Low x LHeC and FCC-eh Studies

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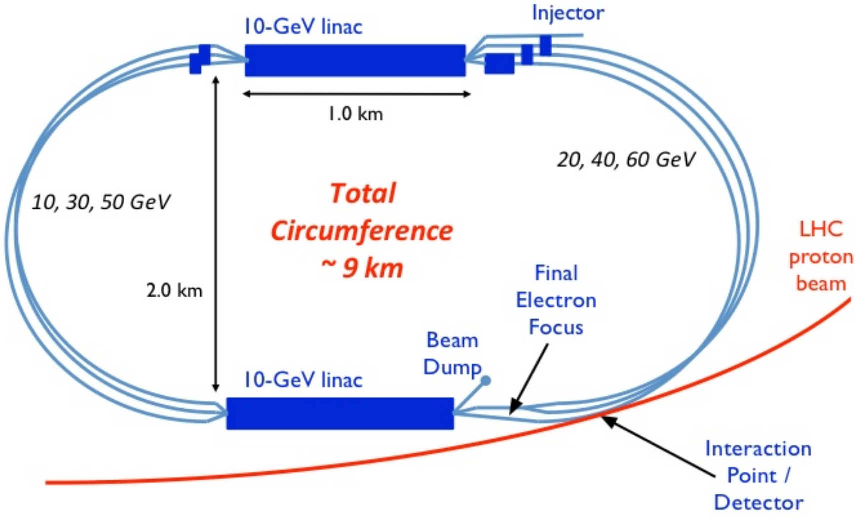
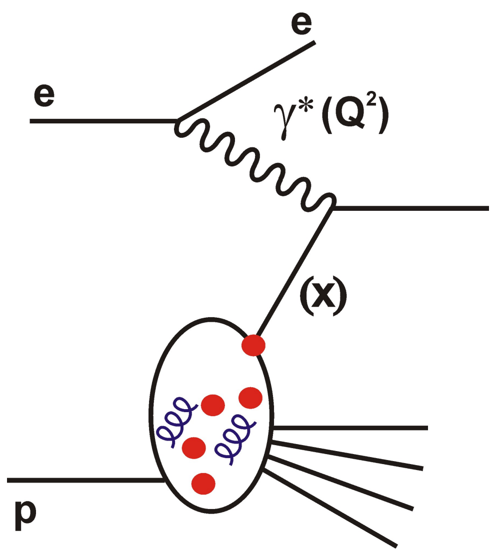


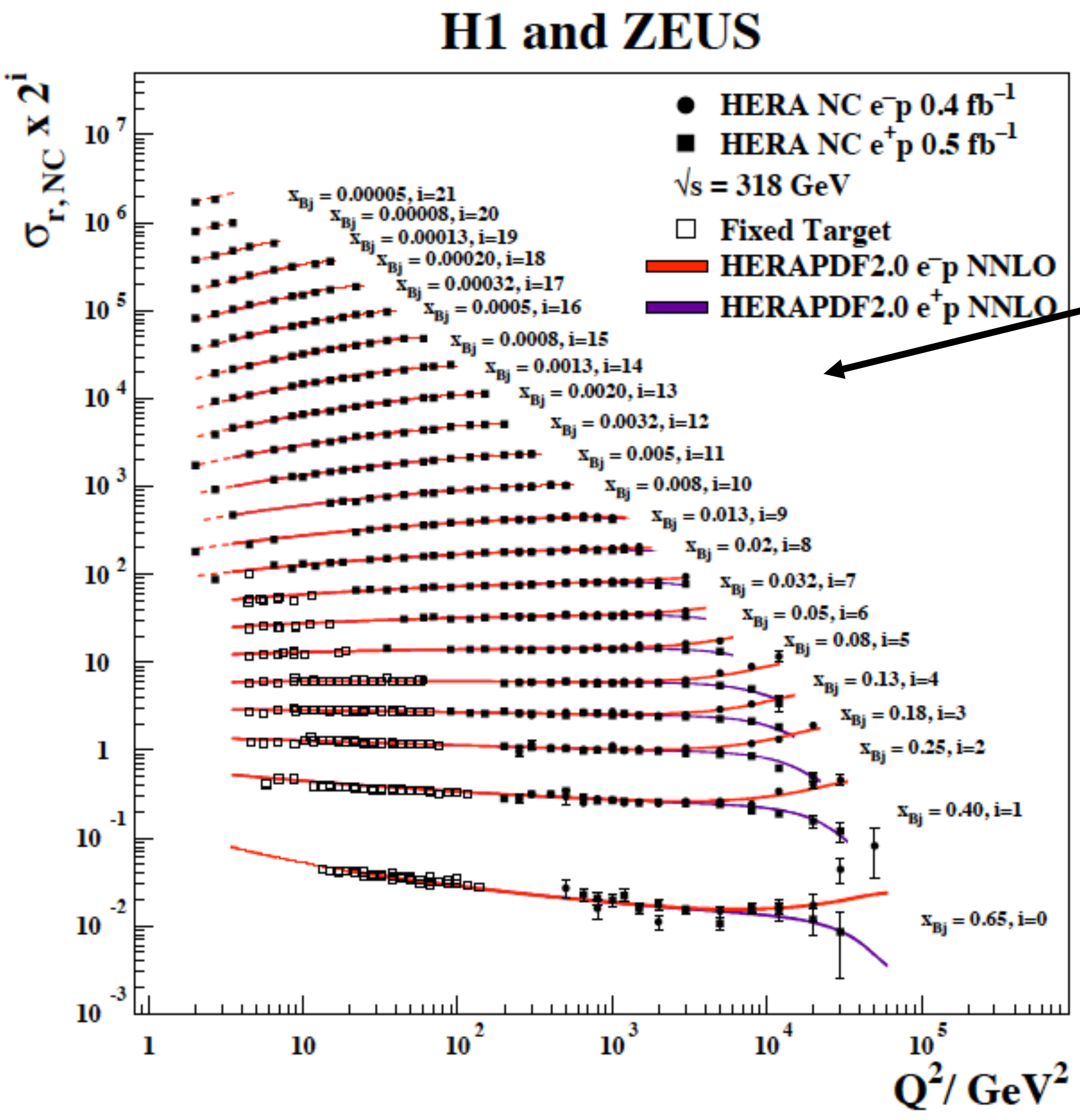
LHeC and FCC-eh Workshop

11-13 September 2017
CERN

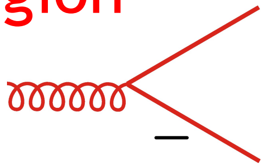


Low x Physics is Driven by the Gluon

… knowledge comes entirely from inclusive NC HERA data …



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

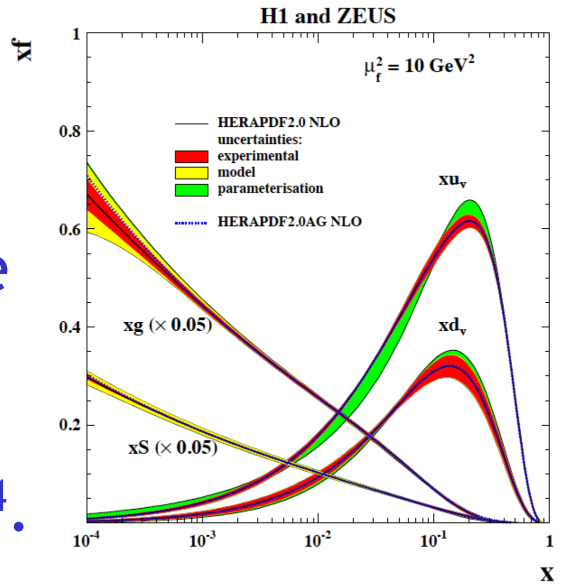


$g \rightarrow q\bar{q}$

- e.g. Prytz approx:

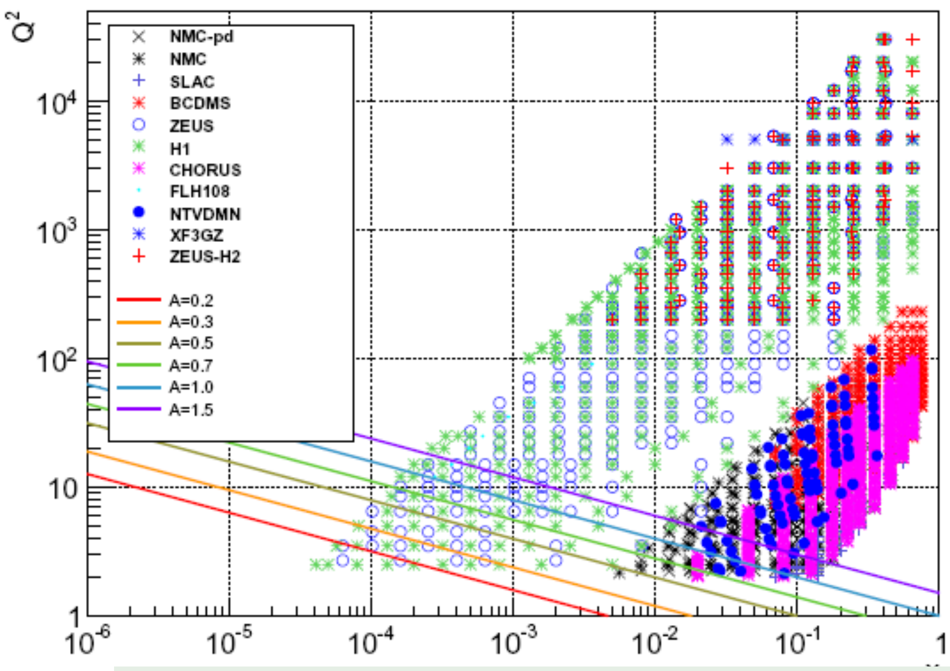
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

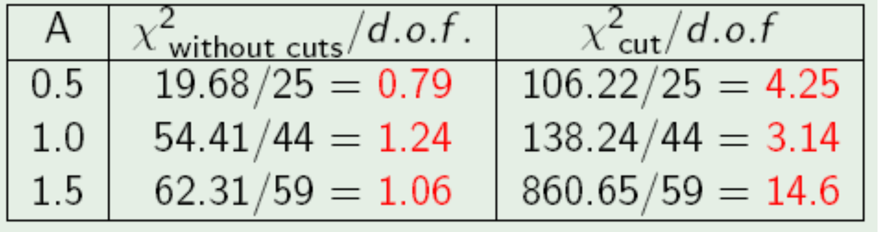
- needs lever-arm in Q^2 … reasonable precision only to $x \sim 10^{-3}/10^{-4}$.



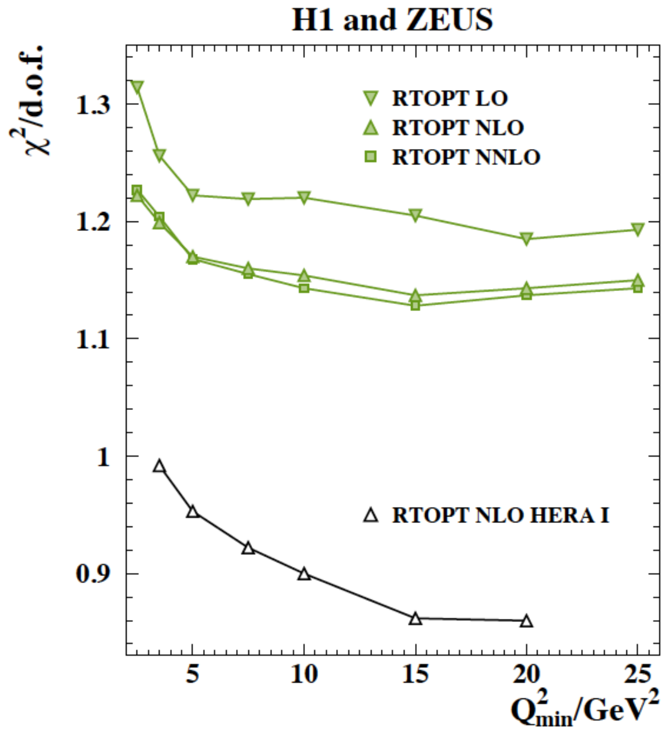
Are there Saturation Effects in low x HERA data?

e.g. NNPDF: NLO DGLAP description deteriorates when adding data in lines $Q^2 > Ax^{-0.3}$ parallel to ‘saturation’ curve in x/Q^2.



