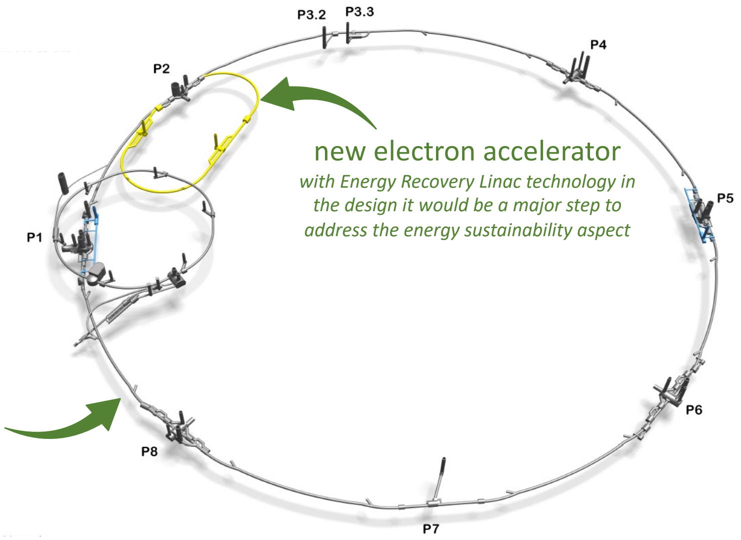
Synergies between EIC and LHeC

[A personal view]

Paul Newman (Birmingham)

EIC Detector-II Workshop
Warsaw, 31 July 2023

LHeC/FCC-eh

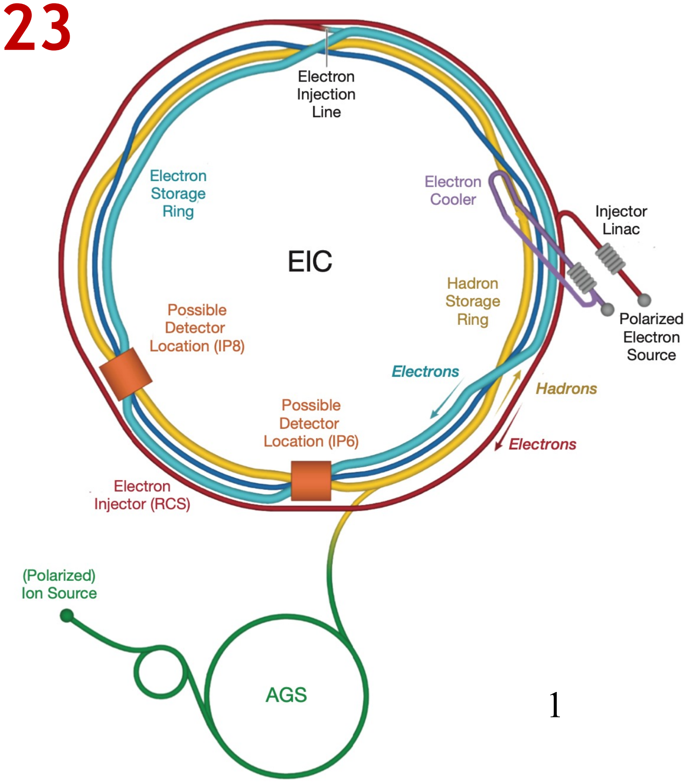


new electron accelerator

with Energy Recovery Linac technology in the design it would be a major step to address the energy sustainability aspect

existing/future proton accelerator

LHC/FCC

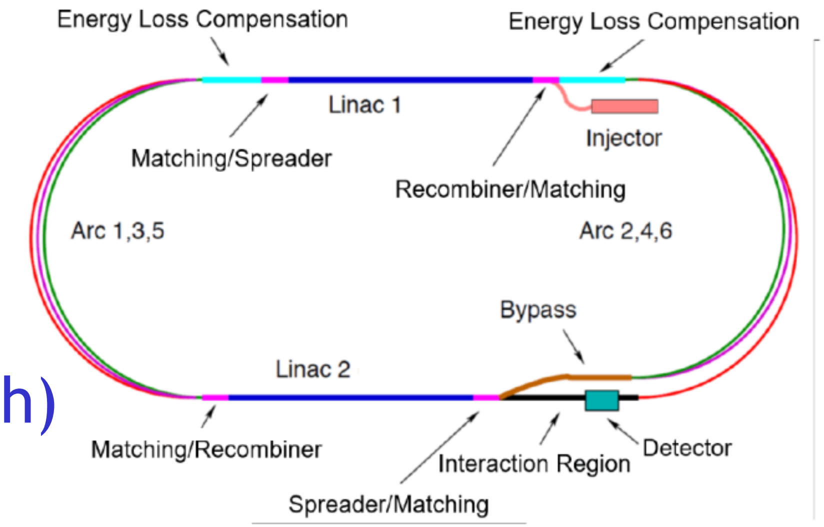


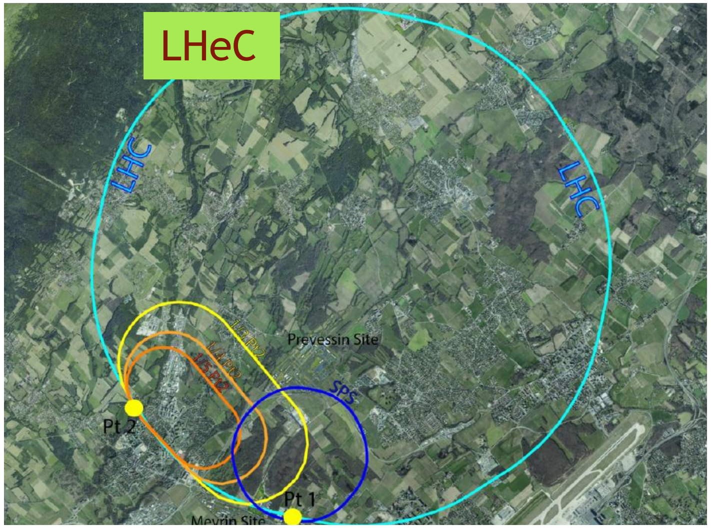
LHeC: LHC x Electron Energy Recovery Linac

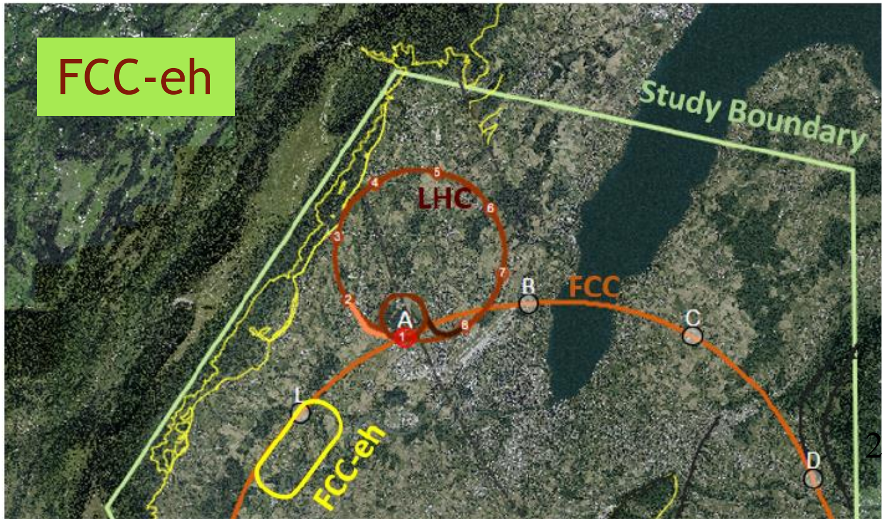
- Power consumption constraint (< 150 MW) and need for high luminosity imply energy recovery for electrons

- With 20 MV/m acceleration, 5.4km racetrack well matched to 50 GeV leptons
(1/5 of LHC circumference).

- ep lumi → 10^{34} cm^{-2} s^{-1}
- $\sqrt{s} = 1.3\ (3.5)$ TeV @ LHeC (FCC-eh)
- eA mode also planned







Possible DIS Futures at CERN?

Revised mandate (2022)

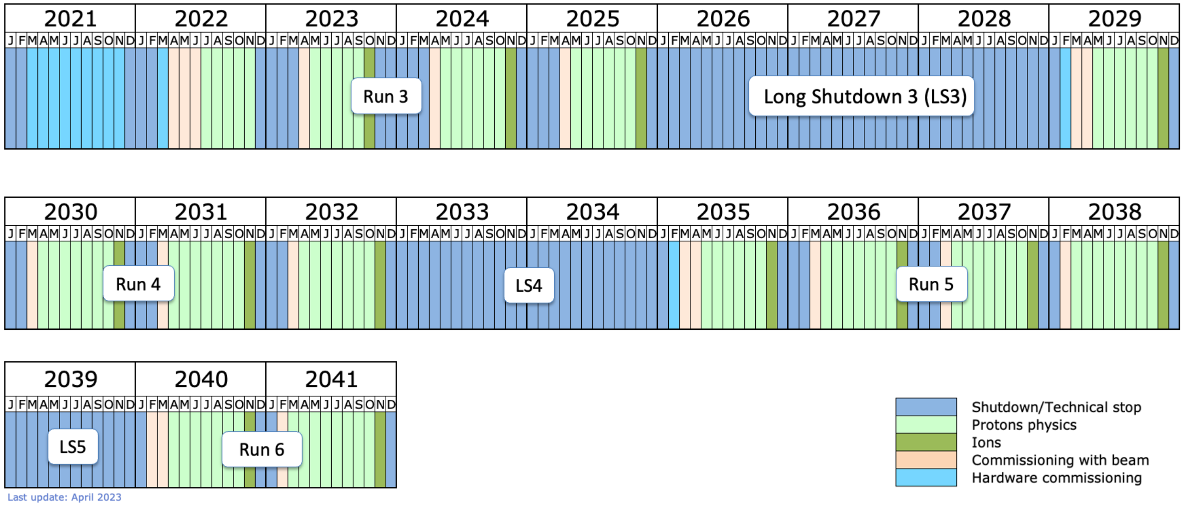
Following the publication of the updated CDR, CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics.

- LHeC might be an option in latter stages of LHC or as an extension

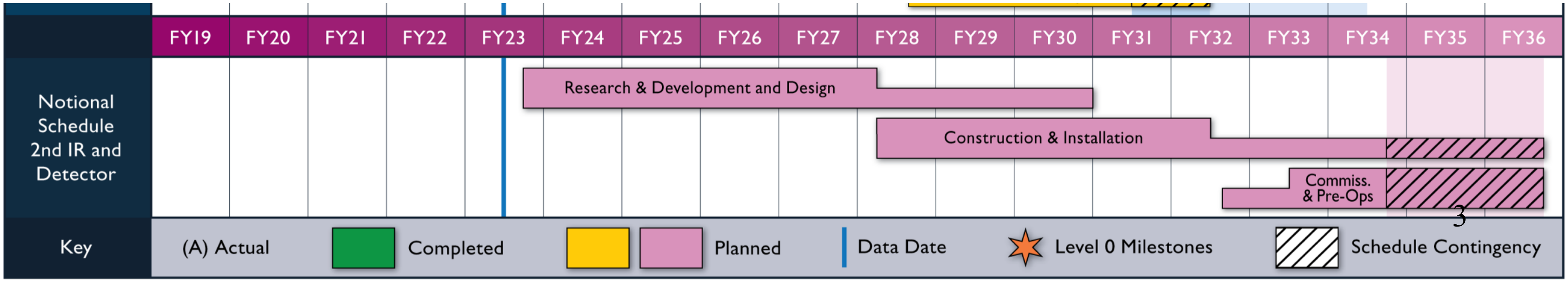
- In current scenario, FCC begins with ee, so eh beyond mid-century?

- No clear LHeC timeline: EIC Detector 2 should be earlier, but surely room for some co-development

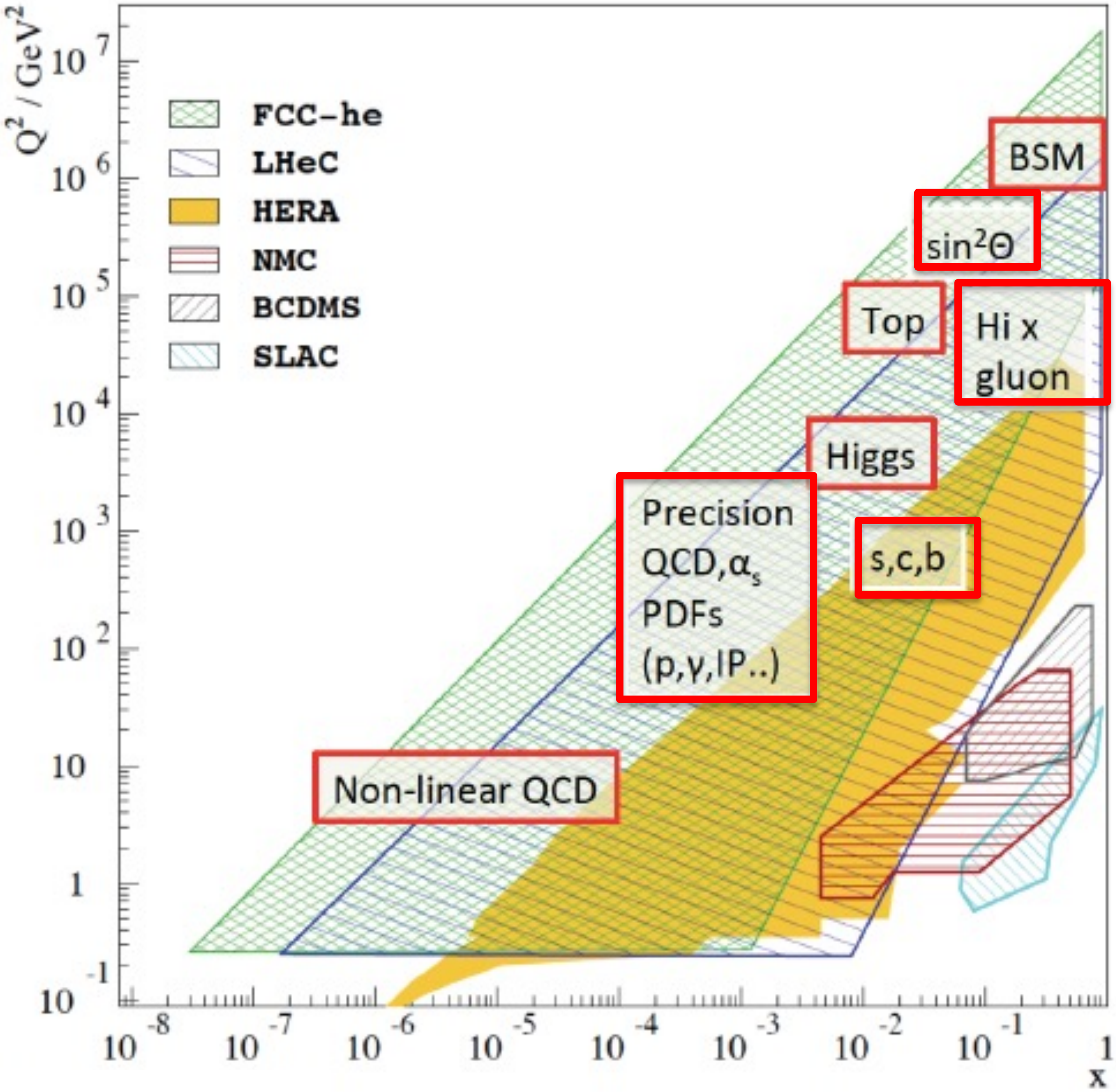
[LHC current schedule]



🟦 Shutdown/Technical stop
🟩 Protons physics
🟩 Ions
🟧 Commissioning with beam
🟦 Hardware commissioning



LHeC Physics Targets and Detector Implications



Standalone Higgs, Top, EW, BSM programme

→ General purpose particle physics detector

→ Good performance for all high p_T particles

→ Heavy Flavour tagging

Precision proton PDFs, including very low x parton dynamics in ep,eA

→ Dedicated DIS exp't

→ Hermeticity

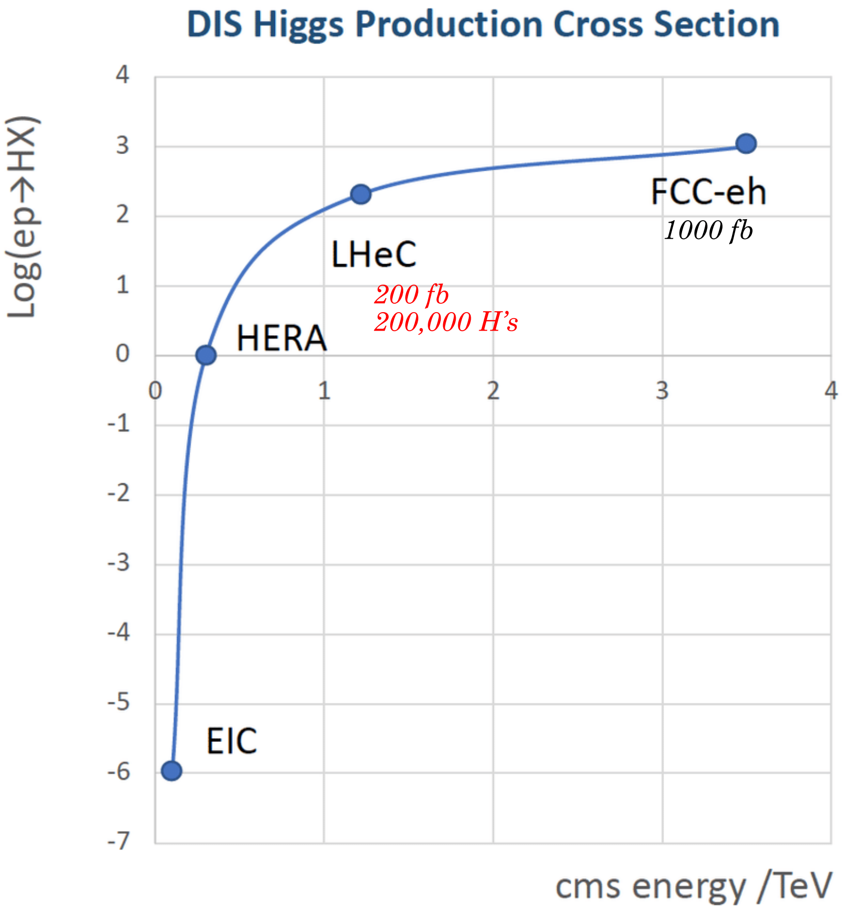
→ Hadronic final state resolution for kinematics

→ Flavour tagging / PID

→ Beamline instruments

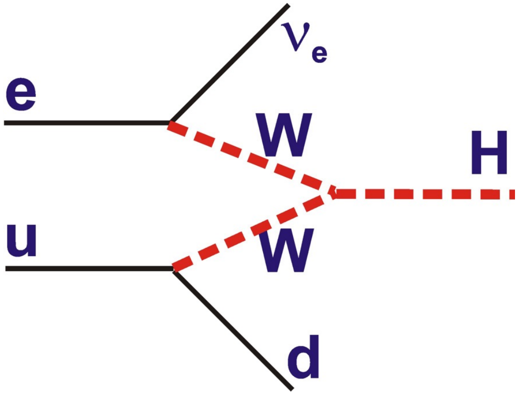
Complementarity with EIC in physics scope, timescale and technologies.

