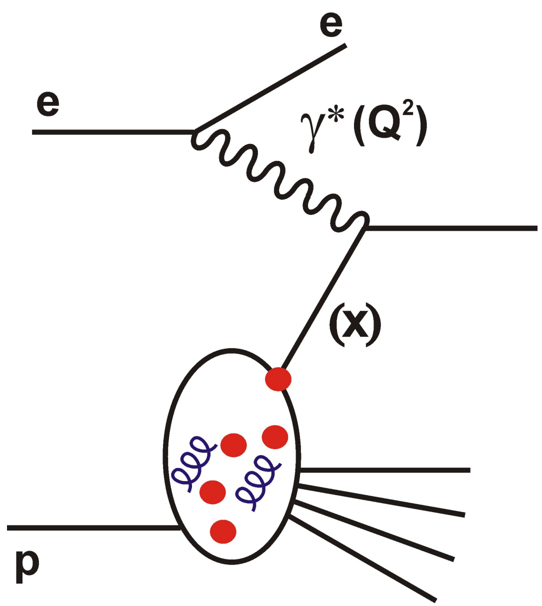
Small-x Physics and Diffraction at the LHeC and FCC-eh

Paul Newman
Birmingham University



Kobe, Japan
14 April 2018

Last Time I was in Japan (DIS'06, Tsukuba)

Diffractive Cross Sections and Parton Densities from Rapidity Gap and Leading Proton Measurements

P.Newman (Birmingham) for the H1 Collaboration

Measurement and QCD Analysis of the Diffractive Deep-Inelastic Scattering Cross Section at HERA

H1 Collaboration

Abstract

A detailed analysis is presented of the diffractive deep-inelastic scattering process $ep \to eXY$, where Y is a proton or a low mass proton excitation carrying a fraction $1 - x_{I\!P} > 0.95$ of the incident proton longitudinal momentum and the squared four-momentum transfer at the proton vertex satisfies $|t| < 1$ GeV^2. Using data taken by the H1 experiment, the cross section is measured for photon virtualities in the range $3.5 \leq Q^2 \leq 1600$ GeV^2, triple differentially in $x_{I\!P}$, Q^2 and $\beta = x/x_{I\!P}$, where x is the Bjorken scaling variable. At low $x_{I\!P}$, the data are consistent with a factorisable $x_{I\!P}$ dependence, which can be described by the exchange of an effective pomeron trajectory with intercept $\alpha_{I\!P}(0) = 1.118 \pm 0.008$ (exp.) $^{+0.029}_{-0.010}$ (theory). Diffractive parton distribution functions and their uncertainties are determined from a next-to-leading order DGLAP QCD analysis of the Q^2 and β dependences of the cross section. The resulting gluon distribution carries an integrated fraction of around 70% of the exchanged momentum in the Q^2 range studied. Total and differential cross sections are also measured for the diffractive charged current process $e^+p \to \bar{\nu}_e XY$ and are found to be well described by predictions based on the diffractive parton distributions. The dynamics of the ratio of the diffractive to the inclusive neutral current ep cross sections are studied. Over most of the kinematic range studied, this ratio shows no significant dependence on Q^2 at fixed $x_{I\!P}$ and x or on x at fixed Q^2 and β fixed.

Diffractive Deep-Inelastic Scattering with a Leading Proton at HERA

H1 Collaboration

Abstract

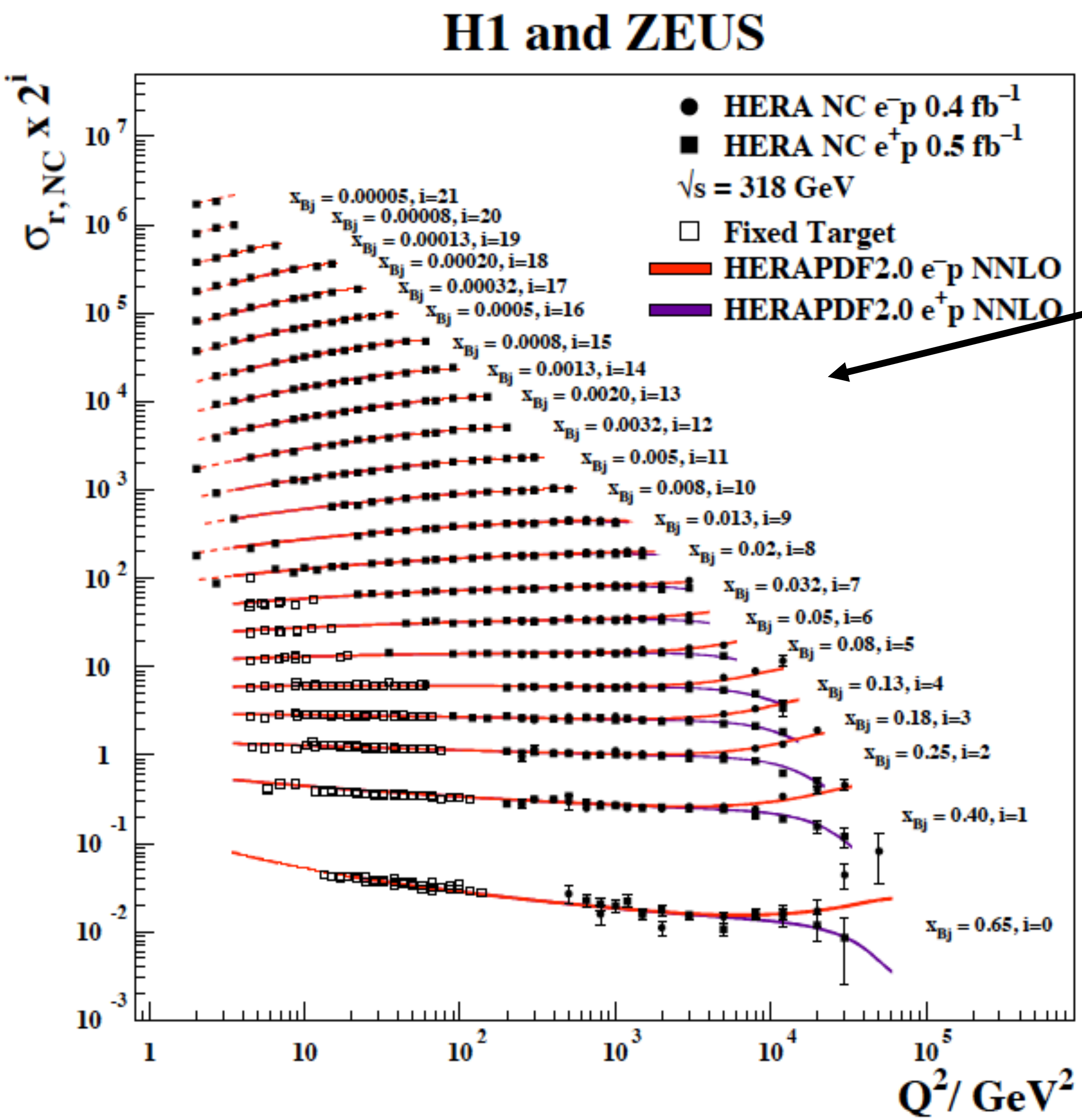
The cross section for the diffractive deep-inelastic scattering process $ep \to eXp$ is measured, with the leading final state proton detected in the H1 Forward Proton Spectrometer. The data analysed cover the range $x_{I\!P} < 0.1$ in fractional proton longitudinal momentum loss, $0.08 < |t| < 0.5$ GeV^{-2} in squared four-momentum transfer at the proton vertex, $2 < Q^2 < 50$ GeV^2 in photon virtuality and $0.004 < \beta = x/x_{I\!P} < 1$, where x is the Bjorken scaling variable. For $x_{I\!P} \lesssim 10^{-2}$, the differential cross section has a dependence of approximately $d\sigma/dt \propto e^{6t}$, independently of $x_{I\!P}$, β and Q^2 within uncertainties. The cross section is also measured triple differentially in $x_{I\!P}$, β and Q^2. The $x_{I\!P}$ dependence is interpreted in terms of an effective pomeron trajectory with intercept $\alpha_{I\!P}(0) = 1.110 \pm 0.018$ (stat.) ± 0.012 (syst.) $^{+0.040}_{-0.020}$ (model) and a sub-leading exchange. The data are in good agreement with an H1 measurement for which the event selection is based on a large gap in the rapidity distribution of the final state hadrons, after accounting for proton dissociation contributions in the latter. Within uncertainties, the dependence of the cross section on x and Q^2 can thus be factorised from the dependences on all studied variables which characterise the proton vertex, for both the pomeron and the sub-leading exchange.

Final results, new for this conference. Everything shown is taken from these two closely related papers.

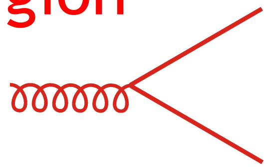
→ H1 2006 Fit B Diffractive PDFs

Low x Physics is Driven by the Gluon

… knowledge comes mainly from inclusive NC HERA data



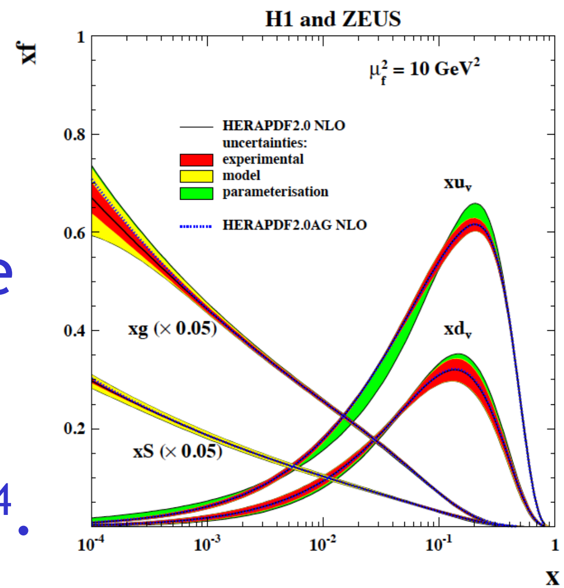
- NC Q^2 dependence in perturbative region driven by …

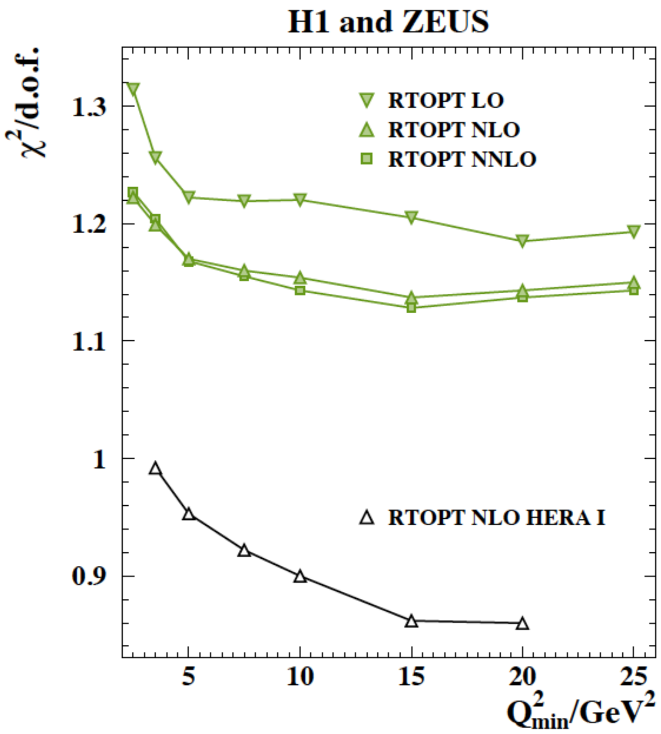


- e.g. Prytz approx:

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

- 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:

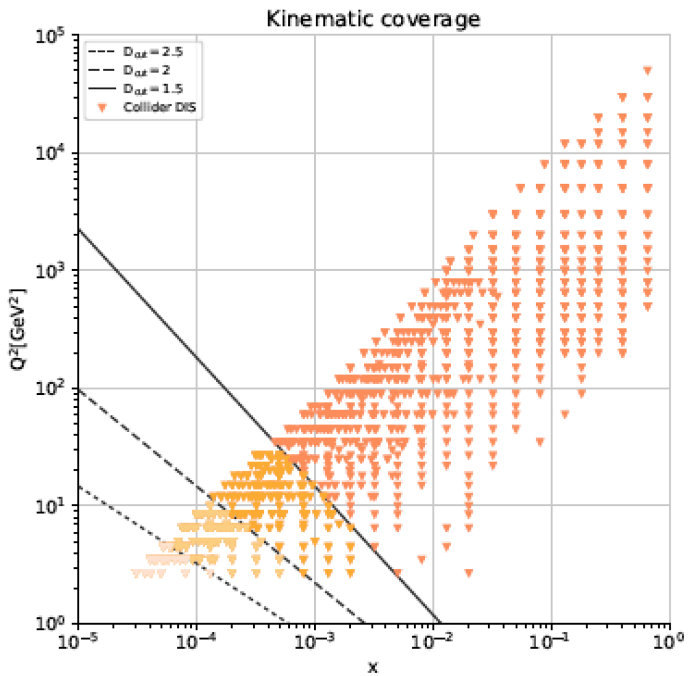
"some tension in fit between low & medium Q^2 data… not attributable to particular x region"

