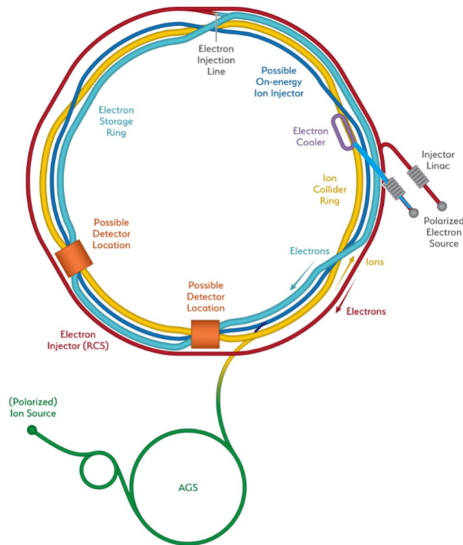
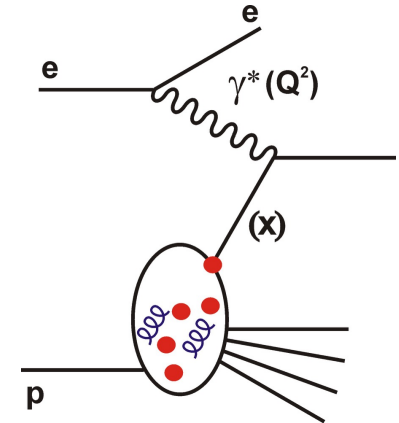
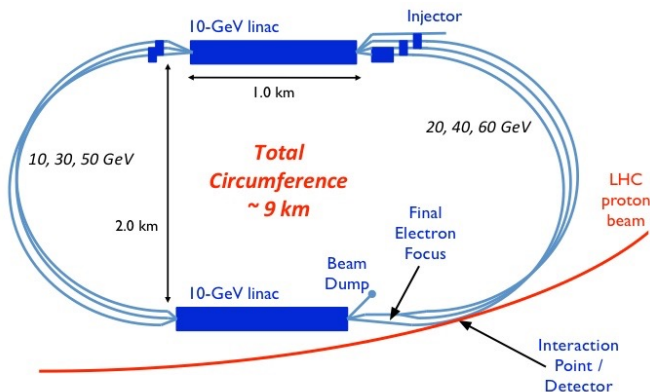


Future Lepton-Hadron Scattering and the Electron Ion Collider

Paul Newman (Birmingham)

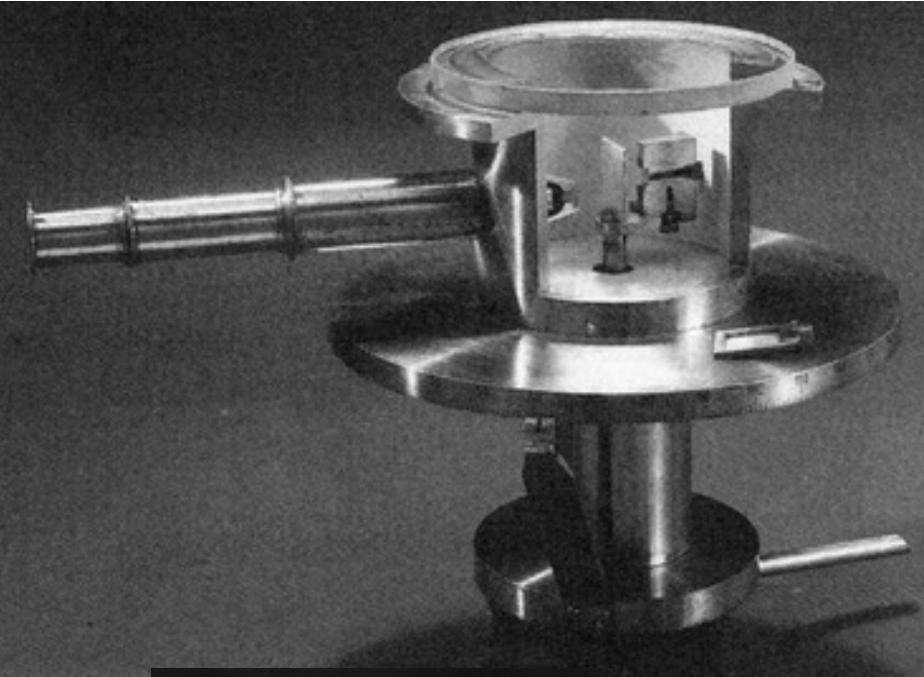


Brussels Seminar
8 October 2026

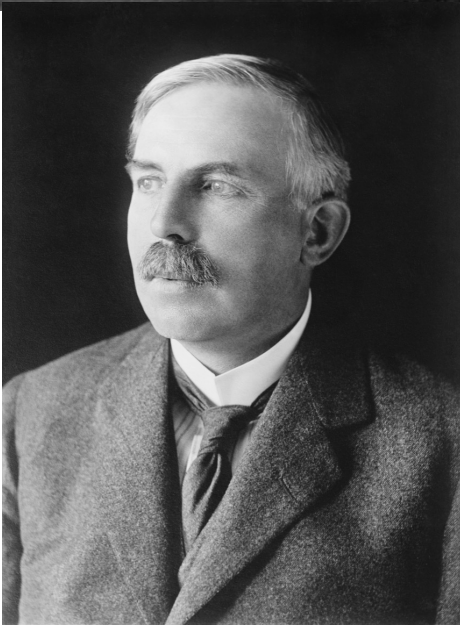


- 1) Deep Inelastic Scattering
- 2) Proton partonic structure
- 3) The Electron Ion Collider
- 4) The Large Hadron electron Collider

Rutherford (1927, as President of Royal Society)



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

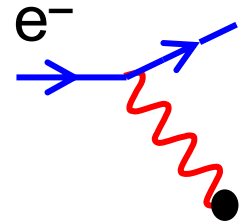


*“It would be of great scientific
interest if it were possible to
have a supply of electrons ...
of which the individual energy
of motion is greater even than
that of the alpha particle.”*

Probing the Proton with Electrons

Simple uncertainty principle arguments:

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



... 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

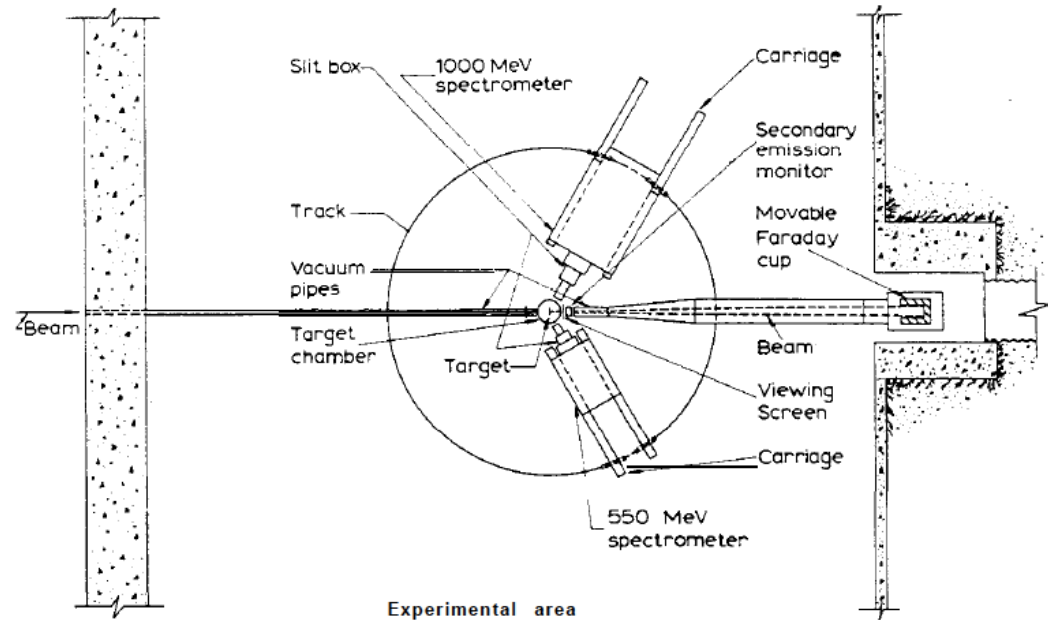
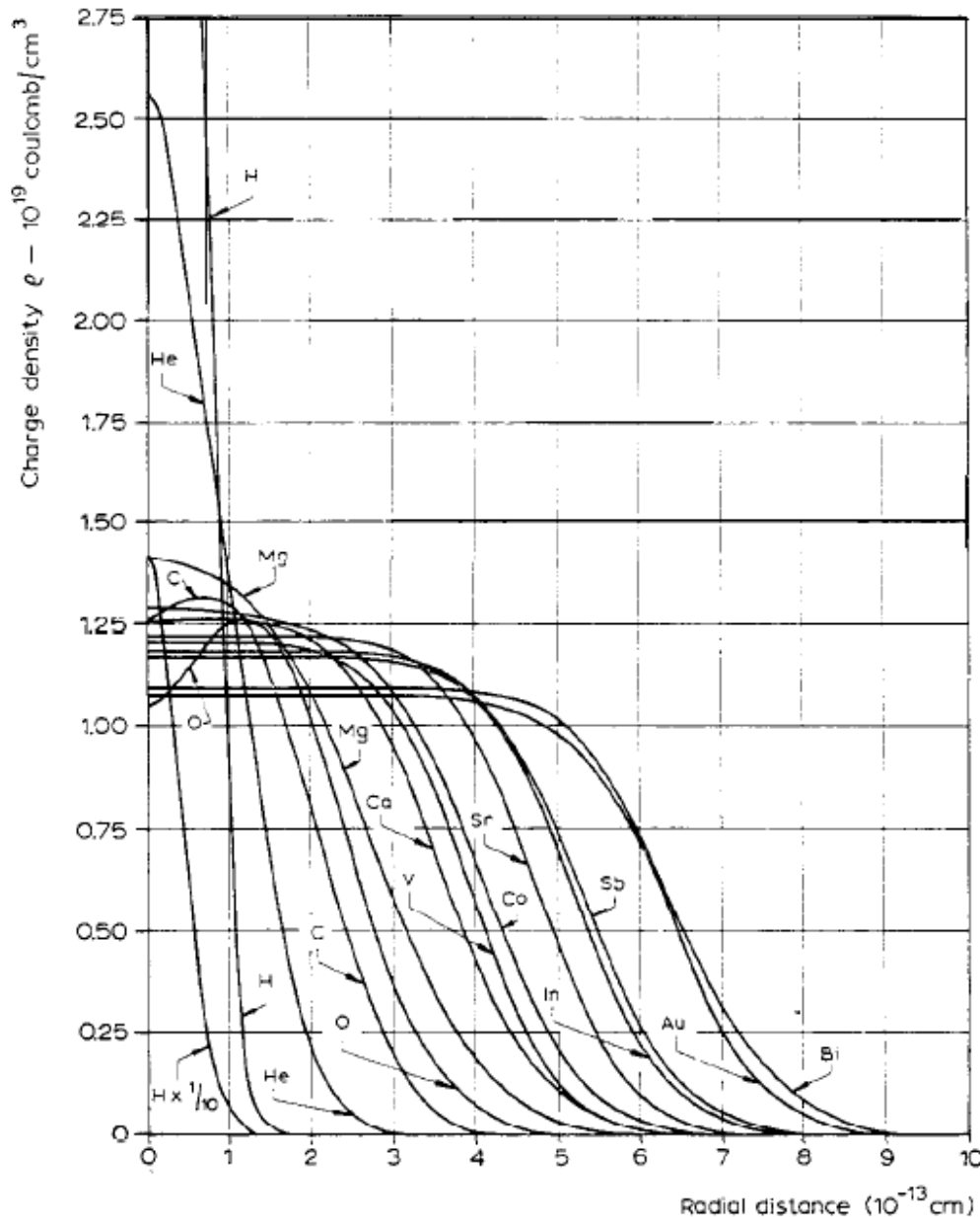


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

Hoffstadter's Results

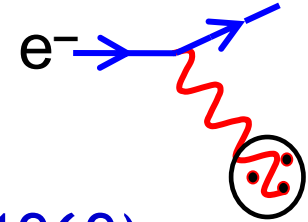
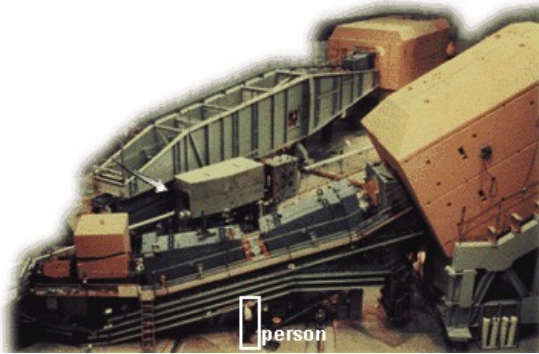


... Interpreting scattered electron pattern to determine spatial distribution of the target charge distribution

→ proton radius ~ 1fm

Probing the Proton with Higher Energy Electrons

... 1-2 more orders of magnitude $\rightarrow$ 0.1-0.01 fm



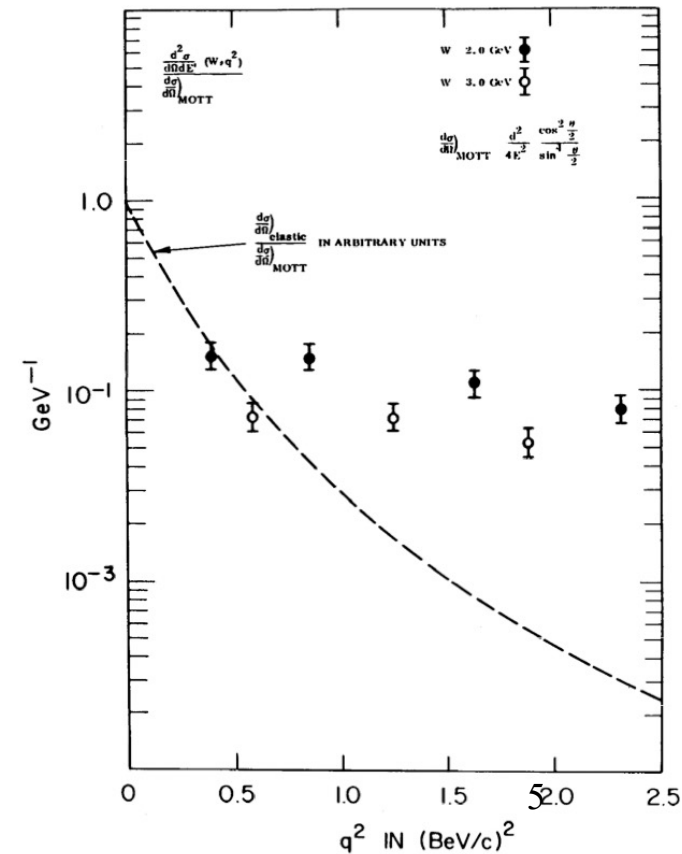
ESA experiment at SLAC (1969)

~20 GeV electrons on fixed proton target



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

(Bjorken Scaling)



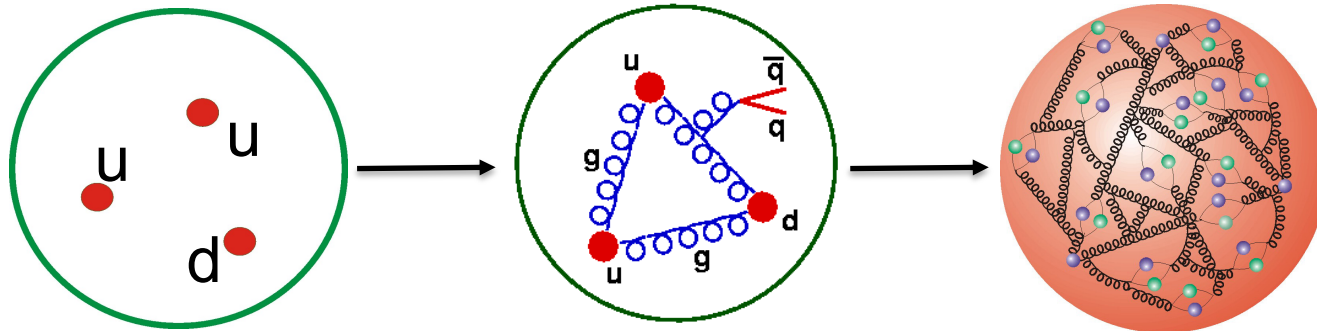
- The only ever collider of electron with proton beams:

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

- Equivalent to 50 TeV electrons on fixed target

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

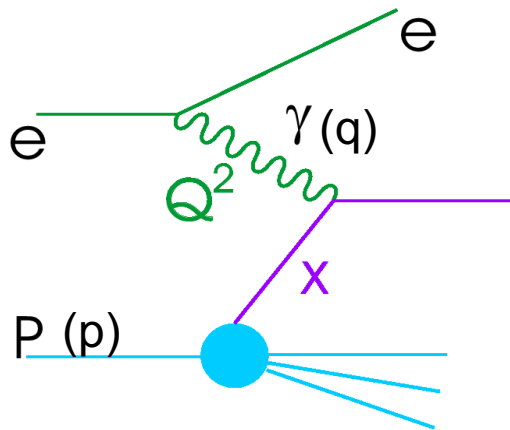
→ Source of much of our knowledge of proton (longitudinal) structure, extending to partons of $x < 10^{-4}$ momentum fraction



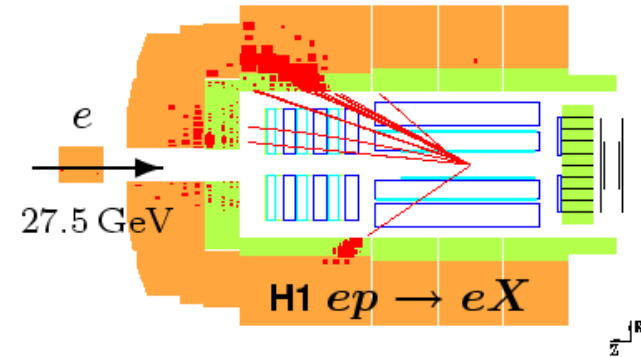
BUT ...

