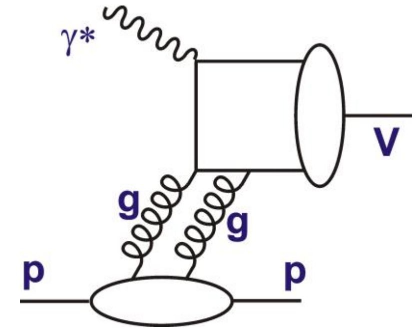
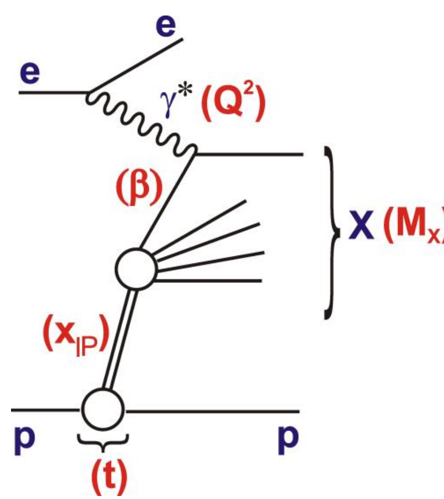
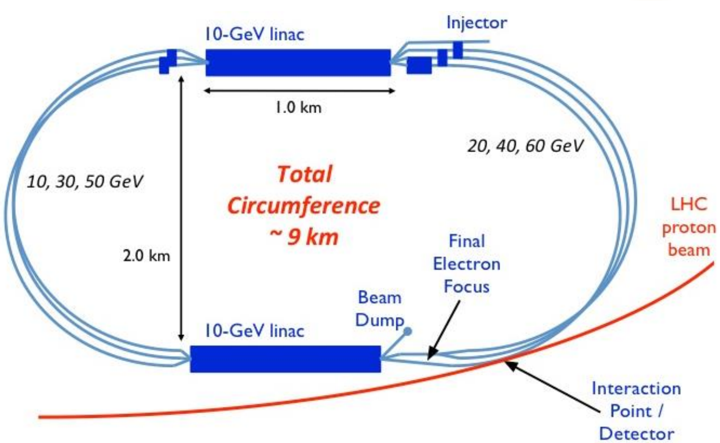
New Simulations of Diffraction at LHeC and FCC-eh



Workshop on LHeC, FCC-eh, PERLE
Chavannes de Bogis
25 October 2019

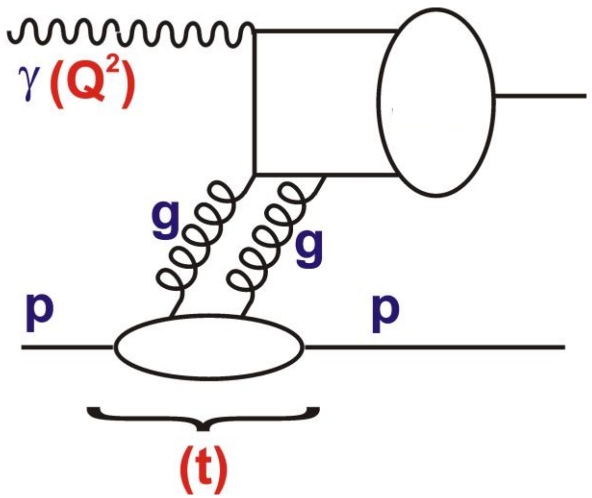
Paul Newman
(University of Birmingham)





1) Motivation
2) Exclusive J/Ψ
3) Inclusive Diffraction

Motivation for Diffraction



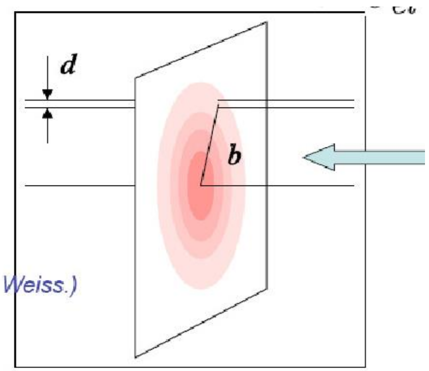
[Low-Nussinov] interpretation as 2 gluon exchange:

1) Sensitivity to correlations between partons and 3D structure

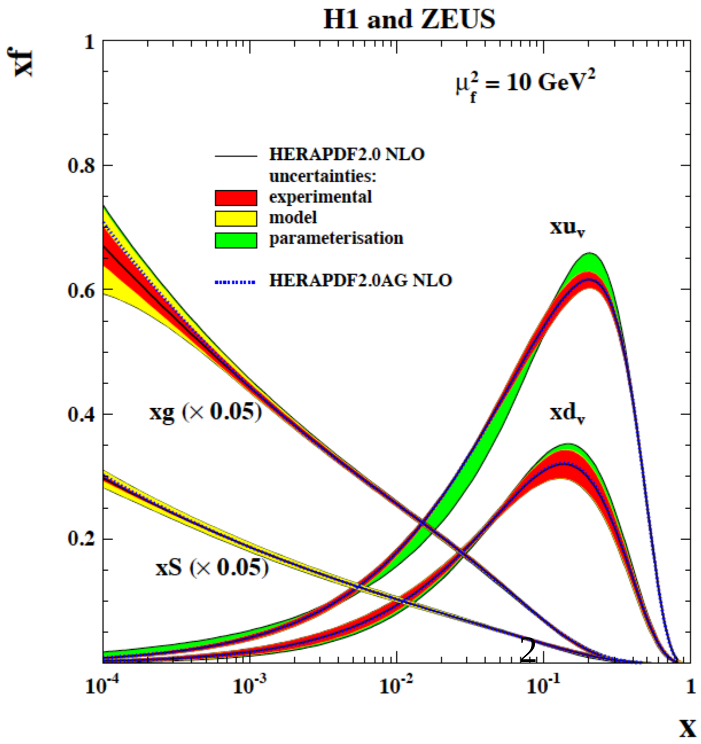
2) Sensitivity to (pathologically rising?) low x gluon → non-linear / saturation?

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

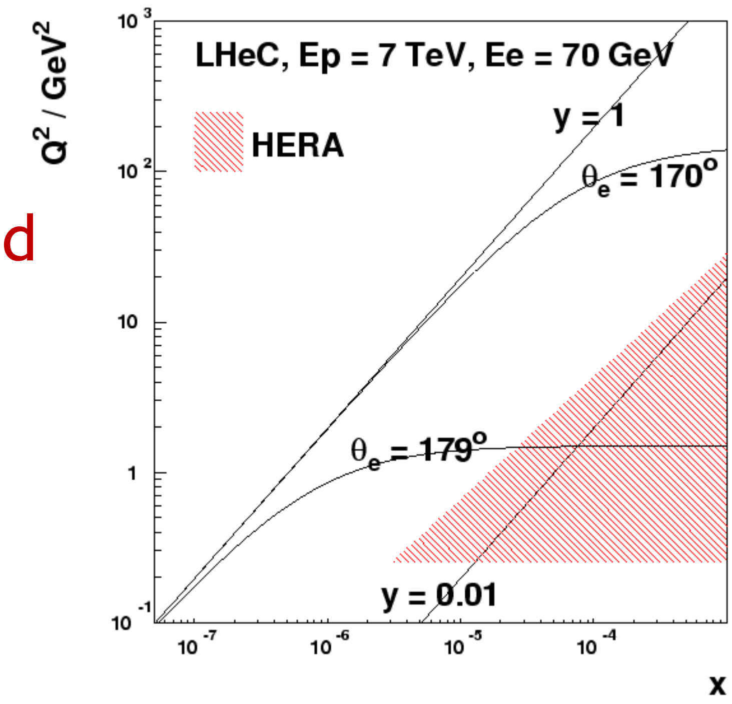
→ Large t (small b) probes densest packed part of proton?..



(figure from C. Weiss.)



Maximal Detector Acceptance is Vital

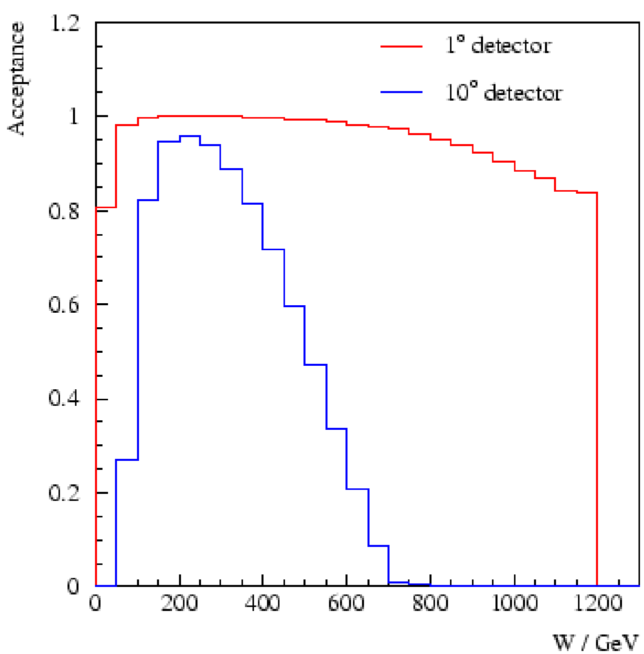


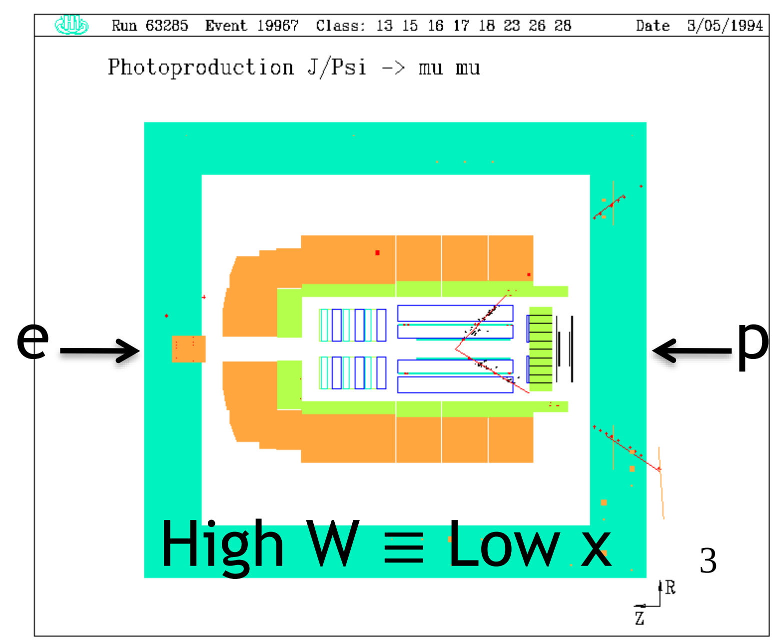
Low x & low Q^2 kinematically correlated

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

Also for exclusive final states …

e.g. muons from exclusive $J/\Psi \rightarrow \mu^+\mu^-$

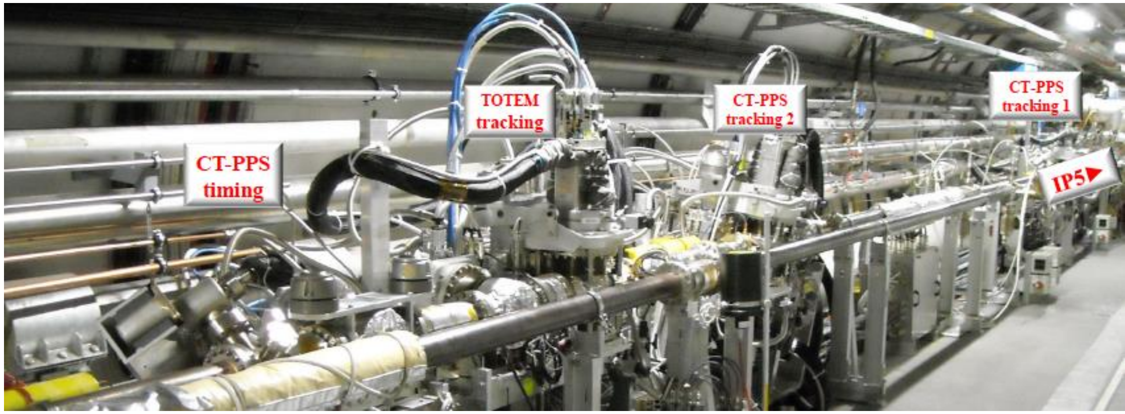


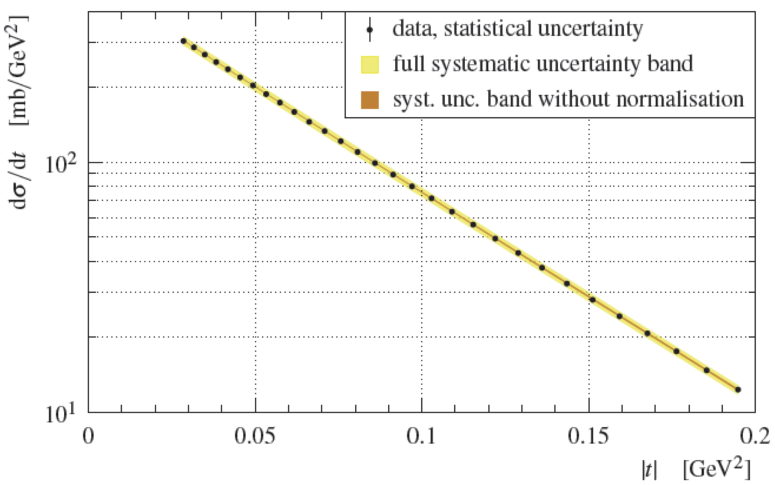


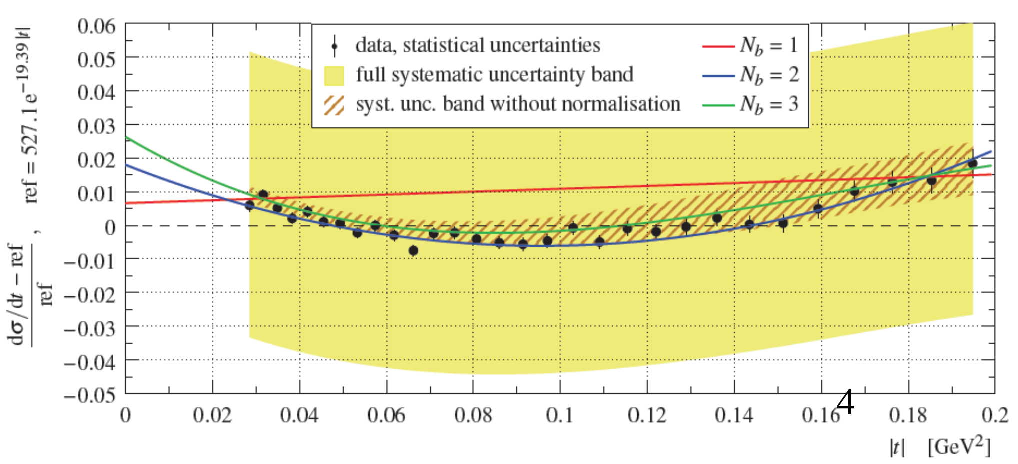
Diffraction at Future Colliders will be Based on Proton Tagging (→ Yuji's talk)

LHC experiments (TOTEM, ALFA@ATLAS) show that precision measurements are possible with Roman pots, covering wide kinematic range and including high lumi (even with pile-up)

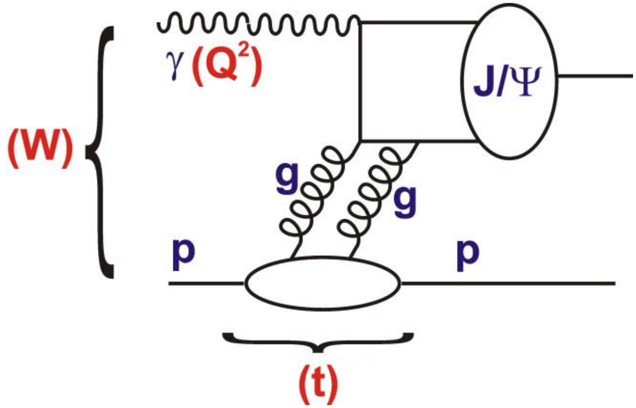
e.g. TOTEM operated 14 pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential t dep …







Exclusive Diffraction: Elastic J/Ψ Photoproduction



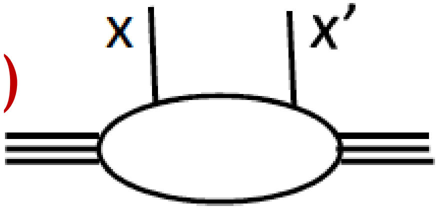
Advantages

- Clean 2 lepton experimental signature

- Scale $Q^2 \sim (Q^2 + M_V^2)/4 \;\; >\sim 3 \; GeV^2$ 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)



