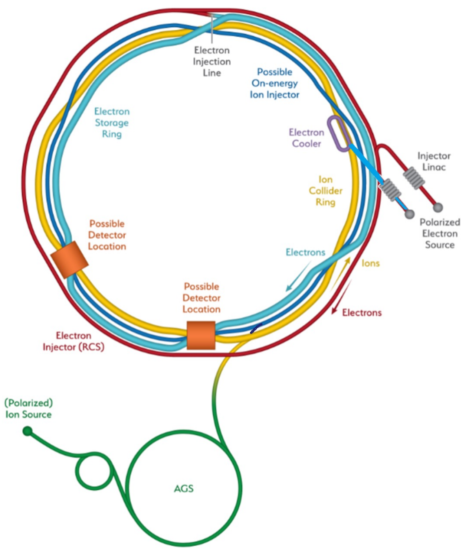
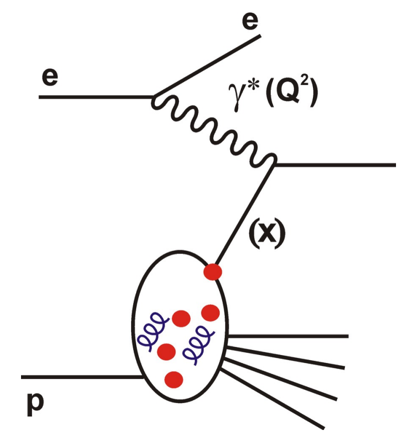
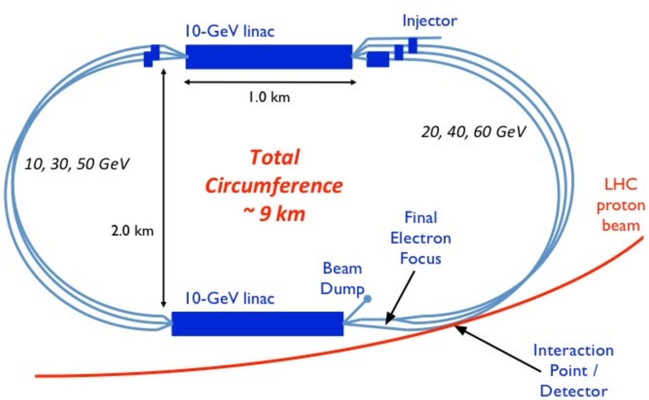
Future Opportunities with Lepton-Hadron Collisions

Paul Newman (Birmingham)





Imperial College Seminar
23 May 2025



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

Input to European PP Strategy Update

arXiv:2503.18208v1 [hep-ex] 23 Mar 2025

Future Opportunities with Lepton-Hadron Collisions*

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March 25, 2025

Abstract

Deep Inelastic lepton-hadron Scattering (DIS) is a cornerstone of particle physics discovery and the precision measurement of the structure of matter. This document surveys the international DIS landscape, exploring current and future opportunities to continue this rich heritage, leading to new understandings and enabling discoveries. Of immediate relevance to the future of the field in Europe, the Large Hadron electron Collider (LHeC) offers an impactful bridge between the end of the HL-LHC and the beginning of the next CERN flagship project, both in terms of technology development and new scientific exploration from Higgs physics to the partonic structure of the proton.

More generally, the facilities described here cover centre-of-mass energies from a few GeV to multiple TeV and address a wide range of physics topics, with unique sensitivity to Quantum Chromodynamics and hadron structure at their core. In addition to their stand-alone importance, these topics enhance the precision measurement and new physics search programmes at hadron-hadron colliders.

The very high luminosity fixed-target CEBAF programme that is in progress at Jefferson Laboratory probes nucleon and light ion structure at large x in novel ways, while high energy neutrino DIS is being enabled at the FASER and SND@LHC experiments by the intense LHC beams; both have exciting potential upgrade programmes. The Electron Ion Collider (EIC) is on course for deployment at Brookhaven in the early 2030s, and will provide lepton-nucleus and double-polarised lepton-proton/light-ion collisions for the first time. Its science includes a 3-dimensional mapping of the internal structure and dynamics of hadrons, leading to a thorough understanding of the mechanisms that generate proton mass and spin, whilst establishing accelerator and detector technologies of direct relevance to next-generation facilities. Adding the LHeC provides a Europe-based lepton-hadron frontier. The LHeC extends DIS capabilities to include a complementary Higgs, top and electroweak programme to the HL-LHC, together with precise determinations of proton and nuclear structure in a kinematic range that improves HL-LHC sensitivities. In the longer term, plasma wakefield acceleration and the Future Circular Collider offer different possible pathways for major steps forward in centre-of-mass energy, extending into a low parton momentum-fraction domain where our present understanding fails and new strong interaction discoveries are guaranteed.

This review emerges from the 'DIS and Related Subjects' conference series, which provides an annual focus for the diverse community of scientists involved in Deep Inelastic Scattering, currently estimated to consist of around 3000 experimental and theoretical particle, nuclear and accelerator physicists worldwide.

The Large Hadron electron Collider as a bridge project for CERN

F. Ahmadova,[1,2] K. André,[3] N. Armesto,[4] G. Azuelos,[5,6] O. Behnke,[7] M. Boonekamp,[8] M. Bonvini,[9] D. Britzger,[1] O. Brüning,[3] T. A. Bud,[3] A. M. Cooper-Sarkar,[10] J. D'Hondt,[11] M. D'Onofrio,[12] O. Fischer,[13] L. Forthomme,[14] F. Giuli,[15] C. Gwenlan,[10] E. Hammou,[16] B. Holzer,[3] H. Khanpour,[14] U. Klein,[12] P. Kostka,[12] T. Lappi,[17,18] H. Mäntysaari,[17,18] P. R. Newman,[19] F. I. Olness,[20] J. A. Osborne,[3] Y. Papaphilippou,[3] H. Paukkunen,[17,18] K. Piotrzkowski,[14] A. Polini,[21] J. Rojo,[11,22] M. Schott,[23] S. Schumann,[24] C. Schwanenberger,[7,25] A. M. Staśto,[26] A. Stocchi,[27] S. Tentori,[28] M. Tevio,[17,18] C. Wang,[29] and Y. Yamazaki[30]

Enabling future detector technology within ePIC at the EIC

Contact persons: S. Dalla Torre*, D. Elia†, P.G. Jones‡, J. Lajoie§ and C. Munoz Camacho¶

On behalf of **the ePIC Collaboration**

Input to the European Strategy for Particle Physics - 2026 update

DRAFT v1.0 - March 21, 2025

Synergies between a U.S.-based Electron-Ion Collider and European Research in Particle Physics

Contact Persons: Stefan Diehl[1], Raphaël Dupré[2], Olga Evdokimov[3], Salvatore Fazio[4], Ciprian Gal[5], Tyler Kutz[6], Rongrong Ma[7], Juliette Mammei[8], Stephen Maple[9], Marco Radici[10], Rosi Reed[11], Ralf Seidl[12], Zhoudunming Tu[13]

On behalf of the ePIC Collaboration and the EIC User Group

CERN-FASER-2025-001

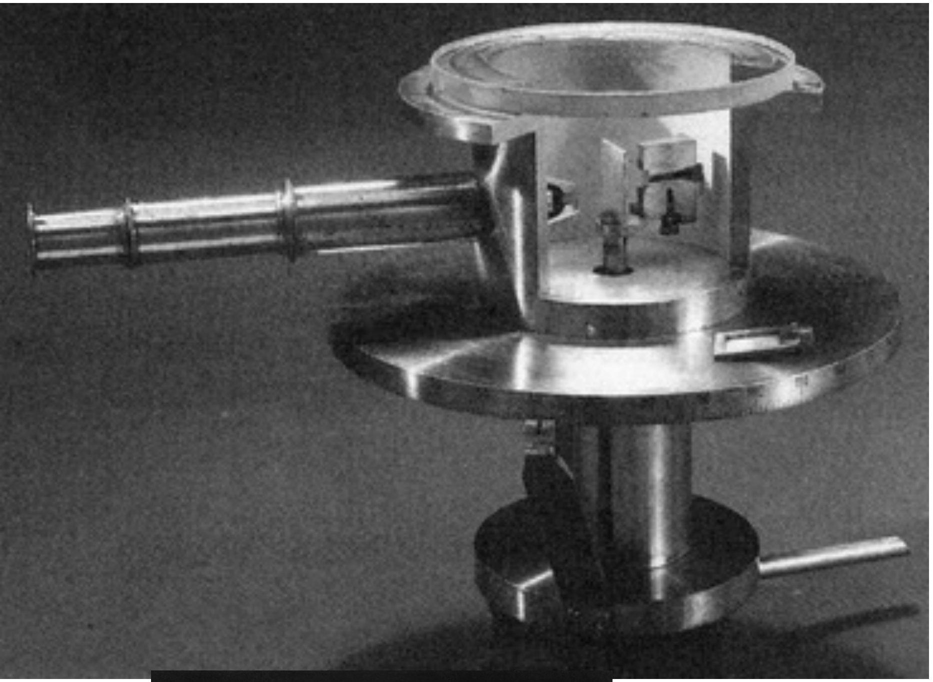
Prospects and Opportunities with an upgraded FASER Neutrino Detector during the HL-LHC era: Input to the EPPSU

FASER Collaboration

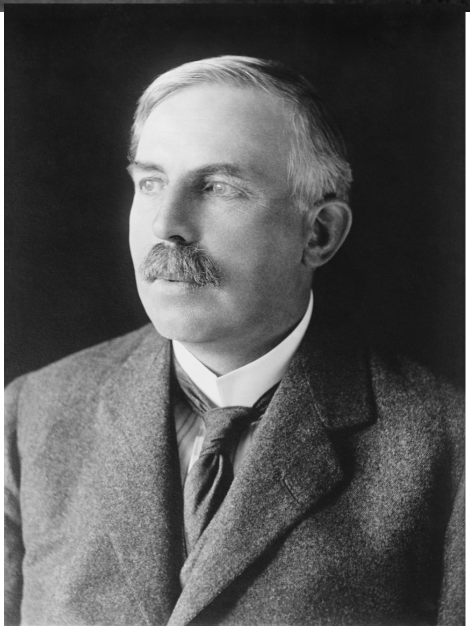
… and several others …

- 'Future Opportunities' document: Overview and vision of current and possible future landscape, centred around DIS conference series
- Supporting and adding context to separate submissions

Rutherford (1927, as President of Royal Society)



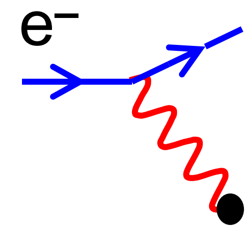
Following from the original scattering experiments (α particles on gold foil target) …



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

Probing the Proton with Electrons

Simple uncertainty principle arguments:



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

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

[1950s Hoffstadter]()

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

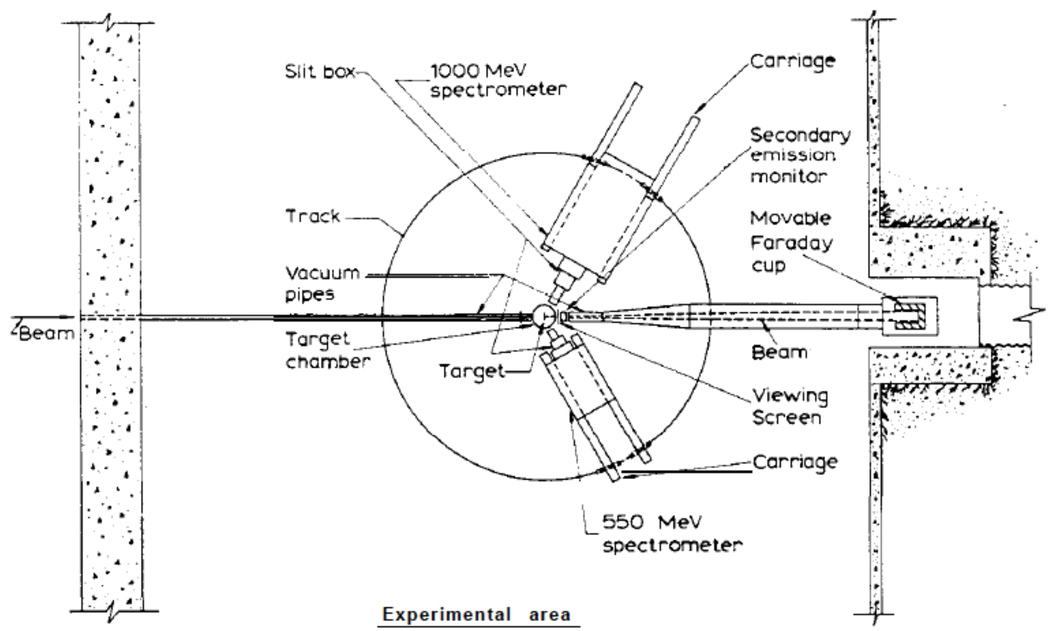
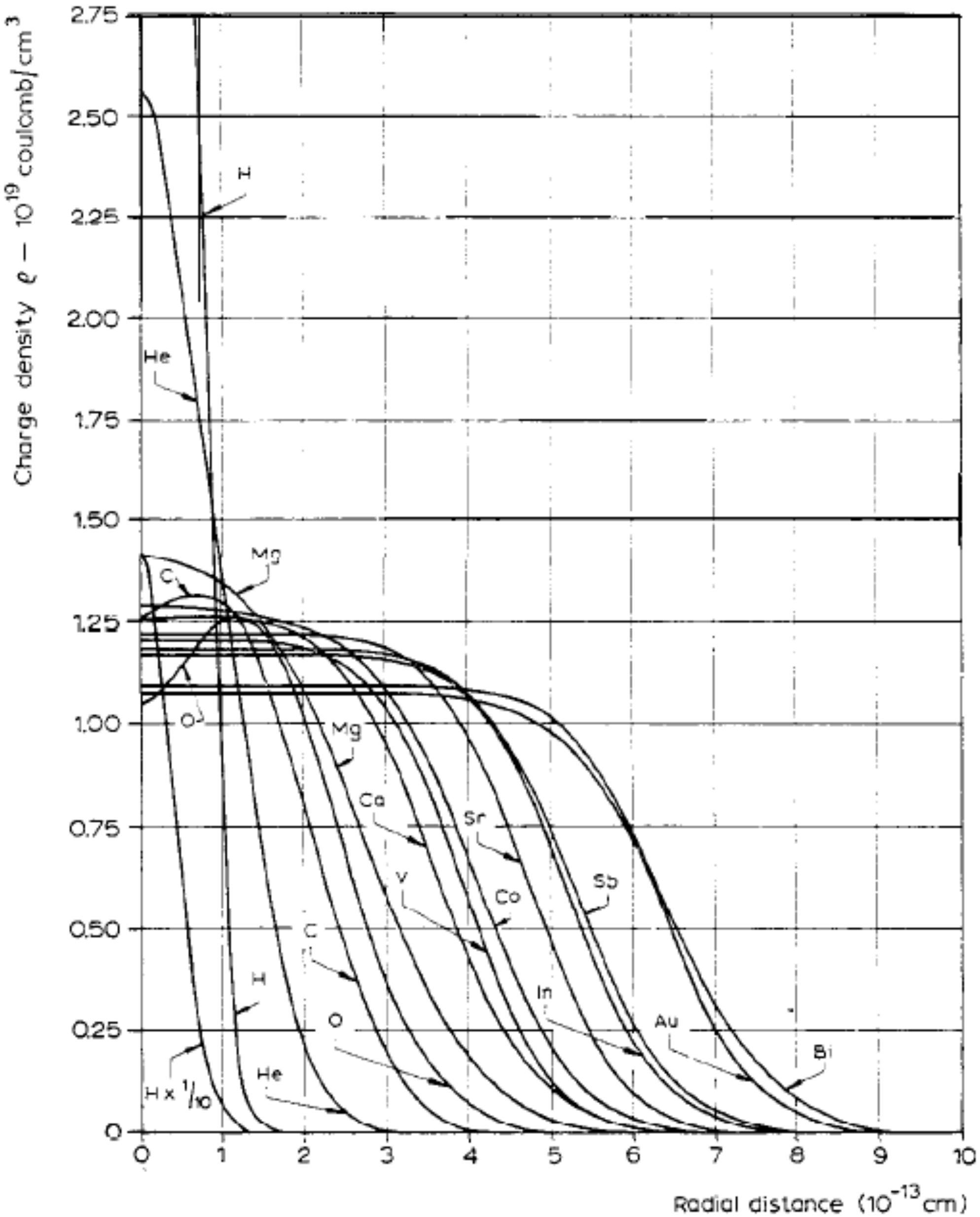


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

Hoffstadter's Results

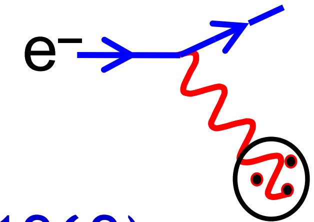


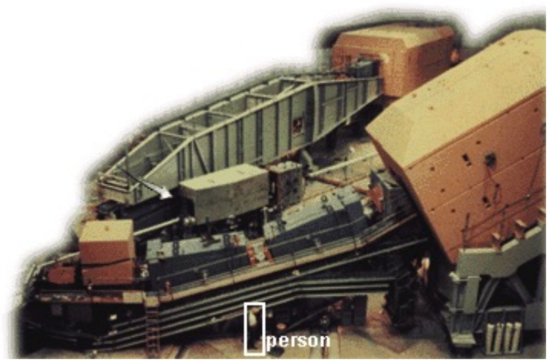
… Interpreting scattered electron pattern to determine spatial distribution of the target charge distribution