- Only $\sim 0.5 \text{ fb}^{-1}$ per experiment
- No deuterons or nuclei
- No polarised targets

Inclusive Neutral Current DIS: $ep \rightarrow eX$... Kinematics



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



x = fraction of proton momentum carried by struck quark

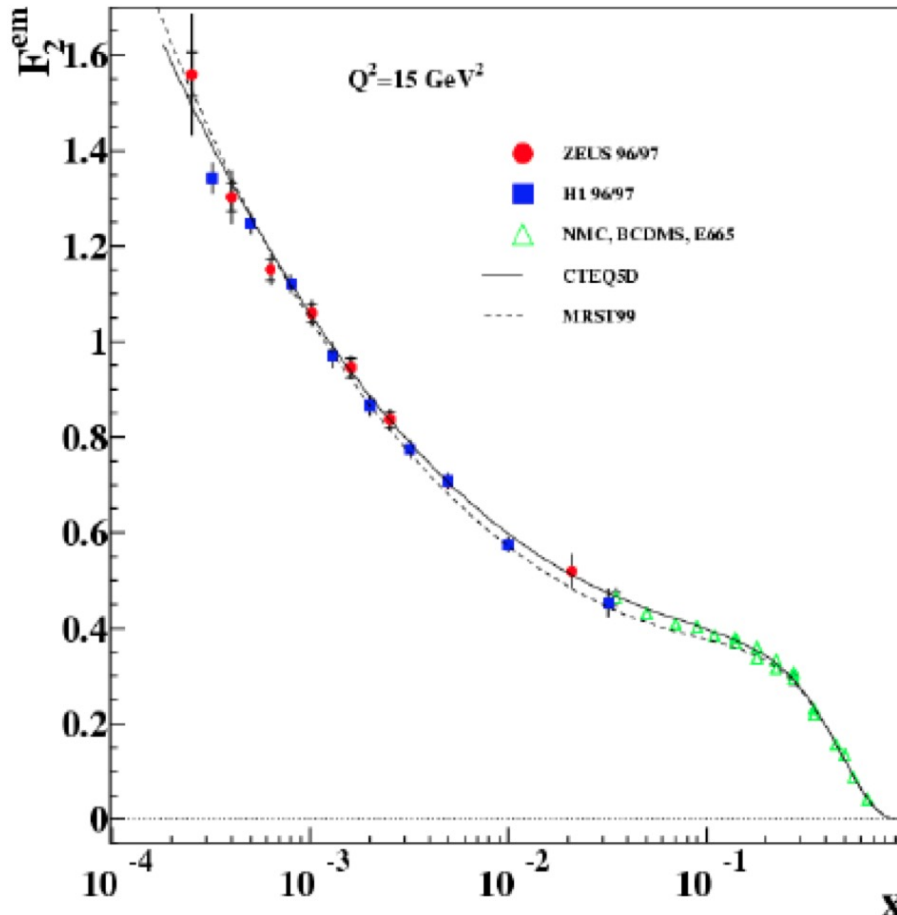
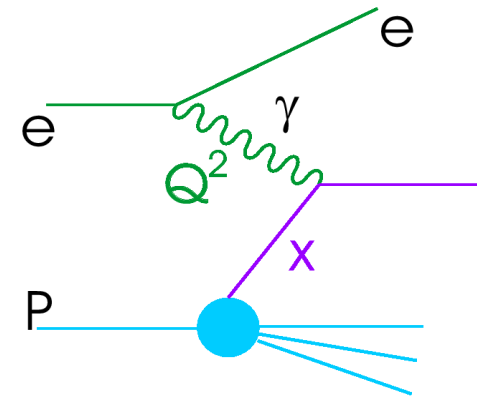
Q^2 = |4-momentum transfer squared| (photon virtuality)
... measures the hardness / scale of collision
... inverse of (squared) resolved dimension

$s = Q^2 / x_y$ with inelasticity $y < 1$

... i.e. Maximum Q^2 and minimum x
governed by CMS energy, $\sqrt{s}$

Example Inclusive Neutral Current Data from HERA / Previous Experiments

Fixed target and (early) HERA data at a single Q^2 value (15 GeV^2)



- Photon-exchange component of NC data measures

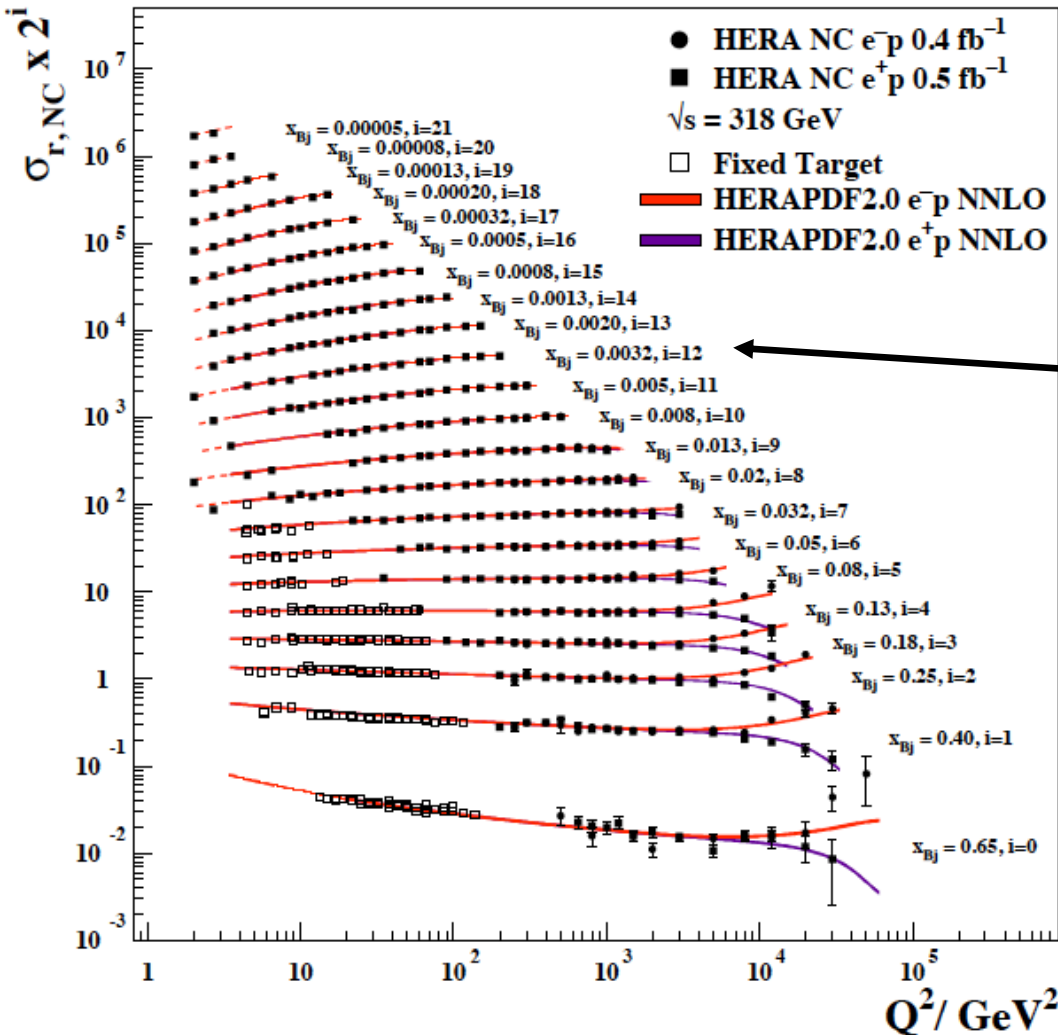
$$\frac{d\sigma}{dx dQ^2} \sim F_2 = \sum_q e_q^2 x (q + \bar{q})$$

- Due to e_q^2 photon coupling, this mainly constrains u & $\bar{u}$... shape of quark densities already qualitatively apparent

Variations of the cross sections with Q^2 tell us about the role of gluons ...

QCD Evolution and the Gluon Density

H1 and ZEUS



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

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

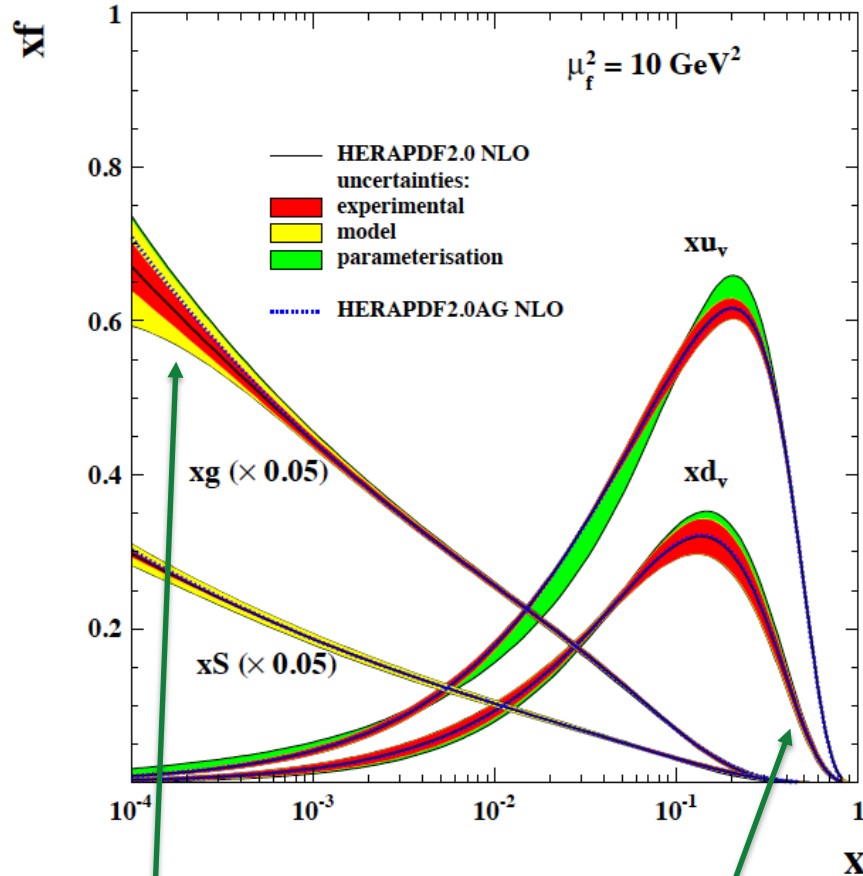
- DGLAP equations describe QCD
evolution (to NNLO and
approximate $N^3\text{LO}$ accuracy)

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

→ Fits to data to extract proton
parton densities

Proton PDFs from HERA only (HERAPDF2.0)

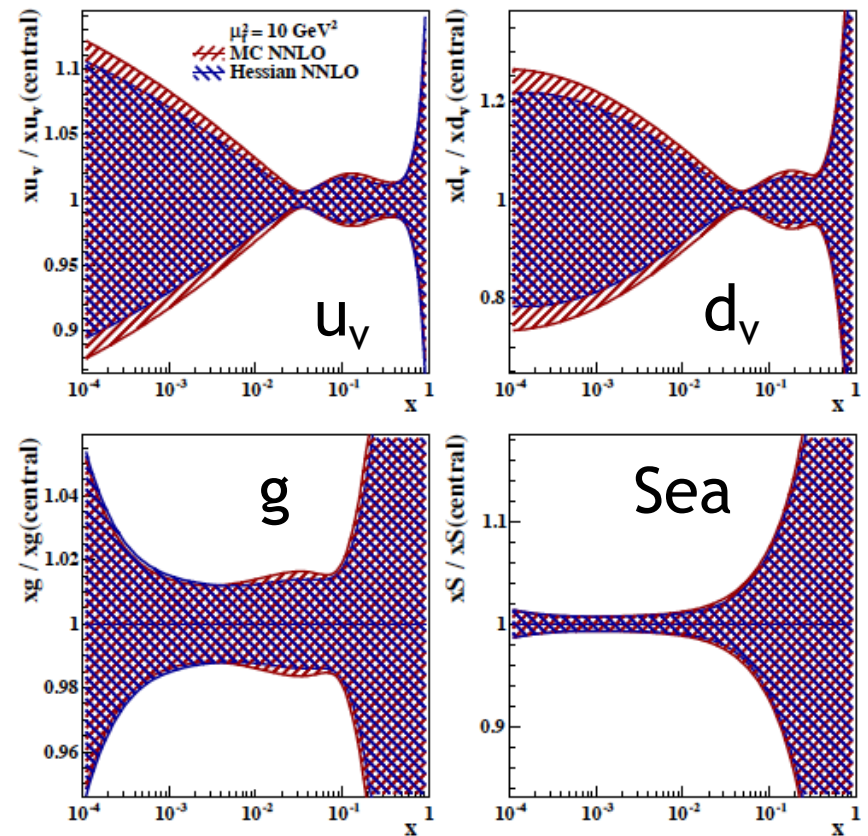
H1 and ZEUS



Strong
interaction
dragons?

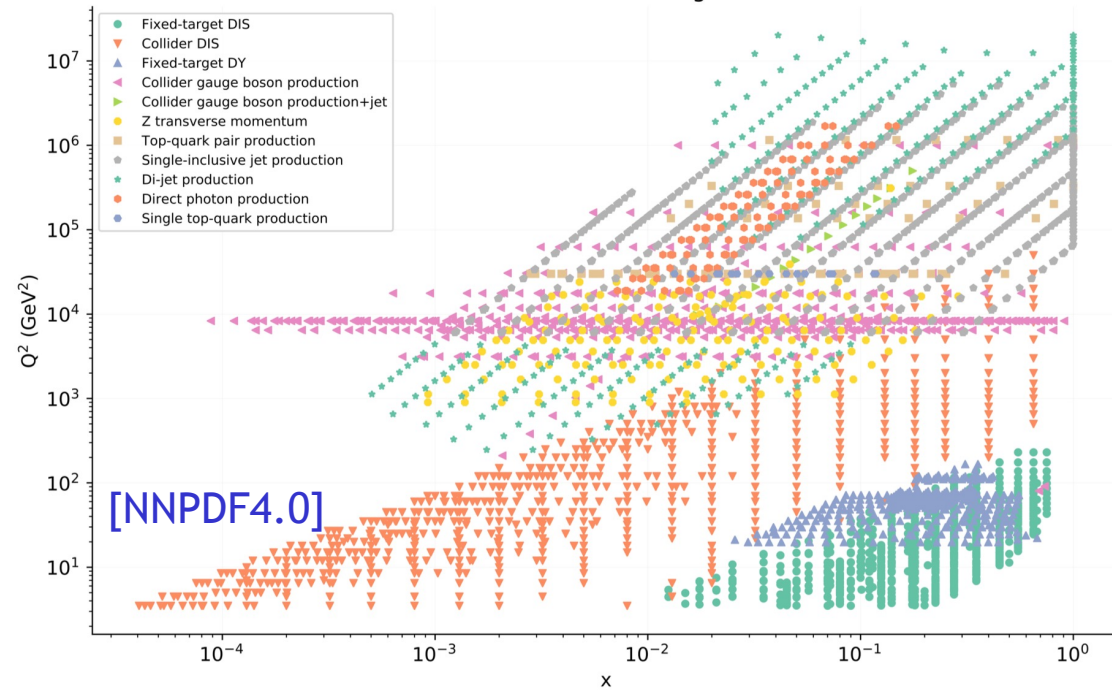
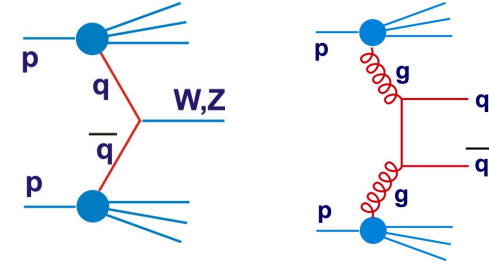
Input to
energy frontier
discovery?

H1 and ZEUS

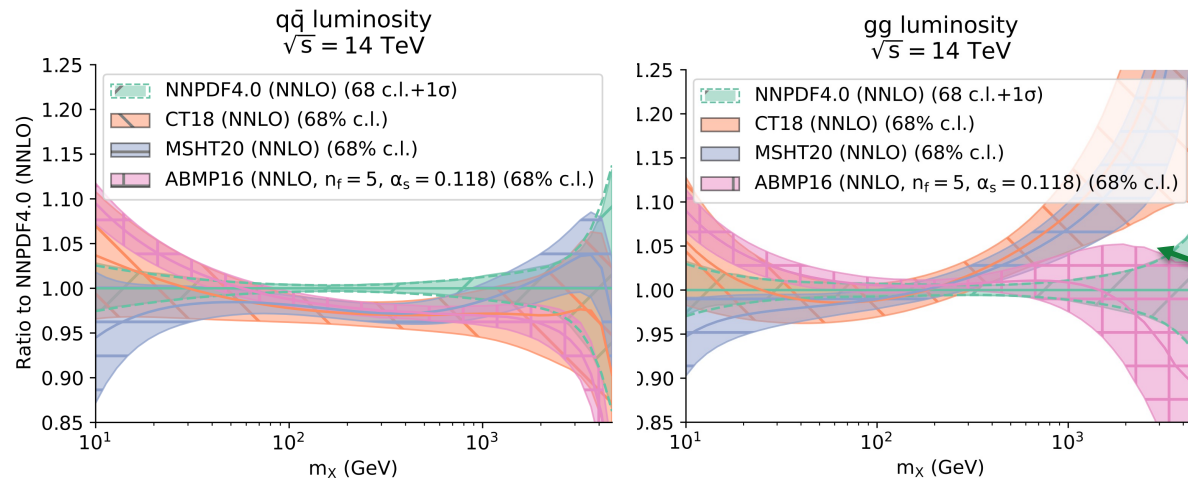


- At $x \sim 10^{-2}$: ~2% gluon, 1% quark precision
- Uncertainty explodes:
 - below $x=10^{-3}$ (kinematic limit)
 - above $x=10^{-1}$ (limited lumi)¹⁰

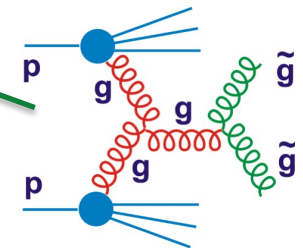
Constraining PDFs with LHC Data



- LHC impacts PDFs mainly at large x & flavour decomposition
- Strong impact, but also tension between different global fitting groups



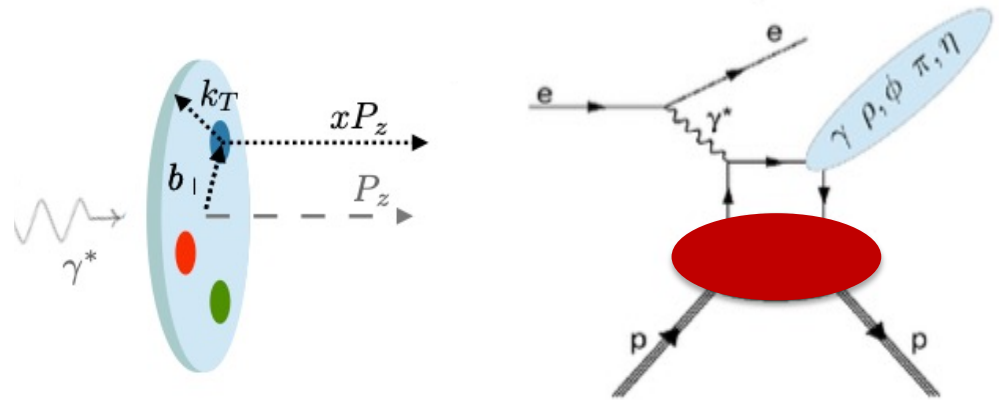
- Large x BSM effects may also get hidden?