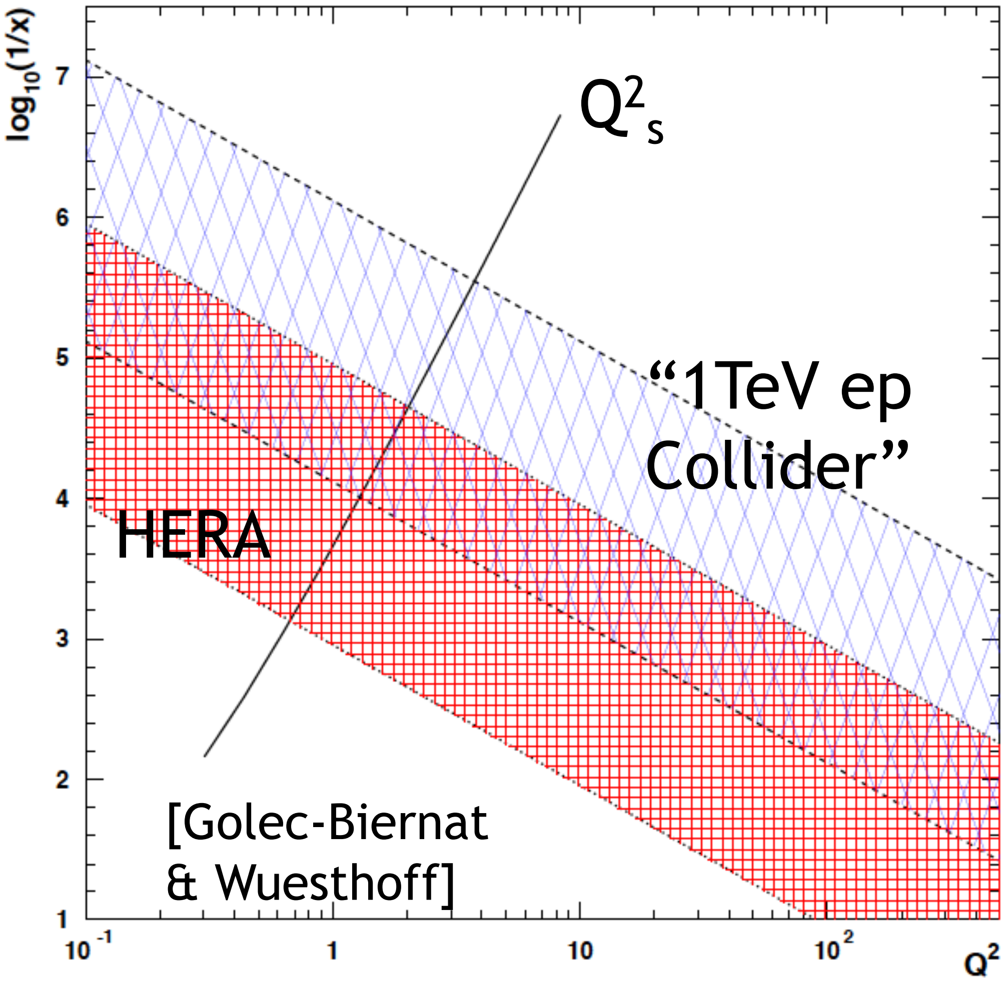


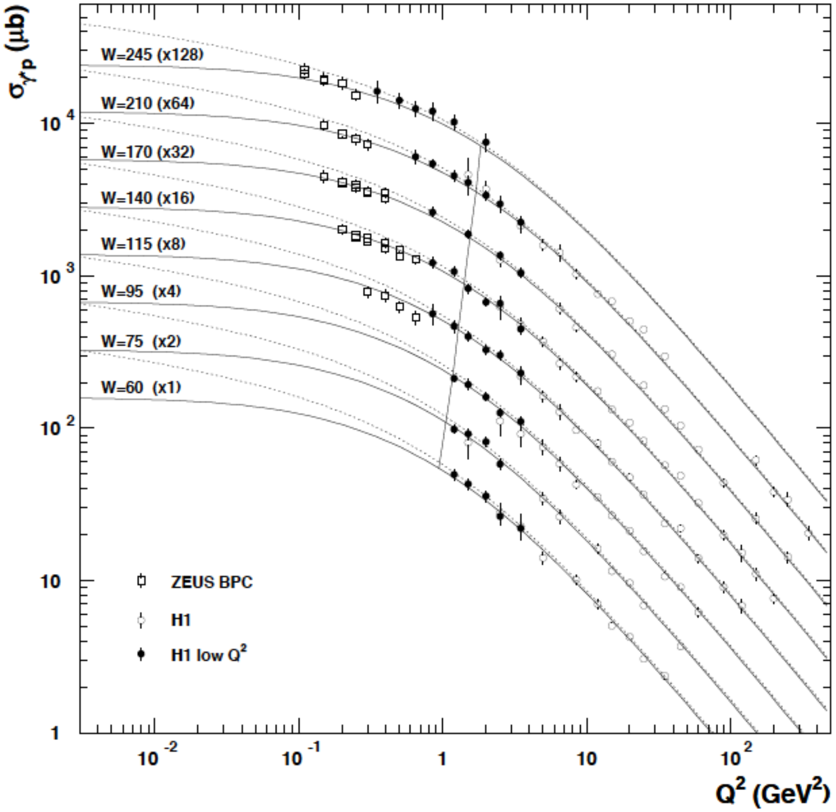
A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	$19.68/25 = 0.79$	$106.22/25 = 4.25$
1.0	$54.41/44 = 1.24$	$138.24/44 = 3.14$
1.5	$62.31/59 = 1.06$	$860.65/59 = 14.6$



Final HERA-2 Combined PDF Paper: “some tension in fit between low & medium Q^2 data… not attributable to particular x region” (though kinematic correlation) **… something probably happens, but subtle … interpretation?**

Introducing $Q^2 < 1$ GeV^2 data … and a Dipole Model with Saturation



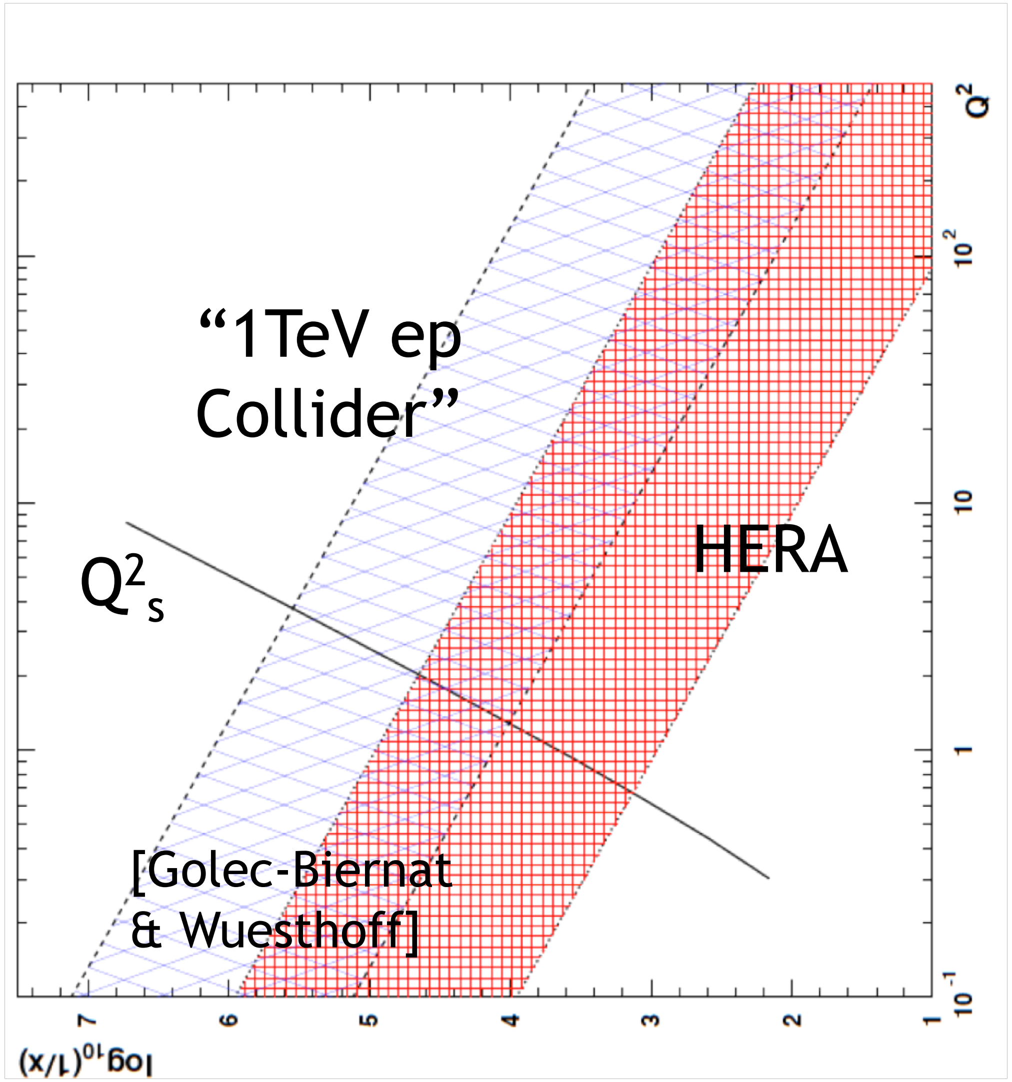


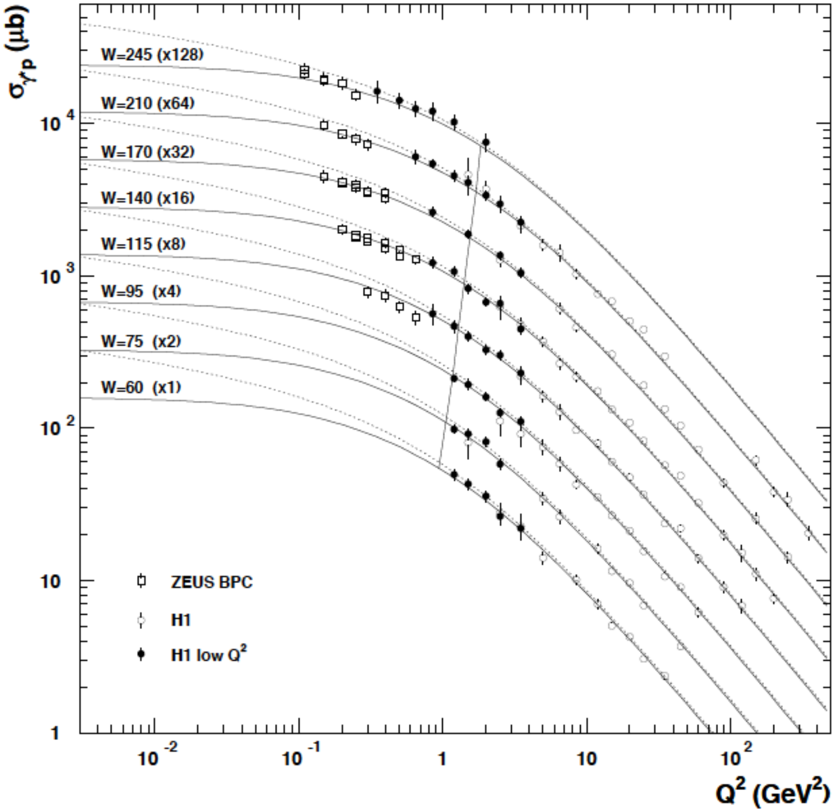
All data ($Q^2 >\sim 0.05$ GeV^2) are well fitted in (dipole) models that include saturation effects

