Low x and Diffractive Physics at FCC-eh

FCC Physics &
Experiments Workshop
CERN
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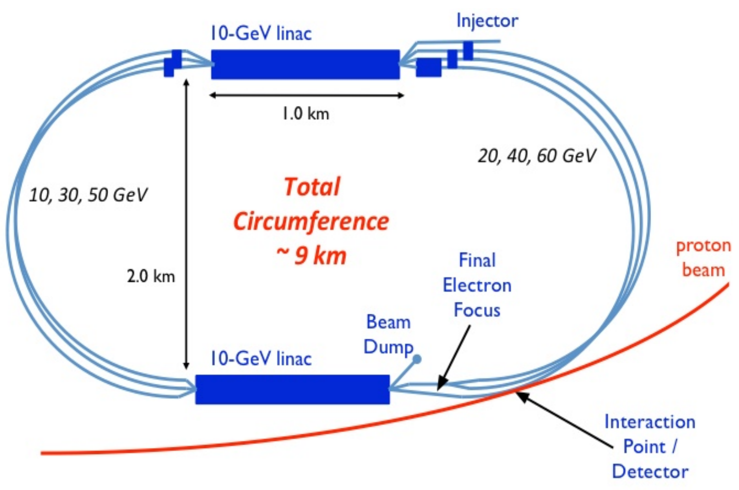


1) Where does HERA leave us?
2) Future DIS facilities
3) Inclusive Deep Inelastic Scattering at Small x
4) Elastic J/Ψ Photoproduction
5) Diffractive Deep Inelastic Scattering

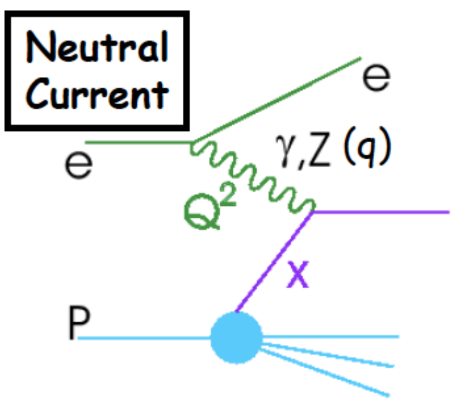
See also Max Klein (PDFs at FCC-eh) and Nestor Armesto (FCC-eA)

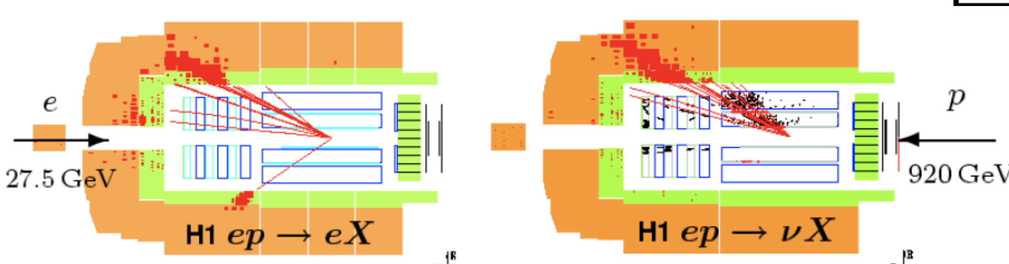
…birth of experimental low x physics

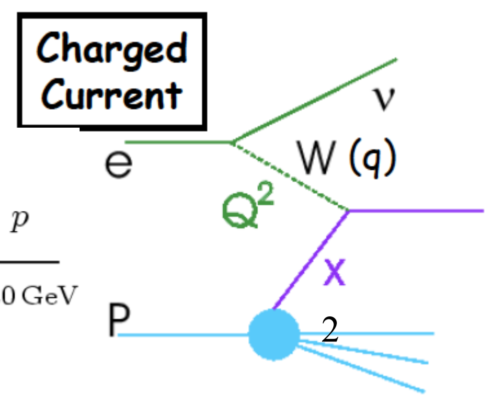
- The only ever collider of electron beams with proton beams:

$$\sqrt{s_{ep}} \sim 300 \text{ GeV}$$

- Extended kinematic range at perturbative Q^2 from $x{\sim}10^{-2}$ to $x{\sim}10^{-4}$

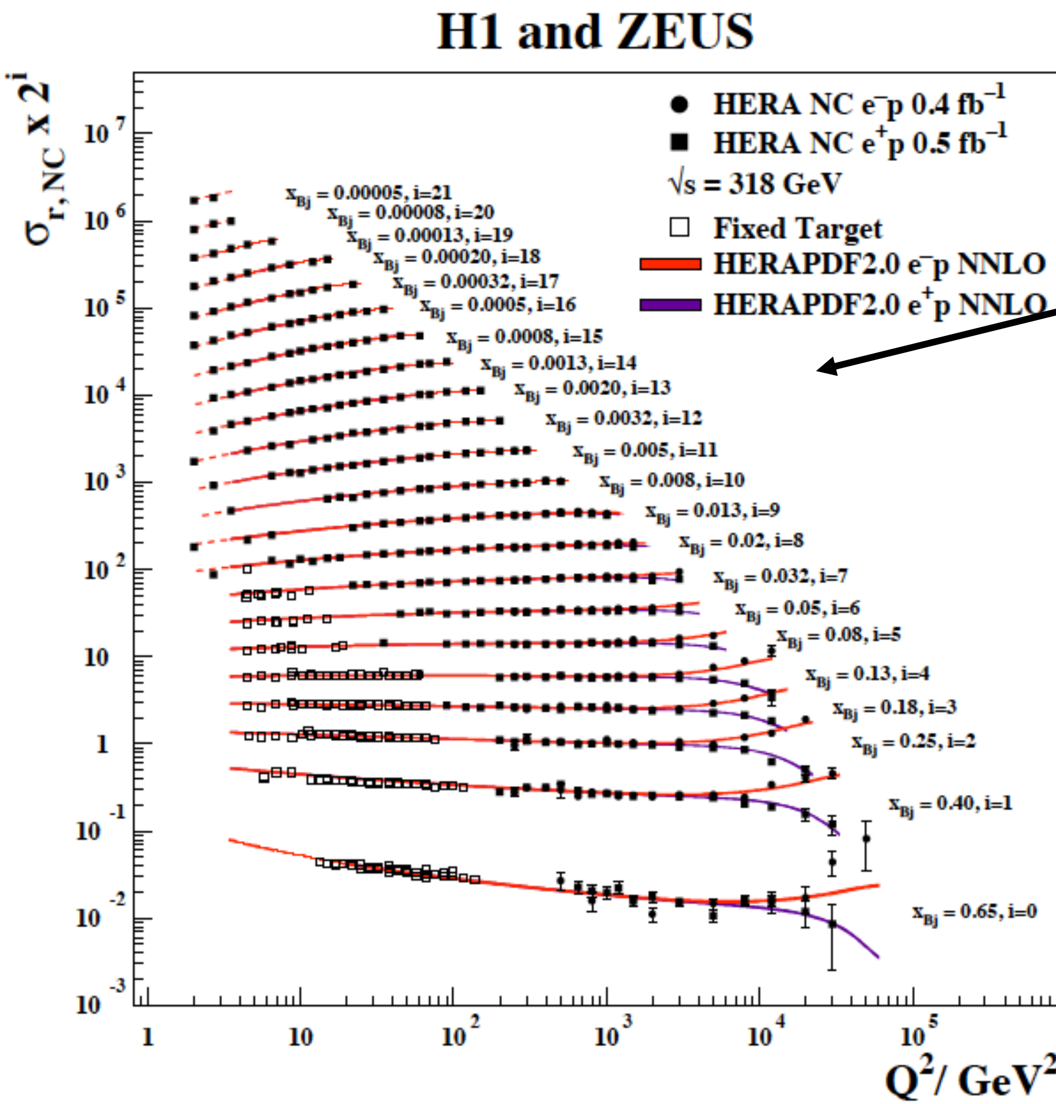




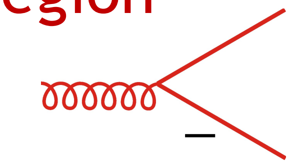


Low x Physics is Driven by the Gluon

… knowledge comes mainly from inclusive NC HERA data



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

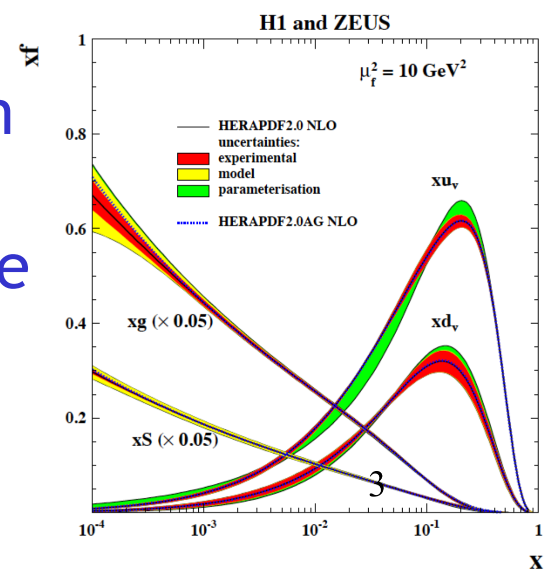


$$g \to q\bar{q}$$

- e.g. Prytz approx:

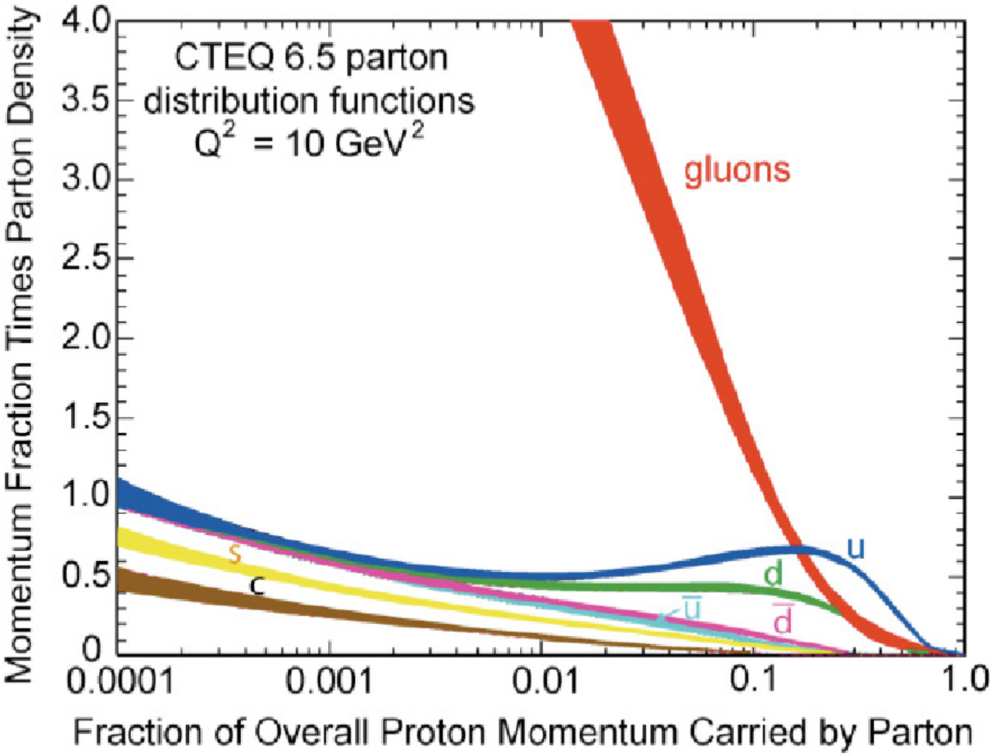
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