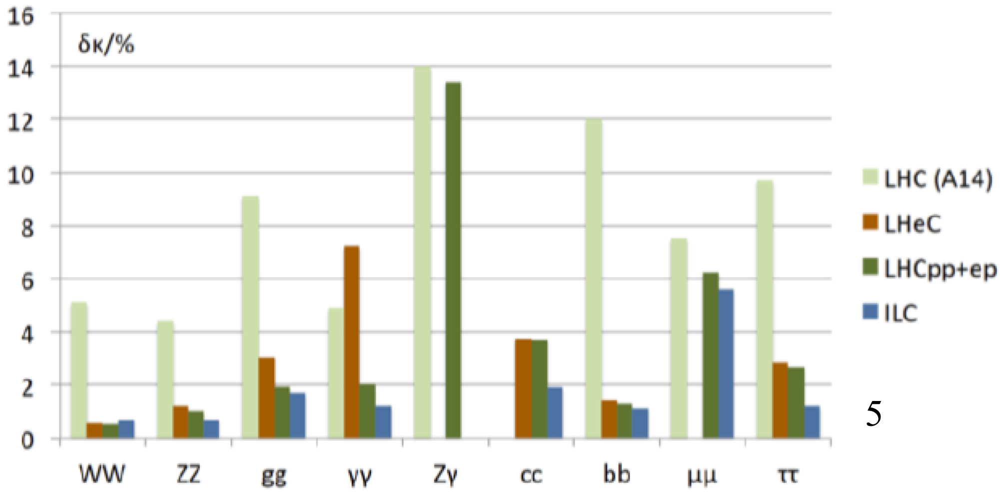
Example Standalone Physics: Higgs



- Signal:Background ~ 1-2 for bbbar

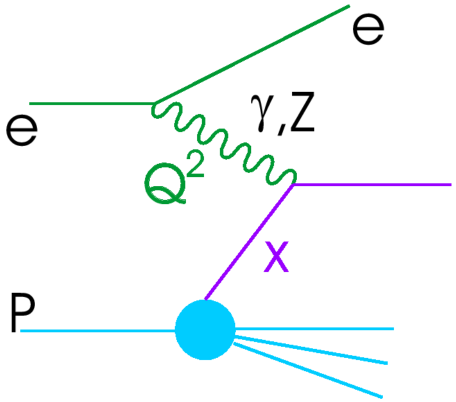
- With 1ab^{-1}, interesting precision for multiple decay modes,complementing pp at LHC





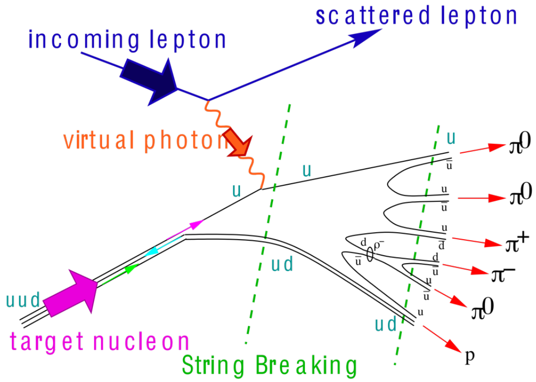
Overlaps with EIC / Detector II Physics

Inclusives



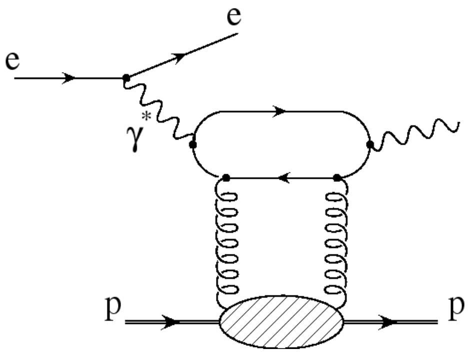
Common approaches, overlapping kinematic ranges

Semi-Inclusives



Limited at LHeC (lacks PID except vertexing)

Exclusive / Diffractive



Similar channels, but different physics focus … low x physics v 3D imaging

Benchmarks

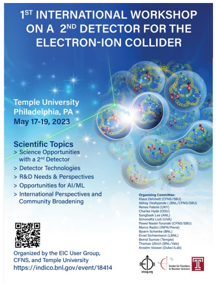
[Pawel]

CHANNEL	PHYSICS	DETECTOR II OPPORTUNITY
Diffractive dijet	Wigner Distribution	detection of forward scattered proton/nucleus + detection of low p_T particles
DVCS on nuclei	Nuclear GPDs	High resolution photon + detection of forward scattered proton/nucleus
Baryon/Charge Stopping	Origin of Baryon # in QCD	PID and detection for low p_T pi/K/p
F_2 at low x and Q^2	Probes transition from partonic to color dipole regime	Maximize Q^2 tagger down to 0.1 GeV and integrate into IR.
Coherent VM Production	Nuclear shadowing and saturation	High resolution tracking for precision t reconstruction

Experimental Overlaps with Detector II

[Rene]

Unique opportunities for Det II @ IP8



1ST INTERNATIONAL WORKSHOP ON A 2ND DETECTOR FOR THE ELECTRON-ION COLLIDER

Temple University
Philadelphia, PA
May 17-19, 2023

Scientific Topics
> Science Opportunities with a 2nd Detector
> Detector Technologies
> R&D Needs & Perspectives
> Opportunities for AI/ML
> International Perspectives and Community Broadening

Organizing Committee:
Klaus Dehmelt (CFNS/SBU)
Abhay Deshpande ((BNL/CFNS/SBU)
Renee Fatemi (UKY)
Charles Hyde (ODU)
Sangbaek Lee (ANL)
Simonetta Liuti (UVA)
Pawel Nadel-Turonski (CFNS/SBU)
Marco Radici (INFN/Pavia)
Bjoern Schenke (BNL)
Ernst Sichtermann (LBNL)
Bernd Surrow (Temple)
Thomas Ullrich (BNL/Yale)
Anselm Vossen (Duke/JLab)

Organized by the EIC User Group, CFNS, and Temple University
https://indico.bnl.gov/event/18414

A. **MAGNETIC FIELD** - Solenoid field up to 3T, allowing for high resolution momentum reconstruction for charged particles.

B. **EXTENDED COVERAGE** for precision electromagnetic calorimetry - important for DVCS on nuclei

C. **MUONS** – enhanced muon ID in backward and barrel region.

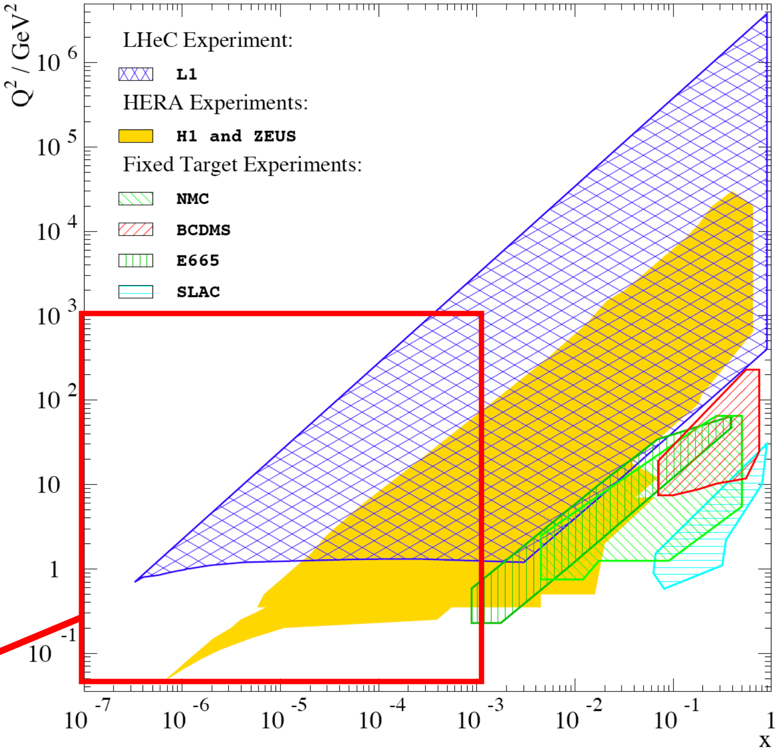
D. **BACKWARD HADRONIC CALO** - Low-x physics, reconstruction of current jets in the approach to saturation

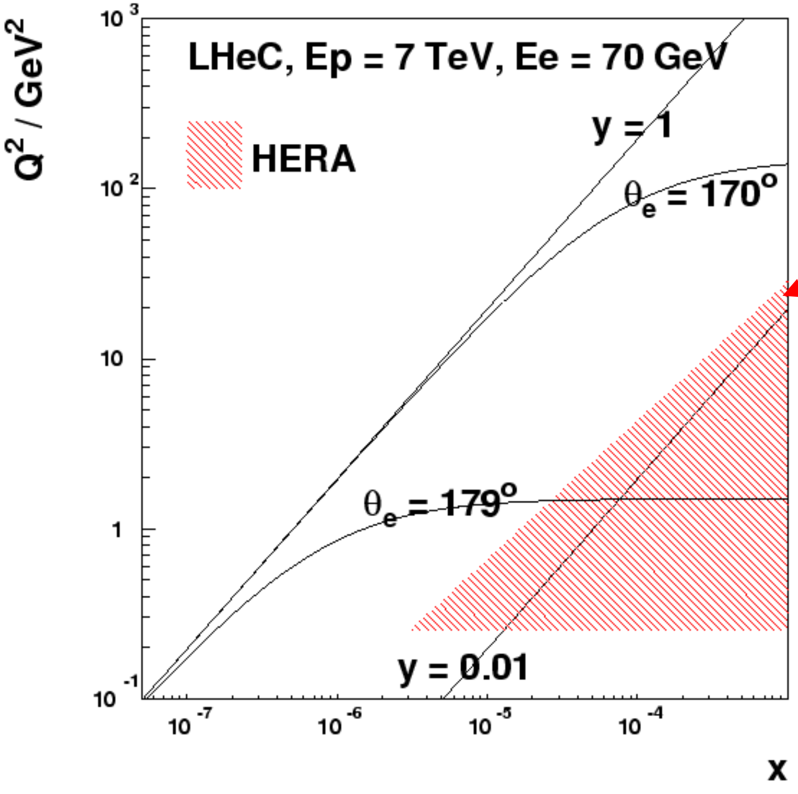
E. **SECONDARY FOCUS** - tagging for nearly all ion fragments and extended acceptance for low pT/ low x protons. Enables detection of short-lived rare isotopes.

- LHeC solenoid is 3.5T … tracking commonality with ‘A’
- ‘B’, ‘C’ and ‘D’ are all major topics for LHeC (see following)
- ‘E’ → Very interesting! Low ξ proton tagging acceptance in ep and ion fragment detection in eA are big challenges …

LHeC Electron Acceptance Requirements

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°



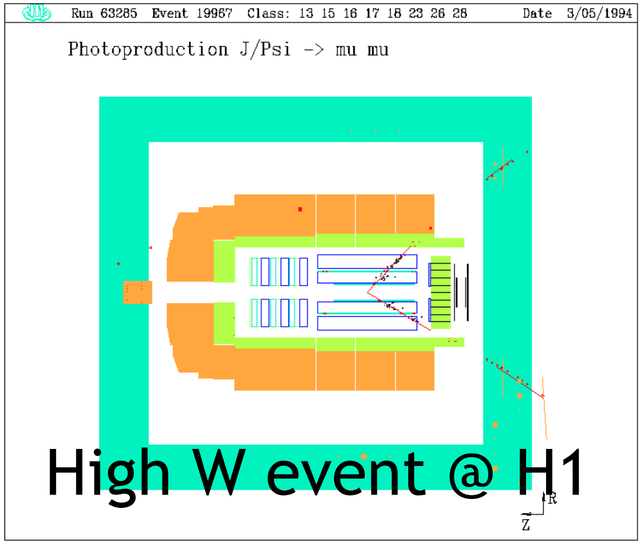


'Even lower' Q^2 region enhances saturation sensitivity and maps transition from partons to hadrons:

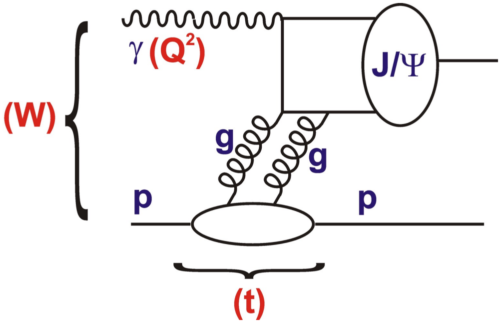
→ $Q^2 < 10^{-2}$ GeV^2 covered by beamline instrumentation

→ $10^{-2} < Q^2 < 1$ GeV^2 curerntly uncovered → cf FDC ideas …

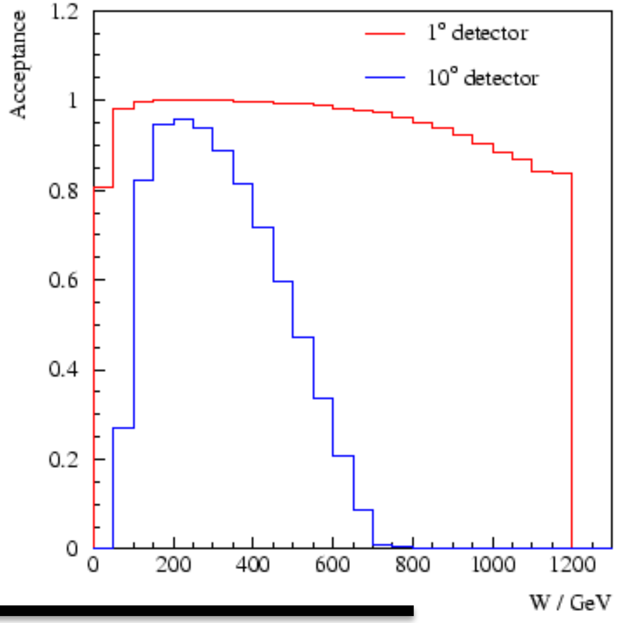
Acceptance Requirements, Final States

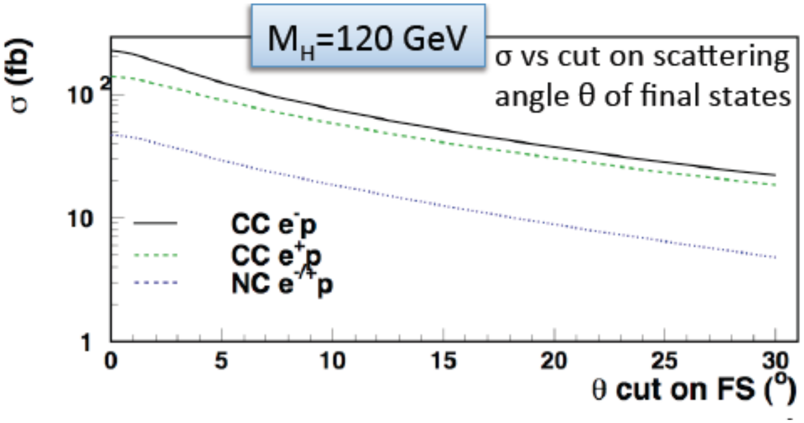


High W event @ H1

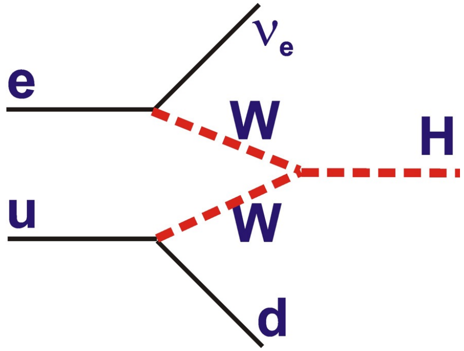


Elastic J/Ψ Photoproduction





Higgs Production



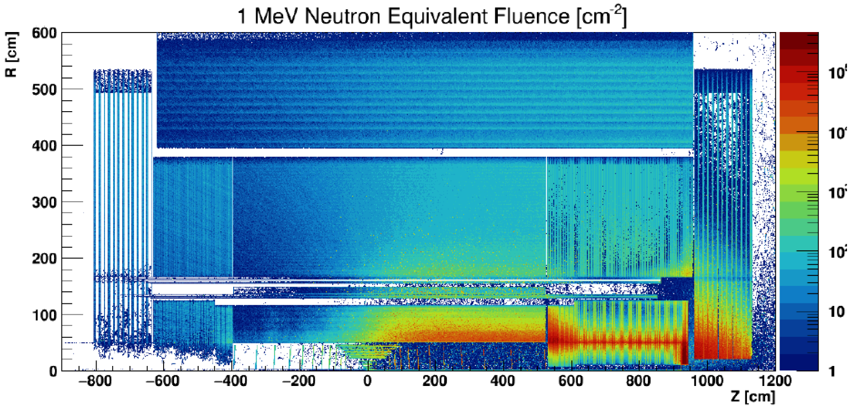
- Also, forward hadrons for kinematic recn at low y / in CC

Hermetic coverage for ECAL, HCAL and muons essential!