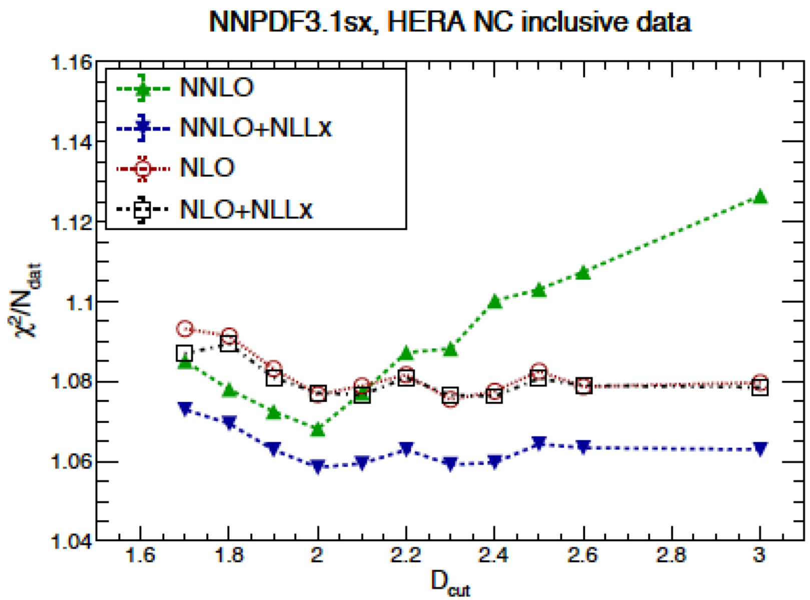
(though there is a kinematic correlation)

→ Saturation (density effects)?

→ Linear resummation (energy effects)?

[Ball et al, also describing F_L]

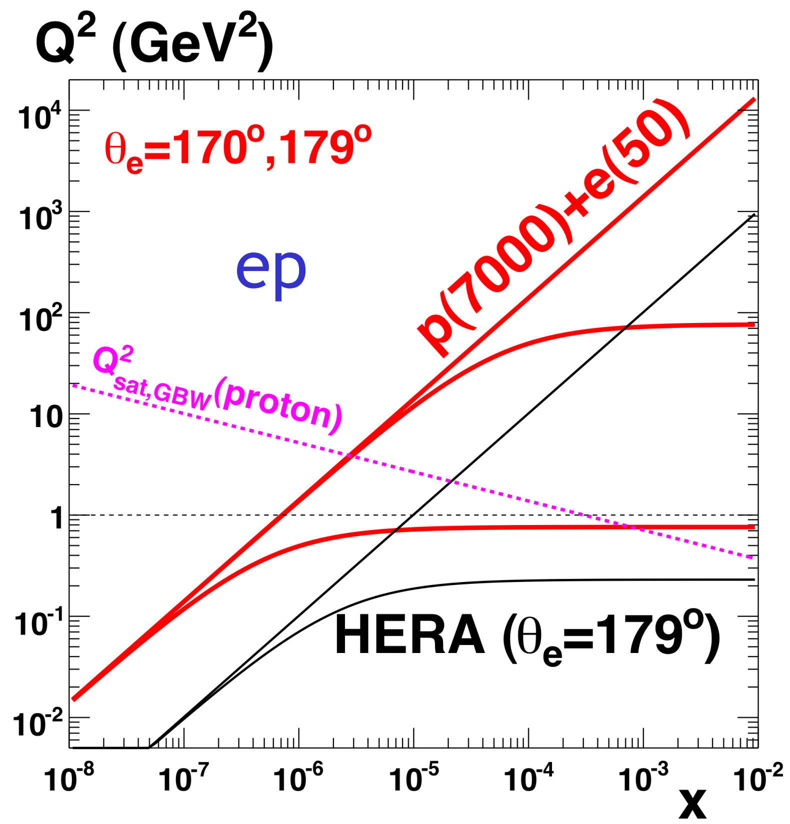


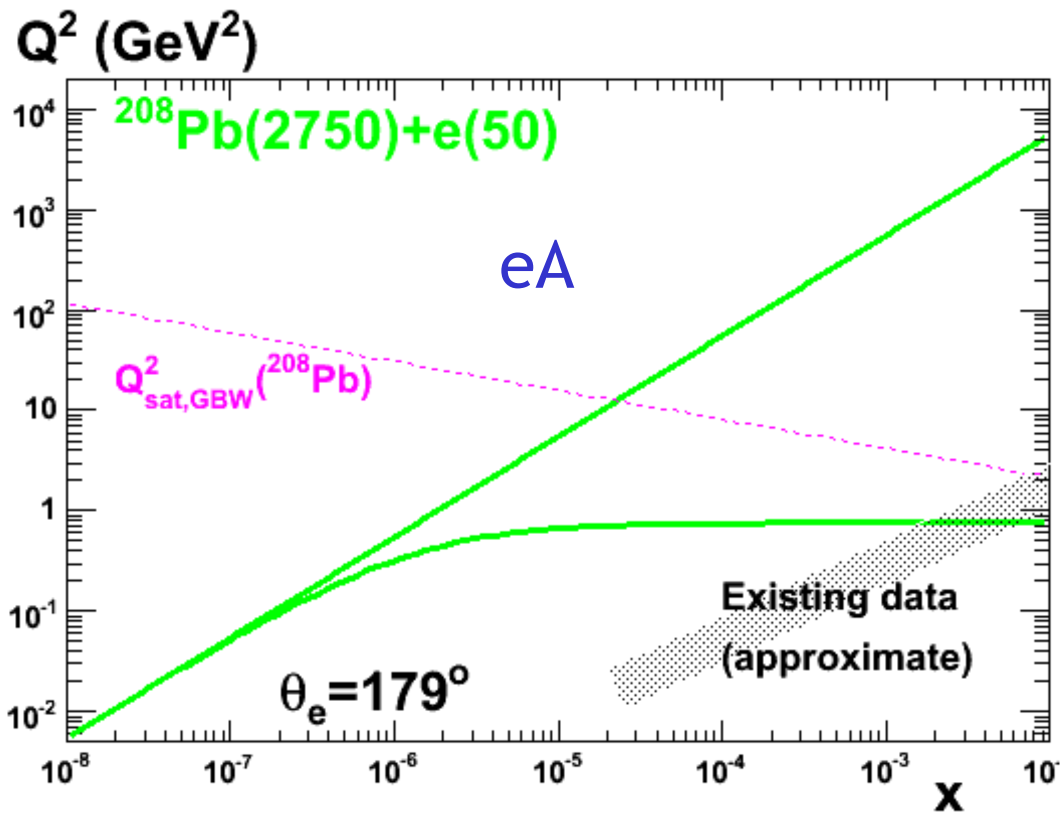


… effects are subtle and live in a small & difficult corner of kinematic plane

LHeC: Accessing low x at large Q^2

- Extending Q^2 range vital to fully unravel complex low x region
- Comparing eA and ep allows energy and density effects to be disentangled

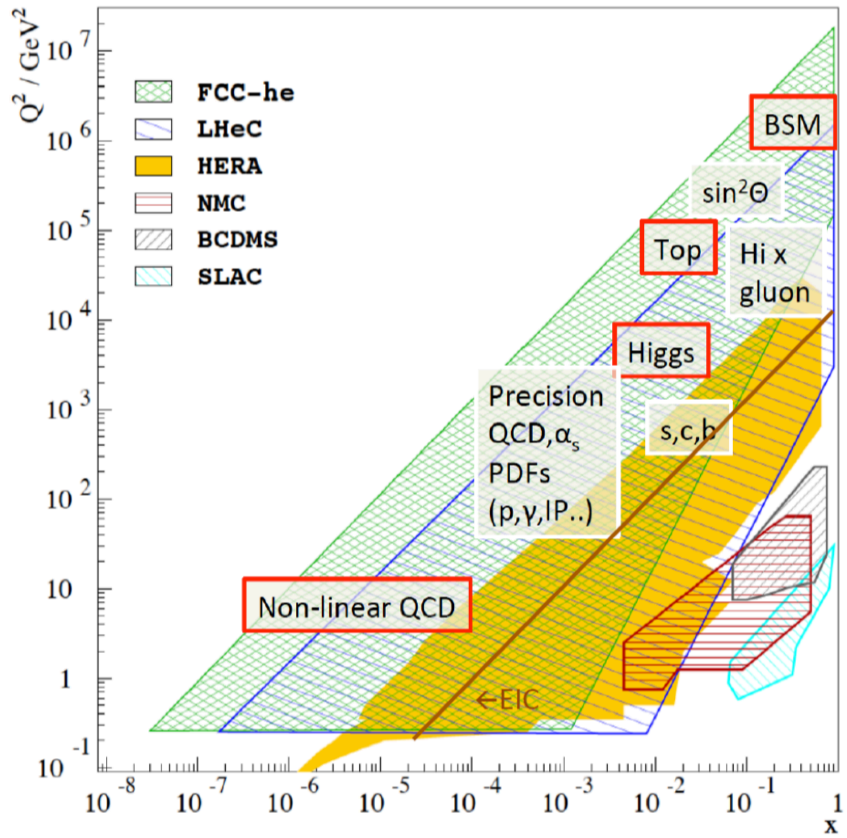




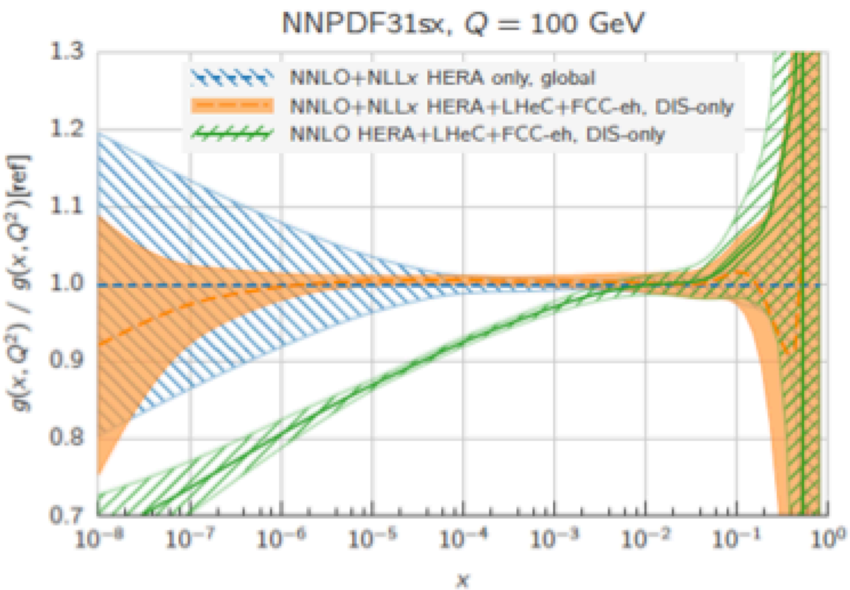
… LHeC reaches saturated region in both ep & eA at perturbative Q2 according to models

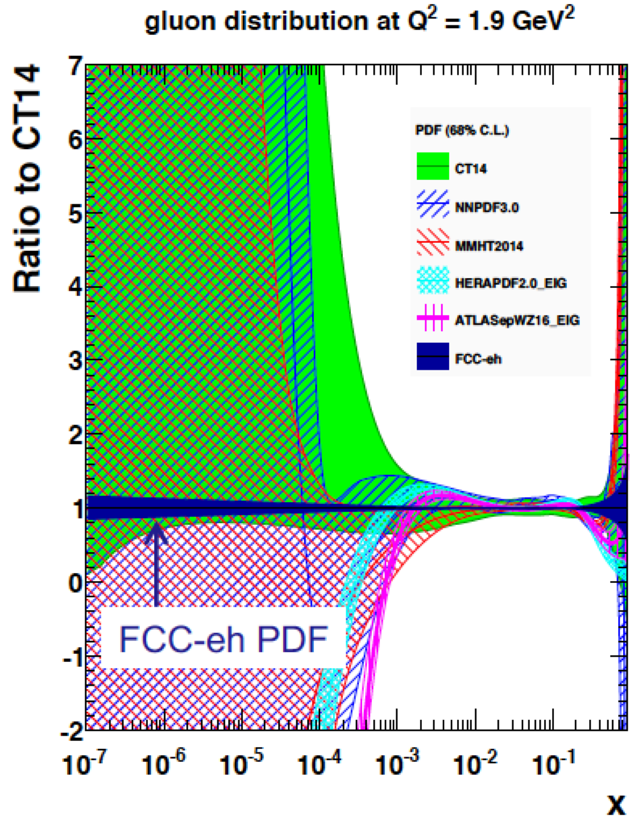
Adding FCC-eh to the Kinematic Place

x → 10^{-7} at $Q^2 > 3$ GeV^2



- Very large predicted effects (eg resummation – Ball et al)
-Ultra-precise PDFs … (Claire's talk)