→ proton radius ~1fm

Probing the Proton with Higher Energy Electrons

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



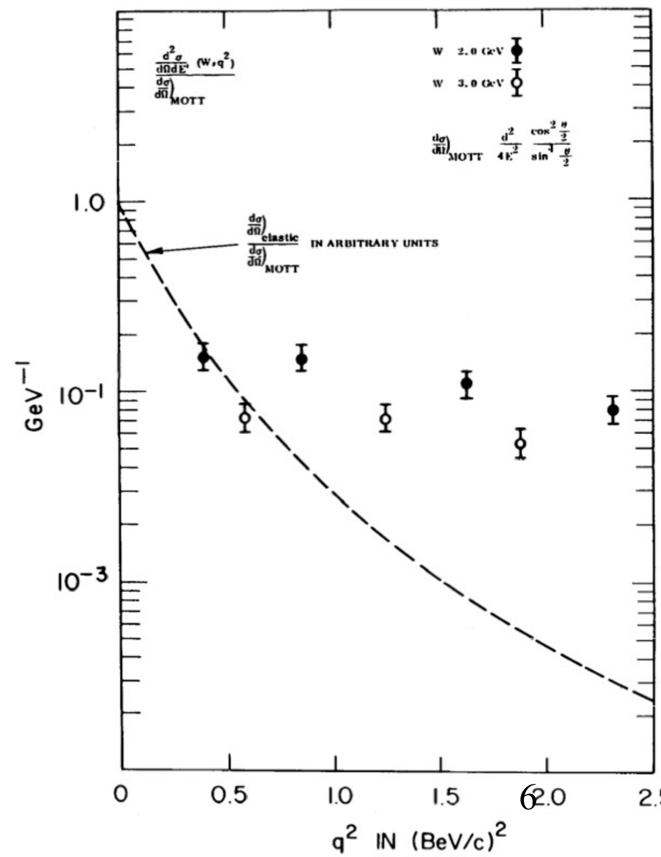


ESA experiment at SLAC (1969)

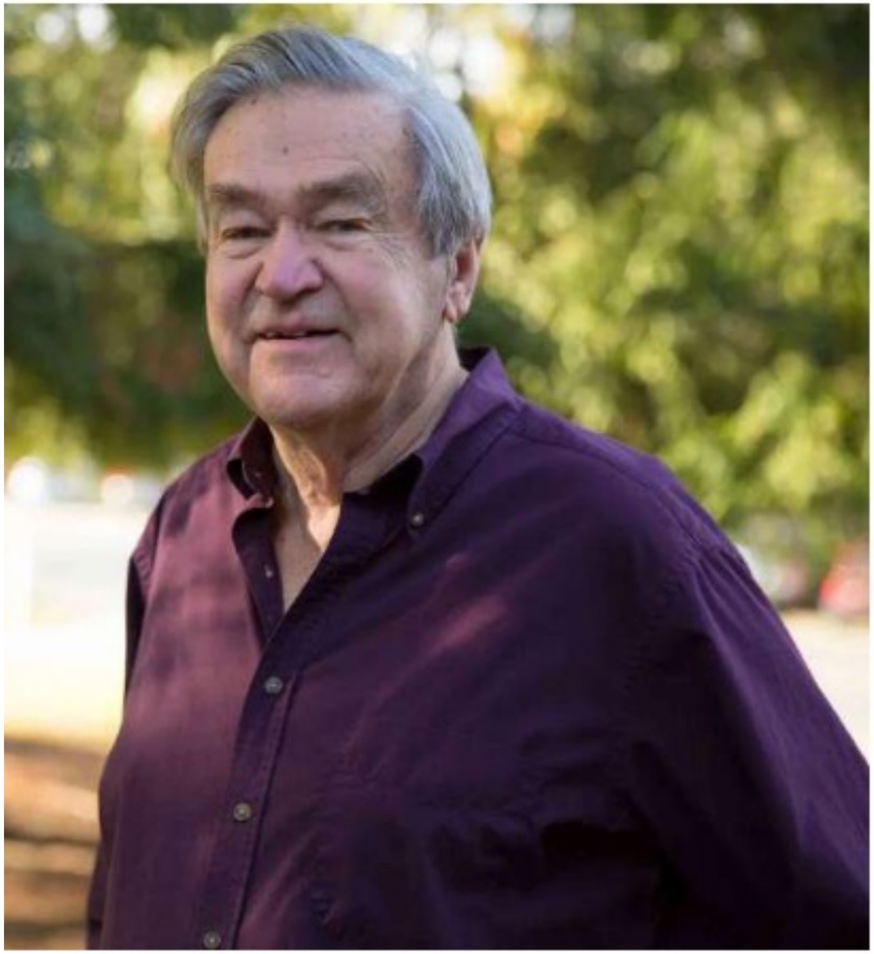
~20 GeV electrons on fixed proton target

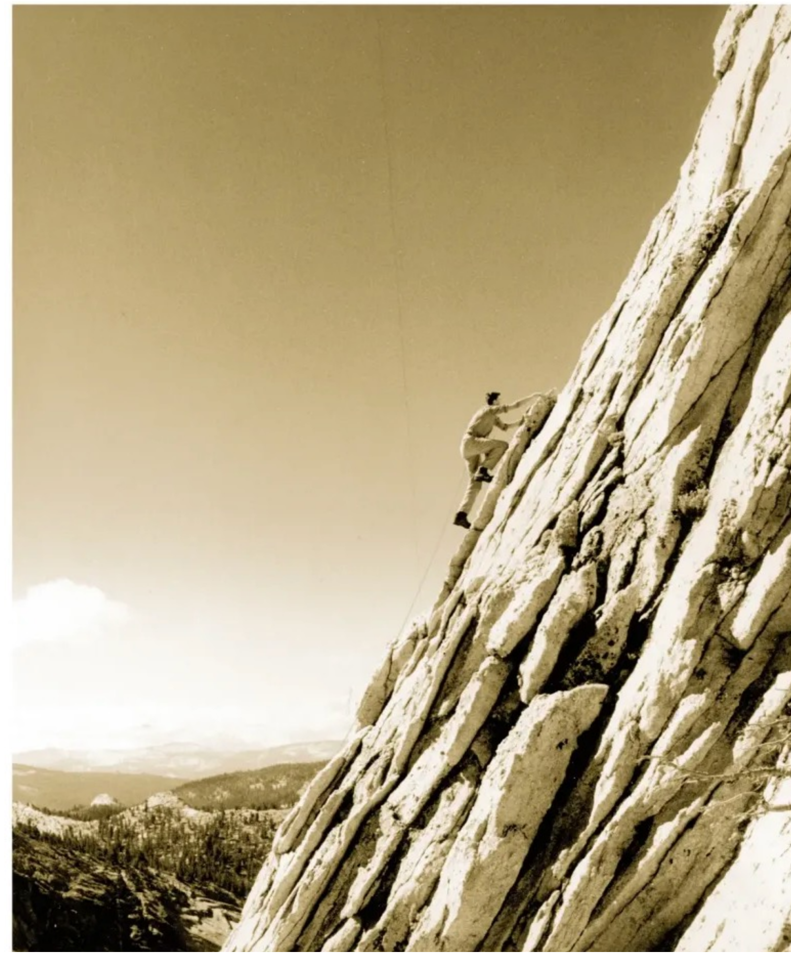
Absence of dependence
of suitably scaled
cross section on
momentum transfer
(wide-angle scattering)
implies point-like
constituents of
target (quarks)

Bjorken Scaling



James Bjorken (22 June 1934 – 6 Aug 2024)



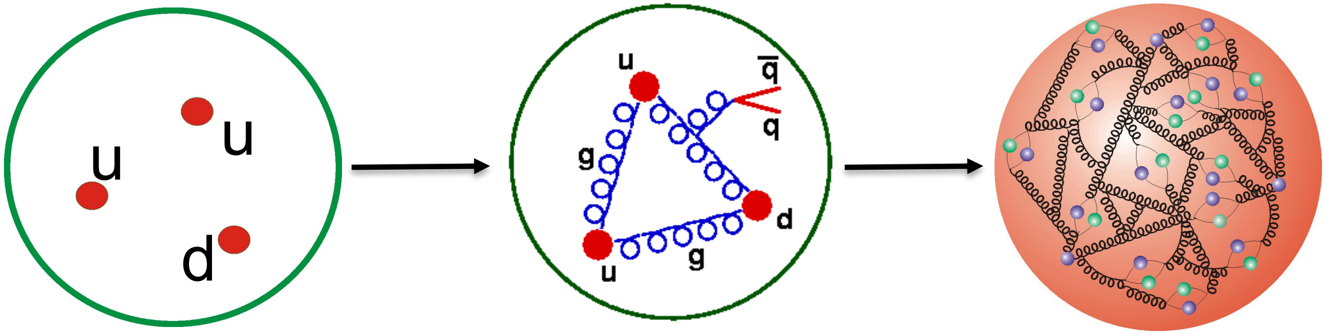


- The only ever collider of electron with proton beams: $\sqrt{s_{ep}} \sim 300$ GeV

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

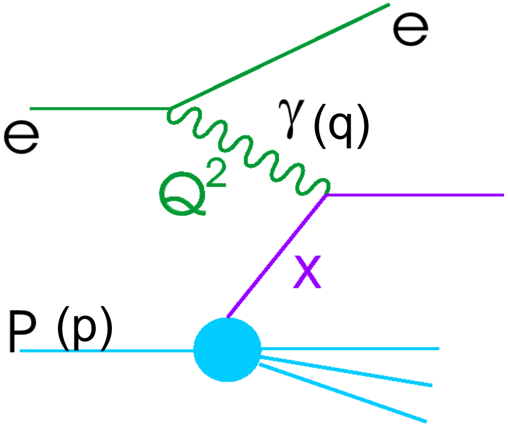
… Resolved dimension $\sim 10^{-20}$ m

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

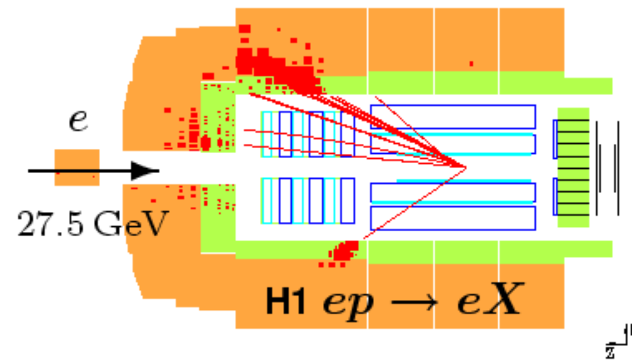


BUT …
→ Only ~0.5 fb^{-1} per experiment
→ No deuterons or nuclei
→ No polarised targets

Inclusive Neutral Current DIS: ep→ eX … Kinematics



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



x = fraction of proton momentum carried by struck quark

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

… measures the hardness /scale of collision

… inverse of (squared) resolved dimension

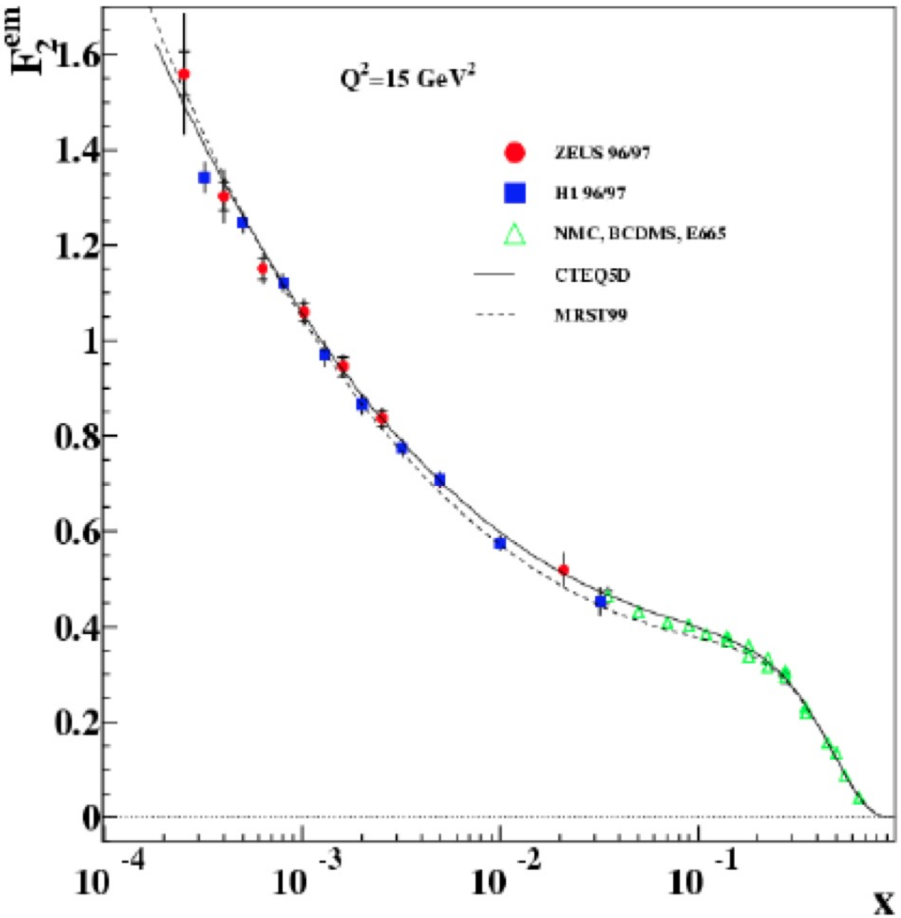
$s = Q^2/_{xy}$ with inelasticity $y < 1$

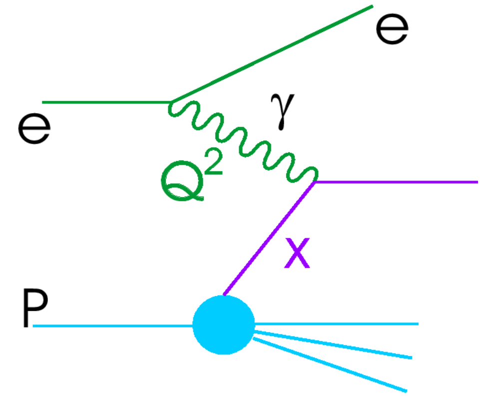
… i.e. Maximum Q^2 and minimum x

governed by CMS energy, $\sqrt{s}$

Example Inclusive Neutral Current Data from HERA / Previous Experiments

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





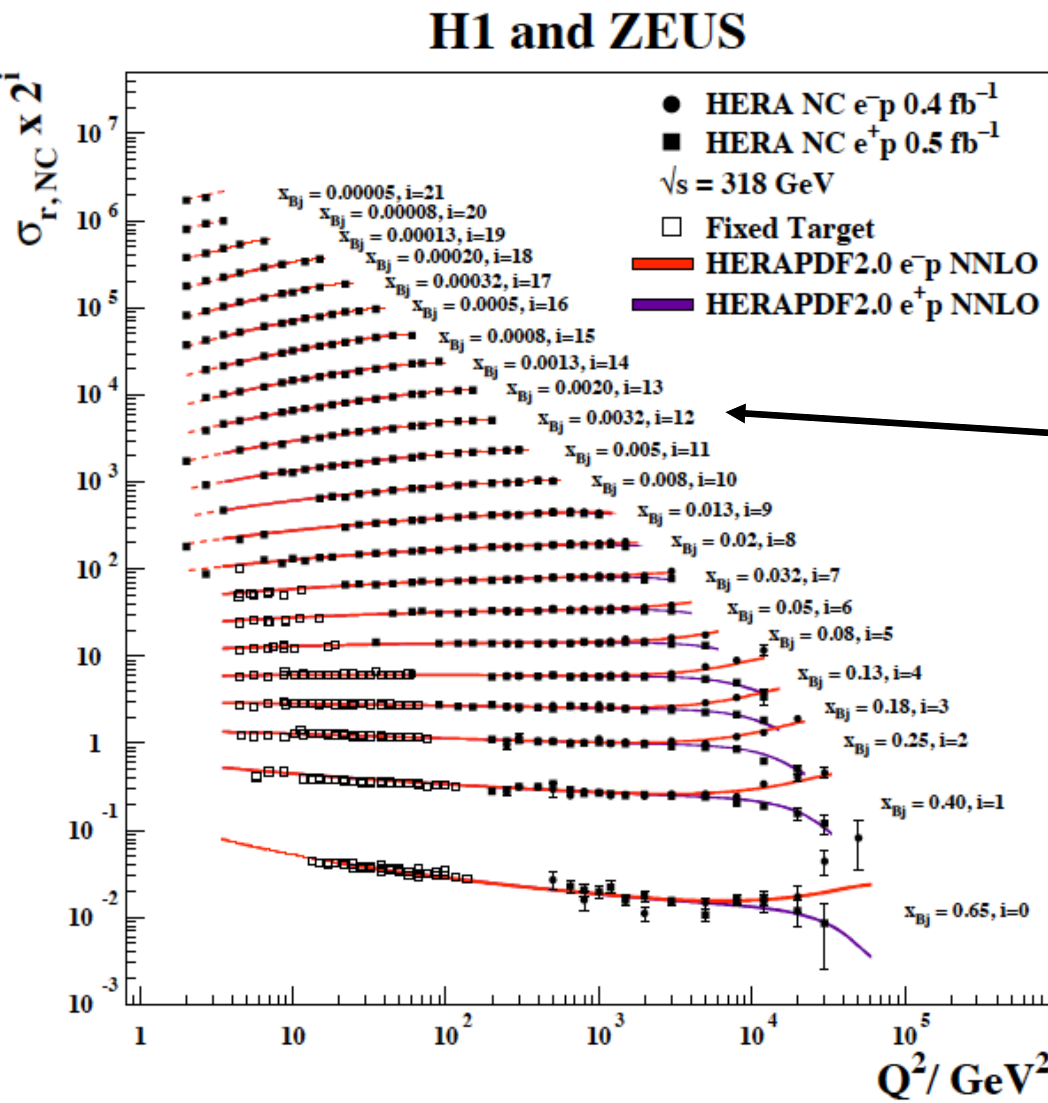
- Photon-exchange component of NC data measures

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

- Due to e_q^2 photon coupling, this mainly constrains **u & ubar** … shape of quark densities already qualitatively apparent

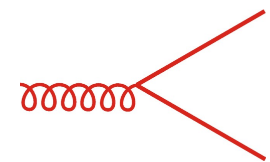
Variations of the cross sections with Q^2 tell us about the role of gluons …