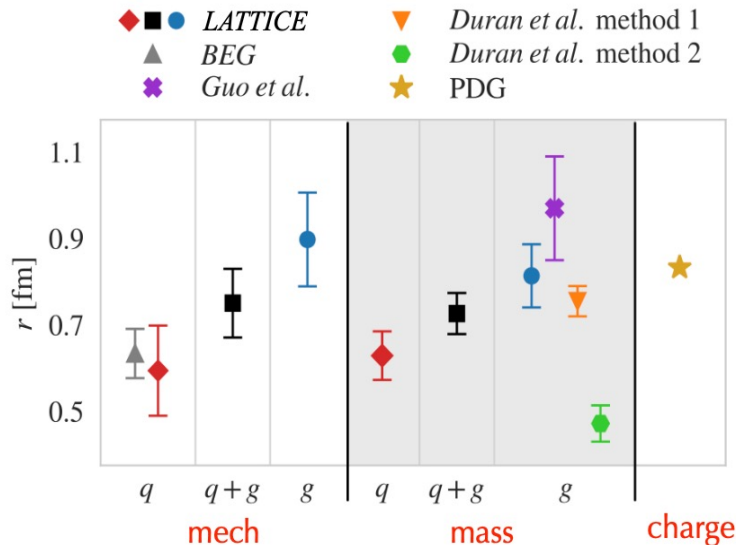
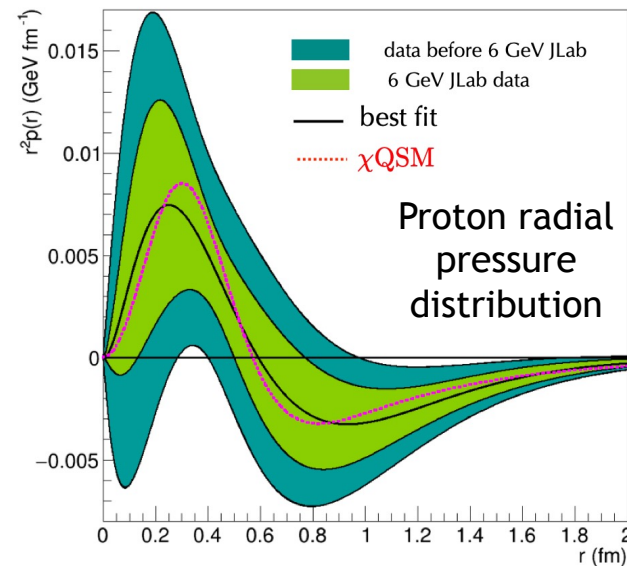
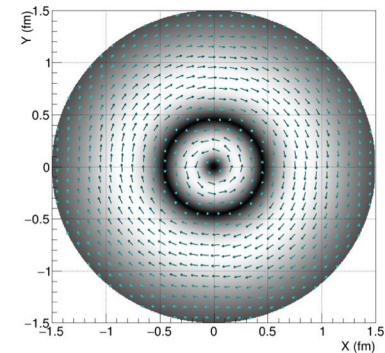
... motivation to further constrain PDFs from DIS data only?..

Hadron Structure and Dynamics are much richer than longitudinal PDFs ...

Transverse degrees of freedom, correlations in momentum and position through exclusive processes (GPDs), SIDIS (TMDs) ...
 → First glimpses of 3D structure & mechanical properties (examples from Jlab data)



Proton size

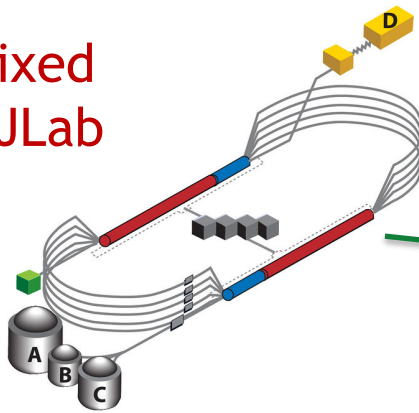


Shear forces

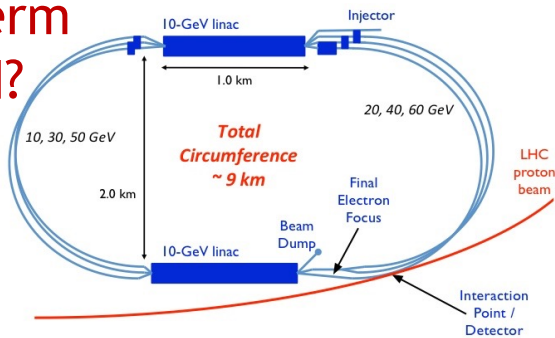
Girod, Elouadrhiri, Burkert, Nature 557 (2018) 7705

Current & Future ep Colliders

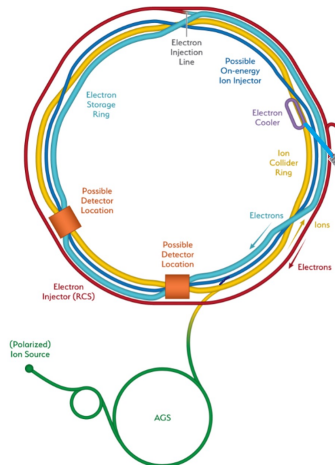
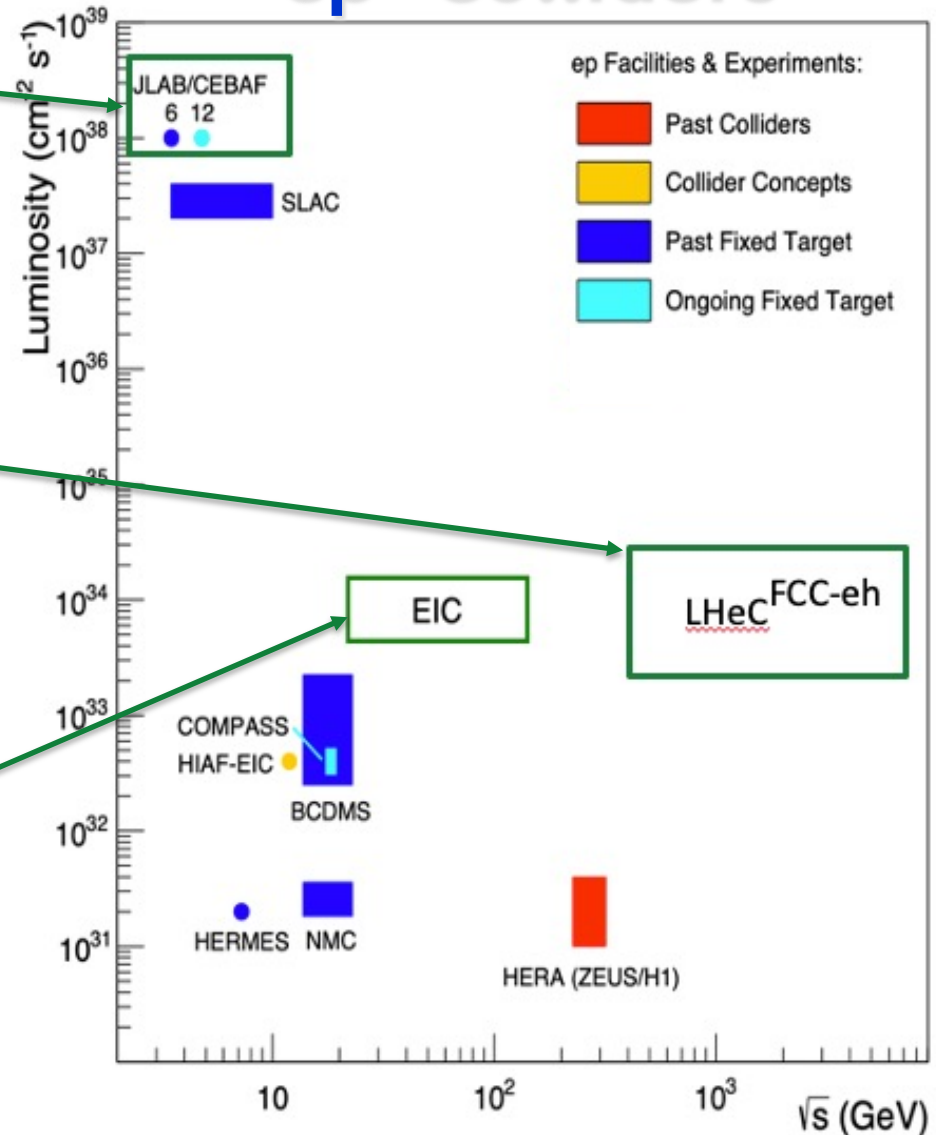
Ongoing fixed target @ JLab



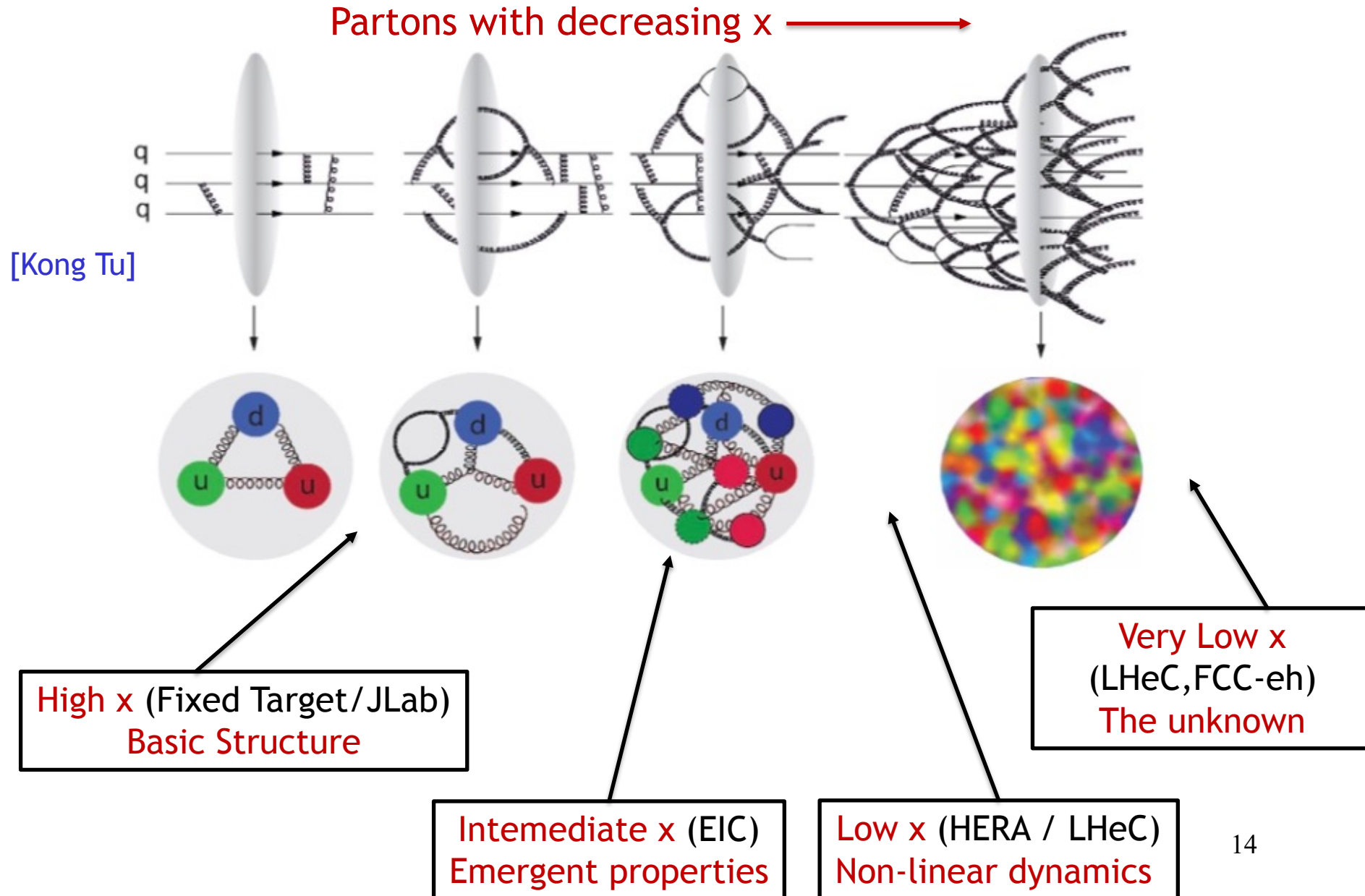
Longer-term @ CERN?



Mid 2030s @ BNL



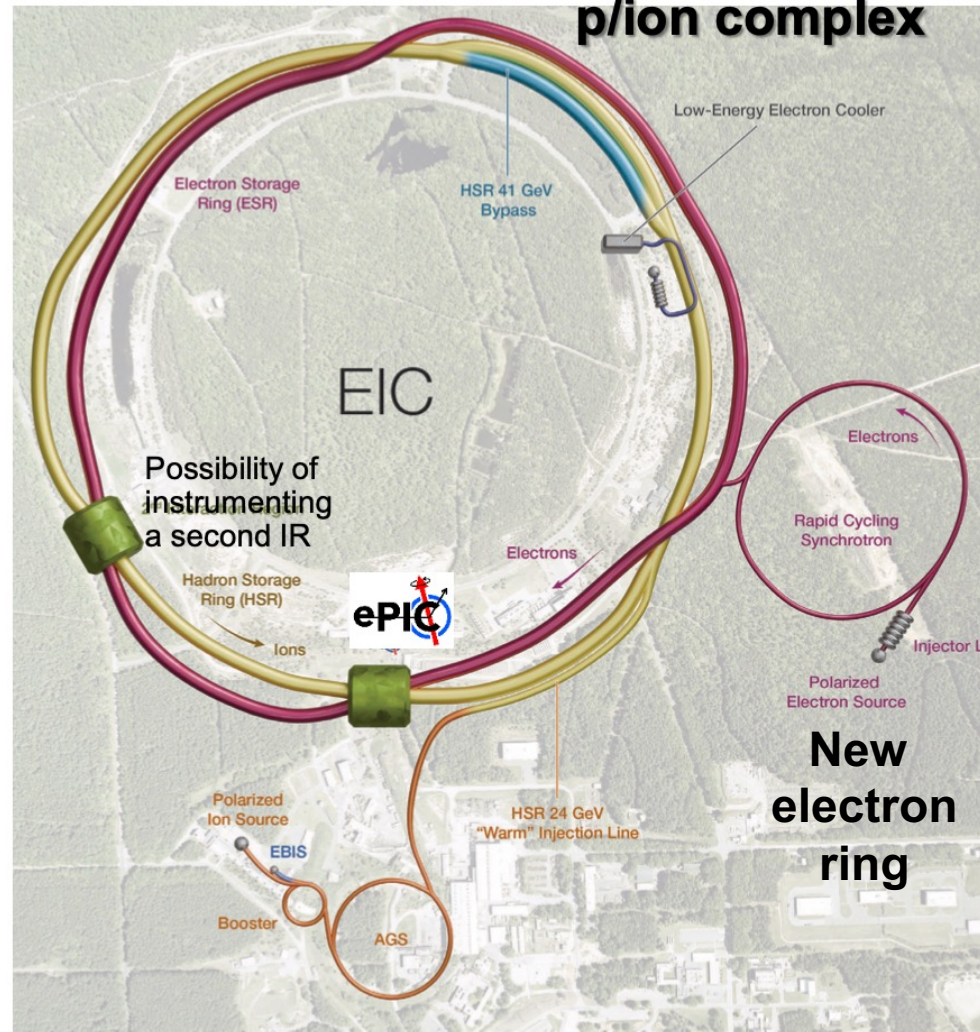
Crude Mapping Between Physics & Facilities



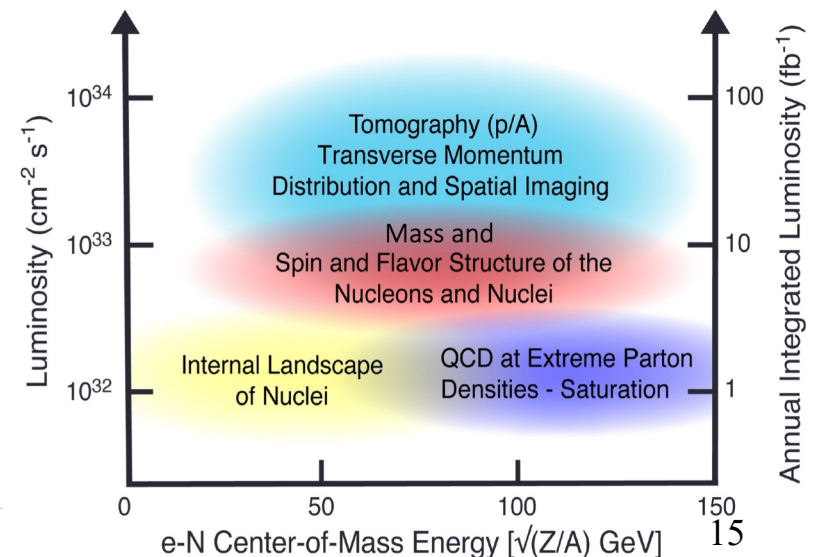
The Electron-Ion Collider (BNL)

Specifications driven by science goals:

Usage of RHIC tunnel and RHIC p/ion complex



- Energy range $28 < \sqrt{s} < 140$ GeV
- World's first ...
- High lumi ep Collider
($\sim 10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
- Double-polarised DIS collider
($\sim 70\%$ for leptons & light nuclei)
- eA collider
(Ions ranging from H to U)



Fundamental questions for EIC

- What does the proton look like in 3D?

