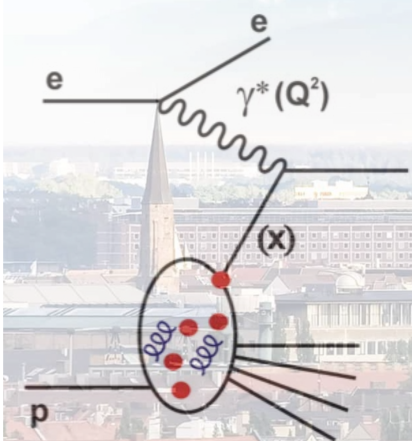
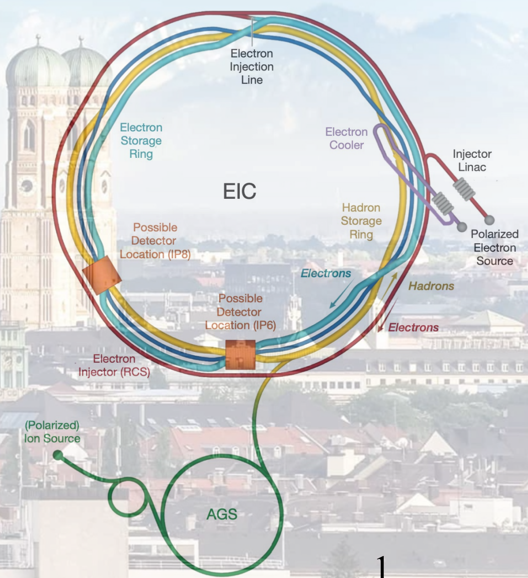
Lepton-Hadron Scattering and The Electron-Ion Collider

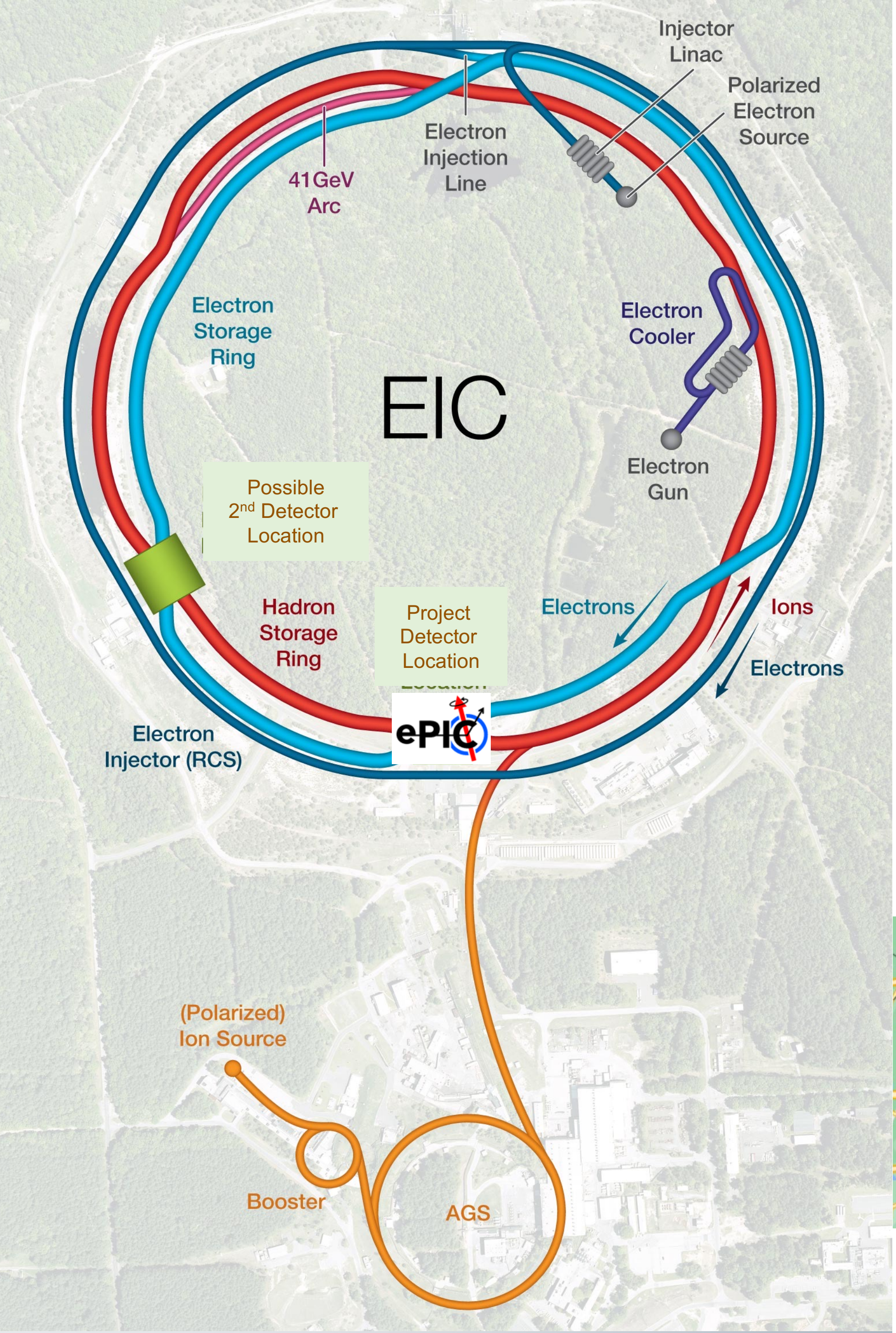
1) DIS History and Context
2) Overview and Machine
3) The ePIC detector
4) Some Physics motivations
5) Timeline

MPI München Colloquium
18 June 2024



Paul Newman (Birmingham)



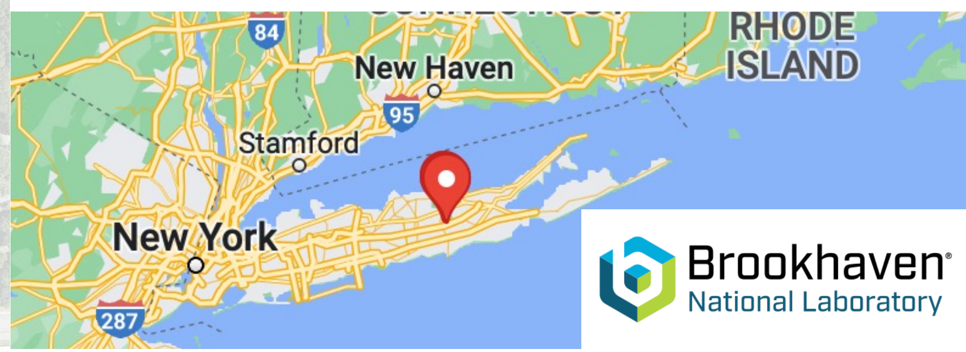


The Electron Ion Collider

New electron storage ring at BNL accelerator complex, to collide with existing RHIC proton / ion beams

On target to be the world's next high energy* collider, starting from the early 2030s

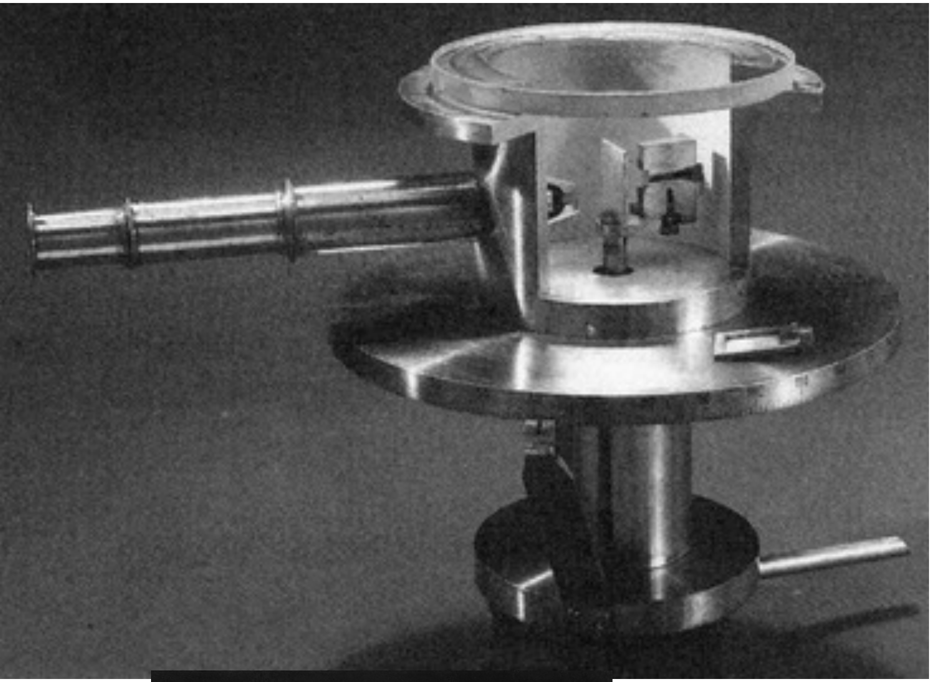
Scientific remit: exploration of strongly interacting matter using Deep Inelastic Scattering



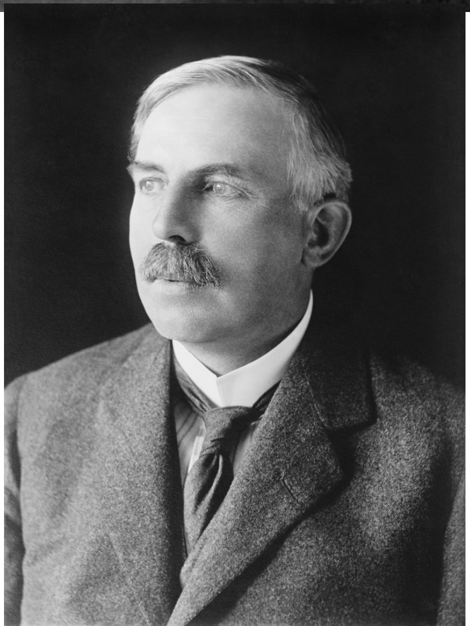
Brookhaven National Laboratory

* High energy ≠ energy frontier

Rutherford (1927, as President of Royal Society)



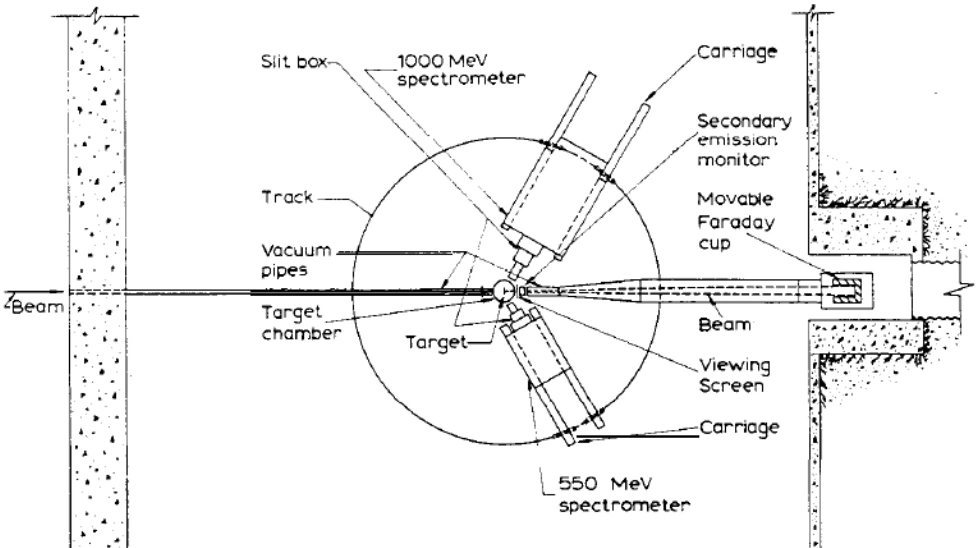
Following from the original scattering experiments (α particles on gold foil target) …



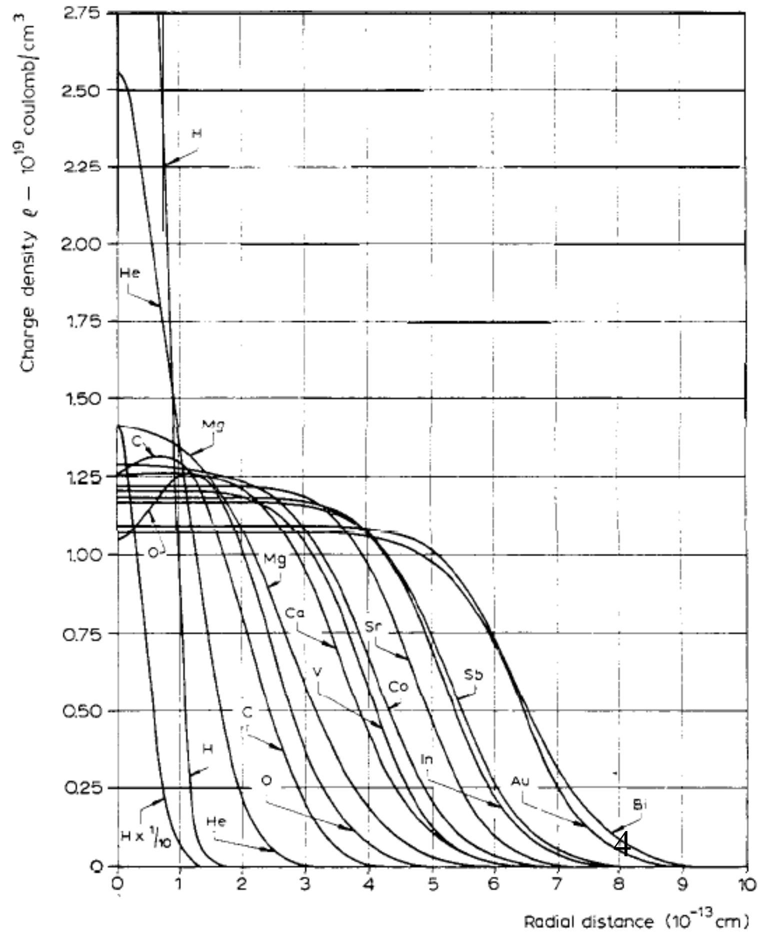
"It would be of great scientific interest if it were possible to have a supply of electrons … of which the individual energy of motion is greater even than that of the alpha particle"

Hofstadter (Nobel Prize 1961)

200 MeV Electrons on a fixed target …



Experimental area



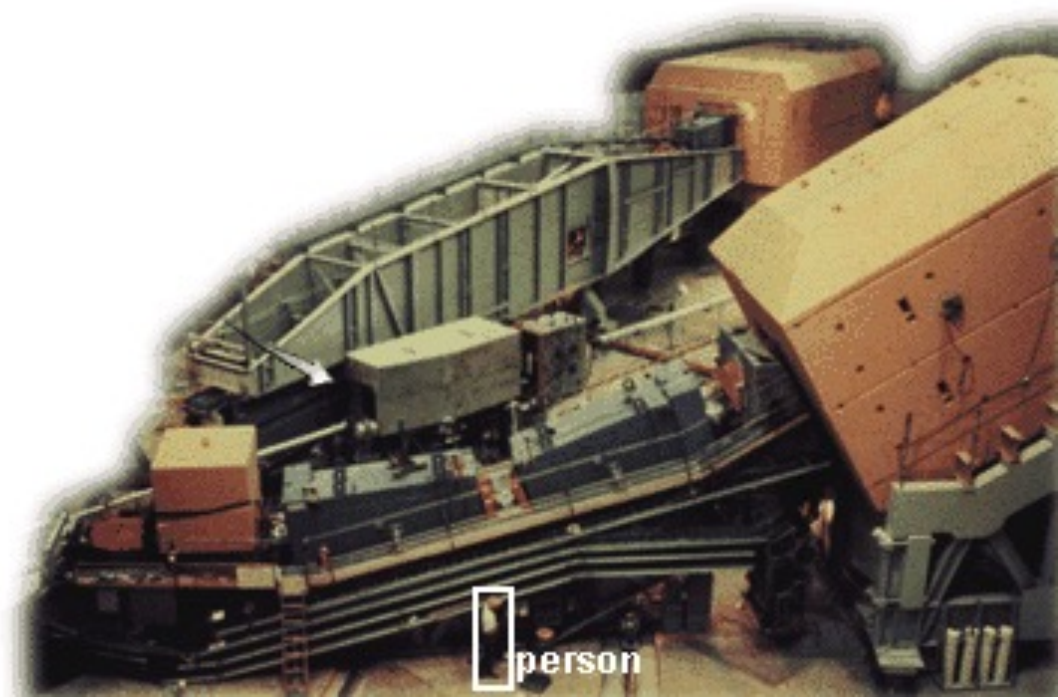
- Electron scattering reveals nuclear form factors (i.e. sizes)

… even a hydrogen nucleus (proton) has finite size

… electric charge uniformly spread?

… "soft spheres" …

SLAC 1969: 20 GeV electrons on protons



… observed significant scattering through wide angles (like Rutherford’s alphas), implying ‘point-like’ scattering centres

First Observation Of Proton Structure

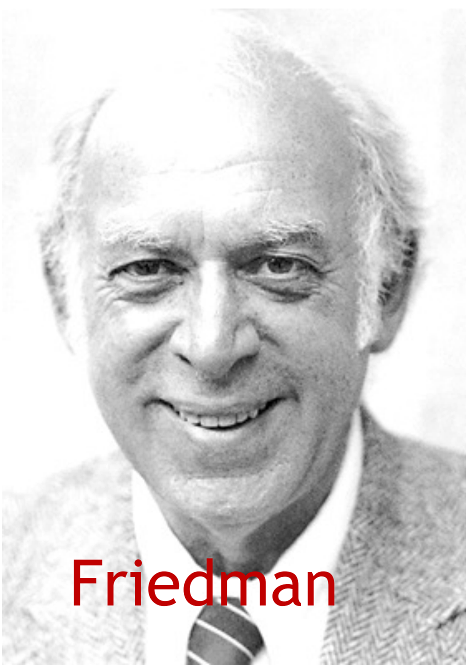
VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

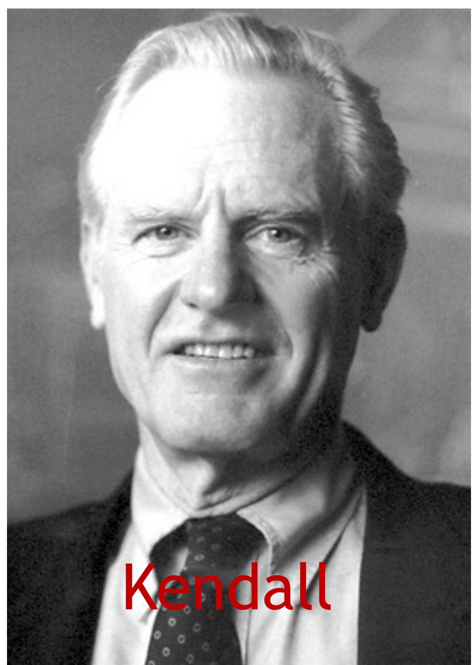
OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

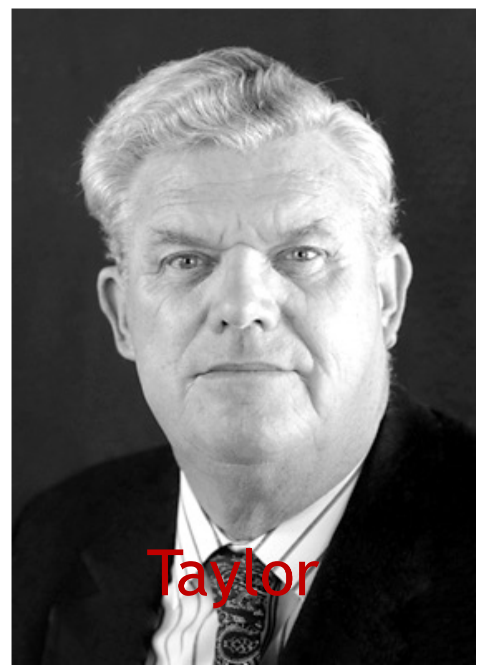
M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)







Nobel Prize 1990

HERA, DESY, Hamburg

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

… equivalent to a 50 TeV beam on a fixed target proton

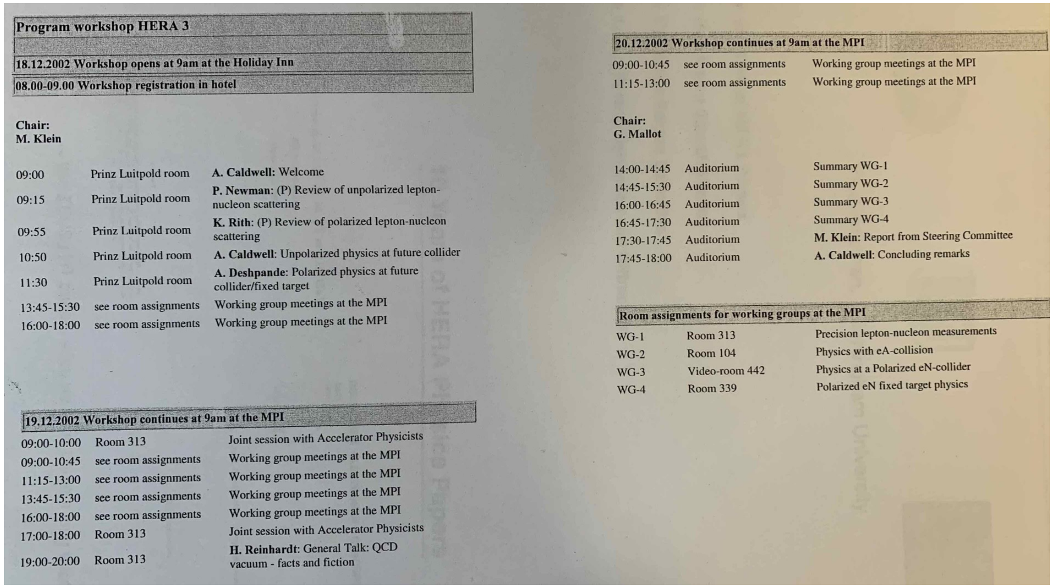
- So far still the only collider of electron and proton beams ever

