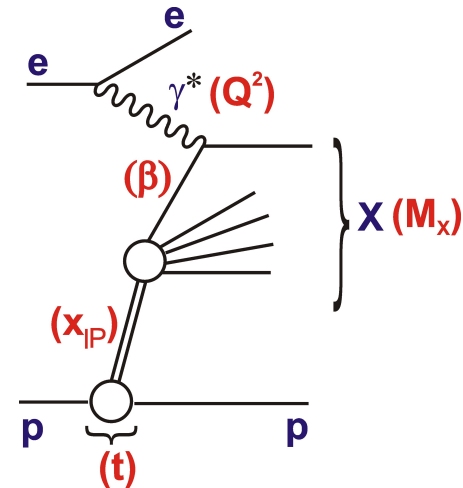
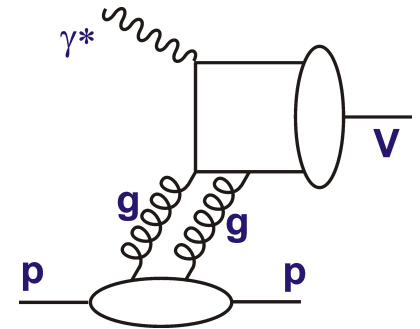


New Simulations of Diffraction at LHeC and FCC-eh

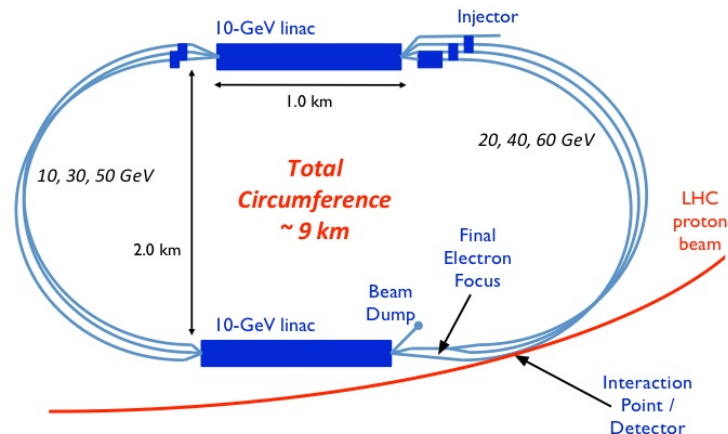


Workshop on LHeC, FCC-eh, PERLE
Chavannes de Bogis