QCD Evolution and the Gluon Density



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

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

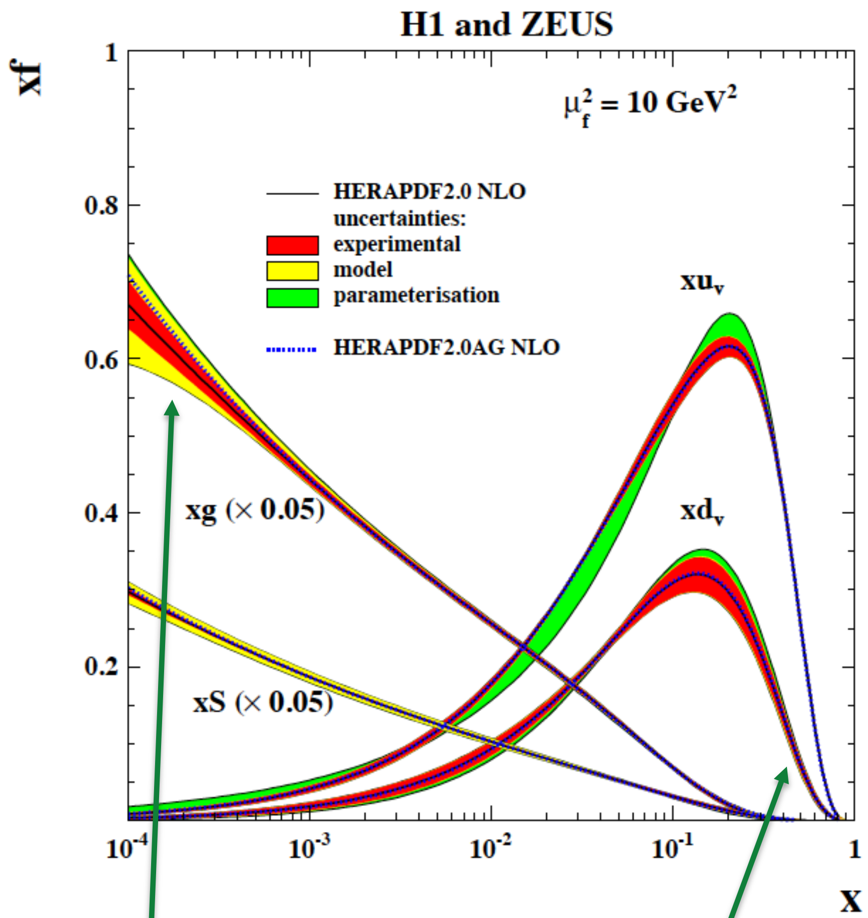


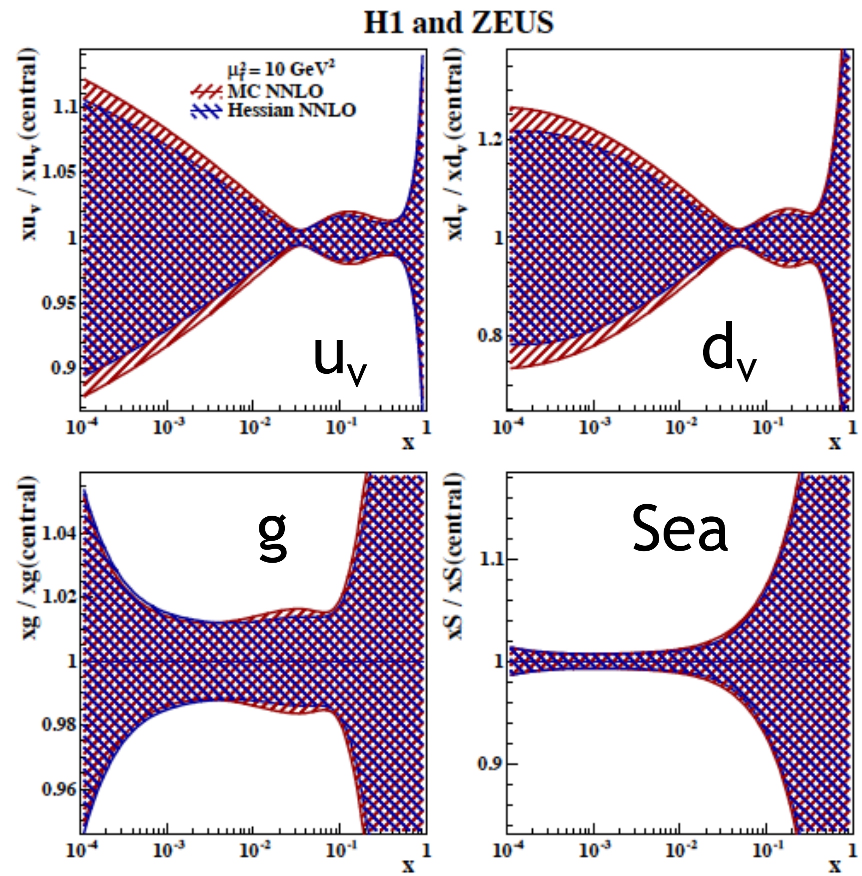
- DGLAP equations describe QCD evolution (to NNLO and approximate N^3LO accuracy)

- 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)





Strong interaction dragons?

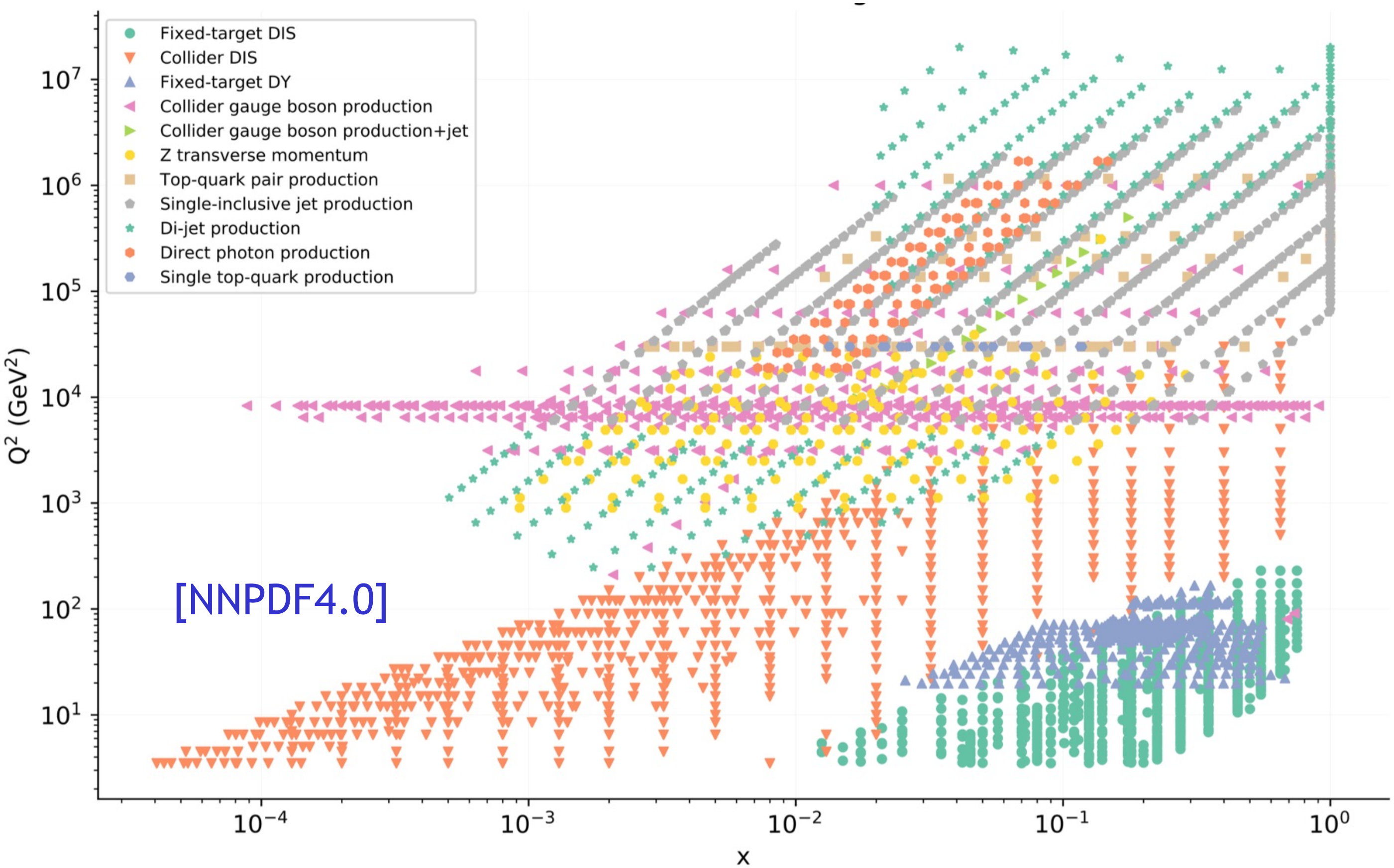
Input to energy frontier discovery?

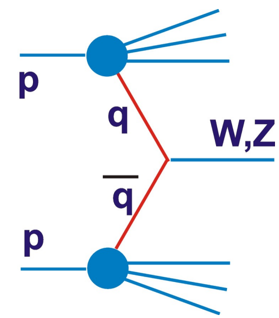
- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

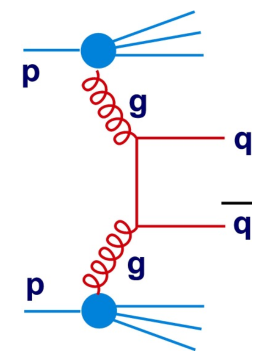
Constraining PDFs with LHC Data

→ Need precise PDFs for interpretation of LHC physics ...BUT ALSO...

→ LHC can tell us more about PDFs → 'Global Fits'





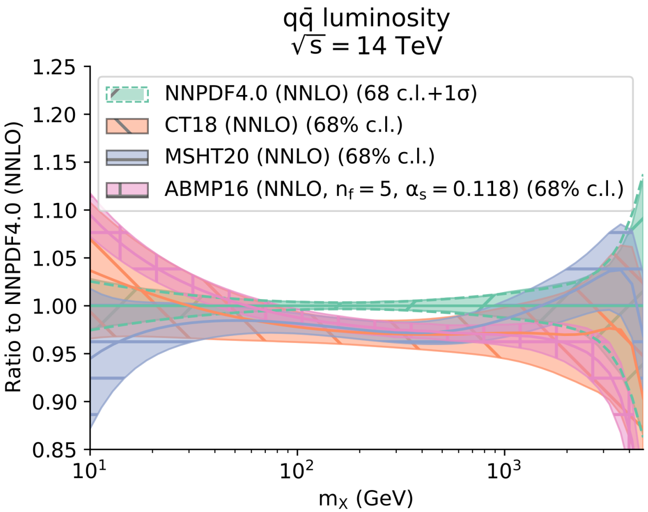


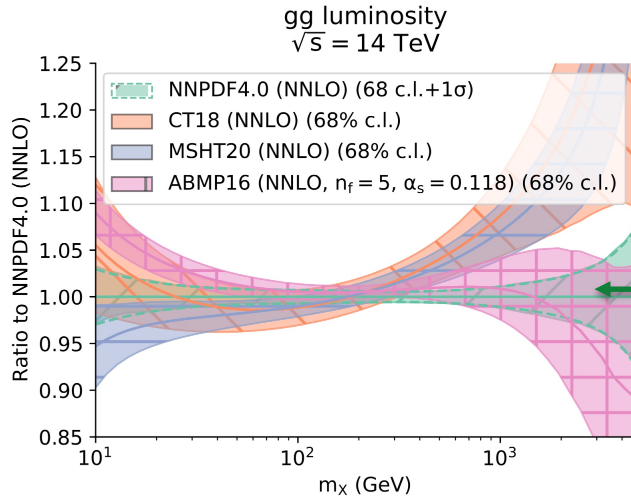
Main observables included in global fits

- Electroweak gauge bosons (and Drell Yan) → quarks
- Jet production → gluons

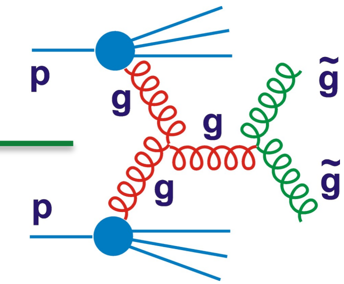
... more forward (i.e. high $|\eta|$) accesses lower x

LHC Parton Luminosities and Physics





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



[Luigi Marchese, Maria Ubiali, DIS25]

- Not fully convergent between different global fitting groups

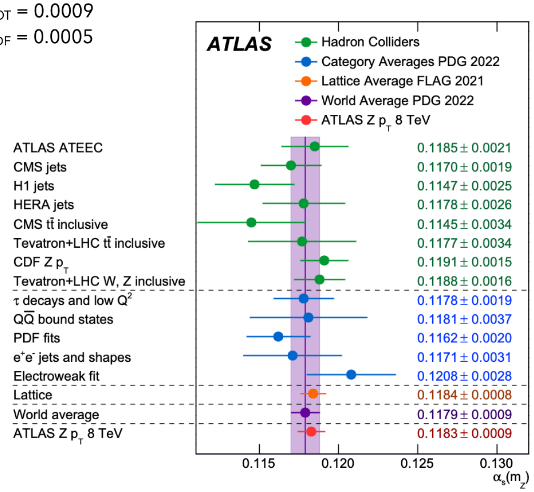
- Large x BSM effects can be hidden

- A limiting factor in precision LHC physics

ATLAS α_S determination

$\Delta_{TOT} = 0.0009$

$\Delta_{PDF} = 0.0005$

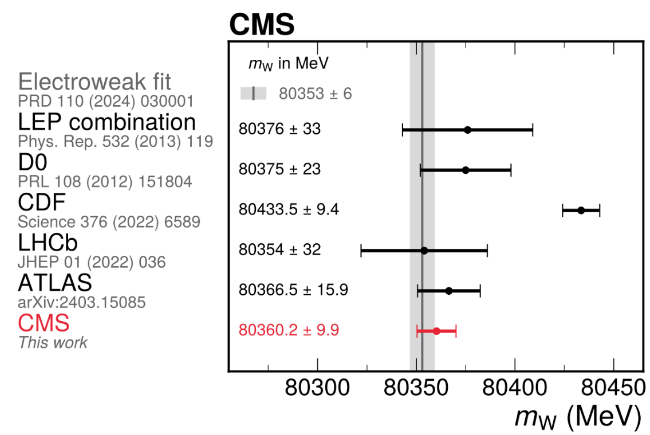


ATLAS collaboration, arXiv: 2309.12986

CMS M_w determination

$\Delta_{TOT} = 9.9$ MeV

$\Delta_{PDF} = 4.4$ MeV



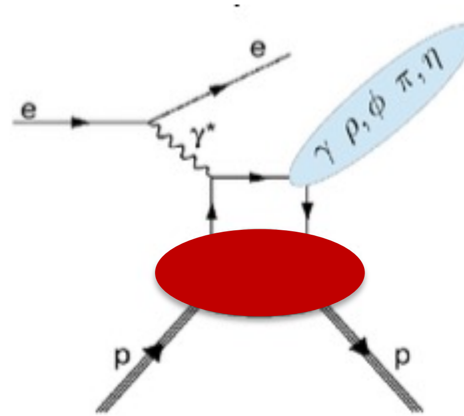
CMS collaboration, arXiv: 2412.13872

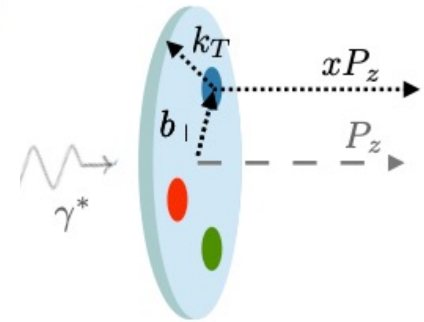
… could many of the tensions between data sets / methodologies be avoided if it were possible to constrain PDFs from DIS data only?..

