The Large Hadron electron Collider

INT Program INT-18-3

Probing Nucleons and Nuclei in High Energy Collisions

October 1 - November 16, 2018

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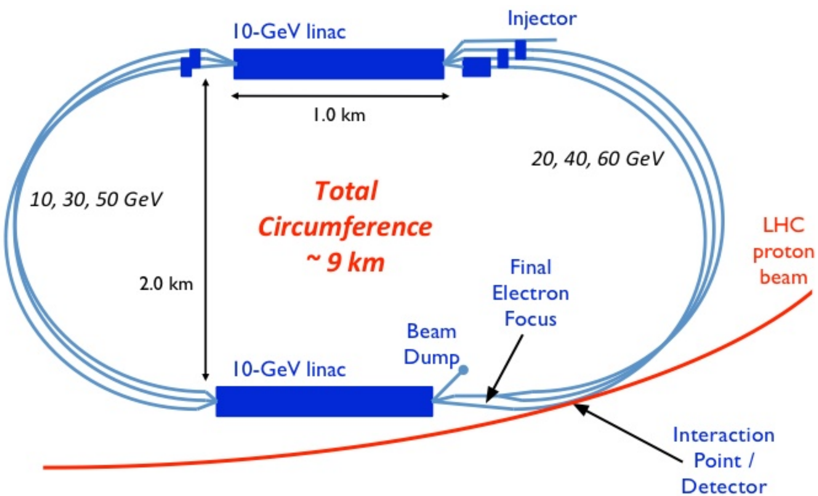
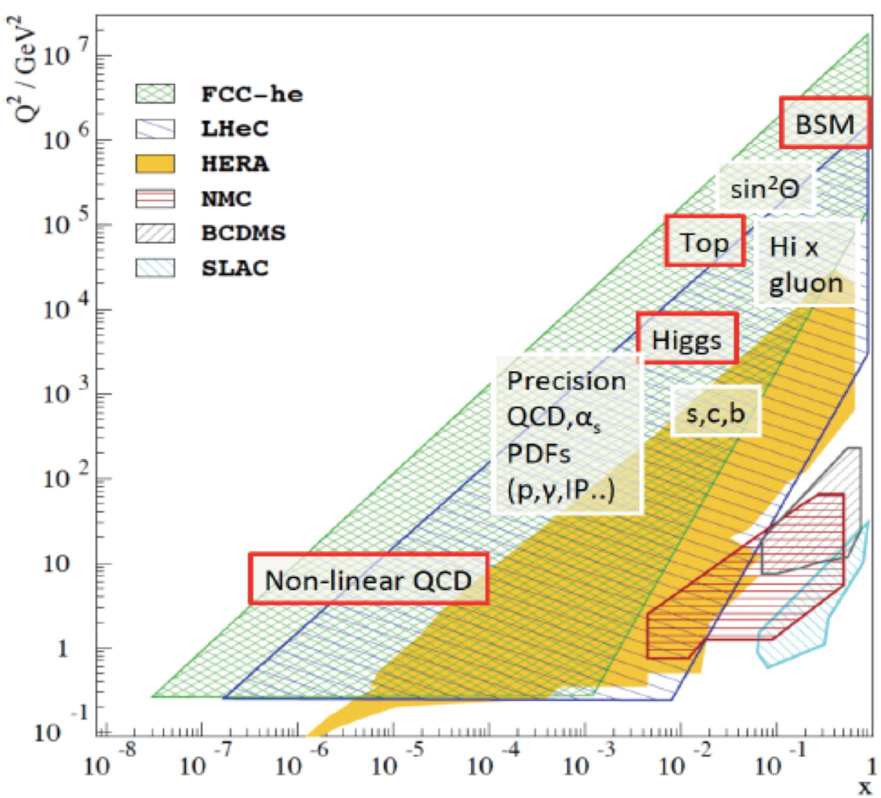
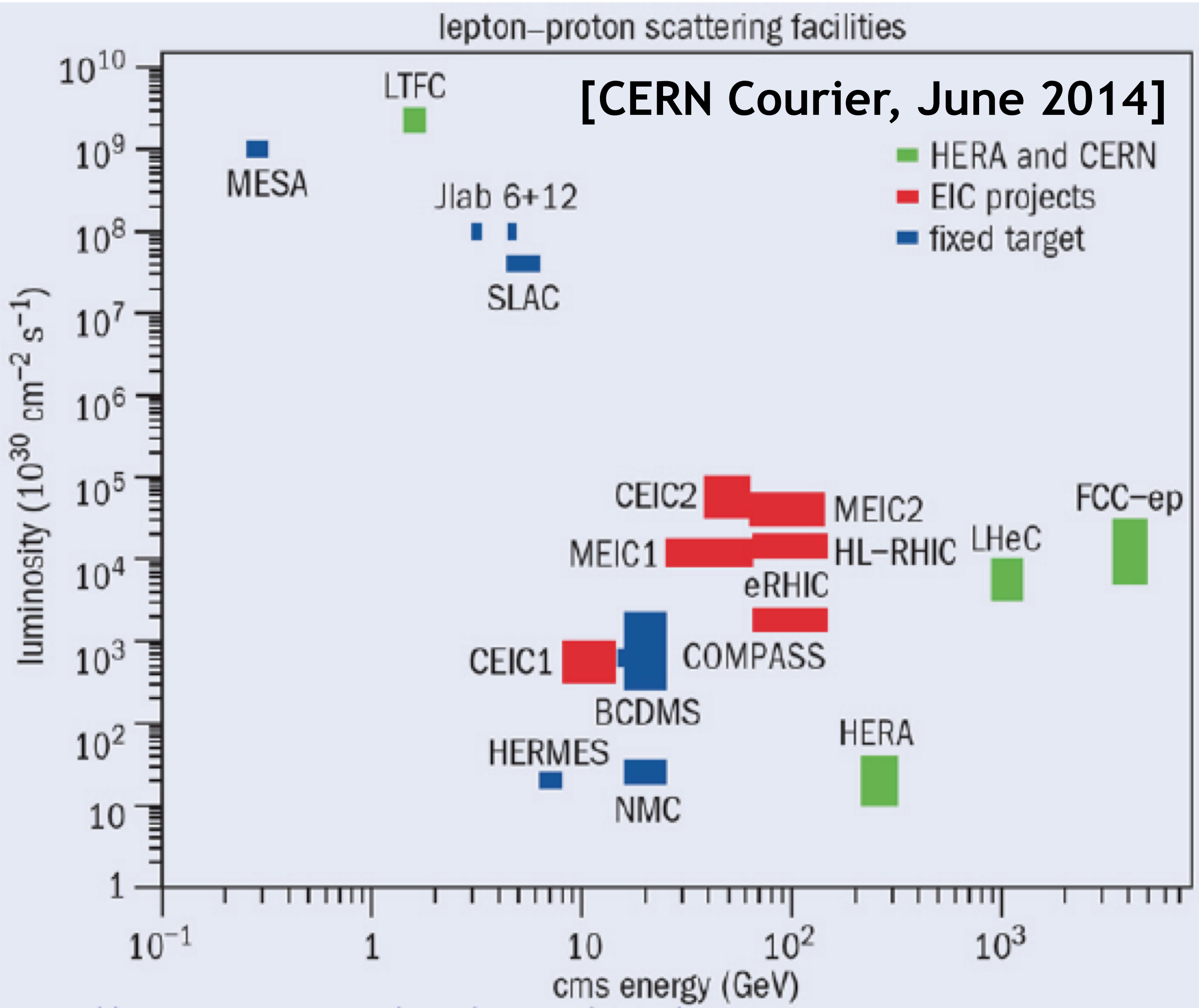




LHeC Context

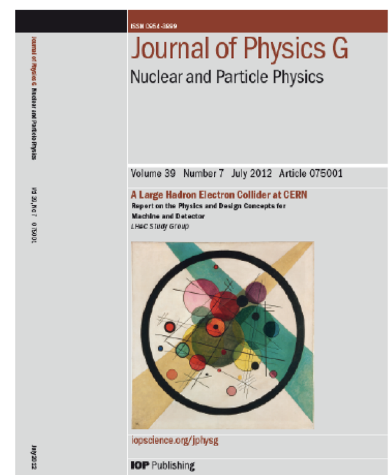


Proposed energy frontier high luminosity ep / eA facility → TeV scale physics at 10^{34} cm^{-2}s^{-1}

LHeC: 60 GeV electrons x LHC protons & ions
→ 10^{34} cm^{-2} s^{-1}
→ Simultaneous running with ATLAS / CMS in HL-LHC period

FCC-ep: 60 GeV electrons x 50 TeV protons from FCC

CDR 2012: "Fake news?" … lots changed



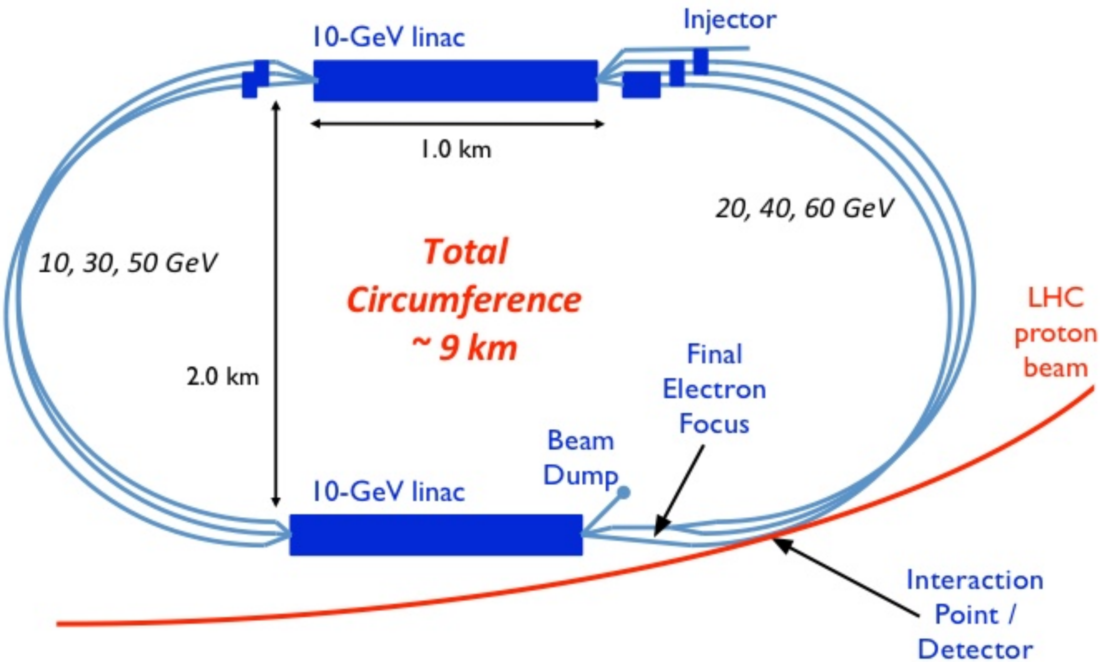
arXiv:1206.2913

Baseline# Design (Electron "Linac")

LHeC CDR, July 2012 [arXiv:1206.2913]

Design constraint: power consumption < 100 MW → E_e = 60 GeV

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures



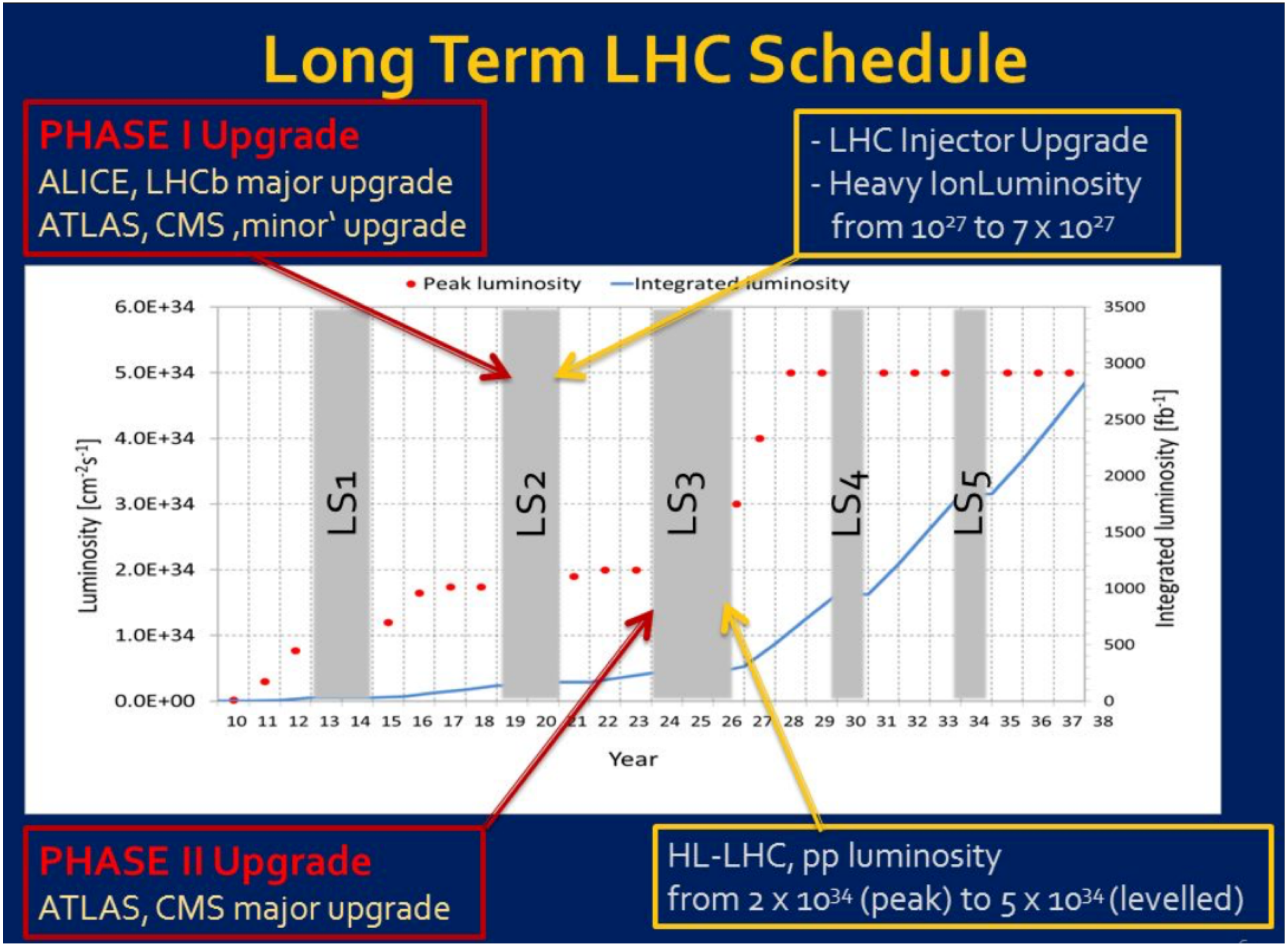
- ep lumi → 10^{34} cm^{-2} s^{-1}

→ ~100 fb^{-1} per year →~1 ab^{-1} total

- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (3.10^{32}) cm^{-2} s^{-1} for eD (ePb)**

Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist

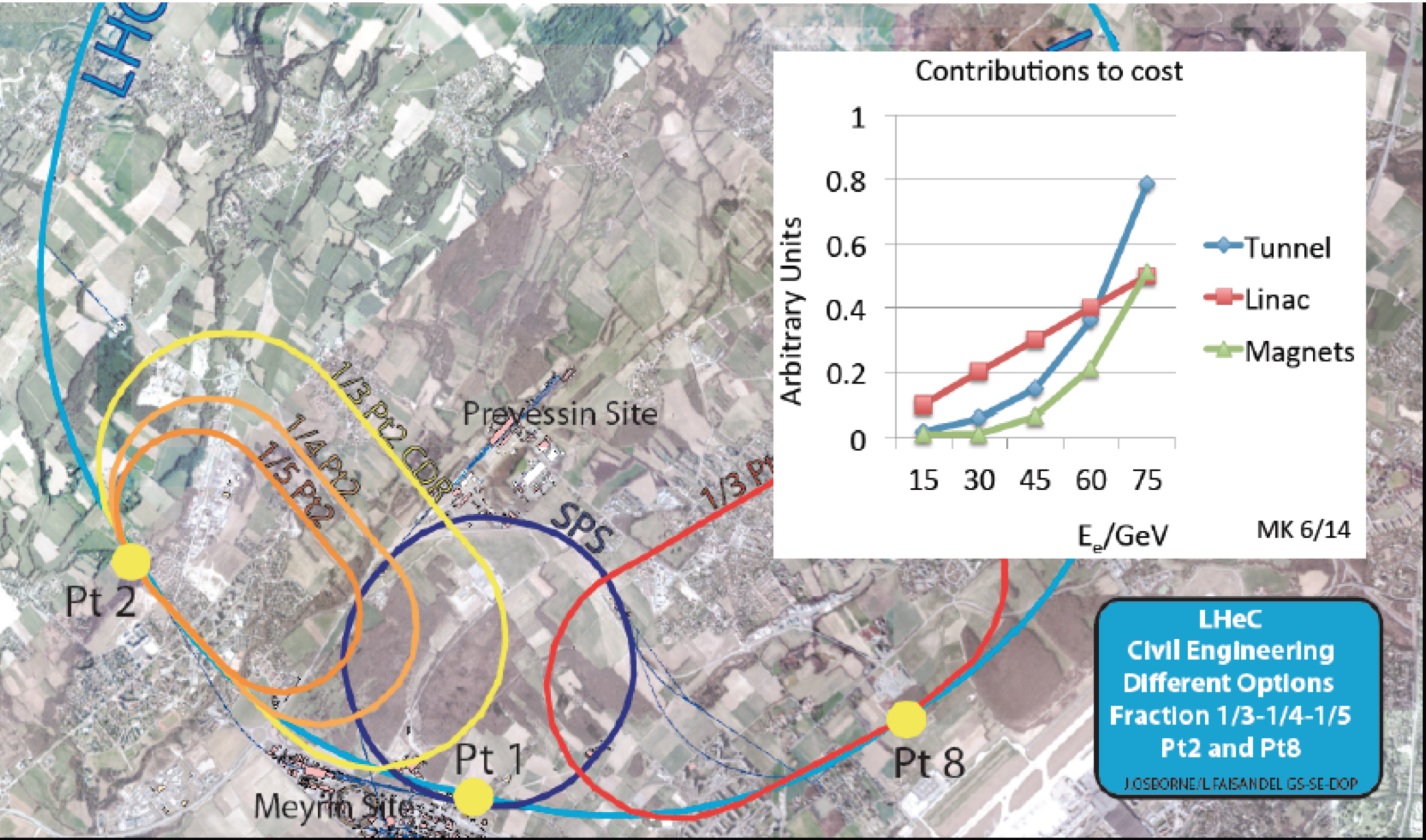
LHeC Timeline



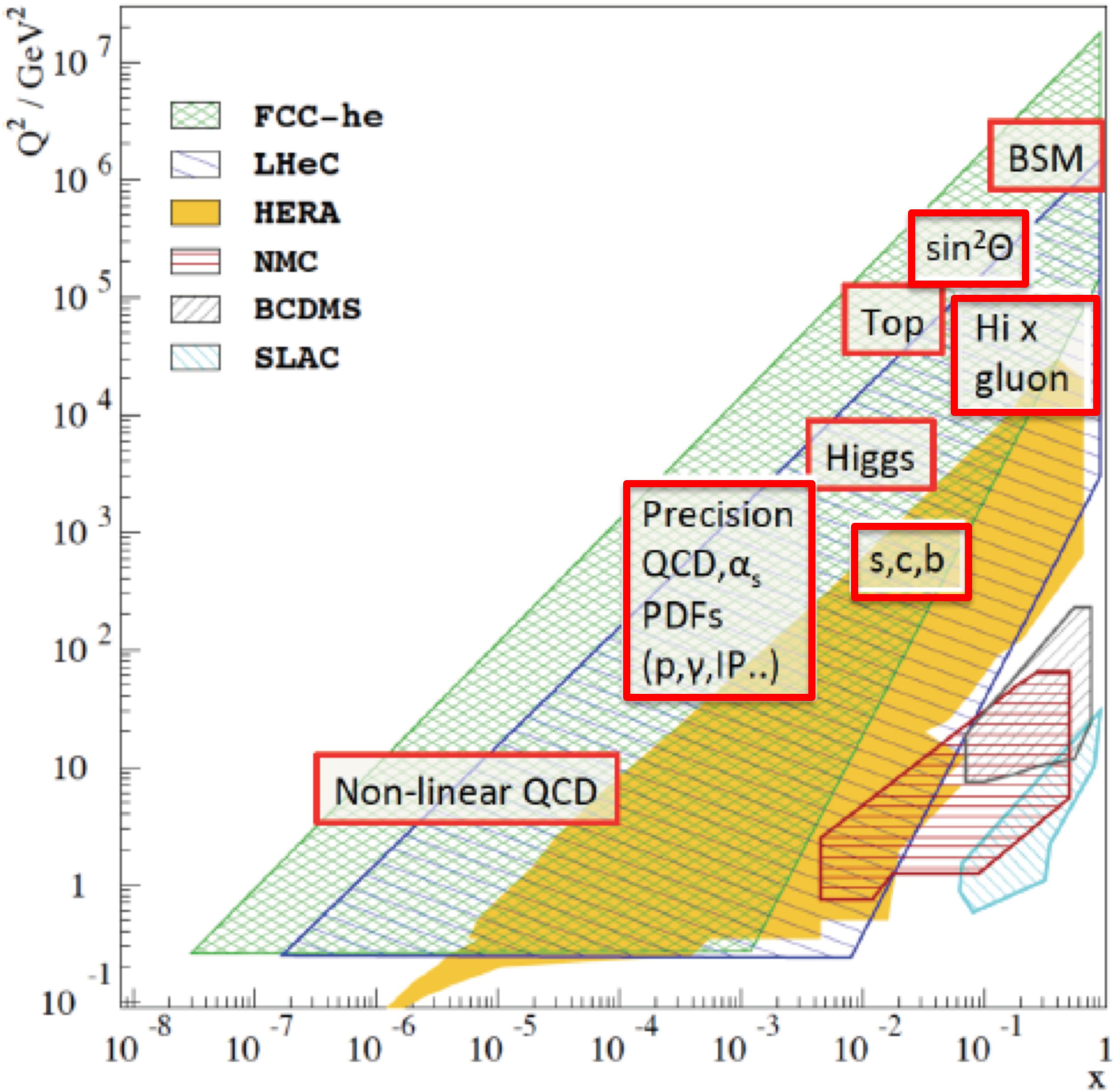
Not defined … but makes best sense in parallel with HL-LHC…
schedule extends to ~2026-2040, with multiple shutdowns

Where could the LHeC be built?