- x dependent "saturation scale", $Q^2_s(x)$

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

Introducing $Q^2 < 1$ GeV^2 data … and a Dipole Model with Saturation



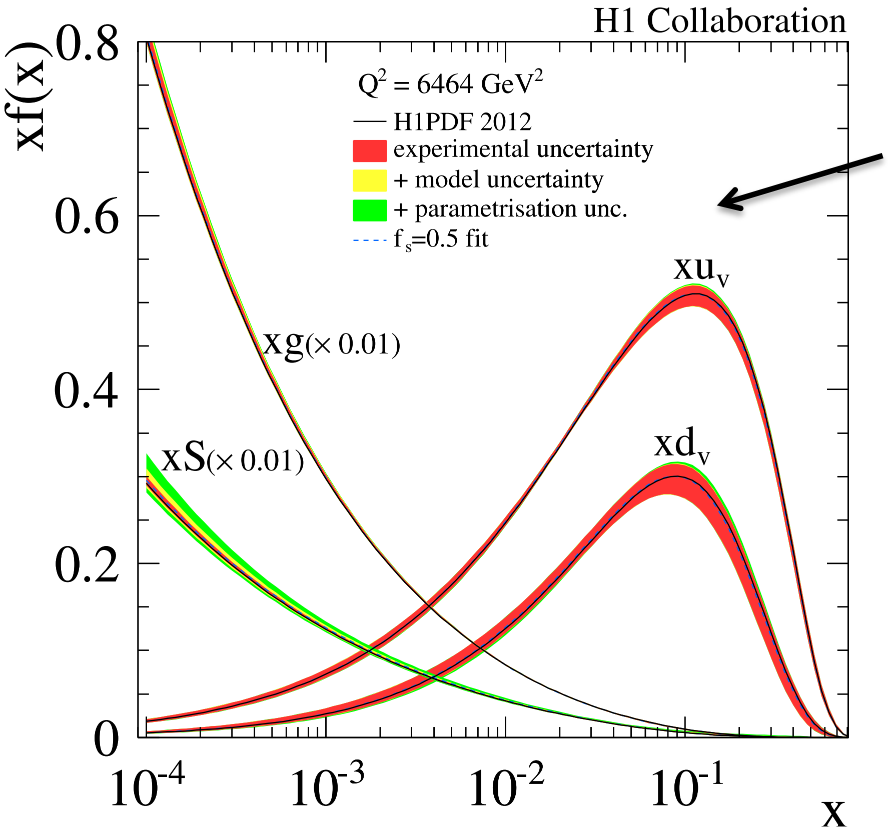


… at HERA, Q^2_s doesn’t get above about 0.5 GeV^2

→Saturation may have been observed at HERA … well described by CGC+dipoles

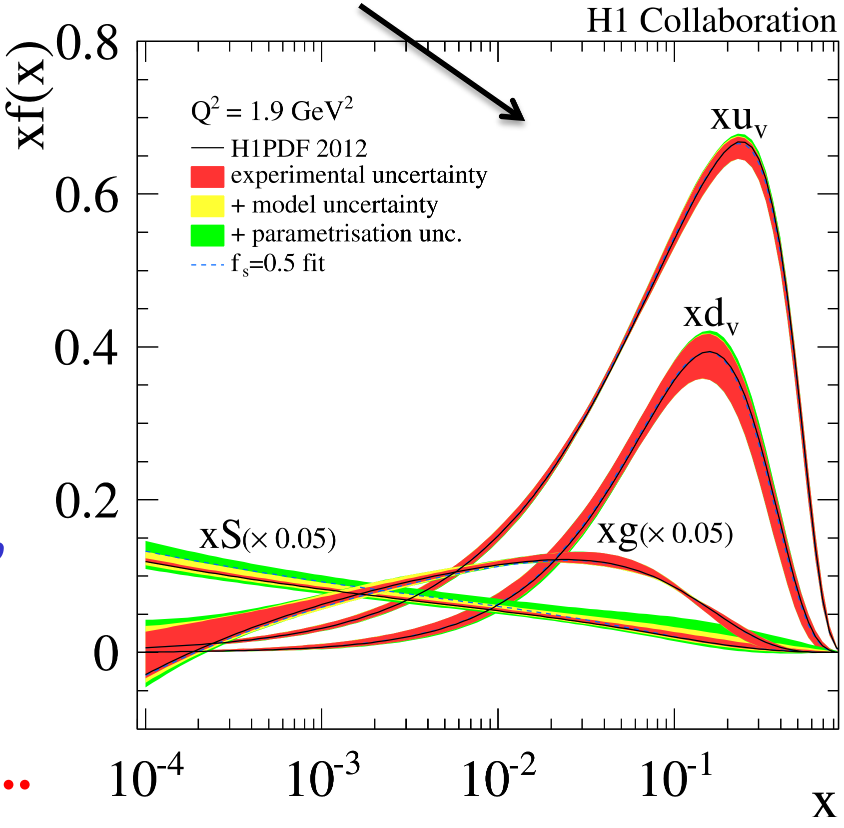
→***Gluon*** sat^n not observed (and may not be in inclusive ep in foreseeable future)

The Gluon Density at Scales other than 10GeV^2



- Electroweak scale ~ M_Z^2 (as relevant to precision LHC physics) … gluon rise gets sharper …

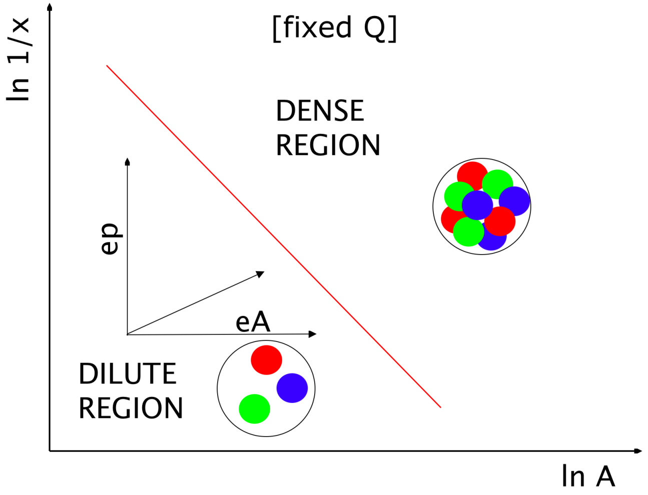
- Starting scale ~ 1.9 GeV^2 (gluon close to 0 in pure DGLAP approach … and coupling not so weak!)



- Saturating hadrons with a small number of (“large”) gluons?
- Alternative language (dipole models, gluons not degrees of freedom)?

… Phase space is vital for a clean partonic investigation of saturation …

LHeC: Accessing saturation region at large Q^2



LHeC delivers a 2-pronged approach:

Enhance target `blackness' by:

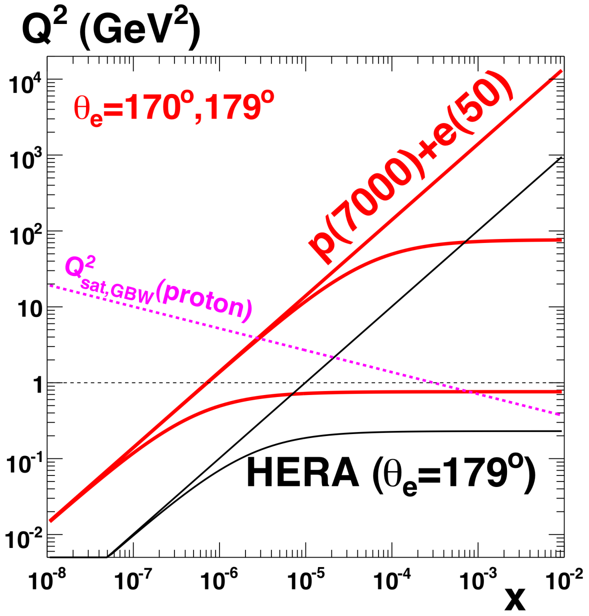
1) Probing lower x at fixed Q^2 in ep

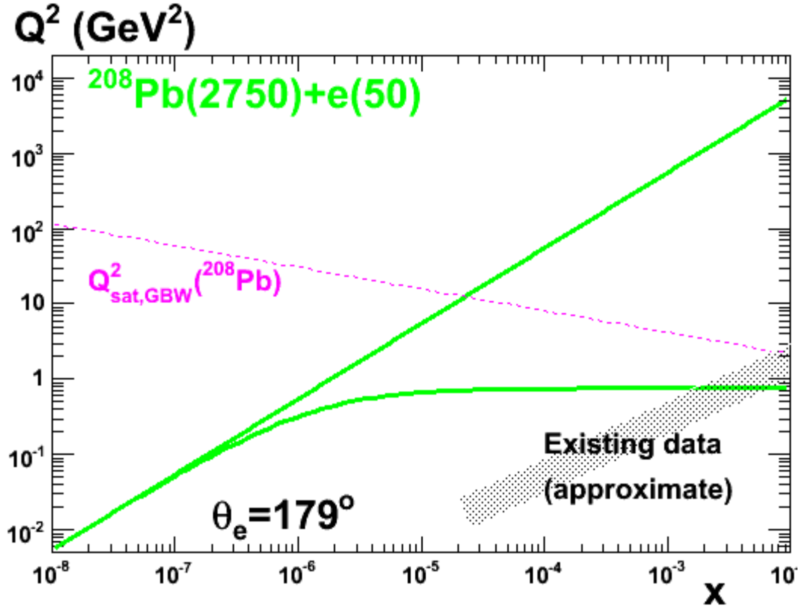
[evolution of a single source]

2) Increasing target matter in eA

[overlapping many sources at fixed kinematics …

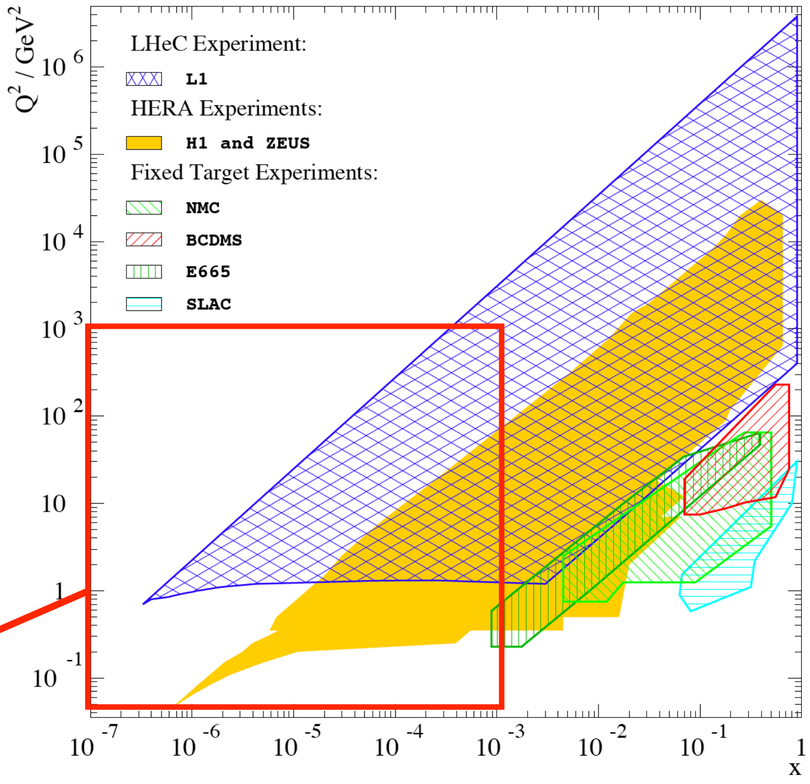
Density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in x]





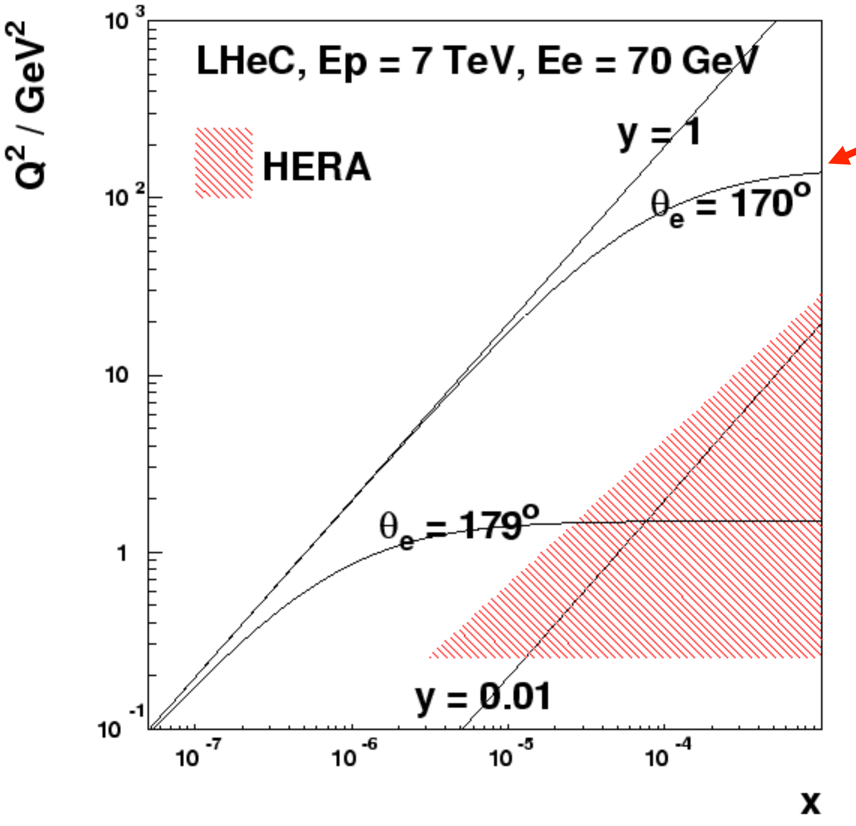
… Reaches saturated region in both ep & eA inclusive data according to models

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°

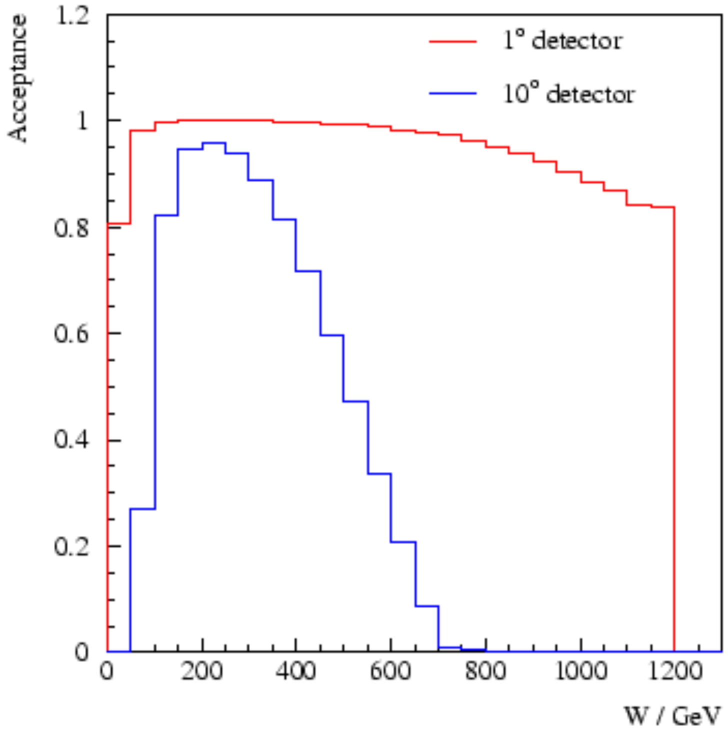


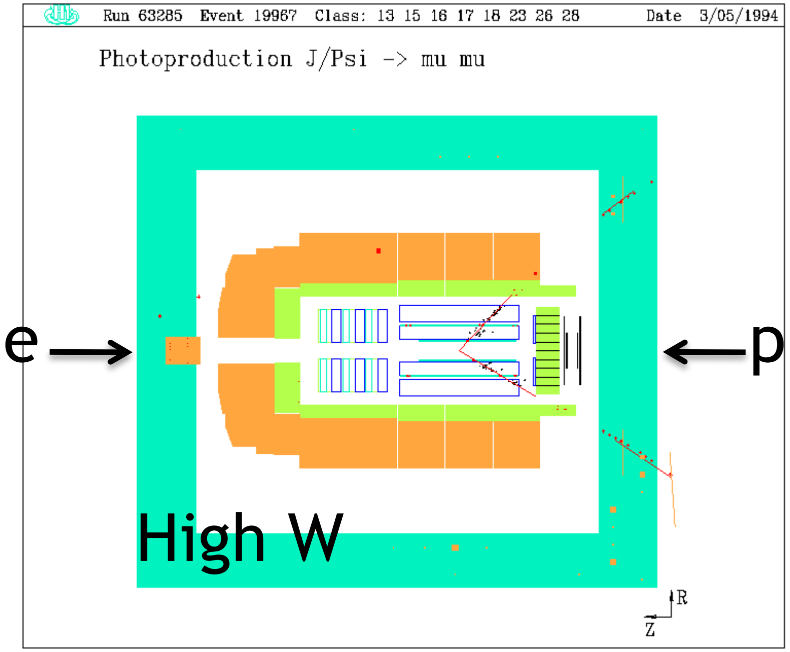
Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, Mueller-Navelet jets, maximise acceptance for new massive particles …

