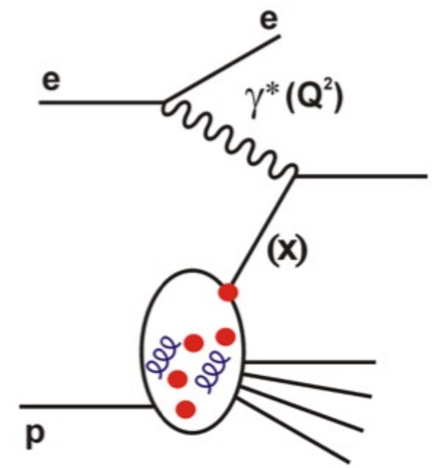
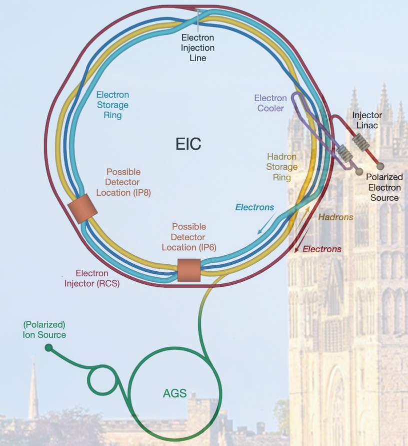
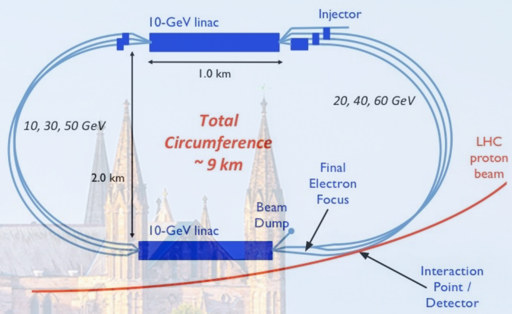
The Deep-Inelastic Scattering Landscape



1) Overall DIS Context
2) The Electron Ion Collider / ePIC Experiment
3) Introduction to the Large Hadron electron Collider

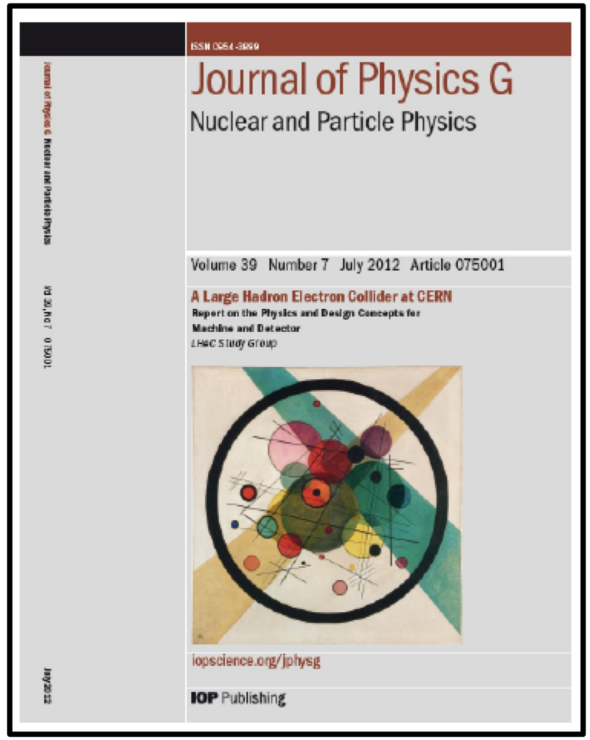


ECFA-UK Meeting on Studies for the ESPPU (Durham)
24 September 2024

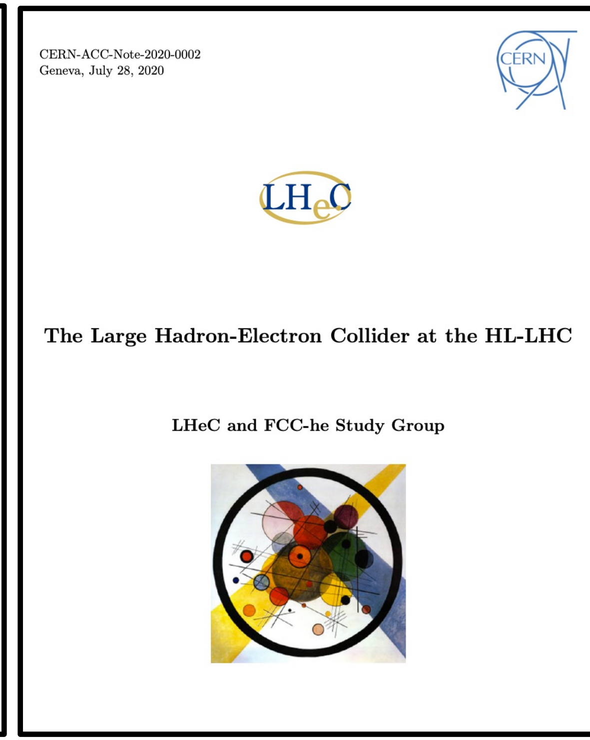


Paul Newman (Birmingham)

Max Klein
13/5/1951 - 23/8/2024



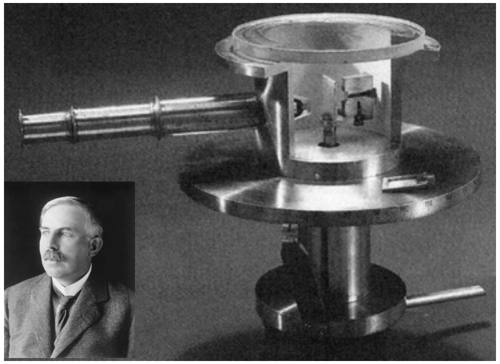
arXiv:1206.2913



arXiv:2007.14491

2008 2009 2010 2012 2014 2015 2017 2018 2019 2022

Scattering Experiments Exploring Matter

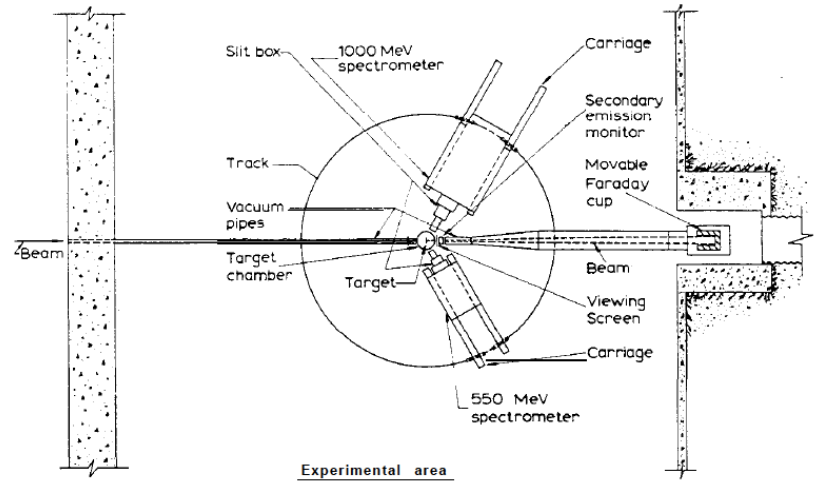


1911, Rutherford discovery of atomic nucleus

"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." [1926]

1950s, Hofstadter, 200 MeV electrons on fixed targets

First observation of finite proton size



1969, SLAC, 20 GeV electrons on fixed targets

Absence of dependence of (suitably expressed) cross section on q^2 (= squared 4 momentum transfer) implies scattering from point-like quarks

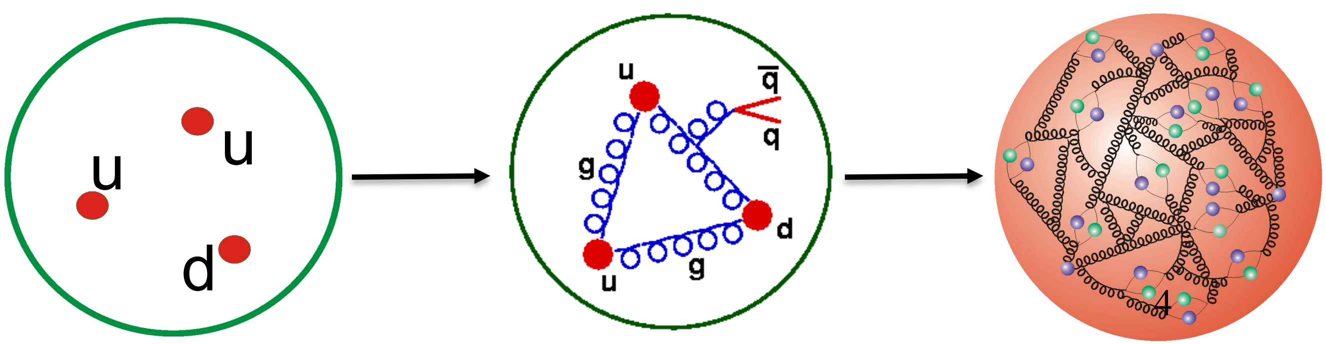
- The only ever collider of electron with proton beams:
  $\sqrt{s_{ep}}$ ~ **300 GeV**

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

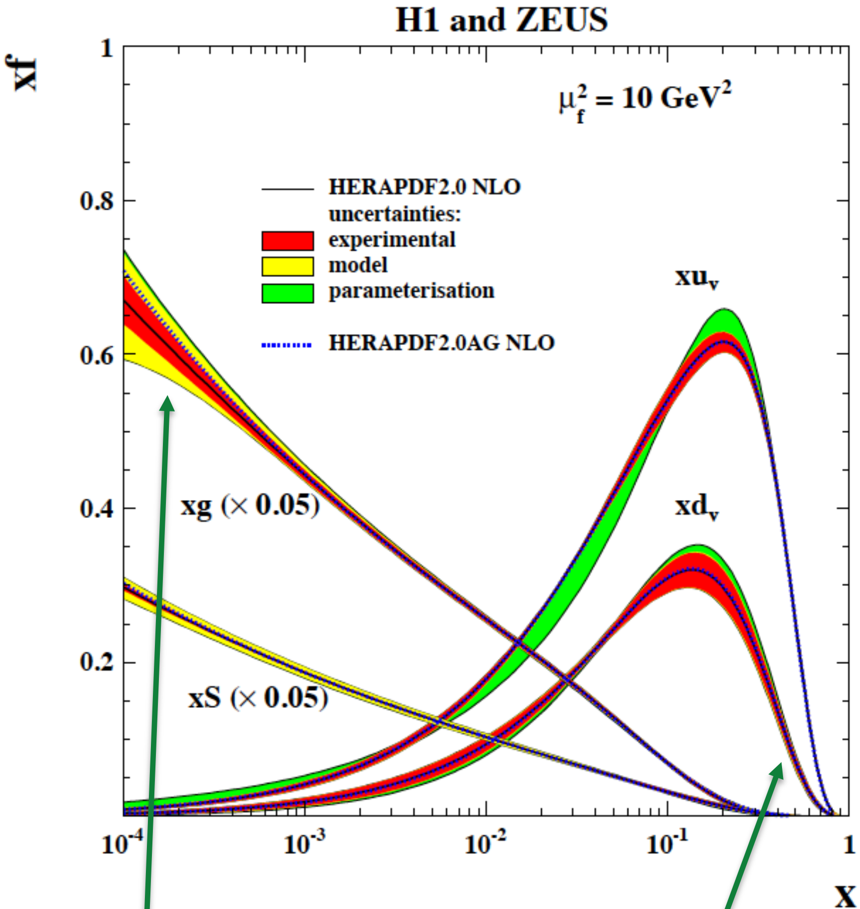
… Resolved dimension
  ~ 10^{-20} m

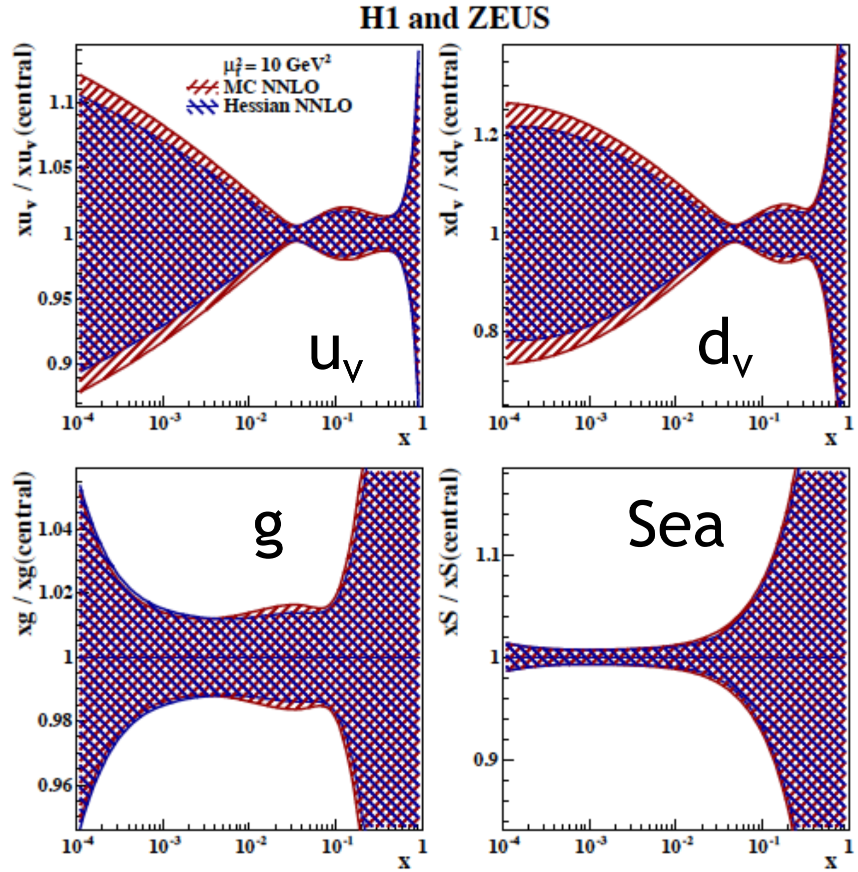
→ Source of much of our knowledge of proton (longitudinal) structure extending to partons of $x<10^{-4}$ mom^{m} fraction