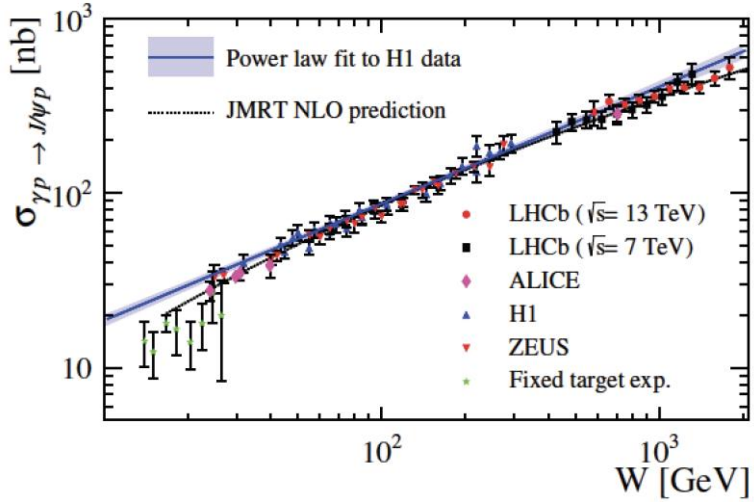
Complications

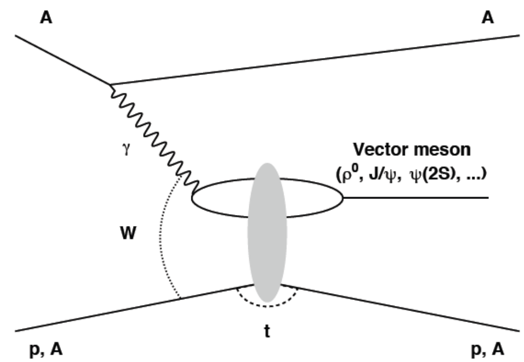
- Vector meson wavefuction

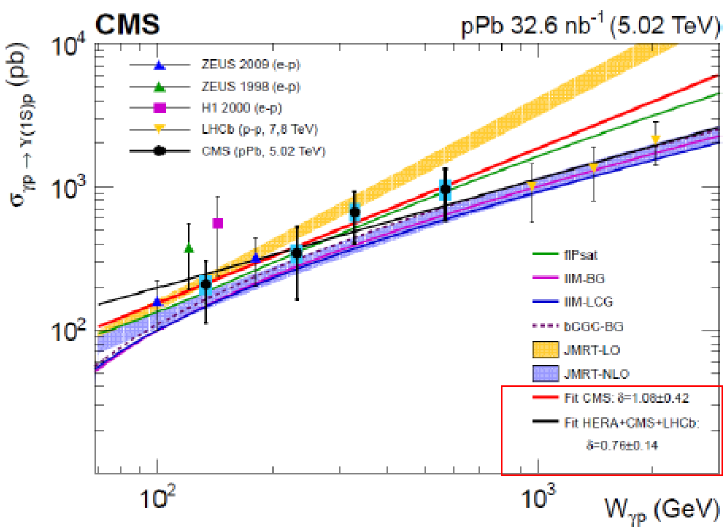
- Large scale uncert's in collinear fac'n (NLO v LO convergence)

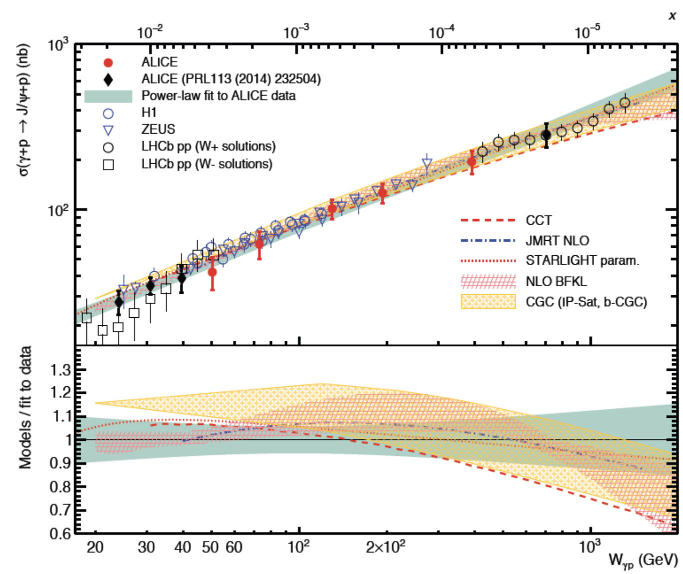
Current Exclusive J/Ψ Data

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



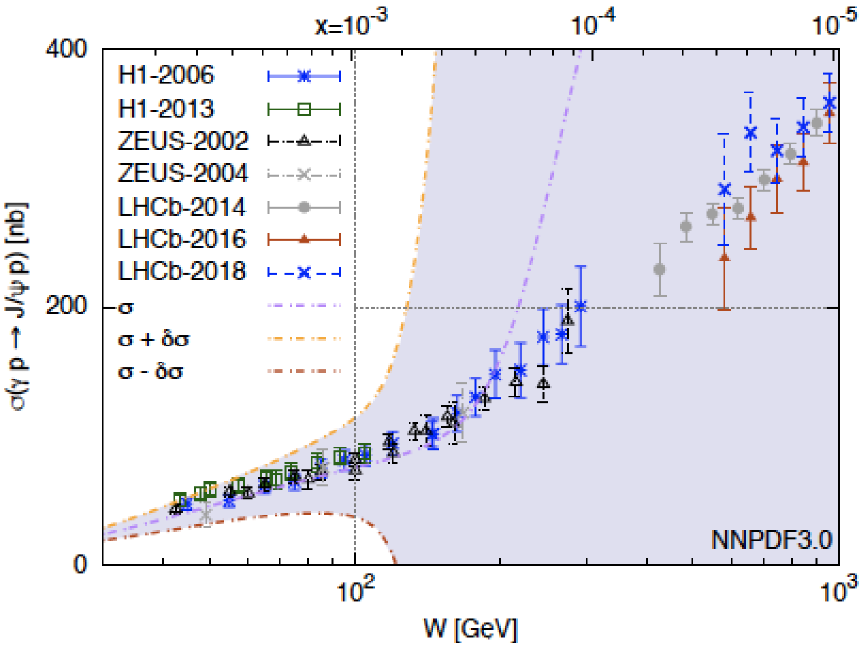






- No sign of saturation (yet)
- JMRT NLO gives excellent 'out-of-box' prediction (k_T fac^n)

Interpretation in JMRT

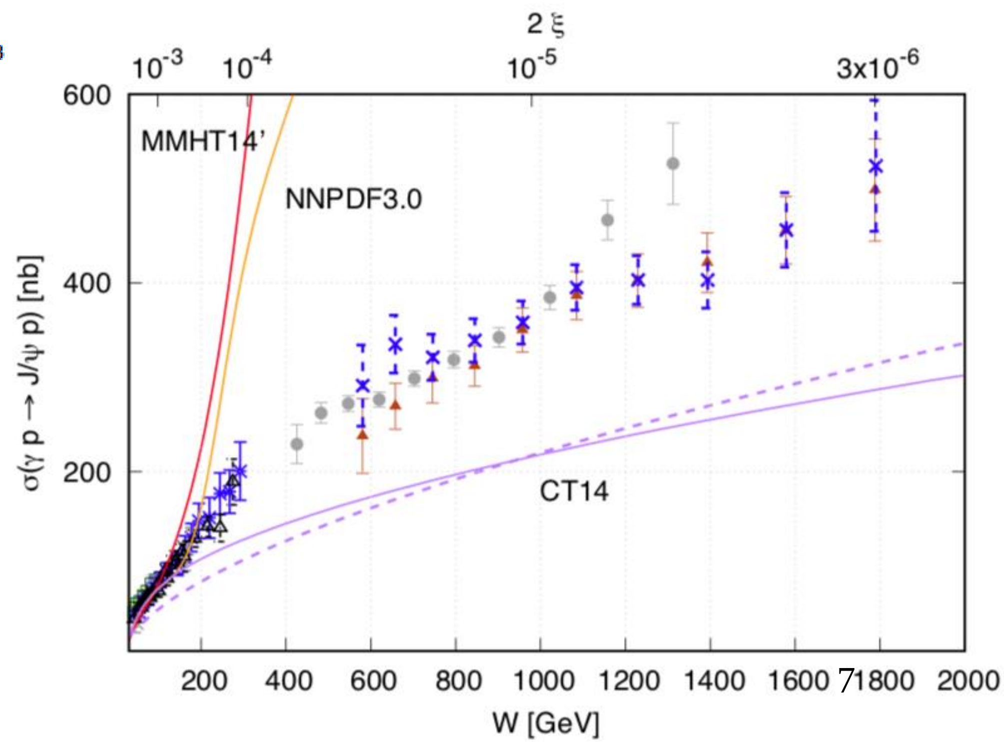


- JMRT k_T factorization model (attempts to) overcome scale problems etc → see recent Flett et al. paper

- Data uncertainties much smaller than PDF theory uncert's (band)

- Apparently remarkable sensitivity to low x gluon → Distinguishes between global PDF sets!

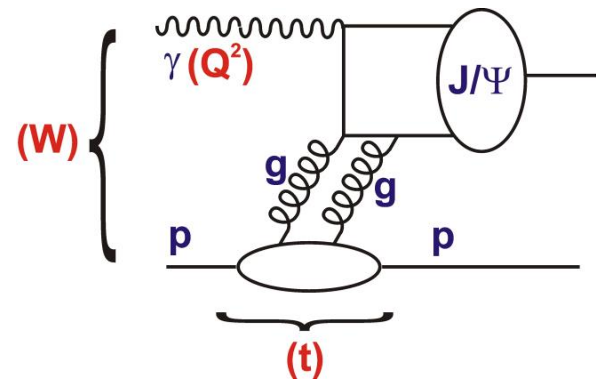
- Not at all well established theoretically, but surely worth pursuing in future ep!

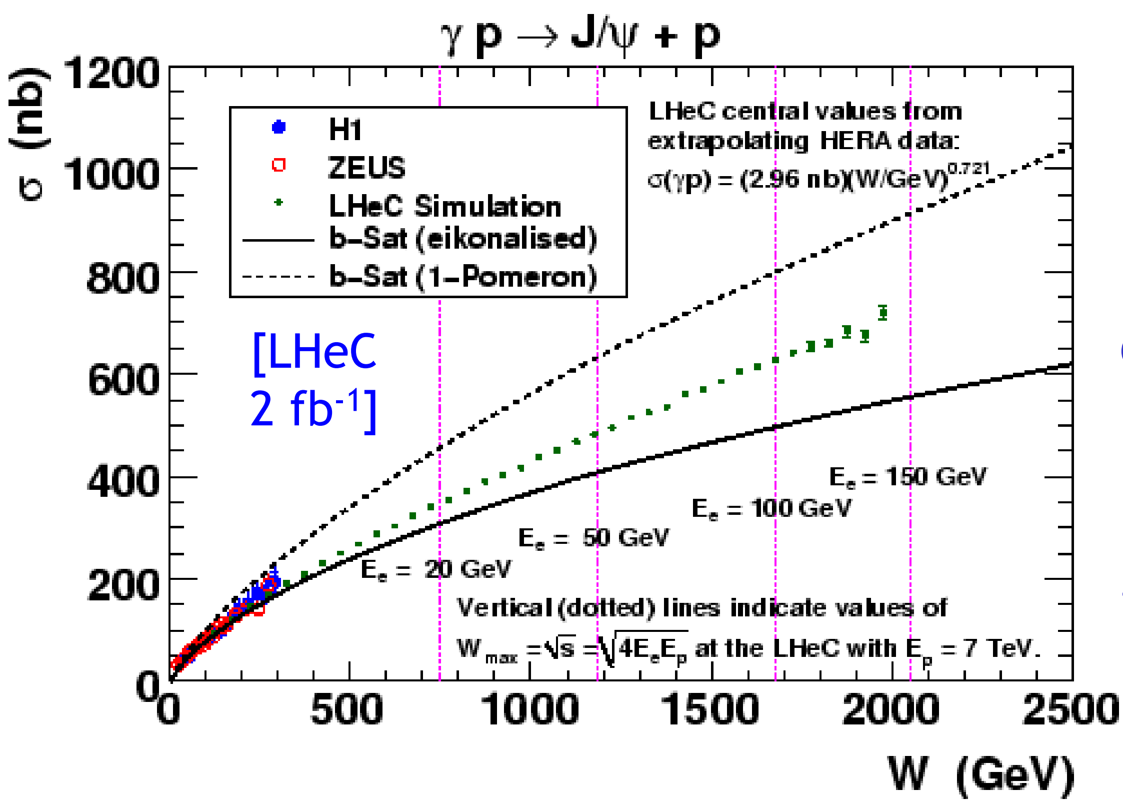


J/Ψ from future ep v Dipole model Predictions

- (Old!) Sim'ns of elastic J/Ψ → μμ photoproduction (DIFFVM)

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



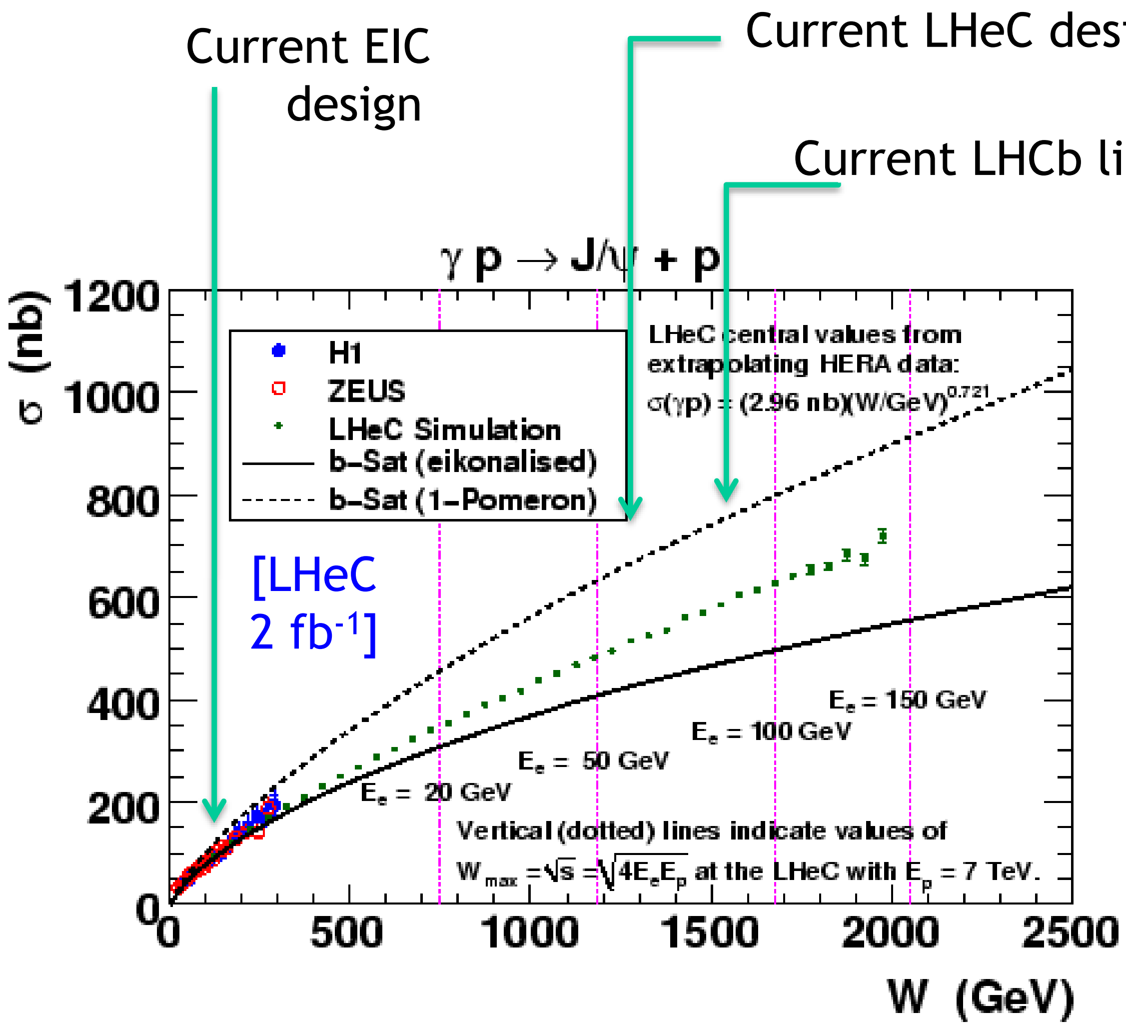


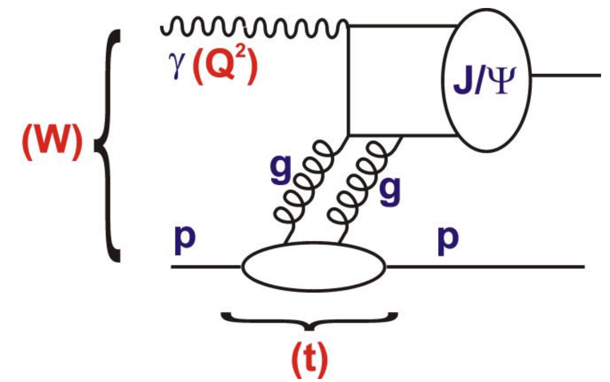
- Significant non-linear effects expected in LHeC kinematic range

... 'smoking gun'?...

