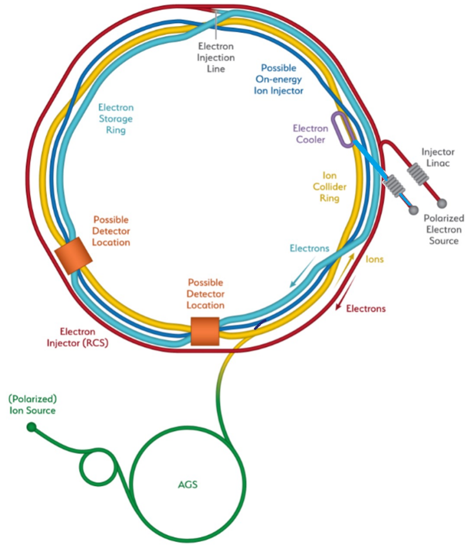
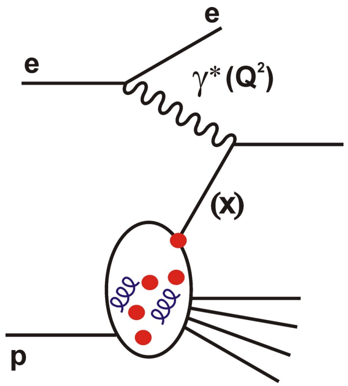
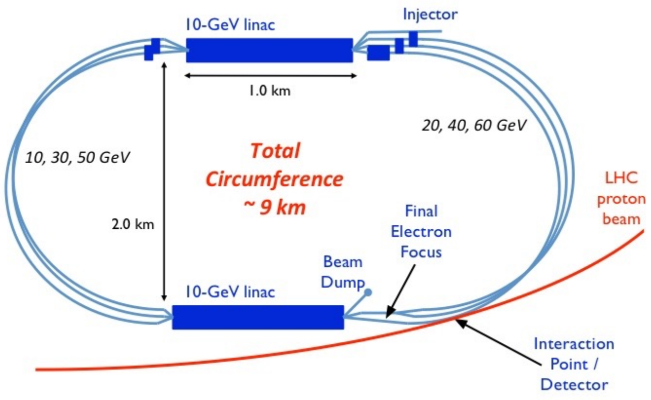
# Deep Inelastic Scattering and the Longitudinal Structure of the Proton



## Paul Newman (Birmingham)

## IJCLab Seminar
## 3 February 2024

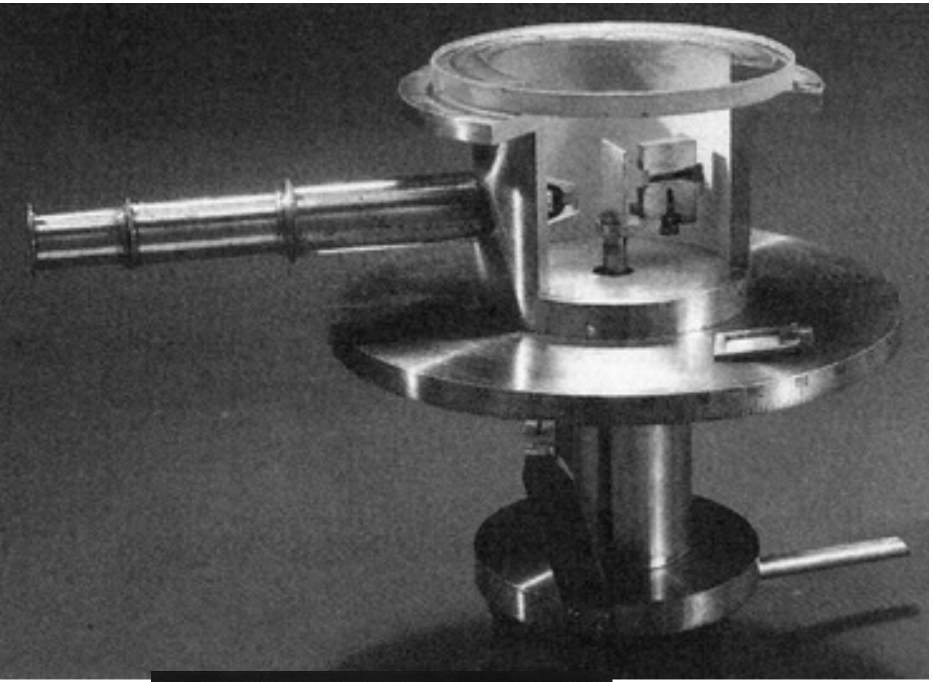




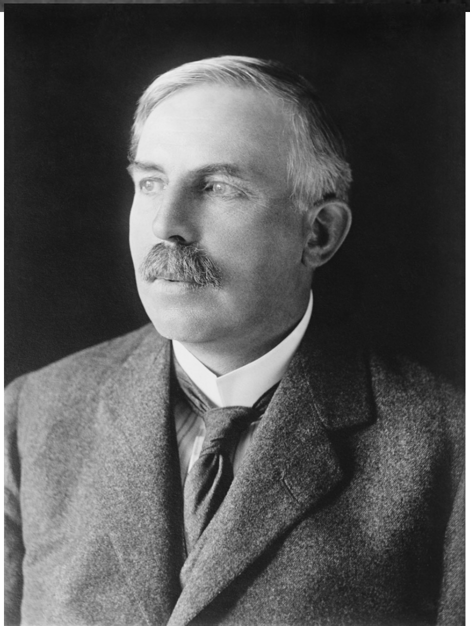
1) DIS History and Context
2) Proton parton densities: status
3) Electron Ion Collider
4) Large Hadron electron Collider

[See also recent IJCLab seminars by Charlotte van Hulse, Rachel Montgomery]

# Rutherford (1927, as President of Royal Society)



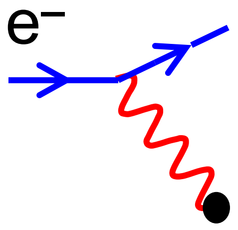
Following from the original scattering experiments ($\alpha$ particles on gold foil target) …



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

# Probing the Proton with Electrons

Simple uncertainty principle arguments:

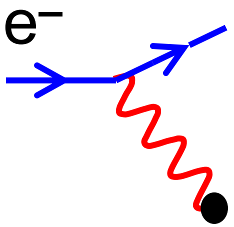


Resolved dimension: $\Delta x \sim \frac{200\text{MeV}}{E}$ fm

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

# Probing the Proton with Electrons

Simple uncertainty principle arguments:



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

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

1950s
Hoffstadter

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

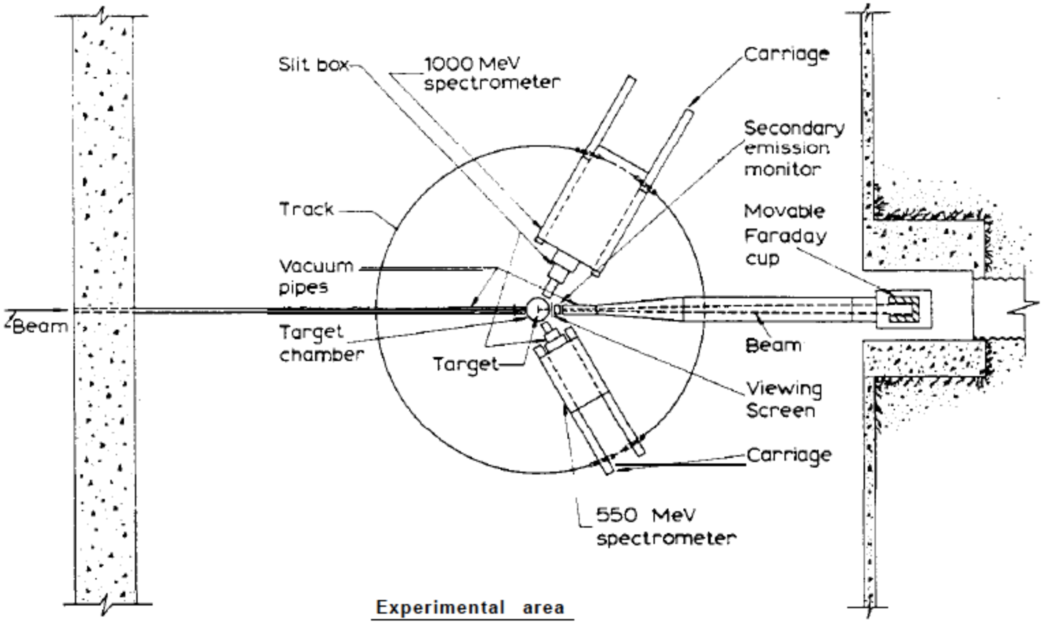
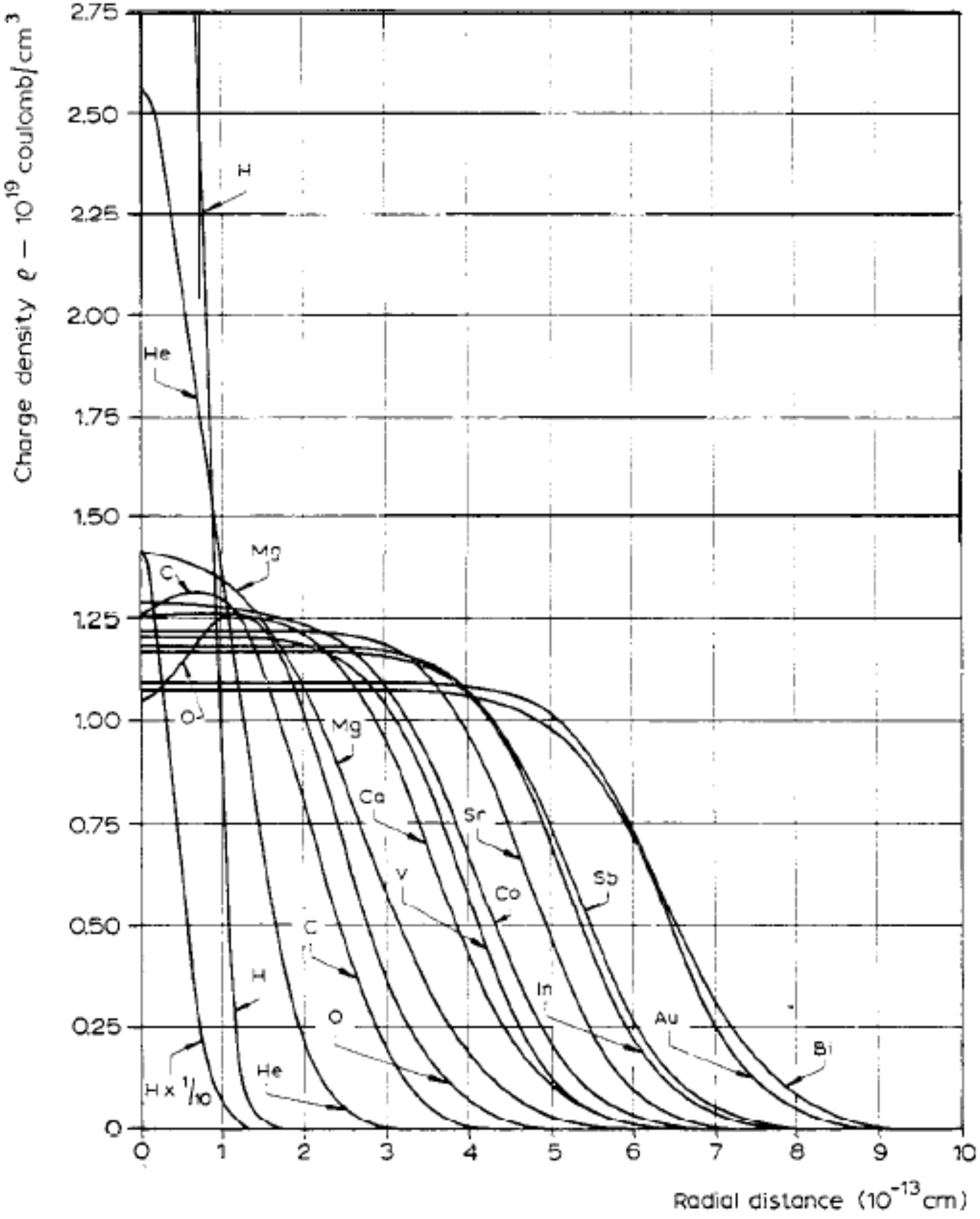


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

# Hoffstadter’s Results

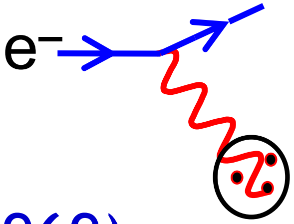


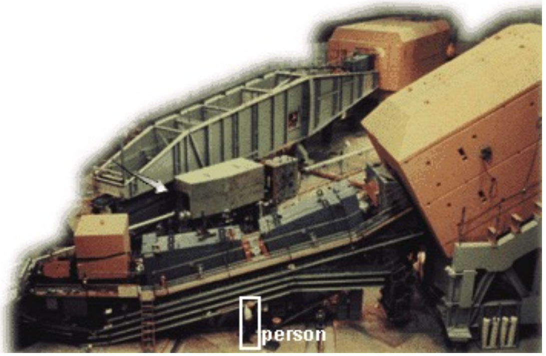
… Fourier transforming scattered electron pattern to determine spatial distribution of the target charge distribution

→ proton radius ~1fm

# Probing the Proton with Higher Energy Electrons

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



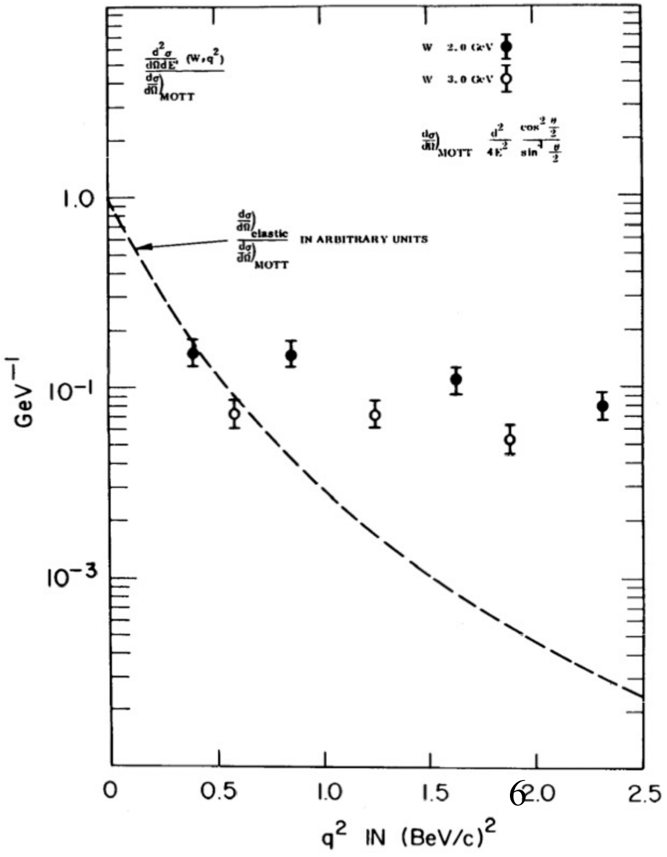


ESA experiment at SLAC (1969)

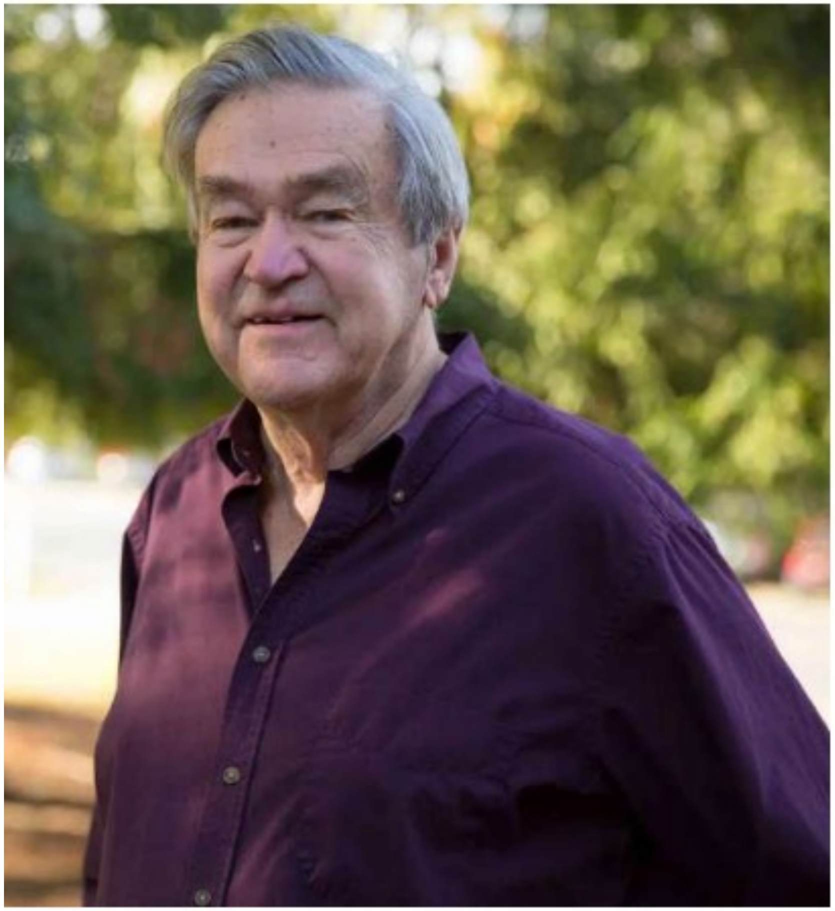
~20 GeV electrons on fixed proton target

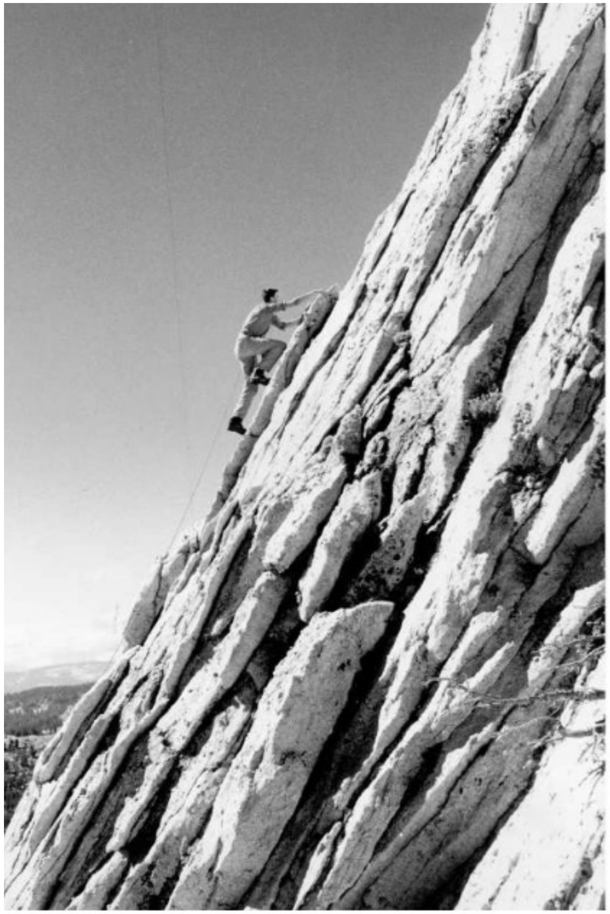
Absence of dependence of suitably expressed cross section on momentum transfer (wide-angle scattering) implies point-like constituents of target (quarks)

**Bjorken Scaling**

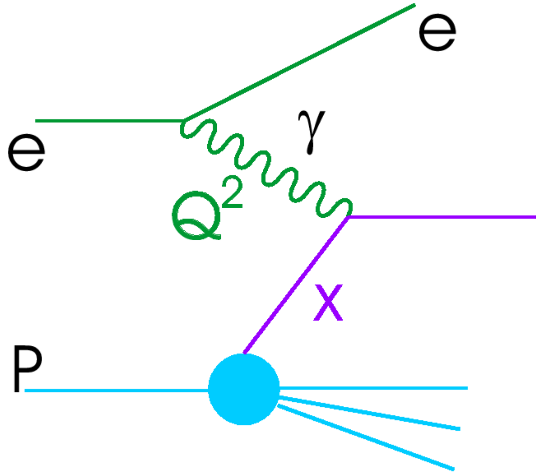


# James Bjorken (22 June 1934 – 6 Aug 2024)





# 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

# HERA, DESY, Hamburg

- The only ever collider of electron with proton beams:

$\sqrt{s_{ep}}$ ~ **300 GeV**

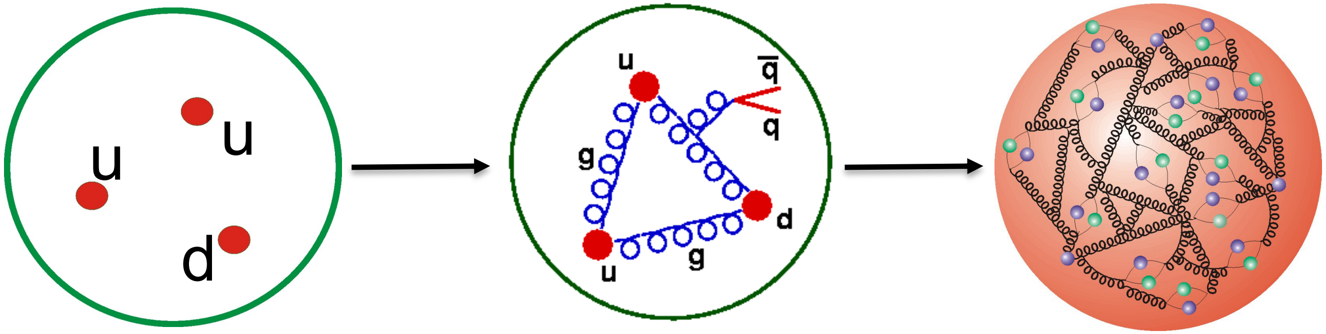
- Equivalent to **50 TeV** electrons on fixed target

… Resolved dimension

~ **$10^{-20}$ m**

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

(1992-2007)



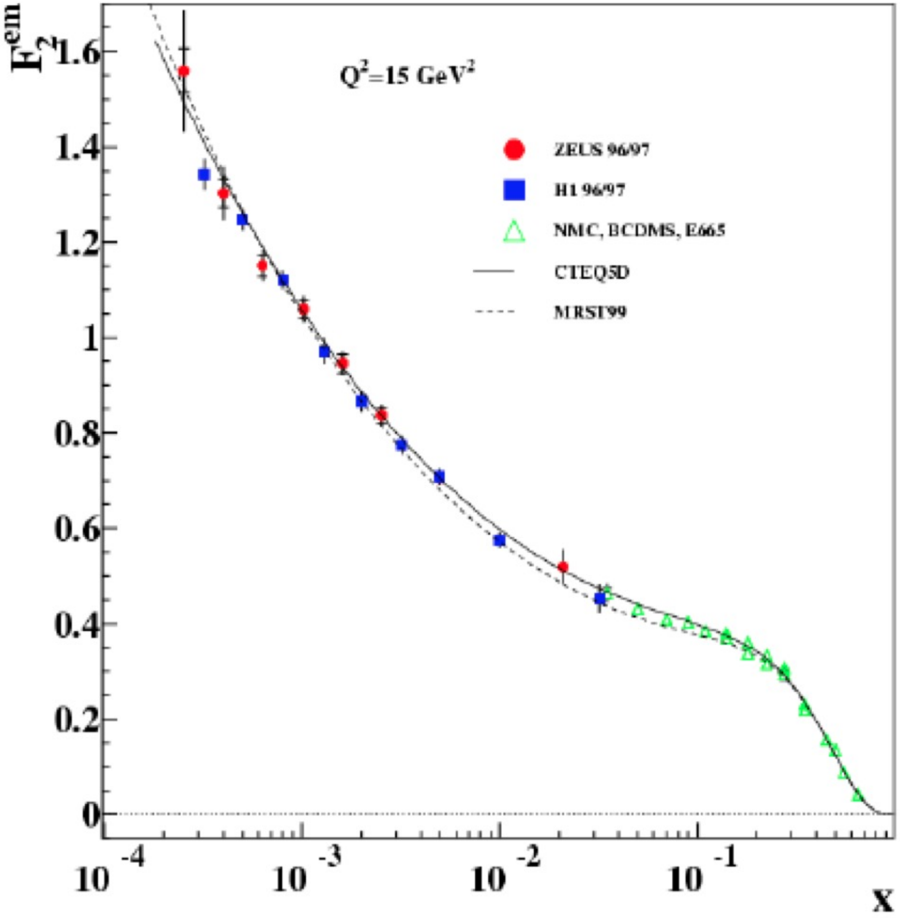
BUT …

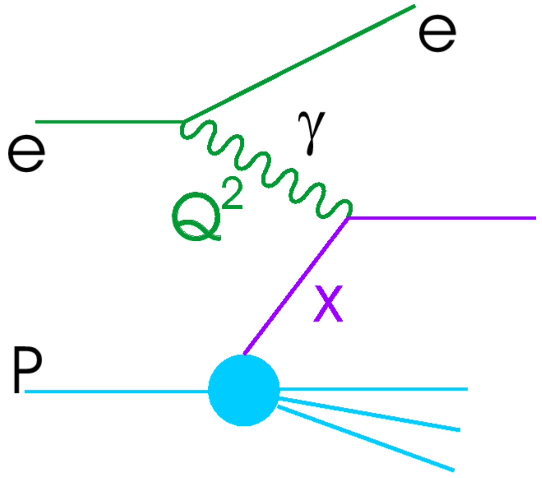
→ Only ~0.5 $fb^{-1}$ per experiment

→ No deuterons or nuclei

→ No polarised targets

# Example Inclusive Neutral Current Data from HERA / Previous Experiments

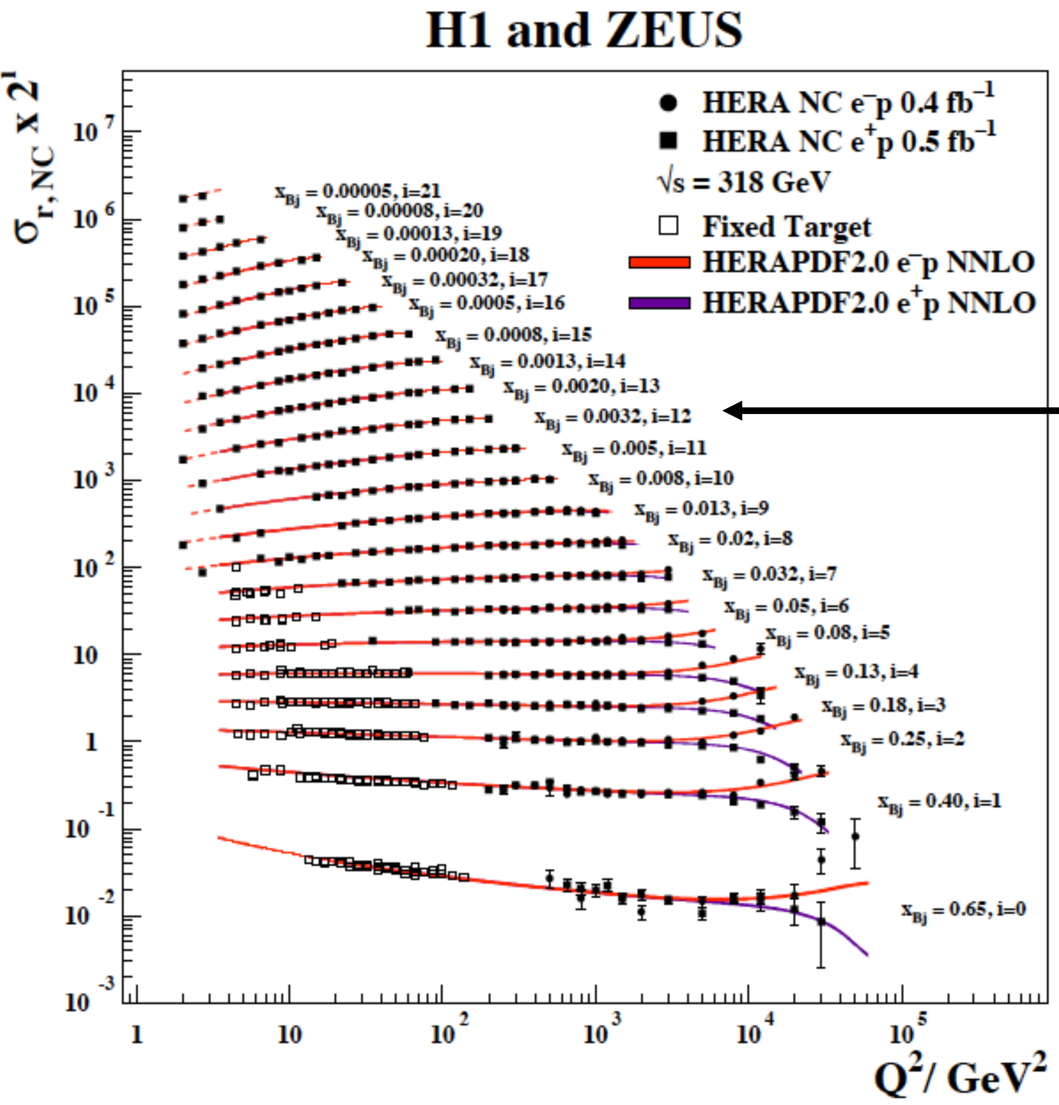




- Inclusive cross section measures (charge-squared weighted) sum of quark densities

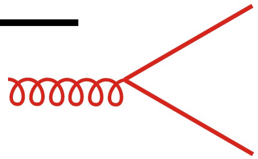
- Similar / better data at many other values of $Q^2$

# QCD Evolution and the Gluon Density



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

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

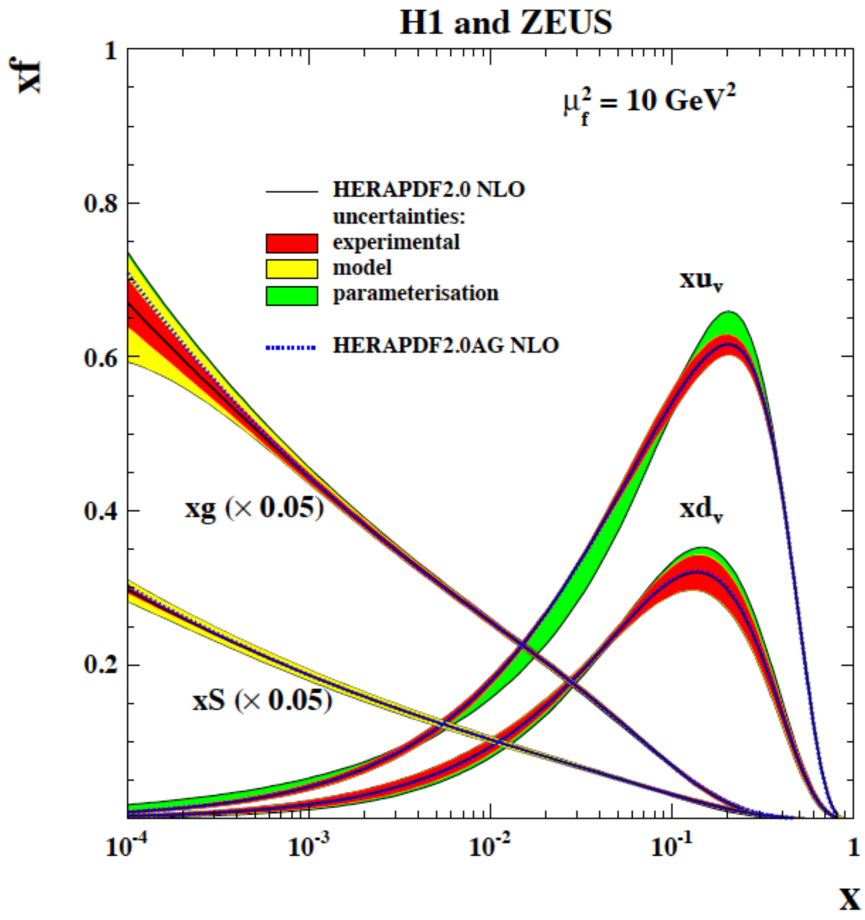


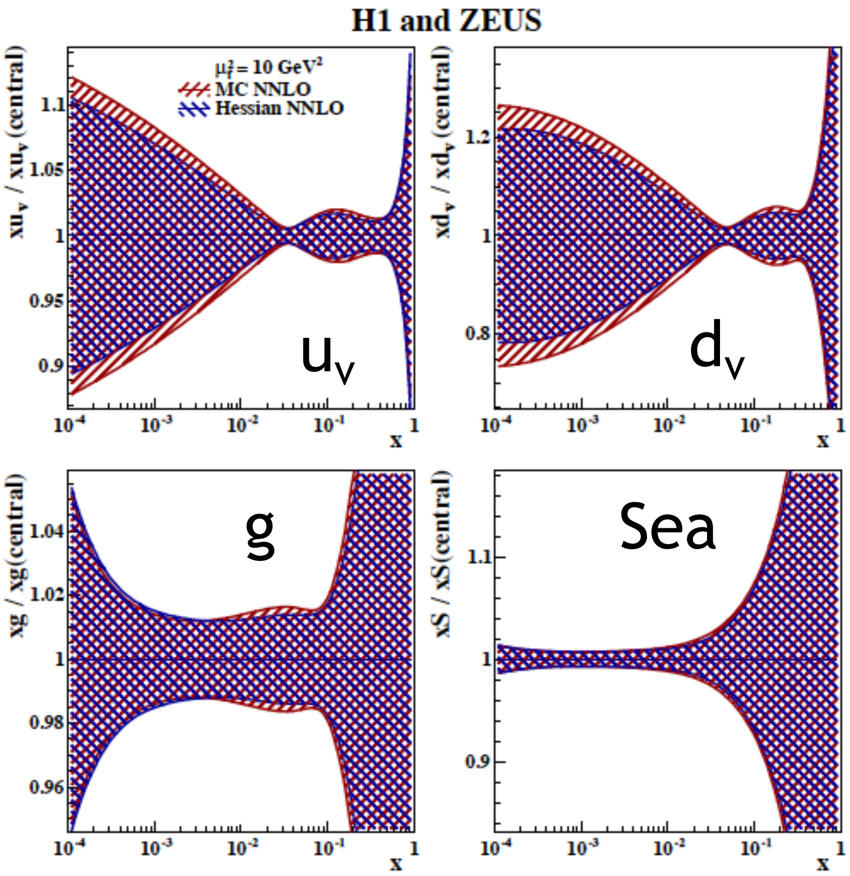
- DGLAP equations describe QCD evolution (to NNLO and approximate $N^3LO$ accuracy)

- 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

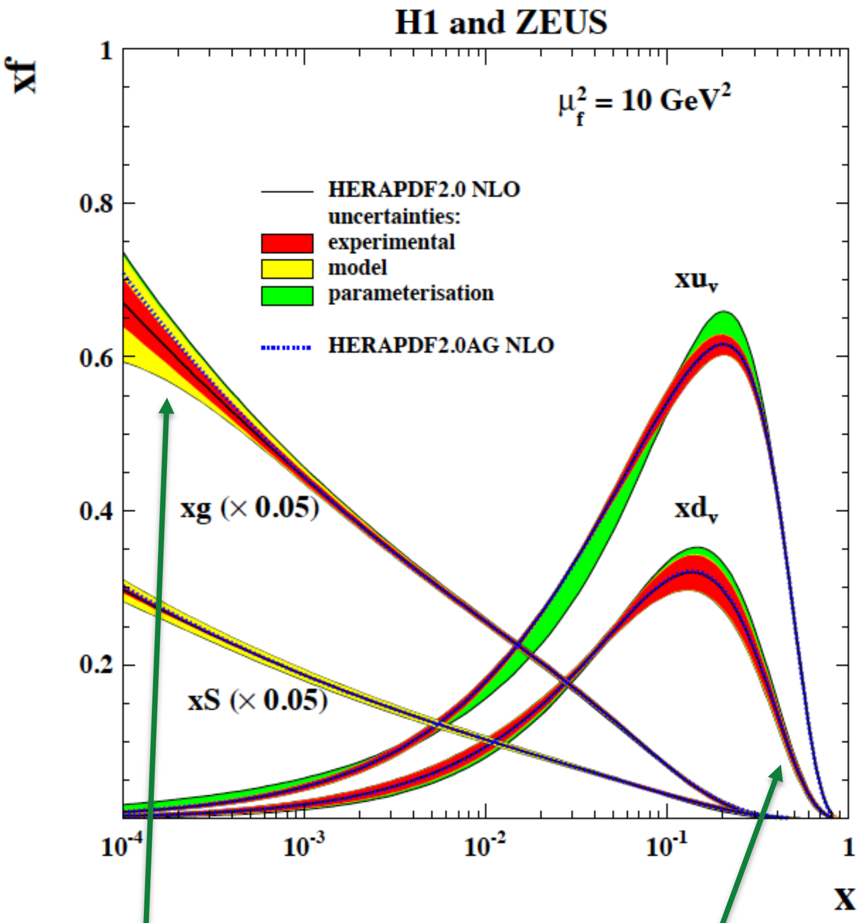
# Proton PDFs from HERA only (HERAPDF2.0)

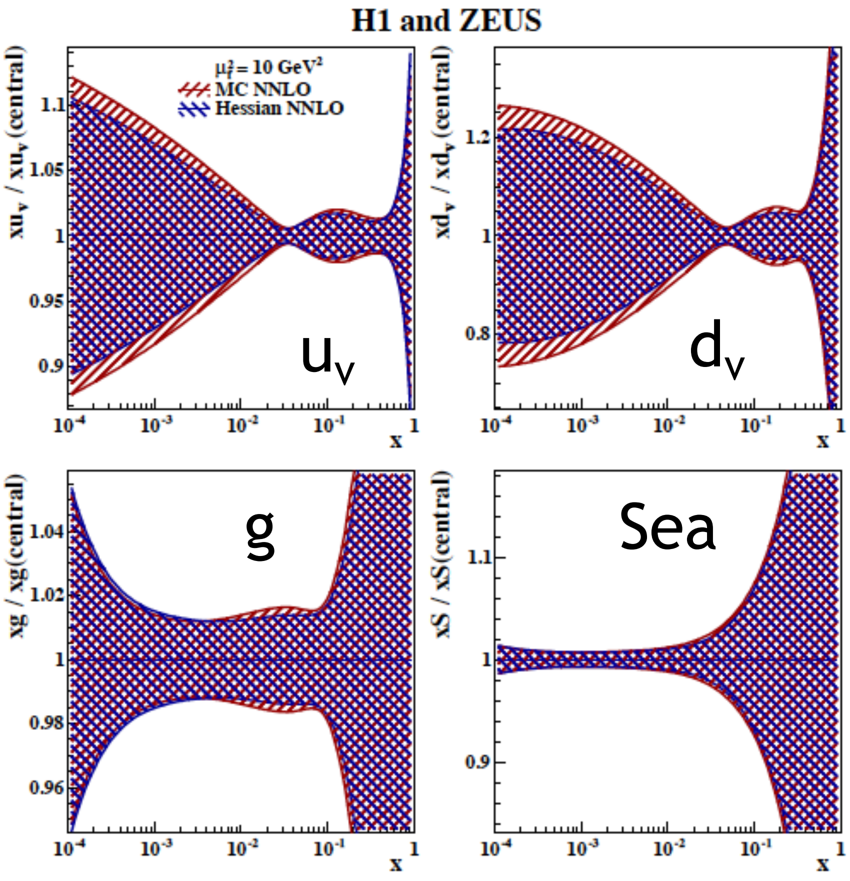




- At x ~ $10^{-2}$ : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=$10^{-3}$ (kinematic limit)
  - above x=$10^{-1}$ (limited lumi)