LHeC Detector Philosophy and Status

- Conditions are relatively ‘easy’
… fluences are $<10^{-2}$ of LHC
… pile-up ~ 0.1 (cf 200 at HL-LHC)

Fluences



- Most challenging technology aspects (not discussed here):
    - Interaction region (dipole → complex synchrotron mitigation)
    - ERL (factor ≥ 100 in power over current systems → PERLE)

- Most of current ‘baseline’ detector leans heavily on LHC (especially ATLAS) technologies
    - Partly over-specified? (e.g. Lar accordion geometry)
    - Sometimes misses ep and eA subtleties? (e.g. beamline)

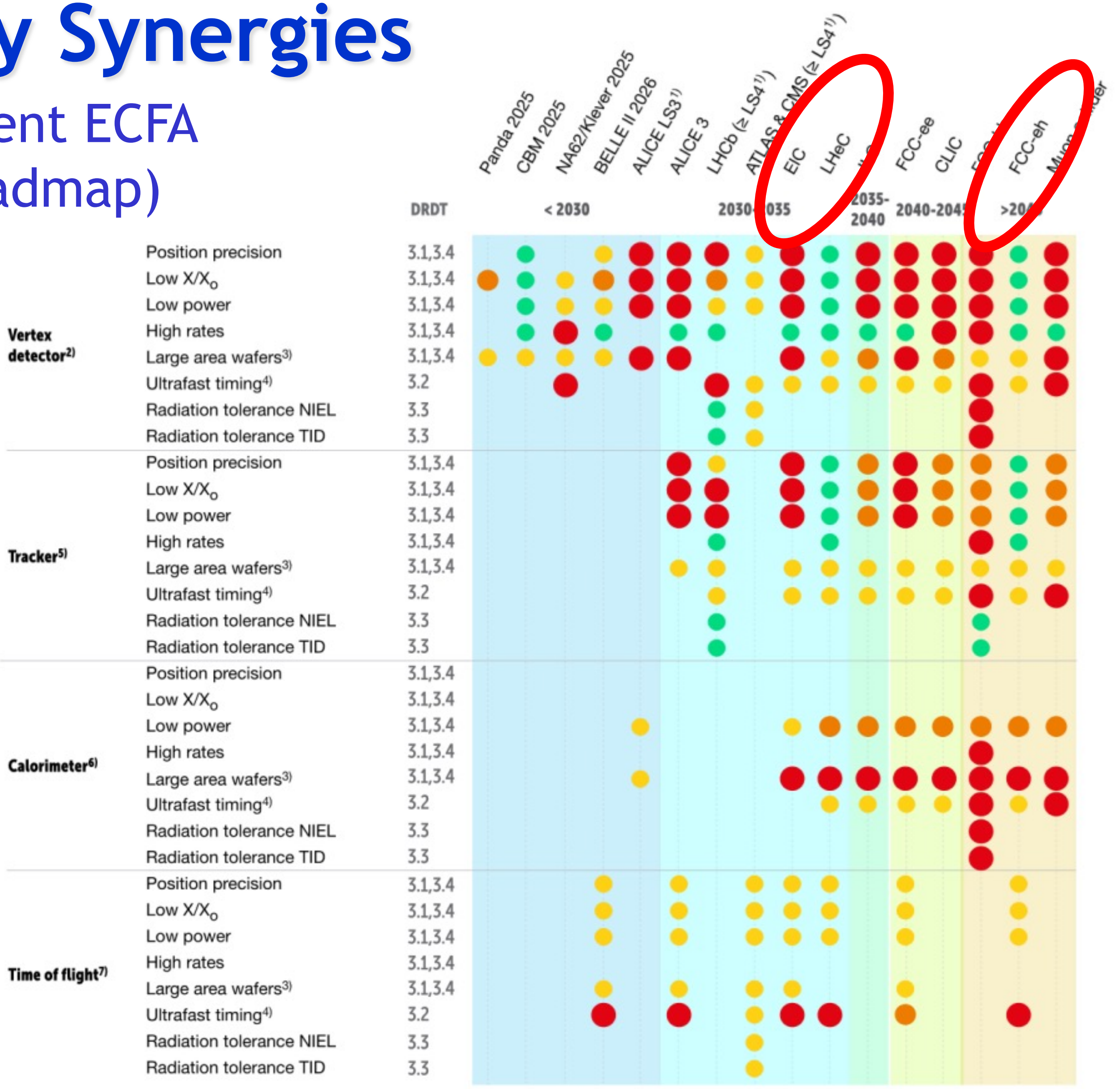
- Current designs are just a ‘sketch’ and detector technologies evolve fast → opportunity to share new ideas with Detector-II

Technology Synergies

(According to recent ECFA European R&D roadmap)

- e.g. solid state devices in → different contexts (EIC harder than LHeC?)

The new R&D organisation in Europe is a significant development that we should engage with

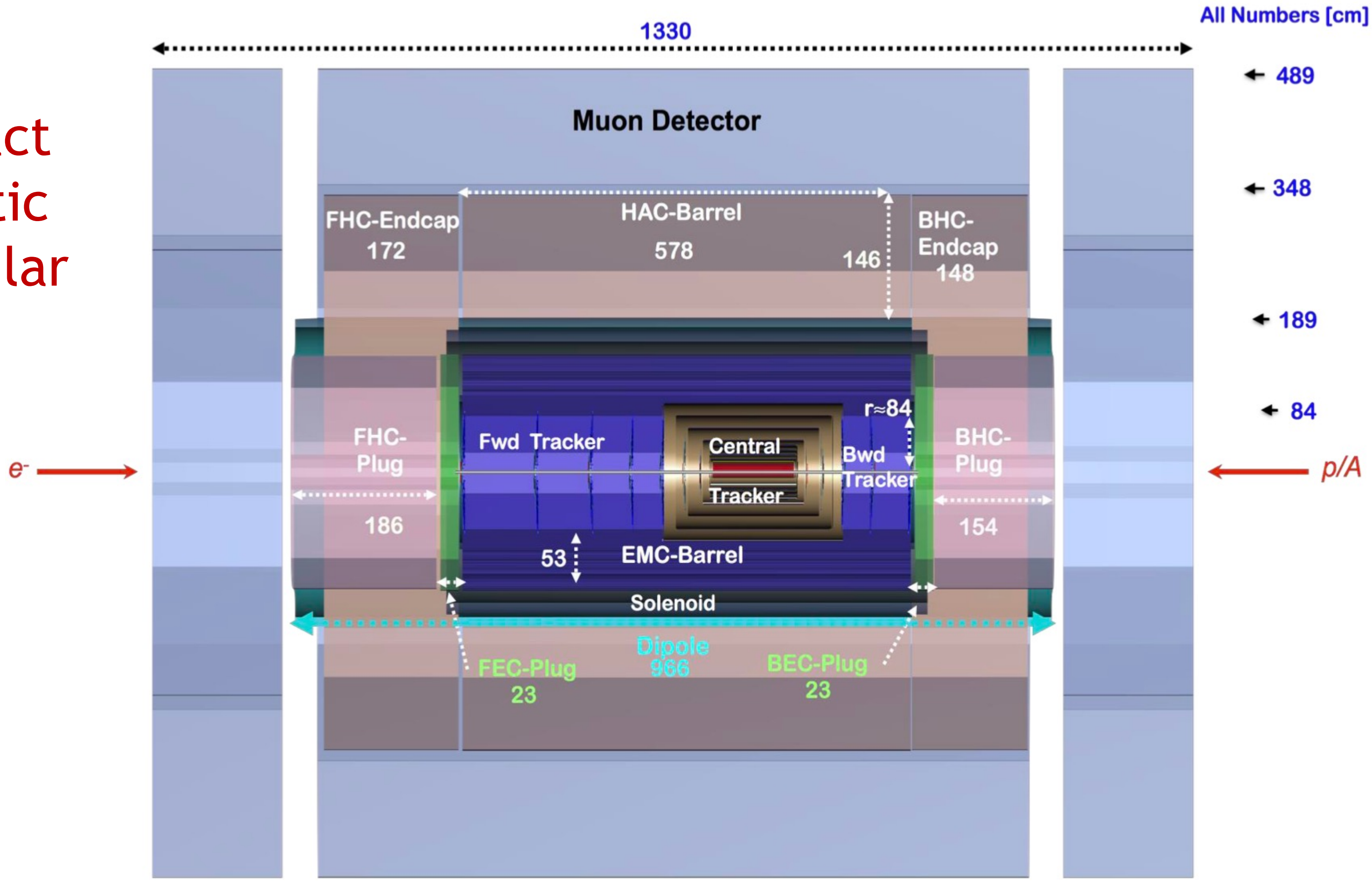


			Panda 2025	CBM 2025	NA62/Klever 2025	BELLE II 2026	ALICE LS3[1]	ALICE 3	LHCb (≥ LS4[1])	ATLAS & CMS (≥ LS4[1])	EIC	LHeC	[illegible]	FCC-ee	CLIC	[illegible]	FCC-eh	Muon [illegible]der
		DRDT	< 2030					2030-2035					2035-2040	2040-204		>20		
Vertex detector[2]	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low X/X_o	3.1,3.4	🟠	🟢	🟡	🟠	🔴	🔴	🟠	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low power	3.1,3.4		🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	High rates	3.1,3.4		🟢	🔴	🟢		🟢	🟢		🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢
	Large area wafers[3]	3.1,3.4	🟡	🟡	🟡	🟡	🔴	🔴			🔴	🟡	🟠	🔴	🟠	🟡	🟡	🔴
	Ultrafast timing[4]	3.2			🔴				🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢	🟡						🔴		
	Radiation tolerance TID	3.3							🟢	🟡						🔴		
Tracker[5]	Position precision	3.1,3.4						🔴	🟡		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low X/X_o	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low power	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	High rates	3.1,3.4							🟢			🟢				🔴	🟢	
	Large area wafers[3]	3.1,3.4						🟡	🟡		🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
	Ultrafast timing[4]	3.2							🟡		🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢							🟢		
	Radiation tolerance TID	3.3							🟢							🟢		
Calorimeter[6]	Position precision	3.1,3.4																
	Low X/X_o	3.1,3.4																
	Low power	3.1,3.4					🟡				🟡	🟠	🟠	🟠	🟠	🟠	🟠	🟠
	High rates	3.1,3.4														🔴		
	Large area wafers[3]	3.1,3.4					🟡				🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	Ultrafast timing[4]	3.2										🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3														🔴		
	Radiation tolerance TID	3.3														🔴		
Time of flight[7]	Position precision	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low X/X_o	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low power	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	High rates	3.1,3.4																
	Large area wafers[3]	3.1,3.4				🟡		🟡		🟡	🟡			🟡				
	Ultrafast timing[4]	3.2				🔴		🔴		🟡	🔴	🔴		🟠			🔴	
	Radiation tolerance NIEL	3.3								🟡								
	Radiation tolerance TID	3.3								🟡								

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Detector Overview (CDR update)

Compact
Hermetic
& Modular



- 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- 1° tracking acceptance forward & backward
- Substantial beamline instrumentation

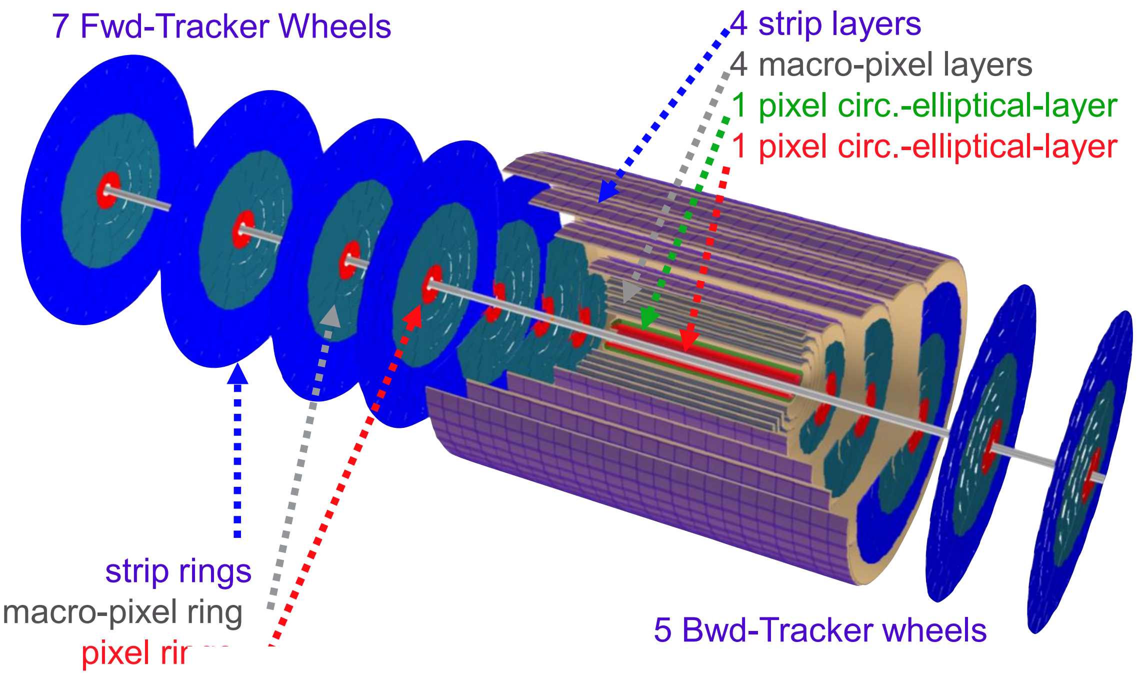
Central Tracker

- All silicon

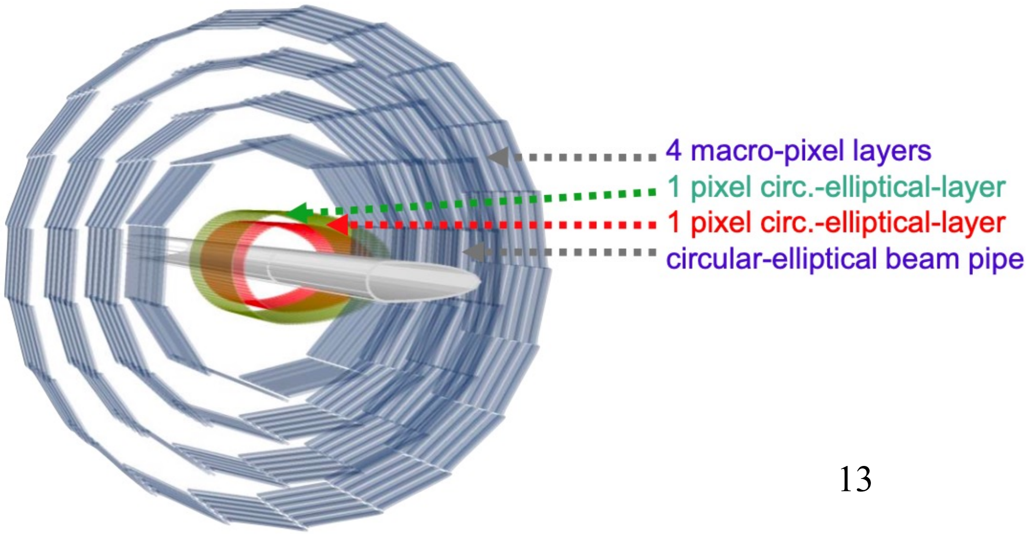
- HV-CMOS DMAPS technology is low material (0.1mm) and cost-effective

- Bent / stitched wafers for inner layers (as ALICE and ePIC)

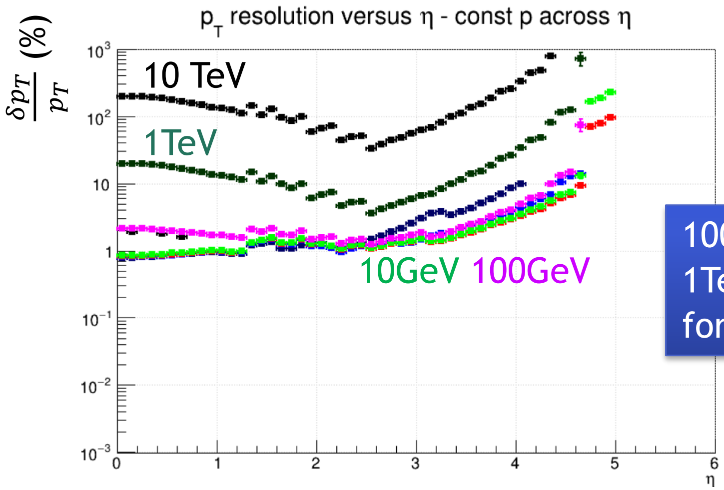
- Semi-elliptical inner layers



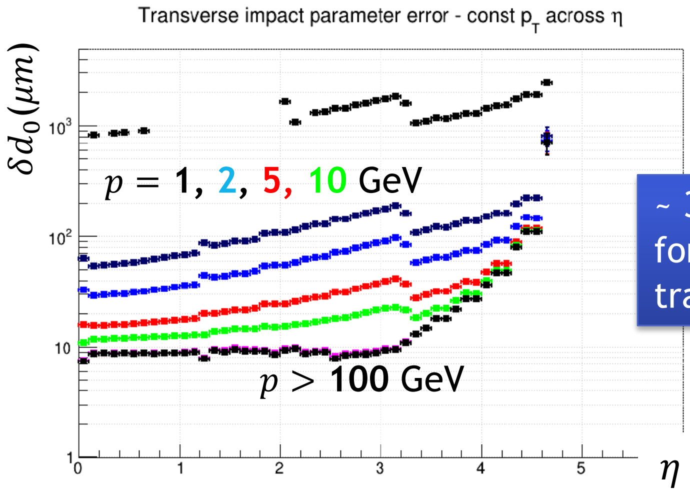
Pitch (μm)	$r\phi$	z
pixel	25	50
macro pixel	100	400
strip	100	10-50mm



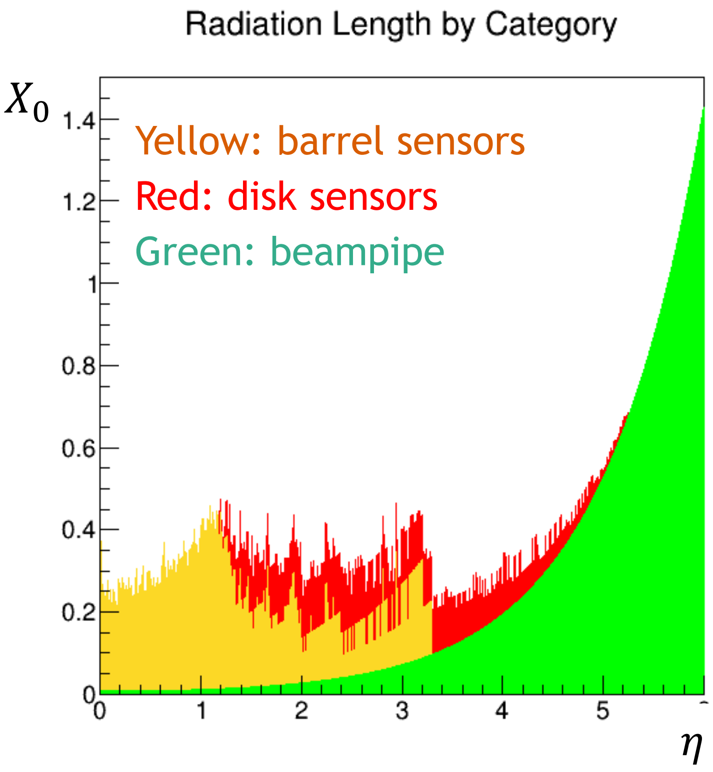
Tracking Performance



100MeV - 100 GeV: 1-3%
1TeV: 5-30%
for $\eta < 4$



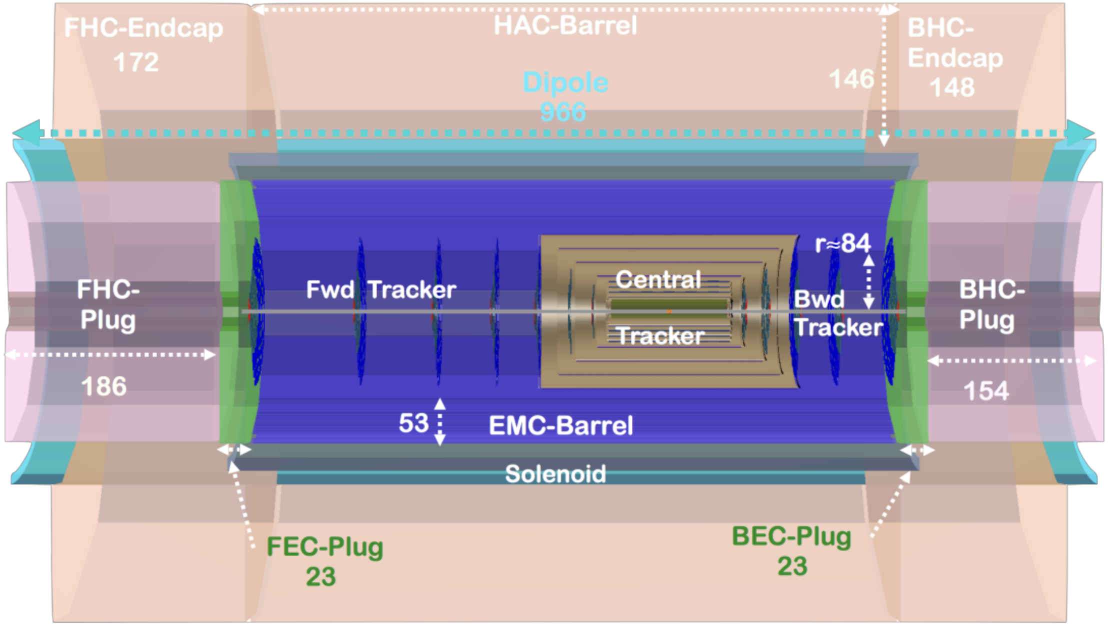
~ 30 μm resolution
for high momentum
tracks at $\eta \sim 4$



- Material budget is ~20% of a radiation length up to η~4.5

- p_T and impact parameter resolutions (from tkLayout) show high performance over wide η range.