Hadron Structure and Dynamics are much richer than longitudinal PDFs …

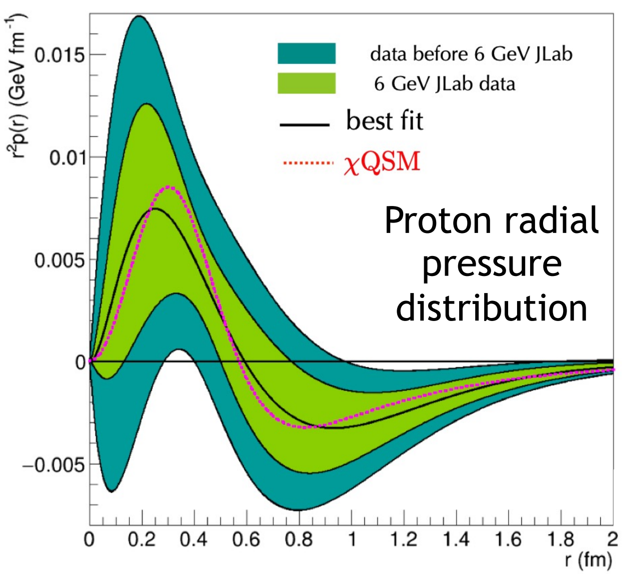
Transverse degrees of freedom, correlations in momentum and position via TMDs, GPDs through exclusive processes, SIDIS …

→ First glimpses of 3D structure & mechanical properties from <u>Jlab data</u>

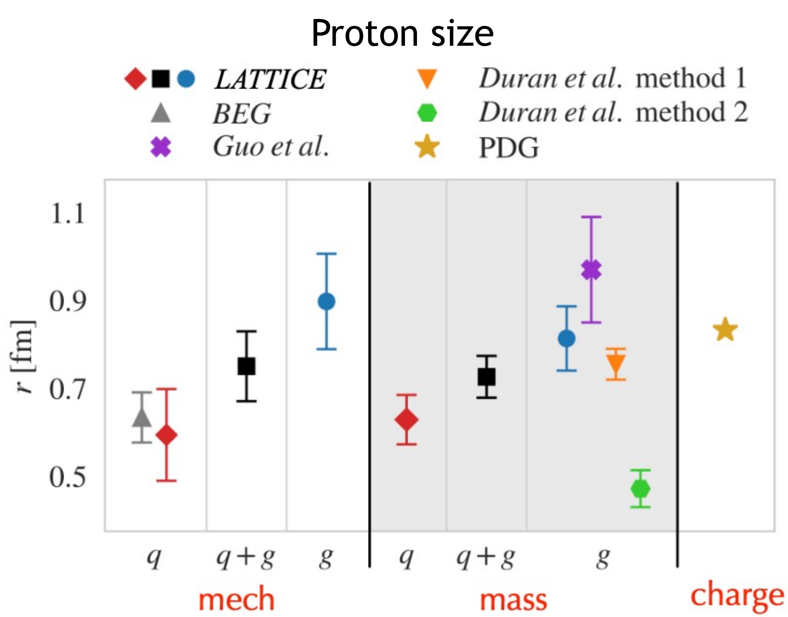


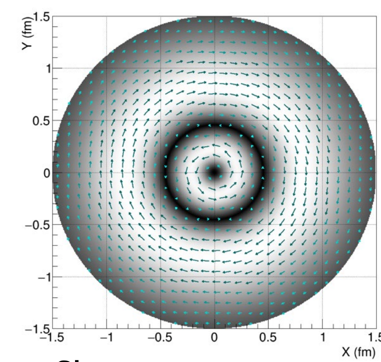


[Barbara Pasquini, Thia Keppel, DIS25]



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





Shear forces

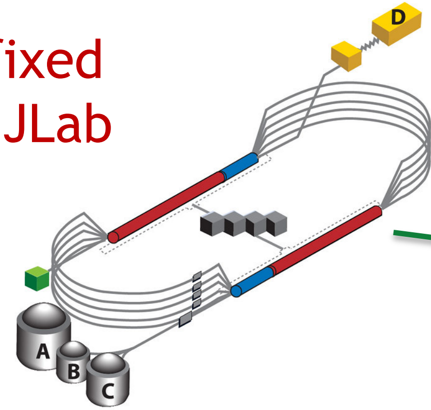
Current & Proposed Lepton-Hadron Facilities

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,^{3}He	Approved
EicC	> Late 2030's	15—20	2 — 3	p $\rightarrow$ U	e,p,d,^{3}He	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

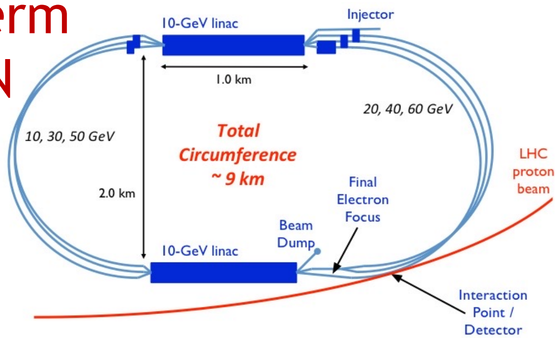
- Ongoing experiments revealing new properties of matter
- An approved new accelerator exploring new fundamental topics
- Longer-term plans aligned with core PP and NP priorities

Current and Future ep Colliders

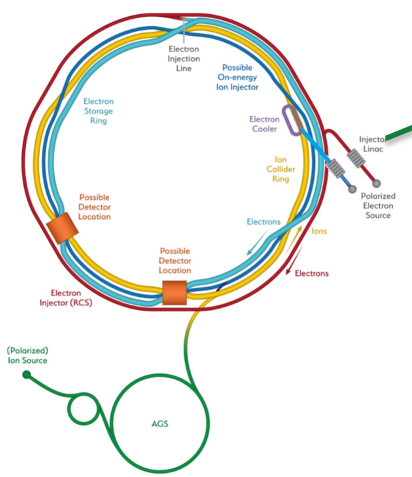
Ongoing fixed target @ JLab

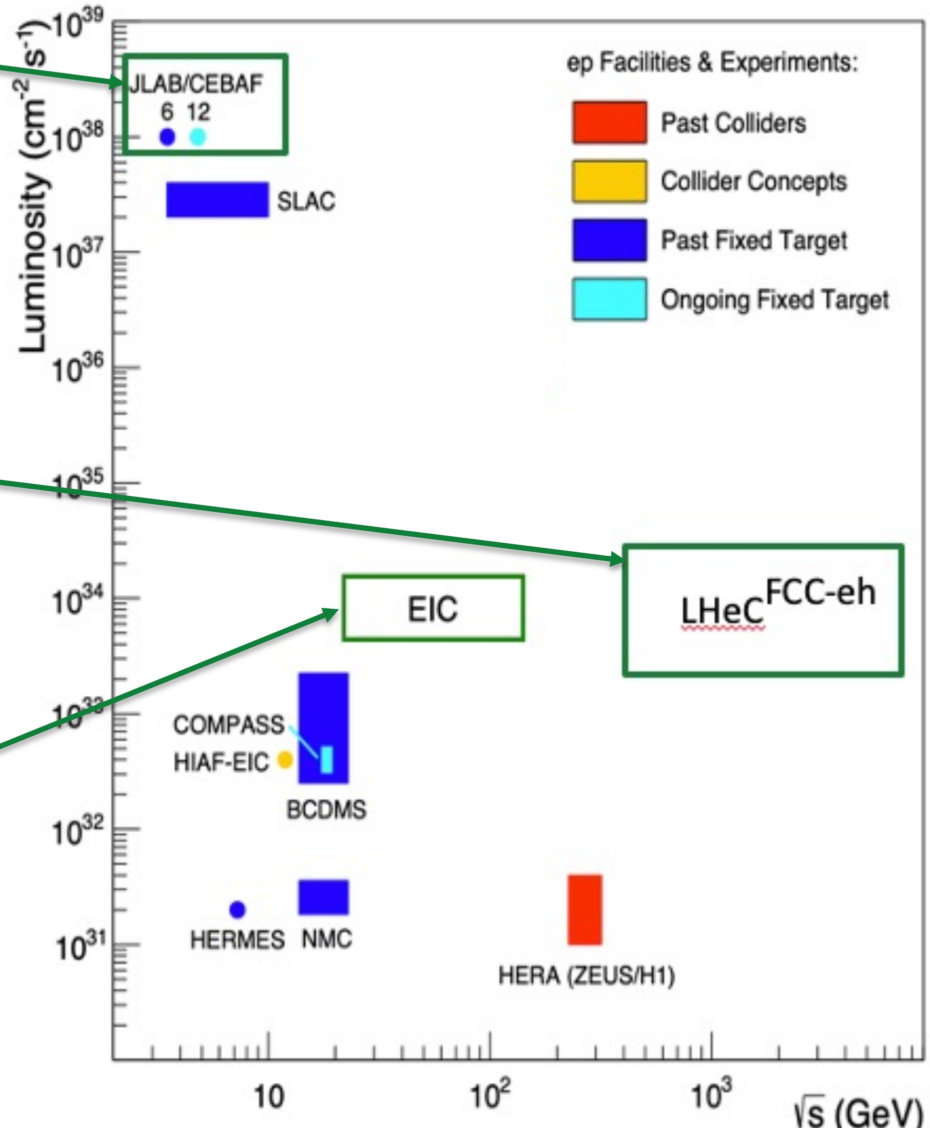


Longer-term @ CERN

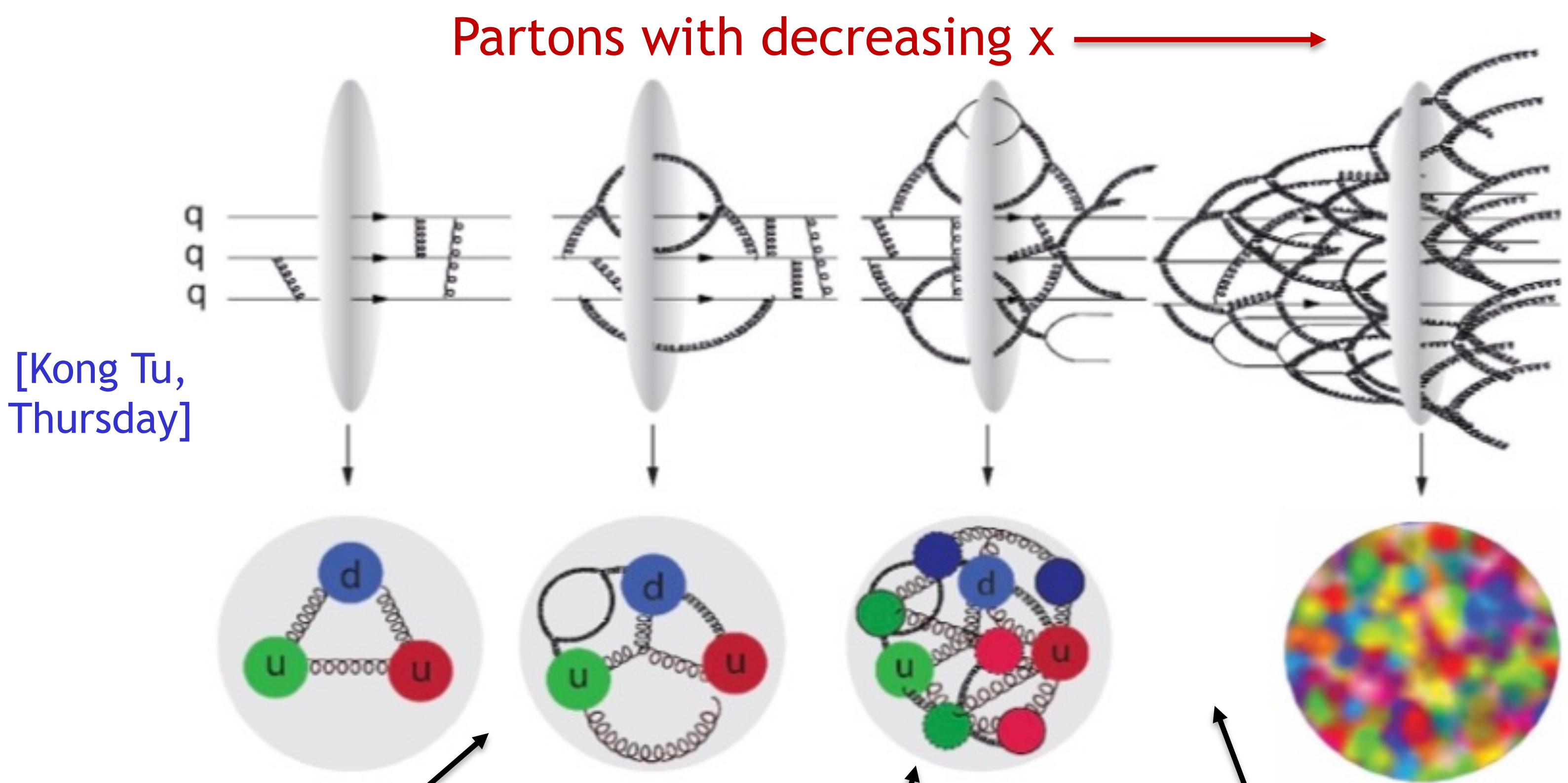


On-target for mid 2030s @ BNL





Crude Mapping Between Physics & Facilities



High x (Fixed Target/JLab)
Basic Structure

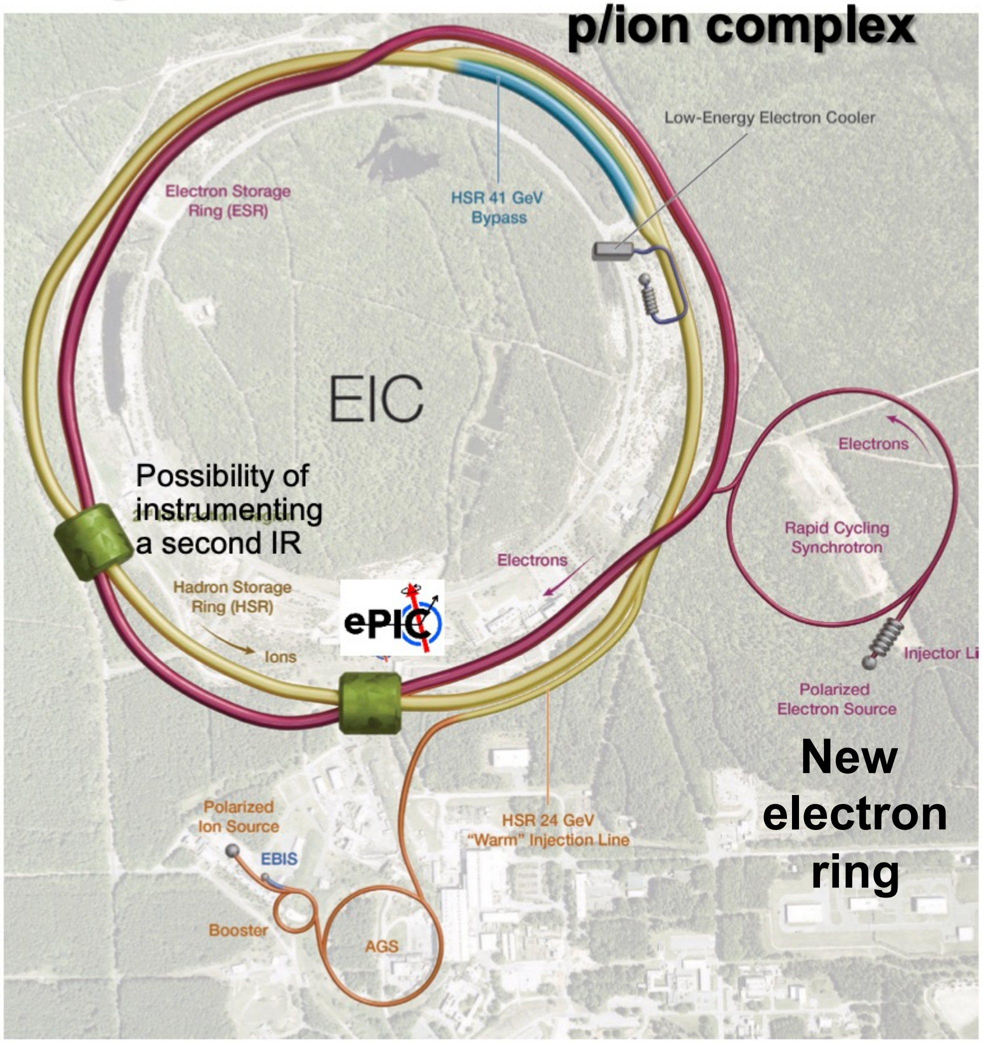
Intemediate x (EIC)
Emergent properties

Low x (HERA / LHeC)
Non-linear dynamics

Very Low x
(LHeC,FCC-eh)
The unknown

The Electron-Ion Collider (BNL)

Usage of RHIC tunnel and RHIC p/ion complex



Specifications driven by science goals:

- Energy range **28 < $\sqrt{s}$ < 140 GeV**

World's first …

- High lumi ep Collider

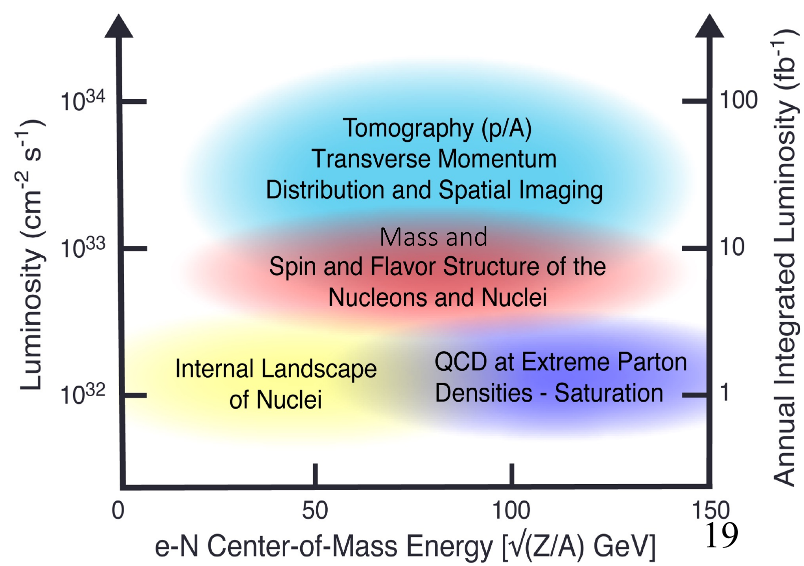
(~ 10^{33} -10^{34} cm^{-2} s^{-1})

- Double-polarised DIS collider

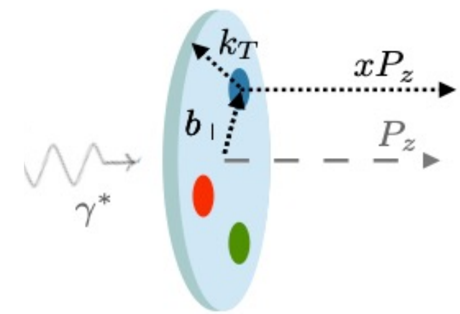
(~70% for leptons & light nuclei)

- eA collider

(Ions ranging from H to U)



Fundamental questions for EIC



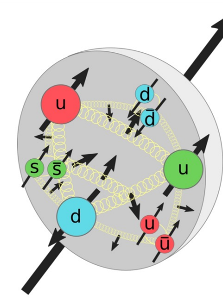
- **What does the proton look like in 3D?**

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

  … How is proton spin generated?

  … What is the mechanism behind confinement?

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

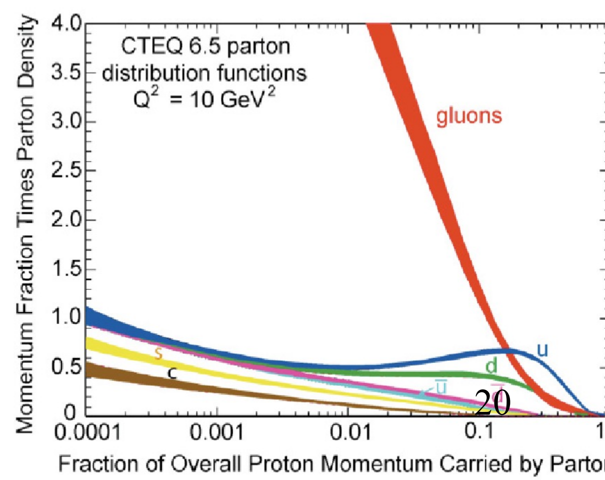


- **How are parton properties and dynamics altered in nuclei?**

  … 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?