# Proton PDFs from HERA only (HERAPDF2.0)



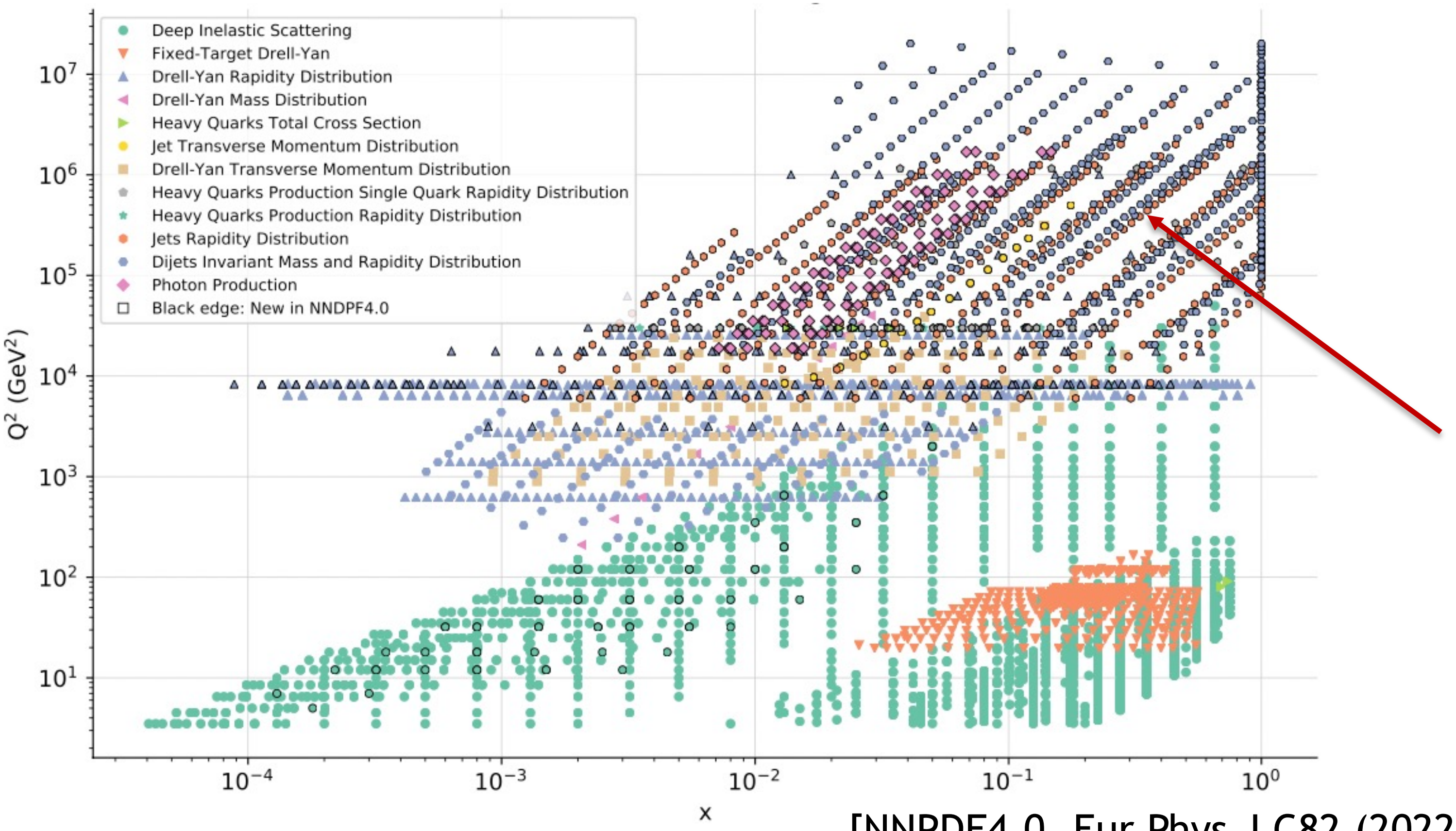


Strong interaction dragons?

Input to energy frontier discovery?

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

# Adding more data: Global PDF fits



Lots of PDF-sensitive observables at LHC with sensitivity to high x partons

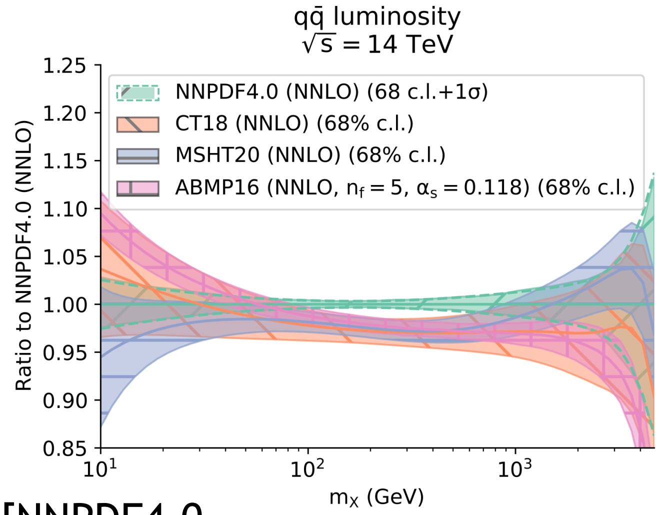
[NNPDF4.0, Eur Phys J C82 (2022) 428]

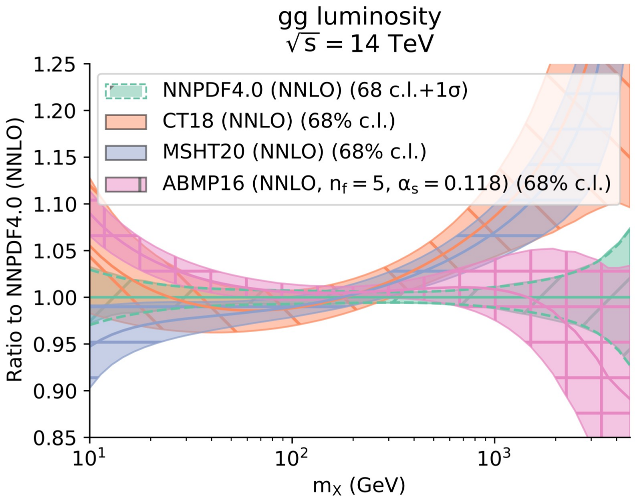
Including LHC data brings:
Advantages: improve precision at mid and high x, exploit all available inputs

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

# Global Fits and LHC Parton Luminosities

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

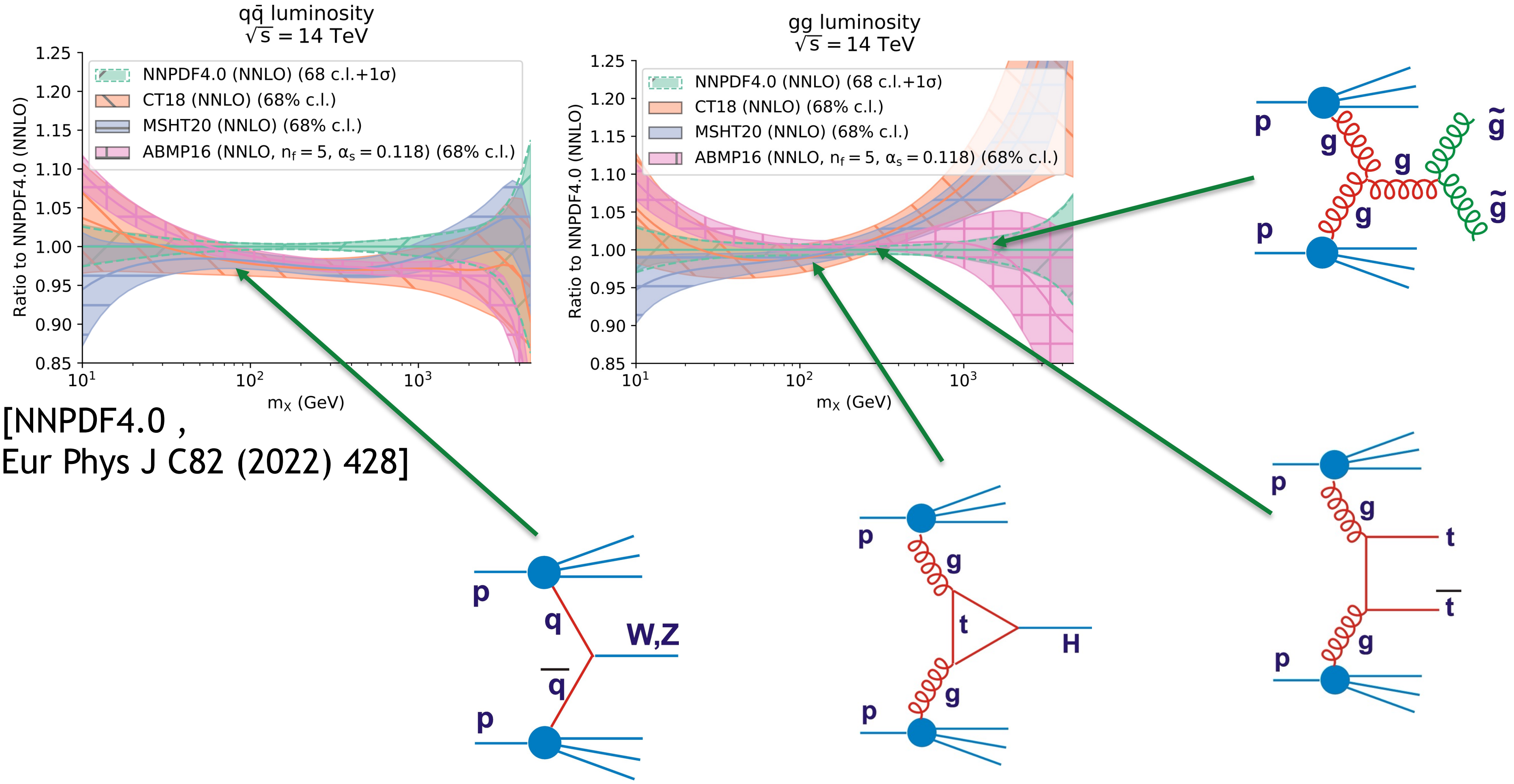




[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]

# Global Fits and LHC Parton Luminosities

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

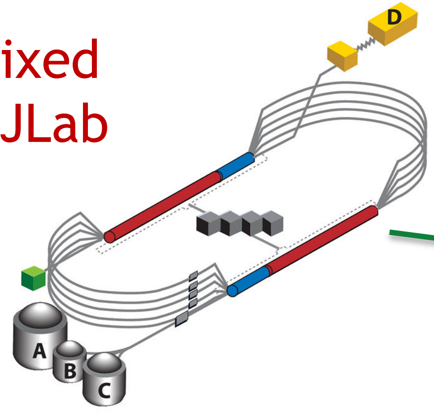


[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]

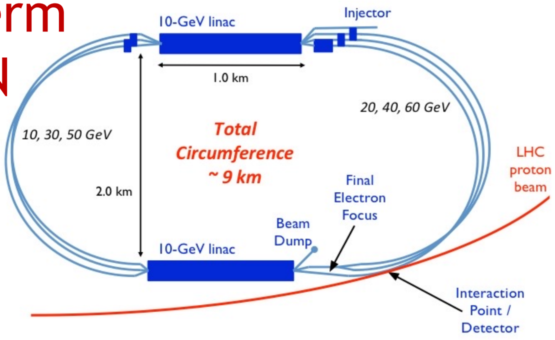
Immense recent progress, but still some tensions between data sets and fitting methodologies

# Current and Future ep Colliders

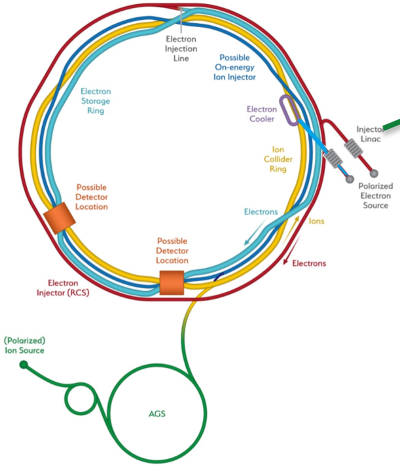
Ongoing fixed target @ JLab

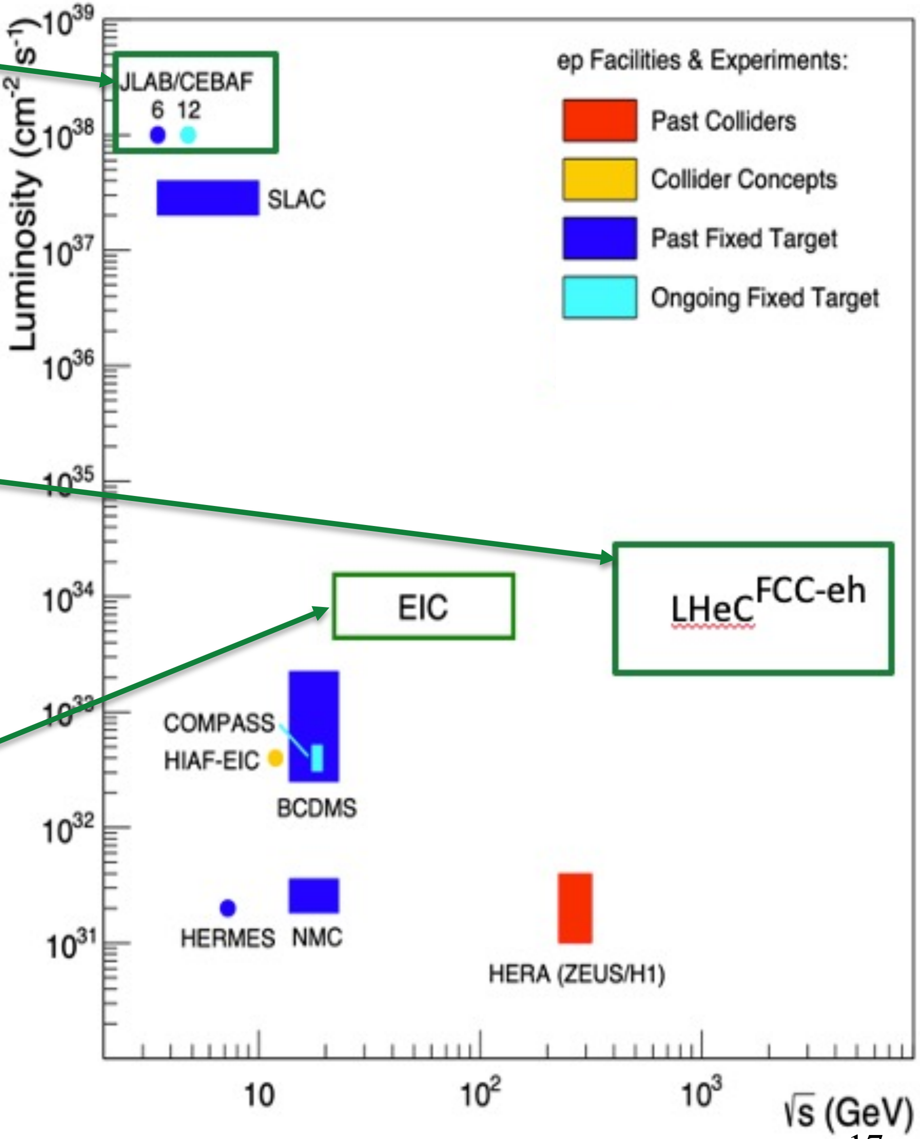


Longer-term @ CERN

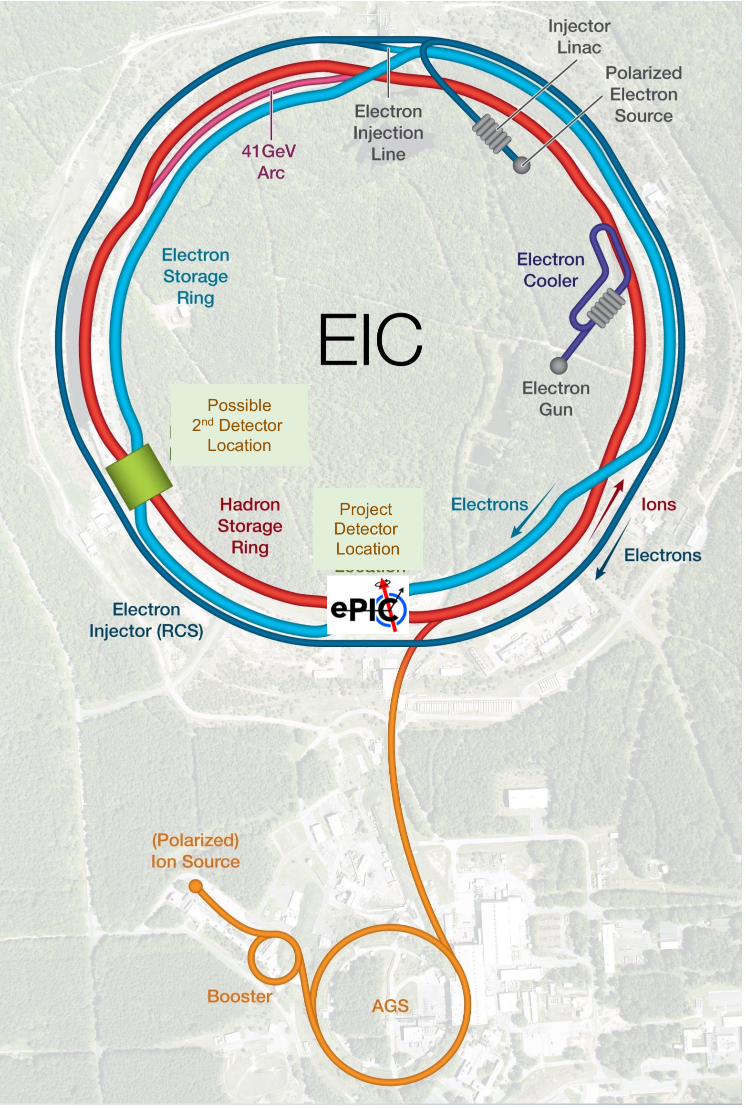


On-target for early 2030s @ BNL





# The Electron-Ion Collider (BNL)



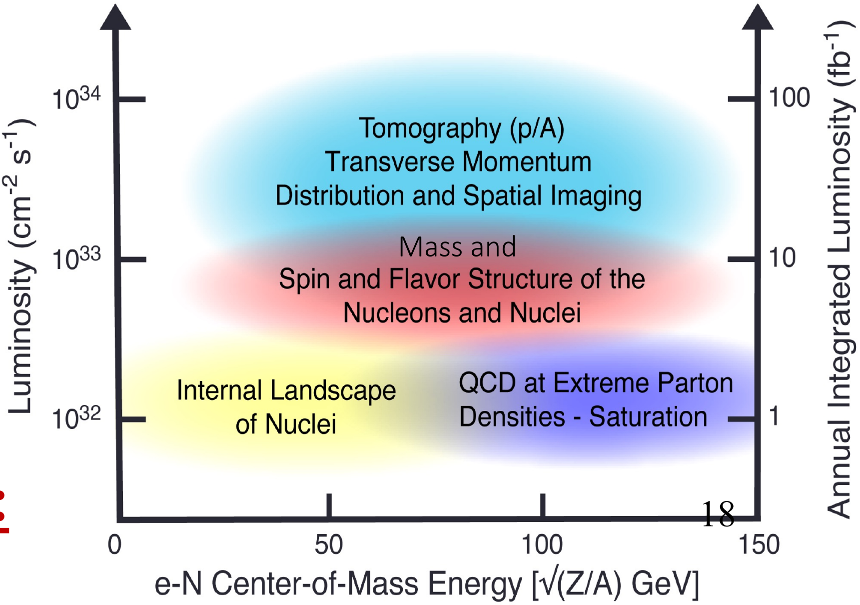
## New electron ring, to collide with RHIC p, A

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

## World's first …

- High lumi ep Collider **(~ $10^{34}$ cm$^{-2}$ s$^{-1}$)**
- Double-polarised DIS collider **(~70% for leptons and light hadrons)**
- eA collider **(Ions ranging from H to U)**

## Specifications driven by science goals:

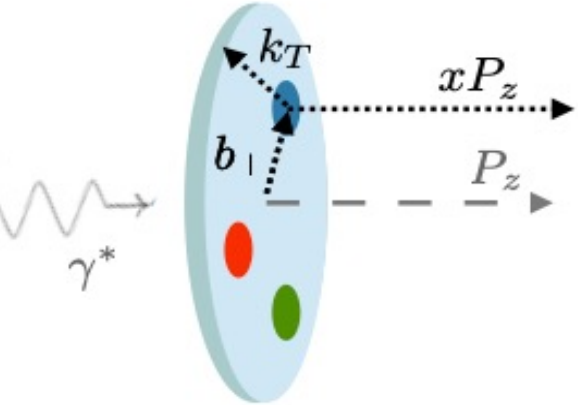


# Some questions to be addressed at EIC

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

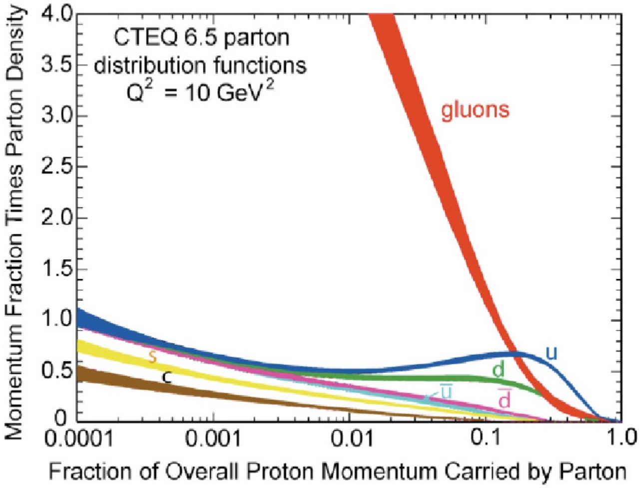
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

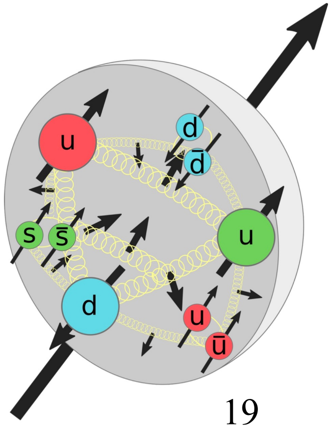
- What does the proton look like in 3D?