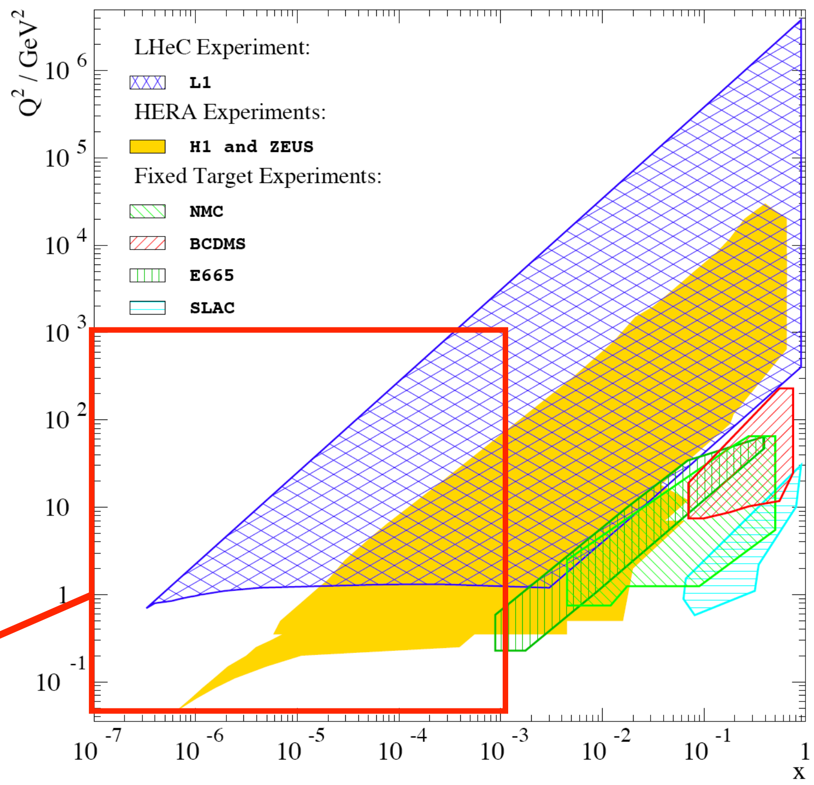


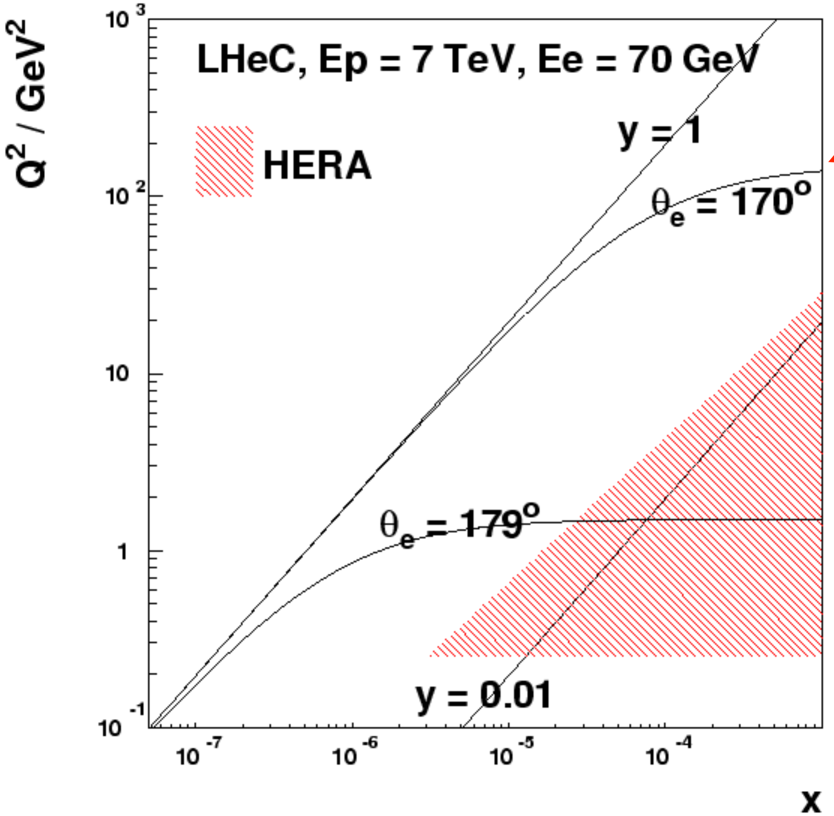


Maximal Detector Acceptance is Vital

eg from LHeC ...

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



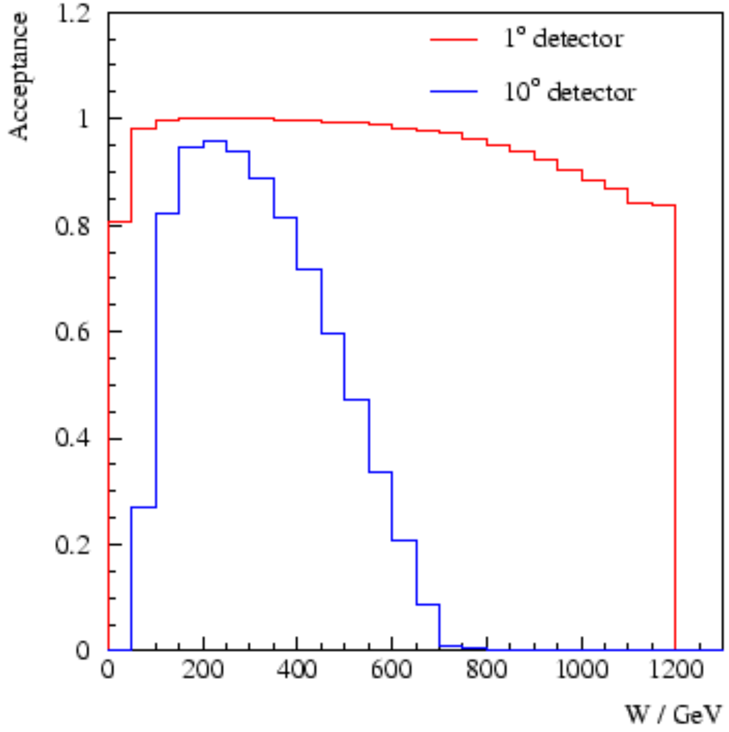


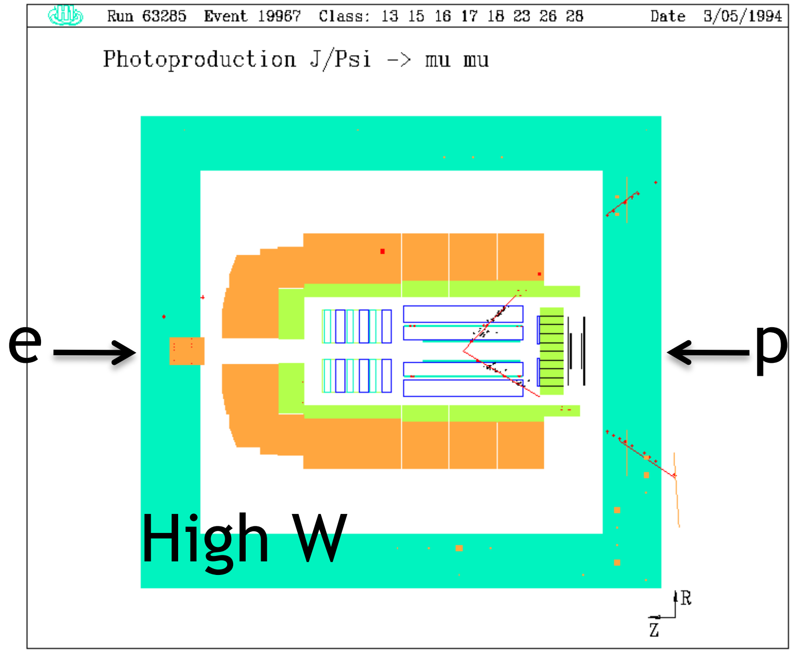
Also need 1° acceptance in proton direction to contain hadrons for low x / high y kinematic reconstruction

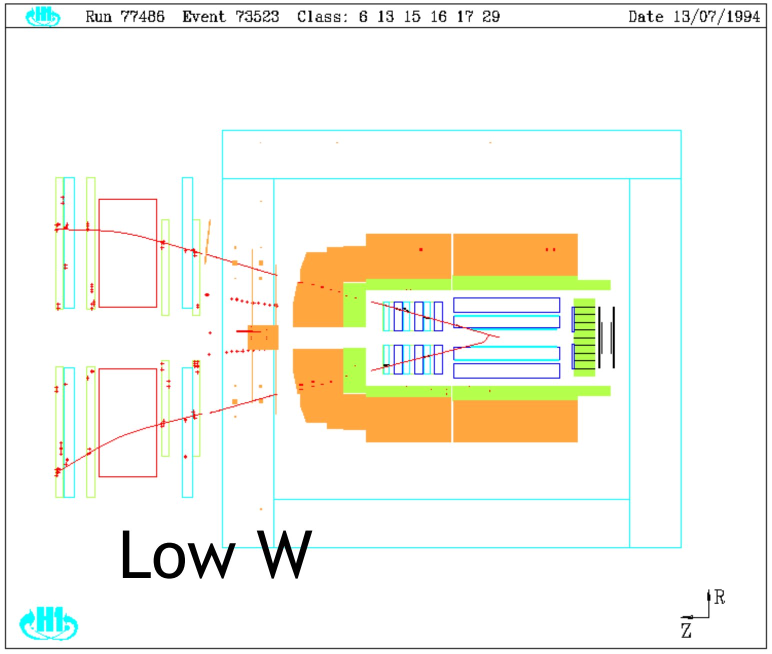
Elastic J/Ψ Kinematics (example from LHeC)

- At fixed $\sqrt{s}$, decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$

- To access highest W, acceptance in outgoing electron beam direction crucial

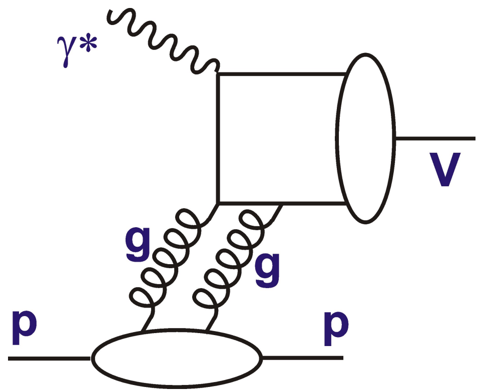






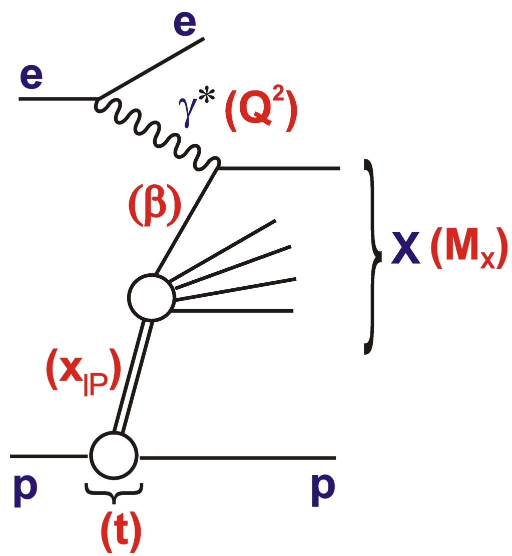
Exclusive / Diffractive Channels and Low x

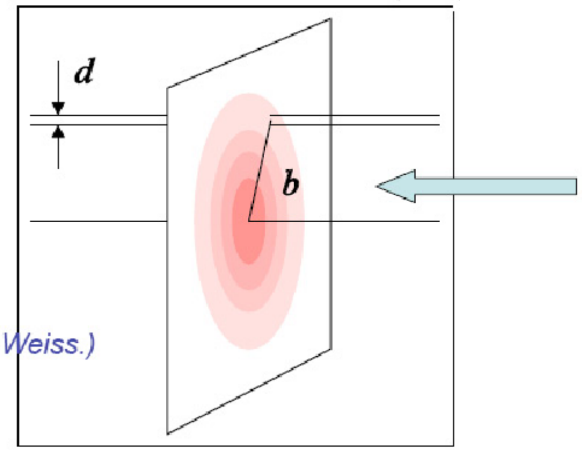
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)



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

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





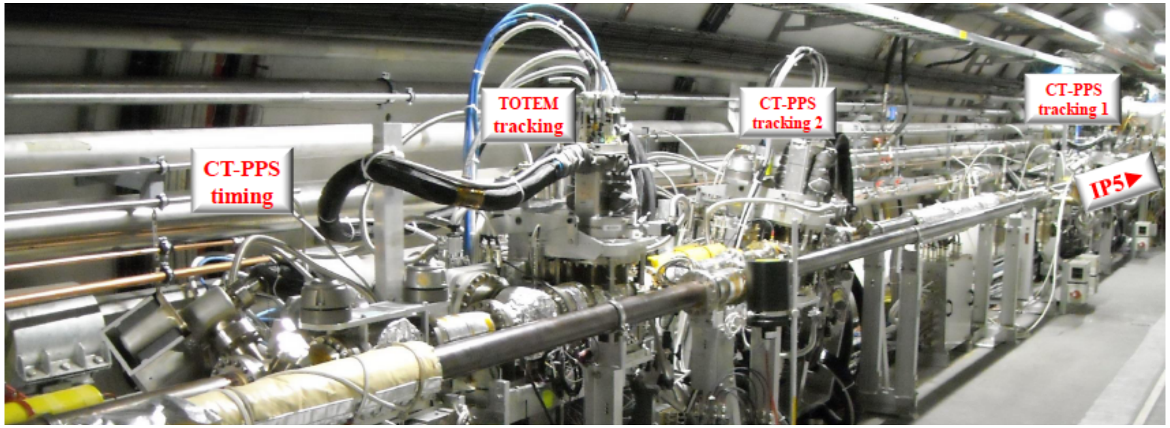
(figure from C. Weiss.)