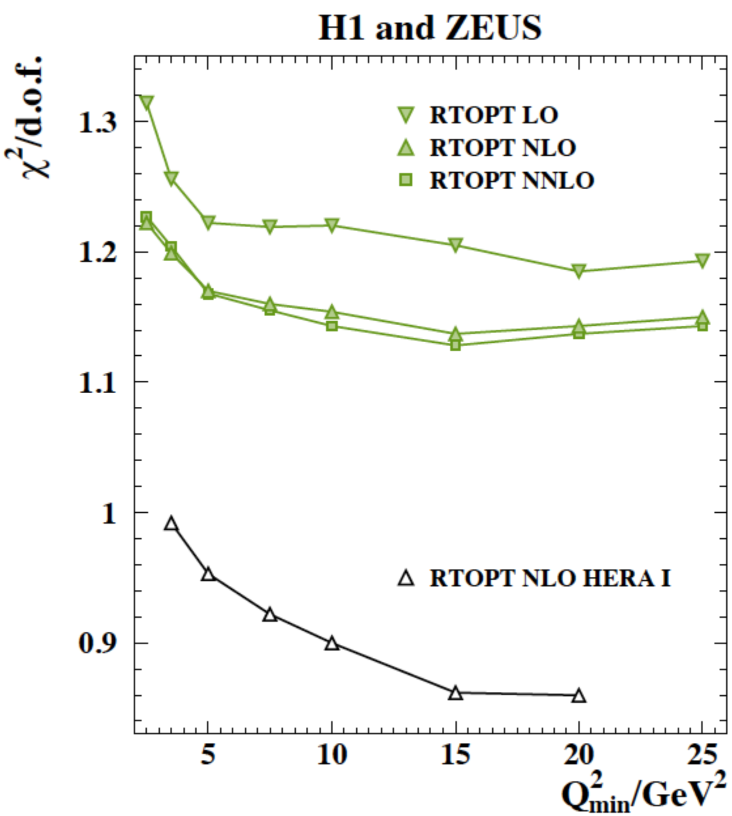
- needs lever-arm in Q^2 … reasonable precision only to $x \sim 10^{-3}$.



The "Pathological" Gluon

- Fast growth of low x gluon appears unsustainable → new low x gluon-driven dynamics?

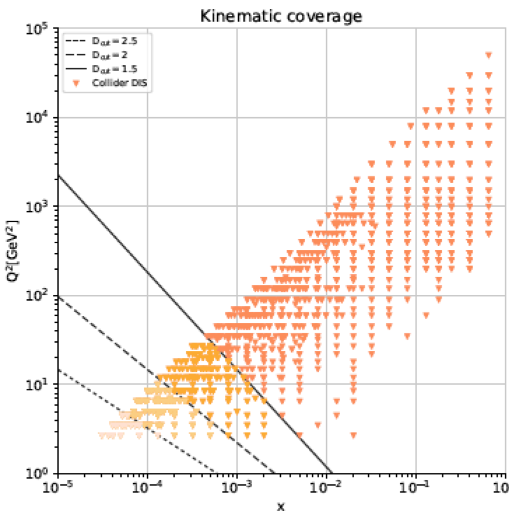


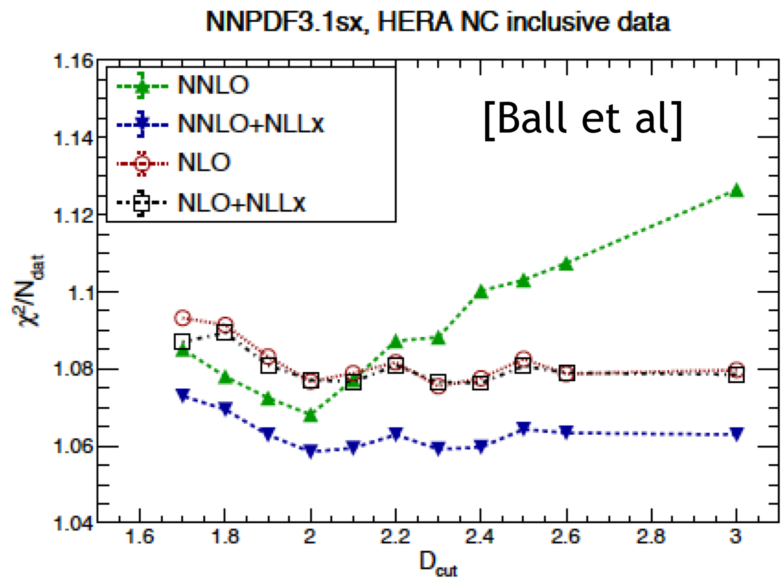


Some evidence for deviations from (NNLO) DGLAP at lowest Q^2 in Final HERA-2 Combined PDF Paper:

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

New Low x effects at HERA?



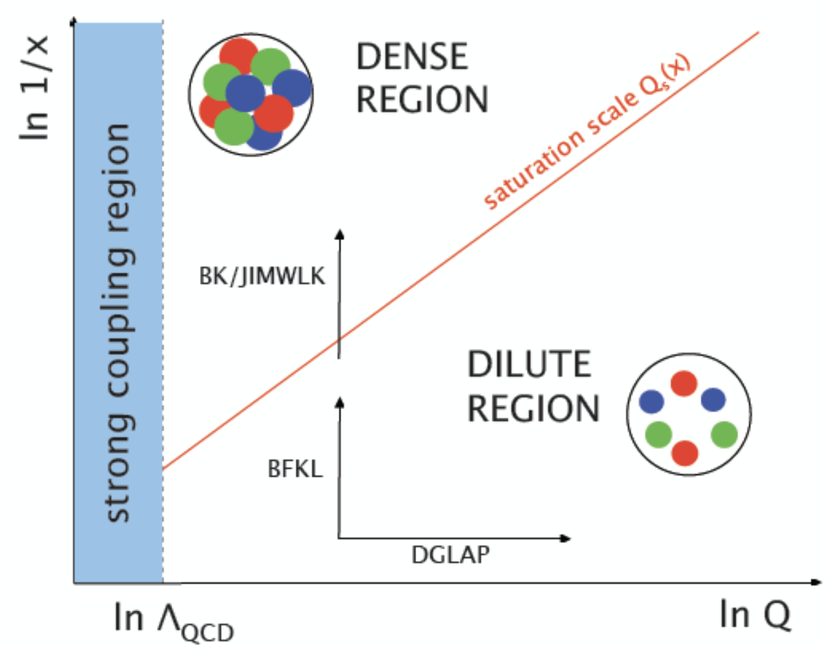


Energy effects?

Including NLL ln(1/x) (BFKL) resummation in fits improves χ^2 and describes difficult low x, low Q^2 region (also improves F_L)

Density effects?

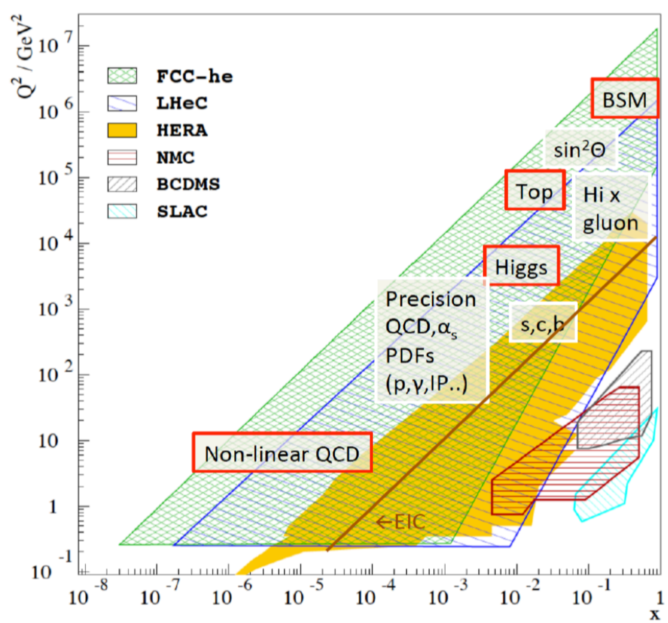
→ Non-linear gluon recombination (gg→g)? `Saturation' models successful in describing HERA data down to lowest x and Q^2 values

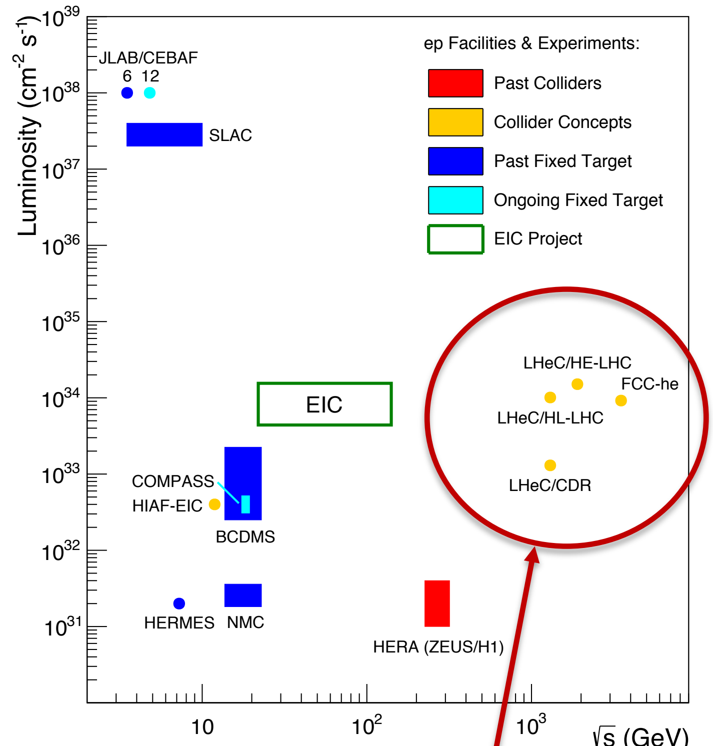


HERA's Limitations

- Limited lumi → restricts searches and precision at high x, Q^2
- Lack of Q^2 lever-arm at low x → restricts low x gluon precision
- No deuterons → limited quark flavour decomposition
- No nuclei → insensitive to nuclear effects
- No polarised targets (except HERMES) → limited access to spin, transverse structure