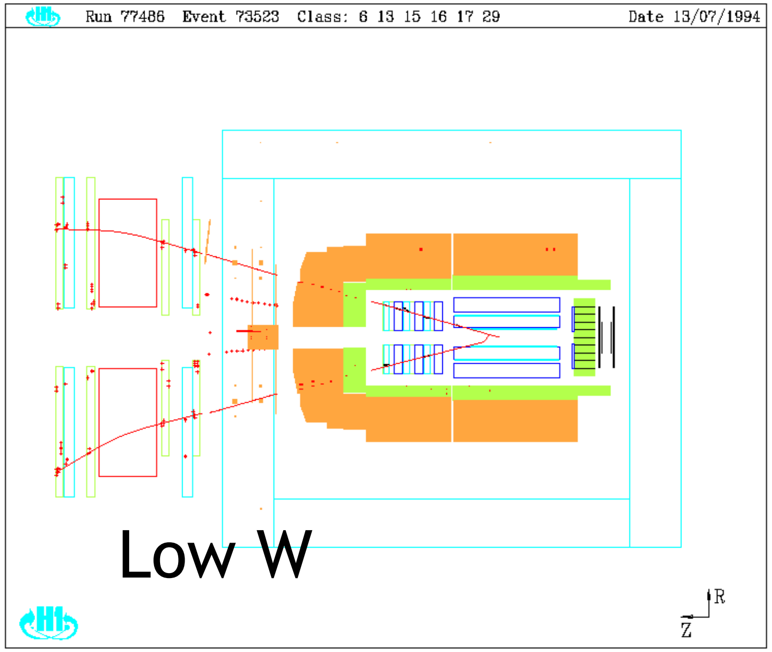
Elastic J/Ψ Kinematics (example from LHeC)

- 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



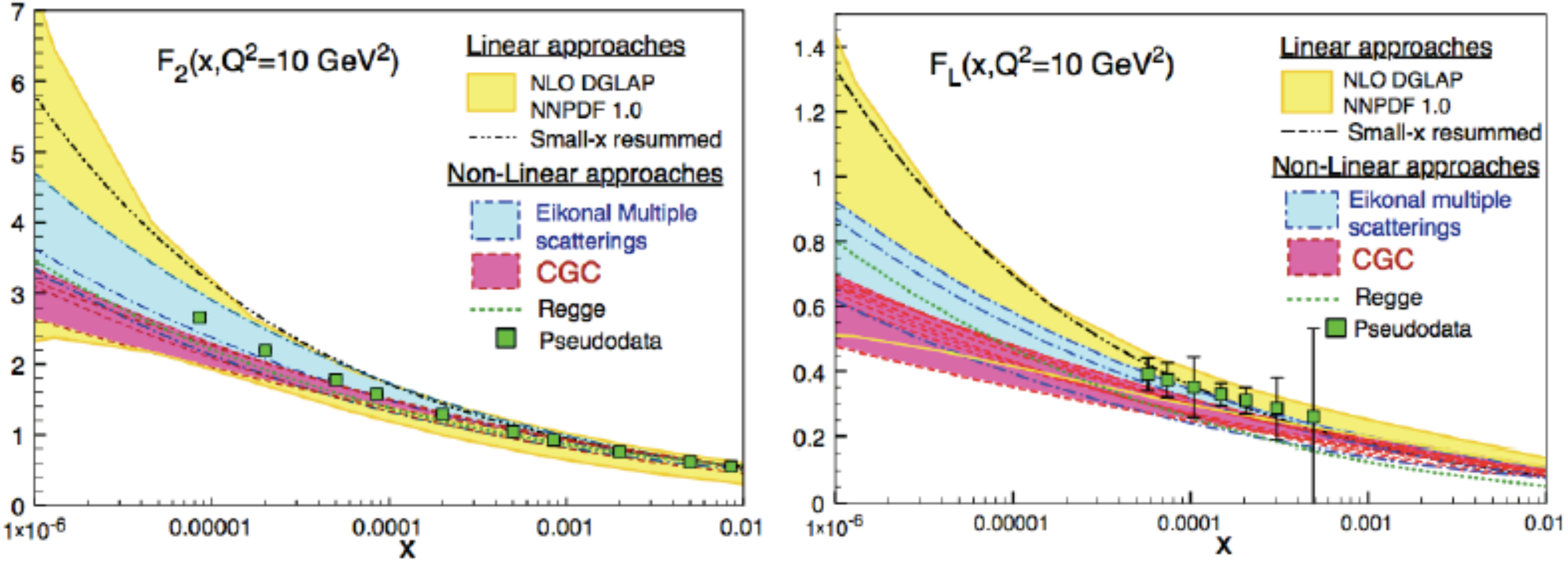




LHeC Sensitivity to Different Saturation Models

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

F_2 and F_L pseudodata at Q^2 = 10 GeV^2



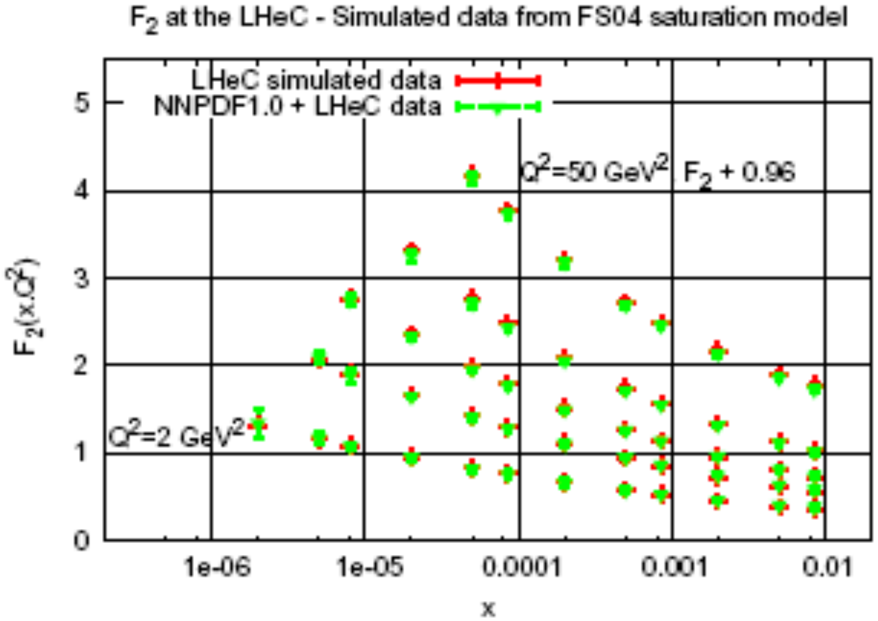
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

… but can sat^n effects hide in standard fit parameterisations?

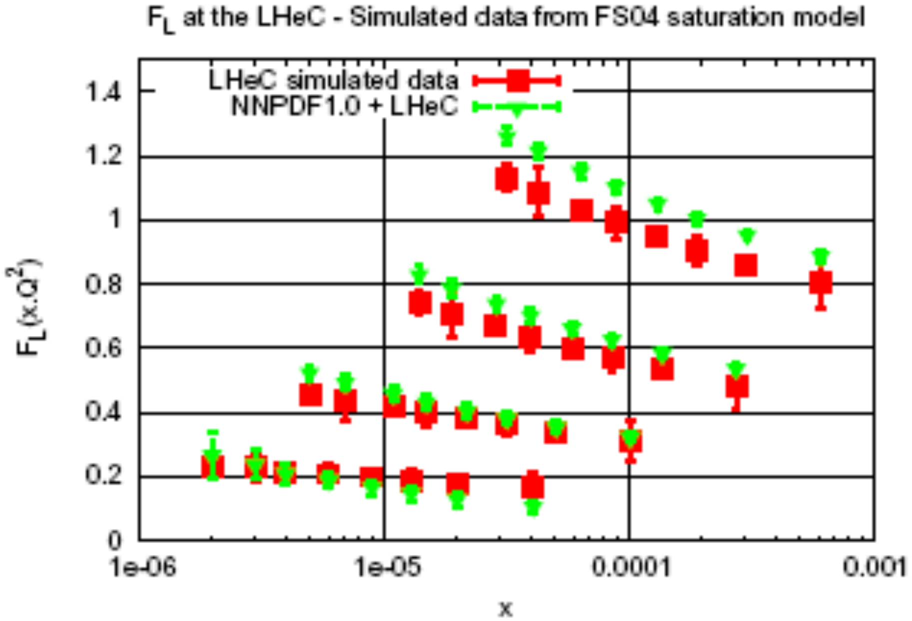
Can Parton Saturation be Established in ep @ LHeC?

Simulated LHeC F_2 and F_L data based on an (old) dipole model containing low x saturation (FS04-sat)… Try to fit in NLO DGLAP

… NNPDF (also HERA framework) DGLAP QCD fits work OK if only F_2 is fitted, but cannot accommodate saturation effects if F_2 and F_L both fitted



F_2 at the LHeC - Simulated data from FS04 saturation model

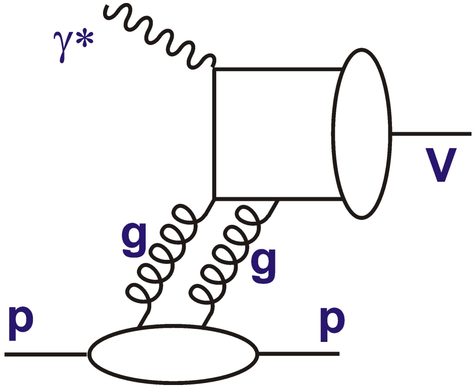


F_L at the LHeC - Simulated data from FS04 saturation model

- 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

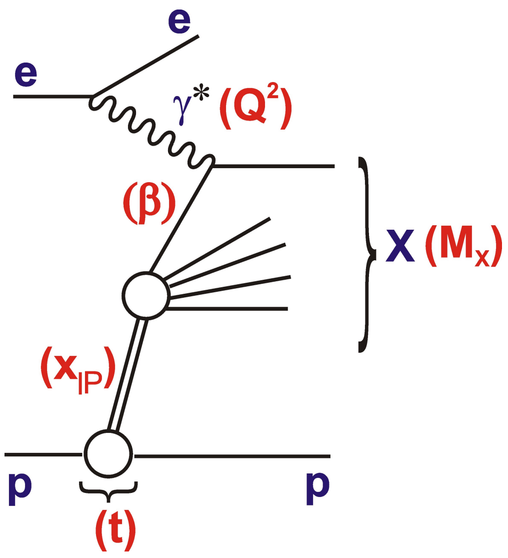
Exclusive / Diffractive Channels and Saturation

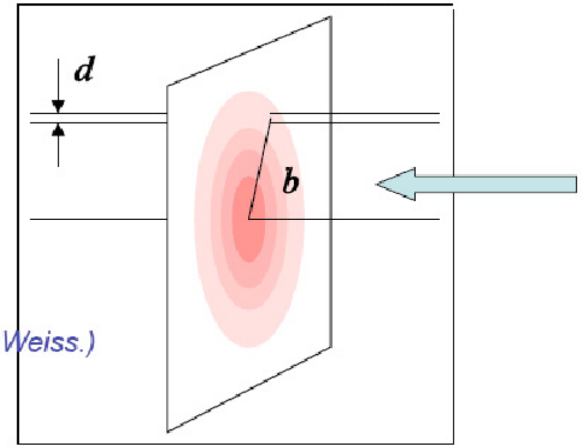
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)



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

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





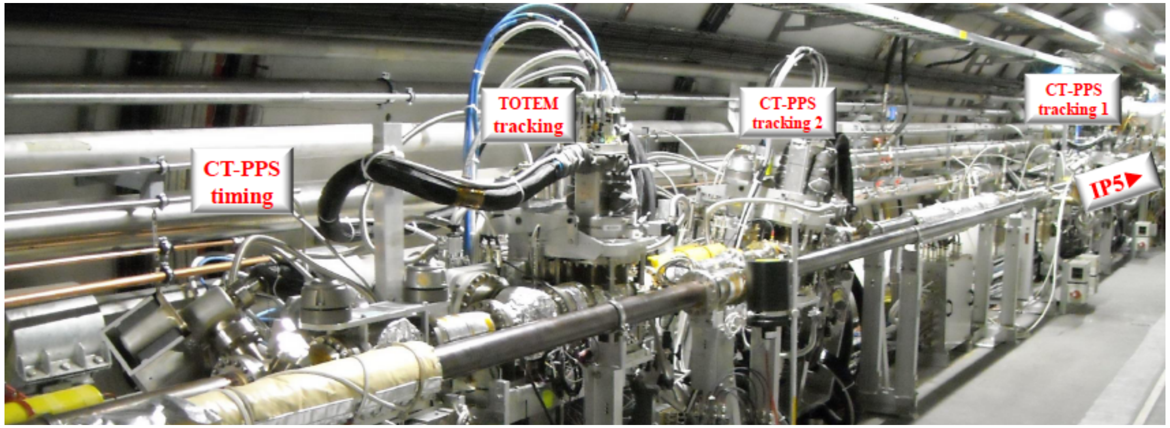
Central black region growing with decrease of x.