J/Ψ from future ep v Dipole model Predictions

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



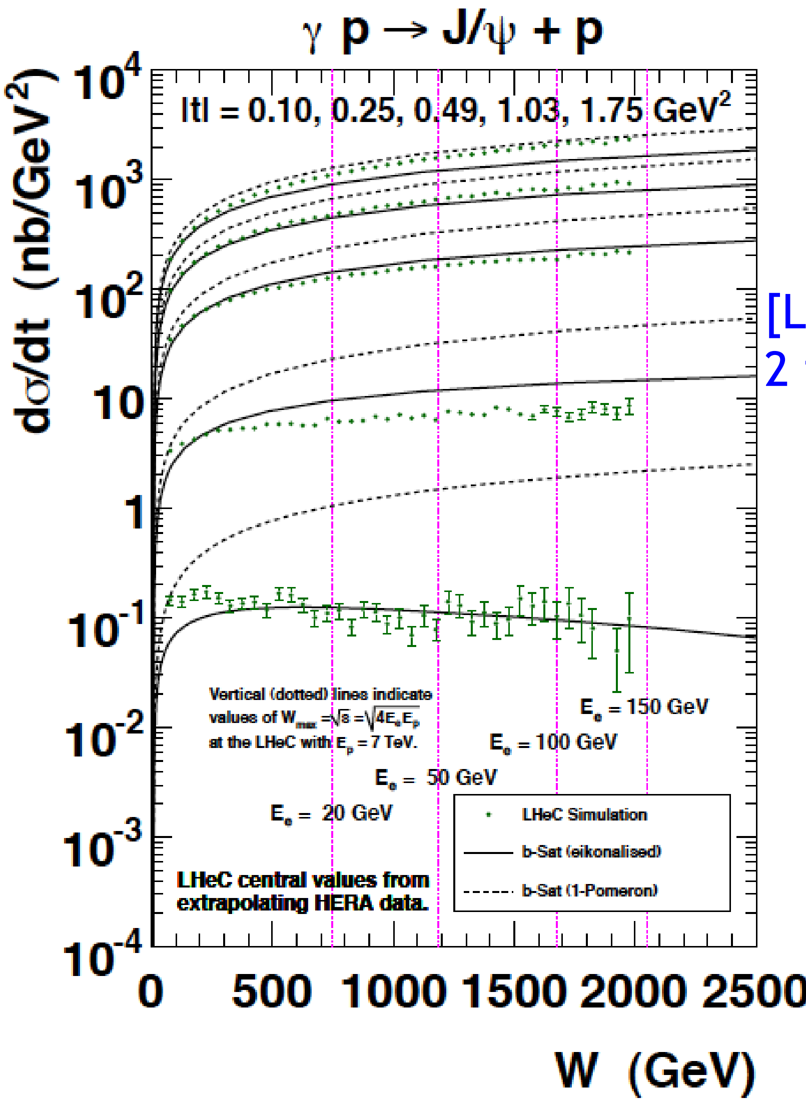


- Lack of sat^n signal at LHC to date suggests increasing energy alone is not the answer

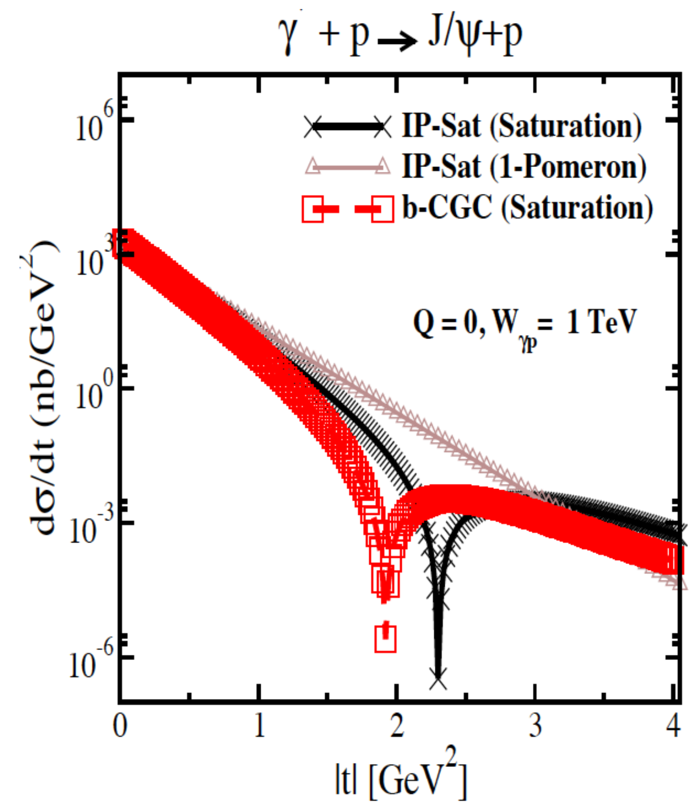
- Need detailed mapping in ep and eA and scanning of t (& maybe also of Q^2).

NEW: t Dependence of Elastic J/ψ in ep LHeC

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



[LHeC 2 fb^{-1}]

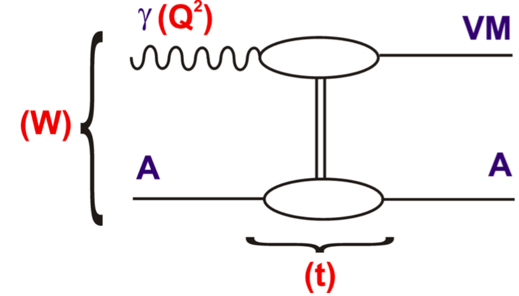


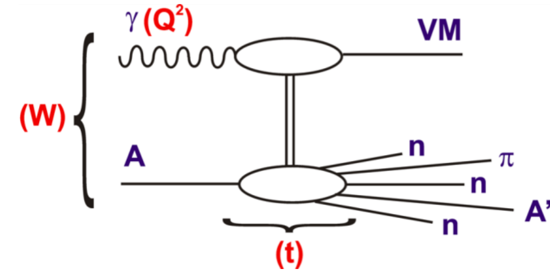
- Dips in t distribution proposed as (model dependent) signature of departure from linear evolution

- Requires large samples / lumi by HERA standards, but not LHeC

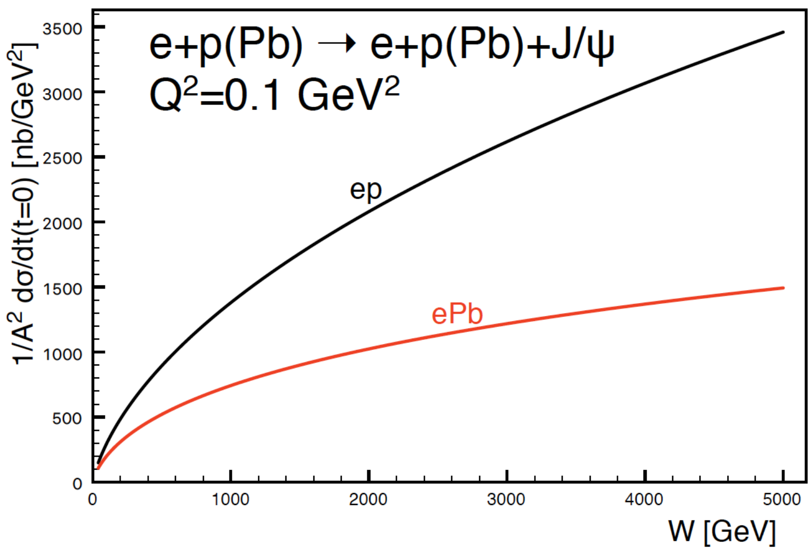
NEW: Exclusive Diffraction in eA

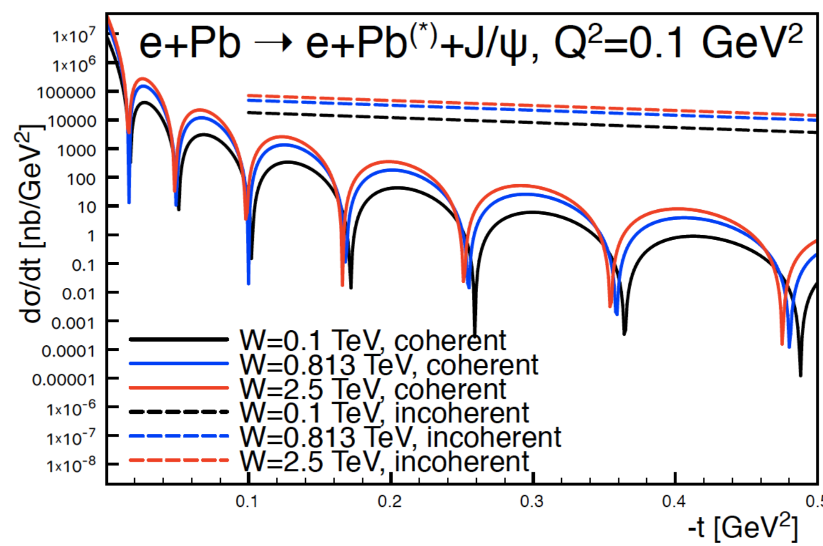
- Large predicted suppression relative to ep
- Saturation effects (eg dips) enhanced beyond ep and occur at smaller |t| in fully coherent case (eA → eVA)
- Experimental challenge is to separate coherent from incoherent



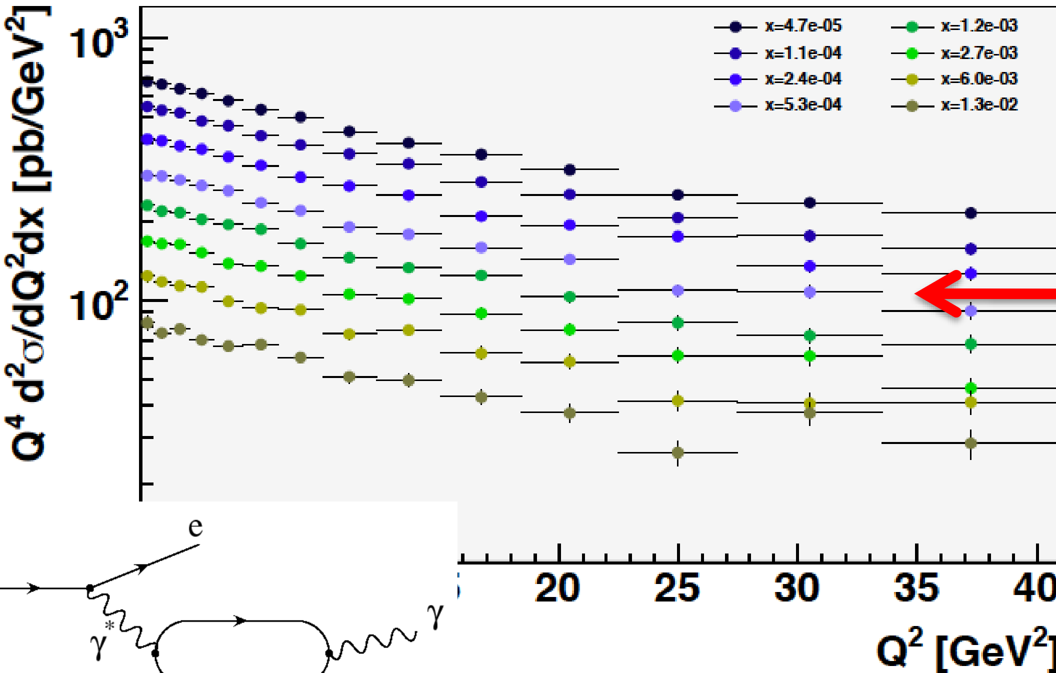


- Roman pots to tag nuclei impractical - tiny scattering angles
- Separation of incoherent diffraction based mainly on neutrons in ZDC … some theoretical uncertainty



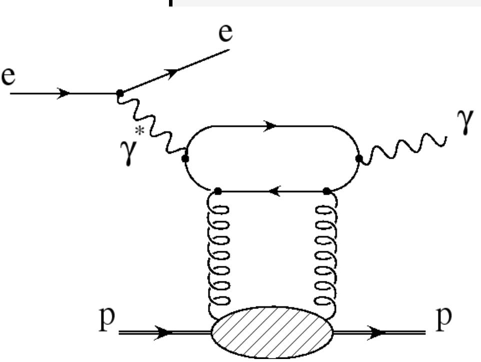


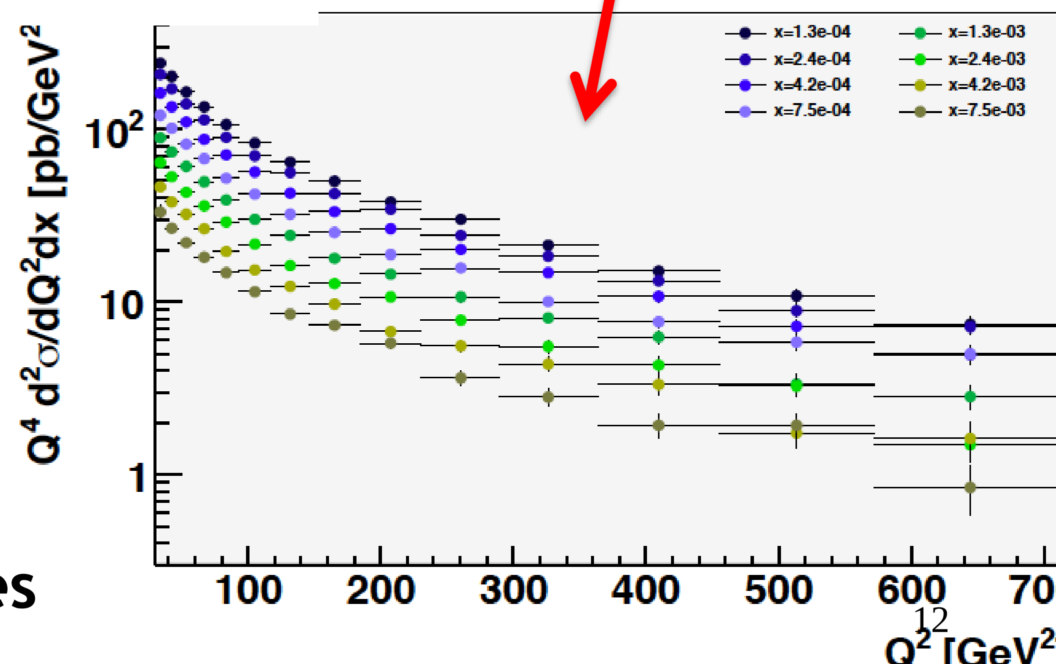
(OLD) DVCS simulation (MILOU)



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

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



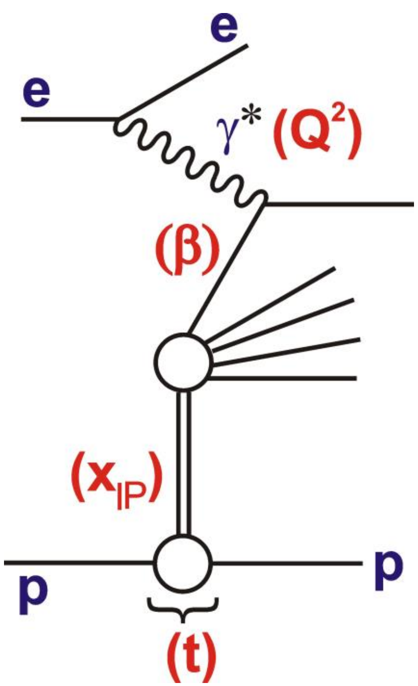


Precise data with
W → 1 TeV, Q^2 → 700 GeV^2,
x → 5.10^{-5}

Still to do:

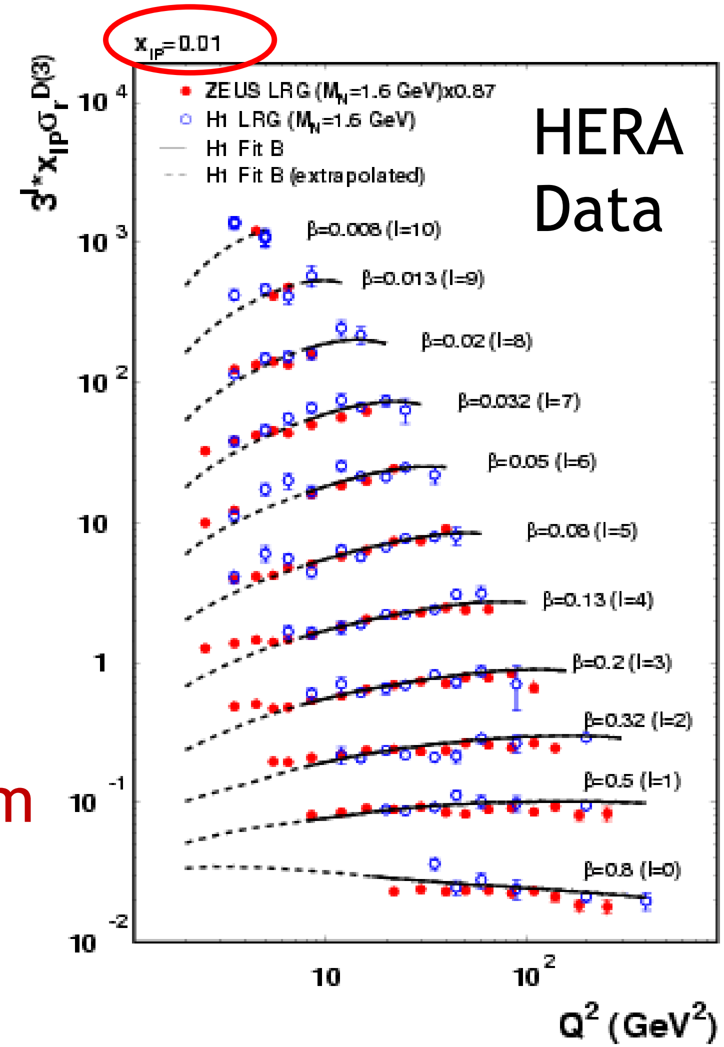
- **Beam charge asymmetries**
- **Sensitivity to GPDs**

