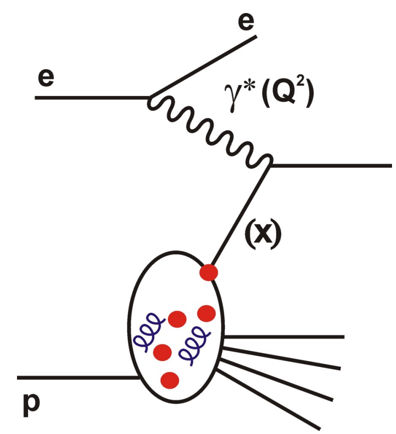
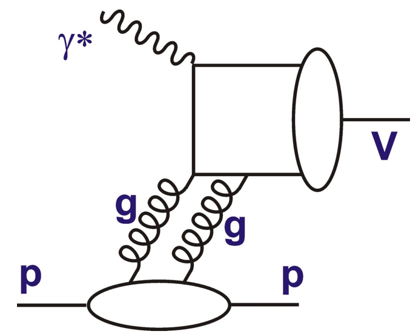
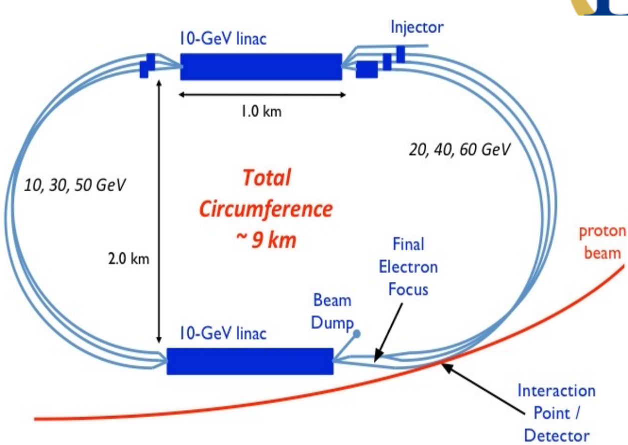
# TeV-scale Small-x Physics at LHeC and FCC-eh



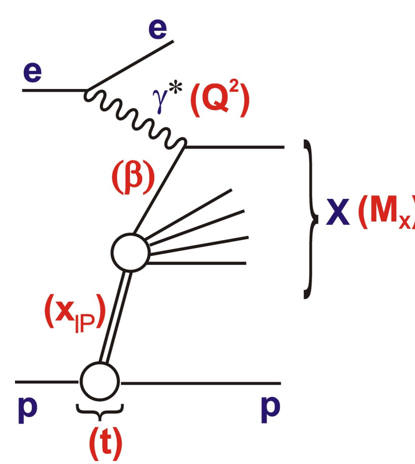

LHeC / FCC-eh / PERLE Workshop
Orsay
26 October 2022

Paul Newman
(University of Birmingham)



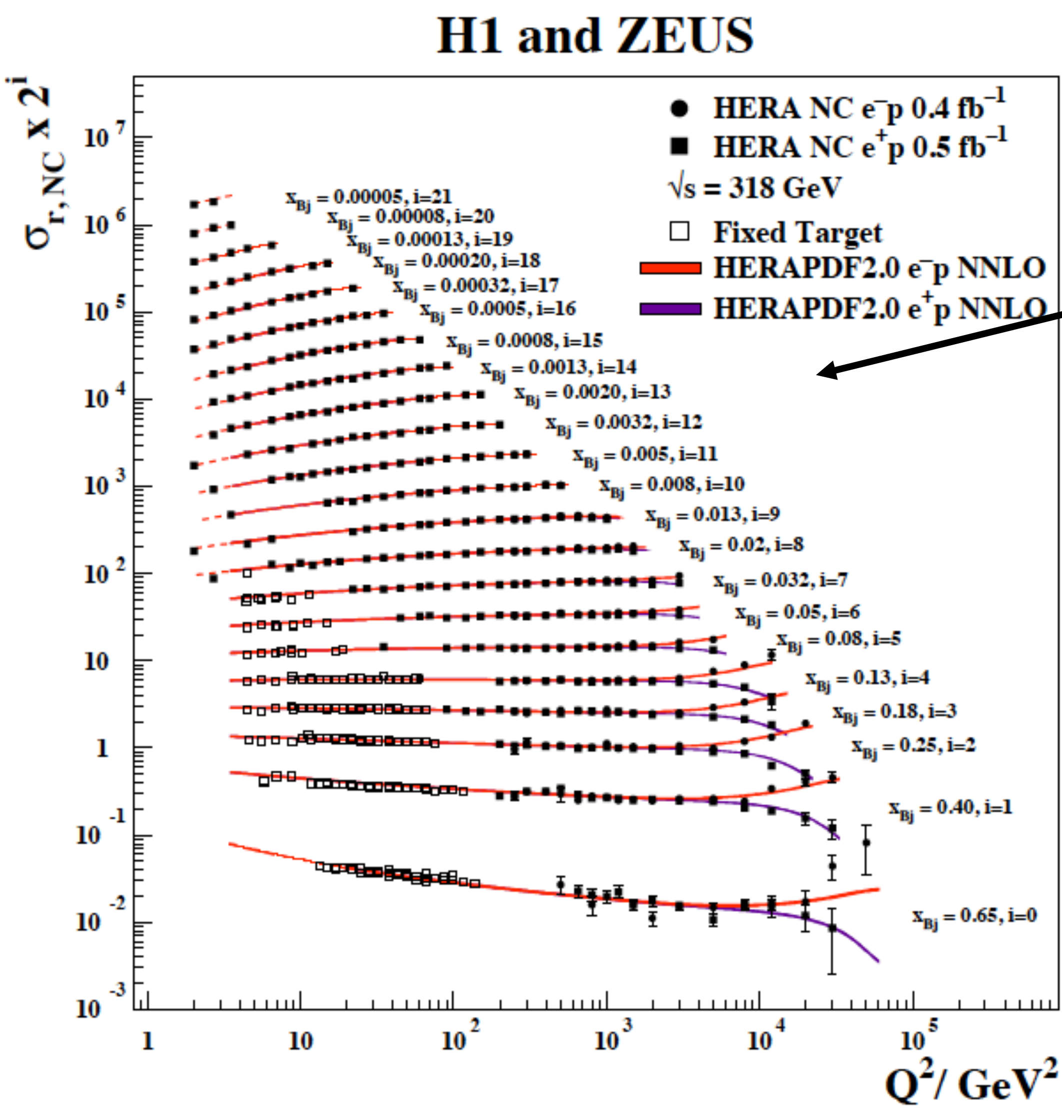




1) Where does HERA leave us?
2) Inclusive DIS at low x
3) Elastic J/Ψ Photoproduction
4) Diffractive DIS

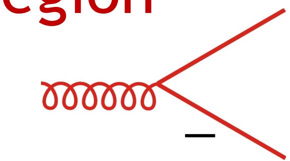


# Low x Physics is Driven by the Gluon

… knowledge comes mainly from inclusive NC HERA data




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

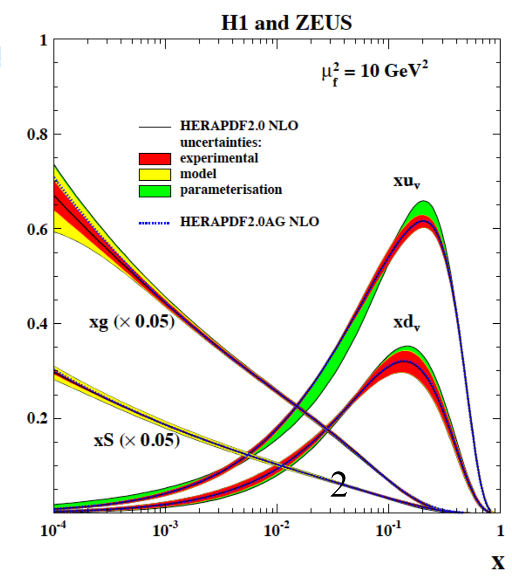


$$g \to q\bar{q}$$

- e.g. Prytz approx:

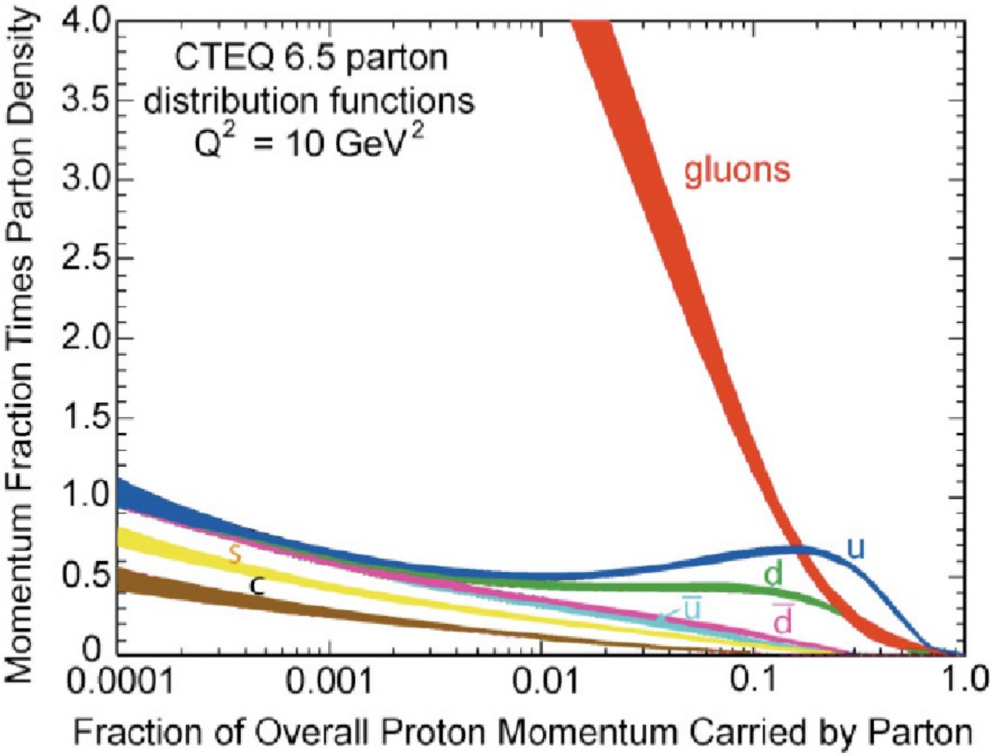
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

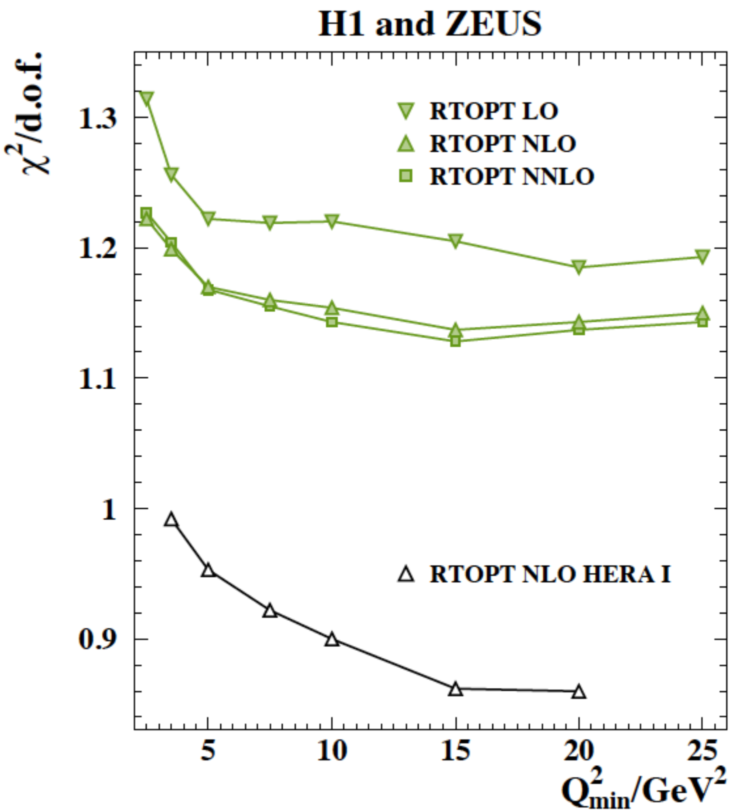
… needs lever-arm in $Q^2$ in pQCD region… reasonable precision to $x \sim 10^{-3}$.



# The "Pathological" Gluon

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

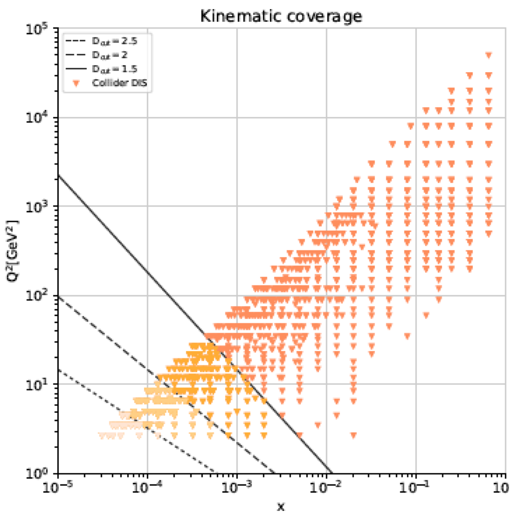


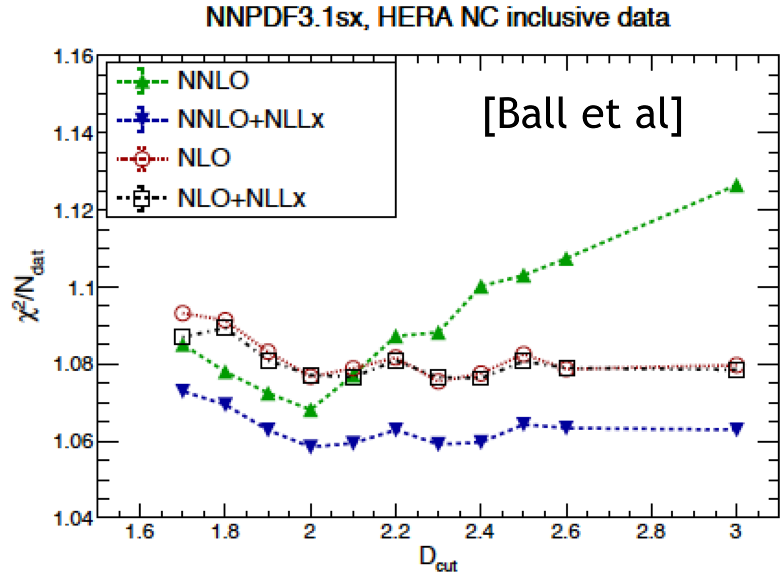




**Some evidence for deviations from (NNLO) DGLAP at lowest $Q^2$ in Final HERA-2 Combined PDF Paper:**

"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?



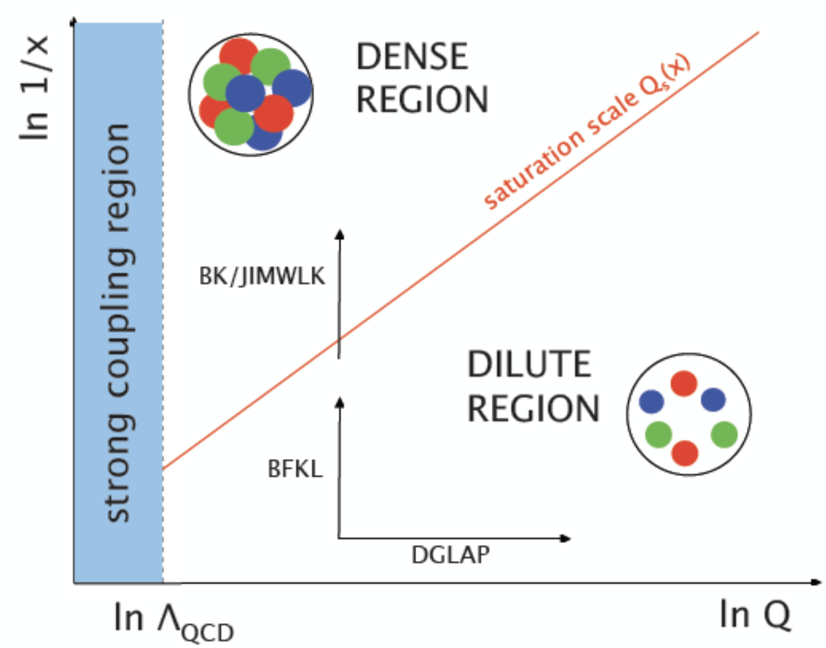

## Energy effects?

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

## Density effects?

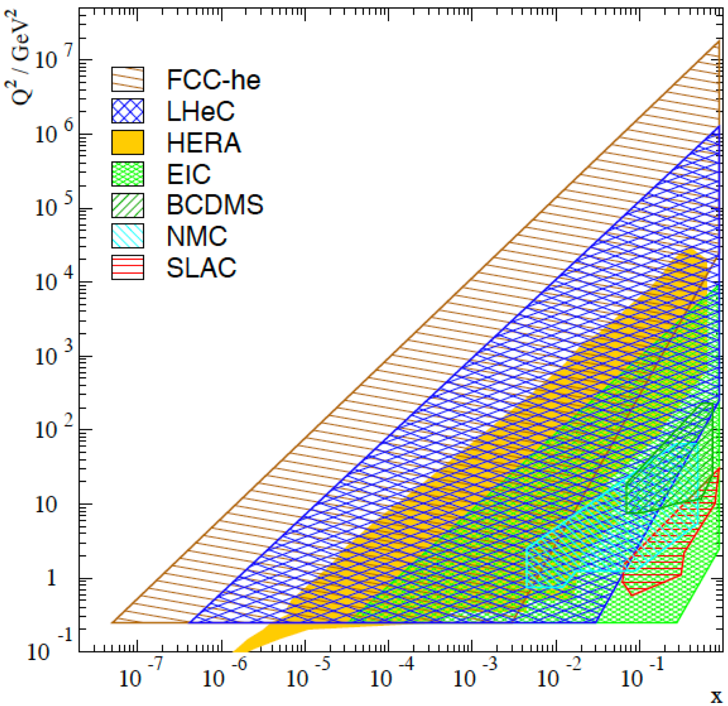
→ Non-linear gluon recombination (gg→g)?

