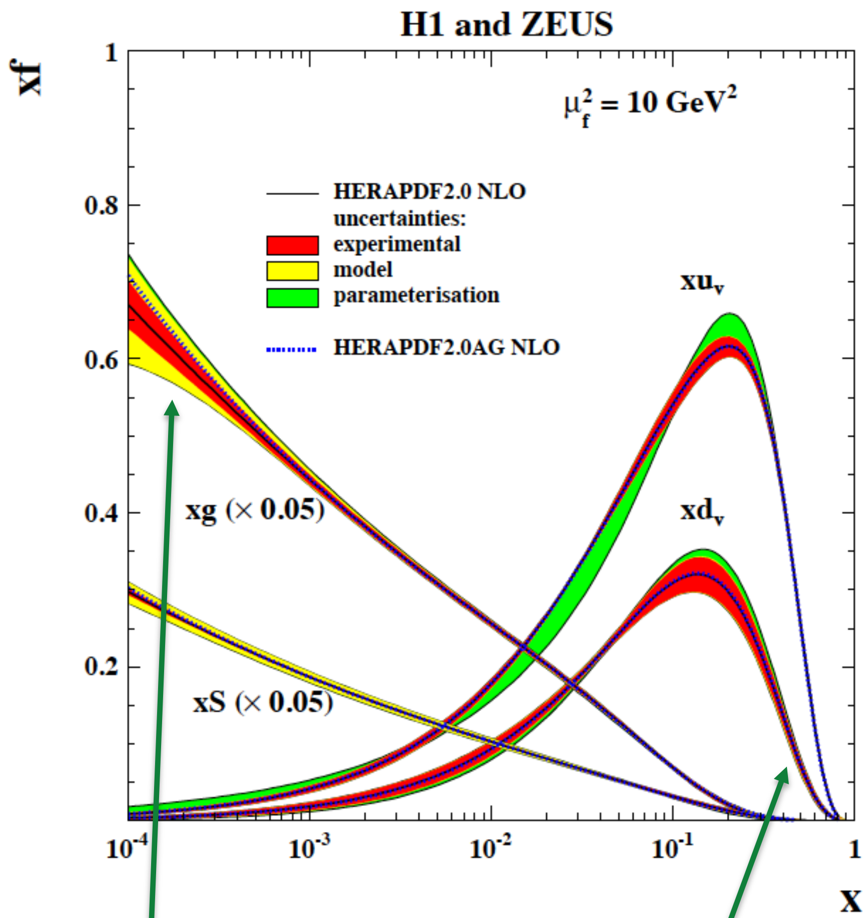
Proton PDFs from HERA only (HERAPDF2.0)

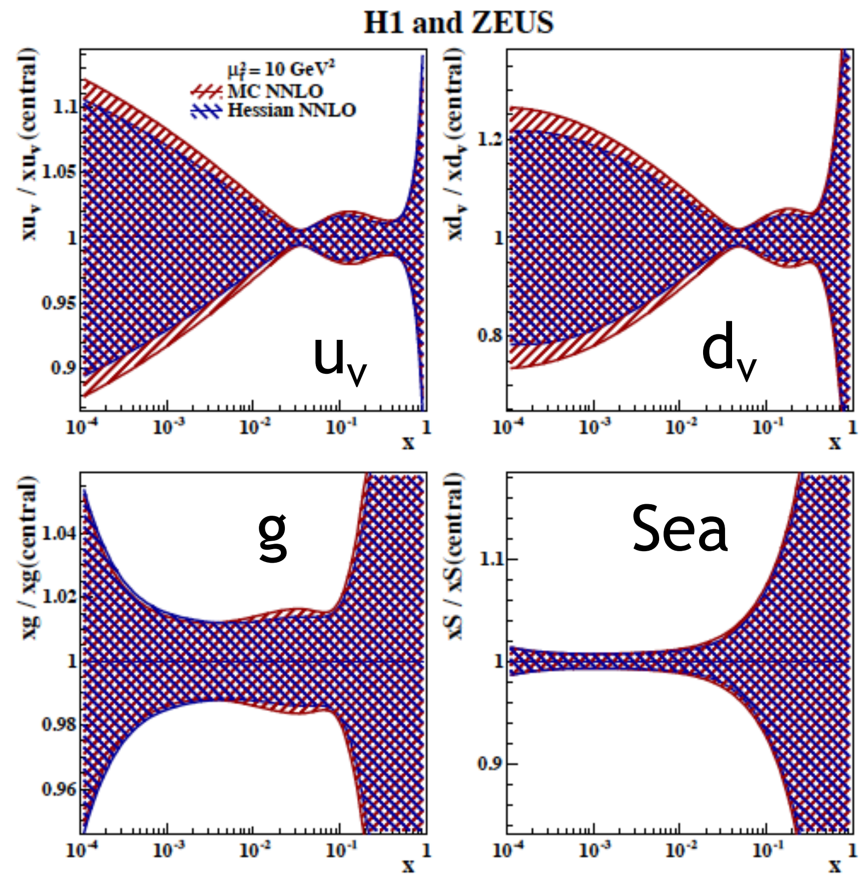




- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below $x=10^{-3}$ (kinematic limit)
  - above $x=10^{-1}$ (limited lumi)

Proton PDFs from HERA only (HERAPDF2.0)



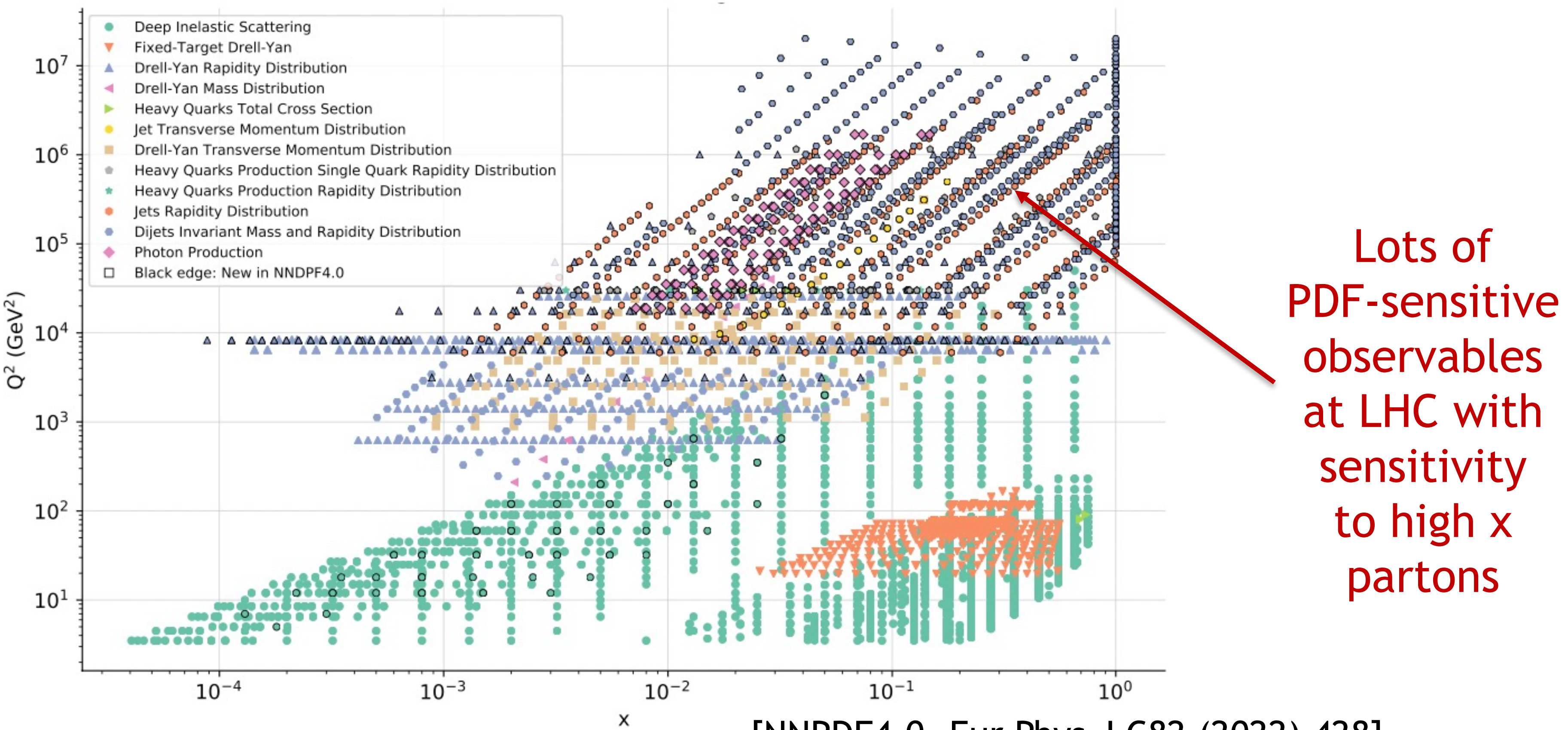


Strong interaction dragons?

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)

Adding more data: Global PDF fits



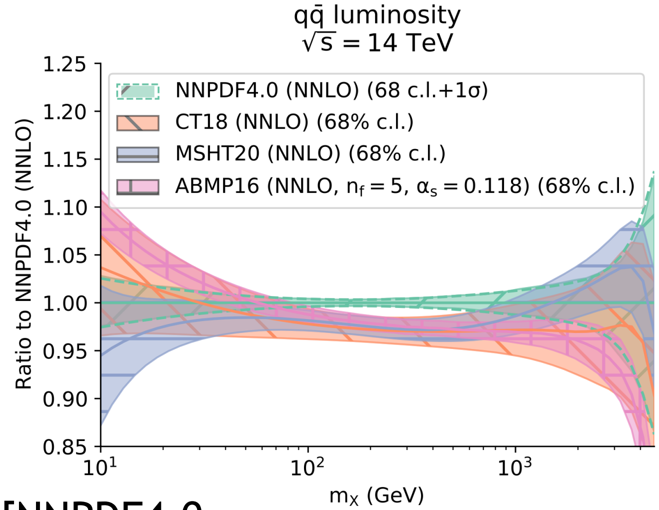
[NNPDF4.0, Eur Phys J C82 (2022) 428]

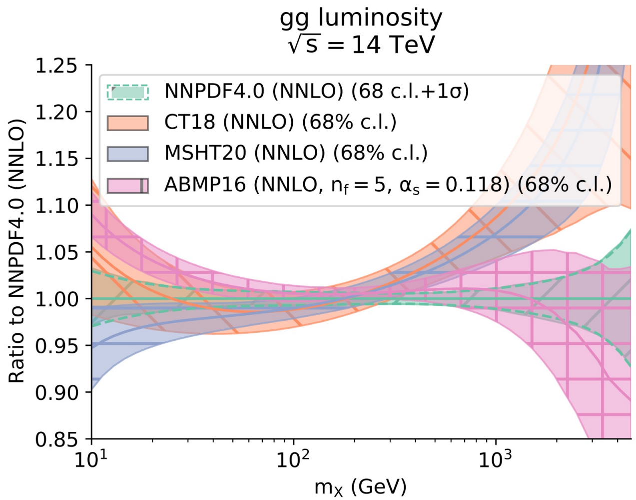
Including LHC data brings:
Advantages: improve precision at mid and high x, exploit all available inputs

Caveats: use of data that may contain BSM effects, theoretical complexity (eg non-perturbative input), some incompatibilities between data sets

Global Fits and LHC Parton Luminosities

e.g. Comparisons between current global fits on LHC $q\bar{q}$ and gg luminosities





[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]

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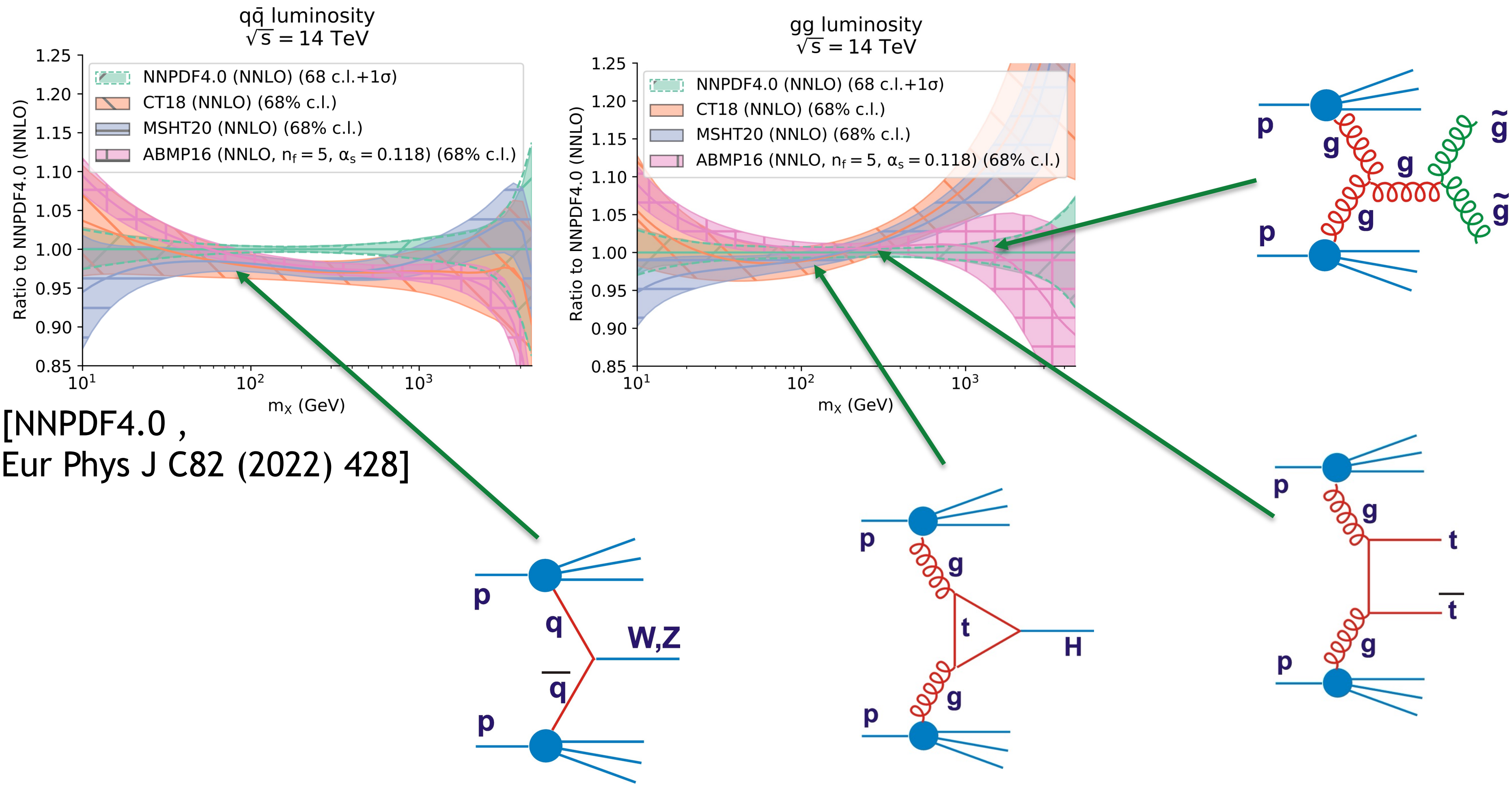
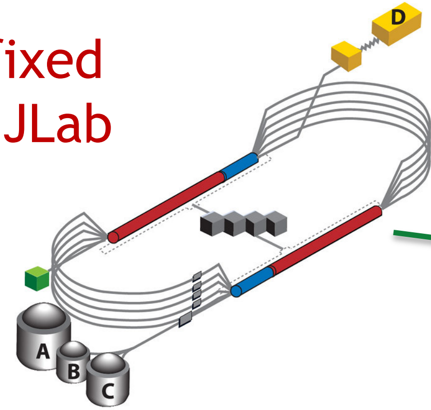


[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]

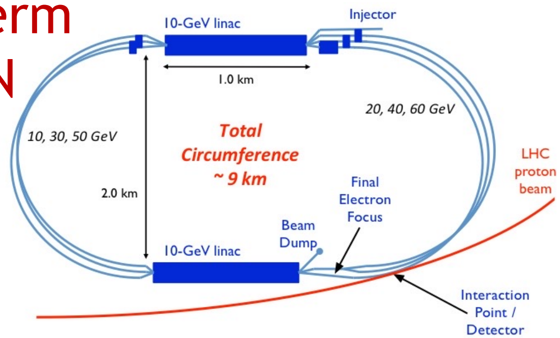
Immense recent progress, but still large uncertainties and some tensions between data sets and fitting methodologies

