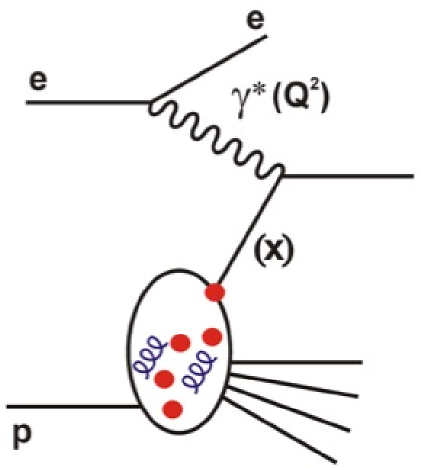
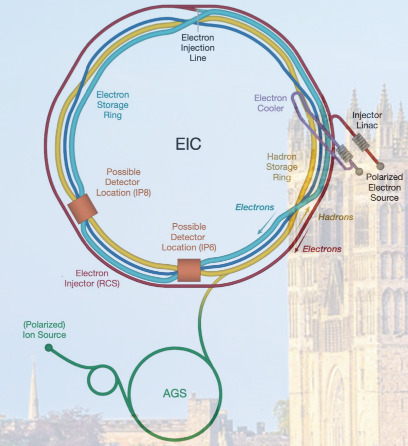
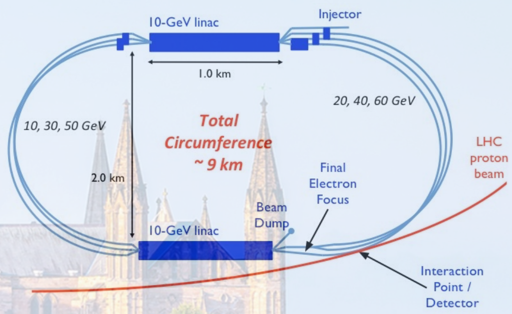
# The Deep-Inelastic Scattering Landscape




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)

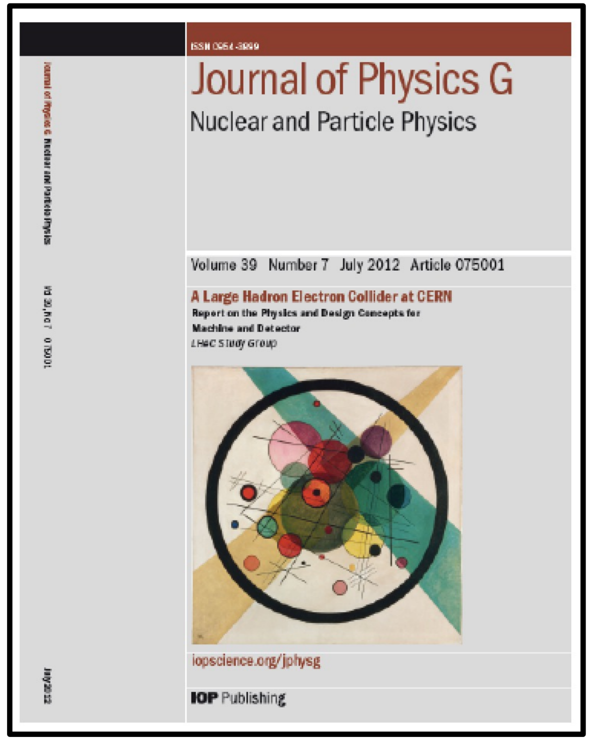
Max Klein
13/5/1951 - 23/8/2024

# Max Klein

## 13/5/1951 - 23/8/2024


2008 2009 2010 2012 2014 2015 2017 2018 2019 2022

Max Klein
13/5/1951 - 23/8/2024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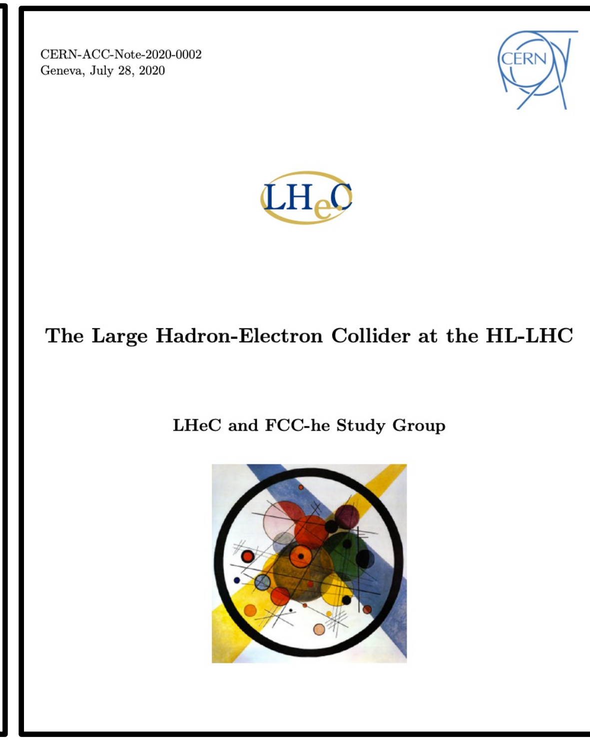
Volume 39 Number 7 July 2012 Article 075001
A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group
iopscience.org/jphysg
IOP Publishing

arXiv:1206.2913

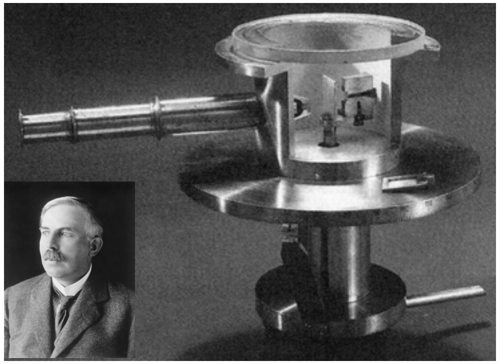

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC
LHeC and FCC-he Study Group

arXiv:2007.14491


2008 2009 2010 2012 2014 2015 2017 2018 2019 2022

# Scattering Experiments Exploring Matter

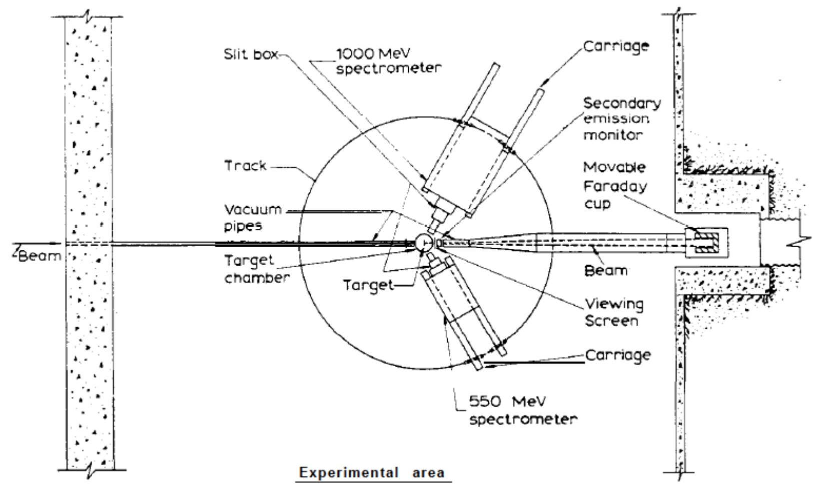


1911, Rutherford discovery of atomic nucleus

*"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

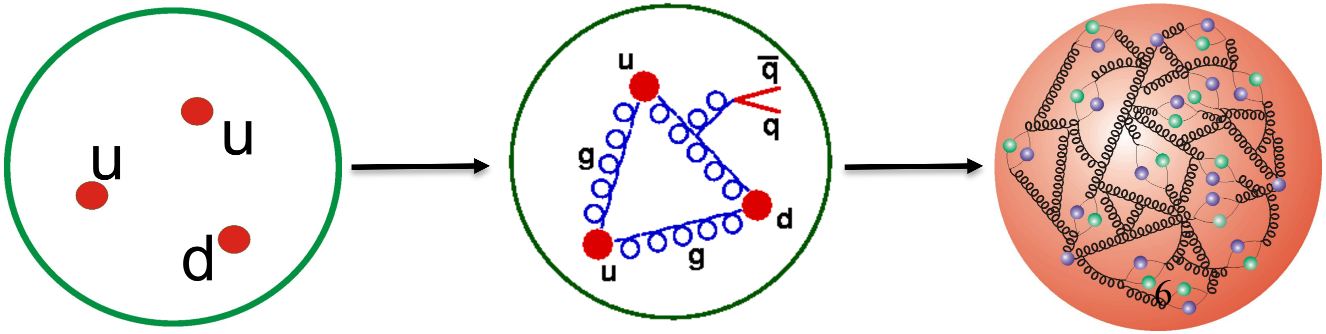
- The only ever collider of electron with proton beams: $\sqrt{s_{ep}} \sim 300$ GeV

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

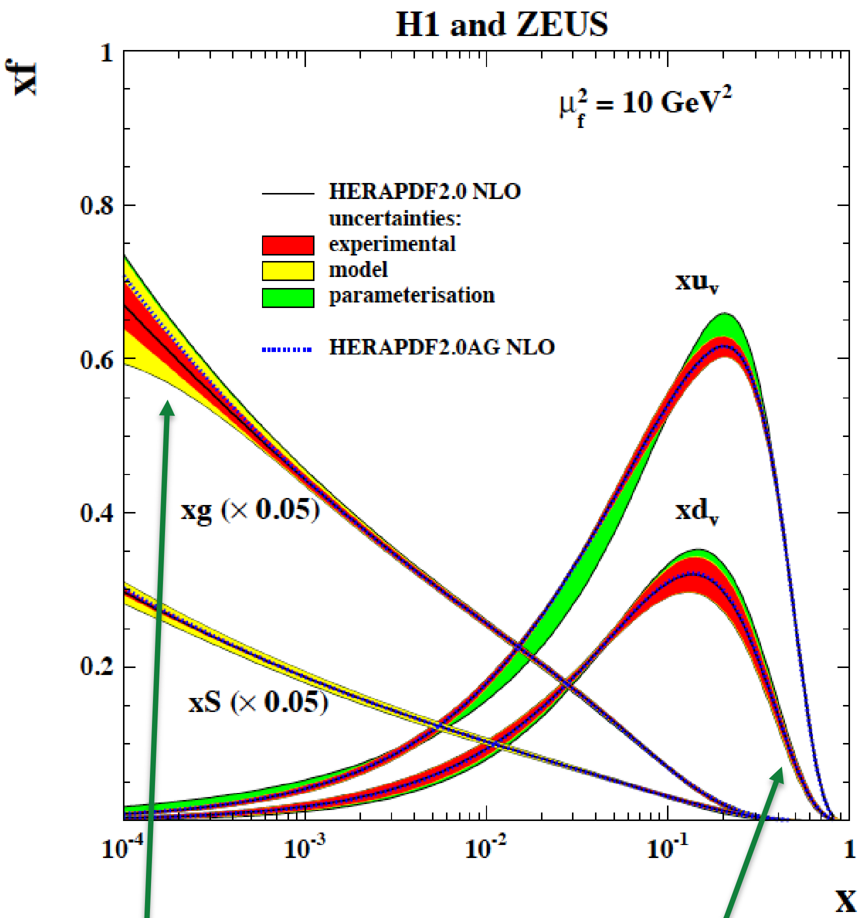
… Resolved dimension $\sim 10^{-20}$ m

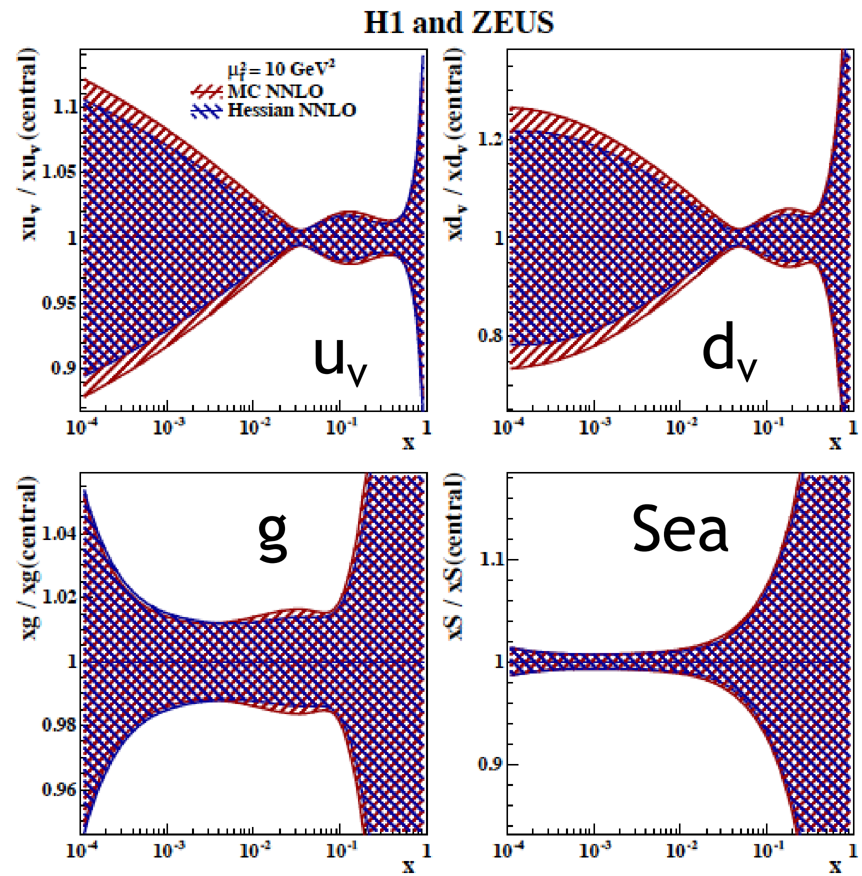
→ Source of much of our knowledge of proton (longitudinal) structure extending to partons of $x<10^{-4}$ mom$^{m}$ fraction


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



# Proton PDFs from HERA (HERAPDF2.0)



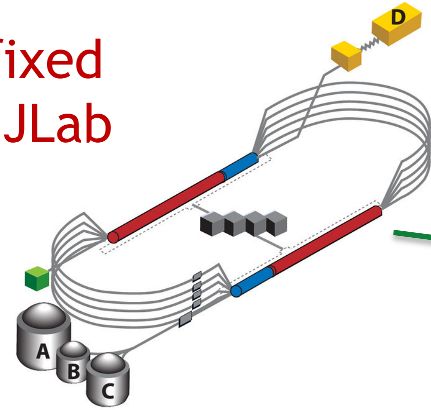

Strong interaction dragons?

Input to energy frontier discovery?

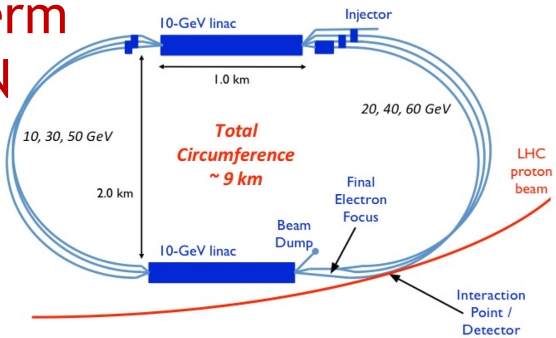
- At x ~ $10^{-2}$ : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=$10^{-3}$ (kinematic limit)
  - above x=$10^{-1}$ (limited lumi)