Calorimetry



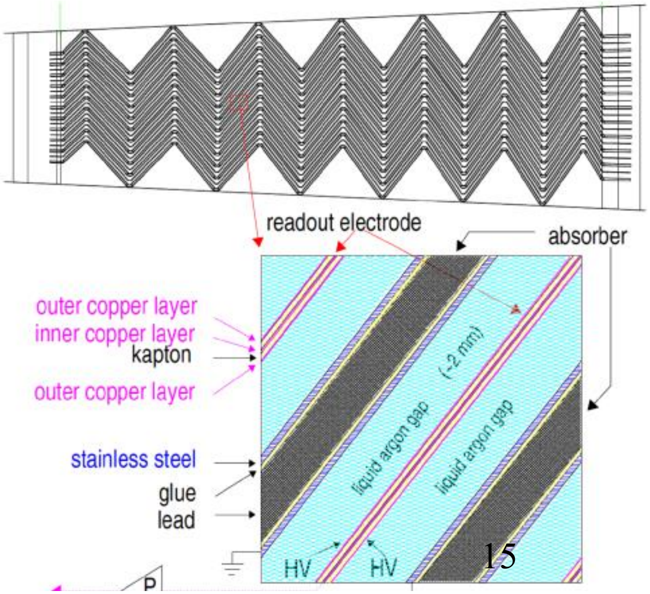
- High performance ‘accordion’ geometry EM Barrel ($|\eta|<2.8$), inside solenoid / dipole

- Plastic-scintillator HCAL for e/h separation

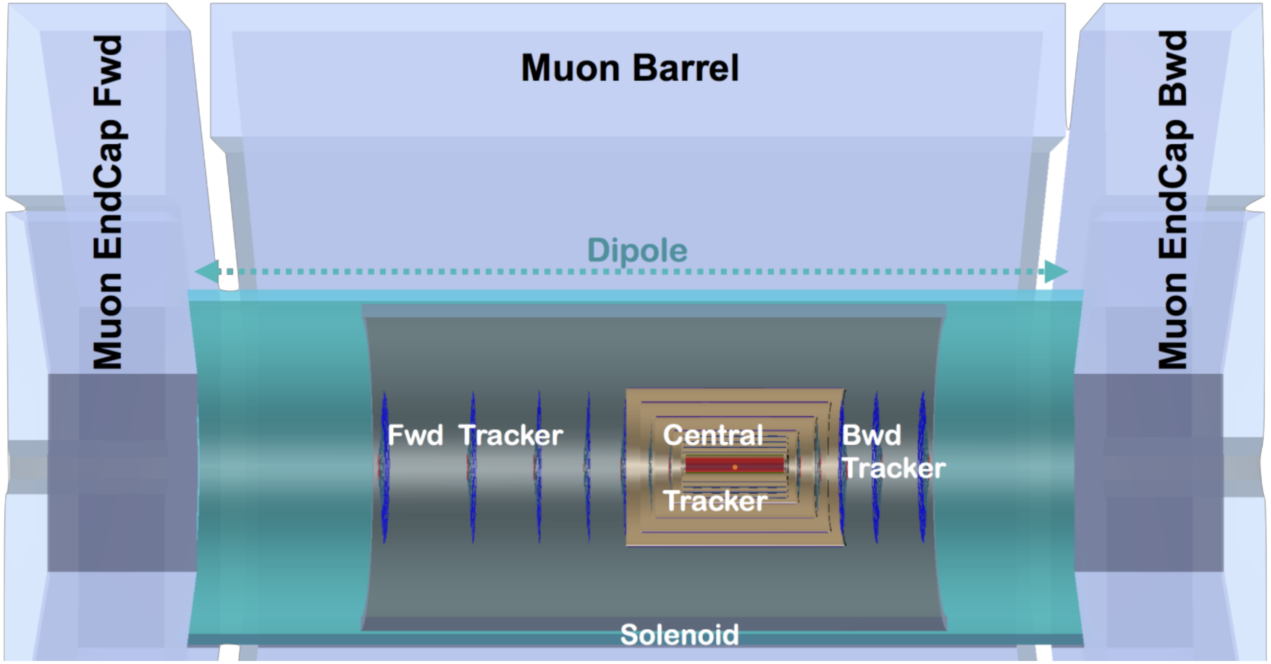
- Finely segmented plugs (W, Pb, Cu) for compact showering, with Si sensors

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

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



Muons



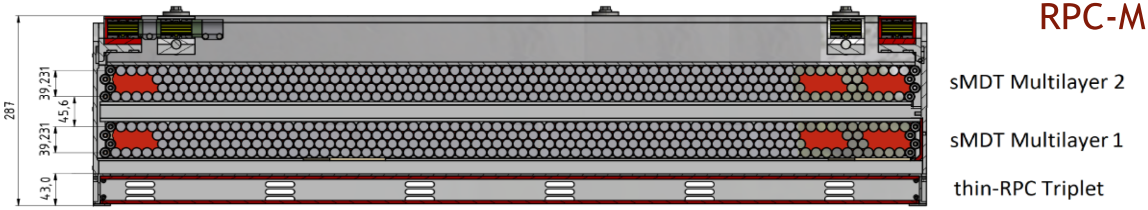
No dedicated outer magnetic field currently forseen

→ Momentum measurement in central tracker.

→ Outer muon detectors for tagging / triggering

HL-LHC technologies are more than adequate

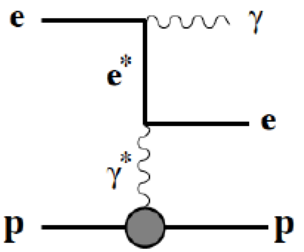
→ Multiple layers of thin RPCs (1mm gas gap) for fast response & small (1.5cm diameter) MDTs for spatial precision

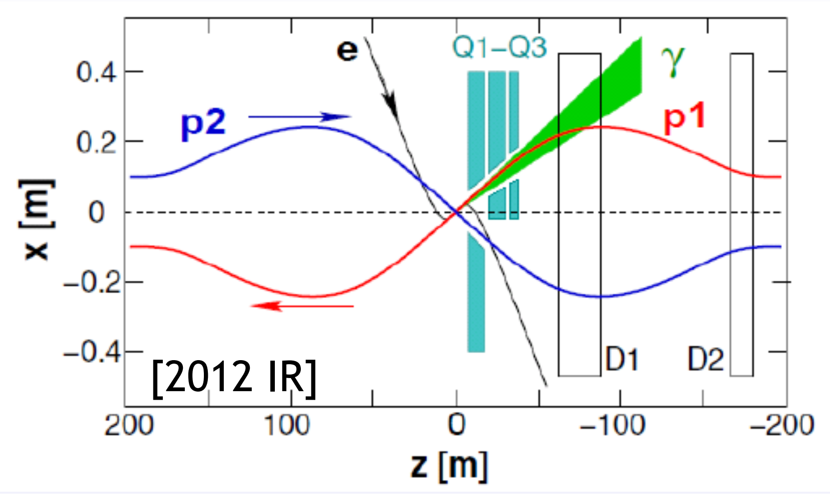


ATLAS Phase-I
RPC-MDT assembly

Beamline Instrumentation

Outgoing electron direction contains photoproduction e-taggers 14-62m and photon detector at around 120m for lumi (Bethe-Heitler ep→epγ)

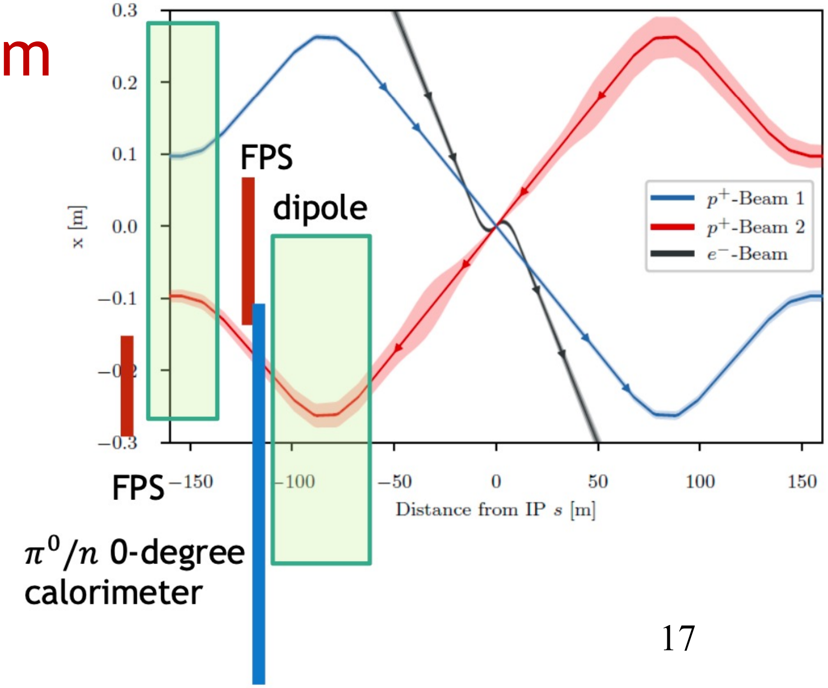




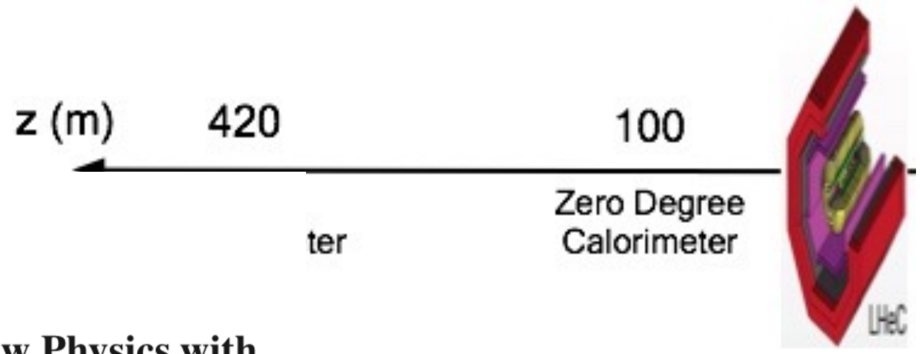
Outgoing proton direction

- Space for ±30cm Si-W ZDC at 110m … could have highly segmented design similar to ALICE FoCAL

- Roman pot-based FPS:
~200m (as per ATLAS/CMS → ξ~0.1)
~120m (new → ξ~0.2)
… challenge for 'real' diffractive region at lowest ξ …

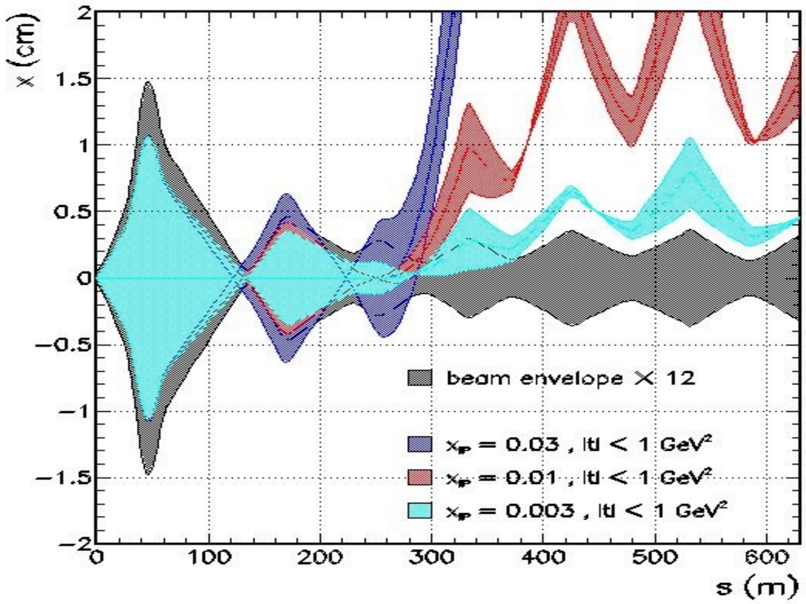


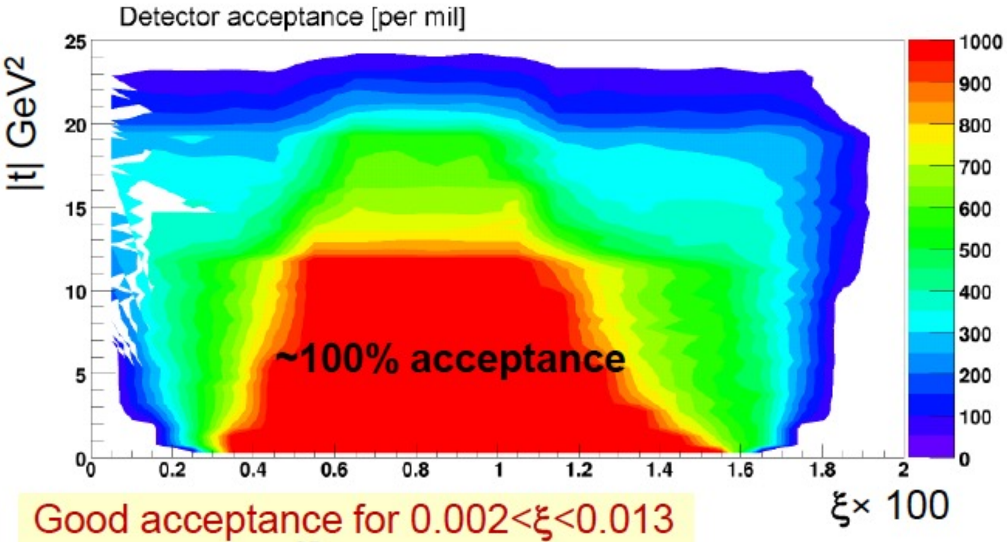
Low ξ p-spectrometer based on FP420?...



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

arXiv:0806.0302v2 [hep-ex] 2 Jan 2009

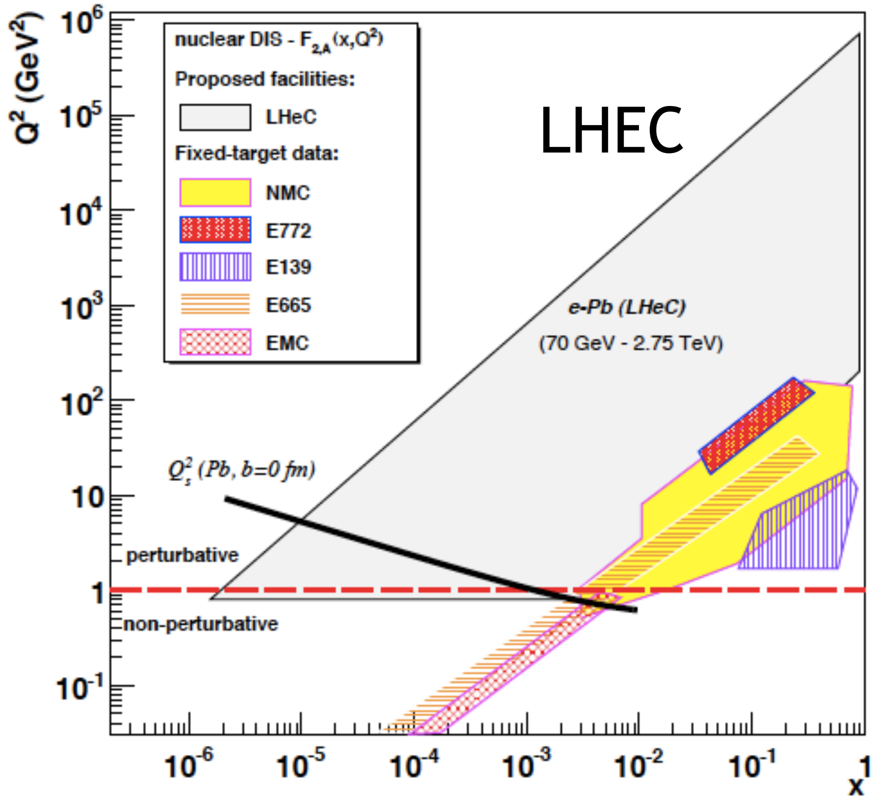


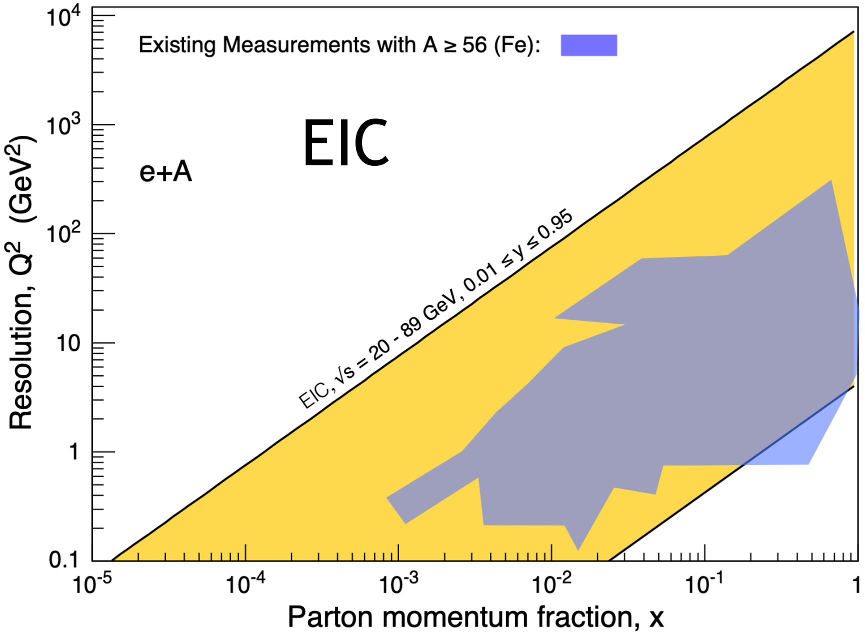


Good acceptance for 0.002<ξ<0.013

- Requires access to beam though cold part of LHC
- Low ξ can also be accessed via rapidity gap method, but with associated systematics

Physics Synergies: Nuclear PDFs





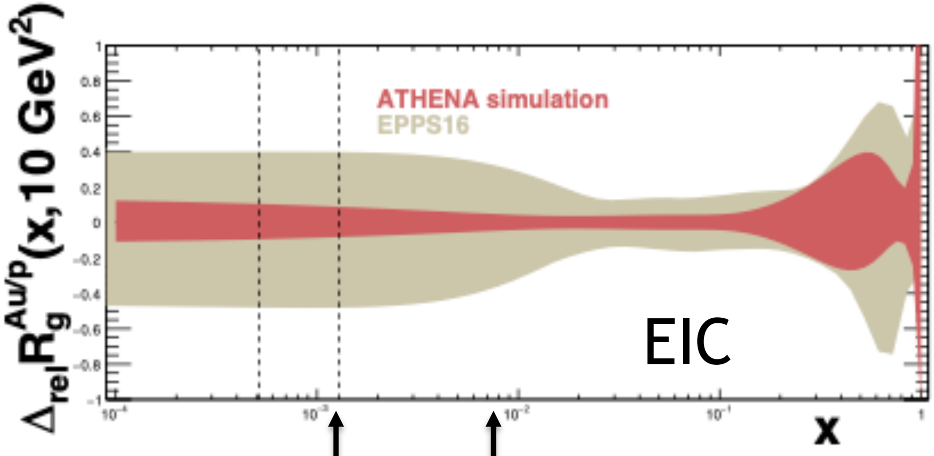
→ Both revolutionise understanding compared with fixed target