→ Taught us much of what we know about proton structure

→ Limied to ~0.5 fb^{-1} per experiment

→ No deuteron or nuclear targets

My first talk in Munich



Program workshop HERA 3

18.12.2002 Workshop opens at 9am at the Holiday Inn

08.00-09.00 Workshop registration in hotel

Chair:
M. Klein

09:00	Prinz Luitpold room	**A. Caldwell:** Welcome
09:15	Prinz Luitpold room	**P. Newman:** (P) Review of unpolarized lepton-nucleon scattering
09:55	Prinz Luitpold room	**K. Rith:** (P) Review of polarized lepton-nucleon scattering
10:50	Prinz Luitpold room	**A. Caldwell:** Unpolarized physics at future collider
11:30	Prinz Luitpold room	**A. Deshpande:** Polarized physics at future collider/fixed target
13:45-15:30	see room assignments	Working group meetings at the MPI
16:00-18:00	see room assignments	Working group meetings at the MPI

19.12.2002 Workshop continues at 9am at the MPI

09:00-10:00	Room 313	Joint session with Accelerator Physicists
09:00-10:45	see room assignments	Working group meetings at the MPI
11:15-13:00	see room assignments	Working group meetings at the MPI
13:45-15:30	see room assignments	Working group meetings at the MPI
16:00-18:00	see room assignments	Working group meetings at the MPI
17:00-18:00	Room 313	Joint session with Accelerator Physicists
19:00-20:00	Room 313	**H. Reinhardt:** General Talk: QCD vacuum - facts and fiction

20.12.2002 Workshop continues at 9am at the MPI

09:00-10:45	see room assignments	Working group meetings at the MPI
11:15-13:00	see room assignments	Working group meetings at the MPI

Chair:
G. Mallot

14:00-14:45	Auditorium	Summary WG-1
14:45-15:30	Auditorium	Summary WG-2
16:00-16:45	Auditorium	Summary WG-3
16:45-17:30	Auditorium	Summary WG-4
17:30-17:45	Auditorium	**M. Klein:** Report from Steering Committee
17:45-18:00	Auditorium	**A. Caldwell:** Concluding remarks

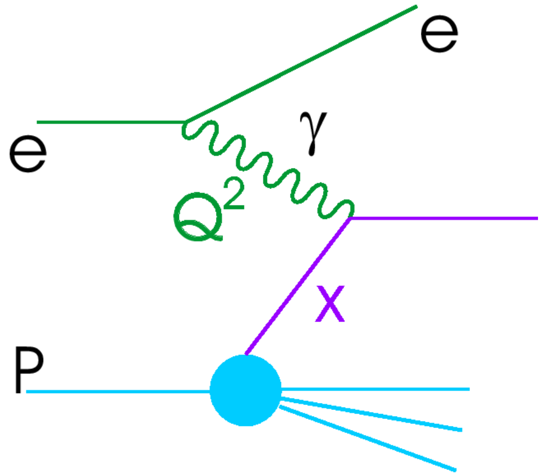
Room assignments for working groups at the MPI

WG-1	Room 313	Precision lepton-nucleon measurements
WG-2	Room 104	Physics with eA-collision
WG-3	Video-room 442	Physics at a Polarized eN-collider
WG-4	Room 339	Polarized eN fixed target physics

… heavy ion physics
… low-x physics
… spin physics

[Ultimately not realised]

Inclusive Neutral Current DIS: ep→ eX … Kinematics



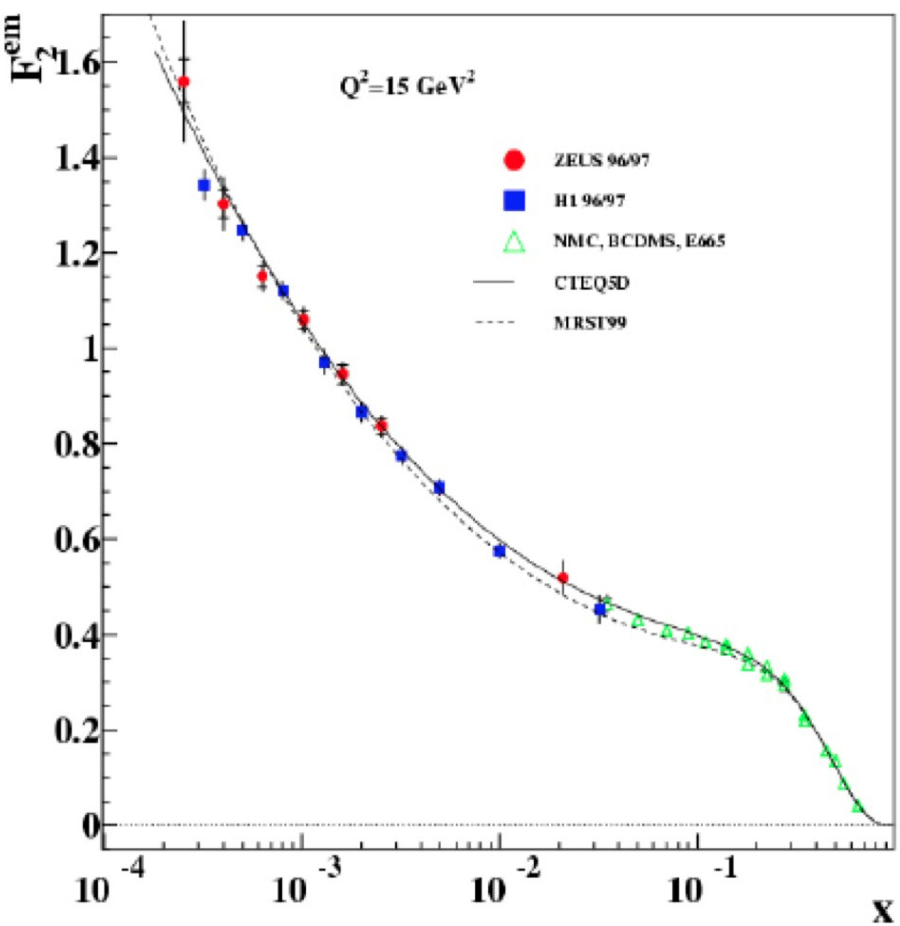
$$Q^2 = -q^2 \qquad x = \frac{-q^2}{2p \cdot q}$$

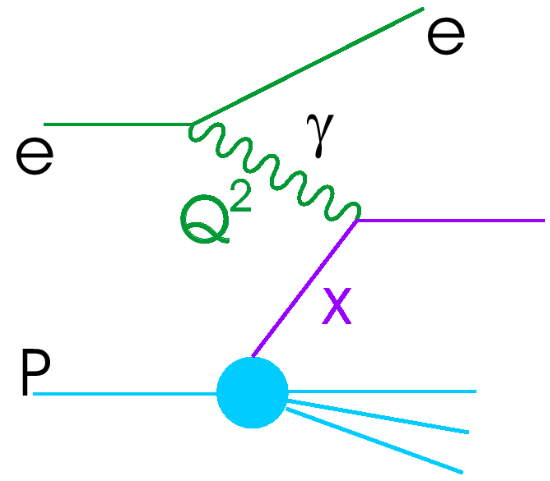
x = fraction of proton momentum carried by struck quark

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

Example Inclusive Neutral Current Data from Previous Experiments

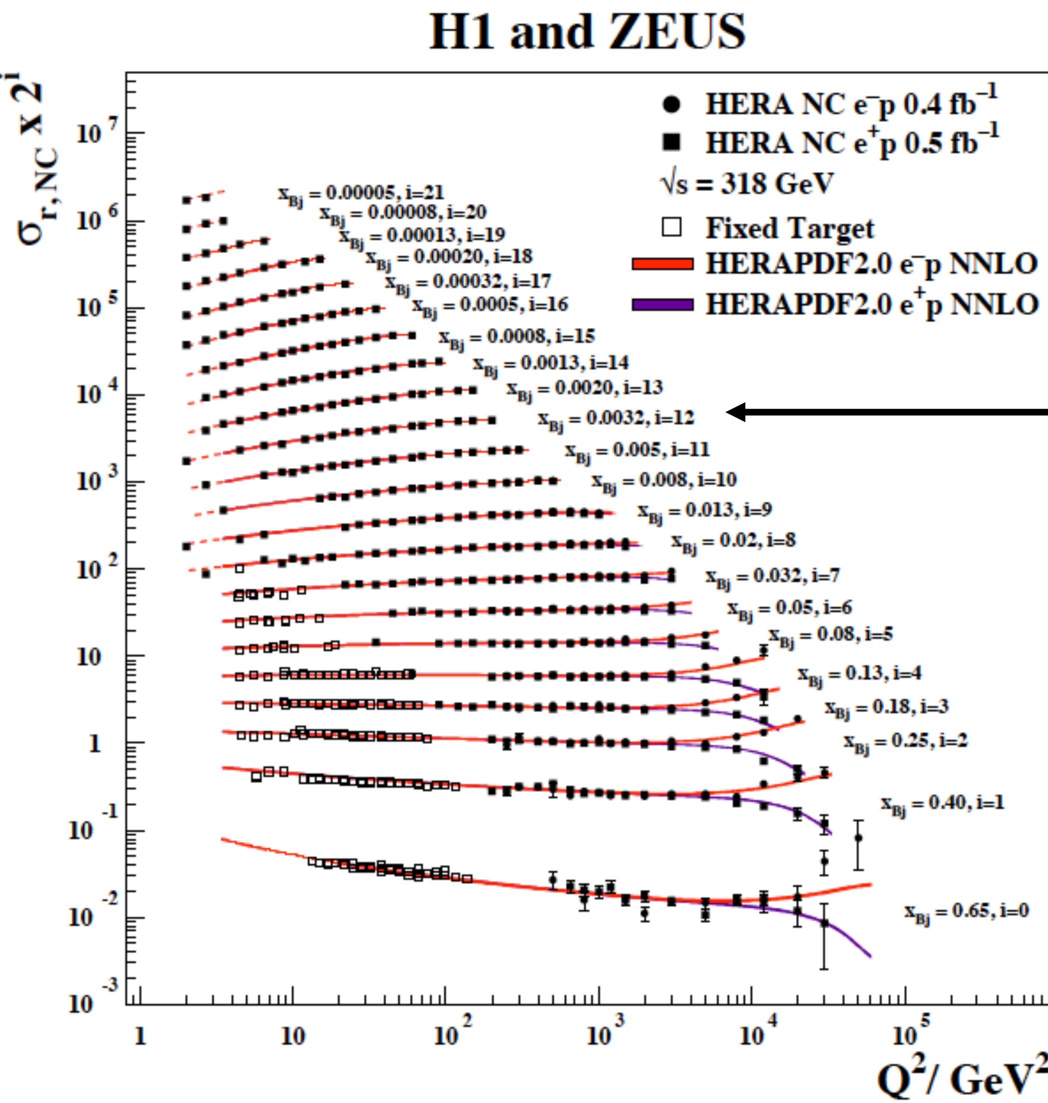




- Inclusive cross section measures (charge-squared weighted) sum of quark densities

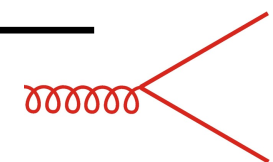
- Similar / better data at many other values of Q^2

QCD Evolution and the Gluon Density



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

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

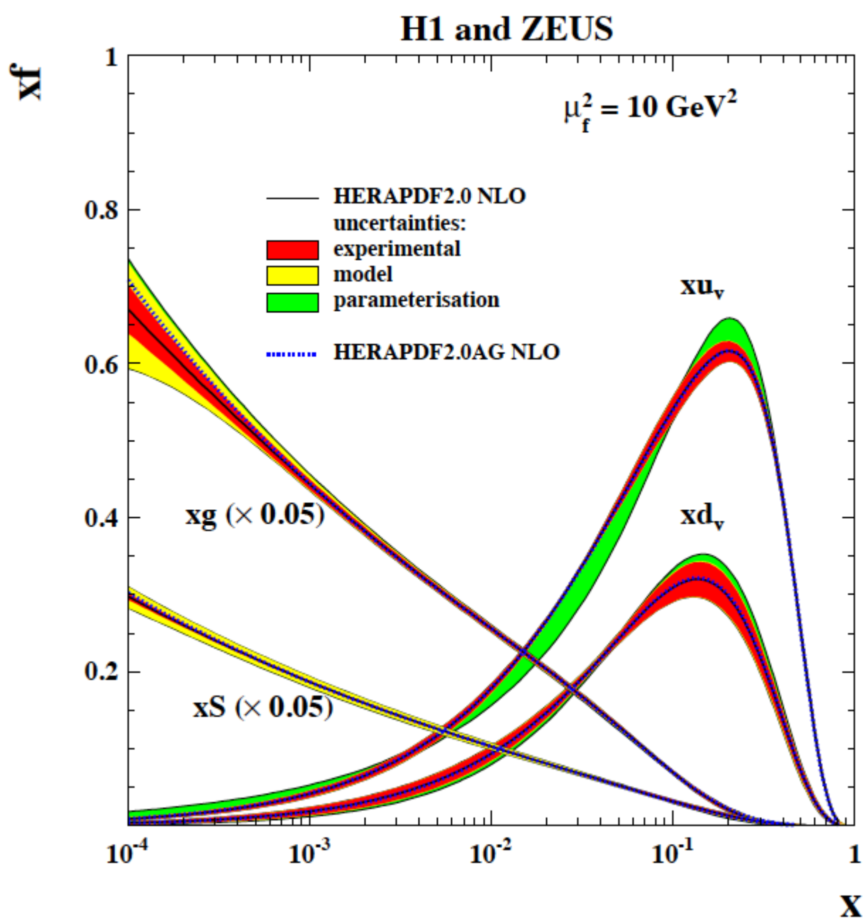


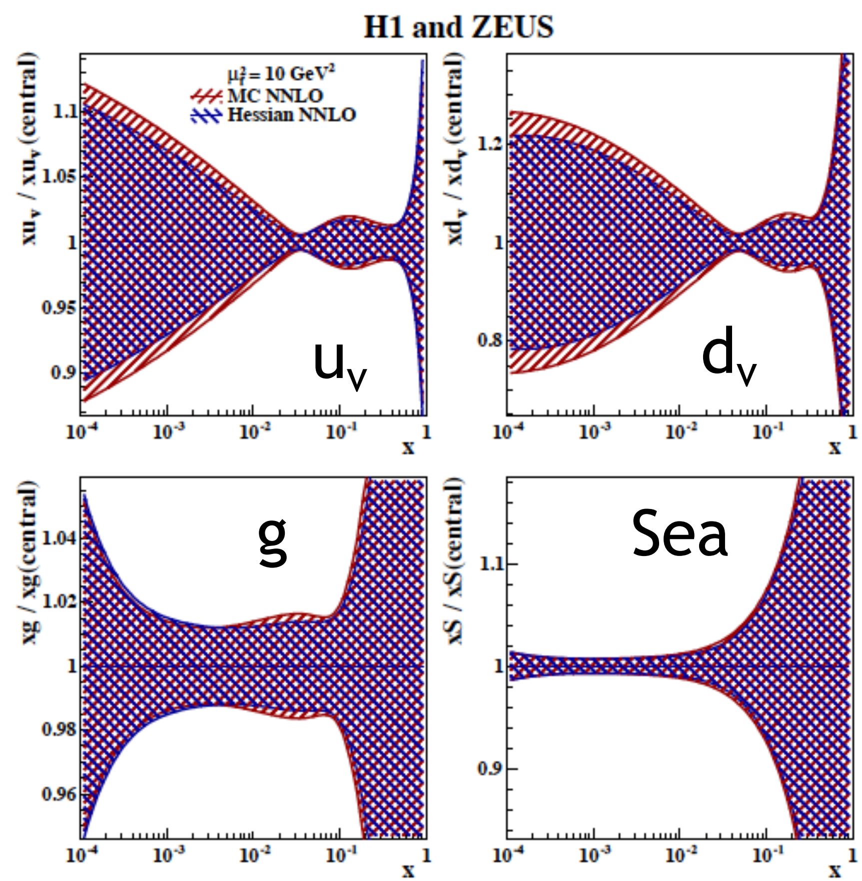
- DGLAP equations describe QCD evolution (to NNLO and approximate N^3LO accuracy)

- 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

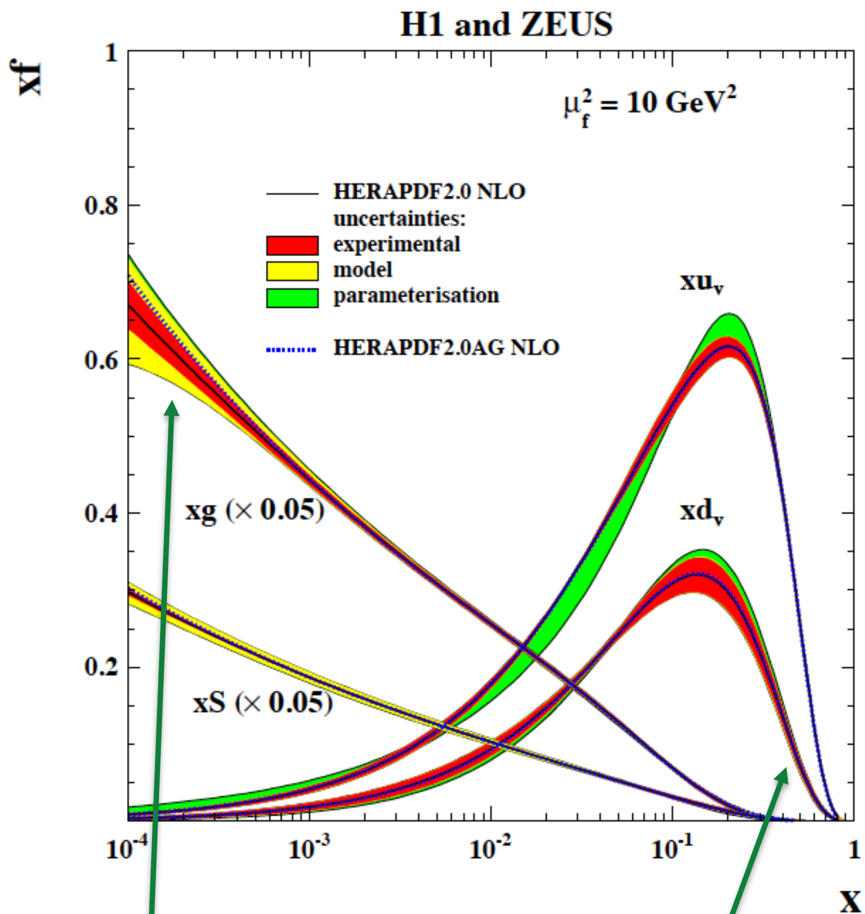
Proton PDFs from HERA only (HERAPDF2.0)

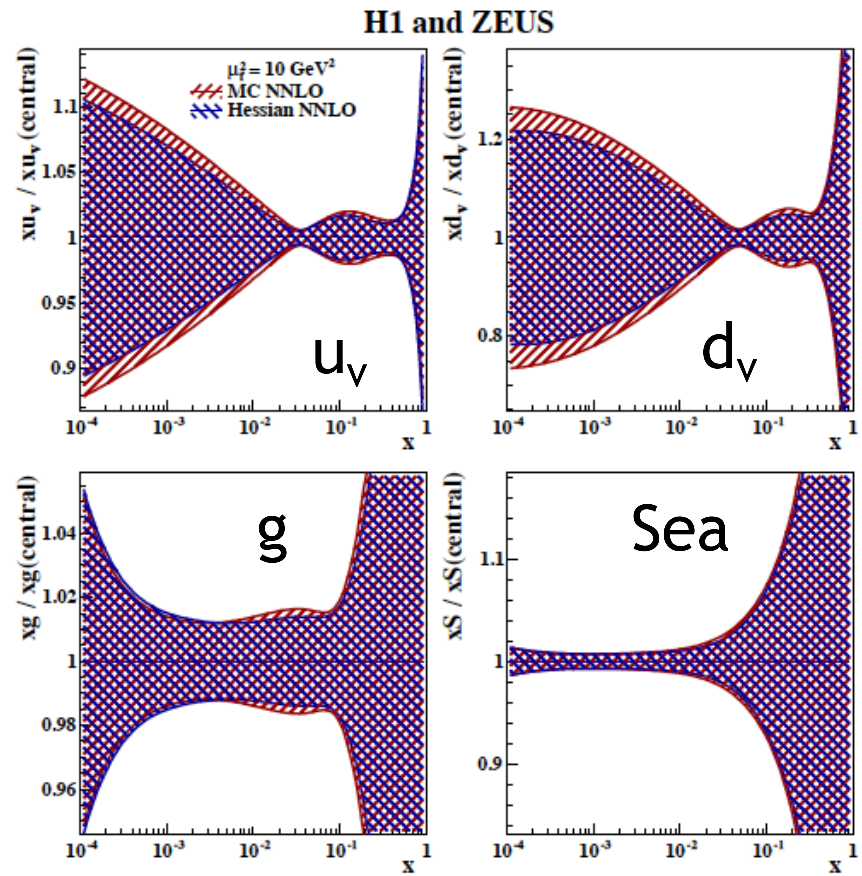




- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

Proton PDFs from HERA only (HERAPDF2.0)