Inclusive Diffraction and Semi-Inclusive (Diffractive) PDFs



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

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

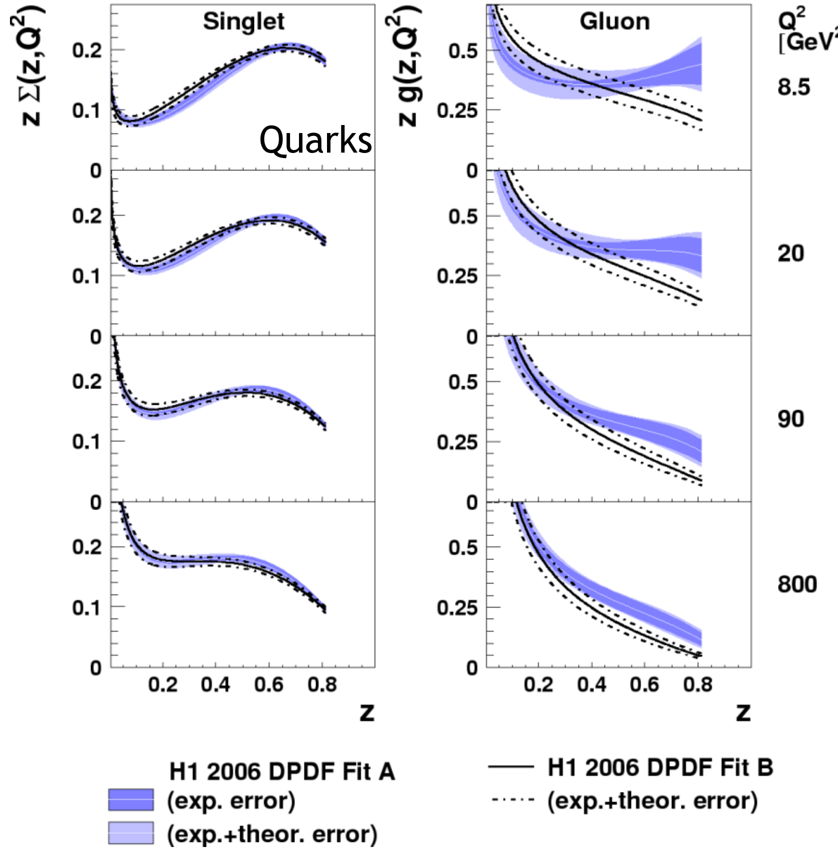


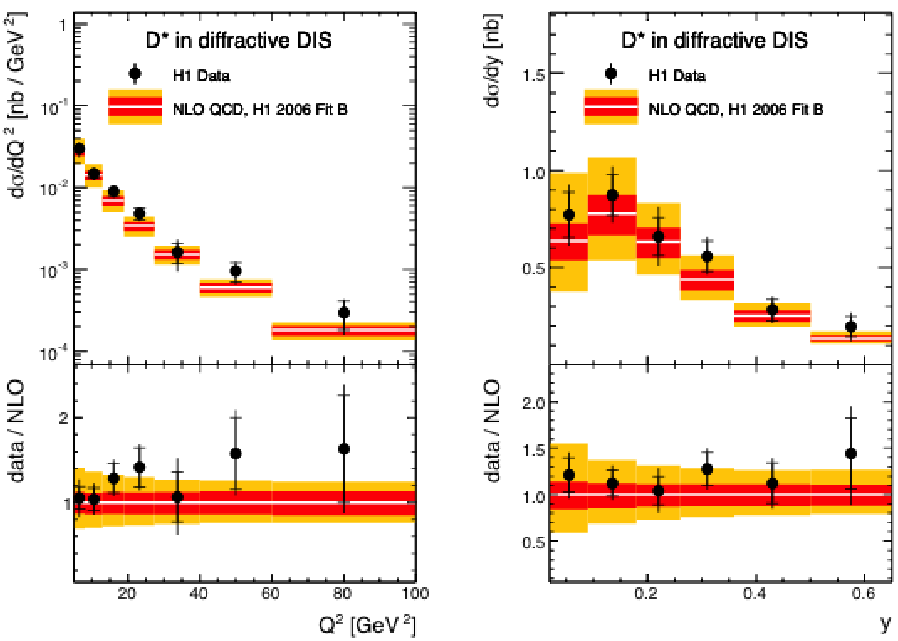
- ep→eXp with proton 4-momentum barely changed has a leading twist contribution at ~10% of total x-sec

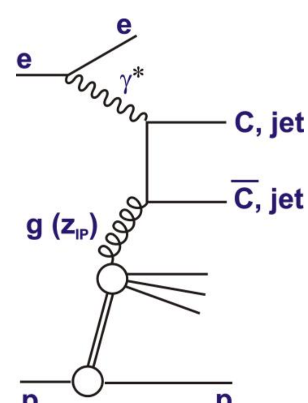
- Huge and rich topic at HERA (>100 publications)

Diffractive Parton Densities (DPDFs) at HERA

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

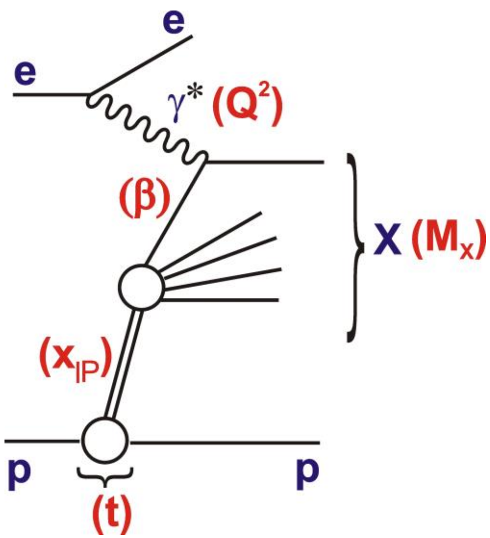






Comparisons limited by available phase space for final states

Inclusive Diffraction at LHeC & FCC-eh (NEW)



PHYSICAL REVIEW D **100,** 074022 (2019)

Inclusive diffraction in future electron-proton and electron-ion colliders

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We analyze the possibilities for the study of inclusive diffraction offered by future electron-proton/nucleus colliders in the tera-electron-volt regime, the Large Hadron-electron Collider (LHeC) as an upgrade of the HL-LHC, and the Future Circular Collider in electron-hadron mode. Compared to *ep* collisions at HERA, we find an extension of the available kinematic range in x by a factor of order 20 and of the maximum Q^2 by a factor of order 100 for LHeC, while the Future Circular Collider (FCC) version would extend the coverage by a further order of magnitude both in x and Q^2. This translates into a range of the available momentum fraction of the diffractive exchange with respect to the hadron (ξ), down to 10^{-4}–10^{-5} for a wide range of the momentum fraction of the parton with respect to the diffractive exchange (β). Using the same framework and methodology employed in previous studies at HERA, considering only the experimental uncertainties and not those stemming from the functional form of the initial conditions or other ones of theoretical origin, and under very conservative assumptions for the luminosities and systematic errors, we find an improvement in the extraction of diffractive parton densities from fits to reduced cross sections for inclusive coherent diffraction in *ep* by about an order of magnitude. For *eA*, we also perform the simulations for the Electron Ion Collider. We find that an extraction of the currently unmeasured nuclear diffractive parton densities is possible with accuracy similar to that in *ep*.

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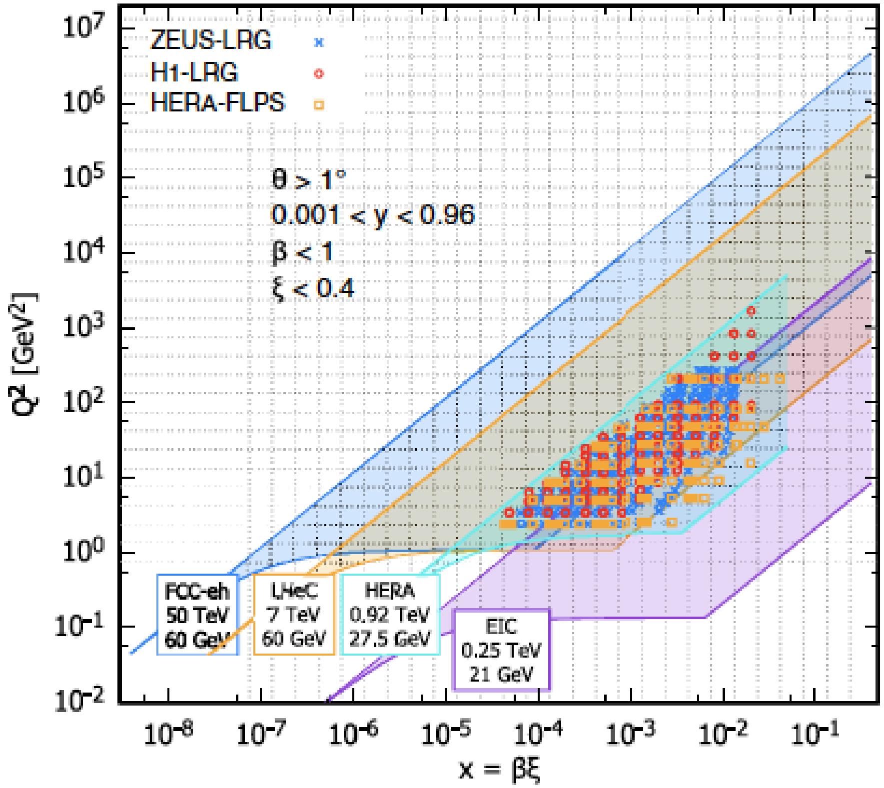
→ Diffractive structure in wider (β, Q^2) range than proton (x, Q^2) range at HERA

- 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 …

Kinematics in (x,Q^2) and Fit Procedure



- 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 (ZEUS version) 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

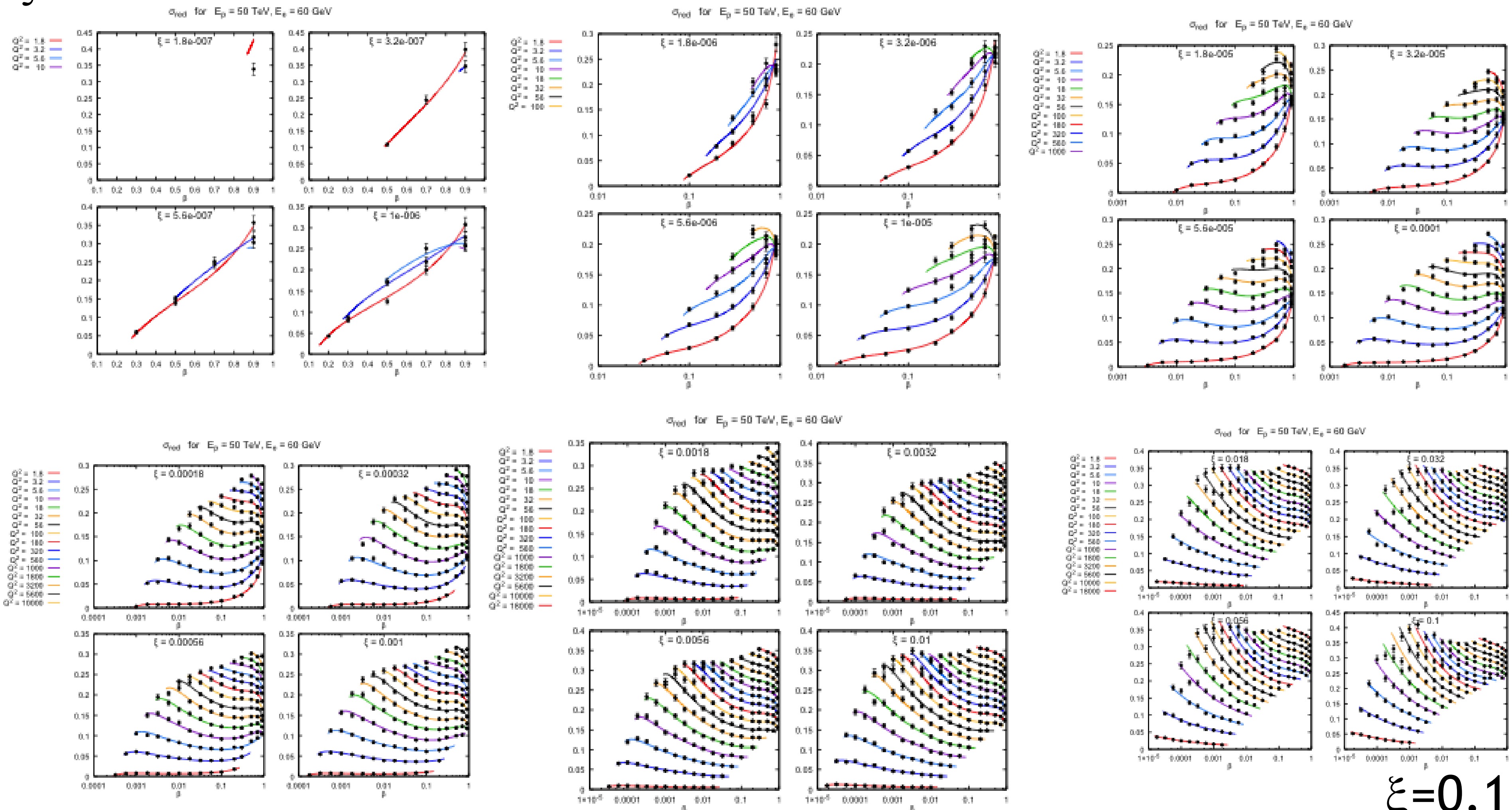
d = u = s = dbar= ubar = sbar

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 $2fb^{-1}$

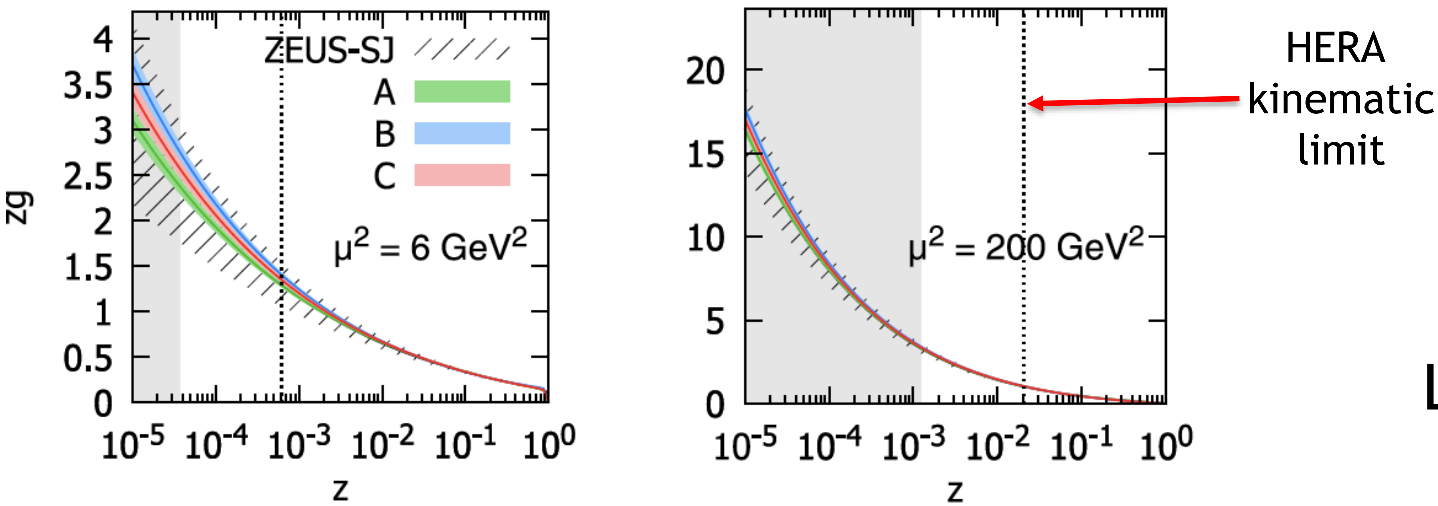
<u>Fit range:</u>

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

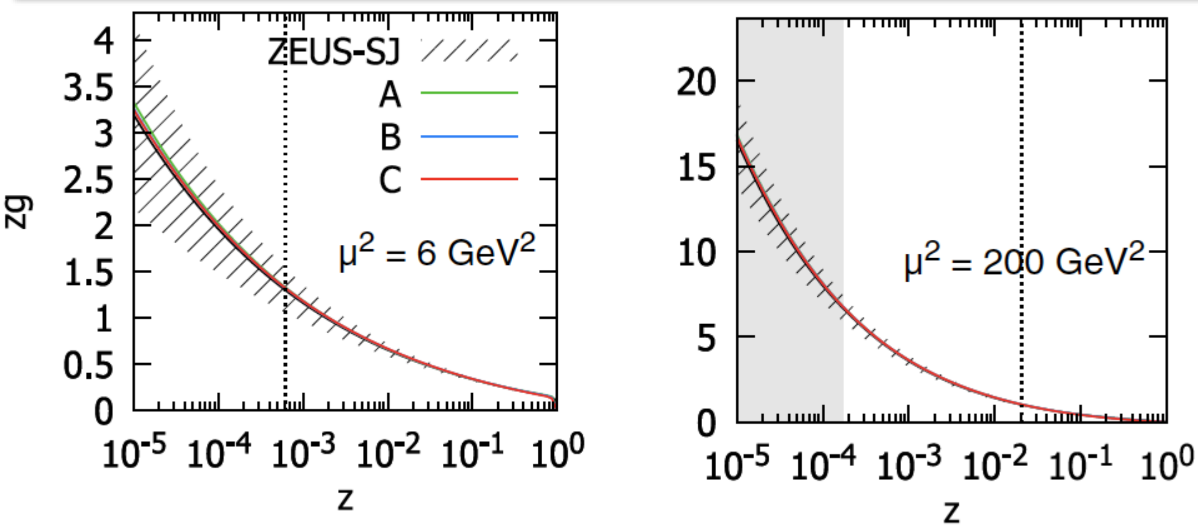
$\xi_{max} = 0.1$

Example Extracted DPDFs and their Precision

- Analysis performed for 3 randomly smeared data sets A,B,C
- Coloured bands indicate DPDF uncertainties (90% CL)
- Grey regions are beyond kinematic limit for direct access