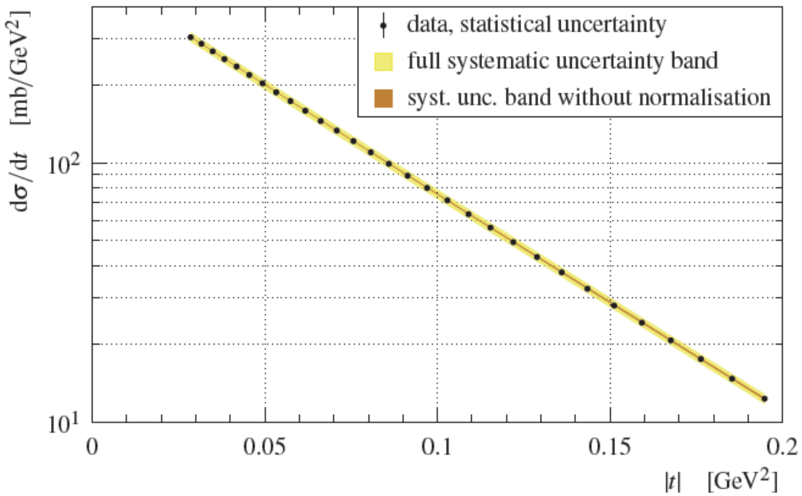
Central black region growing with decrease of x.

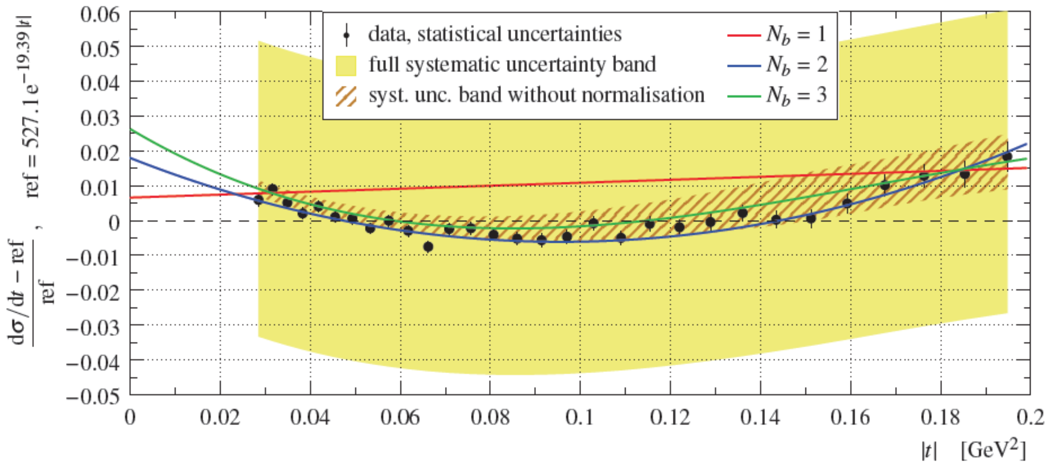
Proton Spectrometers Come of Age

LHC experiments (TOTEM, ALFA@ATLAS) have shown that it's possible to make precision measurements and cover wide kinematic range with Roman pots.

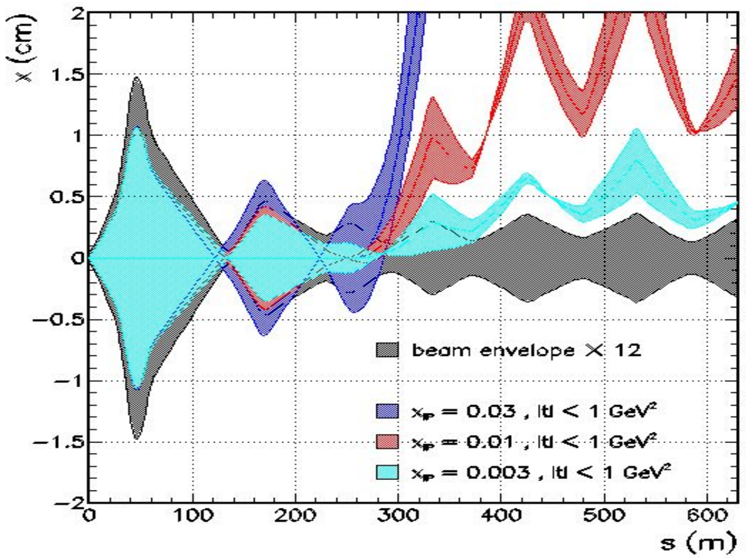
e.g. TOTEM currently operates 14 pots, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential term in elastic t dependence …



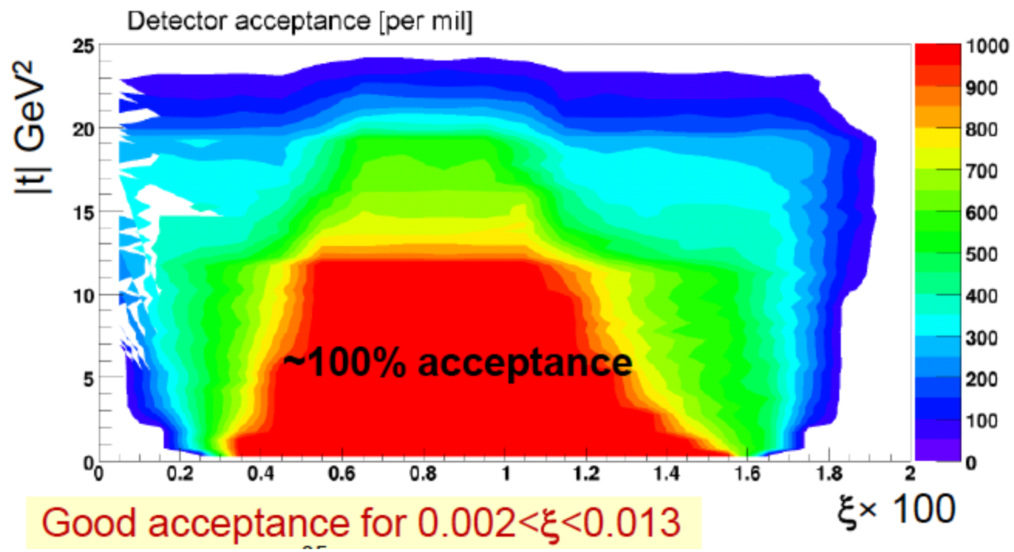




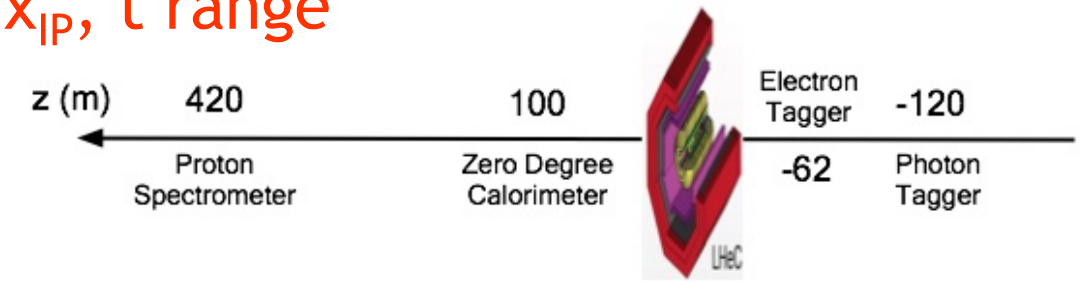
Design for LHeC Forward Proton Spectrometers



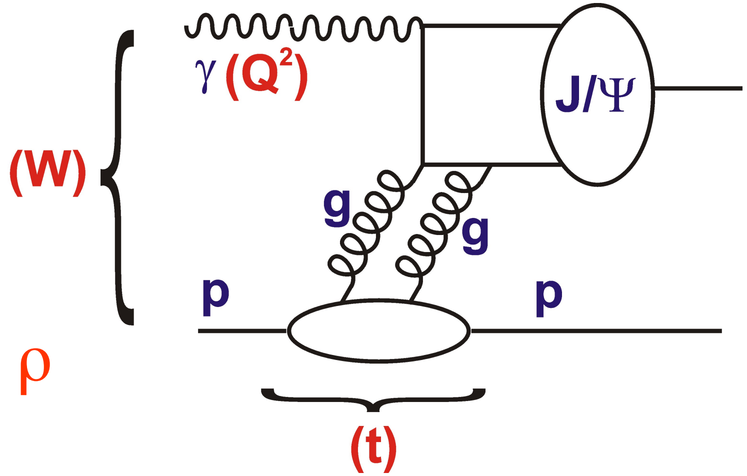
Roman pot forward detector systems with low ξ (= x_{IP}) acceptance integrated into design from outset



- LHeC Proton spectrometer uses outcomes of FP420 project (proposal for low ξ Roman pots at ATLAS / CMS – not yet adopted)
- Tags elastically scattered protons with high acceptance over a wide x_{IP}, t range



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)

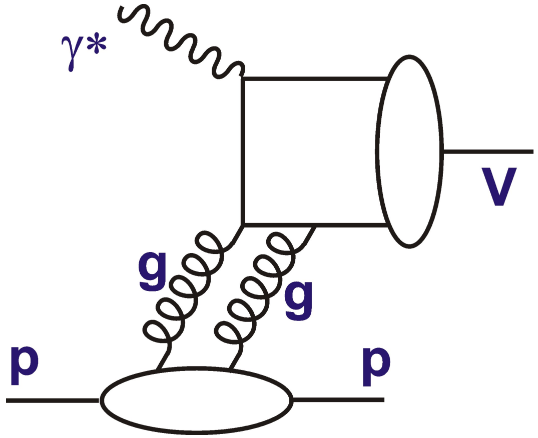
• Scale $\overline{Q^2} \sim (Q^2 + M_V^2) / 4 \;>\sim 3\ \text{GeV}^2$ ideally suited to reaching lowest possible x whilst remaining in perturbative regime