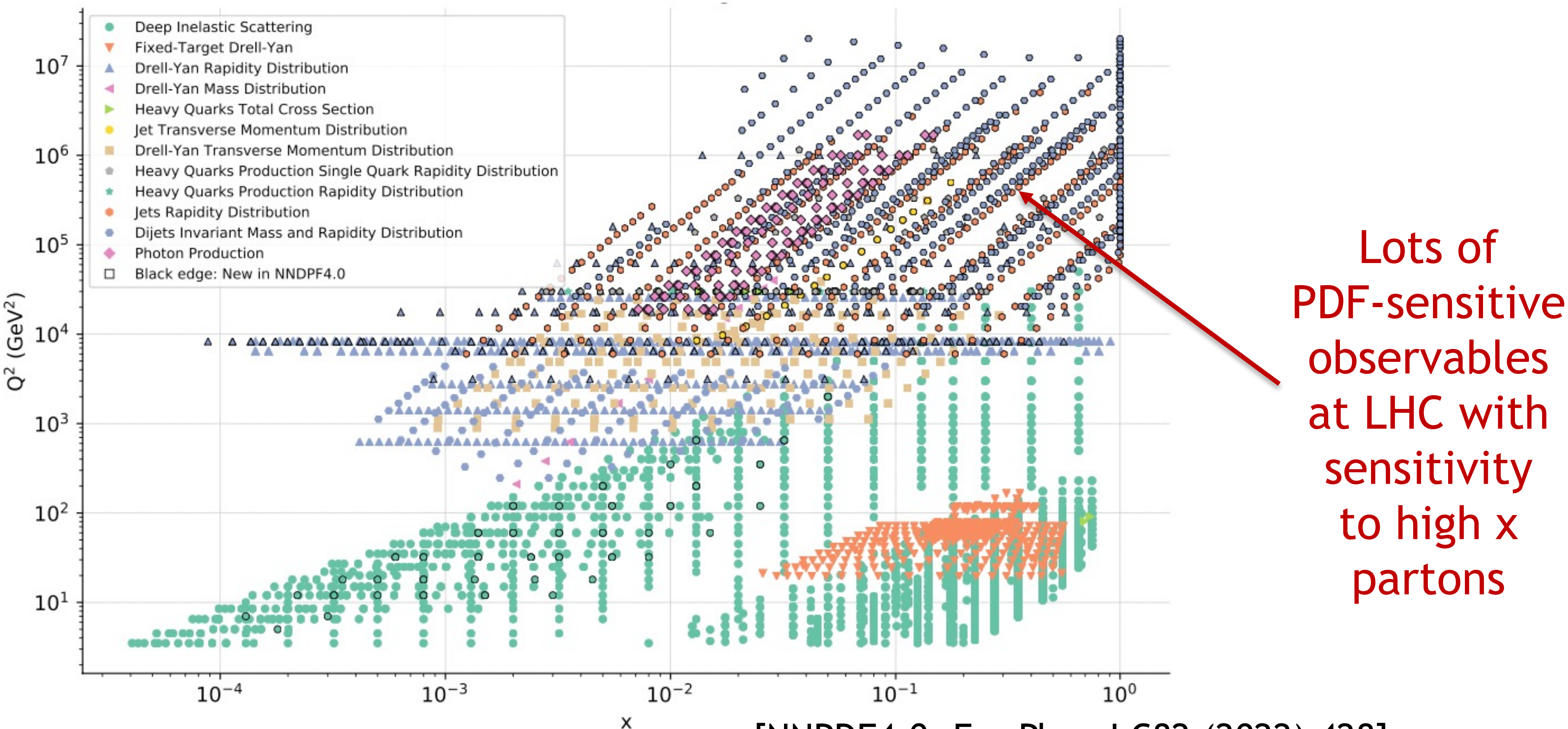


Strong interaction dragons?

Input to energy frontier discovery?

- At x ~ 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



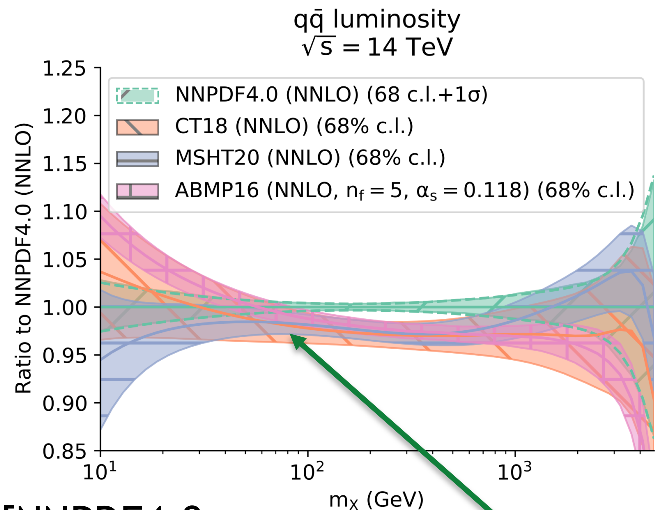
[NNPDF4.0, Eur Phys J C82 (2022) 428]

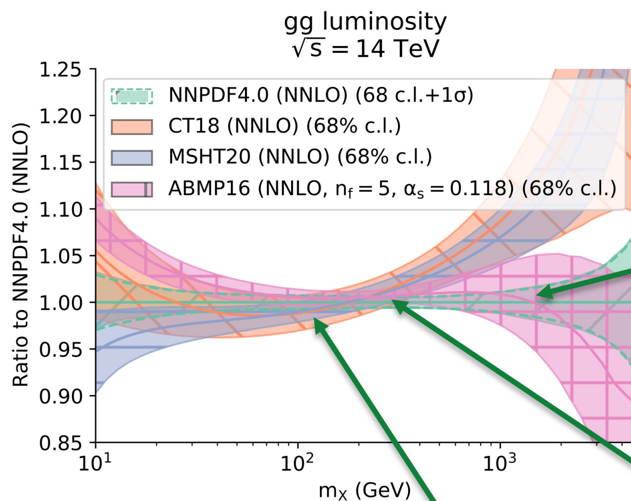
Including LHC data brings:
Advantages: improve precision at mid and high x, exploit all available inputs

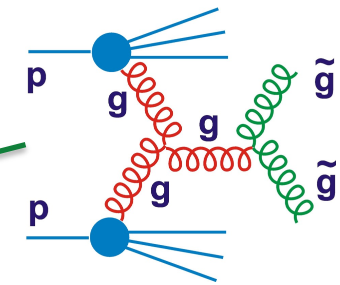
Caveats: use of data that may contain BSM effects, theoretical complexity (eg non-perturbative input), some incompatibilities between data sets

Global Fits and LHC Parton Luminosities

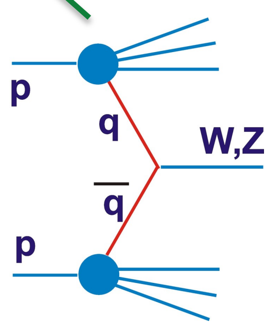
e.g. Comparisons between current global fits on LHC $q\bar{q}$ and gg luminosities

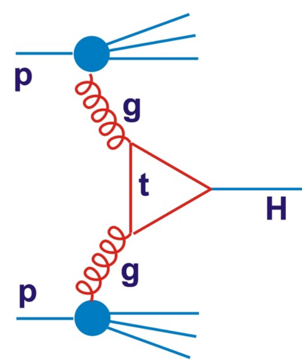


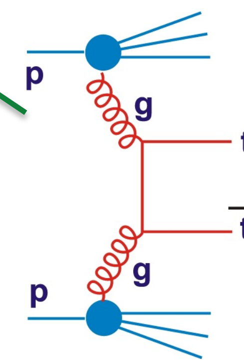




[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]



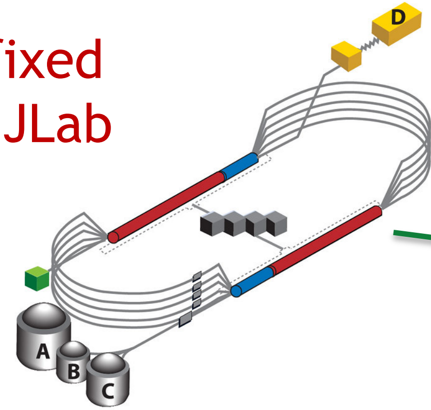




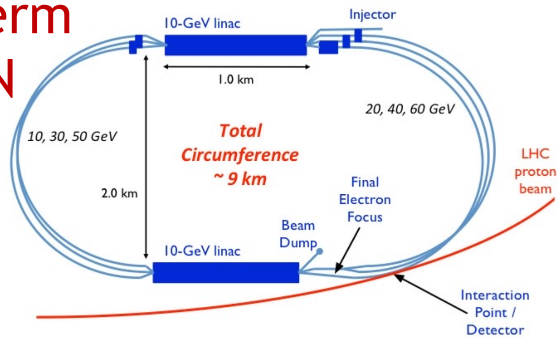
Immense recent progress, but still large uncertainties and some tensions between data sets and fitting methodologies

Current and Future ep Colliders

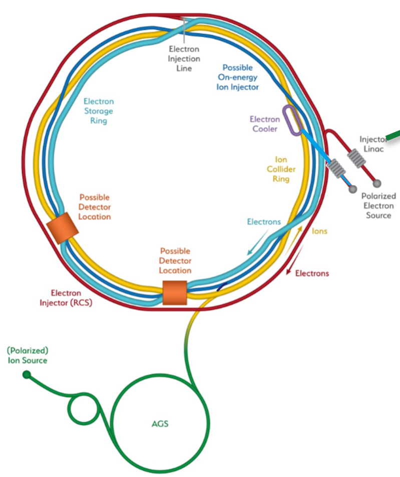
Ongoing fixed target @ JLab

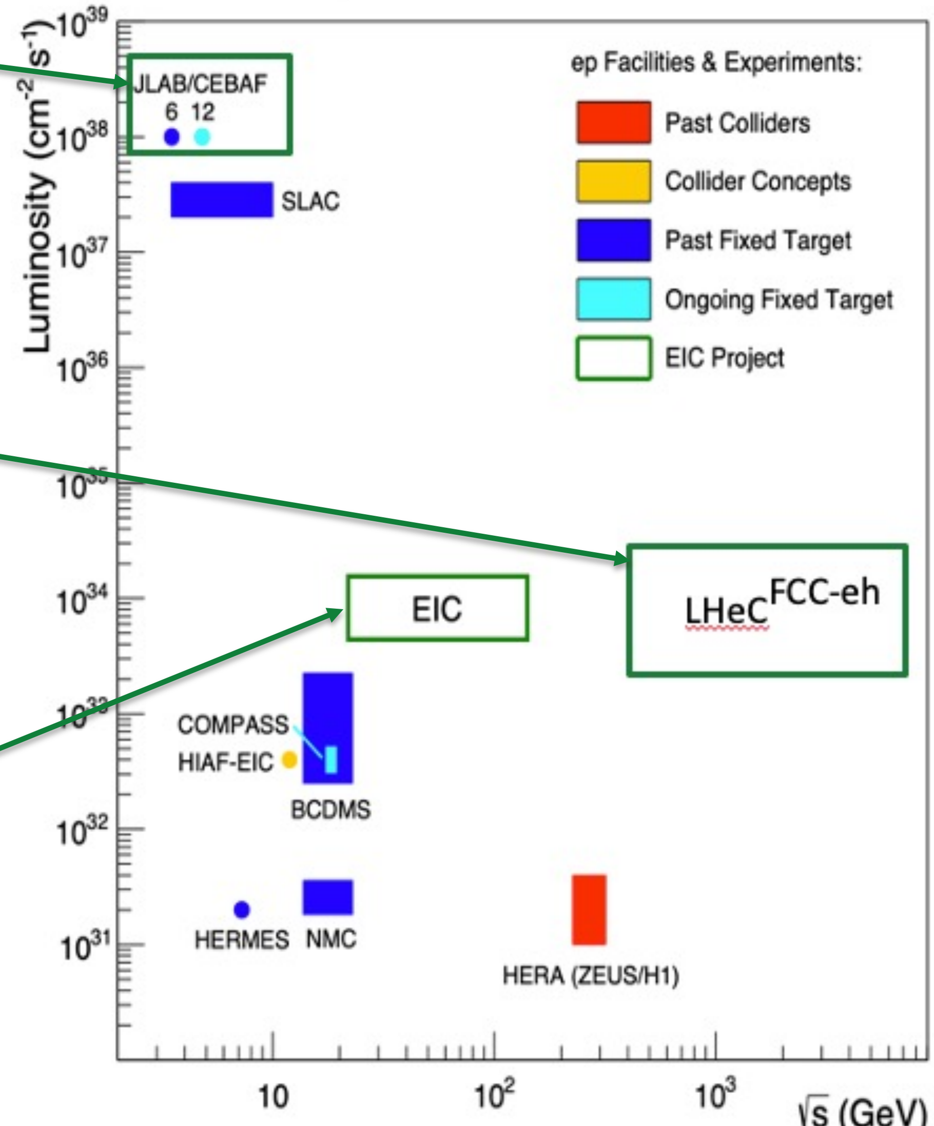


Longer-term @ CERN



On-target for early 2030s @ BNL





My Next Talk in Munich

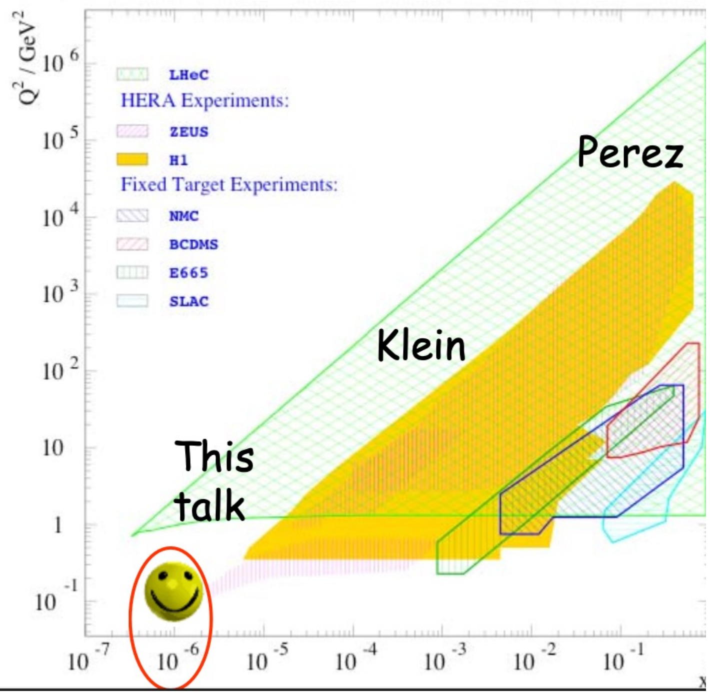
Low x Physics at the LHeC: DIS with E_e=70GeV and E_p=7TeV

[hep-ex/0603016, JINST 1 (2006) P10001]

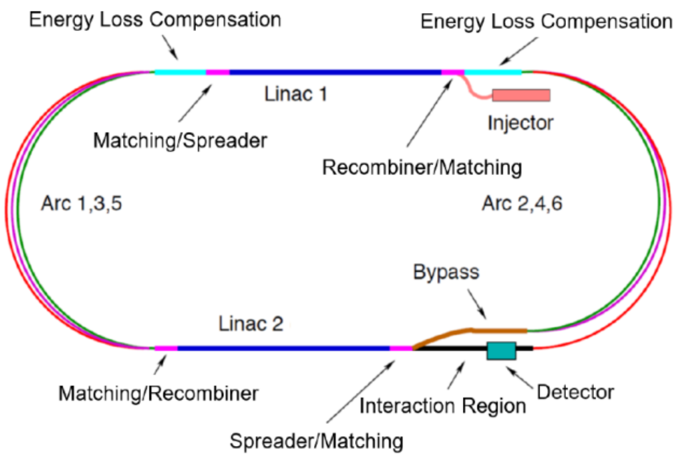
P Newman, Birmingham

DIS2007, Munich
19 April 2007

Thanks to E Avsar, J Dainton, M Diehl, M Klein, L Favart, J Forshaw, L Lonnblad, A Mehta, E Perez, G Shaw, F Willeke



Future High Energy ep and eA Options at CERN

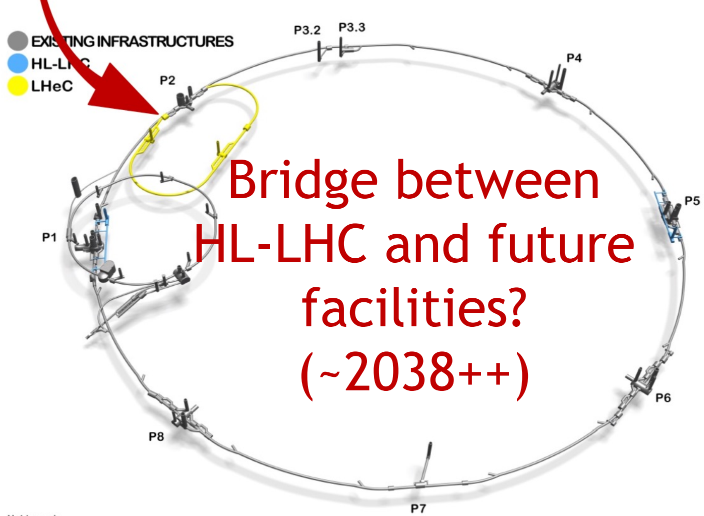


Energy-recovery linac system in collision with LHC or FCC hadrons

Ongoing studies towards Euro strategy

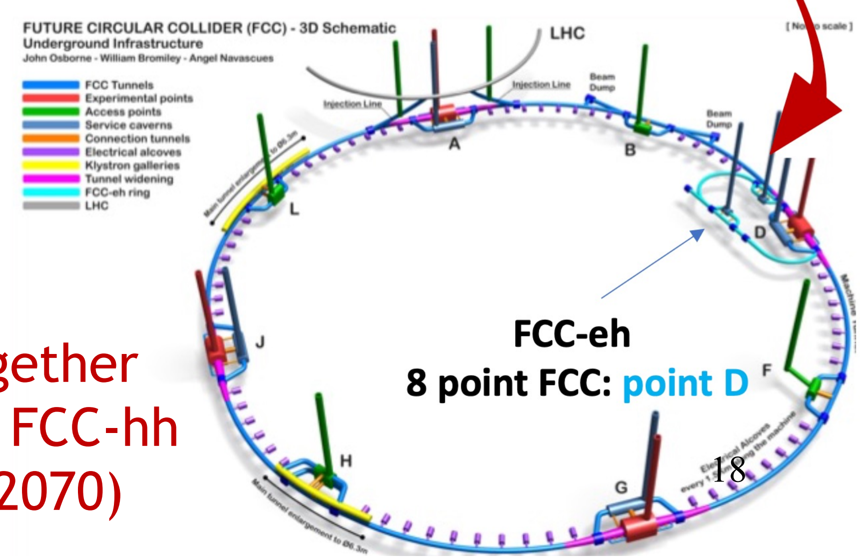
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)

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



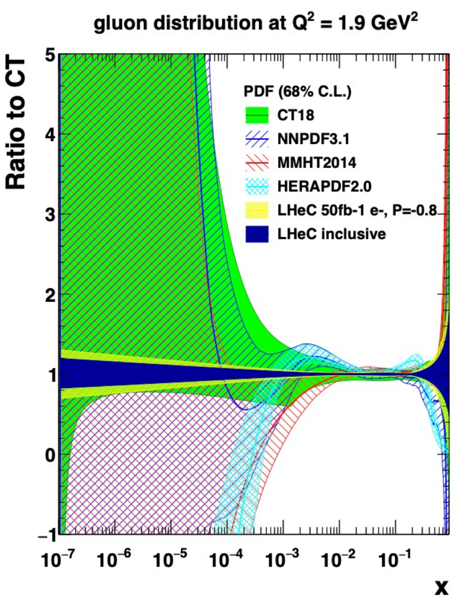
Bridge between HL-LHC and future facilities? (~2038++)

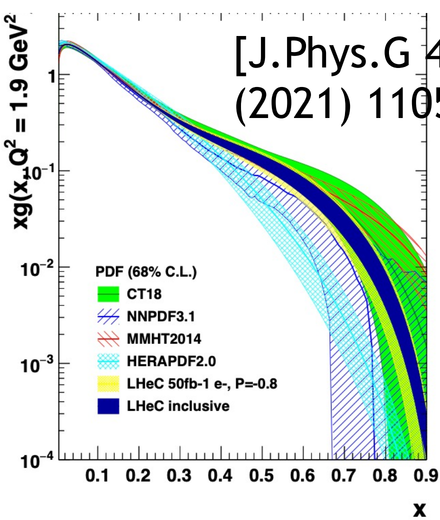
Together with FCC-hh (~2070)