ALL addressed by complementary proposed future DIS projects

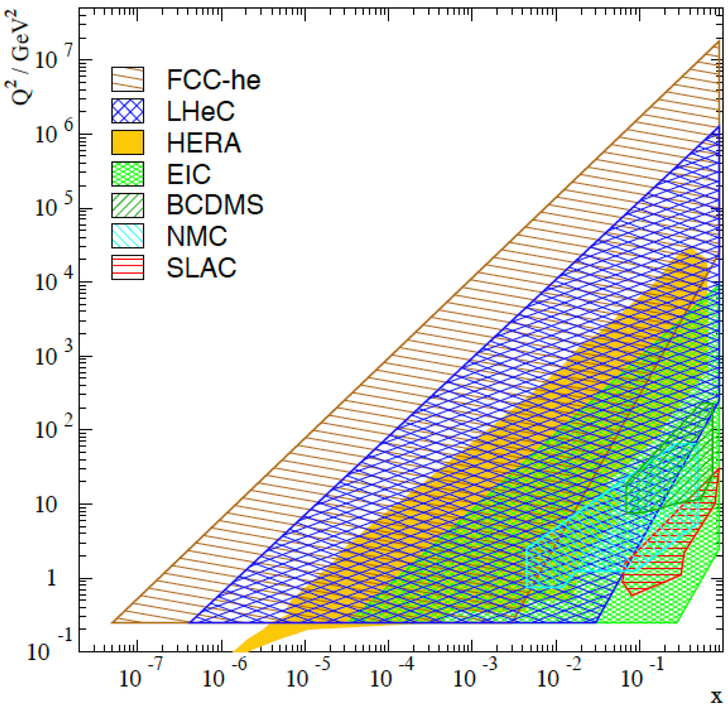




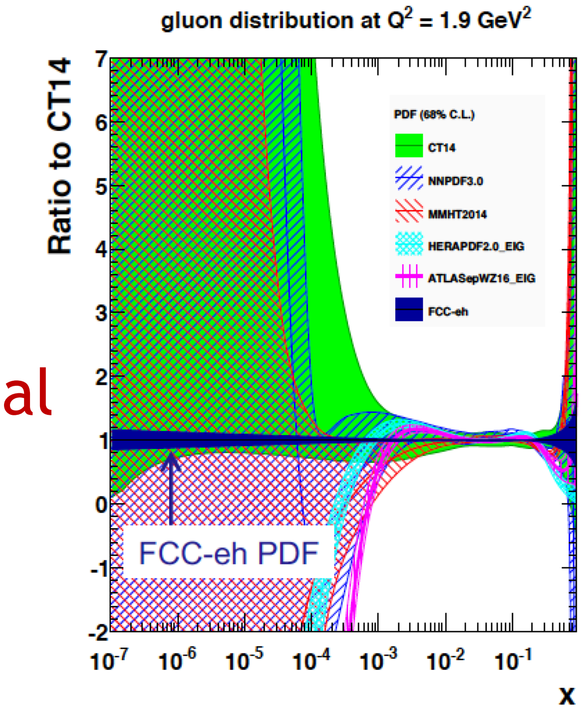
High energy, high luminosity via new e beam + LHC or FCC

Low x Kinematics at FCC-eh

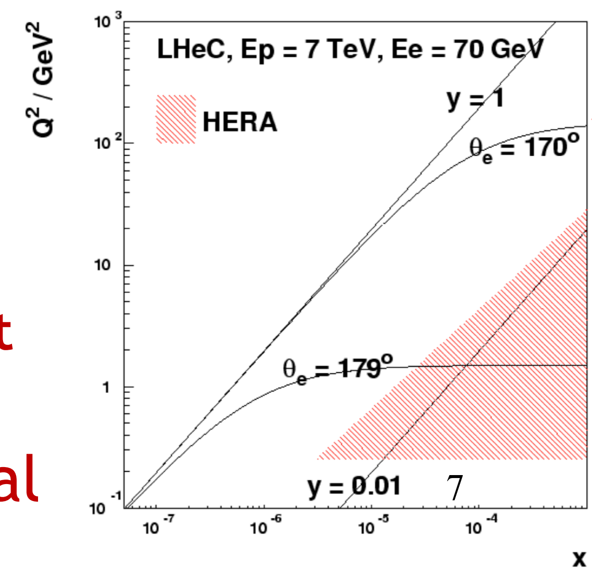
>2 orders of magnitude extension at fixed Q^2 for ep (>4 for eA)



- Transformational impact on PDF kinematic range and precision

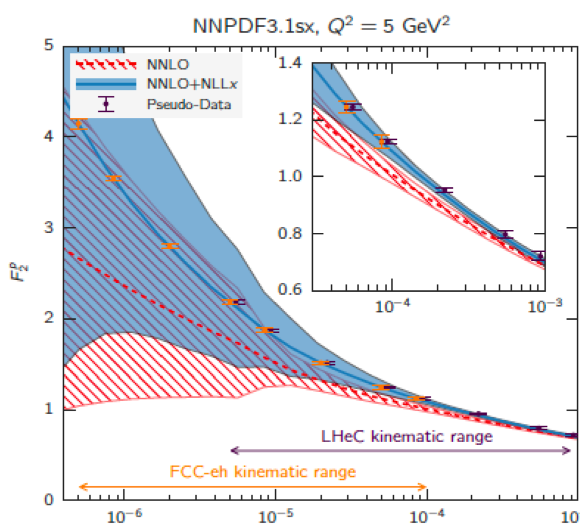


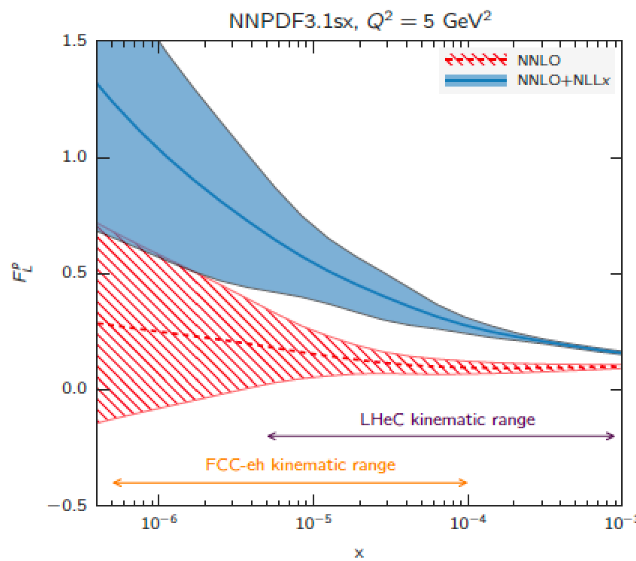
- FCC-eh phase space extends deep into region where both saturation and BFKL resummation effects expected in both ep & eA at perturbative Q^2
- Near hermetic detector acceptance is vital



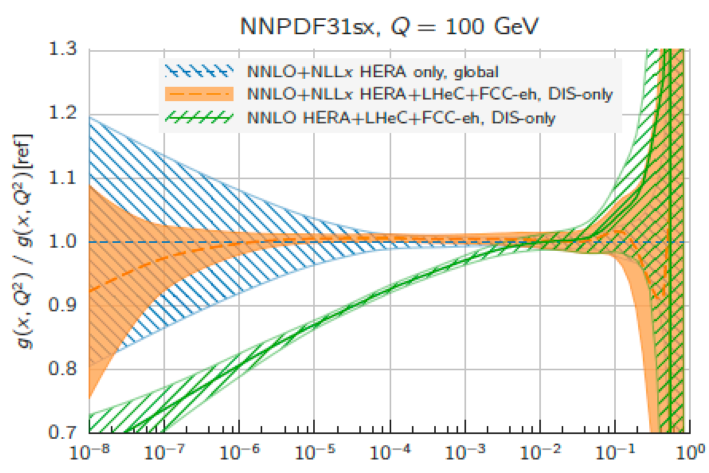
Potential of FCC-eh to establish BFKL effects

- Extrapolated F_2 and F_L predictions in LHeC and FCC-eh regime based on NNPDF fits to HERA data with and without NLL 1/x resummation





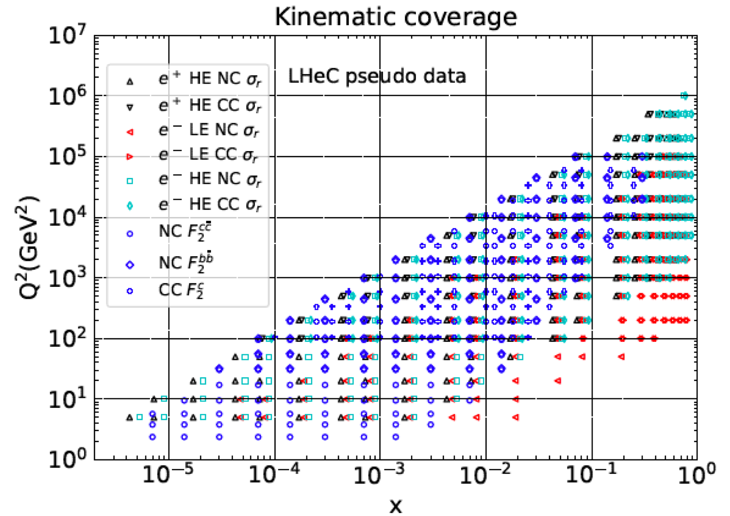
- Huge error bands due to lack of current constraints at $x < 10^{-4}$
- Data precision will distinguish and reveal new dynamics