LHeC gluon



FCC-eh gluon

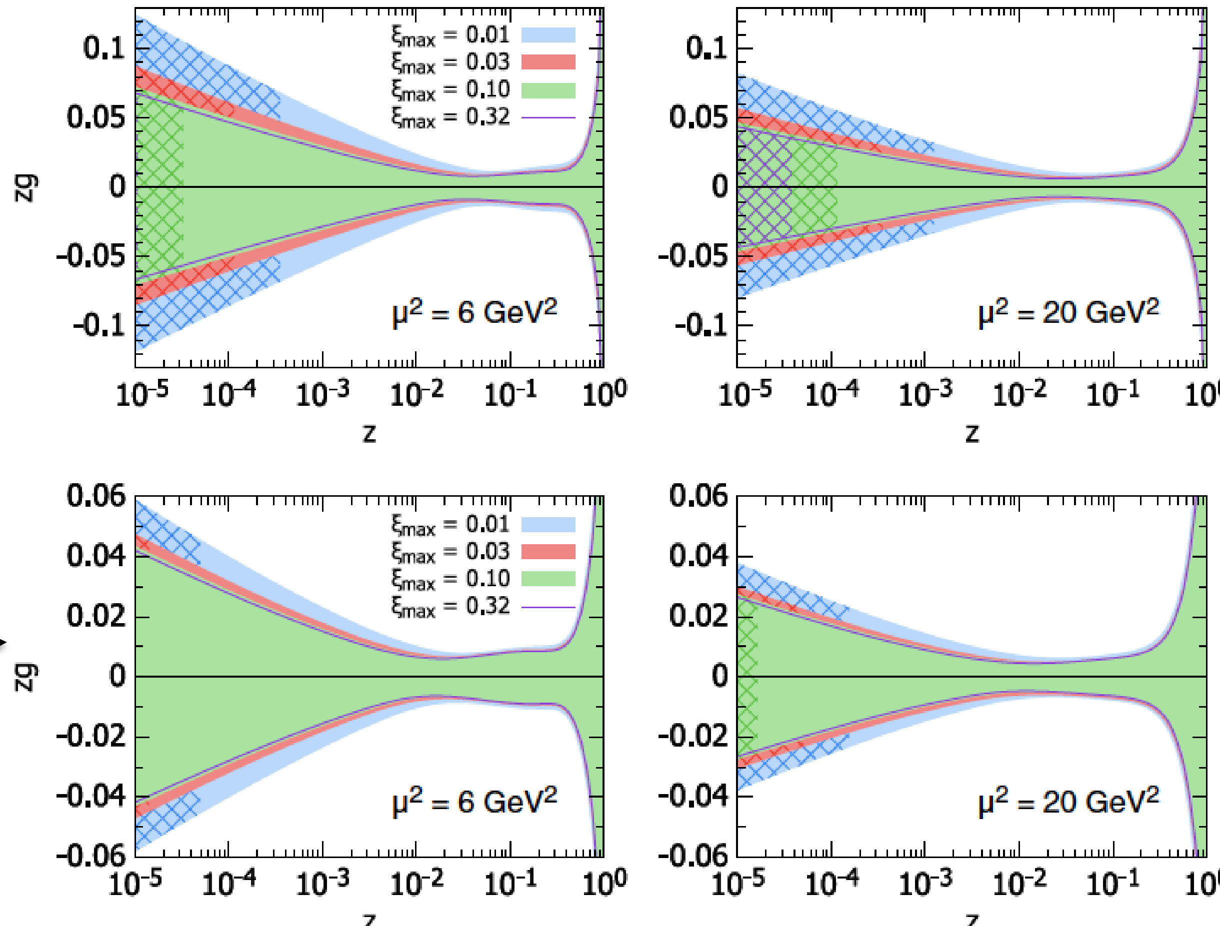
[Absolute values not very meaningful → relative precision]

Relative Precision on Diffractive Gluon Density

LHeC →

[90% CL bands]

FCC-eh →

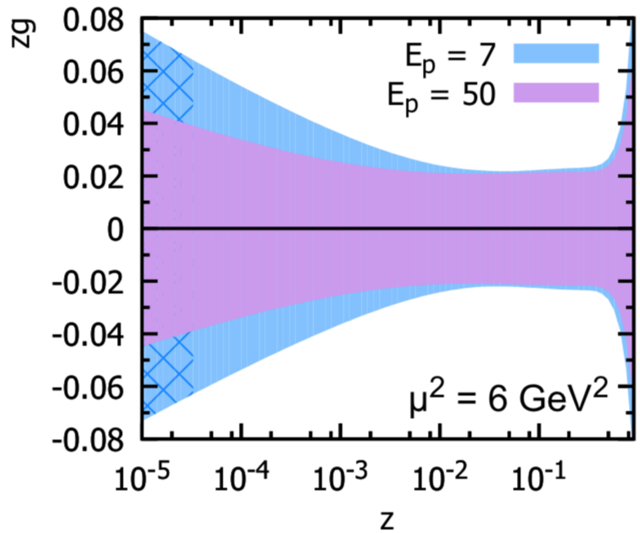


Notes in LHeC context:

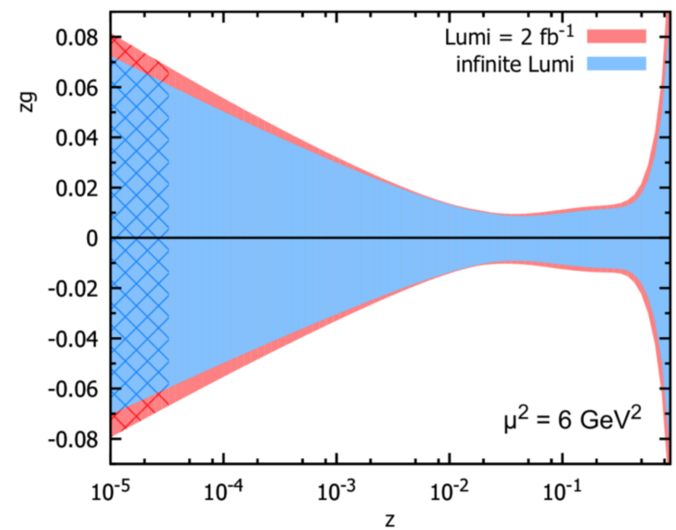
- Well constrained down to β or z ~ 10^{-4} – 10^{-5}
- Experimental precision on quarks <2% (direct from data)
- Experimental precision on gluons few% (scaling viol's)
- No statement on parameterisation or theory uncertainties

More Detail (LHeC version, only gluon shown)

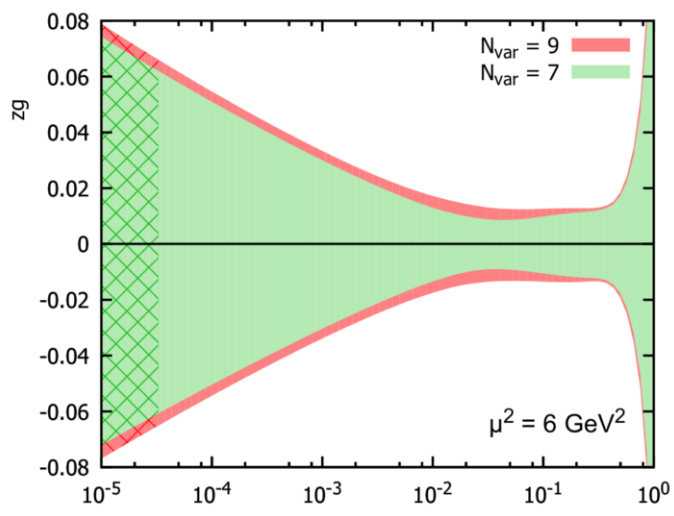
with 2% norm'n uncertainty



$2fb^{-1}$ v infinite lumi



Free IP and IR intercepts



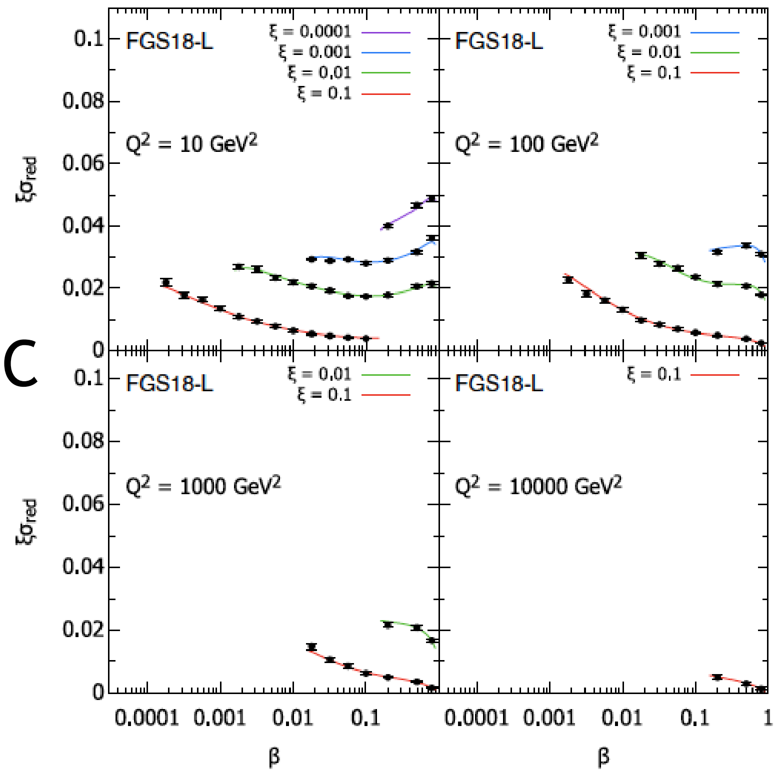
Still open questions:

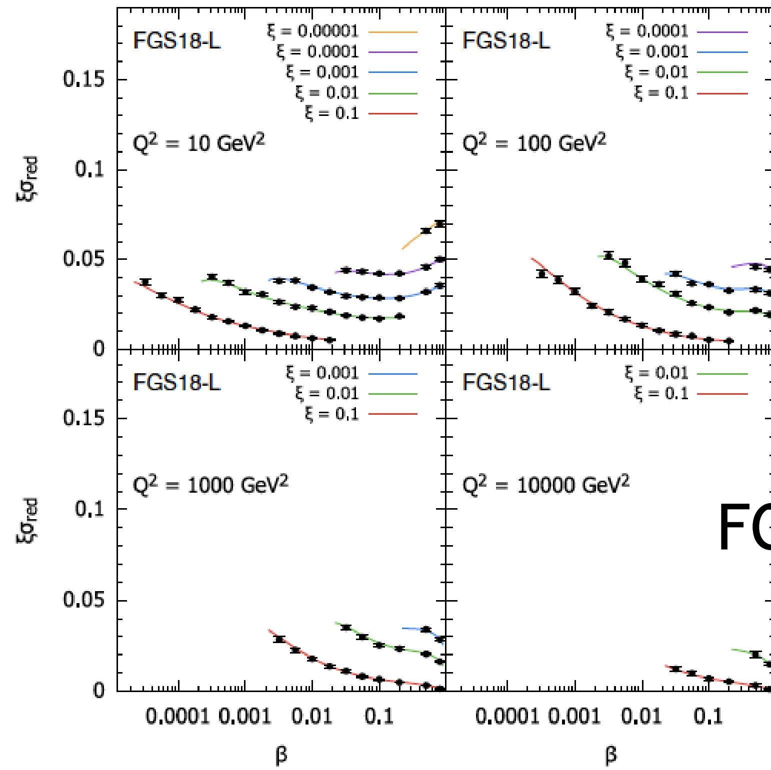
- Parameterisation bias / extrapolation uncertainties
- Sensitivity to flavour decomposition
- Sensitivity to deviations from pure DGLAP

Inclusive Diffraction from Nuclei: Selected Simulated Data for e Pb → e X Pb

- Inclusive diffraction from nuclei never previously studied
- Comparing eA / ep may reveal non-linear (satur'n) dynamics

LHeC





FCC-eh

- Pseudodata (coherent Pb) – based on different versions of FGS model – illustrates accessible kinematic range
- Still to be subjected to DGLAP fits → nuclear DPDFs …

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

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Received: date / Accepted: date

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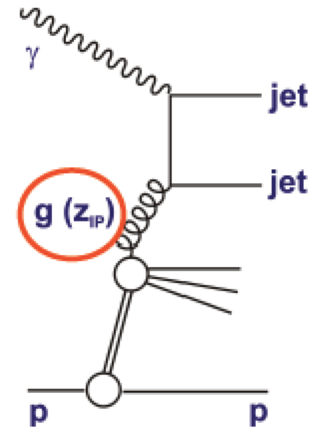
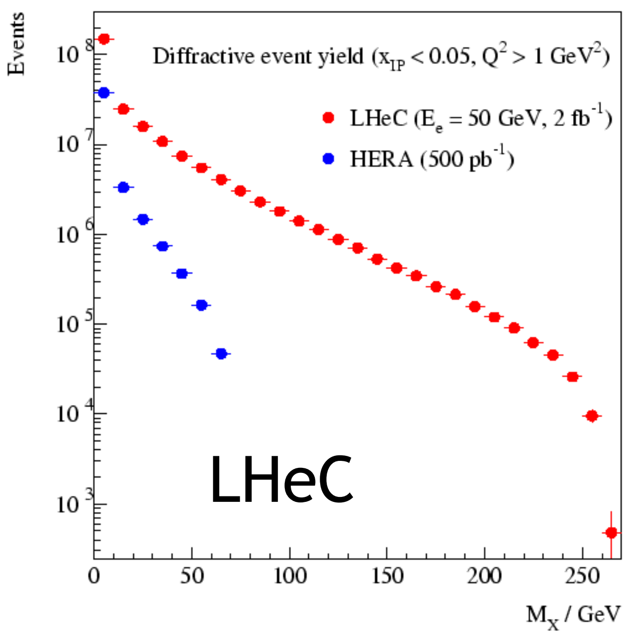
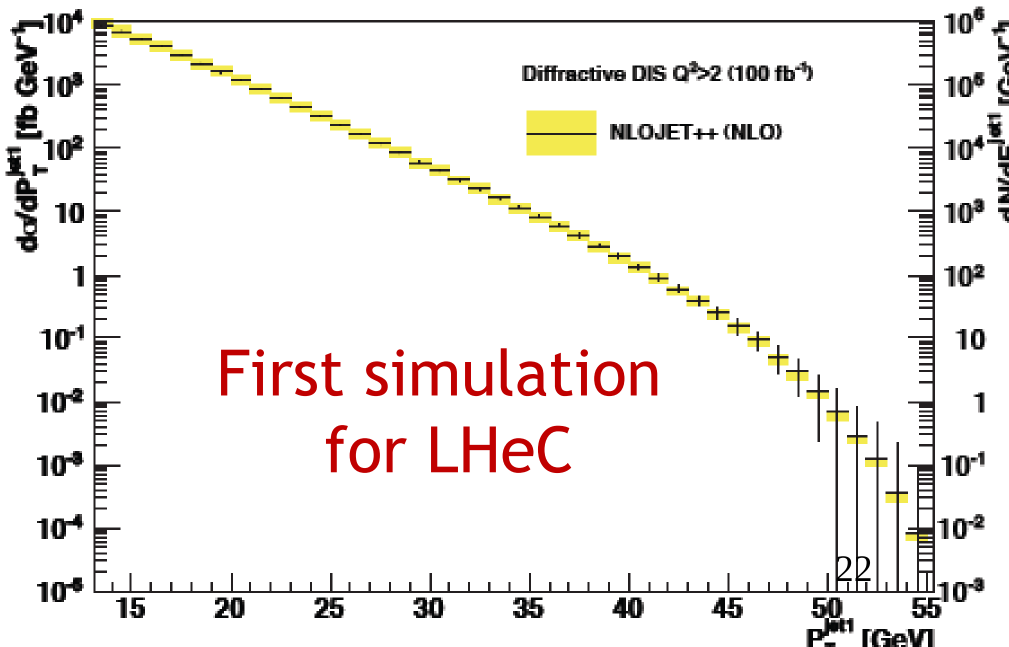
Diffractive DIS Dijets (NEWish)



… precision theory deserves precision data!