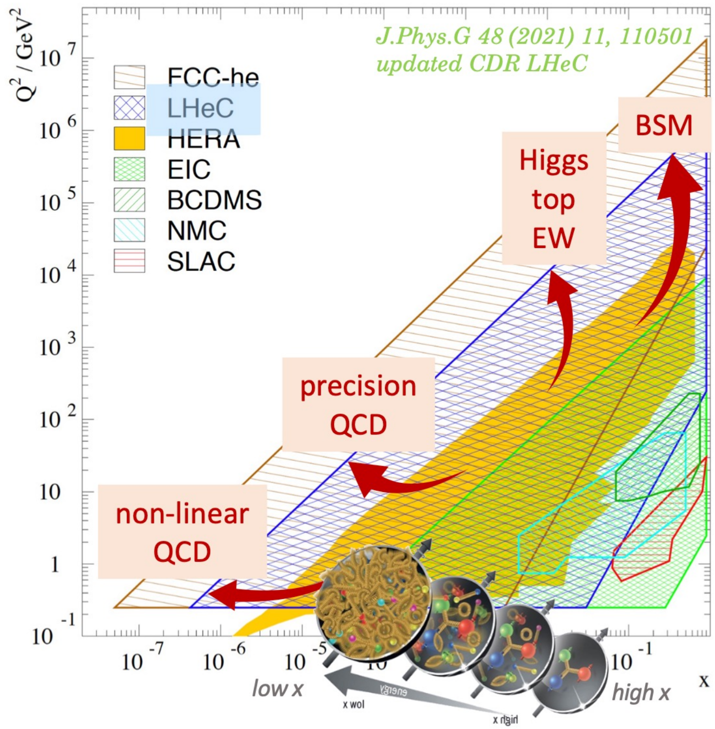
Examples of LHeC Physics Programme

DIS for QCD / hadron structure

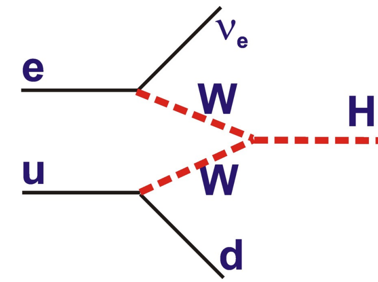


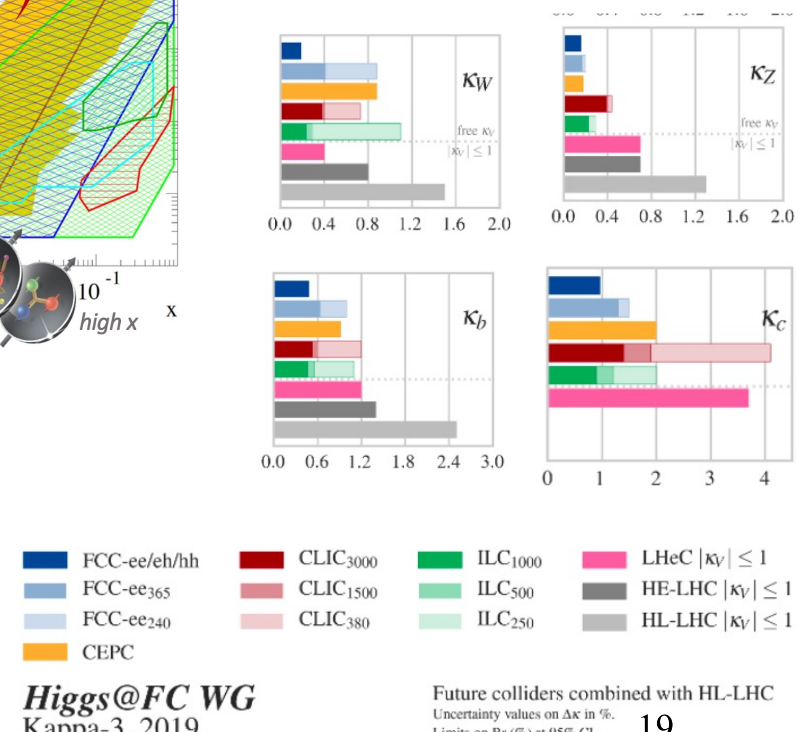


[J.Phys.G 48 (2021) 110501]



Energy-frontier collider (Higgs, searches…)





[JHEP 01 (2020) 139]

Crude Mapping Between Physics & Facilities

Partons with decreasing x →

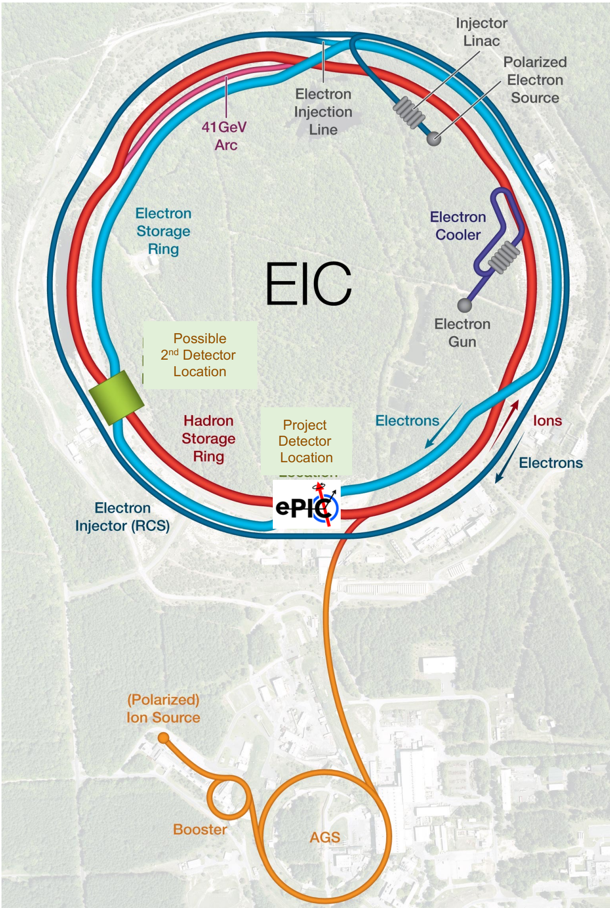
[Kong Tu]

High x (fixed Target)
Basic Structure

Intemediate x (EIC)
Emergent properties

Low x (HERA / LHeC)
QCD radiation
dynamics

The Electron-Ion Collider (BNL)



New electron ring, to collide with RHIC p, A

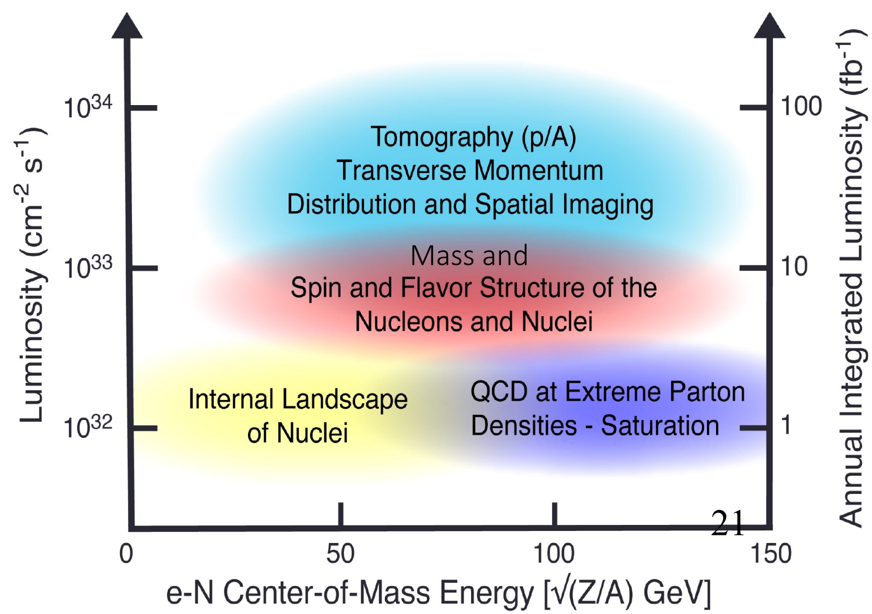
- Energy range **28 < $\sqrt{s}$ < 140 GeV**, accessing moderate / large x values compared with HERA

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:

- 3D proton structure
- Proton mass
- Proton spin
- Dense partonic systems in nuclei



EIC Machine Design Parameters

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

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

→ Synchrotron load management

→ Significant crossing angle

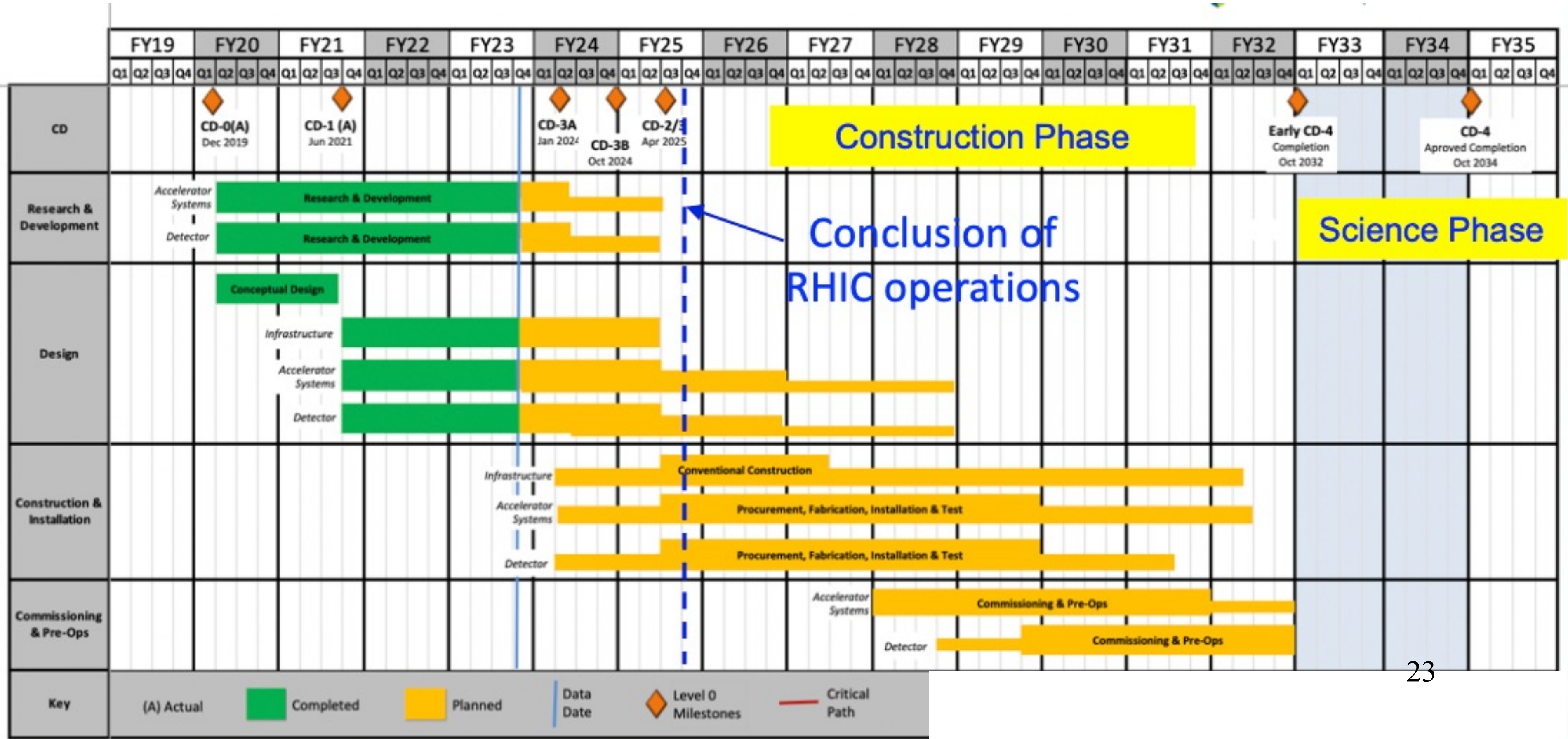
Status / Timeline

- Total cost ~$2Bn (US project funds accelerator + one detector)

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

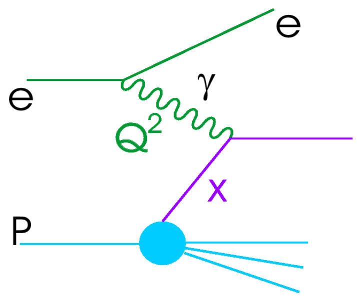
CD-0 (Mission need)	Dec 2019
CD-1 (Cost range)	June 2021
CD-3A (Start construction)	April 2024
CD-3B	Oct 2024?
CD-2 (Performance baseline)	April 2025?
CD-4 (Operations / completion)	2032-34

Technical Design Report: end 2025 (prelim 2024)



Observables / Detector Implications

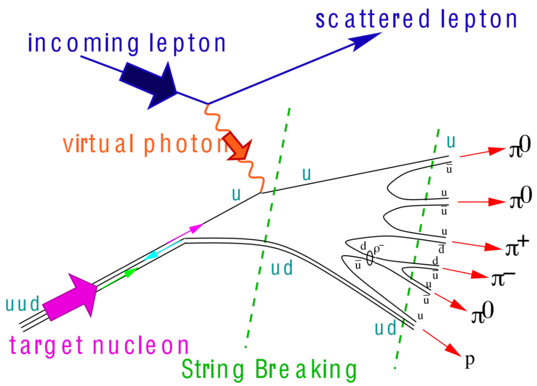
Inclusive



- 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

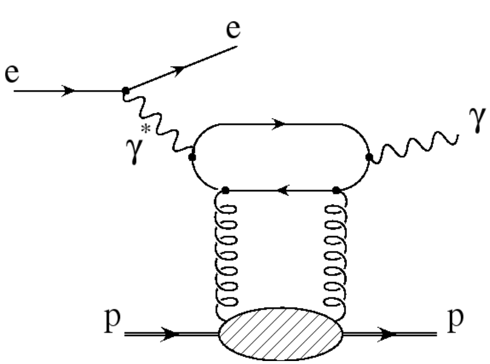
→ Separation of u,d,s,c,b and antiquarks

… tracking and hadronic calorimetry

… heavy flavour identification from vertexing

… light flavours from dedicated PID detectors

Exclusive / Diffractive



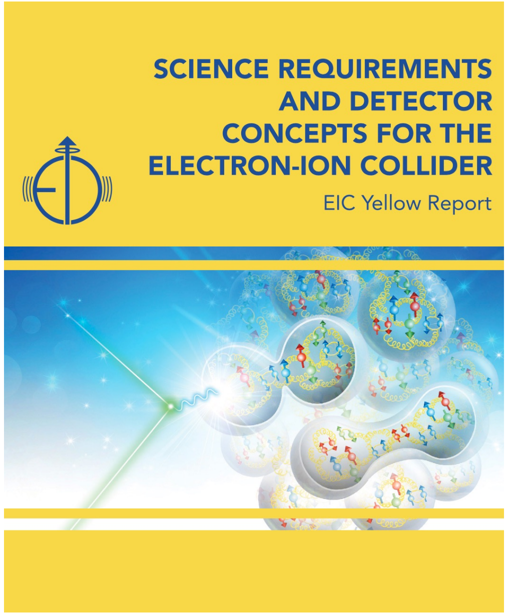
- Processes with final state ‘intact’ protons

→ Correlations in space or momentum between pairs of partons

… efficient proton tagging over wide acceptance range

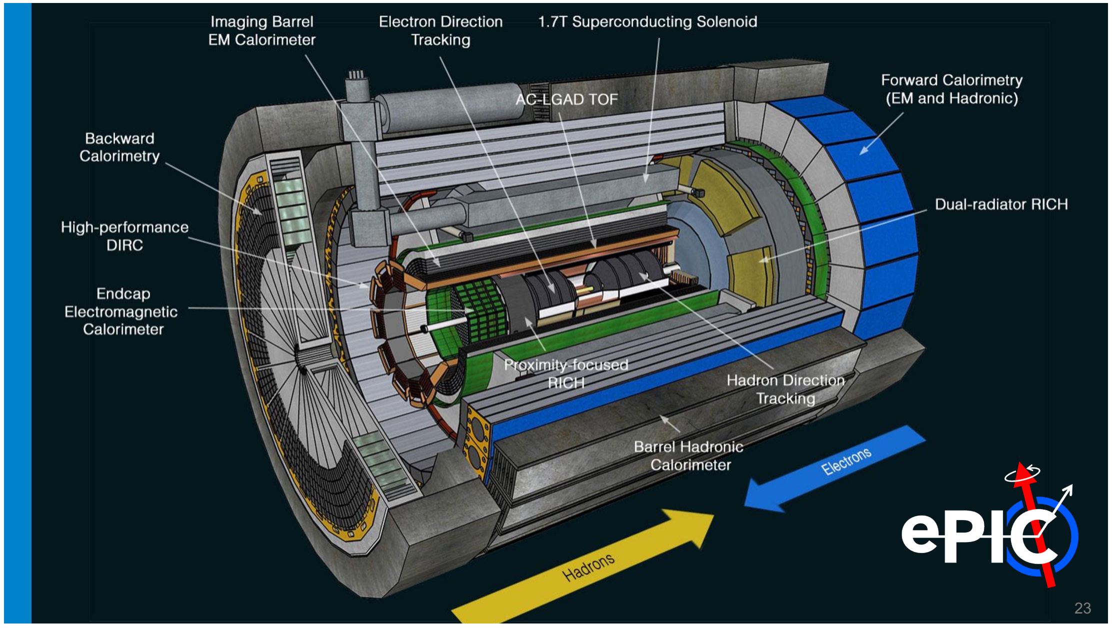
… high luminosity

EIC Experiments



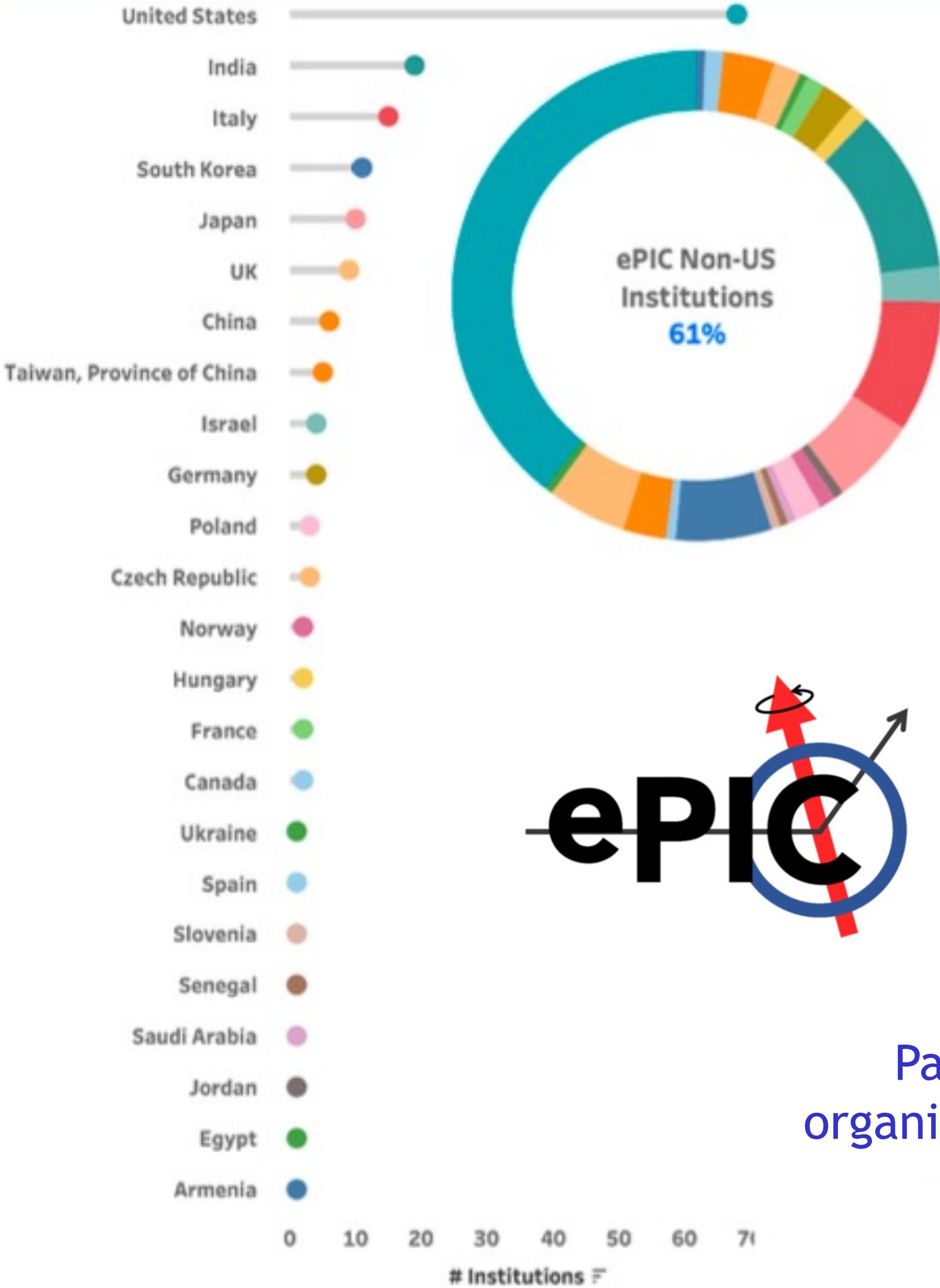
- **Yellow Report (arXiv:2103.05419):**
  … explored physics targets and corresponding detector requirements
  … defined baseline detector