→Low x, Q^2 phase space accesses expected saturated region

→ If non-linear low x dynamics can be established in eA at EIC, they can be fully characterized in both ep & eA at perturbative Q^2 at LHeC

→Ultra-clean probe of passage of `struck' partons through cold nuclear matter

Gluon Nuclear Modification Ratios from EIC / LHeC / FCC-eh Simulations



EIC-only compared with EPPS’16

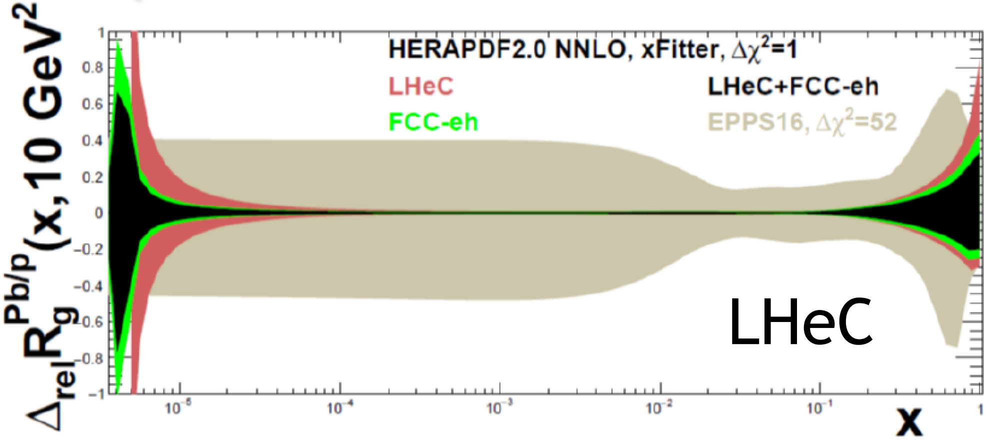
→ Factor ~ 2 improvement at x~0.1

→ Very substantial improvement in newly accessed low x region down to ~10^{-3}

EIC eA limit
~10^{-3}

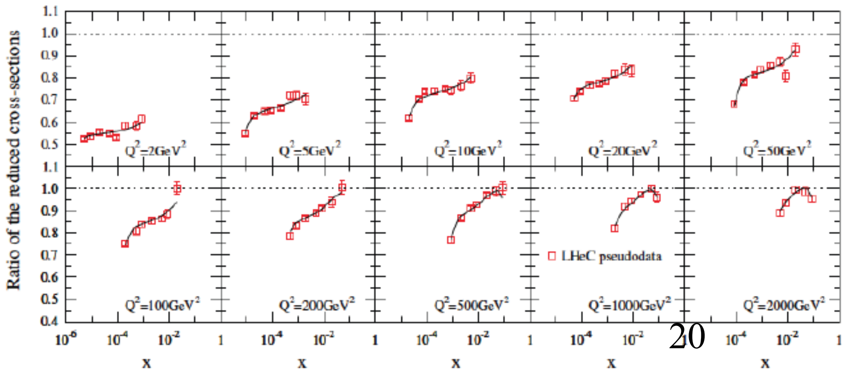
EPPS16 limit
~10^{-2}

FCC-eh limit
~10^{-6}

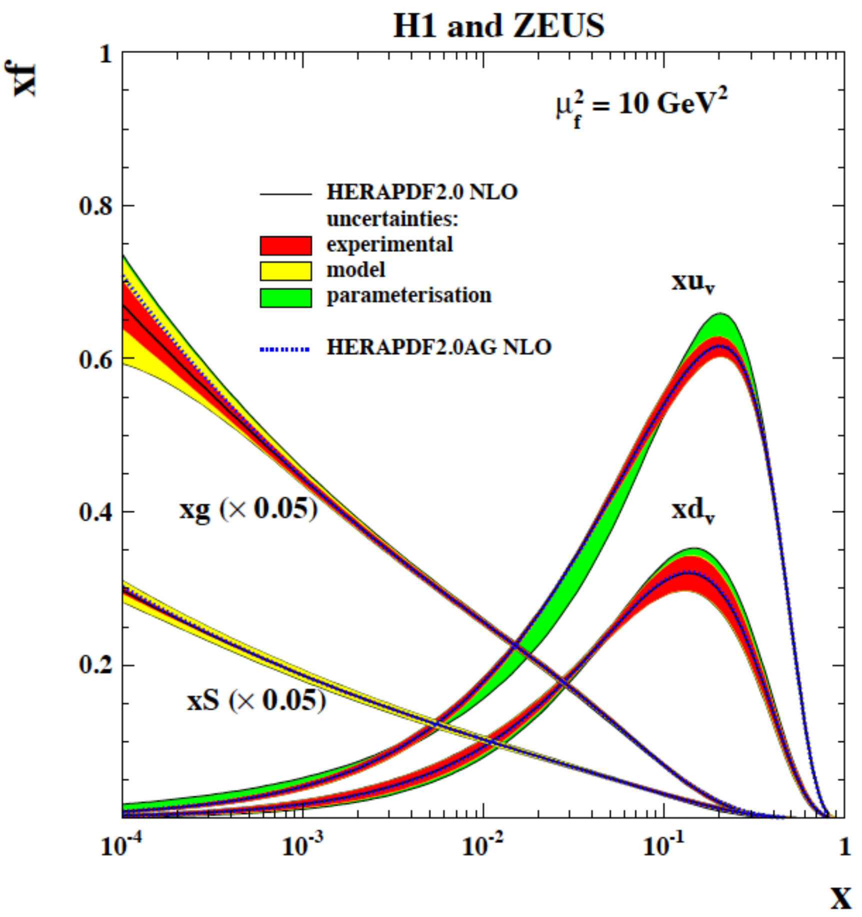


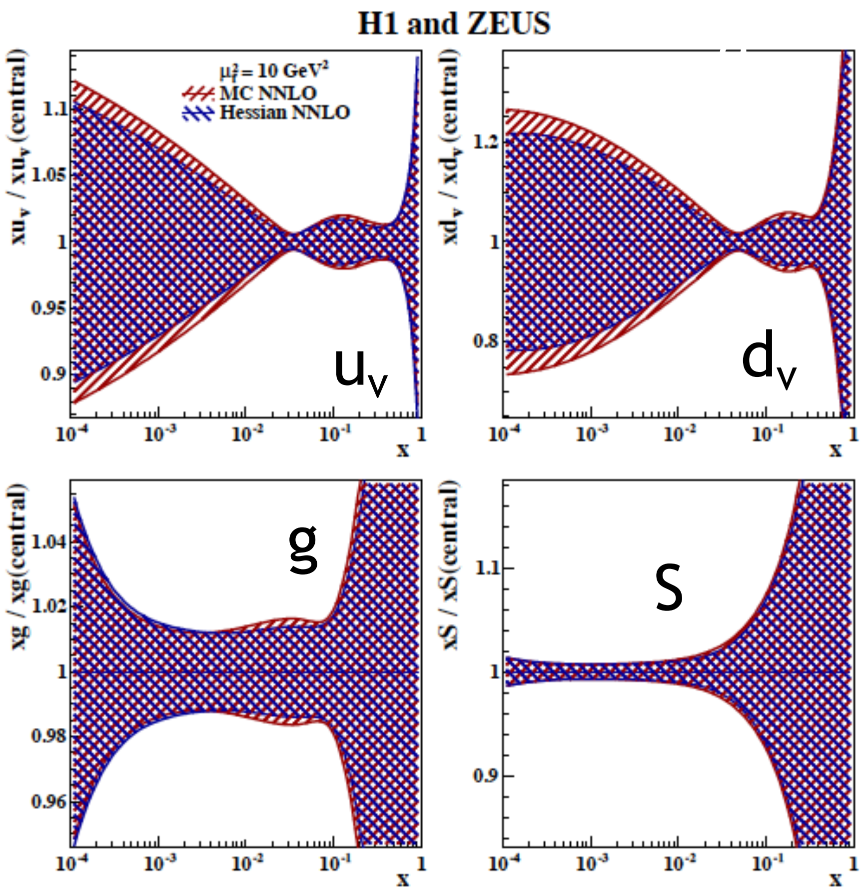
LHeC or FCC-eh only compared with EPPS’16

→ Potential extension to 10^{-6}



Final HERA Picture of Proton (HERAPDF2.0)

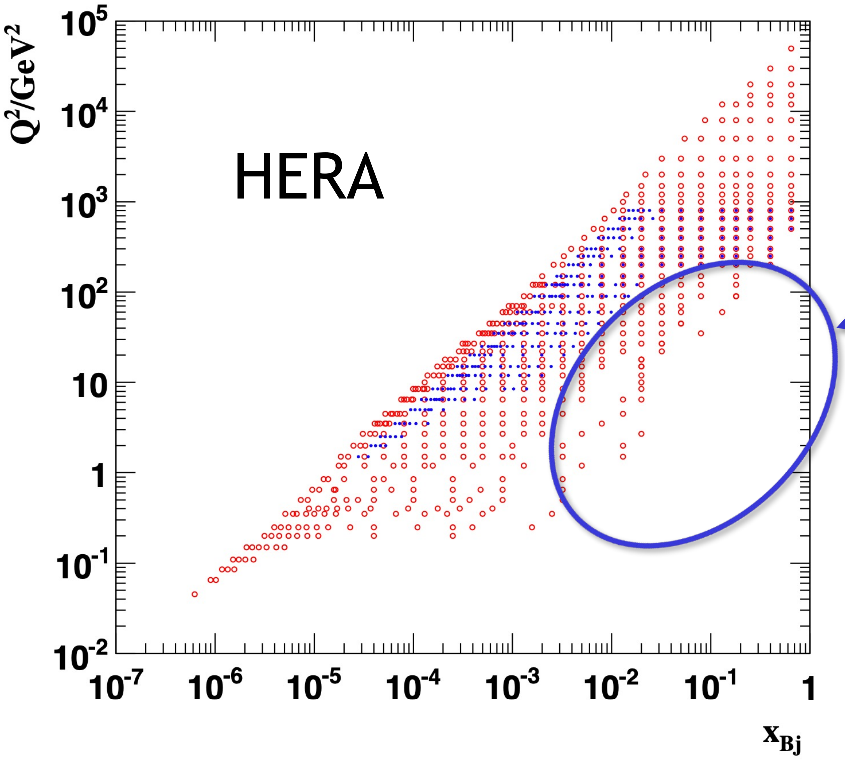




- ~2% gluon precision, 1% on sea quarks for x ~ 10^{-2}
- Low x gluon rising in a non-sustainable way at large Q^2 …
- Uncertainty explodes above $x=10^{-1}$ and below $x=10^{-3}$

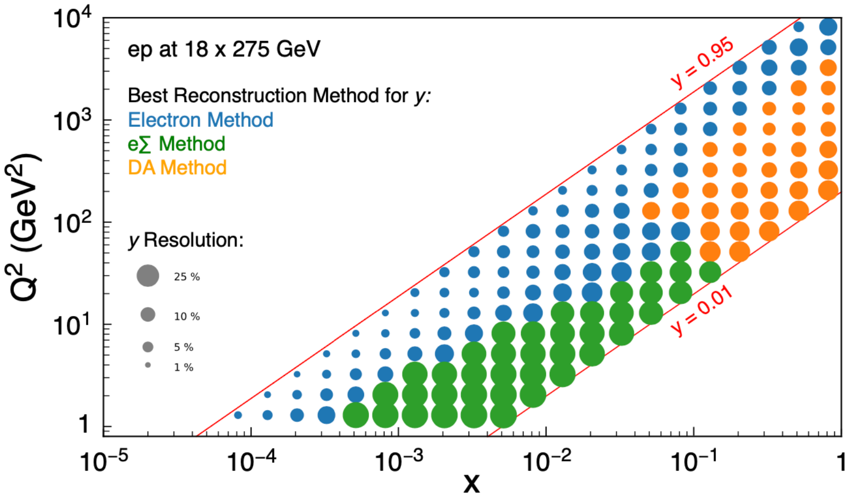
[High x precision ultimately limits LHC search programme!]

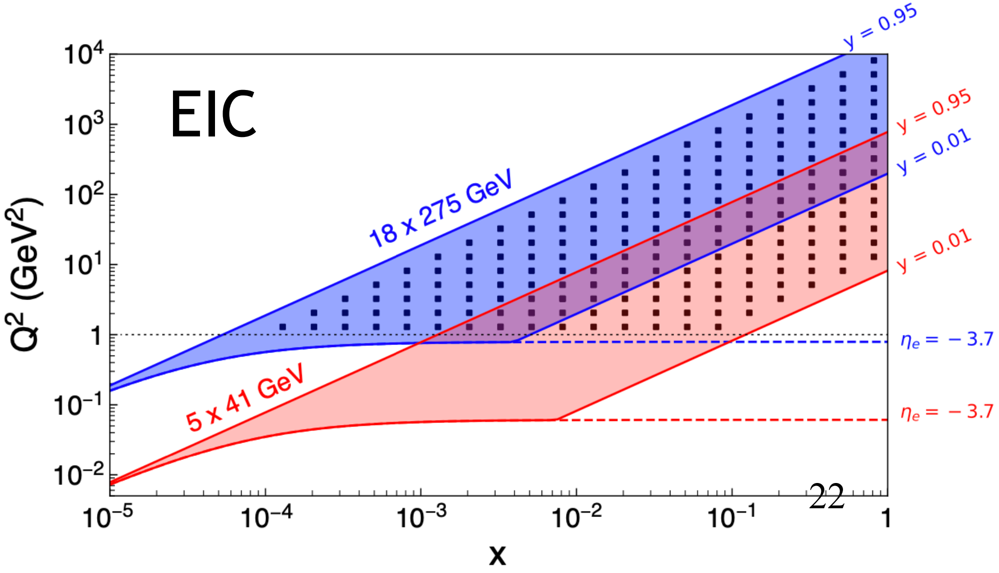
How to Improve High x



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

EIC fills in high x, intermediate Q^2 with overlapping phase space from different $\sqrt{s}$, keeping kinematic rec'n under control



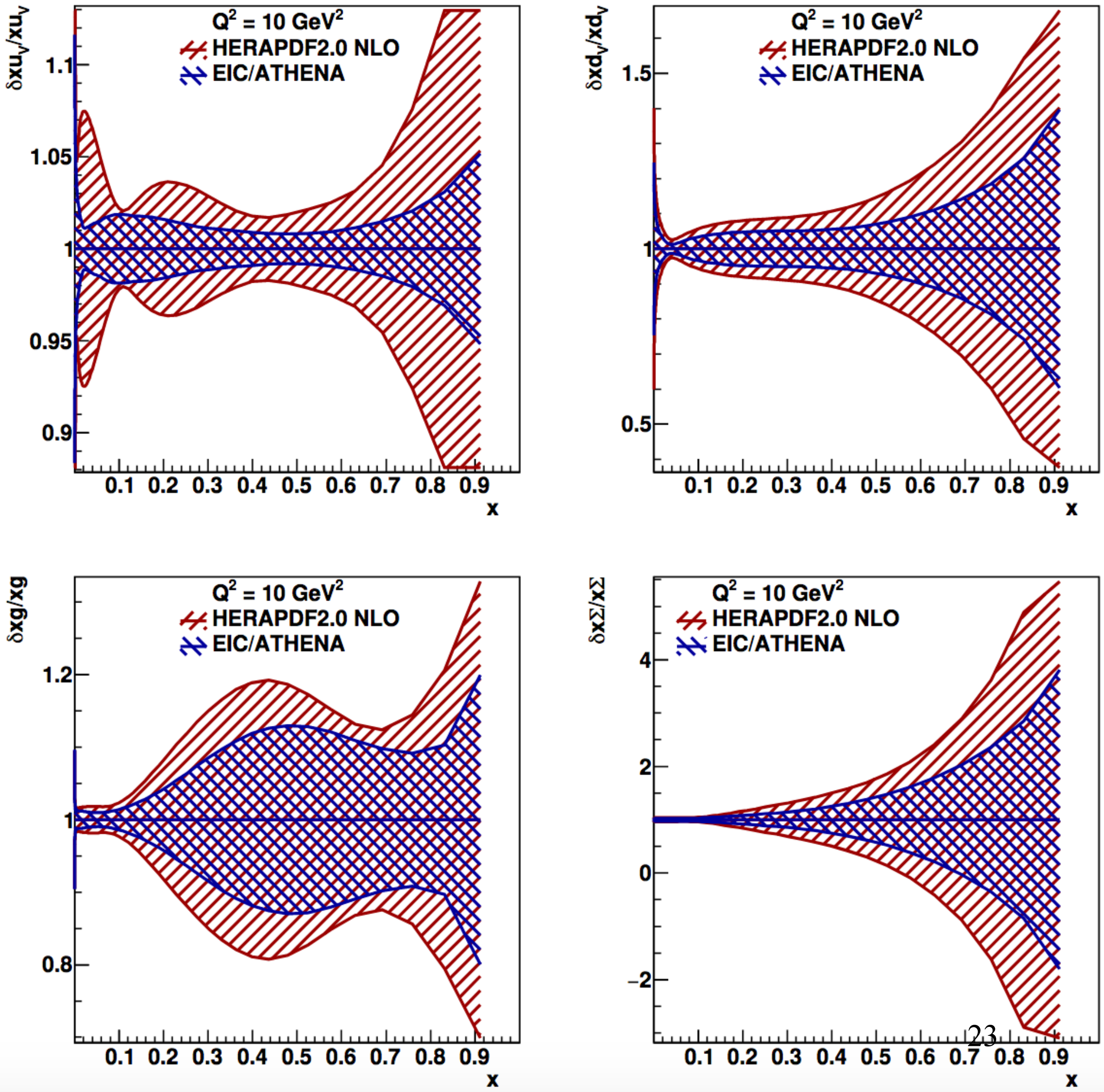


Impact of EIC on HERAPDF2.0

Fractional total uncertainties with / without EIC / ATHENA data included along with HERA