- Default design is 1/3 at Point 2 (currently ALICE)
- Point 8 (currently LHCb) has also been considered



Complementary Physics Programme to EIC



- Standalone Higgs programme

- Revolutionary proton PDF precision, enhancing LHC BSM physics sensitivity

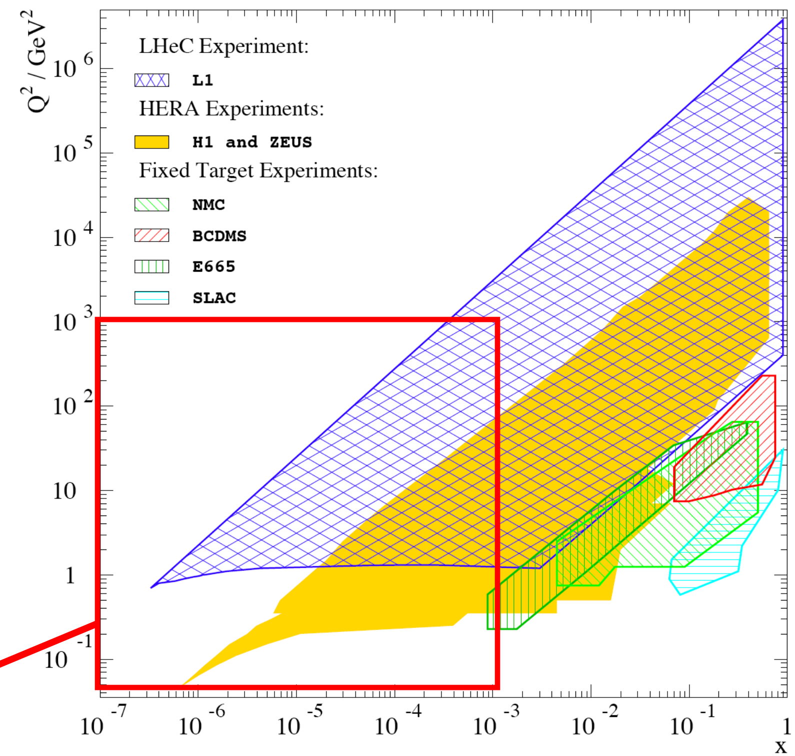
- Elucidates low x dynamics in ep & eA

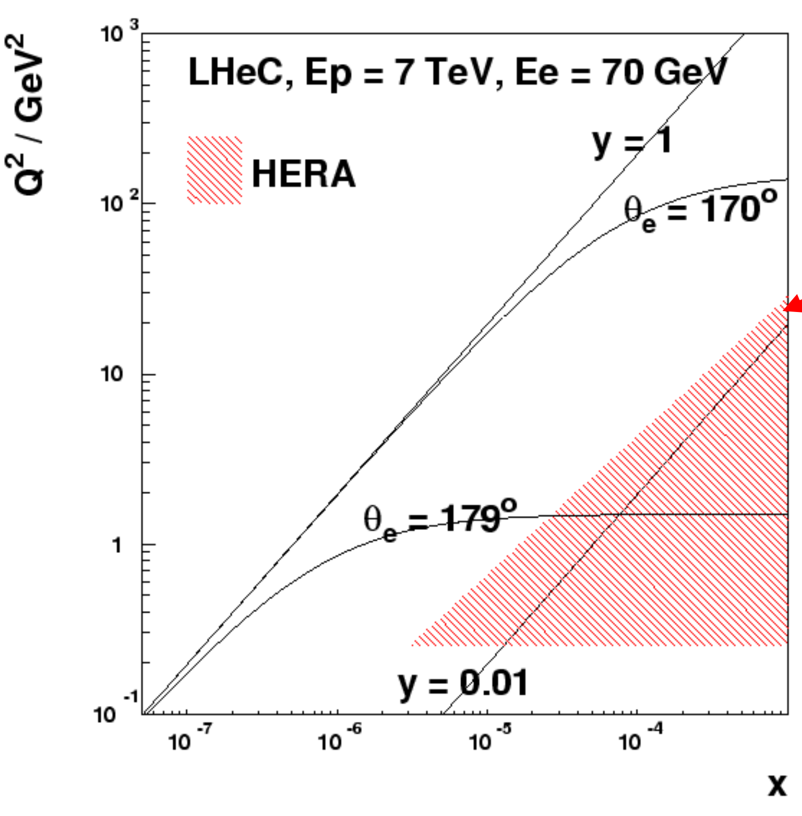
- 4 orders of mag. in kinematic range of nuclear structure

- No polarised targets

LHeC Detector Acceptance Requirements

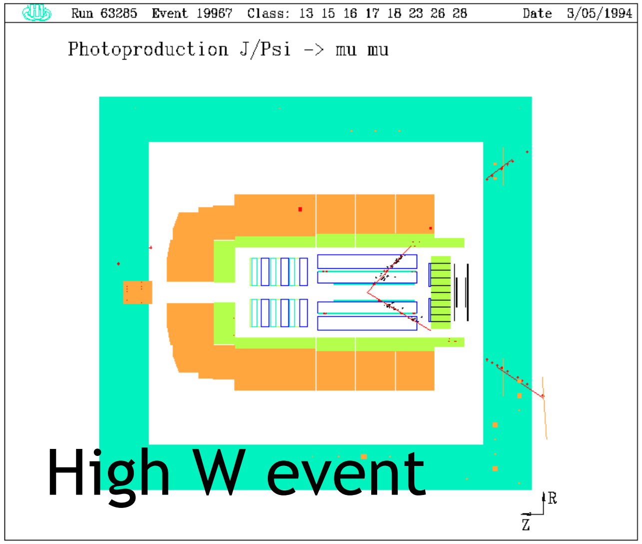
Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°

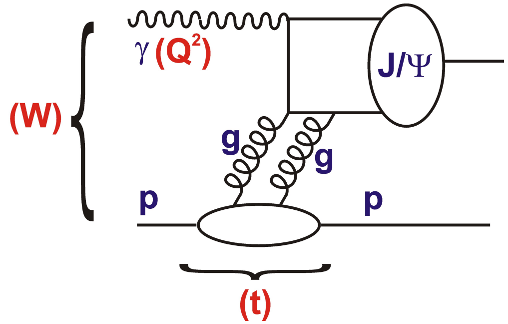




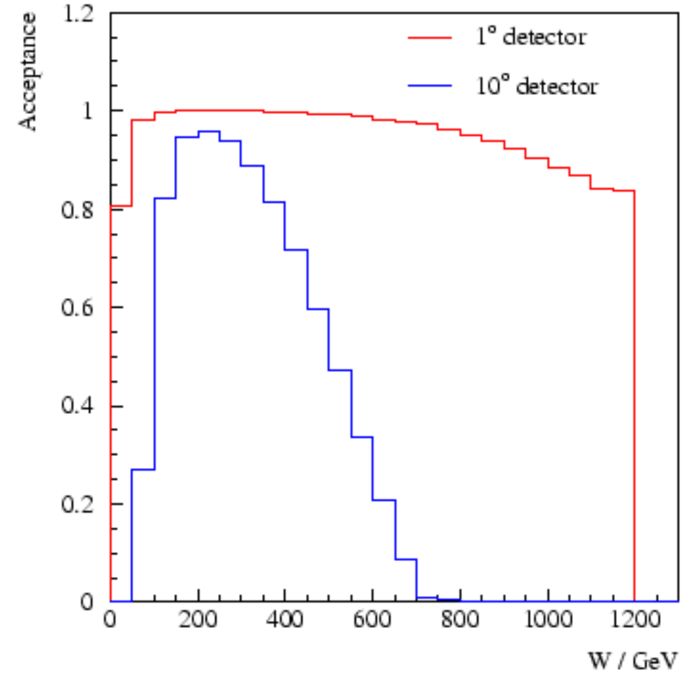
Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high x (essential for good kinematic reconstruction)

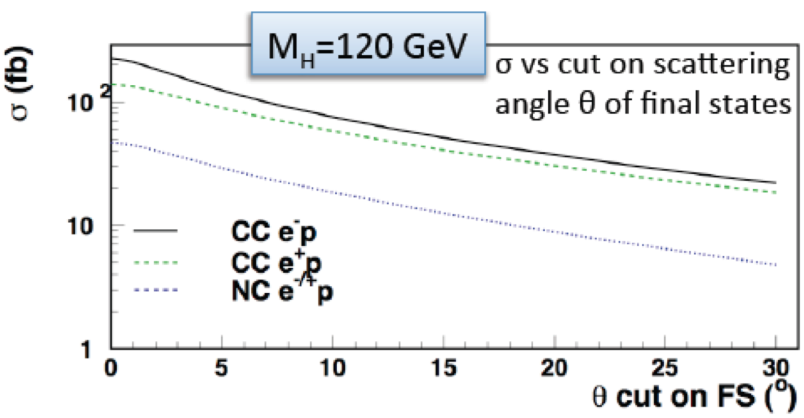
Acceptance Requirements, Final States



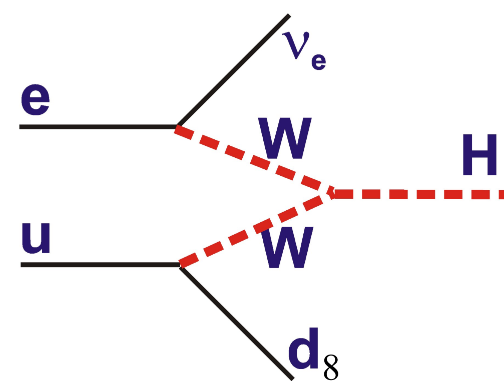


- Elastic J/Ψ Photoproduction





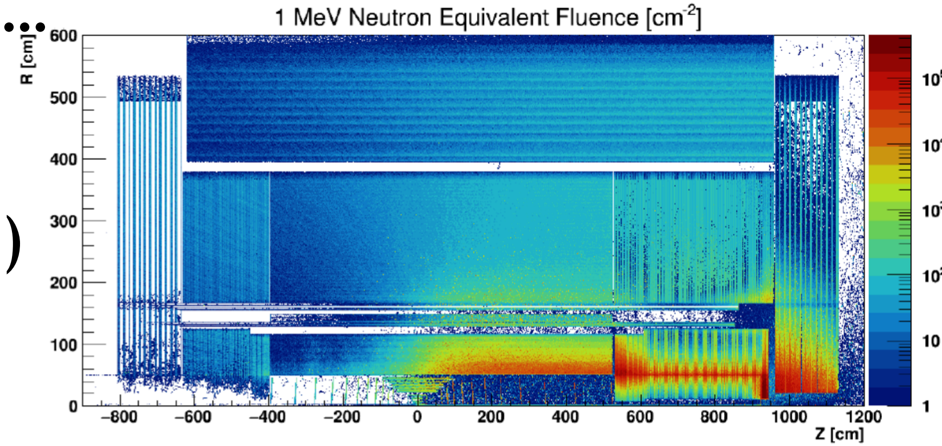
- Higgs Production



Detector Design: Philosophy

- Detector technologies evolve fast; current designs can only be indicative / based on current knowledge … will change

Fluences

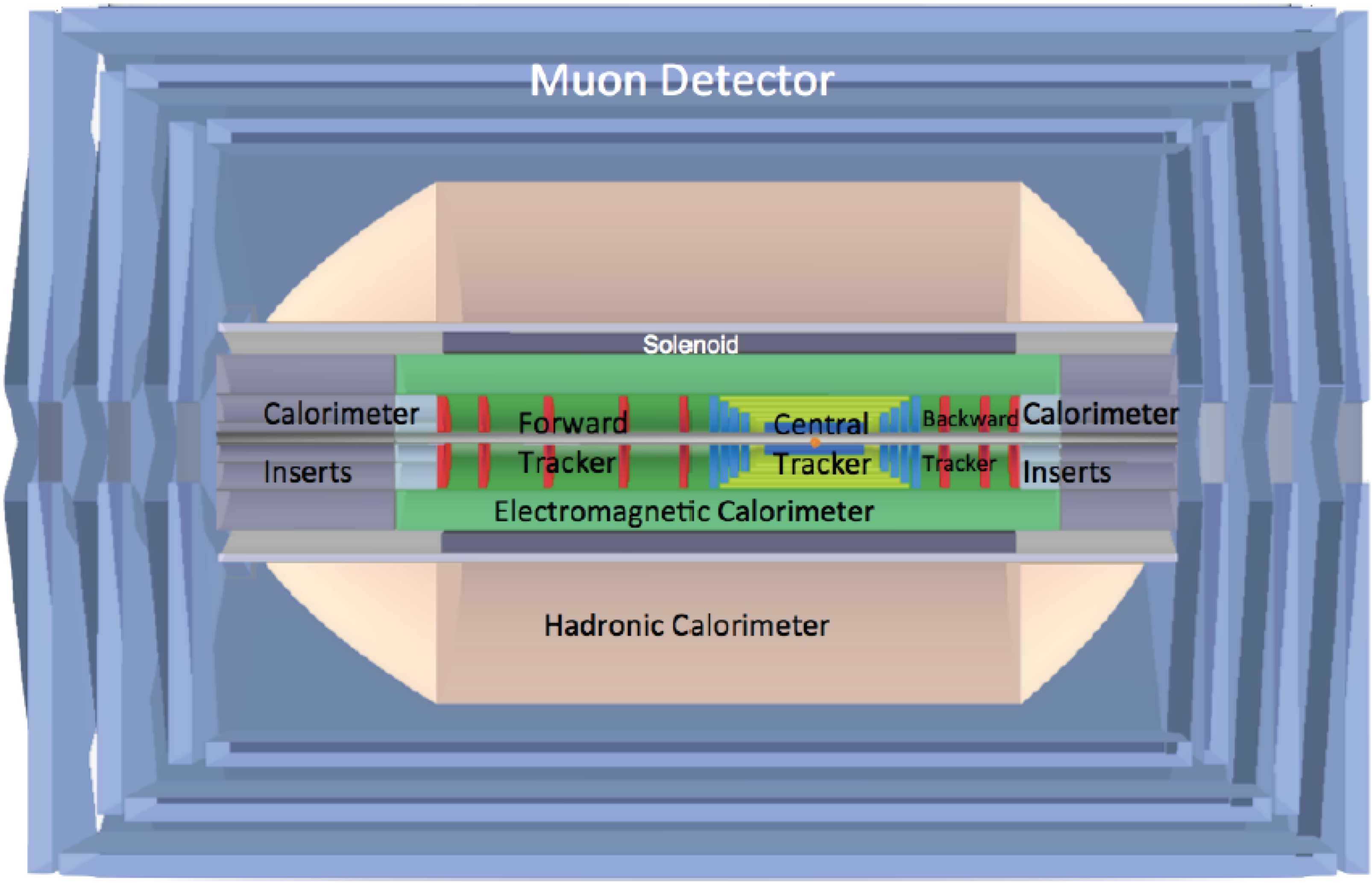


- Conditions are relatively 'easy' …
… fluences <~ 10^5 1 MeV n cm^{-2} equiv (tiny fractions of HL-LHC)
… pile-up ~ 0.1 (cf 200 at HL-LHC)

- Most of current `baseline' remains the 2012 CDR
  → Leans heavily on LHC (esp. ATLAS) technologies
  → Was costed at CHF106M core cost
  → Feasibility and optimisation studies ongoing

- Most challenging technology aspects are interaction region (synchrotron) and ER linac

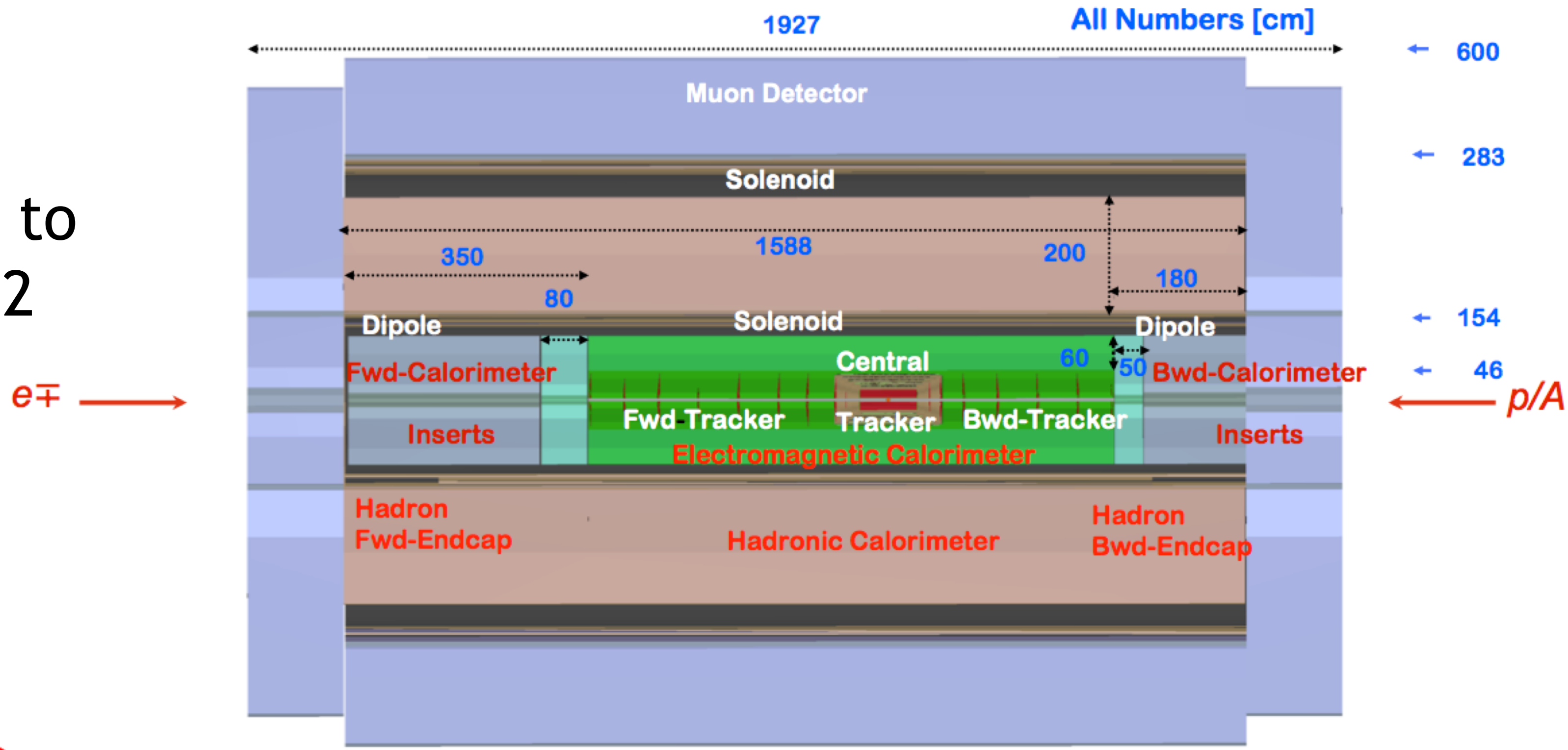
LHeC Detector Design from the CDR (2012)

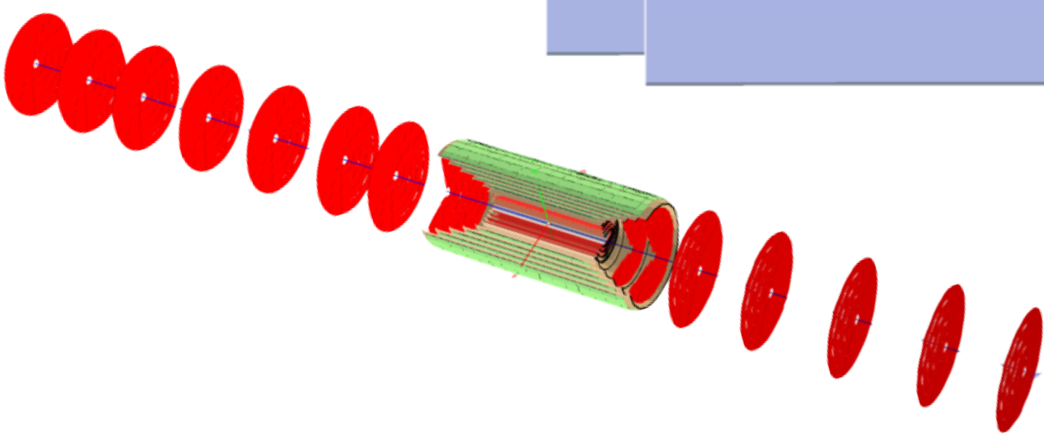


- Size 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- 1º tracking acceptance in both forward & backward directions
- Forward & backward beam-line instrumentation integrated