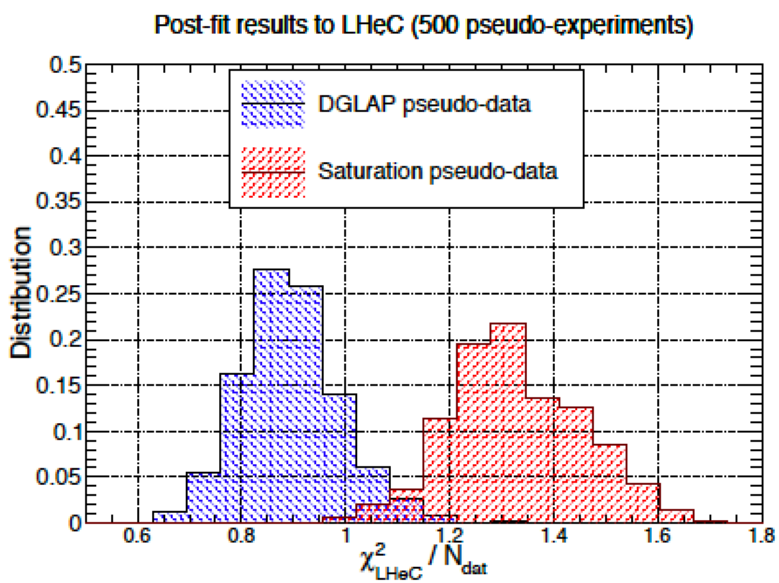


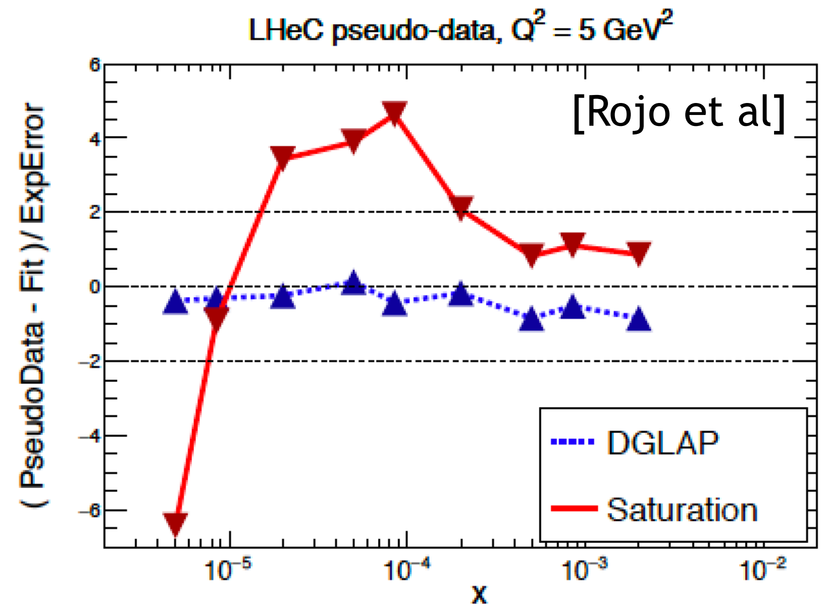
- Extracted PDFs including LHeC and FCC-eh pseudodata highly sensitive to inclusion of NLL 1/x resummation in simulated data

Can Parton Saturation be Established in ep @ LHeC?

Simulated LHeC inclusive and HF pseudodata using extrapolated (DGLAP improved) GBW model fit to HERA data,
→ contains low x saturation for $x<10^{-4}$
→ try to fit using pure NNLO DGLAP
… Cannot absorb all the non-linear effects into the initial conditions



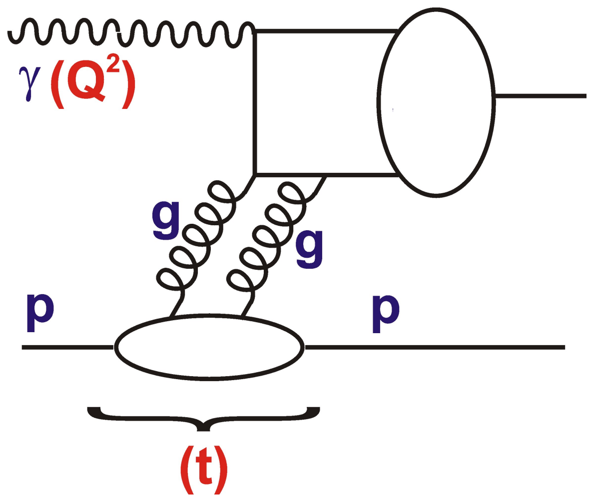




• Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

Motivation for Diffraction

[Low-Nussinov] interpretation as 2 gluon exchange:

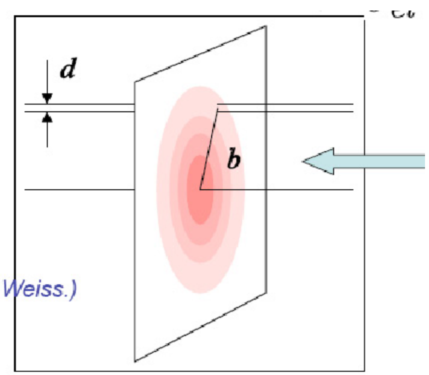


1) Sensitivity to correlations between partons and 3D structure

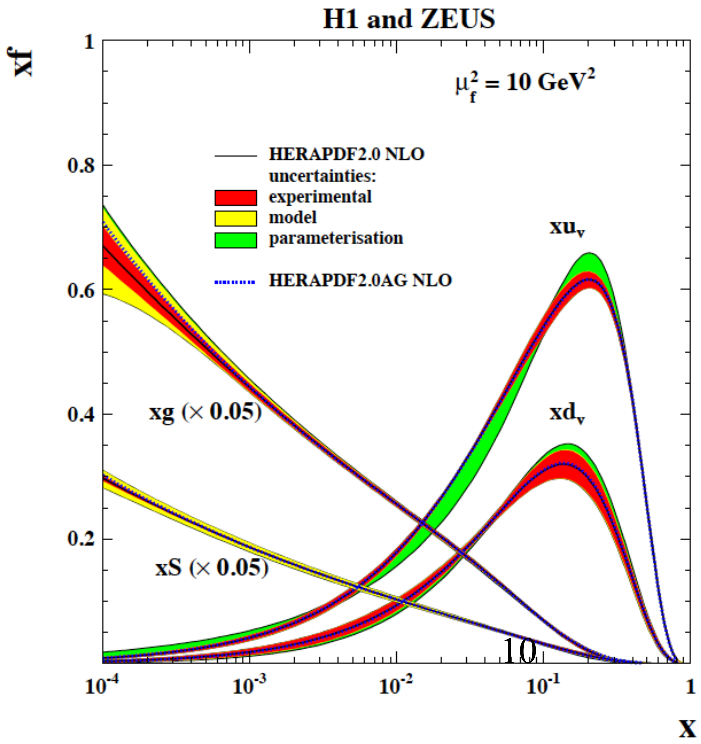
2) Sensitivity to low x gluon → non-linear saturation / BFKL effects?

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

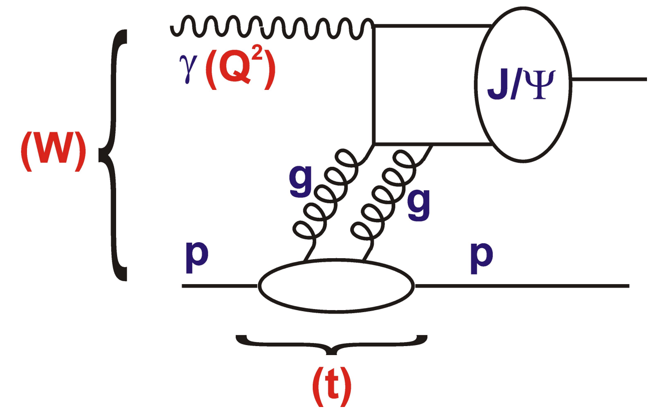
→ Large t (small b) probes densest packed part of proton?..



(figure from C. Weiss.)



Exclusive Diffraction: Elastic J/Ψ Photoproduction



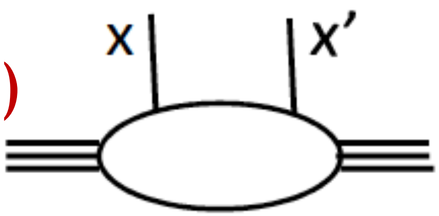
Advantages

- Clean 2 lepton experimental signature

- Scale $\bar{Q}^2 \sim (Q^2 + M_V^2)/4 \;\; >\sim 3\ \mathrm{GeV}^2$ ideally suited to reaching lowest possible x whilst in perturbative regime
  … eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2)\ /\ (Q^2 + W^2) \sim 10^{-5}$

Complementarity

Sensitive to Generalised Parton Densities (correlations /3D info, but still measures low x gluon for x' << x << 1 (theoretically not at same level as collinear PDFs)



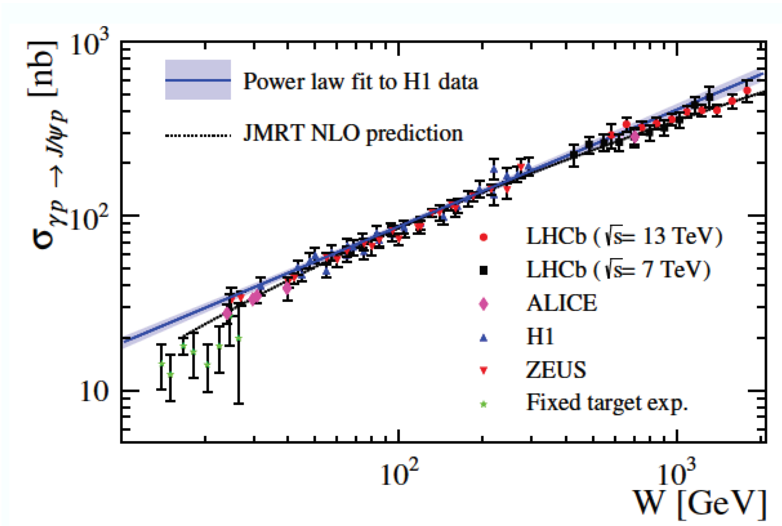
Complications

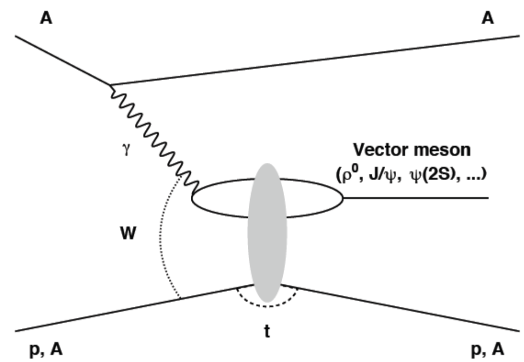
- Vector meson wavefuction

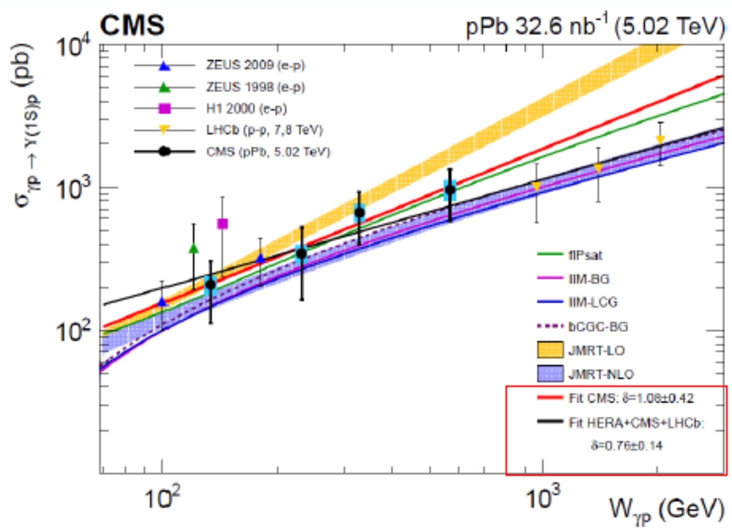
- Large scale uncert's in collinear fac'n (NLO v LO convergence)