- How is proton spin generated?

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





# EIC Machine Design Parameters

<table>
<tr><th colspan="2">Double Ring Design Based on Existing RHIC Facilities</th></tr>
<tr><td><b>Hadron Storage Ring: 40, 100 - 275 GeV</b></td><td><b>Electron Storage Ring: 5 - 18 GeV</b></td></tr>
<tr><td>RHIC Ring and Injector Complex: p to Pb</td><td>9 MW Synchrotron Radiation</td></tr>
<tr><td>1A Beam Current</td><td>Large Beam Current - 2.5 A</td></tr>
<tr><td colspan="2">10 ns bunch spacing and 1160 bunches</td></tr>
<tr><td>Light ion beams (p, d, $^3$He) polarized (L,T) > 70%</td><td>Polarized electron beam > 70%</td></tr>
<tr><td>Nuclear beams: d to U</td><td><b>Electron Rapid Cycling Synchrotron</b></td></tr>
<tr><td>Requires Strong Cooling: new concept →CEC</td><td>Spin Transparent Due to High Periodicity</td></tr>
<tr><td colspan="2"><b>One High Luminosity Interaction Region(s)</b></td></tr>
<tr><td colspan="2">25 mrad Crossing Angle with Crab Cavities</td></tr>
</table>

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

- Synchrotron load management
- ‘Parasitic’ next bunch interactions

→ Significant crossing angle → Crab cavities …

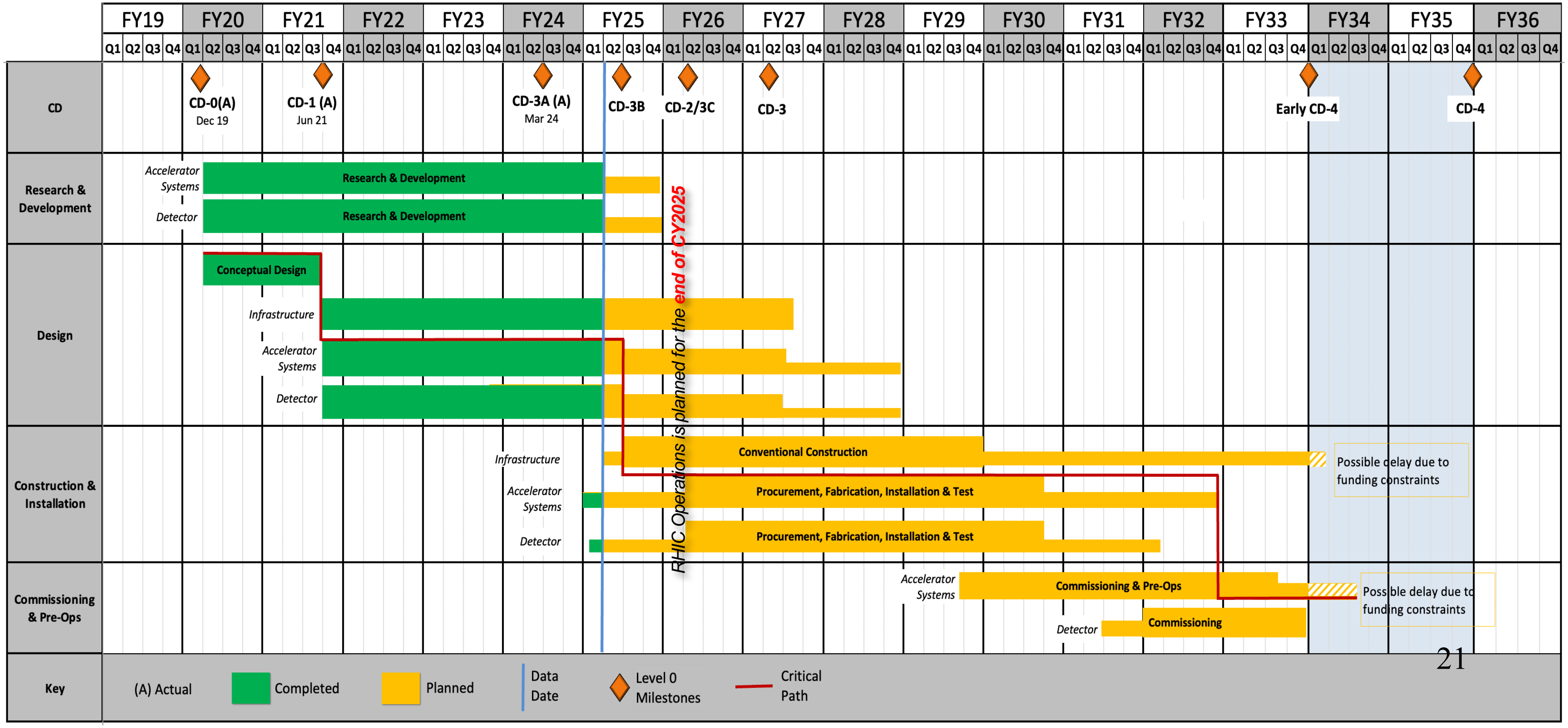
# Status / Timeline

- $2.5Bn project (US DoE funds accelerator + most ofone detector)

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

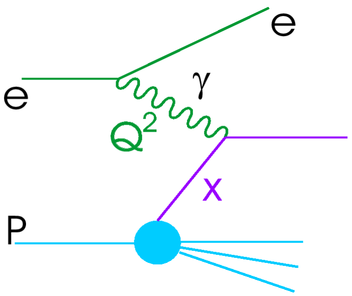
| | |
|---|---|
| CD-0 (Mission need) | Dec 2019 |
| CD-1 (Cost range) | June 2021 |
| CD-3A (Start construction) | April 2024 |
| CD-3B | Under review |
| CD-2 (Performance baseline) | Under review |
| CD-4 (Operations / completion) | 2034-5 |

Technical Design Report: end 2025



# Observables / Detector Implications

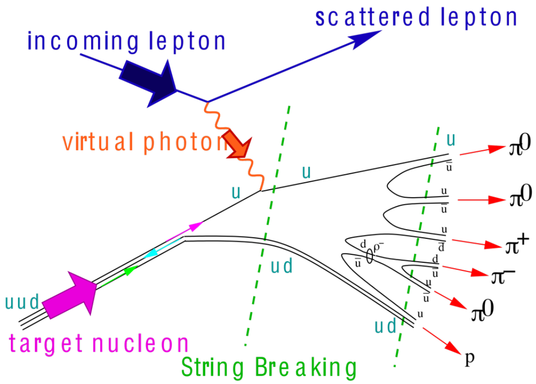
## Inclusive



- Traditional DIS, following on from fixed target experiments and HERA → Longitudinal structure

… high acceptance, high performance electron identification and reconstruction

## Semi-Inclusive



- Single particle, heavy flavour & jet spectra

→ $p_T$ introduces transverse degrees of freedom

- Quark-flavour-identified DIS

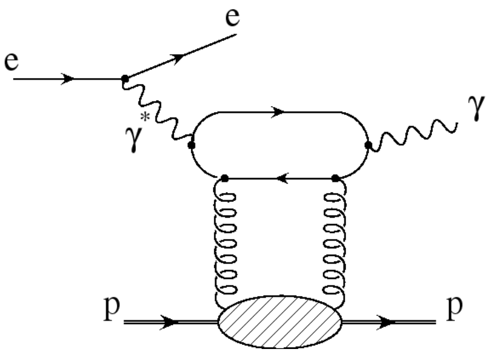
→ Separation of u,d,s,c,b and antiquarks

… tracking and hadronic calorimetry

… heavy flavour identification from vertexing

… light flavours from dedicated PID detectors

## Exclusive / Diffractive



- Processes with final state 'intact' protons

→ Correlations in space or momentum between pairs of partons

… efficient proton tagging over wide acceptance range

… high luminosity

# A Detector for the EIC

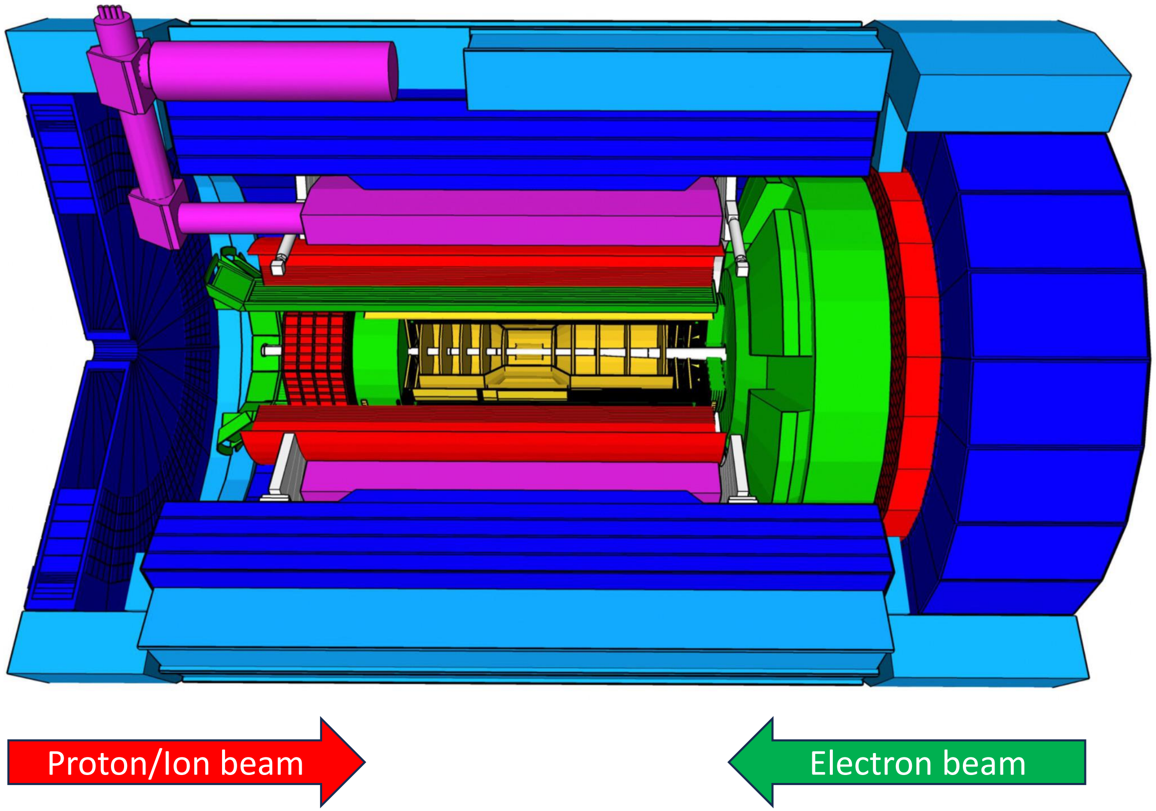
**Magnet**
- New 1.7 T SC solenoid, 2.8 m bore diameter

**Tracking**
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

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

**EM Calorimetry**
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

**Hadron calorimetry**
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



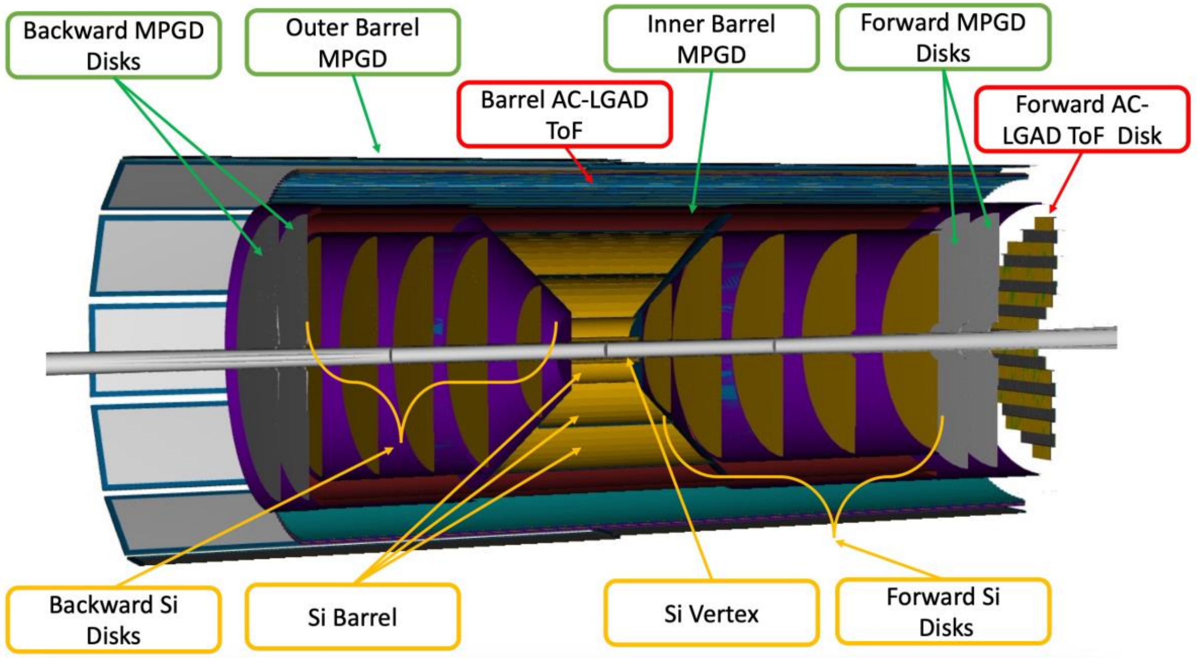
- 9m long x 5m wide
- Hermetic (central detector $-4 < \eta < 4$)
- Extensive beamline instrumentation not shown (see later)

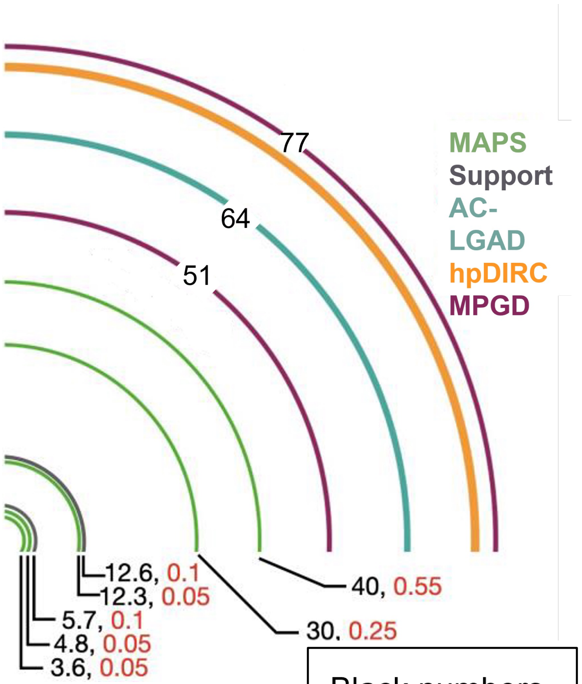
- Much lower radiation fluxes than LHC widens technology options

# Tracking Detectors

Primarily based on MAPS silicon detectors (65nm technology)

- Leaning heavily on ALICE ITS3
- Stitched wafer-scale sensors, thinned and bent around beampipe
  → Very low material budget ($0.05X_0$ per layer for inner layers)
- 20x20μm pixels
- 5 barrel layers + 5 disks (total 8.5m$^2$ silicon)





Black numbers are radii in cm

Red numbers are material in % X0

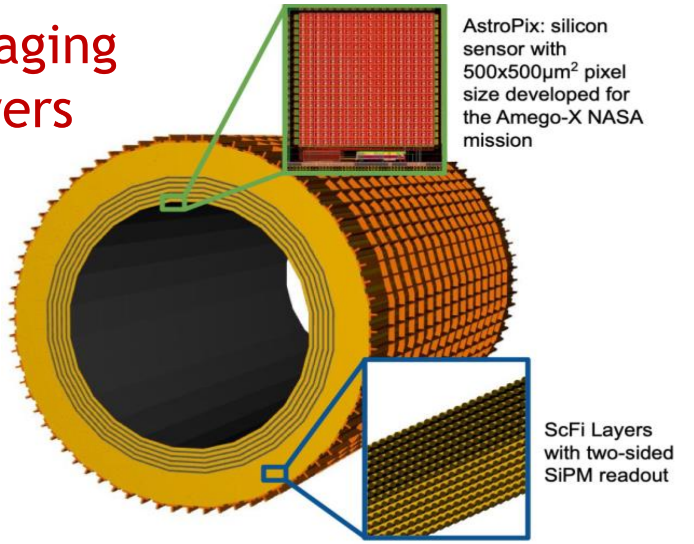
LGAD layers provide fast timing (~20ns)

Outer gaseous detectors add additional hit points for track reconstruction

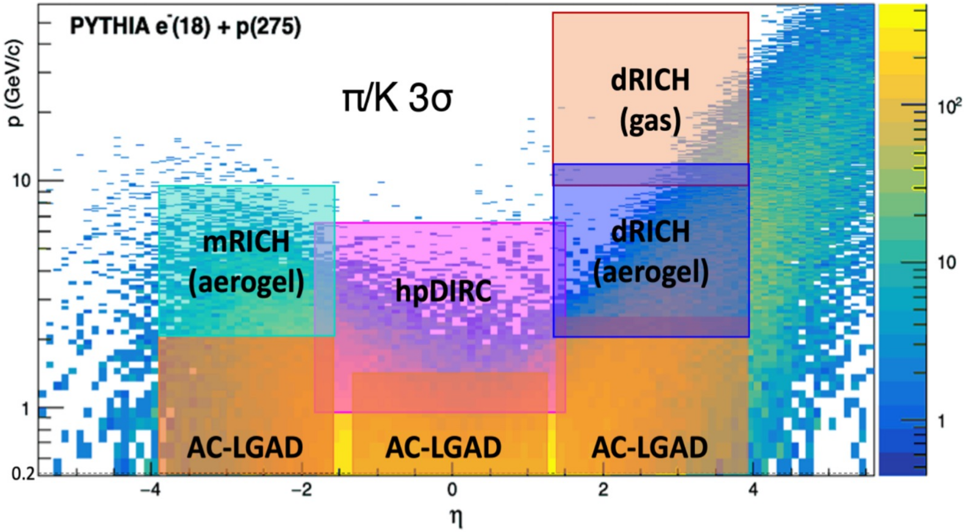
# More Novel Detector Components

## Imaging eCAL

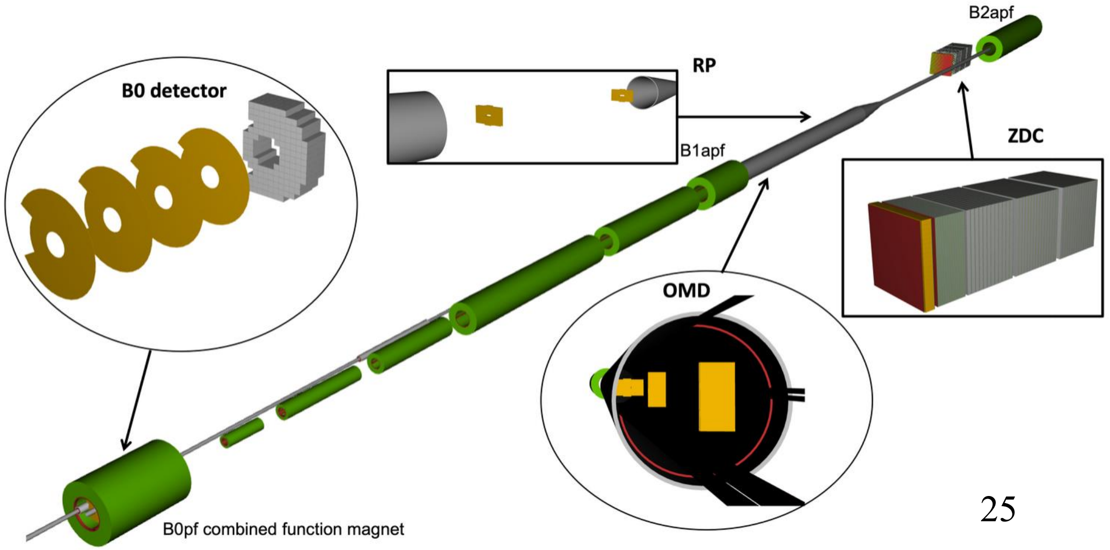
Pb/SciFi sampling + AstroPix imaging layers