A Detector for the EIC

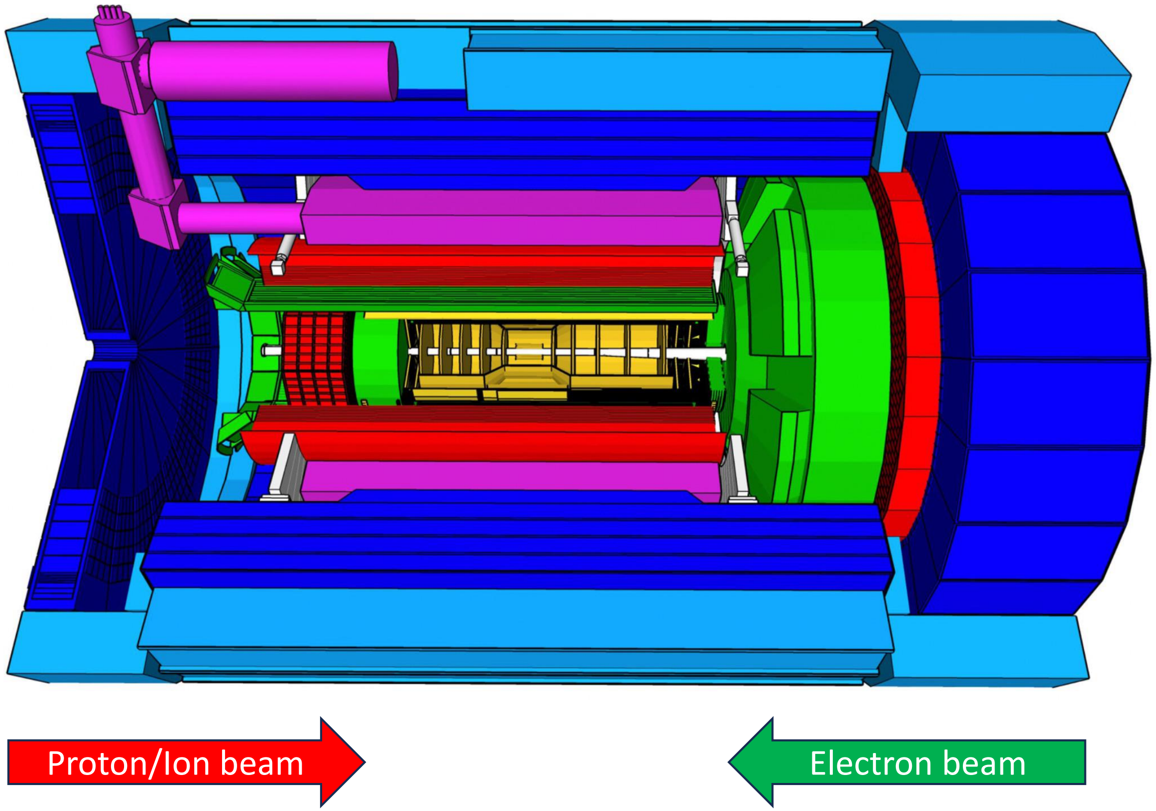
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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 (see later)

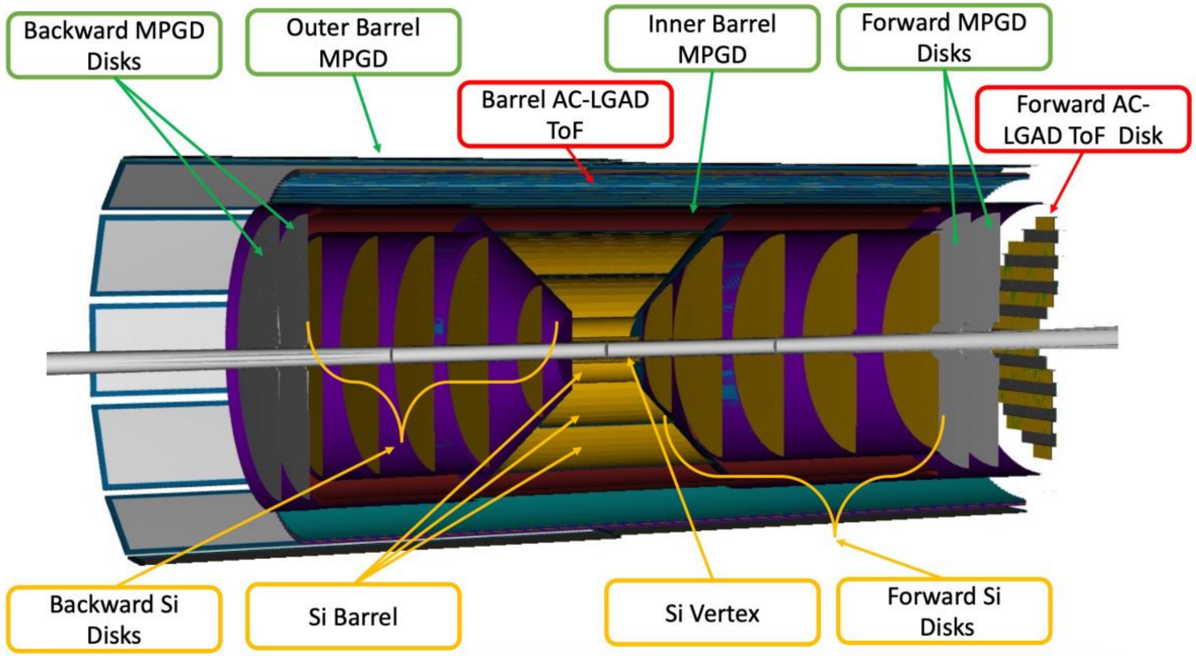
- Much lower radiation fluxes than LHC widens technology options

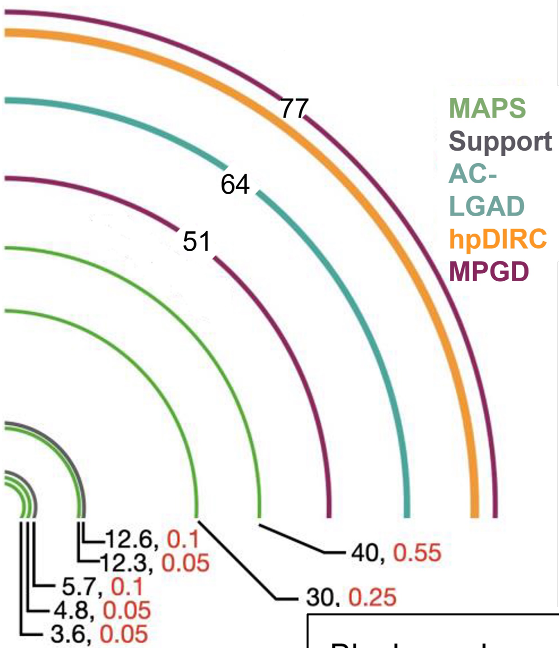
Tracking Detectors

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)
- 20x20μm pixels
- 5 barrel layers + 5 disks (total 8.5m² silicon)





Black numbers are radii in cm

Red numbers are material in % X0

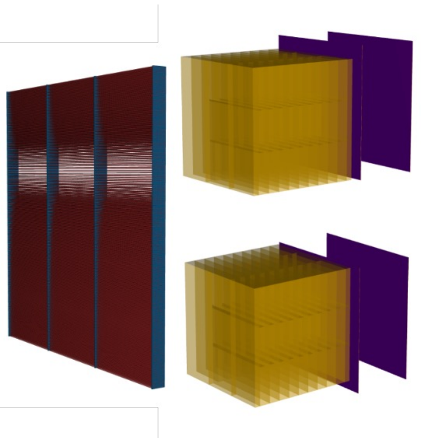
LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

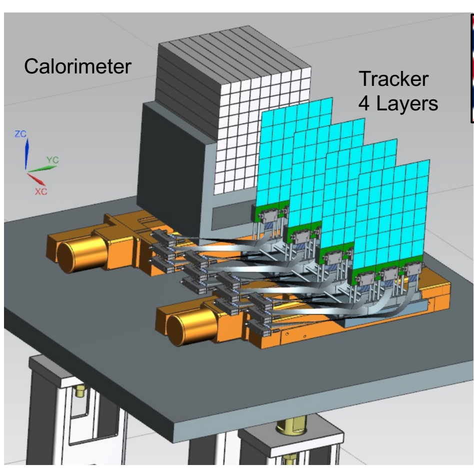
Interaction Region / Beamline Instrumentation

- Extensive beamline instrumentation integrated into IR design

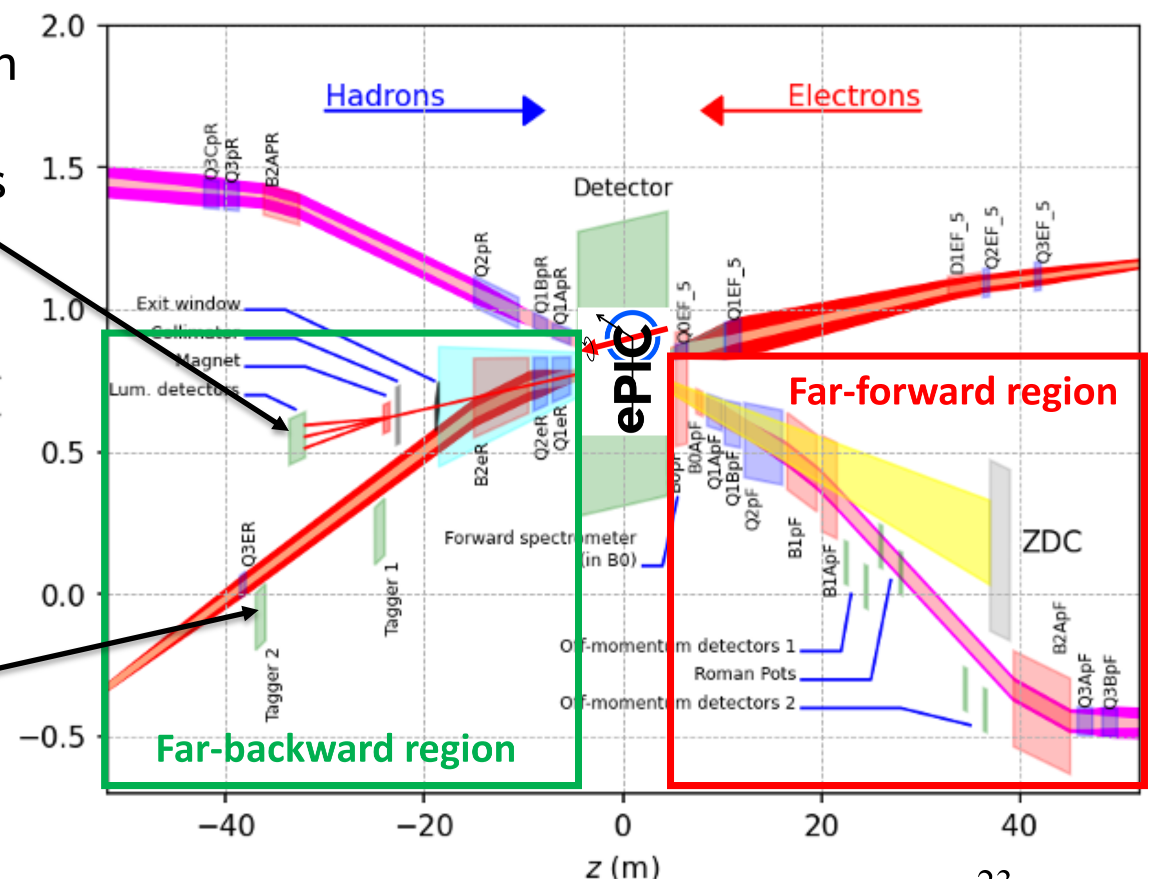
- Tagging electrons and photons in backward direction for lowest Q^2 physics studies and lumi monitoring via photon counting in $ep \rightarrow ep\gamma$



Pair-production lumi spectrometers

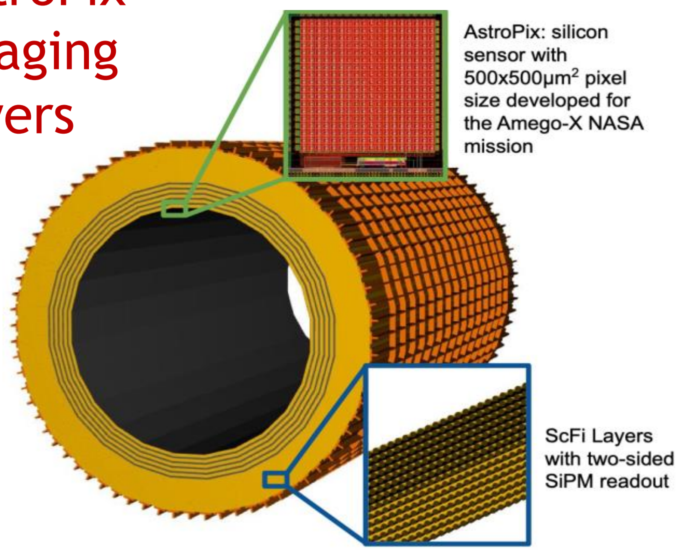


2 low Q^2 electron taggers

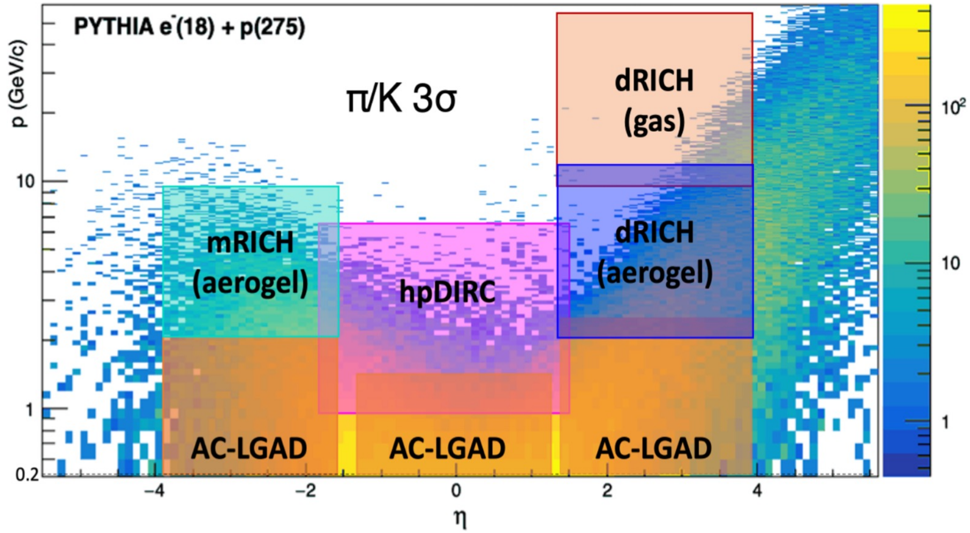


More Novel Detector Components

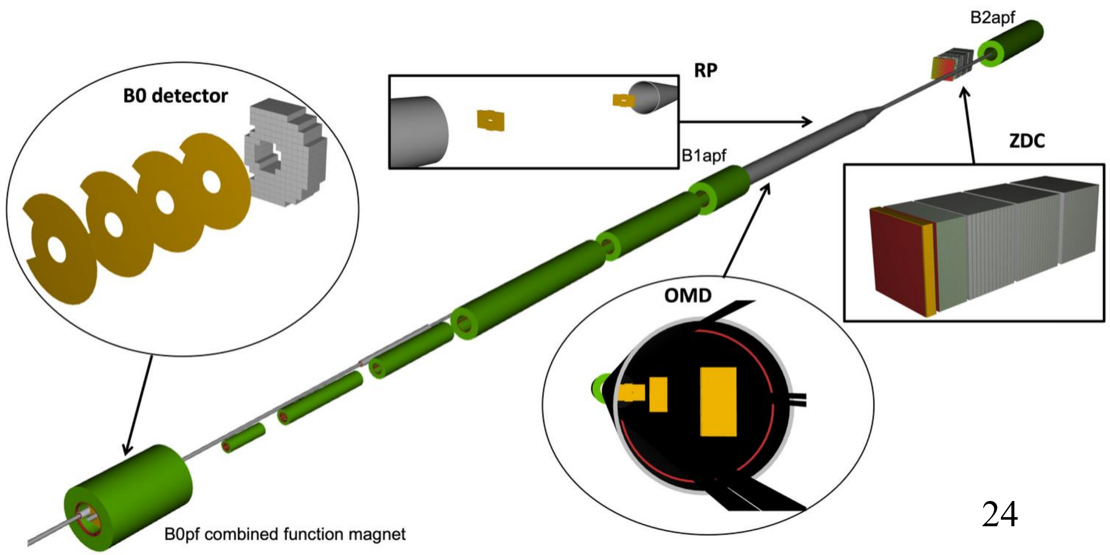
Imaging eCAL
Pb/SciFi sampling + AstroPix imaging layers