… `Saturation' models successful in describing HERA data down to lowest x and $Q^2$ values

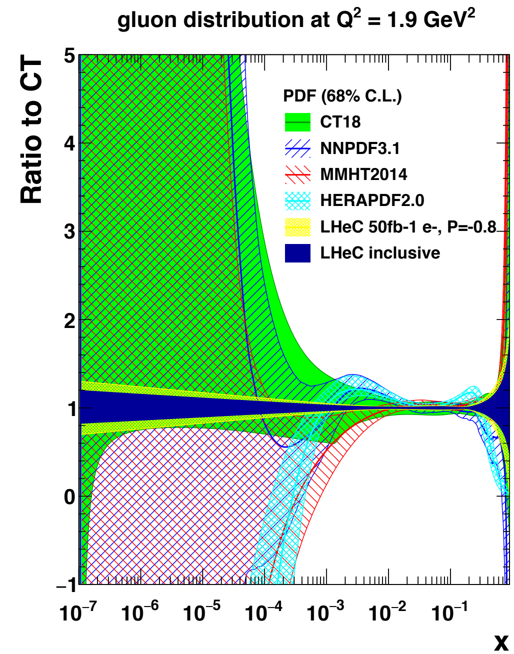


# Low x Kinematics at LHeC and FCC-eh

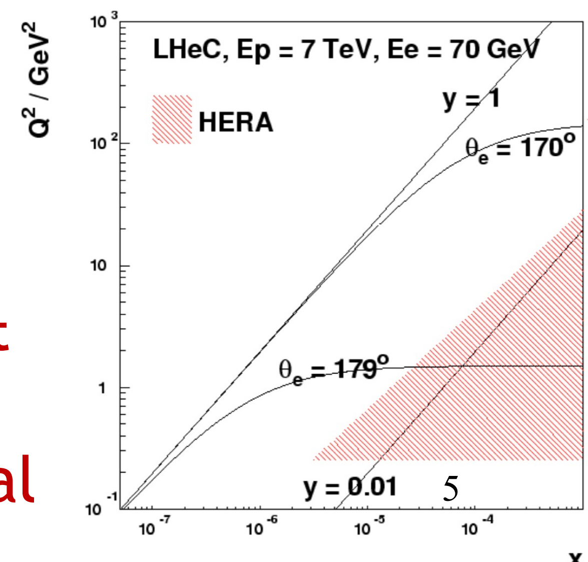
## >2 orders of magnitude extension at fixed $Q^2$ for ep at LHeC




- Transformational impact on PDF kinematic range and precision - to $x \sim 10^{-5}$ or lower.

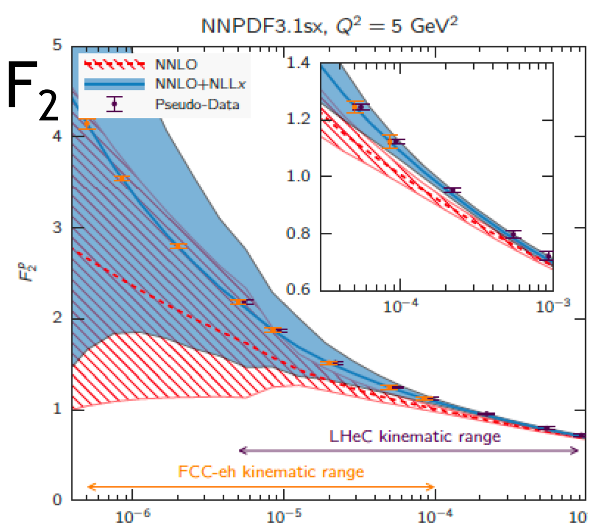


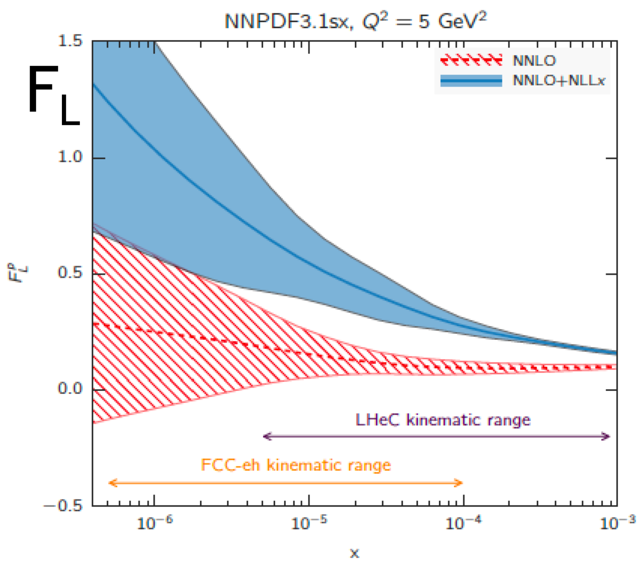

- Phase space extends deep into region where both saturation and BFKL resummation effects expected in both ep & eA at perturbative $Q^2$
- Near hermetic detector acceptance is vital



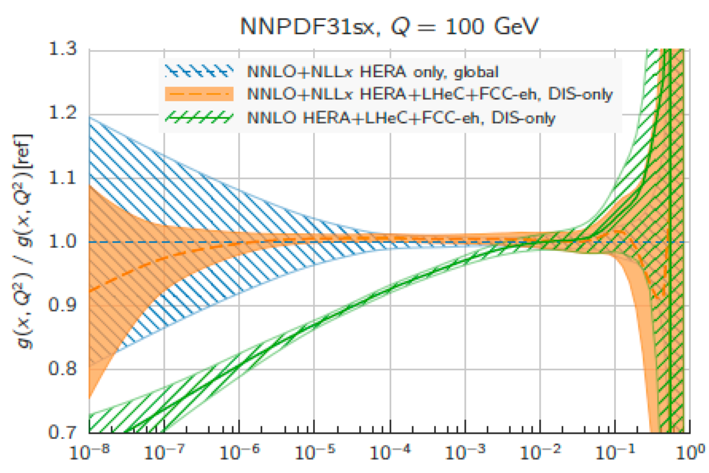
# Potential of LHeC & FCC-eh to establish BFKL

- 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



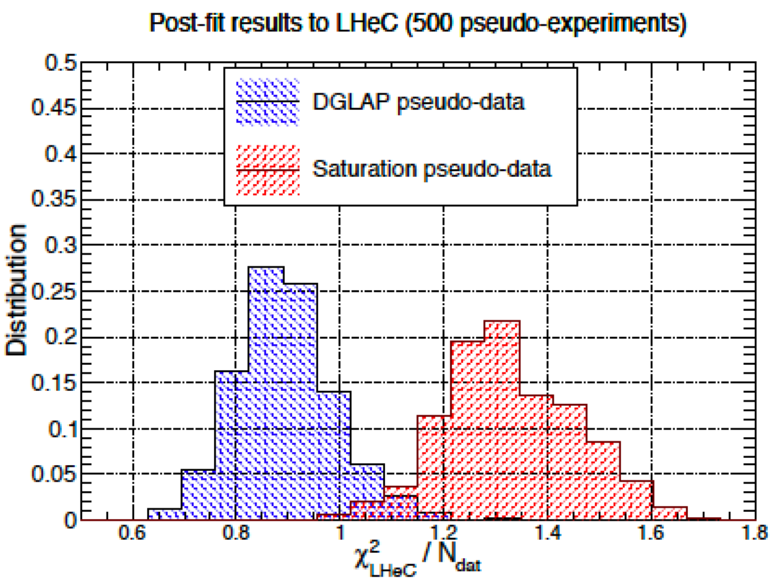

- Extracted PDFs including LHeC and FCC-eh pseudodata highly sensitive to inclusion of NLL 1/x resummation in simulated data

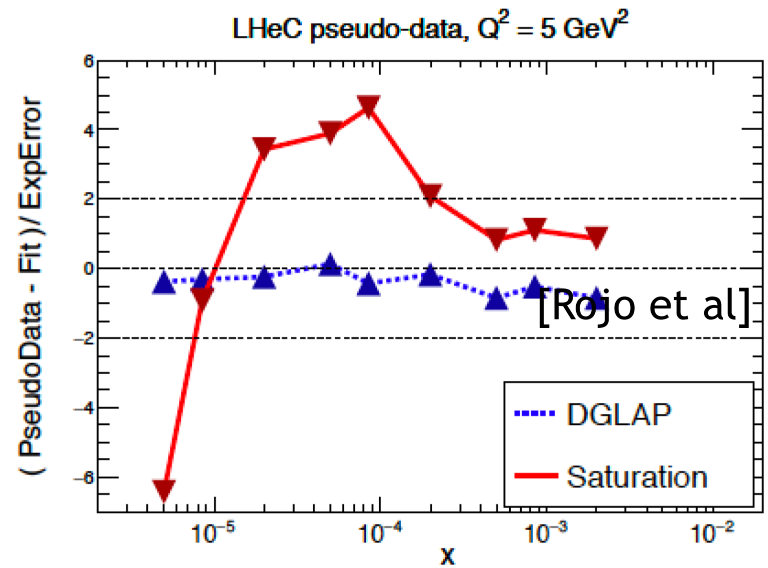
# Can Parton Saturation be Established in ep @ LHeC?