Current and Future ep Colliders

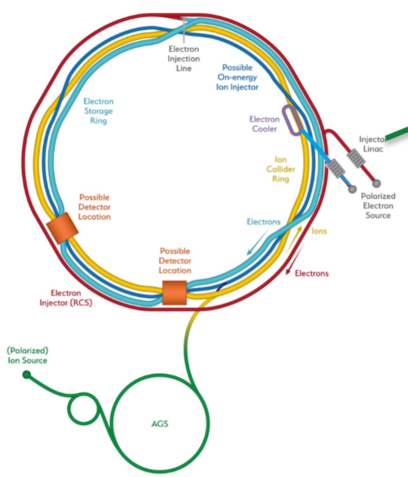
Ongoing fixed target @ JLab

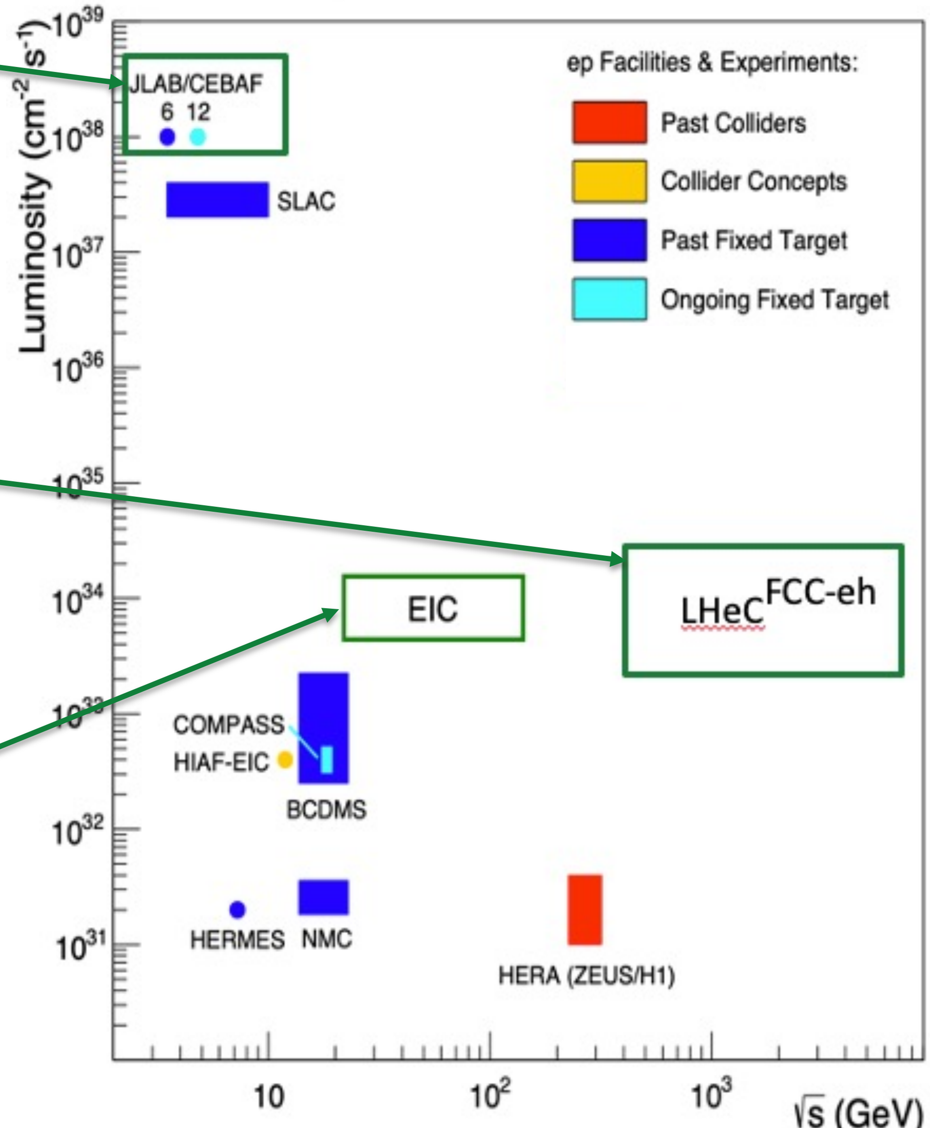


Longer-term @ CERN



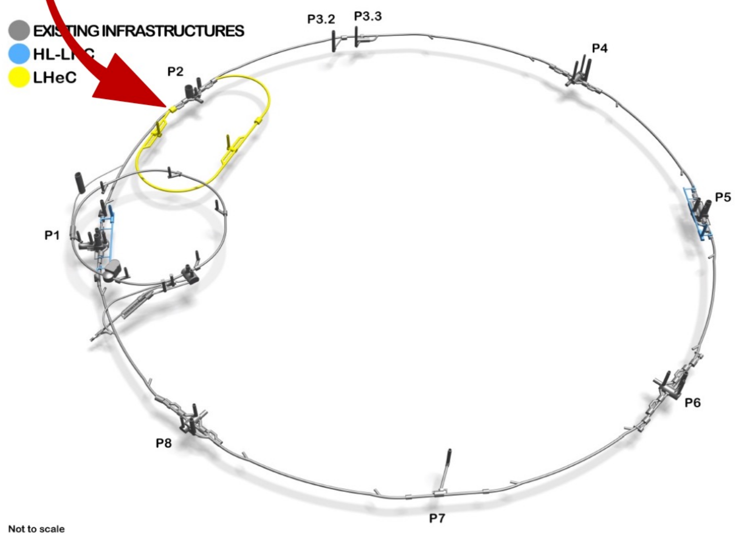
On-target for early 2030s @ BNL



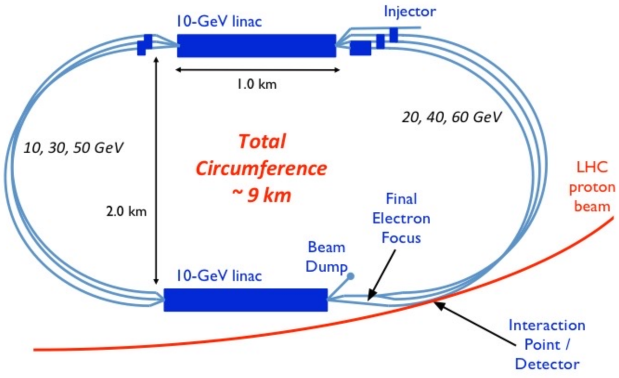


LHeC: Electrons colliding with LHC hadrons

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)



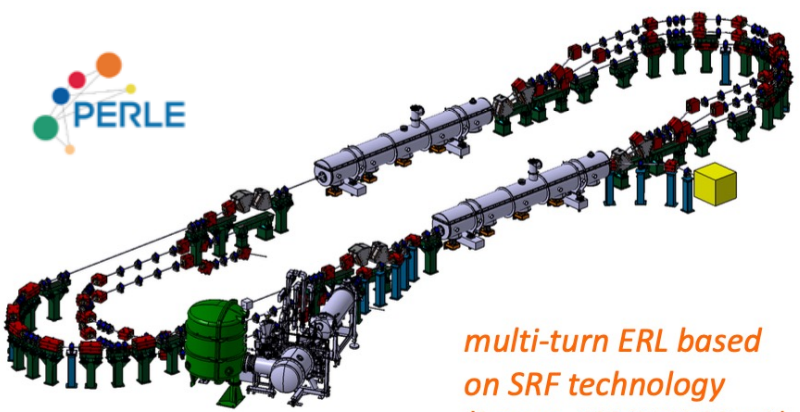
- Recirculating Energy-Recovery Linac (ERL) colliding with LHC (or FCC) hadrons



- 'Sustainable' acceleration (~100 MW; similar to LHC today)

- Accelerator and detector development towards next major machines

- ERL Prototype (PERLE @ IJCLab/Orsay)
… implementation started.
… first stage (one turn) by 2028.

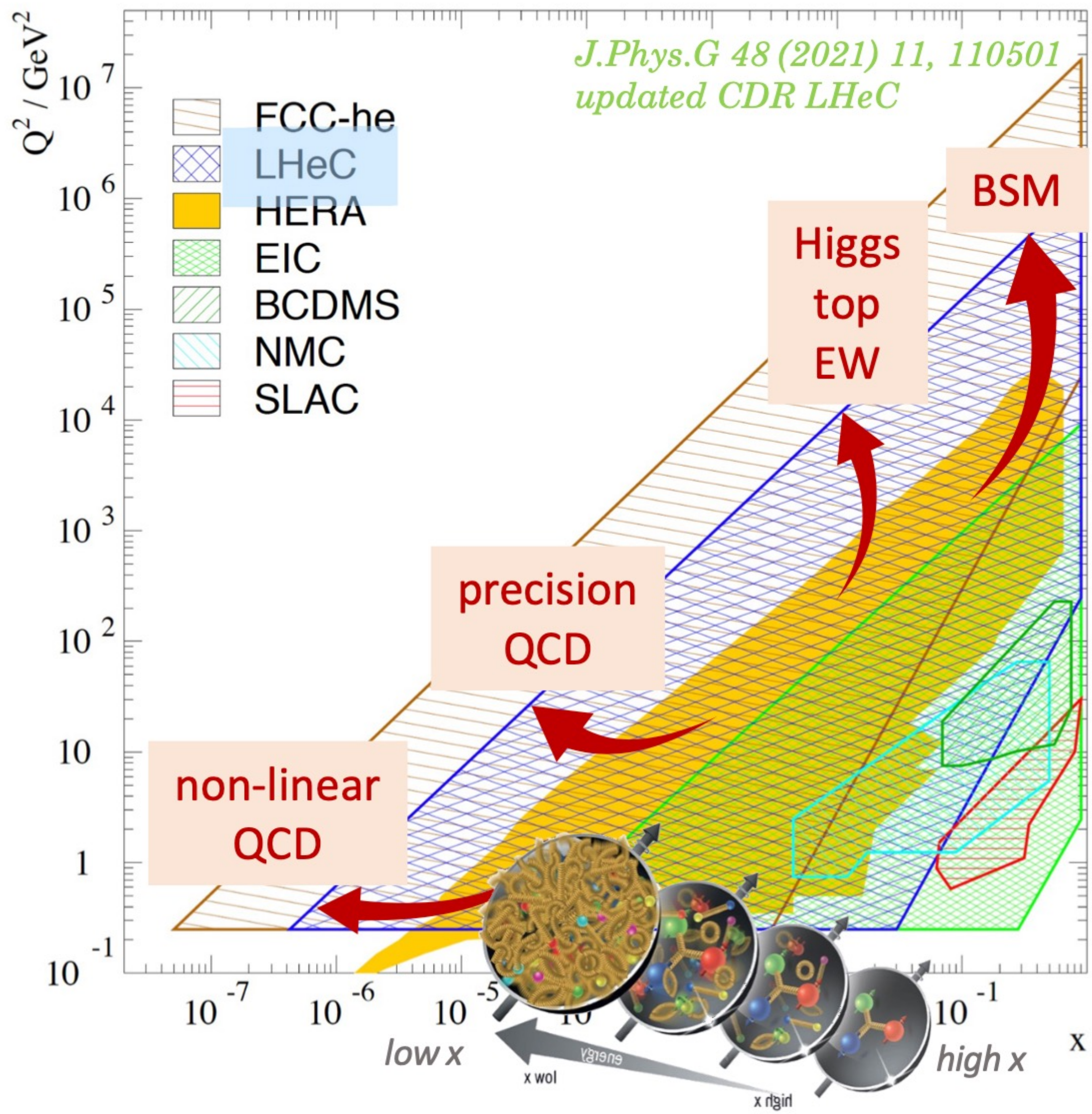


multi-turn ERL based on SRF technology (3-turns, 500 MeV, 20 mA)

CDR: *J.Phys.G* 45 (2018) 6, 065003

'Affordable' bridging project for 2040s?

Overview of LHeC Physics Programme



Higgs, Top, EW and BSM programme

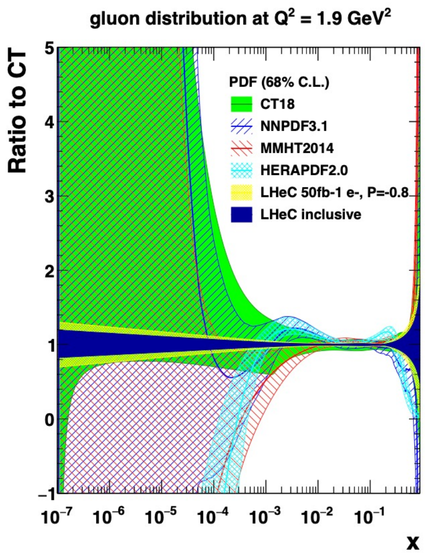
→ General purpose particle physics detector … high p_T capabilities

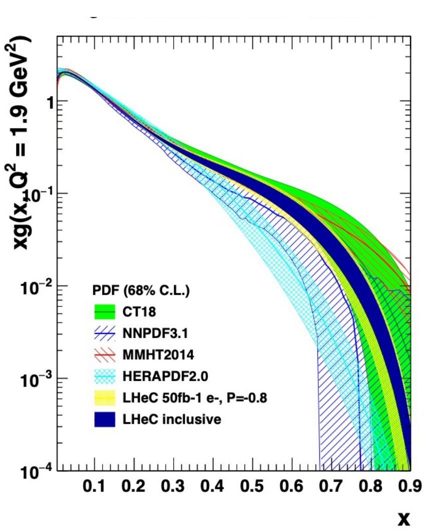
Precision QCD and PDFs, including very low x parton dynamics

→ Dedicated Deep Inelastic Scattering experiment… hermetic & reconstructing all final state particles

LHeC: Revolutionary Proton PDF Precision

e.g. Gluon Density



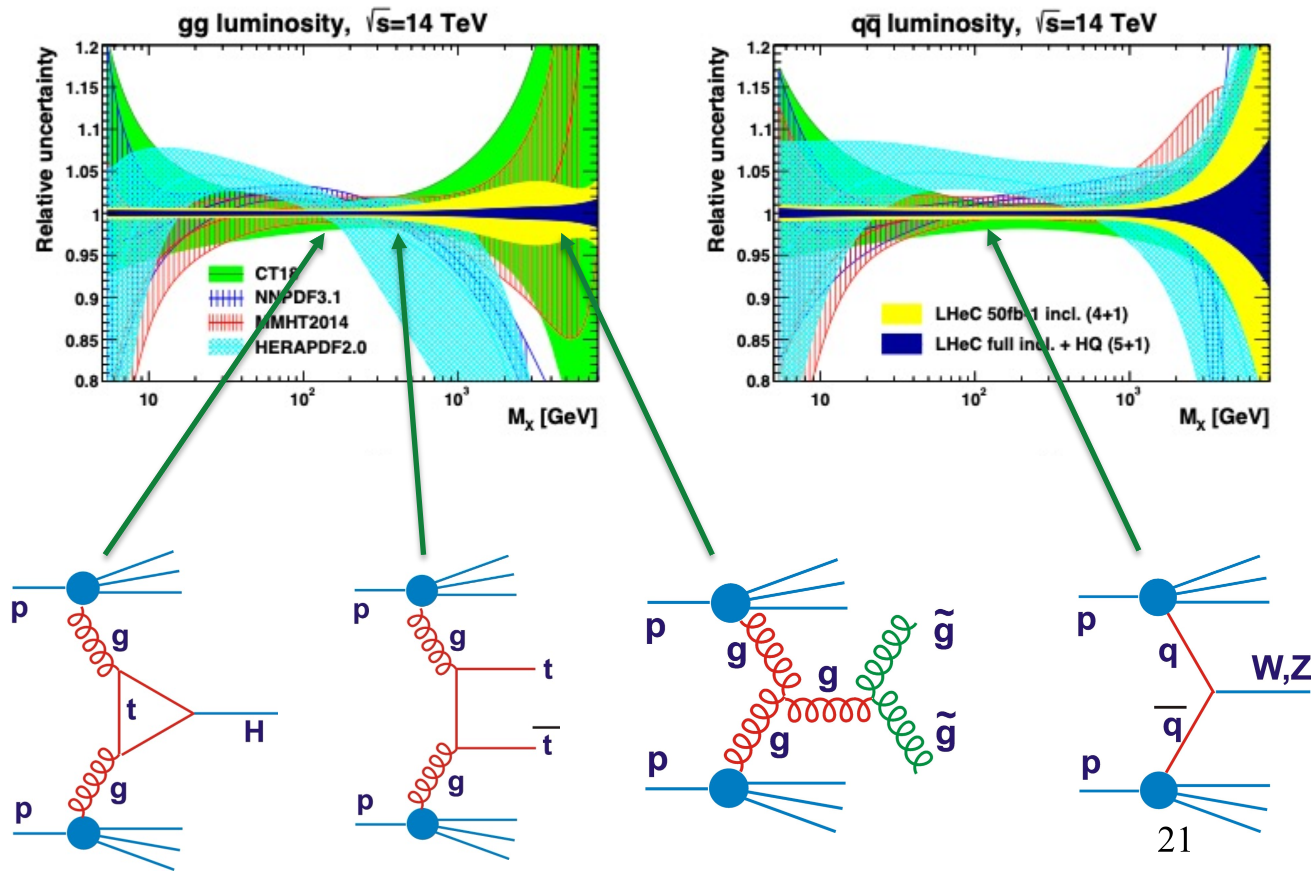


- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements

(e.g. M_W → 2 MeV from PDFs, $\sin^2\theta$ → 0.03%)