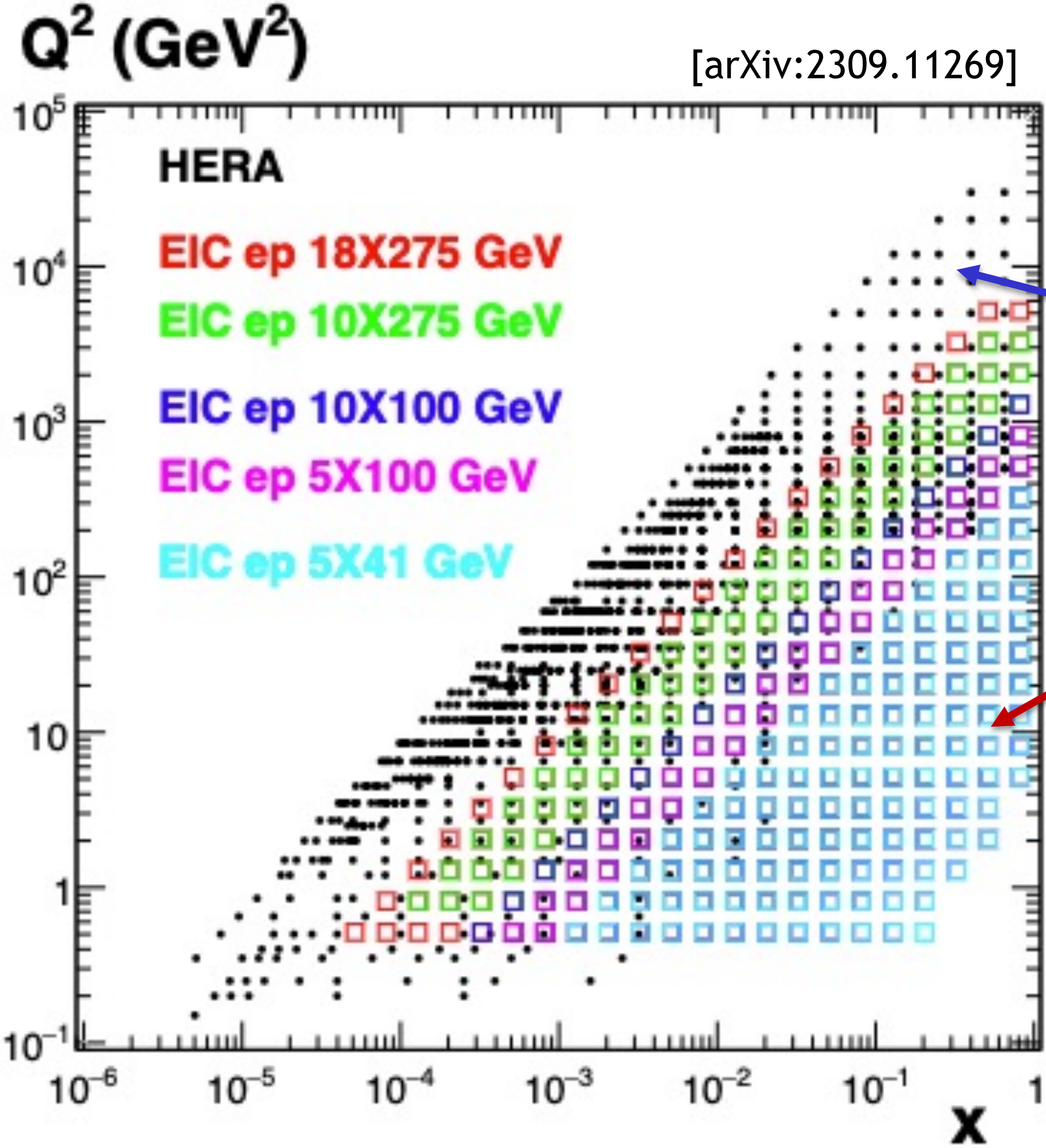
## Comprehensive Particle ID



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



# Inclusive EIC Simulated Data



[arXiv:2309.11269]

HERA data have limited high x sensitivity due to $1/Q^4$ factor in cross section and kinematic $x$ / $Q^2$ correlation

EIC data fills in large x, modest $Q^2$ region with high precision

Estimated annual lumi

| e-beam E | p-beam E | $\sqrt{s}$ (GeV) | inte. Lumi. (fb$^{-1}$) |
|---|---|---|---|
| 18 | 275 | 140 | 15.4 |
| 10 | 275 | 105 | 100.0 |
| 10 | 100 | 63 | 79.0 |
| 5 | 100 | 45 | 61.0 |
| 5 | 41 | 29 | 4.4 |

# EIC Impact on Proton Parton Densities

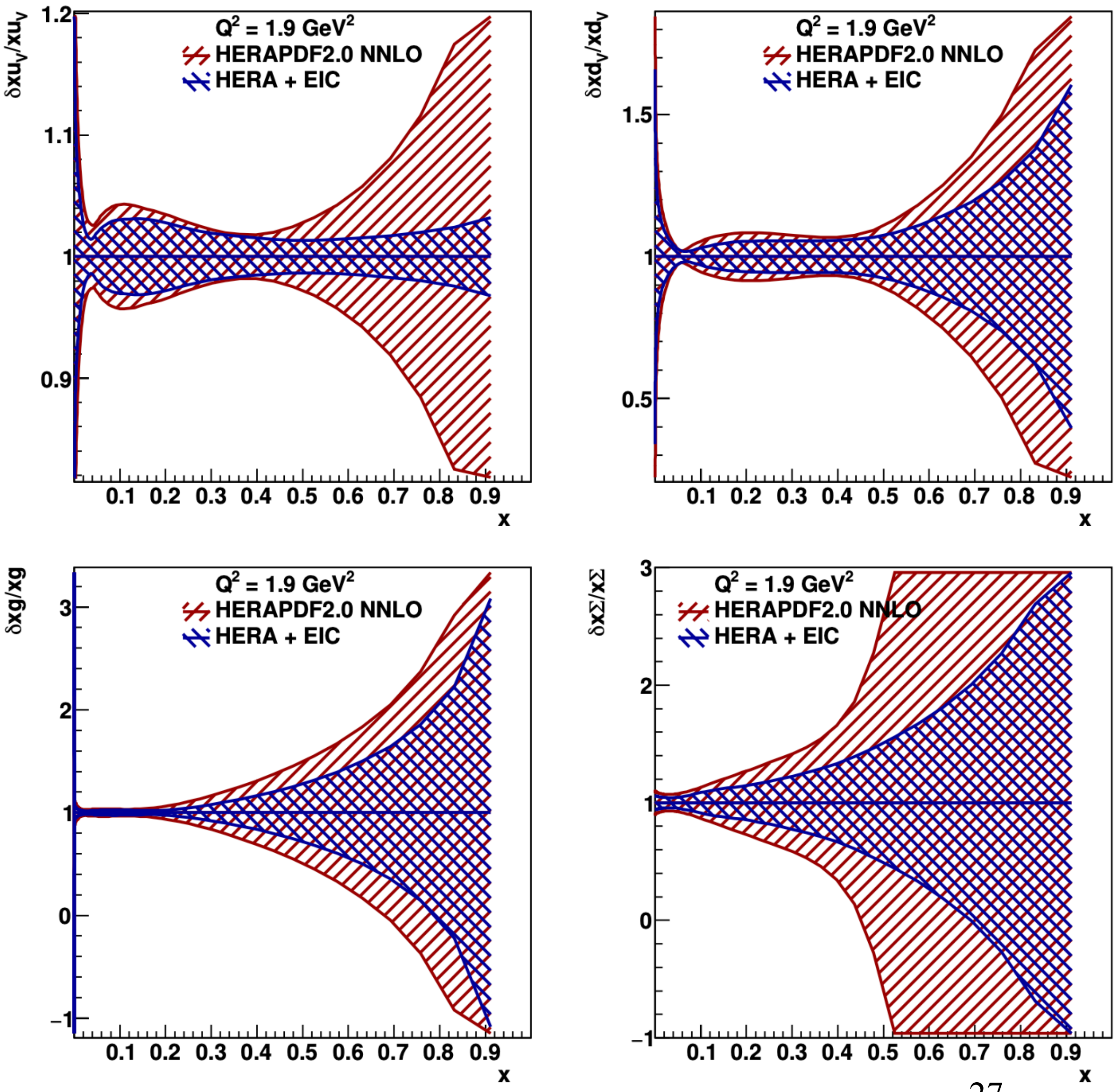
Fractional total uncertainties with / without simulated EIC data added to HERA (lin-x scale)

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

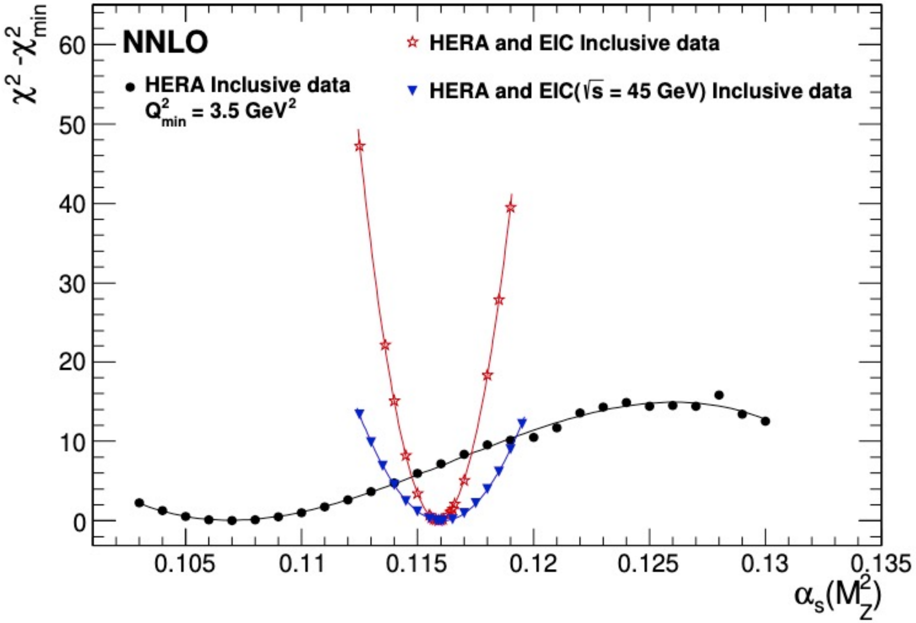
Up quarks improve relative to global fits including LHC (not shown)

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

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



# Taking $\alpha_s$ as an additional free parameter



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

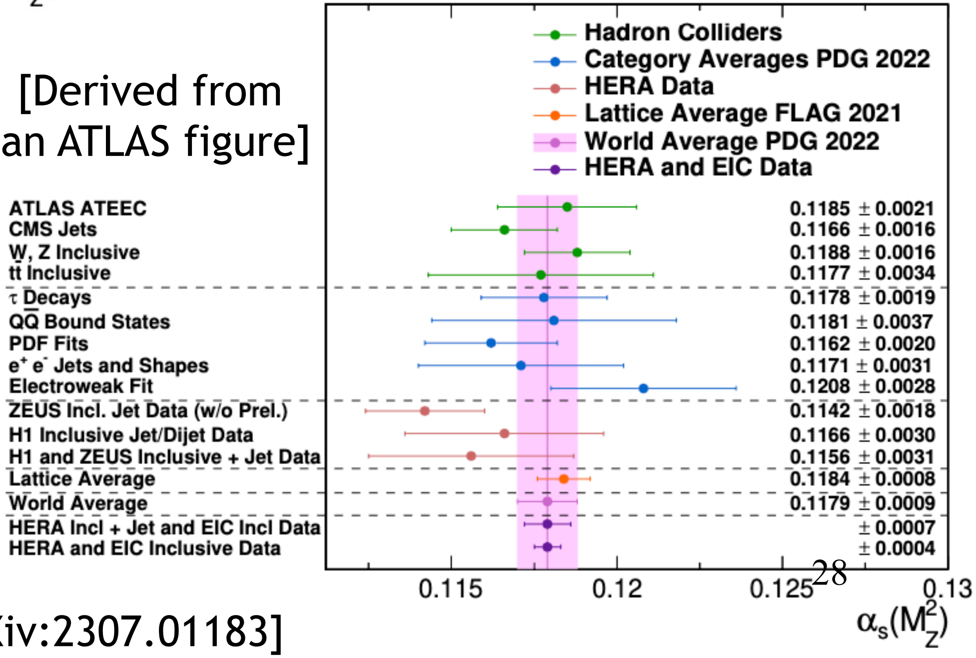
- Adding EIC simulated data has a remarkable impact

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

Adding EIC (<u>precision high x</u>) 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]



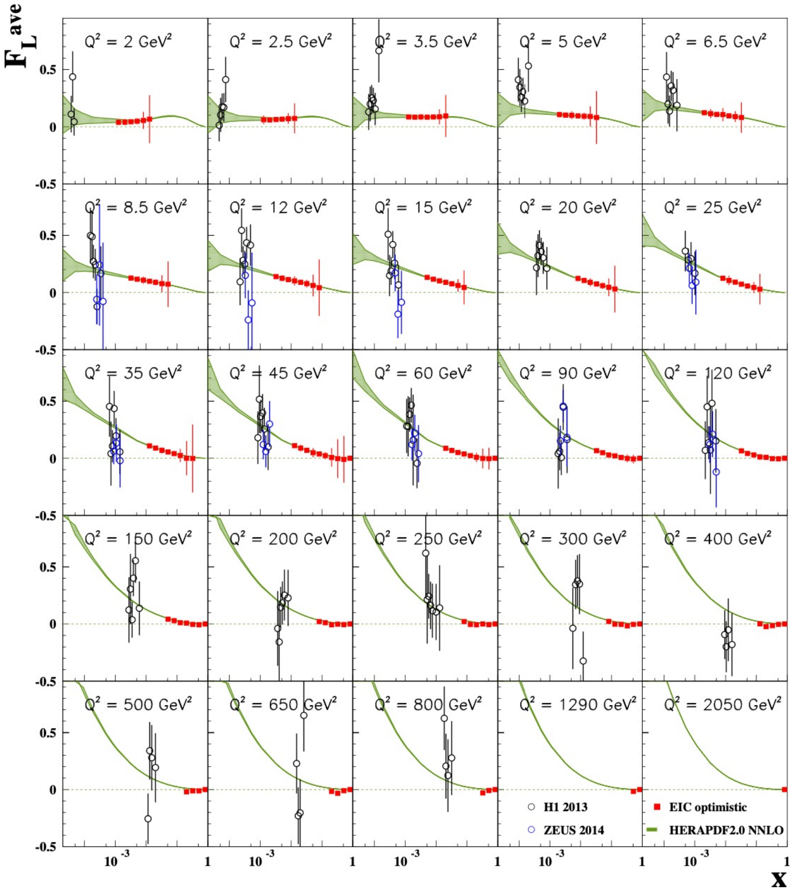
[arXiv:2307.01183]

# Longitudinal Structure Function

- Measuring DIS cross section at multiple $\sqrt{s}$ varies y at fixed x and $Q^2$ → access to $F_L$

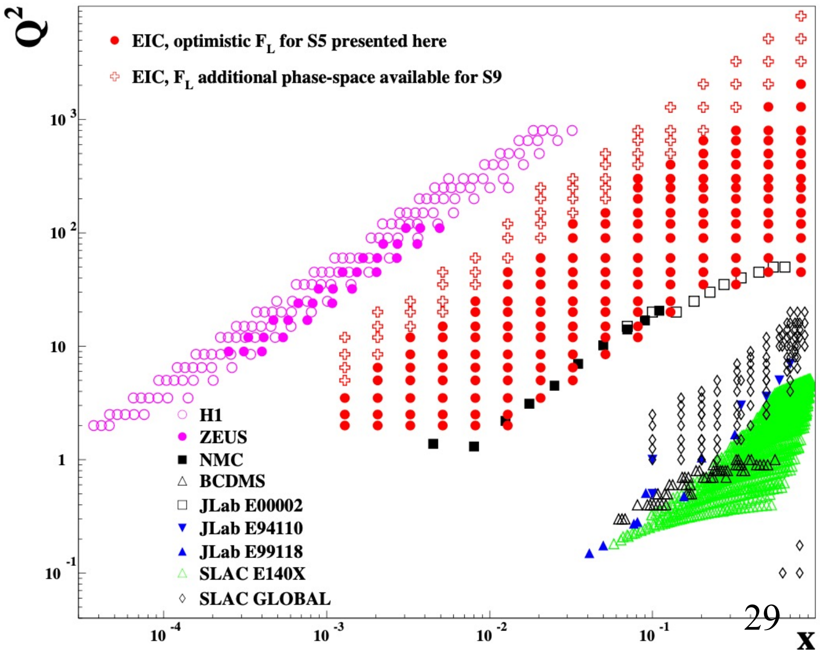
$$\sigma_r(x,Q^2,y) = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)$$

- Special observable: sensitivity to gluon density through $F_L \sim \alpha_s g(x)$



[arXiv:2412.16123]

- Multiple EIC beam energies lead to Precision measurements in region Complementary to HERA & Fixed target



# EIC Impact on Nuclear Parton Densities

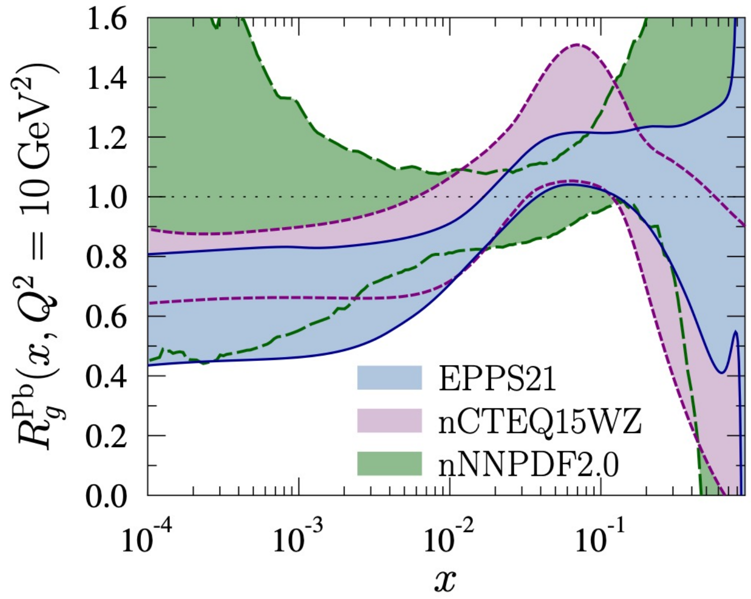
- Nuclei enhance density of partons
  ($\sim A^{1/3}$ factor at fixed x, $Q^2$)