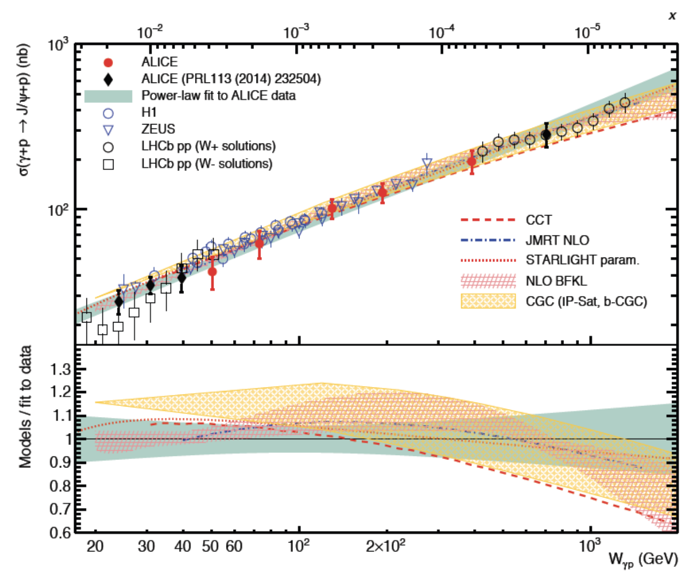
Current Exclusive J/Ψ Data

Already well studied in Photoproduction at HERA and Ultraperipheral Collisions at LHC





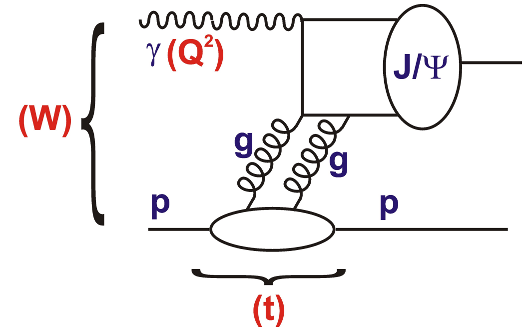


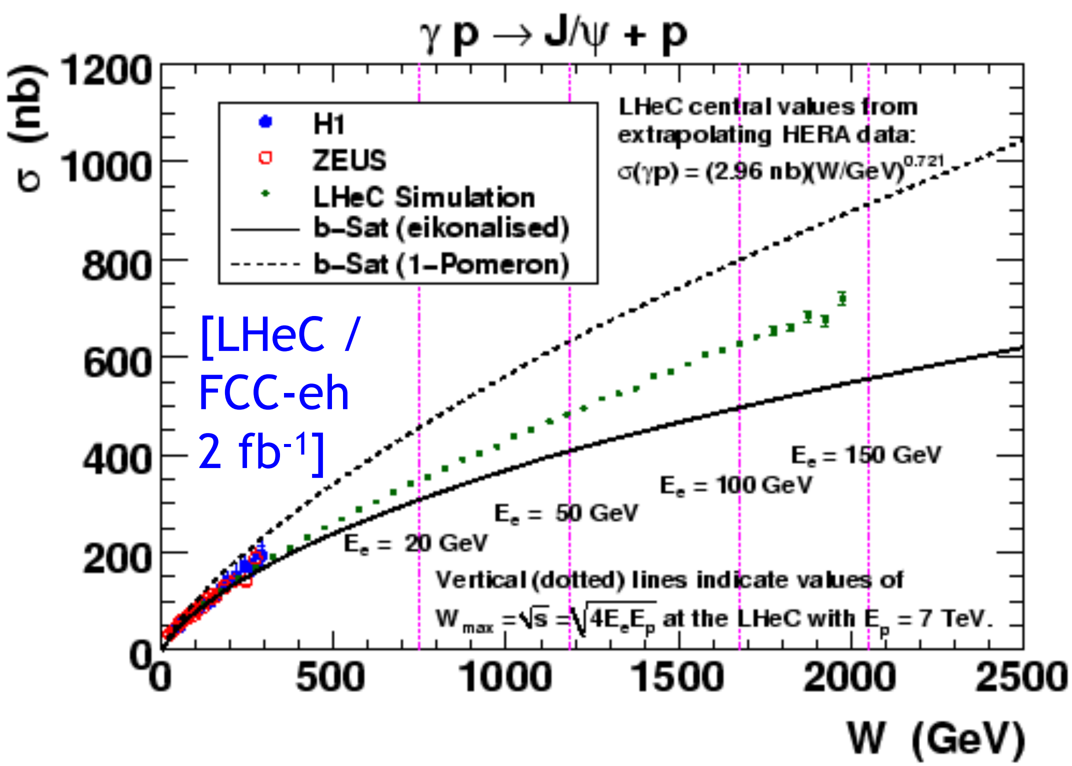


- No sign of deviation from simple power law behaviour (yet)
- JMRT NLO gives excellent 'out-of-box' prediction (k_T fac^n)

J/Ψ from future ep v Dipole model Predictions

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





- Significant non-linear effects expected in LHeC kinematic range
  → 'smoking gun'?

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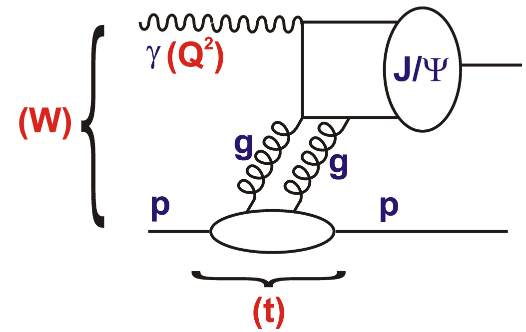

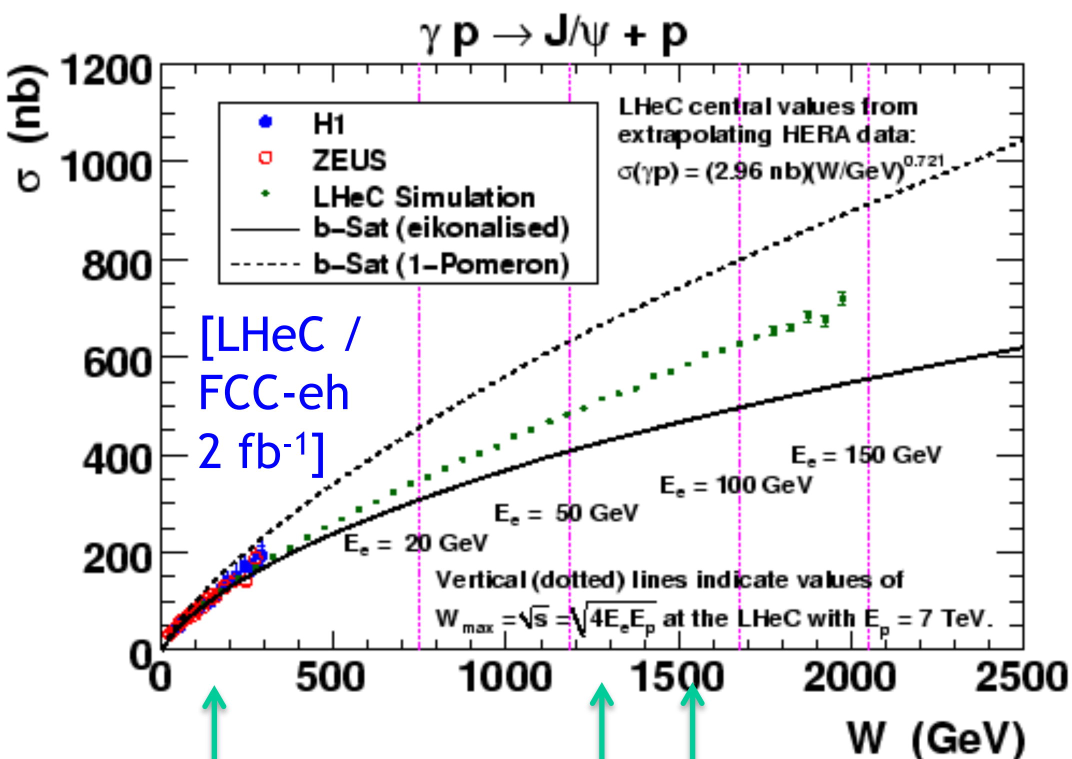

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EIC limit

LHeC limit

Current LHCb limit

FCC-eh limit

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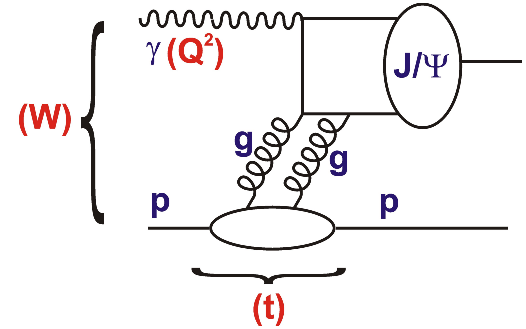
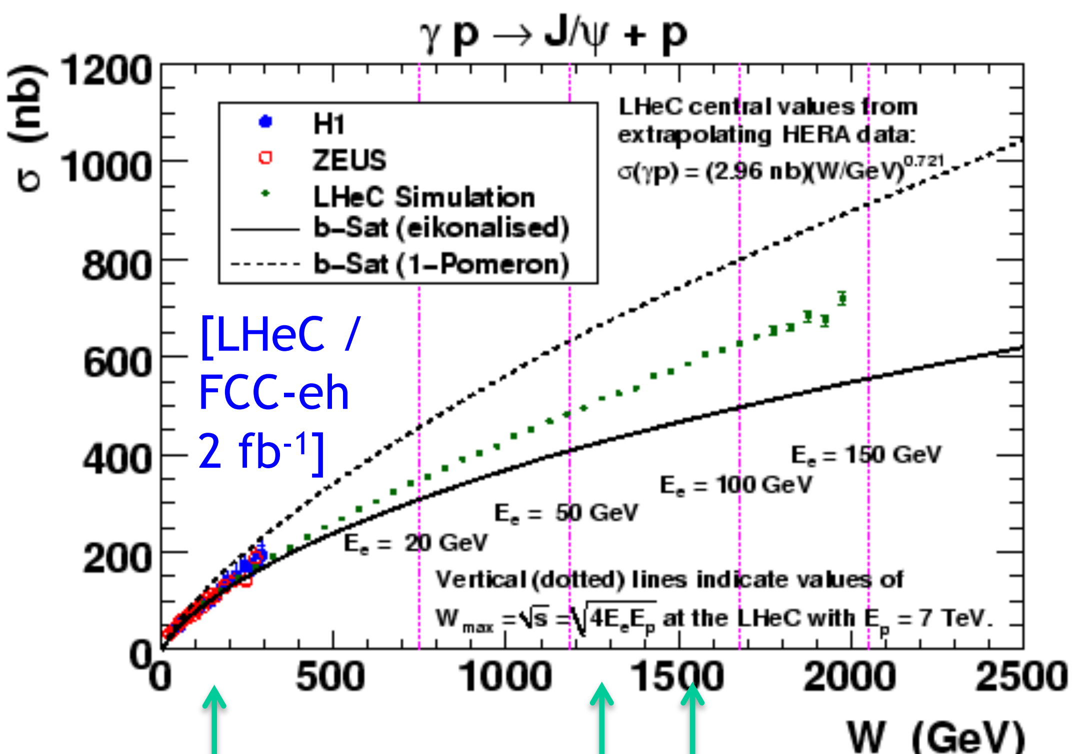