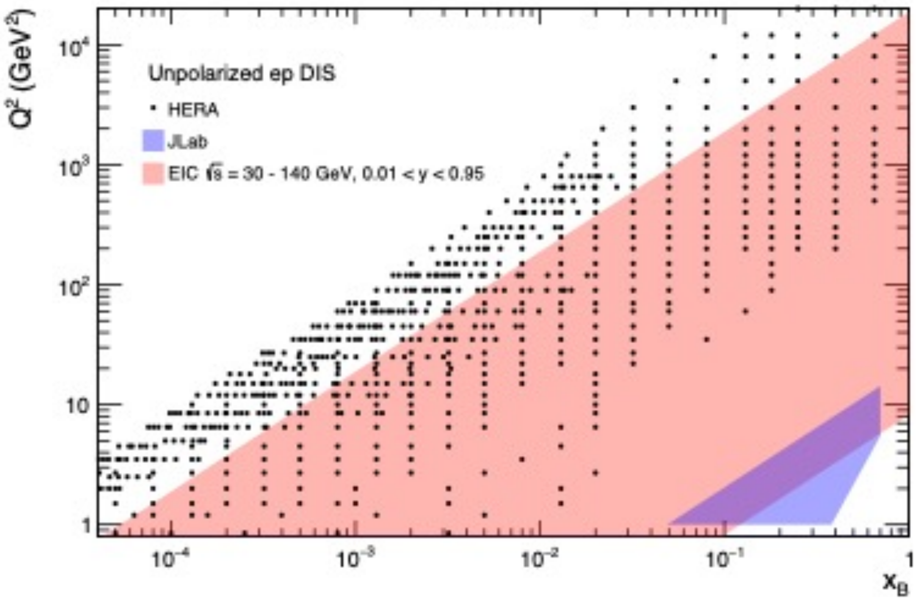
Comprehensive Particle ID



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



EIC Kinematic Range v Previous Data



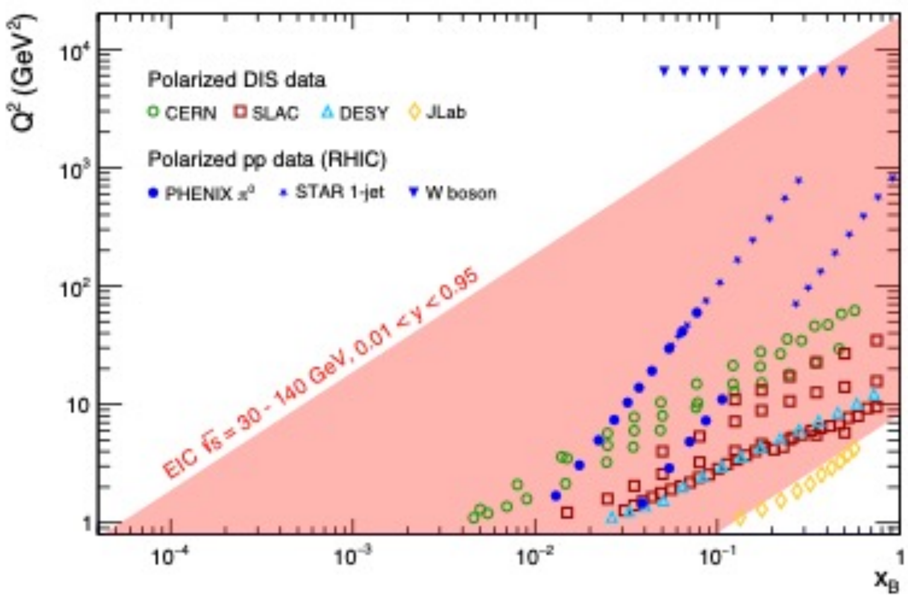
Inclusive ep DIS

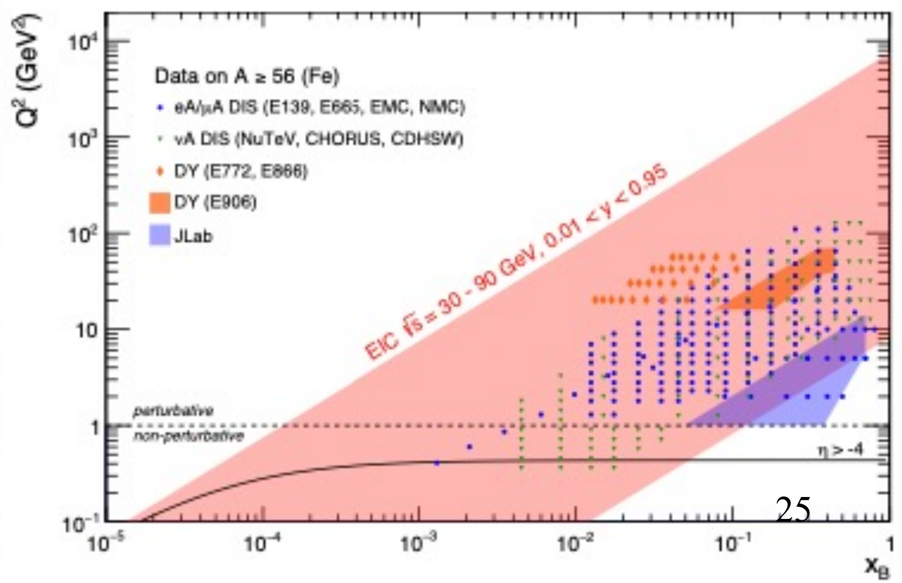
→ Closing gap and overlapping between fixed target & HERA

→ High x, moderate Q^2 precision

Polarised target ep & eA DIS

→ Completely unexplored regions, extending to low x





EIC Impact on Proton Parton Densities

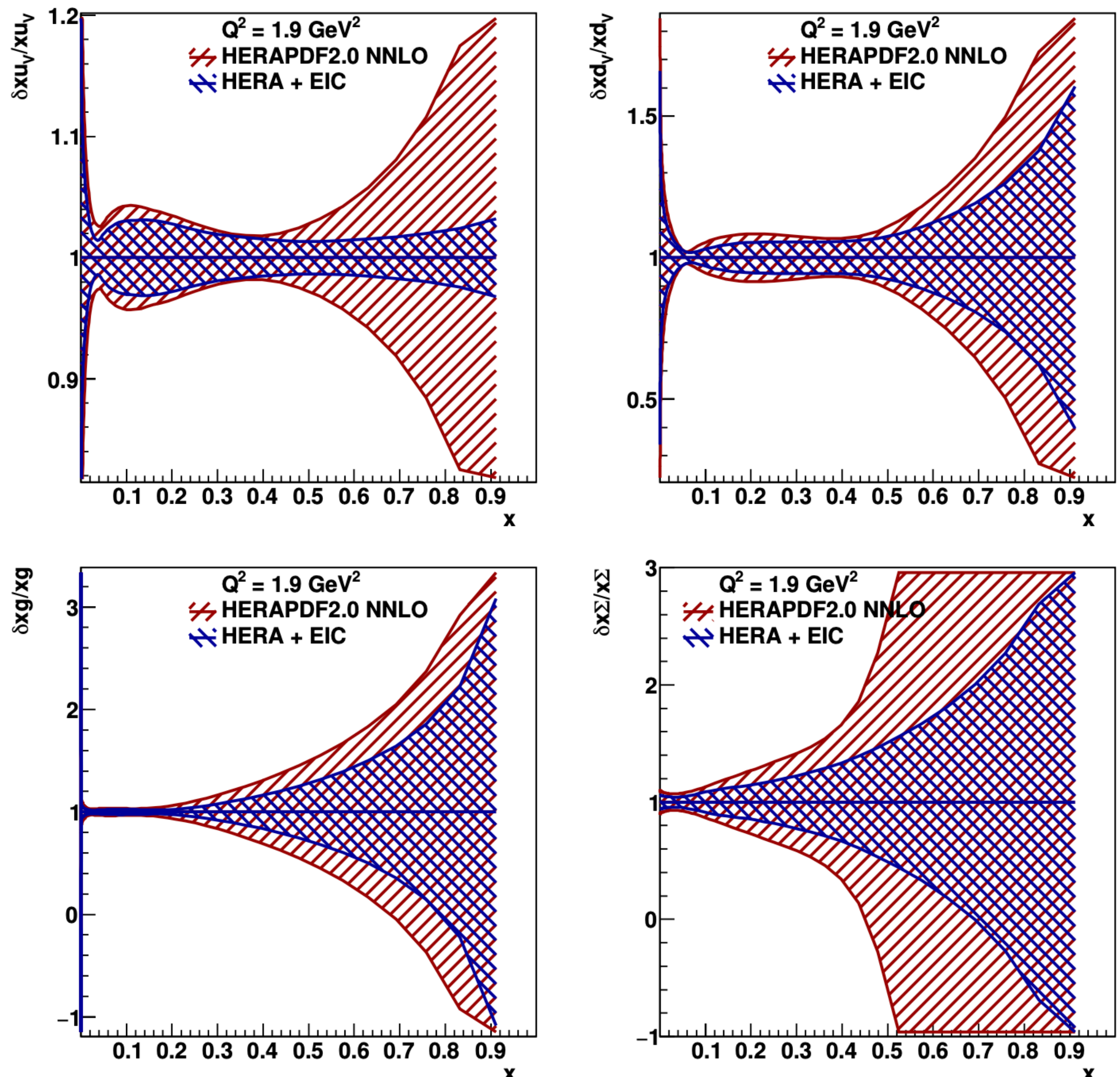
Fractional total uncertainties with / without simulated EIC data added to HERA (lin-x scale)

… 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 → 0.6% now)

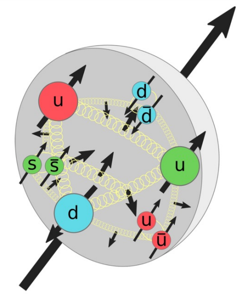


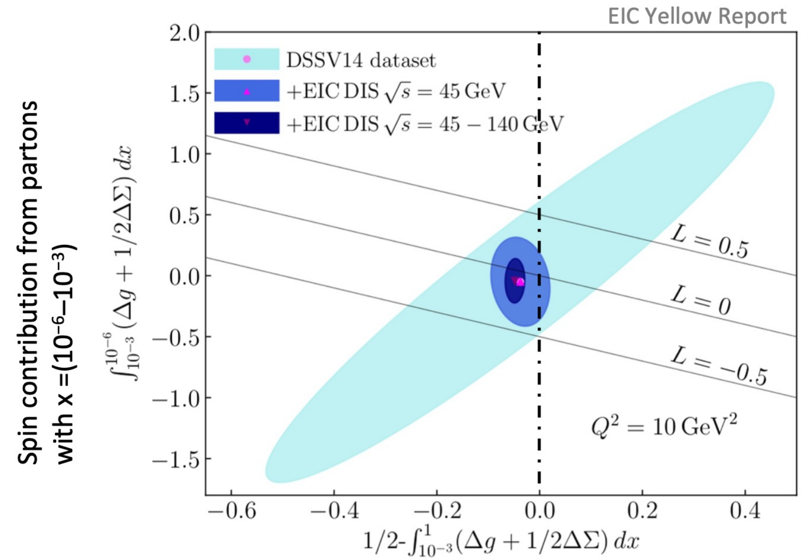
Proton Spin

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

Jaffe-Manohar sum rule:

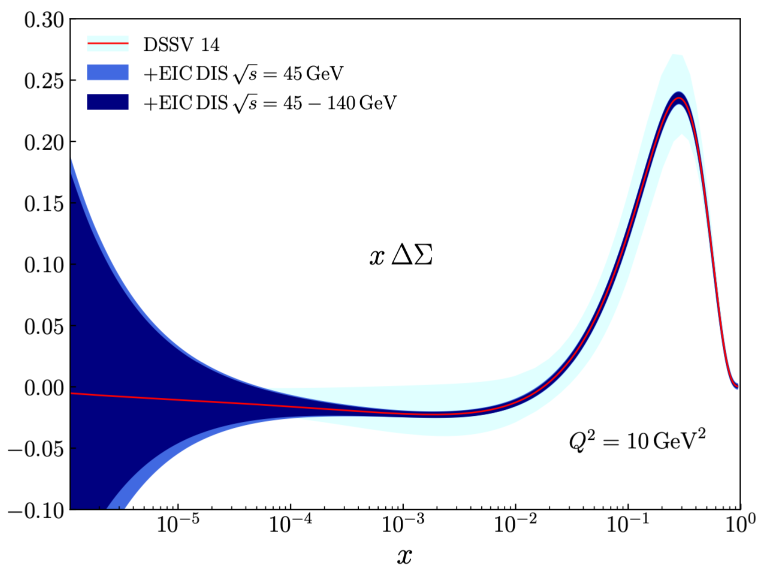
$$\underbrace{\boxed{\Delta\Sigma/2}}_{\text{Quark helicity}} + \underbrace{\boxed{\Delta G}}_{\text{Gluon helicity}} + \underbrace{\boxed{\ell_q}}_{\text{Quark canonical orbital angular momentum}} + \underbrace{\boxed{\ell_g}}_{\text{Gluon canonical orbital angular momentum}} = \hbar/2$$

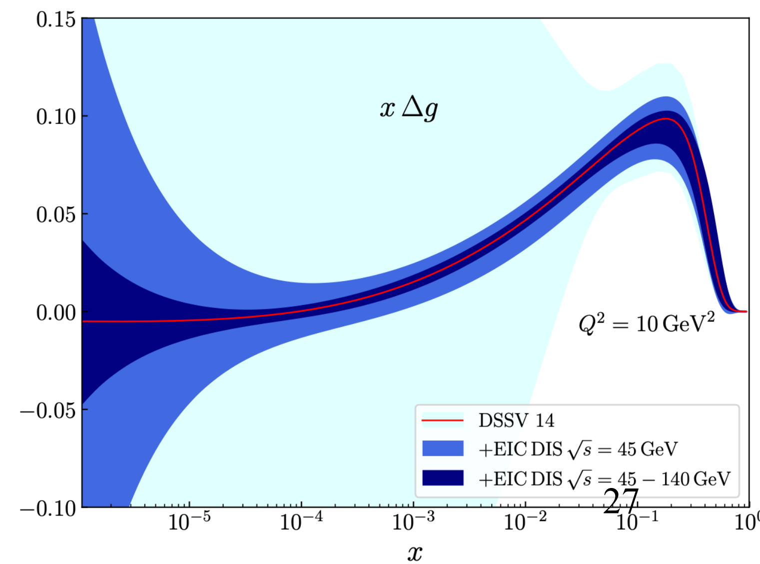




Room left for potential OAM contributions to the proton spin from partons with x > 0.001

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

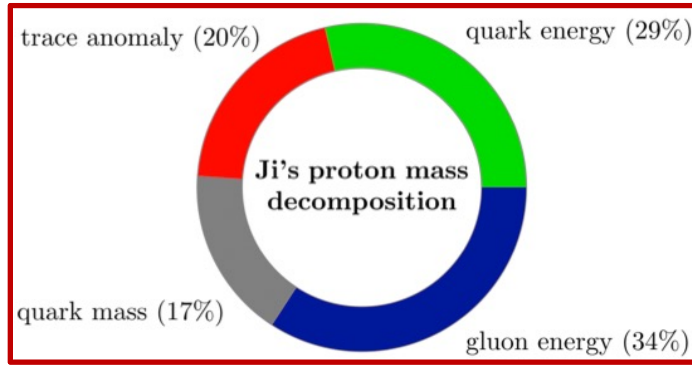




Proton Mass

- Decomposition along similar lines to spin:

$$\boxed{m_p = m_m + m_q + m_g + m_a}$$



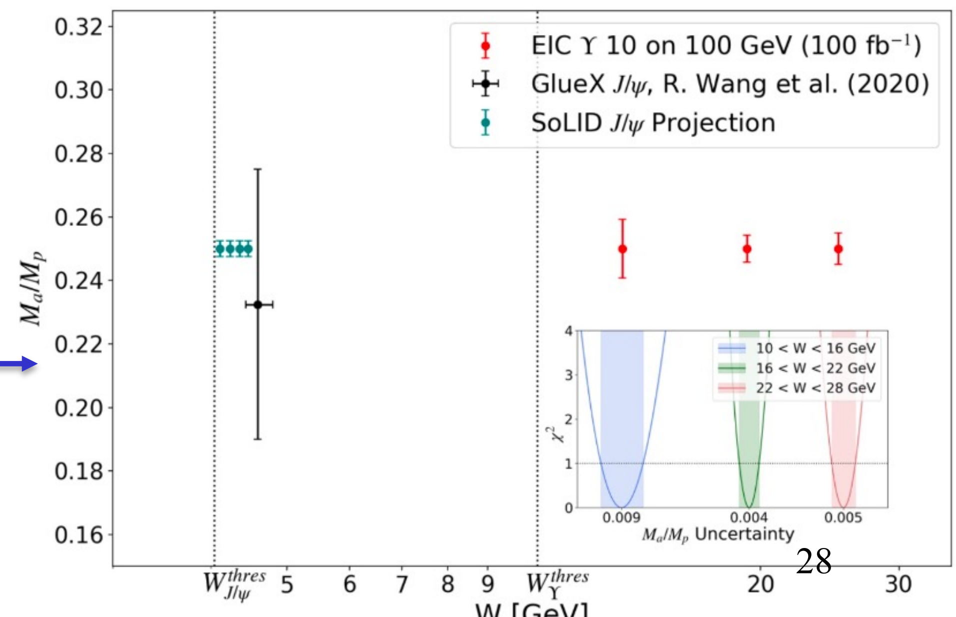
Valence and sea quark masses (including heavy quarks)

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

QCD trace anomaly (purely quantum effect - chiral condensates)

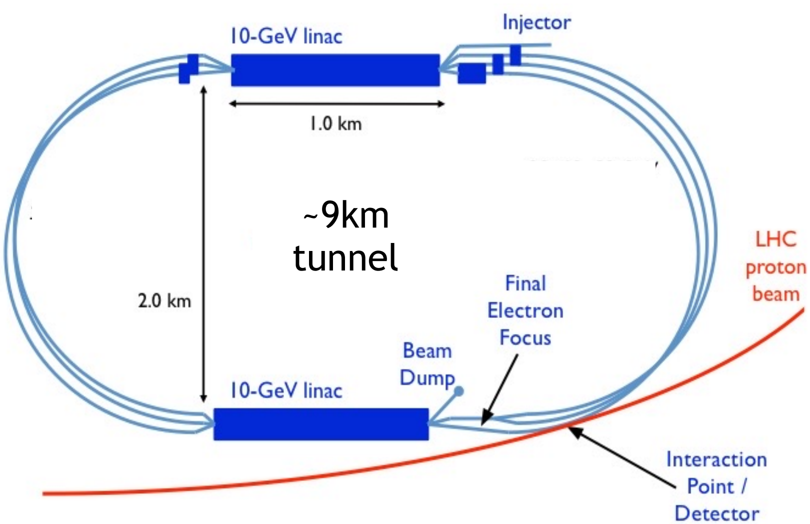
- Relations to experimental observables being understood