- **ePIC = Project detector**
  … funded through US DoE and international partners (now including UK)



- **Second detector?**
  … an essential ingredient, but not yet funded or designed in detail
  … should bring an overlapping, but complementary physics programme

ePIC Collaboration Demographics



Over >850 participants so far, from ~173 institutes in 24 countries

Part of a wider ‘EIC User Group’ organization with around 1400 members, including theorist colleagues

A Detector for the EIC

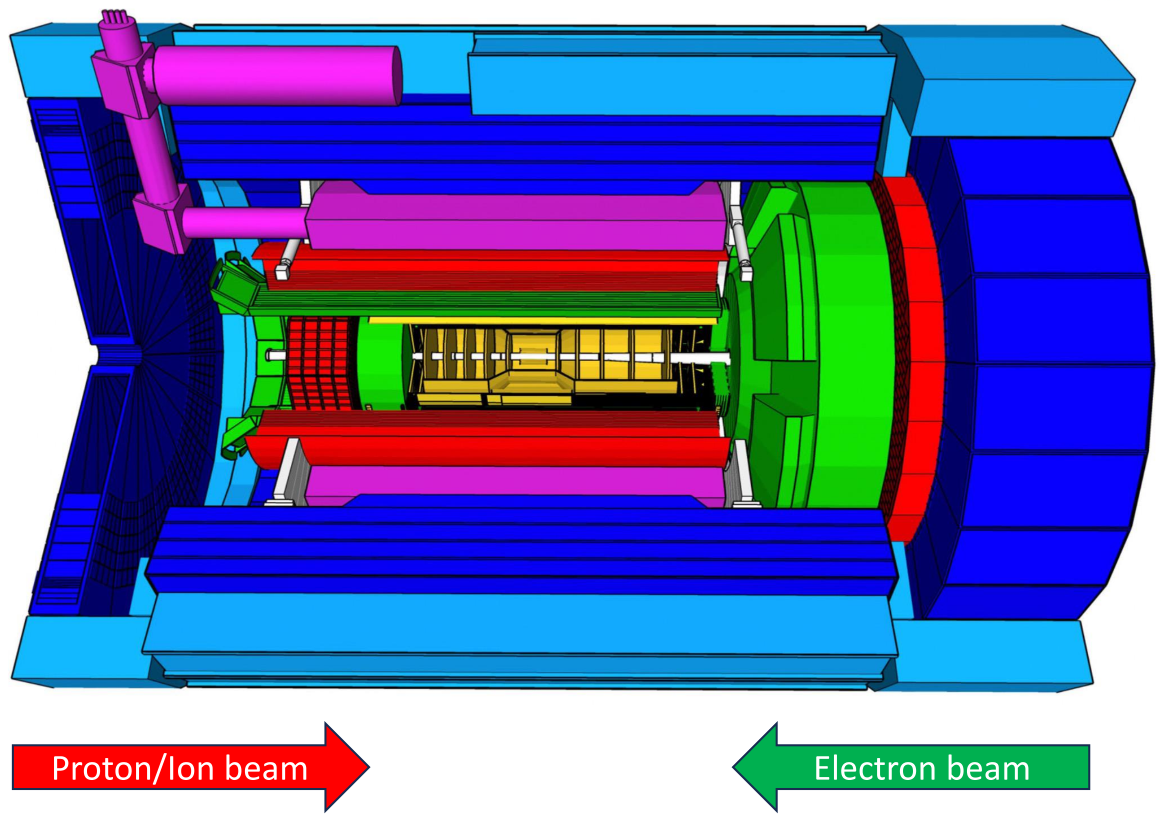
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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)

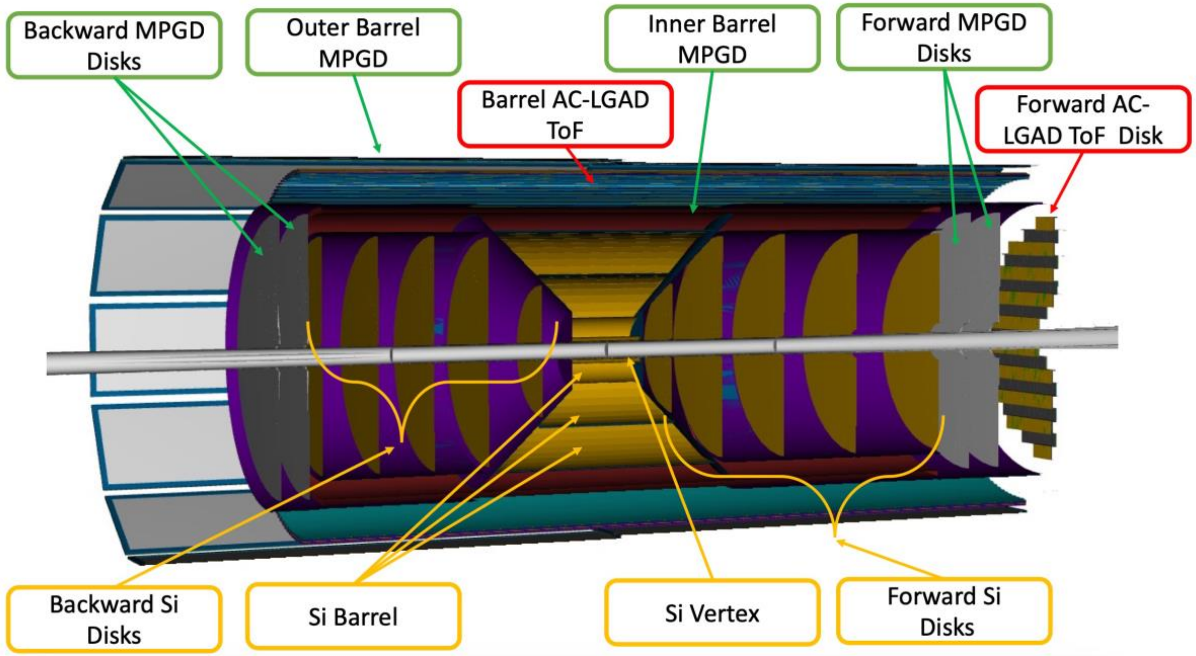


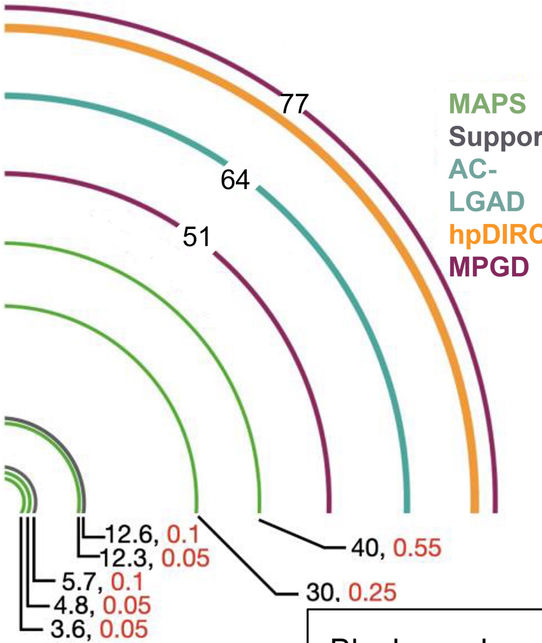
- 9m long x 5m wide
- Hermetic (central detector $-4 < \eta < 4$)
- Extensive beamline instrumentation not shown (see later)
- Continuous streaming readout with emphasis on FEB zero-suppression
- Much lower radiation fluxes than LHC widens technology options

Tracking Detectors

Primarily based on MAPS silicon detectors (65nm CMOS imaging technology)

- Leaning heavily on ALICE ITS3
- Stitched wafer-scale sensors, thinned and bent around beampipe
  → Very low material budget ($0.05X_0$ for inner layers)
- 20x20μm pixels
- 5 barrel layers + 5+5 disks (total 8.5m² silicon)





Black numbers are radii in cm

Red numbers are material in % X0

LGAD layers provide fast timing (~20ns)

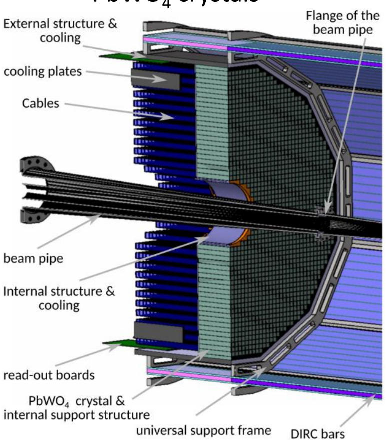
Outer gaseous detectors add additional hit points for track reconstruction

Calorimeter Overview

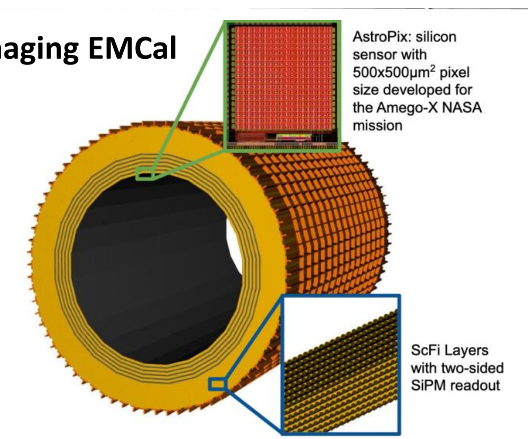
- Different technologies in barrel and end-caps, as required for varying performance targets
- ECAL emphasis: backward (e) and central regions
- HCAL emphasis: forward (p) region
- All read out with Si PMs

Electron Endcap EMCal

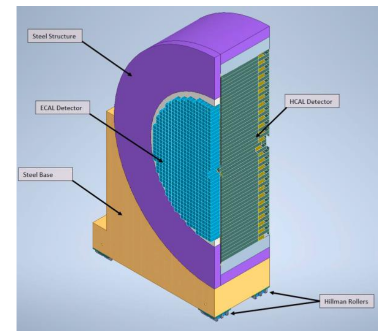
$PbWO_4$ crystals



Barrel Imaging EMCal

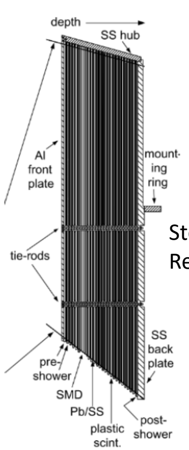


Hadron Endcap EMCal



High granularity W-powder/SciFi EMCal

Electron Endcap HCal



Steel/Scint Sandwich (10
Reuse of STAR scint. tiles

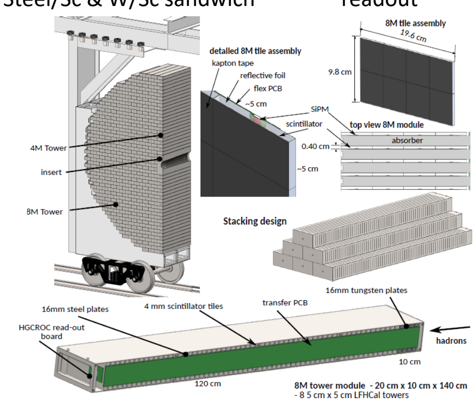
Barrel HCal

sPHENIX barrel calorimeter with new SiPMs

Hadron Endcap HCal

Longitudinally separated HCAL Steel/Sc & W/Sc sandwich

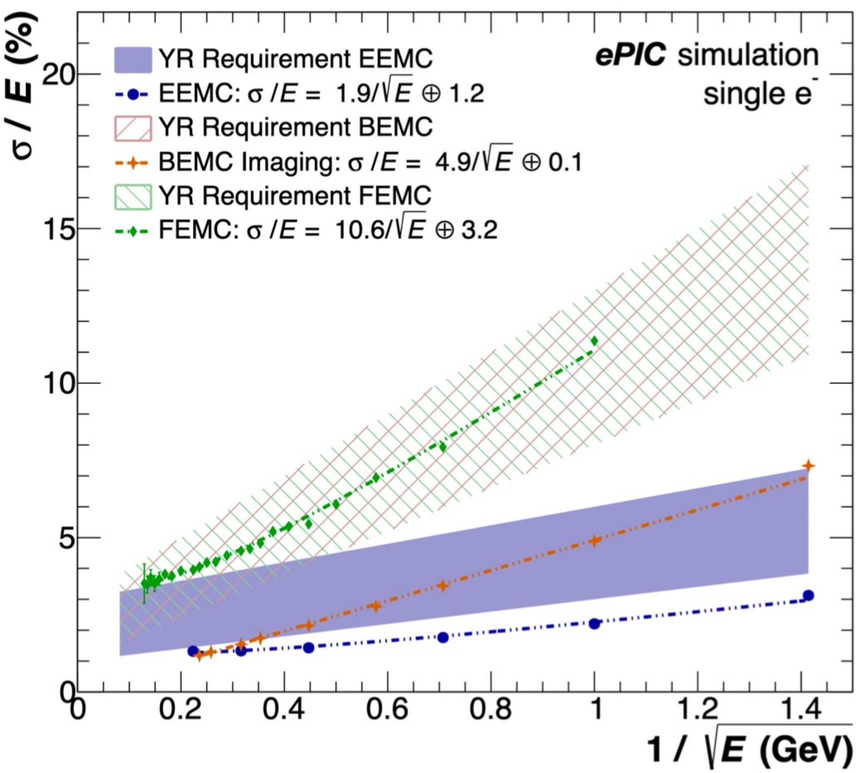
SiPM-on-tile readout

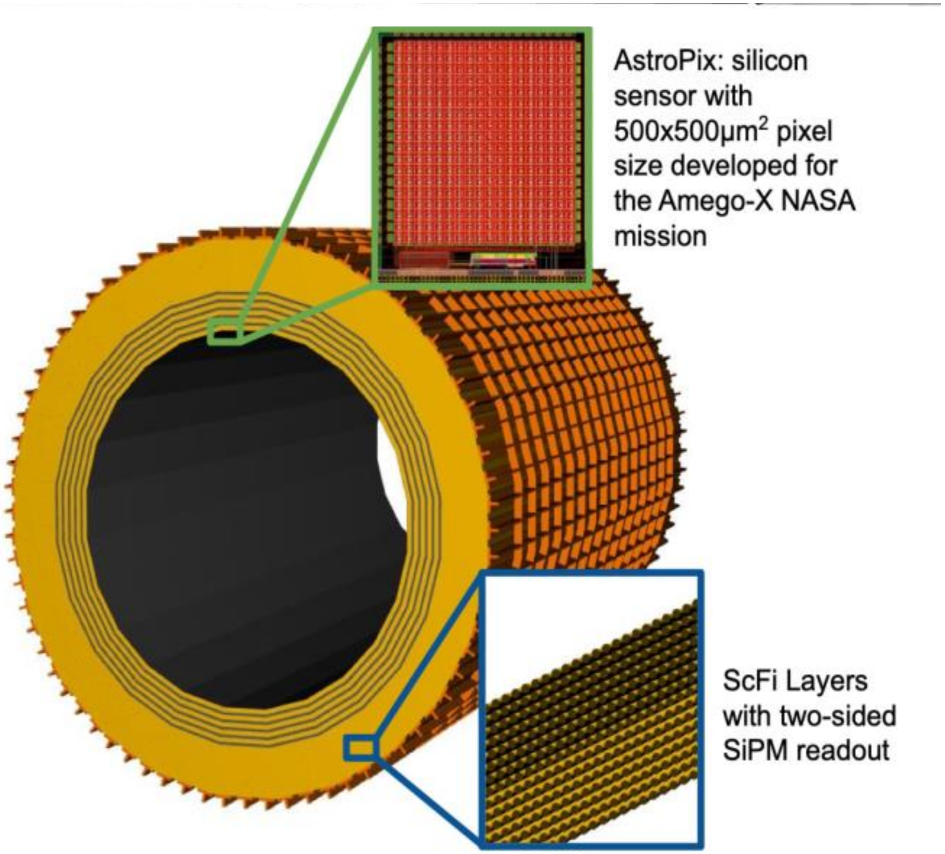


\+ high granularity insert at largest η

Barrel 'Imaging ECAL'

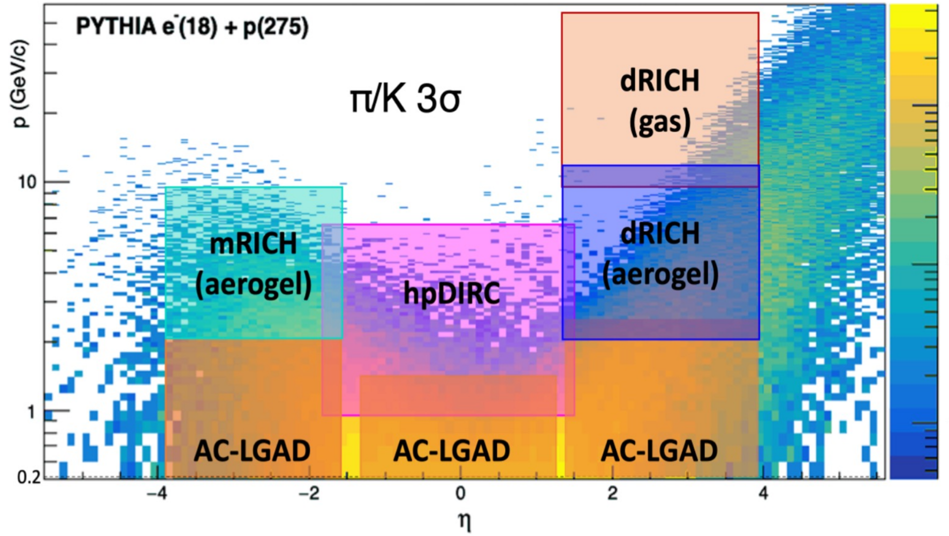
- 4 MAPS (Astropix) layers for position resolution and π^0 rejection
- Interleaved with 5 Pb/SciFi layers for energy resolution
- Followed by large Pb/SciFi section





Particle Identification

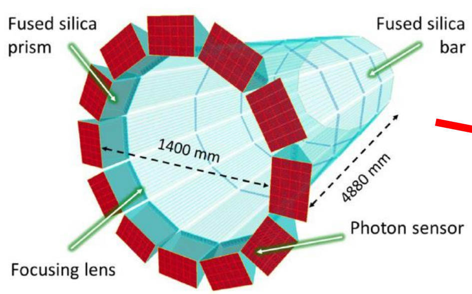
- SIDIS programme relies on π / K / p (and other PID) separation …
- Cerenkov detectors augmented by AC-LGADs (ToF) at low momentum give coverage for 200 MeV - 50 GeV

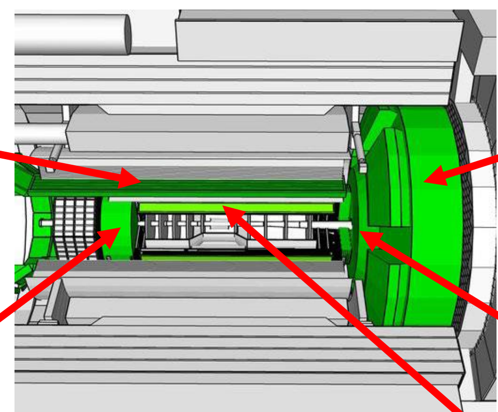


ePIC detector design – PID

High-Performance DIRC

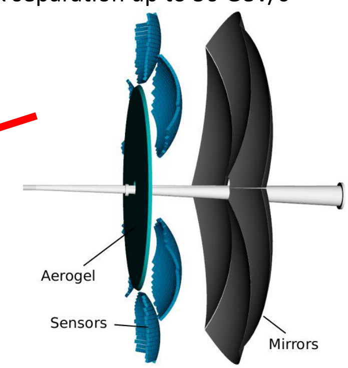
- Quartz bar radiator (reuse BaBAR bars)
- Sensors: MCP-PMTs
- π/K separation up to 6 GeV/c

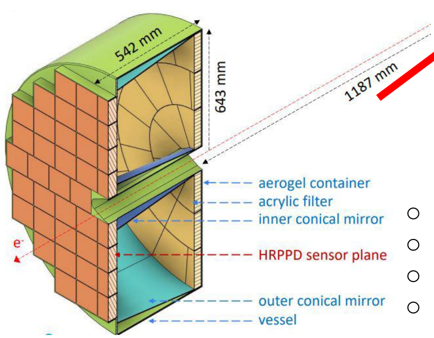




Dual-Radiator RICH (dRICH)

- C_2F_6 Gas Volume and Aerogel
- Sensors: SiPMs tiled on spheres
- π/K separation up to 50 GeV/c



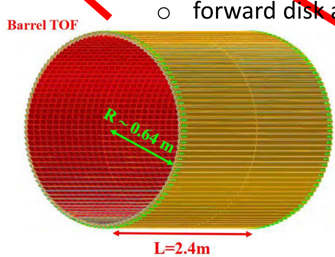


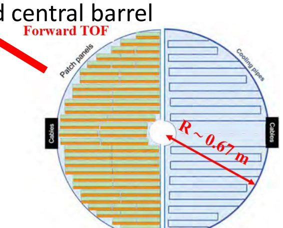
Proximity Focused (pfRICH)