Detector for ep at a Future Circular Collider

-Detector Scales in size by up to ln(50/7)~ 2



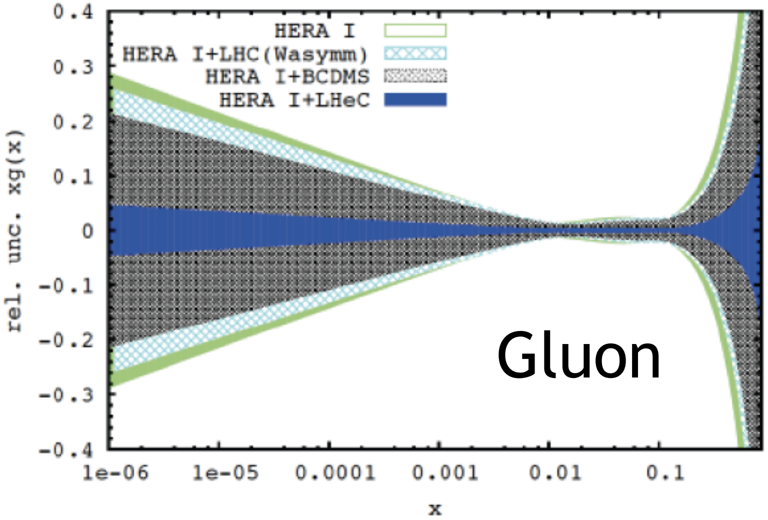


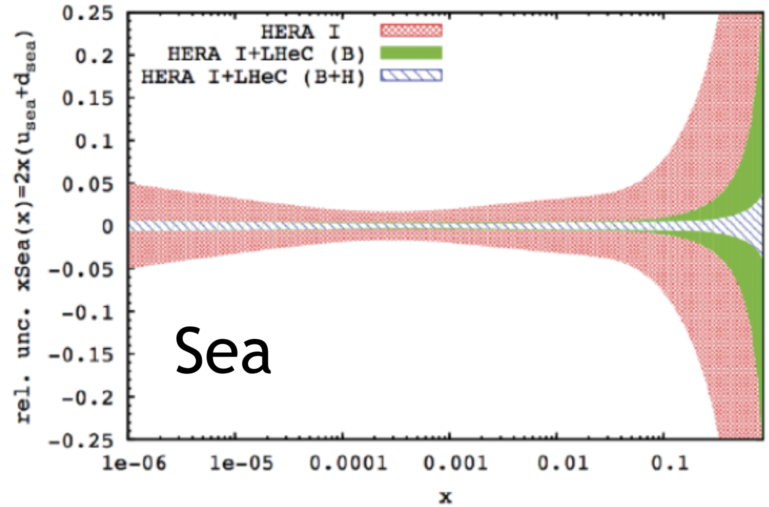
- Double solenoid + Dipole

- Even longer tracking region

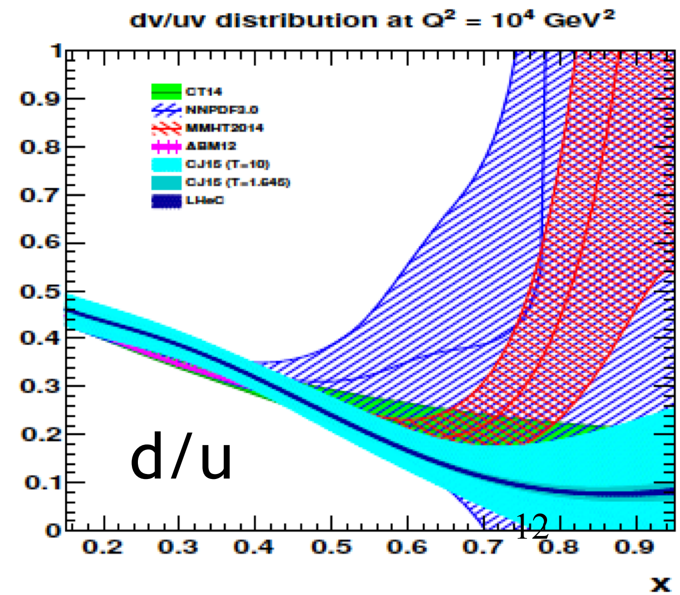
PDF Constraints at LHeC: Example Study

Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

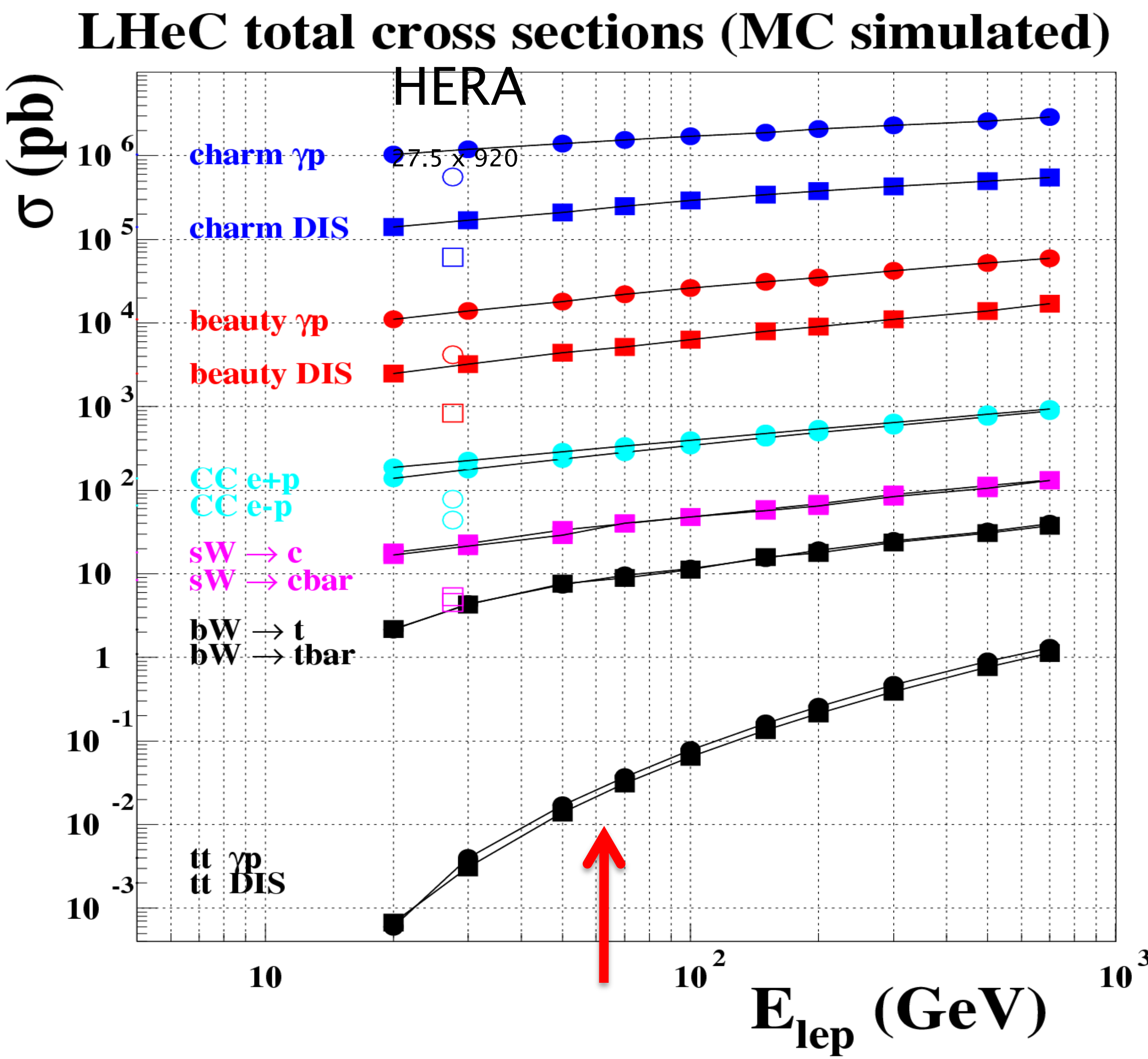




- Low x → novel QCD / unitarity
- Medium x → precision Higgs and EW
- High x → new particle mass frontier
- Per-mille experimental α_s precision
- Full Flavour decomposition



Cross Sections and Rates for Heavy Flavours



Charm [10^{10} / 10 fb^{-1}]

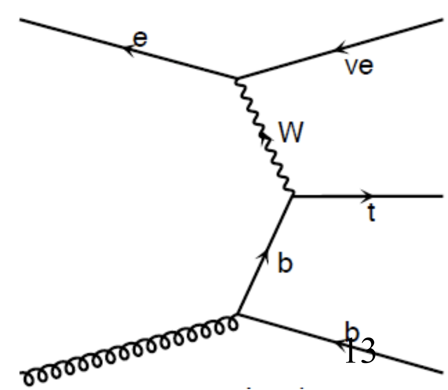
Beauty [10^{8} / 10 fb^{-1}]

cc

sW → c [4.10^{5} / 10 fb^{-1}]

bW → t [10^{5} / 10 fb^{-1}]

ttbar [10^{3} / 10 fb^{-1}]



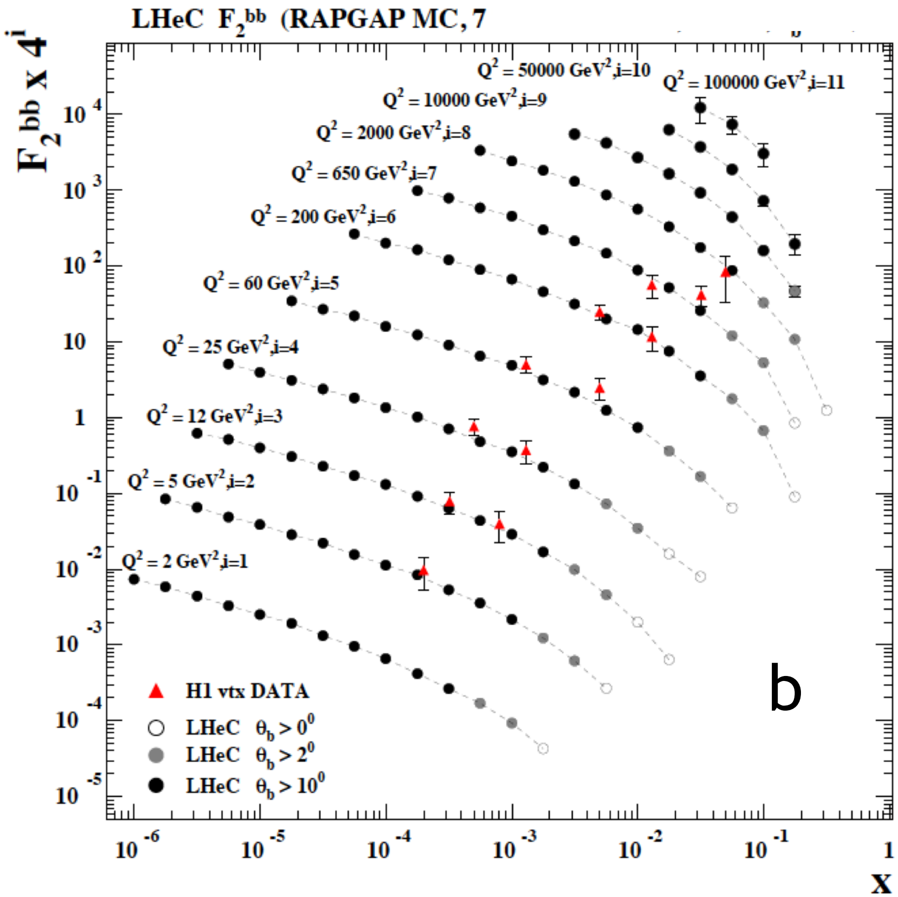
c.f. luminosity of ~10-100 fb^{-1} per year …

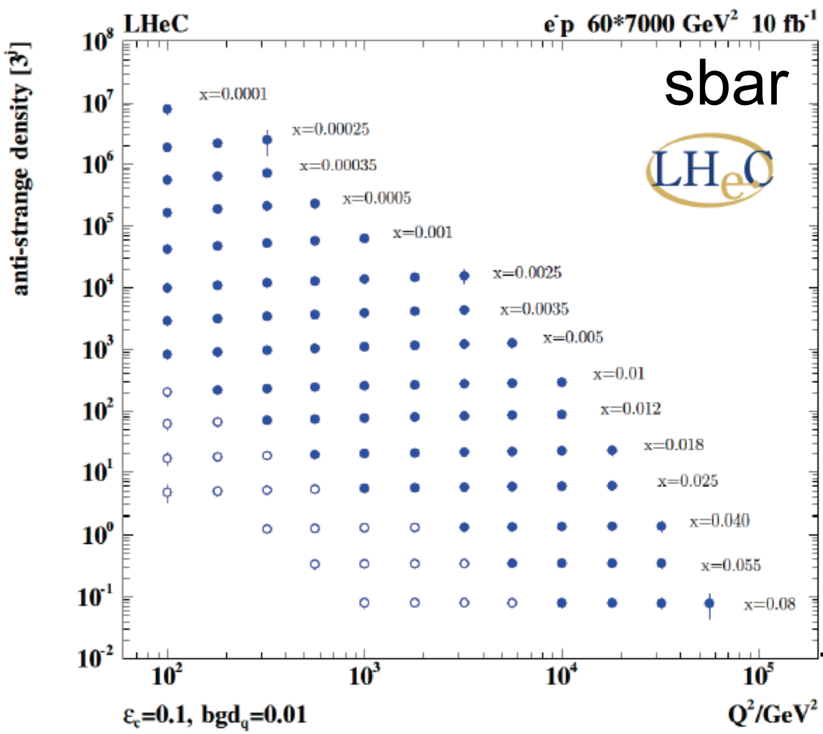
Flavour Decomposition

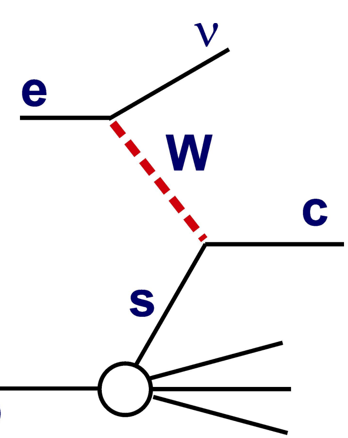
Precision c, b measurements (modern Si trackers, beam spot 15 * 35 μm^2, increased HF rates at higher scales).

Systematics at 10% level

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



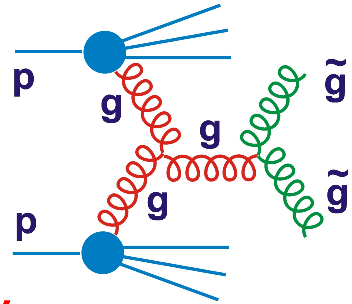


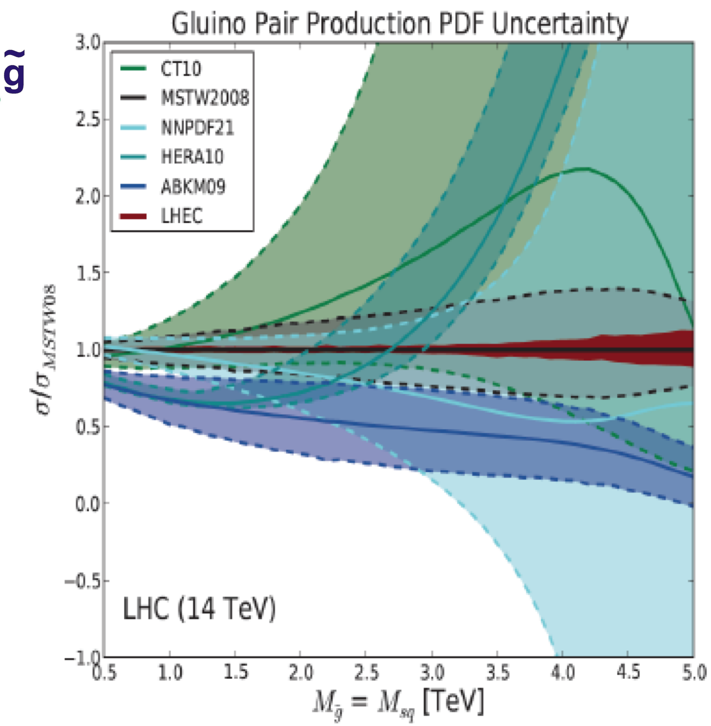


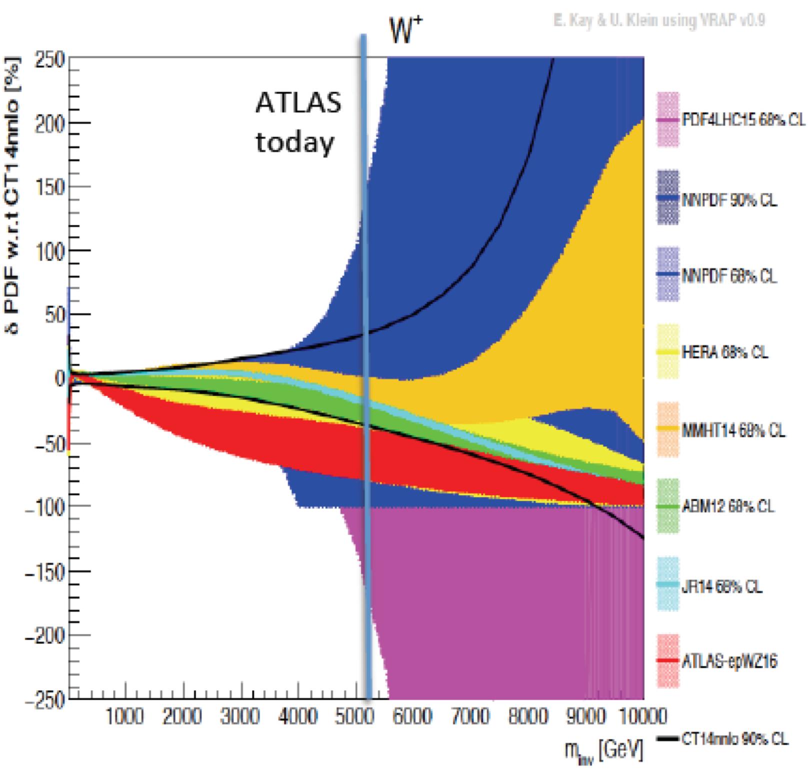
(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

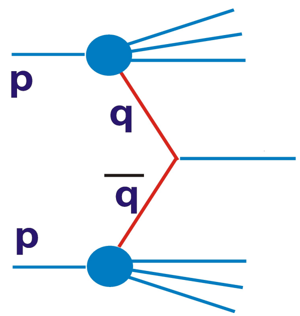
PDFs and New High Mass LHC Particles

- Gluino signature is excess @ large invariant mass
- Both signal & background uncertainties driven by error on gluon density … essentially unknown beyond ~2 TeV









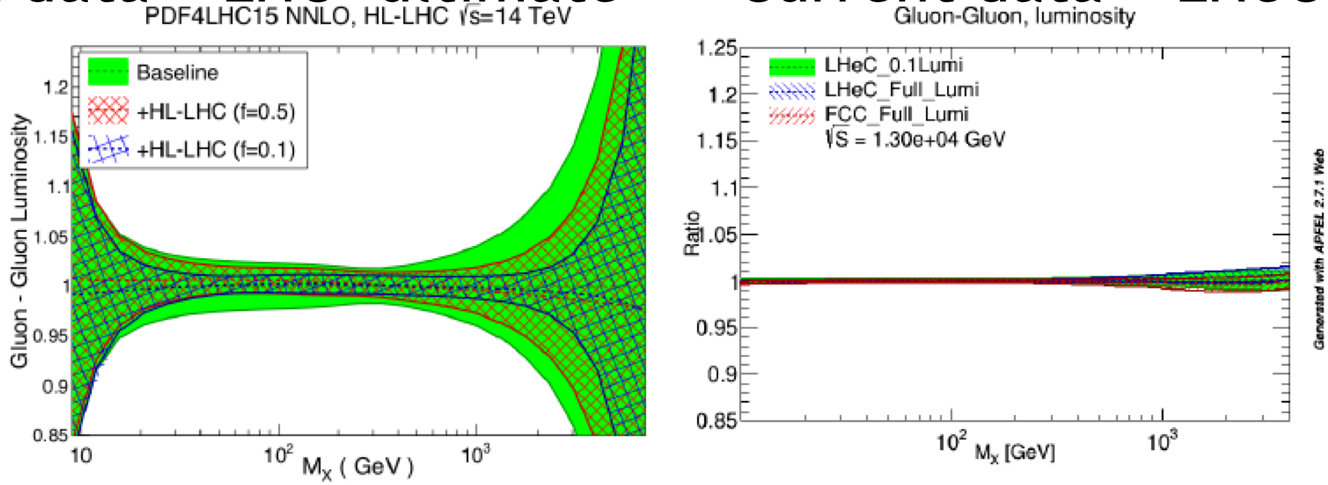
- BSM sensitivity to heavy W boson through excess in high mass lν or jj already limited by high x valence quark and antiquark uncertainties