EIC limit

LHeC limit

Current LHCb limit

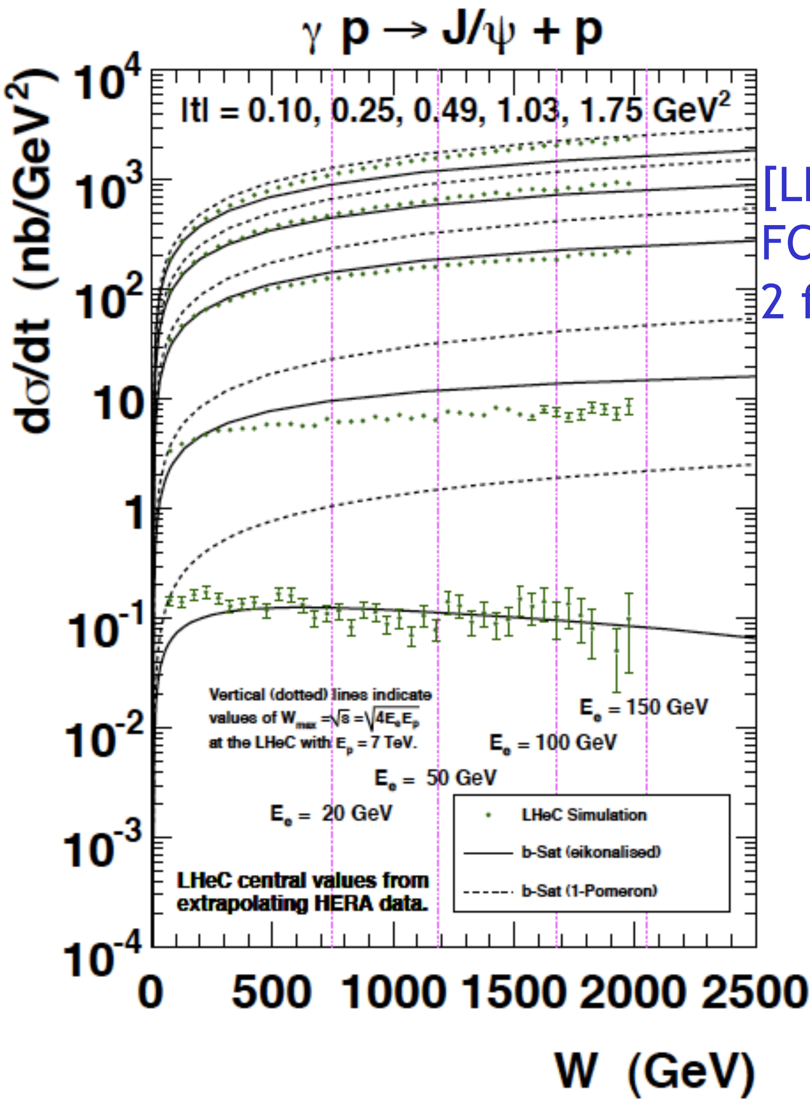
FCC-eh limit

- Significant non-linear effects expected in LHeC kinematic range
  → ‘smoking gun’?

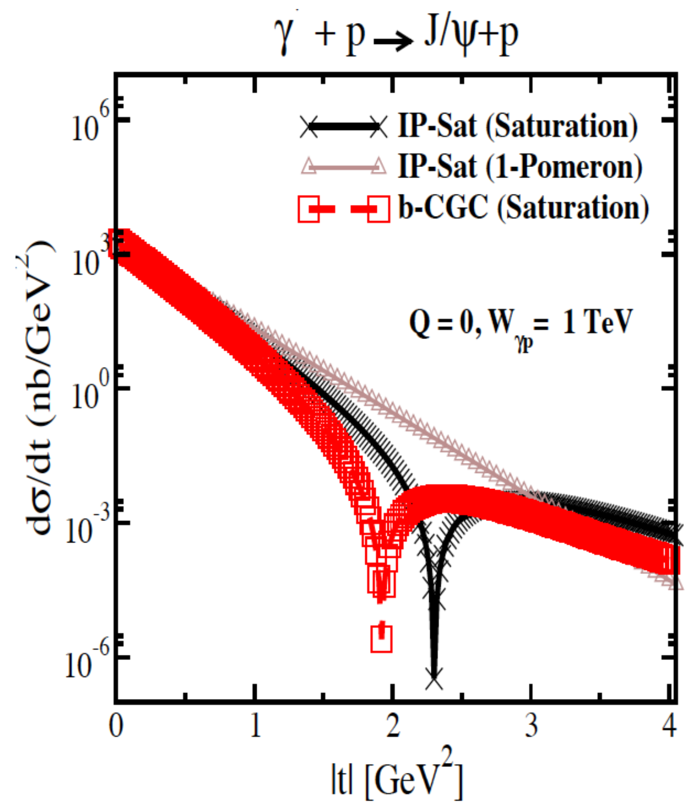
- Lack of clear signal at LHC to date → features are more subtle, require higher energy and more variables (t, Q^2, A)

t Dependence of Elastic J/ψ in ep

- Precise measurement from decay μ tracks extends to large |t|

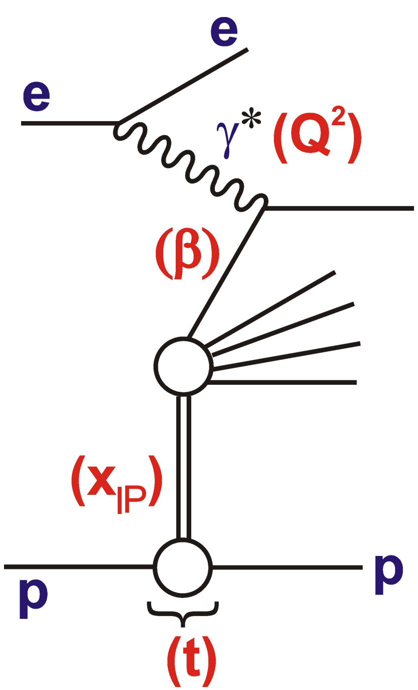


[LHeC/ FCC-eh 2 fb^{-1}]



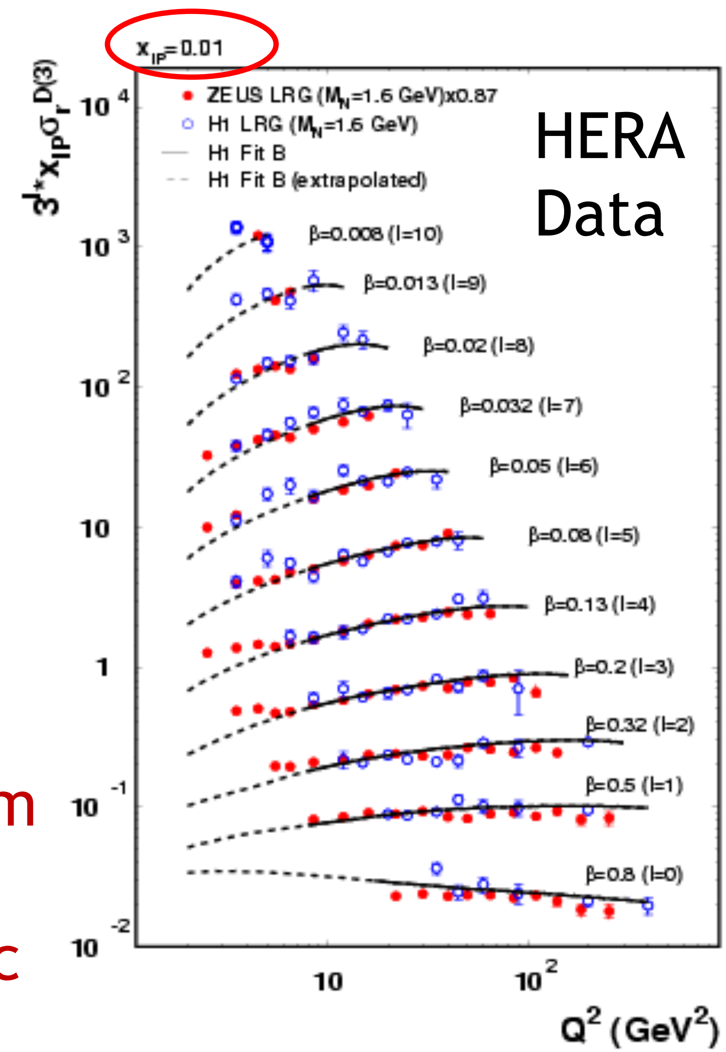
- Dips in t distribution proposed as (model dependent) signature of departure from linear evolution