# Current and Future ep Colliders

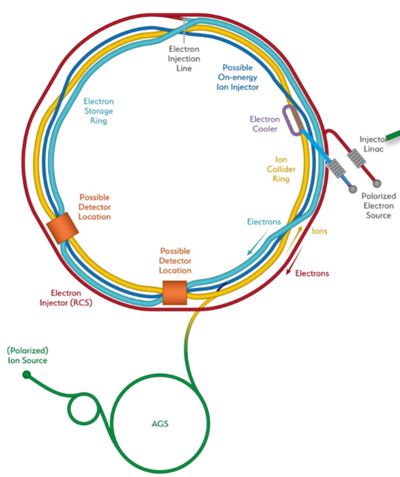
Ongoing fixed target @ JLab

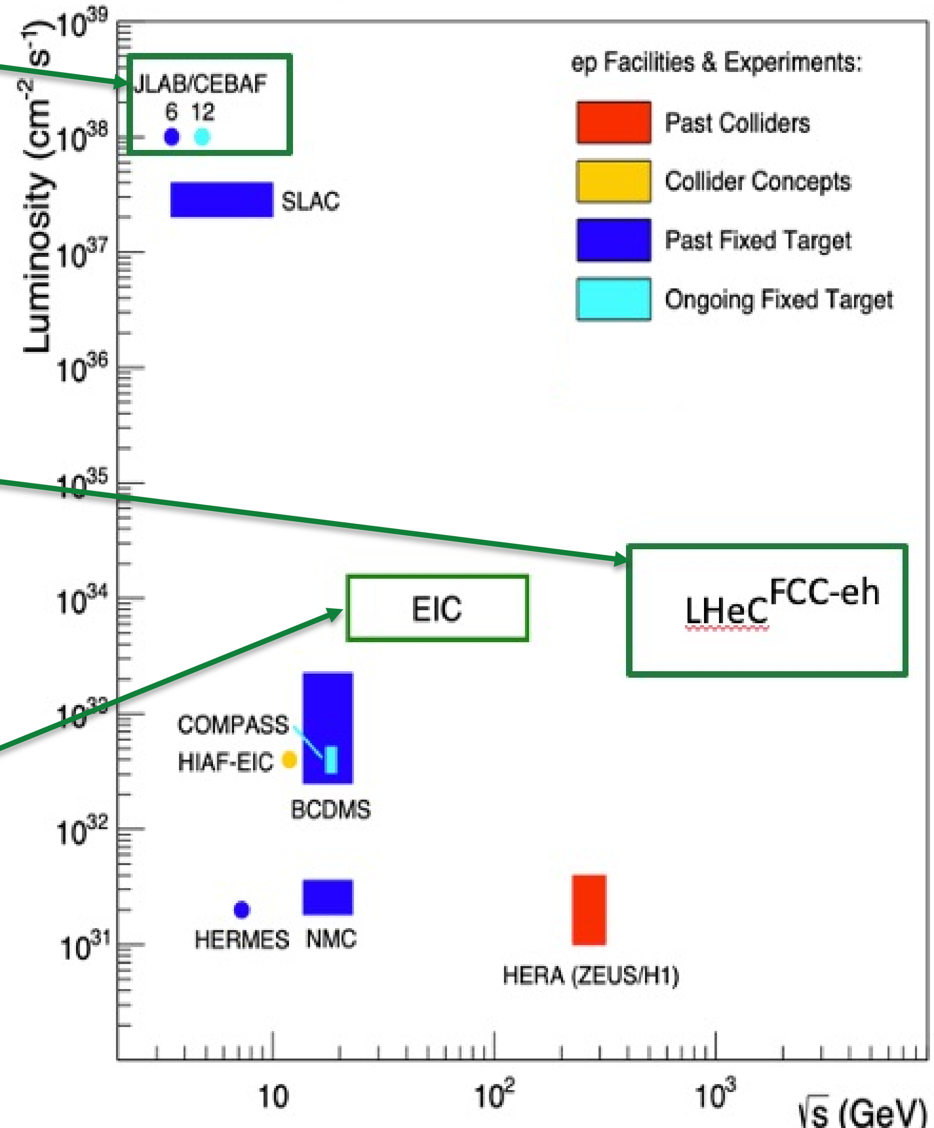



Longer-term @ CERN

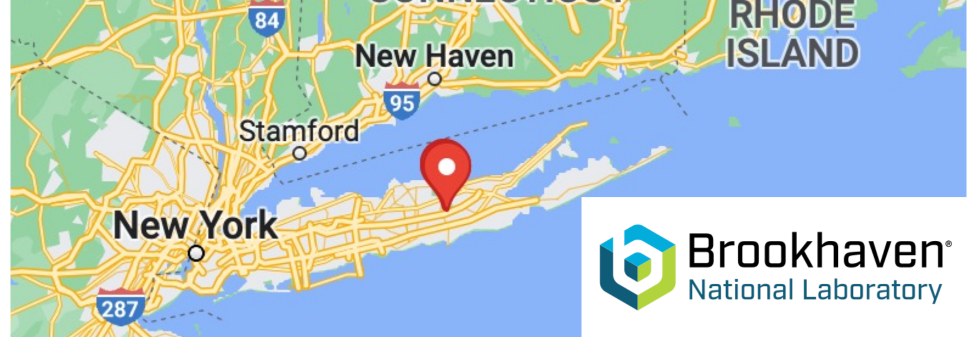


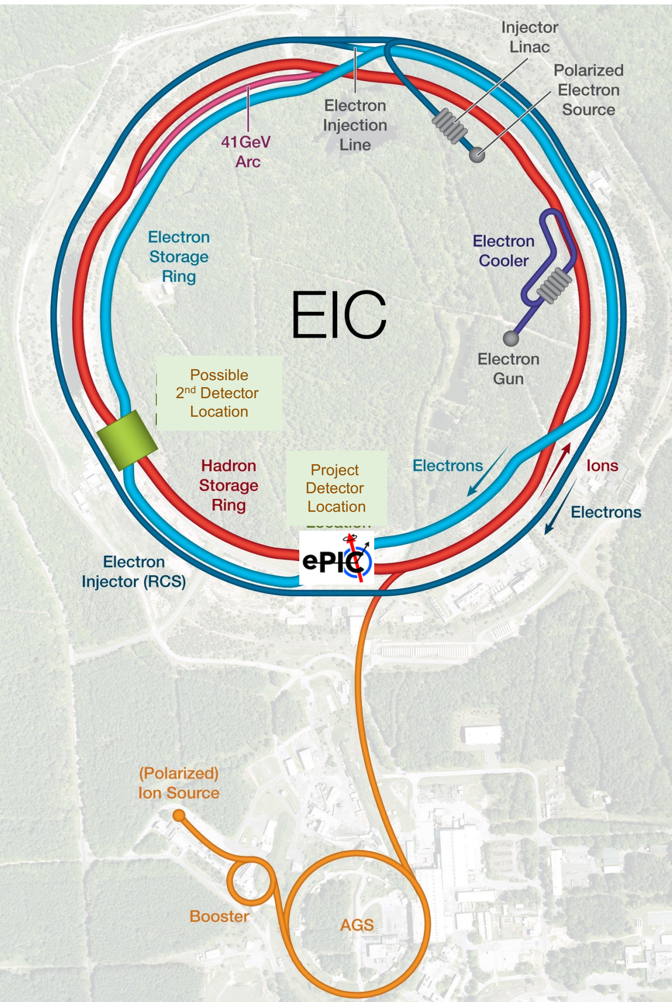

On-target for early 2030s @ BNL



# The Electron-Ion Collider



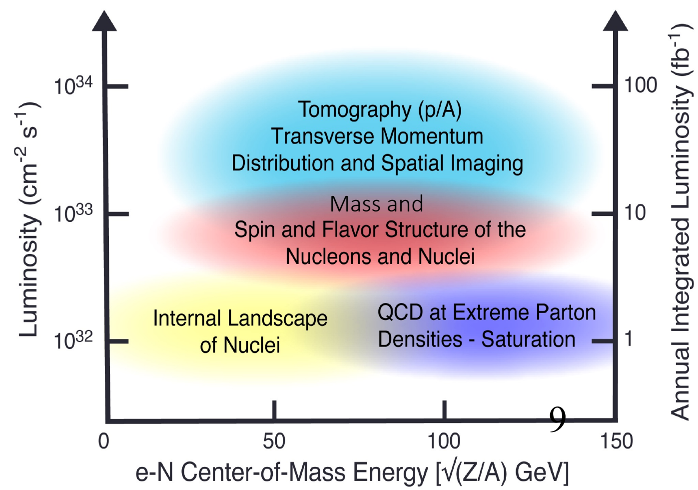

## New electron ring, to collide with RHIC p, A

- 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:

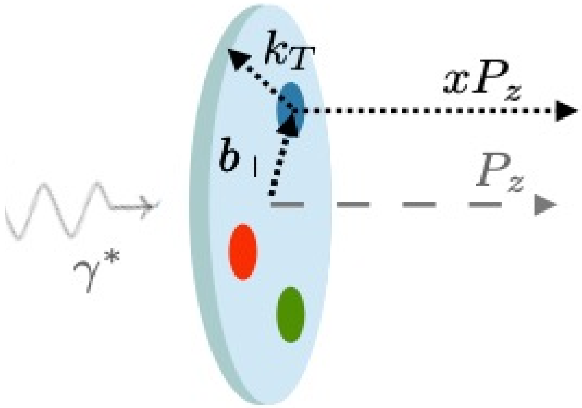


# Physics questions to be addressed at EIC

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

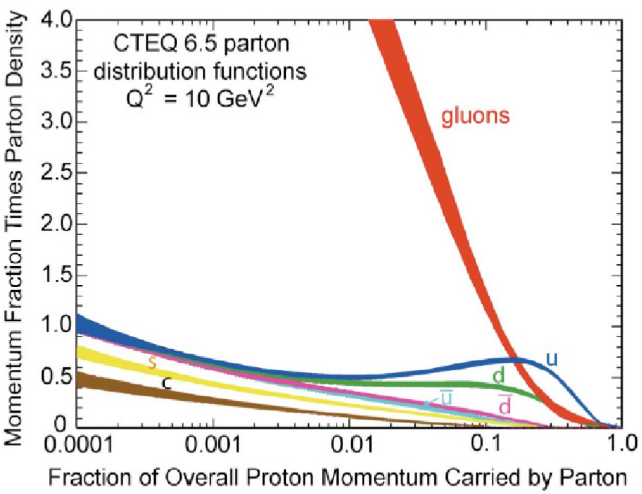
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

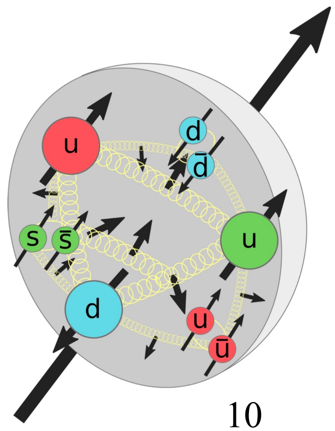
- What does the proton look like in 3D?




- How is proton spin generated?

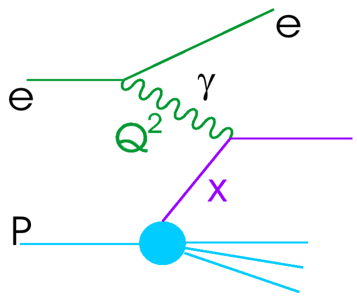
- How do the dynamics of high density systems of gluons tame the low x growth?



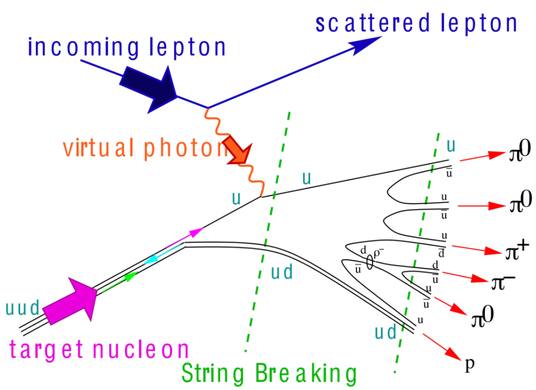
# Observables / Detector Implications

## Inclusive



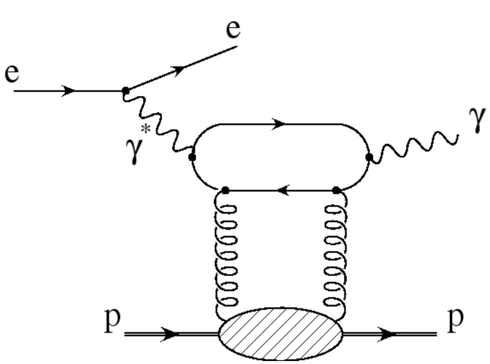

- Traditional DIS, following on from fixed target experiments and HERA → Longitudinal structure
  … high acceptance, high performance electron identification and reconstruction

## 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

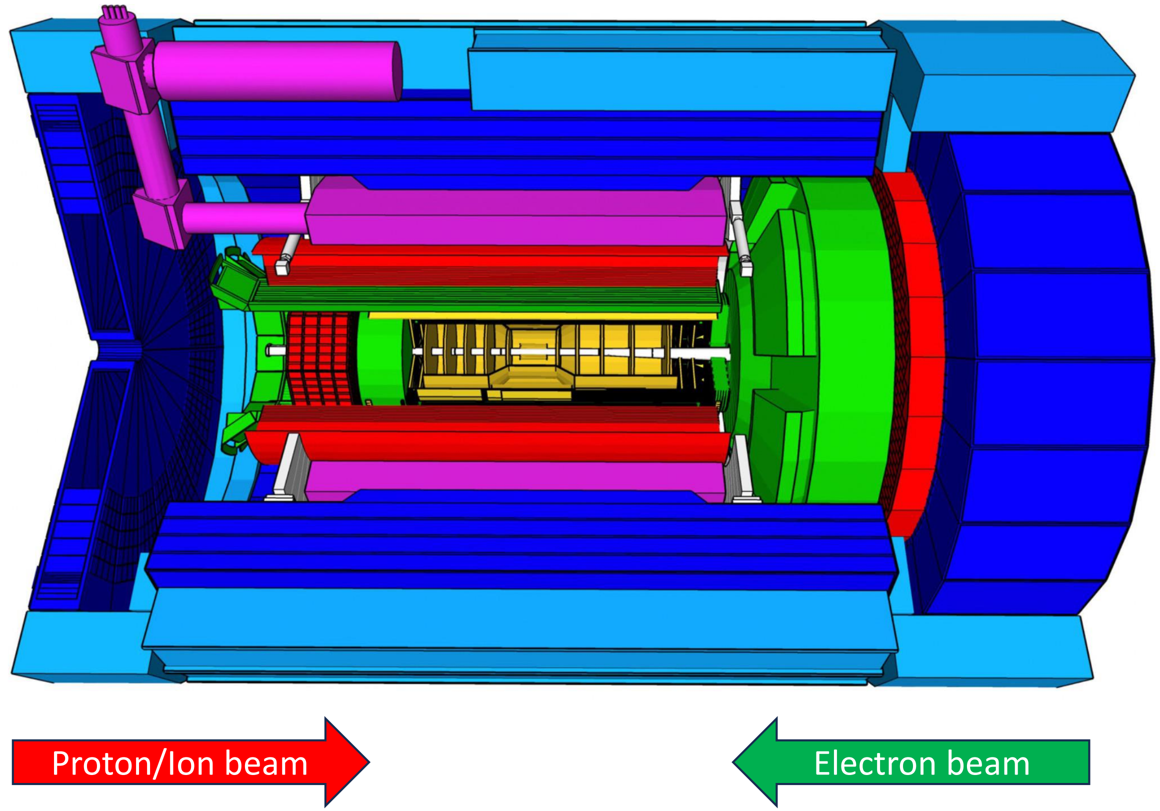
**Magnet**
- New 1.7 T SC solenoid, 2.8 m bore diameter

**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 $Q^2 \to 0$

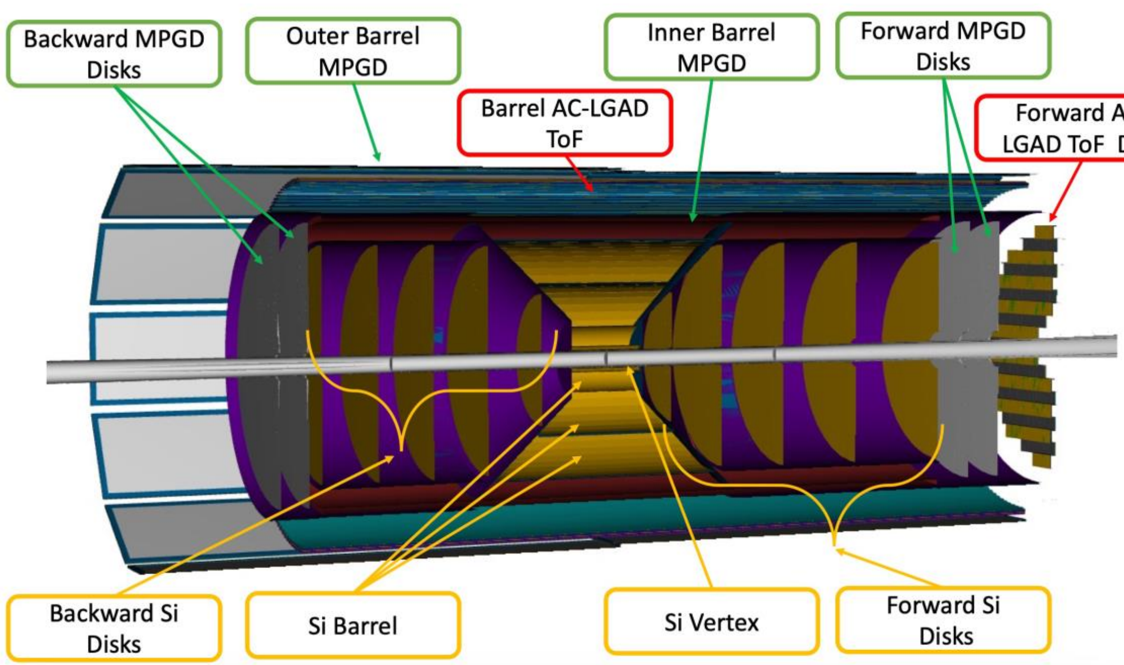
WP3: Lumi Monitoring → Novel pair-spectrometer, beamline $\gamma \to ee$ counting

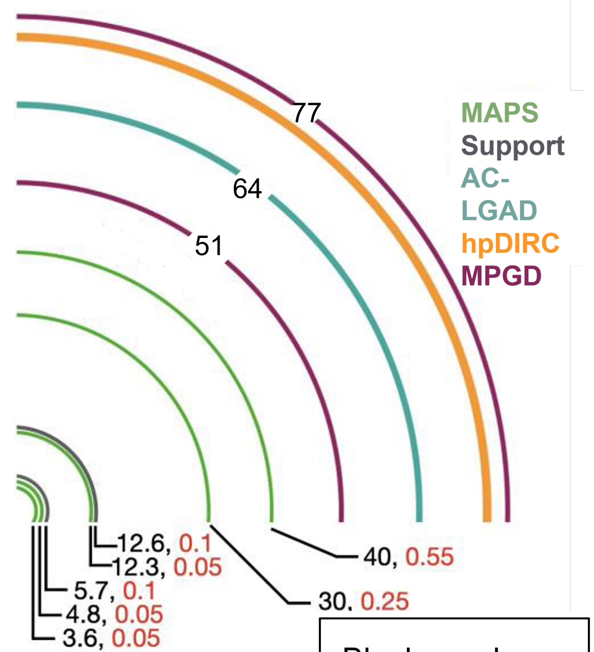
WP4: Accelerator → Primarily SRF systems for Energy Recovery cooler.
→ Also crab-cavity RF synchronisation, beam position monitoring, Energy Recovery modelling and design

# 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)




Black numbers are radii in cm

Red numbers are material in % X0

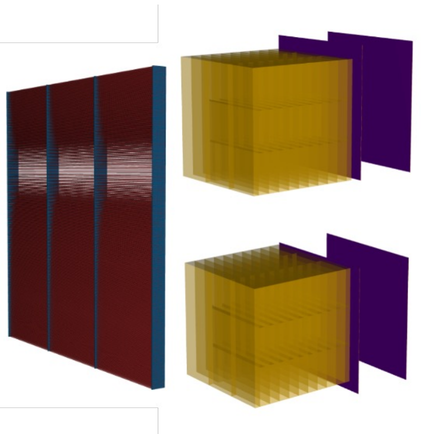
LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

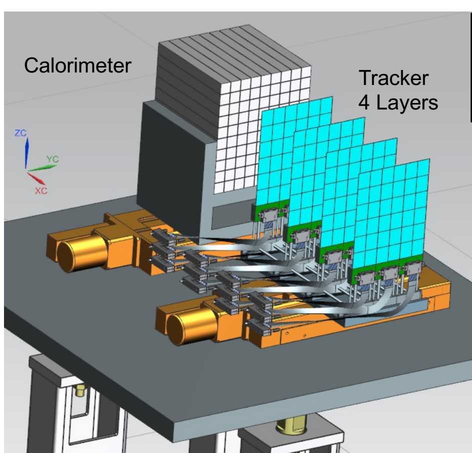
# Interaction Region / Beamline Instrumentation

- Extensive beamline instrumentation integrated into IR design

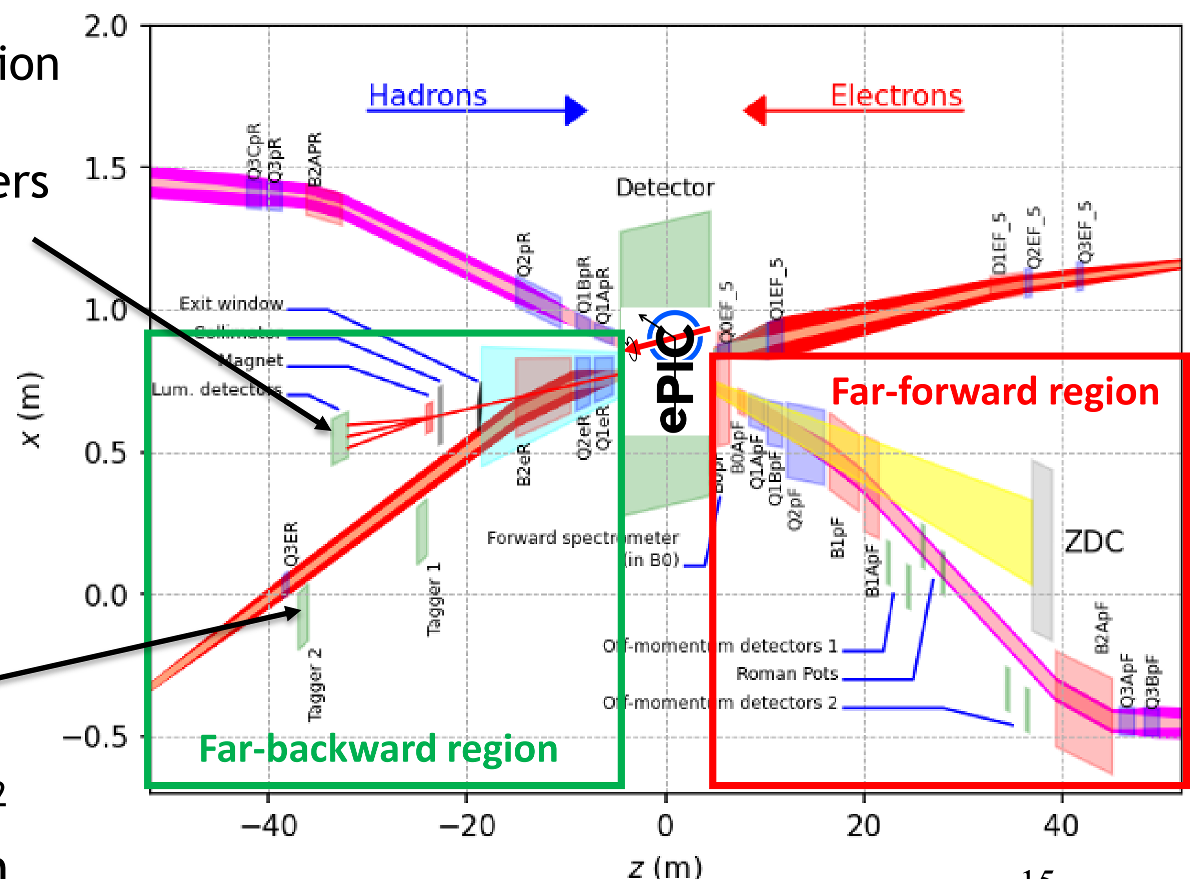
- Tagging electrons and photons in backward direction for lowest $Q^2$ physics studies and lumi monitoring via photon counting in $ep \rightarrow ep\gamma$