25 October 2019

Paul Newman
(University of Birmingham)



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

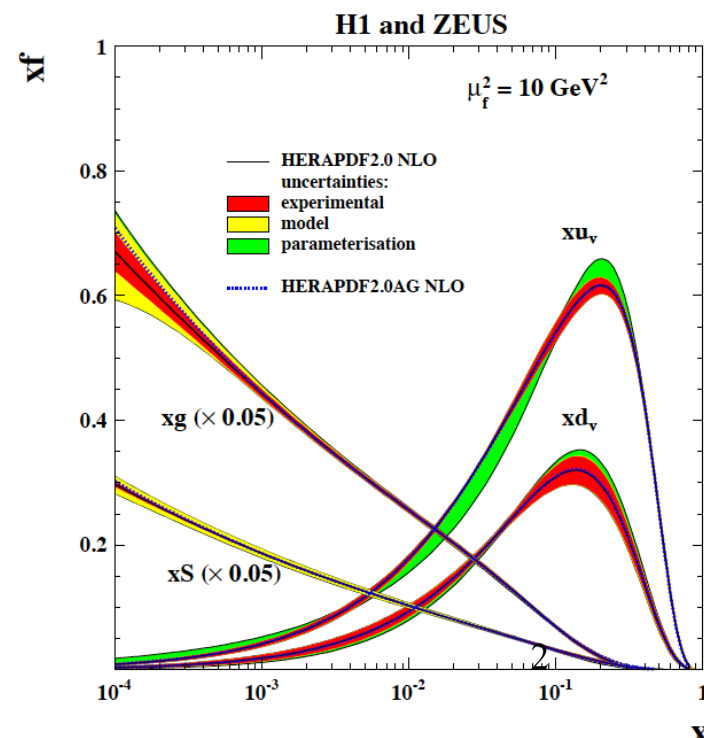
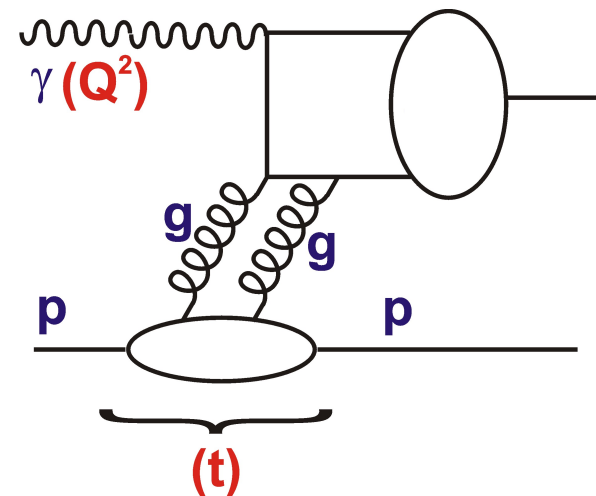
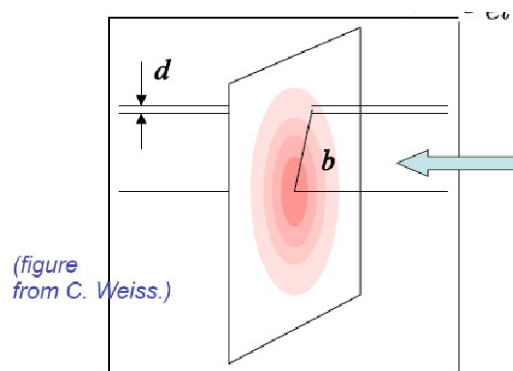