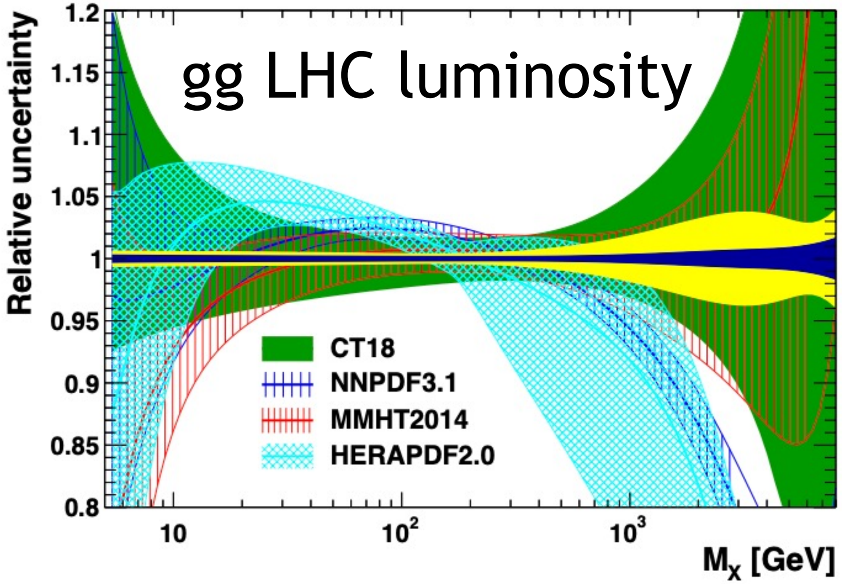
(linear x scale)

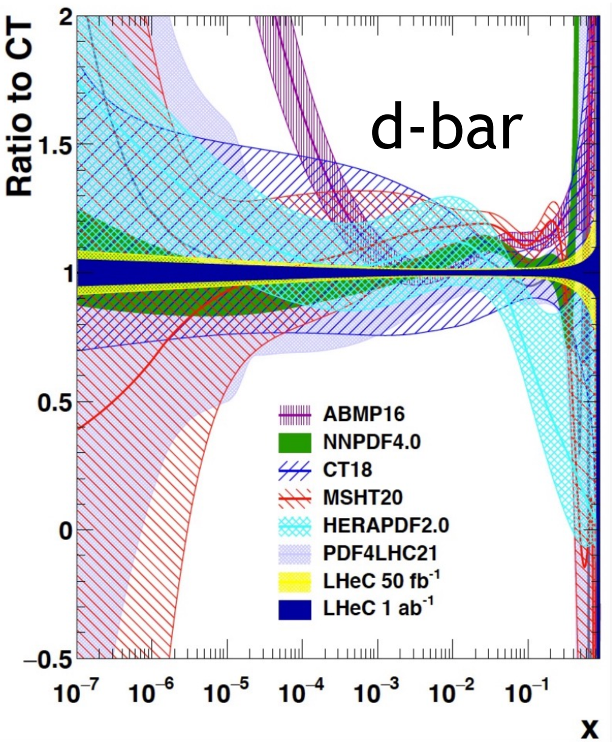
… EIC will bring significant reduction in uncertainties for all parton species at large x

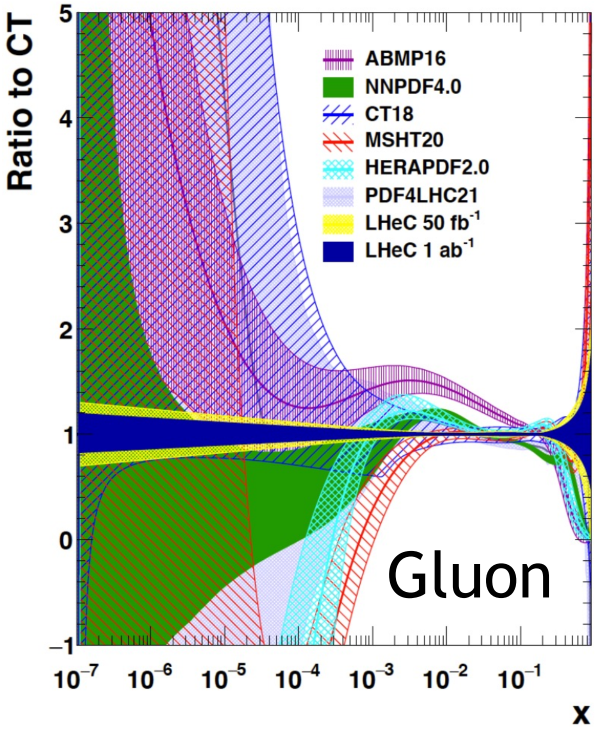


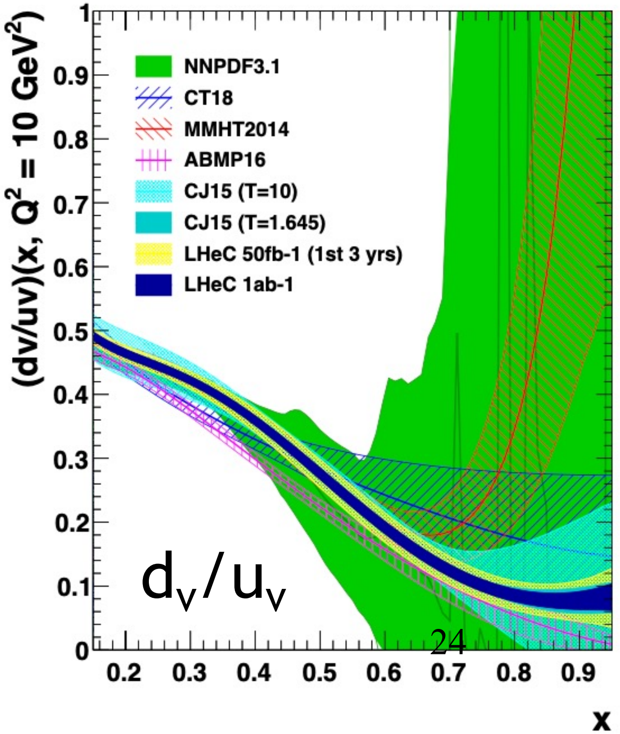
PDF Constraints at LHeC: Most recent study

- Addresses high x in a similar way to EIC
- Additionally revolutionizes low x region → 10^{-6}
  [ep saturation studies]







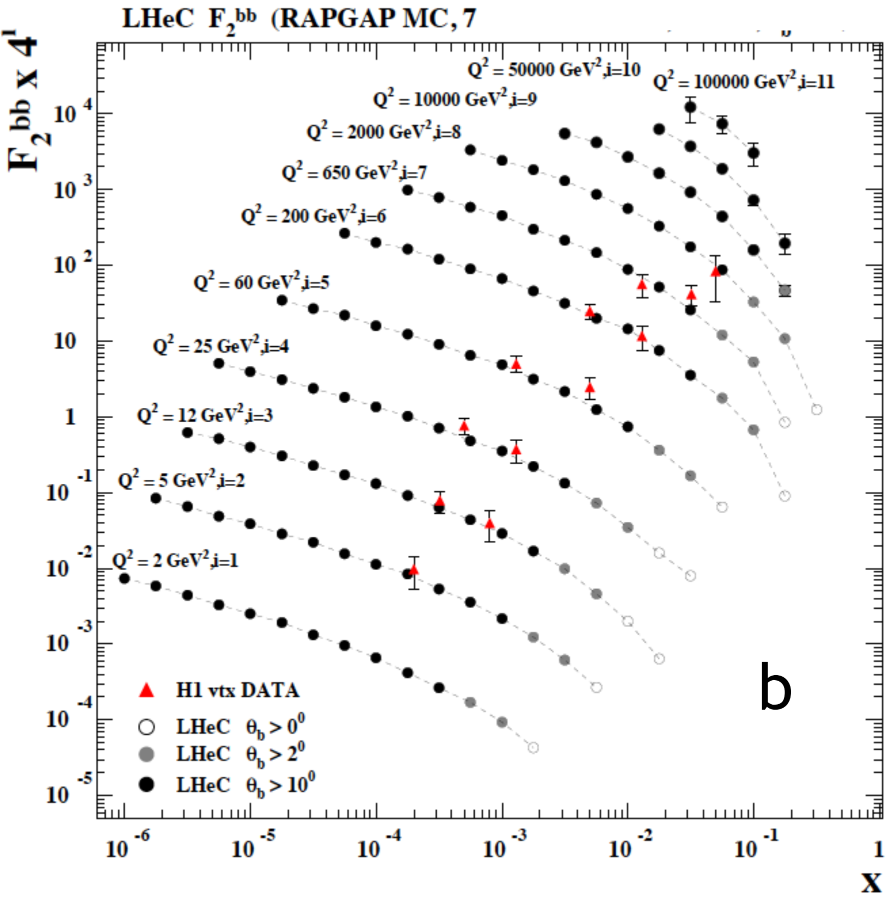


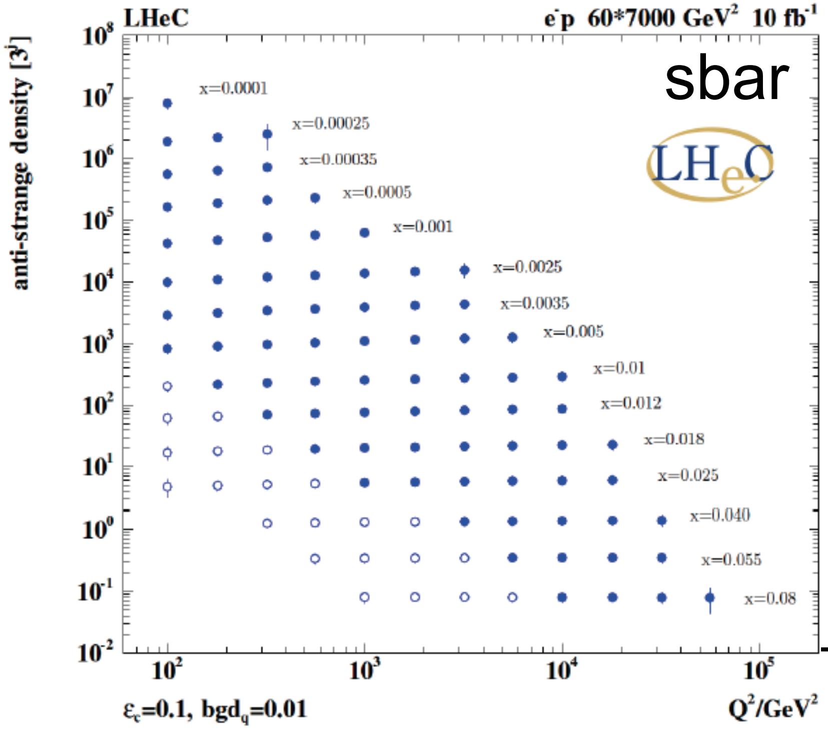
Flavour Decomposition

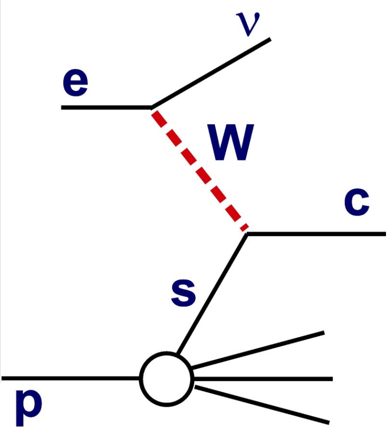
Precision c, b measurements (modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).

Systematics at 10% level

- →beauty as a low x observable
- →s, sbar from charged current

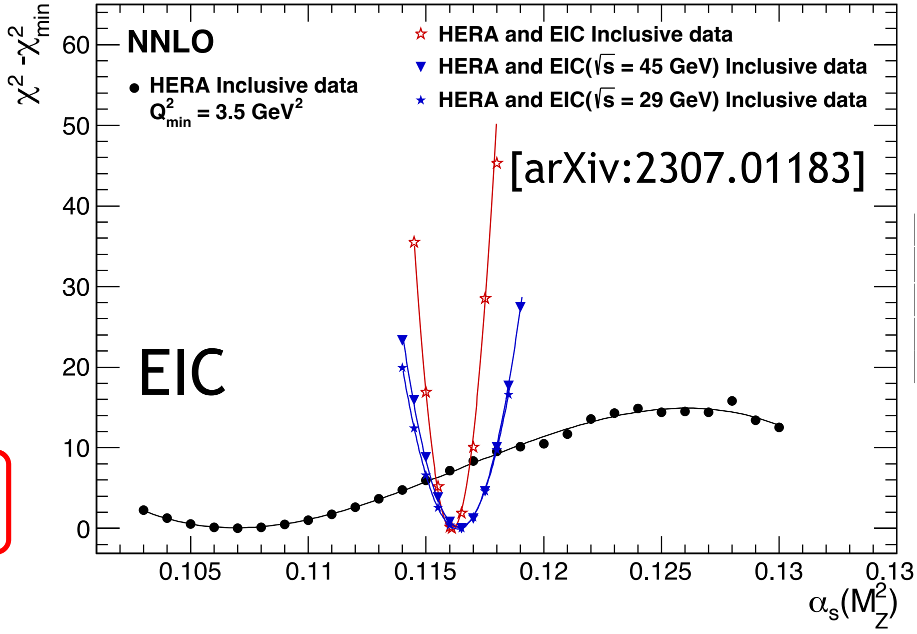






(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

Strong Coupling



[arXiv:2307.01183]

EIC

- Adding EIC EIC (high x, intermediate Q^2) to HERA leads to α_s precision facror Of 3 better than world average from inclusive DIS alone:

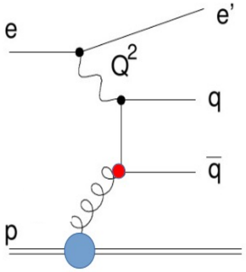
- **EIC and HERA inclusive data, NNLO:**

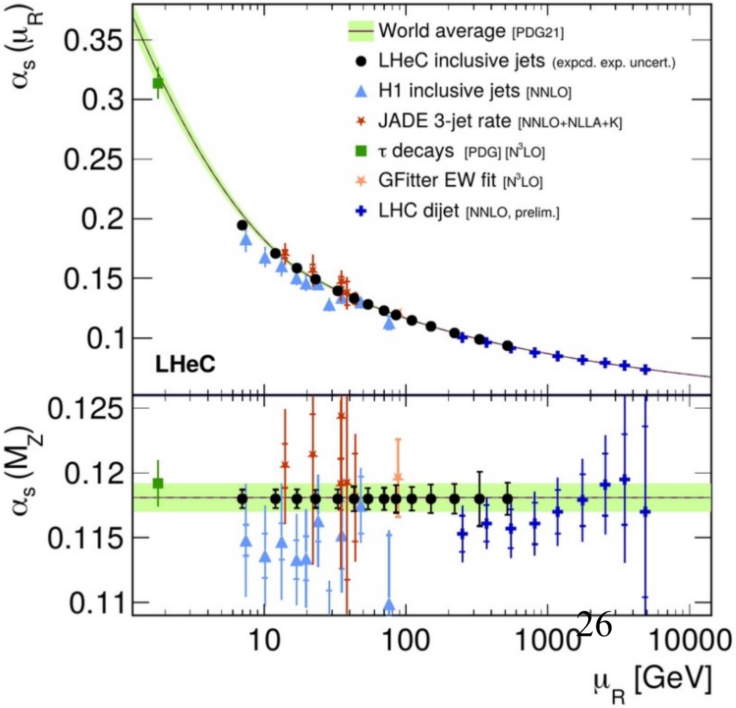
$$\boxed{\alpha_s(M_Z^2) = 0.1161 \pm 0.0003\ (\text{exp})\ \ \pm 0.0001\ (\text{model} + \text{param})}$$

- Similar LHeC study improves slightly:

$$\boxed{\Delta\alpha_s(M_Z)[\text{incl. DIS}] = \pm 0.00022_{(\text{exp+PDF})}}$$

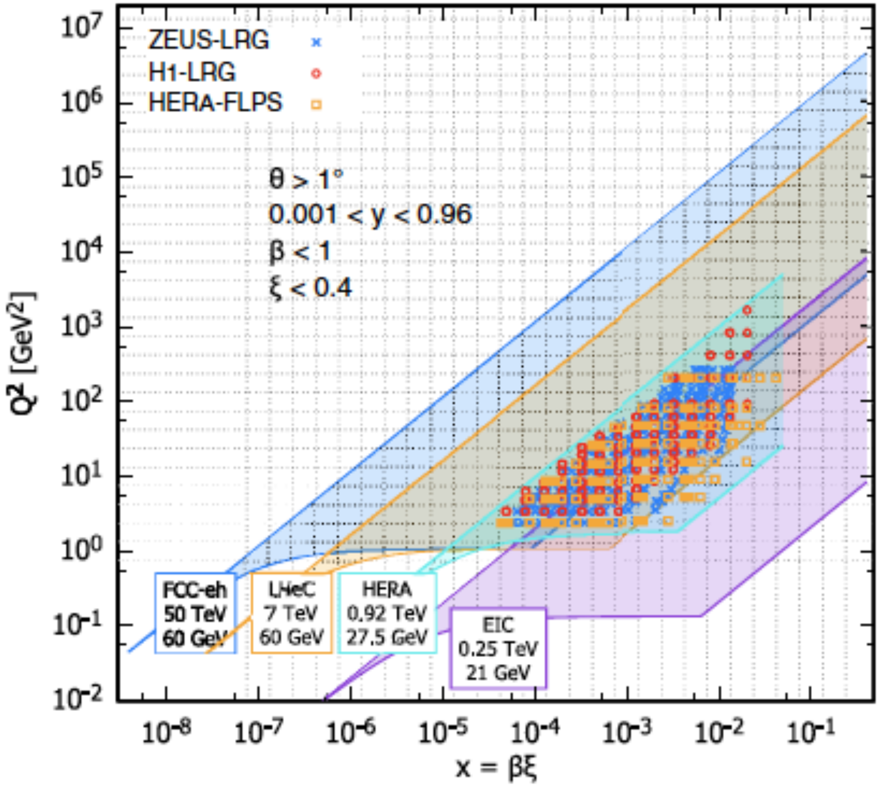
- Adding jet data with huge LHeC Phase-space leads to exquisite precision on running coupling way beyond Z pole





Need to (re)-assert principle that DIS with current and future data is *the* way to measure PDFs and strong coupling

Diffractive Phase Space and EIC Impact

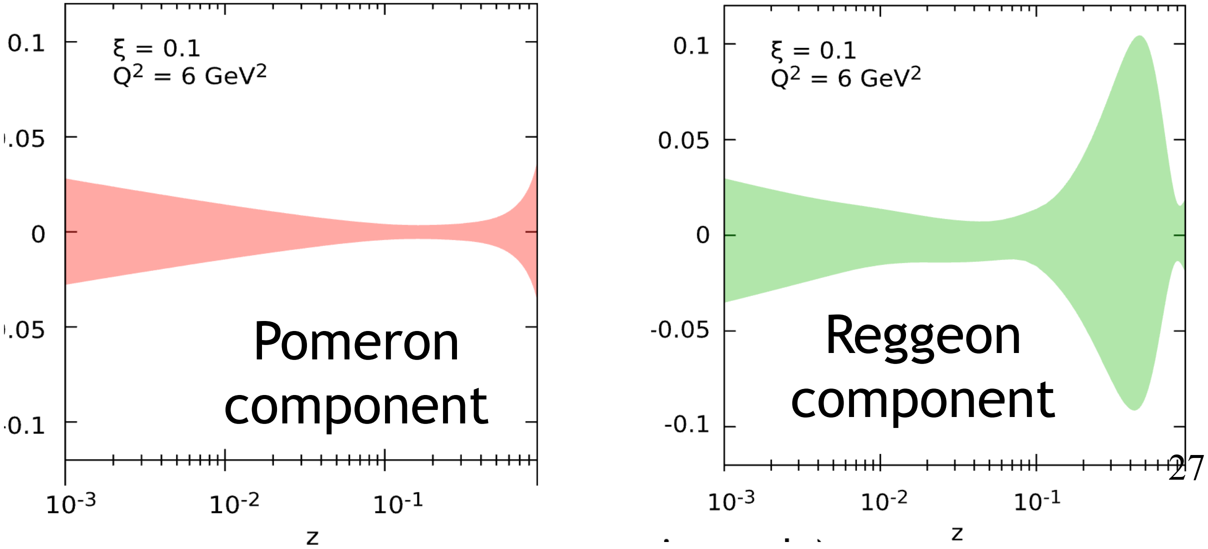


- Genuine EIC-HERA-LHeC synergy in absence of fixed target data

- EIC multiple beam energies ideal for F_L^D extraction

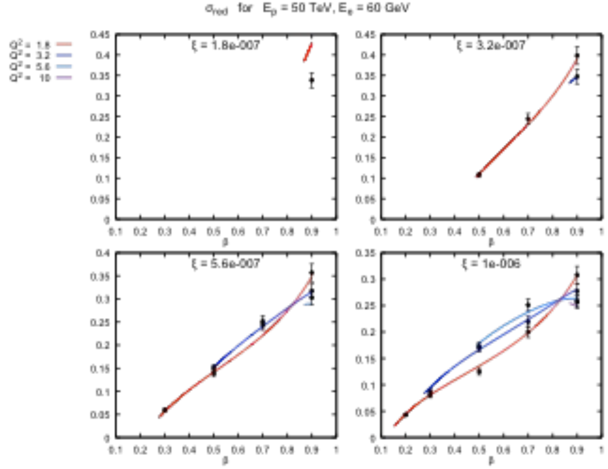
- EIC large x, intermediate Q2 region ideal for understanding sub-leading \`Reggeon' exchange (Anna's talk)