Pair-production lumi spectrometers

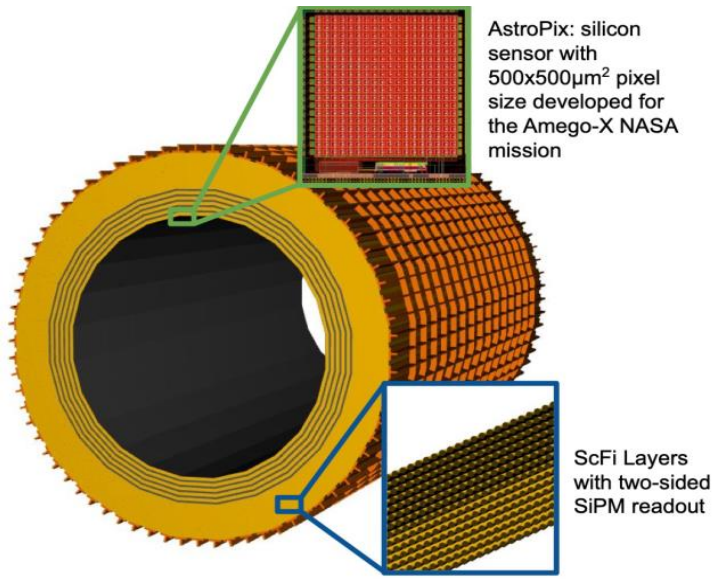



2 low $Q^2$ electron taggers

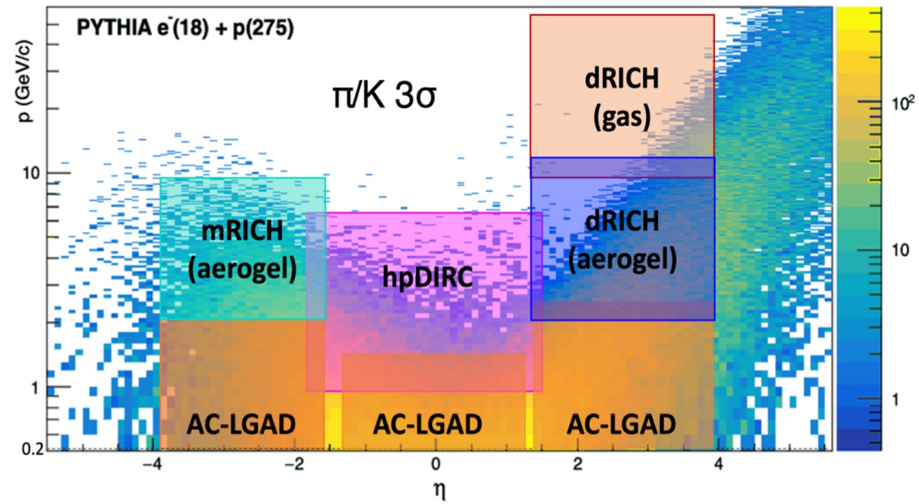


# More ePIC Detector Components with synergies elsewhere in HEP

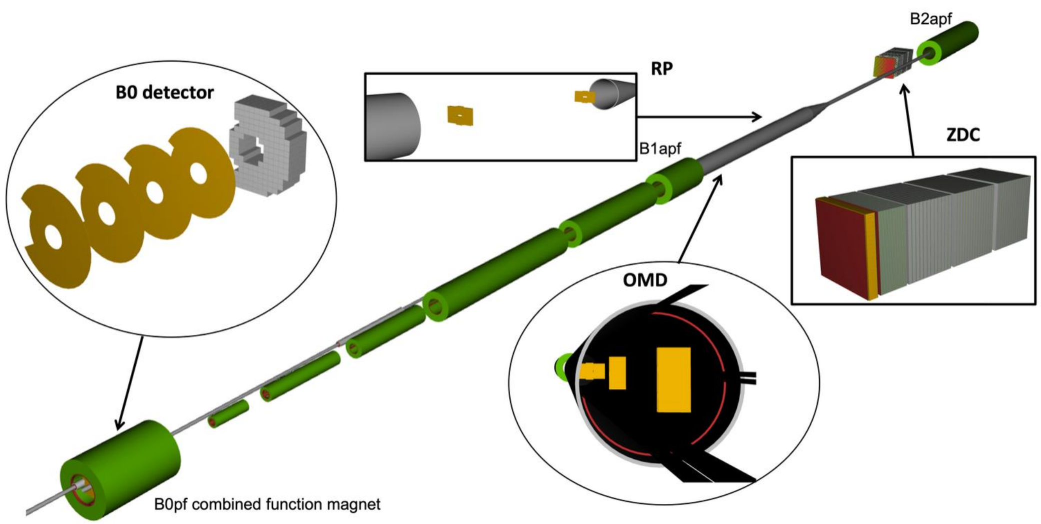
## Imaging eCAL




## Comprehensive Particle ID



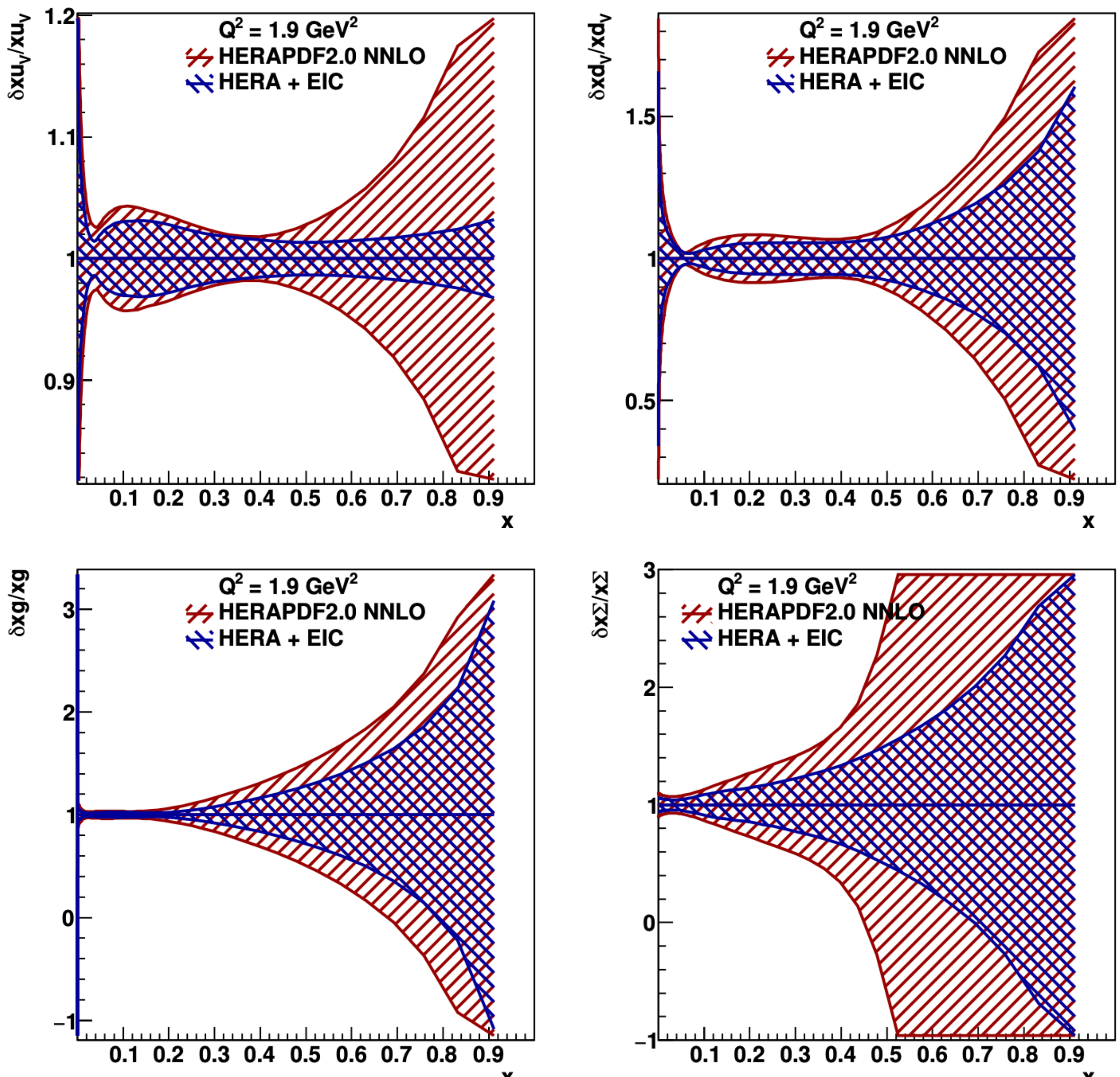

## Forward instrumentation integrated with beamline and magnets



# 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

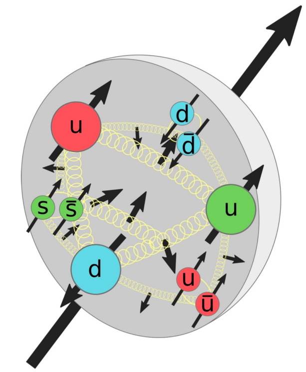



Also:

- $\alpha_s(M_Z^2)$ 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 ↑↑↓ )

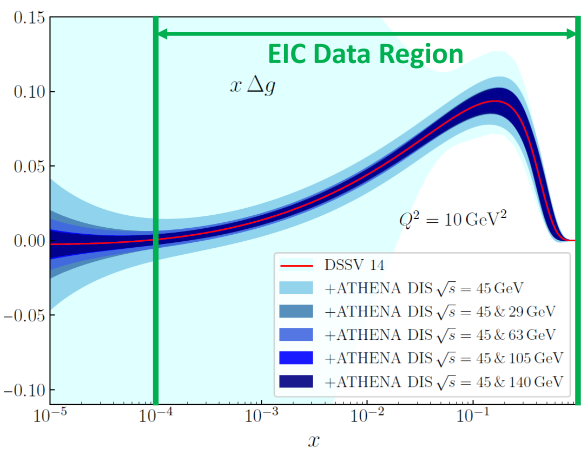
- Very little known about gluon helicity contribution and low x region

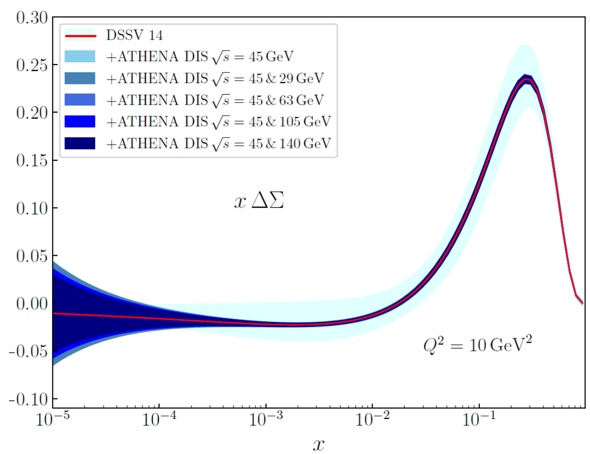
Jaffe-Manohar sum rule:

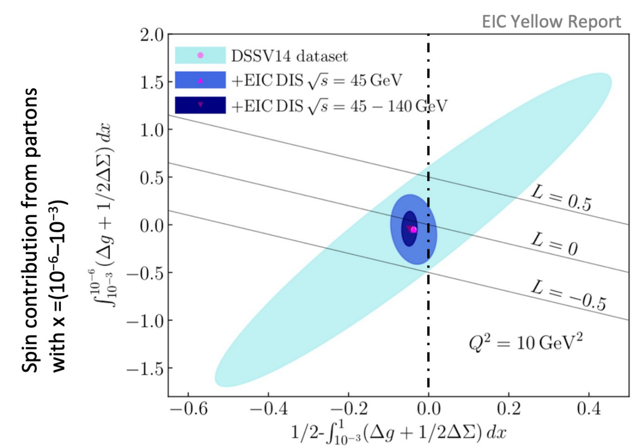
$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

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

- 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



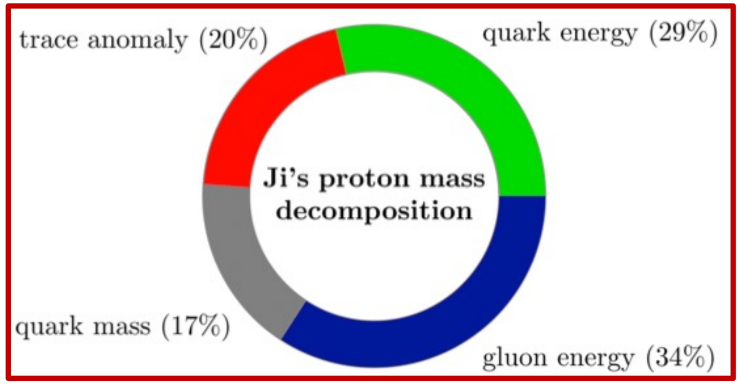

Room left for potential OAM contributions to the proton spin from partons with x > 0.001

# 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

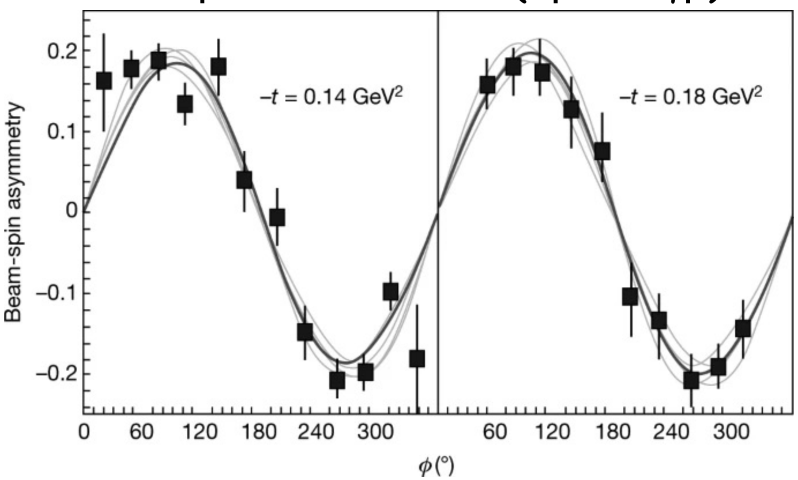
QCD trace anomaly (purely quantum effect - chiral condensates)

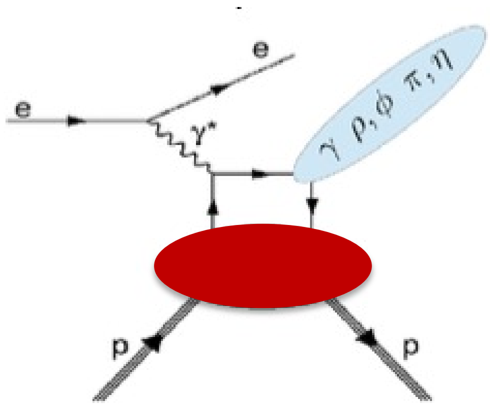
Understanding 3D relative location and motion of partons within proton is pathway to understanding proton mass emergence

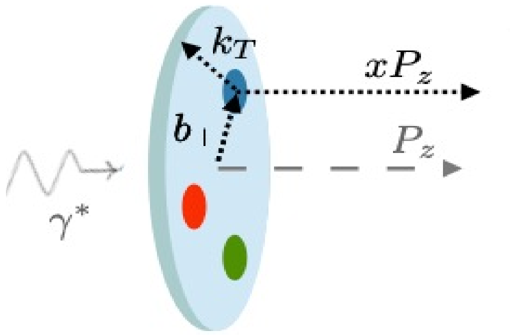
# 3D Structure

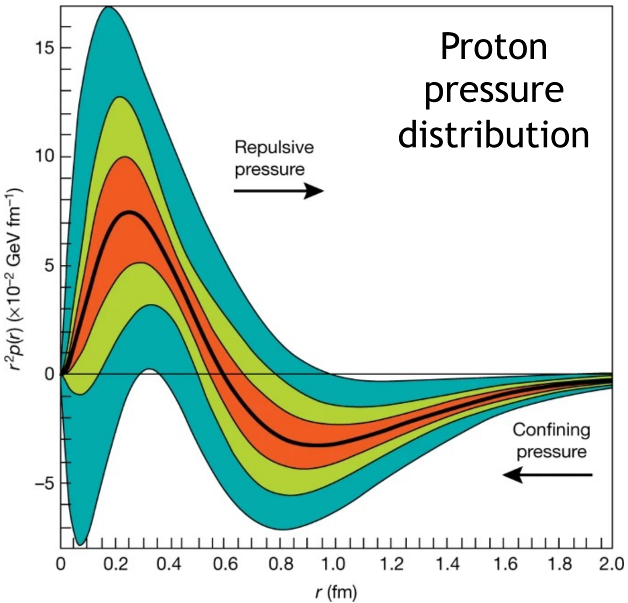
Exclusive processes, yielding intact protons, require exchange of ≥2 partons
→ Sensitive to parton correlations in longitudinal & transverse momentum and spatial coordinates

CLAS experiment: DVCS (ep → eγp)