- Long Proximity gap (~40 cm)
- Sensors: HRPPDs (also provides timing)
- π/K separation up to 10 GeV/c
- e/π separation up to 2.5 GeV/c

AC-LGAD TOF

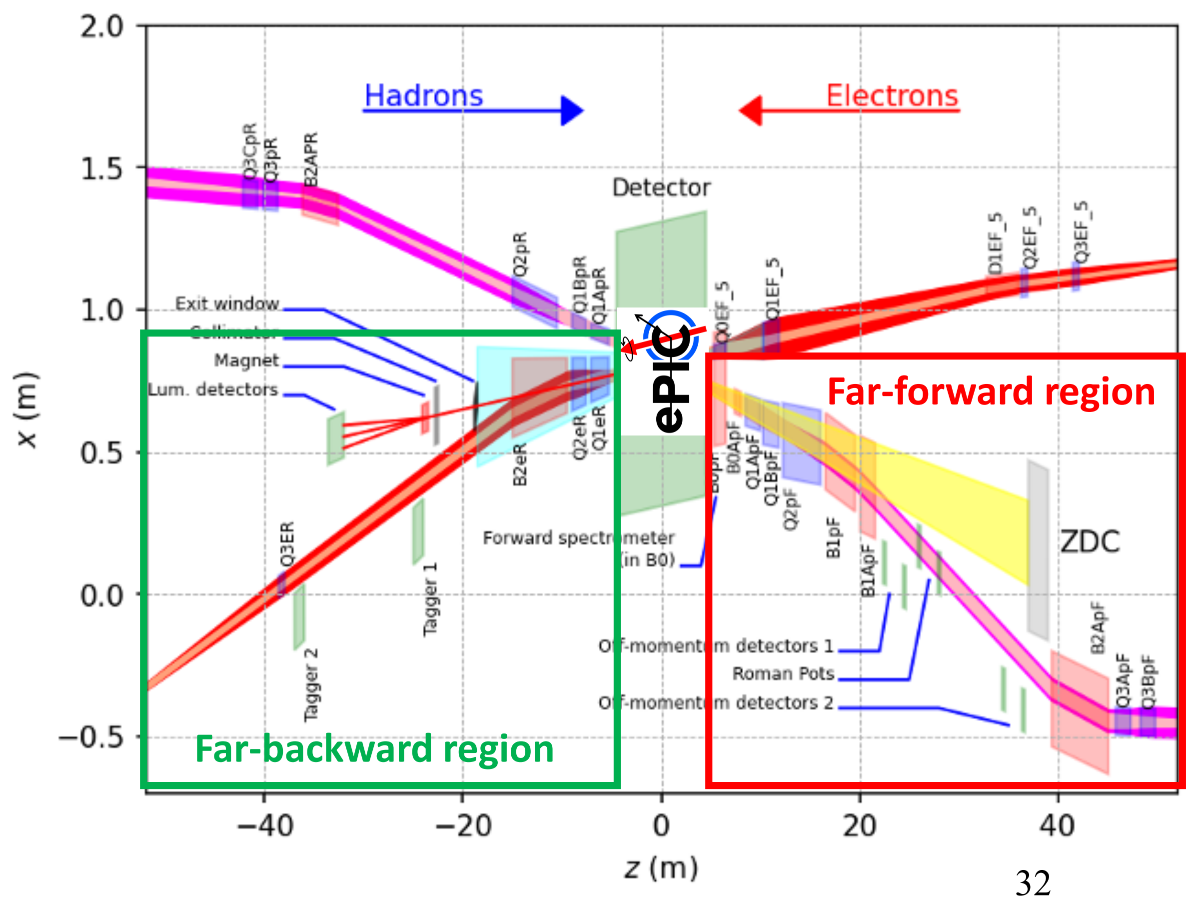
- t = ~30 psec / s = 30 µm
- Accurate space point for tracking
- forward disk and central barrel





Interaction Region / Beamline Instrumentation

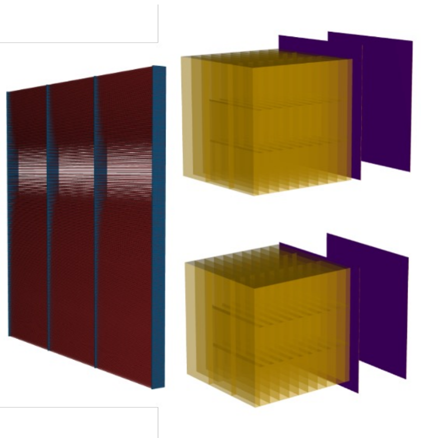
- Extensive beamline instrumentation integrated into IR design



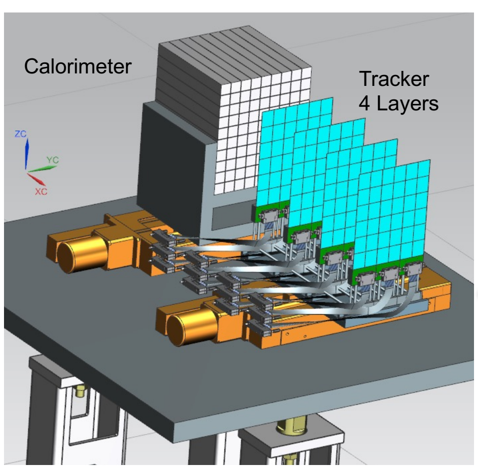
Interaction Region / Beamline Instrumentation

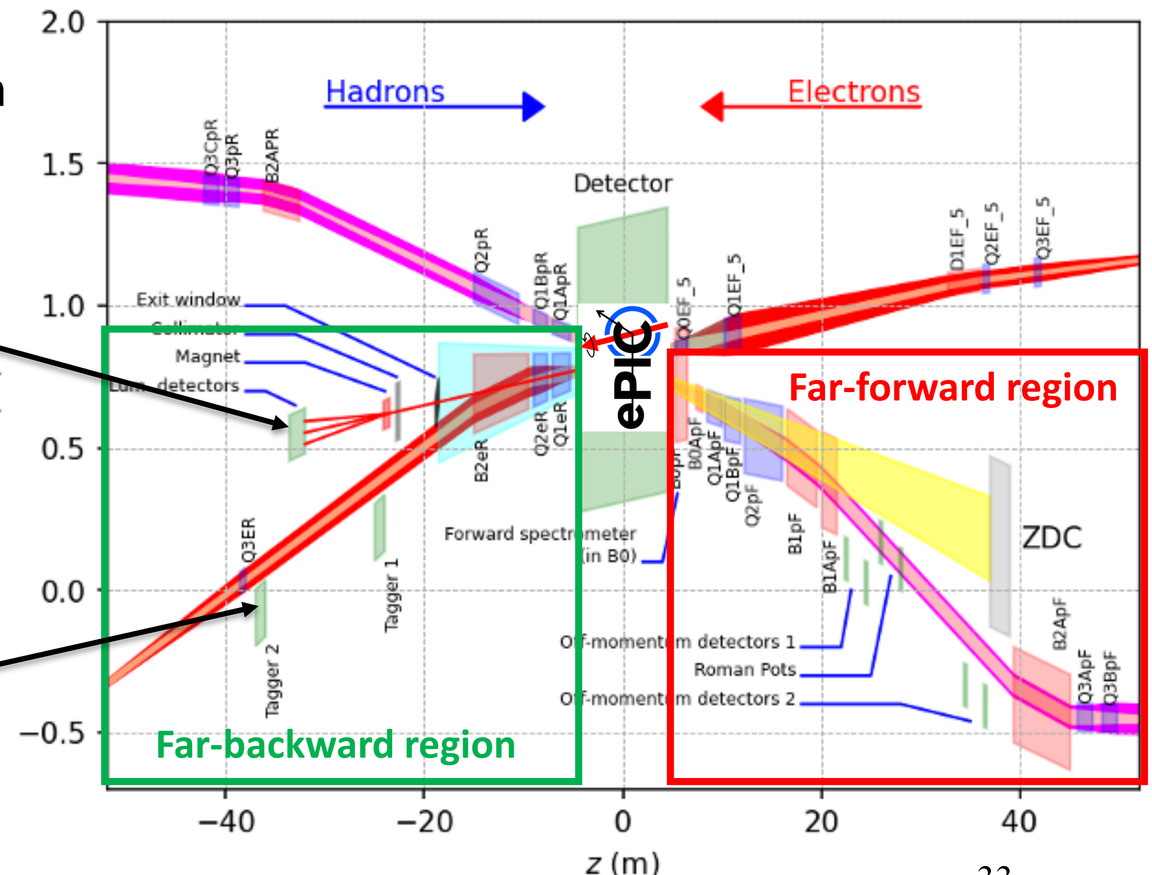
- Extensive beamline instrumentation integrated into IR design

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



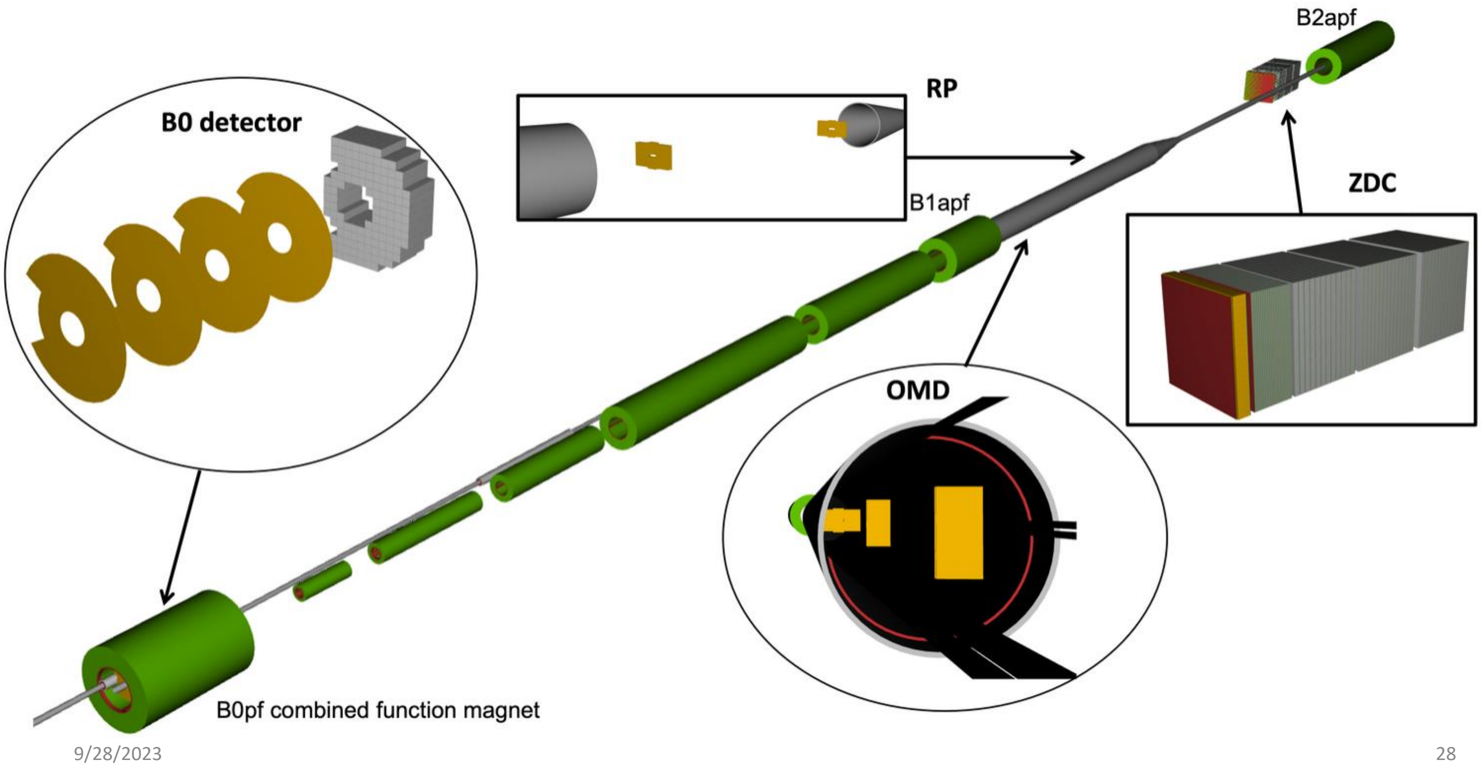
Direct and Pair-production lumi spectrometers





2 low Q^2 electron taggers (tracker + calo)

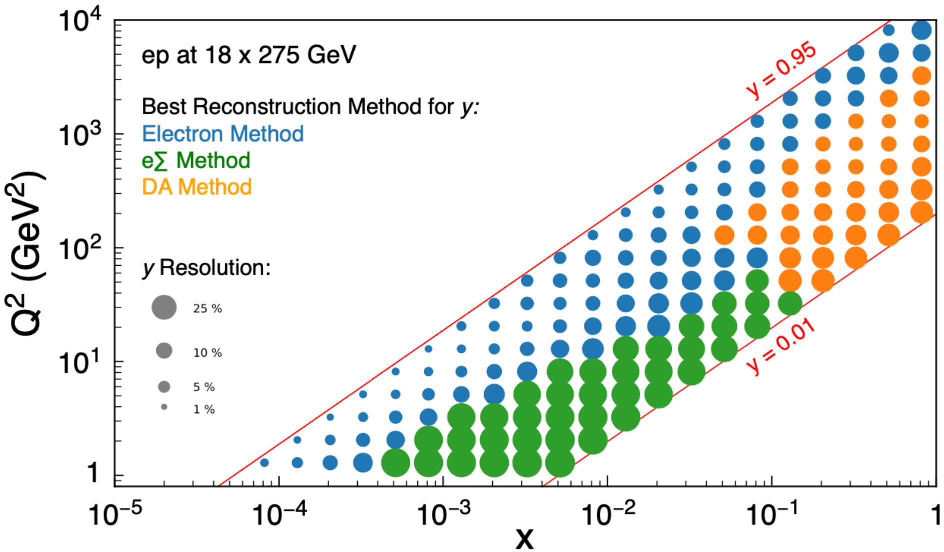
Far Forward Region



- Forward proton coverage outside and inside beampipe ($0.45 < x_L < 0.95$ with RP and OMD, more with B0)
- ZDC (neutrons etc) follows ALICE FOCAL design

Detector	Acceptance	Particles
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5\ mrad$	Neutrons, photons
Roman Pots (2 stations)	$0^* < \theta < 5.0\ mrad$ (*10σ beam cut)	Protons, light nuclei
Off-Momentum Detectors (2 stations)	$0 < \theta < 5.0\ mrad$	Charged particles
B0 Detector	$5.5 < \theta < 20\ mrad$	Charged particles, tagged photons

Performance and Measurement Strategy



- Choose reconstruction methods exploiting the hadronic final state as well as the electron to optimise (x, Q^2) resolutions throughout phase-space

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

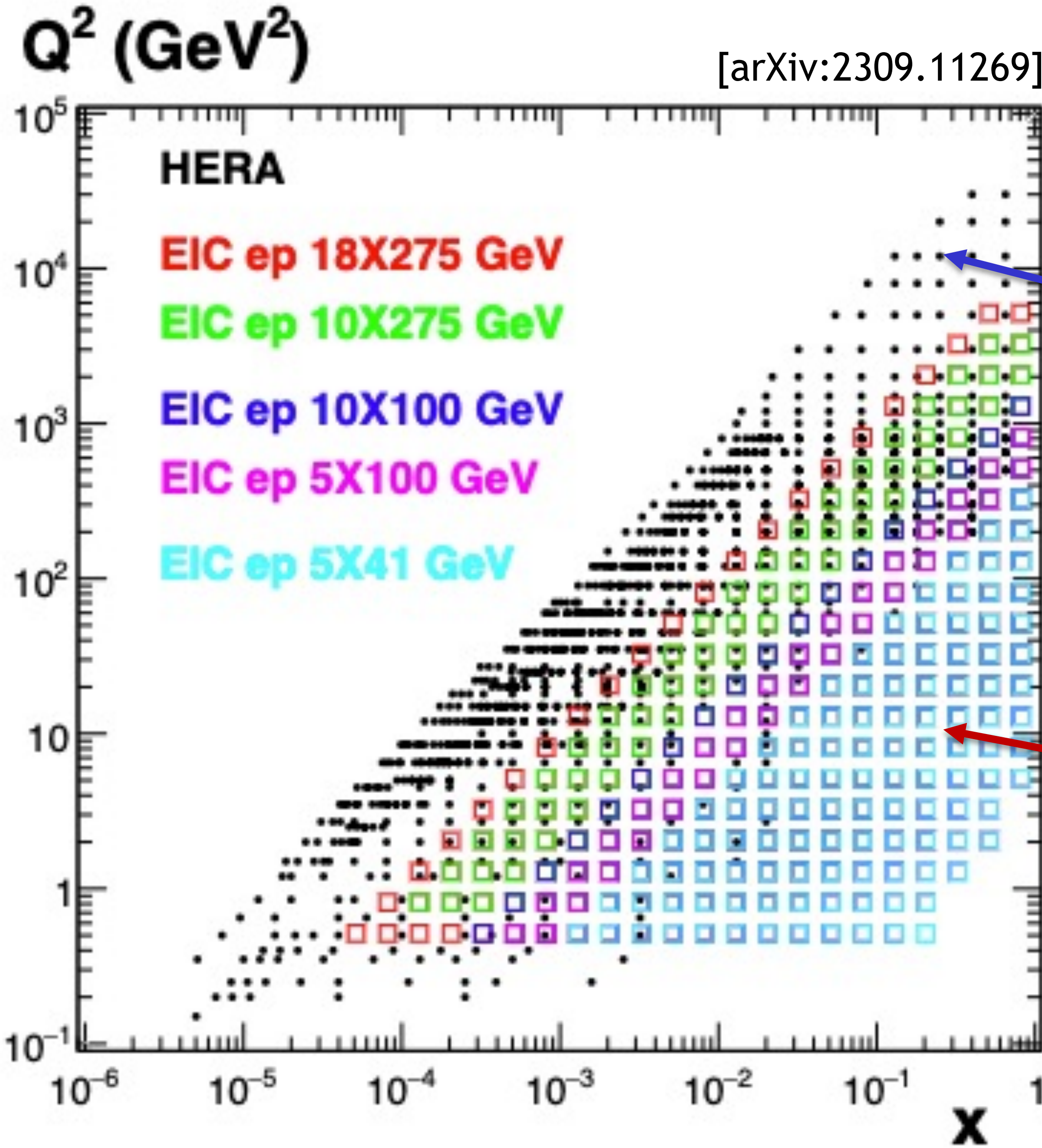
- Exploit overlaps between data at different $\sqrt{s}$ to avoid 'extreme' phase space regions

- Systematic precision estimated from experience at HERA, expected EIC detector performance, and guesswork

Simulations based on precision:
- 1 year of data at each beam config
- 1.5-2.5% point-to-point uncorrelated
- 2.5% normalisation

Inclusive EIC Data Impact on Proton PDFs

[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

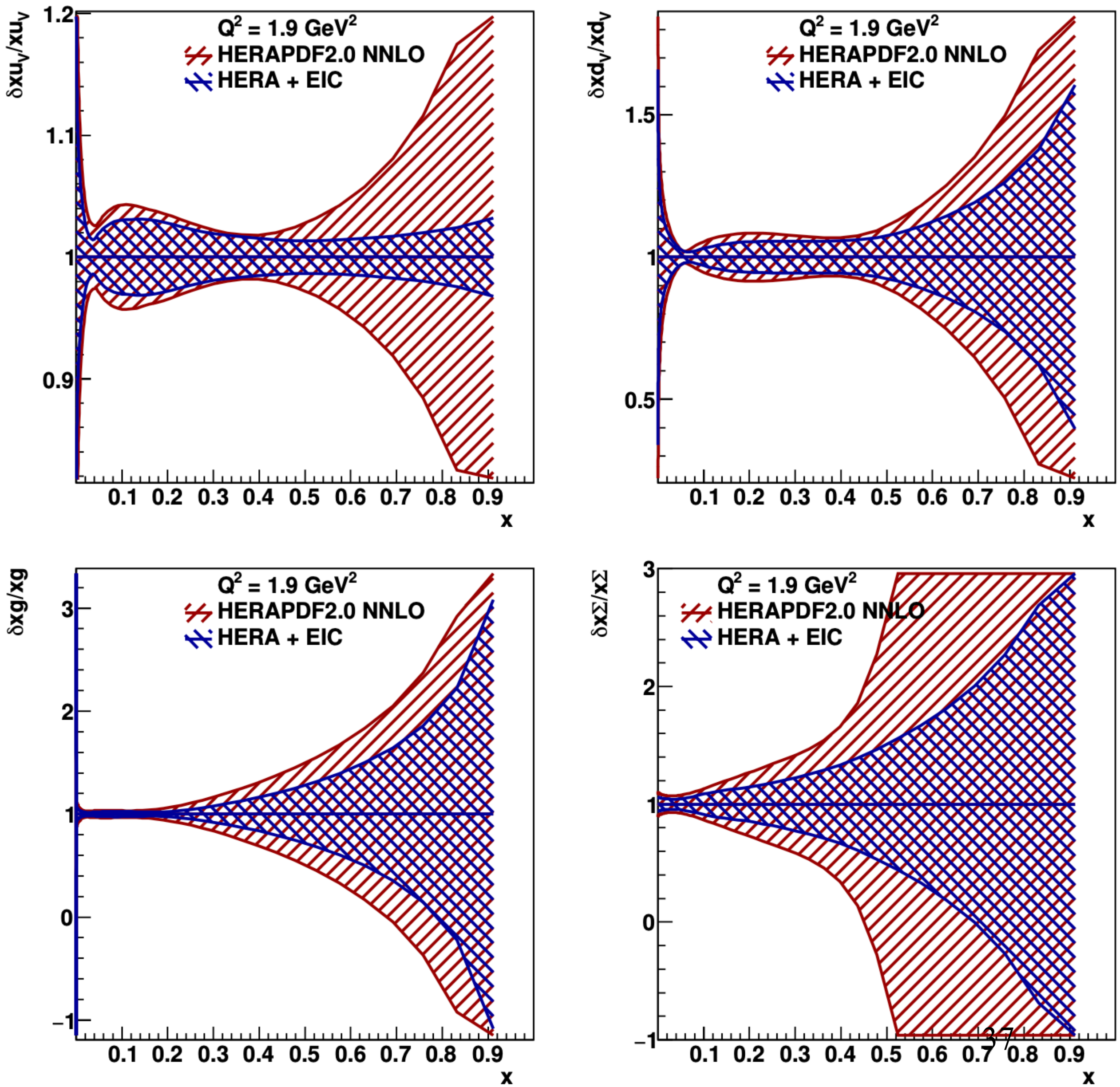
Impact of EIC/ATHENA on HERAPDF2.0

Fractional total uncertainties with / without simulated EIC data included with HERA