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



Proton PDFs from HERA (HERAPDF2.0)





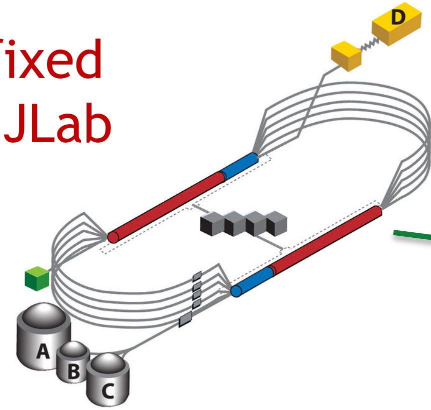
Strong interaction dragons?

Input to energy frontier discovery?

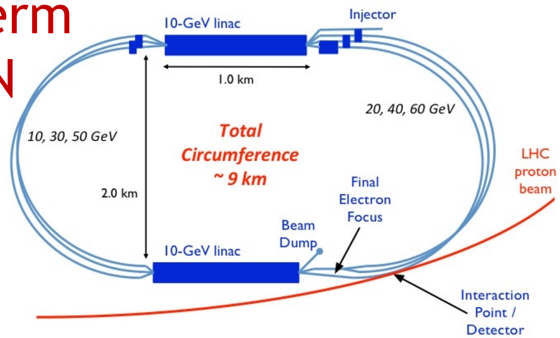
- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

Current and Future ep Colliders

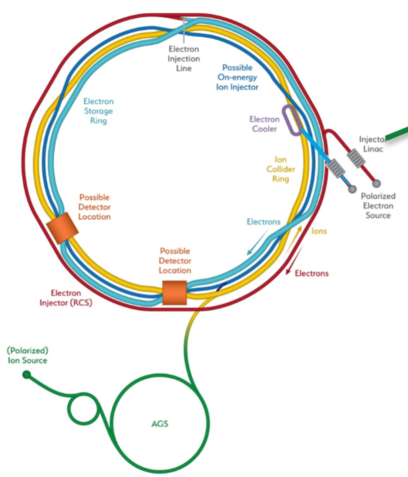
Ongoing fixed target @ JLab

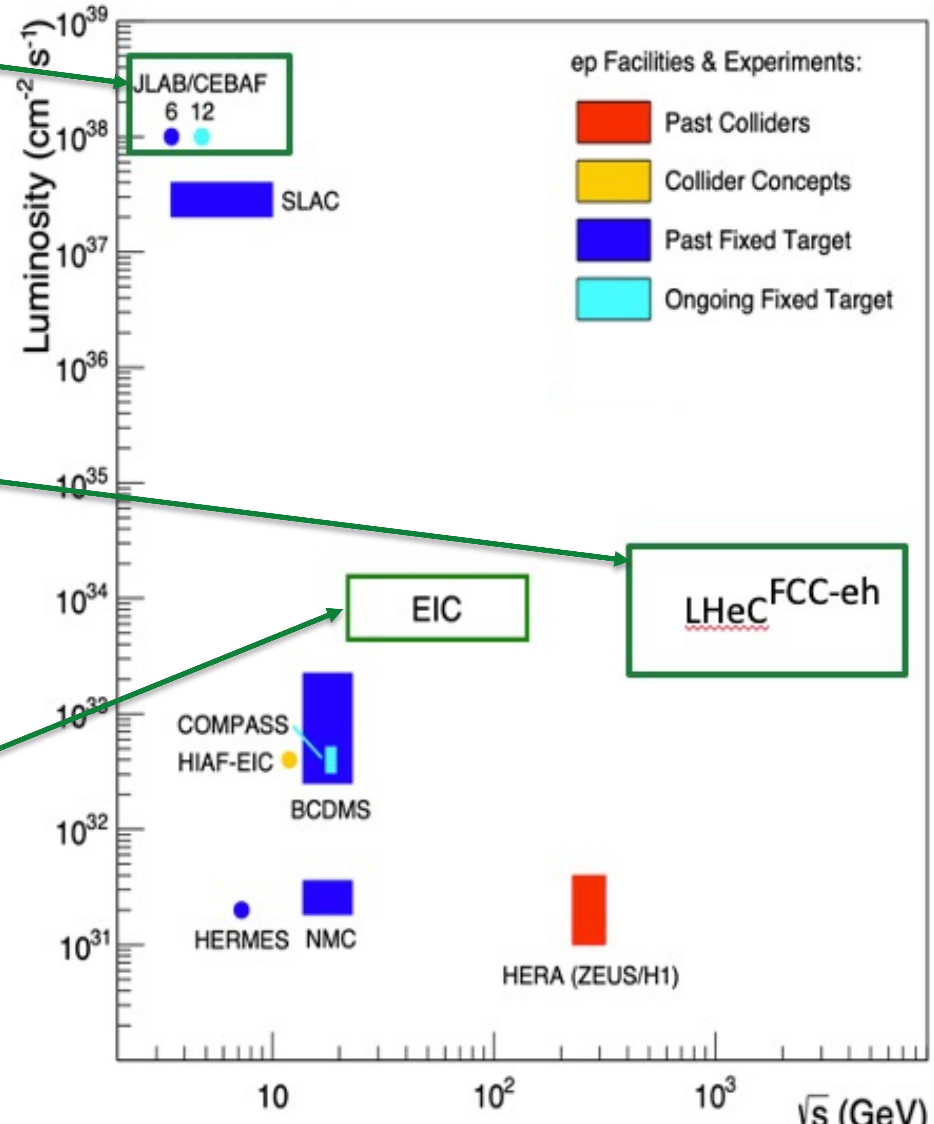


Longer-term @ CERN

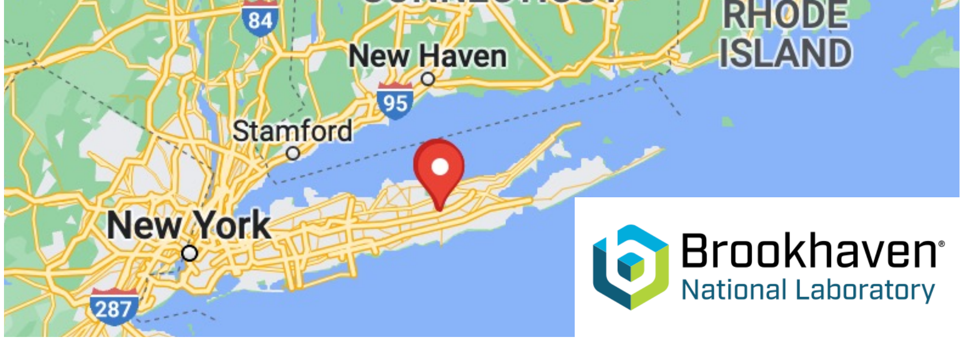


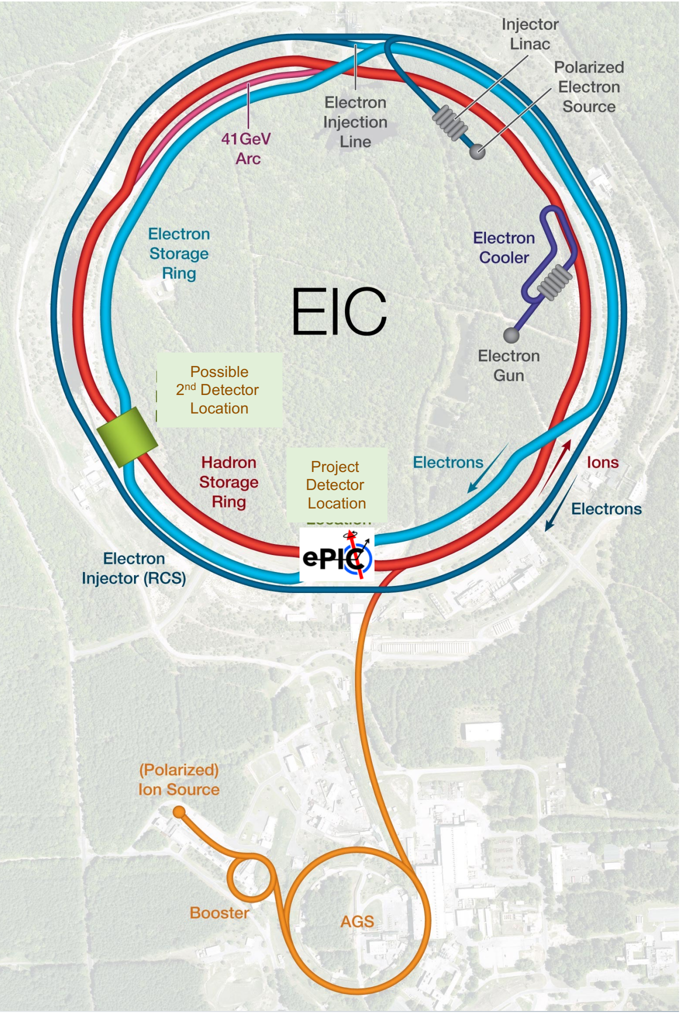
On-target for early 2030s @ BNL





The Electron-Ion Collider





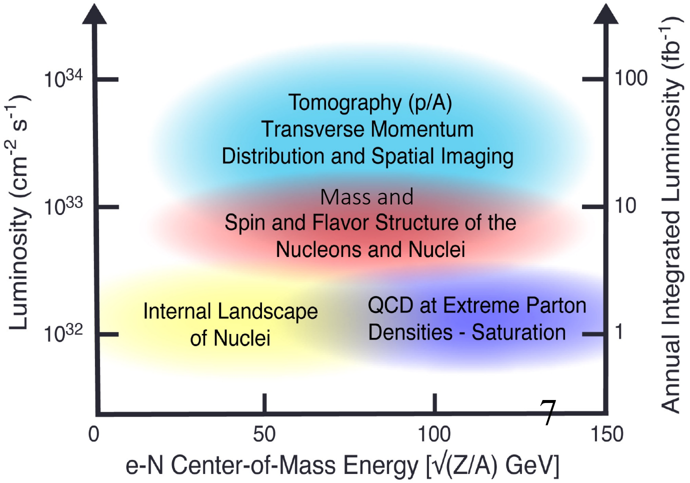
New electron ring, to collide with RHIC p, A

- 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} → ~100 fb^{-1} per year)
- Double-polarised DIS collider
  (~70% for leptons & light hadrons)
- eA collider
  (Ions H to U)

Specifications driven by science goals:

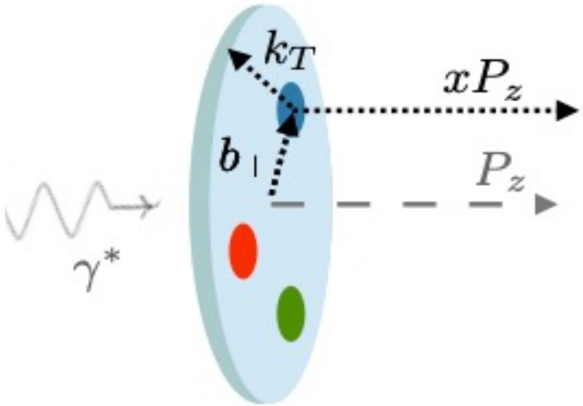


Physics questions to be addressed at EIC

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

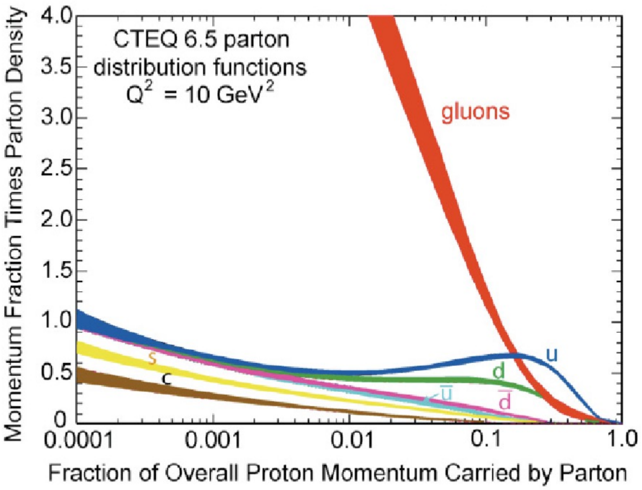
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

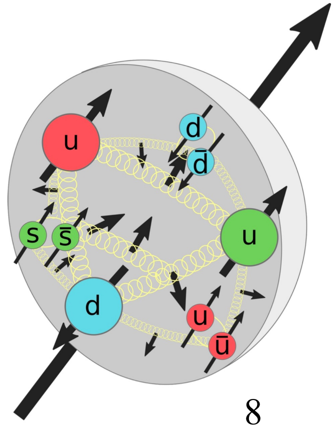
- What does the proton look like in 3D?