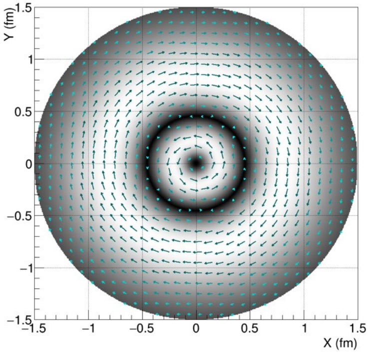




## Hints at rich 3D picture from JLab

- 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



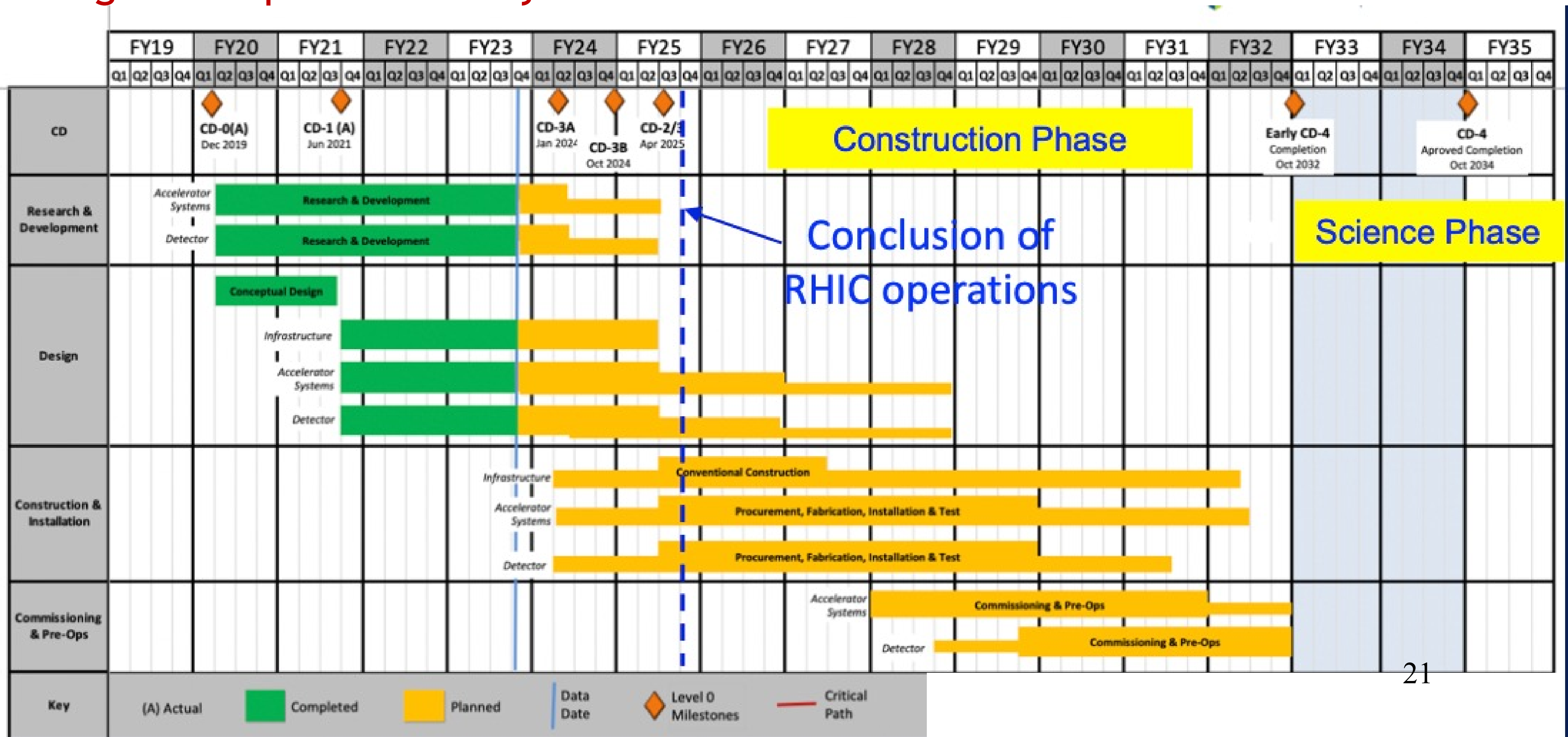
# Status / Timeline

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

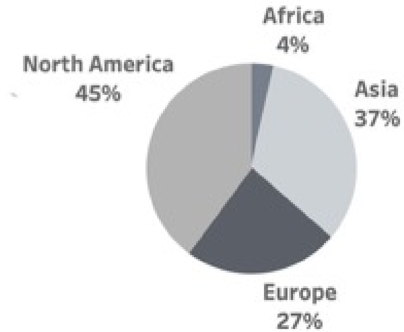
- Still several steps to go, but on target for operation early/mid 30s

| | |
|---|---|
| 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 |

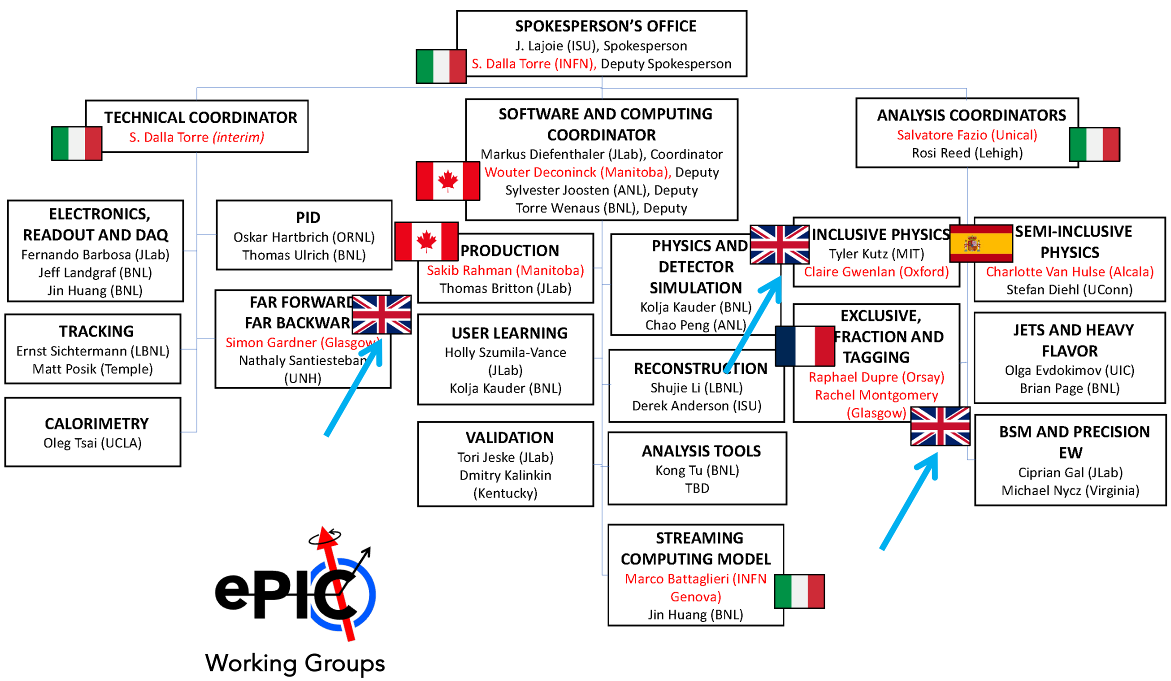
Technical Design Report: end 2025 (prelim 2024)

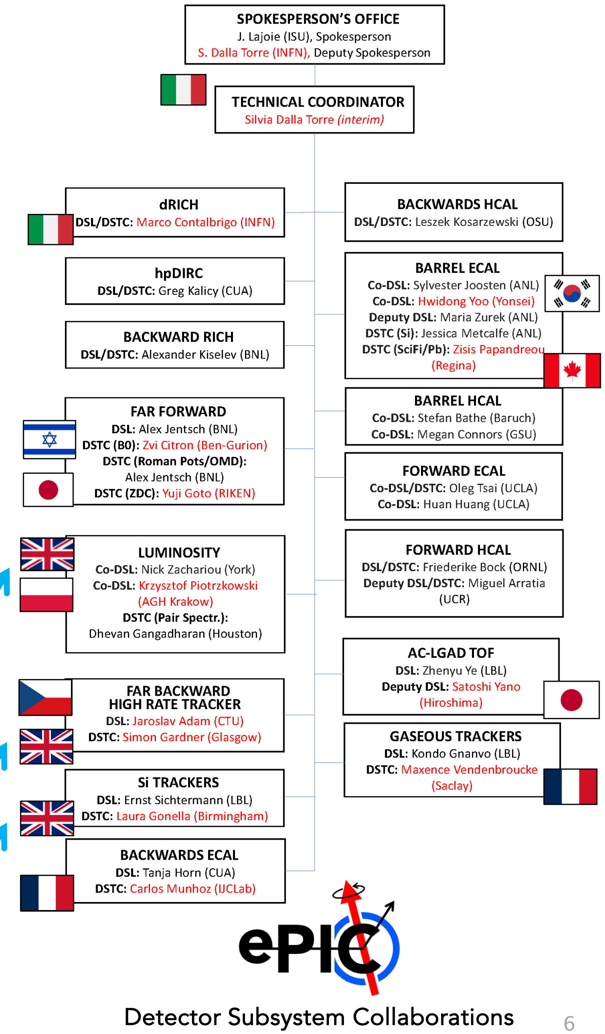


# ePIC demographics and Current UK Leadership



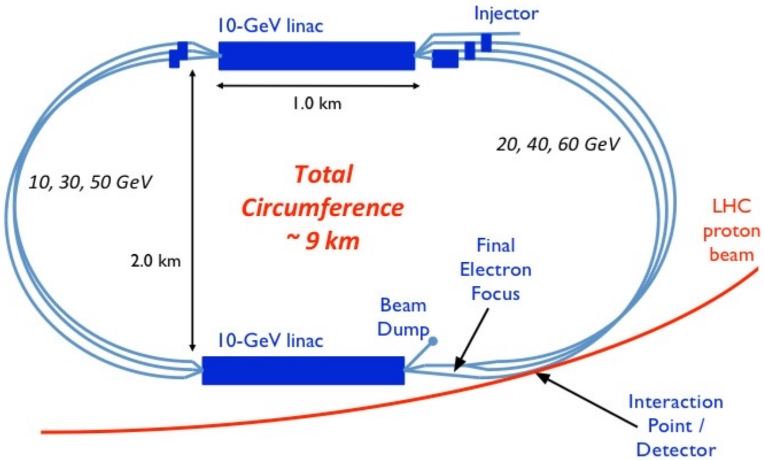

- Currently >850 collaborators (UK is 4th largest)
- UK physicists deeply involved through initial motivation, collaboration formation and now ongoing roles




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

# LHeC and FCC-eh



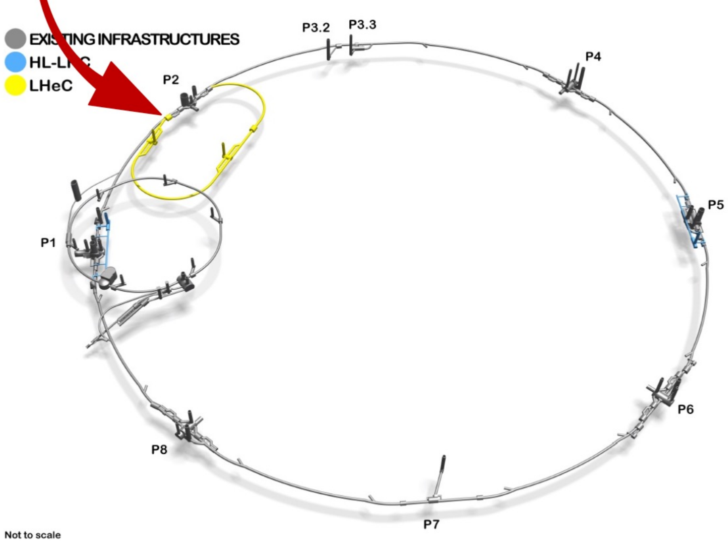

- Recirculating Energy-Recovery Linac (ERL) colliding with LHC (or FCC) hadrons at CERN

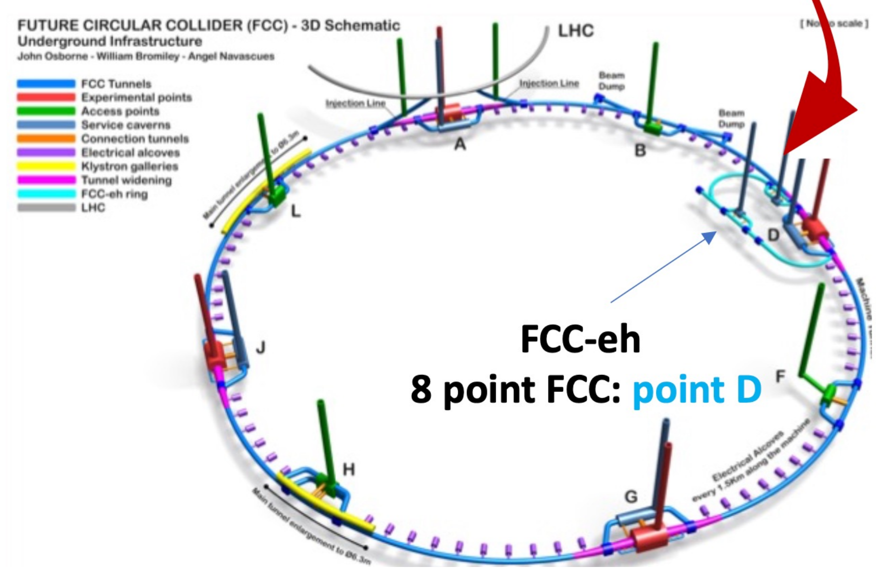
- 'Sustainable' acceleration: ~100 MW (similar to LHC today)

- 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*



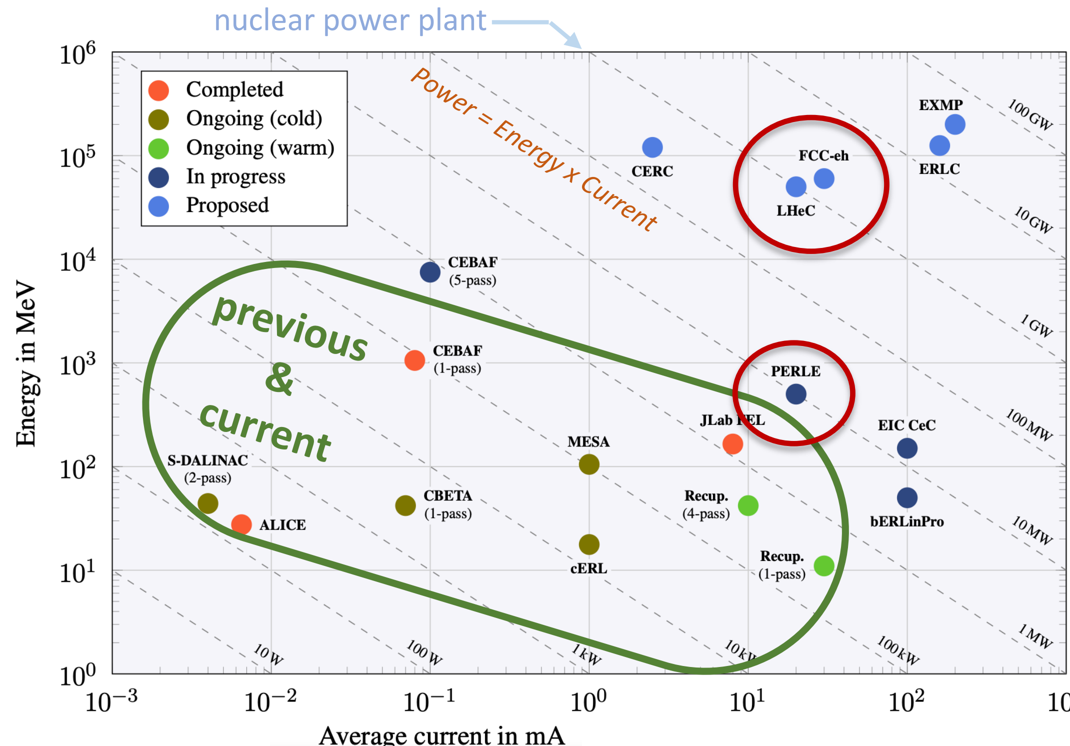



# Energy Recovery Linacs

- Demonstrating ERL scalability is critical path

- Prototype (PERLE @ IJCLab / Orsay) implementation started

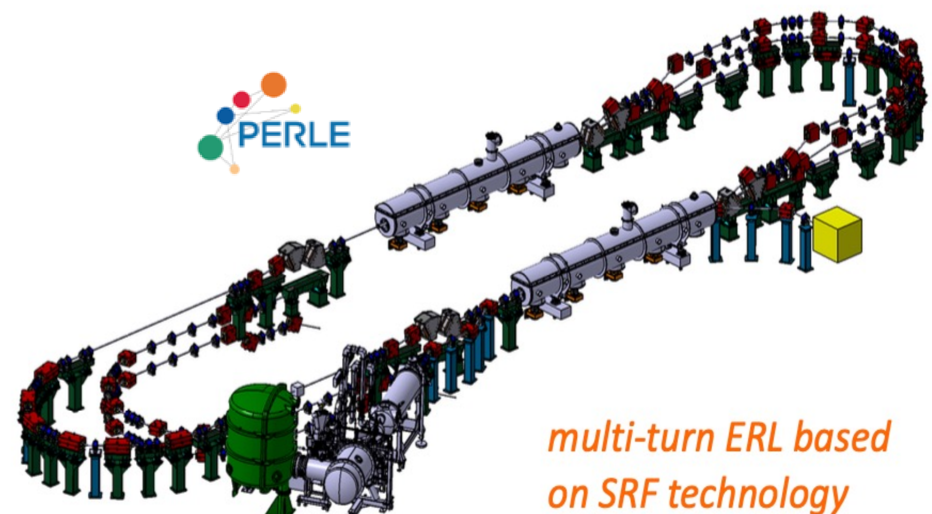
- First stage (one turn) by 2028.




HV tanks

Electron DC-gun

Photo-cathode




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

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

# 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 $N_p/(\gamma\epsilon_p)$ | $10^{17}\mathrm{m}^{-1}$ | 2.2/2.5 | 2.2/2.5 | 2.2/2.5 |
| Electron beam current | mA | 15 | 25 | 50? |
| Proton $\beta^*$ | m | 0.1 | 0.7 | 0.7 |
| Peak luminosity | $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 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. | $\mathrm{fb}^{-1}$ | 20 | 50 | 180 |

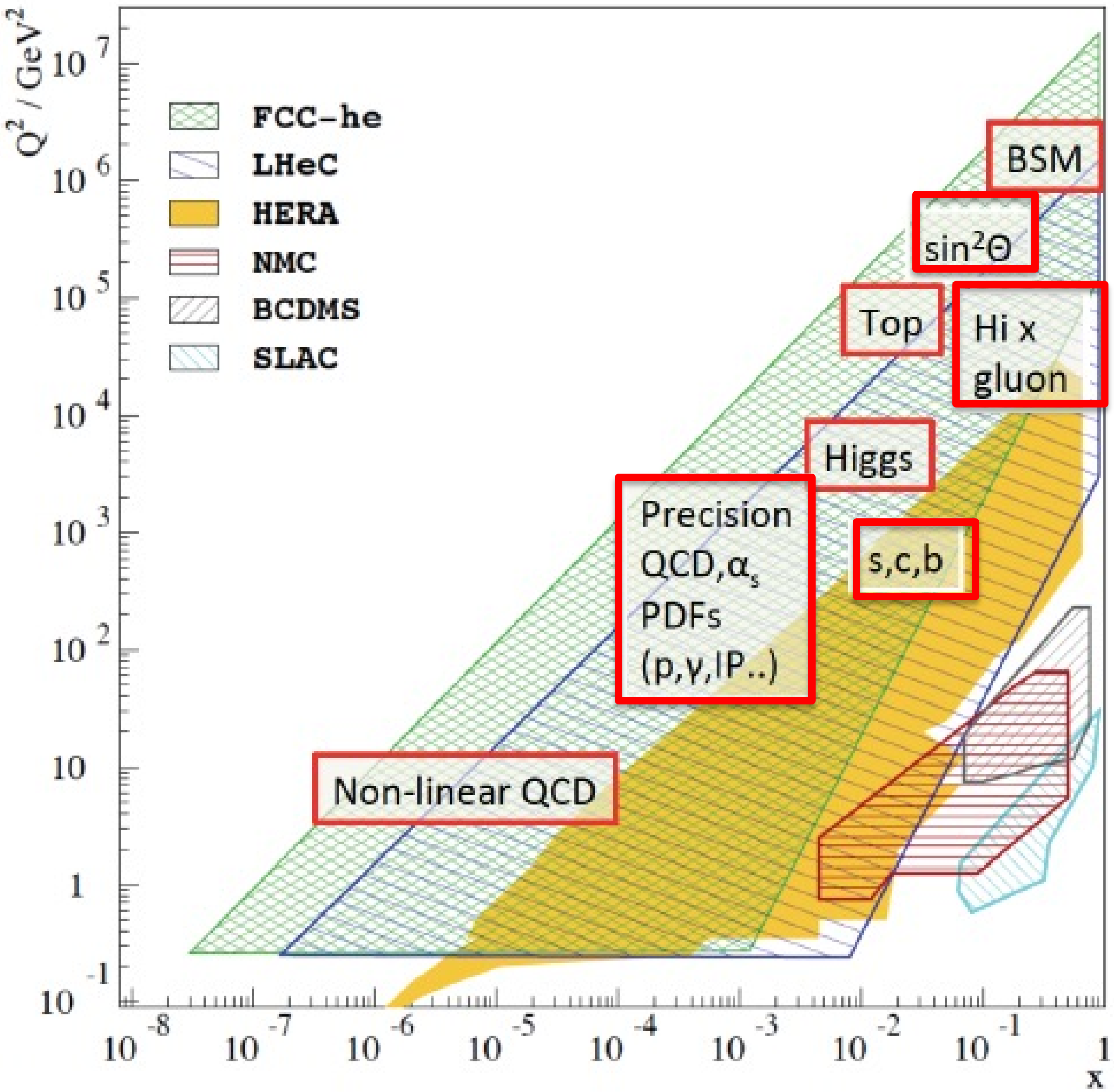
[Pile-up ~0.1]