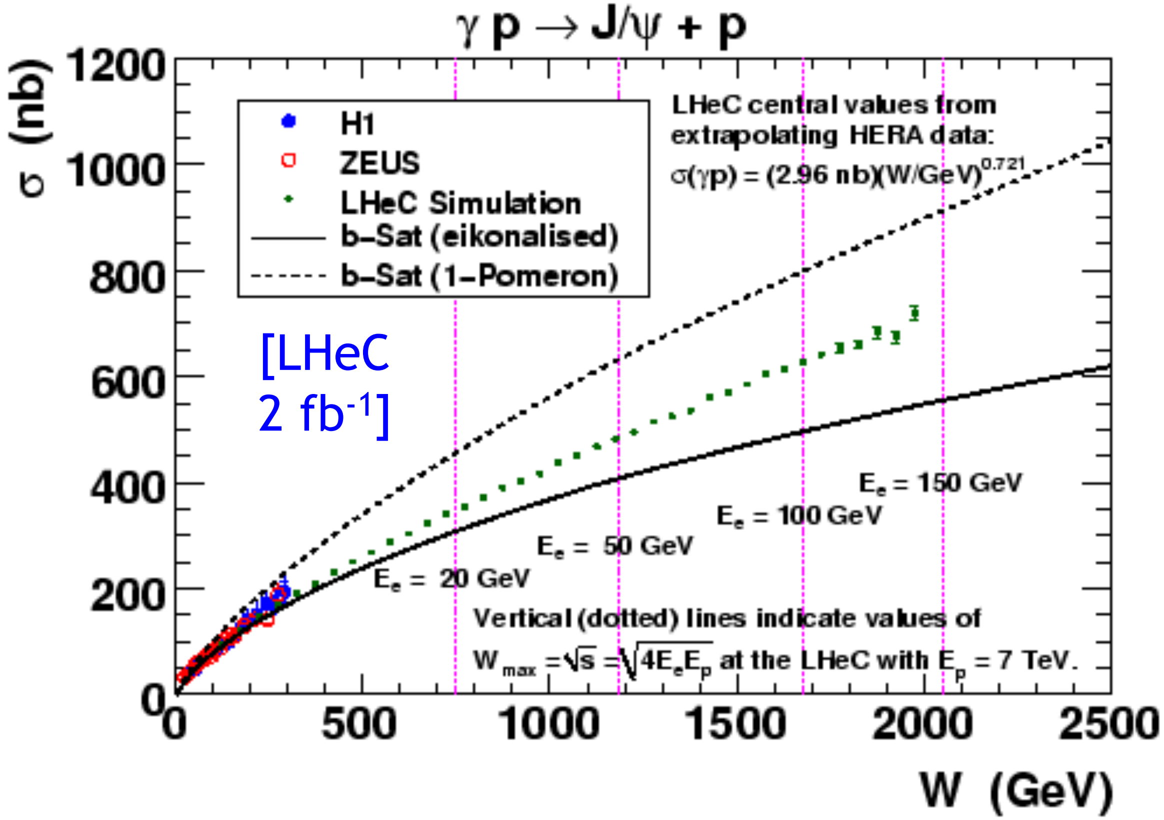
… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

• Simulations (DIFFVM) of elastic J/Ψ → μμ 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



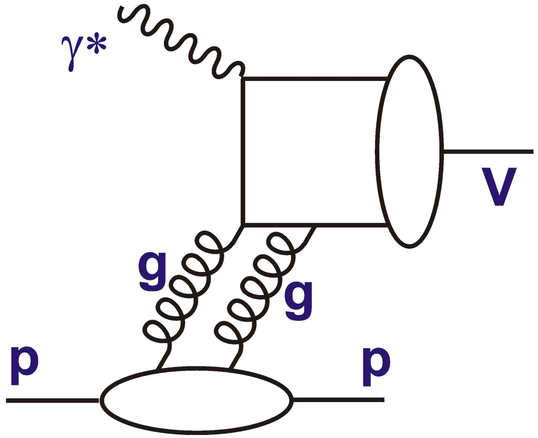


• Significant non-linear effects expected in LHeC kinematic range

… 'smoking gun'?…

J/Ψ from future ep v Dipole model Predictions

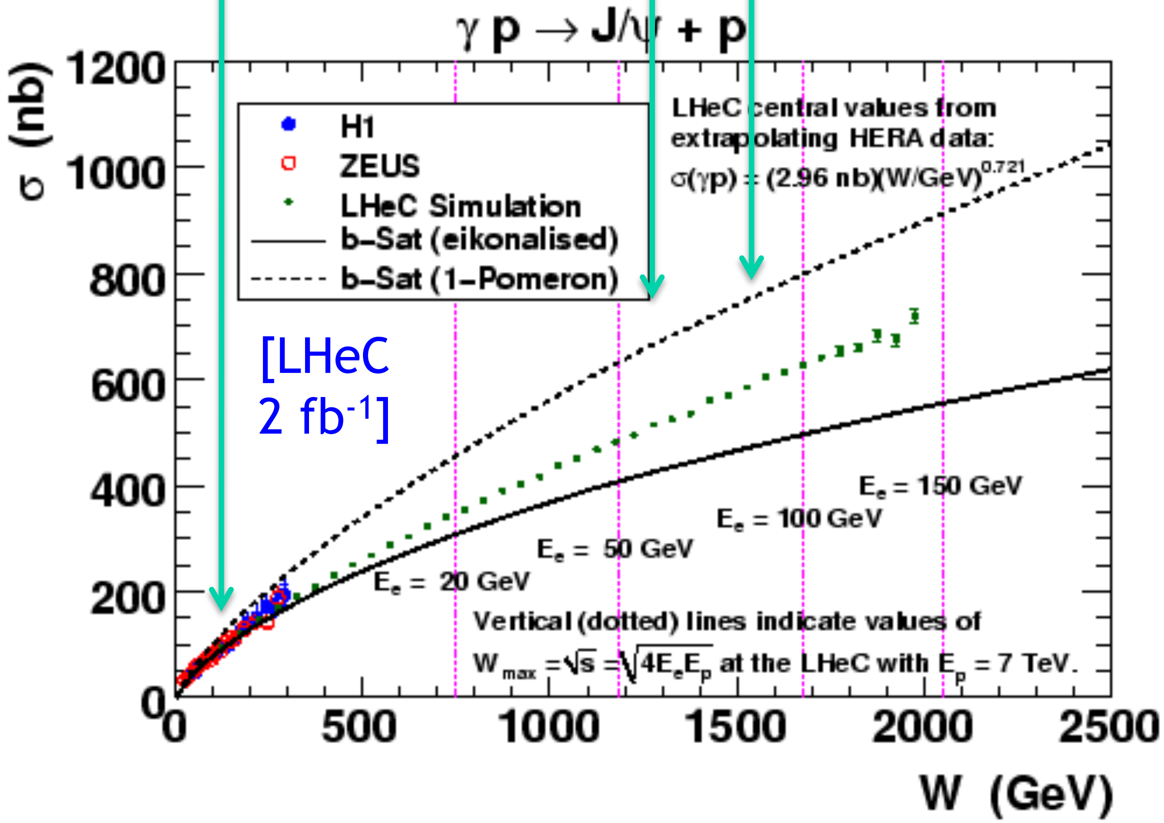
"beware unrealistic non-saturation straw men" [T. Lappi]



Current EIC design

Current LHeC design

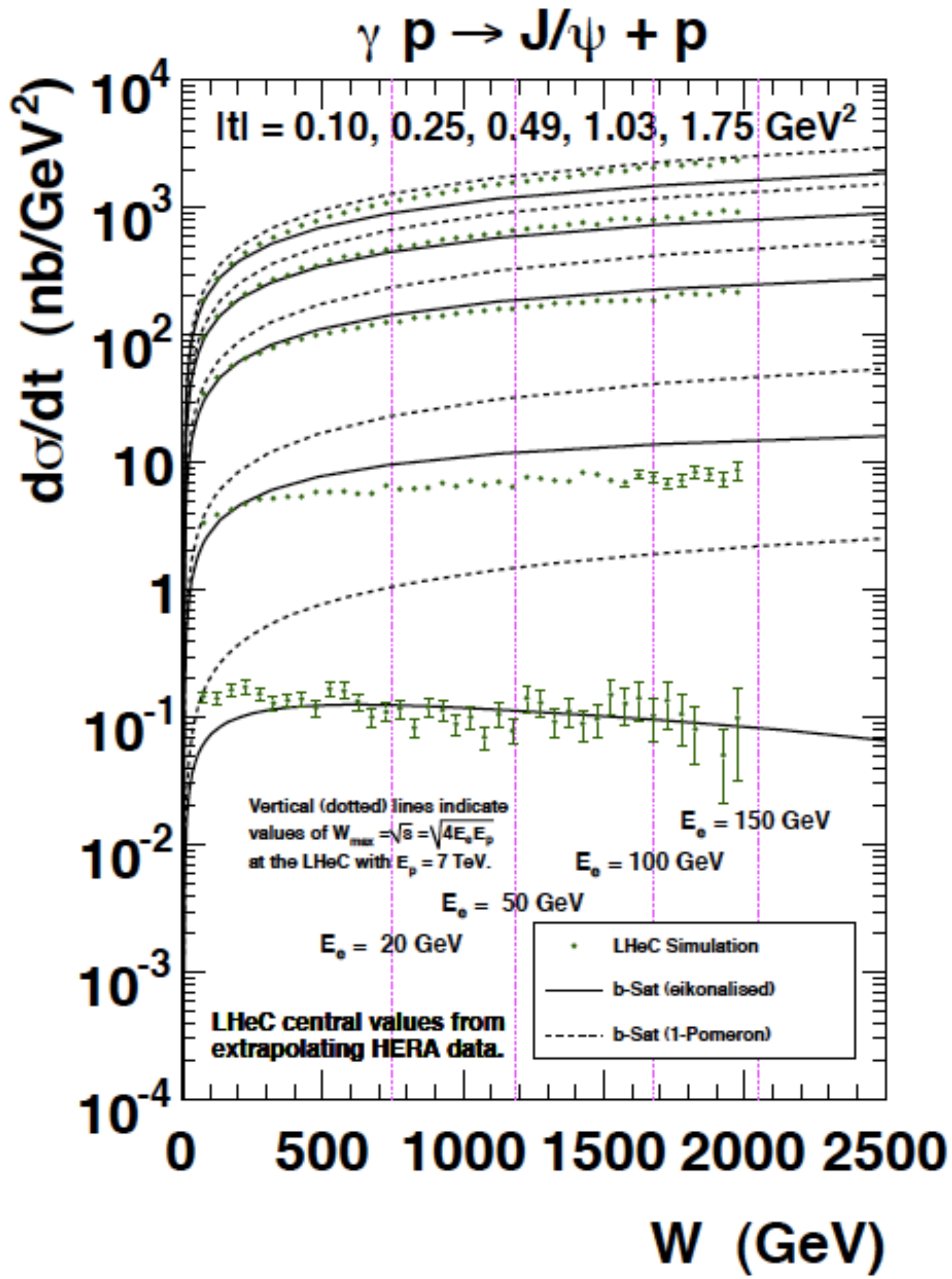
Current LHCb limit



- 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

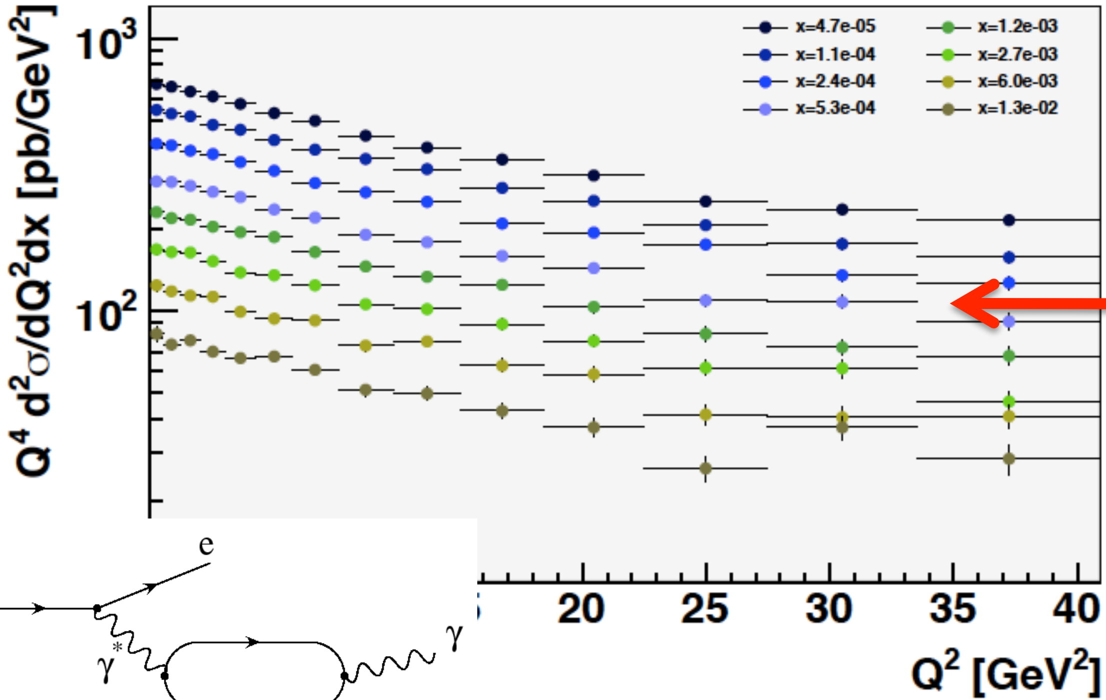


- Precise t measurement from decay μ tracks over wide W range extends to $|t| \sim 2$ GeV^2 and enhances sensitivity to saturation effects