- How is proton spin generated?

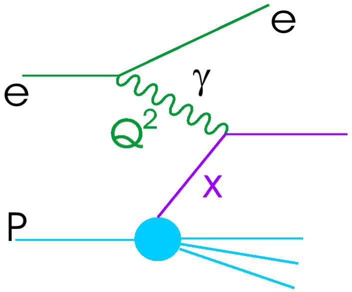
- How do the dynamics of high density systems of gluons tame the low x growth?





Observables / Detector Implications

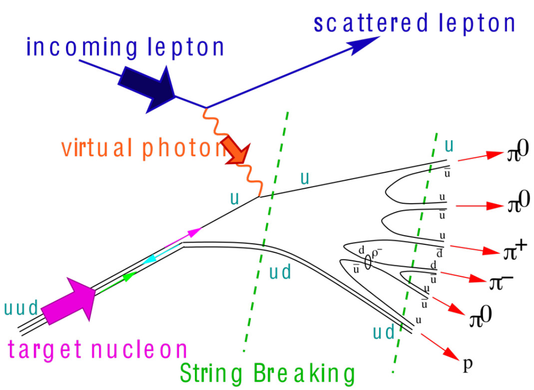
Inclusive



- 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

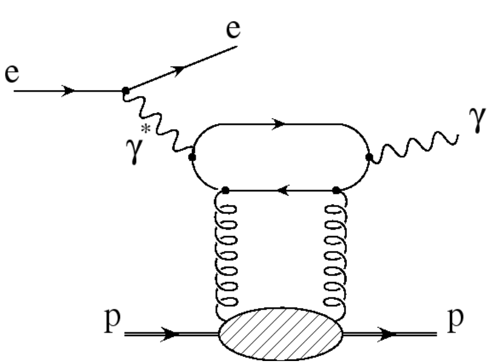
→ Separation of u,d,s,c,b and antiquarks

… 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

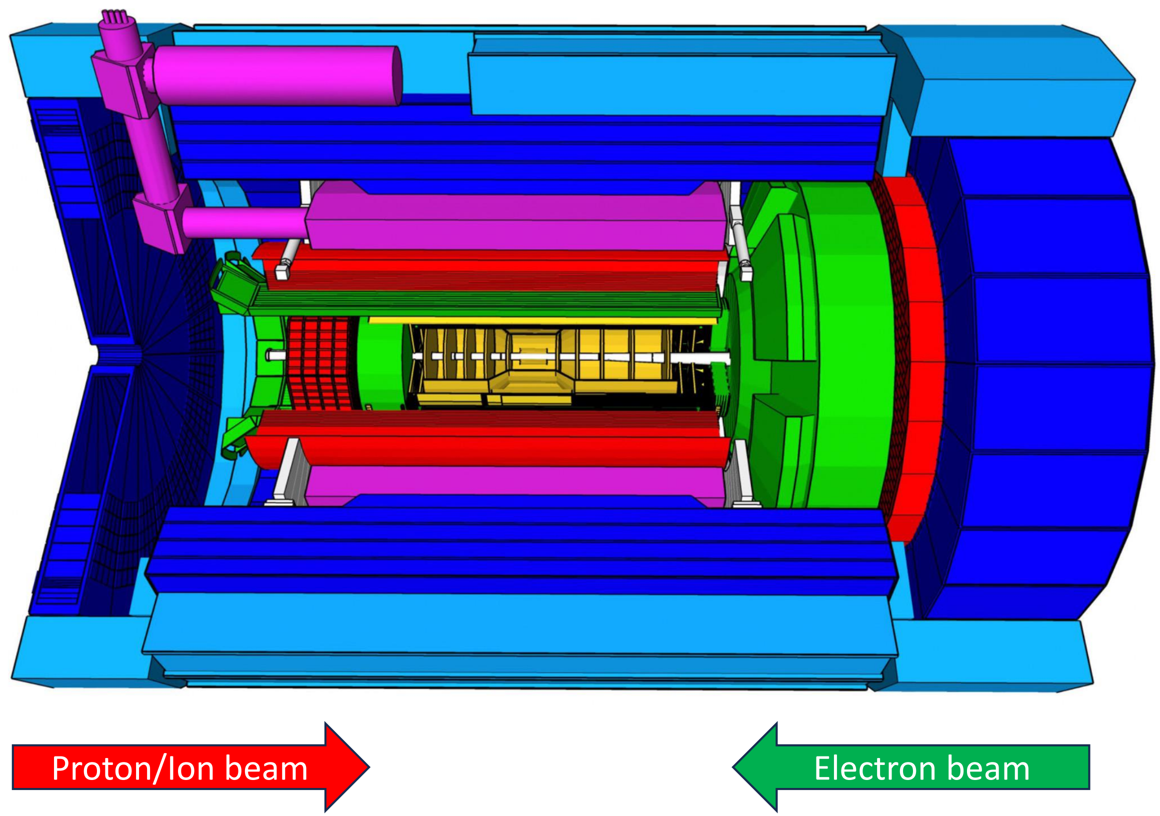
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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

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

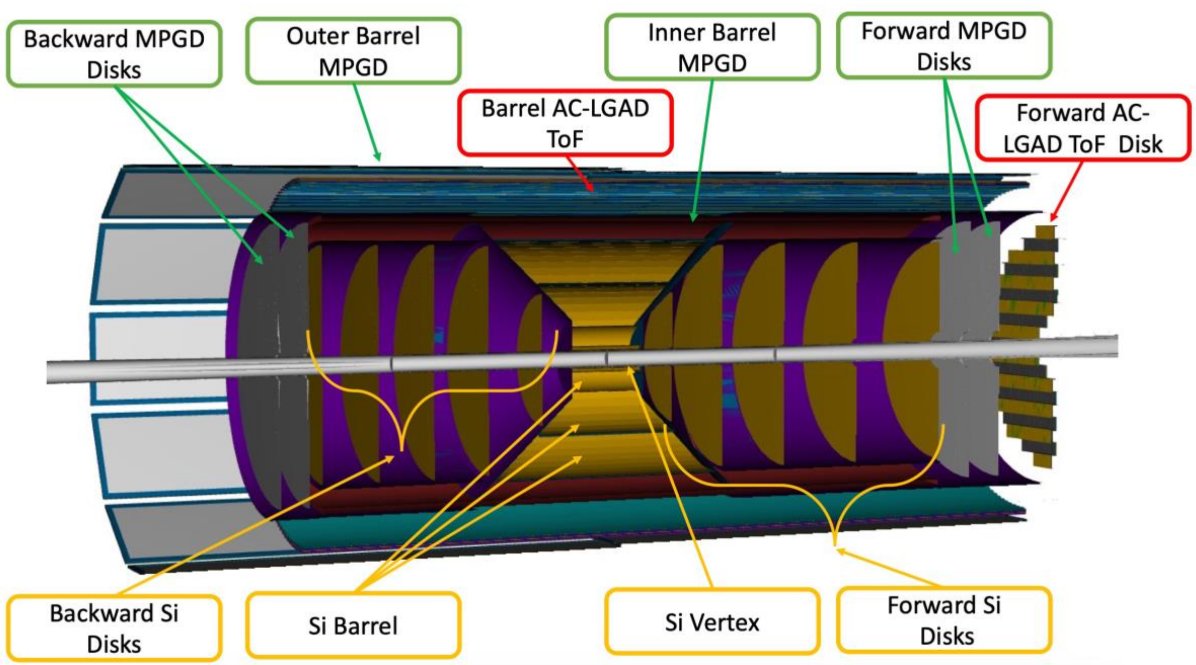
UNIVERSITY OF BIRMINGHAM
Brunel University London
University of Glasgow
Lancaster University
Science & Technology Facilities Council
Daresbury Laboratory
Rutherford Appleton Laboratory
ASTeC
UNIVERSITY OF LIVERPOOL
UNIVERSITY OF OXFORD
UNIVERSITY of York
The Cockcroft Institute of Accelerator Science and Technology
JAI John Adams Institute for Accelerator Science

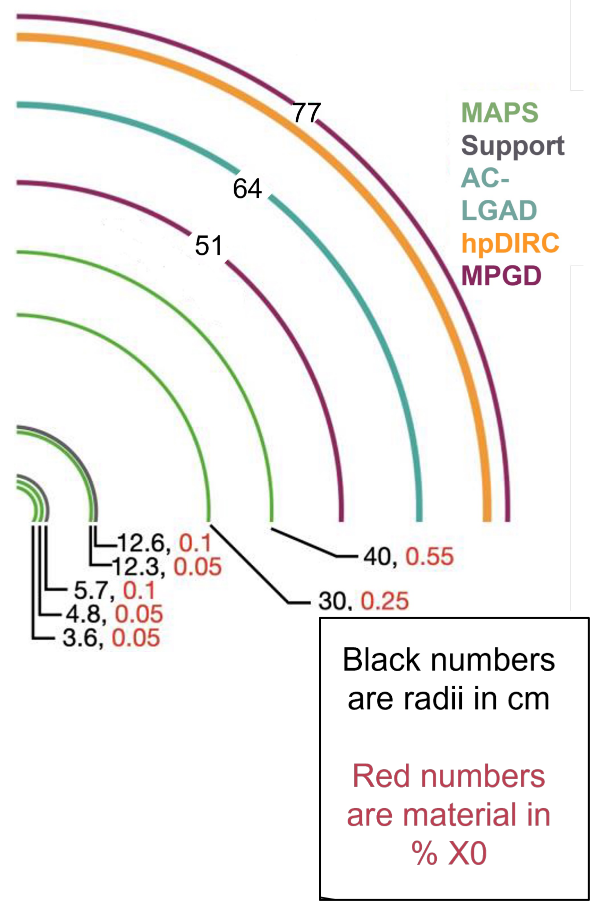
Tracking Detectors

Primarily based on MAPS silicon detectors (65nm technology)

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

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





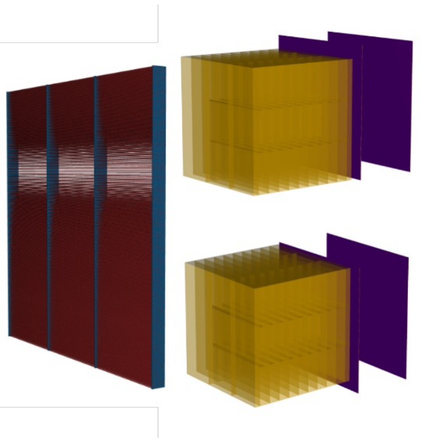
LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

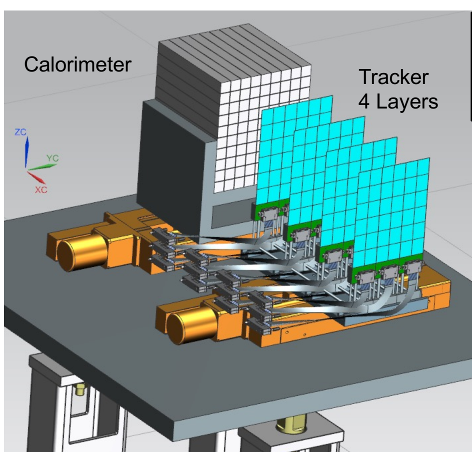
Interaction Region / Beamline Instrumentation