Future PDF precision in the context of LHC discovery potential

… much of LHC physics will become limited by PDFs → high x uncertainties limit searches, medium x limit Higgs precision etc

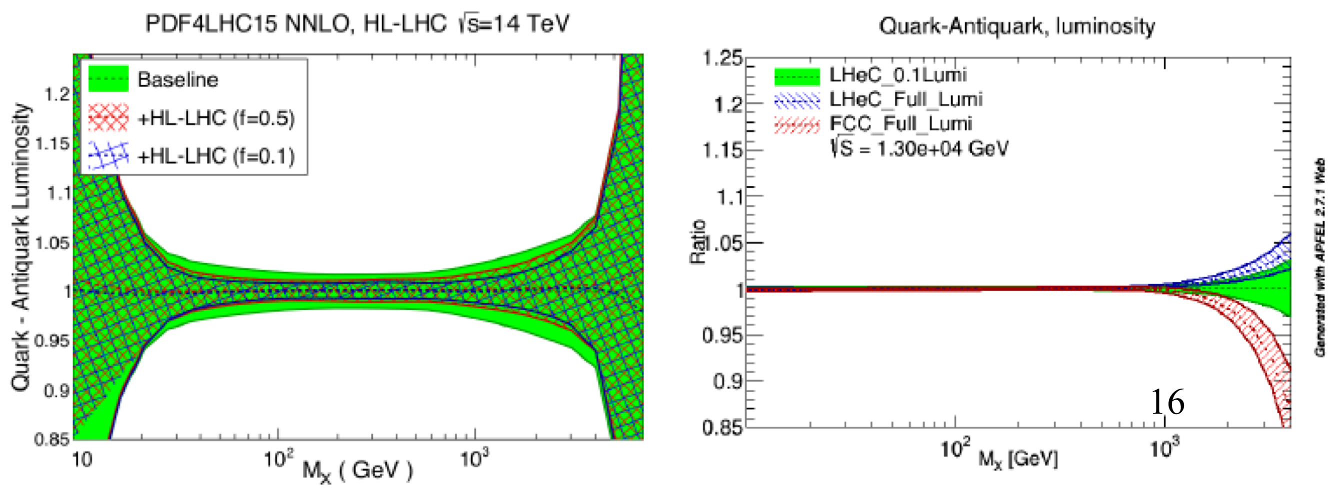
Current data + LHC 'ultimate' Current data + LHeC

gg→X



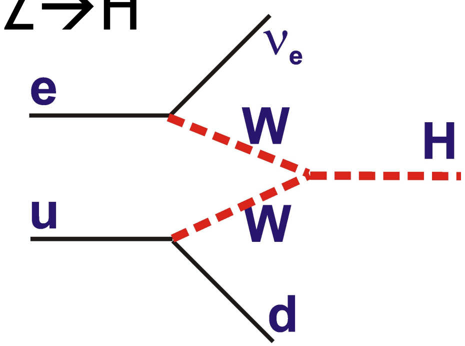
[ongoing study in context of Euro-strategy]

qqbar→X



Higgs Production at LHeC & FCC-eh

Clearly distinguishable WW→H and ZZ→H production modes



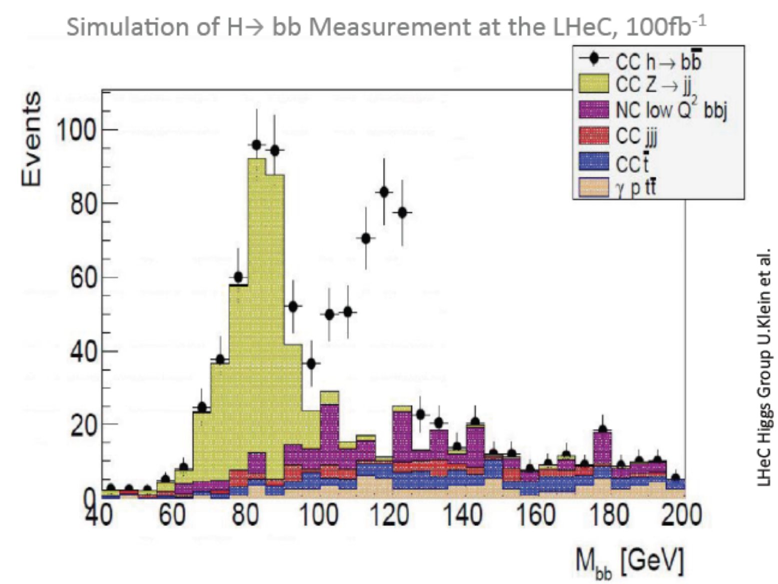
Higgs in $e^- p$		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

Estimated integrated yields …

Example study of H → bbbar in generic simulated LHC detector:

Signal:Background ~ 1-2

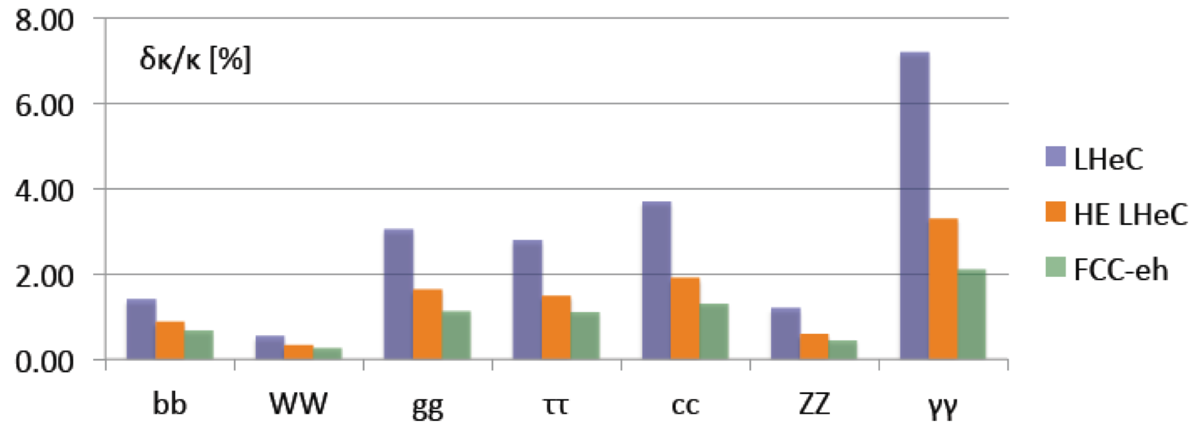
With $1ab^{-1}$, sub-percent level precision seems possible



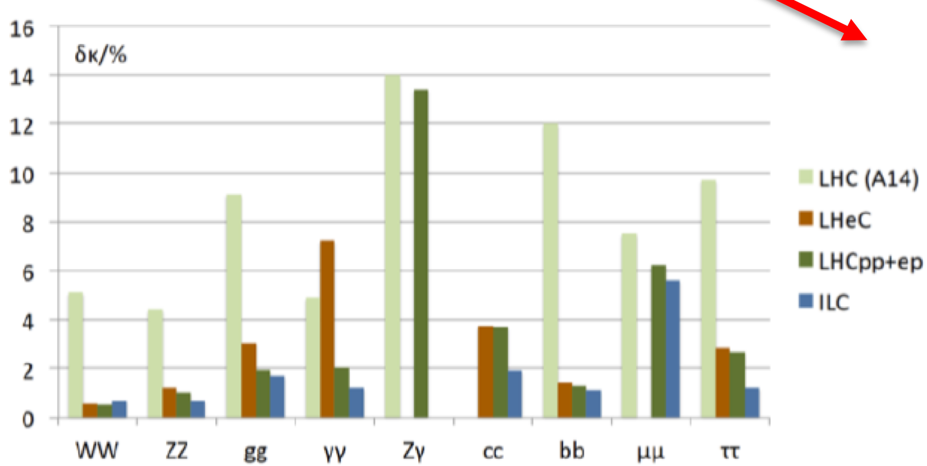
LHeC Standalone Higgs Sensitivity

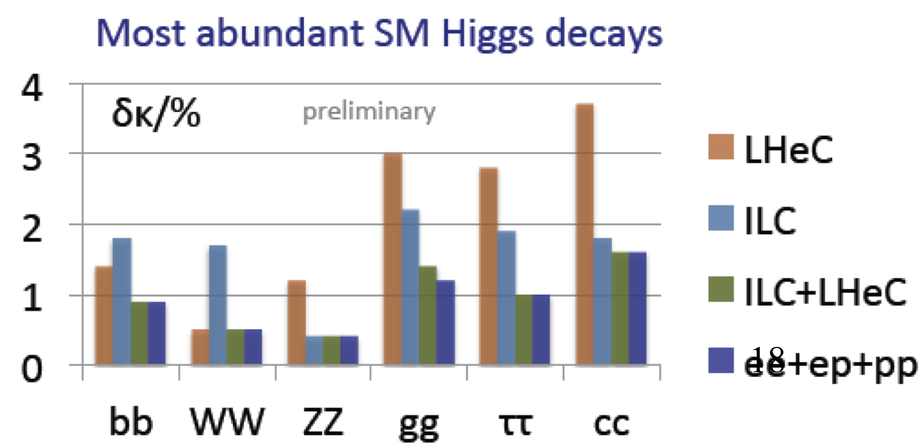
Detailed bbar, ccbar studies, extrapolations of LHC performance for other modes

Comparison of different LHeC versions



Comparisons with ee and pp machines (LHC-alone will improve)





Wide-ranging BSM Interest

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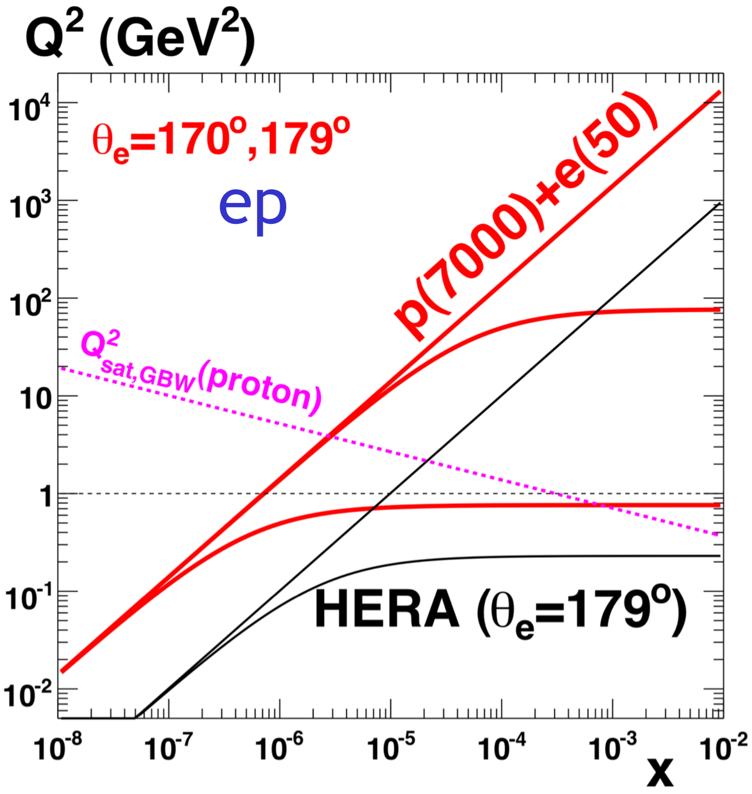
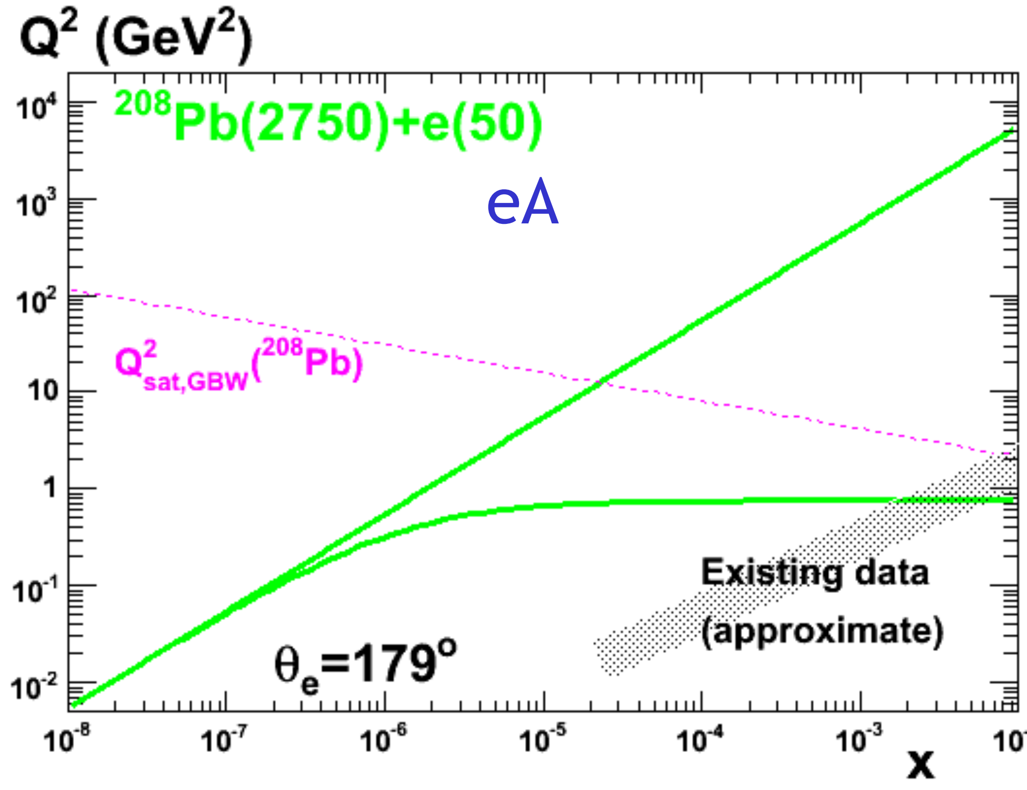
Thanks to Hao Sun

50 journal papers on NP with LHeC in recent years

Low x: 2 orders of magnitude extension for ep, 4 for eA … Saturation at perturbative Q^2

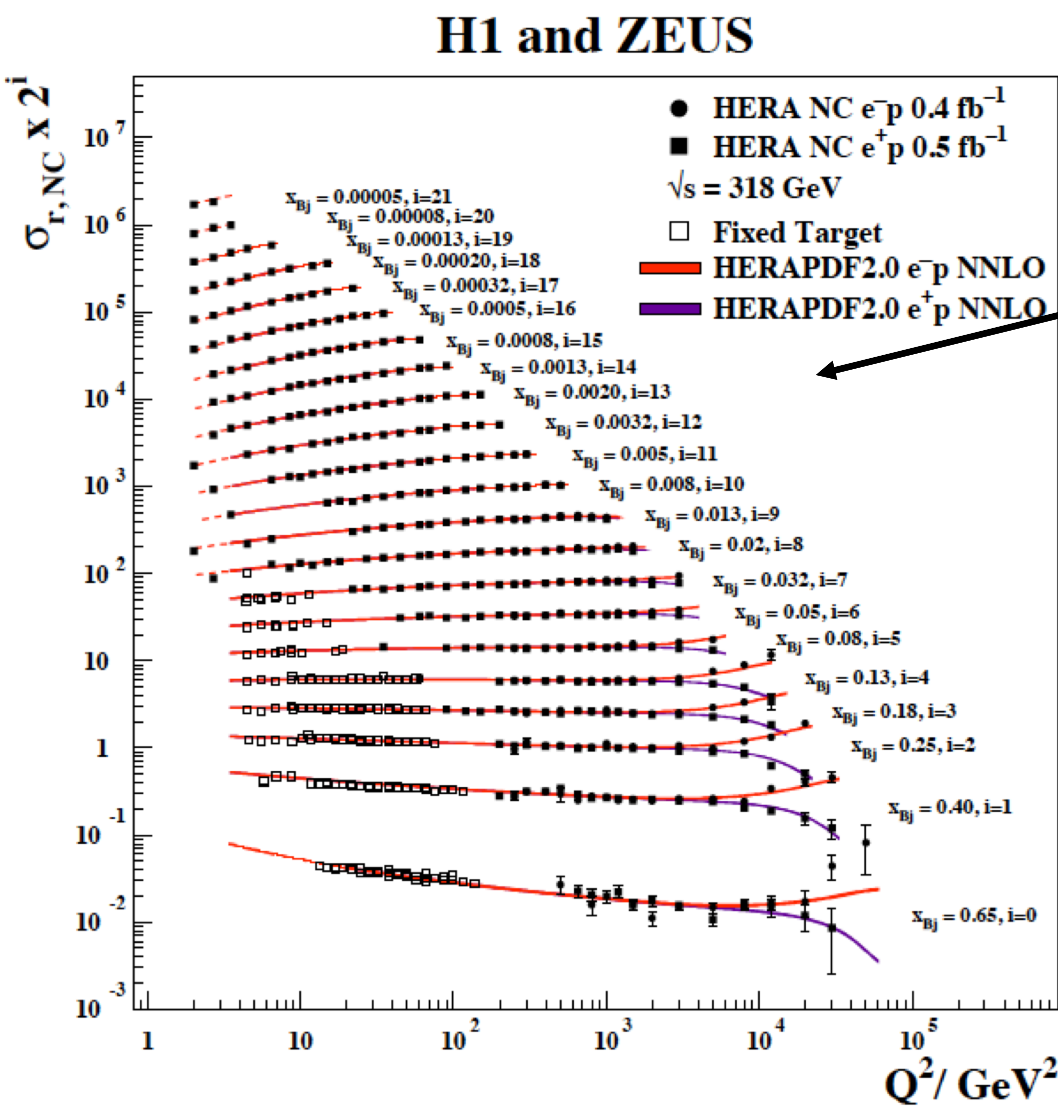




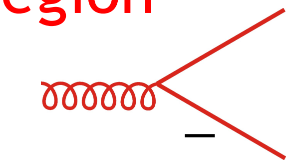
- Low x, Q^2 corner of phase space accesses expected saturated region in both ep & eA at perturbative Q^2 according to models

Low x Physics is Driven by the Gluon

… knowledge comes mainly from inclusive NC HERA data



- NC Q^2 dependence in perturbative region driven by …

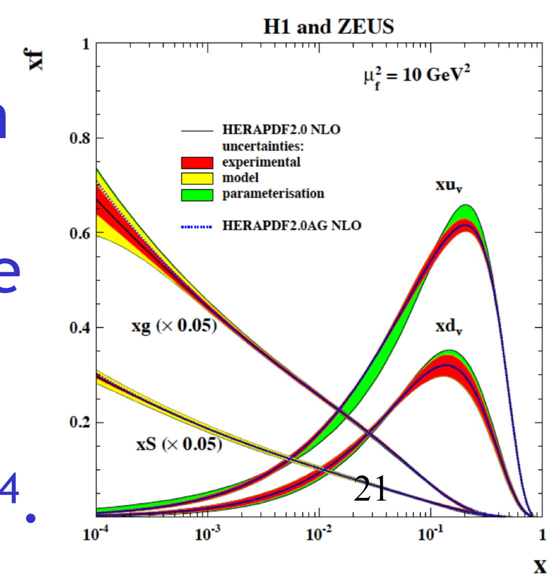


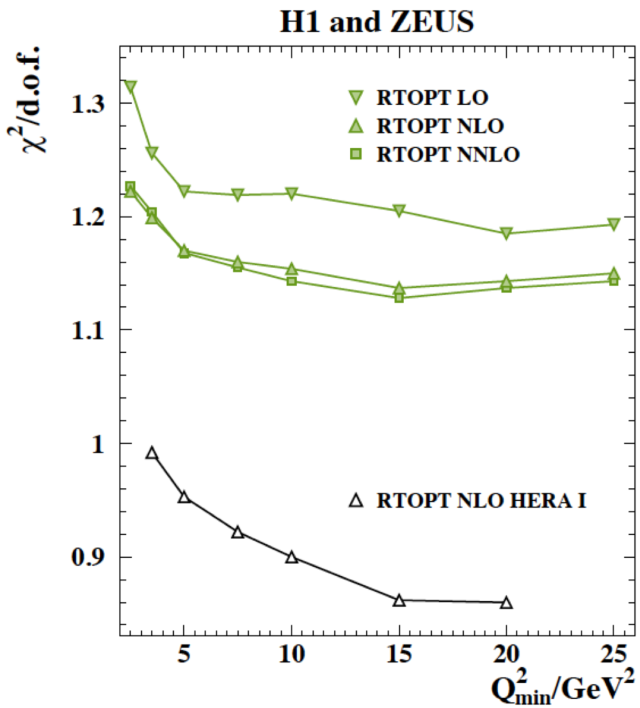
$$g \to q\bar{q}$$

- e.g. Prytz approx:

$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

- needs lever-arm in Q^2 … reasonable precision only to $x \sim 10^{-3}/10^{-4}$.