→ Create LHeC pseudodata including saturation by extrapolating (DGLAP-inproved) GBW model based on fit to HERA data:

→ try to fit using pure NNLO DGLAP machinery

… Cannot absorb the non-linear effects into the initial conditions



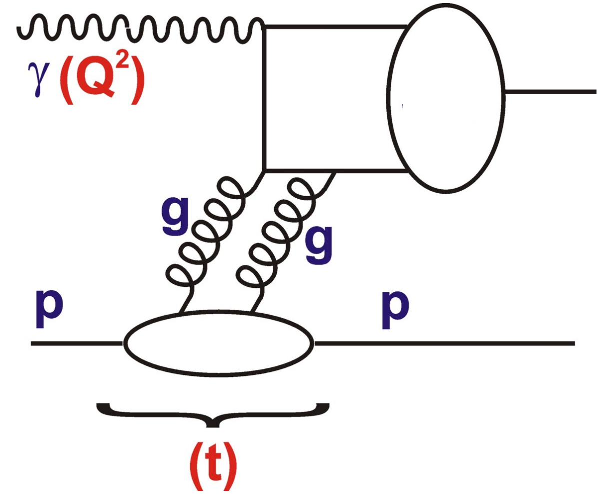

[See also recent study by Nestor et al using BK saturation model]

> If this is not a smoking gun: unambiguous observation of saturation will be based on tension between observables:
> e.g. $F_2$ v $F_L$ in ep, $F_2$ in ep v eA, diffractive channels

# Motivation for Diffraction

[Low-Nussinov] interpretation as 2 gluon exchange:

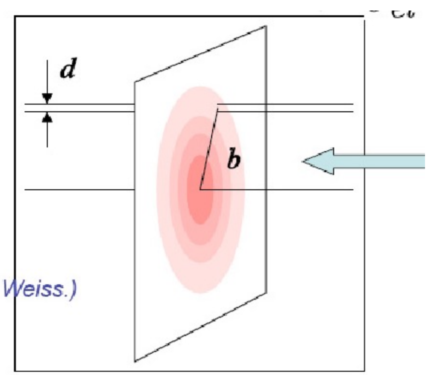
1) Sensitivity to correlations between partons and 3D structure



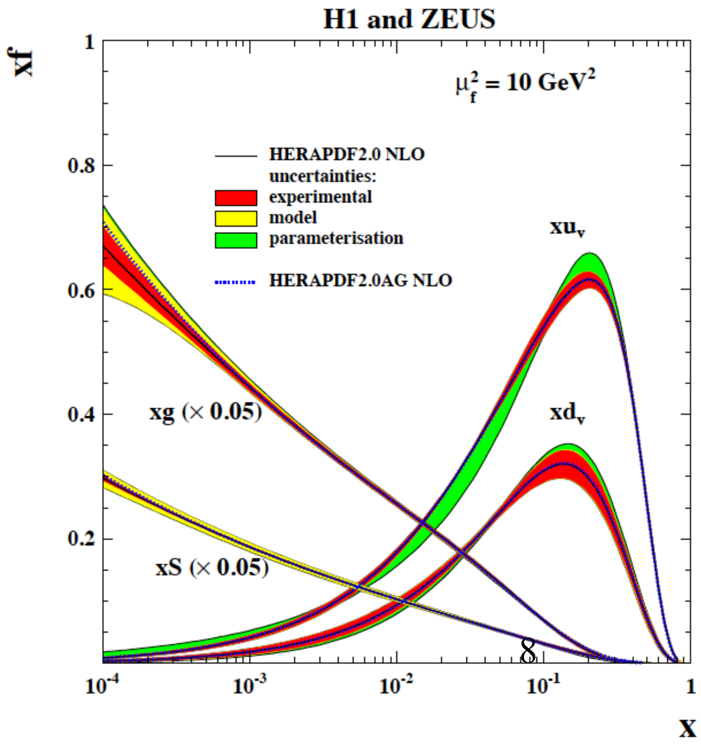

2) Sensitivity to low x gluon → non-linear saturation / BFKL effects?

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

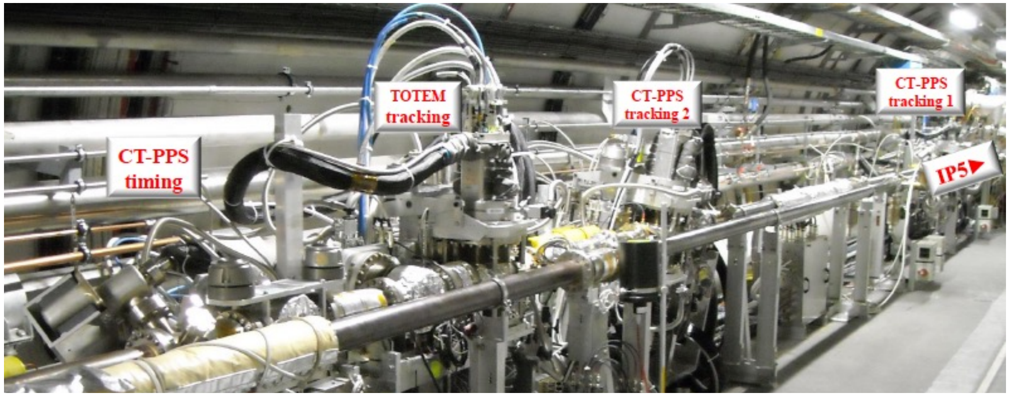
→ Large t (small b) probes densest packed part of proton?..




(figure from C. Weiss.)



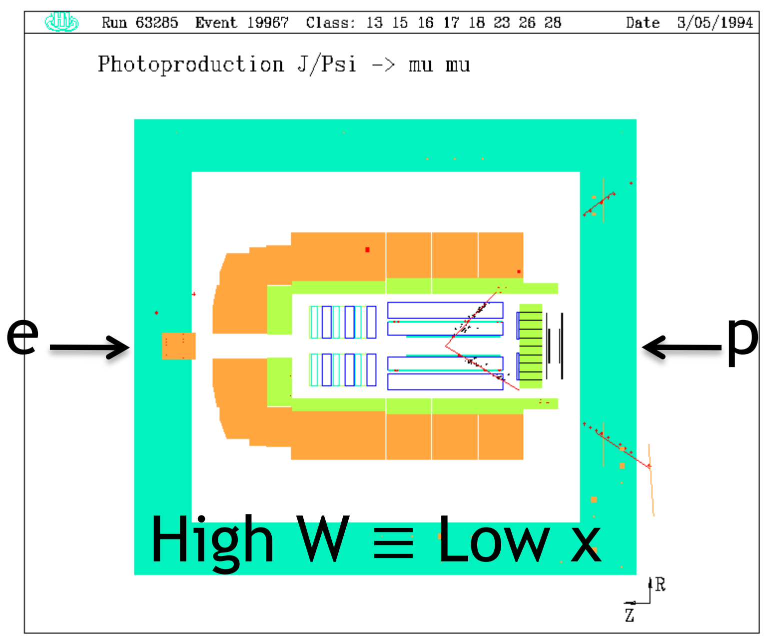
# Experimental Remarks

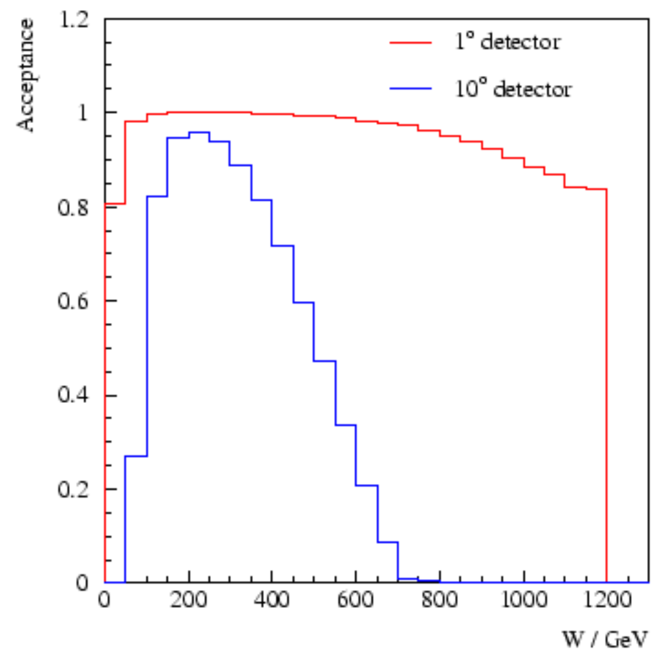



- Proton tagging in Roman Pot detectors evolved since HERA (e.g. CMS/TOTEM have 14[!], giving exquisite tracking & timing precision).