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

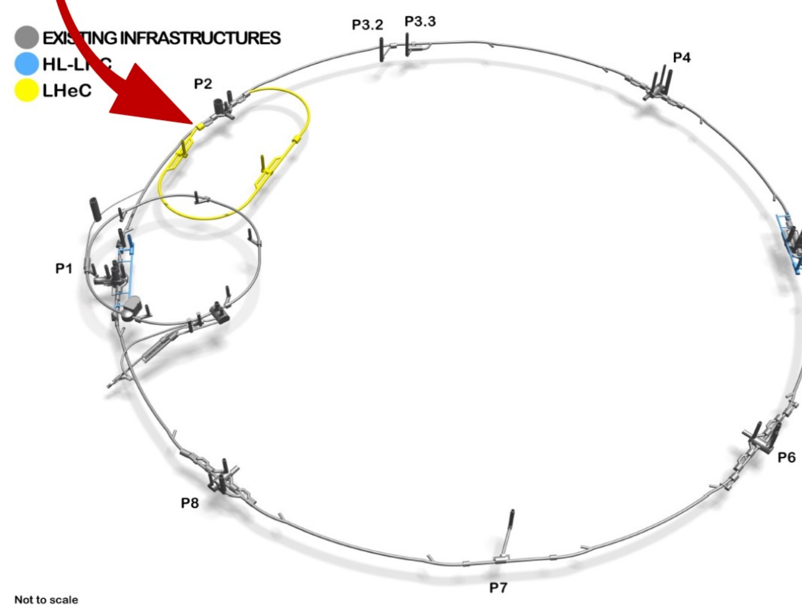


The CERN Large Hadron electron Collider

- 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 → 1ab^{-1}



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)



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

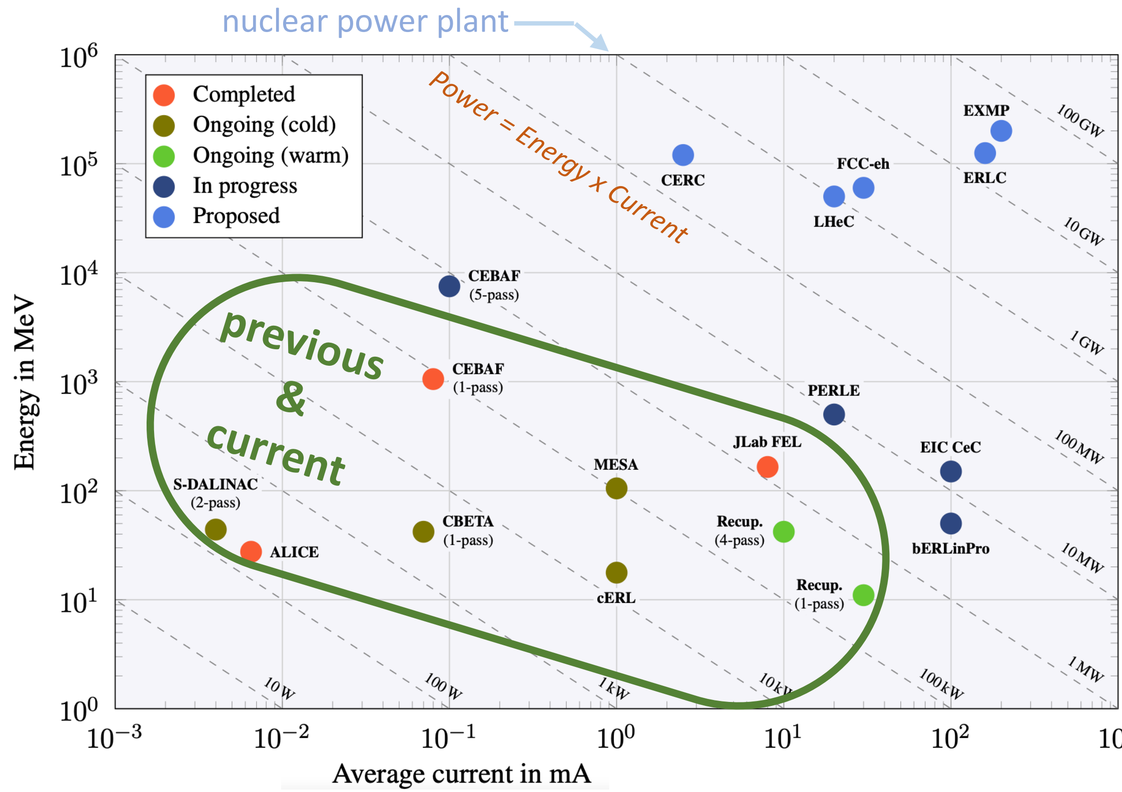
- ‘Sustainable’ acceleration: ~100 MW for ERL

Energy Recover Linacs

- Demonstrating ERL scalability is critical path

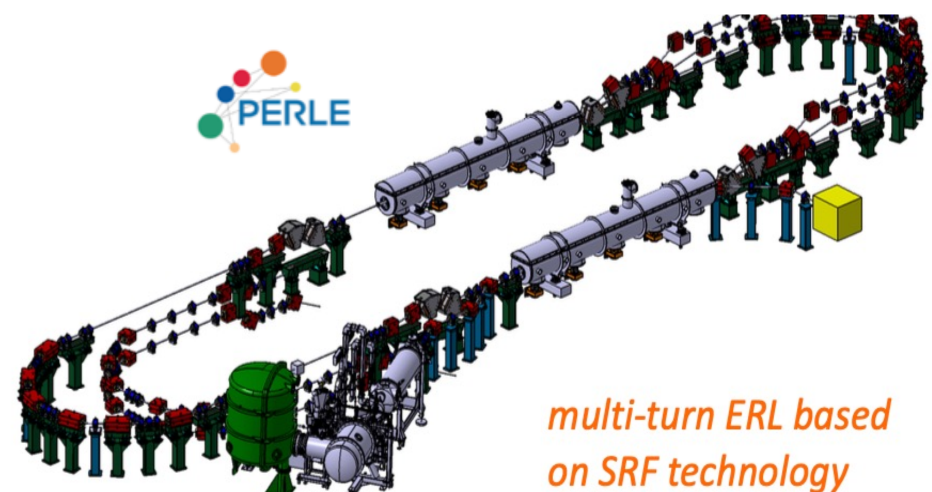
- Prototype (PERLE @ IJCLab) implementation started

- First stage (one turn) by 2028.



Electro.. DC-gun

Photo-cathode

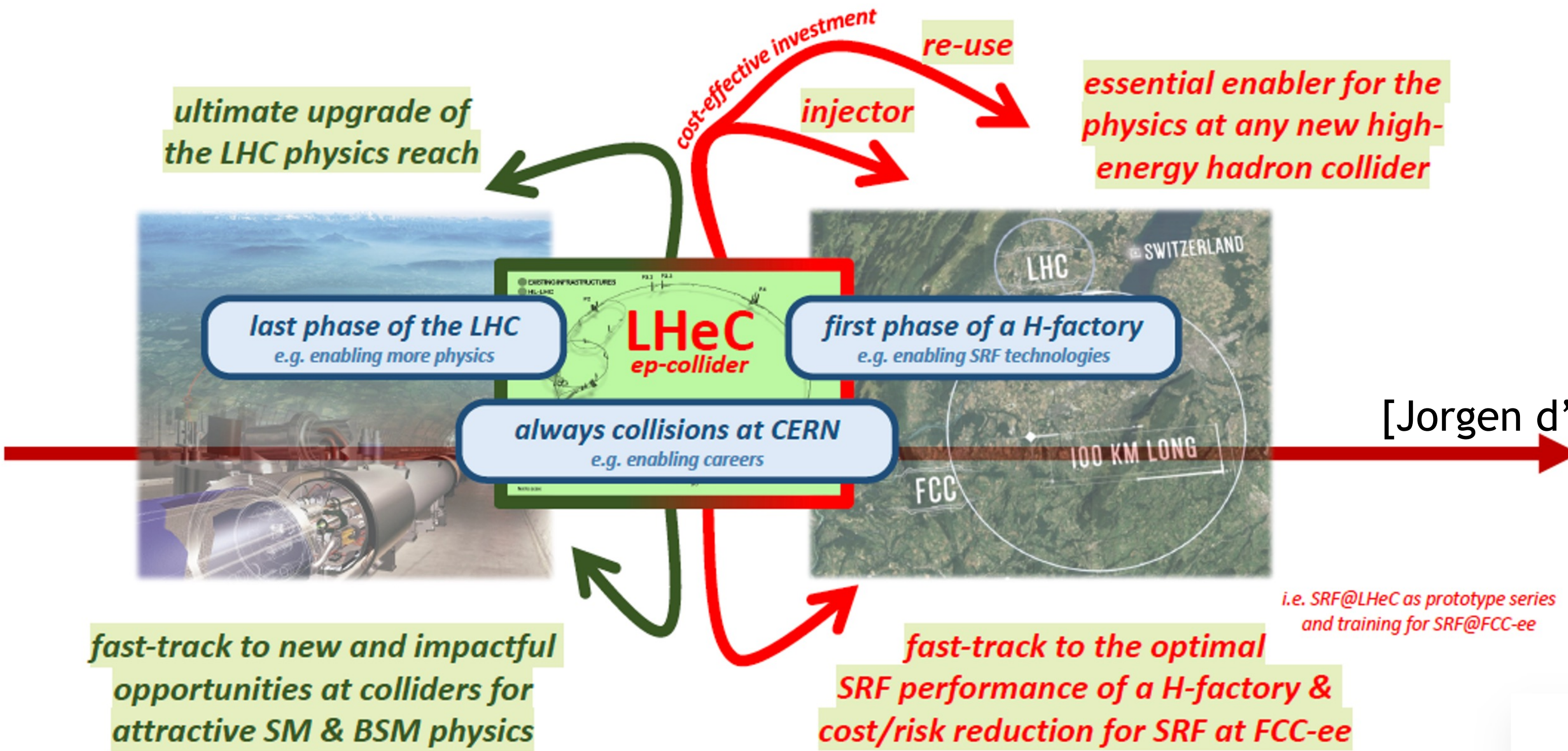


CDR: *J.Phys.G* 45 (2018) 6, 065003

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

How could LHeC fit into global landscape?

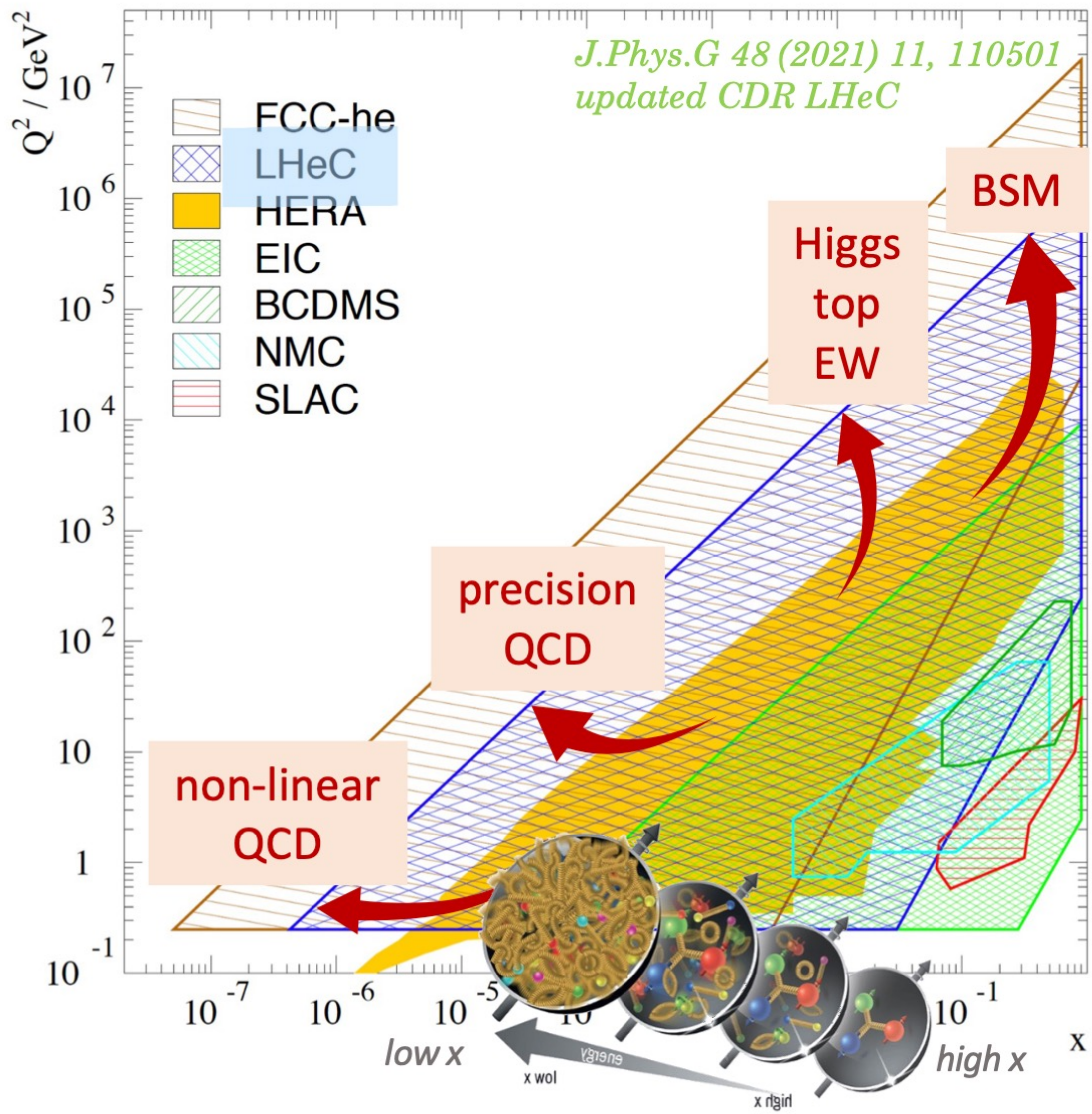
- Not the next CERN flagship project
- Possible ‘bridge’ in event of significant time gap, due to funding constraints or pivot away from FCC-ee due to competition, or scientific developments



[Jorgen d’Hondt]

- Highly impactful science from strong interaction discovery to Higgs
- Opportunity for accelerator and detector technology development

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

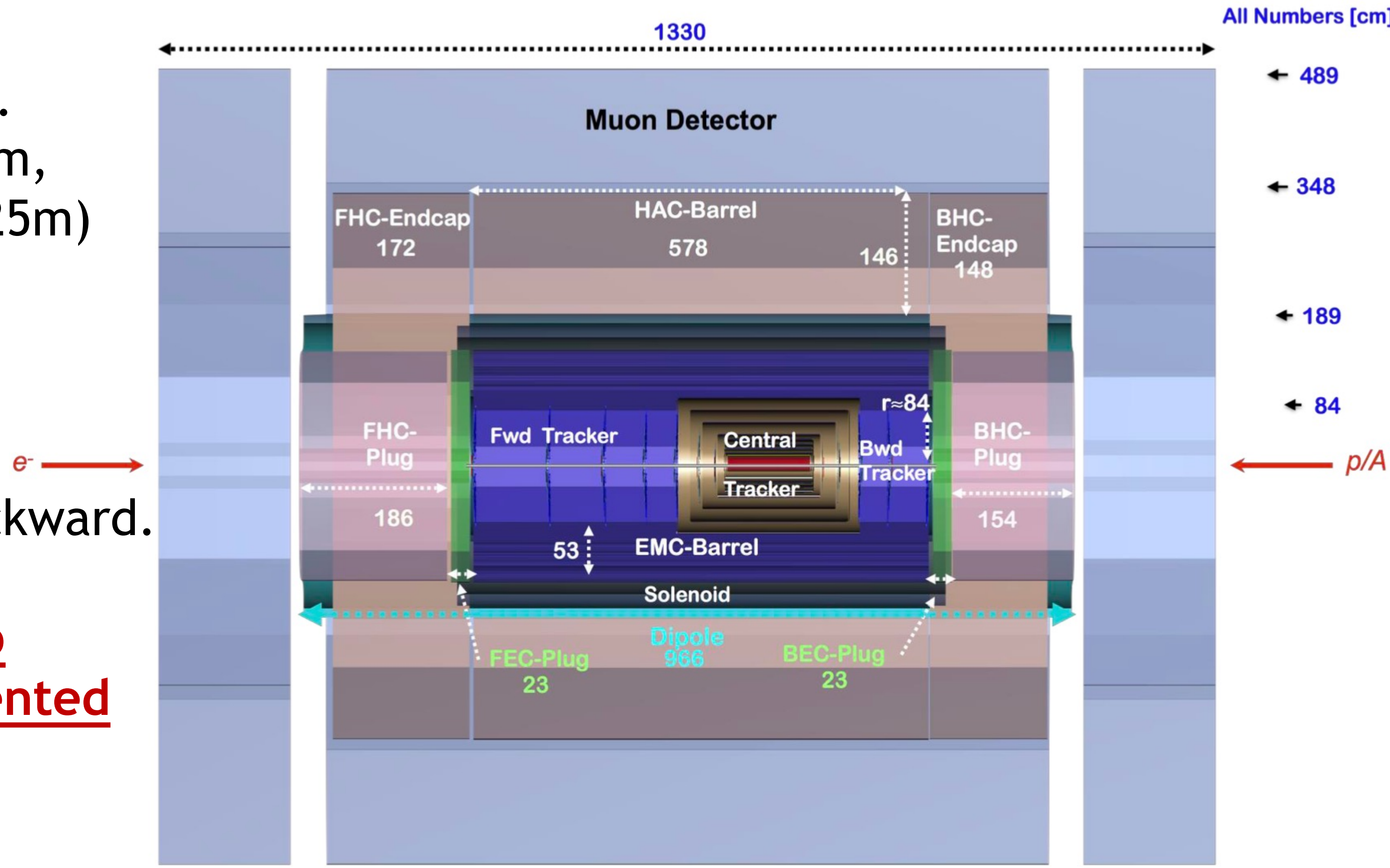
→ Dedicated Deep Inelastic Scattering experiment… hermetic & reconstructing all final state particles