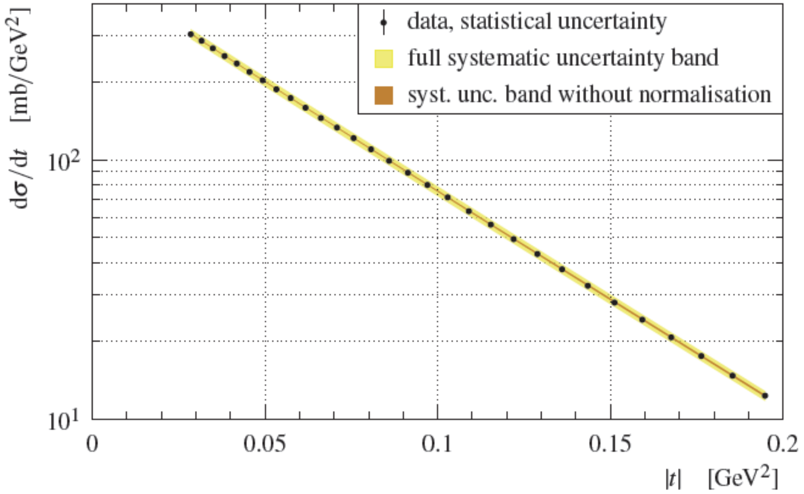
(figure from C. Weiss.)

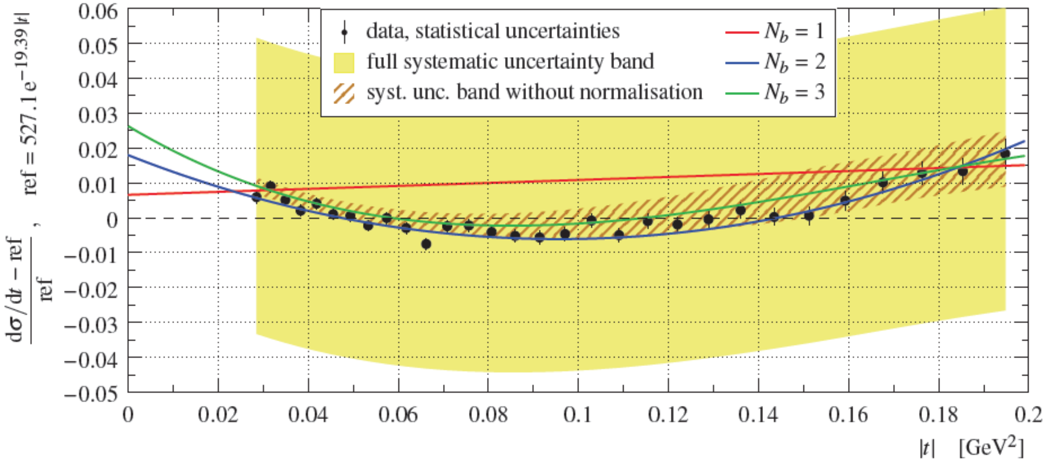
Proton Spectrometers Come of Age

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

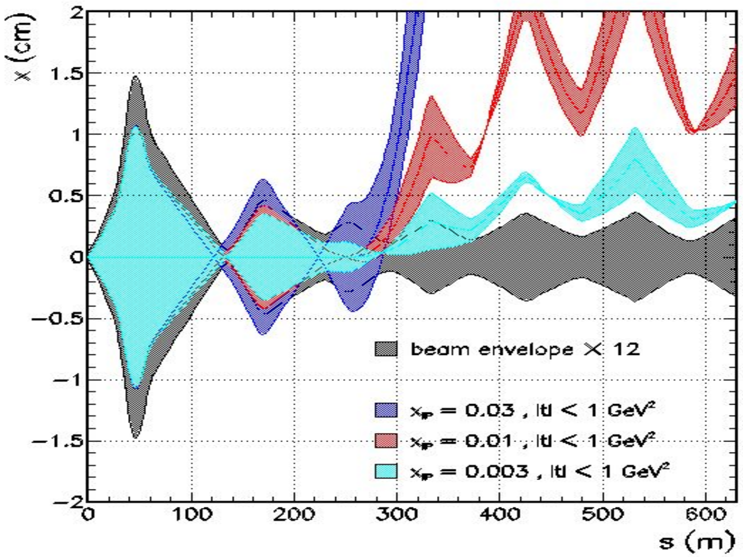
e.g. TOTEM operates 14(?) pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential term in elastic t dependence …





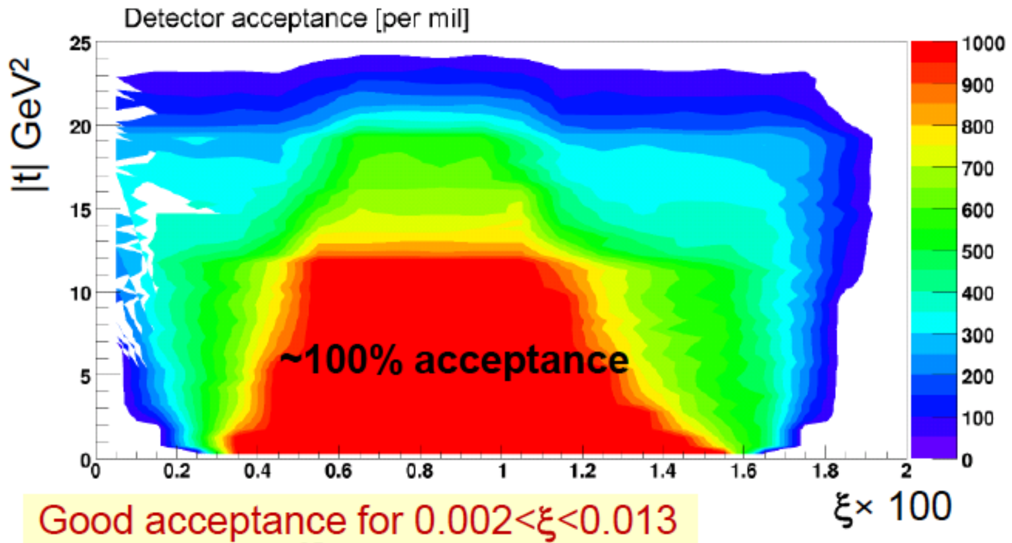


Design for LHeC Forward Proton Spectrometers



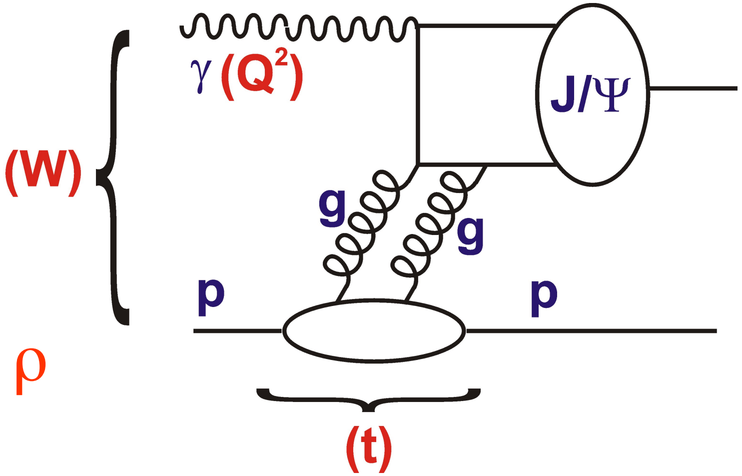
We should ensure full acceptance Roman pot forward detector systems are integrated into our future facility designs from outset

- eg 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



Good acceptance for 0.002<ξ<0.013

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

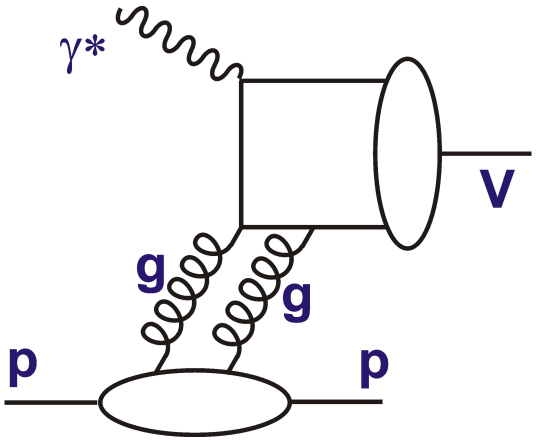
- Clean experimental signature (just 2 leptons)

- 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: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

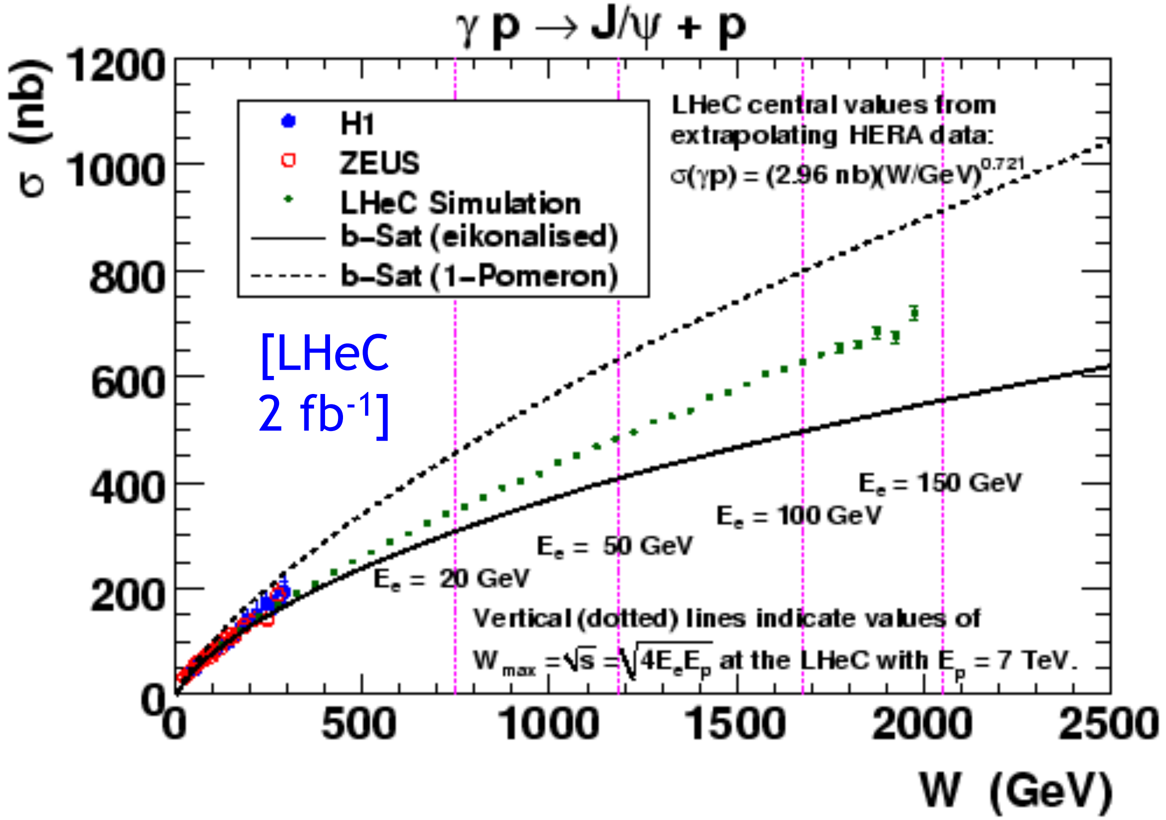
- Simulations (DIFFVM) of elastic J/Ψ → μμ photoproduction
→ scattered electron untagged, 1° acceptance for muons
(similar method to H1 and ZEUS)

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



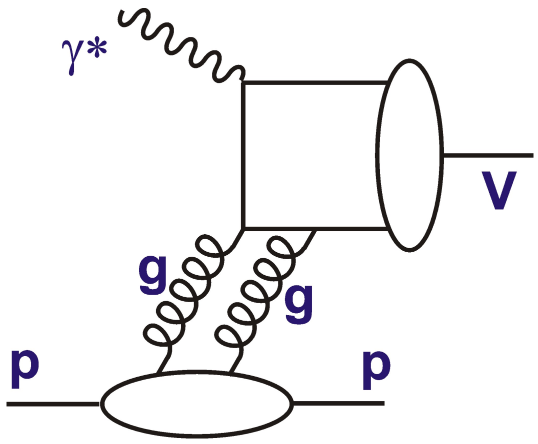
[LHeC 2 fb^{-1}]