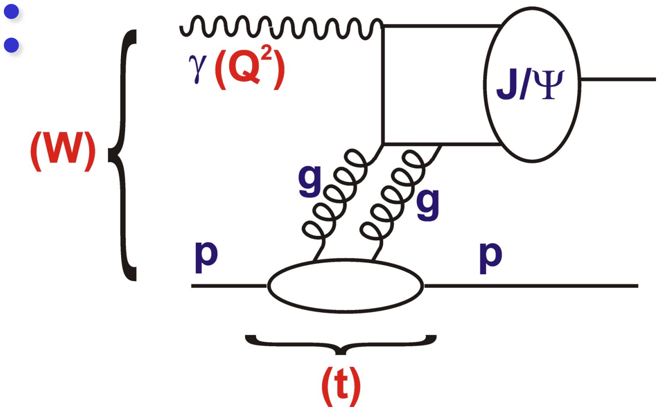
→ Need to build into IR design

- Hermetic tracking (& muon?) coverage vital for acceptance to highest W (i.e. lowest x) e.g. muons from exclusive $J/\Psi \rightarrow \mu^+\mu^-$



# Exclusive Diffraction Example: Elastic J/Ψ Photoproduction




**Favourable Kinematics**

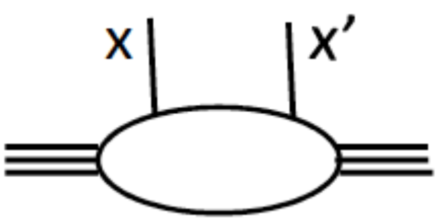
- Clean 2 lepton experimental signature

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

  … eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) \; / \; (Q^2 + W^2) \sim 10^{-5}$

**3-Dimensional Information**

- Sensitive to correlations between parton positions, longitudinal and transverse momenta (Generalised Parton Densities)



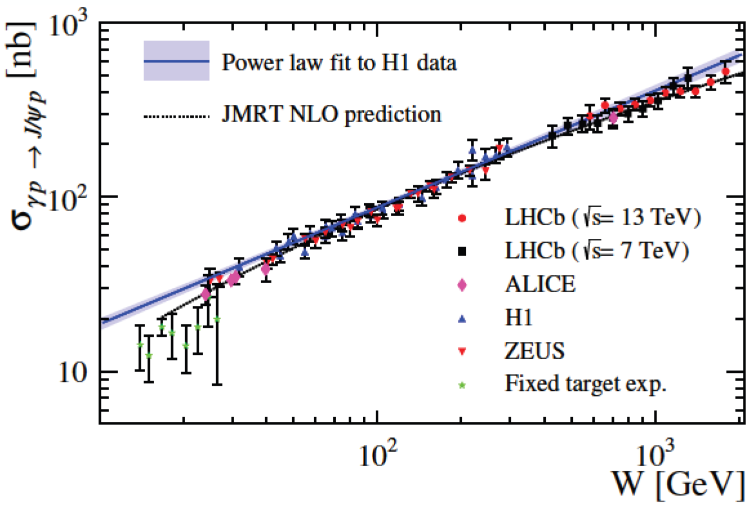

**Complications**

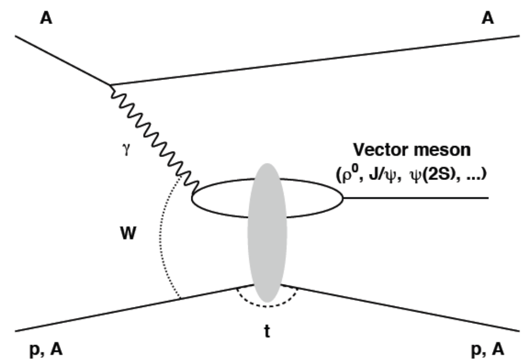
- Vector meson wavefuction

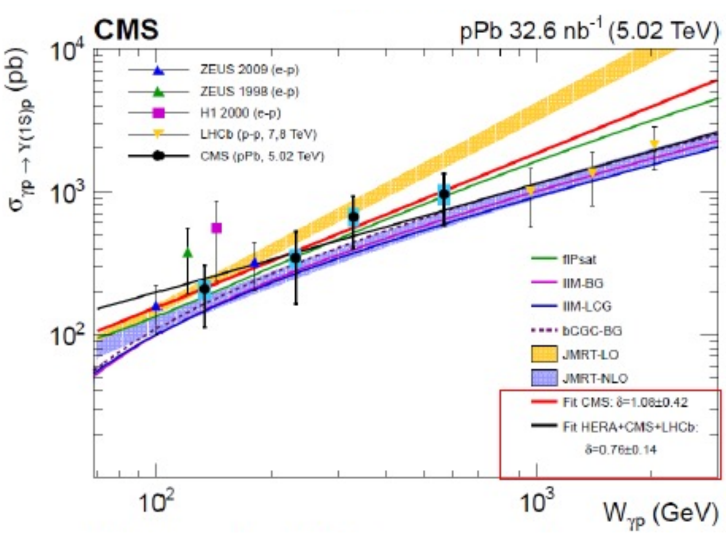
- Large scale uncert's in collinear factorization approaches