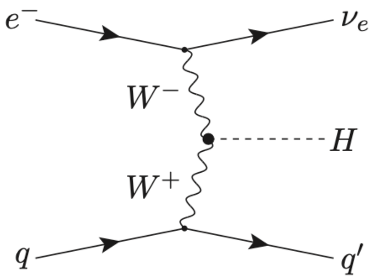
→ Elucidates novel very low x dynamics

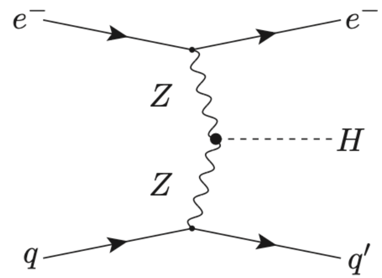
e.g. Parton luminosities for pp at 14 TeV



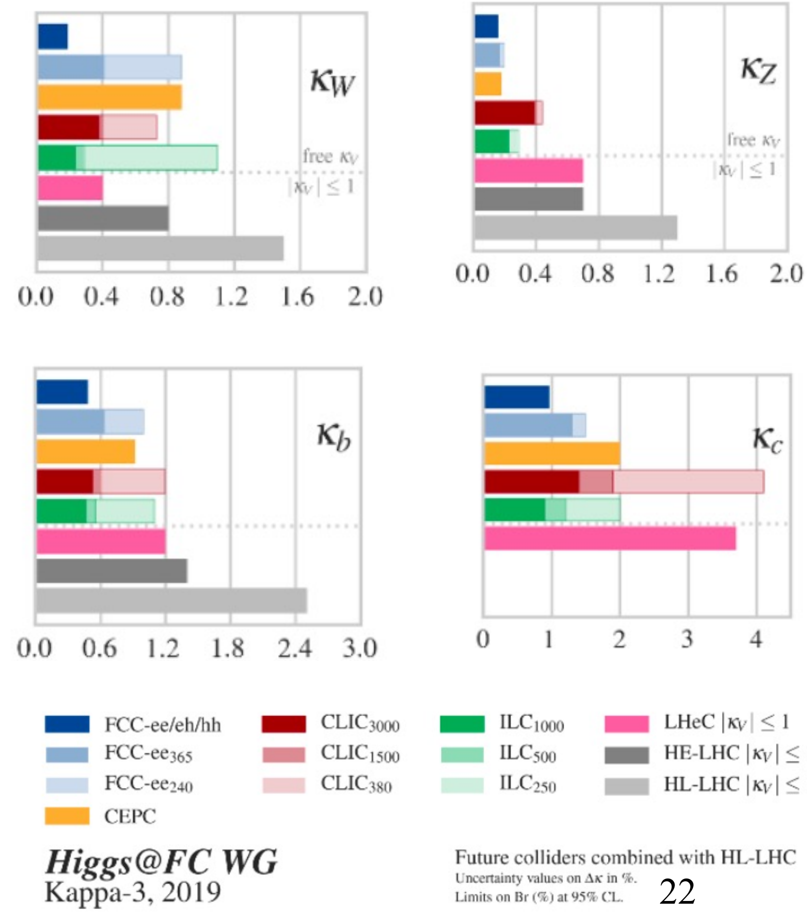
LHeC (SM) Higgs Programme

- Dominant production mechanism charged current (WW), easily distinguished from sub-dominant neutral current (ZZ)





e.g. Expected Future Collider sensitivities combined with HL-LHC

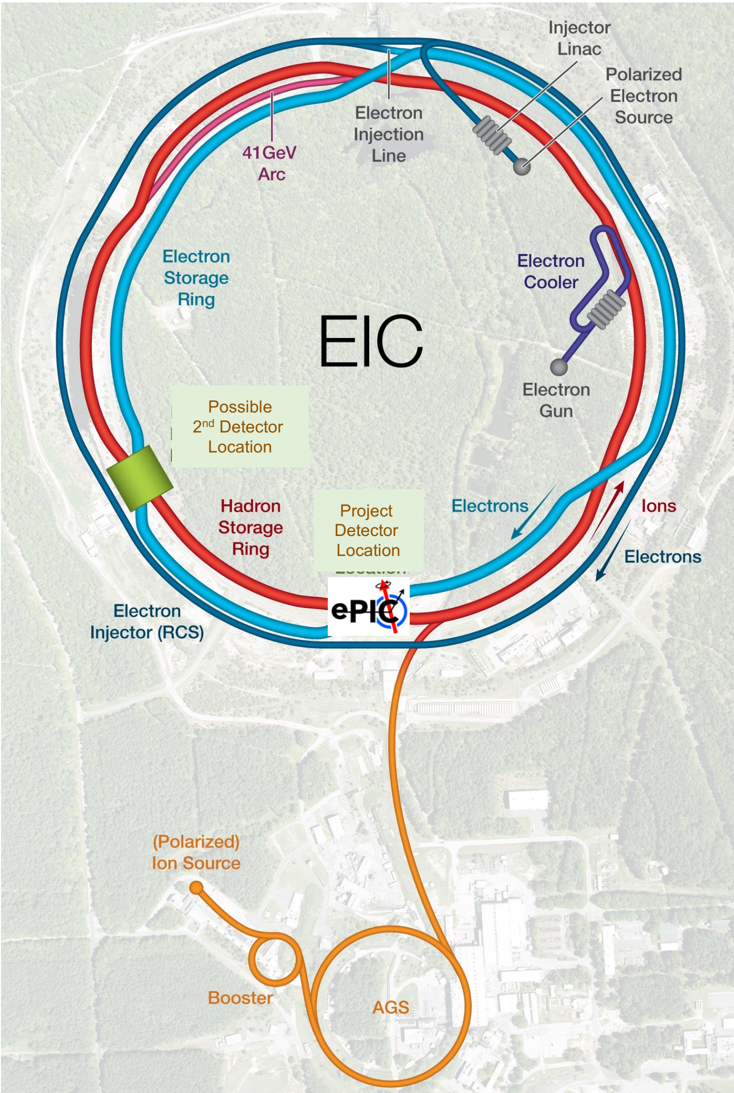


Yields for 1ab^{-1} (LHeC), 2ab^{-1} (FCC-eh) P=-0.8

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
σ [pb]		0.197	1.04	0.024	0.15

[JHEP 01 (2020) 139]

The Electron-Ion Collider (BNL)



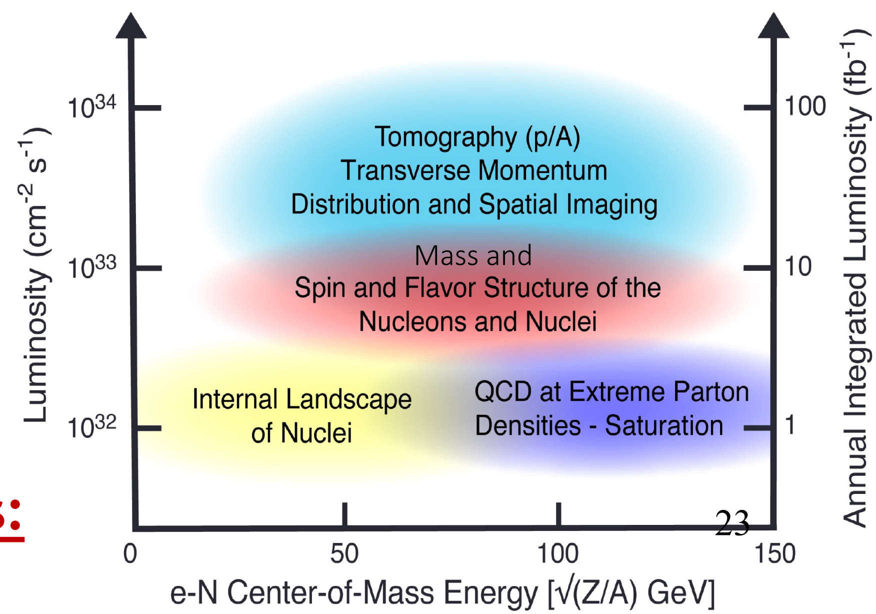
New electron ring, to collide with RHIC p, A

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

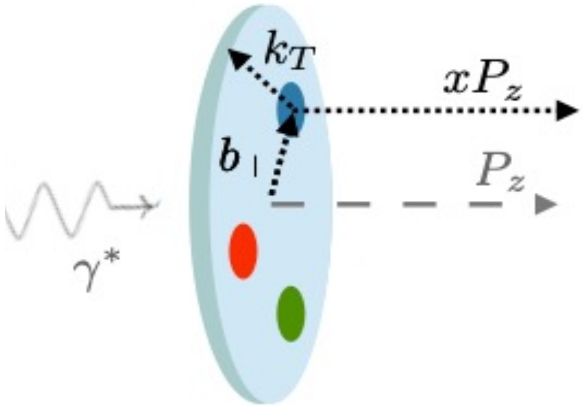


Physics questions to be addressed at EIC

- How is proton mass generated from quark and gluon interactions?

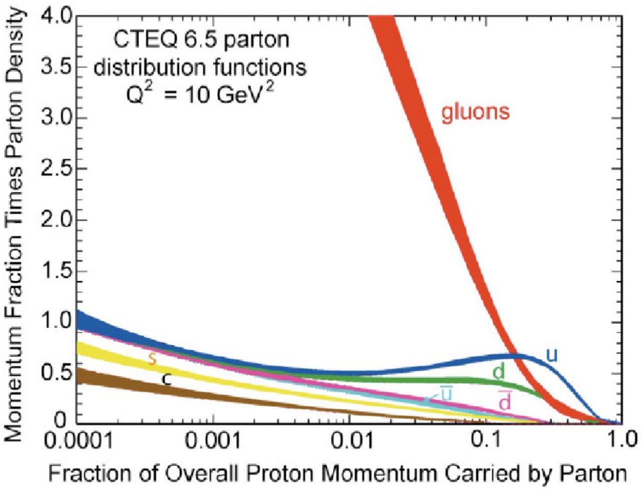
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

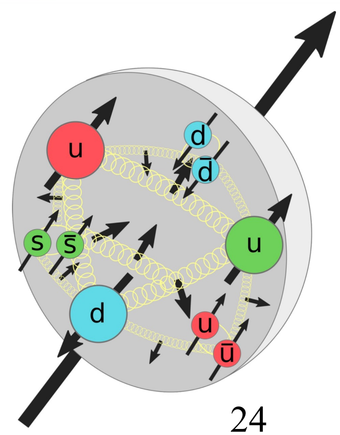
- What does the proton look like in 3D?



- How is proton spin generated?

- How do the dynamics of high density systems of gluons tame the low x growth?





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 high beam currents and correspondingly short bunch spacings:

→ Synchrotron load management

→ Significant crossing angle

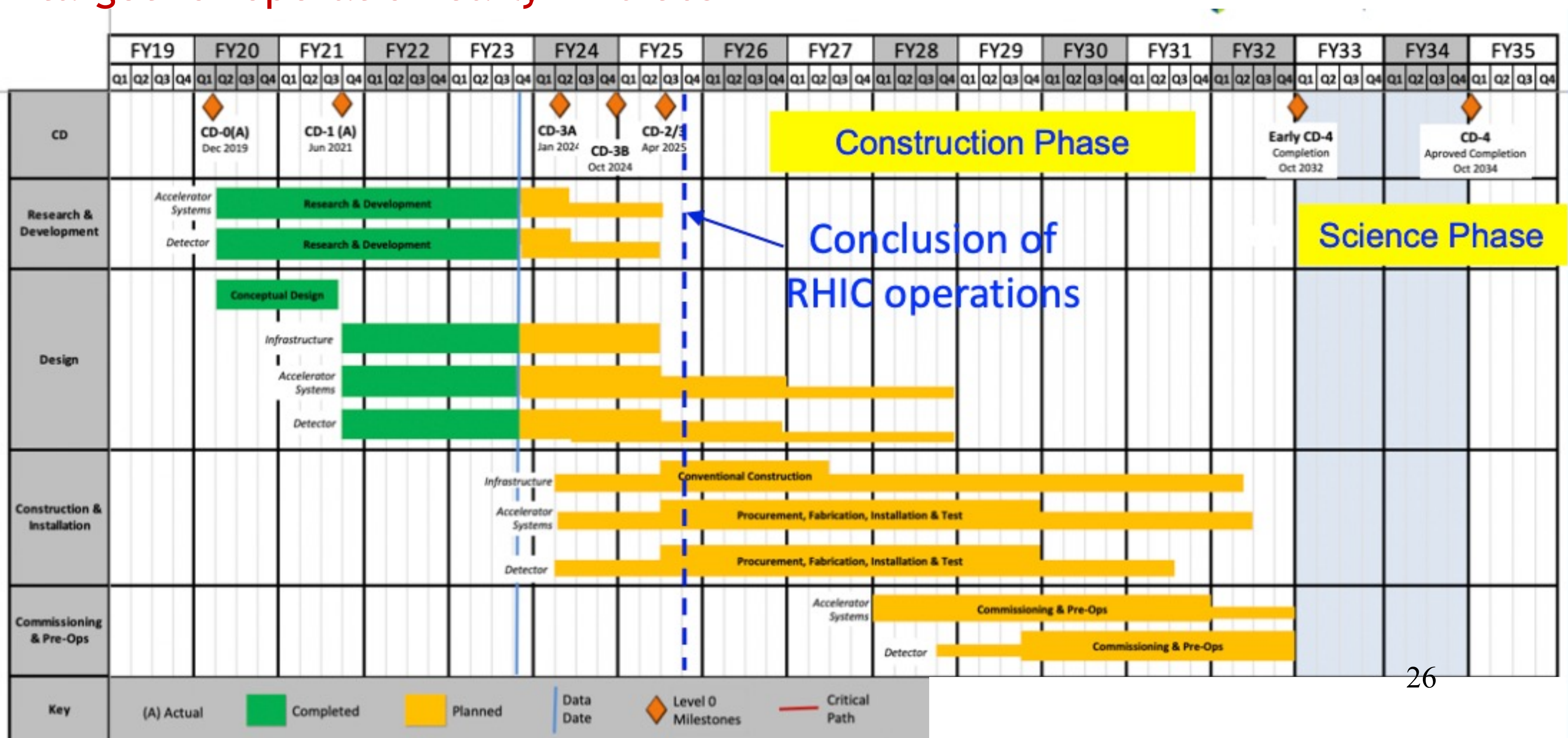
Status / Timeline

- Total cost ~$2.5Bn (US project 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	March 2025
CD-2 (Performance baseline)	2025?
CD-4 (Operations / completion)	2032-34

Technical Design Report: end 2025 (prelim 2024)



UKRI-Infrastructure-Funded UK Involvement

WP1: MAPS → 65nm CMOS (wafer scale) stitched sensors, developed from ALICE-ITS3, to be deployed in central tracker
→ Construction of 2 barrel layers, corresponding to around 1/3 of silicon tracker

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

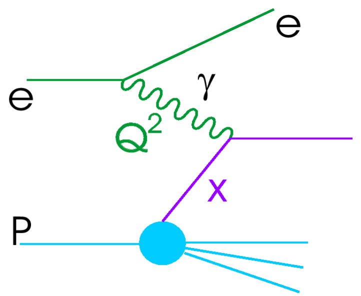
WP3: Lumi Monitoring → Novel pair-spectrometer, beamline $\gamma \rightarrow ee$ counting

WP4: Accelerator → Primarily SRF systems for Energy Recovery cooler.
→ Also crab-cavity RF 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