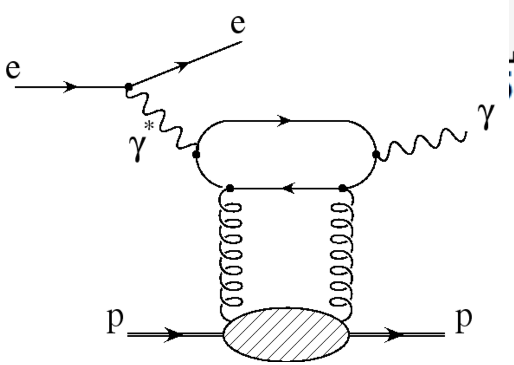
- Measurements also possible in multiple Q^2 bins

… see also eA (Nestor)

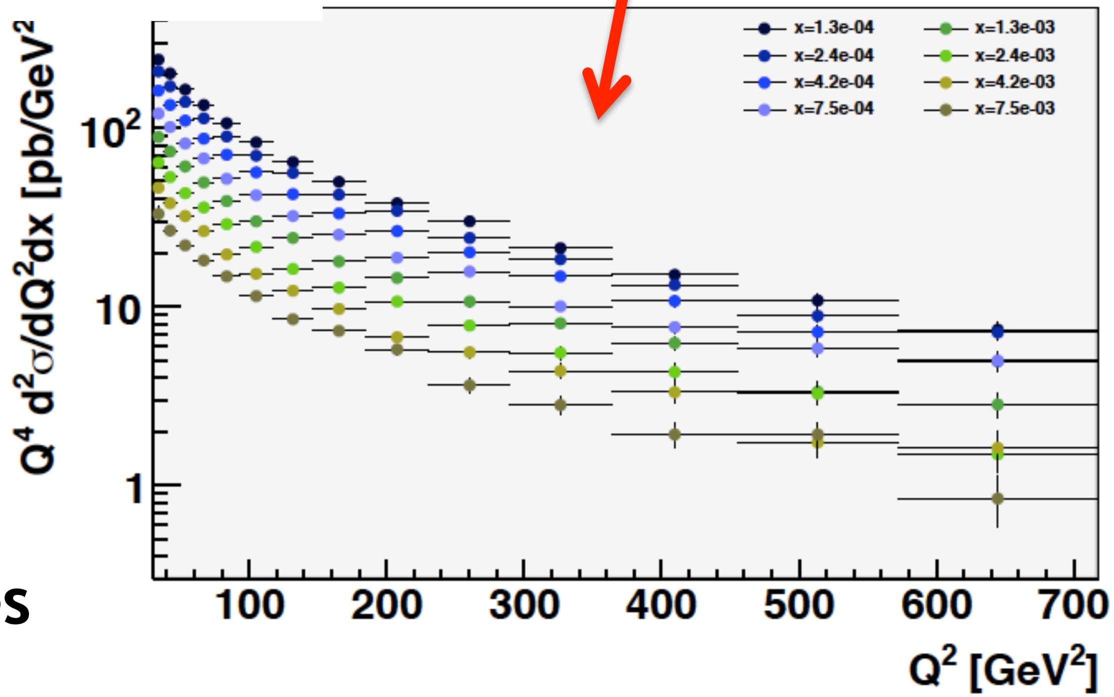
DVCS (MILOU simulation)



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



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

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

Diffractive Dijets

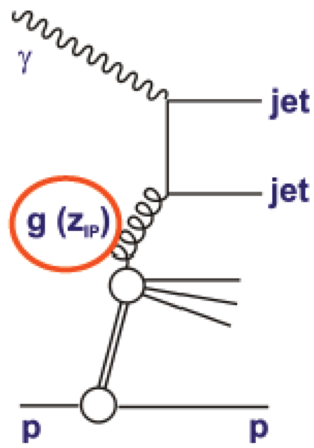
Dijet production in diffractive deep-inelastic scattering in next-to-next-to-leading order QCD

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

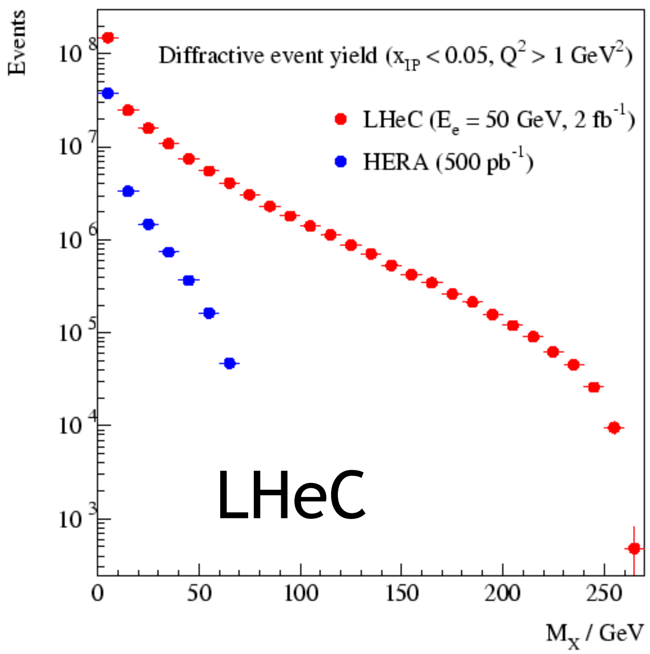
[1] Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
[2] Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, UK
[3] Physik-Institut, Universität Zürich, Winterthurerstraße 190, CH-8057 Zürich, Switzerland
[4] Theoretical Physics Department, CERN, 1211 Geneva, Switzerland
[5] DESY, Notkestraße 85, D-22607 Hamburg, Germany

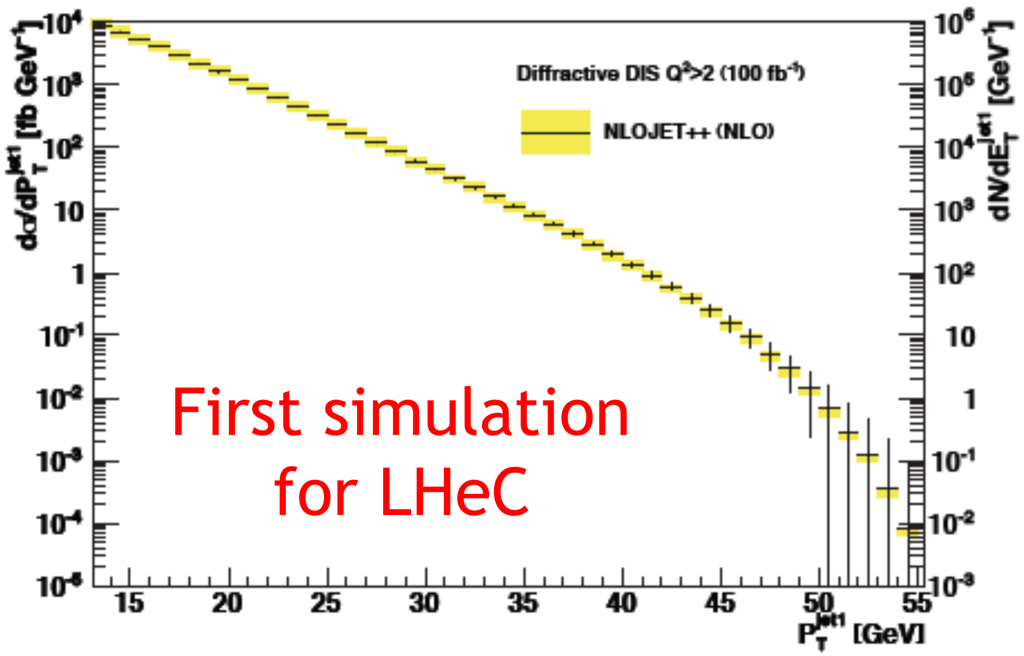
Received: date / Accepted: date

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.



… precision
theory deserves precision
data!





Diffractive Dijets

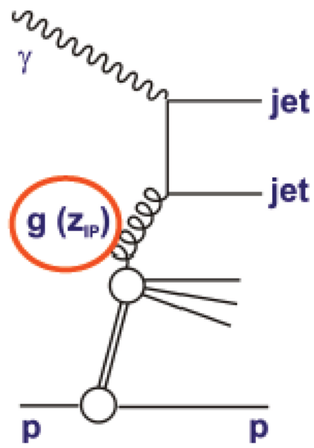
Dijet production in diffractive deep-inelastic scattering in next-to-next-to-leading order QCD

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

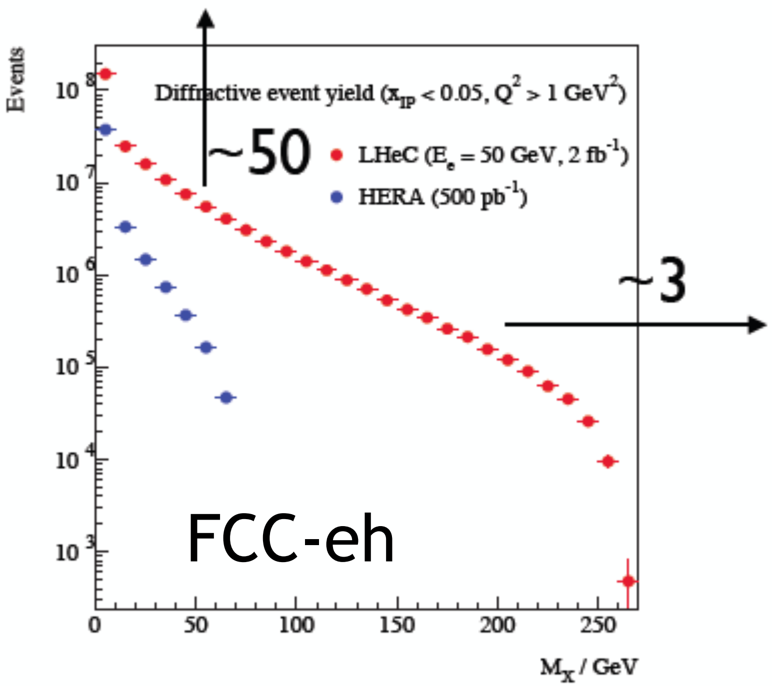
[1] Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
[2] Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, UK
[3] Physik-Institut, Universität Zürich, Winterthurerstraße 190, CH-8057 Zürich, Switzerland
[4] Theoretical Physics Department, CERN, 1211 Geneva, Switzerland
[5] DESY, Notkestraße 85, D-22607 Hamburg, Germany

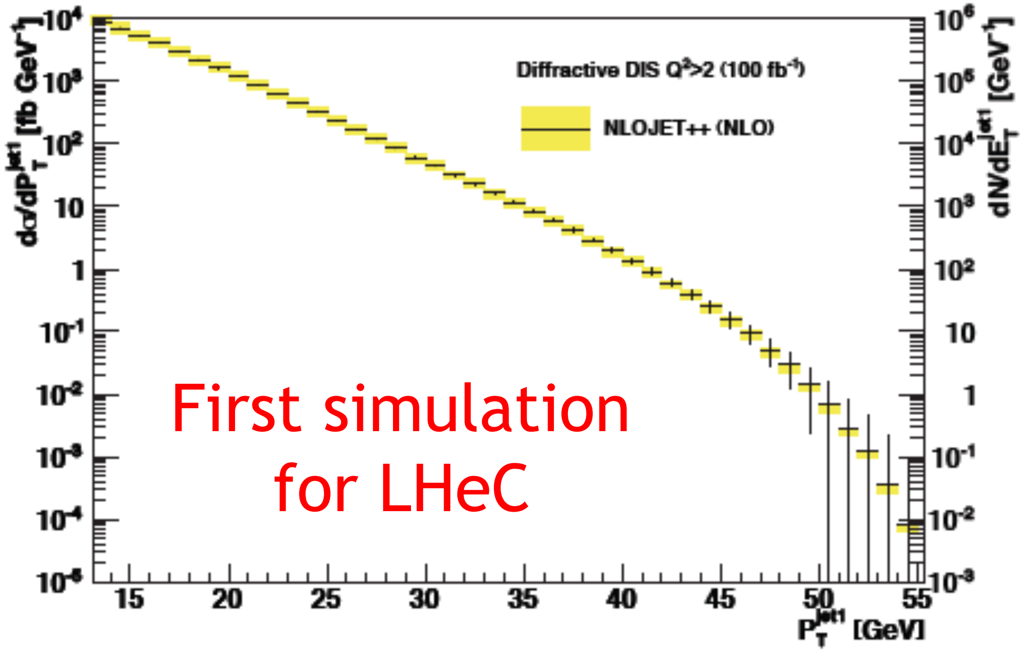
Received: date / Accepted: date

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.