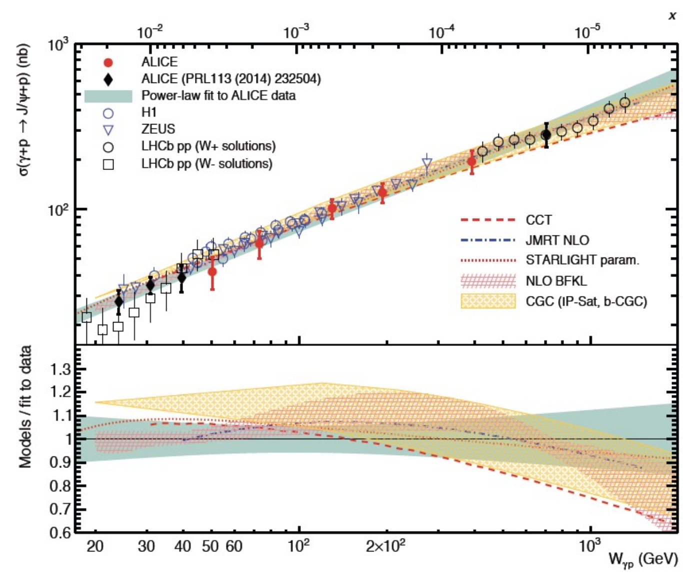
# Impact of LHC Exclusive J/Ψ Data

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



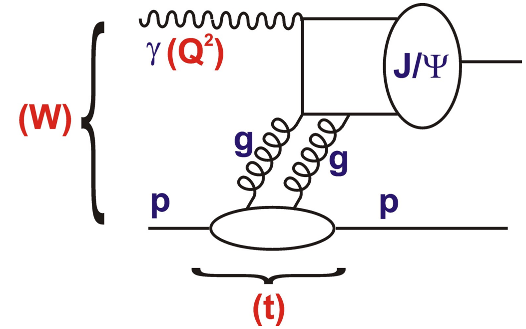



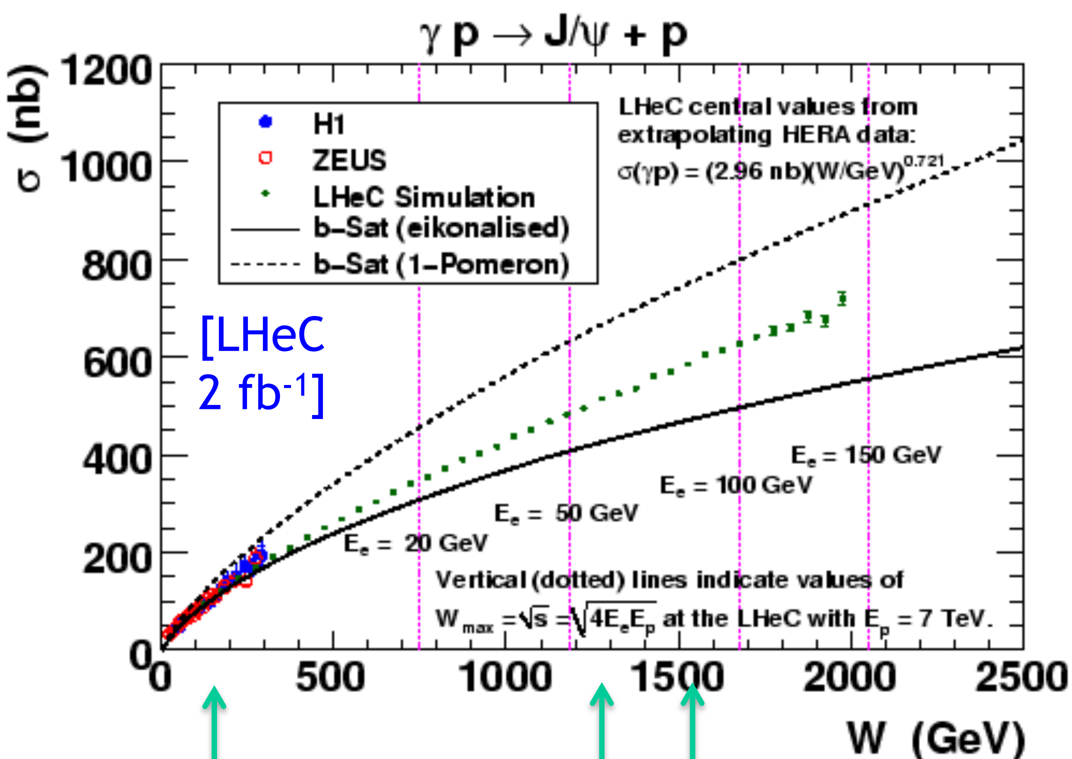




- No sign of deviation from simple power law behaviour (yet)

# 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




EIC limit

LHeC limit

Current LHCb limit

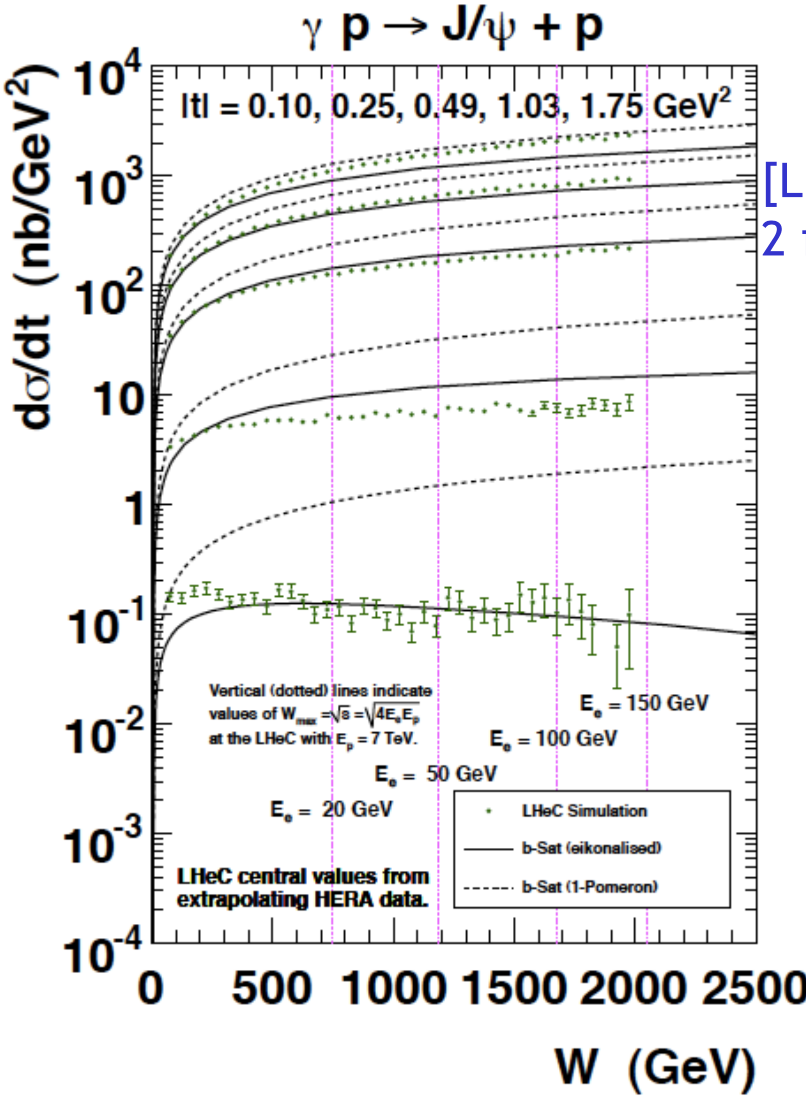
FCC-eh limit

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

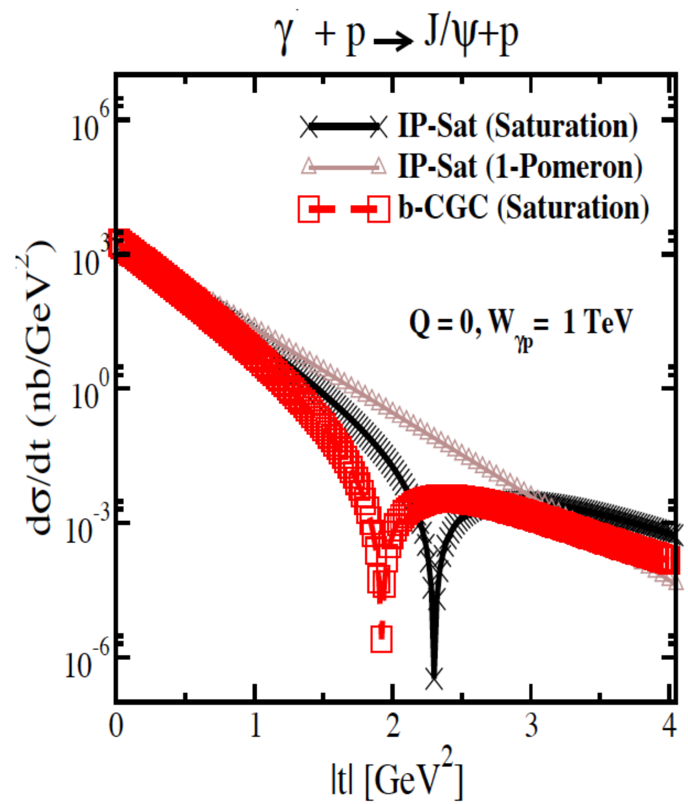
- Lack of clear signal at LHC to date → features are more subtle, require higher energy and more variables (t, $Q^2$, A)

# t Dependence of Elastic J/ψ in ep

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

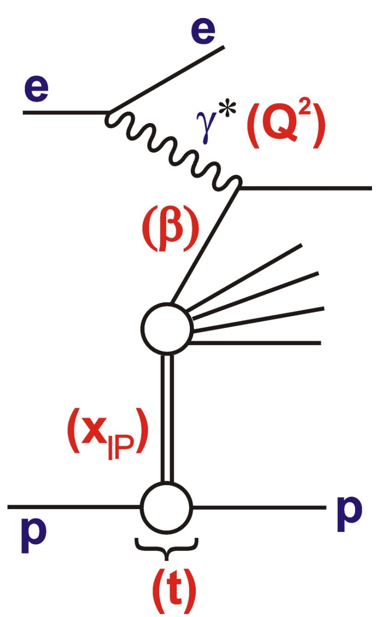


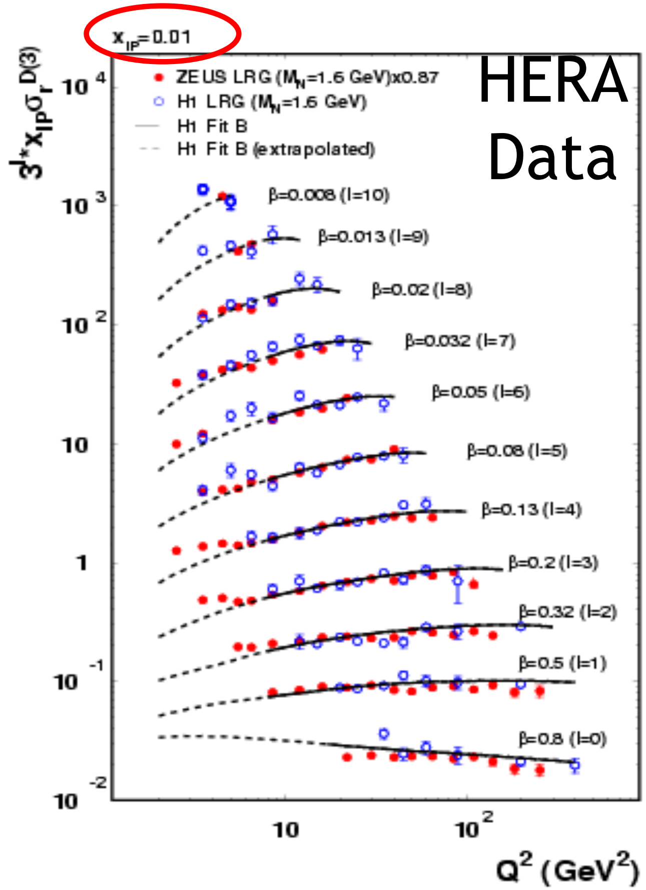

[LHeC/ 2 fb$^{-1}$]