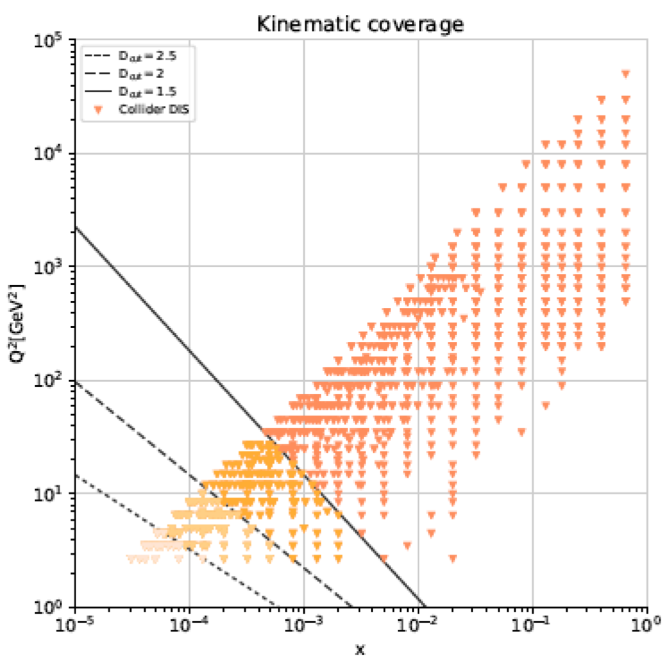
Low x effects in HERA data

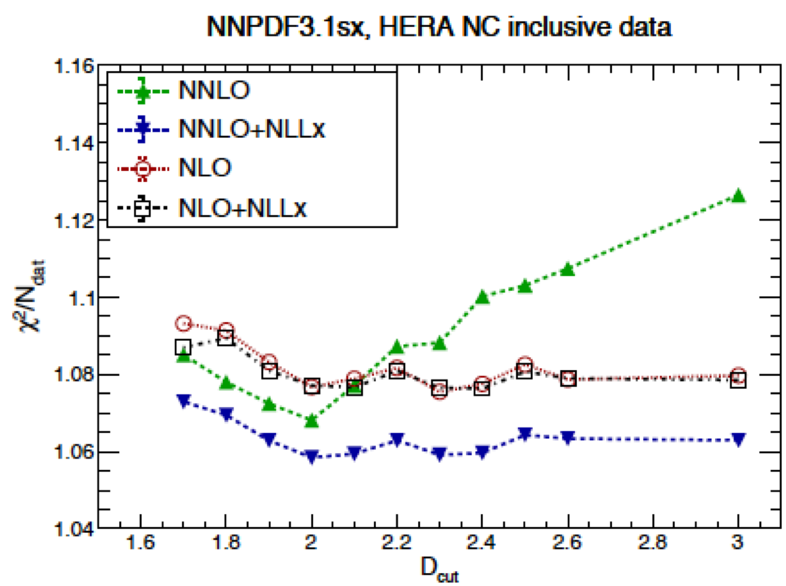
Final HERA-2 Combined PDF Paper:

"some tension in fit between low & medium Q^2 data… not attributable to particular x region"
(though there is a kinematic correlation)

→ Saturation (density effects)?

→ Linear resummation (energy effects)?
[Ball et al, also describing F_L]



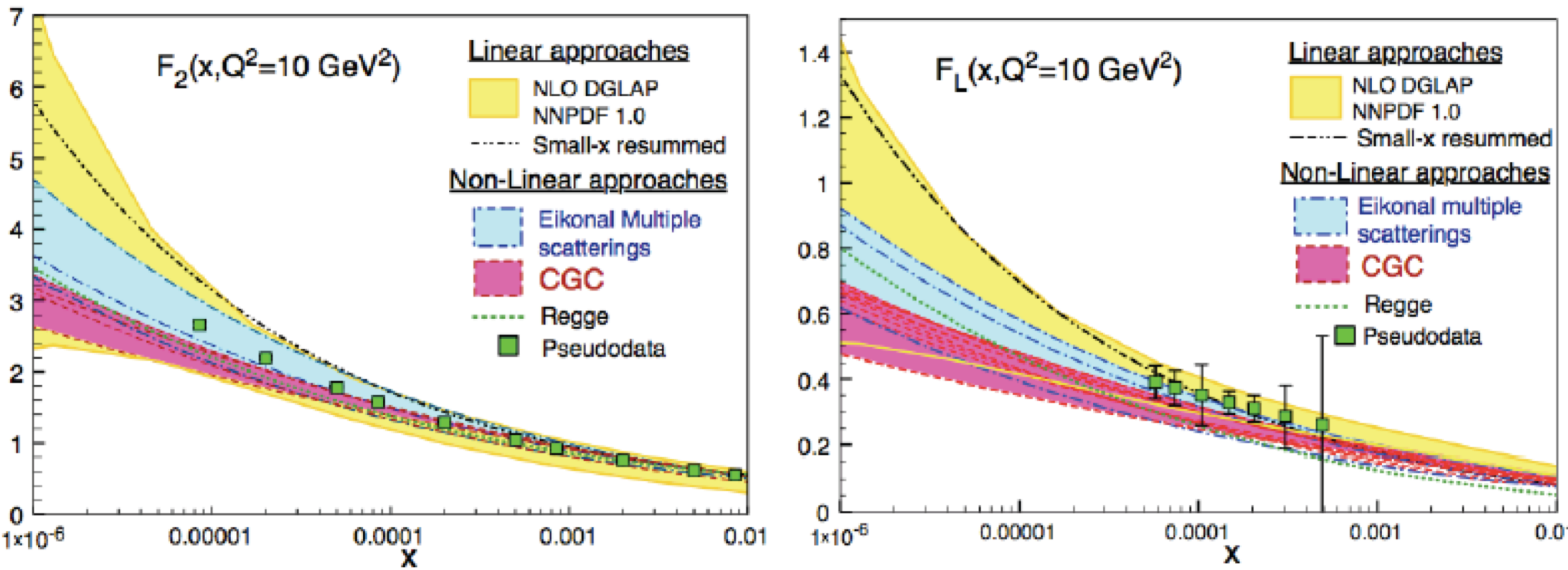


… effects are subtle and live in a small & difficult corner of kinematic plane

LHeC: Establishing & Characterising Saturation

With 1 fb^{-1} (1 month at 10^{33} cm^{-2} s^{-1}), F_2 stat. < 0.1%, syst, 1-3%

F_L measurement to 8% with 1 year of varying E_e or E_p



- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

LHeC: Establishing & Characterising Saturation

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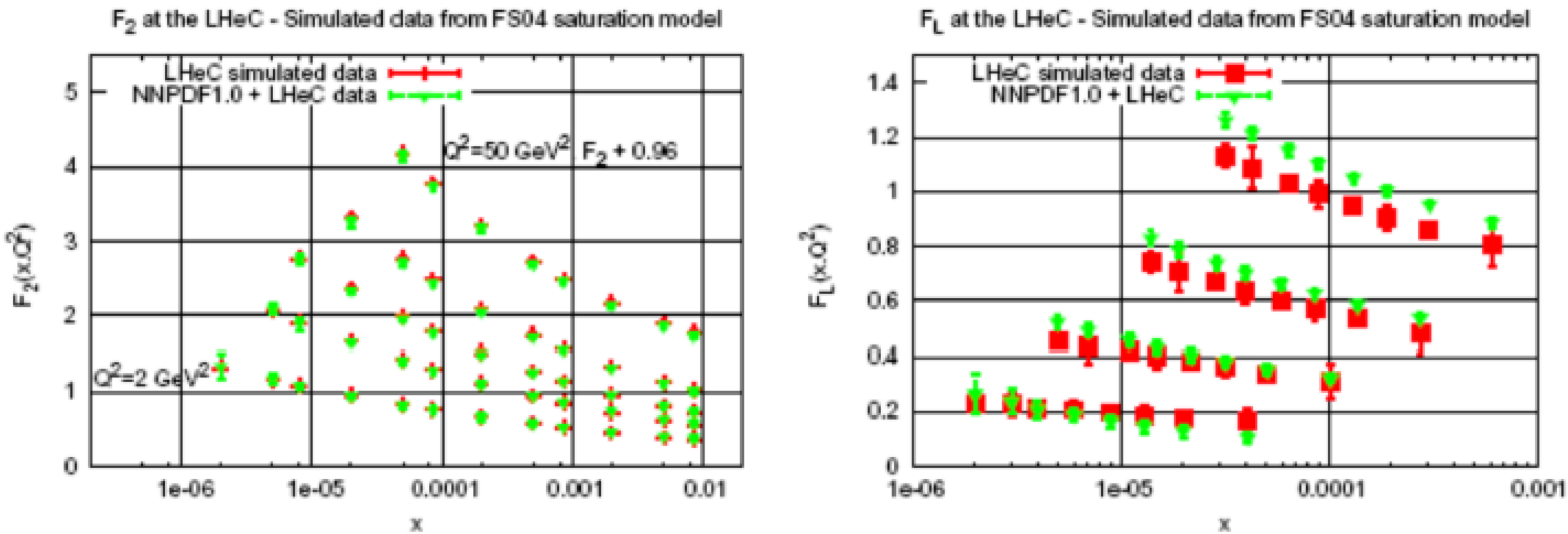


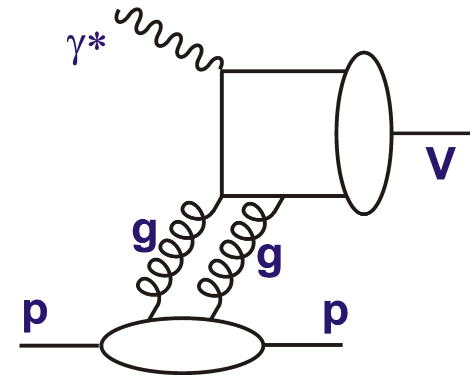
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
- Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

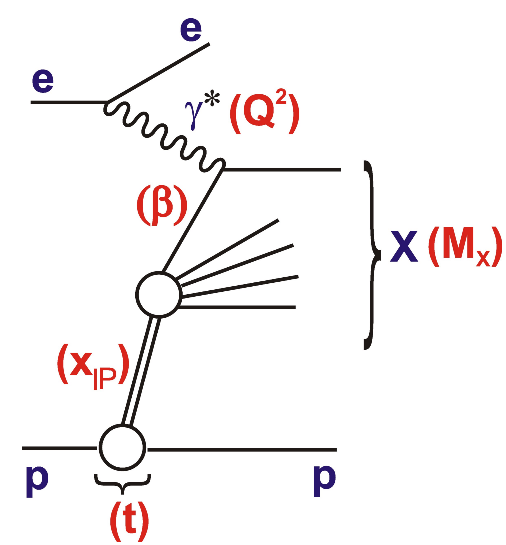
Exclusive / Diffractive Channels and Low x

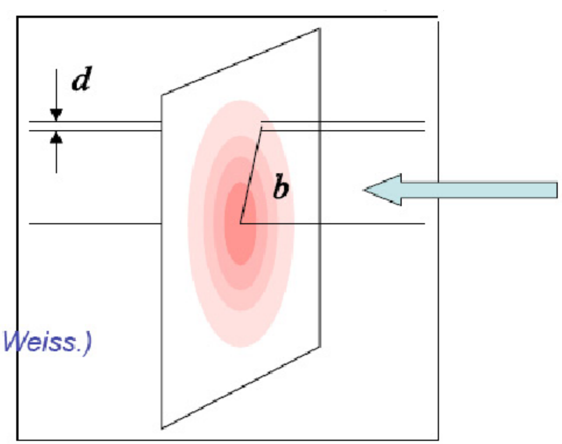
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)

1) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?



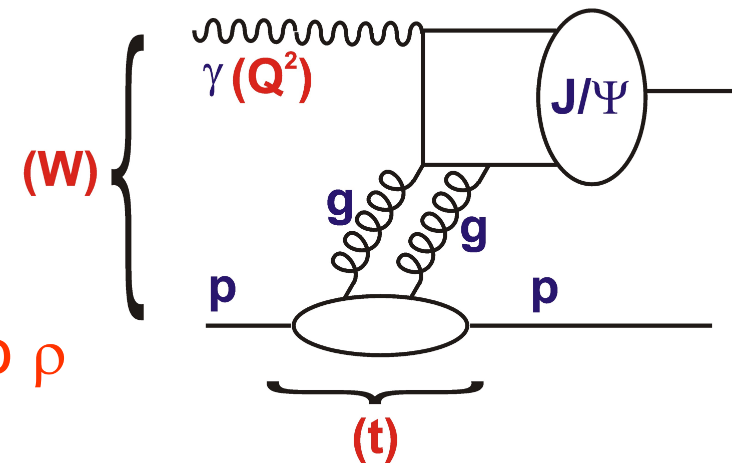




Central black region growing with decrease of x.

(figure from C. Weiss.)

A Test Case: Elastic J/Ψ Photoproduction



• `Cleanly' interpreted as hard 2g exchange coupling to qqbar dipole

• c and c-bar share energy equally, simplifying VM wavefunction relative to ρ

• Clean experimental signature (just 2 leptons)

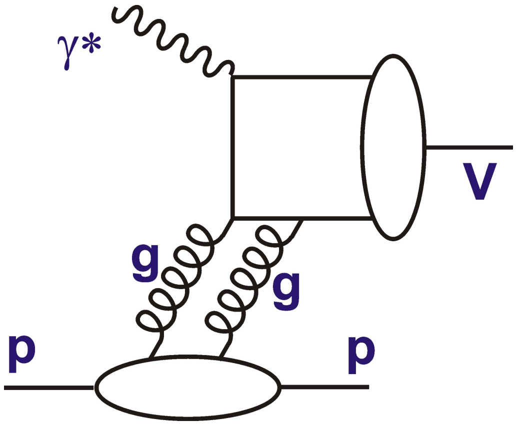
• Scale $\overline{Q^2} \sim (Q^2 + M_V^2) / 4 \gtrsim 3\ \text{GeV}^2$ ideally suited to reaching lowest possible x whilst remaining in perturbative regime

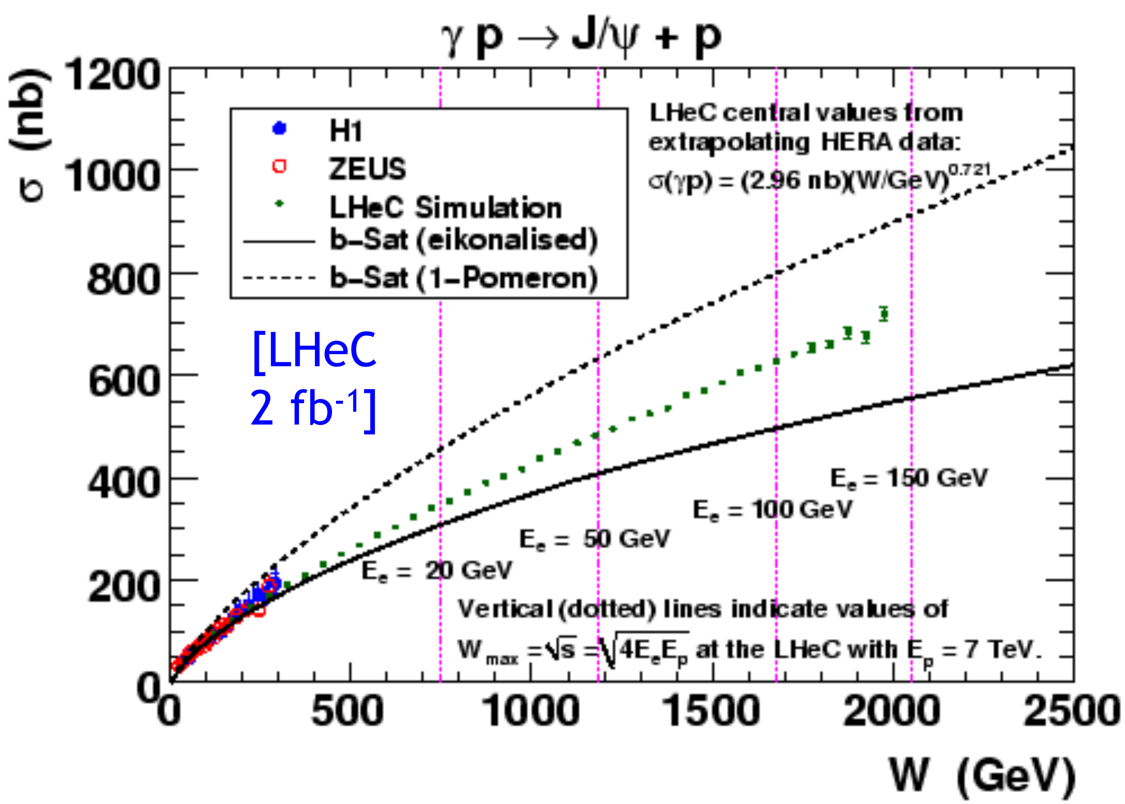
… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

• Simulations (DIFFVM) of elastic J/$\Psi \rightarrow \mu\mu$ photoproduction
→ scattered electron untagged, 1° acceptance for muons
(similar method to H1 and ZEUS)

J/Ψ from future ep v Dipole model Predictions

e.g. "b-Sat" Dipole model
- "eikonalised": with impact-parameter dependent saturation
- "1 Pomeron": non-saturating



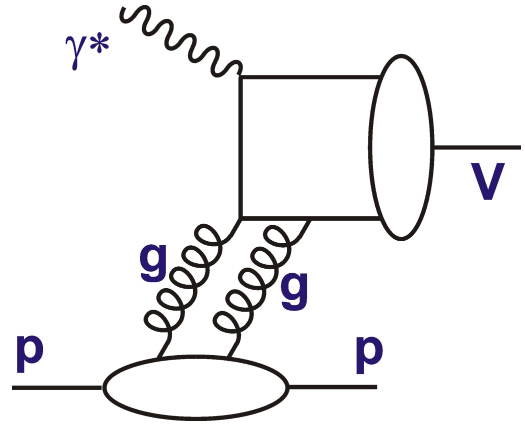


- Significant non-linear effects expected in LHeC kinematic range

... 'smoking gun'?...

J/Ψ from future ep v Dipole model Predictions

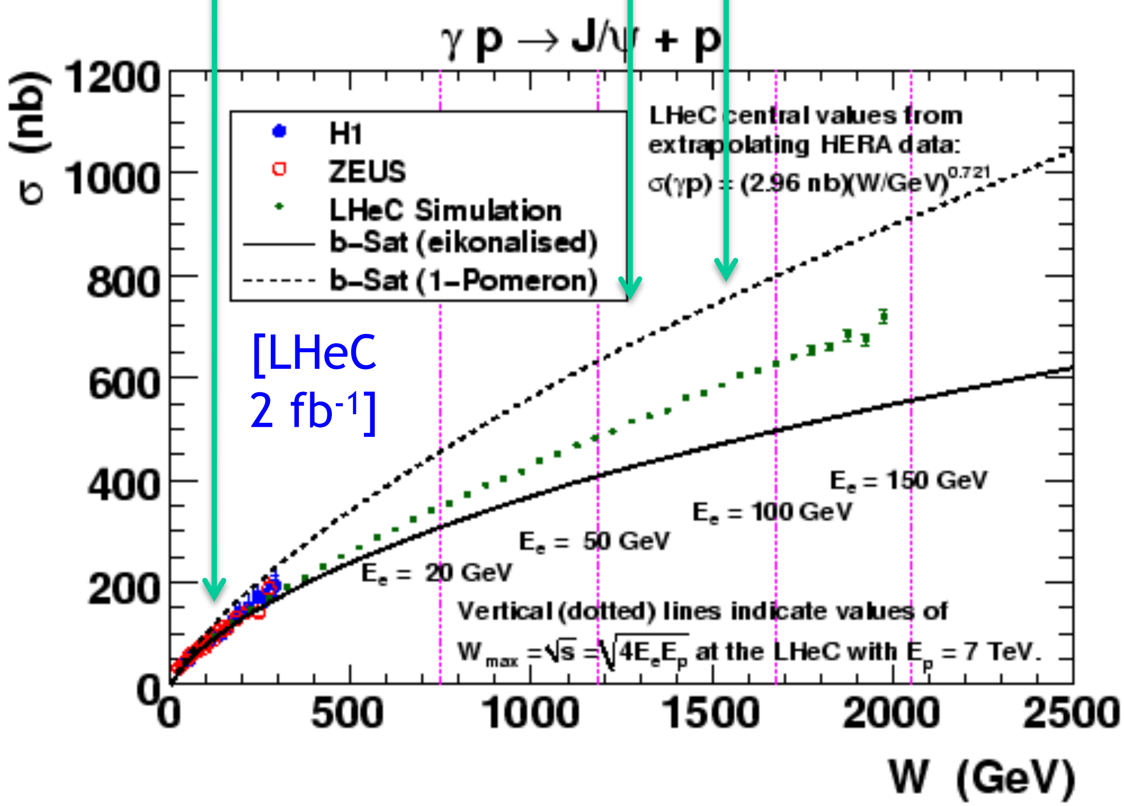
"beware unrealistic non-saturation straw men" [T. Lappi]