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

... How is proton spin generated?

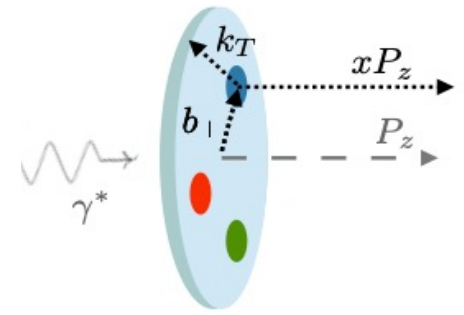
... What is the mechanism behind confinement?

- How are parton properties and dynamics altered in nuclei?

... How do quarks and gluons interact with the nuclear medium?

... What is the QCD-science of high density systems of gluons?

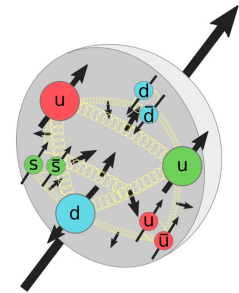
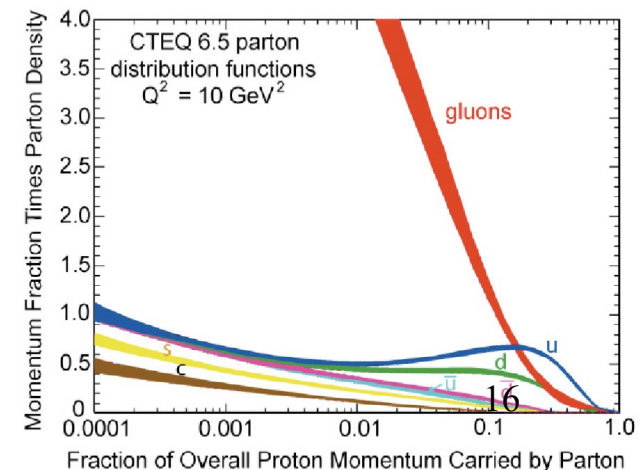
... How is the low x growth of the gluon density tamed?



Atom: Binding/Mass = 0.00000001

Nucleus: Binding/Mass = 0.01

Proton: Binding/Mass = 100



International Community: ePIC Collaboration

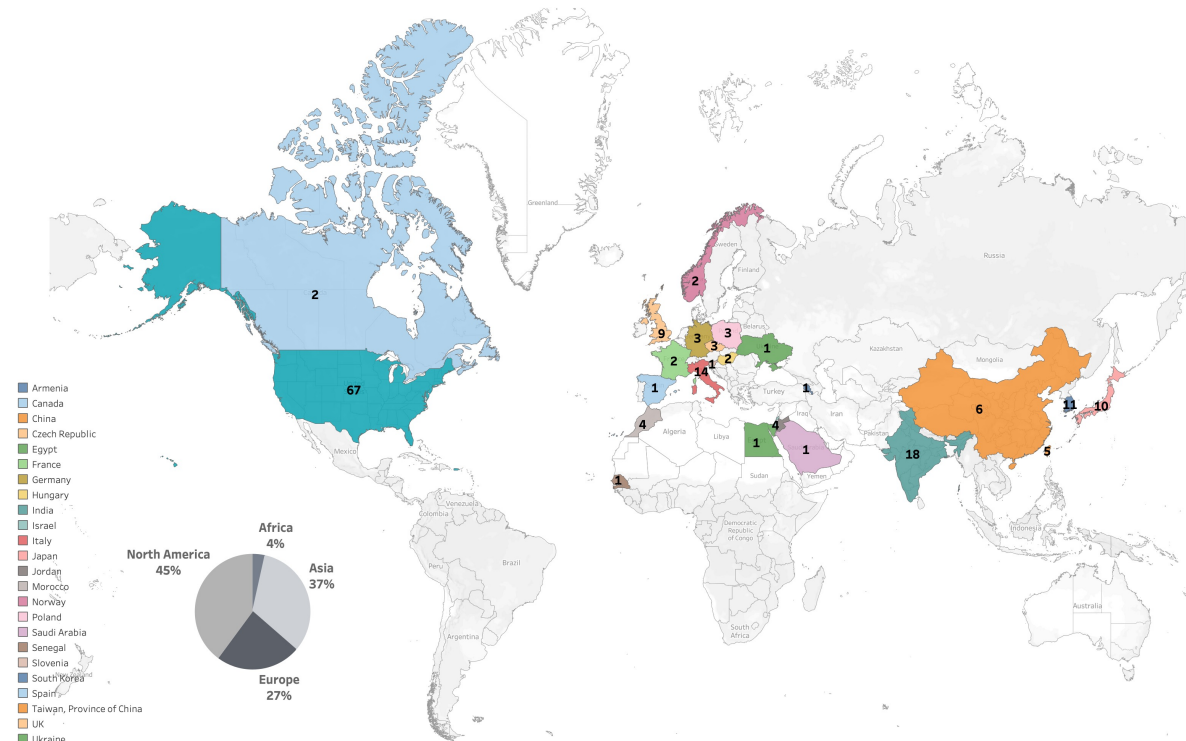


Some of ePIC
Glasgow, July '26



Experimental collaboration
with >1150 collaborators
from 186 institutions in 26
countries (31% Europe)

Part of a wider EIC
User-Group organization
with open membership,
including theorists,
accelerator scientists ...



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 (μ RWELL, MMG) cylindrical and planar

PID

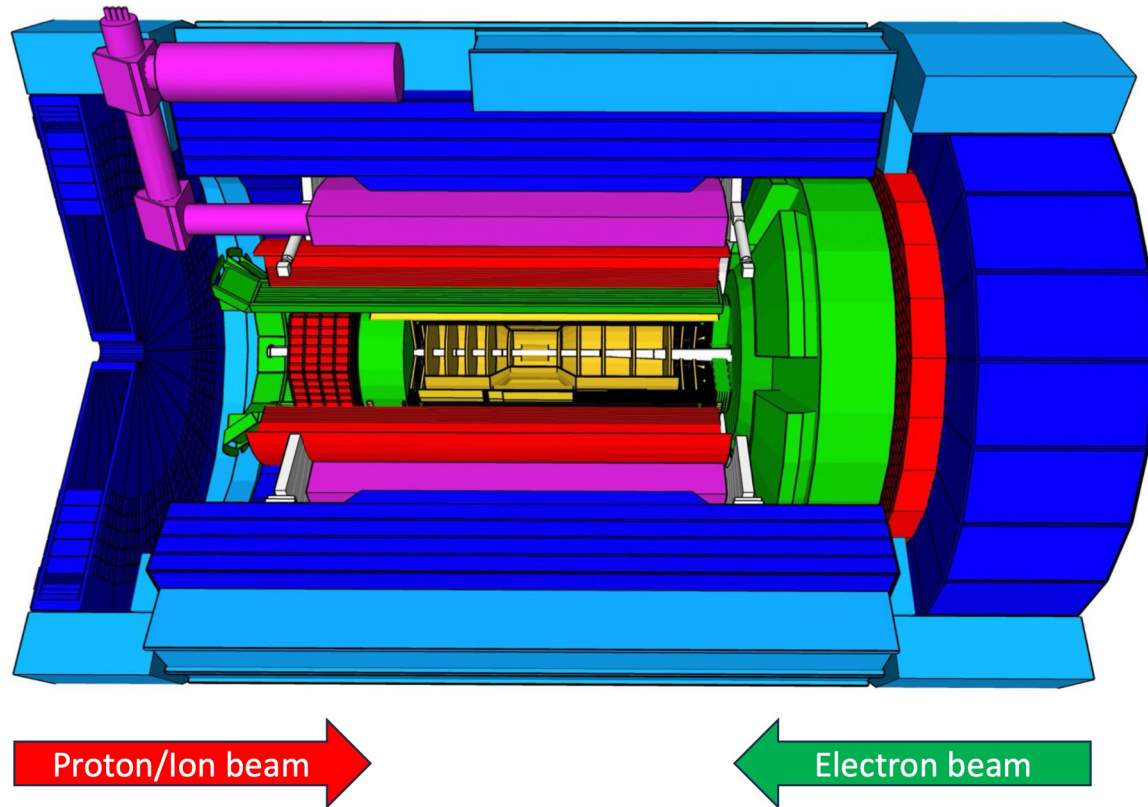
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

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)



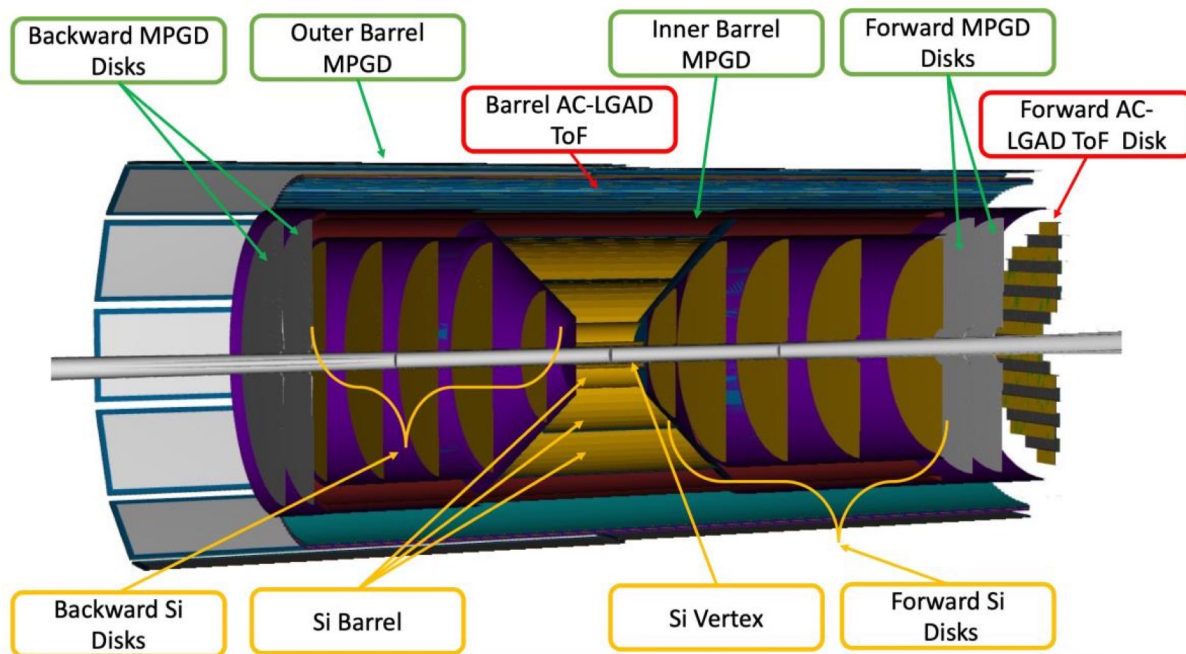
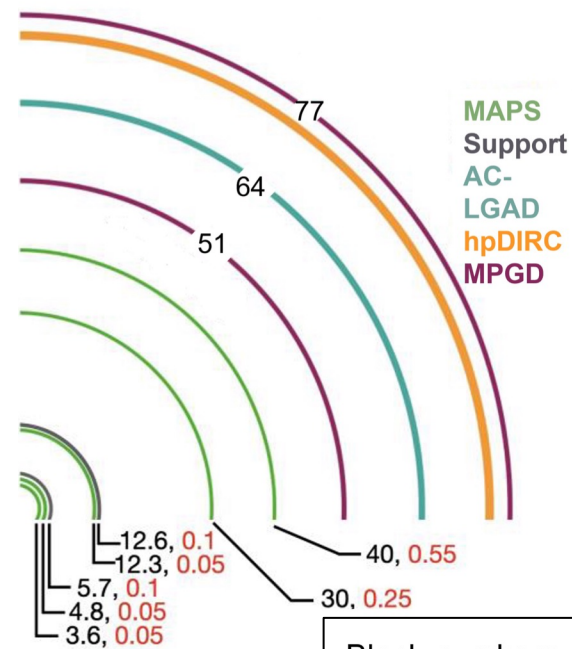
- 9m long x 5m wide
- Hermetic (central detector $-4 < \eta < 4$)
- Extensive beamline instrumentation (see later)
- Much lower radiation fluxes than LHC widens technology options

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 (0.05% X_0 per layer for inner layers)
- 20x20 μm pixels
- 5 barrel layers + 5 disks (total 8.5m² silicon)



Black numbers are radii in cm

Red numbers are material in % X_0

LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

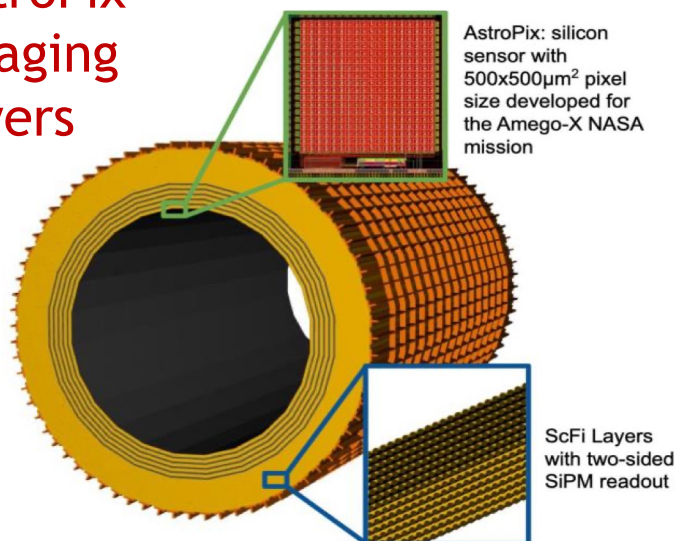
More Novel Detector Components



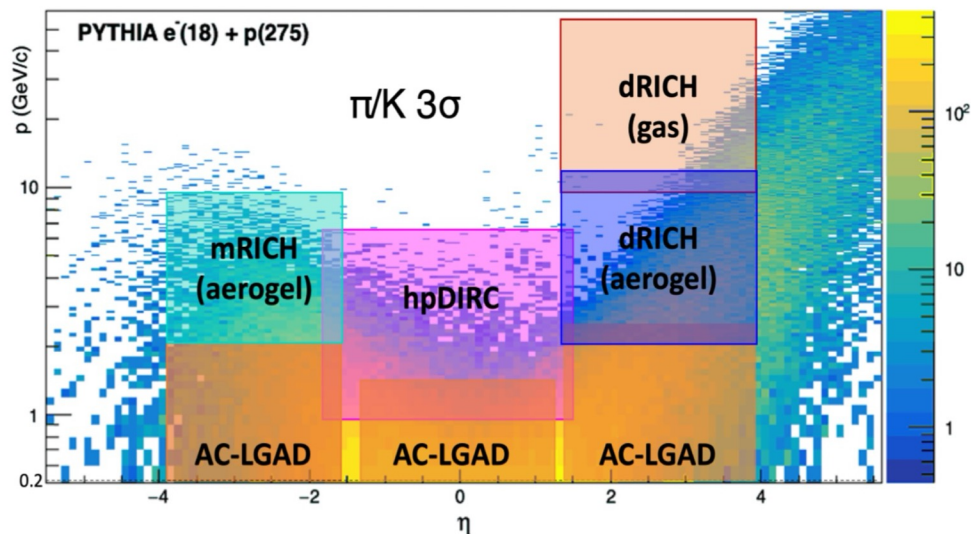
Imaging eCAL

Pb/SciFi sampling +

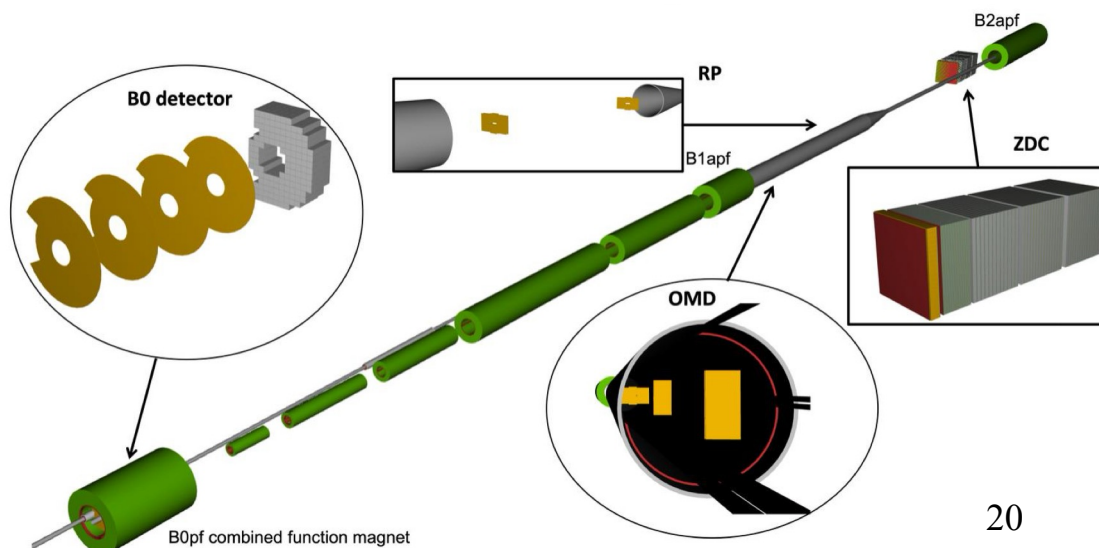
AstroPix
imaging
layers



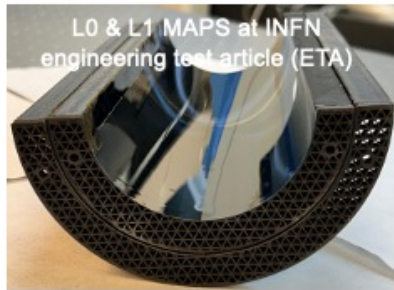
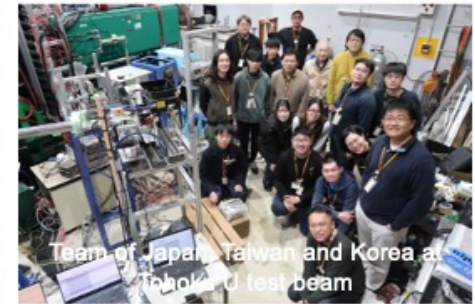
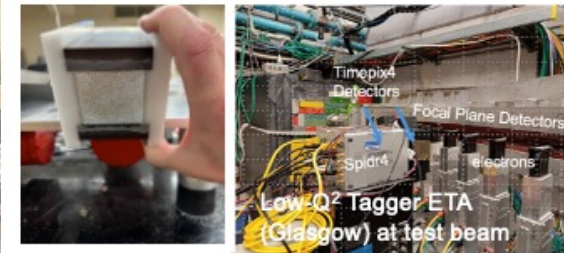
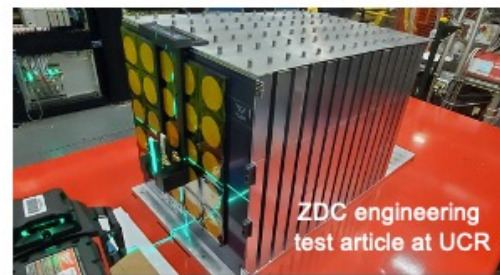
Comprehensive Particle ID