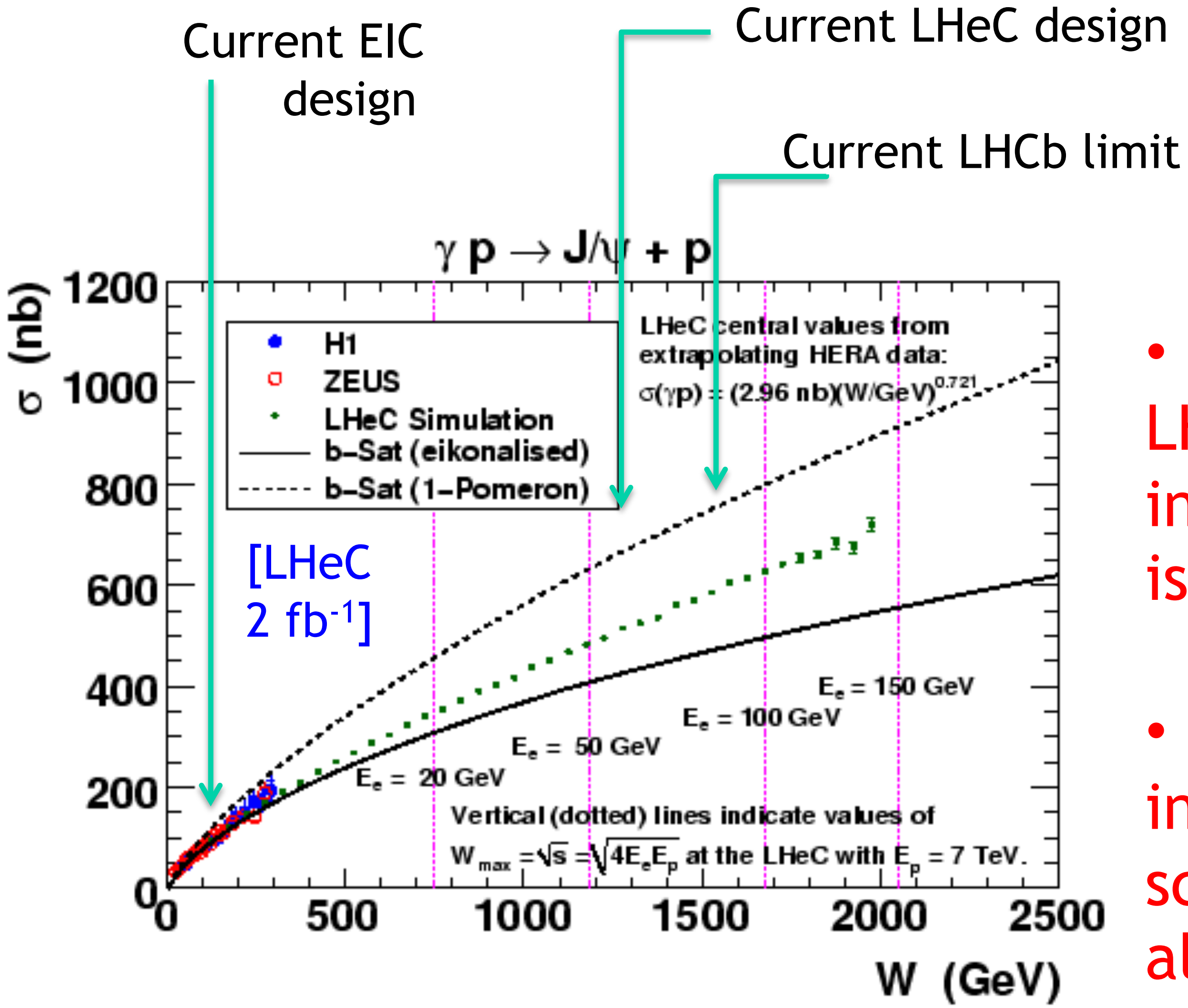
- Significant non-linear effects expected in LHeC kinematic range

… '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

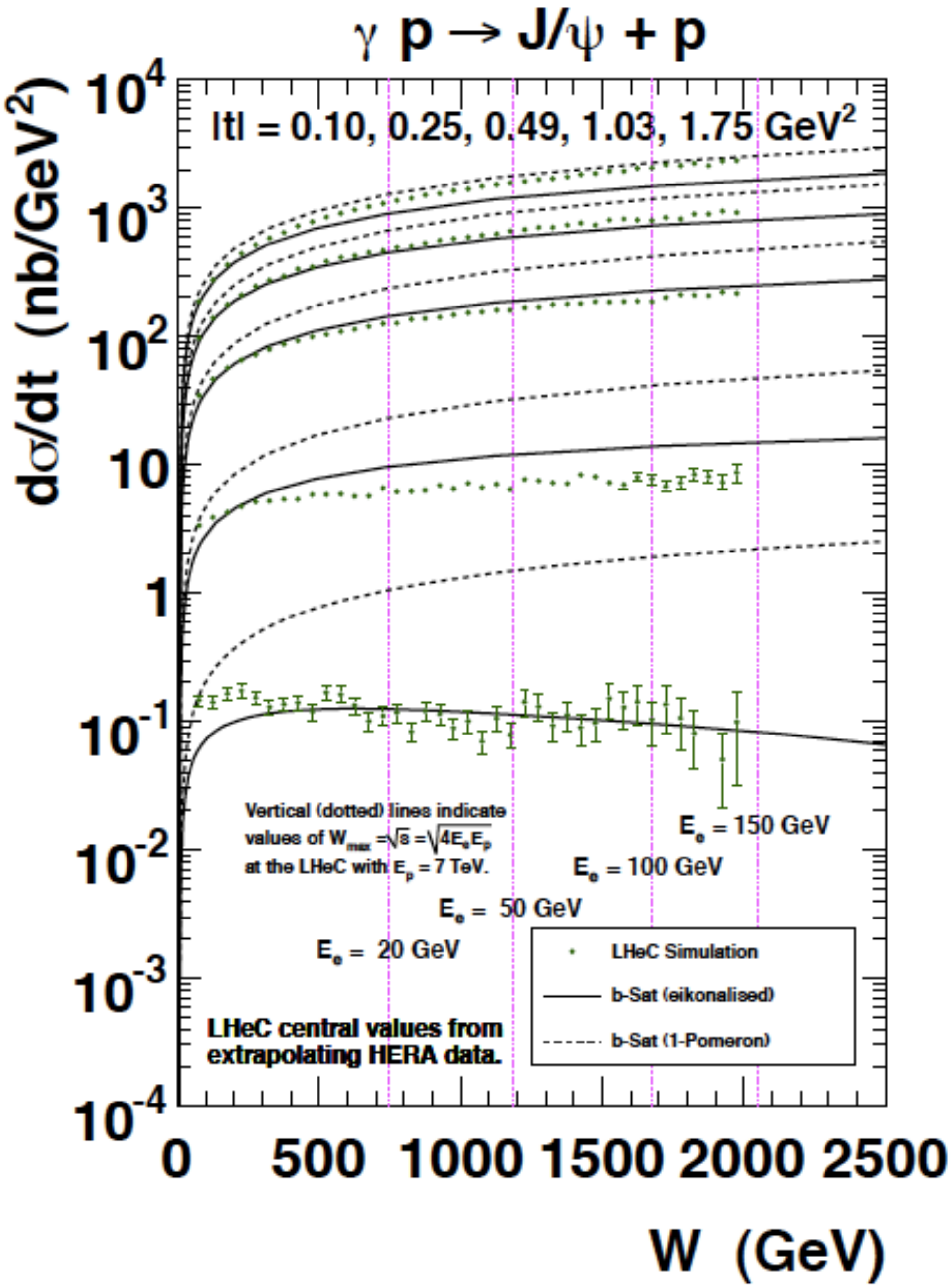
Current LHCb limit

[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).

t Dependence of Elastic J/ψ at LHeC

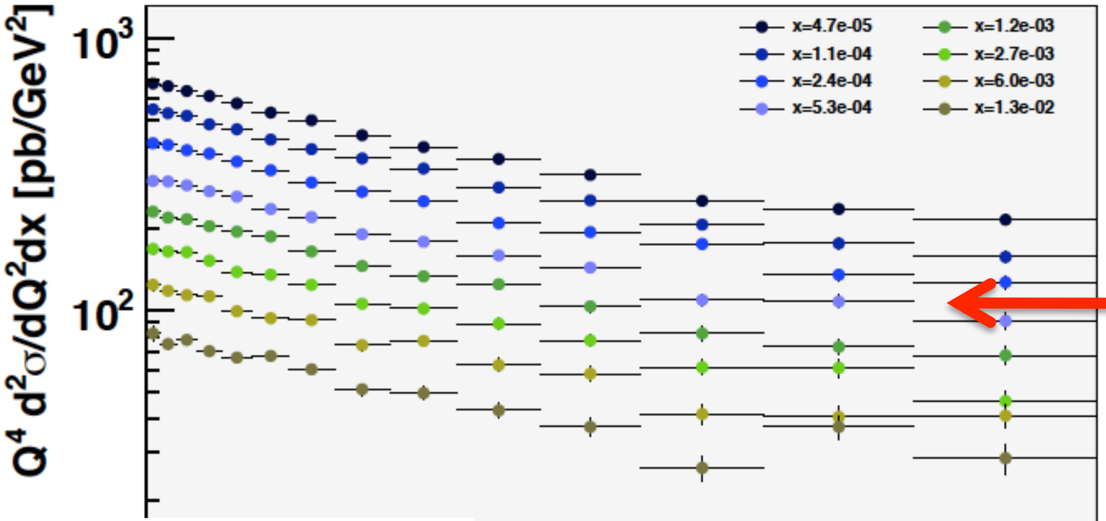


- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV² and enhances sensitivity to saturation effects

- Measurements also possible in multiple Q^2 bins

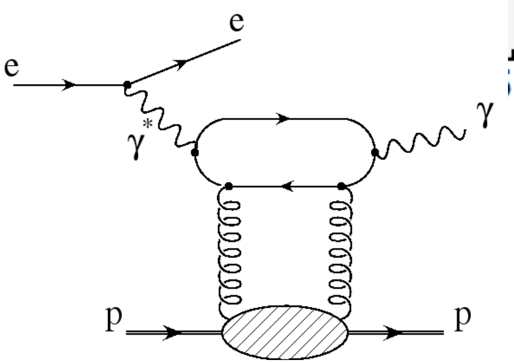
… see also eA (later talks)

DVCS
(MILOU simulation)

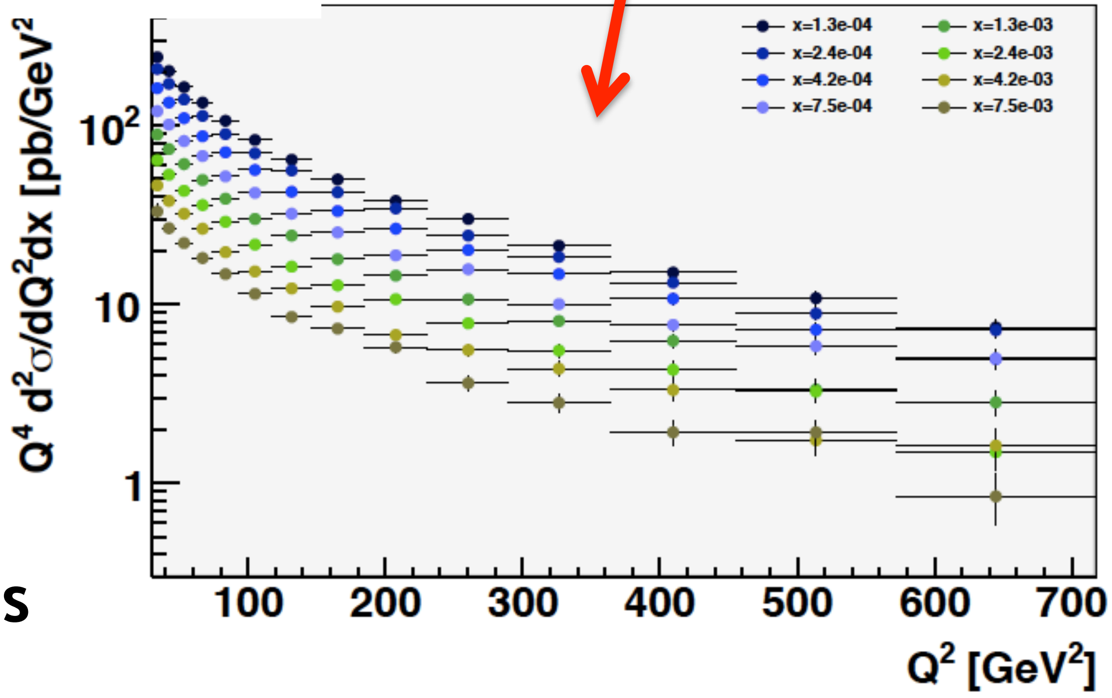


$1\ \text{fb}^{-1}$, $E_e = 50$ GeV,
1° acc'nce, $p_T^{\gamma} > 2$ GeV

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

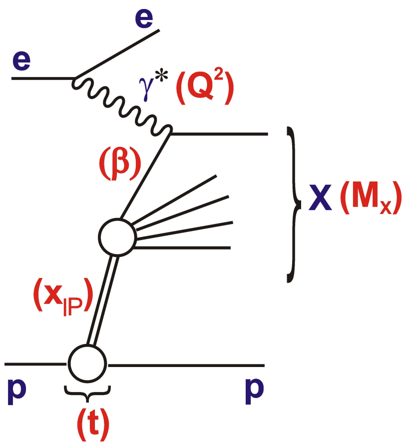


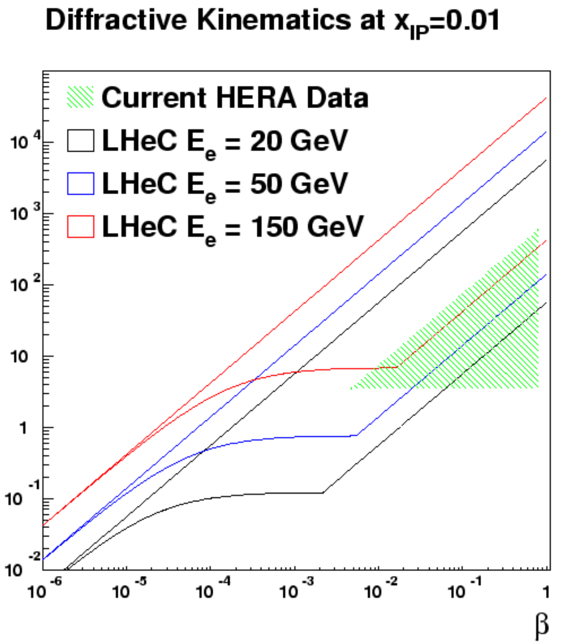
Precise data with
W → 1 TeV, $Q^2 \rightarrow 700$ GeV^2,
$x \rightarrow 5.10^{-5}$