Motivation for Diffraction

[Low-Nussinov] interpretation as 2 gluon exchange:

- 1) Sensitivity to correlations between partons and 3D structure
- 2) Sensitivity to (pathologically rising?) low x gluon $\rightarrow$ non-linear / saturation?
- 3) Additional variable t gives access to impact parameter (b) dependent amplitudes

$\rightarrow$ Large t (small b) probes densest packed part of proton?



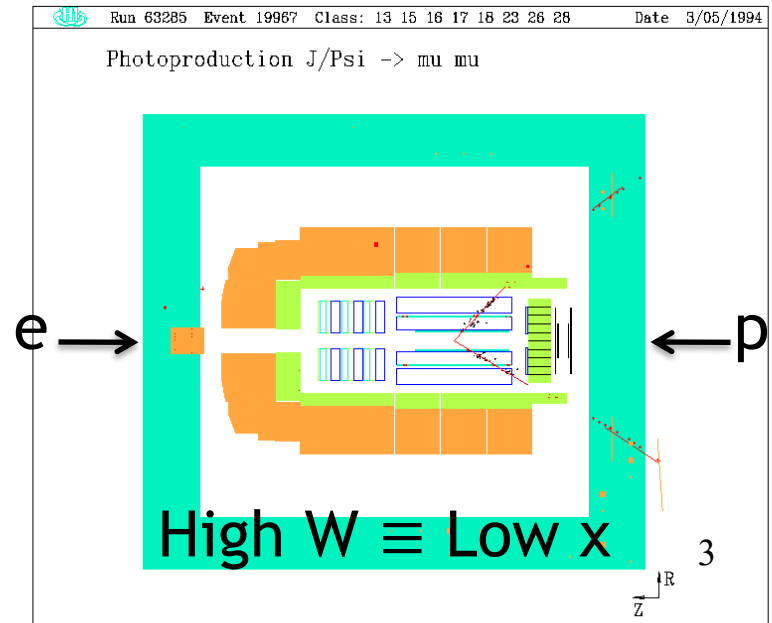
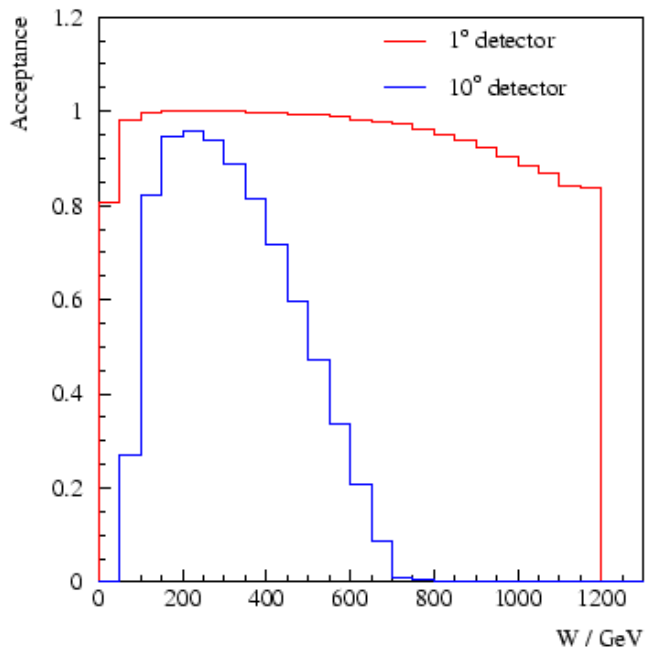
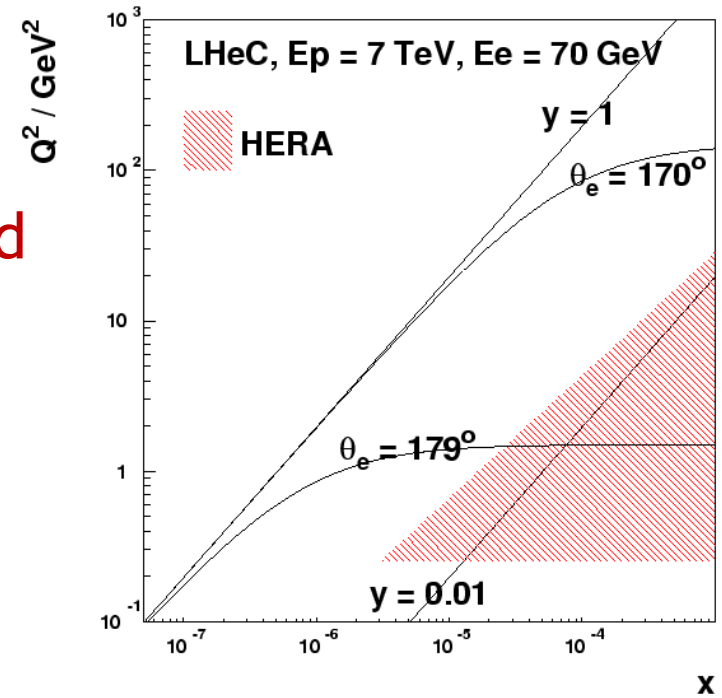
Maximal Detector Acceptance is Vital