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

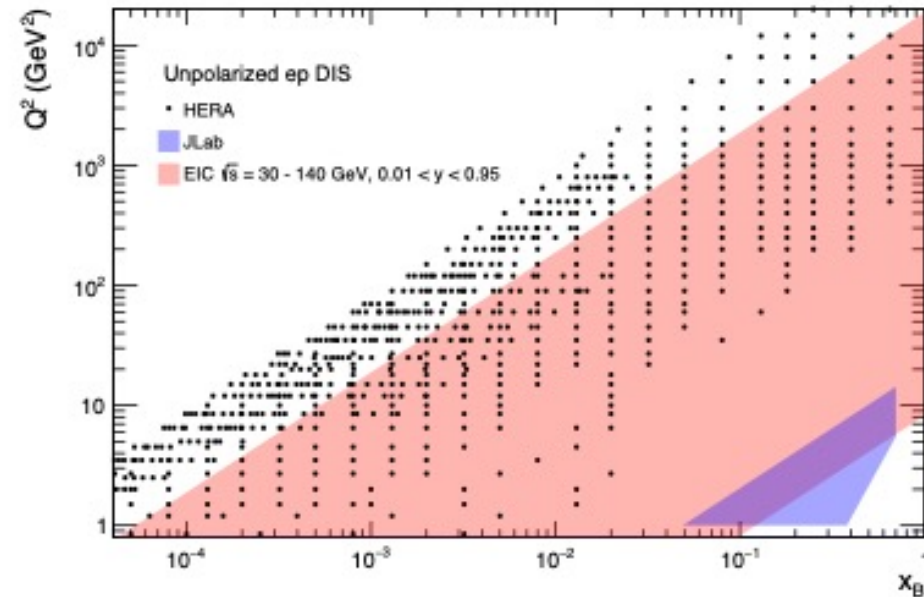


Progress towards Detector Realisation



[Elke Aschenauer, July 2026]

EIC Kinematic Range v Previous Data

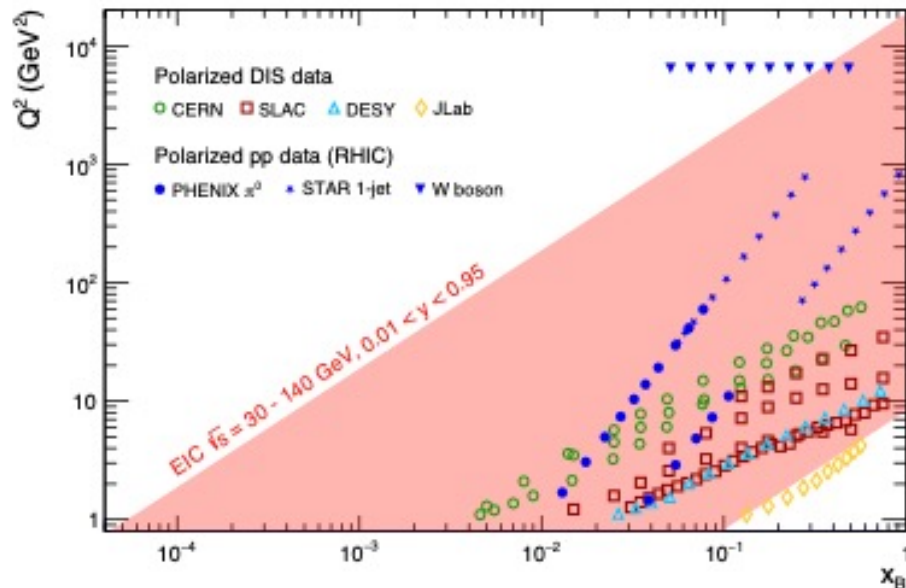
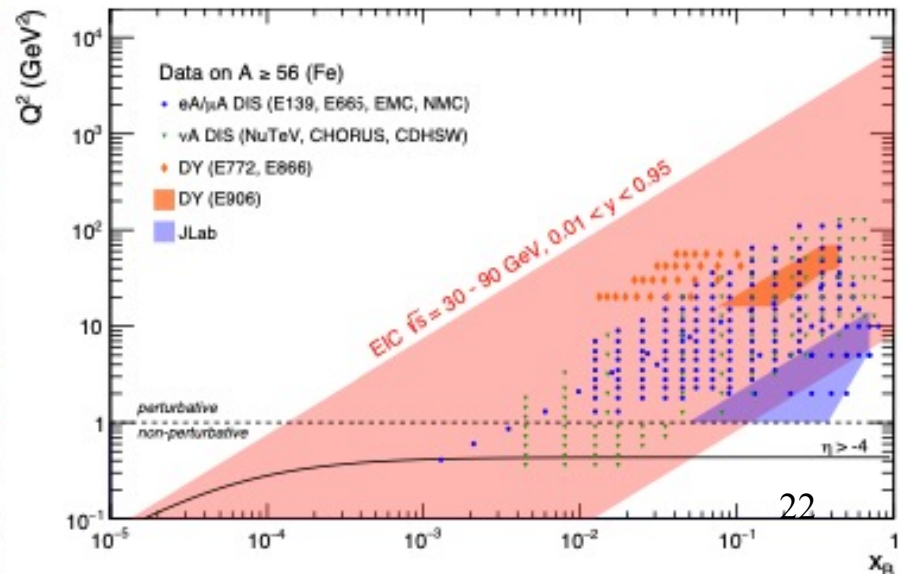


Inclusive ep DIS

→ Closing gap and overlapping between fixed target & HERA
 → High x , moderate Q^2 precision

Polarised target ep & eA DIS

→ Completely unexplored regions, extending to low x



EIC Impact on Proton Parton Densities

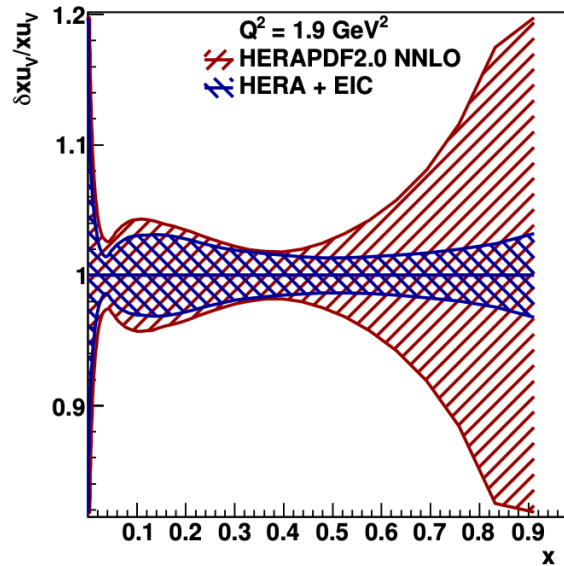
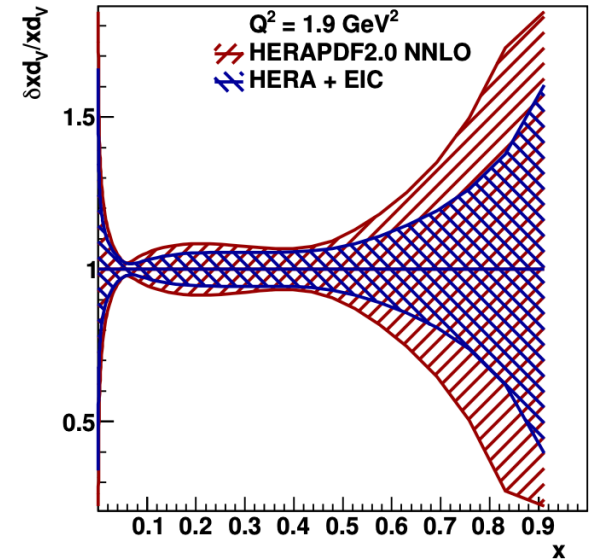
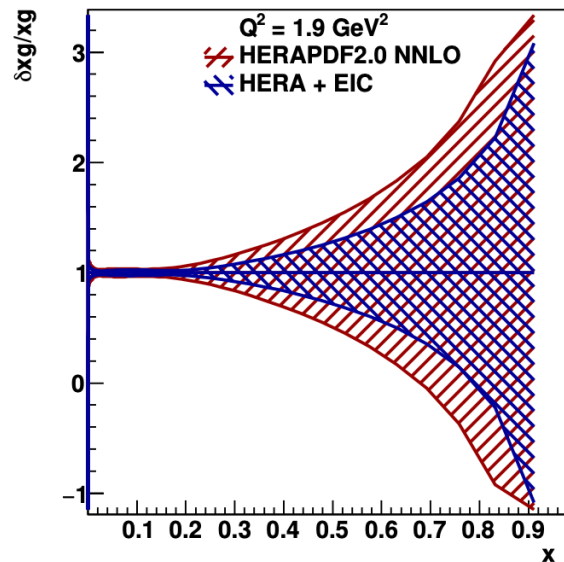
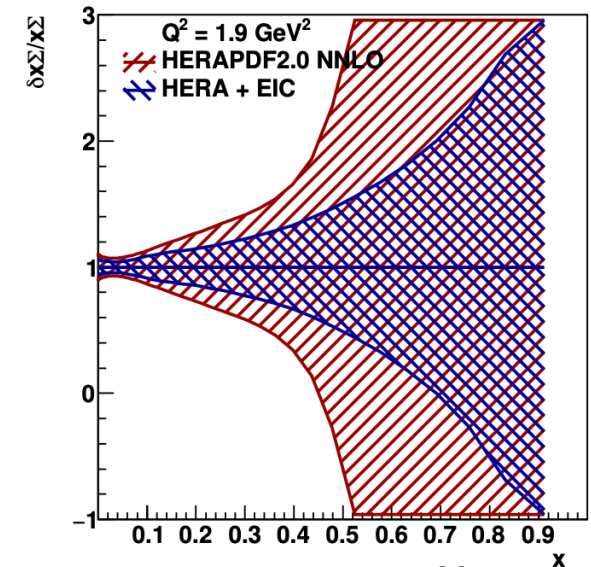
Fractional total uncertainties with / without simulated EIC data added to HERA (lin-x scale)

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

Up quarks improve relative to global fits including LHC (not shown)

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

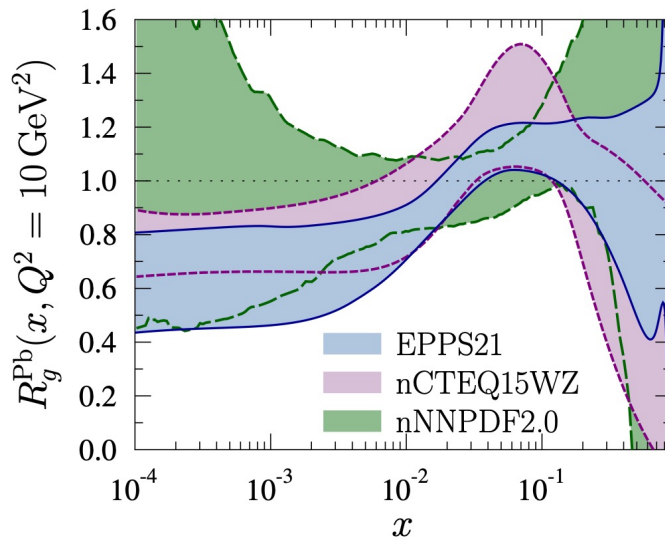
- $\alpha_s(M_Z^2)$ to 0.3%
(cf world data $\rightarrow$ 0.6% now)



EIC Impact on Nuclear Parton Densities

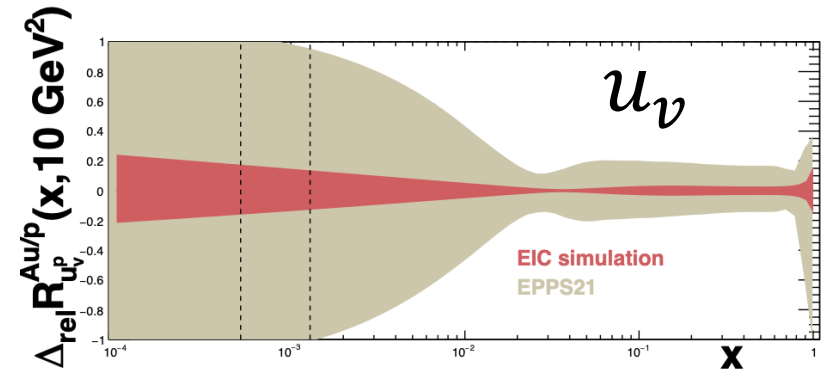
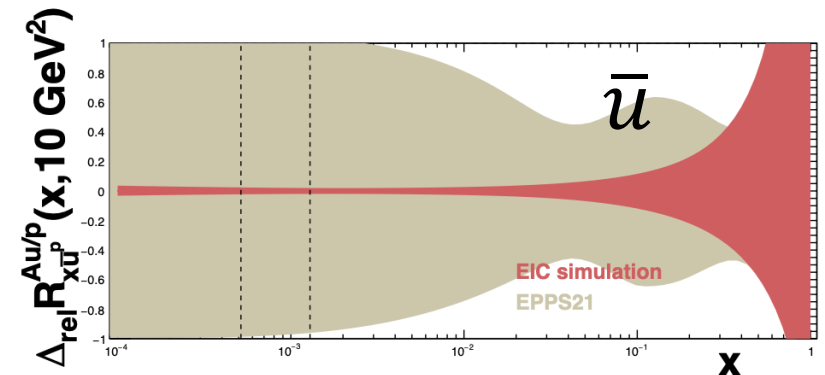
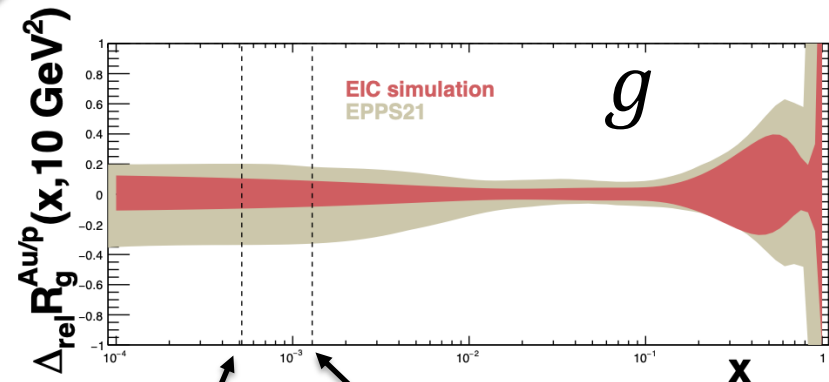
Parton nuclear modification ratio rel to scaled isospin-adjusted nucleons:

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



Sensitivity of EIC-alone relative to EPPS21 global fits (include LHC pA)

- Factor ~ 2 improvement at $x \sim 0.1$
- Very substantial improvement in newly accessed low x region



EIC eA data limit

EPPS21 data limit

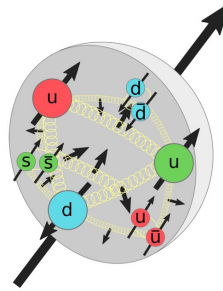
Proton Spin

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

Jaffe-Manohar sum rule:

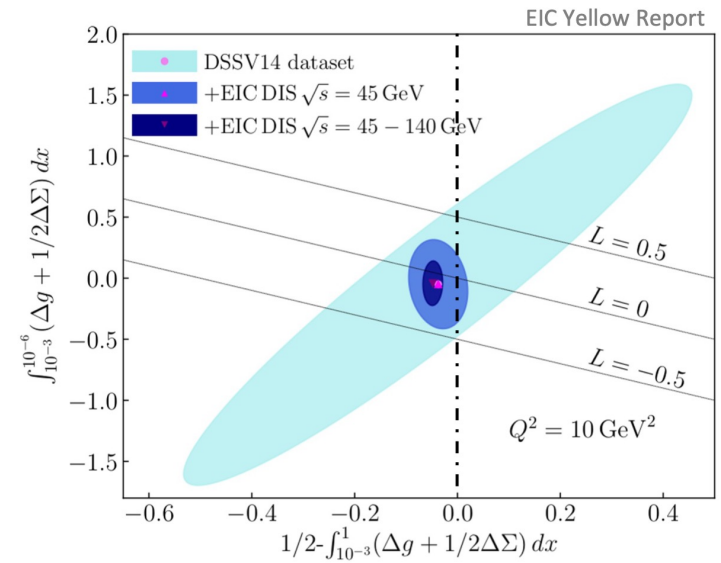
$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

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

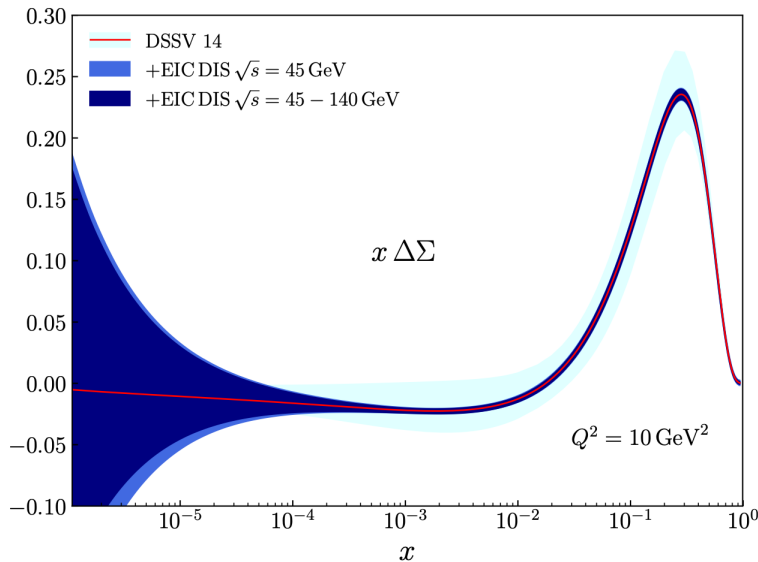
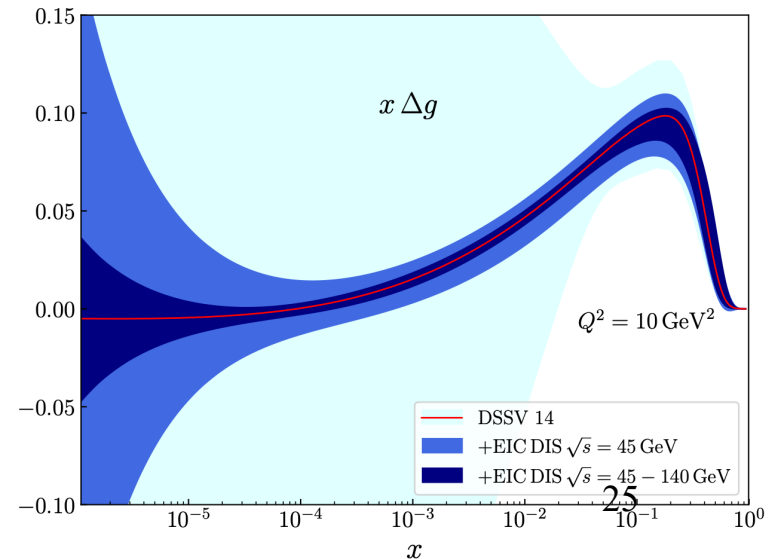


- Simulated EIC inclusive data show very significant impact on polarised gluon and quark densities $\rightarrow$ orbital angular momentum constrained by implication ... Full decomposition down to $x \sim 10^{-3}$.

Spin contribution from partons
with $x = (10^{-6} - 10^{-3})$



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



Proton Mass

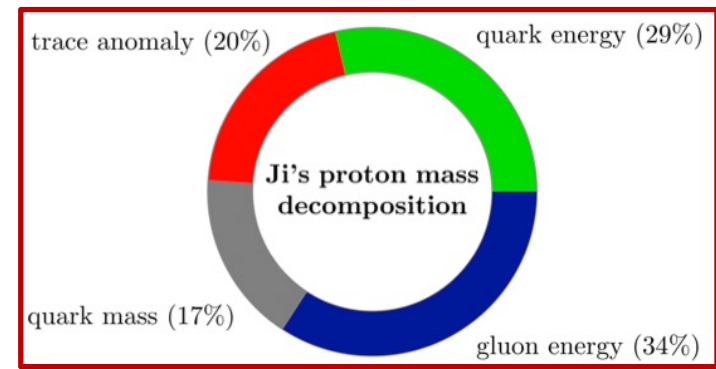
- Decomposition along similar lines to spin:

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

Valence and sea quark masses
(including heavy quarks)

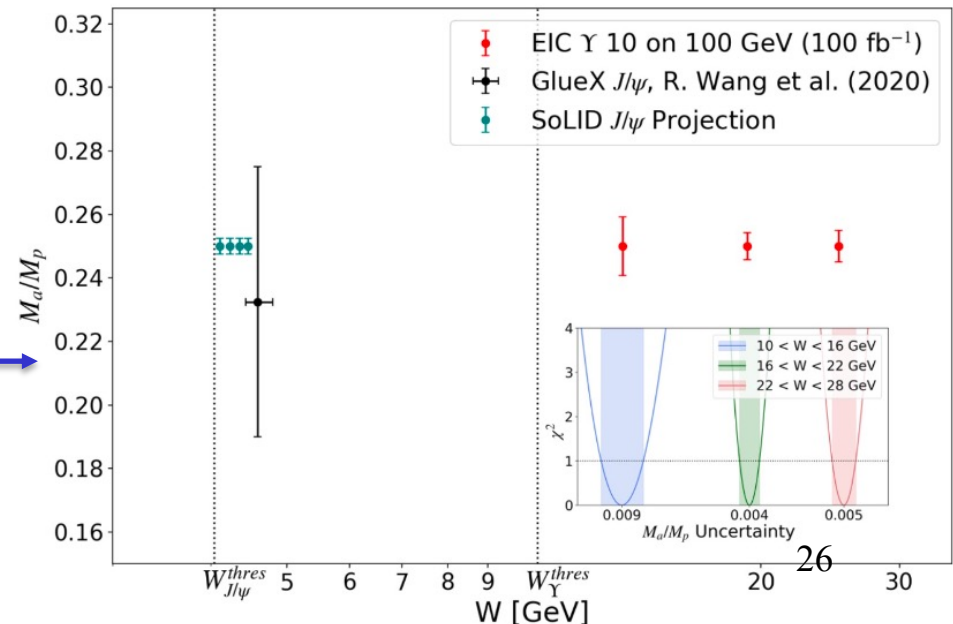
Quark & gluon 'KE' & 'PE': confinement and relative motion

QCD trace anomaly (purely quantum effect - chiral condensates)



- Relations to experimental observables being understood

- eg gluon contribution to trace anomaly from J/Ψ (Jlab, also J/ Ψ -007) to Y (EIC) near threshold



Timeline: as at July 2026

CD-0 (Mission need)	Dec 2019
CD-1 (Cost range)	June 2021
CD-3A (Procurement / Construction)	April 2024
CD-3B (Phase 2 Procurement)	Jan 2026
CD-2 (Performance baseline)	Under review
CD-4 (Operations / completion)	2034-6

DOE ESAAB Approvals

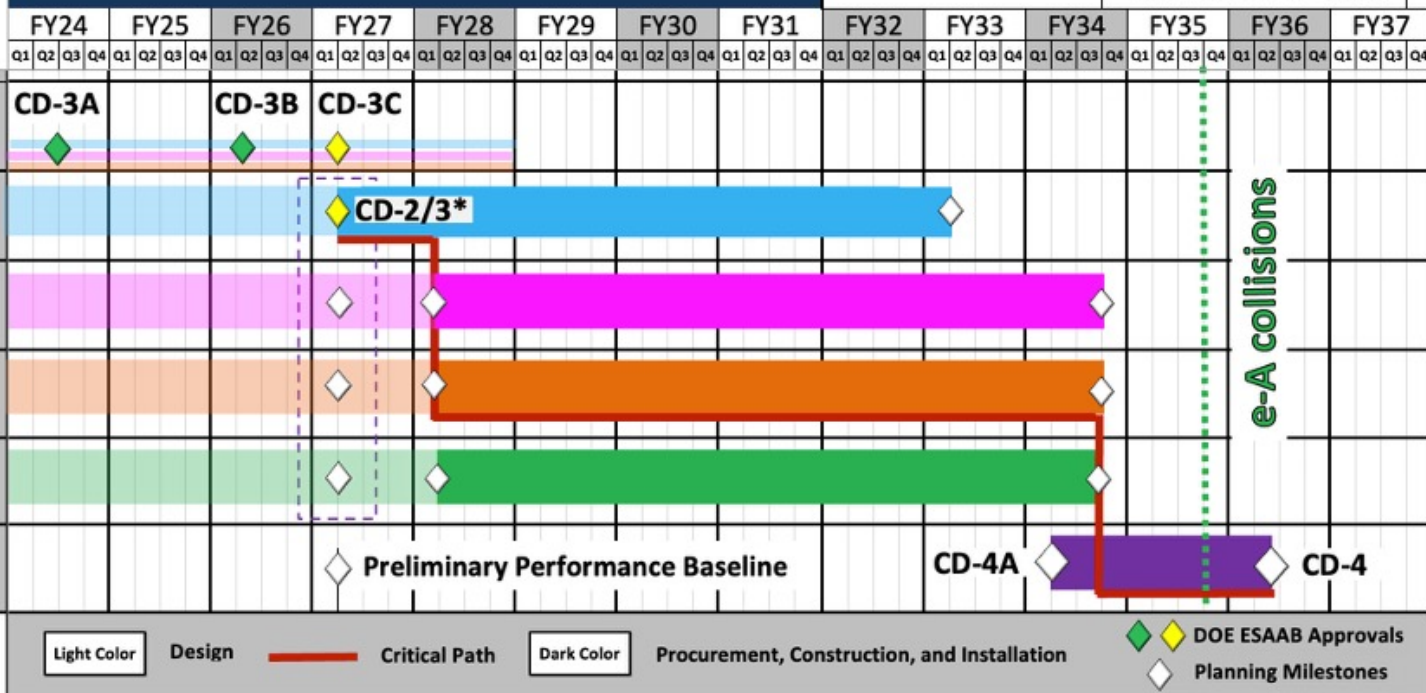
CD-1 Jun 2021

CD-3A Mar 2024

CD-3B Jan 2026

Electron-Ion Collider

Fiscal Year (FY) = Oct 1 - Sep 30



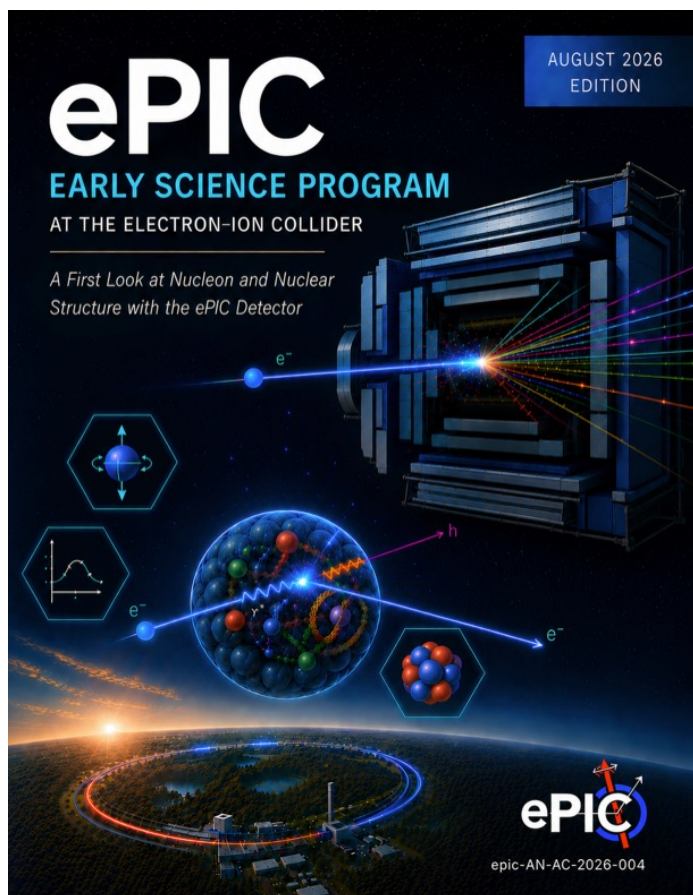
Project constrained to start physics operations within 10 years of RHIC end

Early Running

Strong current focus on evaluating impact of early running

	Species	Energy (GeV)	Luminosity/year (fb ⁻¹)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

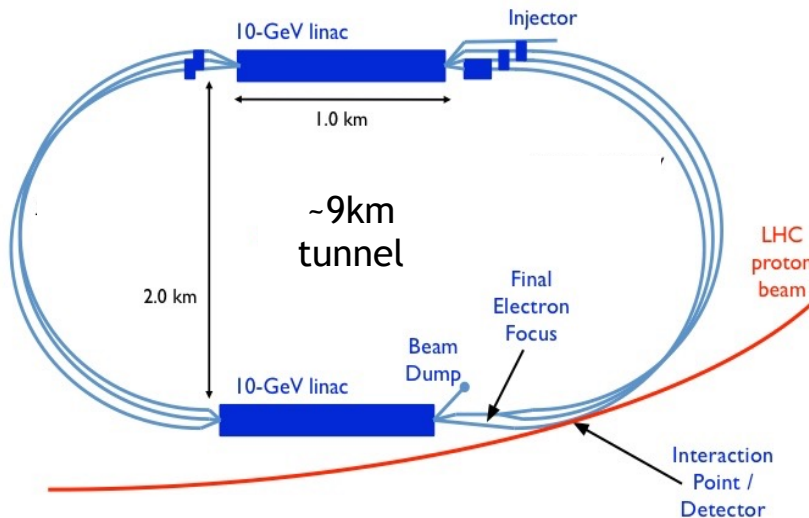


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arXiv:2608:05377, lead editors include Charlotte van Hulse

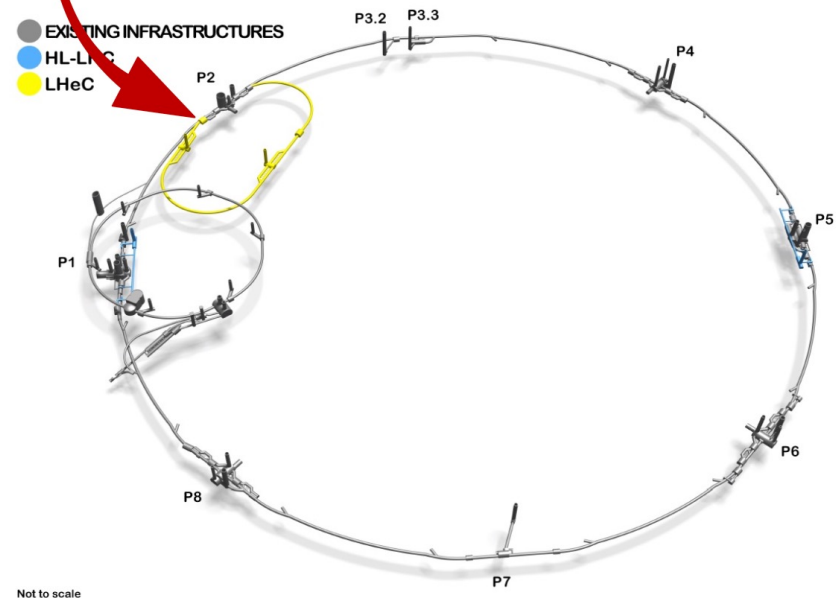
The CERN Large Hadron electron Collider

- Proposal for CERN to further-exploit the LHC in the 2040s
- Add a Recirculating Energy-Recovery Linac (ERL) electron accelerator
- Baseline plan is several years standalone running after HL-LHC $\rightarrow 1\text{ab}^{-1}$



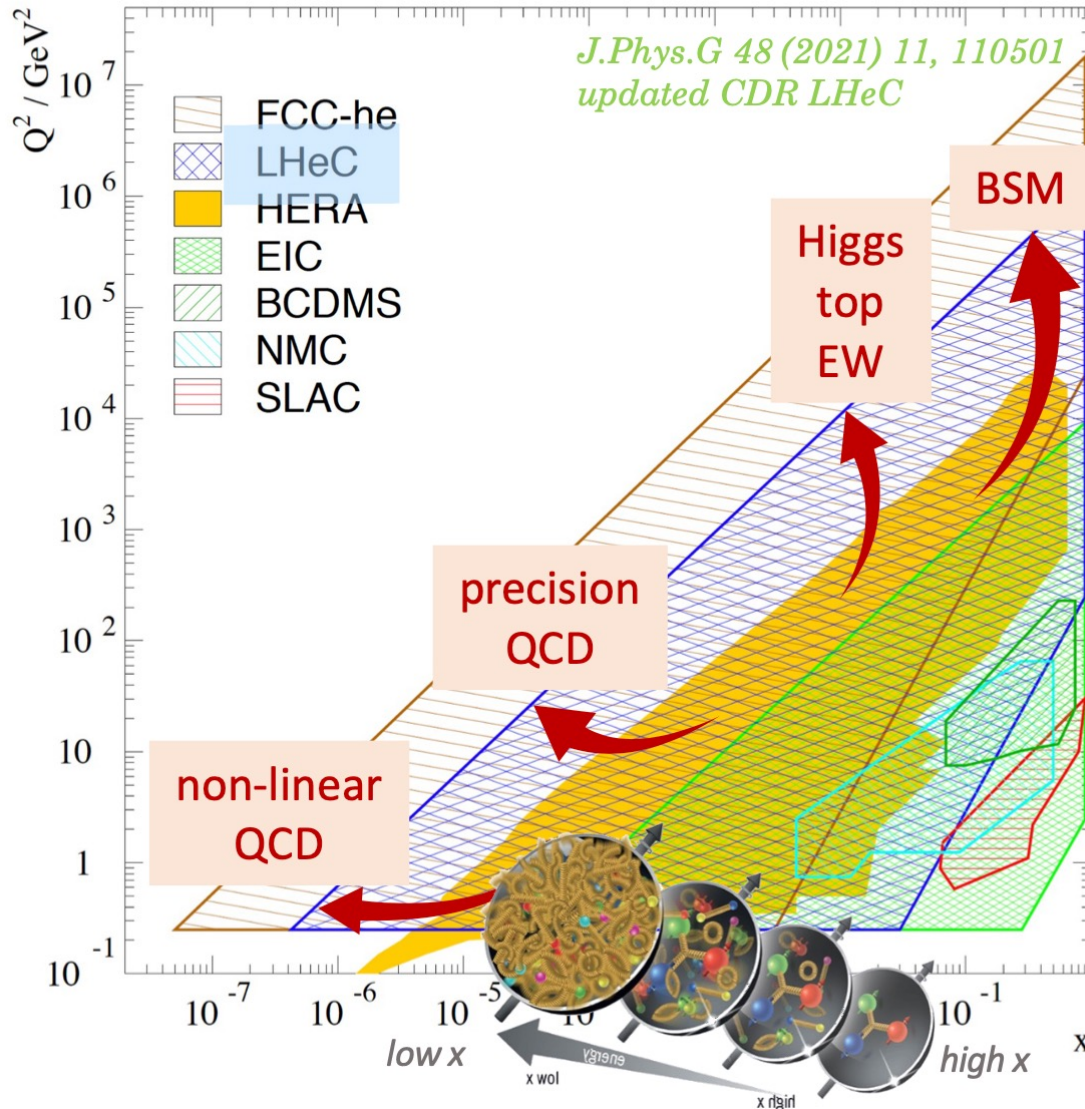
ERL Prototype
(PERLE @ IJCLab, Paris)
... first stage (one turn) 2028.