- Extensive beamline instrumentation integrated into IR design

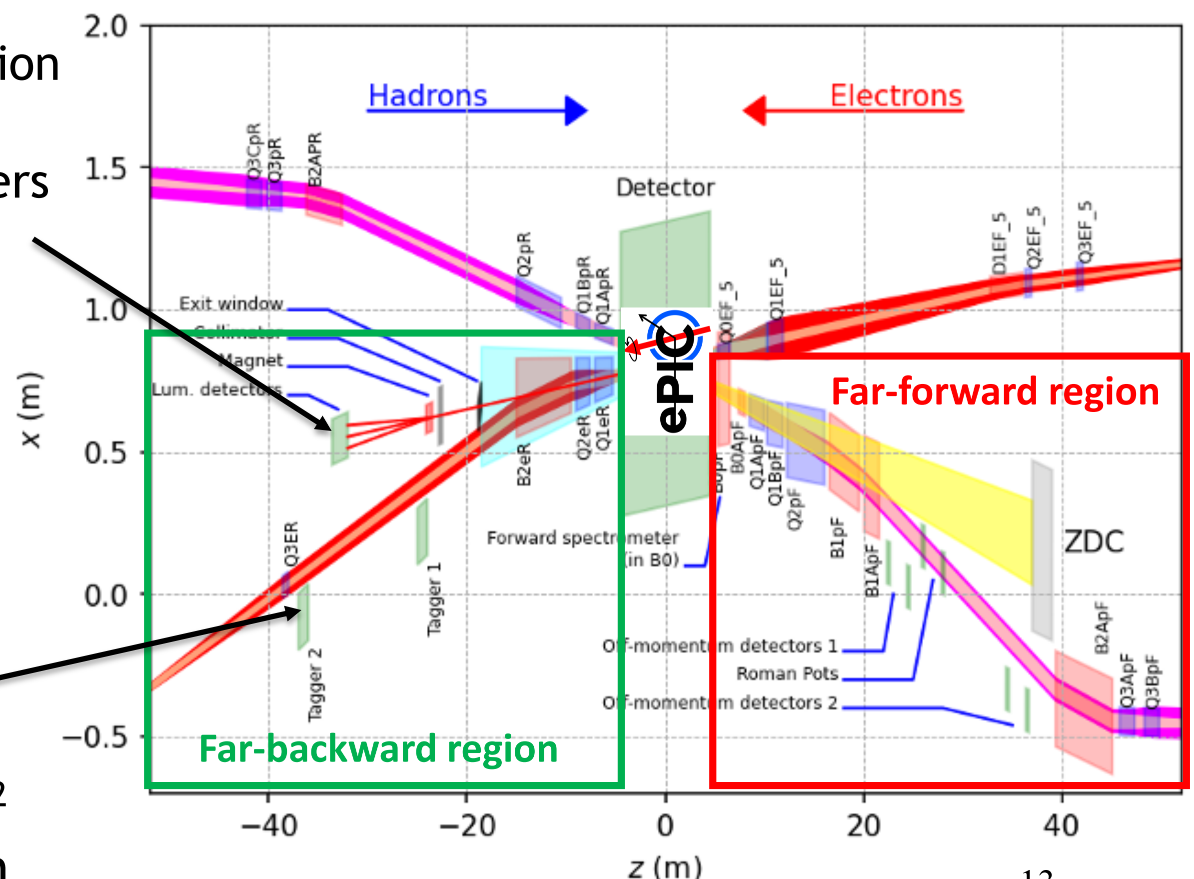
- Tagging electrons and photons in backward direction for lowest Q^2 physics studies and lumi monitoring via photon counting in ep→epγ



Pair-production lumi spectrometers

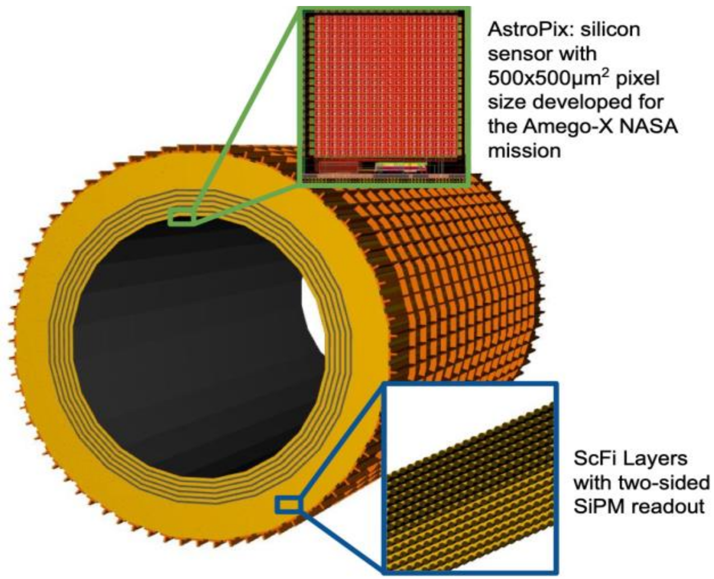


2 low Q^2 electron taggers

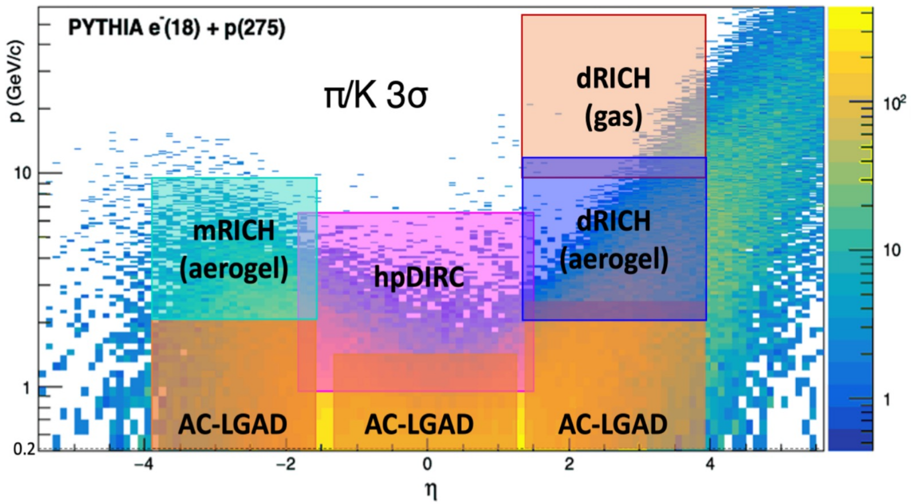


More ePIC Detector Components with synergies elsewhere in HEP

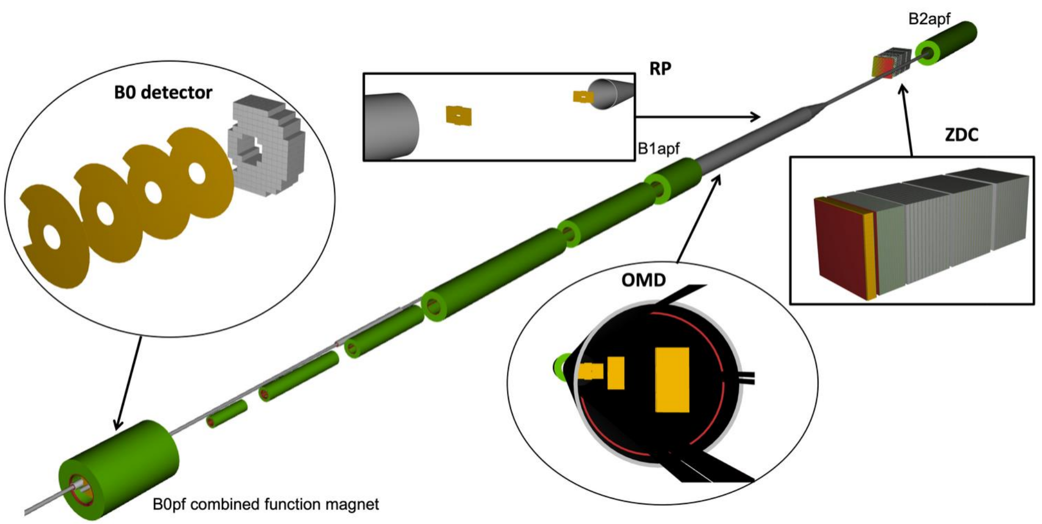
Imaging eCAL



Comprehensive Particle ID



Forward instrumentation integrated with beamline and magnets



Impact of EIC on Parton Densities

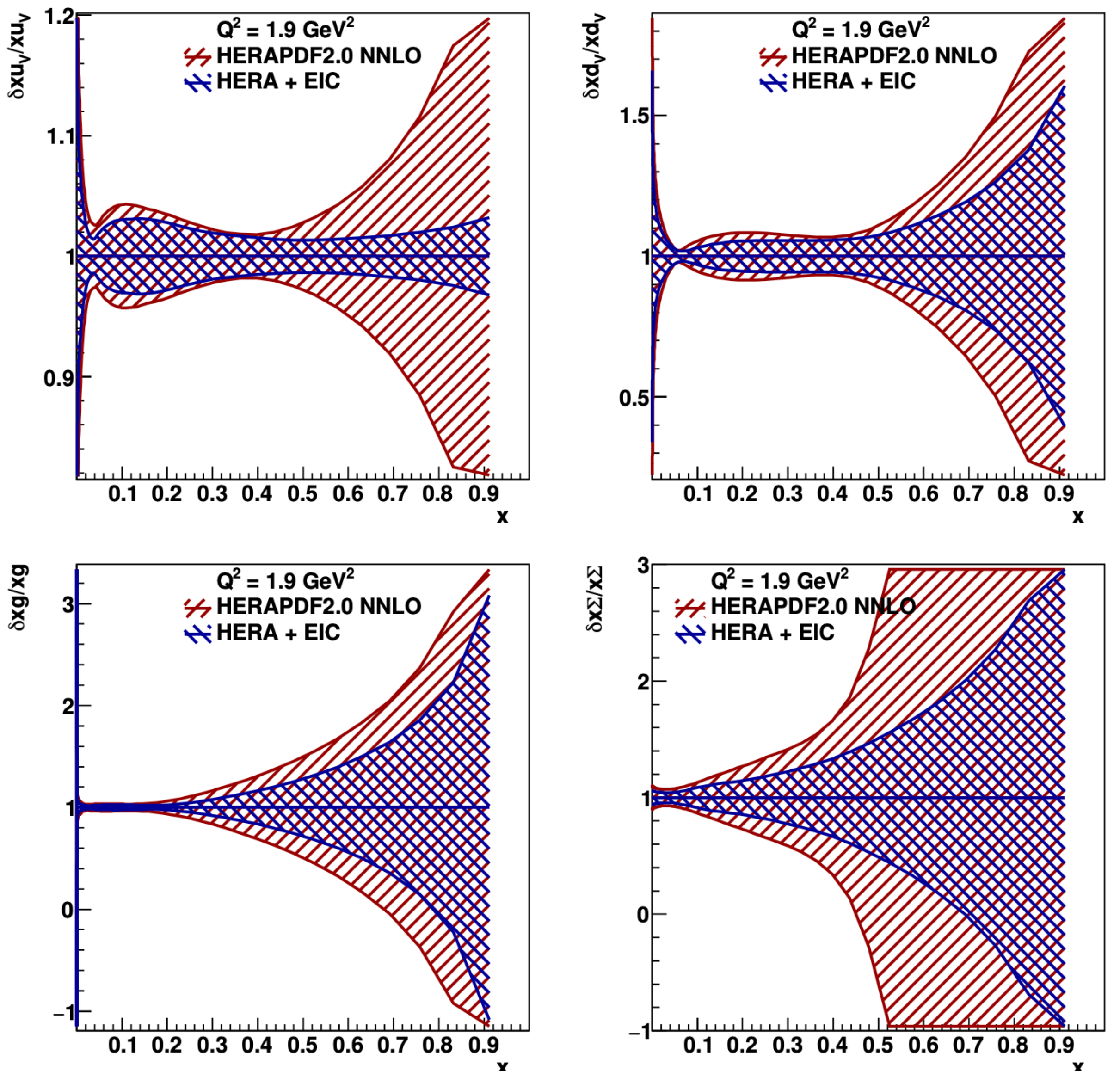
Fractional total uncertainties with / without simulated EIC data added to HERA (linear x scale)

… EIC brings reduction ir large x uncertainties for all parton species

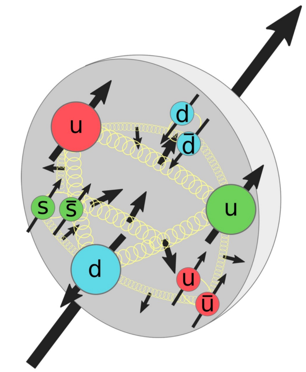
Also:

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

- Nuclear parton densities at low x for the first time



Proton Spin



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

- EMC 'spin crisis' (1987) … quarks only carry ~10% of the nucleon spin (spin ½ more than ↑↑↓)