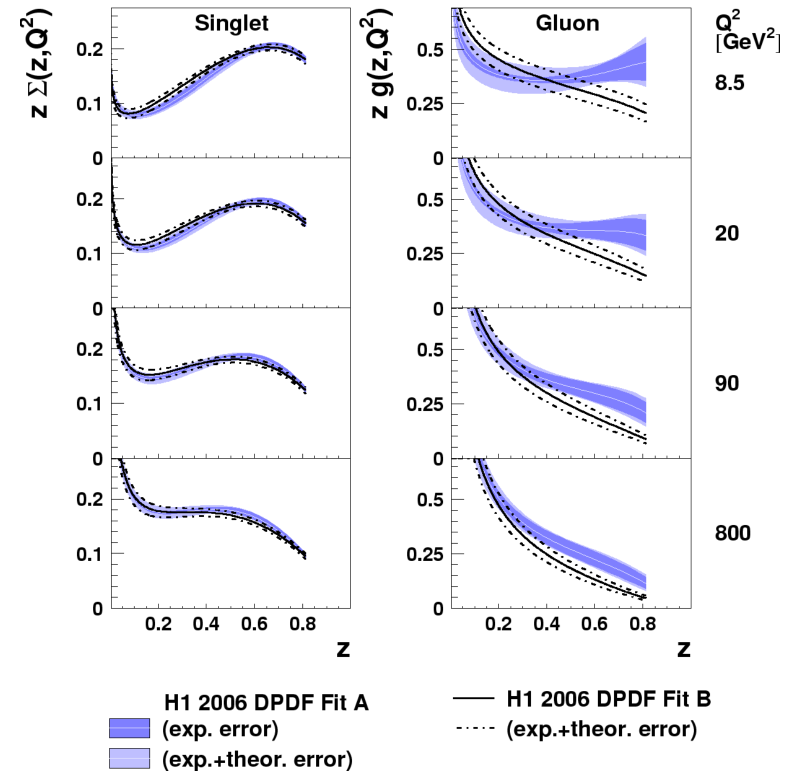



- Dips in t distribution proposed as (model dependent) signature of departure from linear evolution

# Inclusive Diffraction and Diffractive PDFs



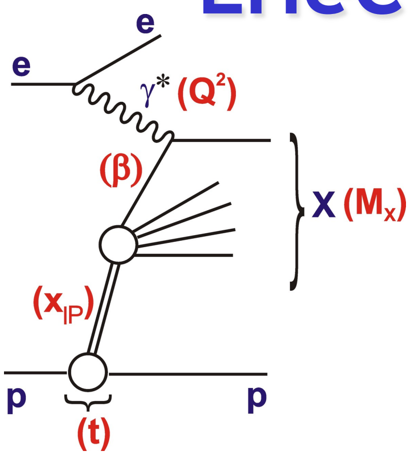



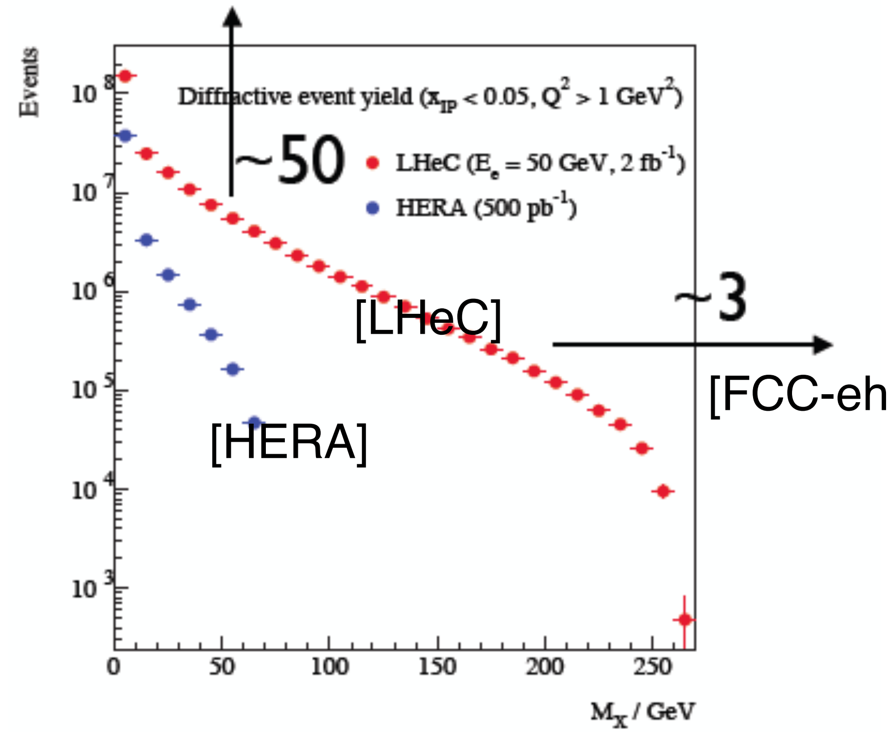

- ep→eXp with proton 4-momentum barely changed has a leading twist contribution ~10% of total DIS x-sec

- (Semi-inclusive) diffractive PDFs extracted from inclusive diffraction describe all aspects of diffractive final states

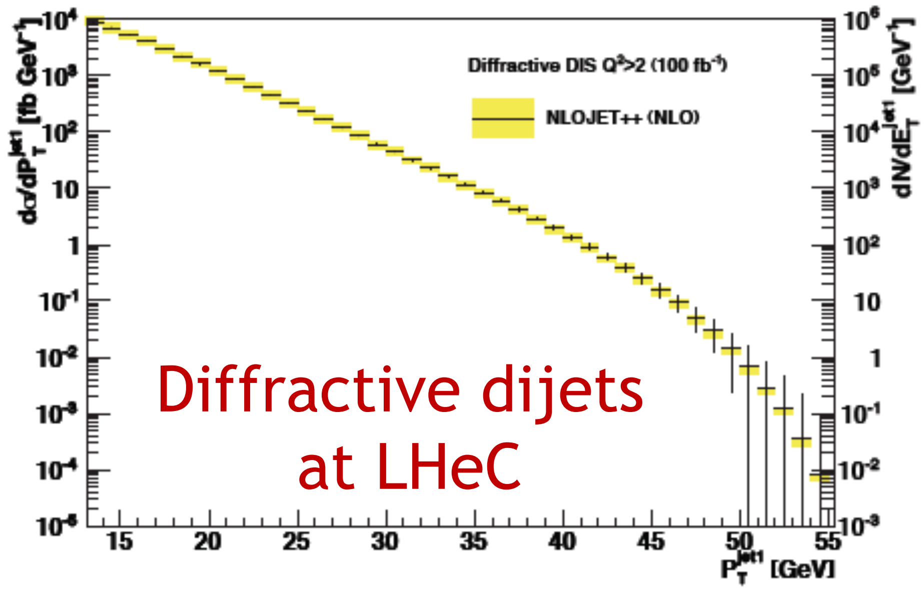
# Inclusive Diffraction at LHeC & FCC-eh