Running concurrently with pp at HL-LHC:
… integrated lumi of 20 fb-1 per year at Run 5 → 50 $\mathrm{fb}^{-1}$ initial dataset
… integrated lumi of 50 fb-1 per year at Run 6 → few 100 $\mathrm{fb}^{-1}$ total @ HL-LHC

Running in standalone ep mode:
… integrated lumi of 180 fb-1 per year → 1 $\mathrm{ab}^{-1}$ 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)

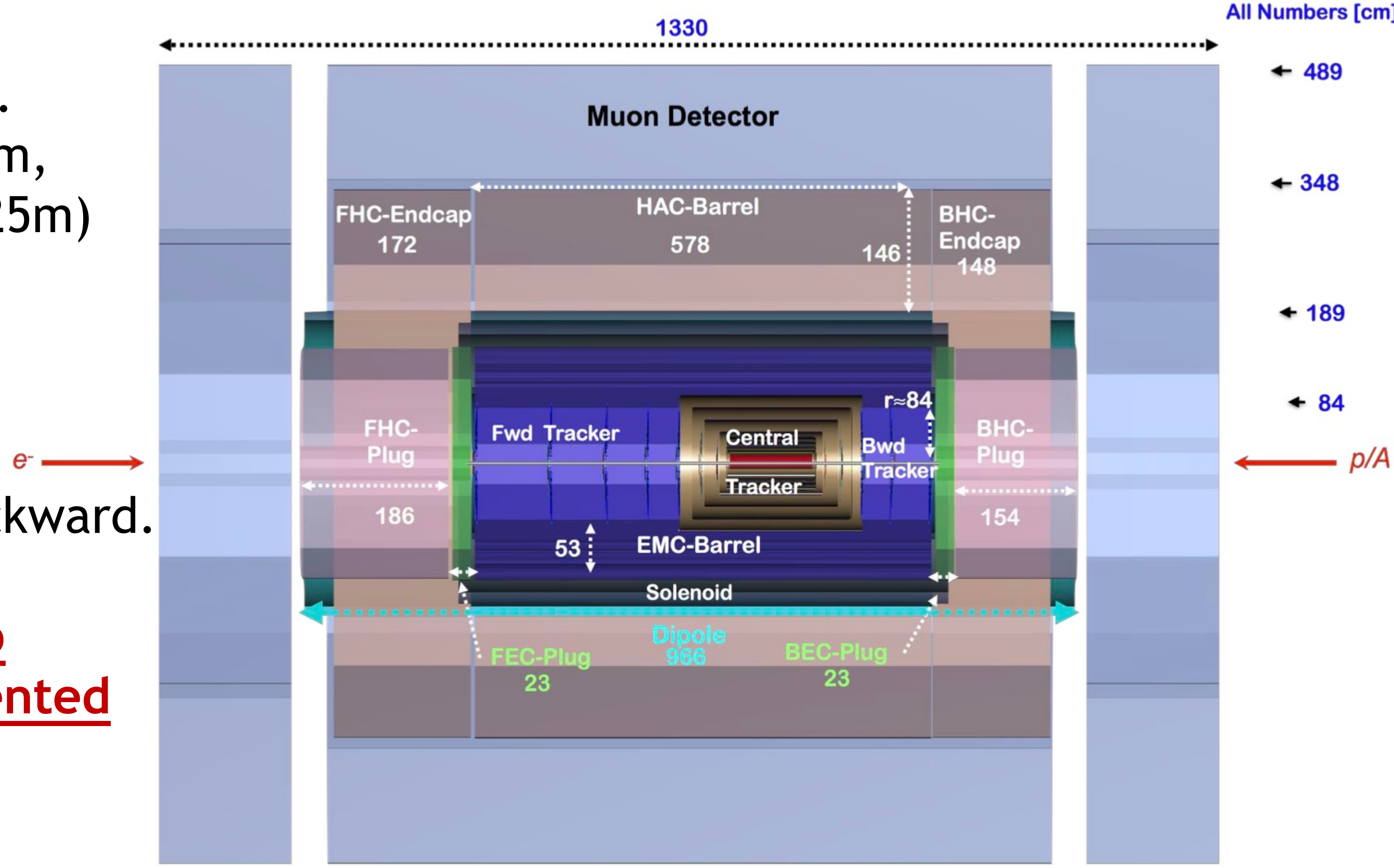
**Compact**

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:

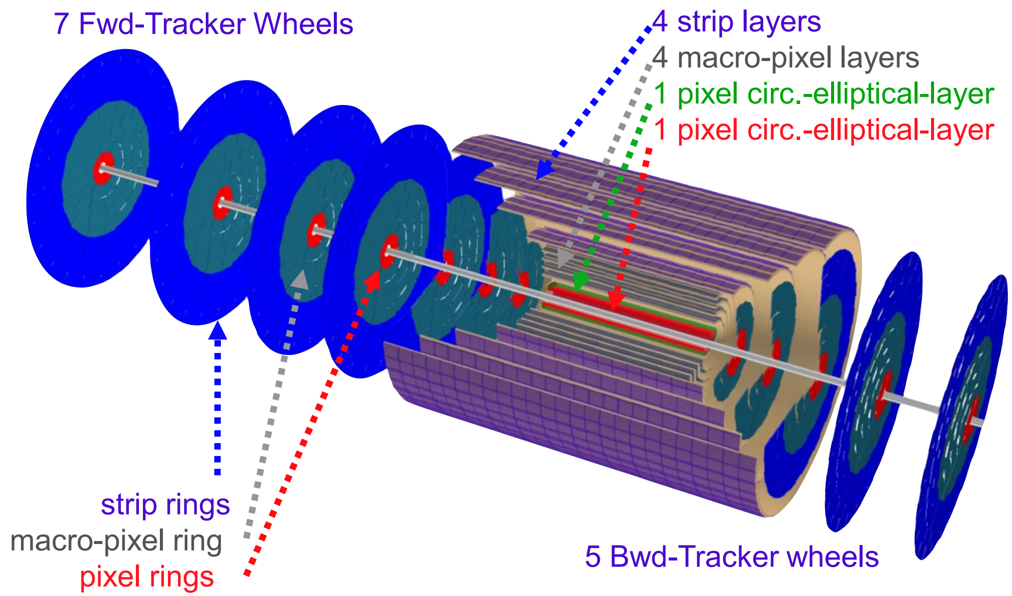
- A snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- Possibly lacking components for some ep/eA physics (eg. Particle ID)
- Not particularly well integrated or optimized

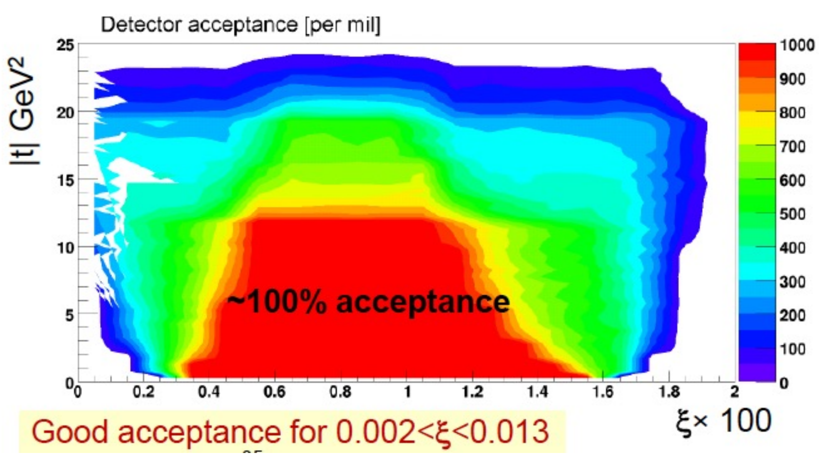
… Synergies with EIC, LHCb, ALICE, future lepton colliders still to be explored

# 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 $\eta$~4.5



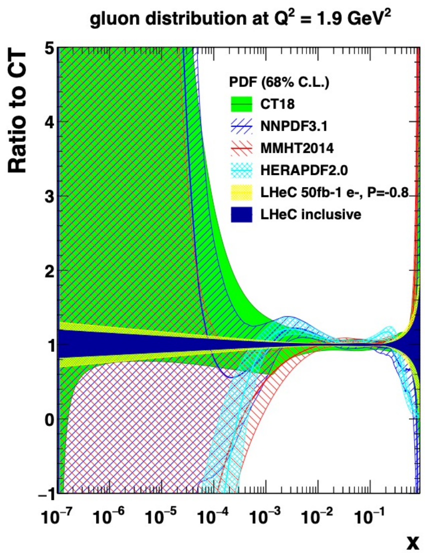

**e.g. Forward proton spectrometer in cold region (~420m)?**

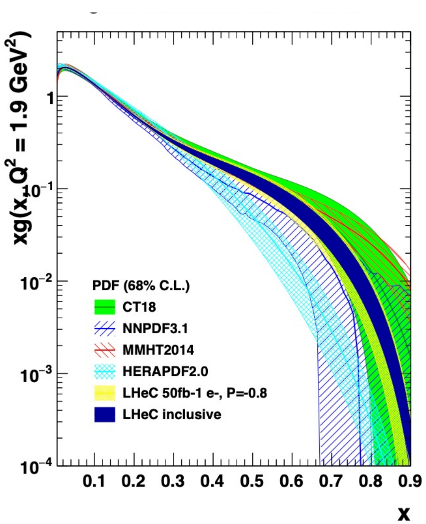
- Reuse of technology proposed for LHC, accessing protons scattered at very low momentum loss

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

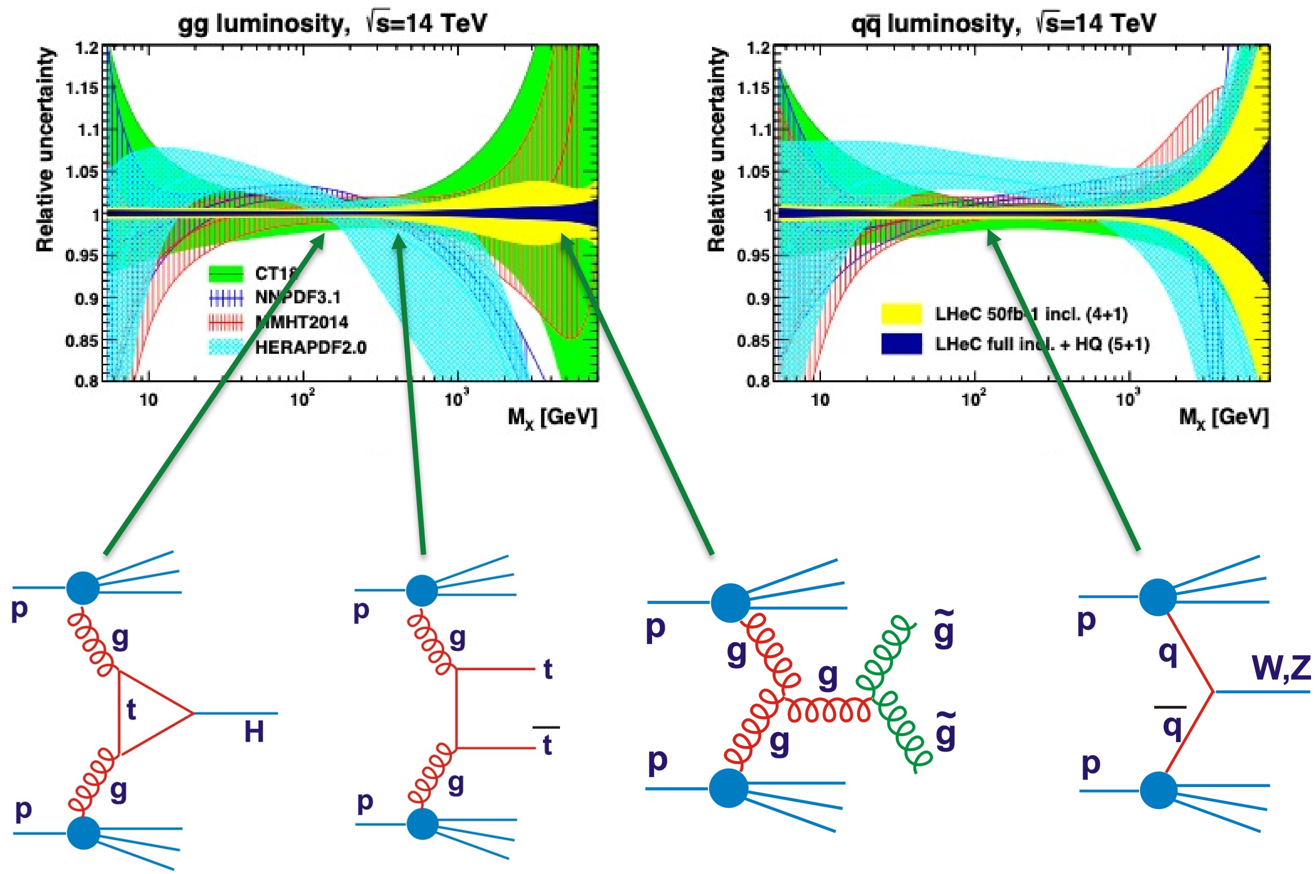



- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements
  (e.g. $M_W \rightarrow$ 2 MeV from PDFs, $\sin^2\theta \rightarrow$ 0.03%)

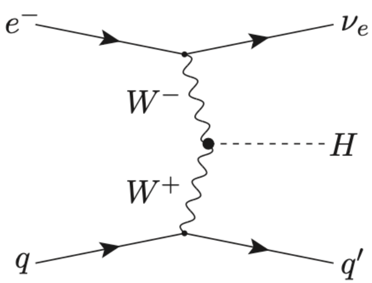
$\rightarrow$ Elucidates novel very low x dynamics

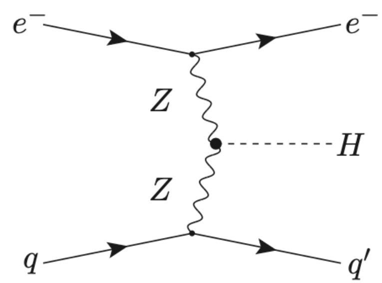
e.g. Parton luminosities for pp at 14 TeV



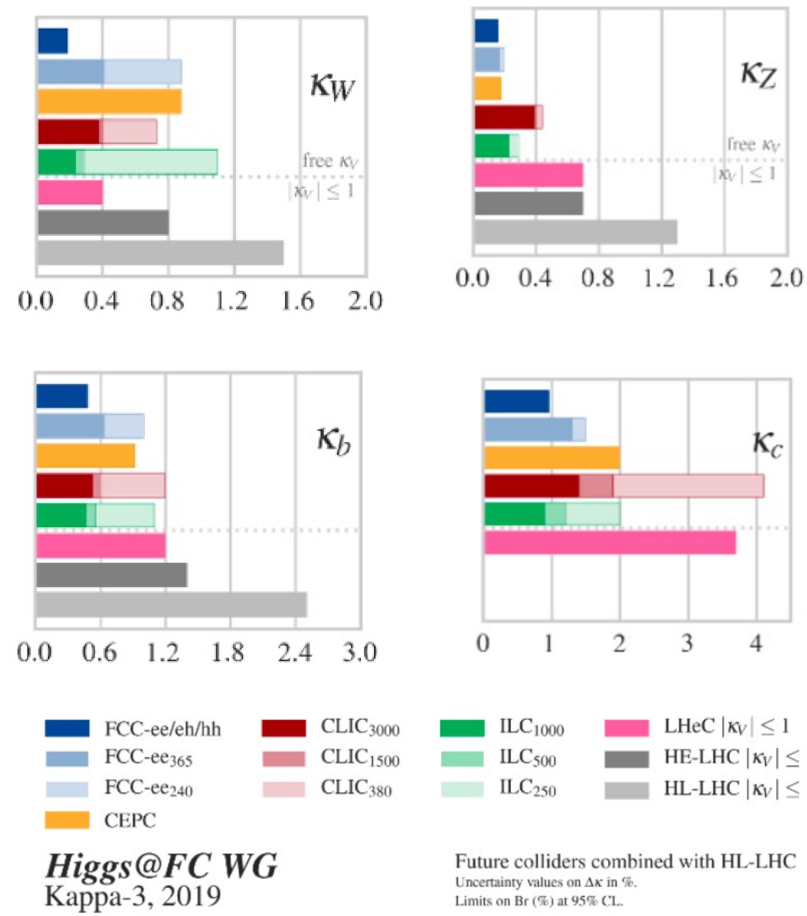
# LHeC (SM) Higgs Programme

- 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 |
| $\sigma$ [pb] | | 0.197 | 1.04 | 0.024 | 0.15 |

[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

# END

# Detector Technologies / Challenges

Requirements considered in 2021 ECFA R&D roadmap
… mostly ready to be built
… synergies / stepping-stones towards other future projects

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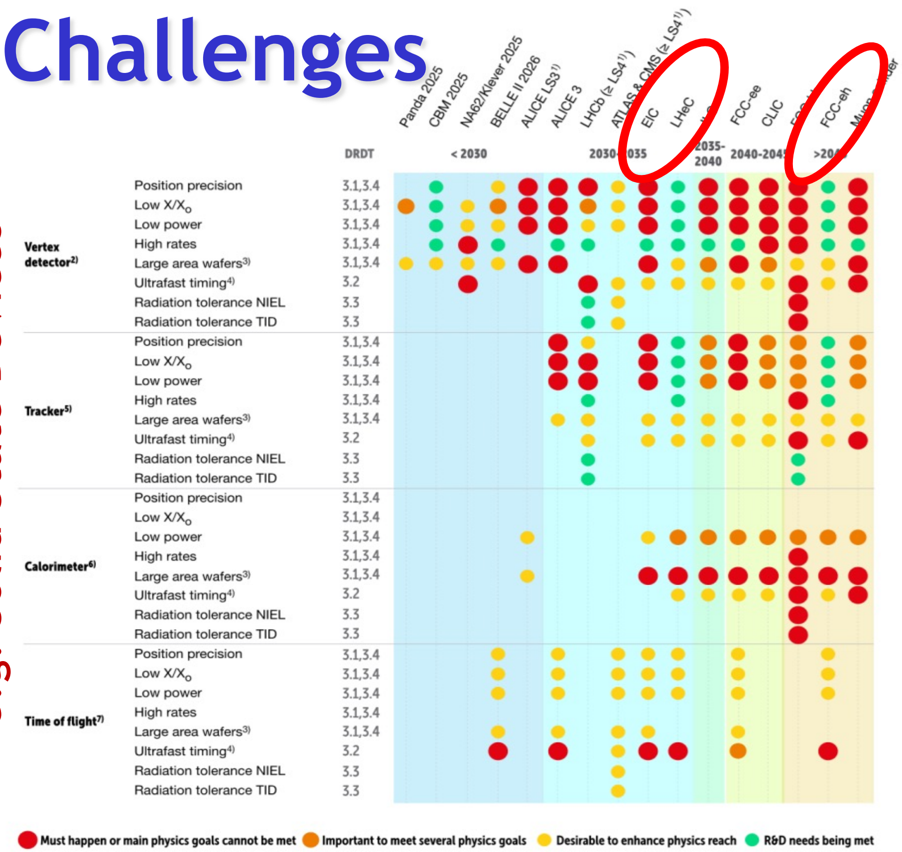
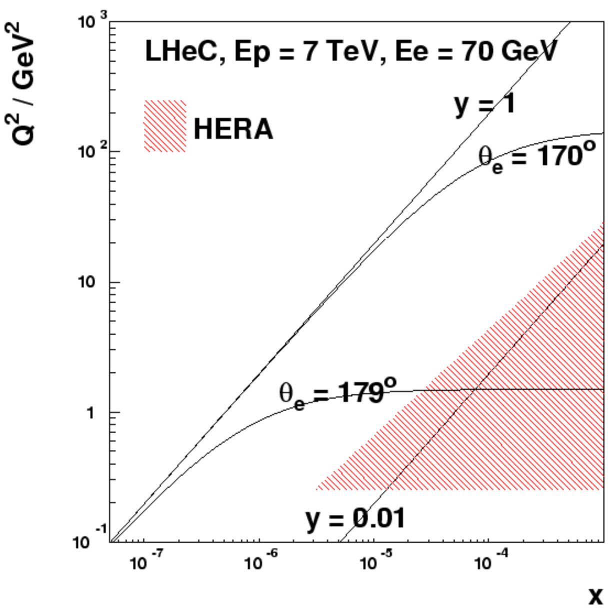
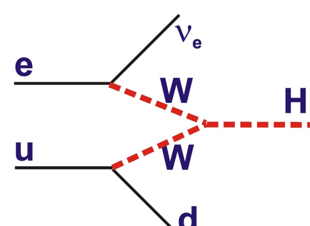
Challenges are synchrotron radiation and hermiticity
… access to $Q^2$=1 $GeV^2$ for all x requires scattered electrons to 179°