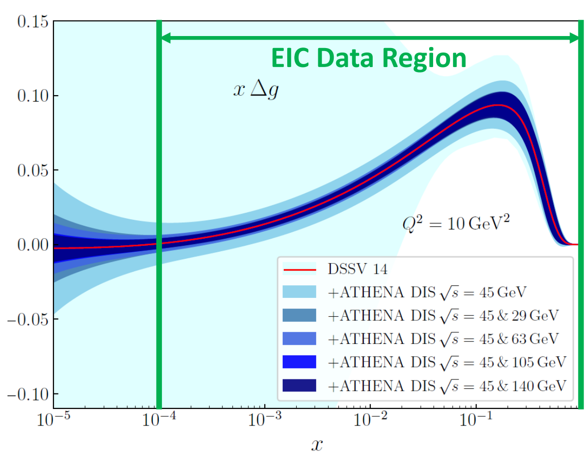
Jaffe-Manohar sum rule:

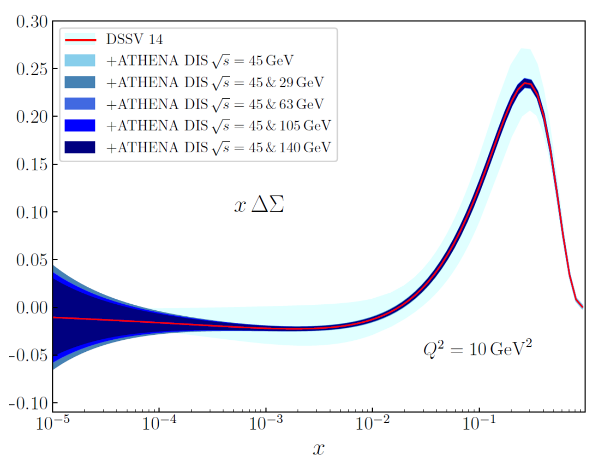
$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

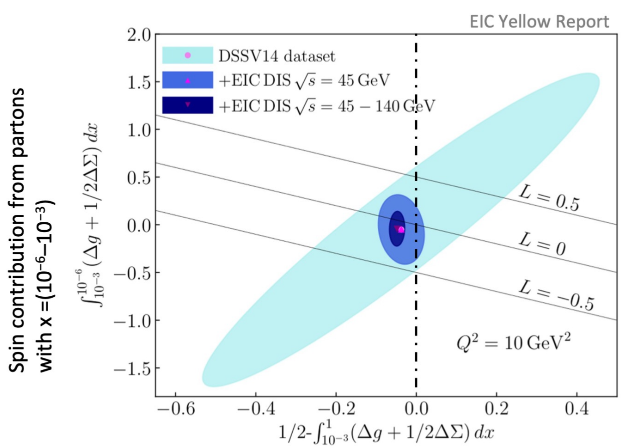
Quark helicity · Gluon helicity · Quark canonical orbital angular momentum · Gluon canonical orbital angular momentum

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

- Simulated EIC inclusive data (15fb^{-1}, 70% e,p Polaris'n) shows very significant impact on polarised gluon and quark densities → orbital angular momentum constrained by implication





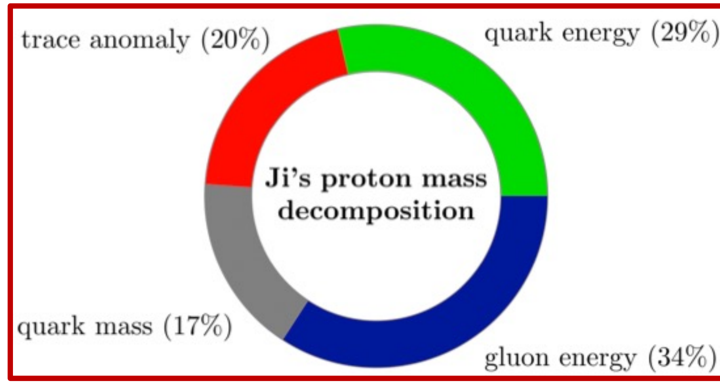


Room left for potential OAM contributions to the proton spin from partons with x > 0.001

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

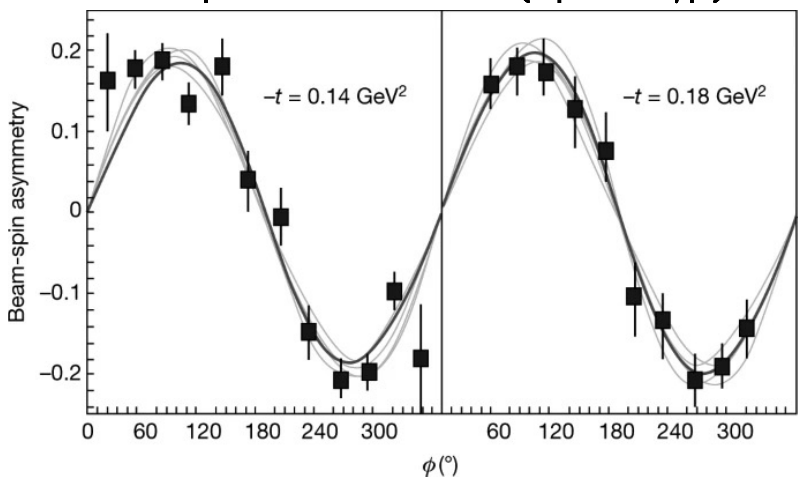
QCD trace anomaly (purely quantum effect - chiral condensates)

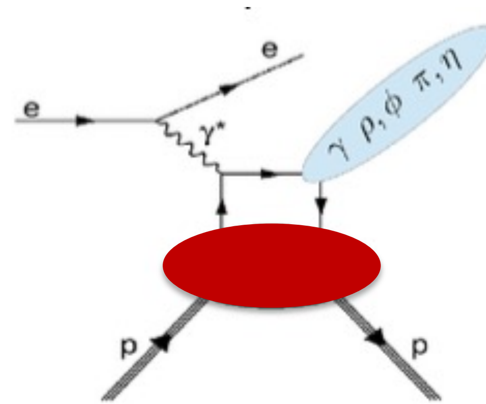
Understanding 3D relative location and motion of partons within proton is pathway to understanding proton mass emergence

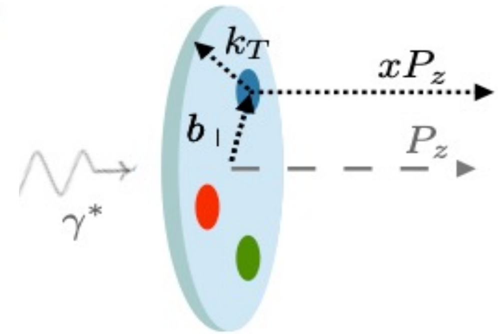
3D Structure

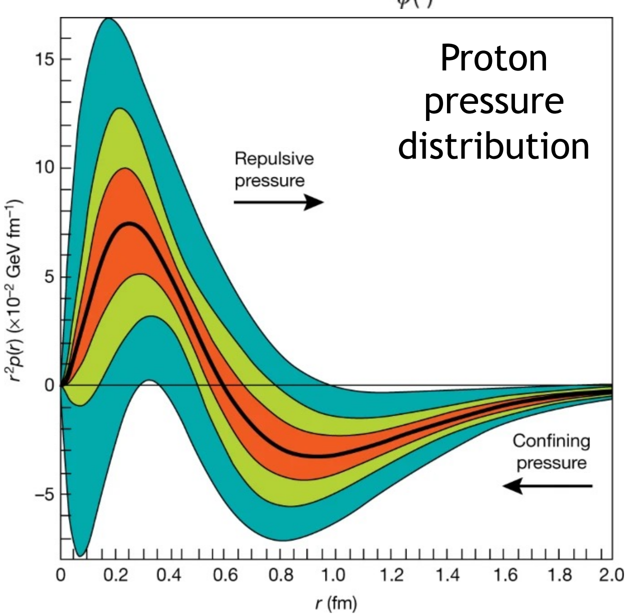
Exclusive processes, yielding intact protons, require exchange of ≥2 partons
→ Sensitive to parton correlations in longitudinal & transverse momentum and spatial coordinates

CLAS experiment: DVCS (ep → eγp)



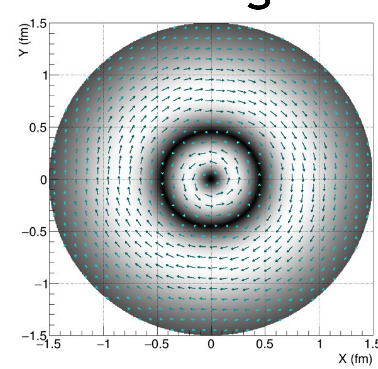






Hints at rich 3D picture from JLab

- 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



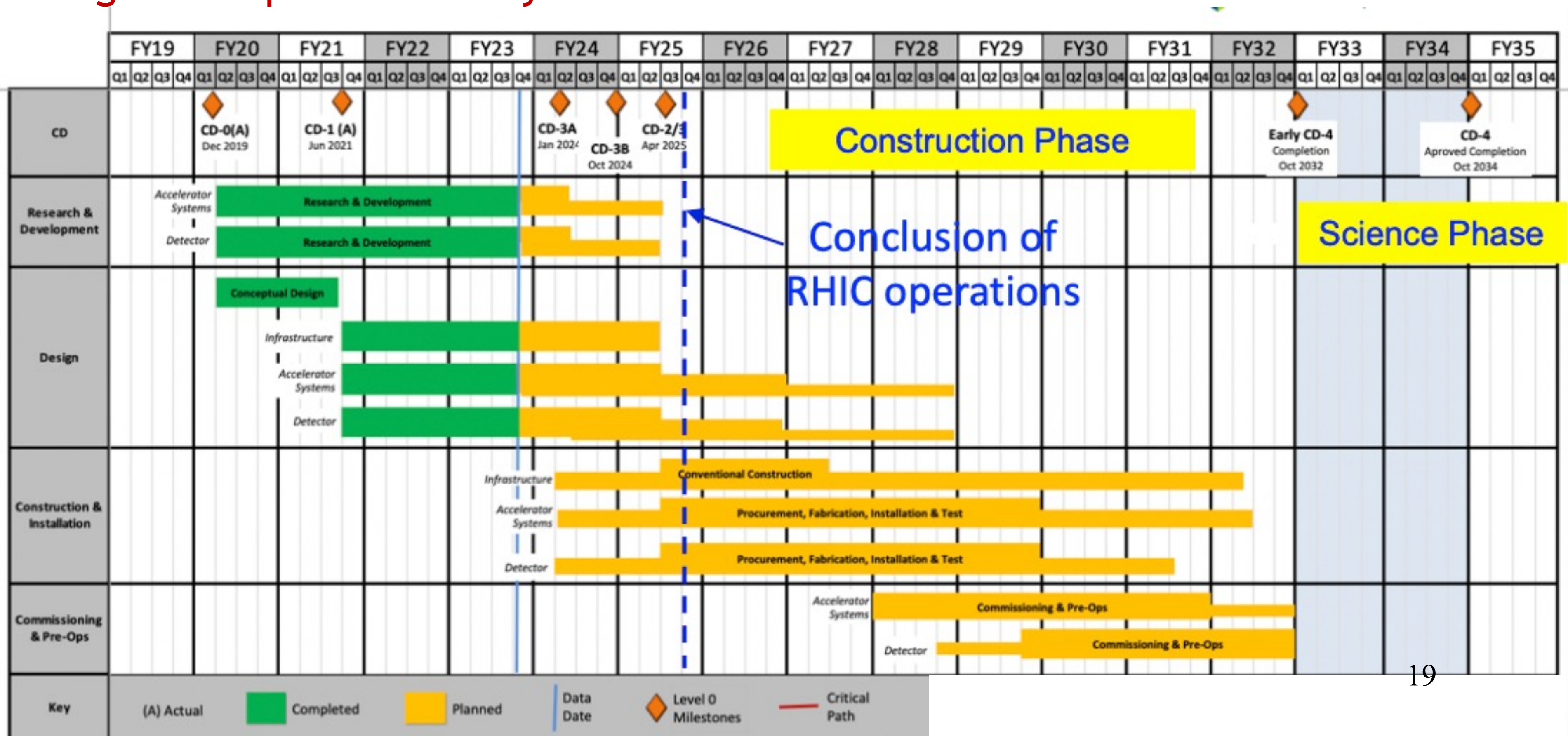
Status / Timeline

- Total cost ~$2.5Bn (US project funds accelerator + most of one detector)