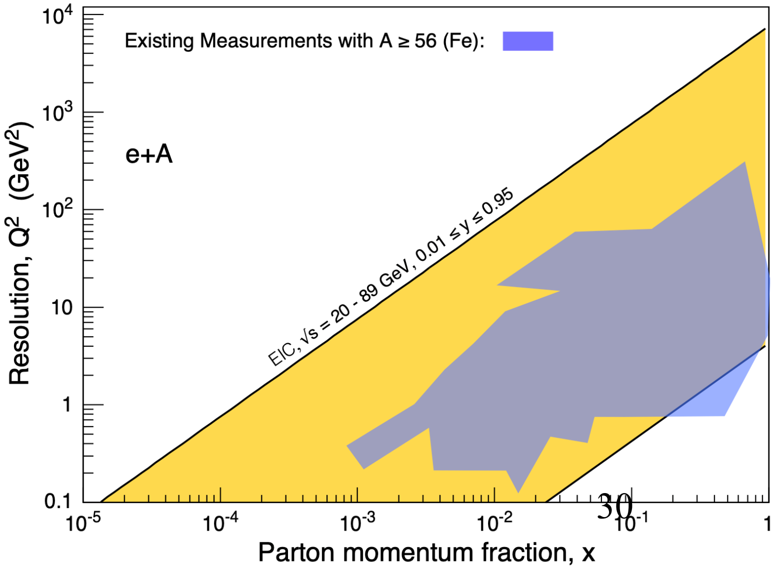
- Results usually shown in terms of nuclear modification ratios: change relative to simple scaling of (isospin-corrected) proton

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

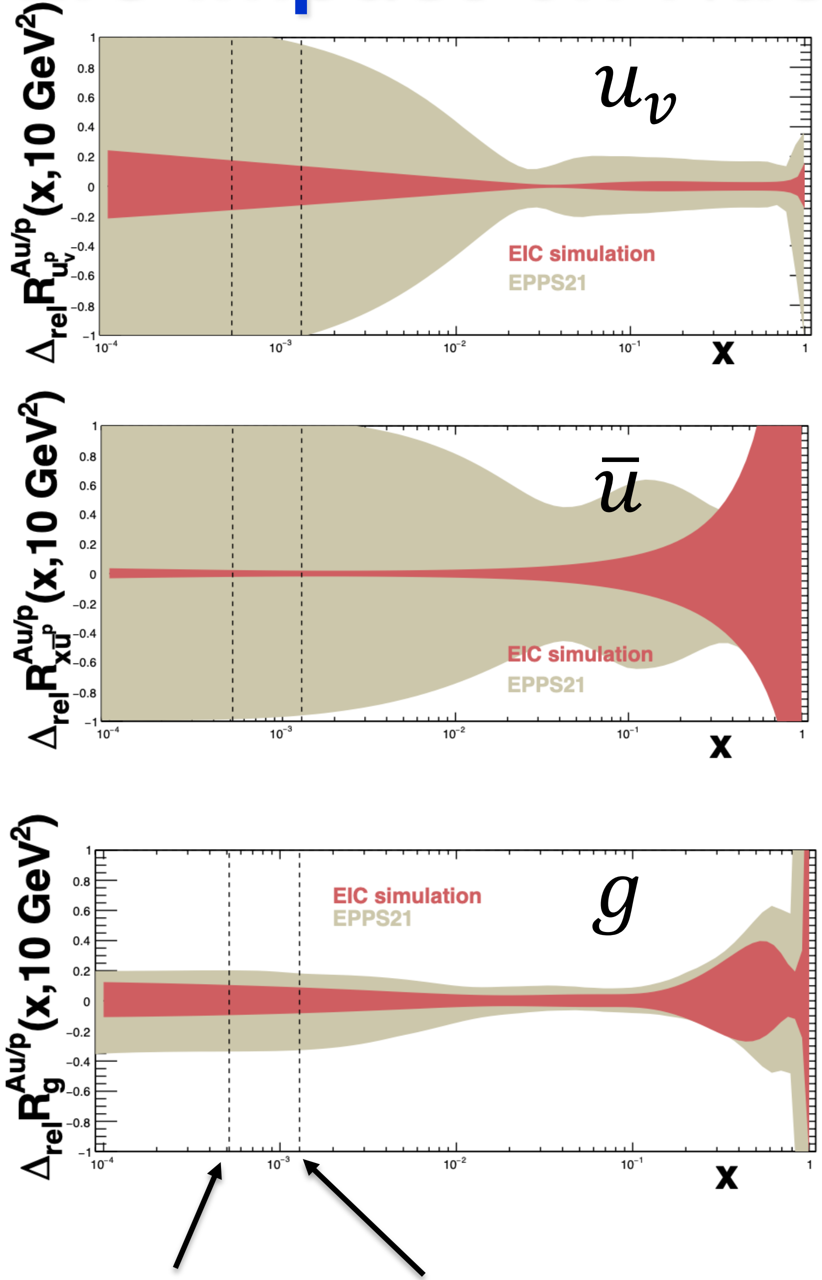
… poorly known, especially for gluon and at low x

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





# EIC Impact on Nuclear Parton Densities



EIC eA data limit

EPPS21 data limit

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

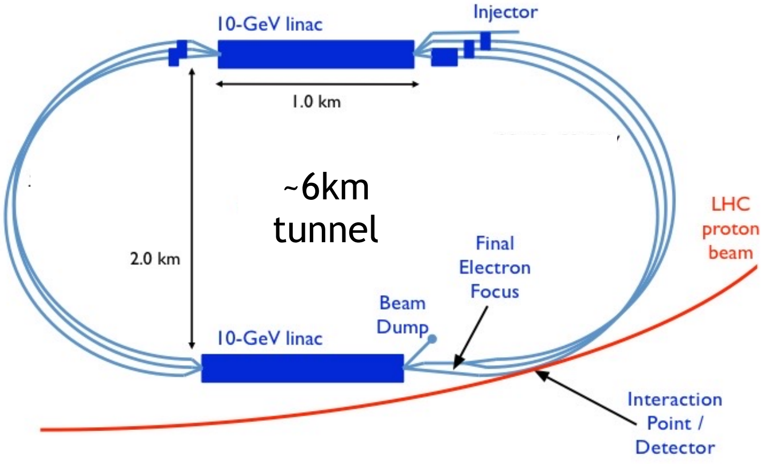
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

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

→ Factor ~ 2 improvement at x~0.1

→ Very substantial improvement in newly accessed low x region

# LHeC and FCC-eh



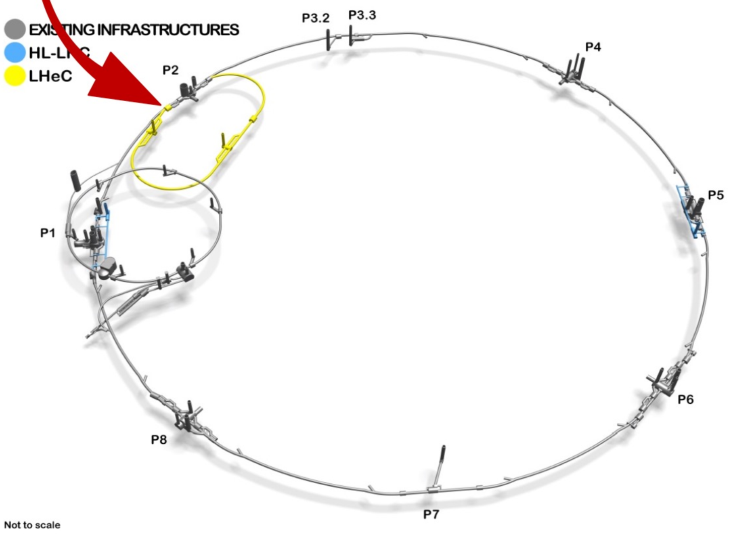
- Recirculating Energy-Recovery Linac (ERL) colliding with LHC (or FCC) hadrons at CERN

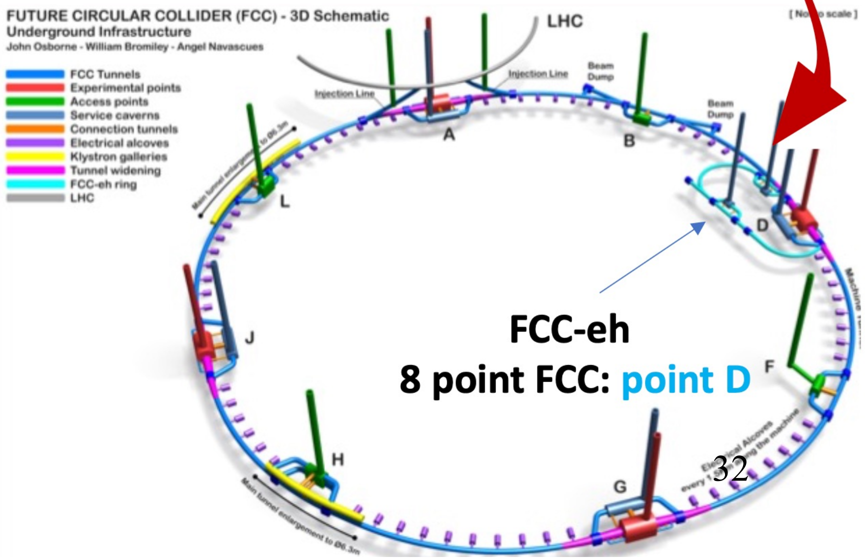
- 'Sustainable' acceleration: ~100 MW (similar to LHC today)

- 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 ($\gtrsim$ 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*





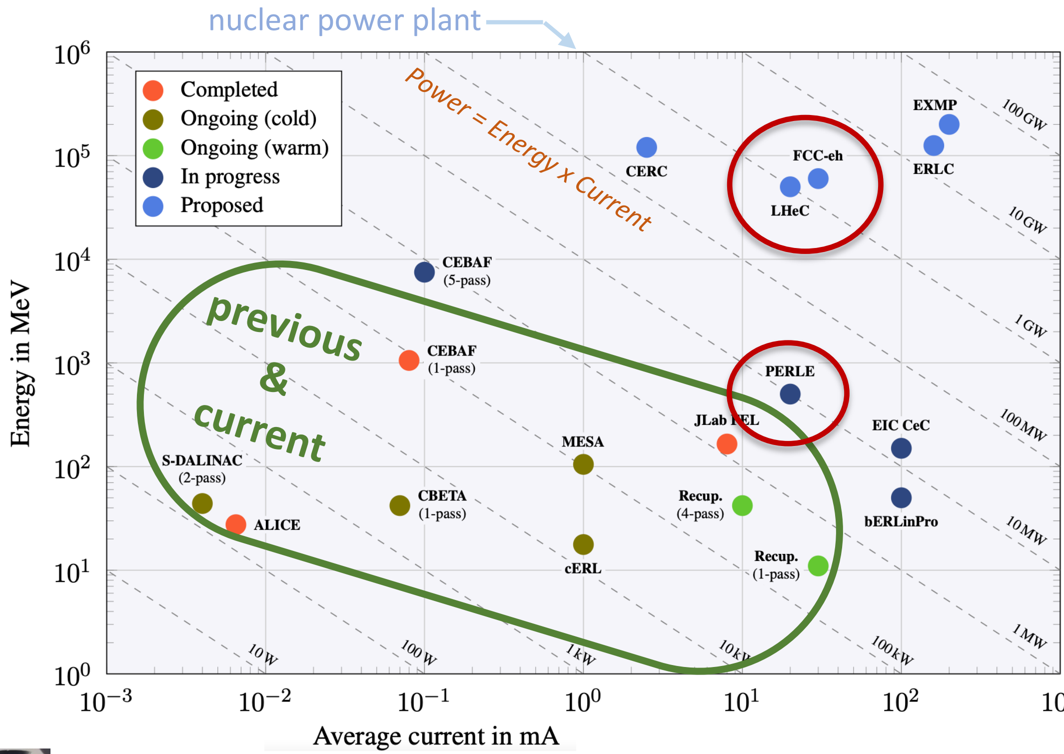
FCC-eh
**8 point FCC: point D**

# Energy Recovery Linacs

- Demonstrating ERL scalability is critical path

- Prototype (**<u>PERLE @ IJCLab / Orsay</u>**) implementation started

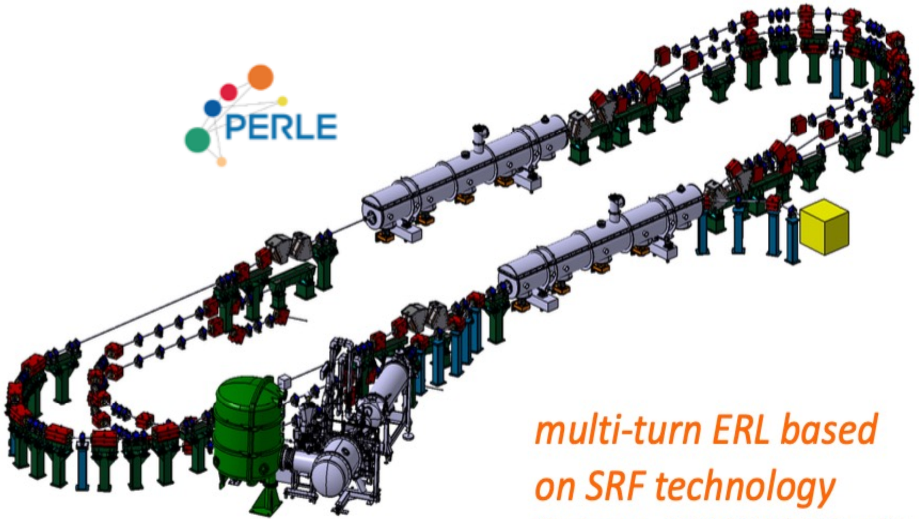
- First stage (one turn) by 2028.



HV tanks

Electron DC-gun

Photo-cathode

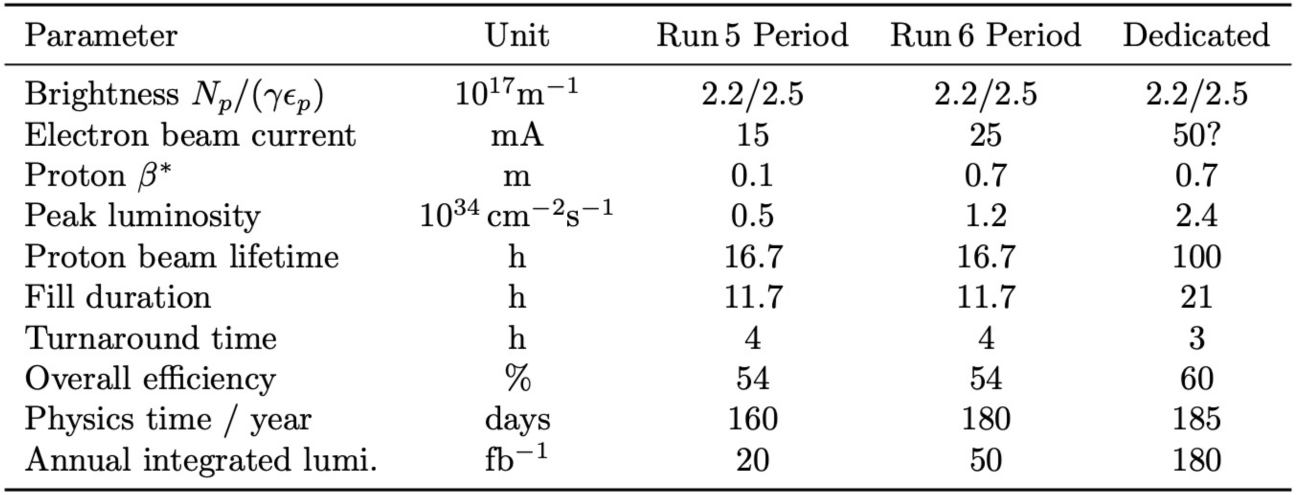


CDR: *J.Phys.G* 45 (2018) 6, 065003

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

# 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 $N_p/(\gamma\epsilon_p)$ | $10^{17}\text{m}^{-1}$ | 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 | $10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ | 0.5 | 1.2 | 2.4 |
| Proton beam lifetime | h | 16.7 | 16.7 | 100 |
| Fill duration | h | 11.7 | 11.7 | 21 |
| Turnaround time | h | 4 | 4 | 3 |
| Overall efficiency | % | 54 | 54 | 60 |
| Physics time / year | days | 160 | 180 | 185 |
| Annual integrated lumi. | $\text{fb}^{-1}$ | 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 $\text{fb}^{-1}$ initial dataset

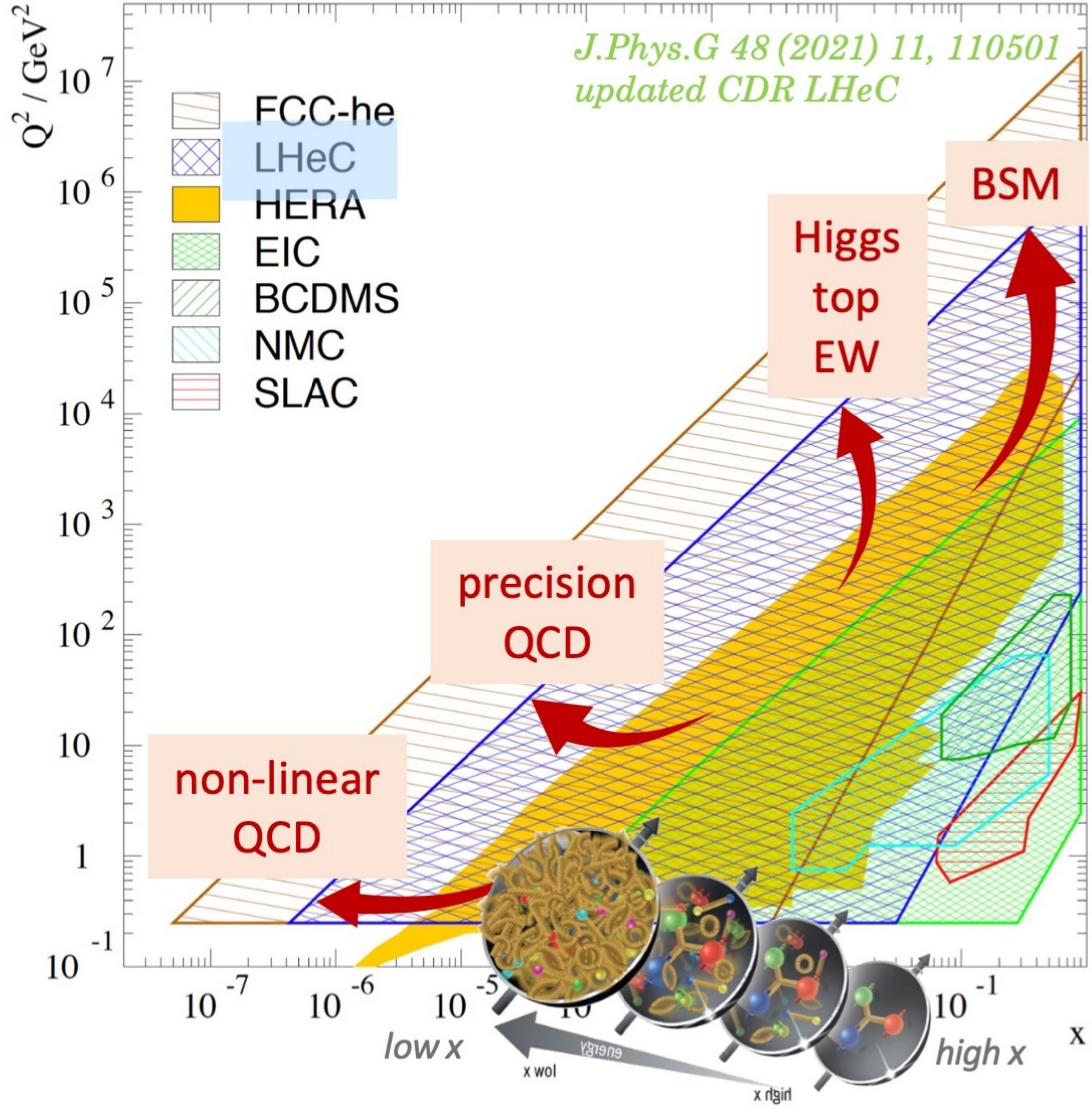
… integrated lumi of 50 fb-1 per year at Run 6 → few 100 $\text{fb}^{-1}$ total @ HL-LHC