Low x & low Q^2 kinematically correlated

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

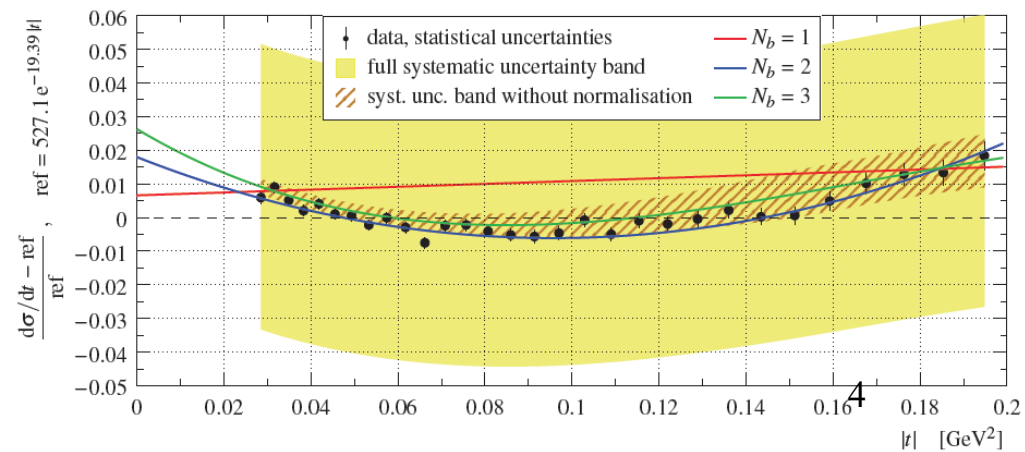
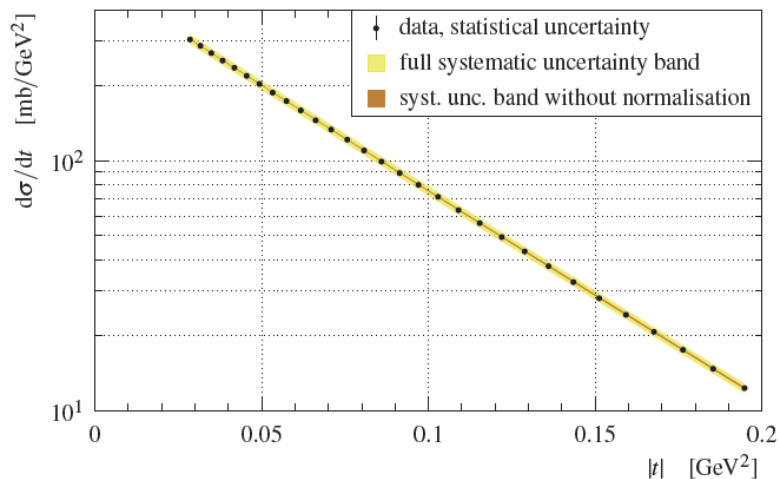
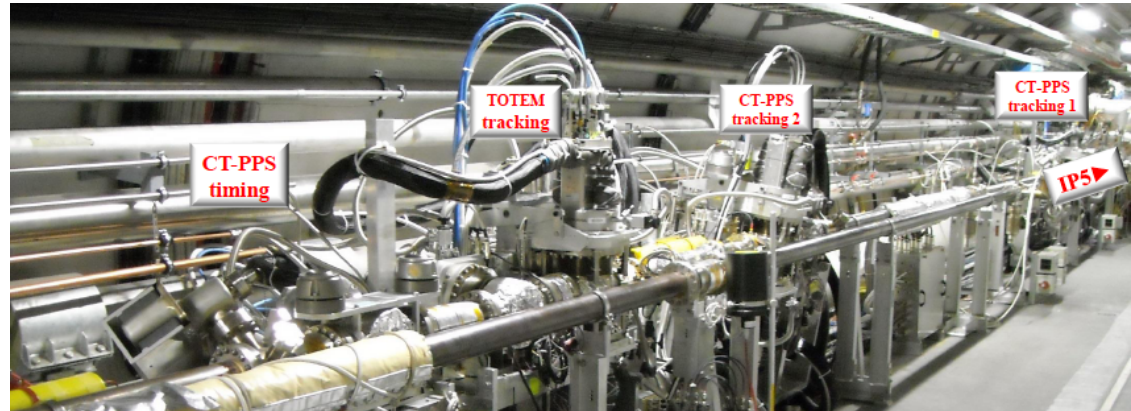
Also for exclusive final states ...

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



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

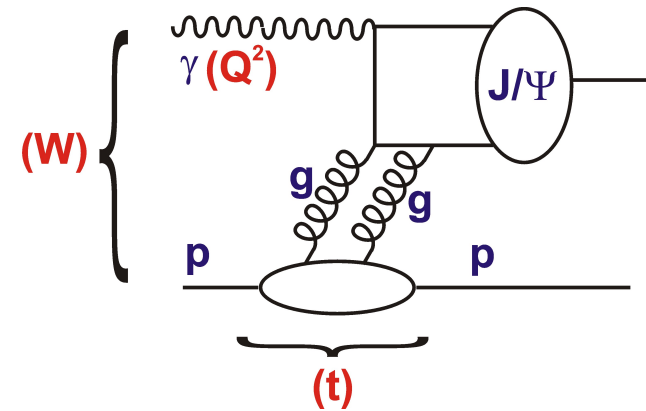
LHC experiments (TOTEM, ALFA@ATLAS) show that precision measurements are possible with Roman pots, covering wide kinematic range and including high lumi (even with pile-up)
 e.g. TOTEM operated 14 pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential t dep ...