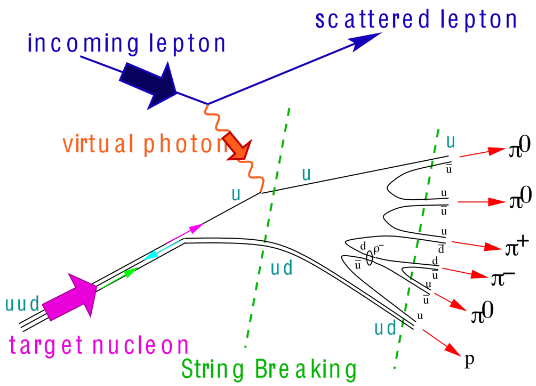
Observables / Detector Implications

Inclusive



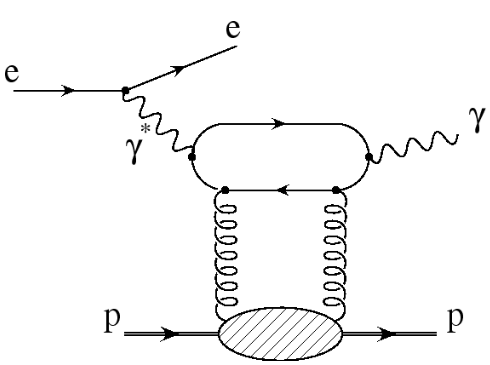
- Traditional DIS, following on from fixed target experiments and HERA → Longitudinal structure
  ... high acceptance, high performance electron identification and reconstruction

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

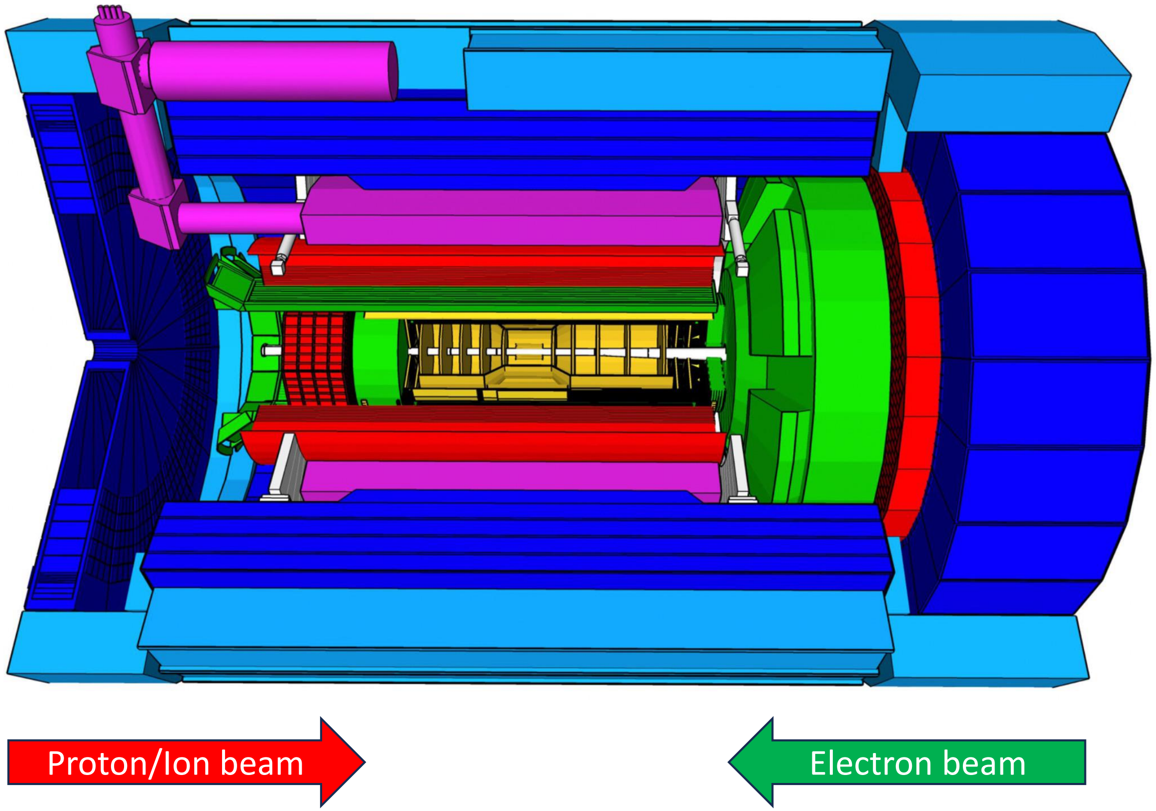
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

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 not shown (see later)

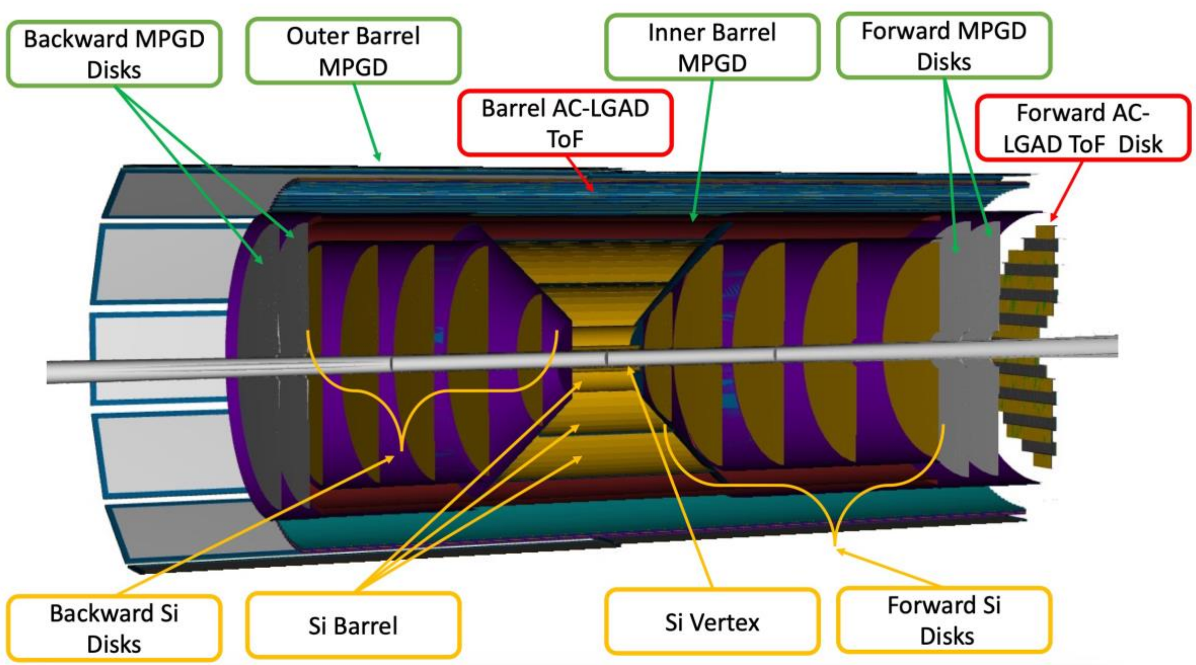
- Much lower radiation fluxes than LHC widens technology options

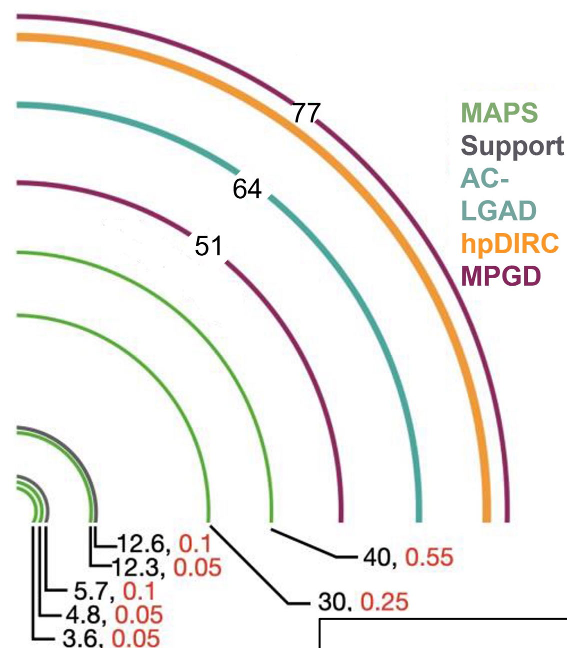
Tracking Detectors

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)
- $20 \times 20 \mu m$ pixels
- 5 barrel layers + 5 disks (total $8.5m^2$ silicon)





Black numbers are radii in cm

Red numbers are material in % X0

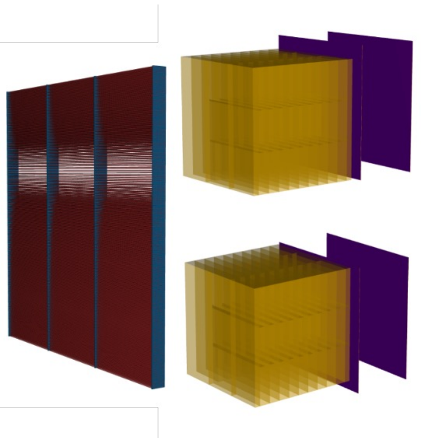
LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

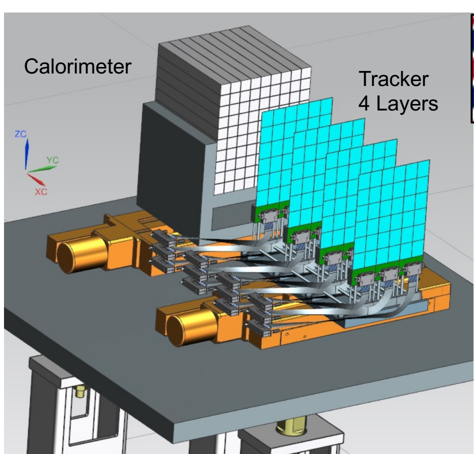
Interaction Region / Beamline Instrumentation

- Extensive beamline instrumentation integrated into IR design

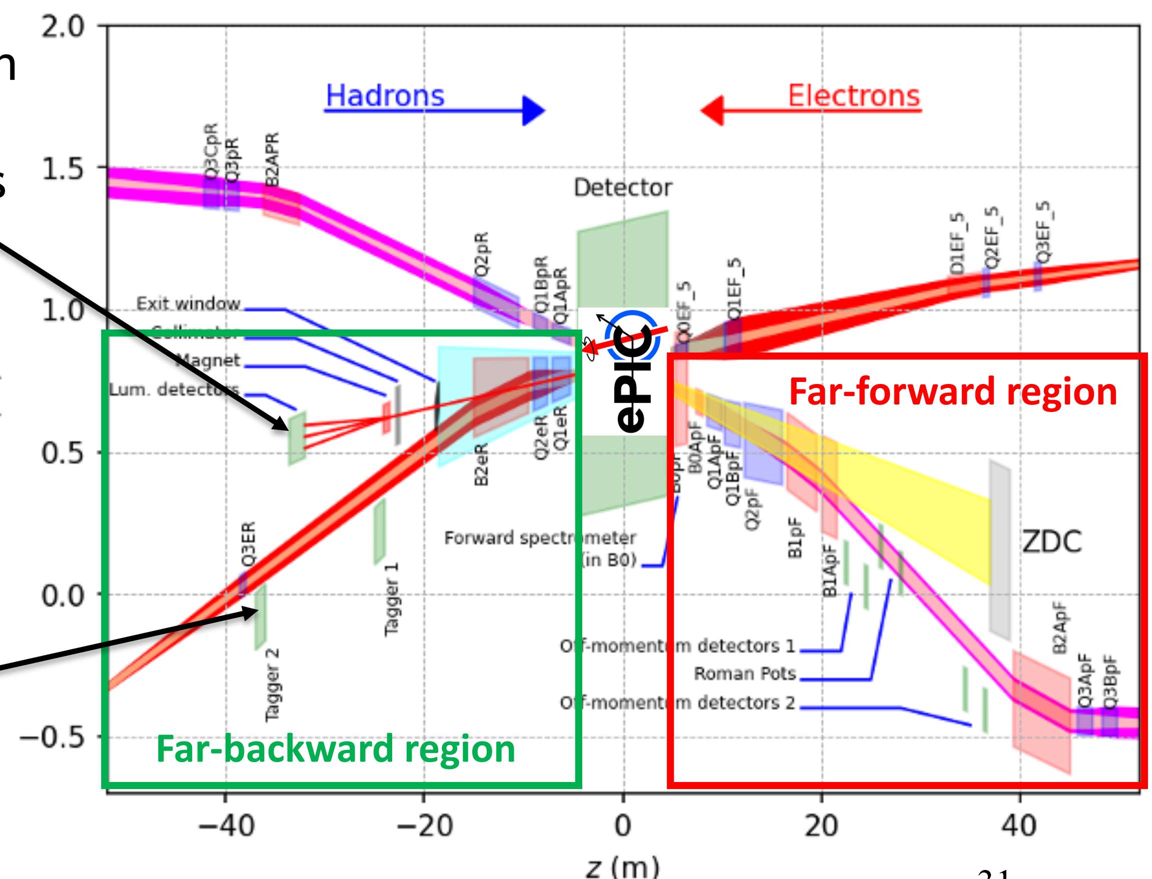
- Tagging electrons and photons in backward direction for lowest Q^2 physics studies and lumi monitoring via photon counting in $ep \rightarrow ep\gamma$



Pair-production lumi spectrometers

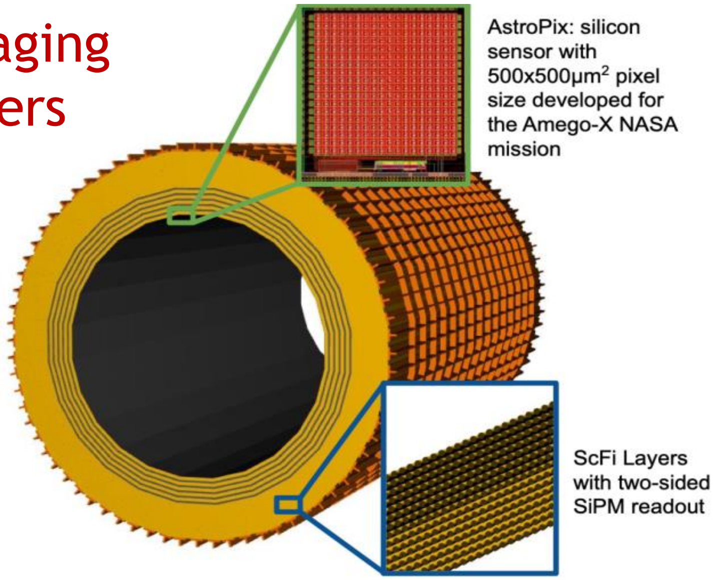


2 low Q^2 electron taggers

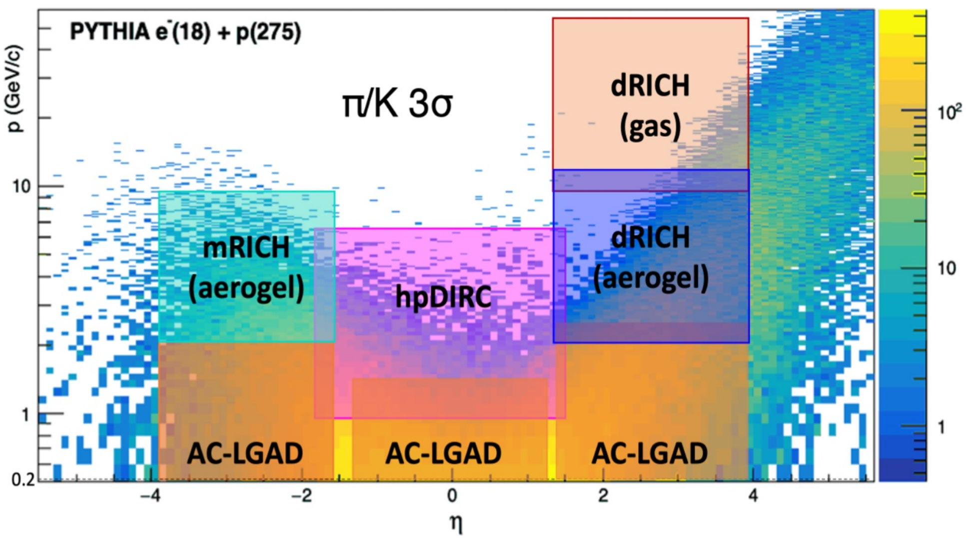


More Novel Detector Components

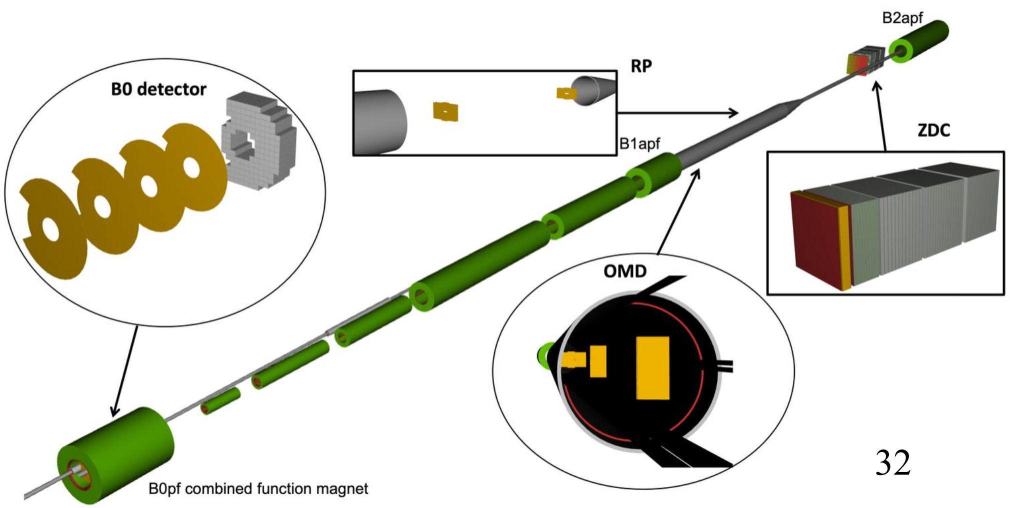
Imaging eCAL
Pb/SciFi sampling +
AstroPix
imaging
layers