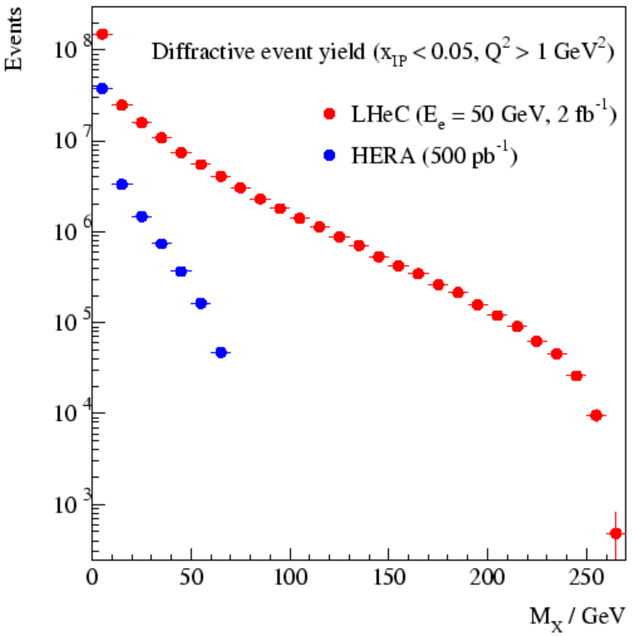
Still to do:
- Beam charge asymmetries
- Sensitivity to GPDs

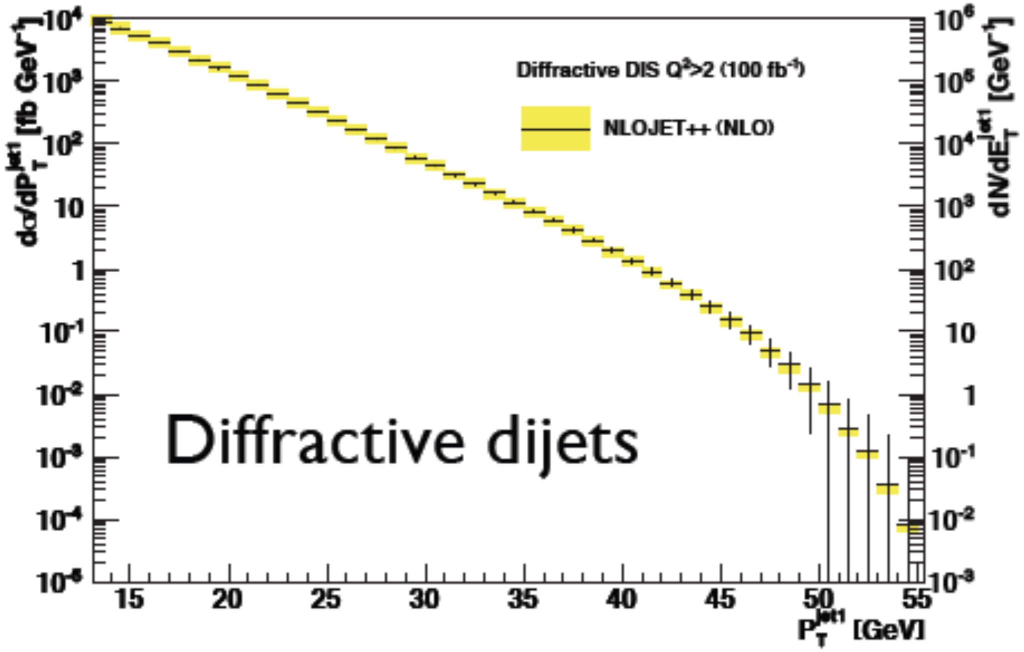
Inclusive Diffraction at LHeC



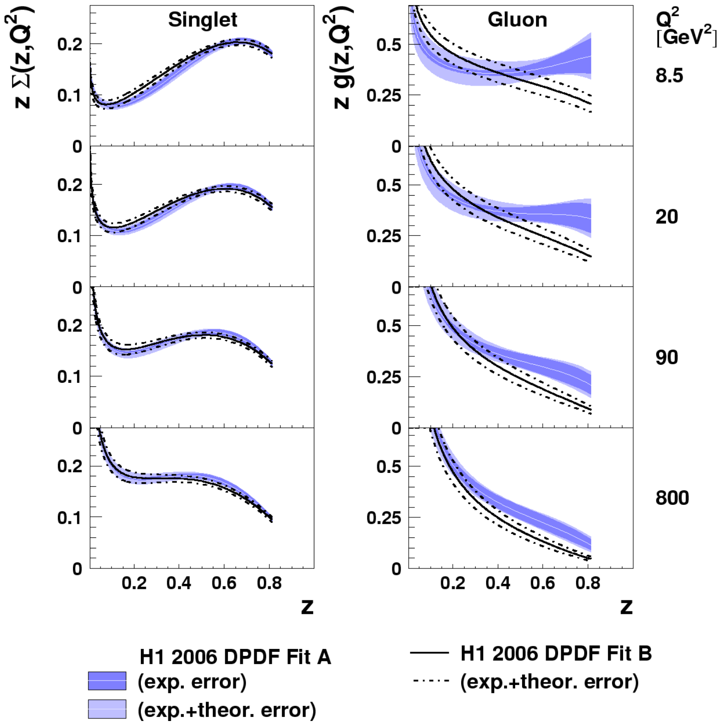


- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x effects
- High Q^2 → Lever-arm for gluon, flavour decomposition
- Large M_X → Jets, heavy flavours, W/Z …
- Large E_T → Precision QCD with jets …





New Study (Wojtek Slominski)



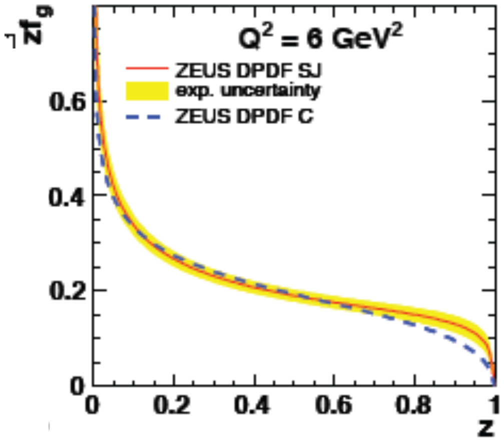
Investigate LHeC potential for diffractive parton densities

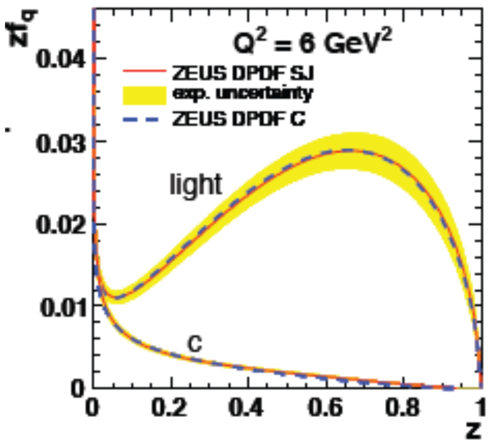
- So far using same framework as at HERA (ZEUS version) with factorising x_{IP} dependence (IP) and (β, Q^2) dependence from NLO DGLAP fit