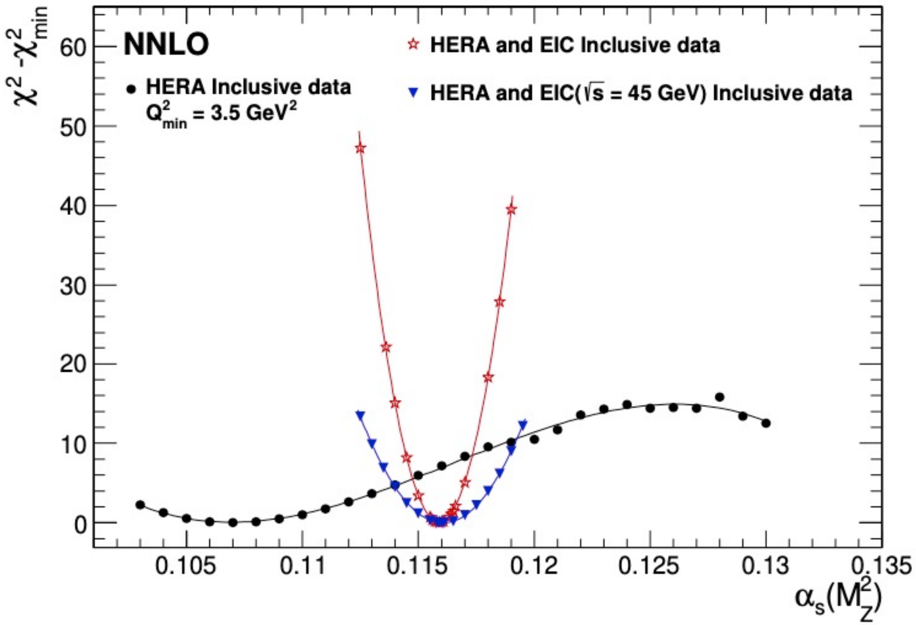
(linear x scale, $Q^2 = Q_0^2$)

… EIC will bring significant reduction in uncertainties for all parton species at large x

… most notable improvements for up quarks (charge-squared weighting)



Taking α_s as an additional free parameter



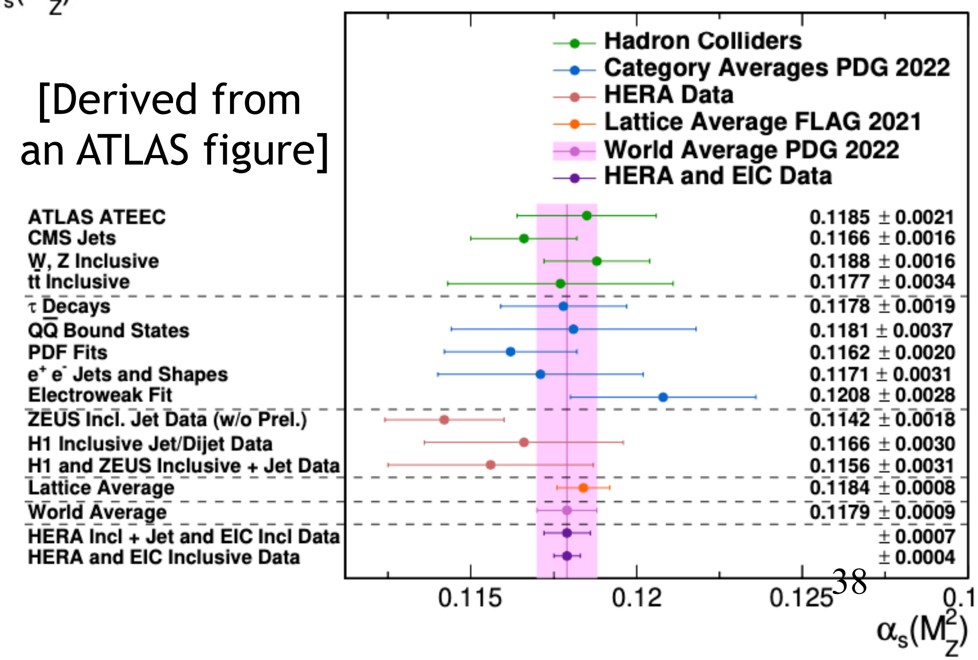
- HERA data alone (HERAPDF2.0) shows only limited sensitivity when fitting inclusive data only.

- Adding EIC simulated data has a remarkable impact

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

Adding EIC (<u>precision high x</u>) data to HERA can lead to α_s precision a factor ~2 better than current world experimental average, and than lattice QCD average

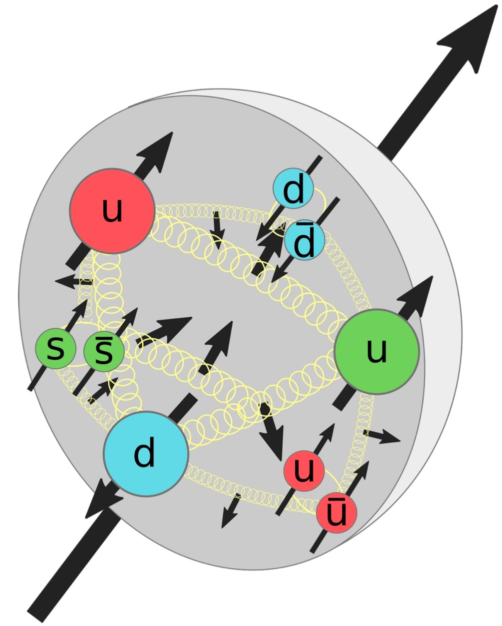
[Derived from an ATLAS figure]



Scale uncertainties remain to be understood (ongoing work)

Physics Motivation: Proton Spin

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



- EMC 'spin crisis' (1987) … quarks only carry about 10% of the nucleon spin

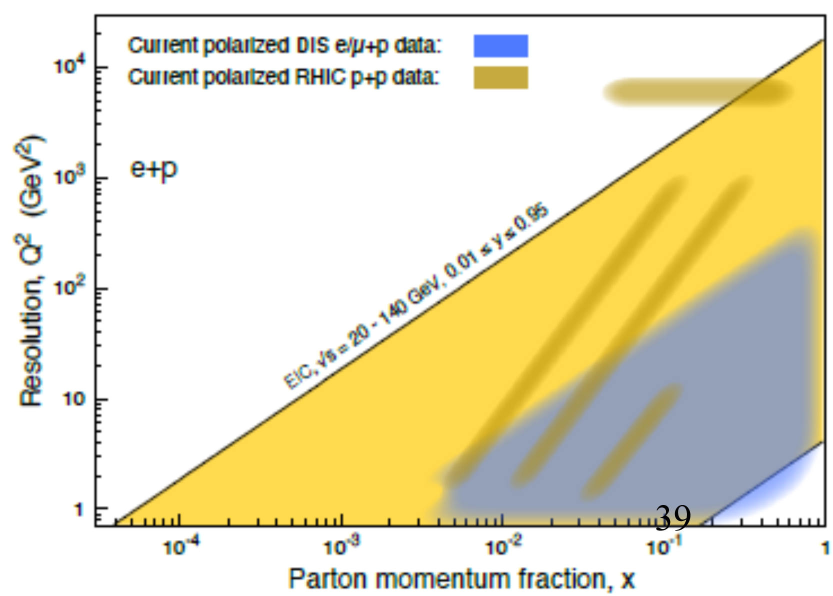
- Viewed at the parton level, complicated mixture of quark, gluon and relative orbital motion, evolving with Q^2, but always = ½

Jaffe-Manohar sum rule:

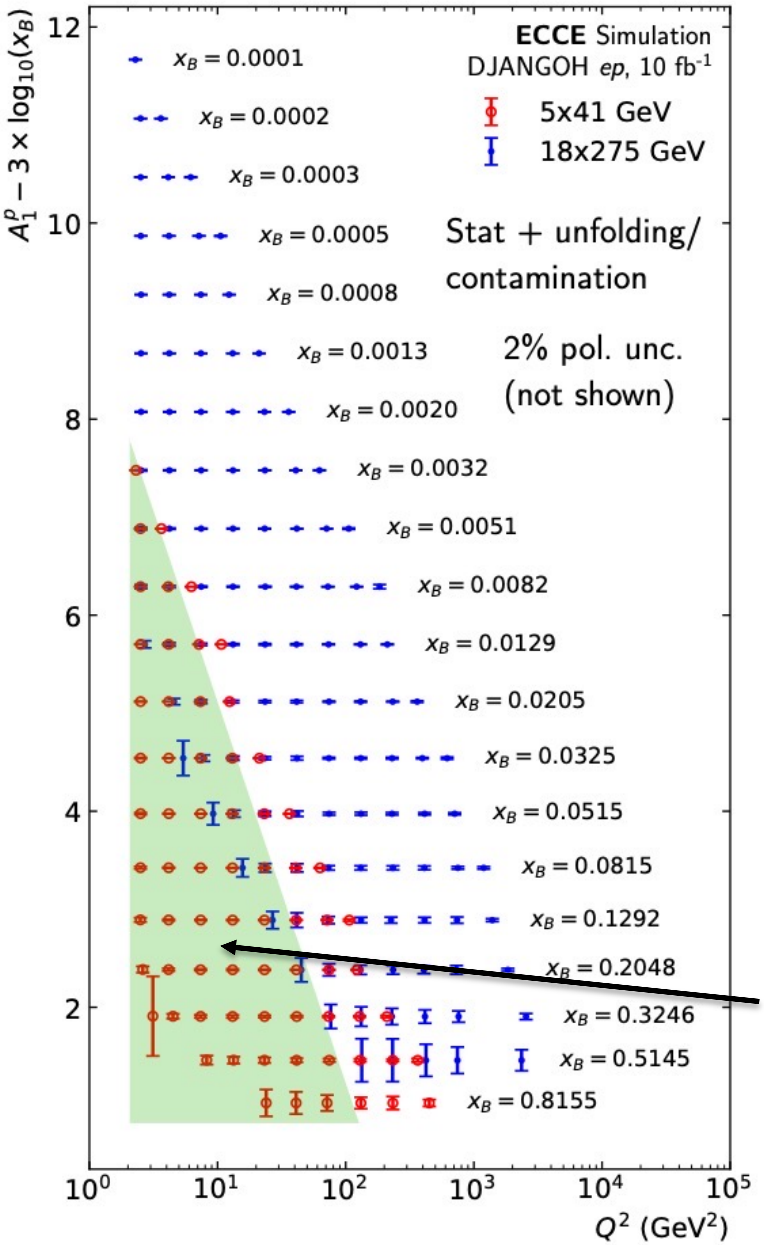
$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

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

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



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



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

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

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

… measure the quark and antiquark helicity distributions …

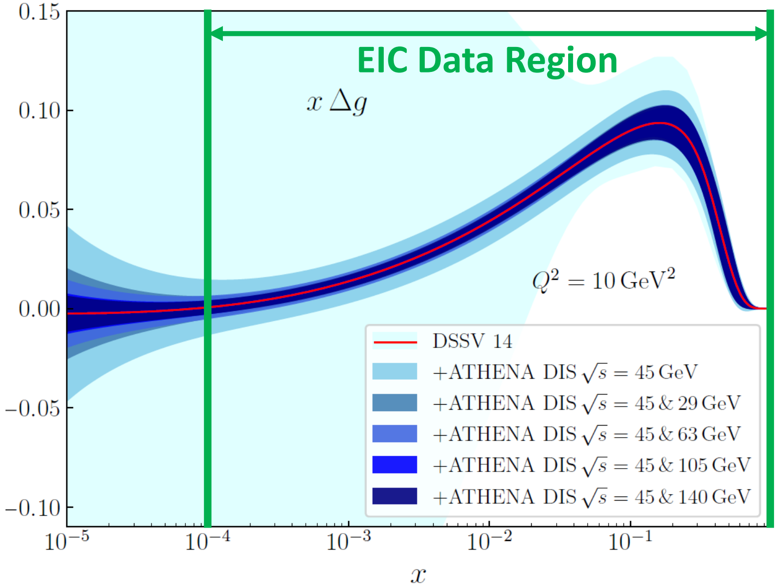
$$g_1(x) = \sum \left(\Delta q(x) + \Delta \bar{q}(x)\right)$$

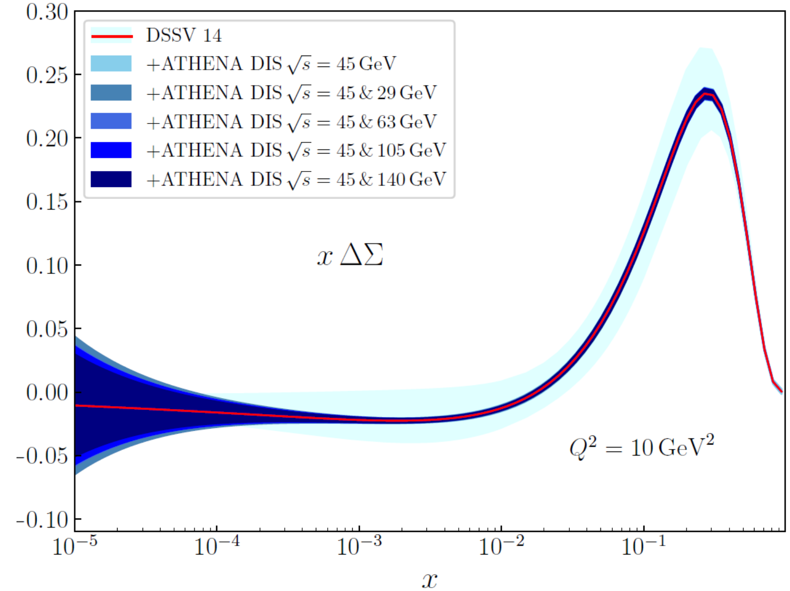
… which gives gluon sensitivity from Q^2 dependence (scaling violations)

Previously measured region (in green)

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

Impact on Helicity Distributions

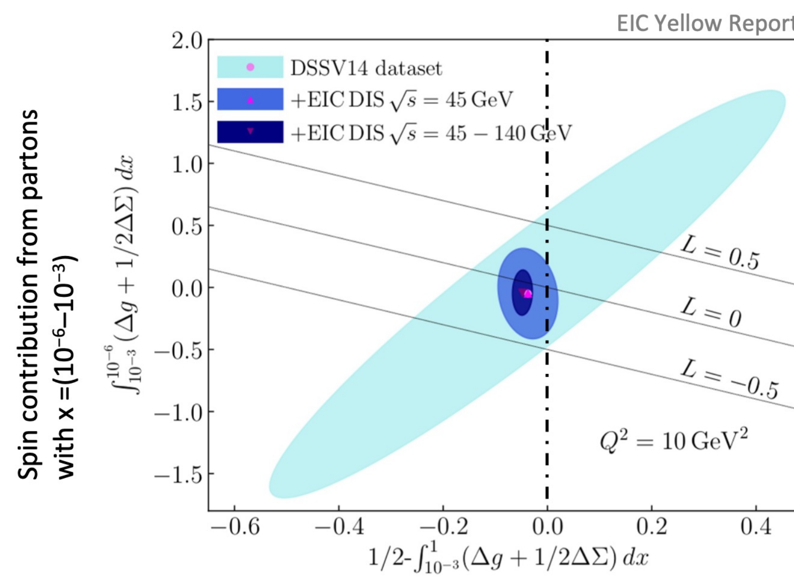




- Simulated NC data with integrated luminosity 15fb^{-1}, 70% e,p Polaris'n

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

- Orbital angular momentum similarly constrained by implication



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

EIC nuclear PDFs: high parton densities

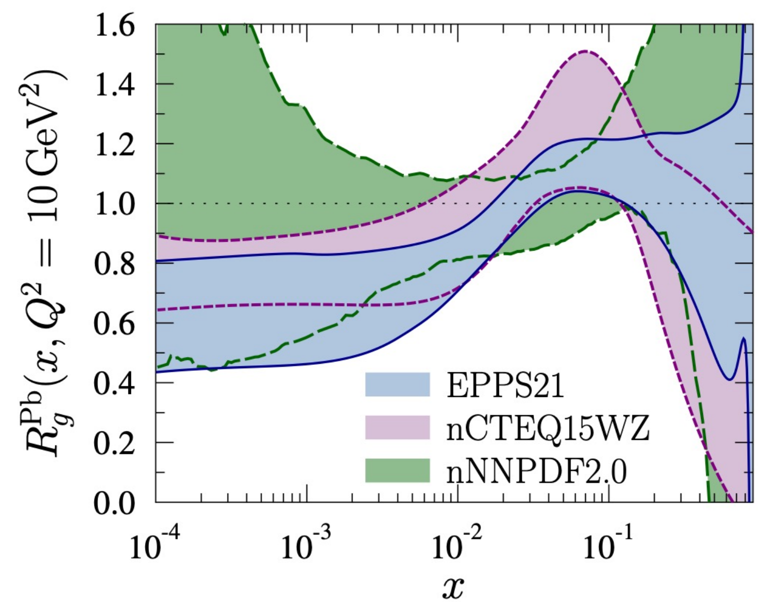
- Nuclei enhance density of partons
  ($\sim A^{1/3}$ factor at fixed x, Q^2)

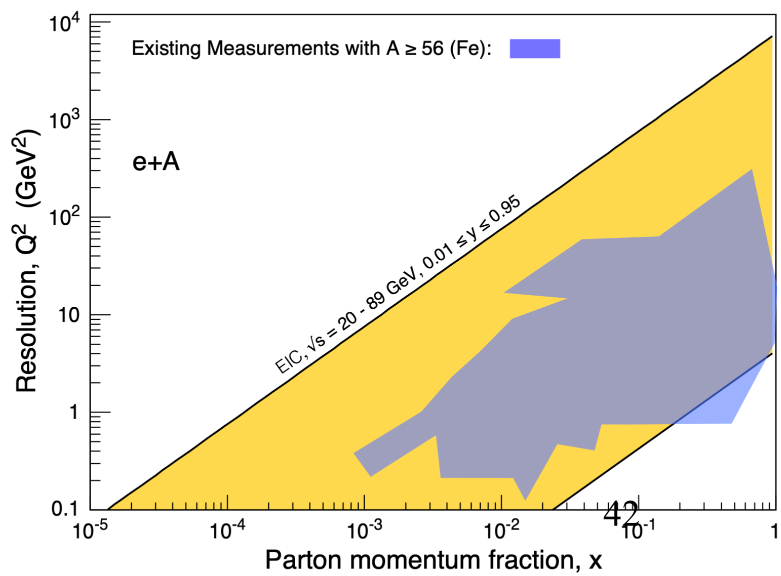
- Results usually shown in terms of nuclear modification ratios: change relative to simple scaling of (isospin-corrected) proton