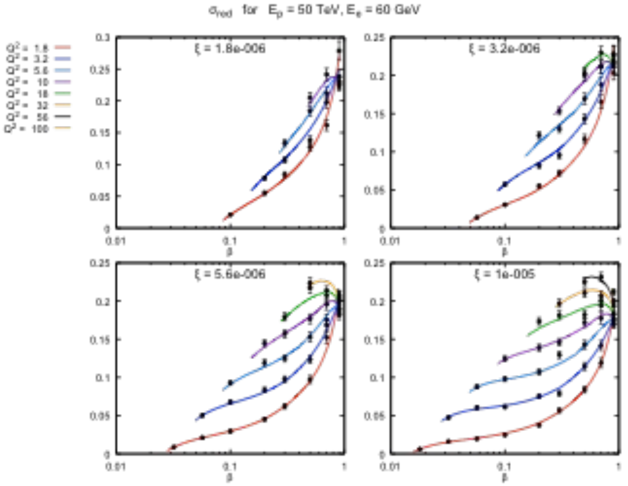
Diffractive gluon density from fit to EIC only →

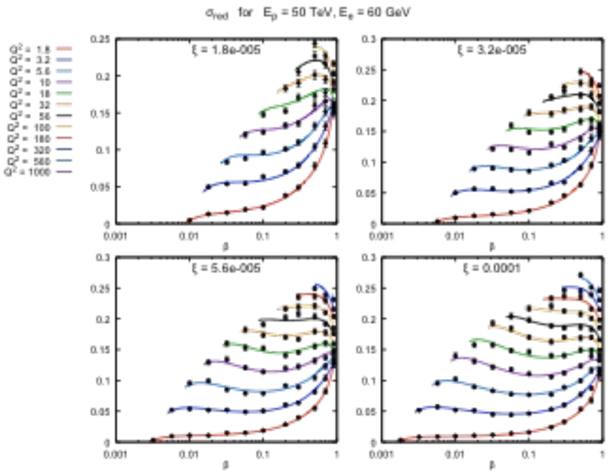


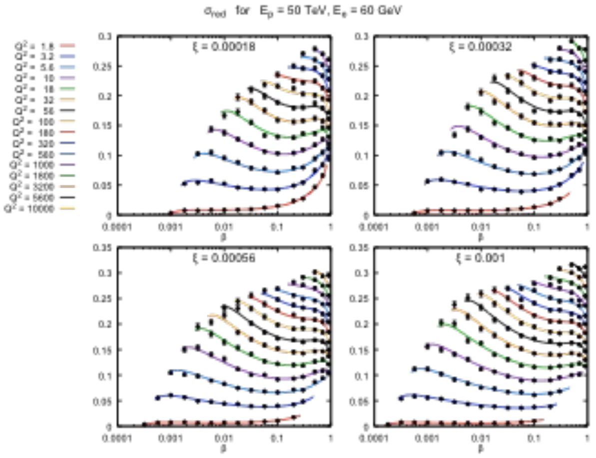
All F_2^D pseudodata bins at FCC-eh

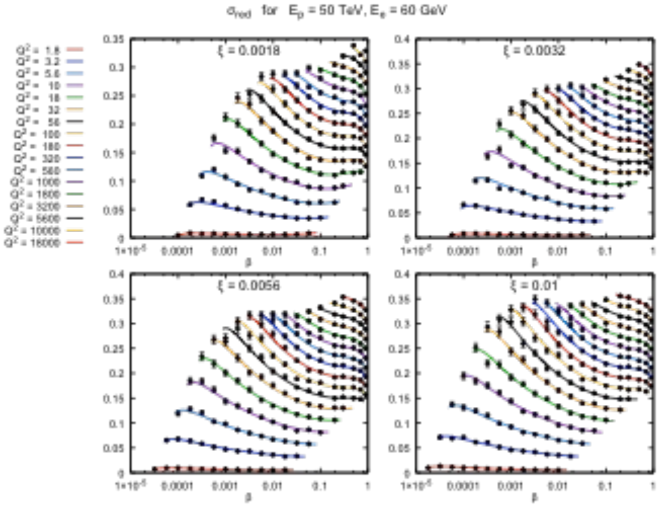
ξ=1.8 x 10^{-7}

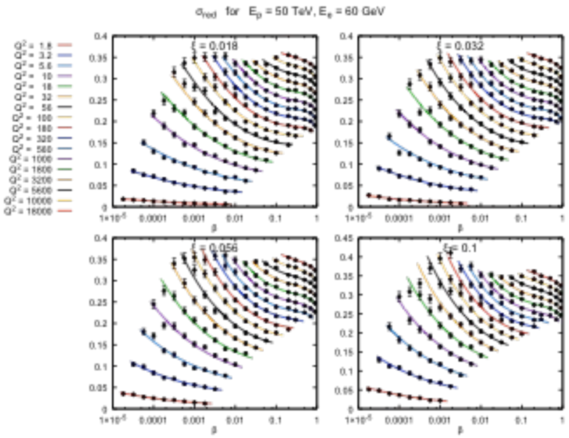












ξ=0.1

Data uncertainties:

- 5% uncorrelated systematic
- Statistical uncertainty based on 2fb^{-1}

Fit range:

Q^2_{min} = 5 GeV^2

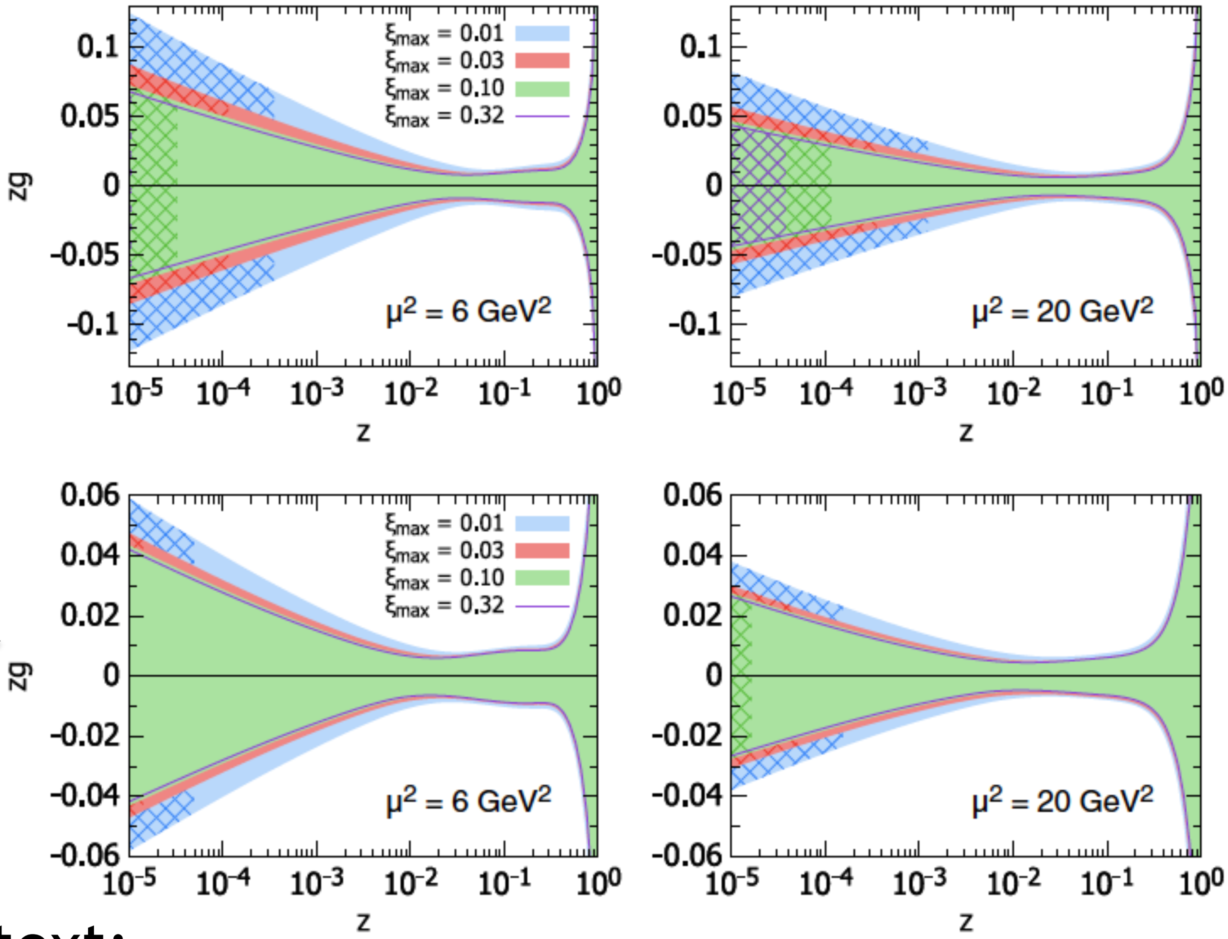
ξ_{max} = 0.1

Relative Precision on Diffractive Gluon Density

LHeC →

[90% CL bands]

FCC-eh →

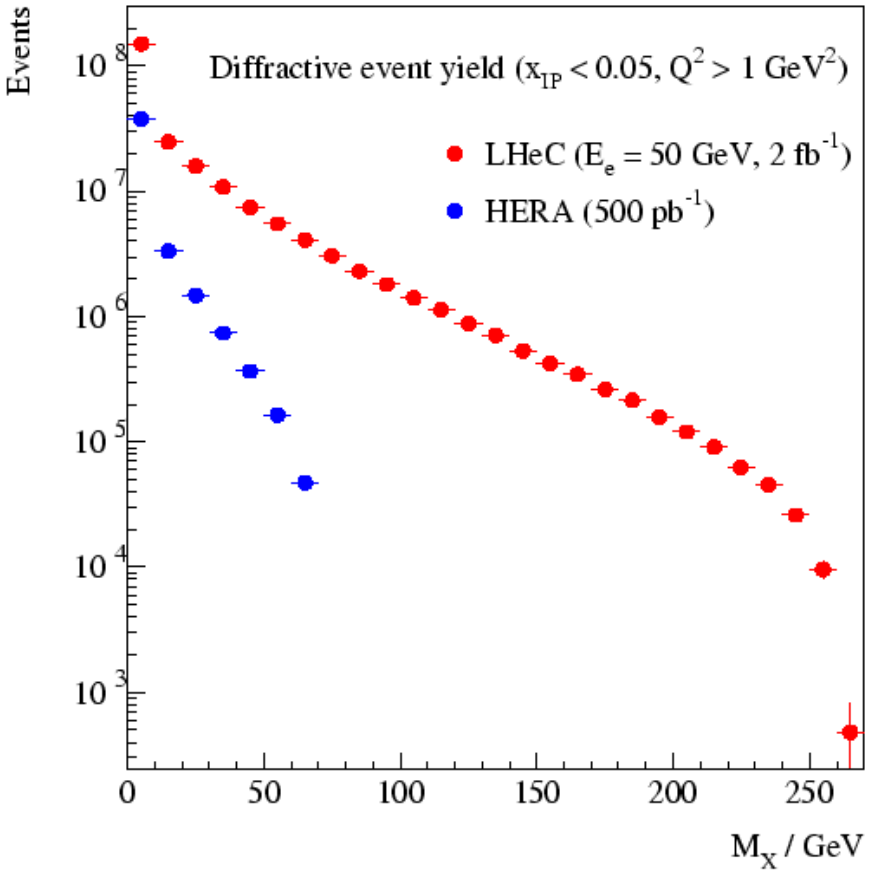


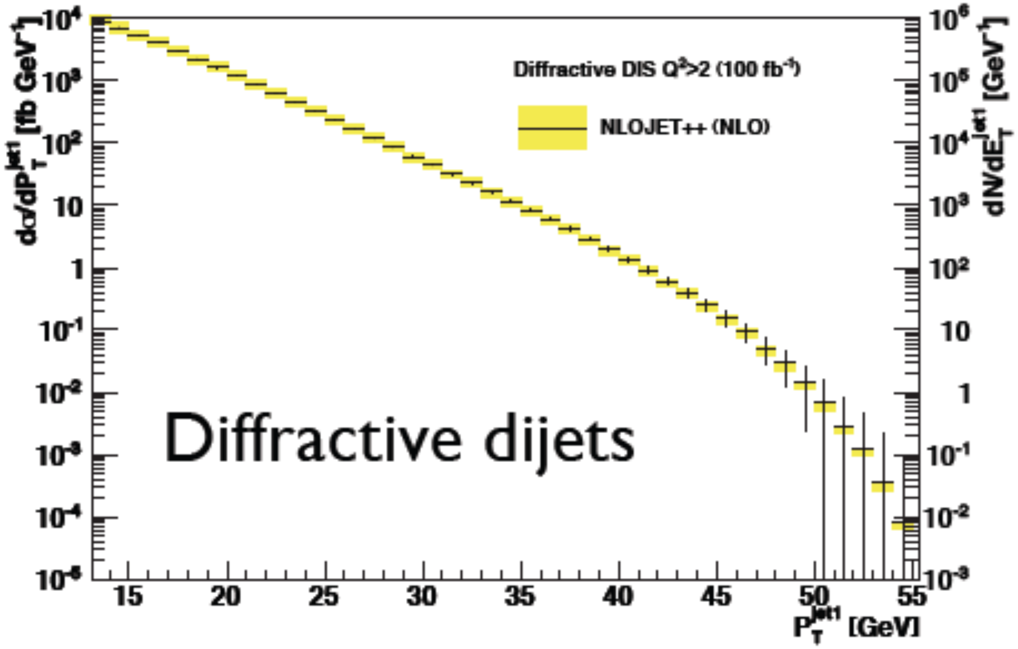
Notes in LHeC context:

- Well constrained down to β or z ~ 10^{-4} – 10^{-5}
- Experimental precision on quarks <2% (direct from data)
- Experimental precision on gluons few% (scaling viol's)
- No statement on parameterisation or theory uncertainties

LHeC and Large Diffractive Masses

- HERA (and EIC) diffractive final states limited to low masses / p_T
- LHeC diffractive jets up to $p_T > 50$ GeV
- FCC-eh extends by further factor of 3



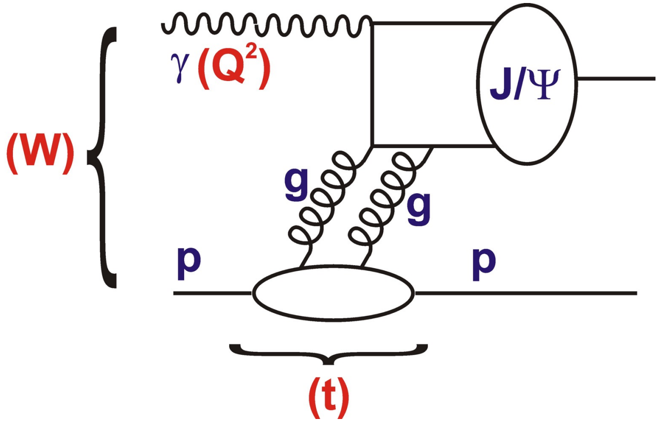


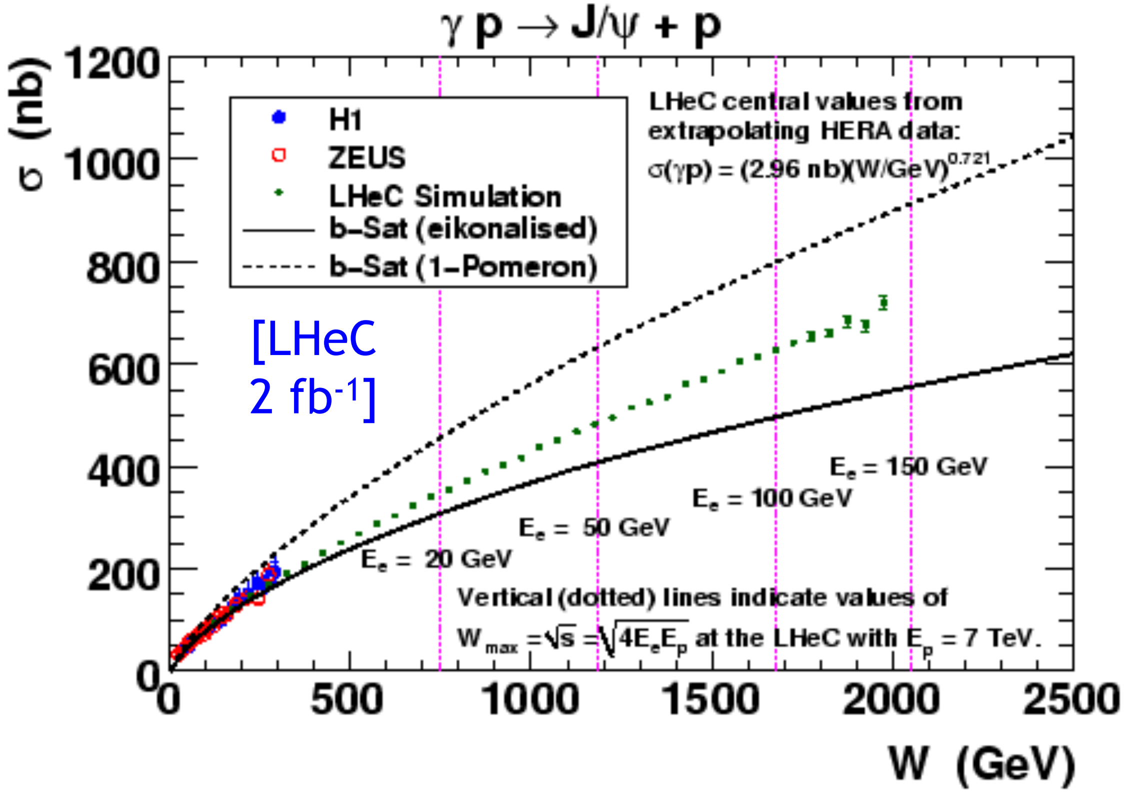
- Precision comparison with theory for jets and charm
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new 1^- states