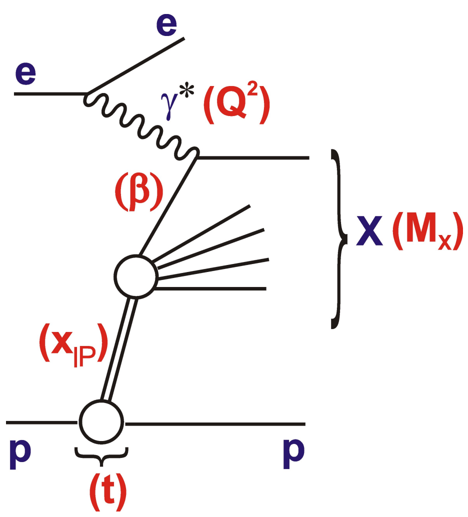


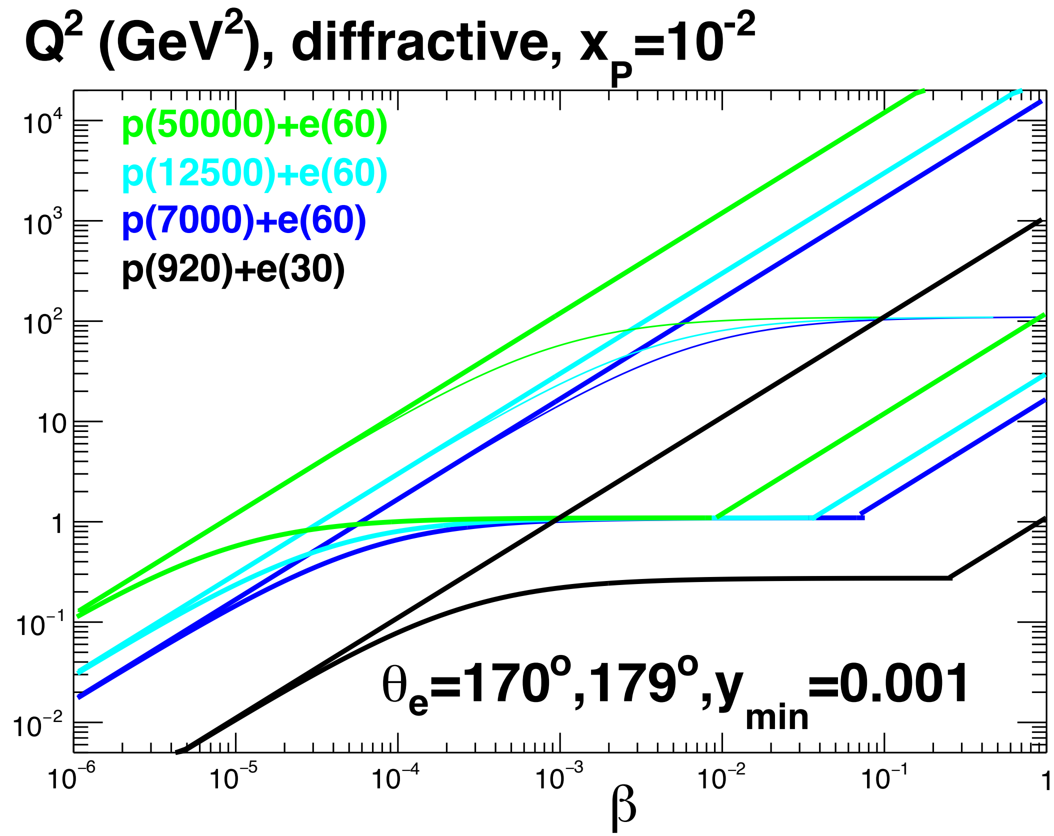
... precision
theory deserves precision
data!





Inclusive Diffraction at LHeC and FCC-eh

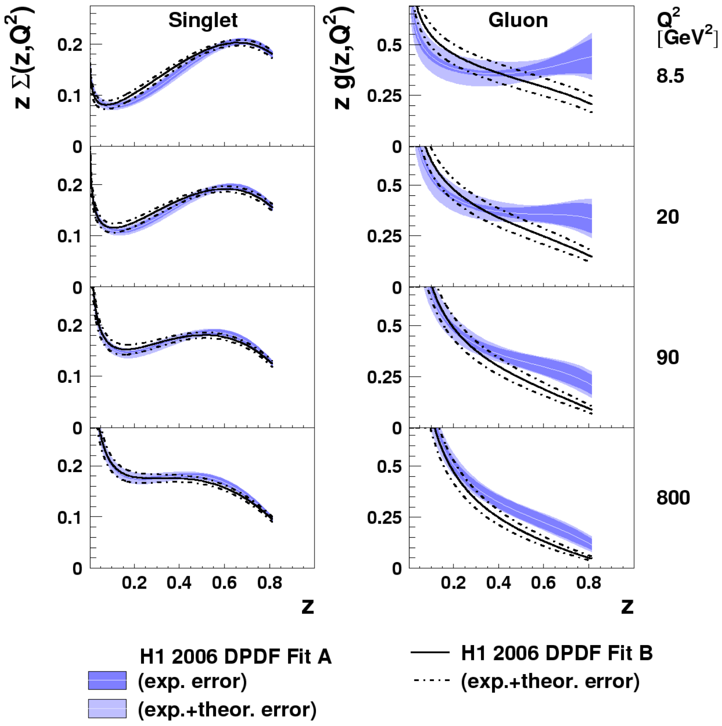




→ Diffractive structure in wider (β,Q^2) range than proton (x,Q^2) range at HERA

- 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 …

New Study (Wojtek Slominski)



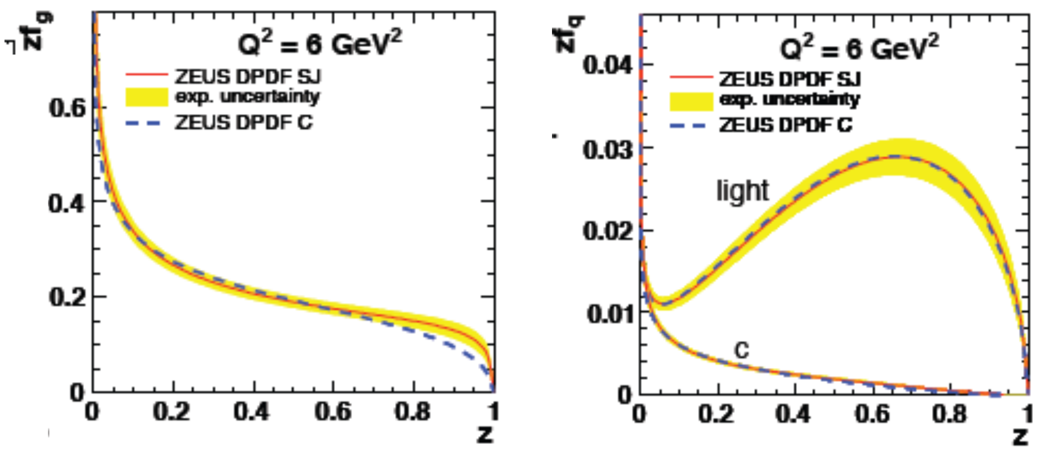
Investigate LHeC and FCC-eh potential for diffractive parton densities