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

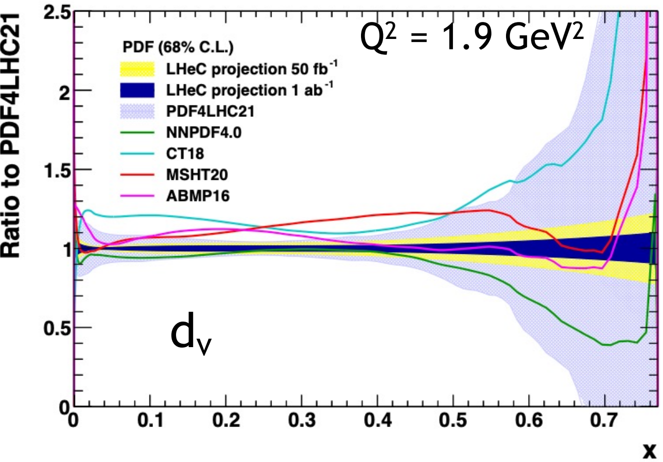


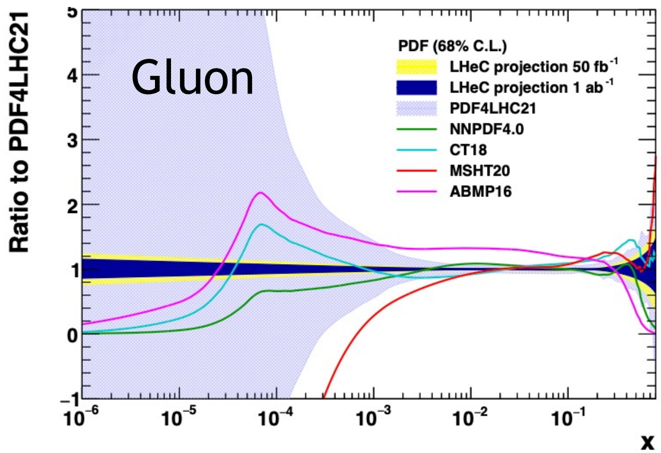
'Could be built now', but many open questions:

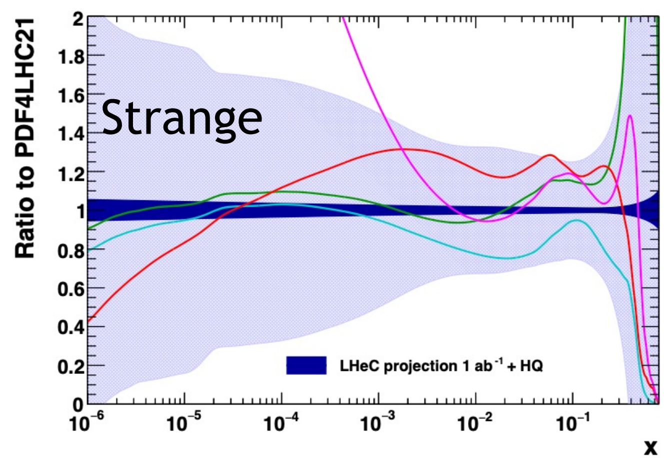
- A snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- Possibly lacking components for some ep/eA physics (eg. Particle ID)
- Not particularly well integrated or optimized

… Synergies with EIC, LHCb, ALICE, future e^+e^- or $\mu^+\mu^-$ colliders

Proton PDF Precision





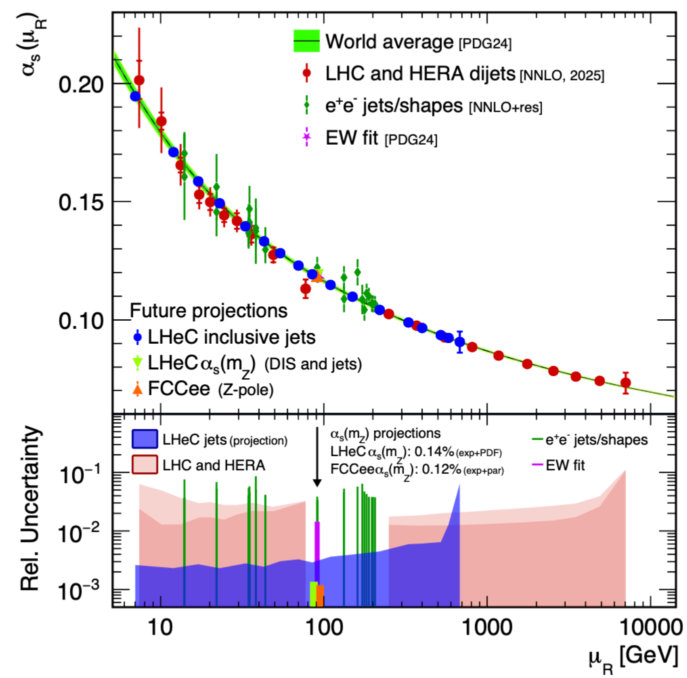


- PDF knowledge transformed over wide kinematic range, extending from $x \sim 10^{-6}$ to $x \rightarrow 1$

- Resolving current ambiguities

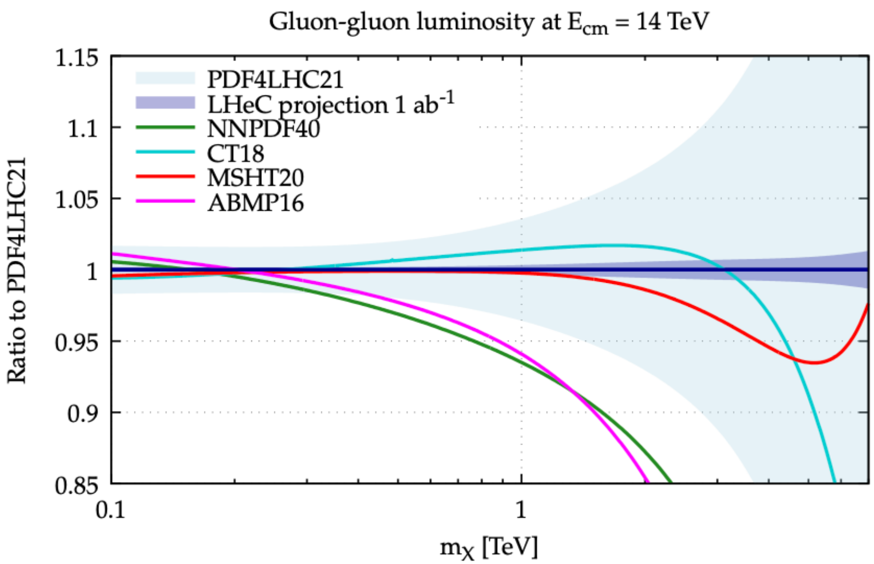
- First full and precise flavour decomposition

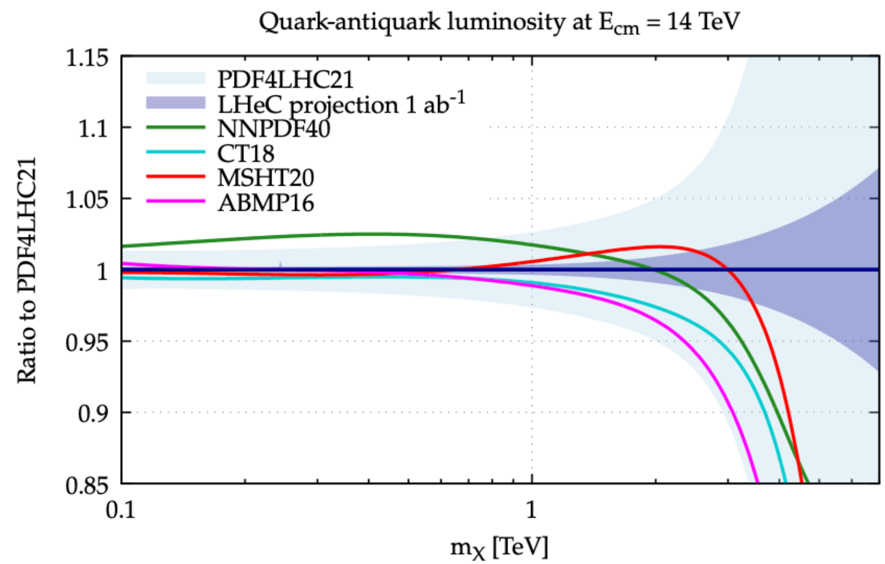
- α_s to 0.14%, including running



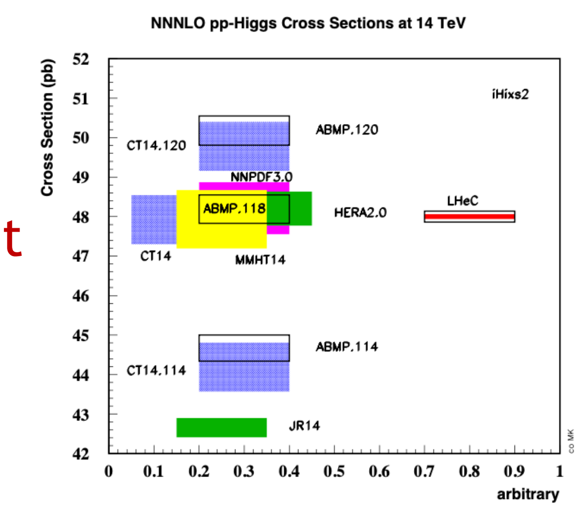
- M_W to few MeV
- $\sin^2\theta_W$ to 0.0002 including running
- Best axial and vector Z-light quark couplings

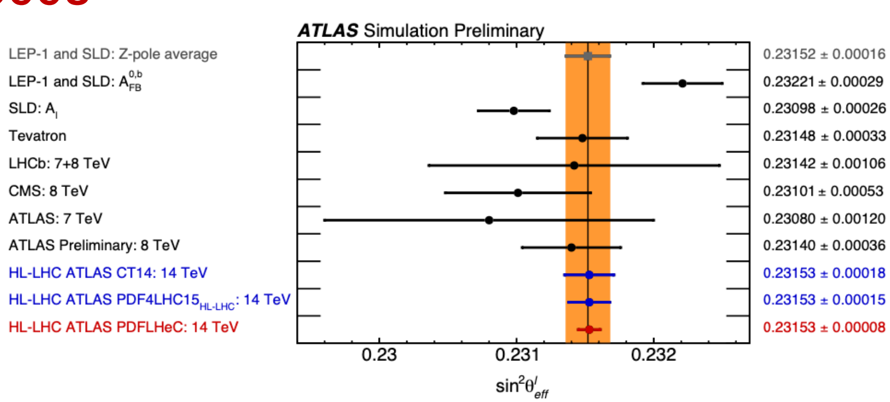
Enabling HL-LHC: parton lumi's revisited





- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements
  …Theory uncertainty on LHC Higgs cross section
  … M_W PDF systs → 2 MeV, enabling 3 MeV measurement
  … $\sin^2\theta_W$ → 0.0008
  …

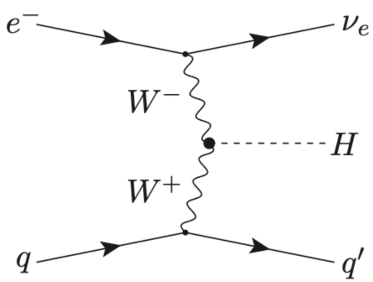


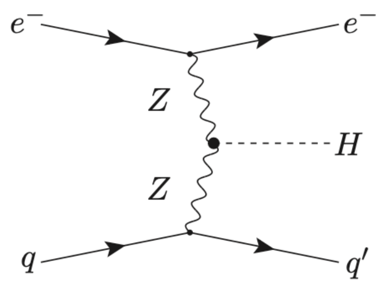


Influence on LHC Higgs Programme

LHeC extends Higgs programme at the LHC by:

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





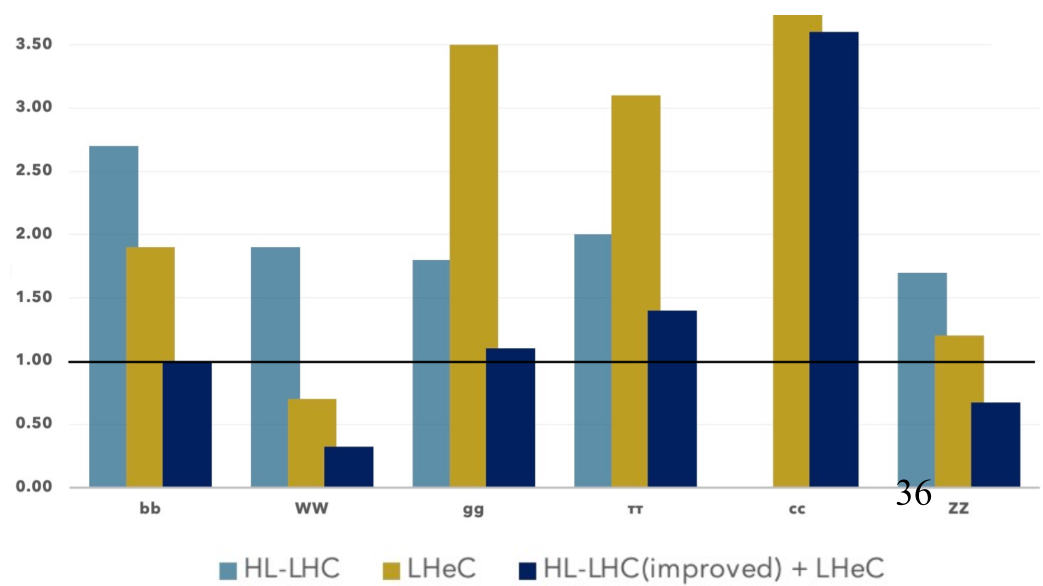
Dominant production mechanism charged current (WW), distinguished event-by-event from sub-dominant neutral current (ZZ)

Charged Current cross section ~ 0.2pb for P=-0.8 → ~200,000 events for 1ab^{-1}

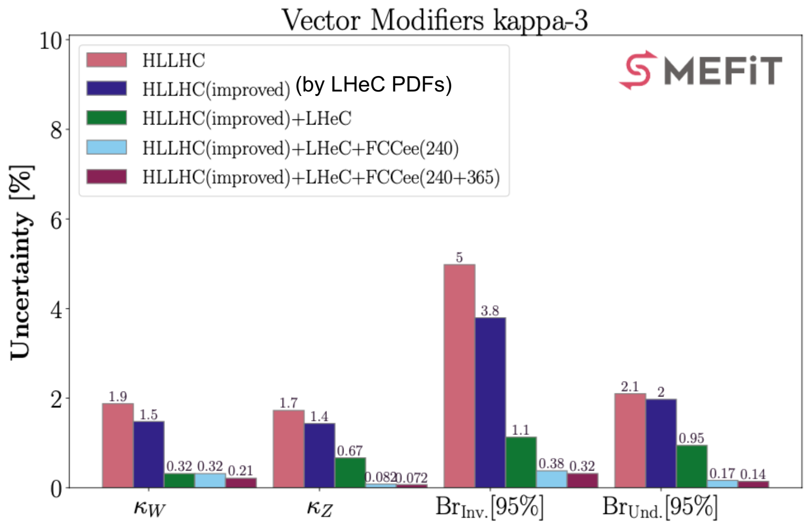
Studies in Kappa-3 framework (SMEFIT group)

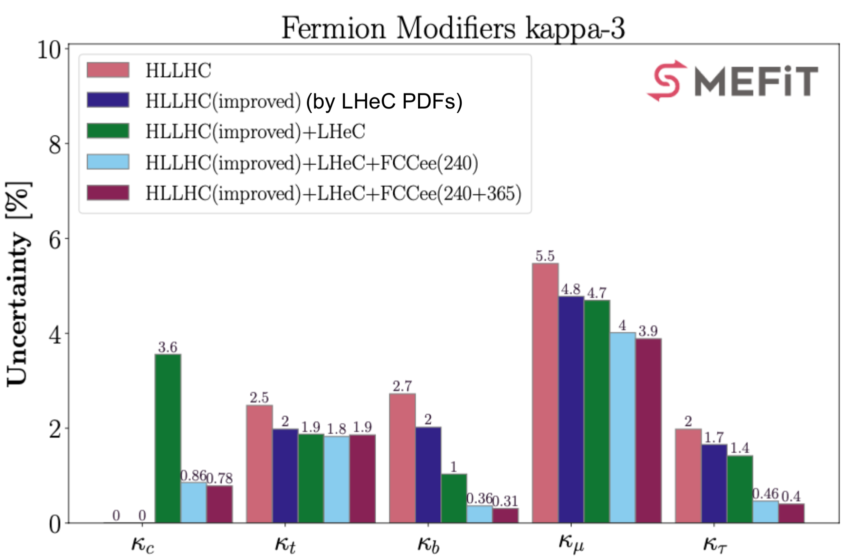
'HL-LHC (improved)' shows Impact of LHeC PDFs

… improvements HL-LHC → LHeC about same as LHC → HL-LHC



Influence on Higgs Coupling Precision



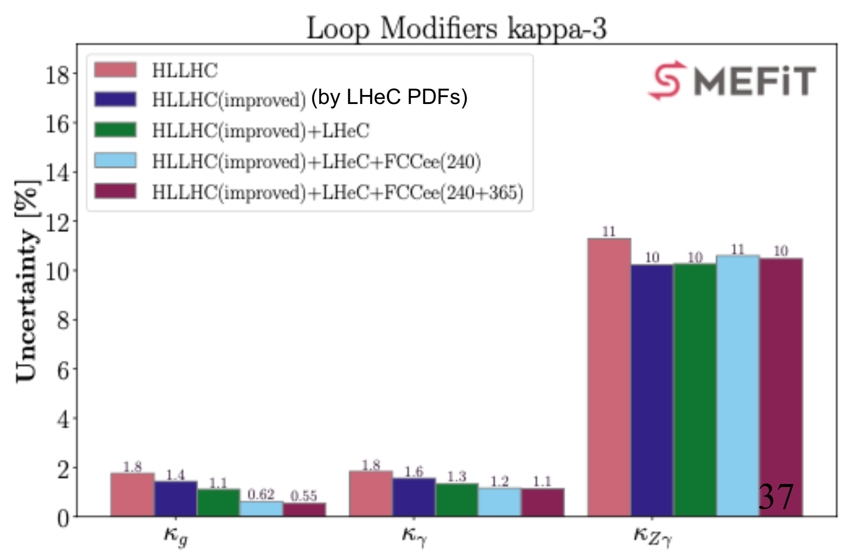


eg for HL-LHC → LHeC → FCC-ee …

- 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



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 early 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 can enable LHC discovery via precision, discover new strong interaction phenomena, and explore the Higgs sector in complementary ways

“Circles in a circle”, Wassily Kandinsky (1923), Philadelphia Museum of Art