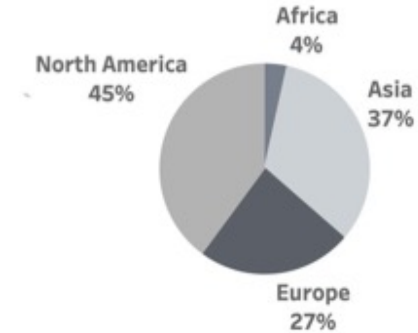
- Still several steps to go, but on target for operation early/mid 30s

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

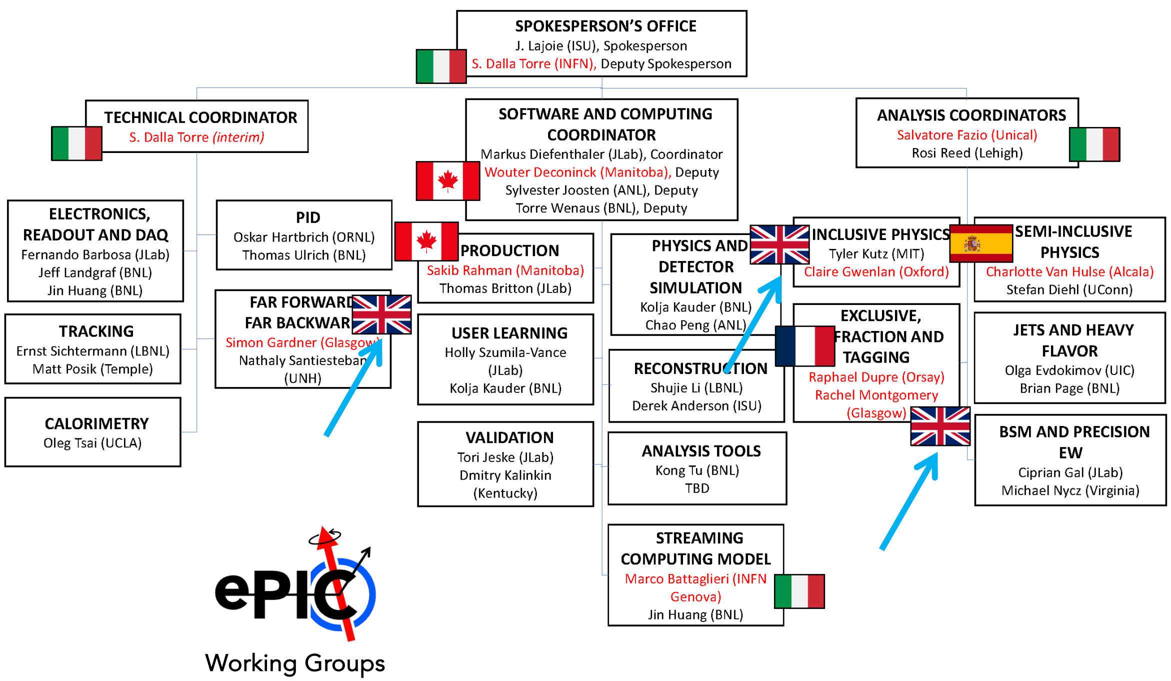
Technical Design Report: end 2025 (prelim 2024)

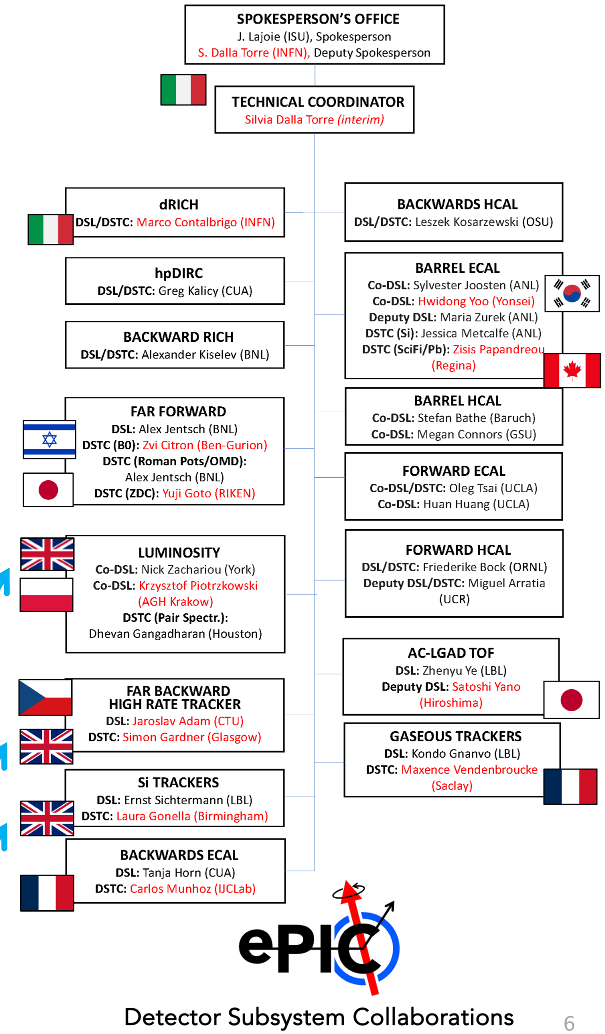


ePIC demographics and Current UK Leadership



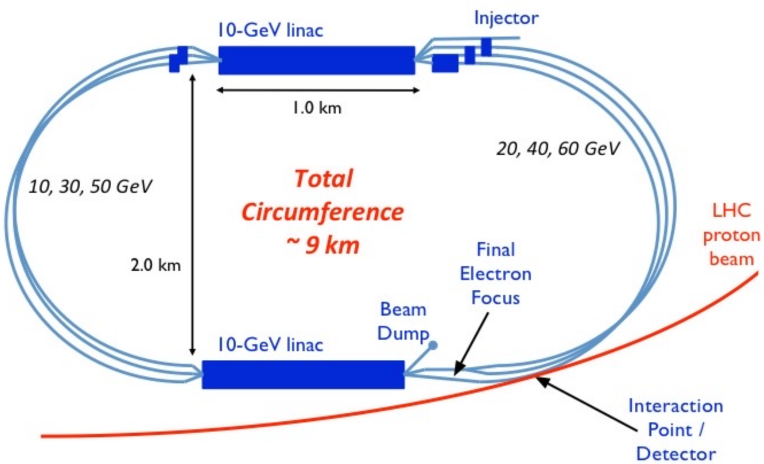
- Currently >850 collaborators (UK is 4th largest)
- UK physicists deeply involved through initial motivation, collaboration formation and now ongoing roles





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

LHeC and FCC-eh

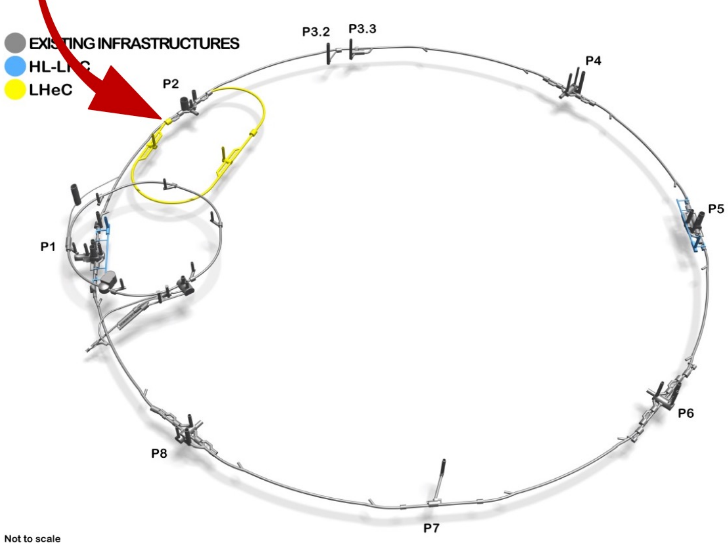


- Recirculating Energy-Recovery Linac (ERL) colliding with LHC (or FCC) hadrons at CERN

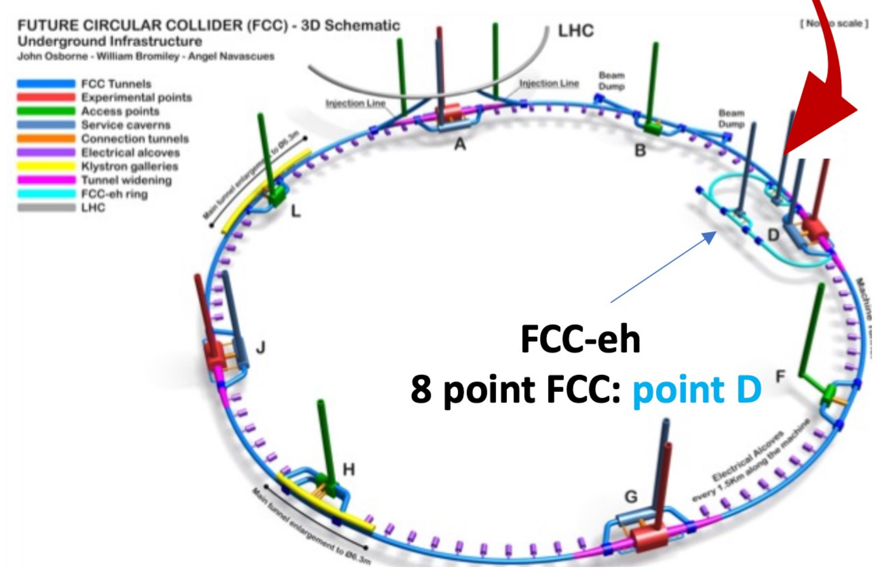
- 'Sustainable' acceleration: ~100 MW (similar to LHC today)

- Technology development for electron machines or injectors?

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)

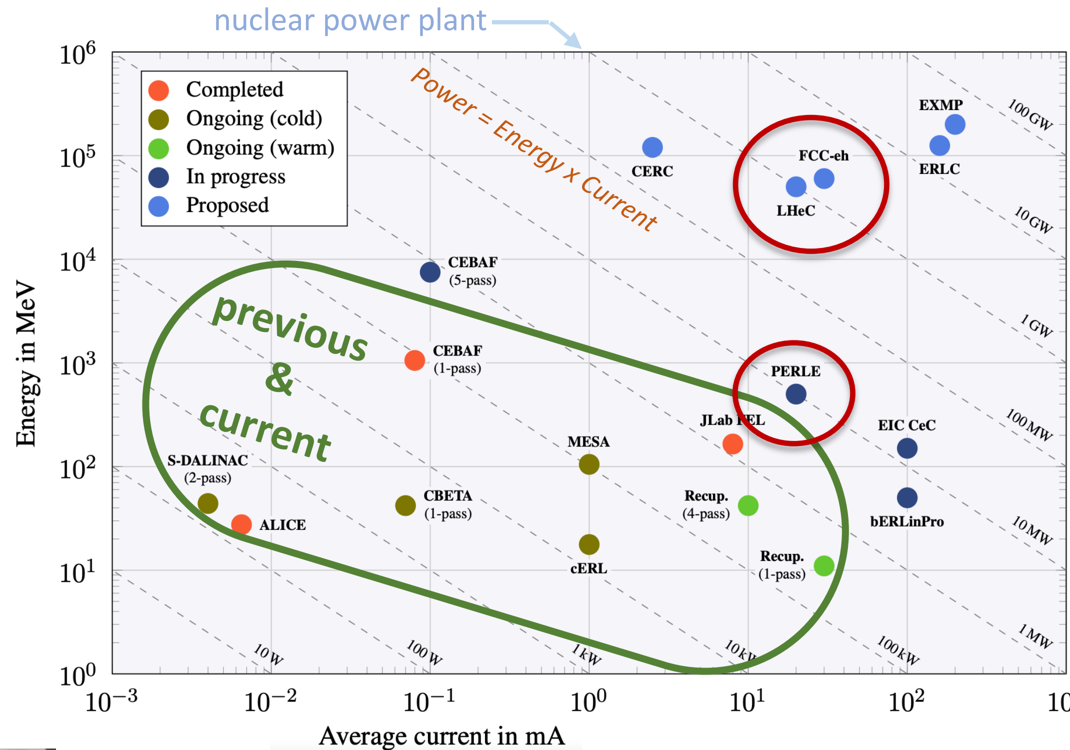


FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



Energy Recovery Linacs

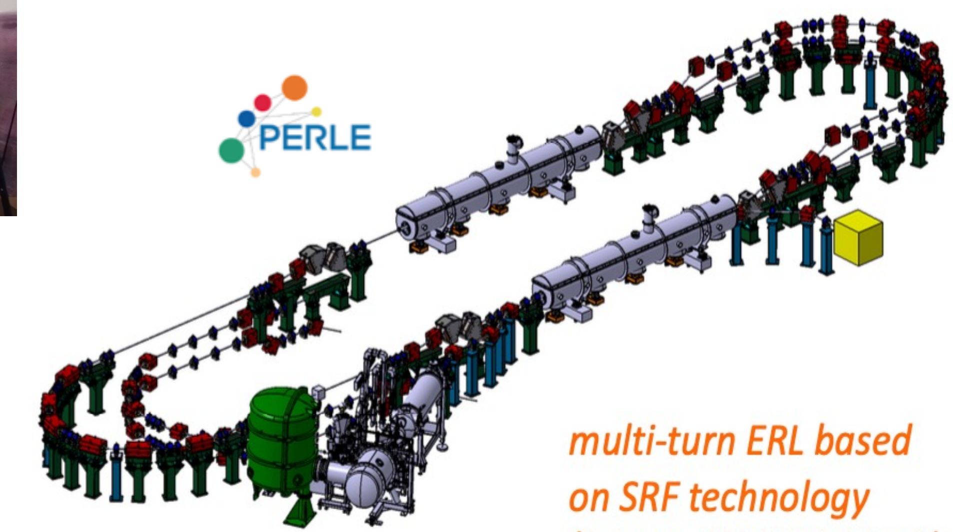
- Demonstrating ERL scalability is critical path
- Prototype (PERLE @ IJCLab / Orsay) implementation started
- First stage (one turn) by 2028.