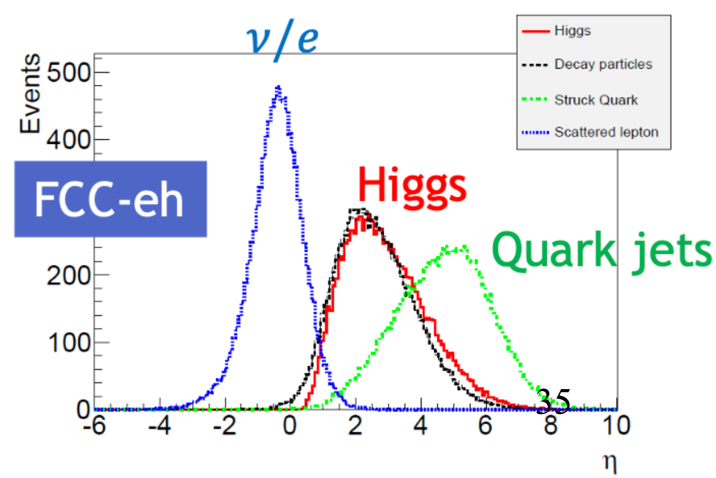
e.g. Solid State Devices



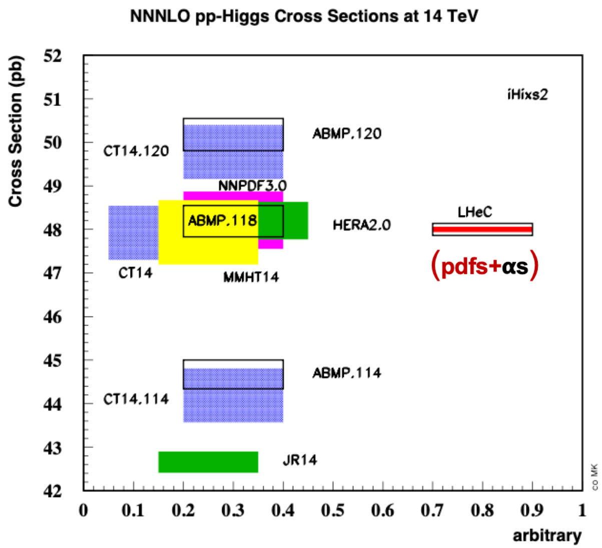




… Higgs production dominated by forward jet configurations

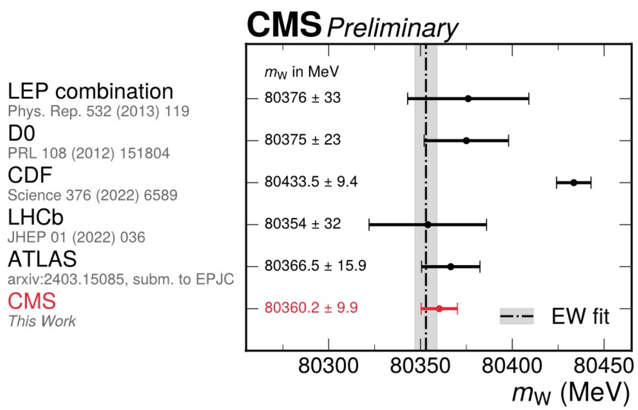


# LHeC PDFs Empowering LHC

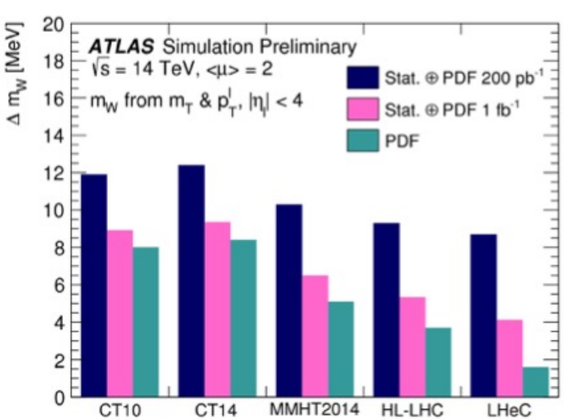


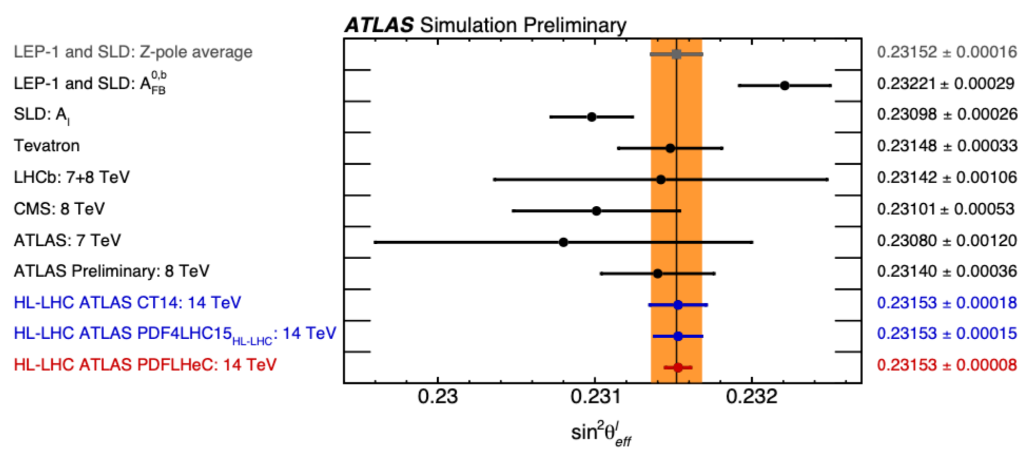

- Theory uncertainty on LHC Higgs production cross section improves dramatically compared with current PDF and $\alpha_s$ knowledge.



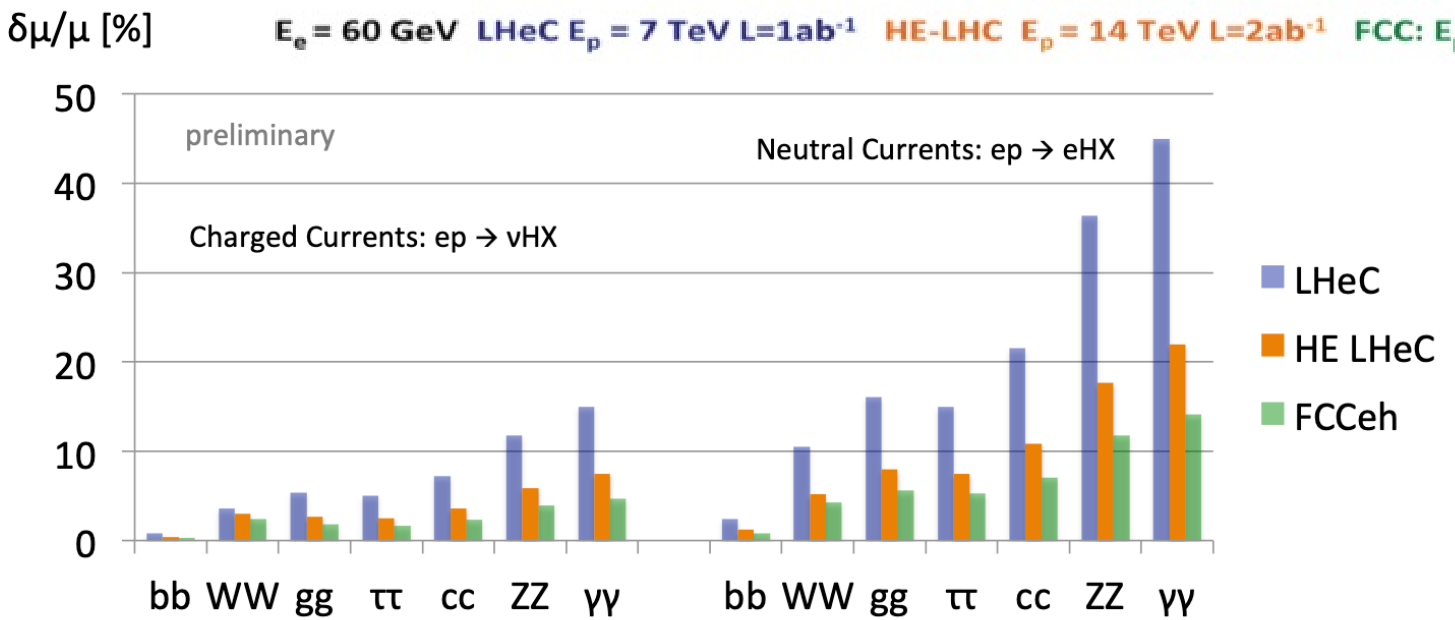

- PDF-related systematics on EW measurements are significant (e.g. LHeC enables $\sin^2\theta$ → 0.03% and reduces $\delta_{PDF}$ on $M_W$ → 2 MeV in ATLAS studies)

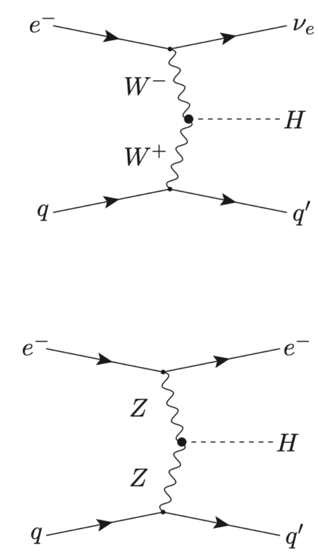
- Many BSM scenarios ultimately limited by high x PDFs



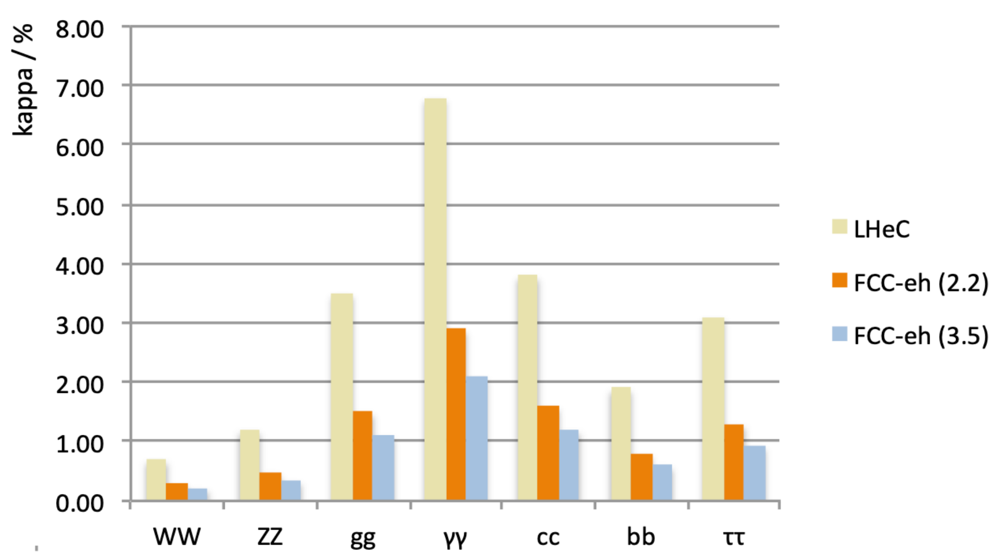
# ep Standalone Higgs Sensitivity



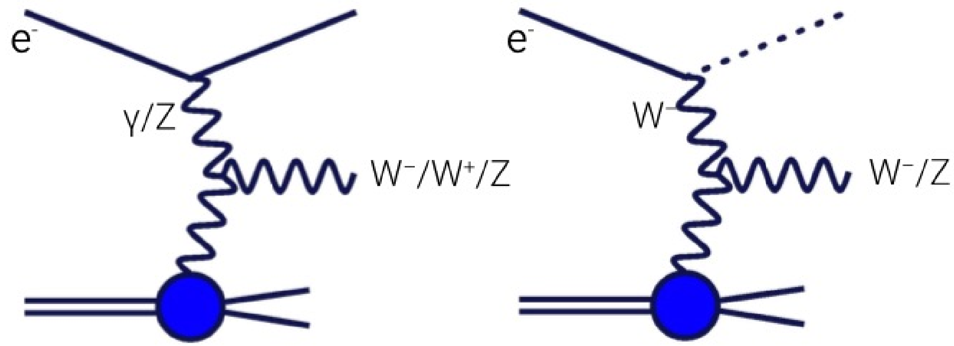

- CC Signal strength uncertainties at 1% level for $H \to b\bar{b}$ , 7% for $H \to c\bar{c}$ …

- Including initial-state couplings in $\kappa$-framework analysis leads to sub-1% $WWH$ coupling precision

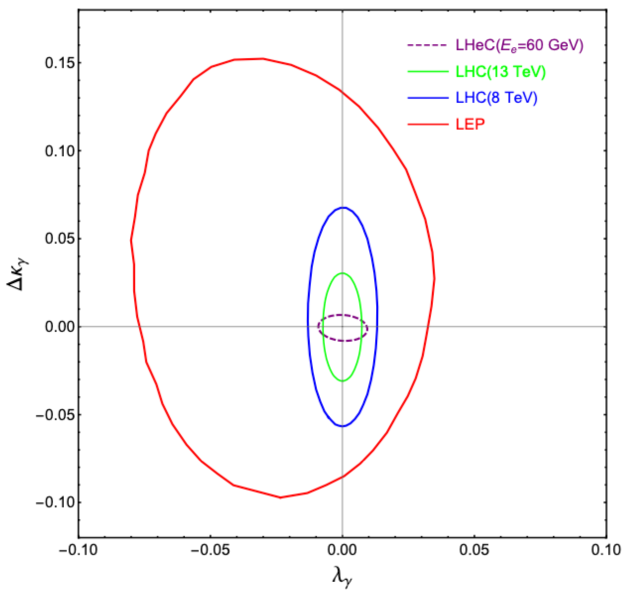


# Electroweak Gauge Bosons

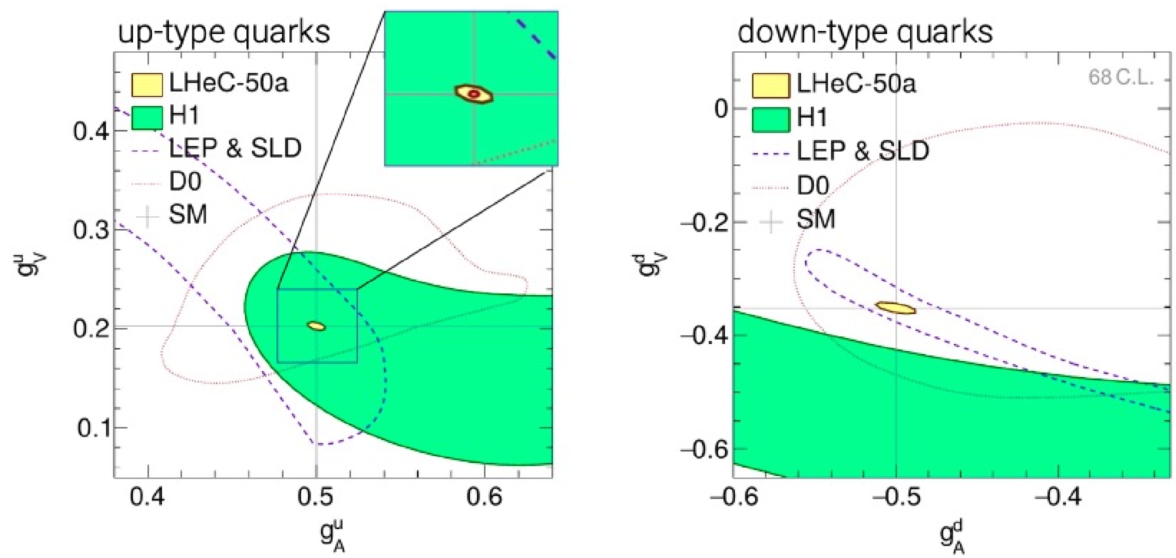
LHeC: σ(H)~ 0.2pb
σ(W)~ 3pb
σ(Z)~ 2pb
σ(t)~ 1pb



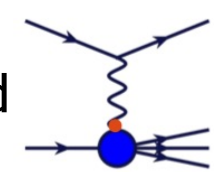

… W, Z and (single) top samples ~$10^6$ events each



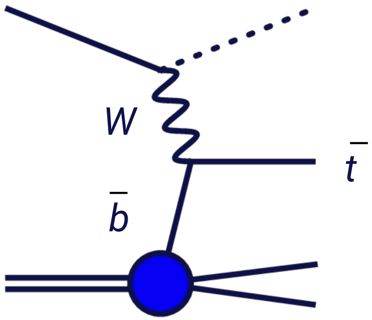

Sensitivity to anomalous TGCs



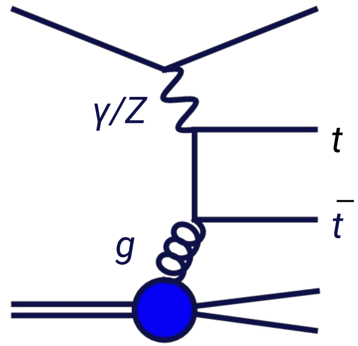

Vector and Axial couplings of Z to light quarks tightly constrained from t-channel Z exchange



# Example Top Physics at LHeC

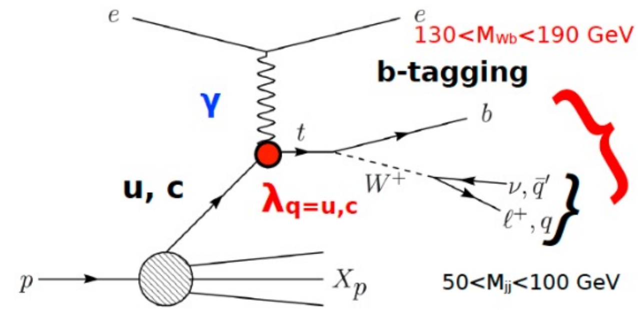



LHeC σ~ 1.9pb
FCC-eh σ~15.3pb



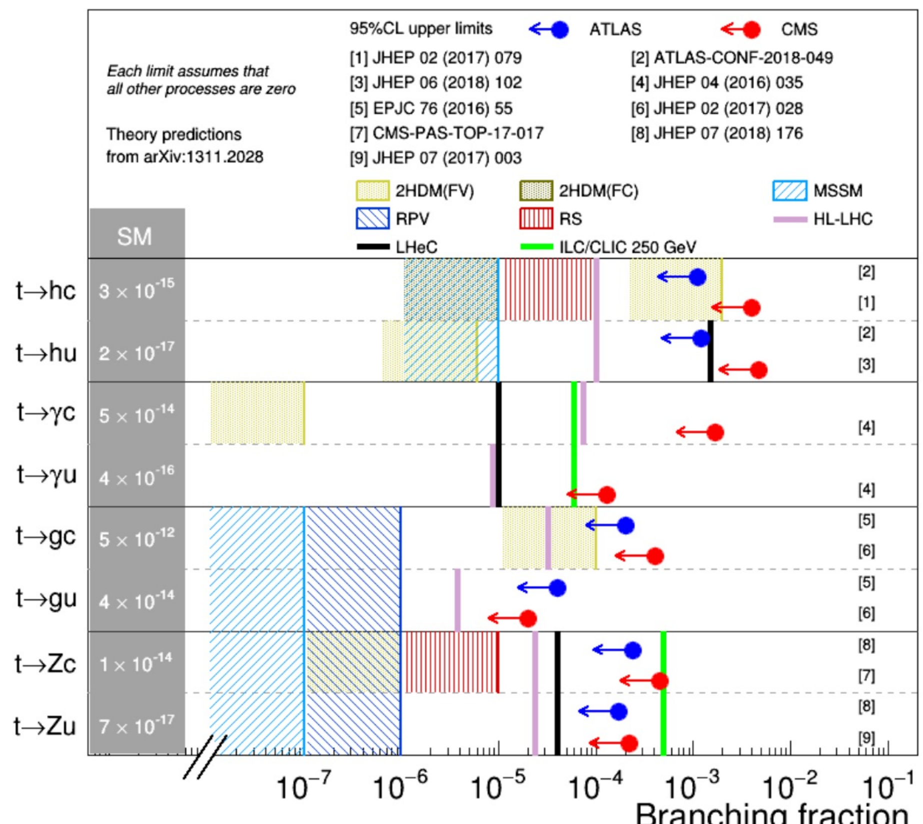

LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

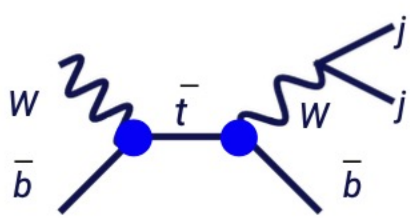
[~$10^6$ single top events]