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

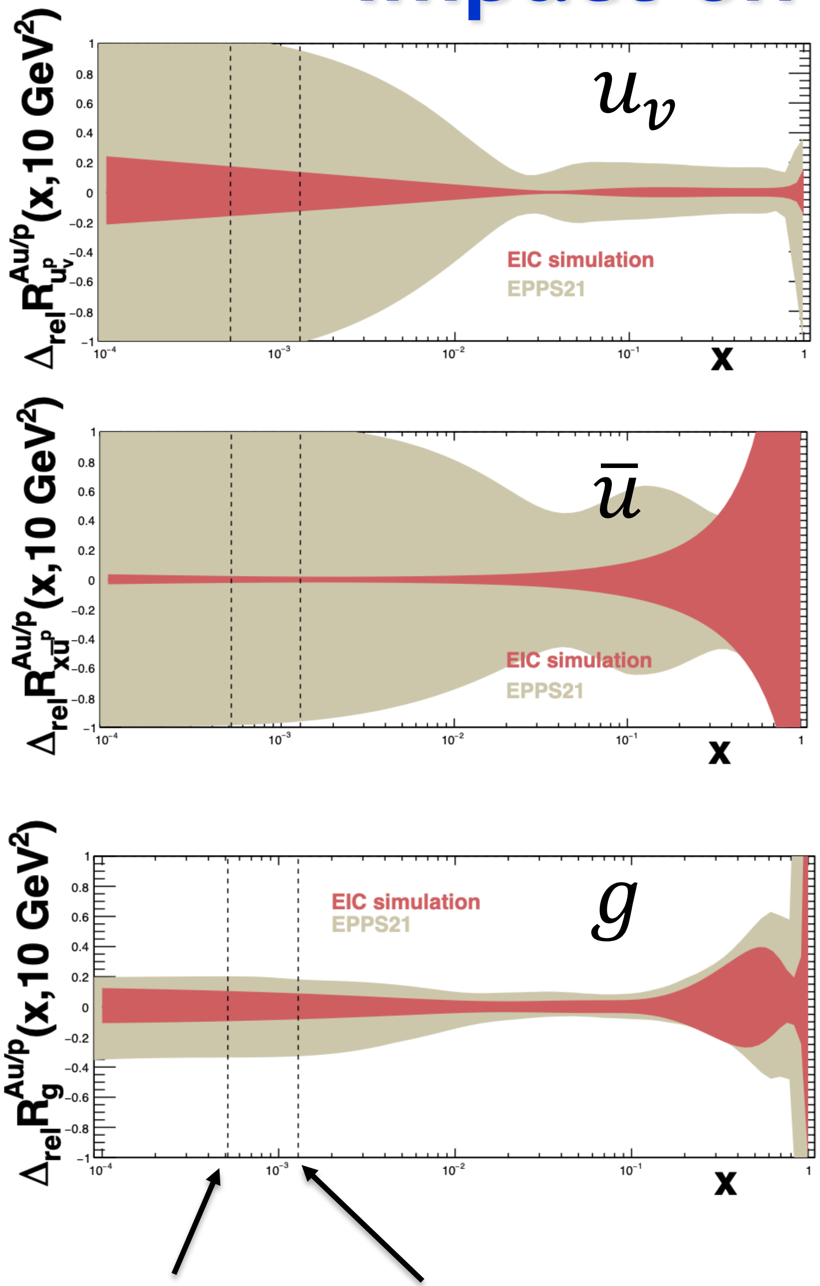
... poorly known, especially for gluon and at low x

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





Impact on Nuclear PDFs



EIC eA data limit
EPPS21 data limit

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

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

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

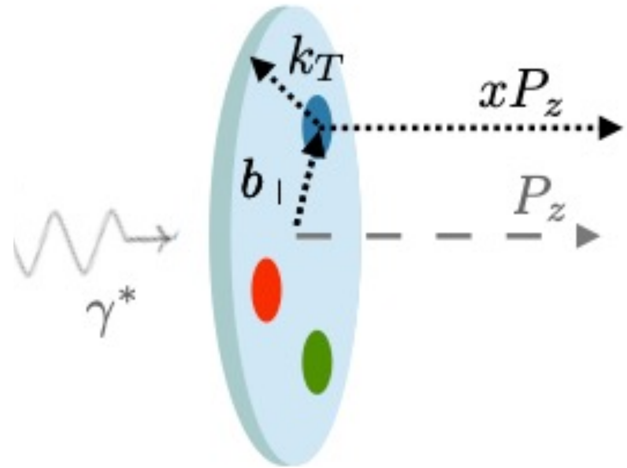
Sensitivity of EIC relative to EPPS21 recent nuclear PDFs (EIC-only fit)

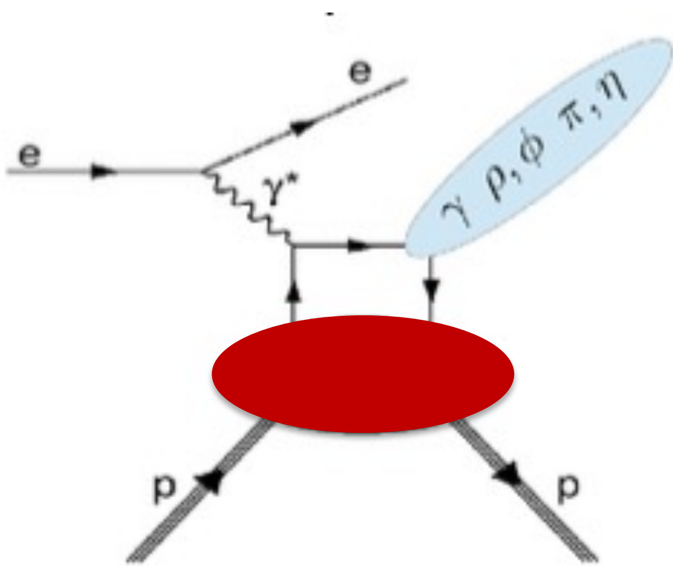
→ Factor ~ 2 improvement at x~0.1

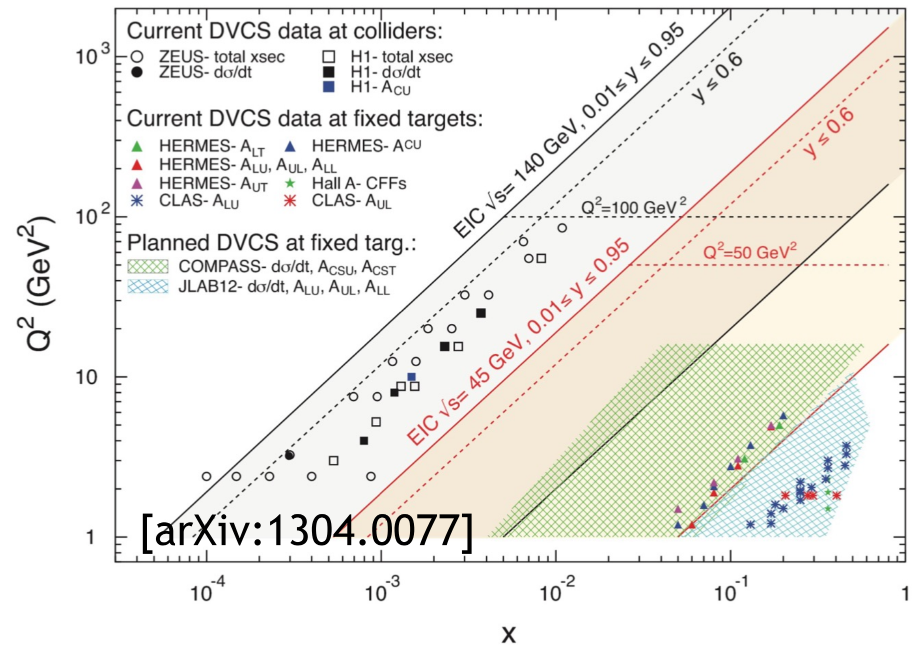
→ Very substantial improvement in newly accessed low x region

Physics Motivation: 3D Structure

Exclusive processes, yielding intact protons, require (minimum) 2 partons exchanged
→ Sensitivity to correlations between partons in longitudinal / transverse momentum and spatial coordinates
→ access to 3D tomography





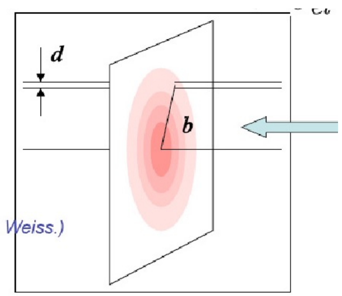


e.g. Deeply Virtual Compton Scattering, ep → eγp:
EIC fills gap between (high stats) fixed target & (low stats) HERA data

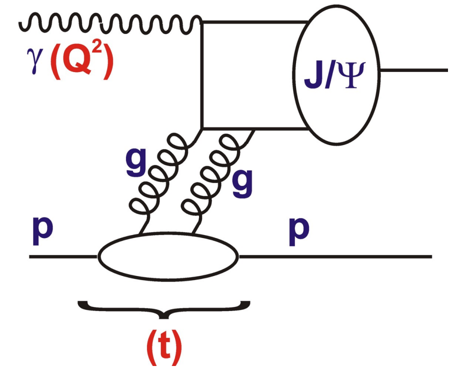
Exclusive Processes and Dense Systems

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

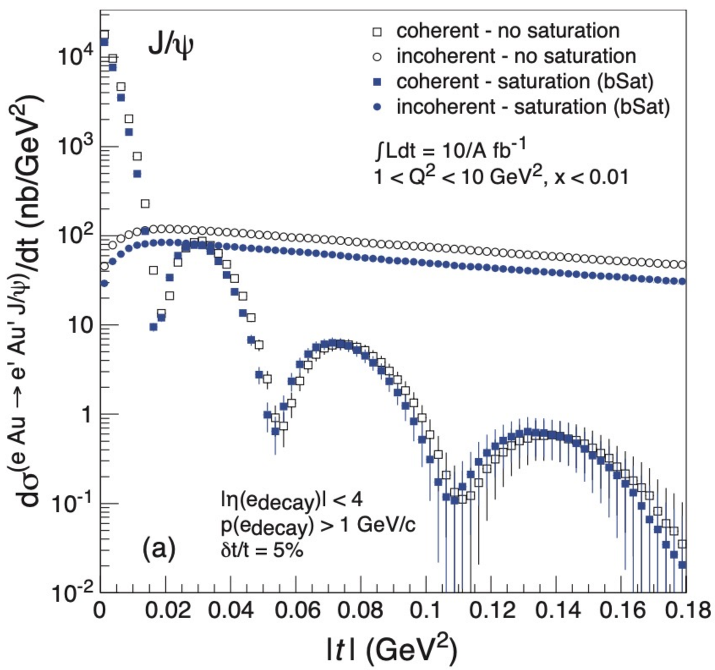
→ Large t (small b) probes small impact parameters etc.



(figure from C. Weiss.)

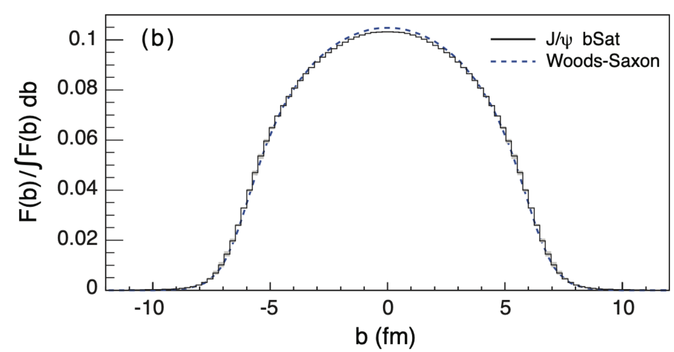


[arXiv:1211.3048]



e.g. Coherent J/Ψ production at small t in eAu measures average density profile, with dips at larger t sensitive to saturation or other novel effects in dense regions

→ Fourier transform

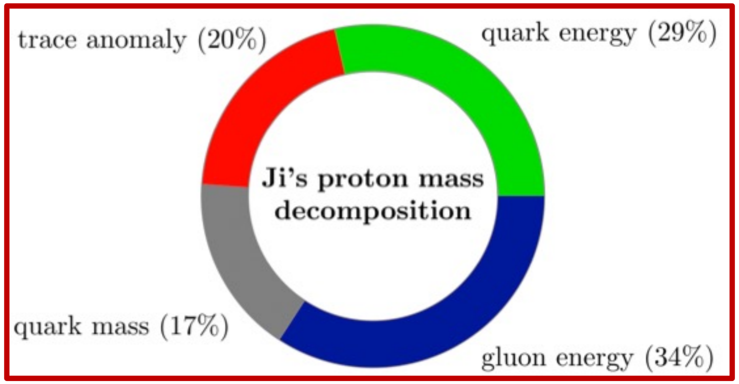


Experimental challenges from incoherent background and resolving dips

Physics Motivation: Proton Mass

- Constituent quark masses contribute ~1% of the proton mass

- Remainder is `emergent' → generated by (QCD) dynamics of multi-body strongly interacting system



- Decomposition along similar lines to spin:

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

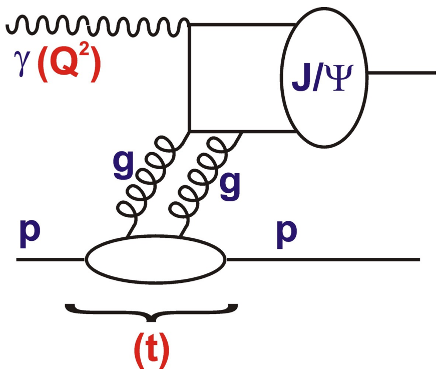
Valence and sea quark masses (including heavy quarks)

Quark and gluon 'KE' from confinement and relative motion

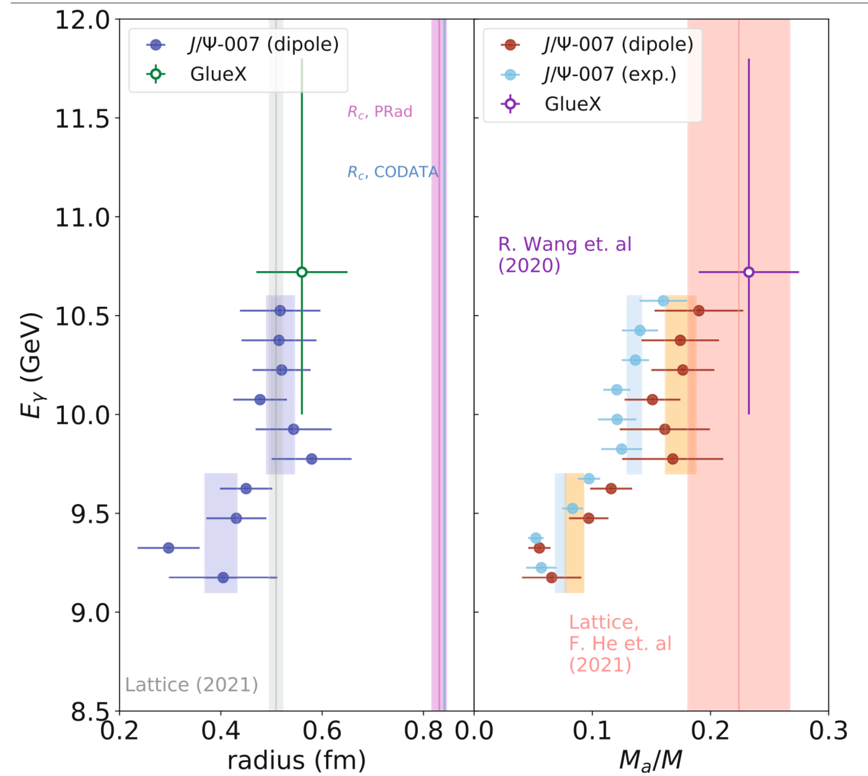
QCD trace anomaly (purely quantum effect - chiral condensates)

- Relations to experimental observables still being understood.
- Recent progress, eg with gravitational form factors of the proton

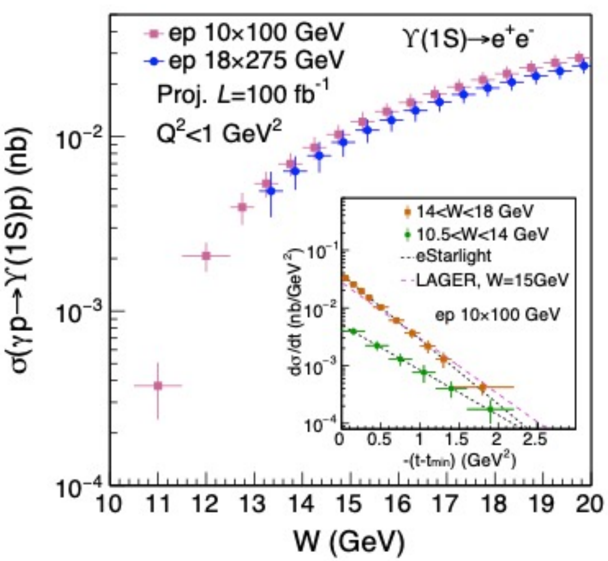
Proton Mass & Exclusive Vector Mesons

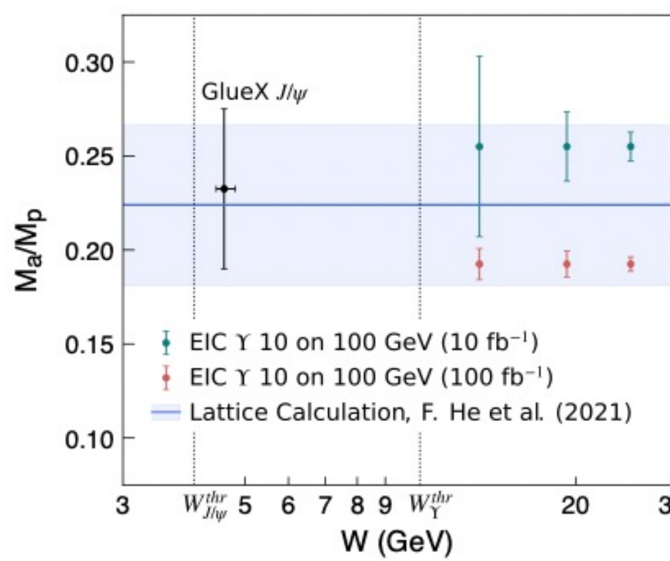


- Recent Jlab data on t dependences of J/Ψ production near threshold → Gravitational form factors



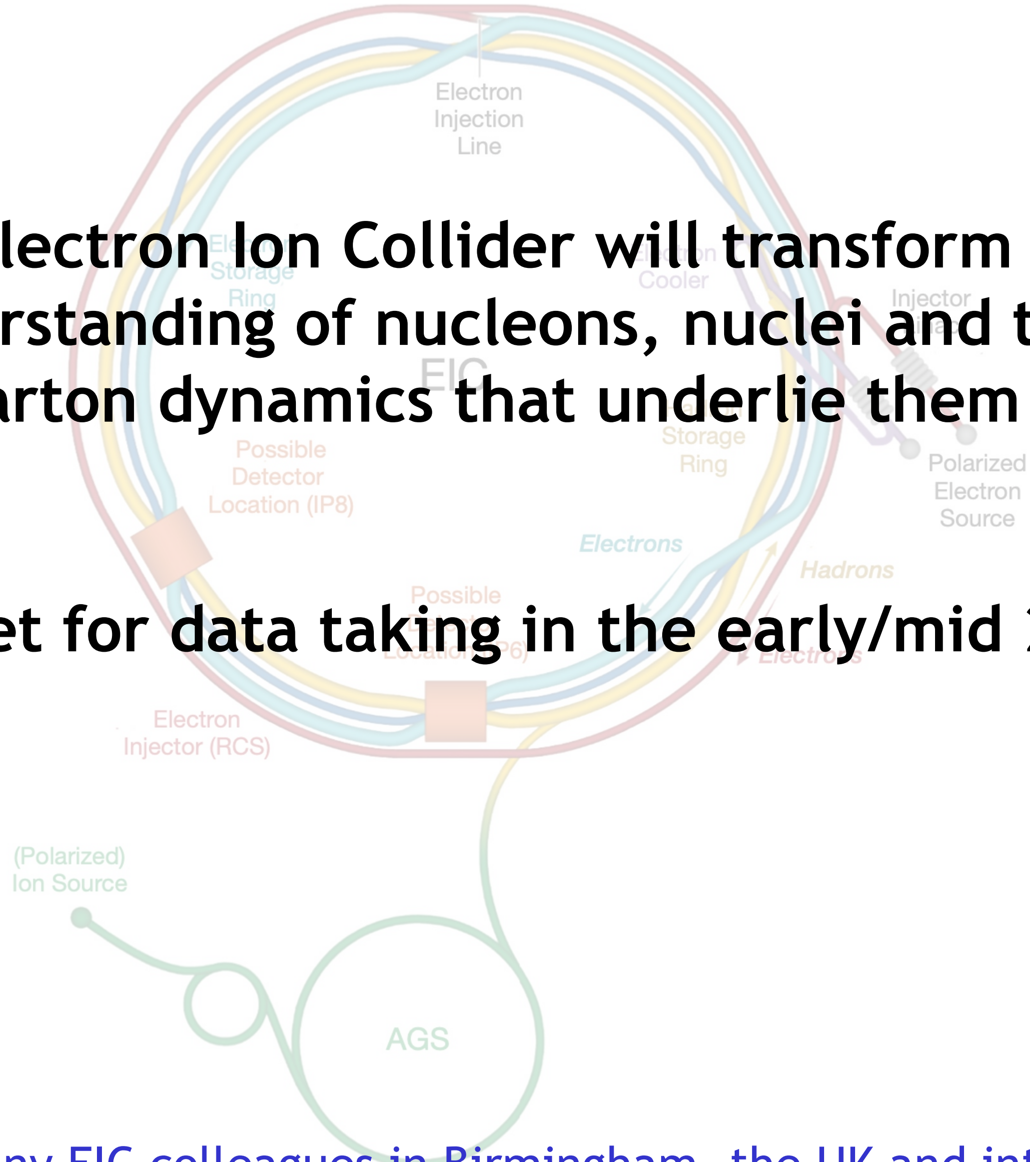
- Gluon radius smaller than charge radius
- Interpreted in terms of trace anomaly





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

Summary



The Electron Ion Collider will transform our understanding of nucleons, nuclei and the parton dynamics that underlie them

On target for data taking in the early/mid 2030s

[with thanks to many EIC colleagues in Birmingham, the UK and internationally]