Exclusive Diffraction: Elastic J/Ψ Photoproduction

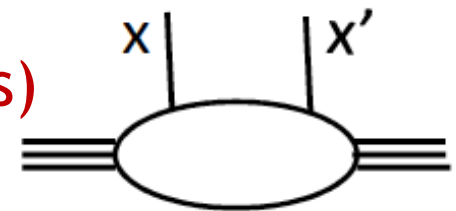
Advantages

- Clean 2 lepton experimental signature
- Scale $Q^2 \sim (Q^2 + M_V^2)/4 > \sim 3 \text{ GeV}^2$ 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 $x' \ll x \ll 1$ (theoretically not at same level as collinear PDFs))

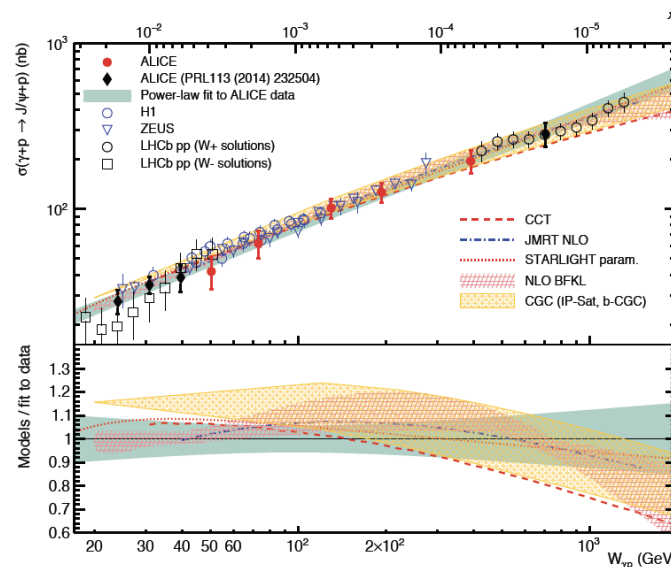
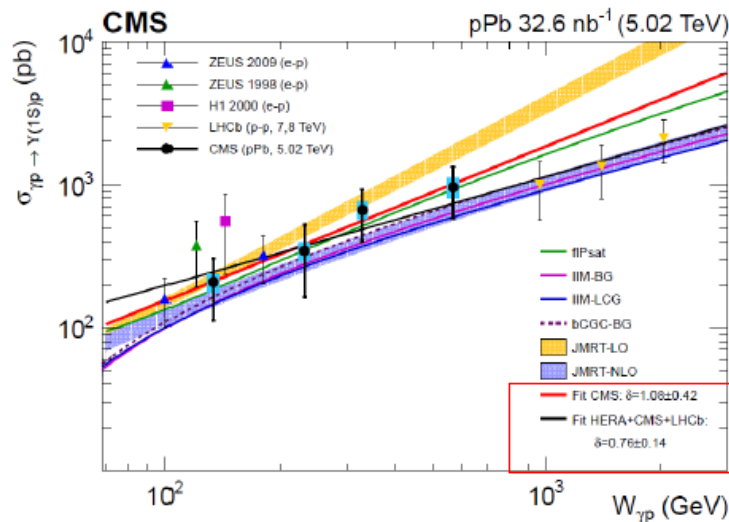
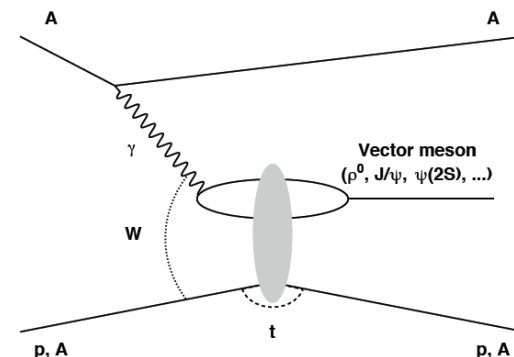
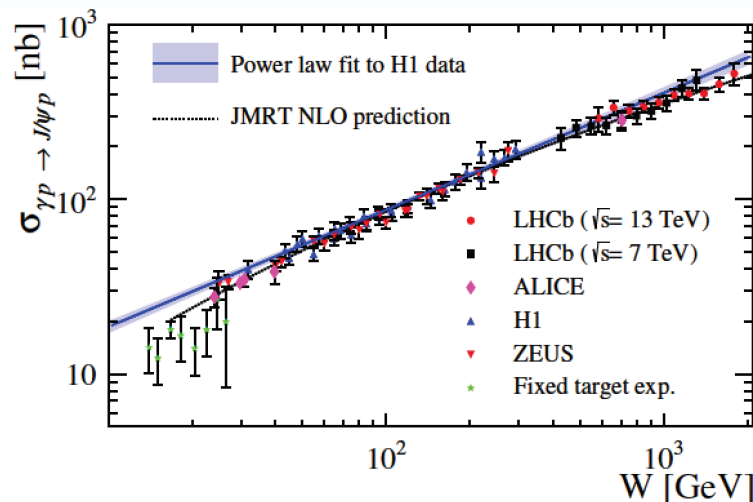