## FCNC

Comparable sensitivity to HL-LHC in tγc, tγu coupling sensitivities




## CKM

Cut-based simulation in hadronic channel

→ 1% $V_{tb}$ precision (now ~5%)

→ Improved $V_{ts}$, $V_{tb}$ constraints

# 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 | |

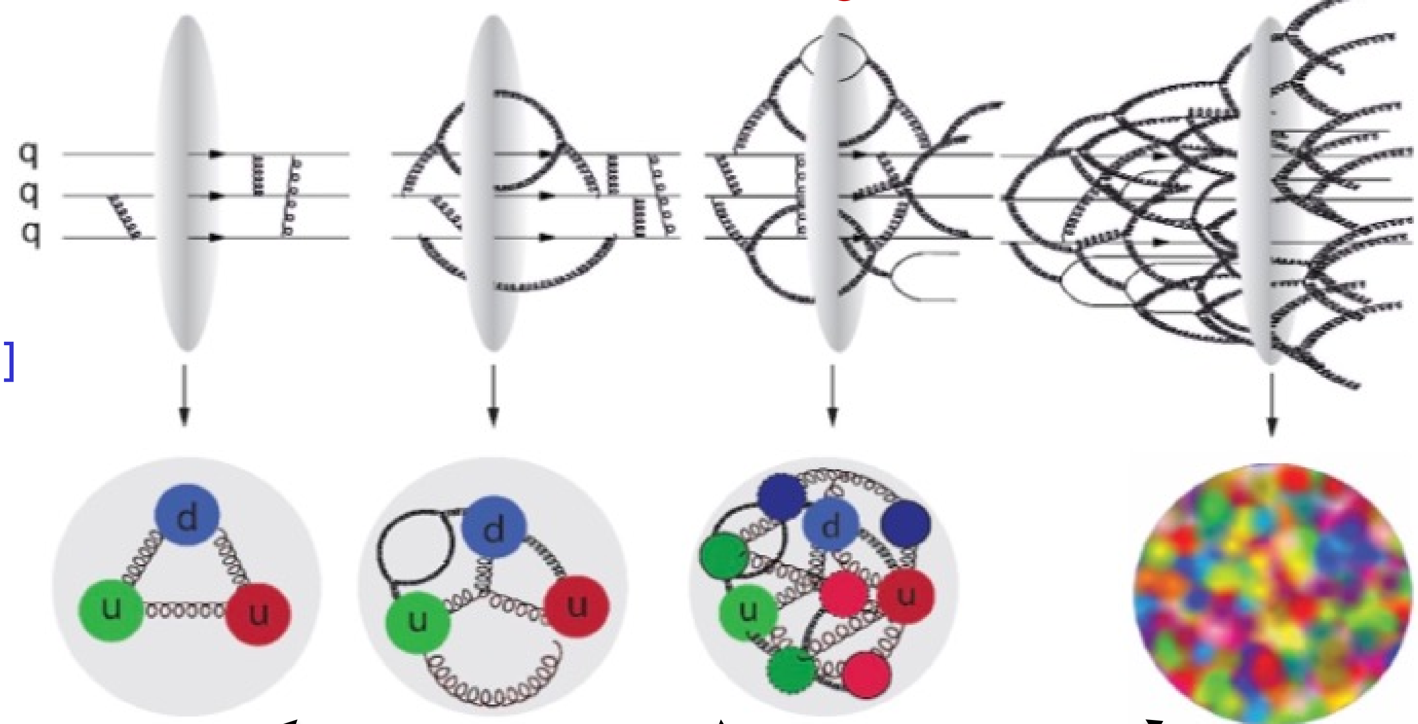
Challenges from high lumi requirement include high beam currents and correspondingly short bunch spacings:

- → Synchrotron load management
- → Significant crossing angle

# Crude Mapping Between Physics & Facilities

Partons with decreasing x →

[Kong Tu]

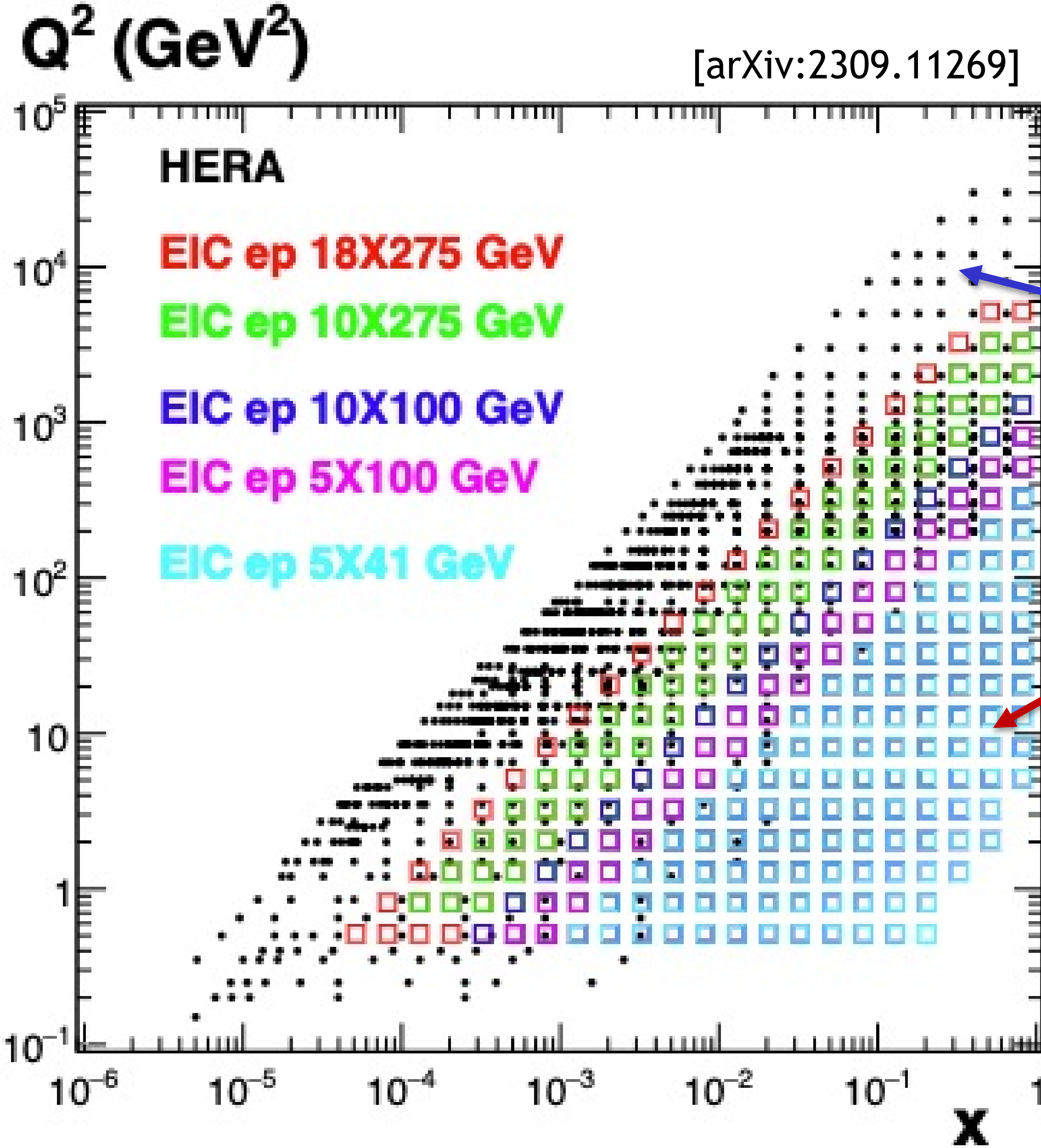



High x (fixed Target)
Basic Structure

Intemediate x (EIC)
Emergent properties

Low x (HERA / LHeC)
QCD radiation
dynamics

# Inclusive EIC Data 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

| 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 nuclear PDFs: high parton densities

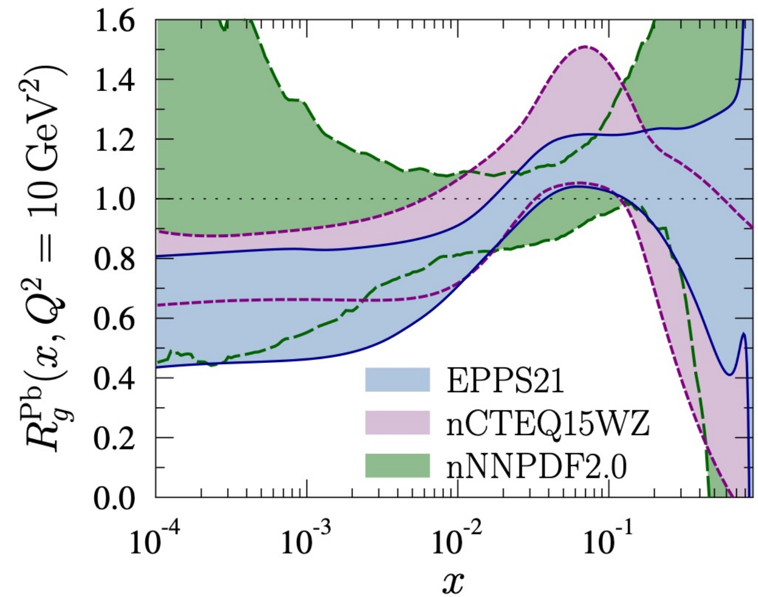
- Nuclei enhance density of partons
  (~$A^{1/3}$ factor at fixed x, $Q^2$)

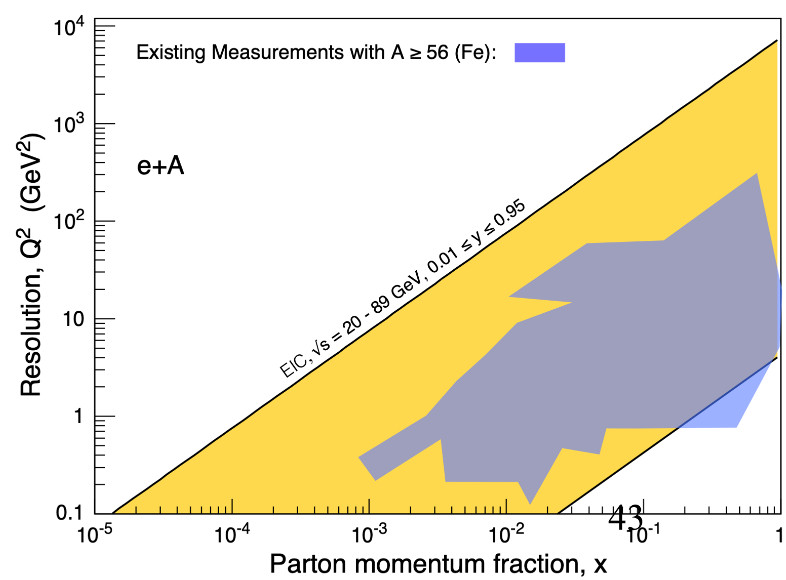
- Results usually shown in terms of nuclear modification ratios: change relative to simple scaling of (isospin-corrected) proton

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

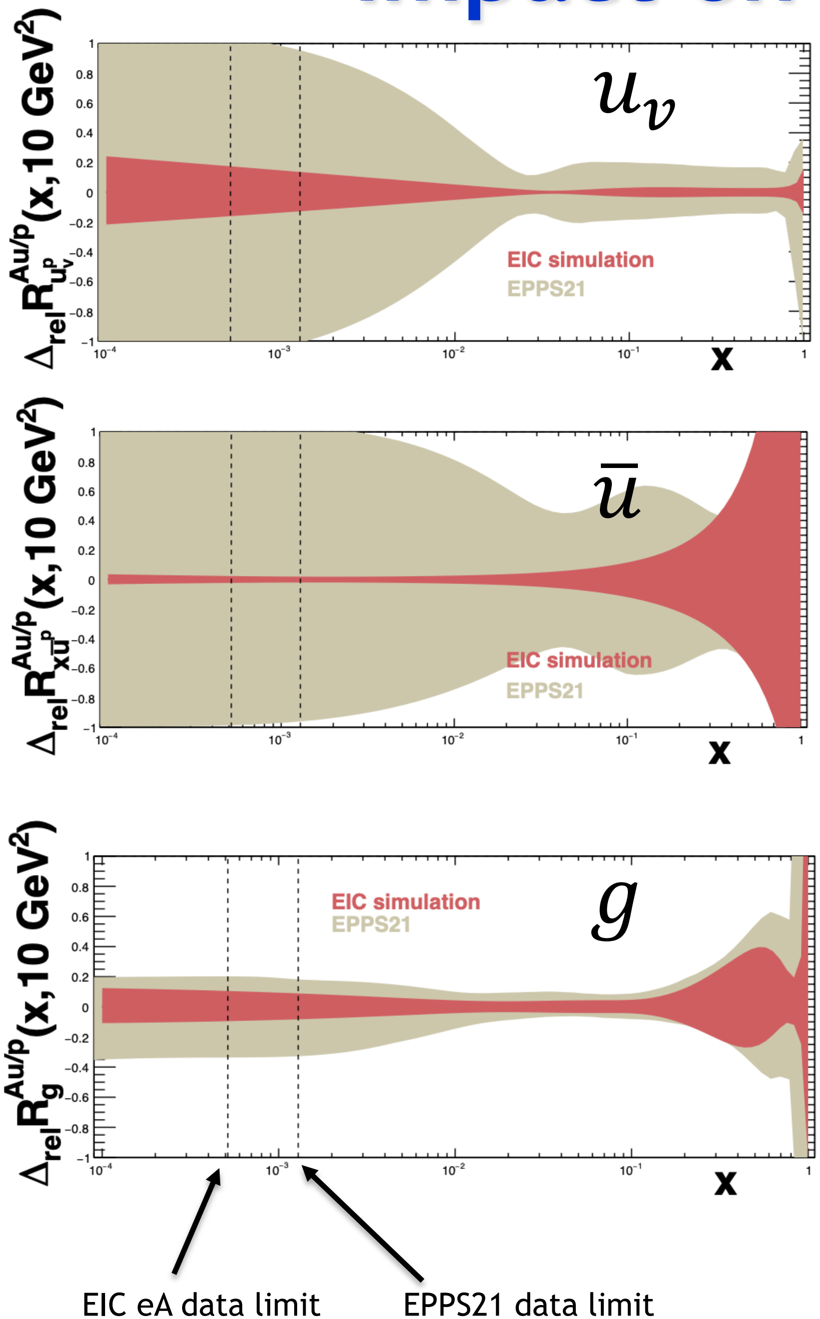
… poorly known, especially for gluon and at low x

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



# Impact on Nuclear PDFs




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

Usually expressed in terms of nuclear modification ratio relative to scaled isospin-adjusted nucleons:

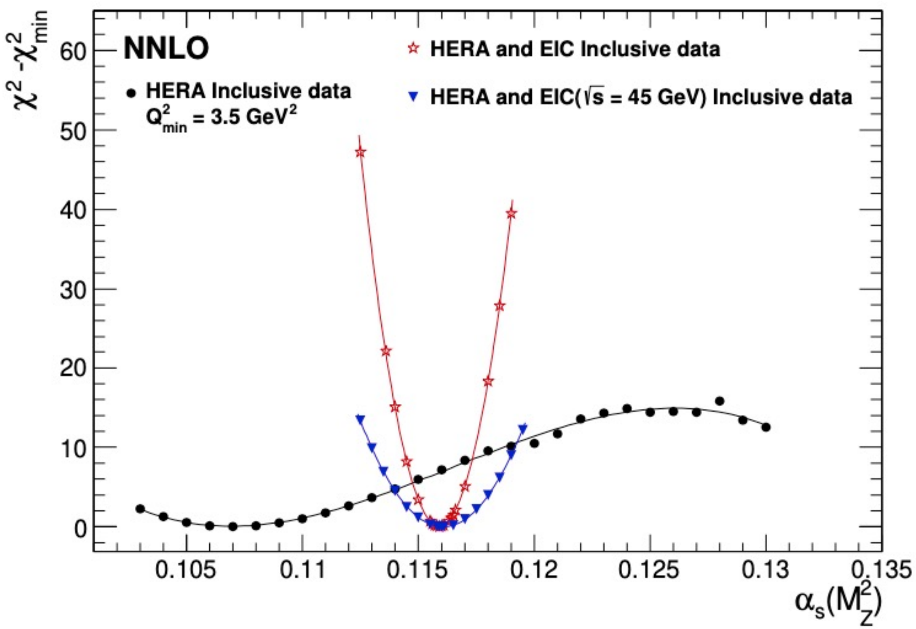
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

Sensitivity of EIC relative to EPPS21 recent nuclear PDFs (EIC-only fit)

→ Factor ~ 2 improvement at x~0.1

→ Very substantial improvement in newly accessed low x region

# Taking $\alpha_s$ as an additional free parameter




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

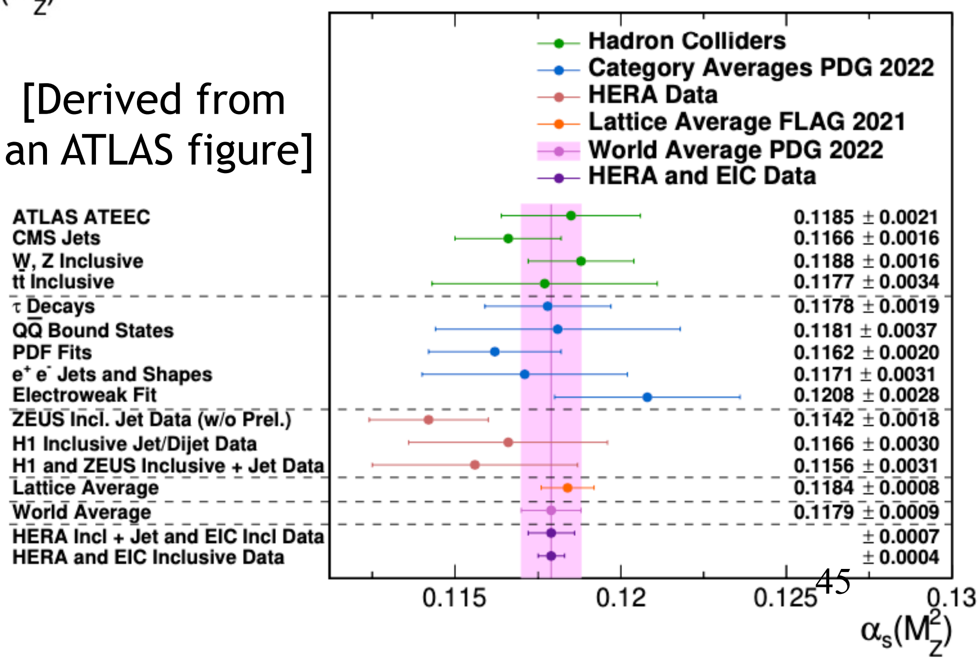
- Adding EIC simulated data has a remarkable impact