Diffractive DIS Dijets (NEW)

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

D. Britzger[a1], J. Currie[b2], T. Gehrmann[c3], A. Huss[d4], J. Niehues[e2], R. Žlebčík[f5]

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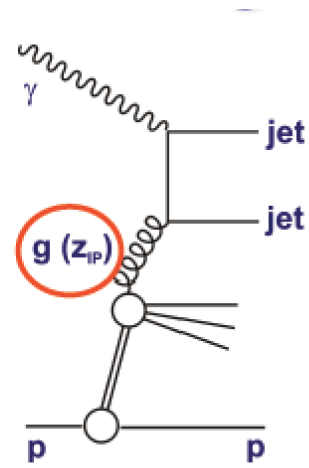

… precision
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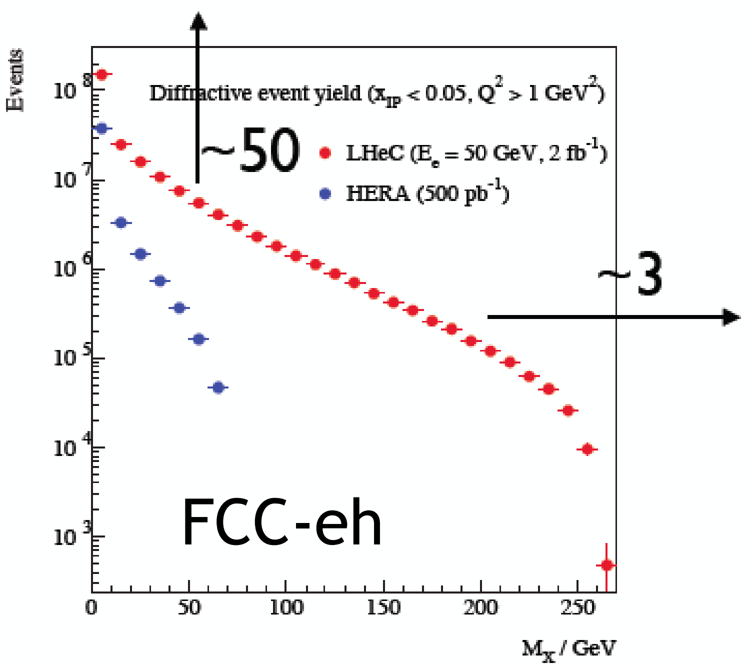
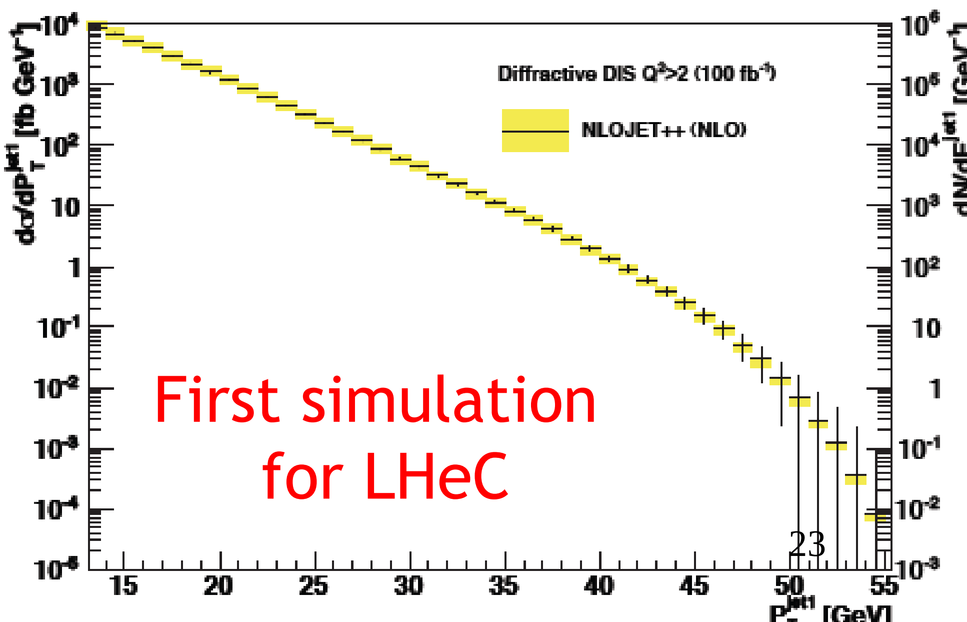




Summary

- Low x QCD is a future frontier → emergent phenomena at high parton densities, strong coupling (resummation, saturation, confinement, mass). Diffraction is a huge part of programme

- LHeC / FCC-eh expands phase space, opens new observables and sensitivities at high precision

- Progress since 2012 CDR in J/Ψ and sensitivity to DPDFs

- Lots of this is "day 1" physics … simulations are $2fb^{-1}$

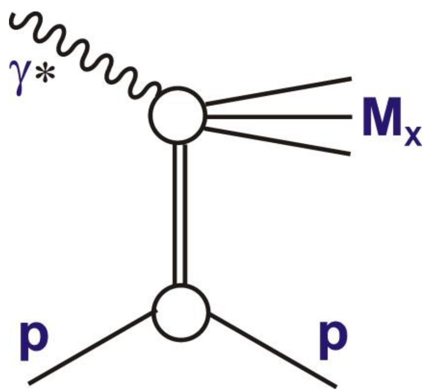
- Plenty more to do … some sort of wish list
  - → DVCS (and VM) → GPD / TMD sensitivity
  - → More on jets / HF at NNLO → diffractive gluon
  - → Interface detector simulations → realistic systematics
  - → More detailed forward instrumentation design

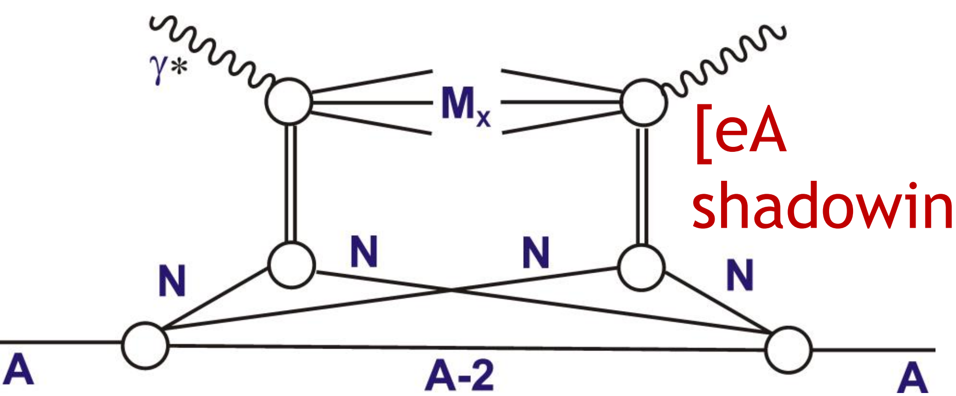
[Thanks Nestor Armesto, Heikki Mantysaari, Amir Rezaeian, Woijtek Smolinski, Anna Stasto, Radek Zlebcik and many others]

F_2^D and Nuclear Shadowing

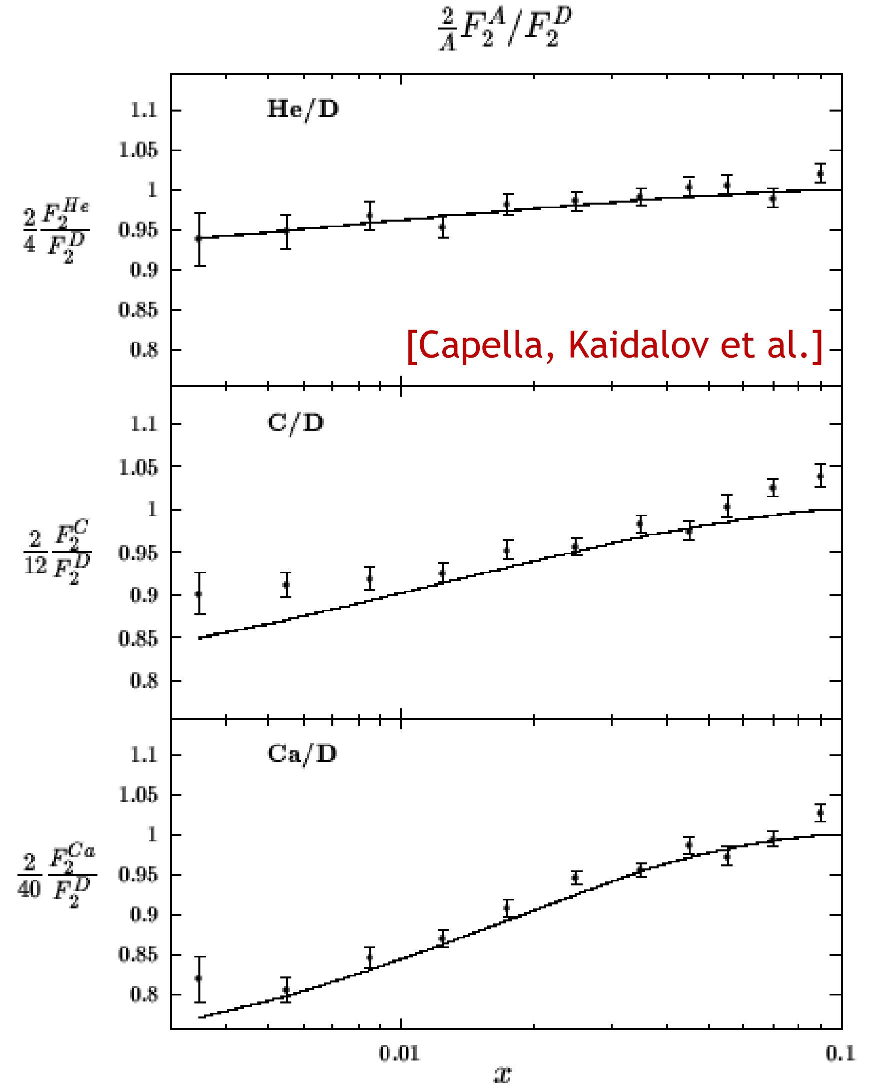
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]



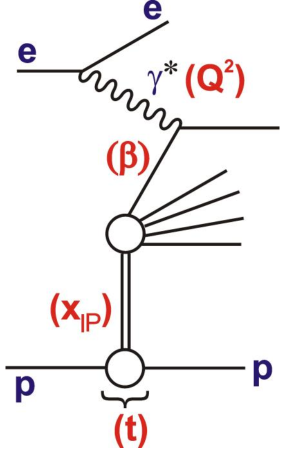


[eA shadowing]

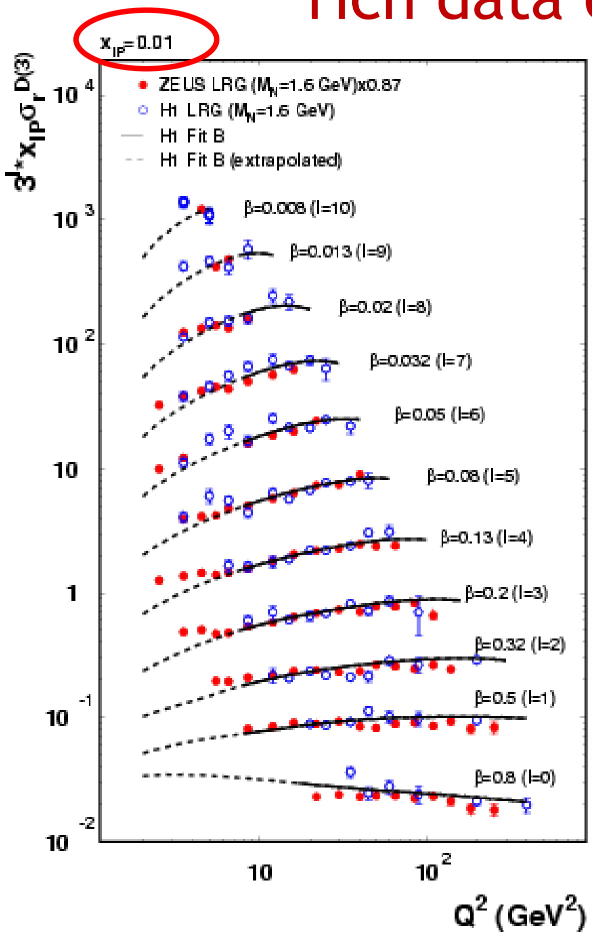


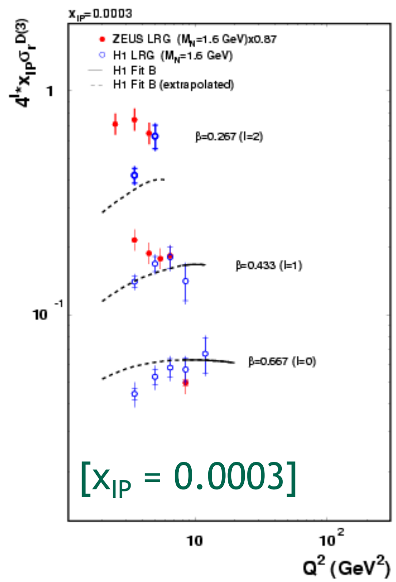
… starting point for extending precision LHeC studies into eA collisions

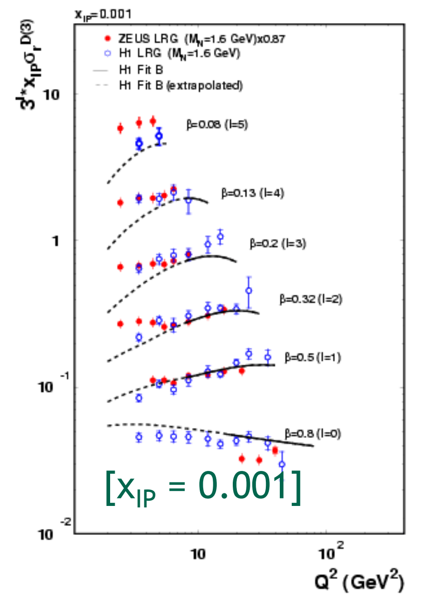
Inclusive Diffraction at HERA and Semi-Inclusive (Diffractive) PDFs

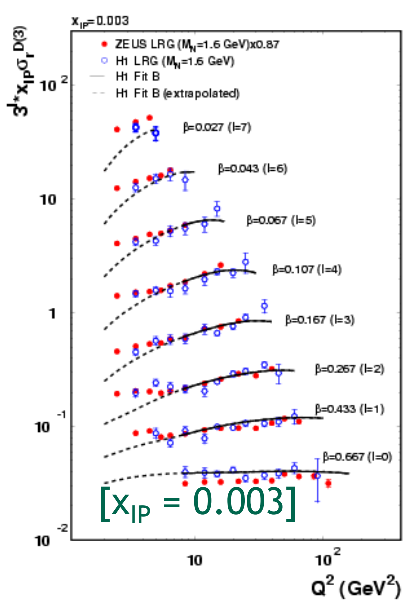


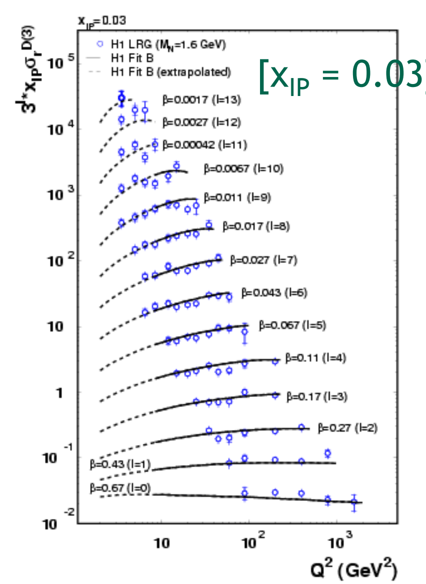
- Leading twist and ~10% of total x-sec
- Huge topic with rich data outputs



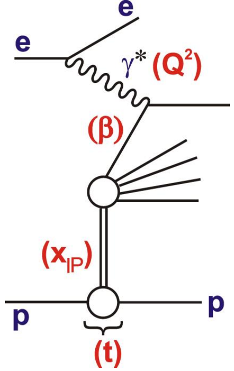




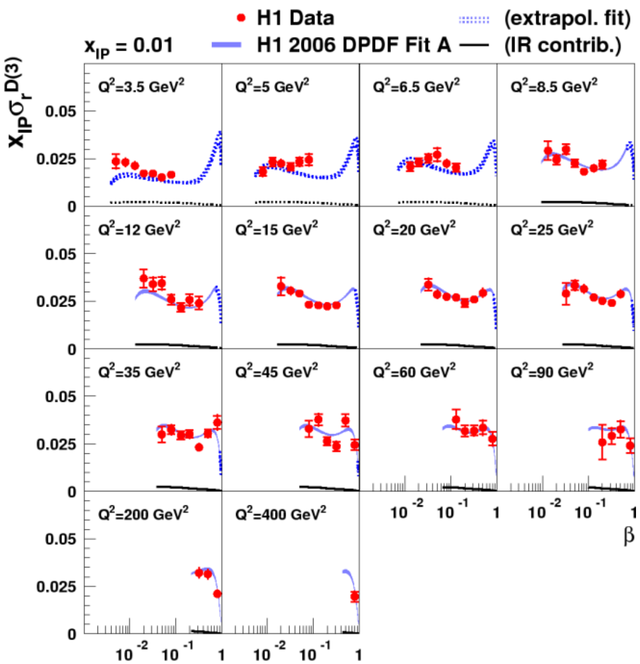


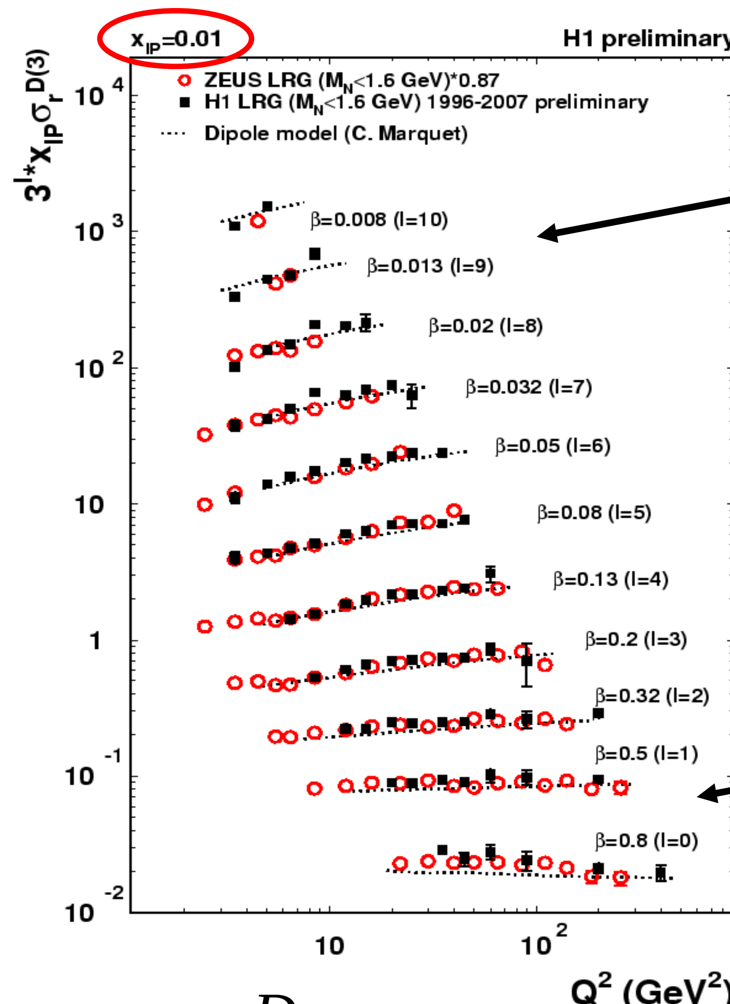


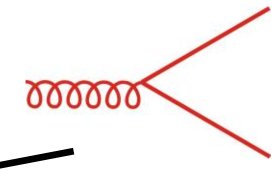
Sensitivity to Diffractive Quarks & Gluons