Current EIC design

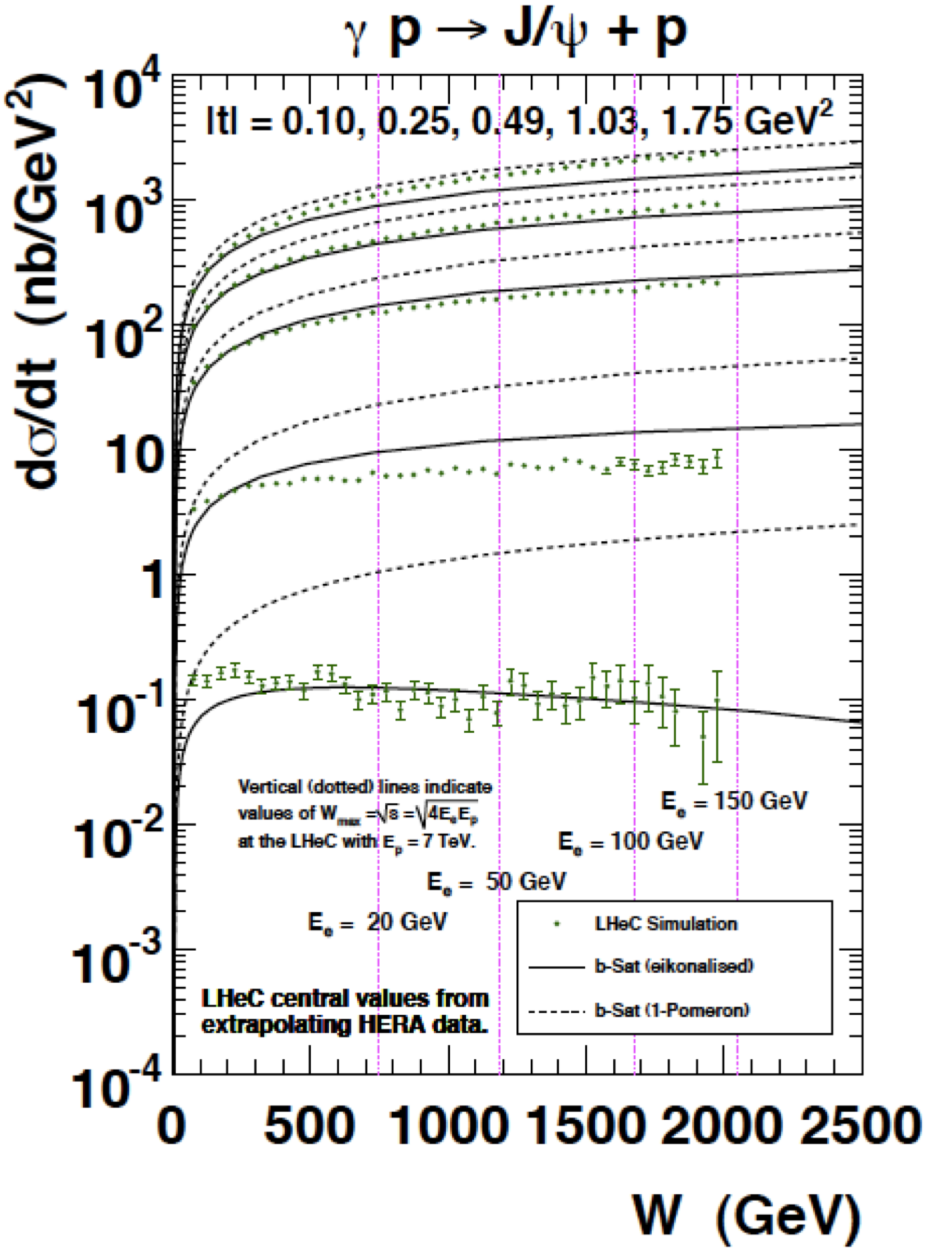
Current LHeC design

Current LHCb limit



- 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).

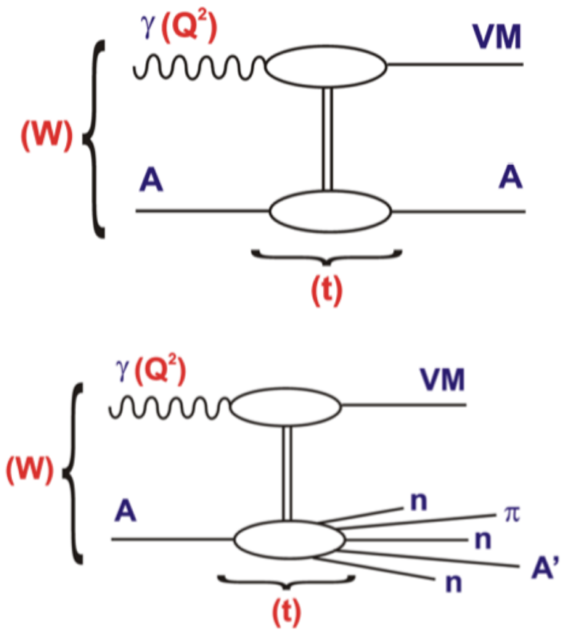
t Dependence of Elastic J/ψ at LHeC

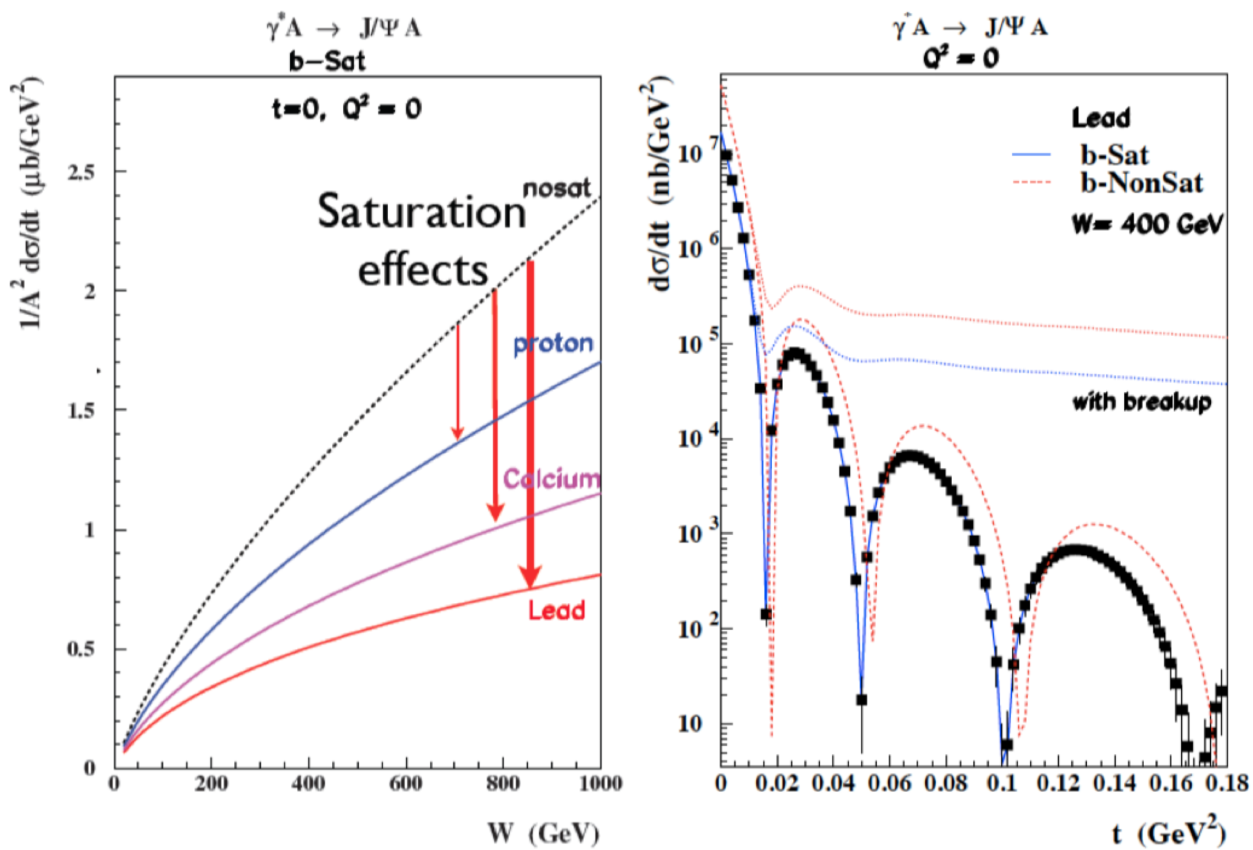


- Precise t measurement from decay μ tracks over wide W range extends to $|t| \sim 2$ GeV² and enhances sensitivity to saturation effects
- Measurements also possible in multiple Q^2 bins

Exclusive Diffraction in eA

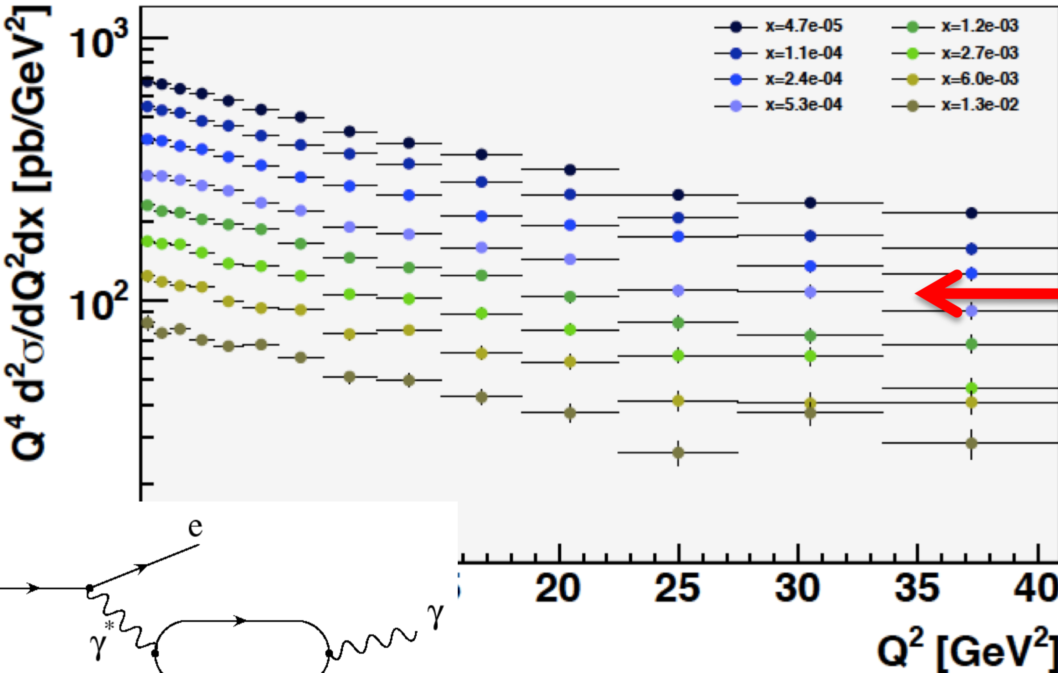
Experimentally clear signatures and theoretically cleanly calculable saturation effects in coherent diffraction case (eA → eVA)





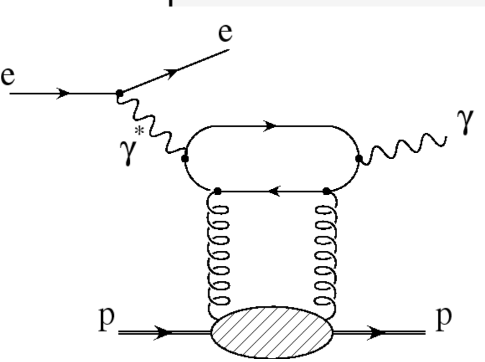
Experimental separation of incoherent diffraction based mainly on ZDC

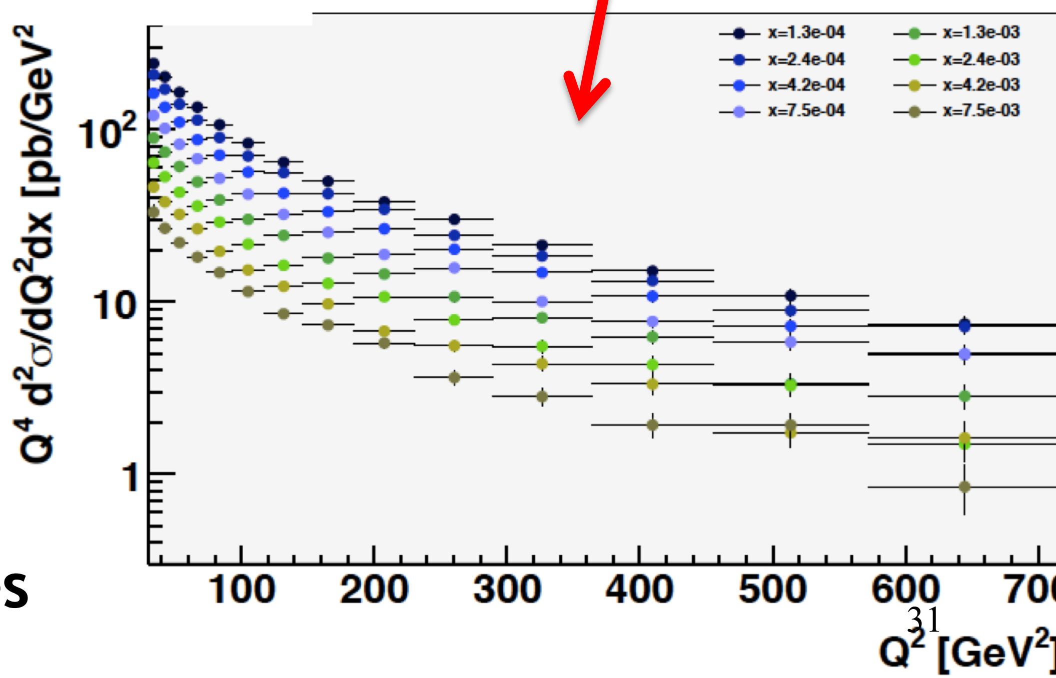
DVCS (MILOU simulation)



$1\ fb^{-1}$, $E_e = 50$ GeV, 1^o acc'nce, $p_T^\gamma > 2$ GeV

$100\ fb^{-1}$, $E_e = 50$ GeV, 10^o acc'nce, $p_T^\gamma > 5$ GeV

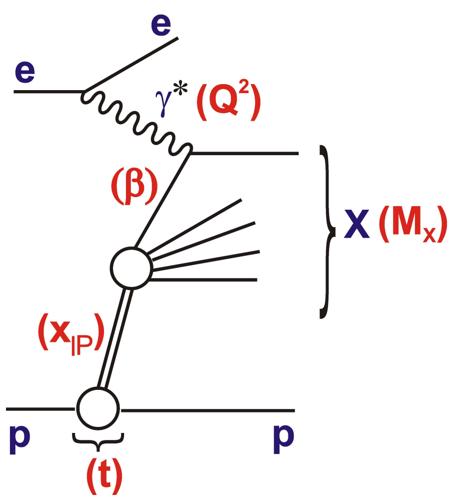


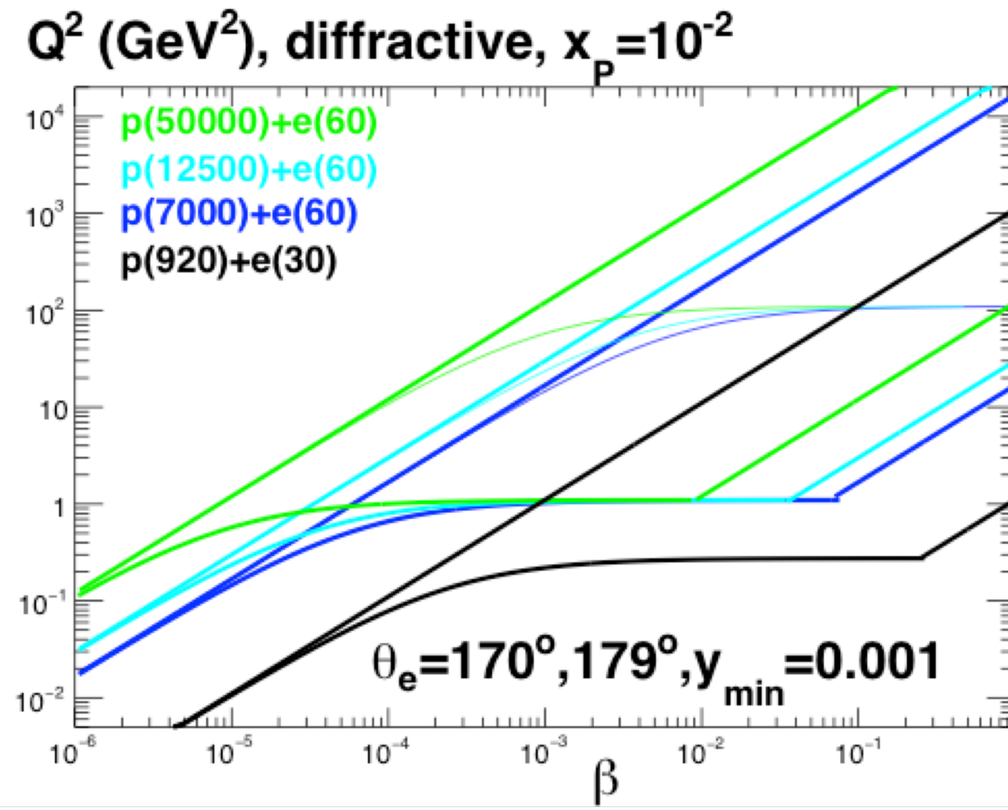


Precise data with
W → 1 TeV, Q^2 → 700 GeV^2,
x → 5.10^{-5}

Still to do:
- **Beam charge asymmetries**
- **Sensitivity to GPDs**

Inclusive Diffraction at LHeC and FCC-eh





→ Diffractive structure in wider (β, Q^2) range than proton (x, Q^2) range at HERA

- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x effects
- High Q^2 → Lever-arm for gluon, flavour decomposition
- Large M_X → Jets, heavy flavours, W/Z …
- Large E_T → Precision QCD with jets …

Dijet production in diffractive deep-inelastic scattering in next-to-next-to-leading order QCD

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[2] Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, UK
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[4] Theoretical Physics Department, CERN, 1211 Geneva, Switzerland
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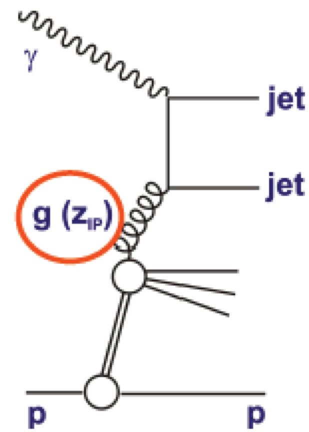
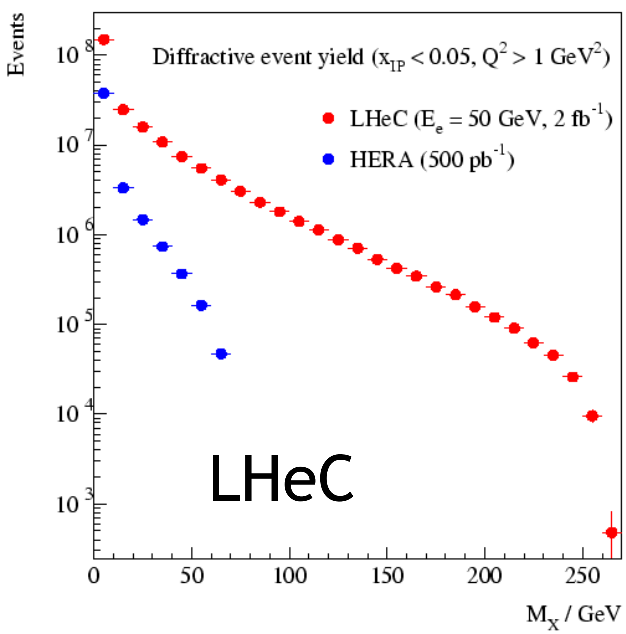
Received: date / Accepted: date

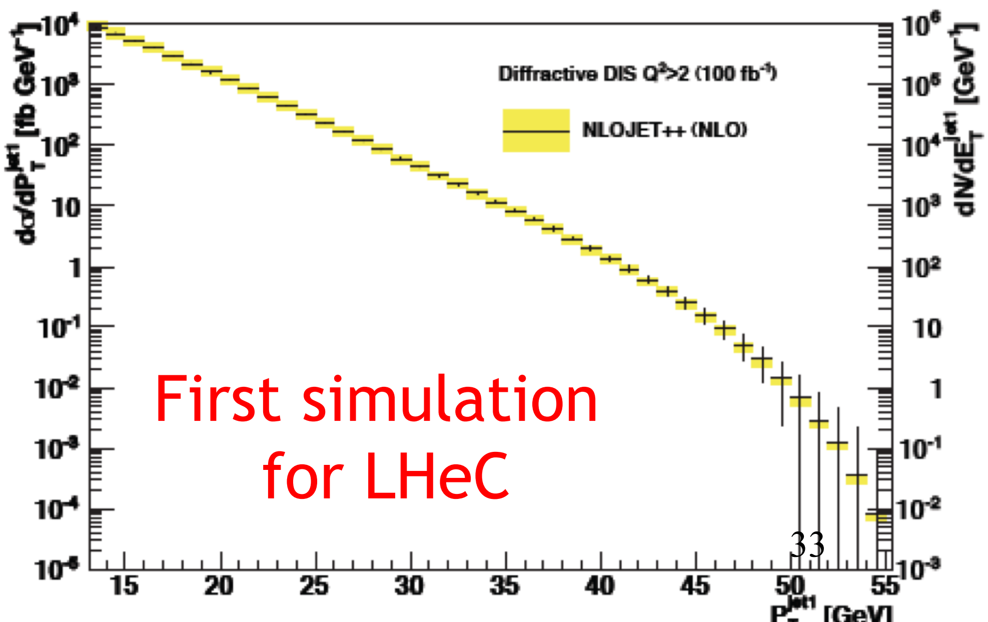
Abstract Hard processes in diffractive deep-inelastic scattering can be described by a factorisation into parton-level subprocesses and diffractive parton distributions. In this framework, cross sections for inclusive dijet production in diffractive deep-inelastic electron-proton scattering (DIS) are computed to next-to-next-to-leading order (NNLO) QCD accuracy and compared to a comprehensive selection of data. Predictions for the total cross sections, 39 single-differential and four double-differential distributions for six measurements at HERA by the H1 and ZEUS collaborations are calculated. In the studied kinematical range, the NNLO corrections are found to be sizeable and positive. The NNLO predictions typically exceed the data, while the kinematical shape of the data is described better at NNLO than at next-to-leading order (NLO). A significant reduction of the scale uncertainty is achieved in comparison to NLO predictions. Our results use the currently available NLO diffractive parton distributions, and the discrepancy in normalisation highlights the need for a consistent determination of these distributions at NNLO accuracy.