HV tanks

Electron DC-gun

Photo-cathode



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

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

Structure of CERN-mandated LHeC / FCC-eh study towards European Strategy

More information:
https://indico.cern.ch/event/1335332/

2023 | WS | 2024 | WS | 2025 | TWS | *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces
Nestor Armesto, Claire Gwenlan, Paul Newman

general-purpose high-energy physics program: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions
Monica D'Onofrio, Uta Klein, Christian Schwanenberger

ep/eA-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics program
Maarten Boonekamp, Daniel Britzger, Christian Schwanenberger

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics
Paul Newman, Yuji Yamazaki

developing a sustainable LHeC and FCC-eh collider program
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …
Oliver Bruning, Yannis Papaphilippou

- five thematic physics and technology working groups
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)

Subscribe to mailing lists via https://e-groups.cern.ch/ : use the search option, and search for "lhec-fcceh-all" or "ep-eA-WG" in all e-groups

[Coordinator Jorgen d'Hondt]

A largely UK-conceived project and still with UK leadership throughout

Running Scenarios Considered in CDR

- $e^{\pm}p$ 50 GeV x 7 TeV with lepton polarization +0.8 / 0 / -0.8

Parameter	Unit	Run 5 Period	Run 6 Period	Dedicated
Brightness $N_p/(\gamma\epsilon_p)$	10^{17}m^{-1}	2.2/2.5	2.2/2.5	2.2/2.5
Electron beam current	mA	15	25	50?
Proton β^*	m	0.1	0.7	0.7
Peak luminosity	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	0.5	1.2	2.4
Proton beam lifetime	h	16.7	16.7	100
Fill duration	h	11.7	11.7	21
Turnaround time	h	4	4	3
Overall efficiency	%	54	54	60
Physics time / year	days	160	180	185
Annual integrated lumi.	fb^{-1}	20	50	180

[Pile-up ~0.1]

Running concurrently with pp at HL-LHC:

… integrated lumi of 20 fb-1 per year at Run 5 → 50 fb^{-1} initial dataset

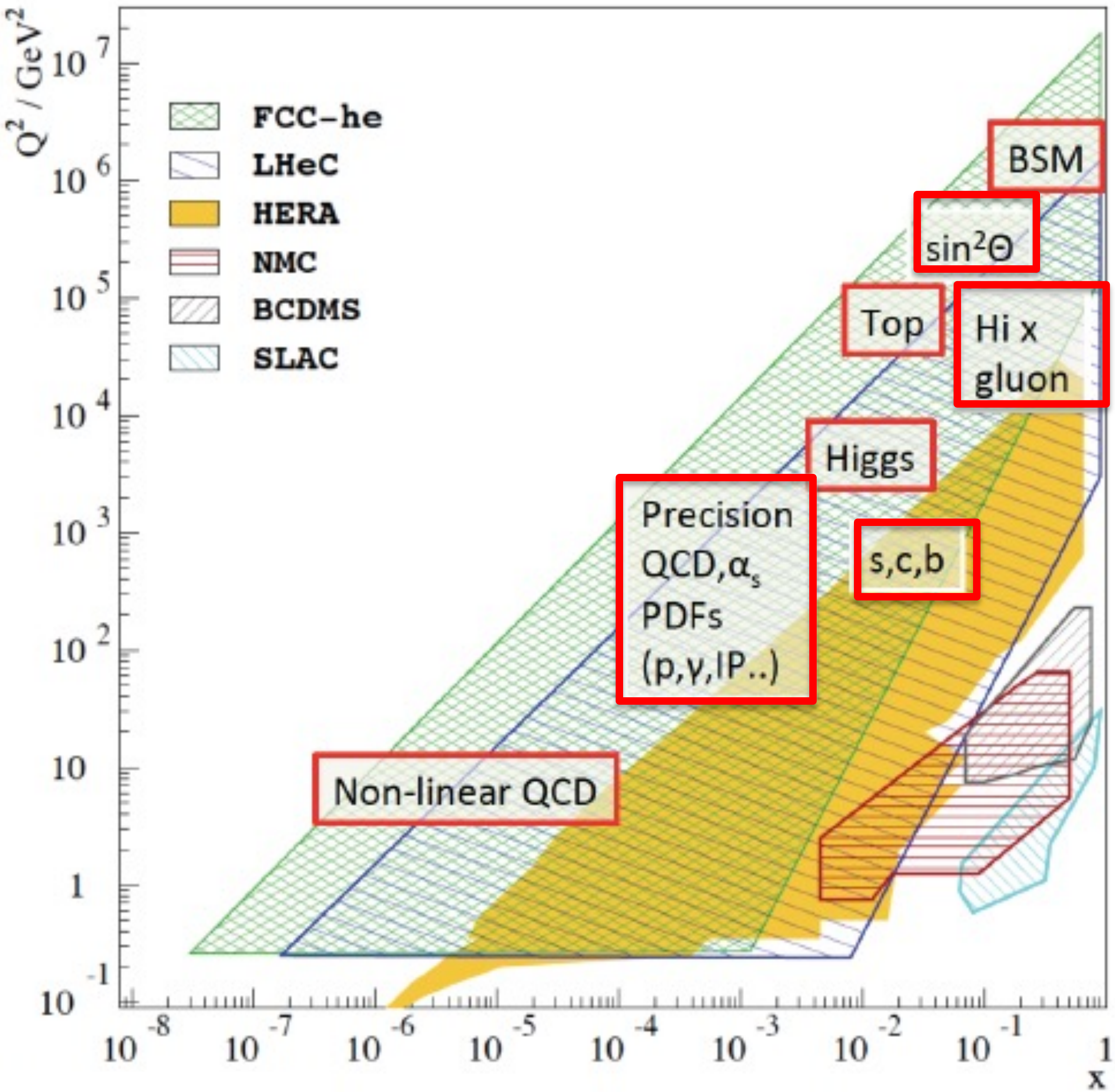
… integrated lumi of 50 fb-1 per year at Run 6 → few 100 fb^{-1} total @ HL-LHC

Running in standalone ep mode:

… integrated lumi of 180 fb-1 per year → 1 ab^{-1} total target in a few years

- eA 50 GeV x 2.76 TeV at 10 fb-1 per year

LHeC Physics Targets and Detector Implications



Standalone Higgs, Top, EW, BSM programme

→ General purpose particle physics detector
→ Good performance for all high p_T particles
→ Heavy Flavour tagging

Precision proton PDFs, including very low x parton dynamics in ep,eA

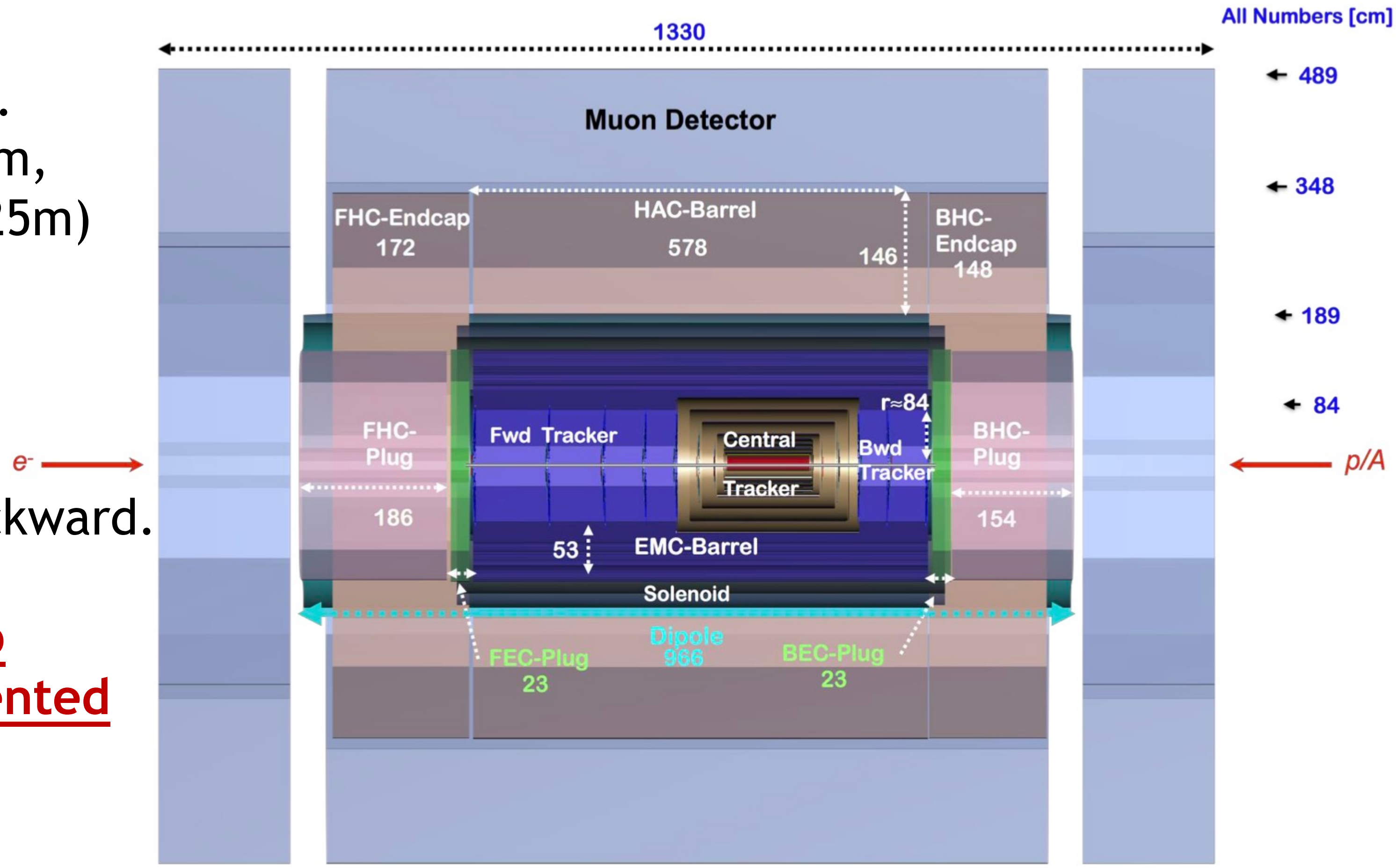
→ Dedicated DIS exp't
→ Hermeticity
→ Hadronic final state resolution for kinematics
→ Flavour tagging / PID
→ Beamline instruments

Detector Overview (as in 2020 CDR Update)

Compact
13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

Hermetic
- 1° tracking acceptance forward & backward.