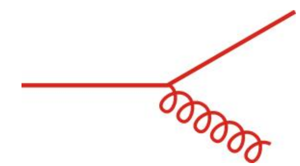
Similarly to Inclusive DIS …







Q^2 dependence tells us gluon density via DGLAP eqns



Diffractive cross section measures quark density

$$F_2^D = \sum_q e_q^2 \, \beta \, (q + \bar{q})$$

$$\frac{d\sigma_r^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes q\right]$$

Selected Pseudodata (LHeC Version)

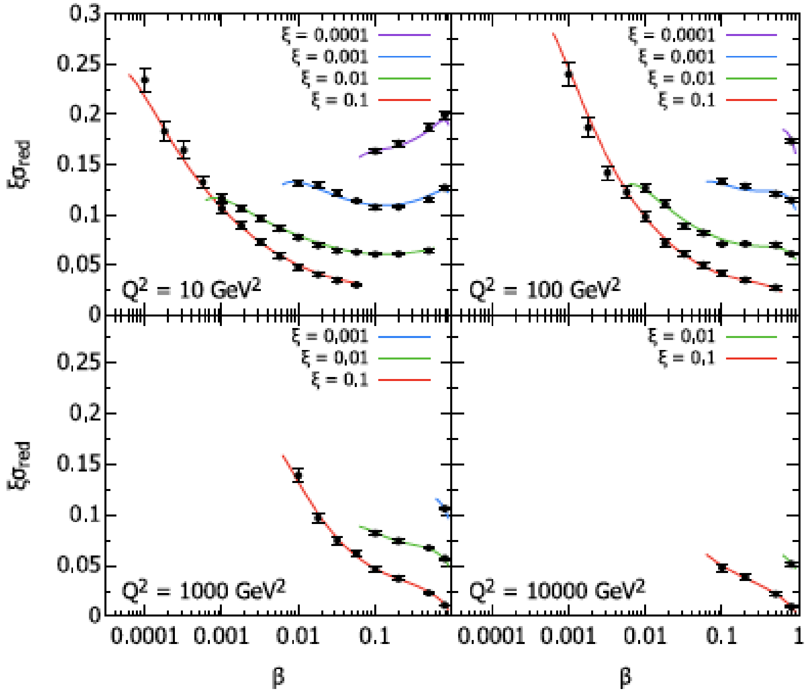


FIG. 6. Selected subset of the simulated data for the diffractive reduced cross section as a function of β in bins of ξ and Q^2 for ep collisions at the LHeC. The curves for $\xi = 0.01,\ 0.001,\ 0.0001$ are shifted up by 0.04, 0.08, 0.12, respectively.

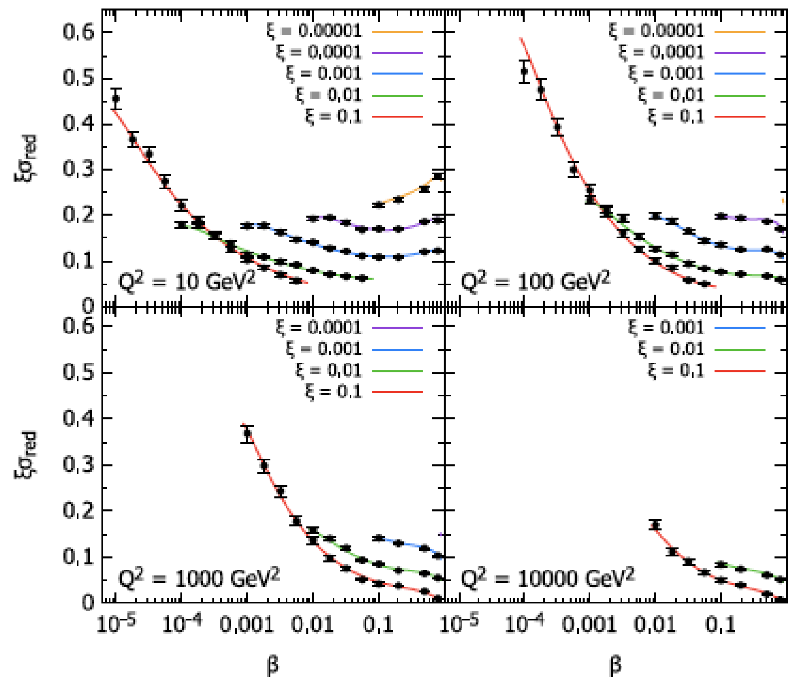


FIG. 7. Selected subset of the simulated data for the diffractive reduced cross section as a function of β in bins of ξ and Q^2 for ep collisions at the FCC-eh. The curves for $\xi = 0.01,\ 0.001,\ 0.0001,\ 0.00001$ are shifted up by 0.04, 0.08, 0.12, 0.16, respectively.

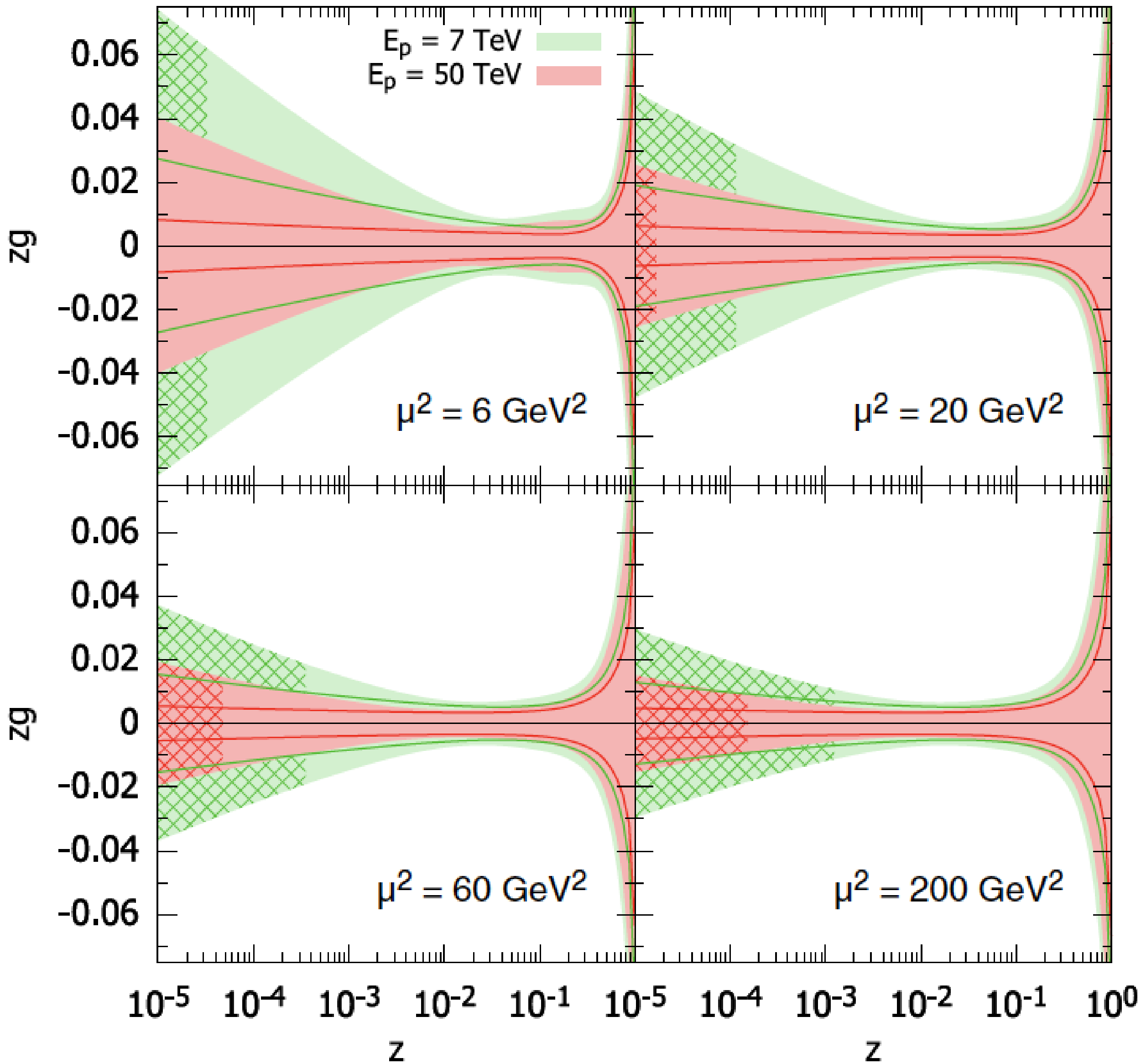
Assumed uncertainties on pseudodata:

- 5% uncorrelated systematic
- 2% statistical uncertainty

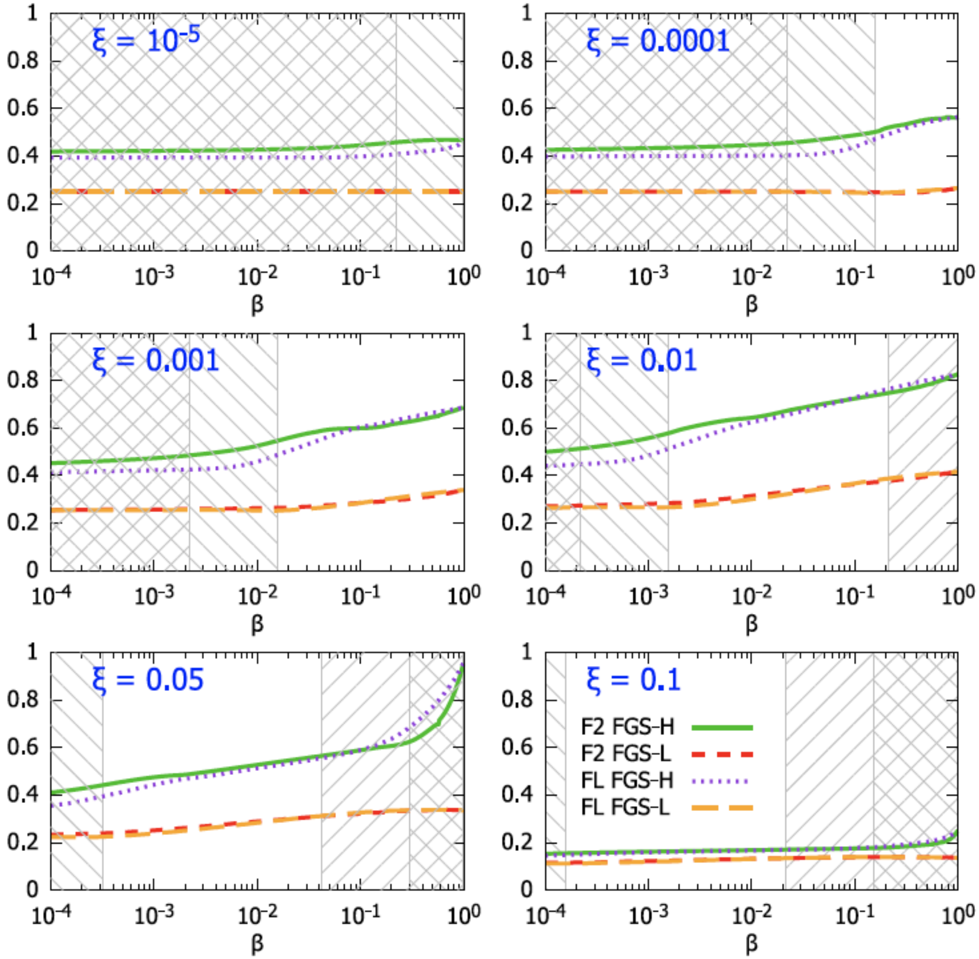
Fit range:

Q^2_{min} = 5 GeV^2 ξ_{max} = 0.1

Newly Published Result

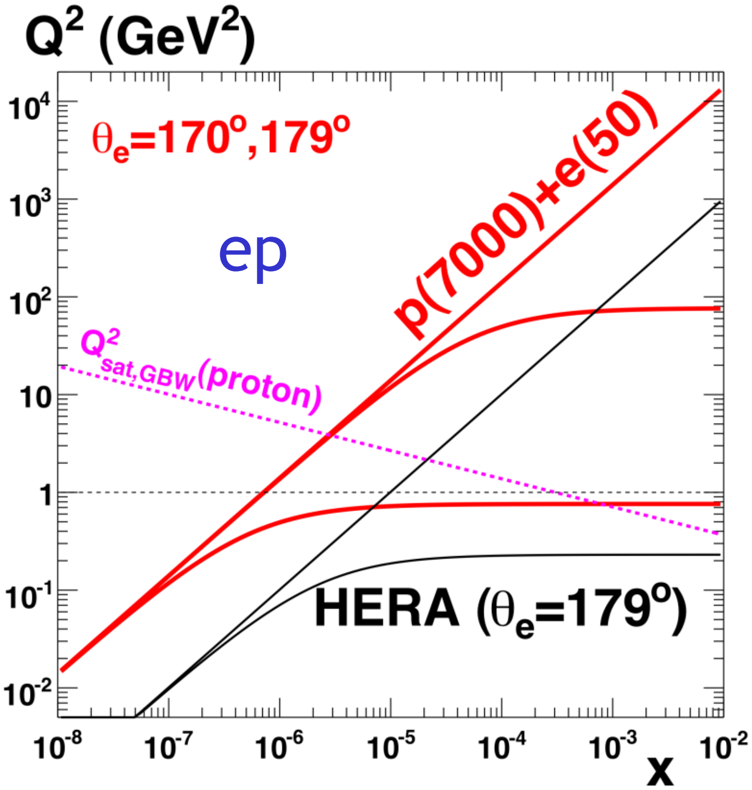


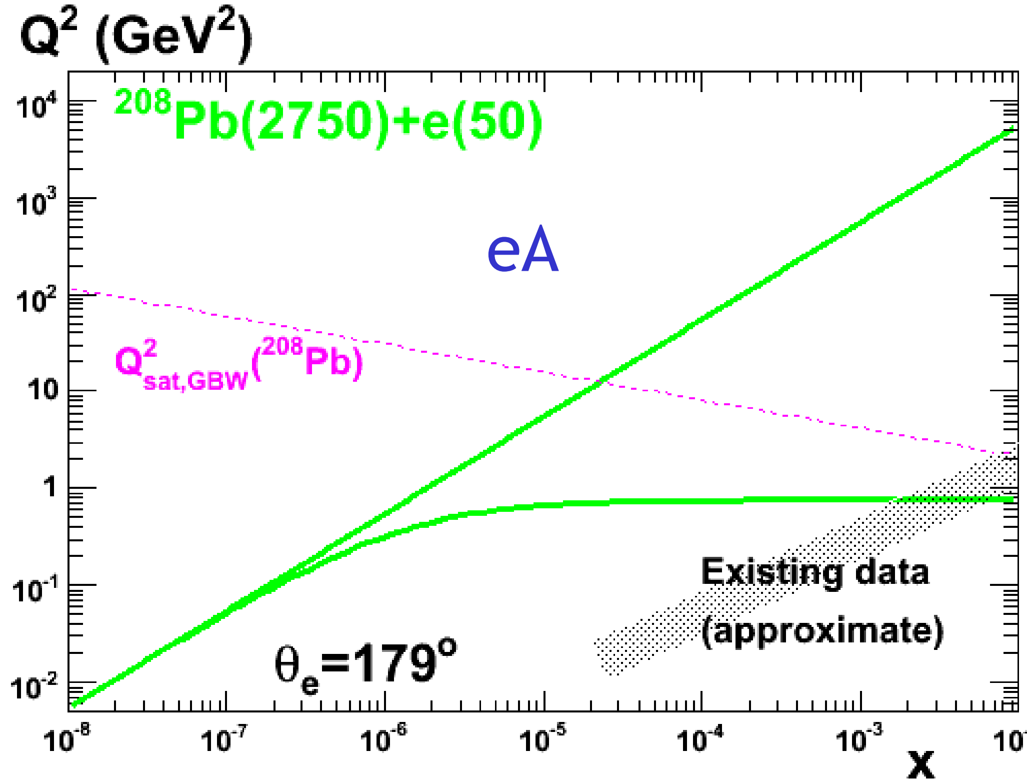
Newly Published Result



LHeC: Accessing low x at large Q^2

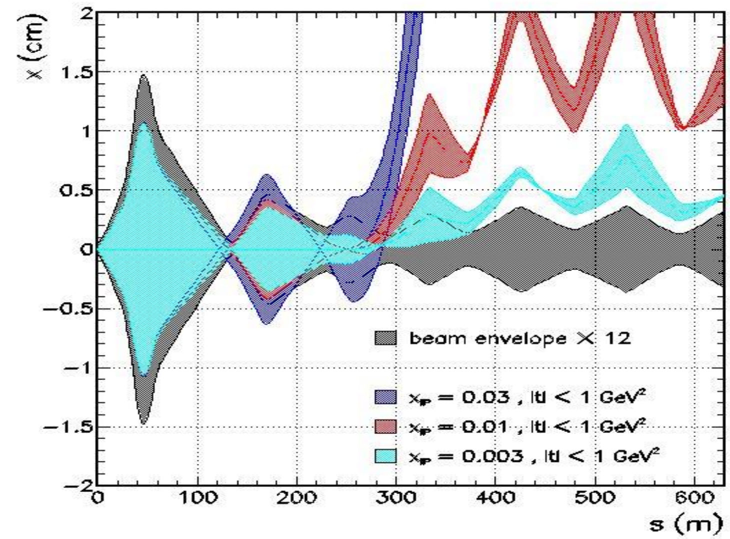
- Extending Q^2 range vital to fully unravel complex low x region
- Comparing eA and ep allows energy and density effects to be disentangled