- 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

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

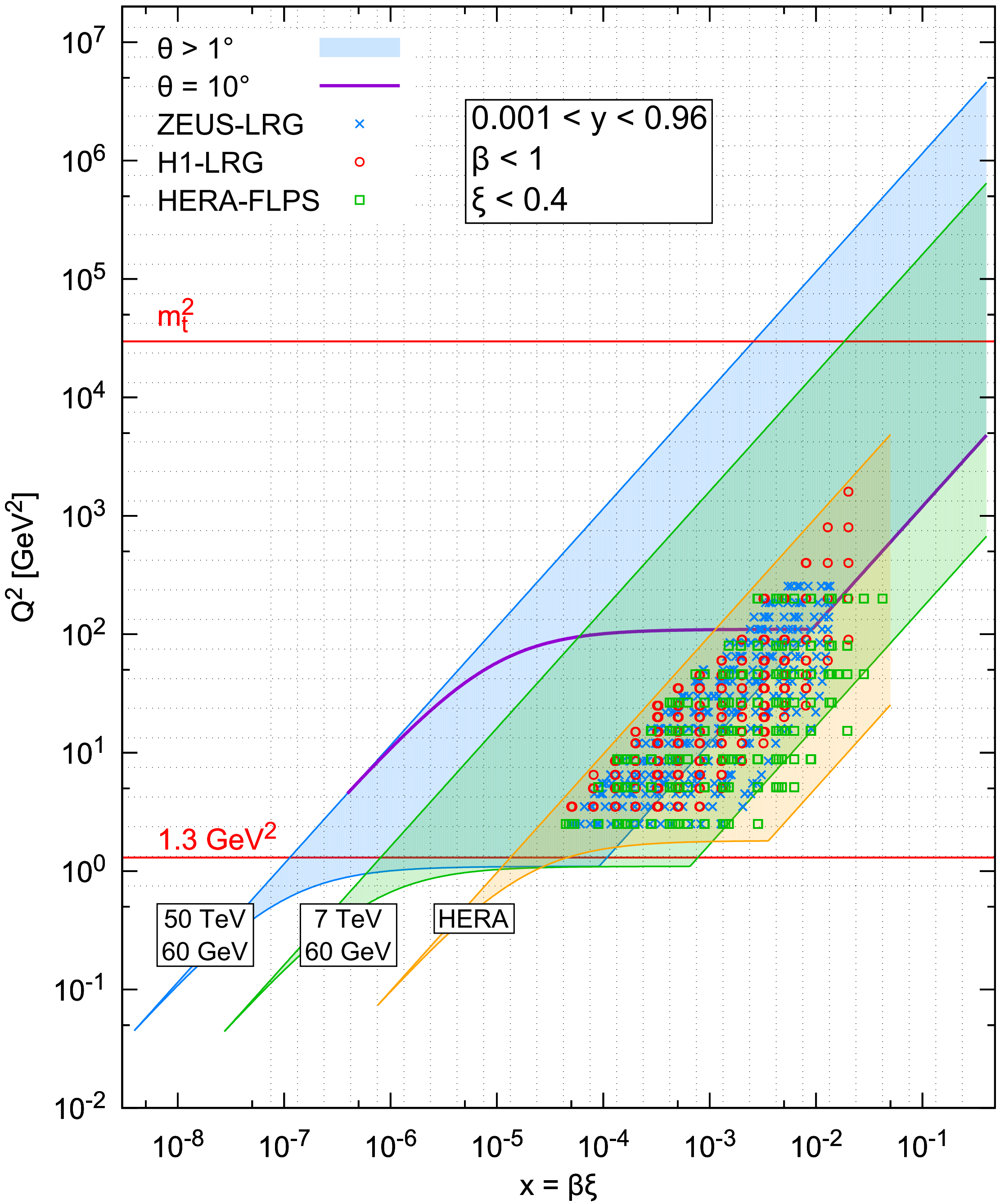
k=g,d and A_k, B_k, C_k free

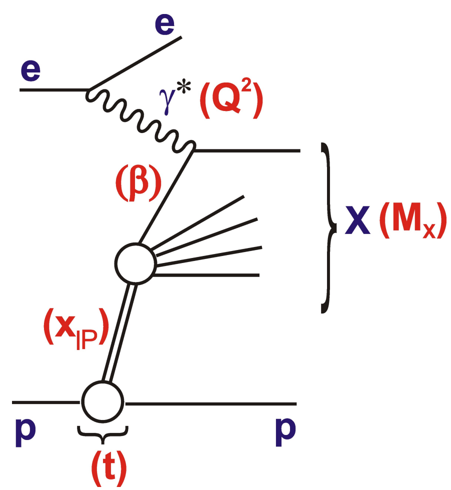
d = u = s = dbar= ubar = sbar



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

HERA Data v LHeC and FCC-eh Phase Space



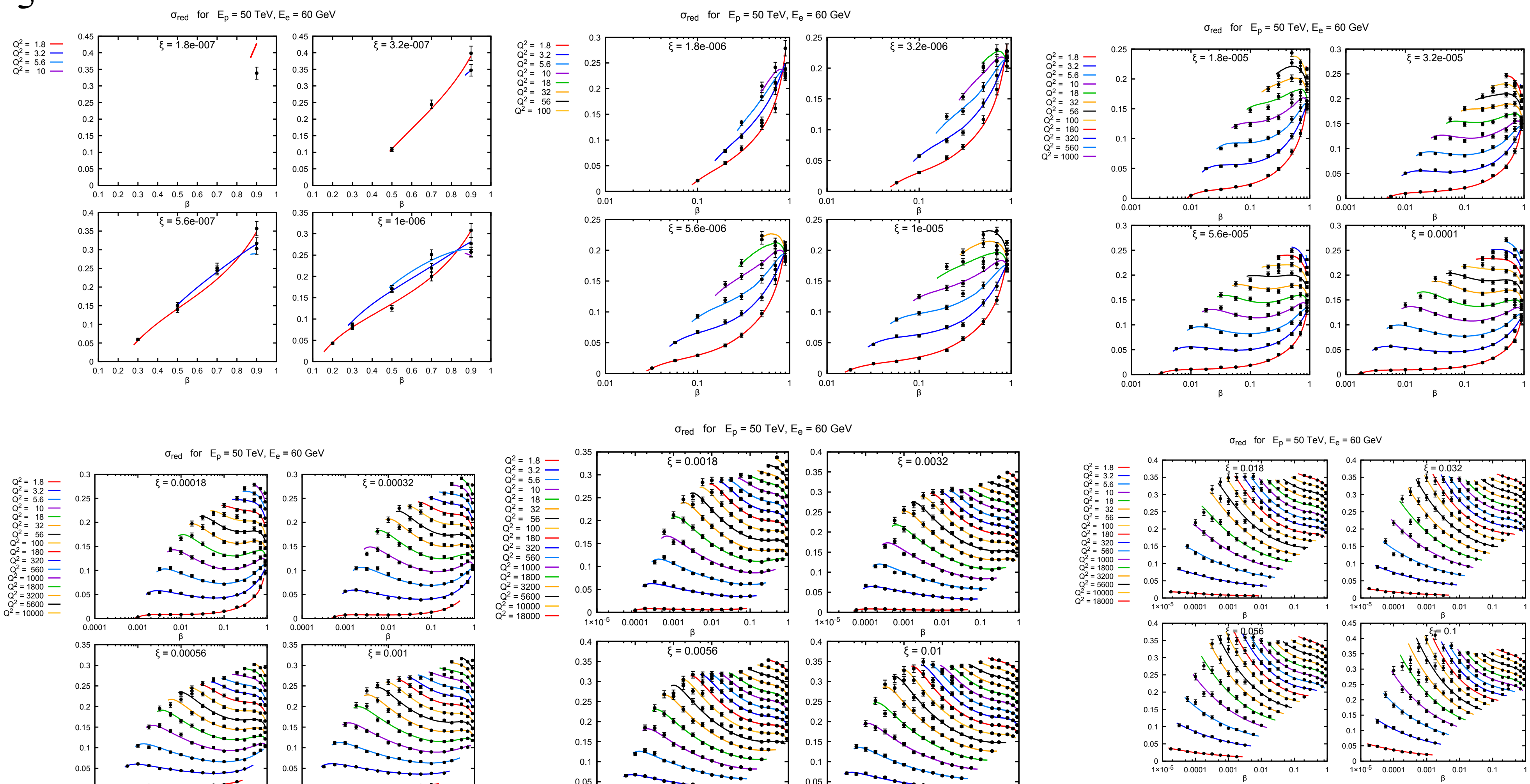


- Start with HERA data

- 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:

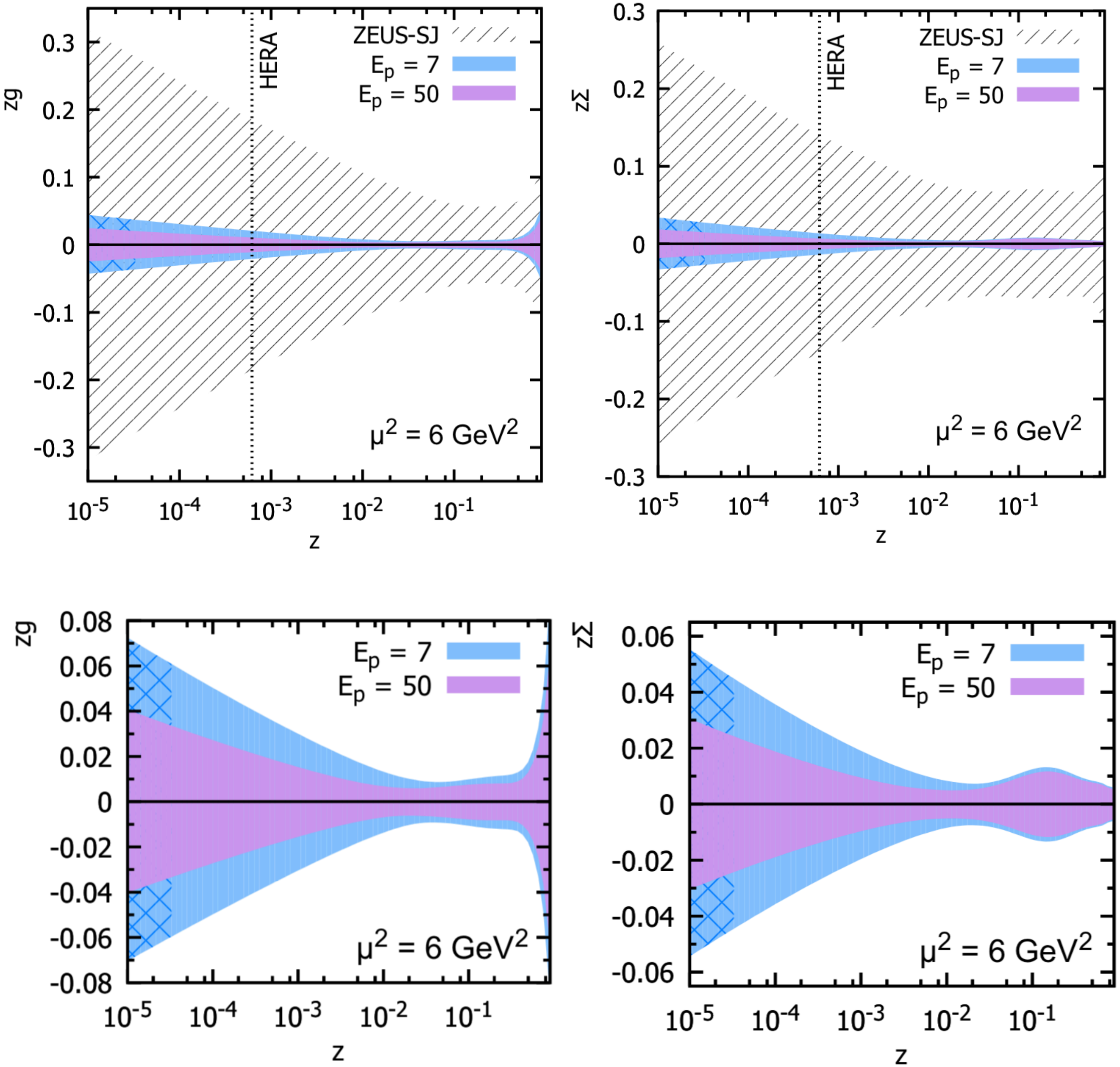
- 5% uncorrelated systematic
- 2% statistical uncertainty

Fit range:

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

Simulated DPDF Precision

Gluons | Quarks



→ 2-4% precision on gluon density at low momentum fraction

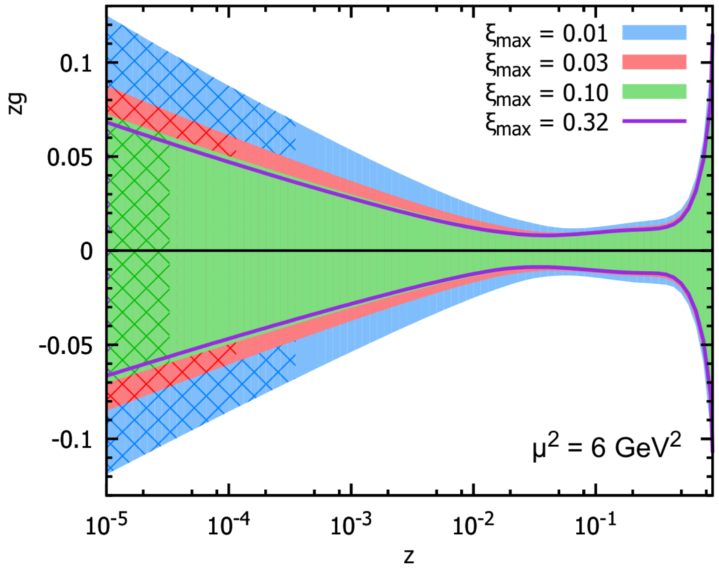
Still ongoing:

- Parameterisation bias / extrapolation uncertainties
- Sensitivity to flavour decomposition
- Sensitivity to deviations from pure DGLAP

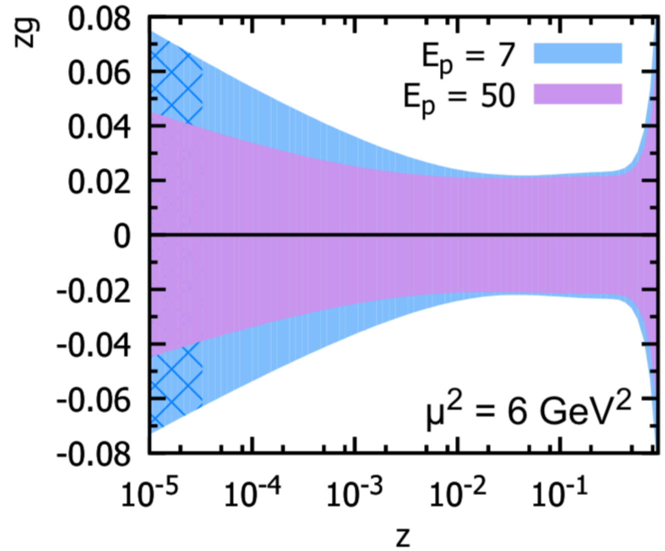
- ePb

More Detail (LHeC version, only gluon shown)

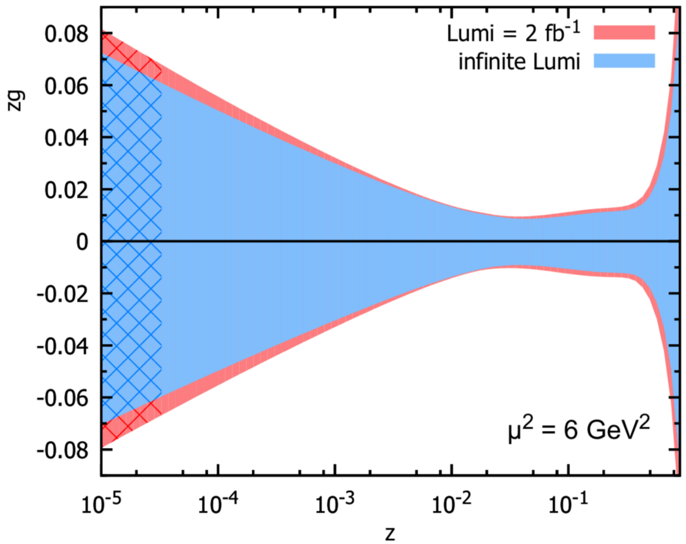
ξ_{max} dependence



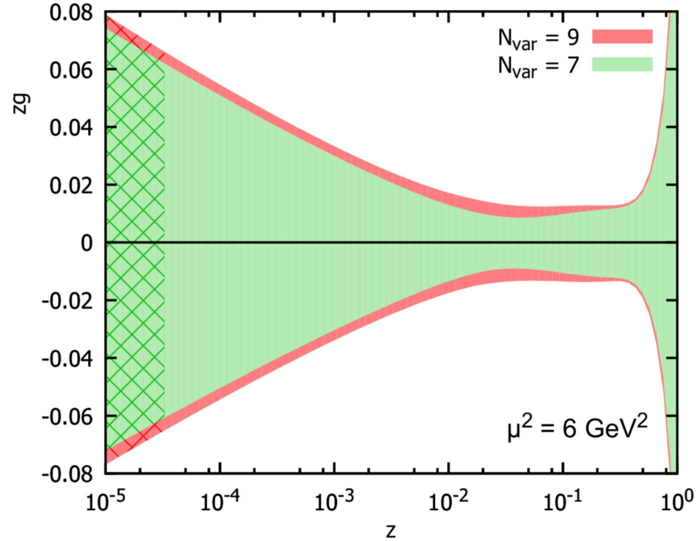
with 2% norm'n uncertainty



2fb^{-1} v infinite lumi



Free IP and IR intercepts



Summary

- Low x QCD is a frontier of the future → emergent phenomena at high parton densities and strong coupling (resummation, saturation, confinement, mass)

- LHeC / FCC-eh expands phase space to explore in detail

- Recent progress in sensitivity to diffractive PDFs

- Plenty more to do … wish list
  - → DVCS and GPD / TMD sensitivity
  - → Diffractive jets / HF at NNLO
  - → Lots of FCC-eh simulations
  - → Interface detector simulations → realistic systematics
  - → More detailed forward instrumentation design

[Thanks: Nestor Armesto, Anna Stasto, Wojtek Slominski …]