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 ($\gtrsim$ Run5)



- ‘Sustainable’ acceleration: ~ 100 MW for ERL

Overview of LHeC Physics Programme



Higgs, Top, EW and BSM programme

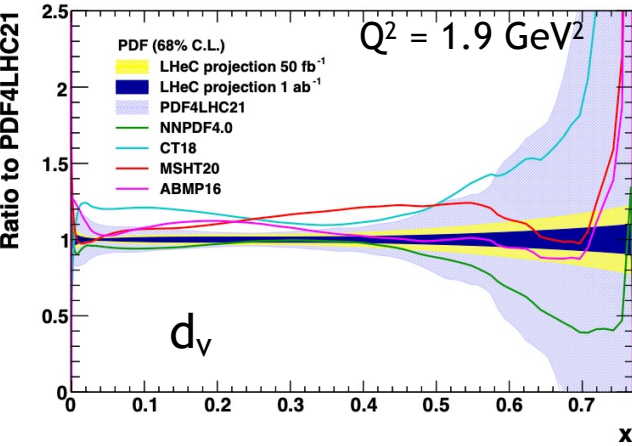
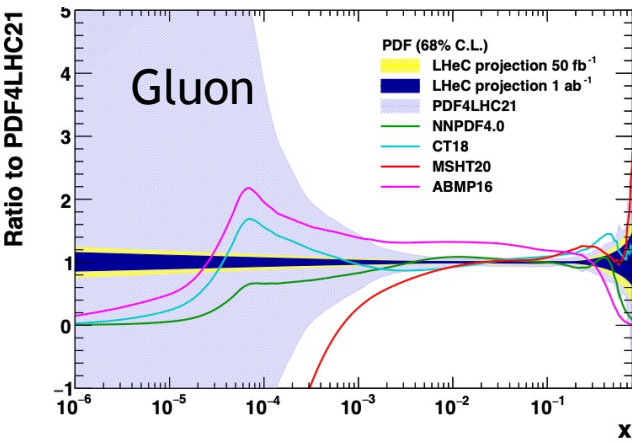
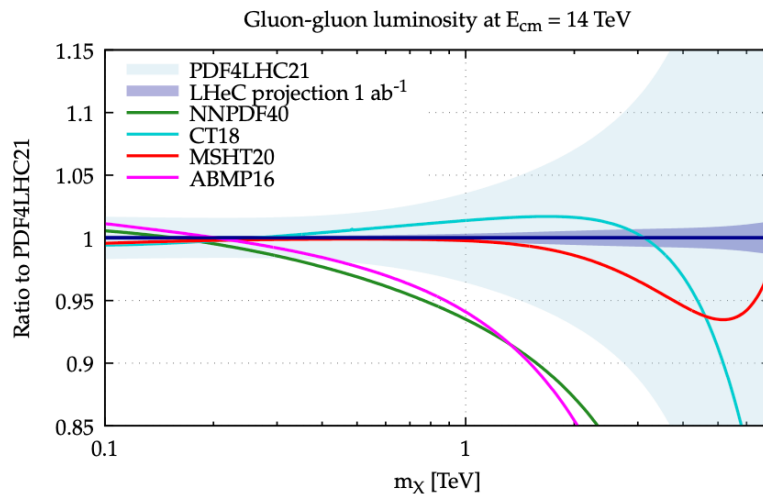
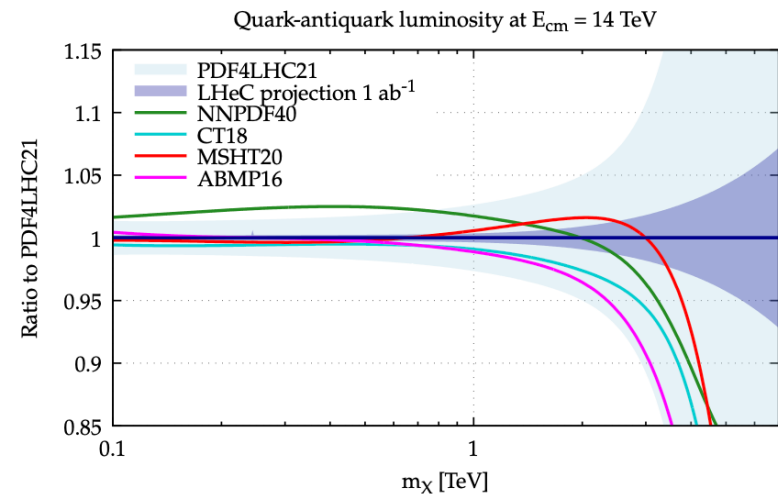
→ General purpose particle physics detector
... high p_T capabilities

Precision QCD and PDFs, including very low x parton dynamics

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

Proton PDF Precision

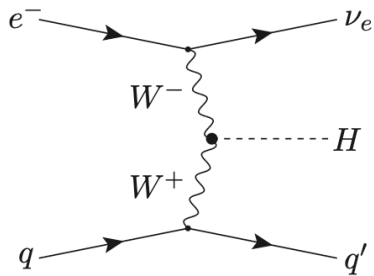
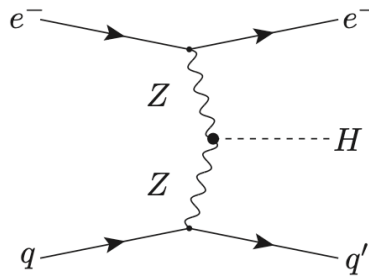
- PDF knowledge transformed over wide kinematic range, extending from $x \sim 10^{-6}$ to $x \rightarrow 1$
- First full and precise flavour decomposition
- α_s to 0.14%, M_W to few MeV, $\sin^2\theta_w$ to 0.0002, best axial and vector Z-light quark couplings
- Extends upper mass reach of LHC BSM searches
- Facilitates LHC precision measurements



Influence on LHC Higgs Programme

LHeC extends Higgs programme at the LHC by:

- 1) Improving HL-LHC pp precision through PDFs
- 2) The LHeC Higgs production programme



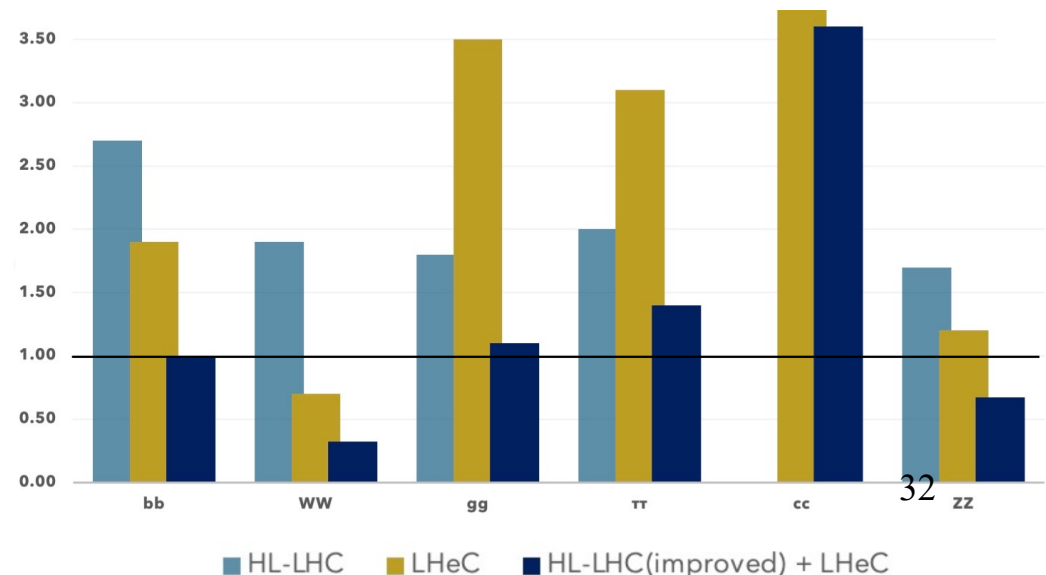
Dominant production mechanism charged current (WW), distinguished event-by-event from sub-dominant neutral current (ZZ)

Charged Current cross section $\sim 0.2\text{pb}$ for $P=-0.8 \rightarrow \sim 200,000$ events for 1ab^{-1}

Studies in Kappa-3 framework (SMEFIT group)

‘HL-LHC (improved)’ shows Impact of LHeC PDFs

... improvements HL-LHC $\rightarrow$ LHeC about same as LHC $\rightarrow$ HL-LHC



SUMMARY

Historically:

Lepton-hadron scattering consistently led to surprises and discoveries about the structure of matter

Vibrant field with running and fast-developing projects

Jlab Fixed target, LHC Neutrinos ...

From the mid 2030s:

The Electron Ion Collider will transform our understanding of nucleon and nuclear structure, including emergent properties such as mass and spin

From the early 2040s:

The Large Hadron electron Collider could enable LHC discovery via precision, discover new strong interaction phenomena, and explore Higgs sector in complementary ways

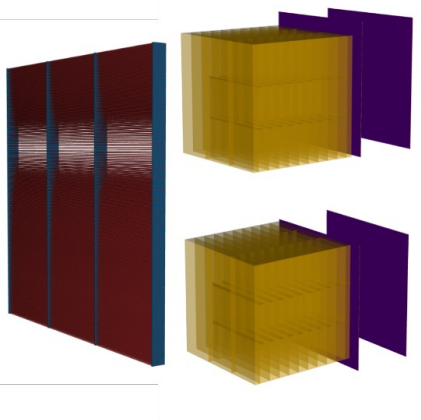
Current & Proposed Lepton-Hadron Facilities

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33}/cm^2/s$)	Ions *(depends on)	Polarisation	Status
JLab 11 JLab 22	Running Late 2030's	4.5 — 6.5	10^2 — 10^6	$p \rightarrow Pb$	e, p, Light nuclei	Running Concept
FASER FPF/AdvSND	Running 2030's	30 — 90	0.3 — 10	W, Ar	no	Running Advanced
EIC	> 2034	30 — 140	1 — 10	$p \rightarrow U$	e,p,d, ^3He	Approved
EicC	> Late 2030's	15—20	2 — 3	$p \rightarrow U$	e,p,d, ^3He	Concept
LHeC	> Late 2030's	1200	24	*LHC	e possible	Advanced
Plasma-based schemes	2040's	530 — 9000	10^{-5} — 10^{-1}	*SPS/LHC	e possible	Concept
FCC-eh	> 2050	3500	15	*FCC-hh	e possible	Concept

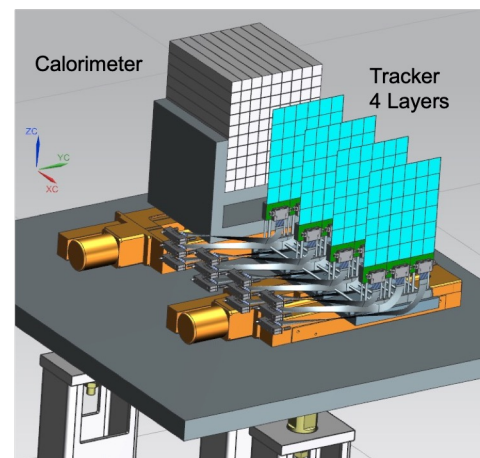
- Ongoing experiments revealing new properties of matter
- An approved new accelerator exploring new fundamental topics
- Longer-term plans aligned with core PP and NP priorities

Interaction Region / Beamline Instrumentation

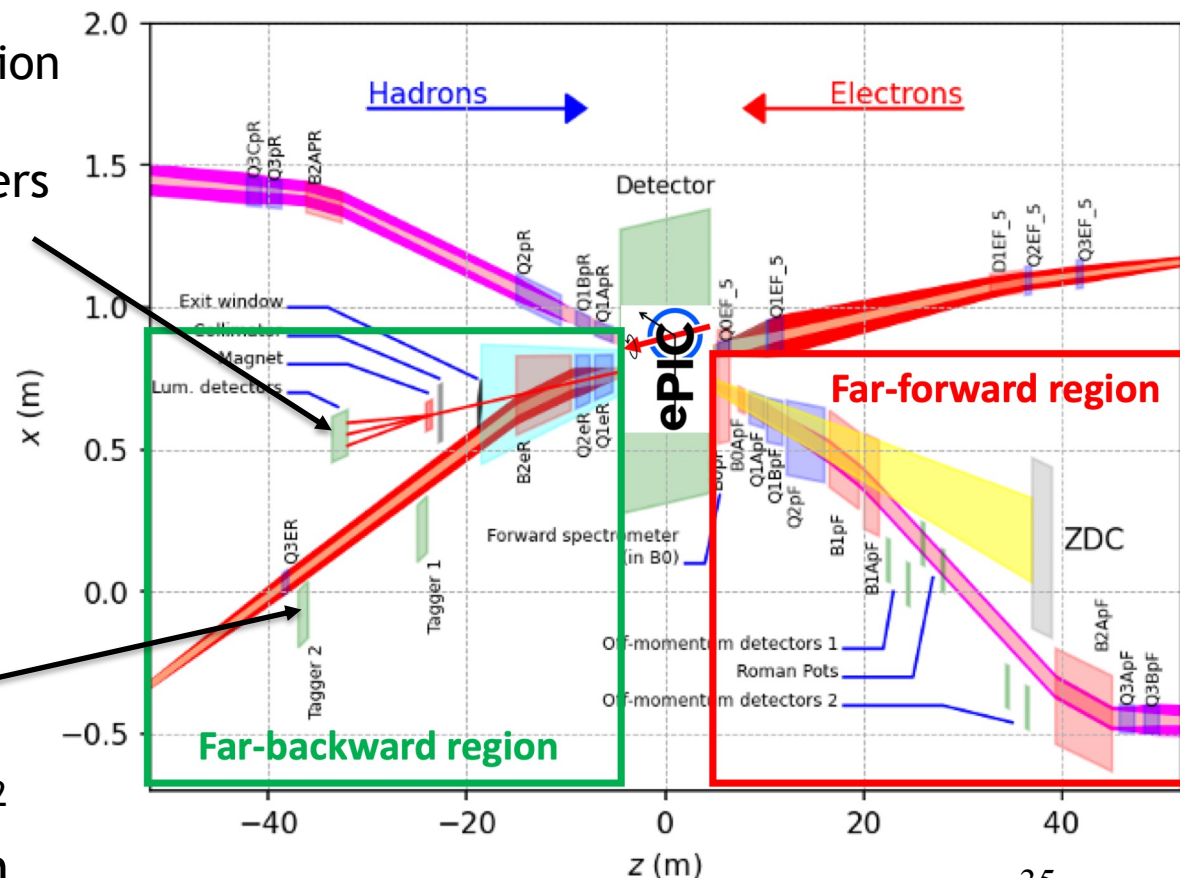
- Extensive beamline instrumentation integrated into IR design
- Tagging electrons and photons in backward direction for lowest Q^2 physics studies and lumi monitoring via photon counting in $ep \rightarrow e\gamma$