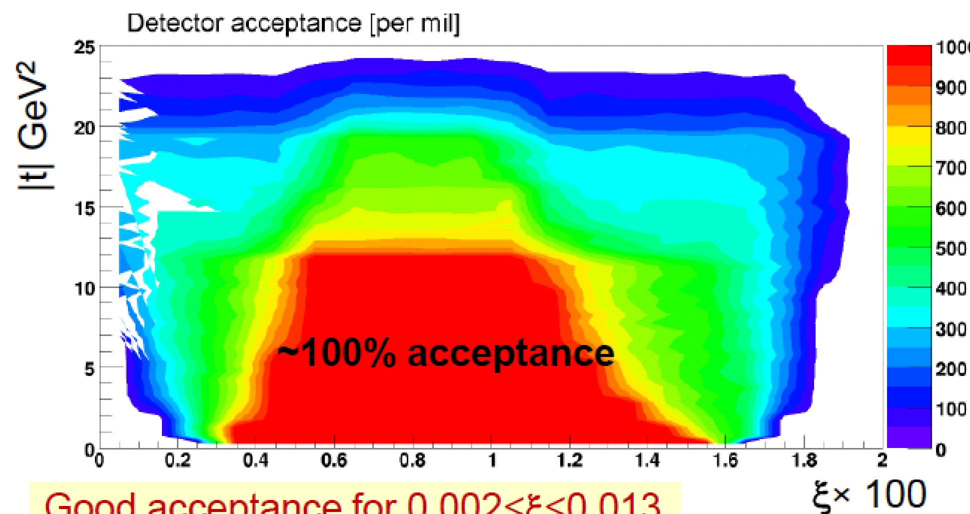
… LHeC reaches saturated region in both ep & eA at perturbative Q2 according to models

Design for LHeC Forward Proton Spectrometers

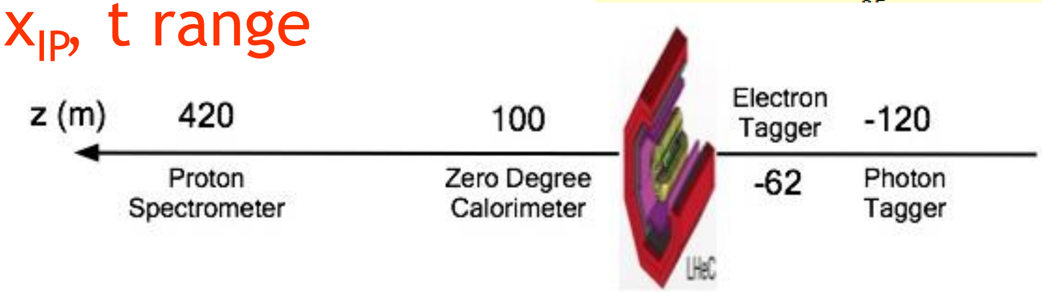


Roman pot forward detector systems with low ξ (= x_{IP}) acceptance integrated into design from outset

- 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

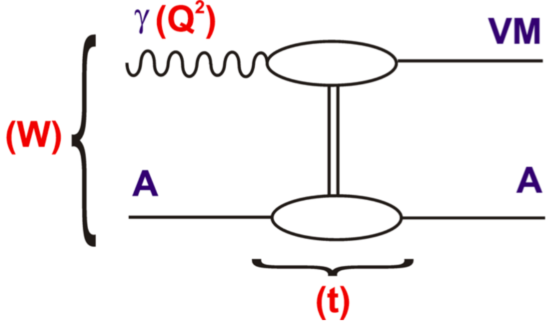


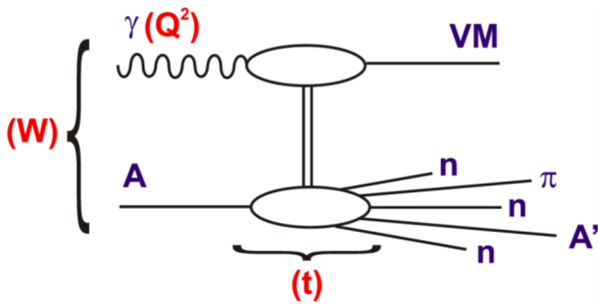
Good acceptance for 0.002<ξ<0.013

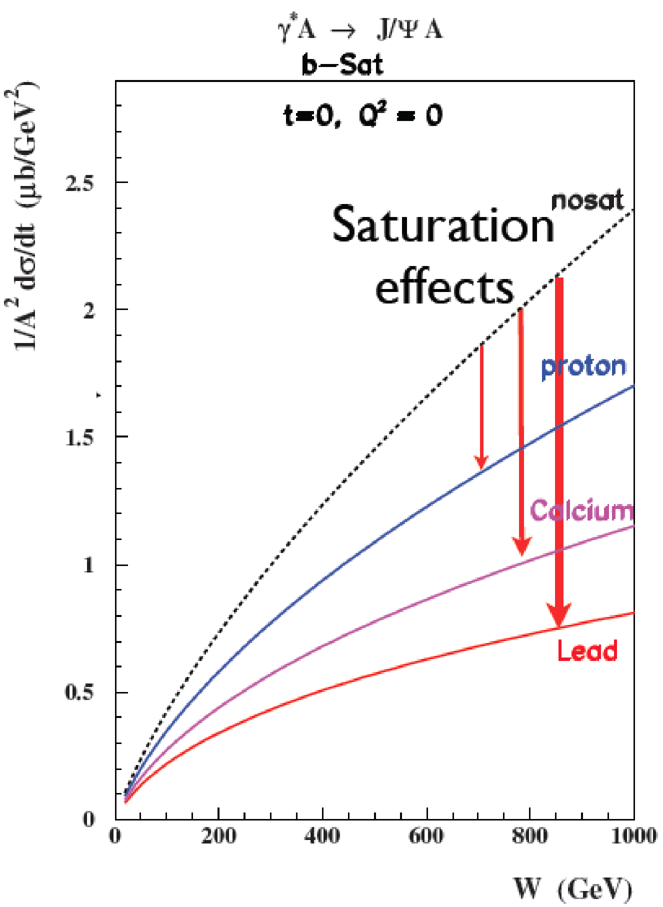


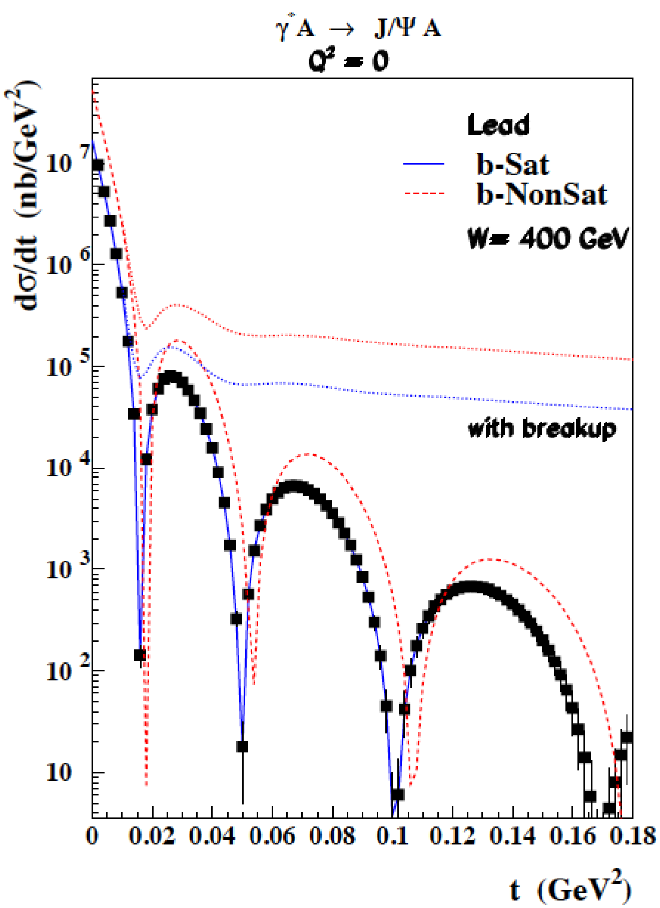
Exclusive Diffraction in eA

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





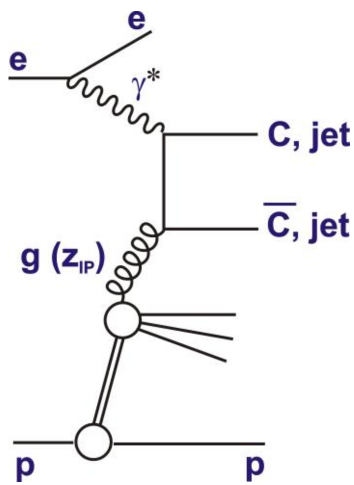


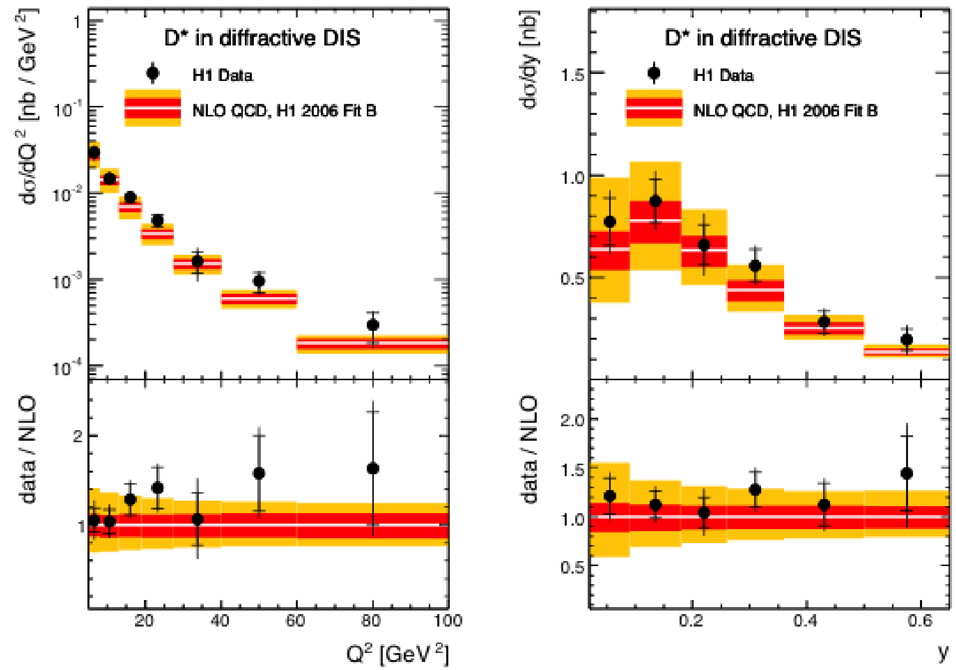


Experimental separation of incoherent diffraction based mainly on ZDC (Roman pots Impractical due to very low

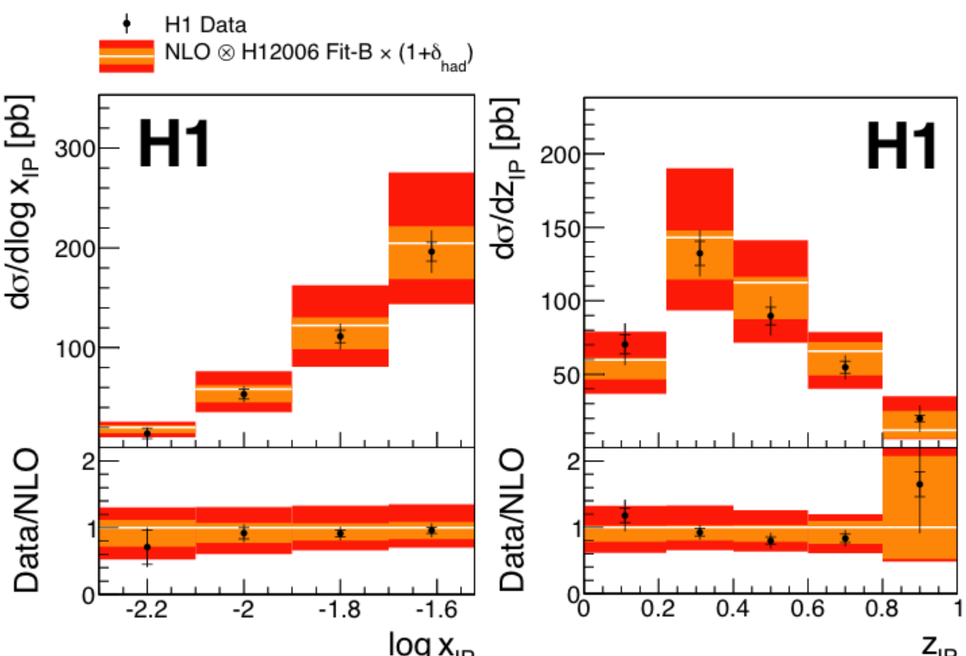
Testing Factorisation; HERA Jets & Charm

Remarkably good description of all variables over a wide kinematic range

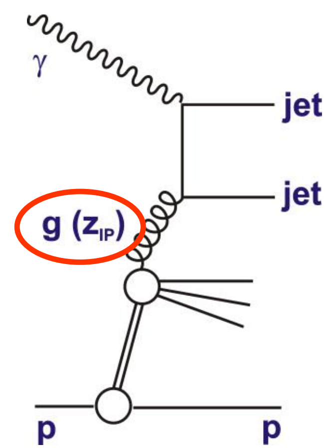




Charm in DIS



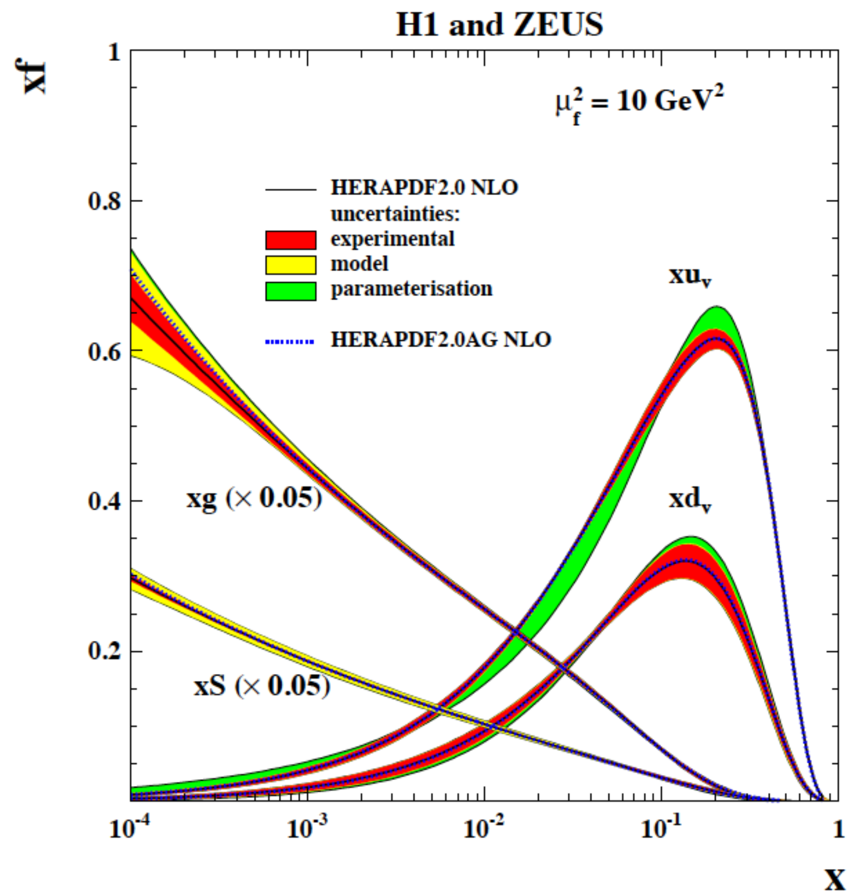
Dijets in DIS



Low x Physics is Driven by the Gluon

- Knowledge almost entirely from inclusive NC HERA data
- Needs lever-arm in Q^2 … reasonable precision only to $x \sim 10^{-3}$

- **Fast (pathological?) growth of low x gluon appears unsustainable → new low x gluon-driven dynamics?**



- Recombine (gg→g), non-linear / saturation / (density effects)?
- Log(1/x) resummation (energy effects)?
- Just DGLAP (+ Higher twists)?

→ Our understanding of the implications of the high density, small coupling, regime of parton dynamics is in its infancy