Inclusive Diffraction and Semi-Inclusive (Diffractive) PDFs



$$x_{IP} \equiv \xi = x_{IP/p}$$

$$\beta \equiv z = x_{q,g/IP}$$

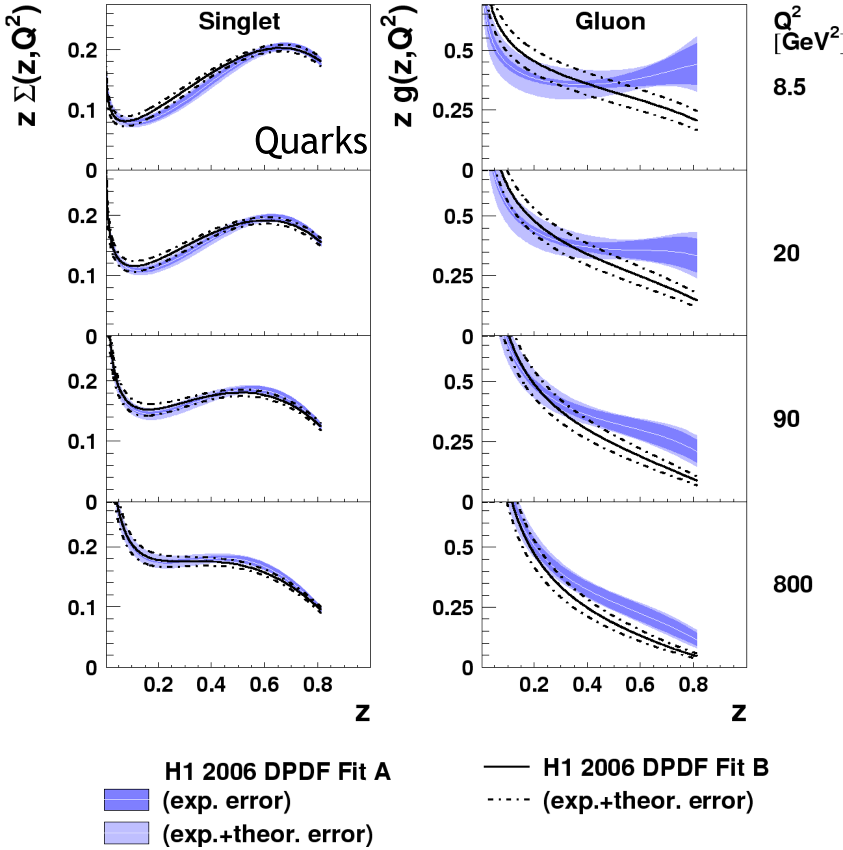


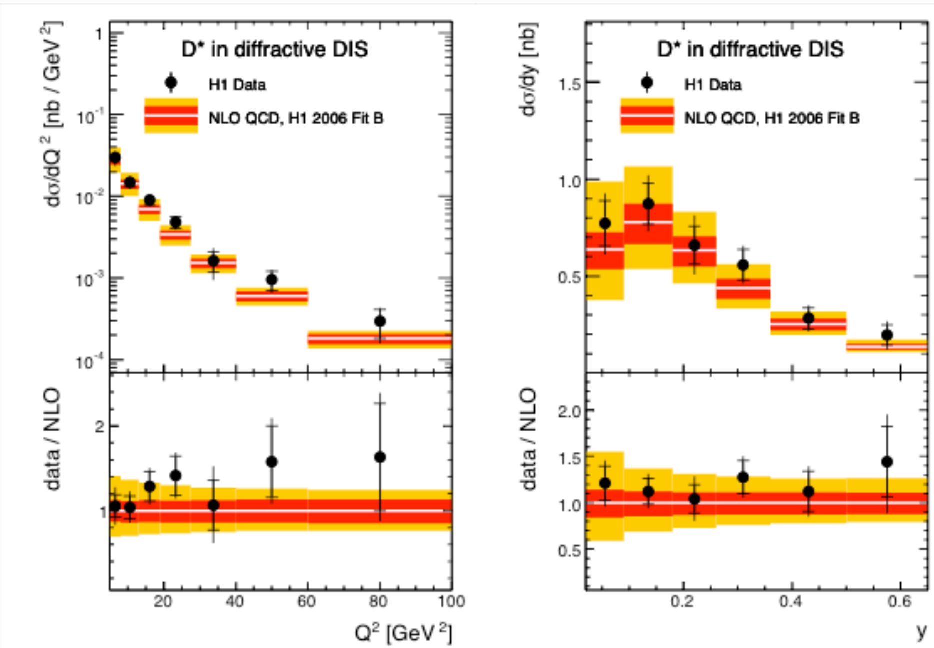
- ep→eXp with proton 4-momentum barely changed has a leading twist contribution ~10% of total DIS x-sec

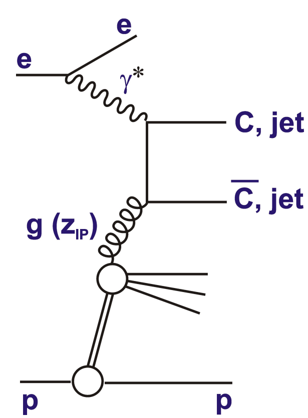
- Rich topic at HERA (>100 publications)

Diffractive Parton Densities (DPDFs) at HERA

- DPDFs extracted from HERA inclusive (F_2^D) data
- Recently also extracted at NNLO (Khanpour, H1)
- Provide remarkably good description of all final state diffractive observables throughout HERA range

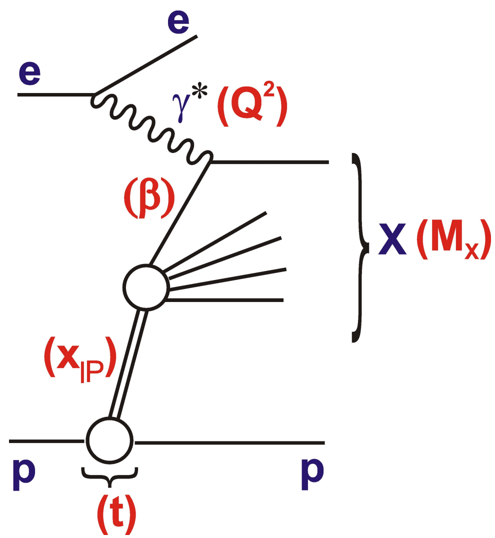


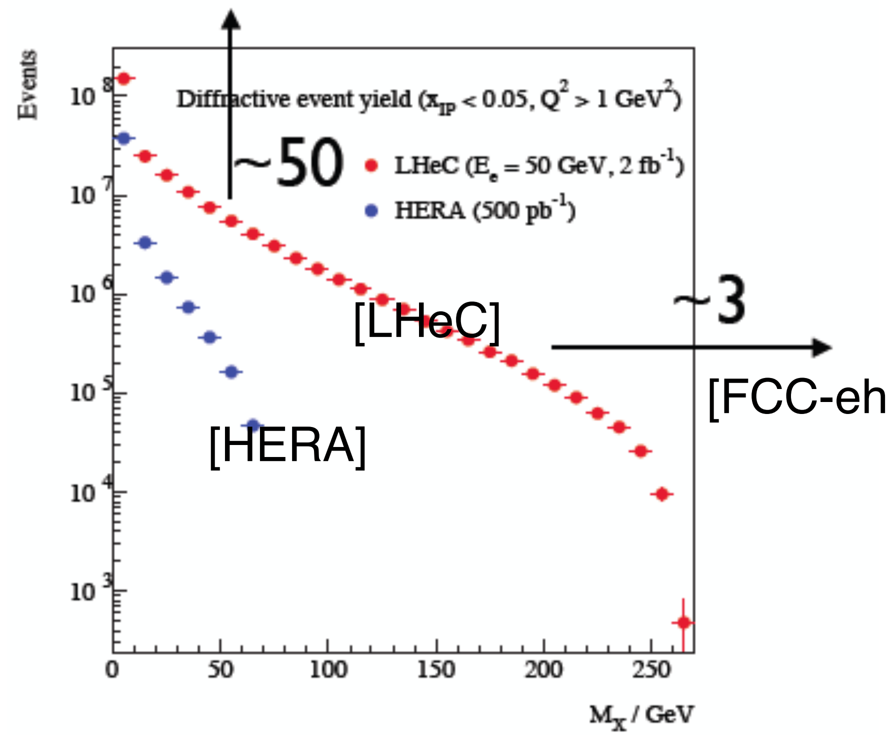




Comparisons limited by available phase space for final states

Inclusive Diffraction at LHeC & FCC-eh

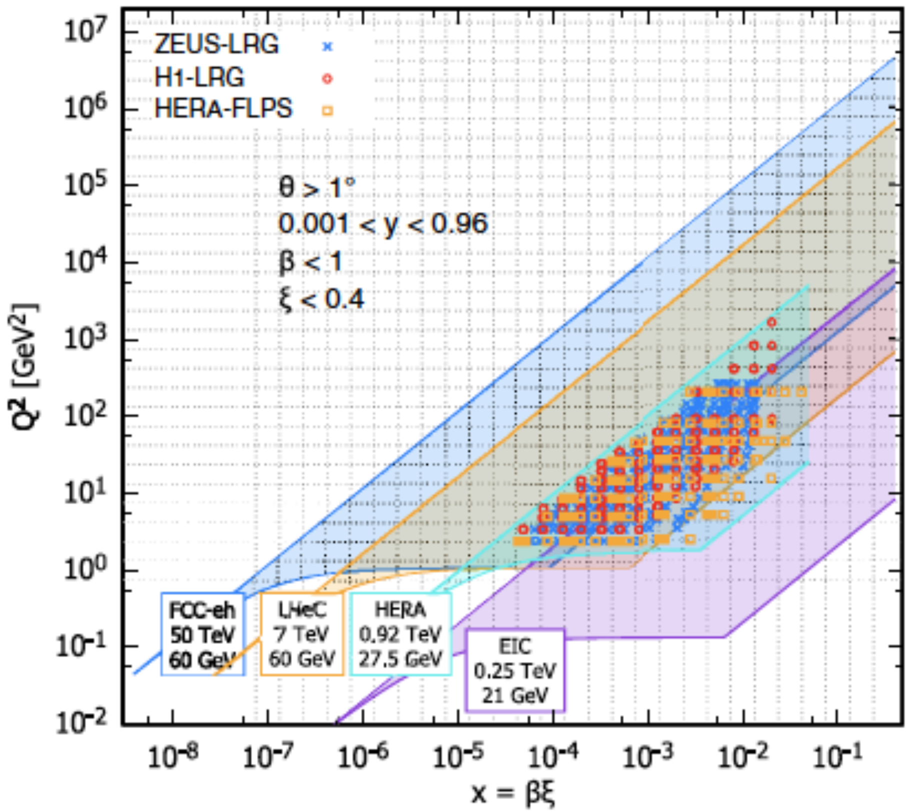




→ Diffractive structure in wider (β, Q^2) range than proton (x, Q^2) range at HERA

- 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 …

Diffractive PDF Fits at FCC-eh / LHeC



- Combined fits to HERA data and pseudodata from LHeC / FCC-eh (2 fb^{-1}), extrapolated using ZEUS-SJ fits (4 bins per decade in each of ξ, β, Q2)

- Same fitting framework as HERA with factorising x_{IP} dependence and (β, Q^2) dependence from NLO DGLAP fit