Complications

- Vector meson wavefunction
- Large scale uncert's in collinear fac'n (NLO v LO convergence)⁵

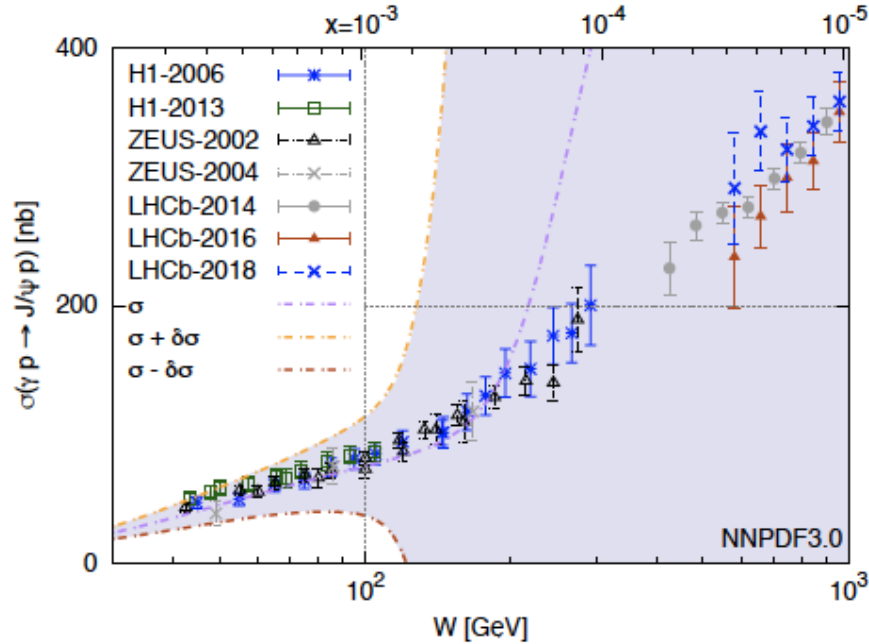
Current Exclusive J/ψ Data

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



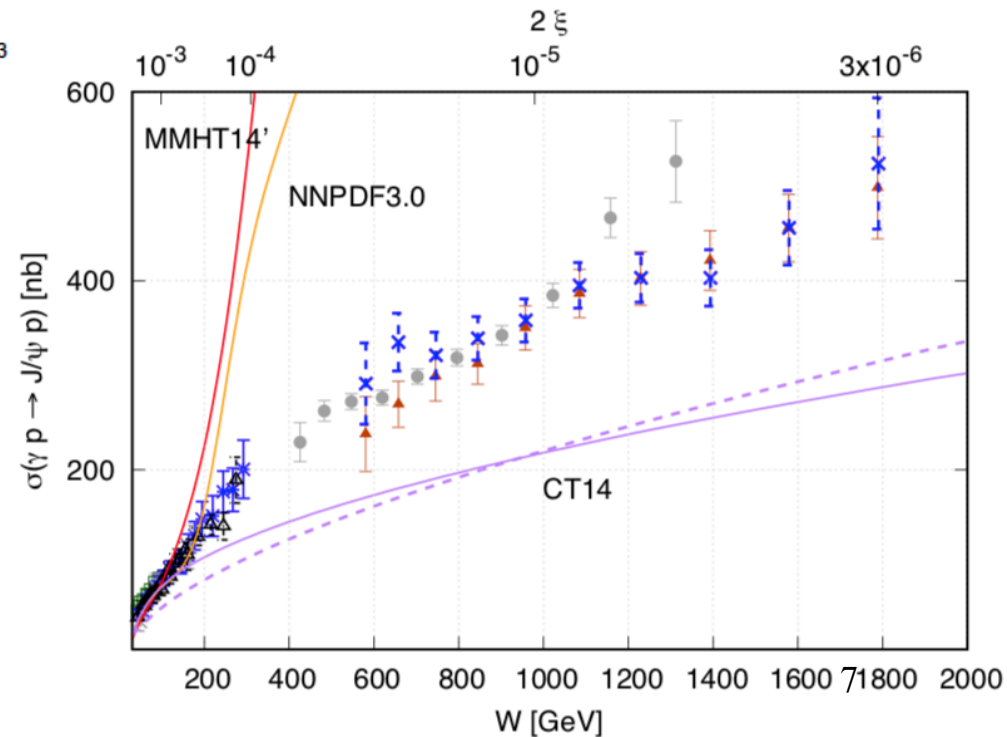
- No sign of saturation (yet)
- JMRT NLO gives excellent ‘out-of-box’ prediction (k_T facⁿ)