Diffractive Dijets



… precision theory deserves precision data!





Dijet production in diffractive deep-inelastic scattering in next-to-next-to-leading order QCD

D. Britzger[a,1], J. Currie[b,2], T. Gehrmann[c,3], A. Huss[d,4], J. Niehues[e,2], R. Žlebčík[f,5]

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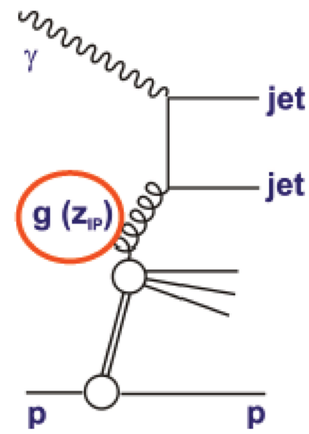
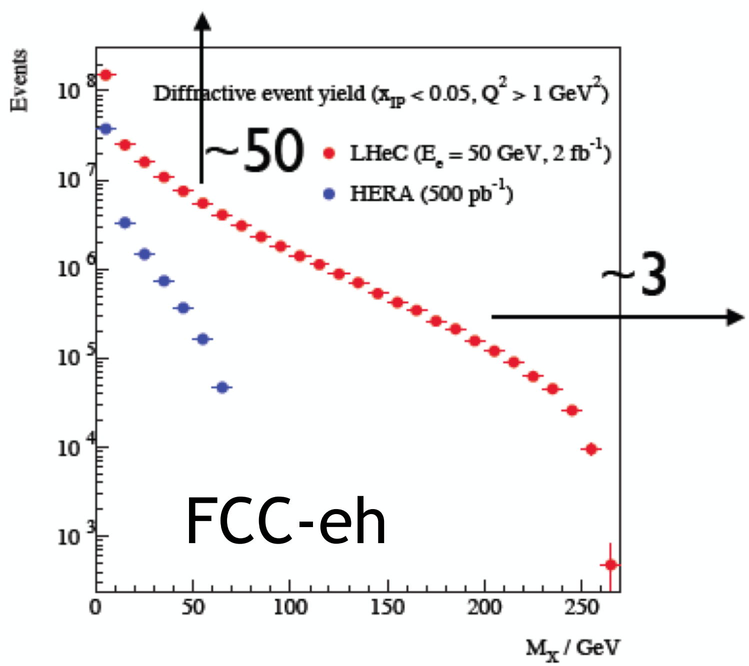
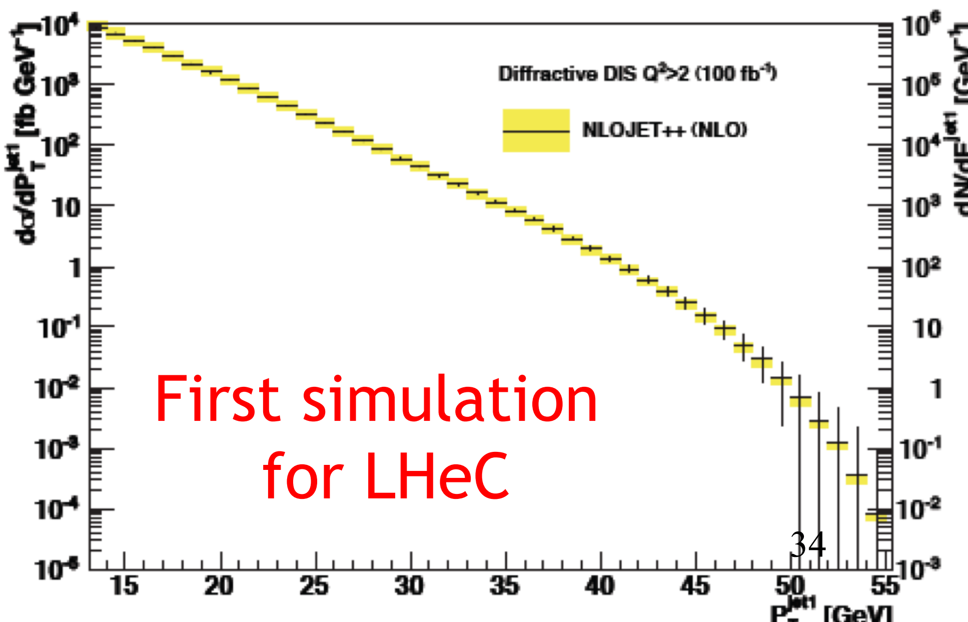
Diffractive Dijets



… precision
theory deserves precision
data!





LHeC and Diffractive PDFs

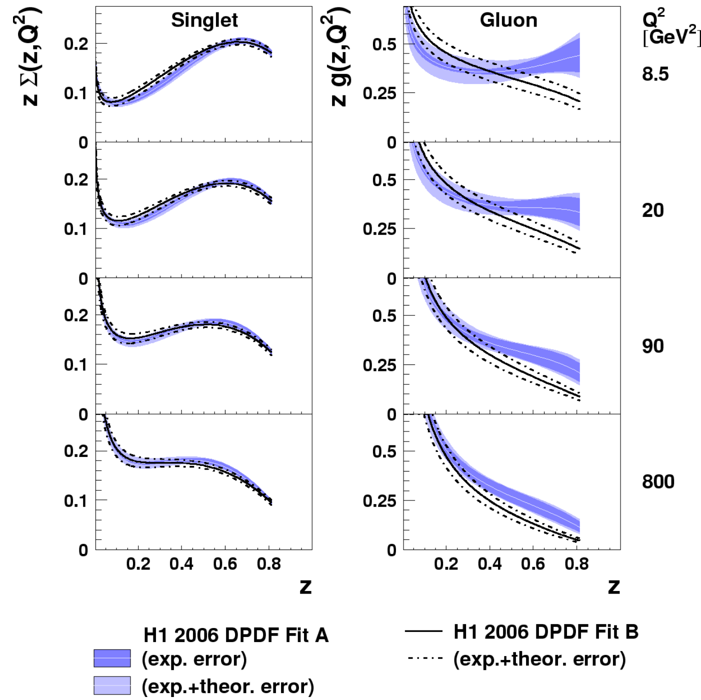
Investigate LHeC and FCC-eh potential for diffractive parton densities

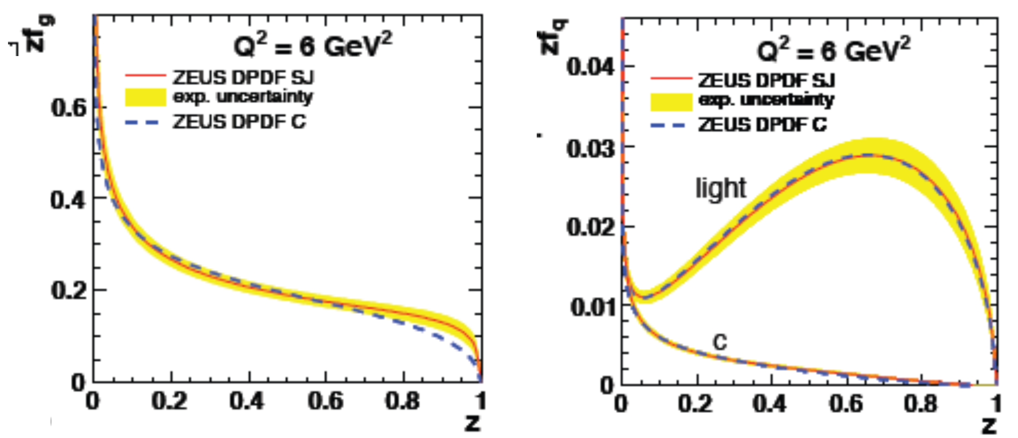
- So far using same framework as at HERA (ZEUS version) with factorising x_{IP} dependence (IP) and (β,Q^2) dependence from NLO DGLAP fit

$$f_k = A_k x^{B_k} (1-x)^{C_k}$$

k=g,d and A_k, B_k, C_k free

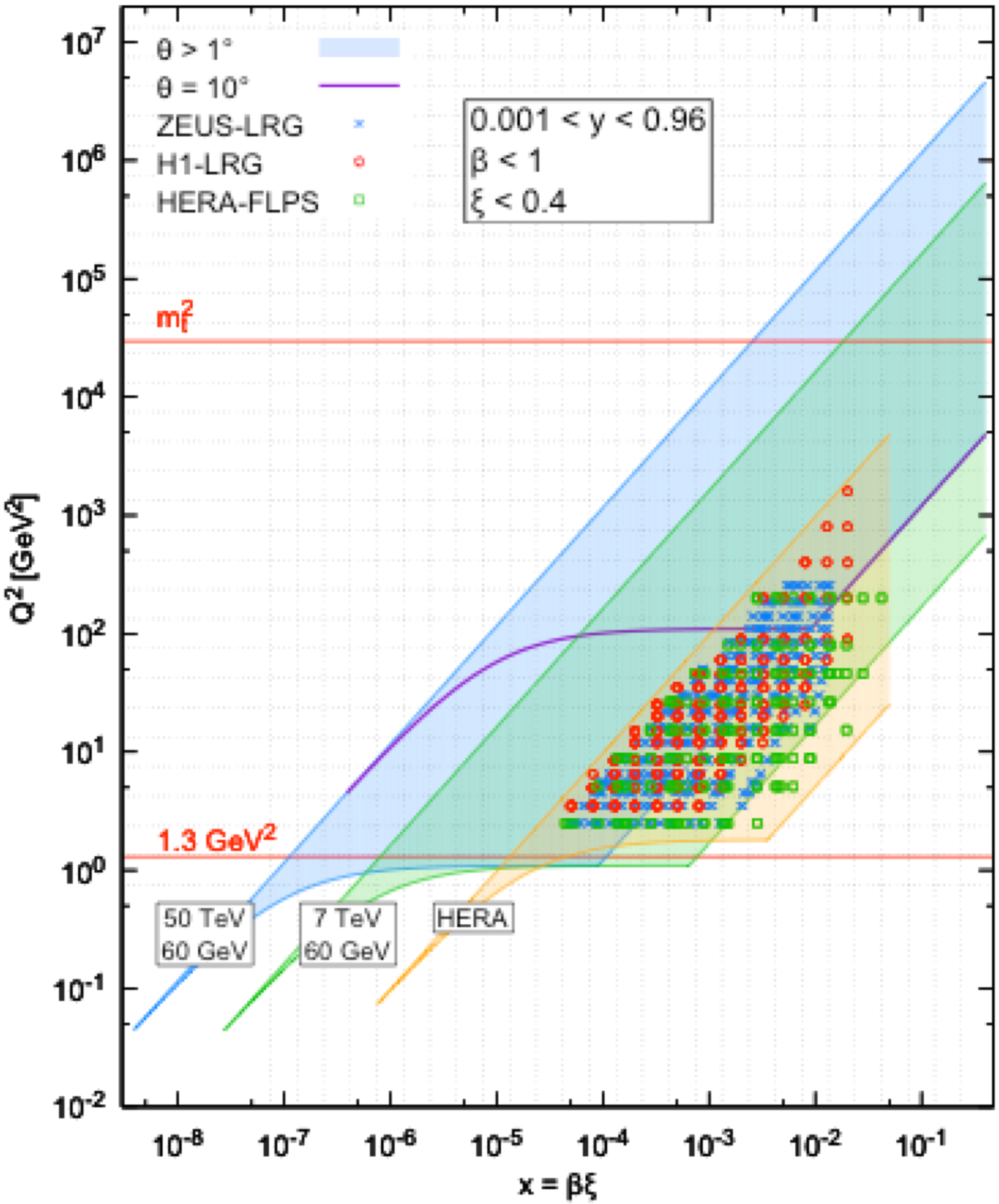
d = u = s = dbar= ubar = sbar

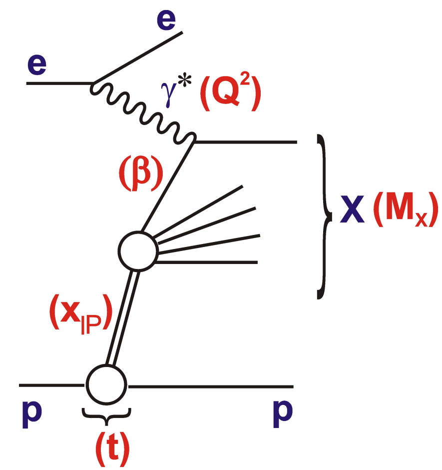




- Small sub-leading (IR) exchange required at largest x_{IP}

HERA Data v LHeC and FCC-eh Phase Space



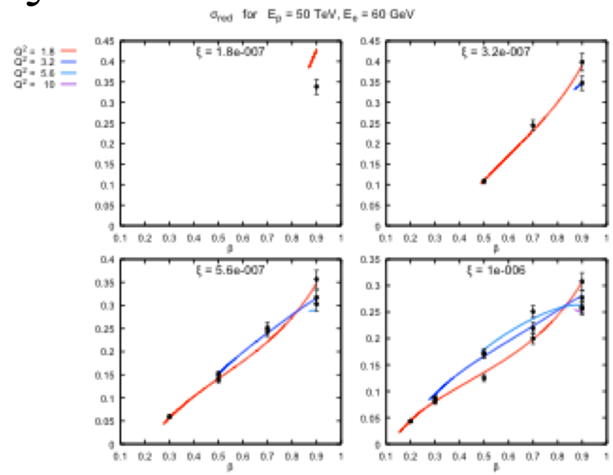


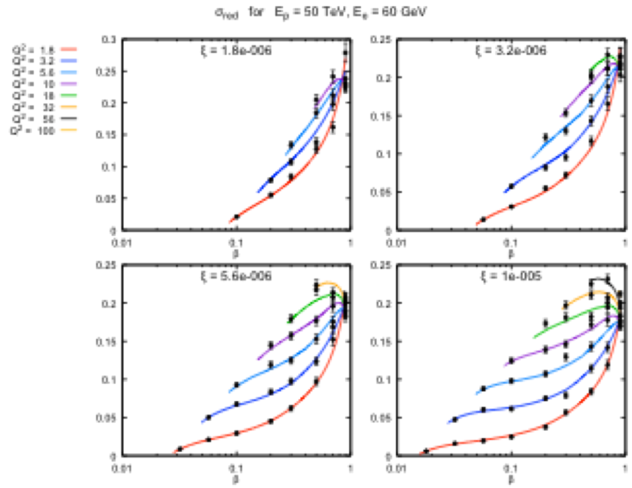
- Start with HERA data

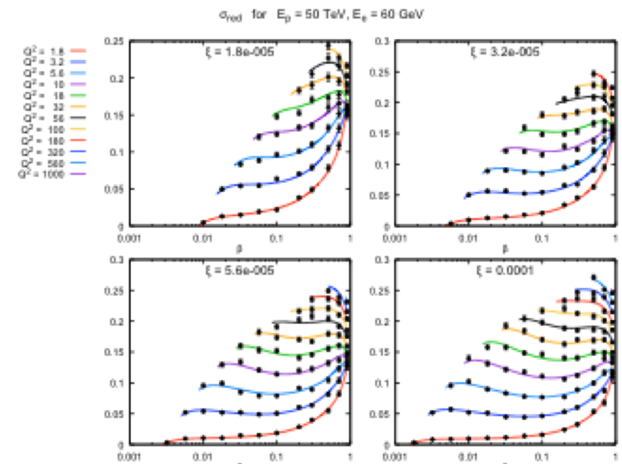
- Add LHeC and FCC-eh bins according to extrapolated ZEUS-SJ fits (4 bins per decade in each of ξ, β, Q2)

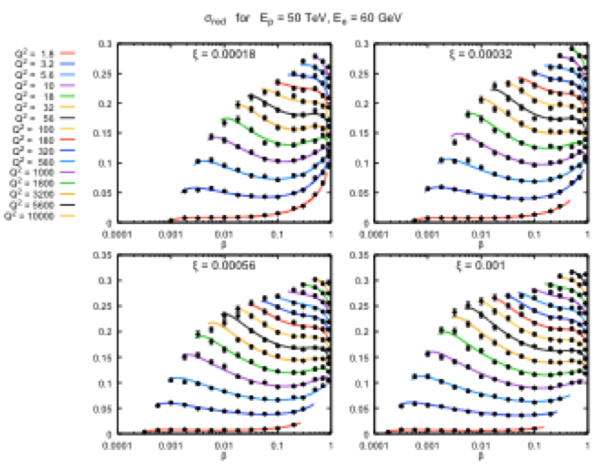
All pseudodata bins at FCC-eh

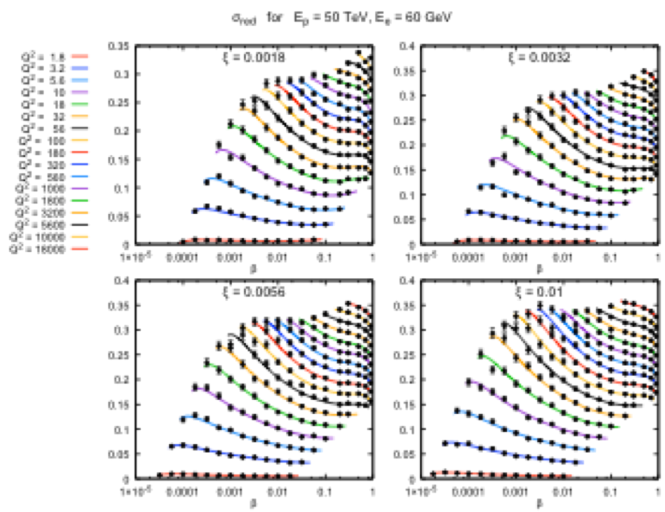
$\xi = 1.8 \times 10^{-7}$

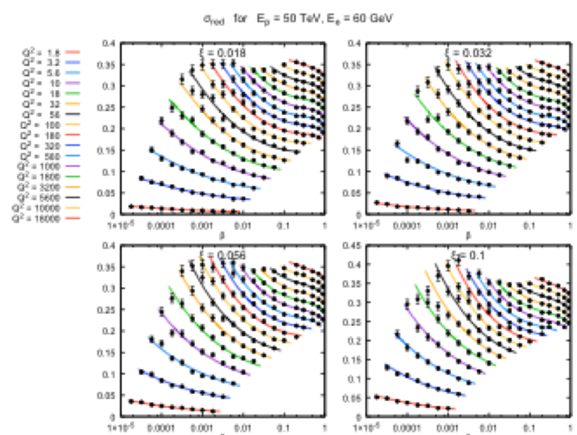












$\xi = 0.1$

Data uncertainties:

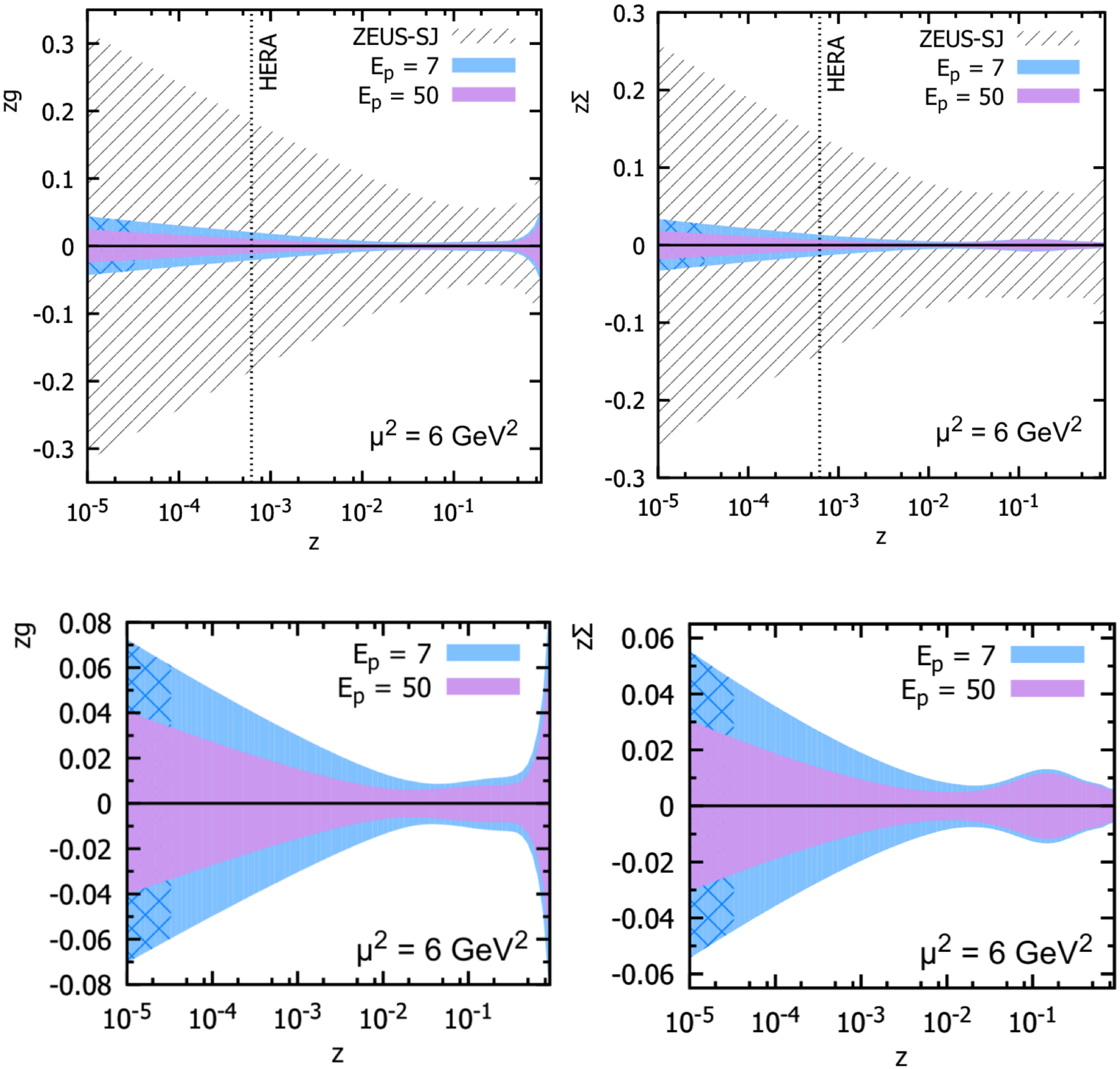
- 5% uncorrelated systematic
- 2% statistical uncertainty

Fit range:

$Q^2_{min} = 5\ \text{GeV}^2$ $\xi_{max} = 0.1$

Simulated DPDF Precision

Gluons Quarks



→ 2-6% precision on gluon density at low momentum fraction

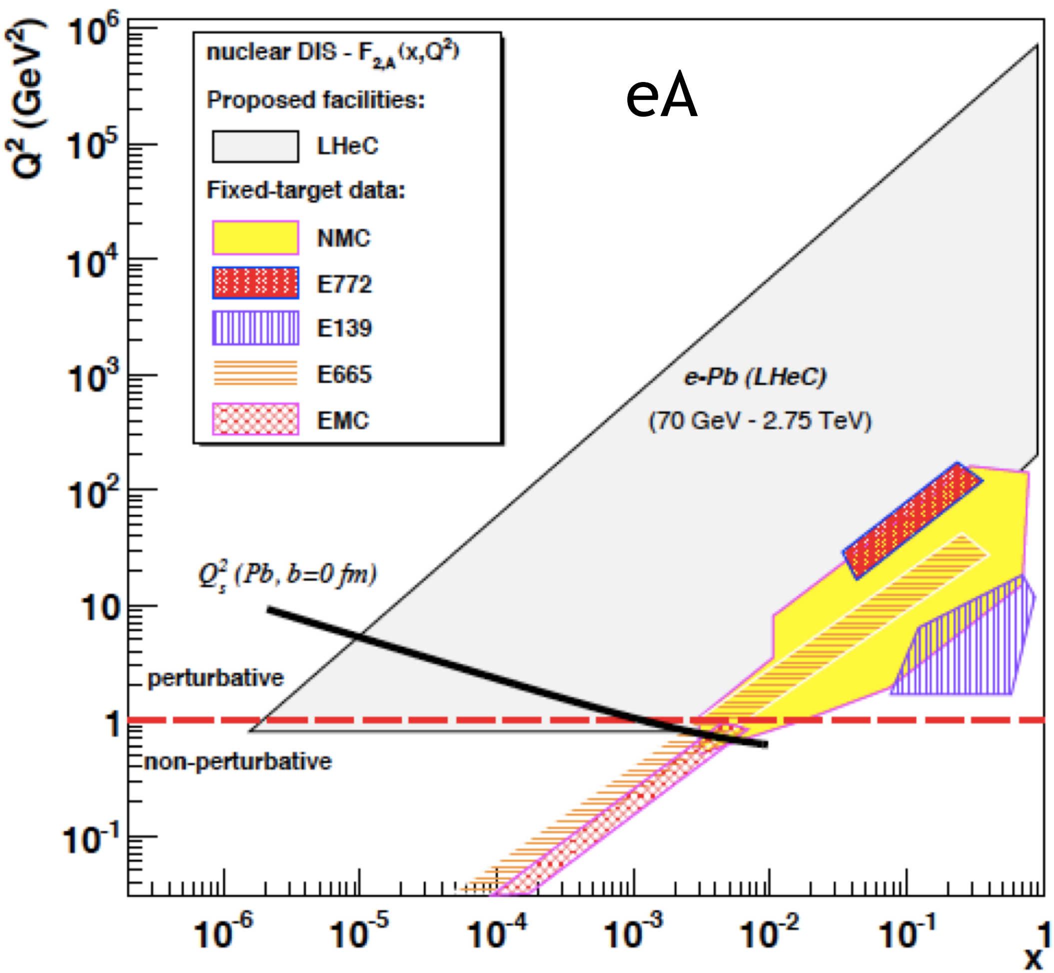
→ Not lumi limited ($2 fb^{-1}$ is enough)

→ Can also constrain `pomeron Intercept'

[Zoom]

LHeC as an Electron-Ion Collider

Four orders of magnitude increase in kinematic range over previous DIS experiments → Wide ranging programme …

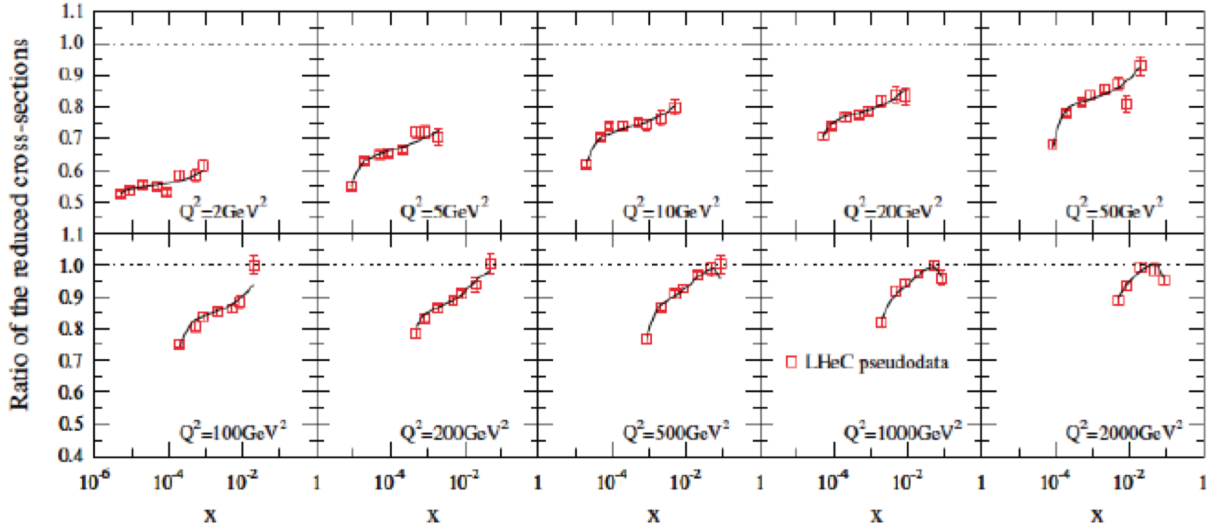


→ Revolutionises knowledge of nuclear partonic structure

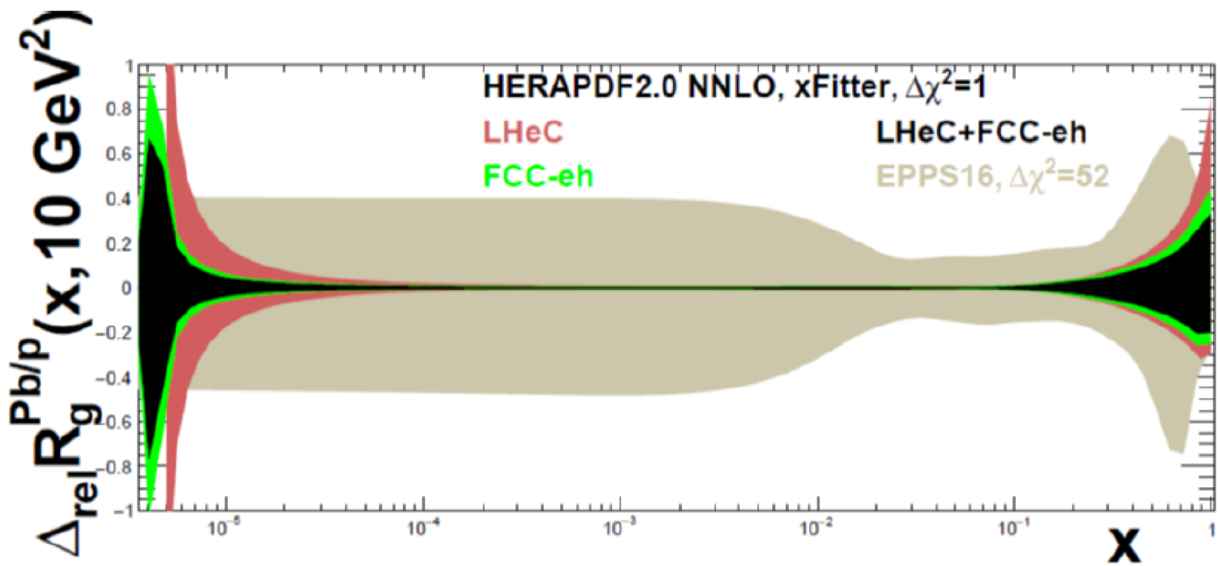
→ Low x / diffactive eA programme gives additional lens on densely packed, weakly coupled, partons

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

Impact of Simulated ePb LHeC F_2 & F_L data



- Recent fits to detailed LHeC pseudodata
- LHeC data have huge impact on low x gluon & sea uncertainties



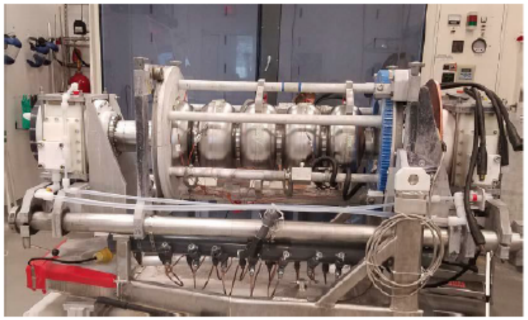
Relative error on R_g = Nuclear gluon / (A * proton gluon)

Critical Path Towards Realisation: PERLE

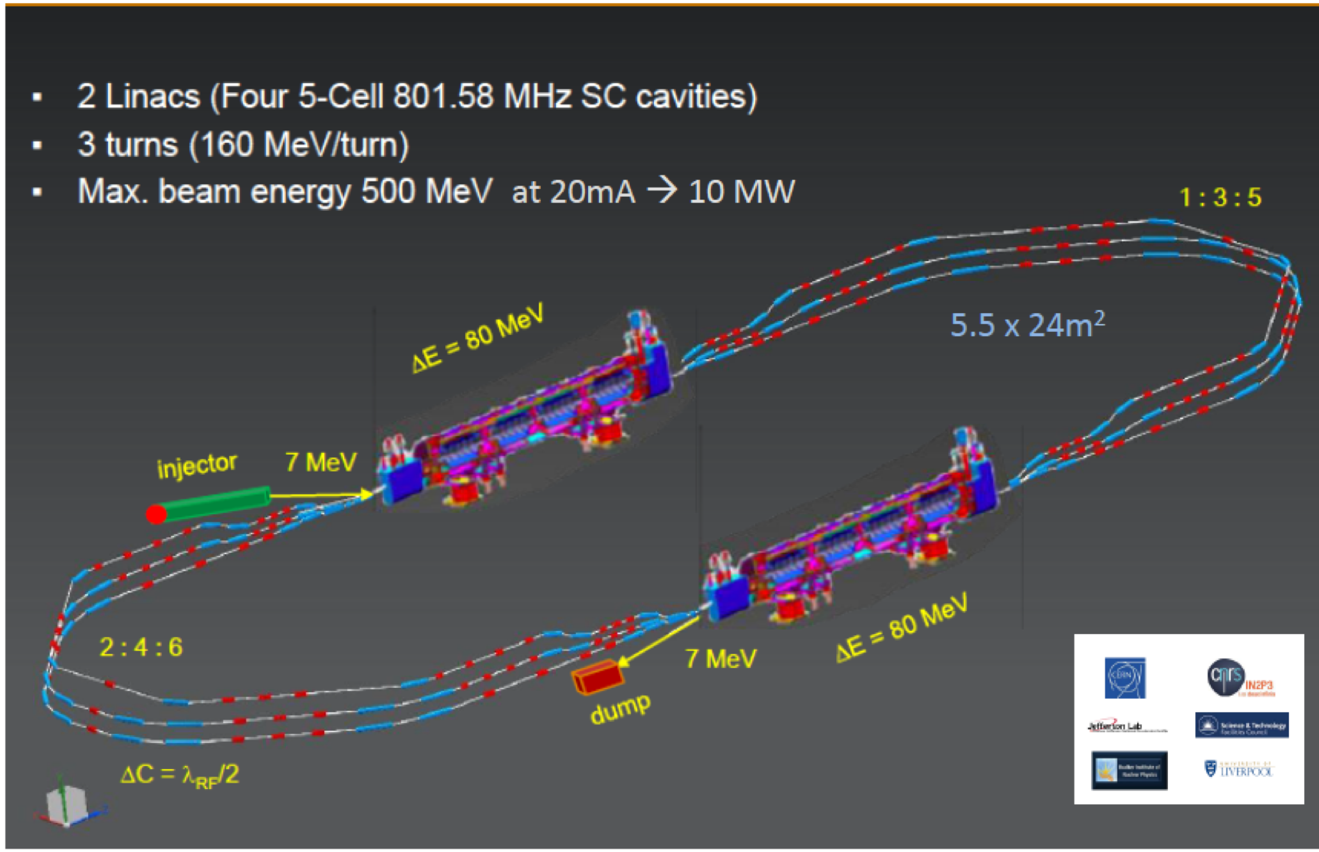
… Prototype high current energy recovery linac with superconducting RF …

Powerful ERL for Experiments at Orsay

First 802 MHz cavity successfully built (Jlab)



… with excellent performance …

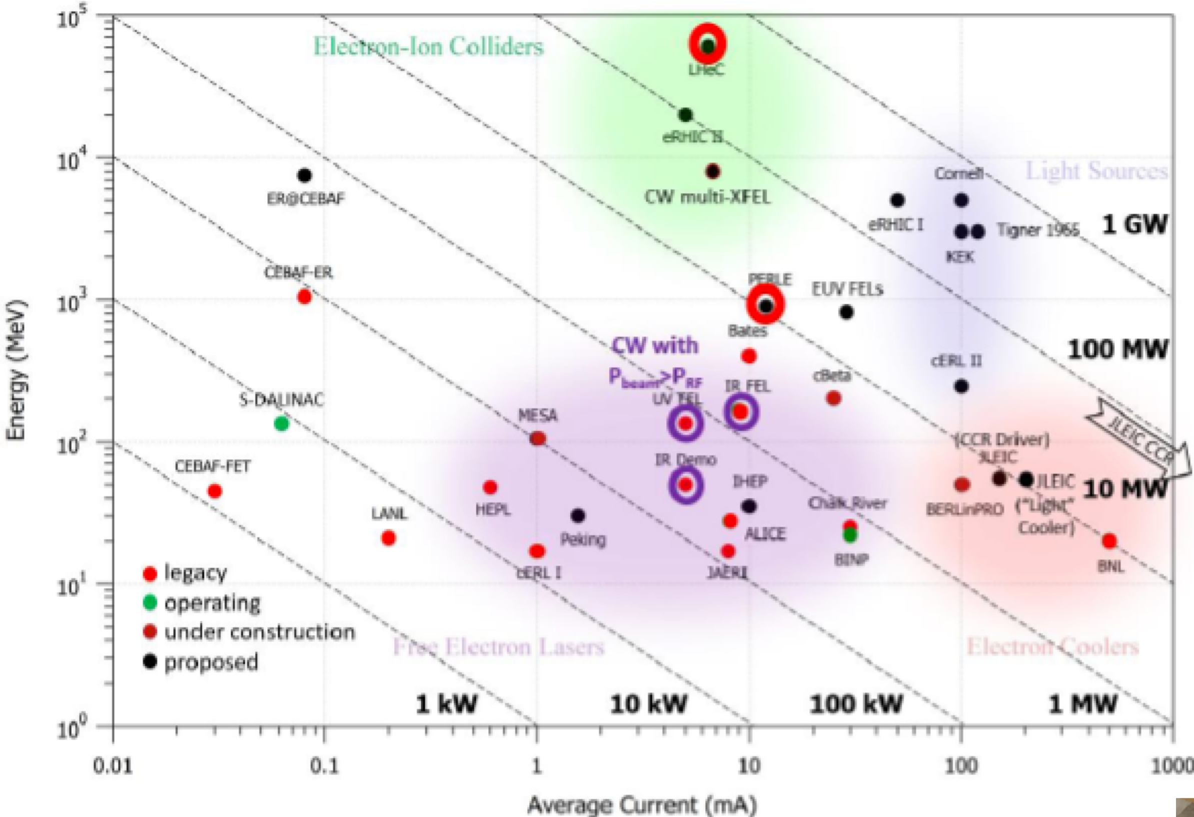


cf Walid Kaabi at Amsterdam FCC

New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

- Test centre for LHeC accelerator development with significant standalone physics potential (EW parameters, proton radius, photonuclear physics, dark photons

PERLE status and plans

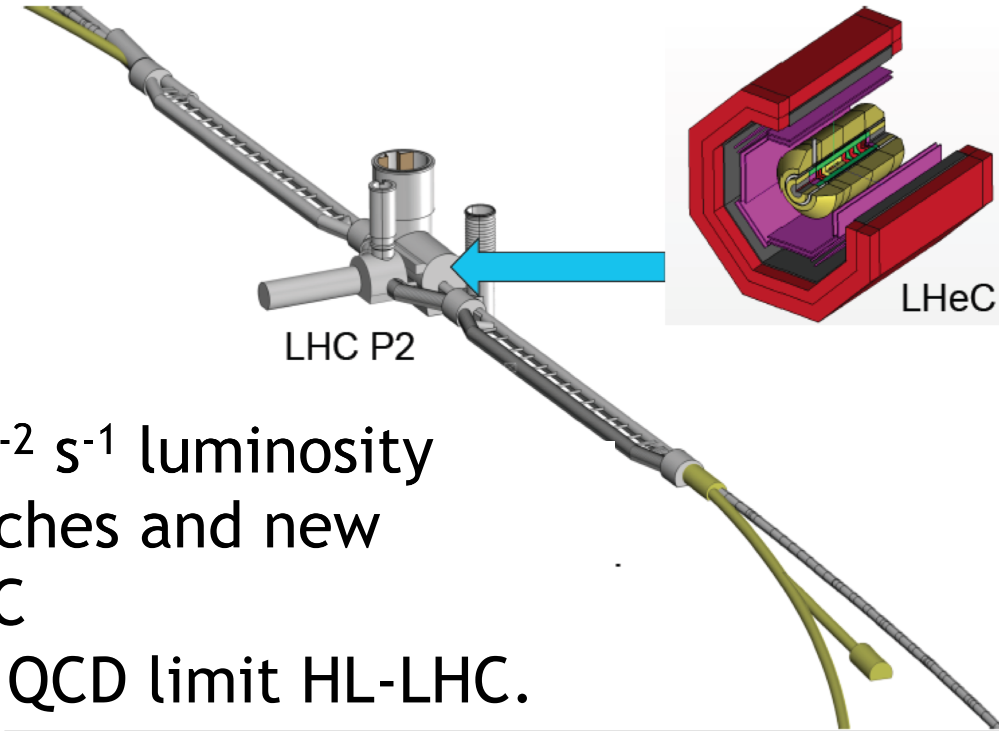


- ➔Currently Only 1 operating SRF ERL!!!
- ➔Current only demonstrated 1MW beam power in single ERL turn
- ➔Only 3 ERLs had demonstration of operation with P_{beam} > P_{RF}!!!

- Orsay experimentatal hall allocated with support for infrastructure

- MoU's being written, funding model being investigated, CDR exists, TDR and detailed costing planned for mid 2019.

LHeC Summary



- CDR 2012

- Changes since then …
    1) Possibility of 10^{34} cm^{-2} s^{-1} luminosity
    2) Higgs discovery, searches and new measurements at LHC
       → PDFs & QCD limit HL-LHC.
    3) Technical interest (high gradient cavities, ER linacs …)
    4) Longer term perspective of FCC

- Next goals …
    1) Preparing input to 2020 Euro Strategy
    2) TDR for PERLE
    3) Further development of FCC concept and physics

    …