Quark and gluon param's $f_k = A_k\, x^{B_k}\, (1-x)^{C_k}$ A_k, B_k, C_k free

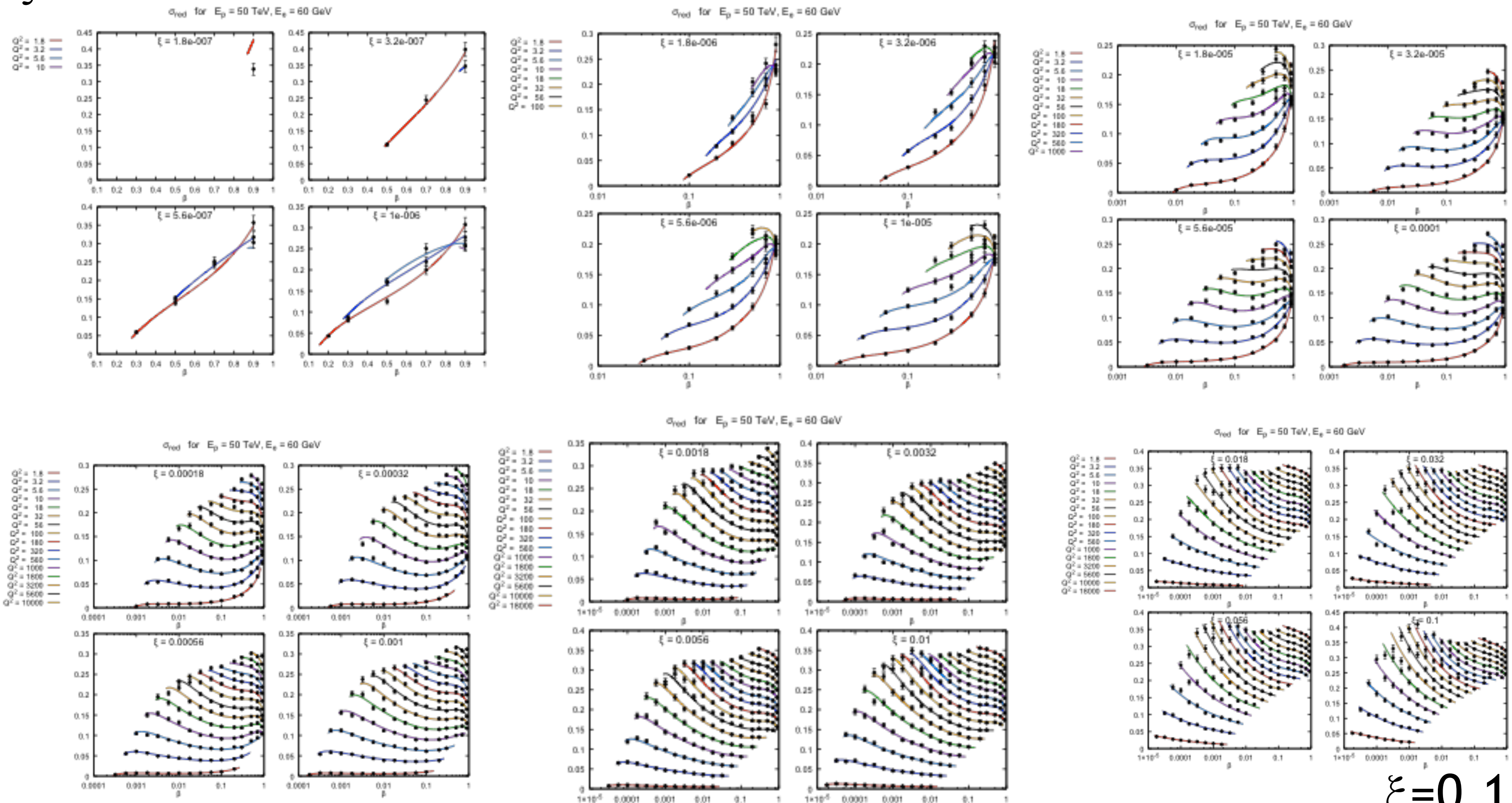
d = u = s = dbar= ubar = sbar

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

GM-VFNS heavy flavour scheme

All pseudodata bins at FCC-eh

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



$\xi = 0.1$

<u>Data uncertainties:</u>

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

<u>Fit range:</u>

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

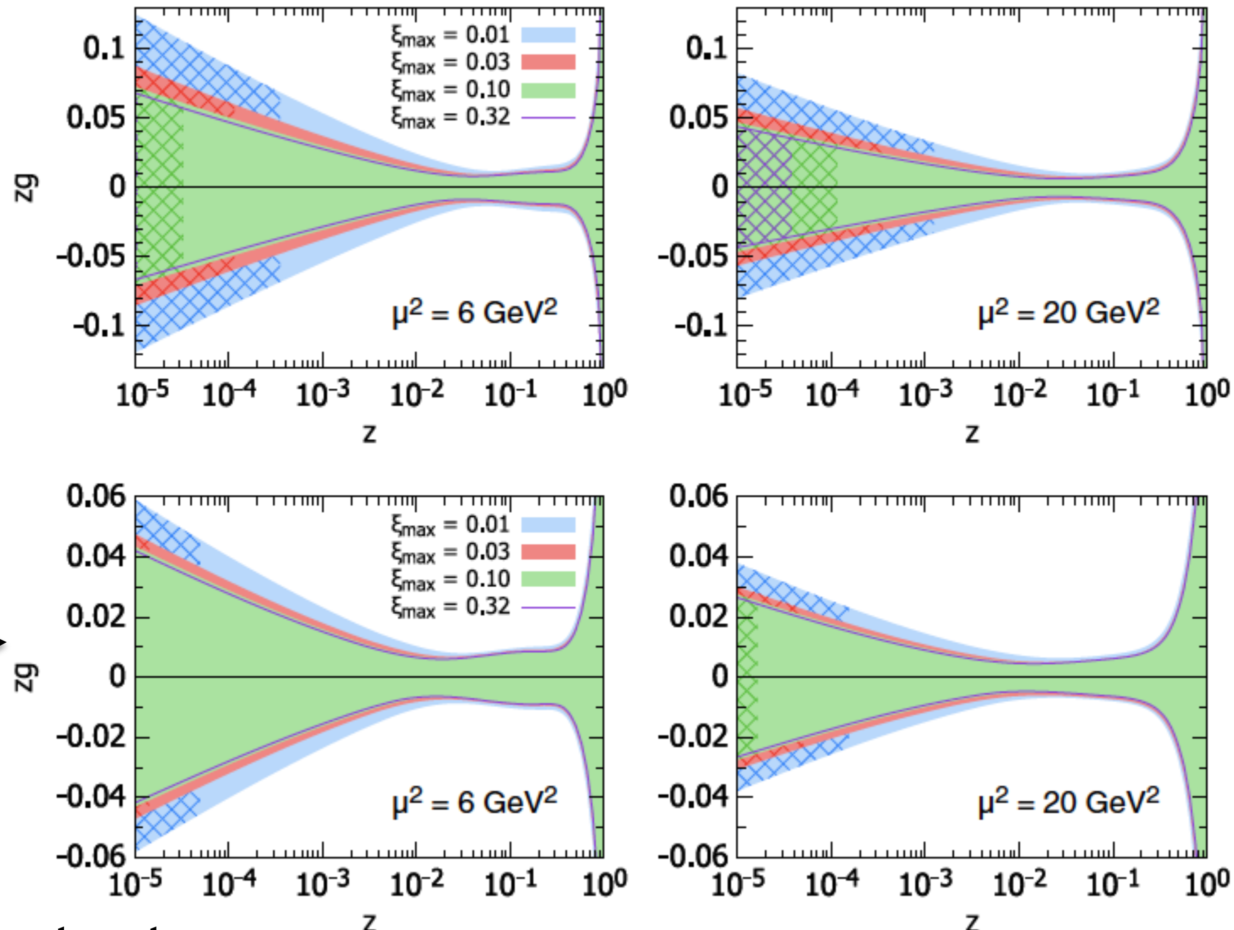
$\xi_{max} = 0.1$

Relative Precision on Diffractive Gluon Density

LHeC →

[90% CL bands]

FCC-eh →

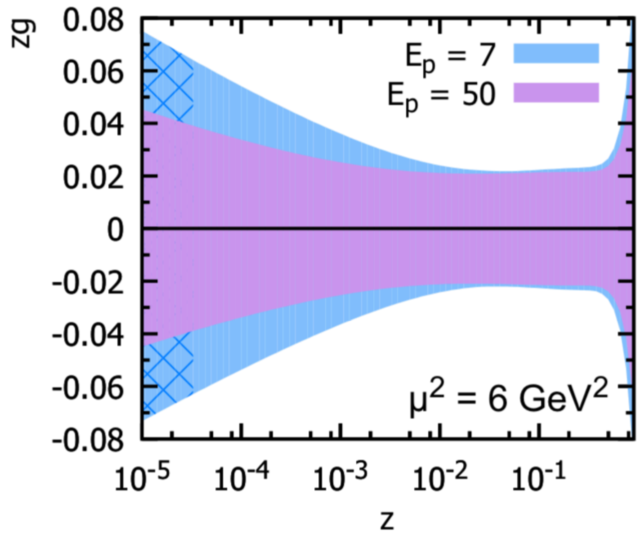


Notes in FCC-eh context:

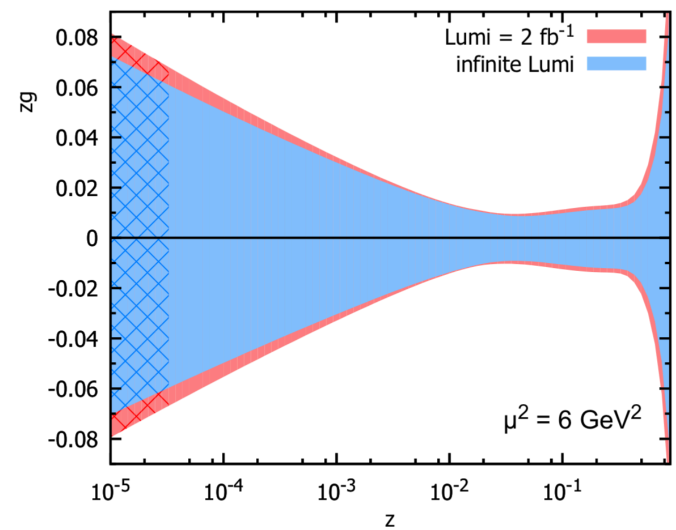
- Well constrained down to β or z ~ 10^{-4} – 10^{-5}
- Experimental precision on quarks <2% (direct from data)
- Experimental precision on gluons few% (scaling viol's)
- No statement on parameterisation or theory uncertainties

More Detail (only gluon shown)

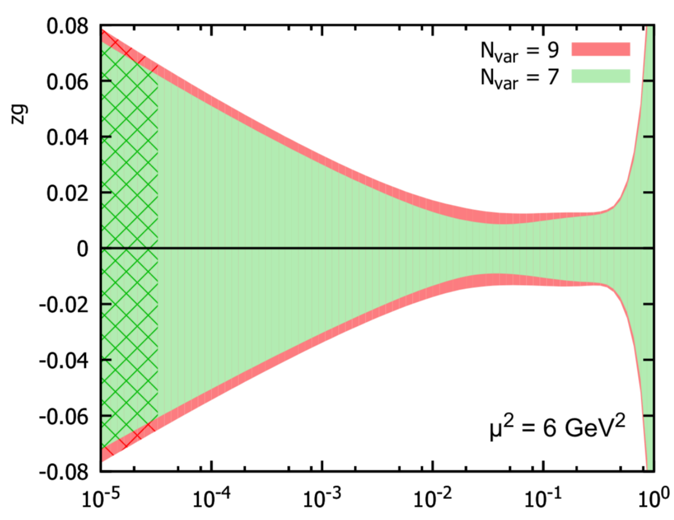
with 2% norm'n uncertainty



$2fb^{-1}$ v infinite lumi (LHeC)



Free IP and IR intercepts (LHeC)



Still open questions:
- Parameterisation bias / extrapolation uncertainties
- Sensitivity to flavour decomposition
- Sensitivity to deviations from pure DGLAP

Summary

- Low x QCD is a future frontier → emergent phenomena at high parton densities (resummation, saturation, confinement, mass).

- HERA opened up the field and showed central role of gluon

- Some progress at LHC, eg with Ultraperipheral J/Ψ

- Full understanding and unfolding of subtle, competing effects will require multiple observables at a higher energy ep collider

- FCC-eh (and LHeC) expands phase space, opens new observables and sensitivities at high precision → towards a complete picture.

- Most of simulations shown here are “1 day” physics … 2-5 fb^{-1}