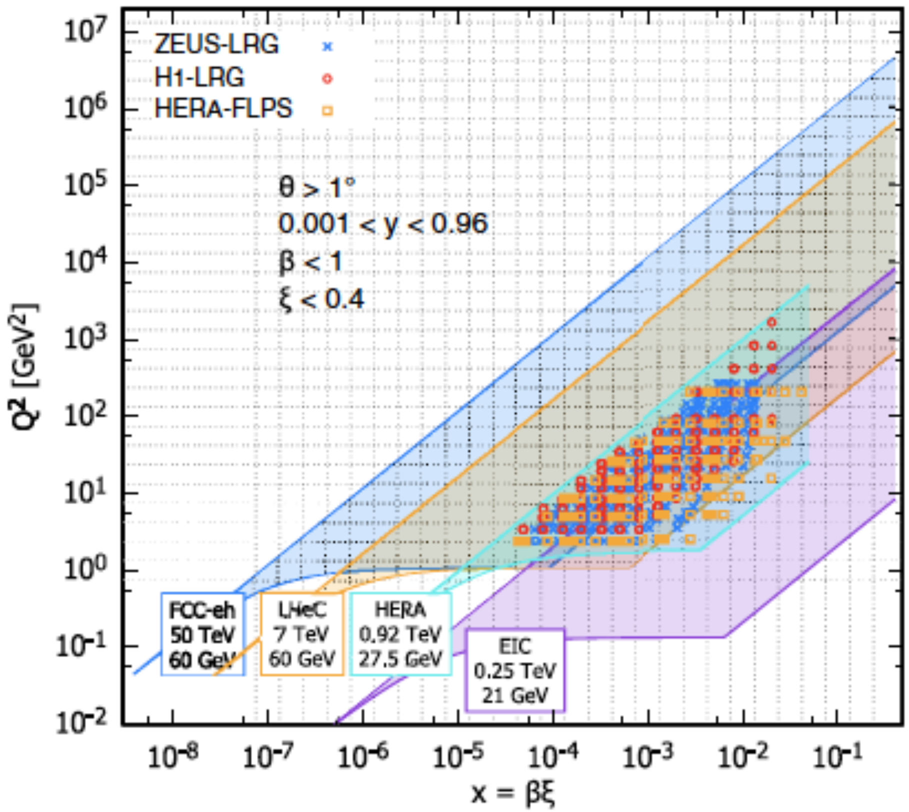

… Diffractive structure in wider $(\beta, Q^2)$ range than proton $(x, Q^2)$ range at HERA




- Low $x_{IP}$ → cleanly separate diffraction
- Low $\beta$ → 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 etc.



# 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 $(\beta, Q^2)$ 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

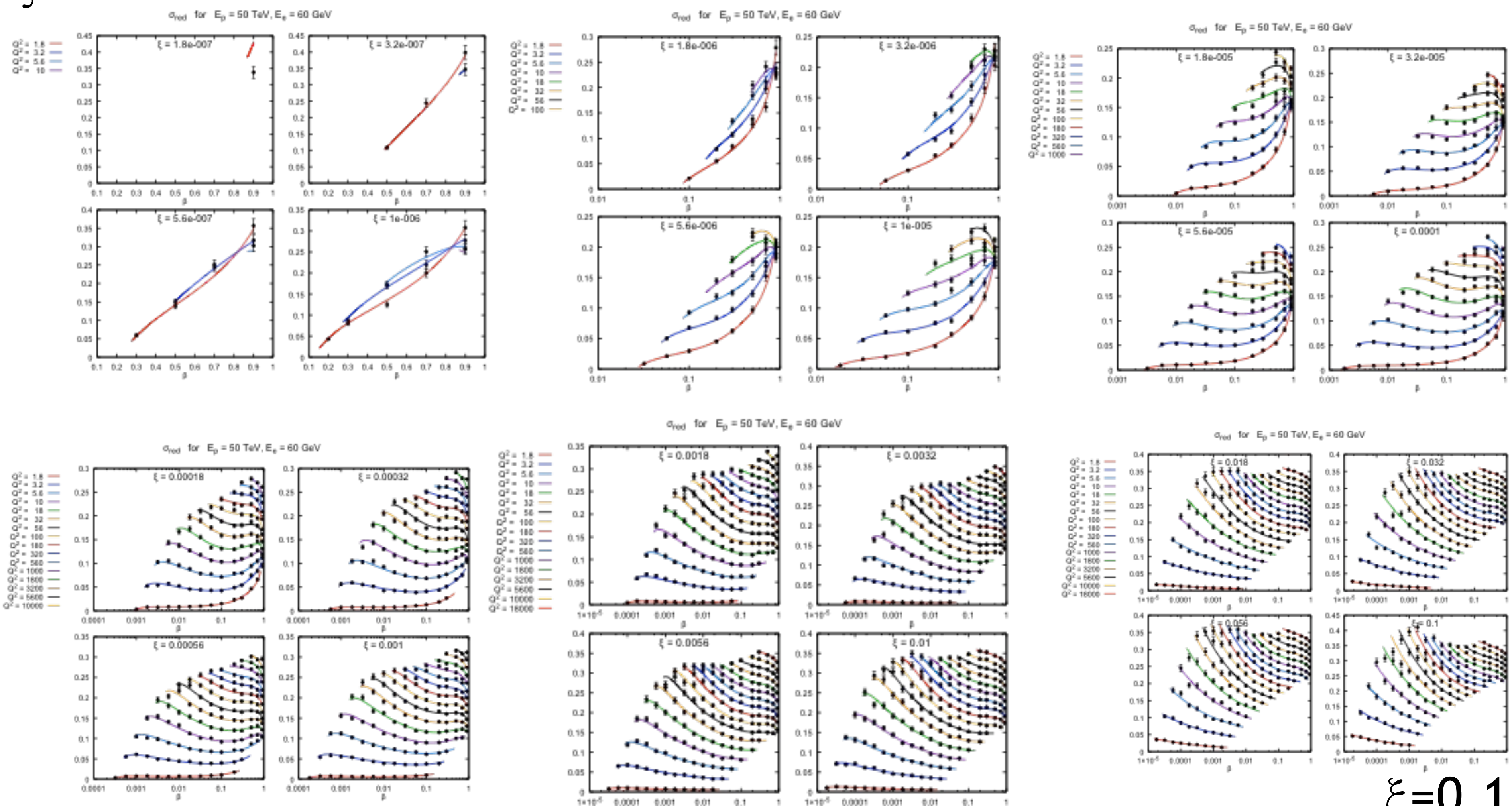
d = u = s = dbar= ubar = sbar

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>

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

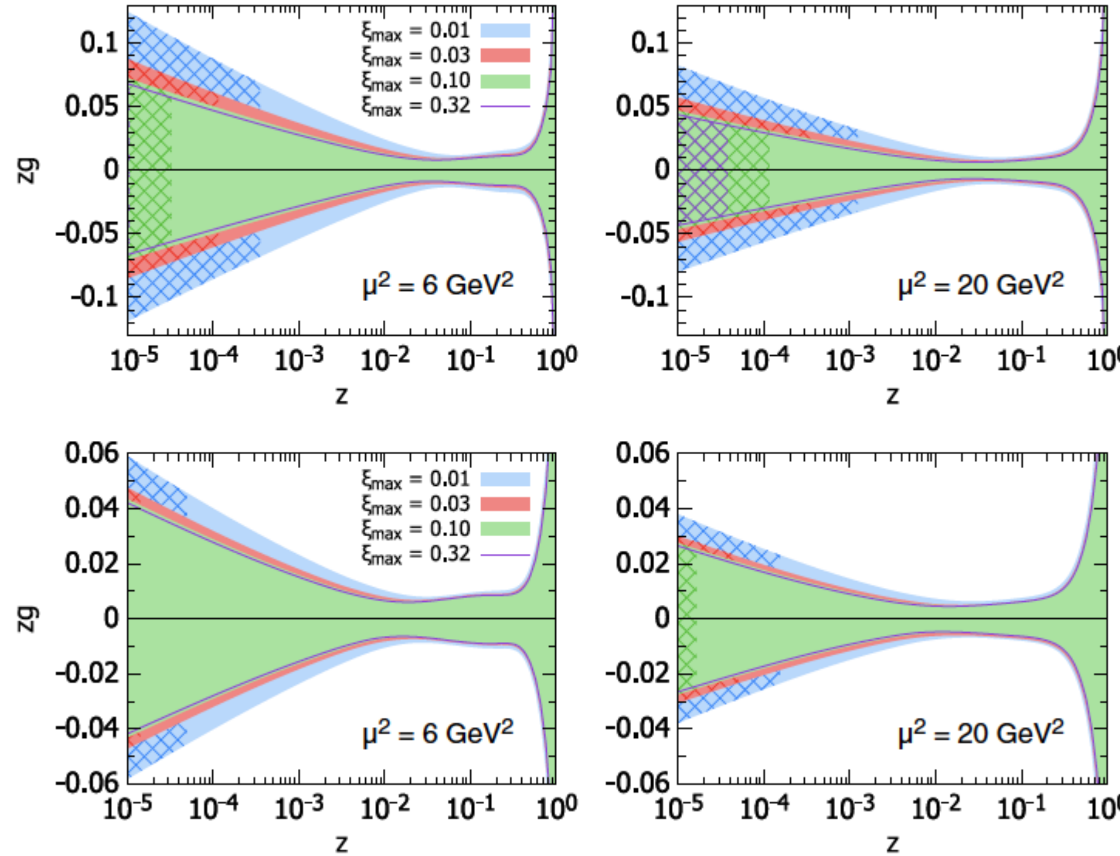
$\xi_{max} = 0.1$

# Relative Precision on Diffractive Gluon Density

LHeC →

[90% CL bands]

FCC-eh →




Notes:

- 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)
- Parameterisation / theory uncertainties not included
- Sensitivity to flavour decomposition still to be evaluated
- Sensitivity to pure DGLAP still to be evaluated

# 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/$\Psi$

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

- LHeC and FCC-eh expand phase space, open new observables and sensitivities at high precision → towards a complete picture.

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