Beamline also well instrumented



'Could be built now', but many open questions:

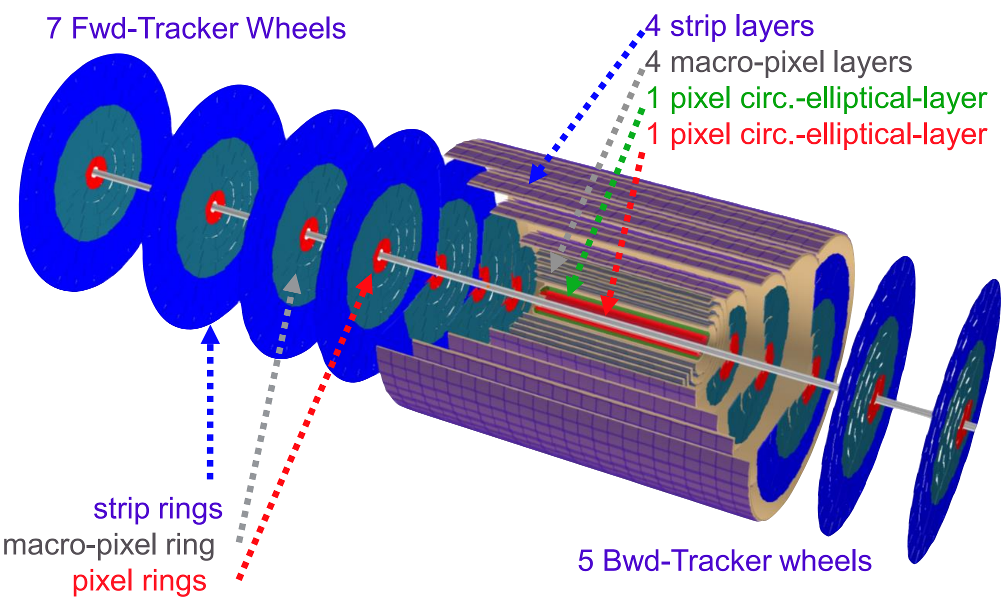
- A snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- Possibly lacking components for some ep/eA physics (eg. Particle ID)
- Not particularly well integrated or optimized

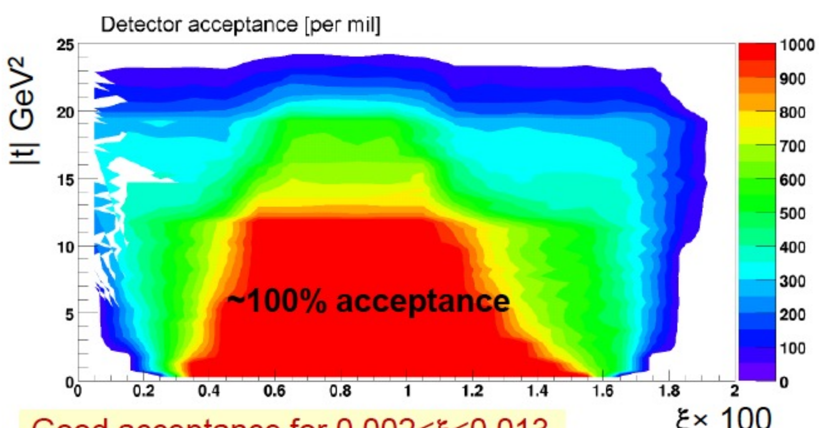
… Synergies with EIC, LHCb, ALICE, future lepton colliders still to be explored

Detector technologies build on LHC and EIC and inform future lepton colliders

e.g. Silicon tracker design in CDR

- HV-CMOS MAPS with bent / stitched wafers (as ALICE and ePIC) and semi-elliptical inner layers to cope with synchrotron fan → ~20% X_0 / layer up to η~4.5





Good acceptance for 0.002<ξ<0.013

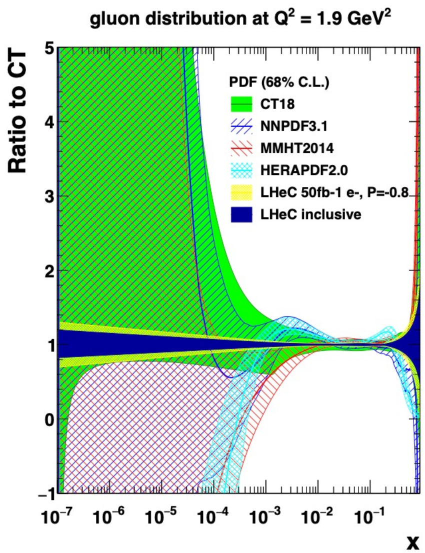
e.g. Forward proton spectrometer in cold region (~420m)?

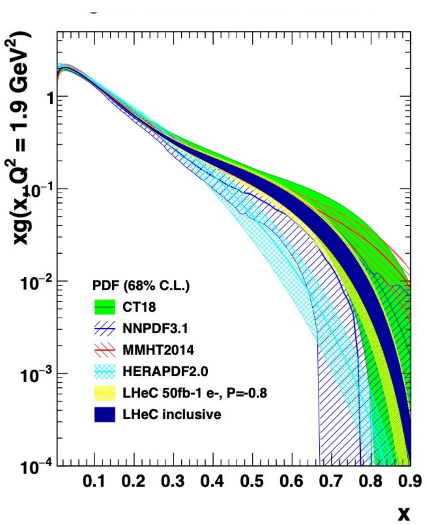
- Reuse of technology proposed for LHC, accessing protons scattered at very low momentum loss

The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC

LHeC: Revolutionary Proton PDF Precision

e.g. High x
Gluon Density

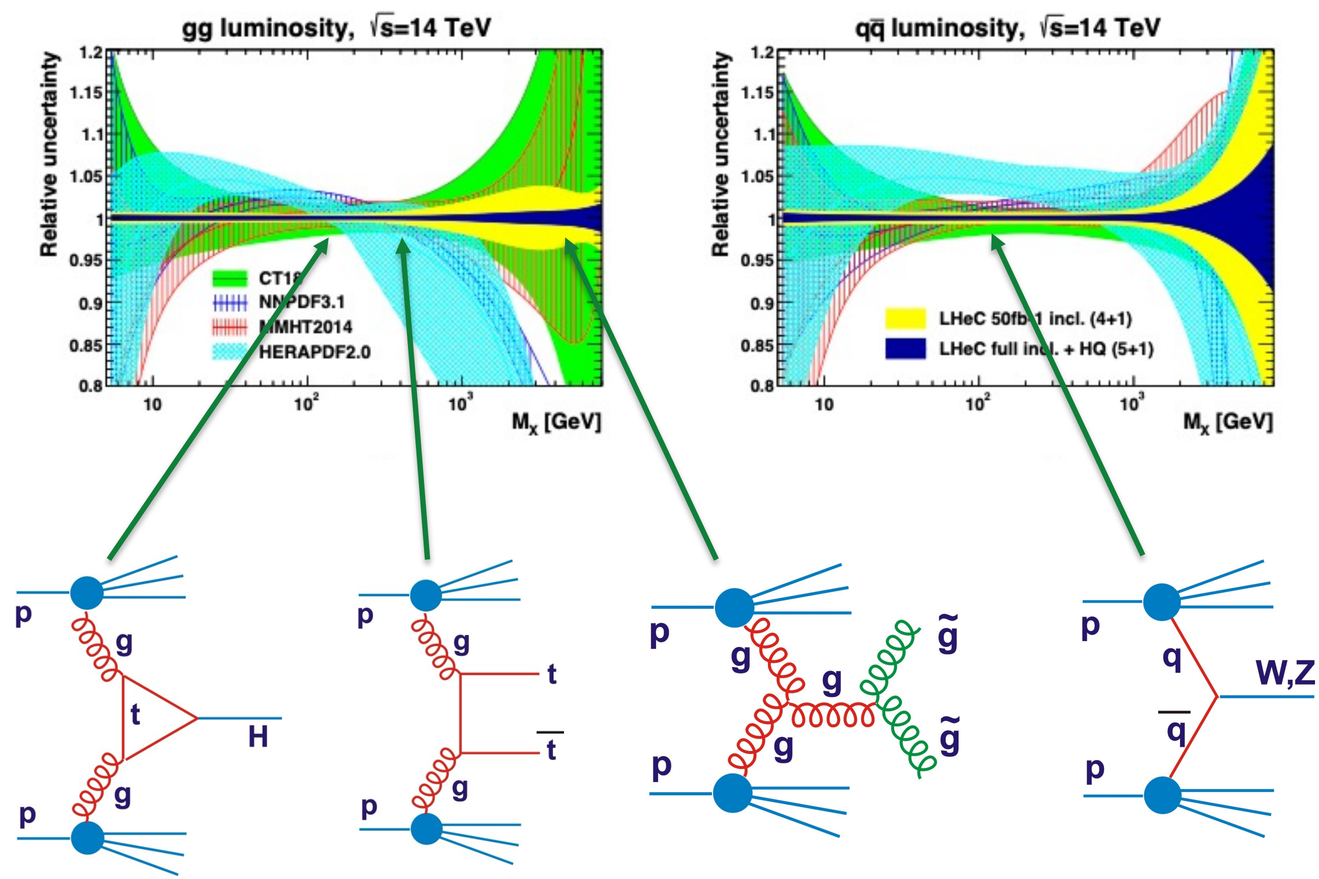




- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements
  (e.g. M_W → 2 MeV from PDFs, $\sin^2\theta$ → 0.03%)

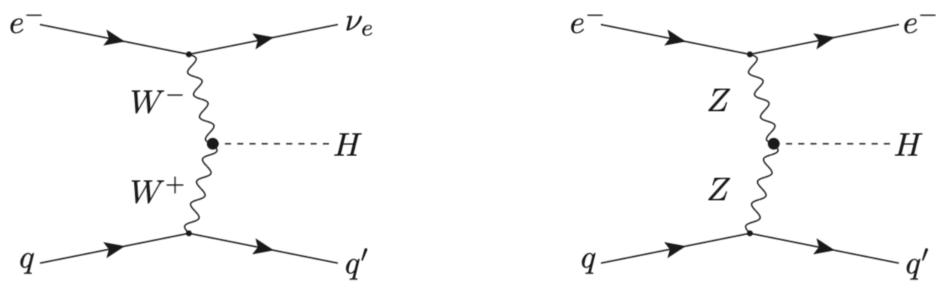
→ Elucidates novel very low x dynamics

e.g. Parton luminosities for pp at 14 TeV



LHeC (SM) Higgs Programme

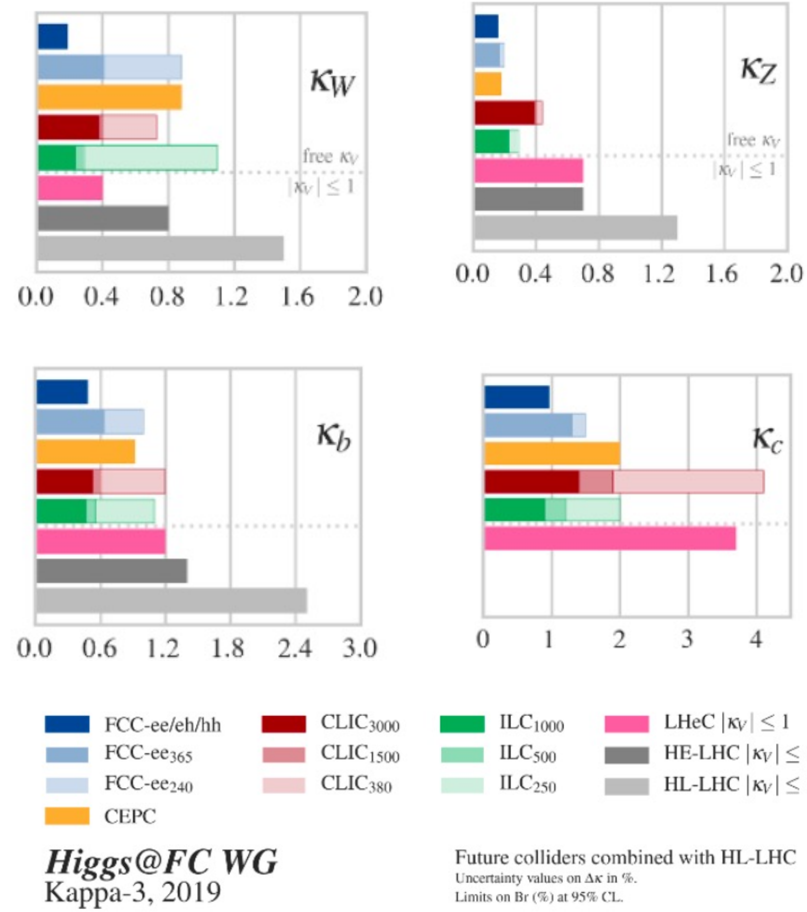
- Dominant production mechanism charged current (WW), easily distinguished from sub-dominant neutral current (ZZ)



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

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



[JHEP 01 (2020) 139]

A 2040s Bridging Opportunity?

- LHeC is not the next major new collider for CERN

- LHeC could be an impactful final upgrade to LHC …

    - potentially 'affordable' on required timescale
    - technically realisable for late 2030s
      (ERL technology = critical path)
    - extending energy frontier sensitivity within a
      few years of running
    - complementing and enabling HL-LHC programme
    - ensuring continuity of collisions and scalar sector
      exploration in the 2040s
    - exploring SRF, ERL options & detector technologies

… as a testing ground (injector?) for a future major facility

SUMMARY

From the early 2030s:
The Electron Ion Collider will transform our understanding of nucleon and nuclear structure, scientifically complementing past / future energy frontier DIS facilities.

From the late 2030s:
The Large Hadron electron Collider offers an achievable bridging project for CERN, with an impactful physics programme, including further empowerment of the LHC and exploration of the scalar sector.

… see following talks from Claire & Monica

"Circles in a circle"
Wassily Kandinsky (1923)
Philadelphia Museum of Art