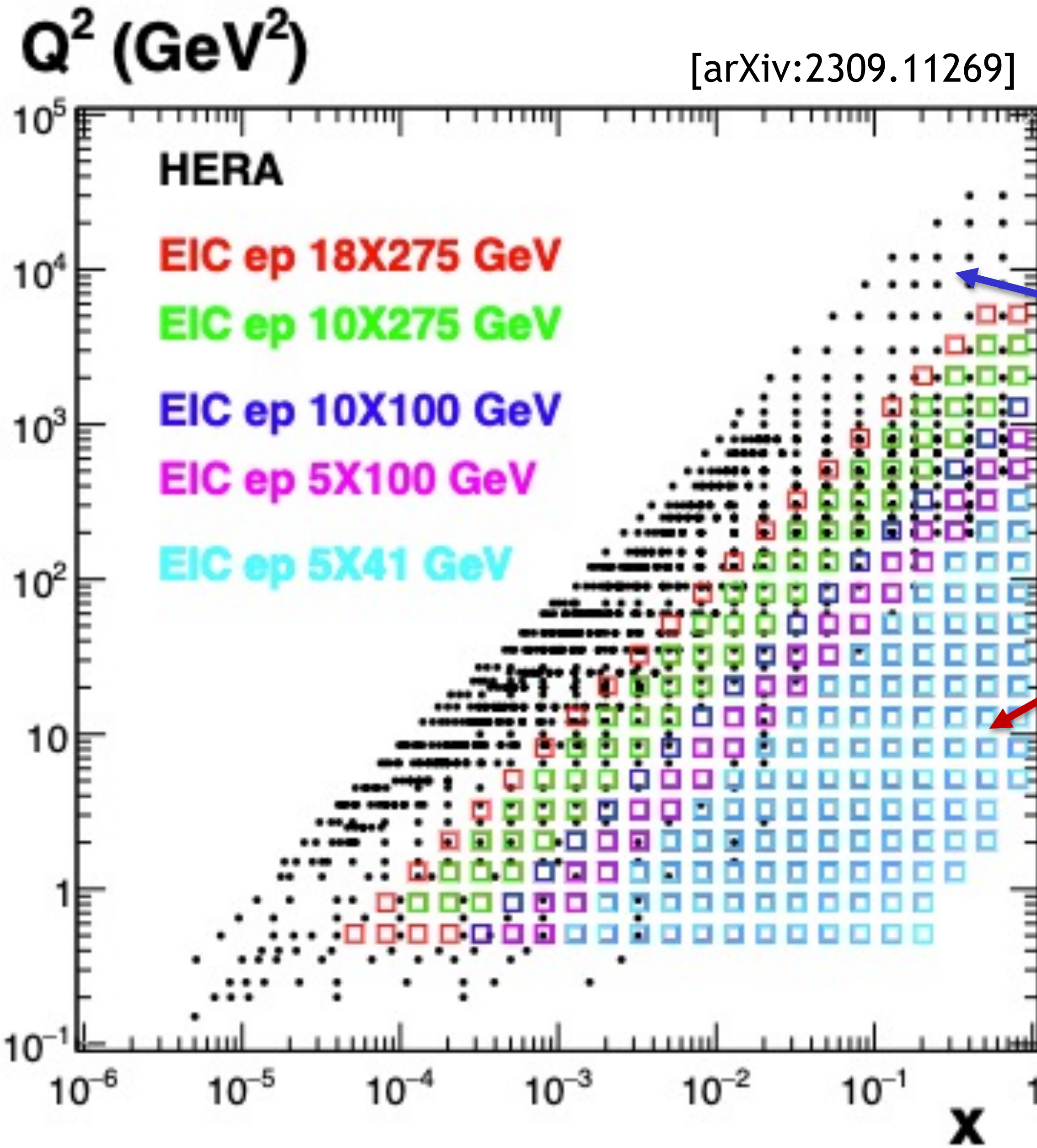
Comprehensive Particle ID



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



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

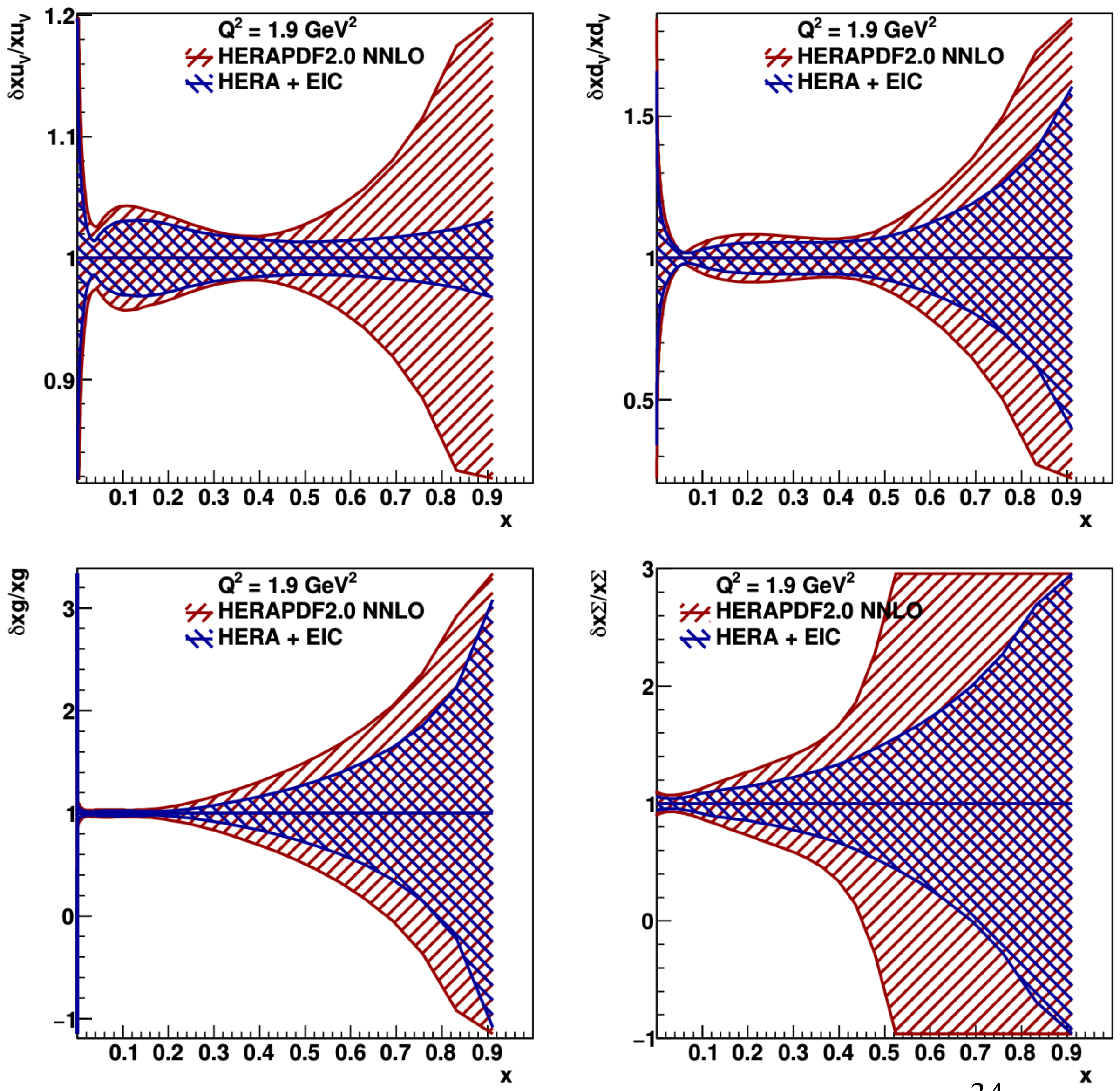
Fractional total uncertainties with / without simulated EIC data added to HERA (lin-x scale)

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

Up quarks improve relative to global fits including LHC

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

- $\alpha_s(M_Z^2)$ to 0.3% (cf 0.6% now)



EIC Impact on Nuclear Parton Densities

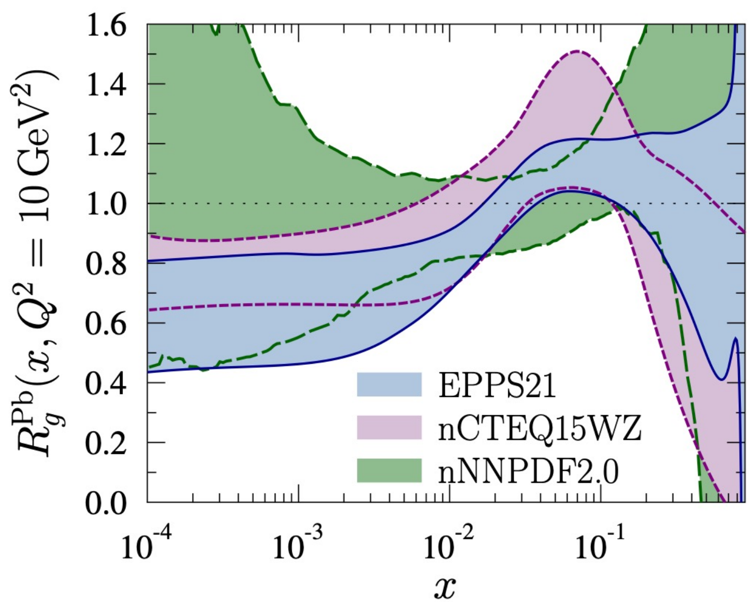
- Nuclei enhance density of partons
  ($\sim A^{1/3}$ factor at fixed x, Q^2)

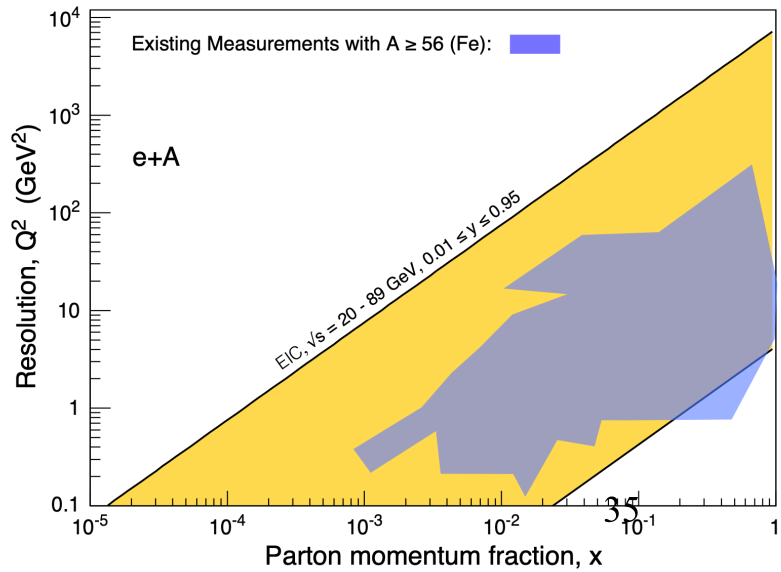
- Results usually shown in terms of nuclear modification ratios: change relative to simple scaling of (isospin-corrected) proton

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

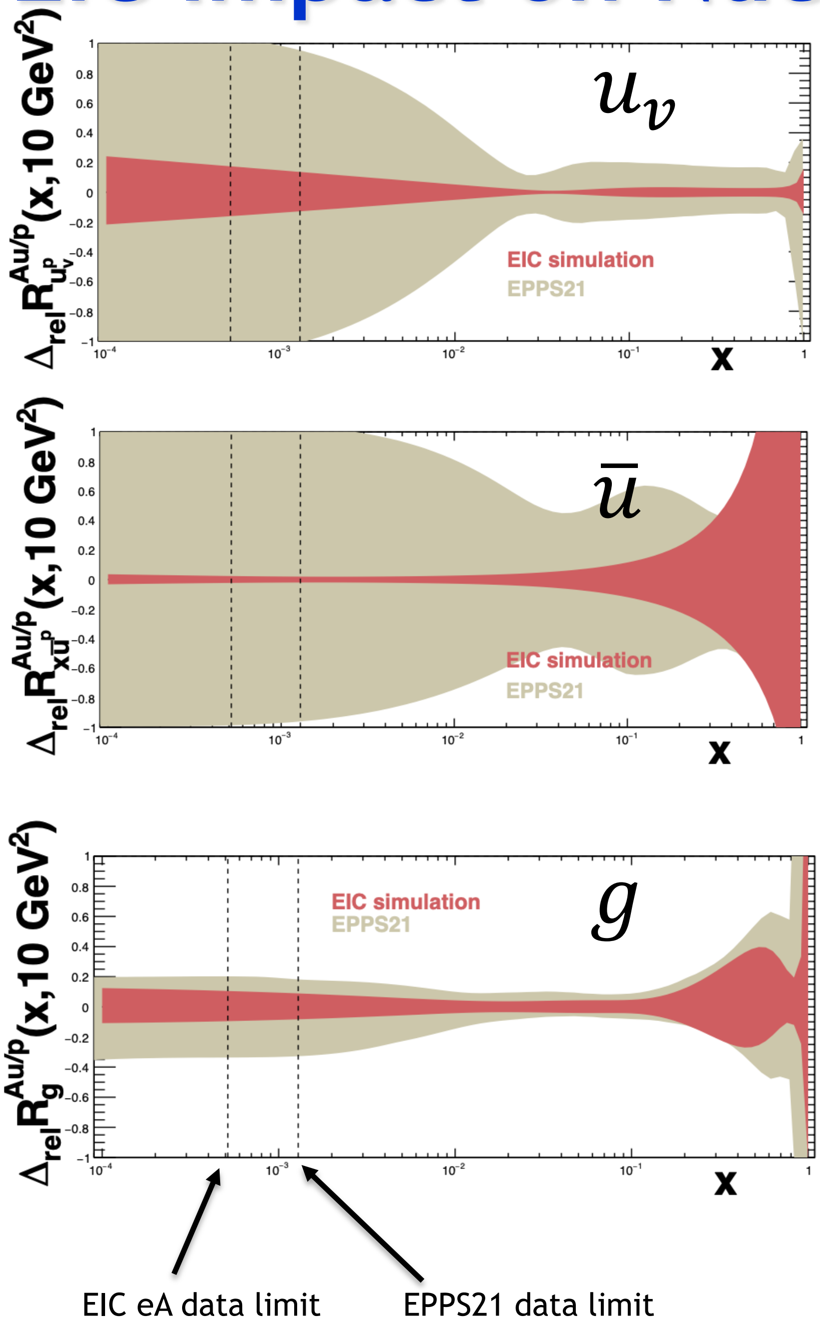
… poorly known, especially for gluon and at low x

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





EIC Impact on Nuclear Parton Densities



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

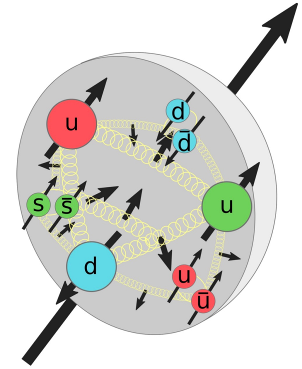
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

Sensitivity of EIC-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 Measurements



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

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

Jaffe-Manohar sum rule:

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

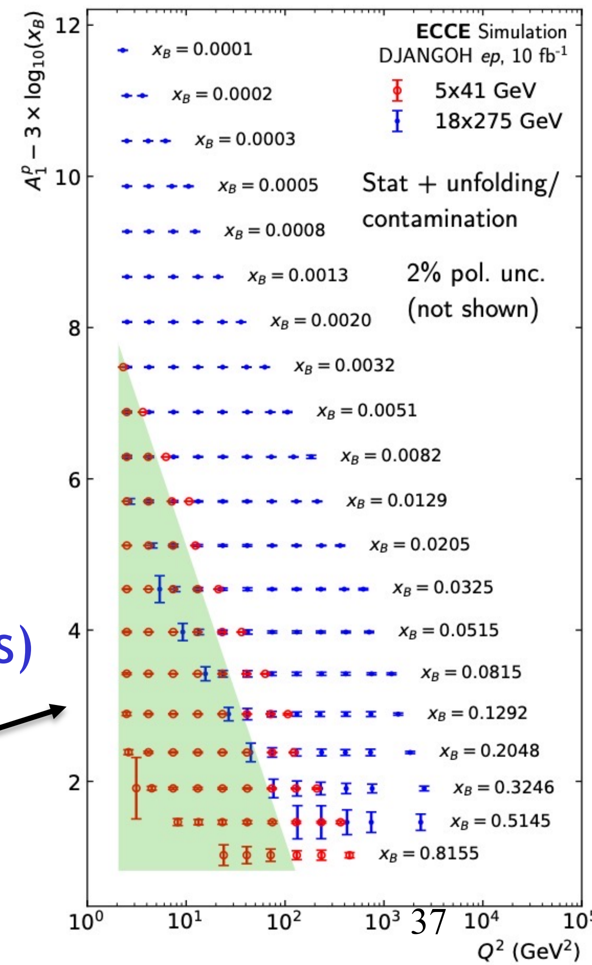
Quark helicity — Gluon helicity — Quark canonical orbital angular momentum — Gluon canonical orbital angular momentum

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

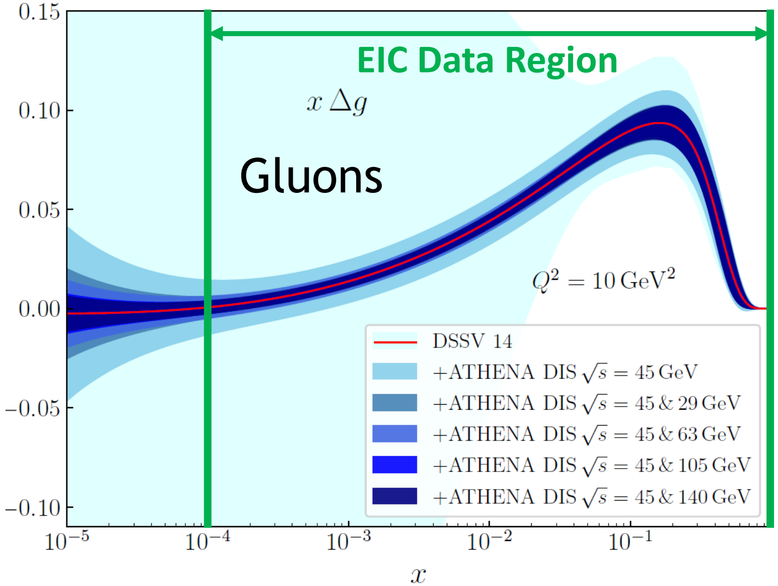
… Asymmetries between NC cross sections with different lepton and proton polarisations measure quark helicity (gluon helicity from scaling violations)

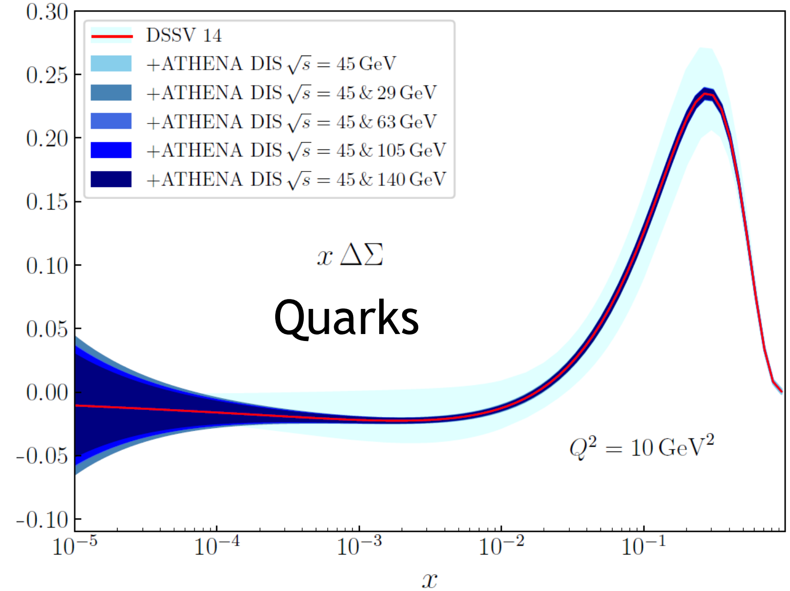
Previously measured region (in green)

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



EIC Impact on Proton Spin Decomposition

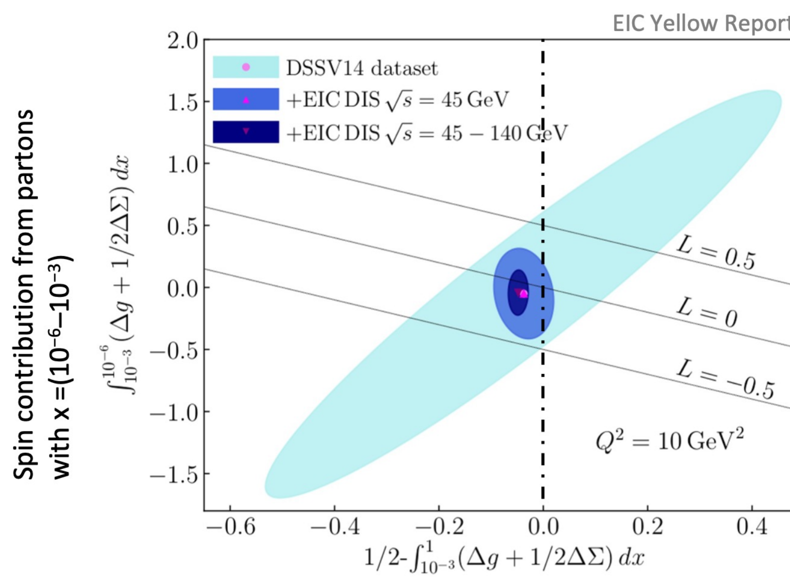




- Simulated NC data with integrated luminosity 15fb^{-1}, 70% e,p Polaris'n

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

- Orbital angular momentum similarly constrained by implication

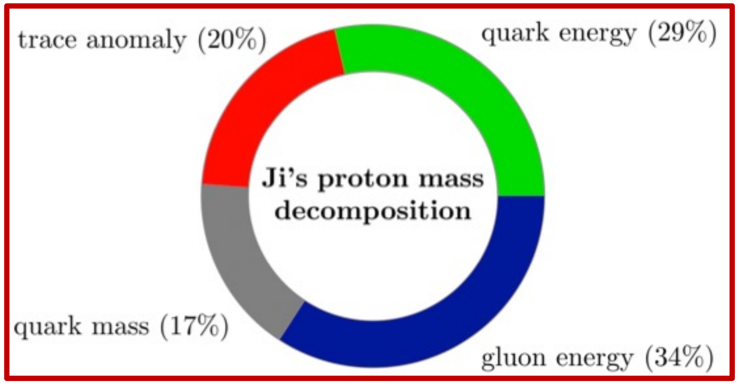


Room left for potential OAM contributions to the proton spin from partons with x > 0.001

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' and 'PE' from confinement and relative motion

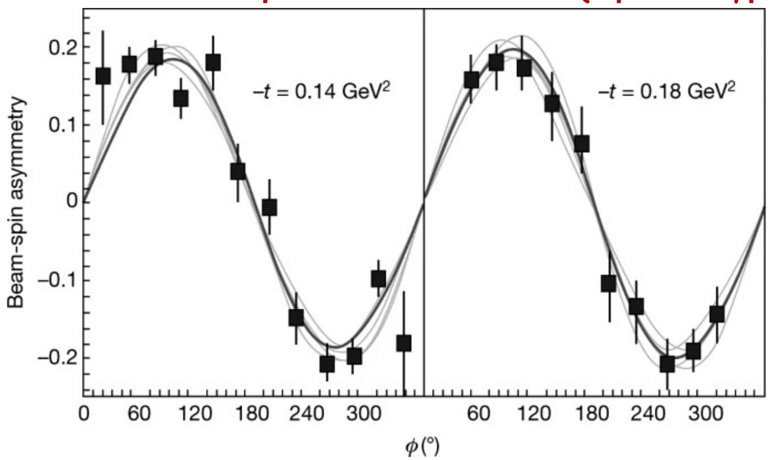
QCD trace anomaly (purely quantum effect - chiral condensates)

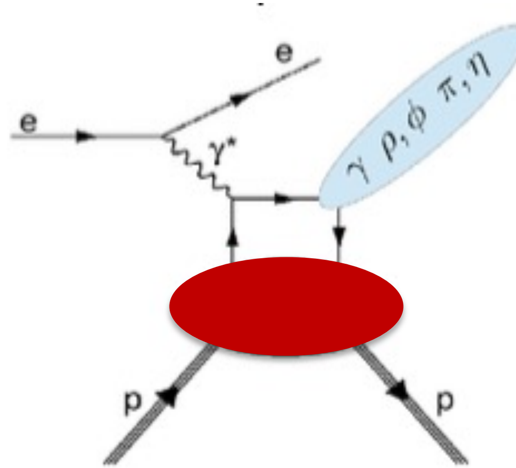
Understanding 3D relative location and motion of partons within proton is pathway to understanding proton mass emergence

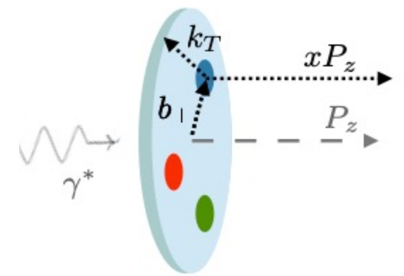
Proton 3D Structure and Mechanics

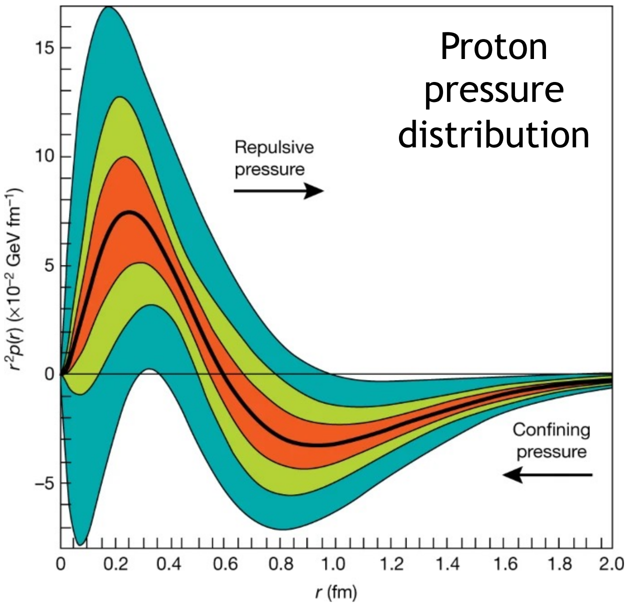
Exclusive processes, yielding intact protons, require exchange of ≥2 partons
→ Sensitive to parton correlations in longitudinal & transverse momentum and spatial coordinates

Jlab CLAS experiment: DVCS (ep → eγp)



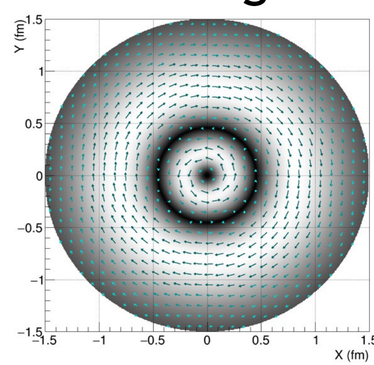






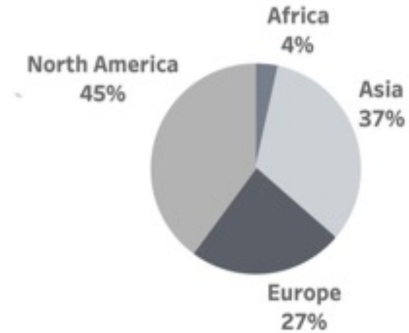
Hints at rich 3D picture from JLab

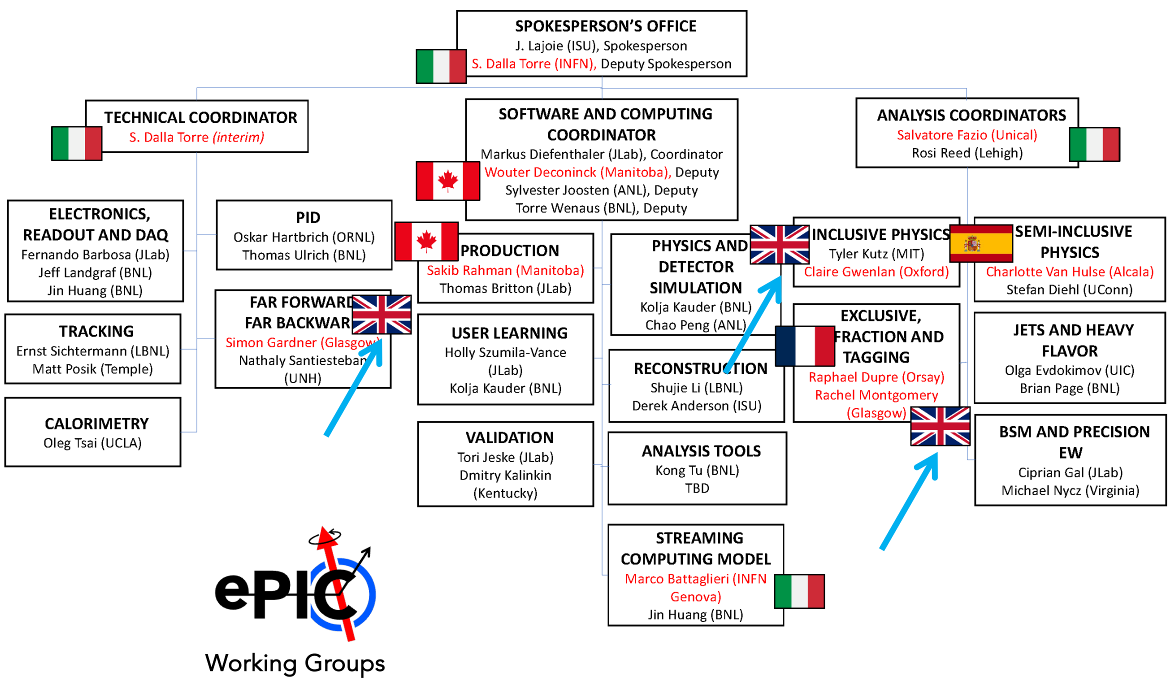
- Gluon radius (~0.5fm) smaller than charge radius (~0.85 fm)
- Repulsive inner core and attractive outer region
- Peak pressure greater than core of neutron star
- Tangential stress forces change direction near r=0.45fm

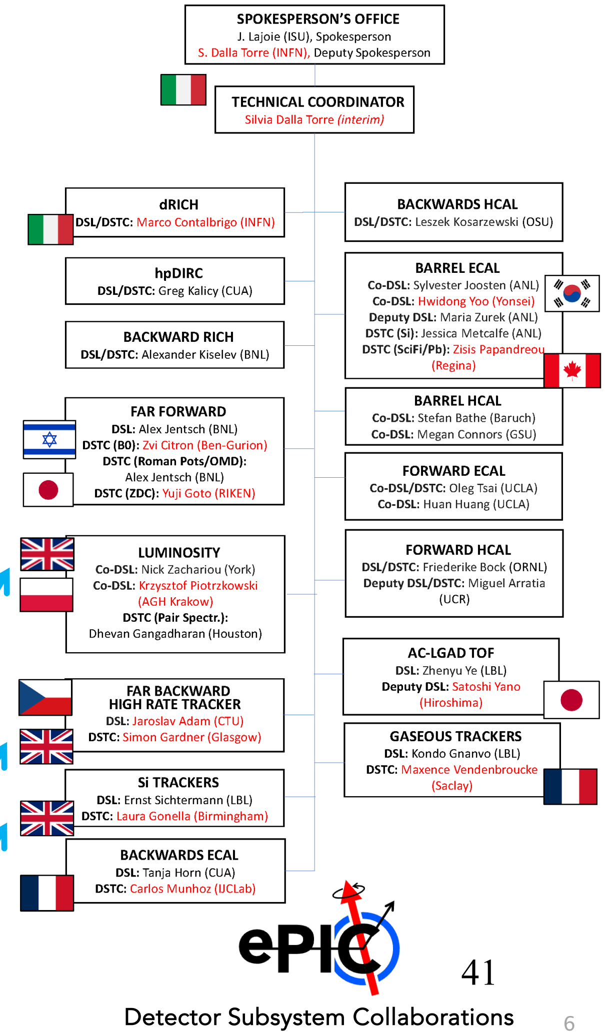


ePIC Demographics and Current UK Leadership

- Currently >850 ePIC collaborators (UK is 4th largest)
- UK physicists deeply involved through motivation, collaboration formation and now ongoing roles
- Part of wider user group with 1400 members