Exclusive J/Ψ in ep v Saturation Predictions

Exclusive physics at LHeC focused on low-x effects …

Simulated data v “b-Sat” Dipole model
- “eikonalised”: impact-parameter dependent saturation
- “1 Pomeron”: non-saturating





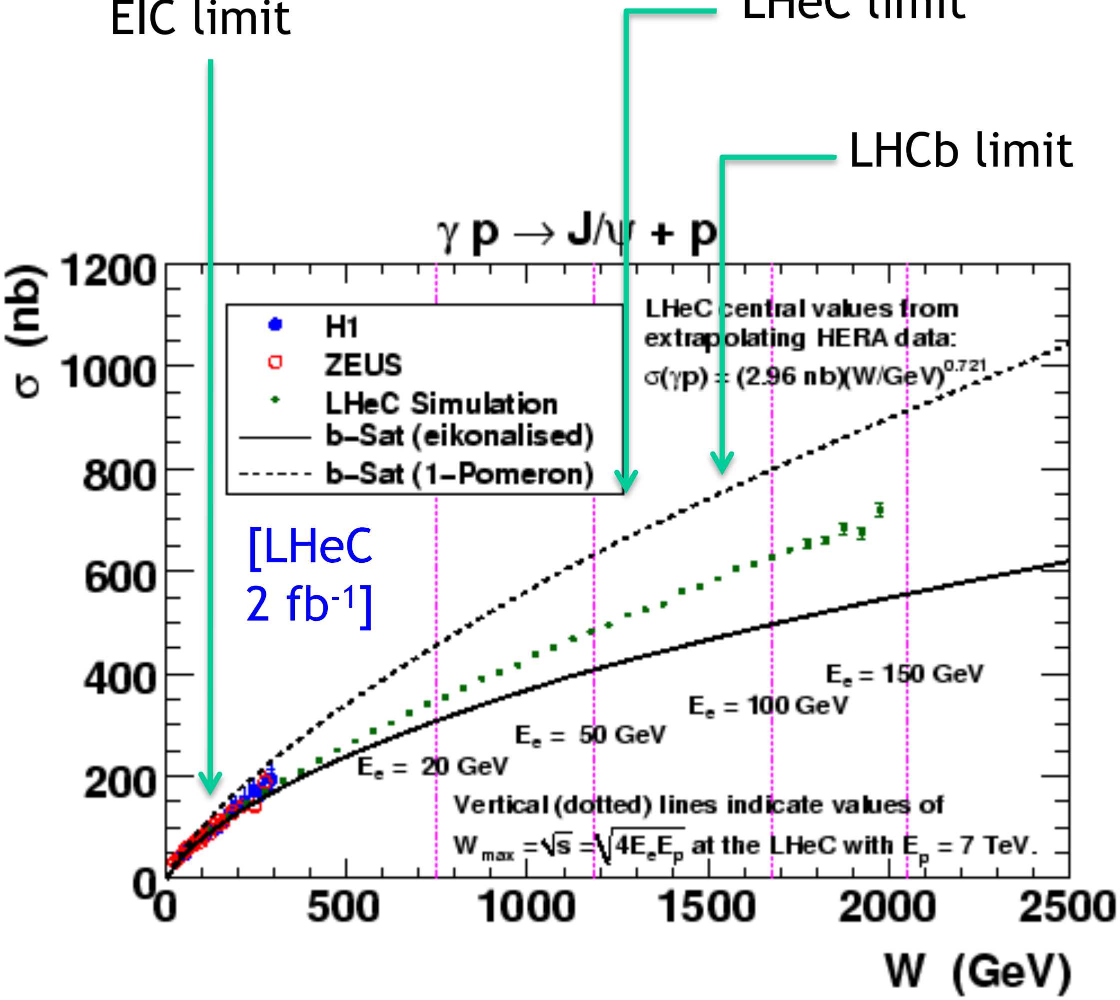
[LHeC 2 fb^{-1}]

- Significant non-linear effects expected in LHeC kinematic range

… ‘smoking gun’?...

J/Ψ from future ep v Dipole model Predictions

BUT …

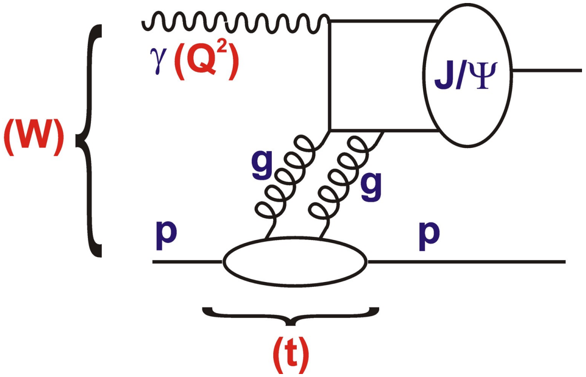


EIC limit

LHeC limit

LHCb limit

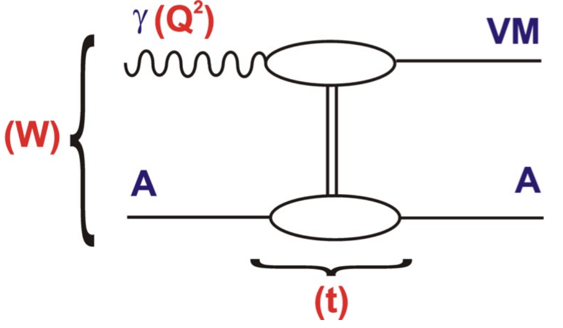
[LHeC
2 fb^{-1}]

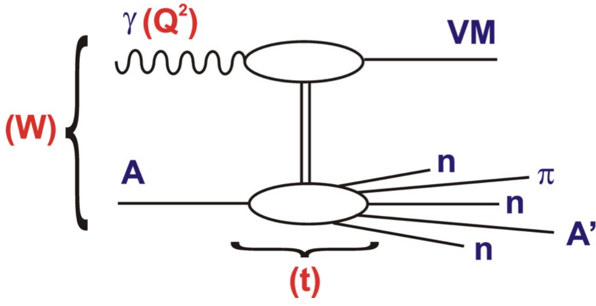


- Lack of sat^n signal at LHC to date suggests increasing energy alone is not the answer

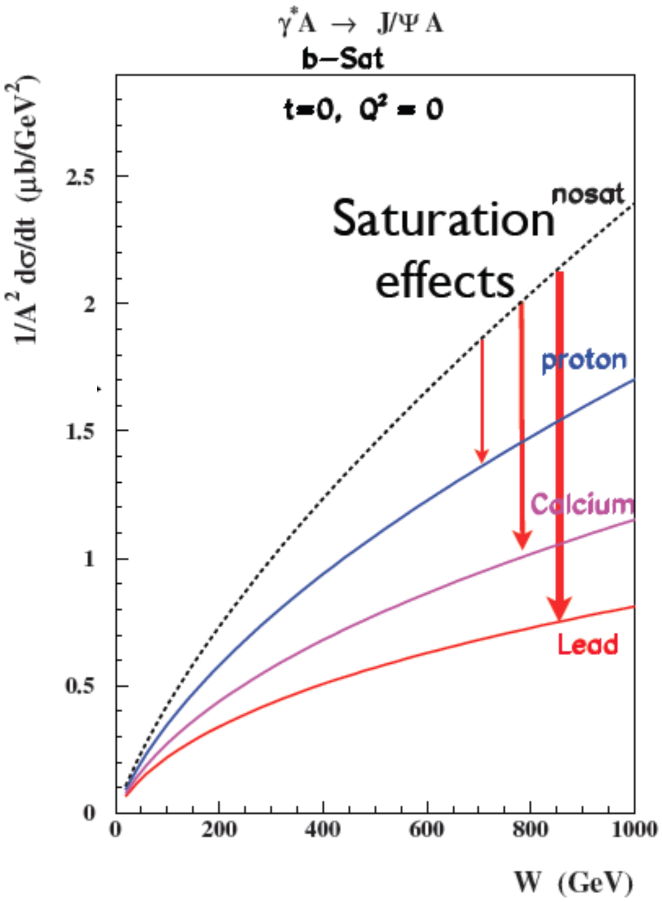
- Need detailed mapping in ep and eA and scanning of t (& maybe also of Q^2).

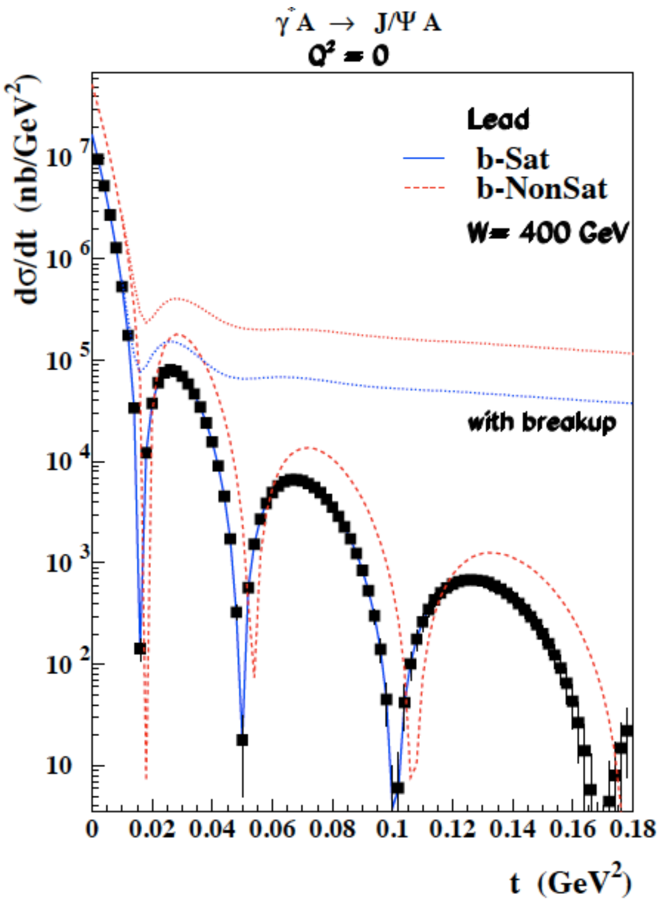
e.g. Exclusive Diffraction in eA





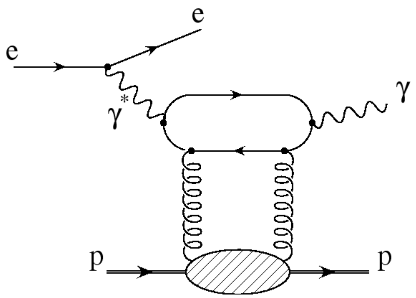
Experimentally clear saturation signatures and theoretically cleanly calculable effects (eg ‘dips’) in coherent diffraction case (eA → eVA)

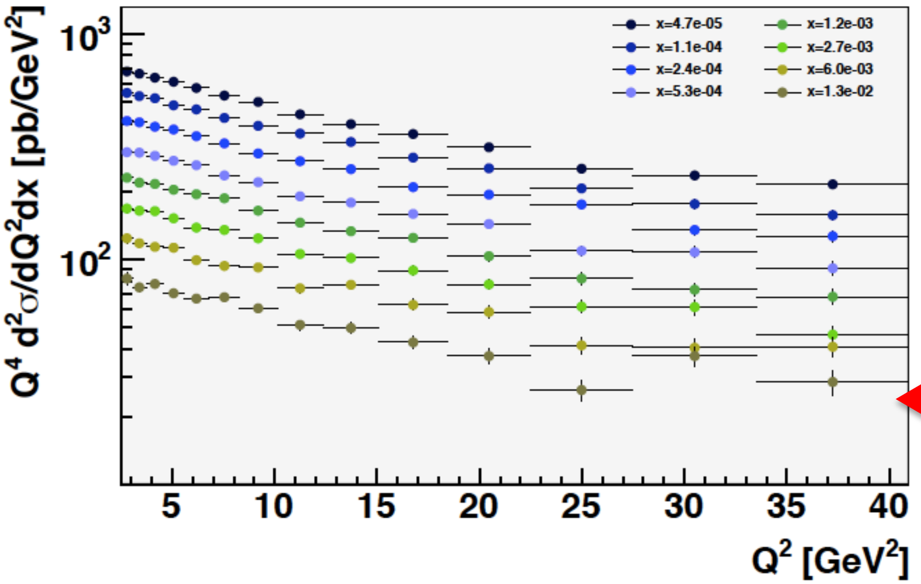




As at EIC, experimental challenge to separate coherent from incoherent (mainly ZDC) and resolve dips

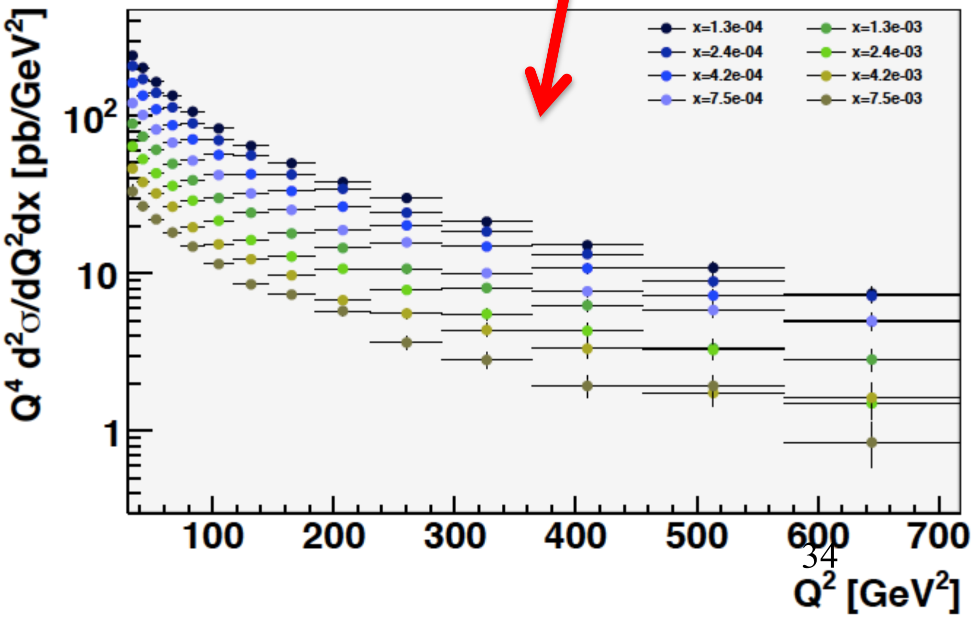
A word on DVCS at LHeC





1 fb^{-1}, E_e = 50 GeV, 1° acc'nce, p_T^γ > 2 GeV

100 fb^{-1}, E_e = 50 GeV, 10° acc'nce, p_T^γ > 5 GeV

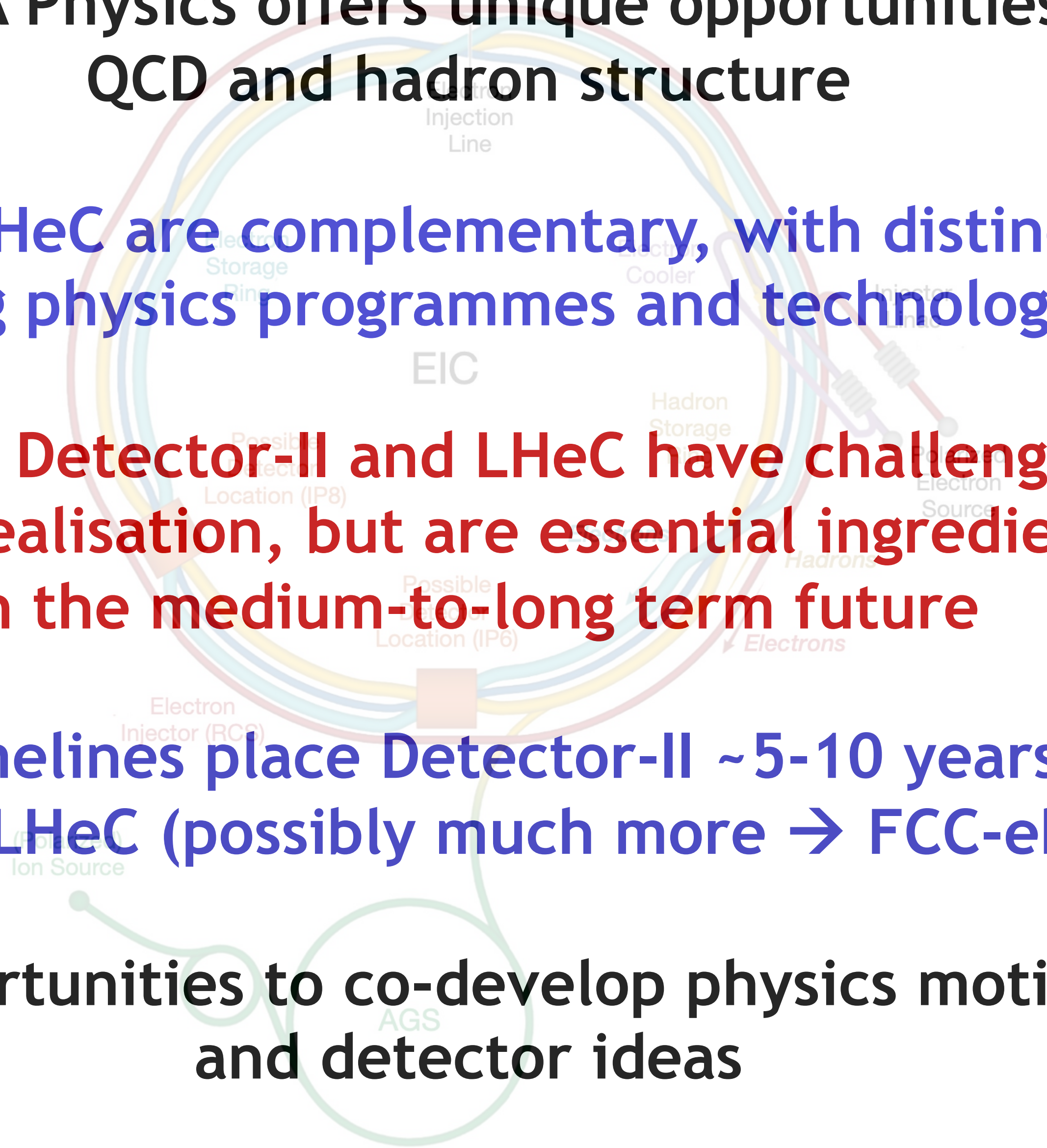


- HERA lacked the luminosity for a major DVCS programme
- LHeC simulations show good sensitivity at large Q^2, low x
- Very different kinematic regime from EIC (large x, emphasising 3D structure …)

Still to do:

- **Beam charge asymmetries**
- **Sensitivity to low x GPDs**

Summary



ep / eA Physics offers unique opportunities in QCD and hadron structure

EIC and LHeC are complementary, with distinct but overlapping physics programmes and technology needs

Both EIC Detector-II and LHeC have challenges in their realisation, but are essential ingredients in the medium-to-long term future

Possible timelines place Detector-II ~5-10 years earlier than LHeC (possibly much more → FCC-eh)

Clear opportunities to co-develop physics motivations and detector ideas