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

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

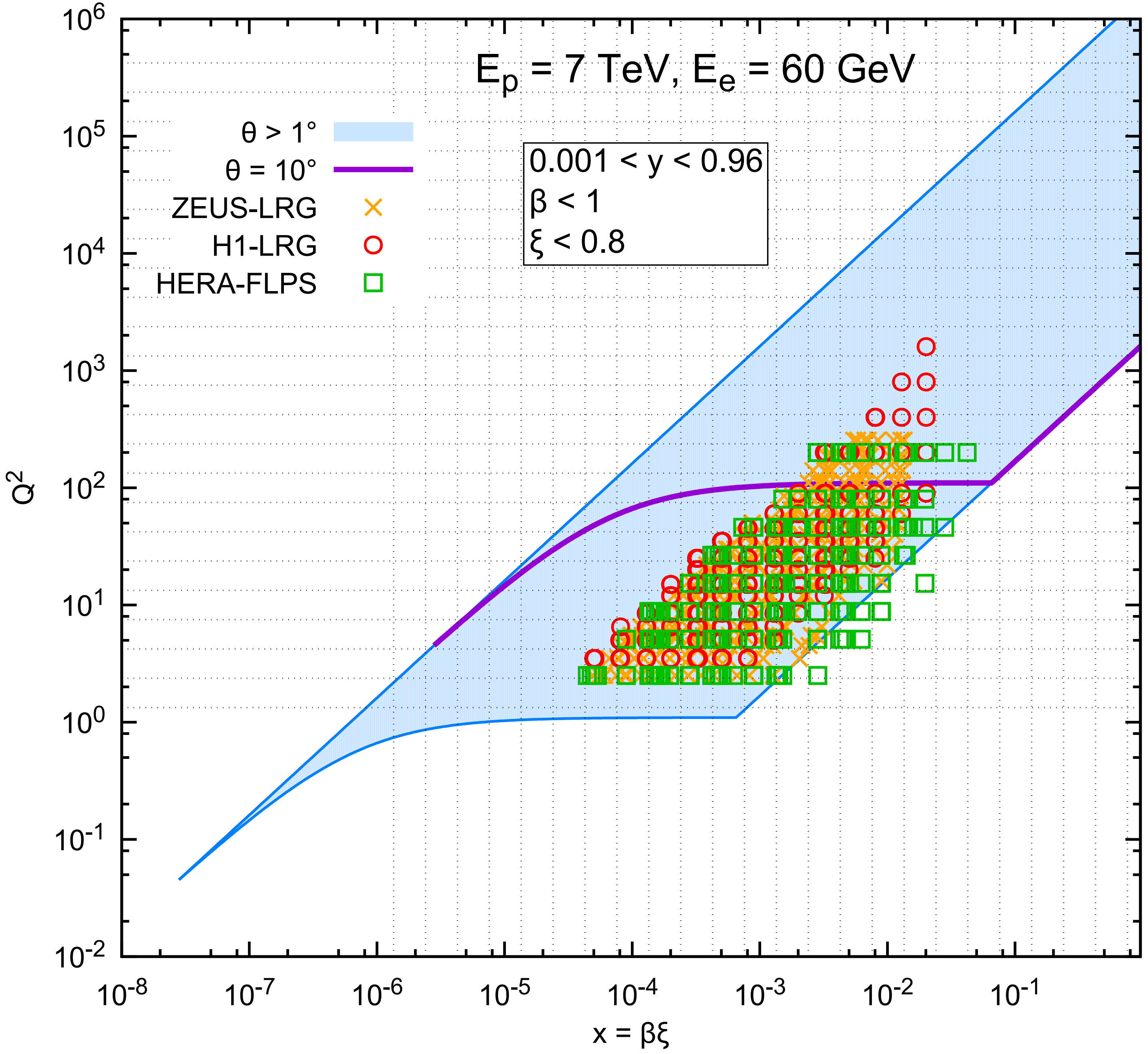
d = u = s = dbar= ubar = sbar



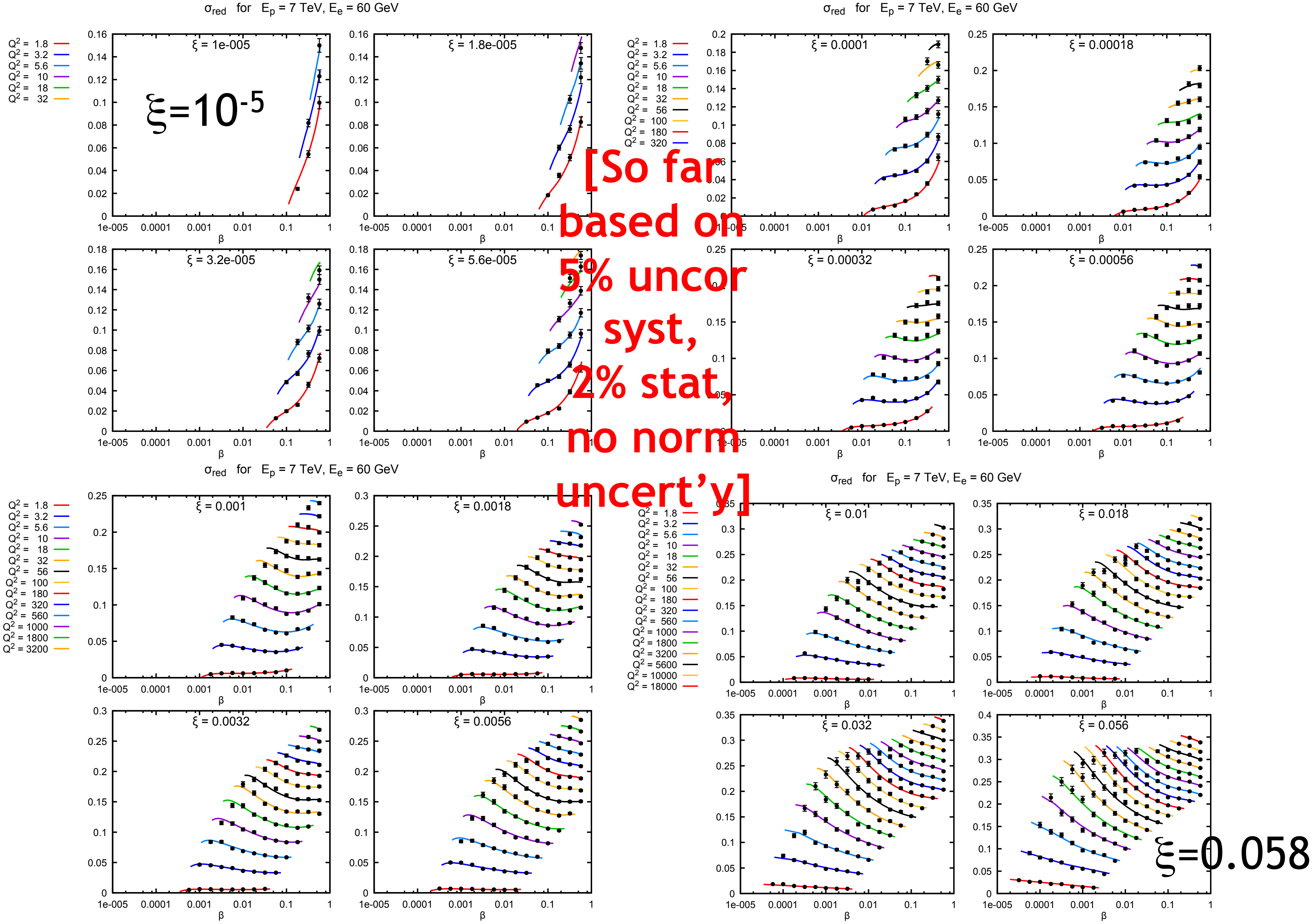


- Small sub-leading (IR) exchange required at largest x_{IP}

HERA Data v LHeC Phase Space



LHeC Simulated Data (ZEUS-SJ extrapolation)

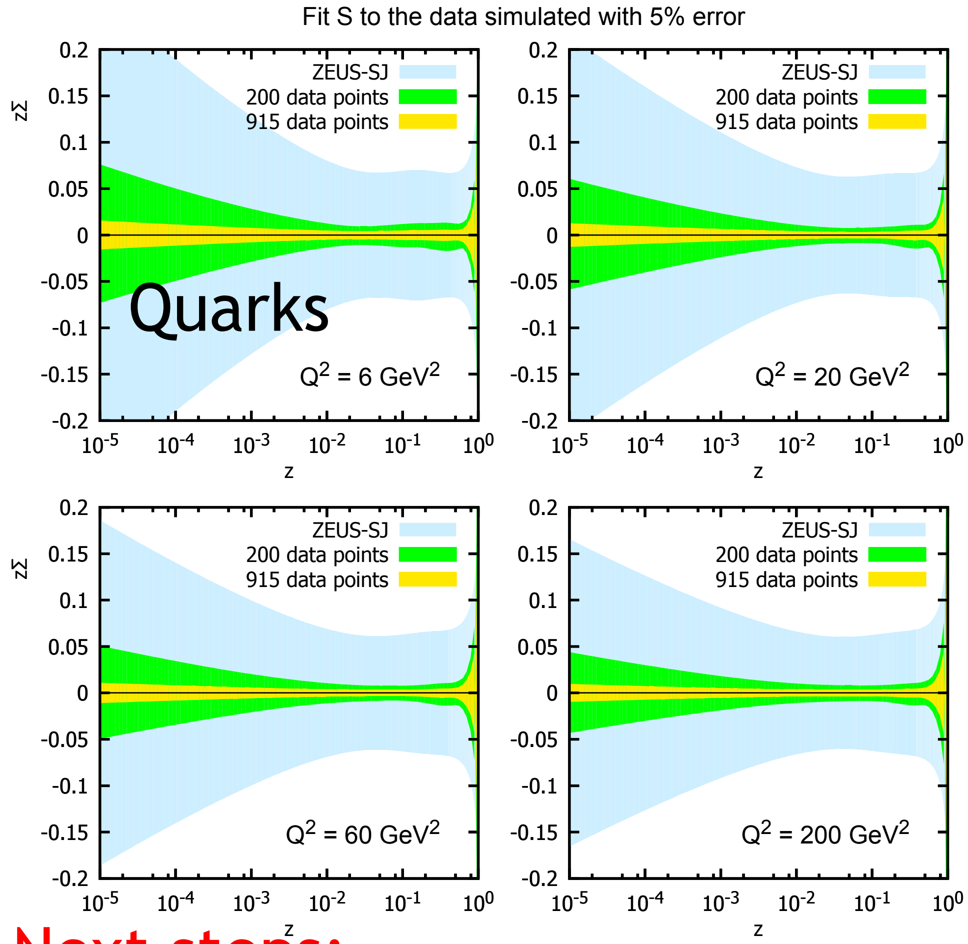


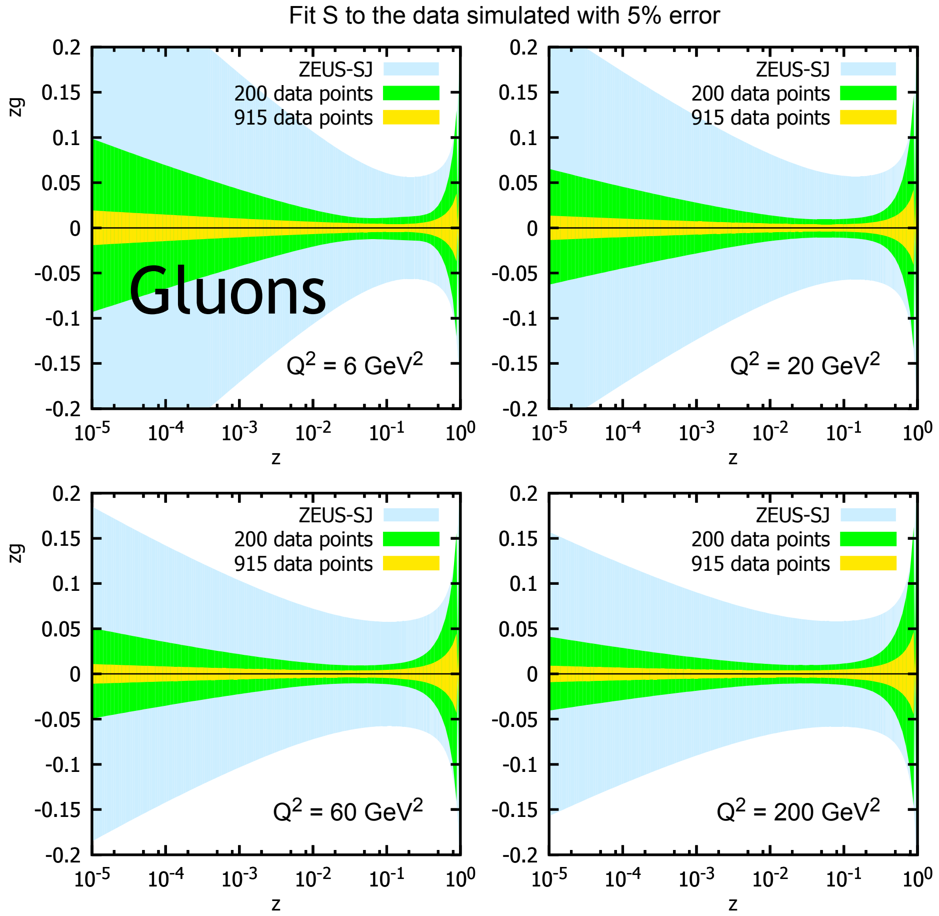
$\xi=10^{-5}$

[So far based on 5% uncor syst, 2% stat, no norm uncert’y]

$\xi=0.058$

Simulated DPDF Precision (work in progress)

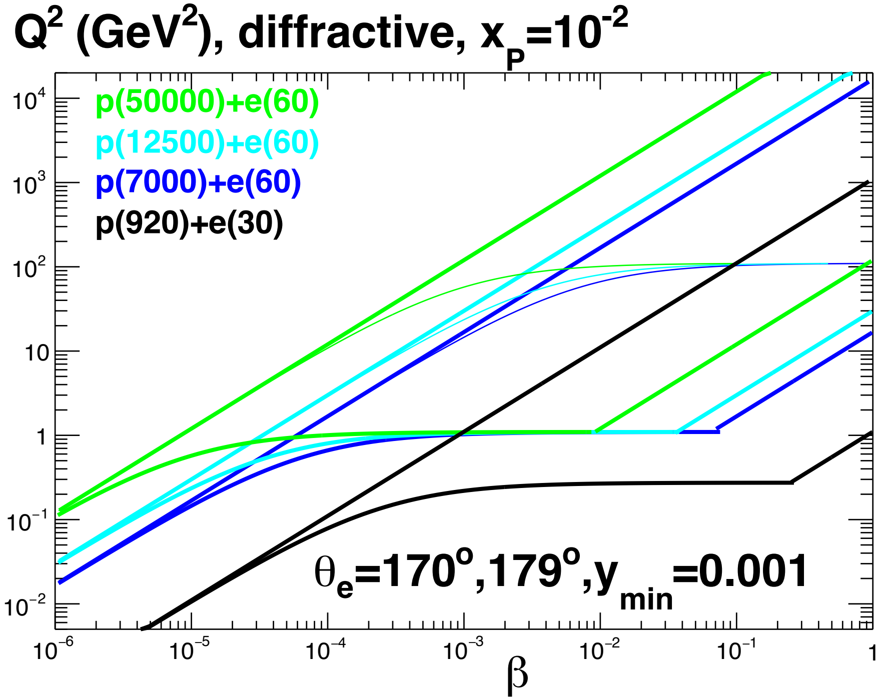




Next steps:

- Normalisation uncertainties
- Parameterisation bias etc?
- Optimise binning
- Sensitivity to flavour decomp
- Sensitivity to deviations from pure DGLAP

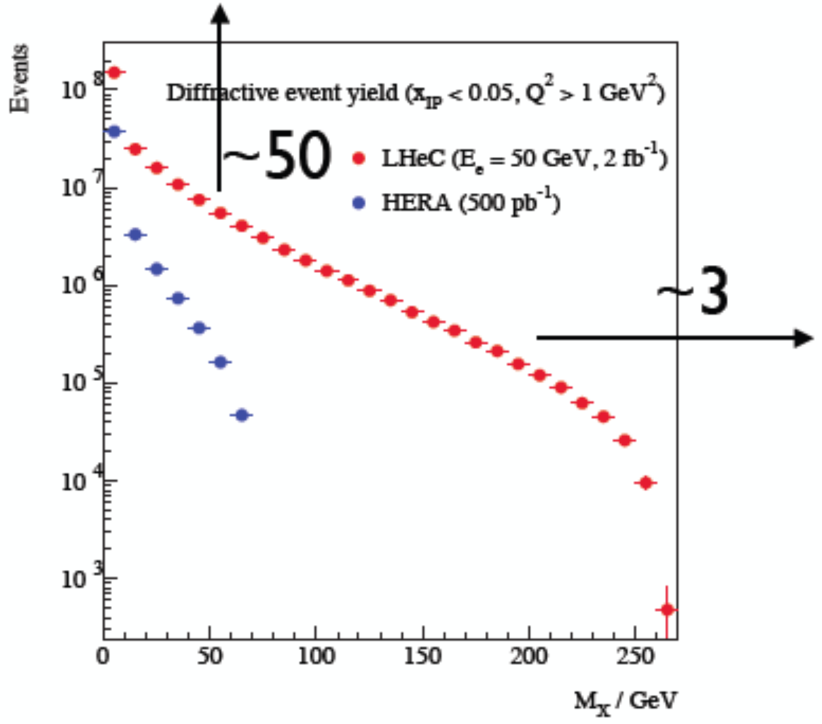
Diffraction at FCC-eh in 1 slide



FCC-eh kinematics sensitive to diffractive structure in larger (β,Q^2) range than (x,Q^2) range sampled for the proton @ HERA!

- Similarly for masses and transverse momenta of jets.

- W range for VMs → multi-TeV



Summary

- Low x QCD is a frontier of future → emergent phenomena at high density, strong coupling (saturation, confinement, mass)

- LHeC / FCC-eh addresses this physics better than any other future facility

- Recent progress in sensitivity to diffractive PDFs

- Still plenty more to do … wish list
    - → DVCS and GPD / TMD sensitivity
    - → Lots of FCC-eh simulations
    - → Any simulations with real attempts at systematics
    - → More detailed forward instrumentation design
    - → …

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