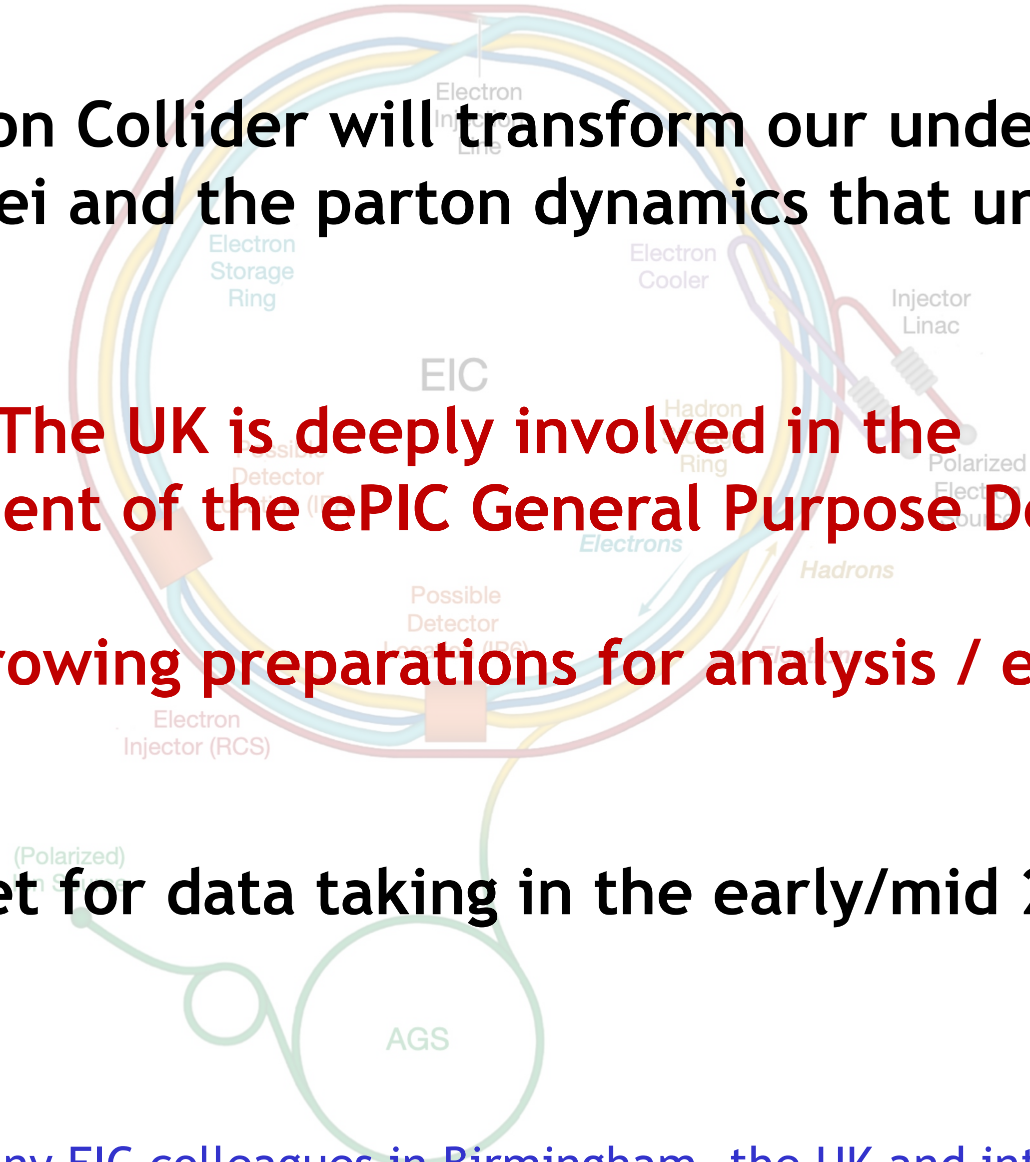






Paul Newman (Birmingham) – Executive Board
Nick Zachariou (York) – Conferences and Talks Committee

Summary



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

The UK is deeply involved in the development of the ePIC General Purpose Detector

… also with growing preparations for analysis / exploitation

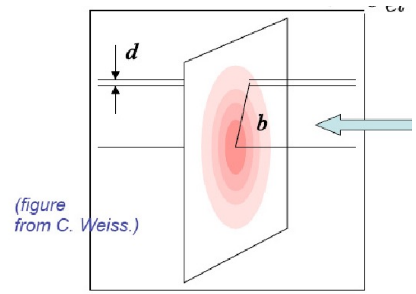
On target for data taking in the early/mid 2030s

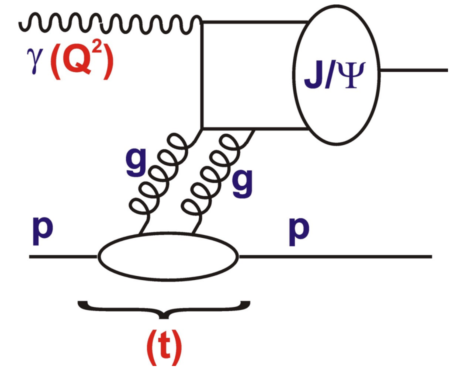
[with thanks to many EIC colleagues in Birmingham, the UK and internationally]

Exclusive Processes and Dense Systems

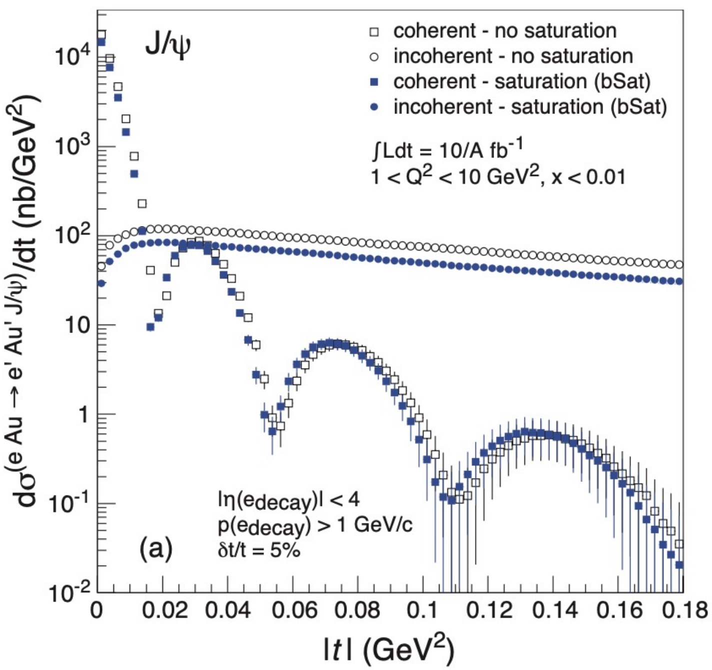
Additional variable (Mandelstam) t is conjugate to transverse spatial distributions

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



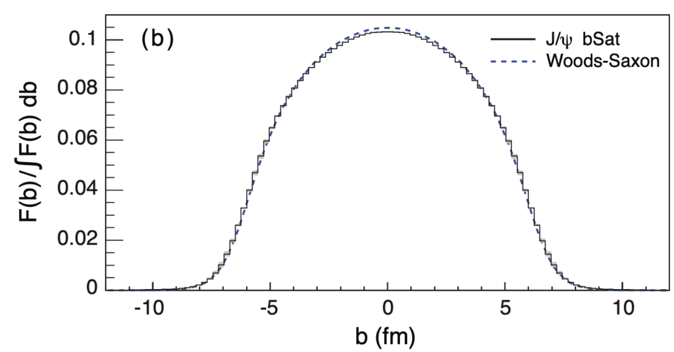


[arXiv:1211.3048]



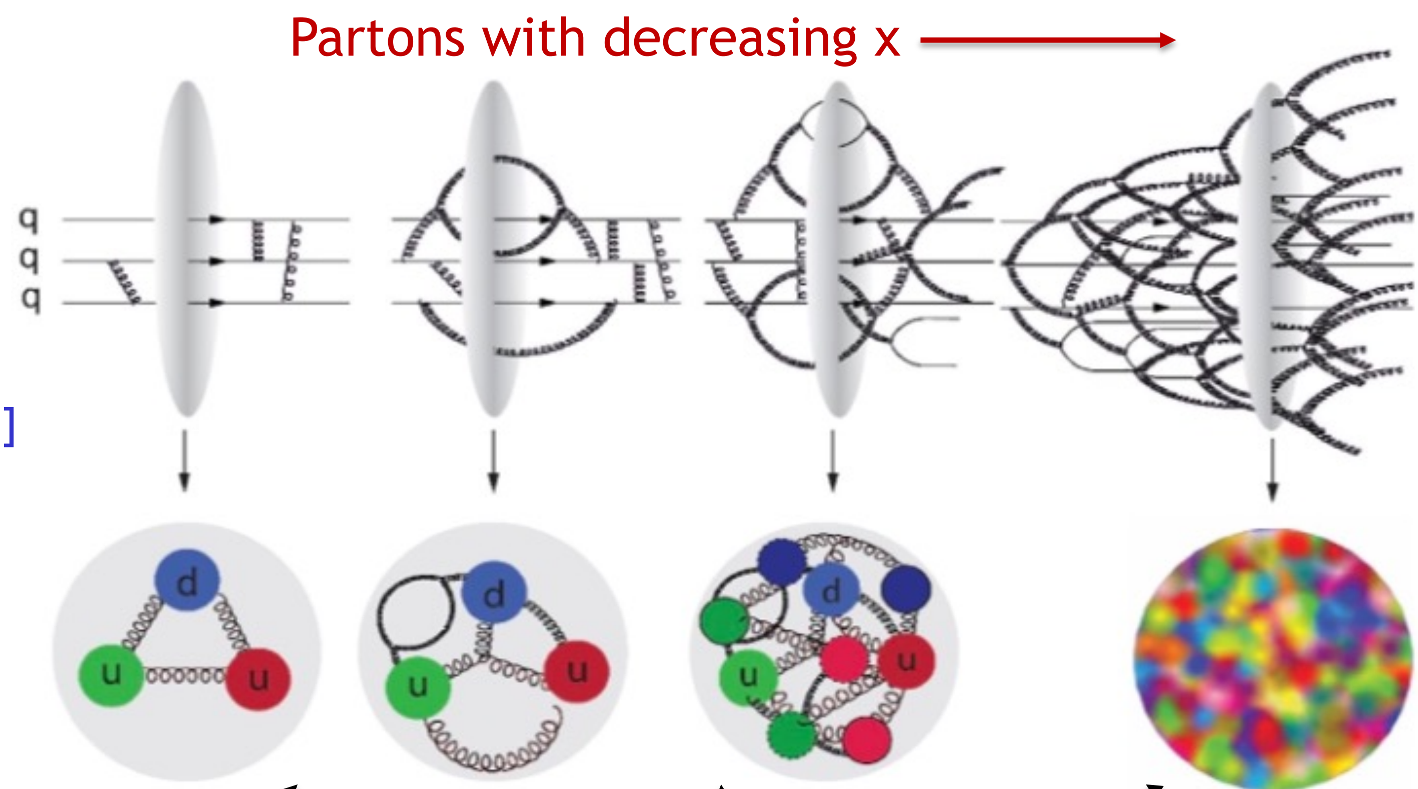
e.g. Coherent J/Ψ production at small t in eAu measures average density profile, with dips at larger t sensitive to saturation or other novel effects in dense regions

→ Fourier transform



Experimental challenges from incoherent background and resolving dips

Crude Mapping Between Physics & Facilities



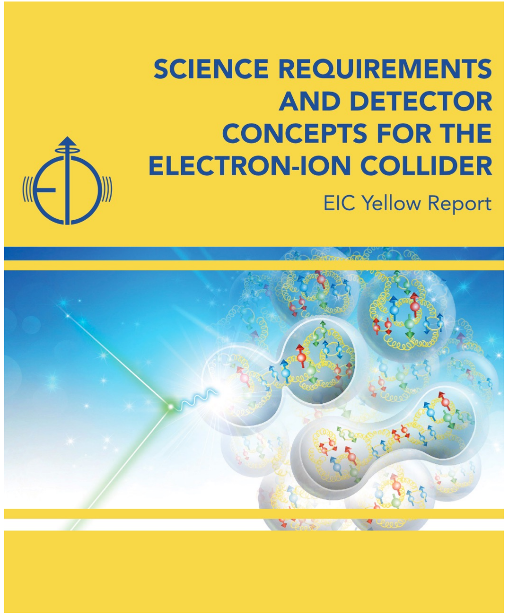
[Kong Tu]

High x (fixed Target)
Basic Structure

Intemediate x (EIC)
Emergent properties

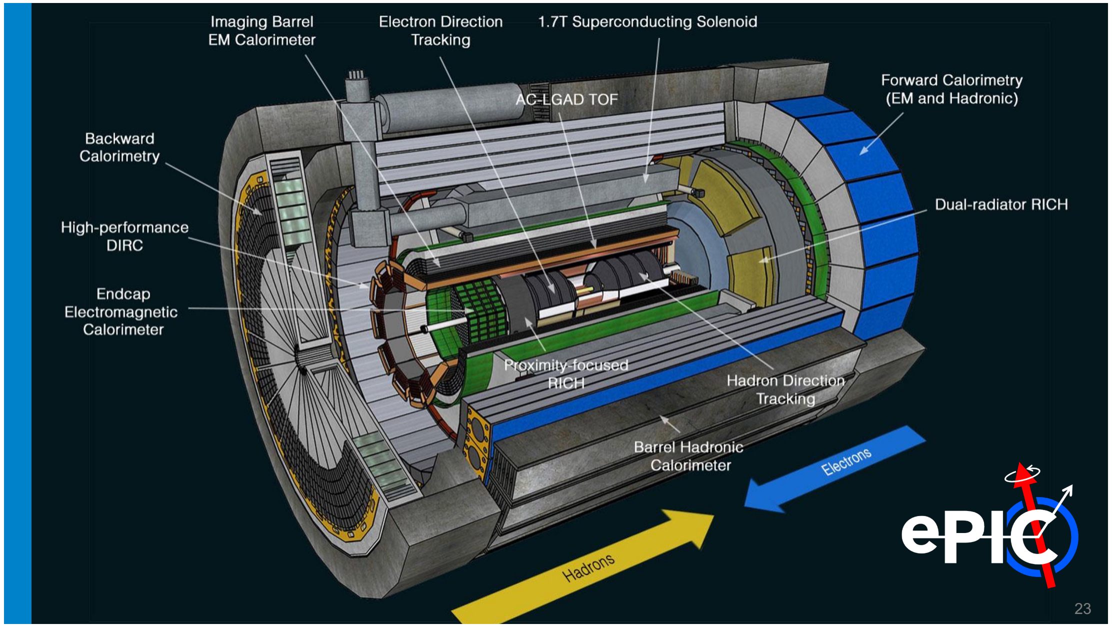
Low x (HERA / LHeC)
QCD radiation dynamics

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 £58M UK investment)



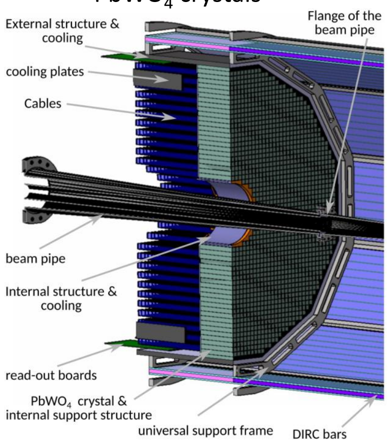
- **Second detector?**
  … not yet funded or designed in detail
  … should bring an overlapping, but complementary programme