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

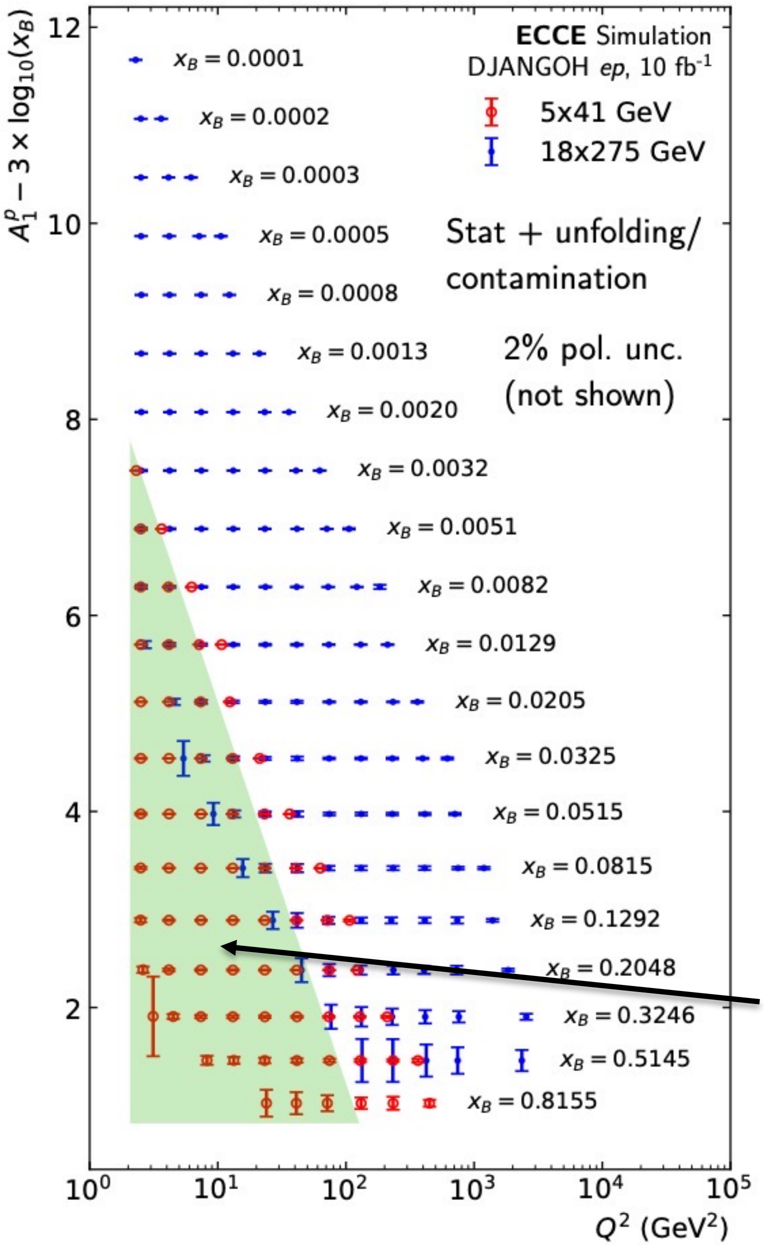
Adding EIC (precision high x) data to HERA can lead to $\alpha_s$ precision a factor ~2 better than current world experimental average, and than lattice QCD average

Scale uncertainties remain to be understood (ongoing work)

[Derived from an ATLAS figure]



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




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

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

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

… measure the quark and antiquark helicity distributions …

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

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

Previously measured region (in green)

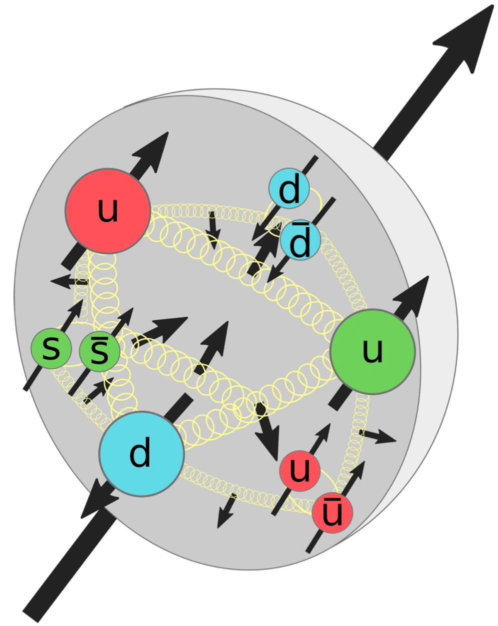
EIC measures down to x ~ 5 x $10^{-3}$ for 1 < $Q^2$ < 100 $GeV^2$

# More 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

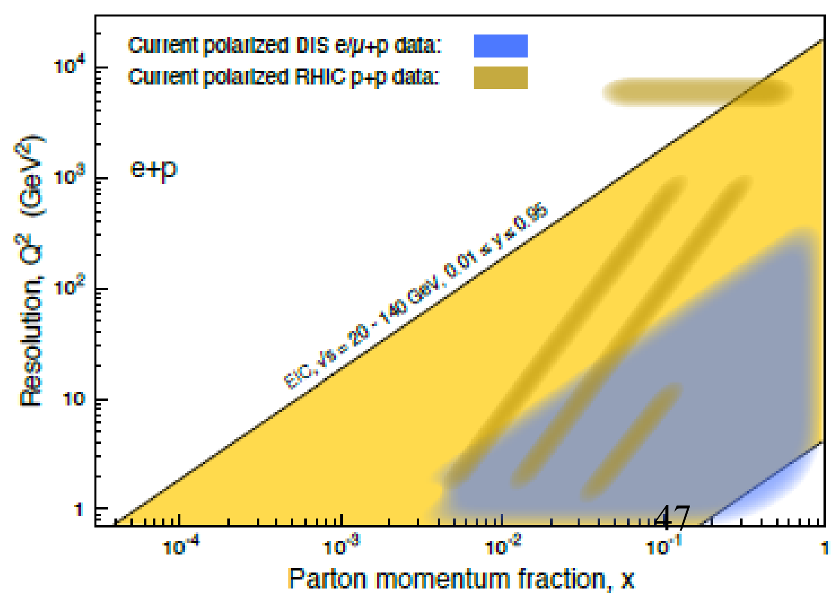



Jaffe-Manohar sum rule:

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

Quark helicity | Gluon helicity | Quark canonical orbital angular momentum | Gluon canonical orbital angular momentum

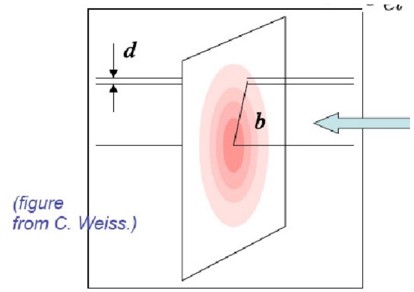
- Very little known about gluon helicity contribution or importance of low x region

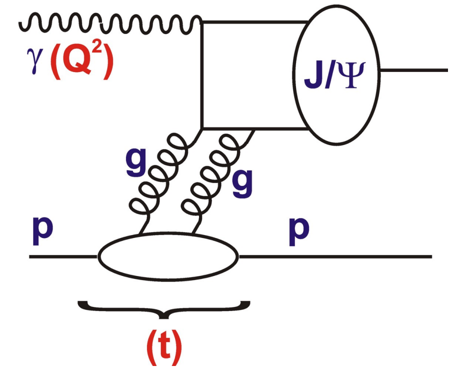


# Exclusive Processes and Dense Systems

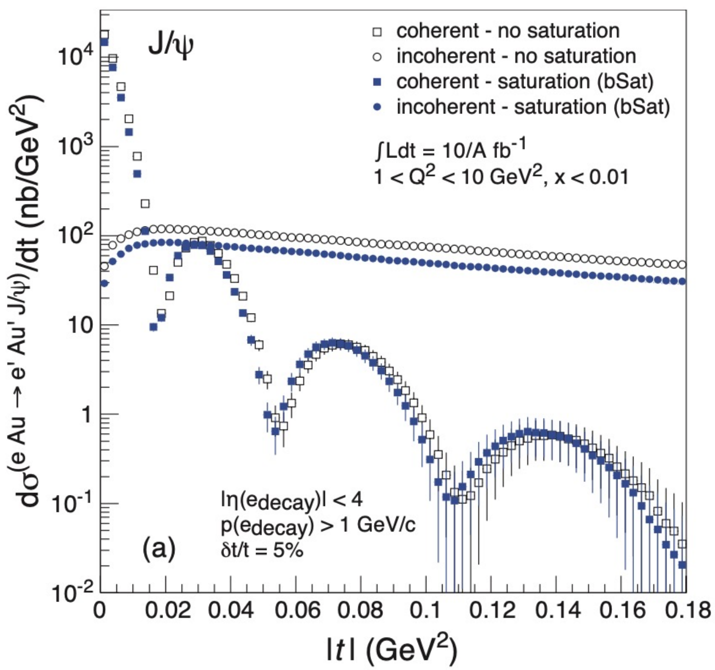
Additional variable (Mandelstam) t is conjugate to transverse spatial distributions

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



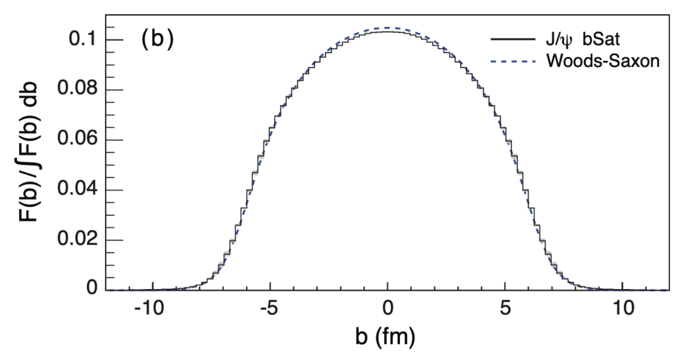




[arXiv:1211.3048]




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

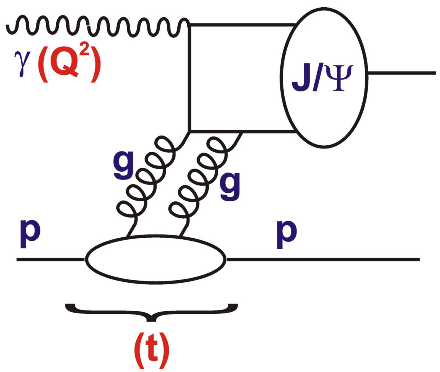
→ Fourier transform



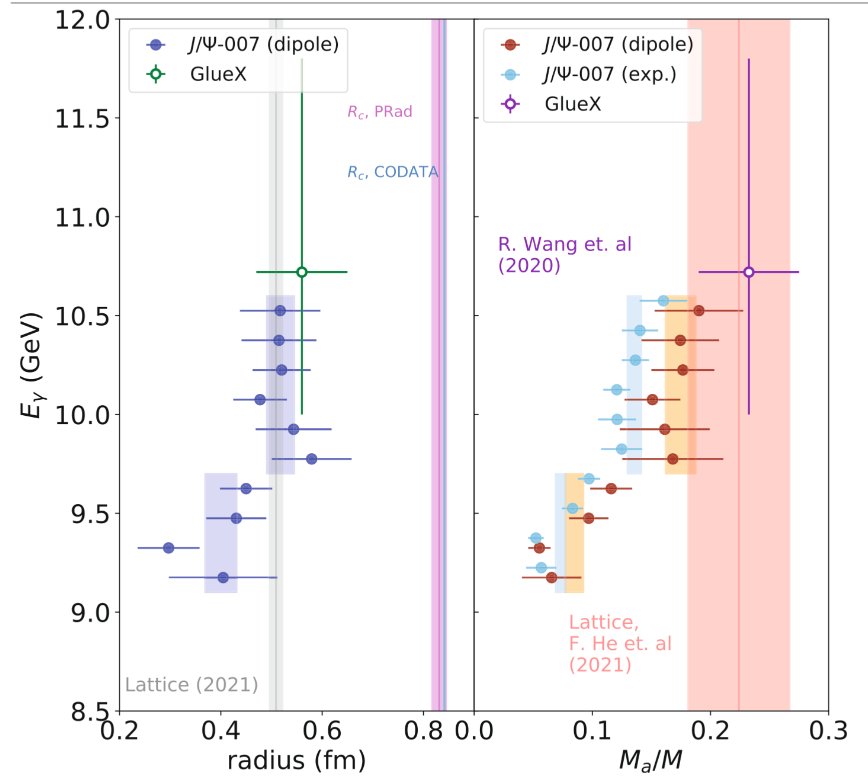



Experimental challenges from incoherent background and resolving dips

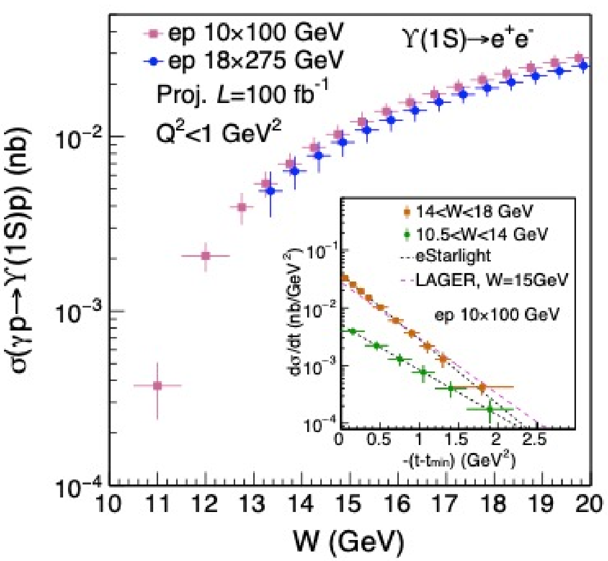
# Proton Mass & Exclusive Vector Mesons

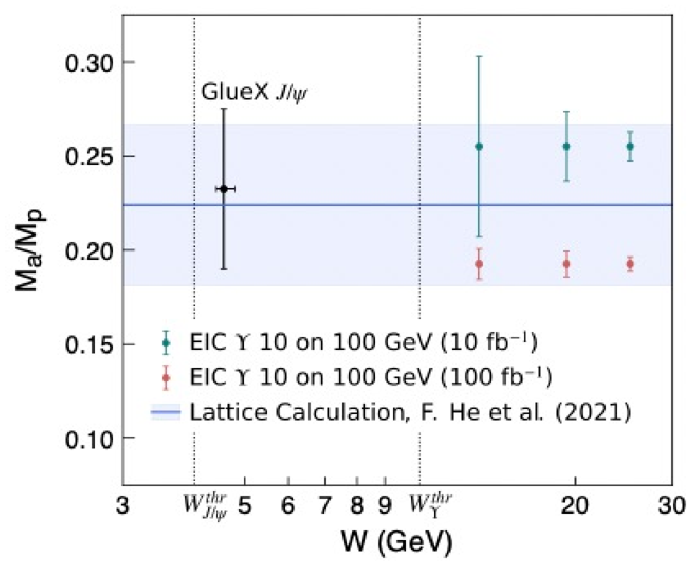



- Recent Jlab data on t dependences of J/Ψ production near threshold → Gravitational form factors



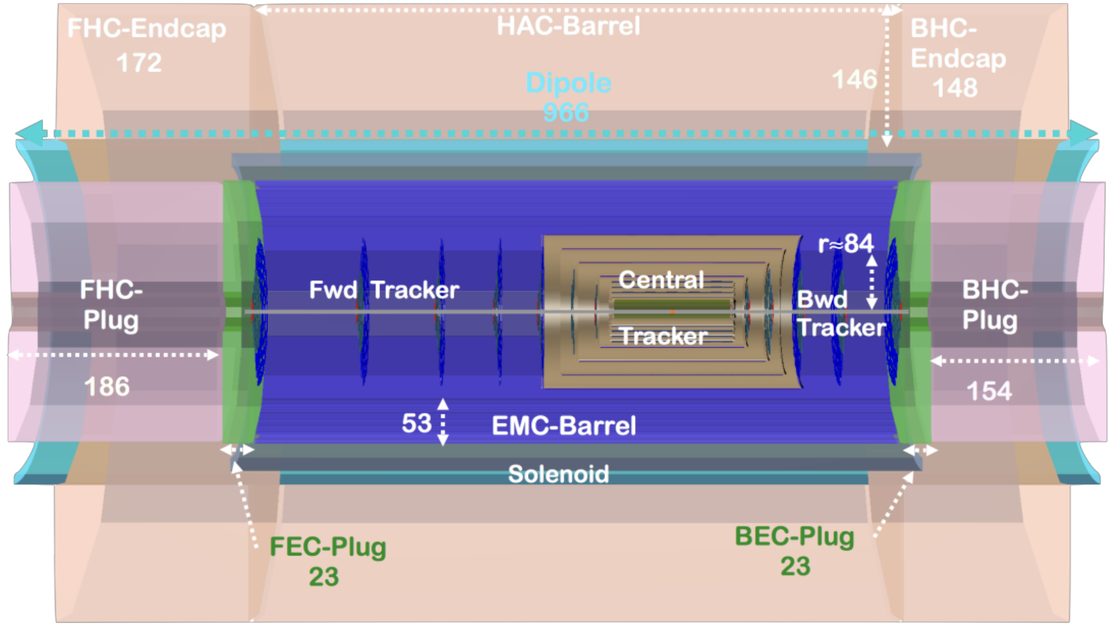

- Gluon radius smaller than charge radius
- Interpreted in terms of trace anomaly




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

# Calorimetry in CDR-Update

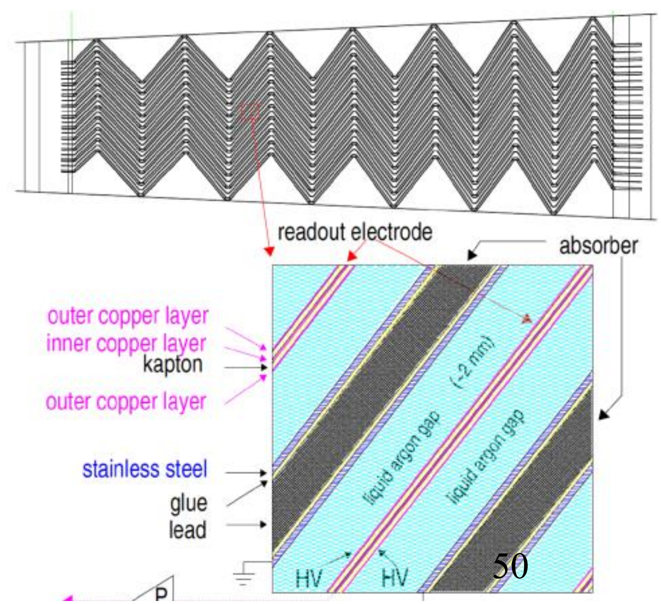



- 'Accordion' geometry Lar EM Barrel (|η|<2.8), inside solenoid / dipole

- Plastic-scintillator HCAL for e/h separation

- Finely segmented plugs (W, Pb, Cu) for compact showering, with Si sensors

- 25-50 $X_0$ and ~10λ throughout acceptance region




| Baseline configuration | | $\eta$ coverage | angular coverage |
|---|---|---|---|
| EM barrel + small $\eta$ endcap | LAr | $-2.3 < \eta < 2.8$ | 6.6° – 168.9° |
| Had barrel+Ecap | Sci-Fe | (~ behind EM barrel) | |
| EM+Had very forward | Si-W | $2.8 < \eta < 5.5$ | 0.48° – |
| EM+Had very backward | Si-Pb | $-2.3 < \eta < -4.8$ | –179.1° |