Running in standalone ep mode:

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

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

# 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**

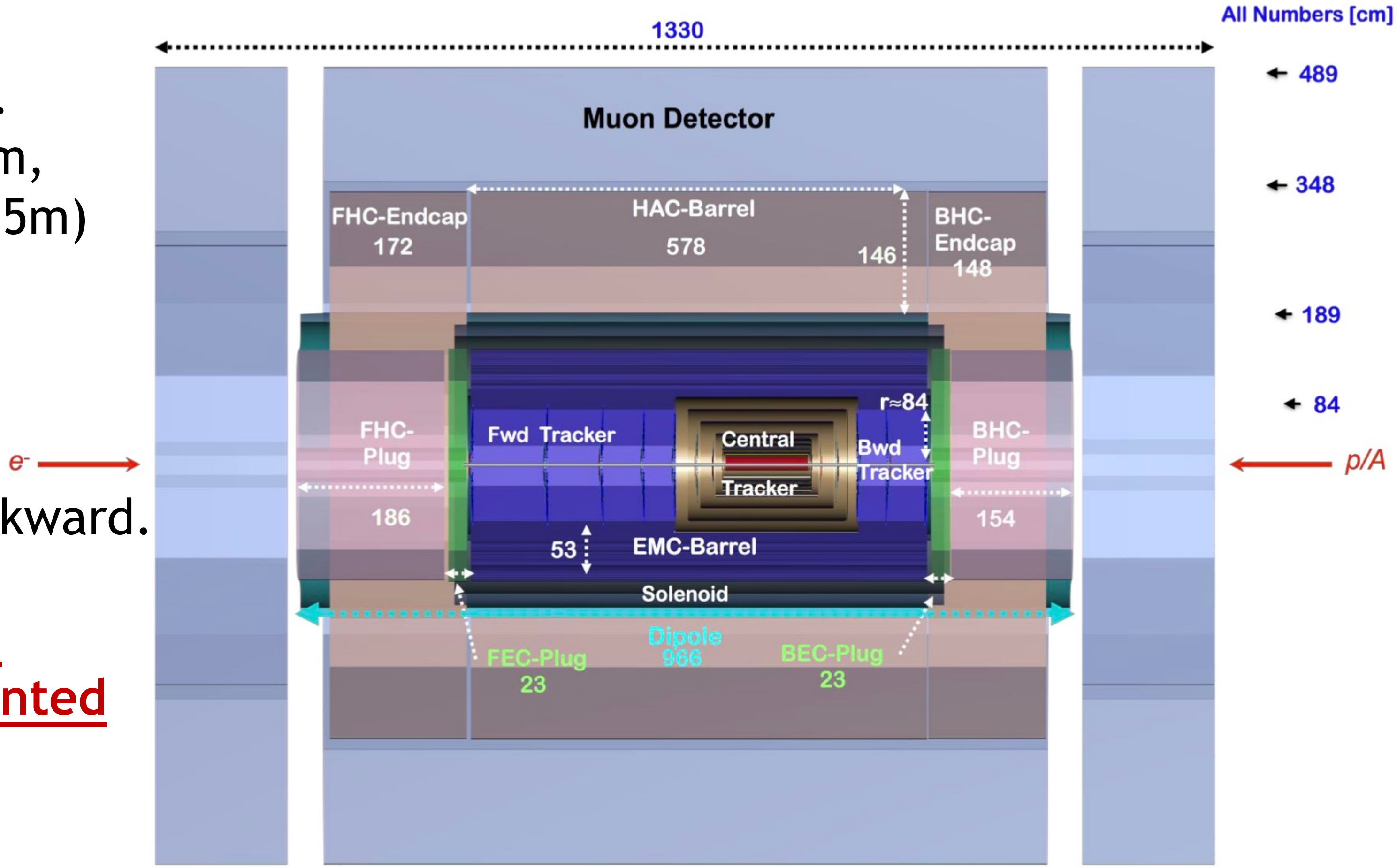
→ Dedicated Deep Inelastic Scattering experiment… hermetic & reconstructing all final state particles

# 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:

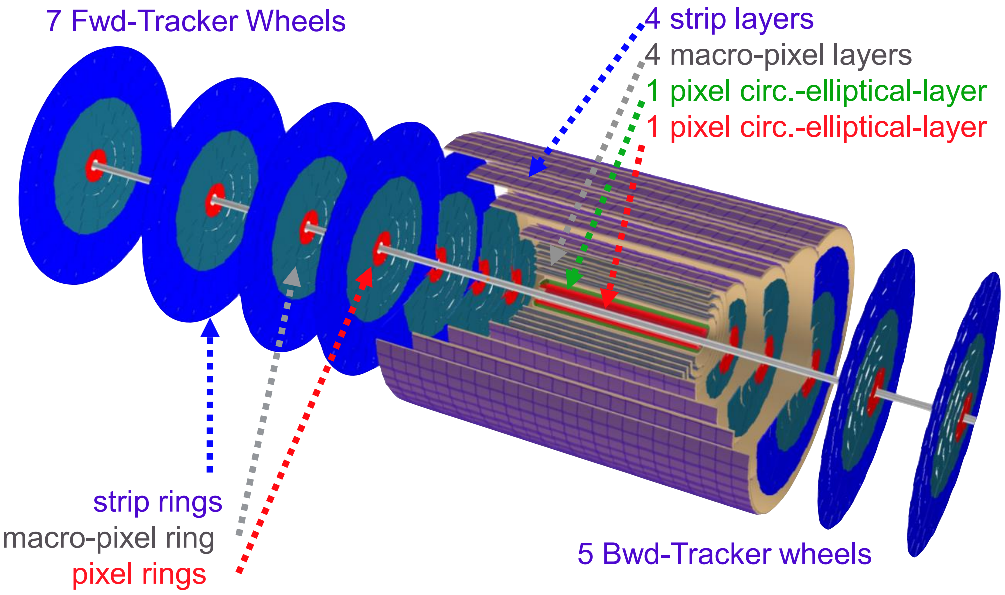
- A snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- Possibly lacking components for some ep/eA physics (eg. Particle ID)
- Not particularly well integrated or optimized

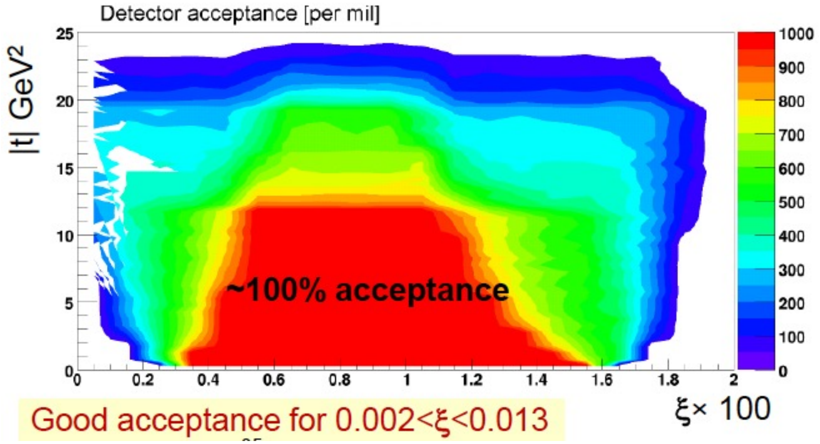
… Synergies with EIC, LHCb, ALICE, future lepton colliders still to be explored

# 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





Good acceptance for 0.002<ξ<0.013

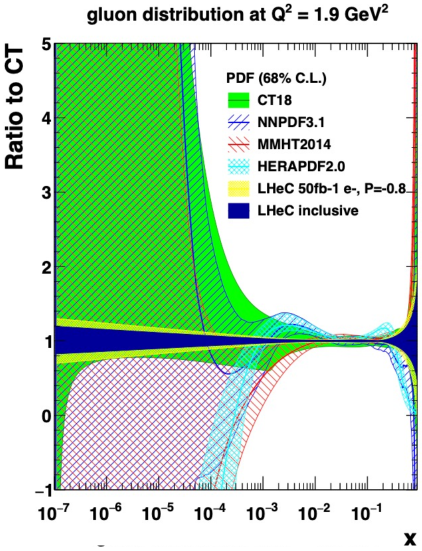
## e.g. Forward proton spectrometer in cold region (~420m)?

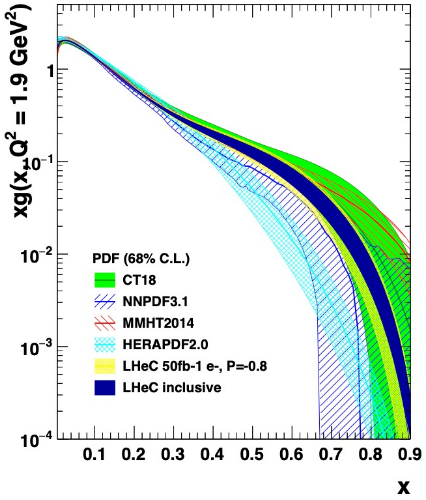
- Reuse of technology proposed for LHC, accessing protons scattered at very low momentum loss

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

# e.g. Proton PDF Precision: Enabling HL-LHC

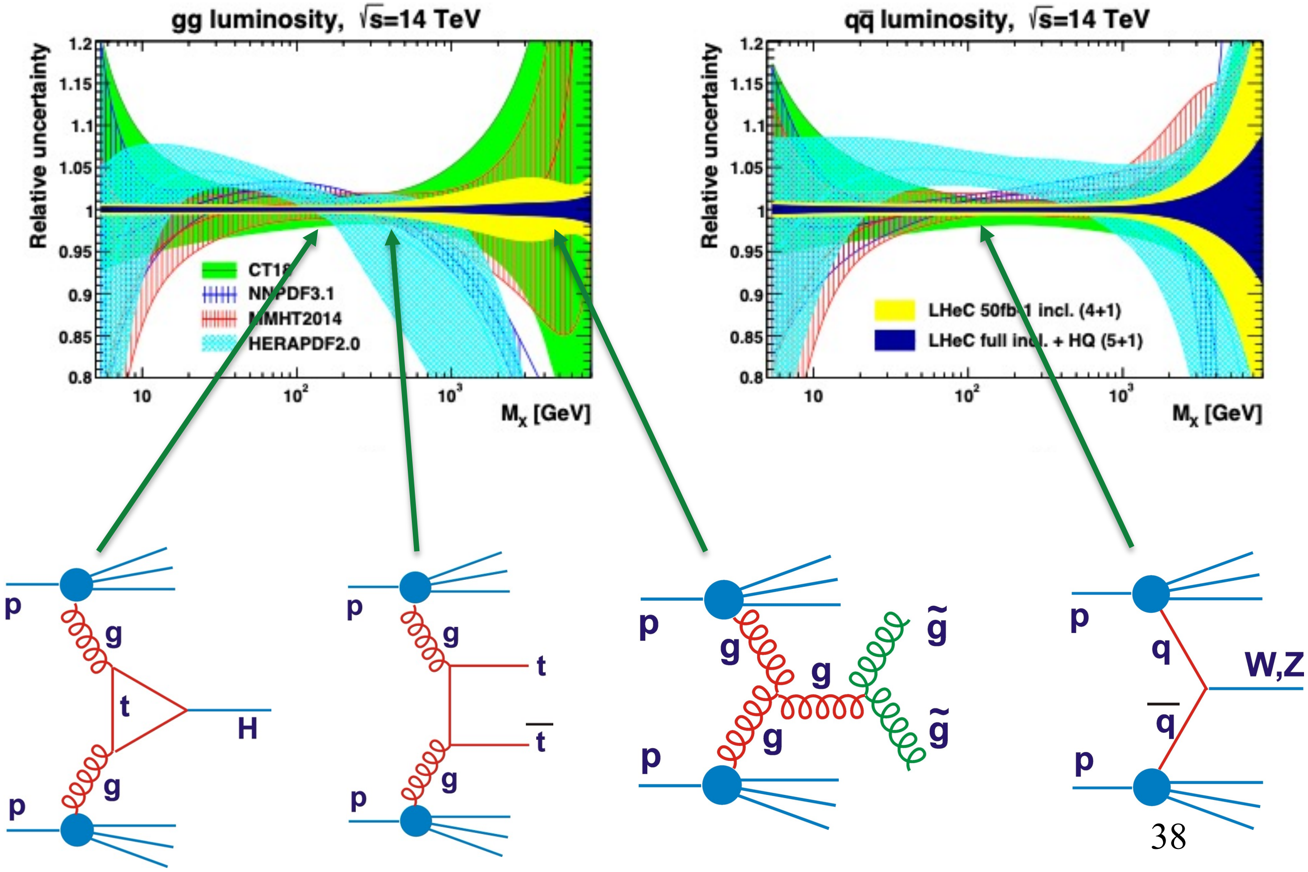
e.g. Gluon Density precision transformed in >1 year running





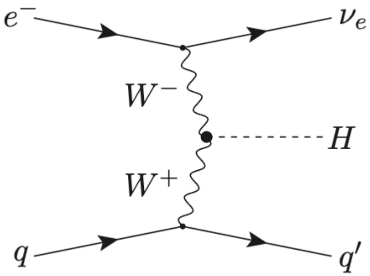
- Extends upper mass reach of many LHC BSM searches
- Discovers novel low x dynamics
- Strong coupling $\alpha_s$ to 0.2% …

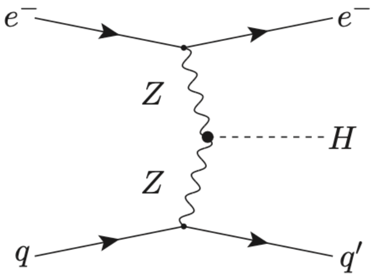
Parton luminosities for pp at 14 TeV



# ep Standalone Higgs Sensitivity

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

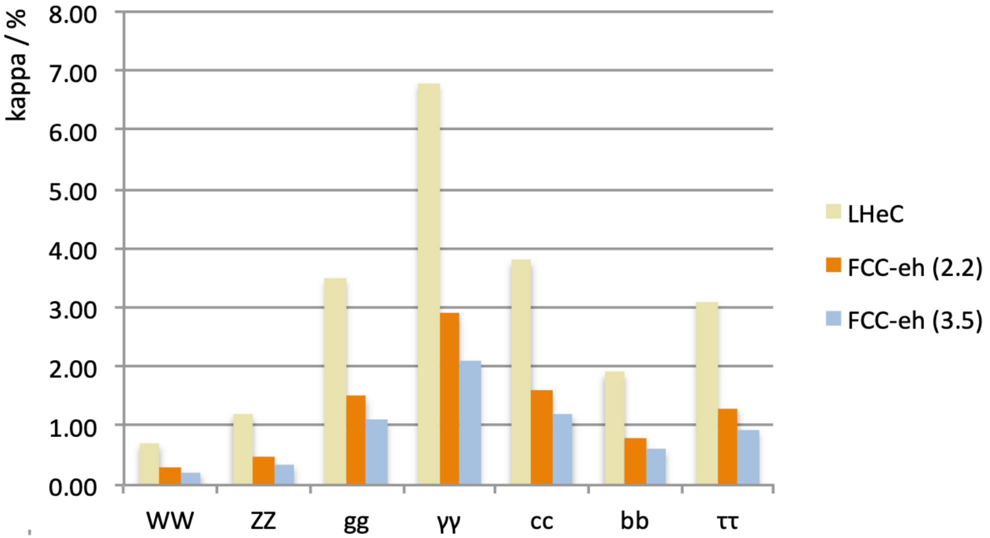




Dominant production mechanism charged current (WW), distinguished event-by-event from sub-dominant neutral current (ZZ)

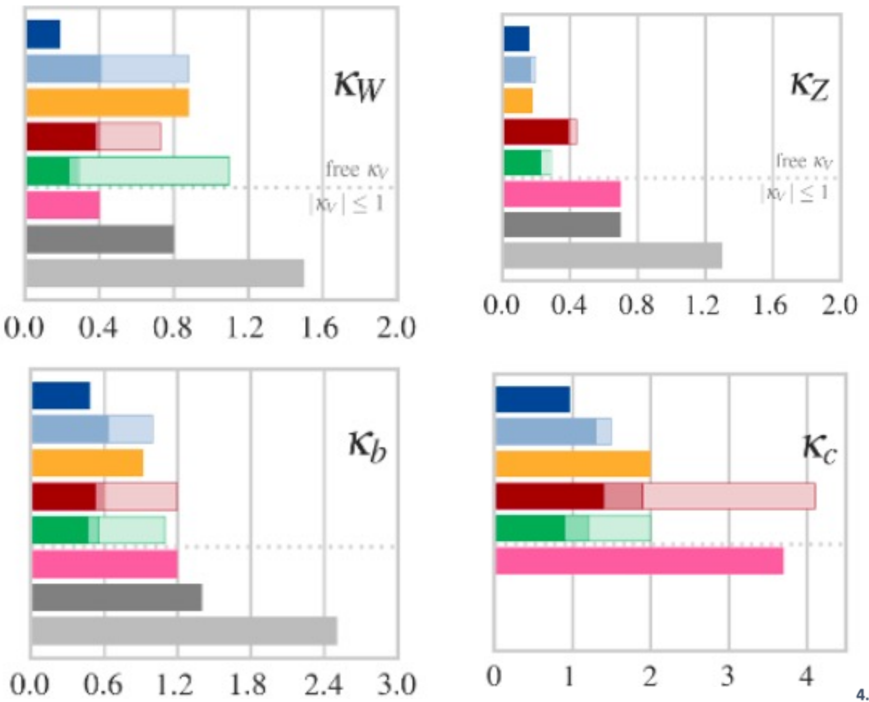
LHeC standalone precision on κ parameters …

Including initial and final-state couplings in $\kappa$-framework analysis …

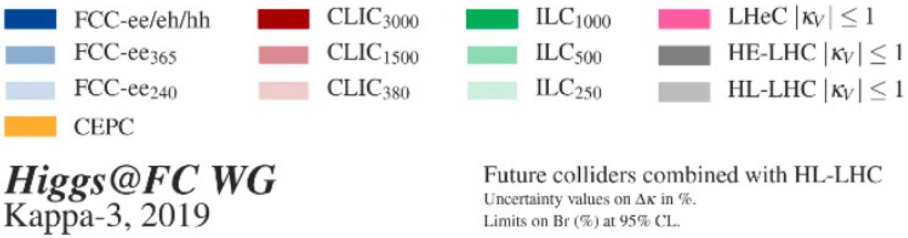


$E_e$ = 60 GeV LHeC $E_p$ = 7 TeV L=1ab$^{-1}$ HE-LHC $E_p$ = 14 TeV L=2ab$^{-1}$ FCC: $E_p$ = 50 TeV L=2ab$^{-1}$

# Sensitivities combined with HL-LHC



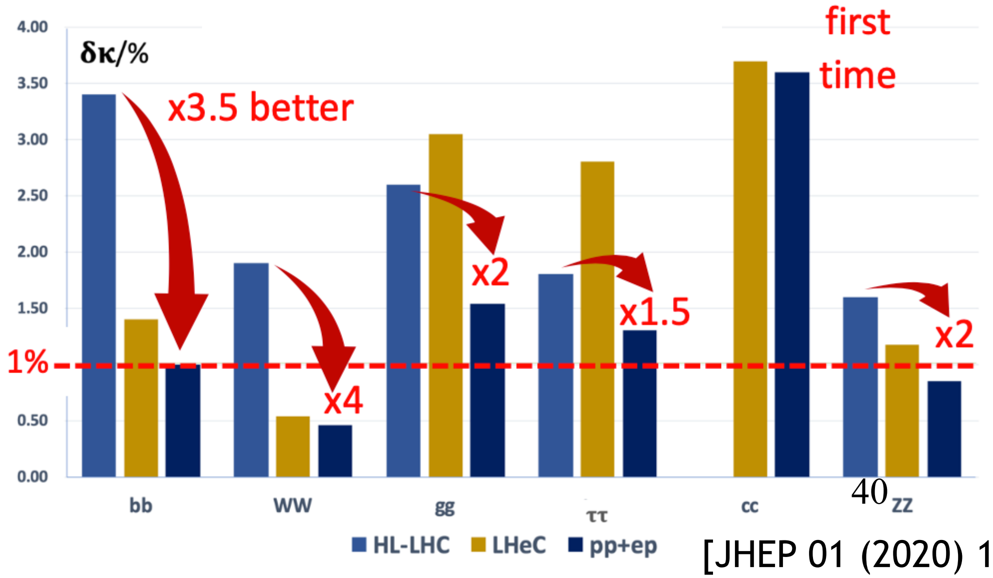
[JHEP 01 (2020) 139]