Calorimeter Overview

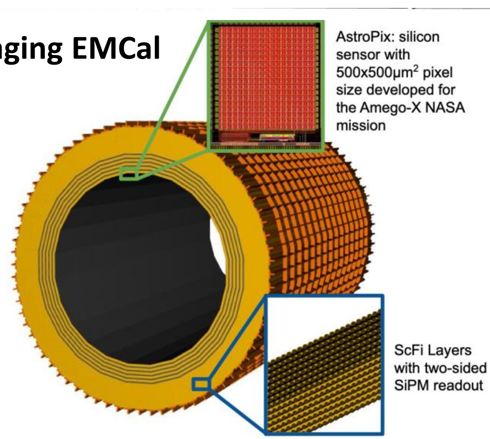
- Different technologies in barrel and end-caps, as required for varying performance targets
- New ECAL designs / technologies,
- HCAL partially recycles previous detectors
- All read out with Si PMs

Electron Endcap EMCal

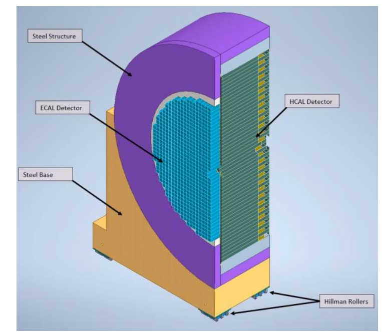
$PbWO_4$ crystals



Barrel Imaging EMCal

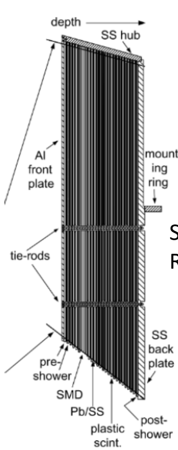


Hadron Endcap EMCal



High granularity W-powder/SciFi EMCal

Electron Endcap HCal



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

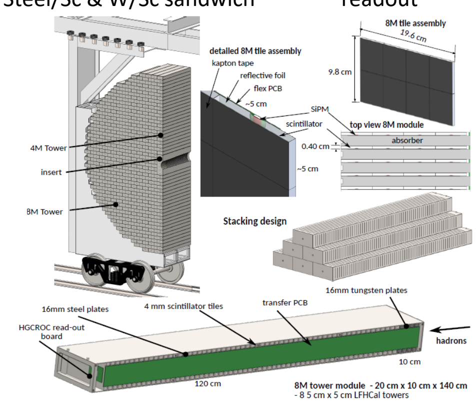
Barrel HCal

sPHENIX barrel calorimeter with new SiPMs

Hadron Endcap HCal

Longitudinally separated HCAL Steel/Sc & W/Sc sandwich

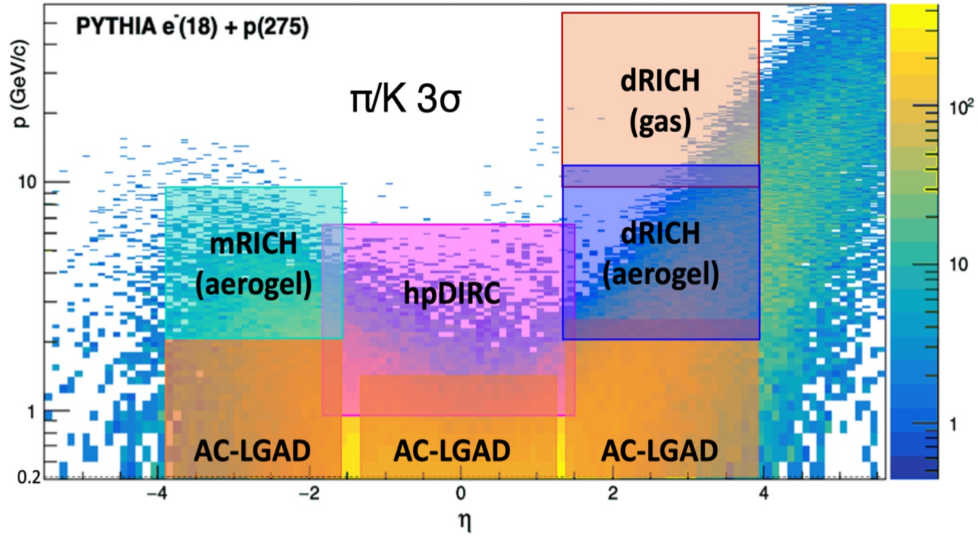
SiPM-on-tile readout



+ high granularity insert at largest η

Particle Identification

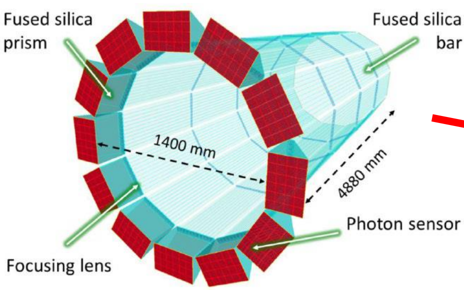
- SIDIS programme relies on π / K / p (and other PID) separation …
- Cerenkov detectors augmented by AC-LGADs (ToF) at low momentum give coverage for 200 MeV - 50 GeV



ePIC detector design – PID

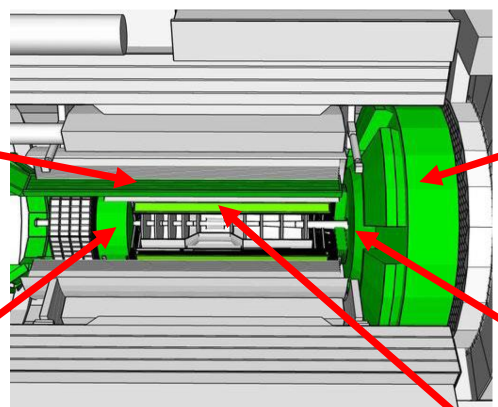
High-Performance DIRC

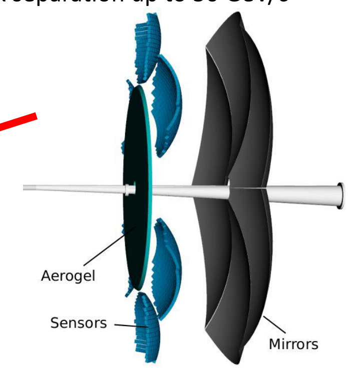
- Quartz bar radiator (reuse BaBAR bars)
- Sensors: MCP-PMTs
- π/K separation up to 6 GeV/c

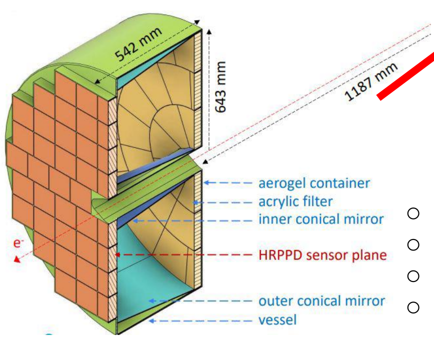


Dual-Radiator RICH (dRICH)

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





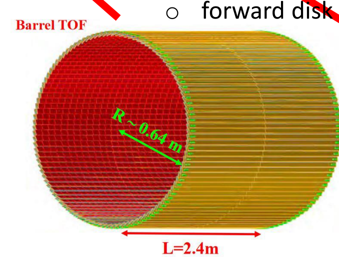


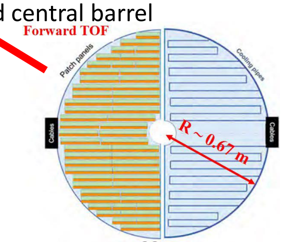
Proximity Focused (pfRICH)

- 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

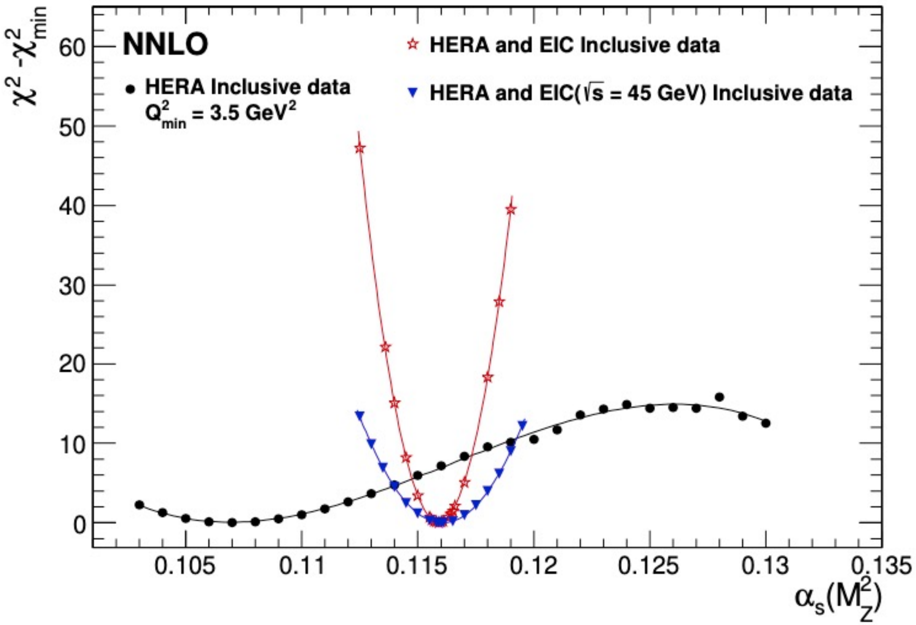
AC-LGAD TOF

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





Taking α_s as an additional free parameter



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

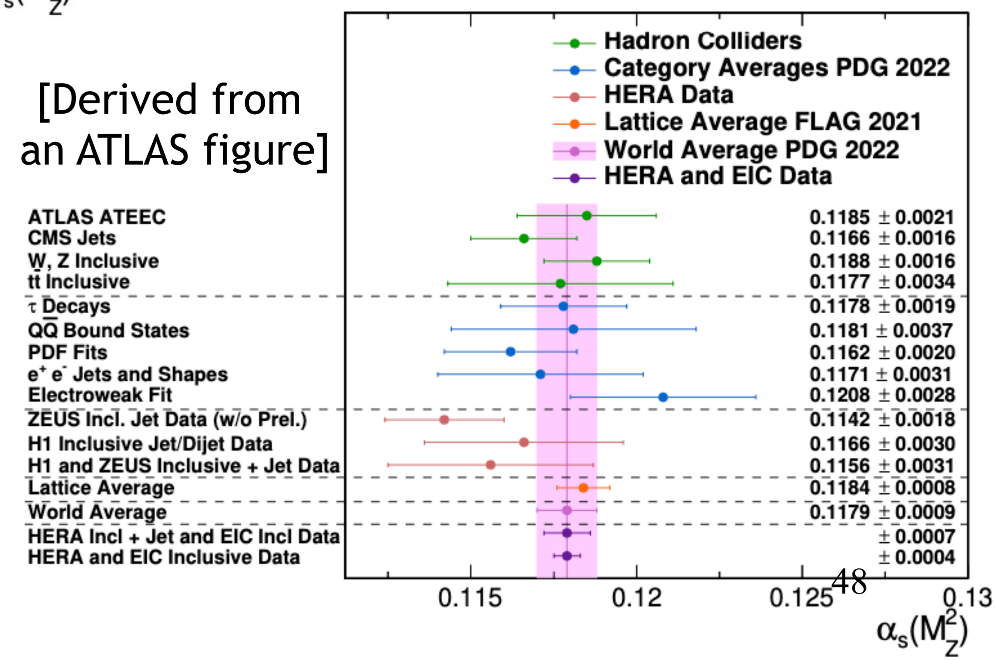
- Adding EIC simulated data has a remarkable impact

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

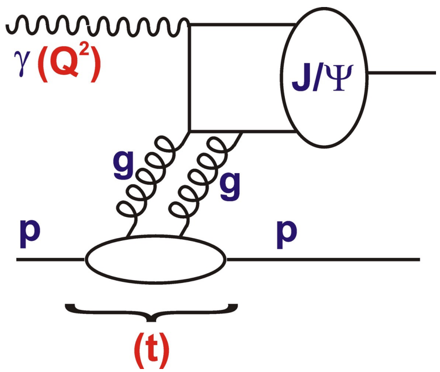
Adding EIC (precision high x) data to HERA can lead to α_s precision a factor ~2 better than current world experimental average, and than lattice QCD average

Scale uncertainties remain to be understood (ongoing work)

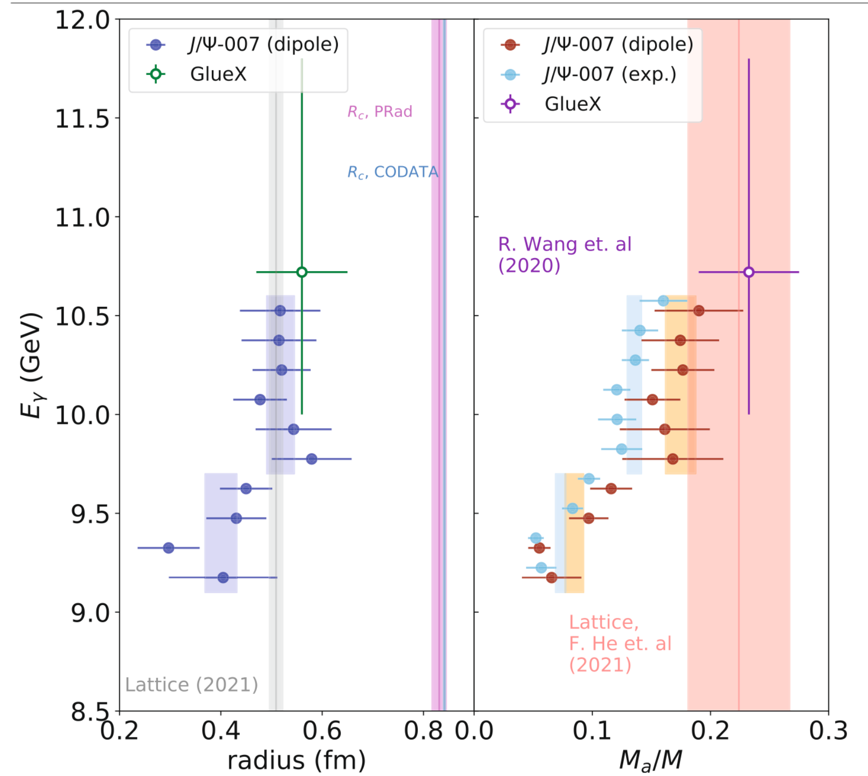
[Derived from an ATLAS figure]



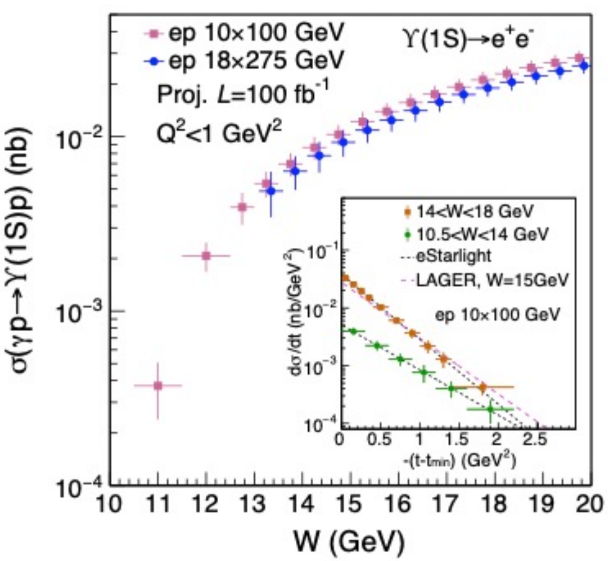
Proton Mass & Exclusive Vector Mesons

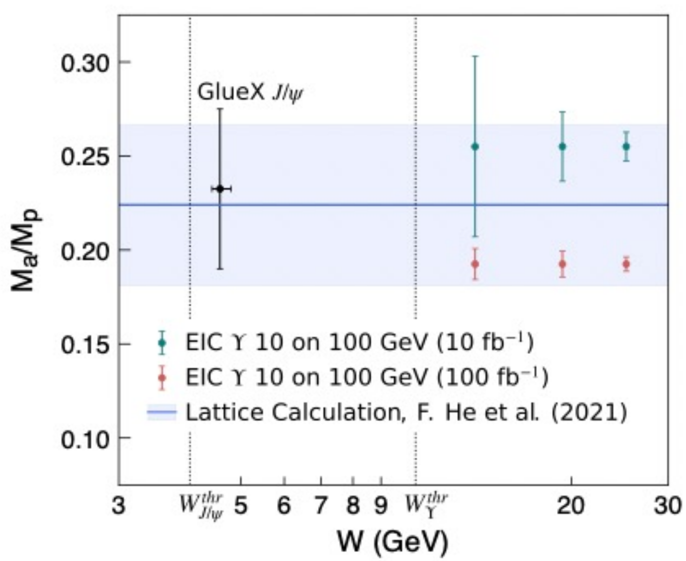


- Recent Jlab data on t dependences of J/Ψ production near threshold → Gravitational form factors



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





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