Pair-production
lumi
spectrometers

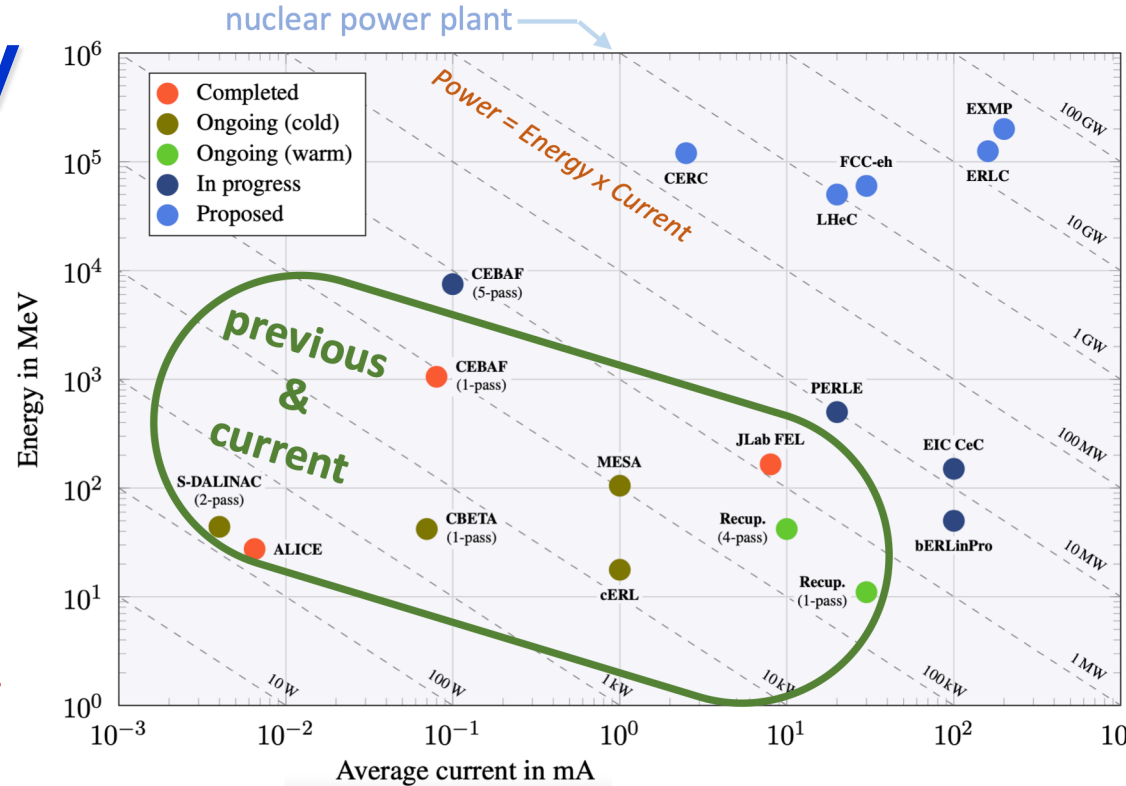


2 low Q^2
electron
taggers



Energy Recovery Linacs

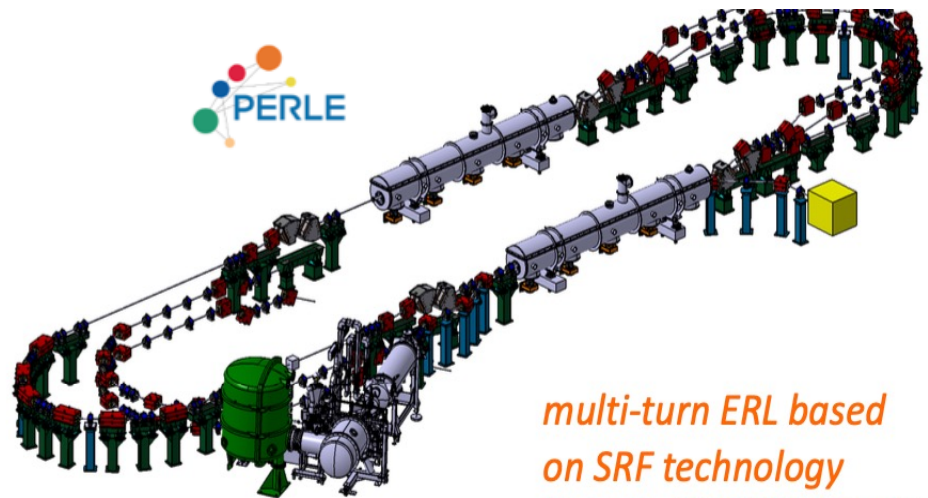
- Demonstrating ERL scalability is critical path
- Prototype (PERLE @ IJCLab) implementation started
- First stage (one turn) by 2028.



Electro-DC-gun



Photo-cathode



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

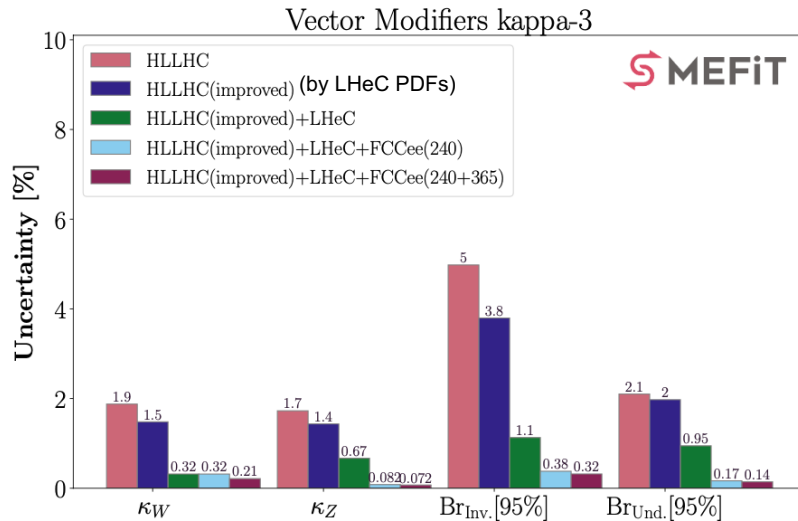
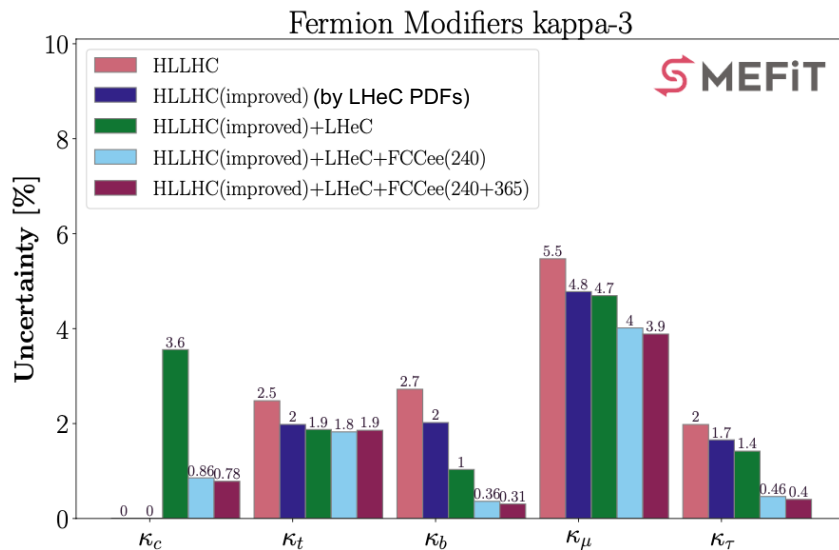
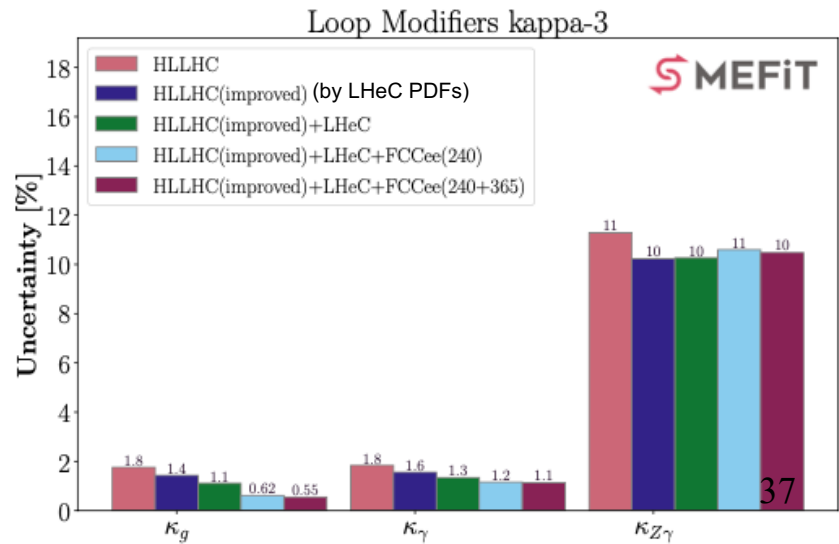
Influence on Higgs Coupling Precision

eg for HL-LHC → LHeC → FCC-ee ...

- LHeC PDF constraints already improve HL-LHC substantially

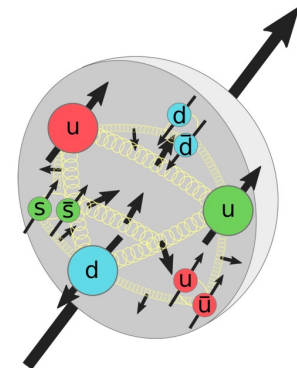
- LHeC impact for most couplings
 - Dominates W throughout
 - Major impact for Z
 - Likely first 5σ c observation
 - Also invisible, undetected

pp, ee, ep synergies for best results



Proton Spin Measurements

- Spin $\frac{1}{2}$ is much more complicated than $\uparrow\uparrow\downarrow \dots$
- EMC 'spin crisis' (1987) ... quarks only carry $\sim 10\%$ of the nucleon spin



Jaffe-Manohar sum rule:

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

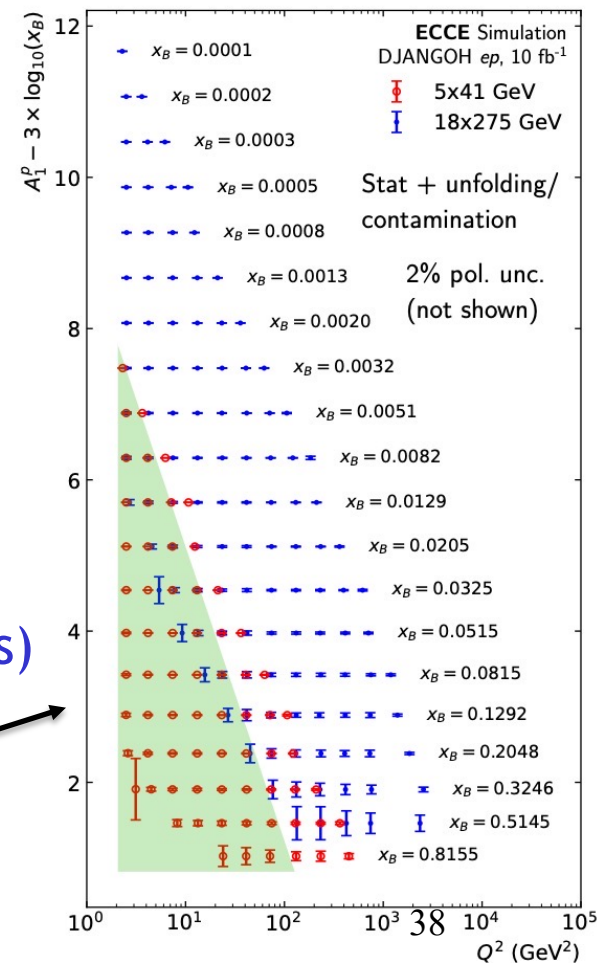
Quark helicity Gluon helicity Quark canonical orbital angular momentum Gluon canonical orbital angular momentum

- 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)

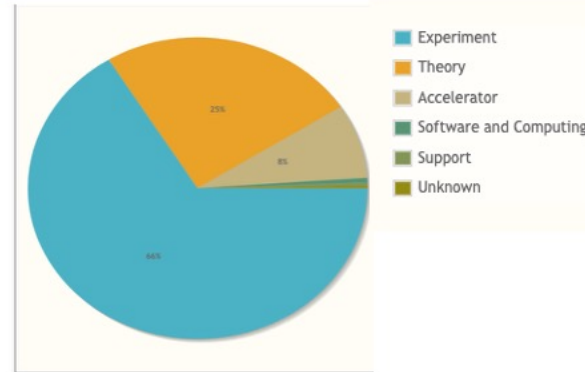
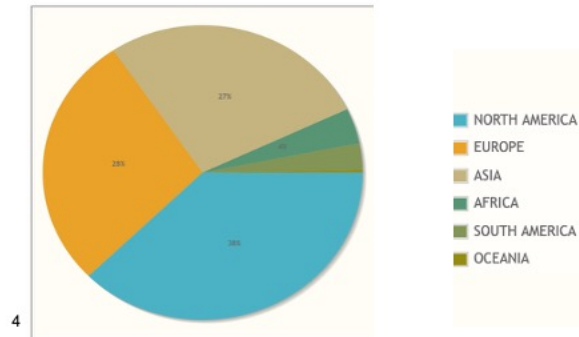
EIC measures down to $x \sim 5 \times 10^{-3}$
for $1 < Q^2 < 100 \text{ GeV}^2$



International Community: ePIC Collaboration

Organization and Structure

- **1547** members. **(-9)**
- **311** institutions **(+4)**
- **41** countries (**6** world regions)
 - Experiment Scientists: **1024 (-7)**,
 - Theory Scientists: **383**,
 - Accelerator Scientists: **124 (+1)** ,
 - Computer Scientists: **8. (-1)**,
 - Support: **5**, Other: **3**

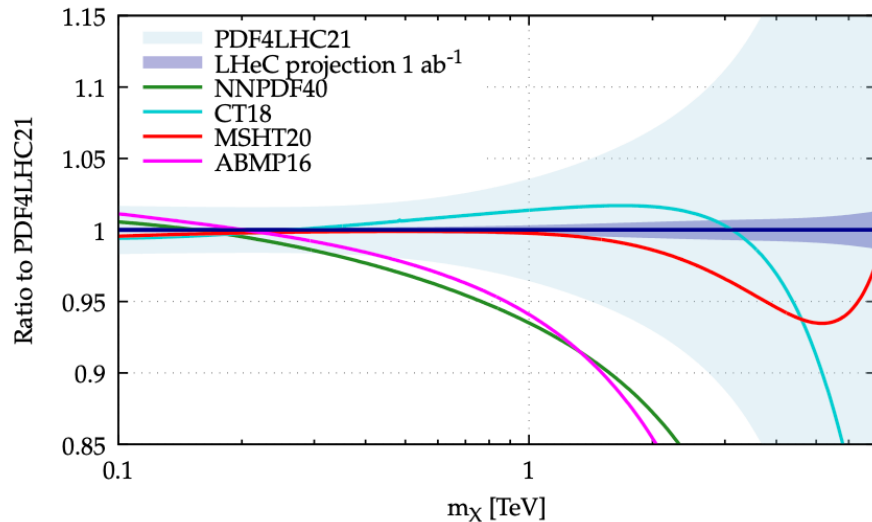


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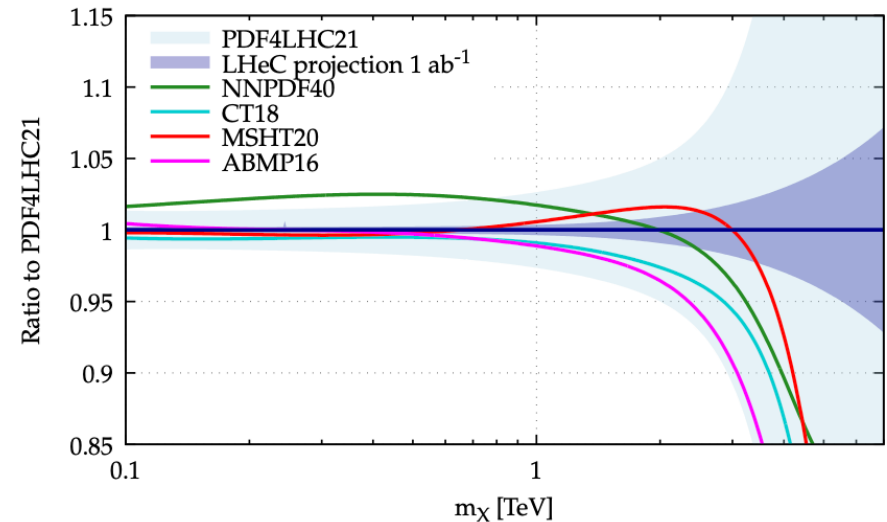
User Group @Glasgow

Enabling HL-LHC: parton lumi's revisited

Gluon-gluon luminosity at $E_{\text{cm}} = 14$ TeV



Quark-antiquark luminosity at $E_{\text{cm}} = 14$ TeV



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

...Theory uncertainty on LHC Higgs cross section

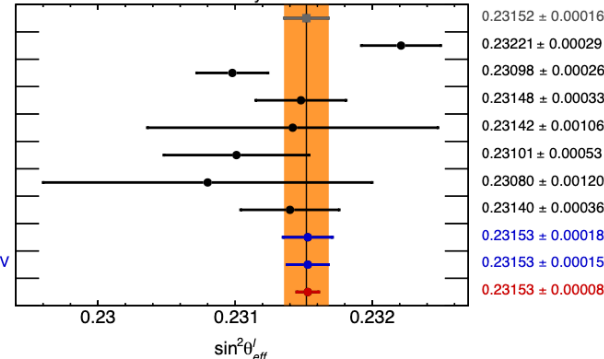
... M_W PDF systs $\rightarrow$ 2 MeV, enabling 3 MeV measurement

... $\sin^2\theta_W \rightarrow 0.0008$

...

LEP-1 and SLD: Z-pole average
 LEP-1 and SLD: $A_{\text{FB}}^{0,b}$
 SLD: A_1
 Tevatron
 LHCb: 7+8 TeV
 CMS: 8 TeV
 ATLAS: 7 TeV
 ATLAS Preliminary: 8 TeV
 HL-LHC ATLAS CT14: 14 TeV
 HL-LHC ATLAS PDF4LHC15_{HL-LHC}: 14 TeV
 HL-LHC ATLAS PDFLHeC: 14 TeV

ATLAS Simulation Preliminary



NNNLO pp-Higgs Cross Sections at 14 TeV