[Updates in progress for ongoing EPPSU exercise]

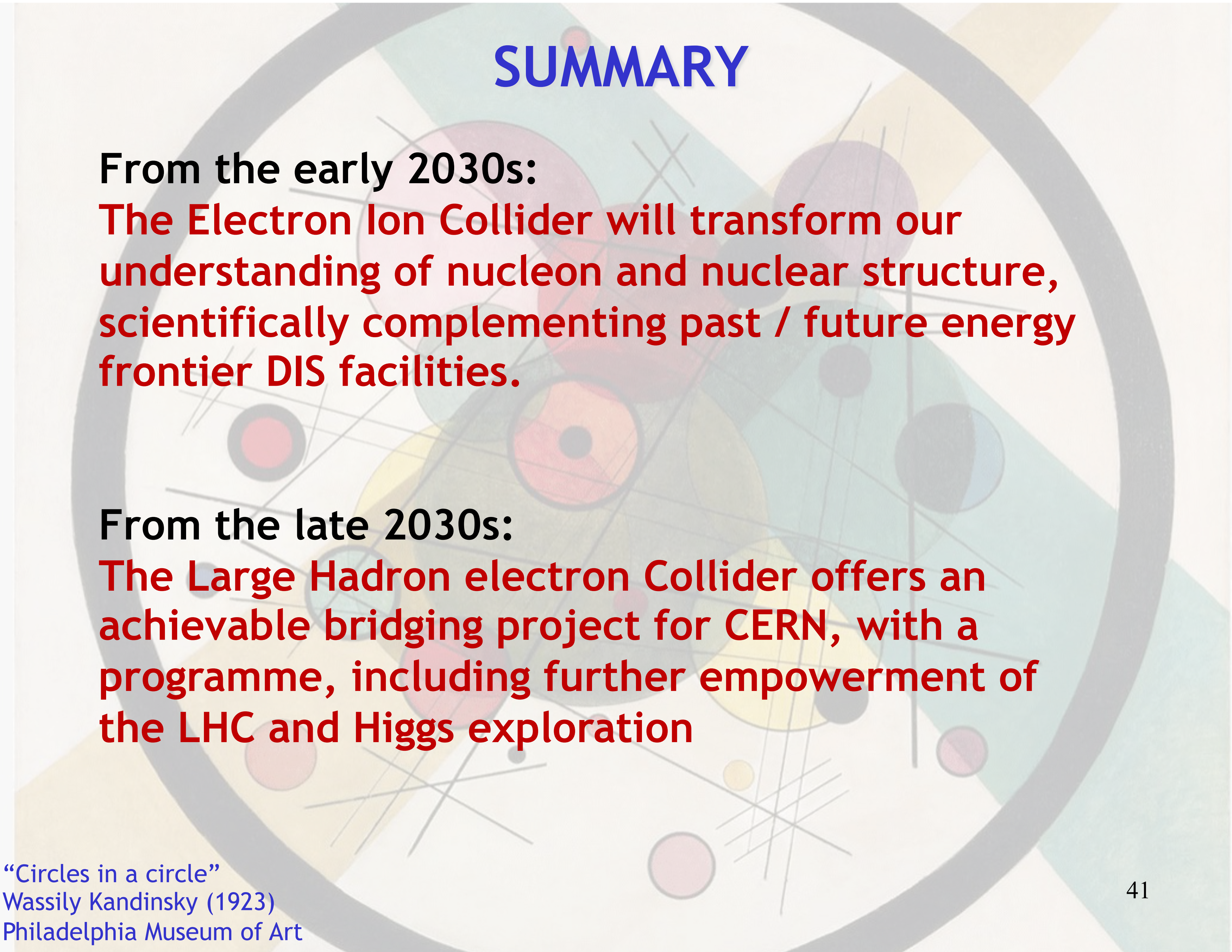
LHeC
with respect to HL-LHC

ep:pp complementarity leads to full exploitation of LHC capability for scalar sector



[JHEP 01 (2020) 139]

# 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 a programme, including further empowerment of the LHC and Higgs exploration

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

# Crude Mapping Between Physics & Facilities

Partons with decreasing x →

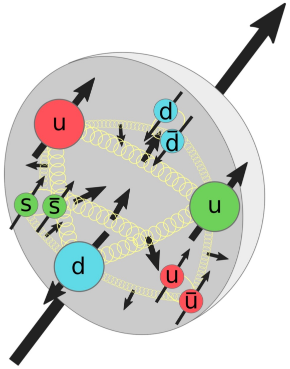
[Kong Tu]

High x (fixed Target)
Basic Structure

Intemediate x (EIC)
Emergent properties

Low x (HERA / LHeC)
QCD radiation
& non-linear
dynamics

# Proton Spin Measurements



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

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

Jaffe-Manohar sum rule:

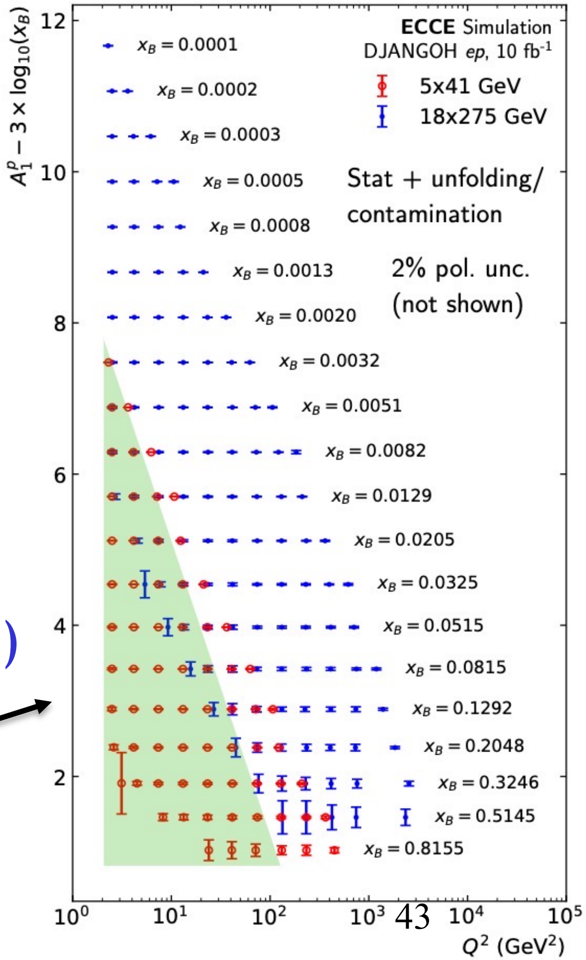
$$\underbrace{\boxed{\Delta\Sigma/2}}_{\text{Quark helicity}}+\underbrace{\boxed{\Delta G}}_{\text{Gluon helicity}}+\underbrace{\boxed{\ell_q}}_{\text{Quark canonical orbital angular momentum}}+\underbrace{\boxed{\ell_g}}_{\text{Gluon canonical orbital angular momentum}}=\hbar/2$$

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

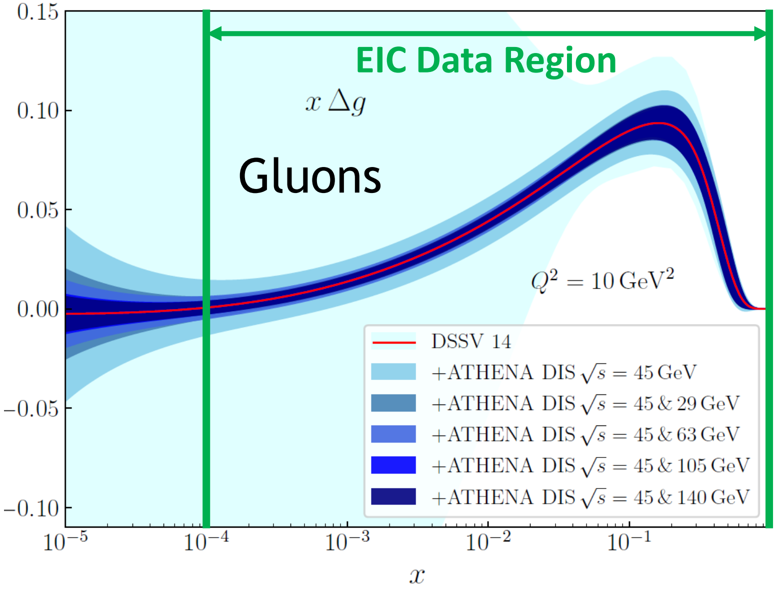
… Asymmetries between NC cross sections with different lepton and proton polarisations measure quark helicity (gluon helicity from scaling violations)

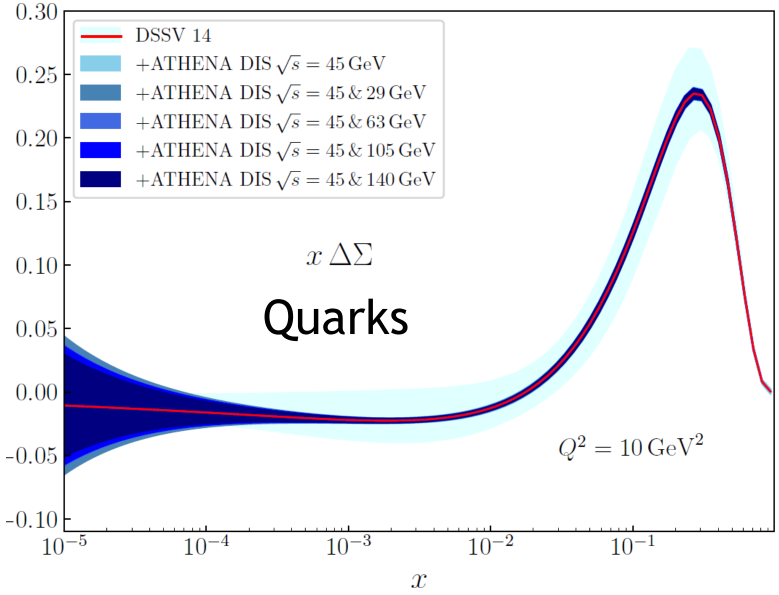
Previously measured region (in green)

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



# EIC Impact on Proton Spin Decomposition



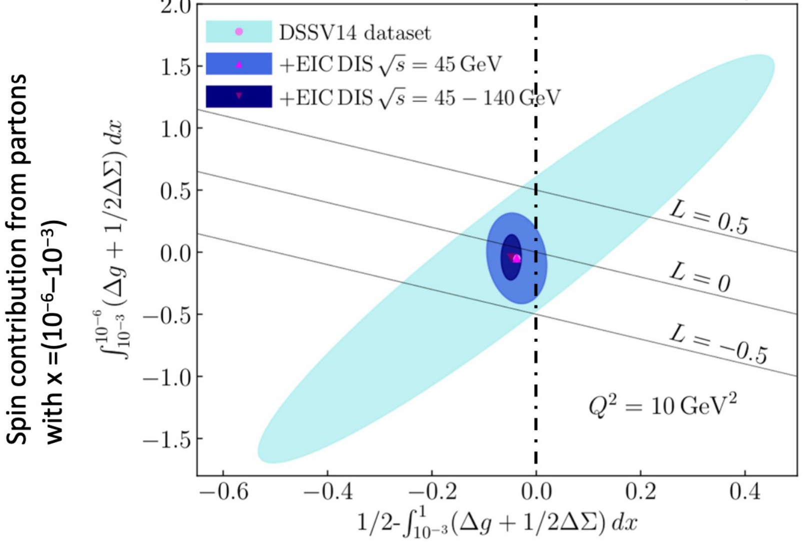


- Simulated NC data with integrated luminosity 15fb$^{-1}$, 70% e,p Polaris'n

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

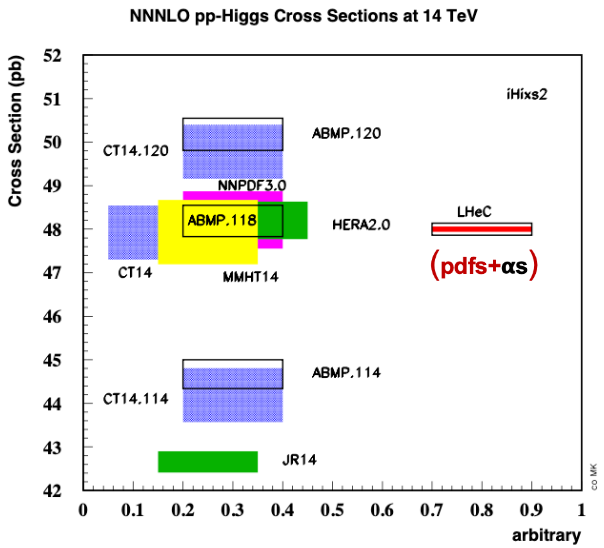
- Orbital angular momentum similarly constrained by implication

EIC Yellow Report



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

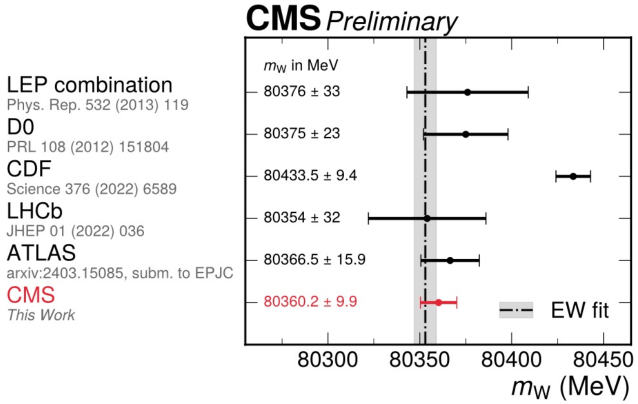
# LHeC PDFs Empowering LHC

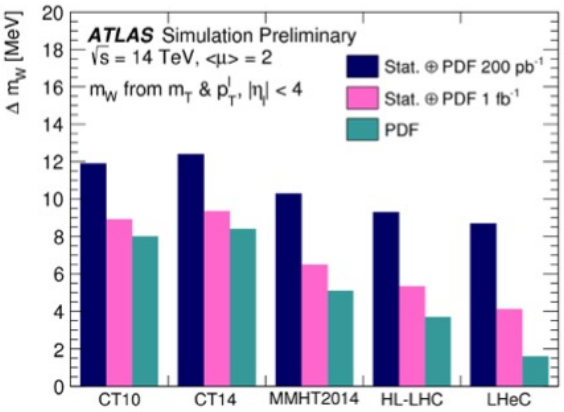


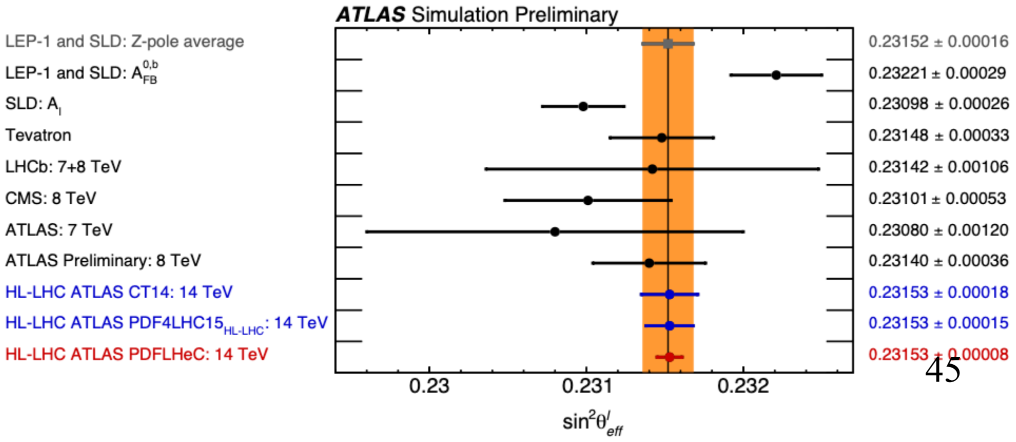
- Theory uncertainty on LHC Higgs production cross section improves dramatically compared with current PDF and $\alpha_s$ knowledge.

- PDF-related systematics on EW measurements significantly reduced (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

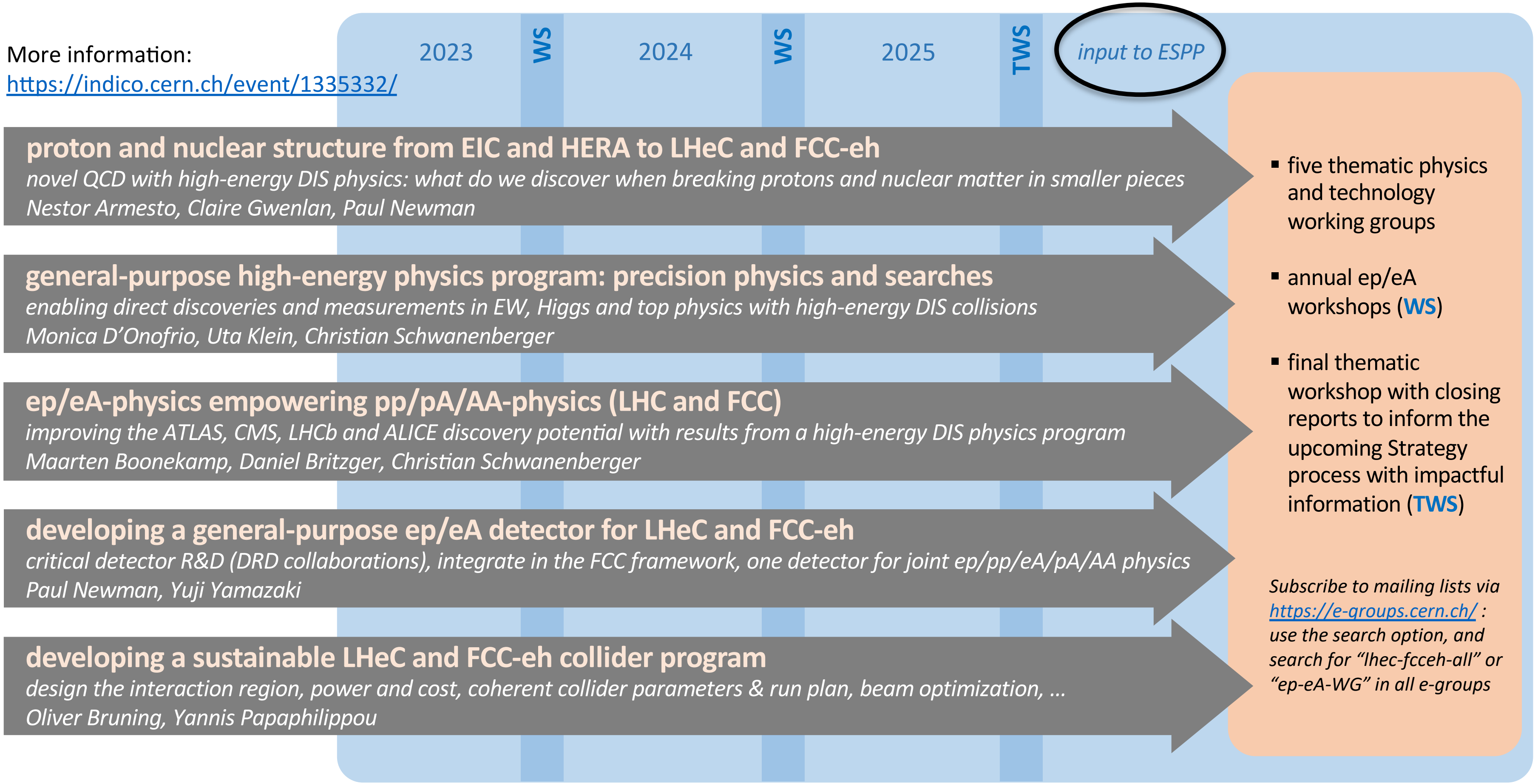






# Structure of CERN-mandated LHeC / FCC-eh study towards European Strategy

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



**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]