Interpretation in JMRT



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

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



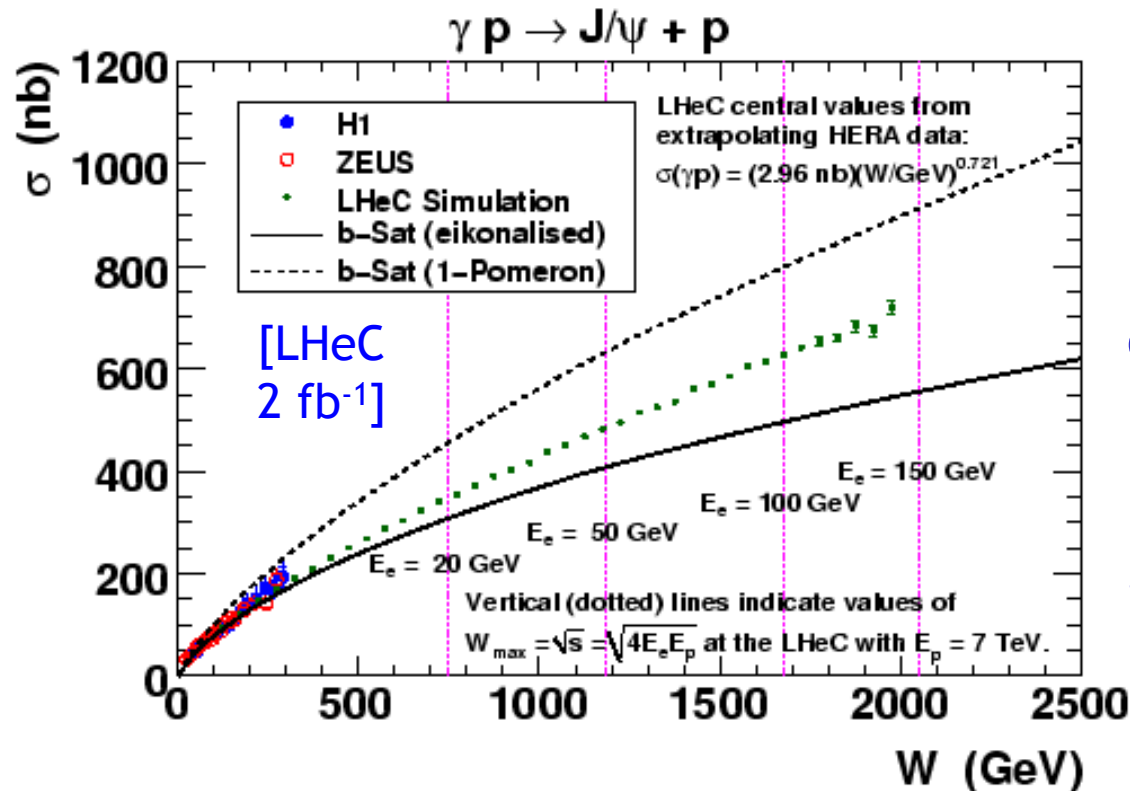
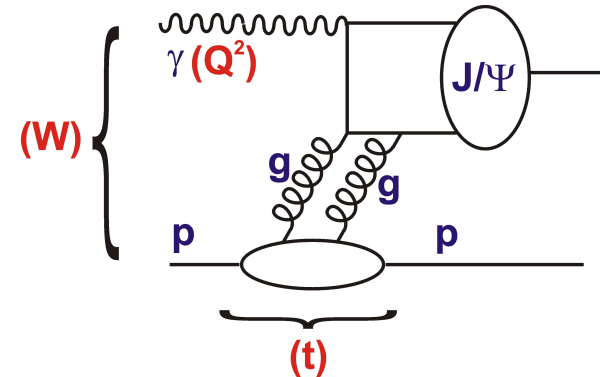
- Apparently remarkable sensitivity to low x gluon $\rightarrow$ Distinguishes between global PDF sets!
- Not at all well established theoretically, but surely worth pursuing in future ep!

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

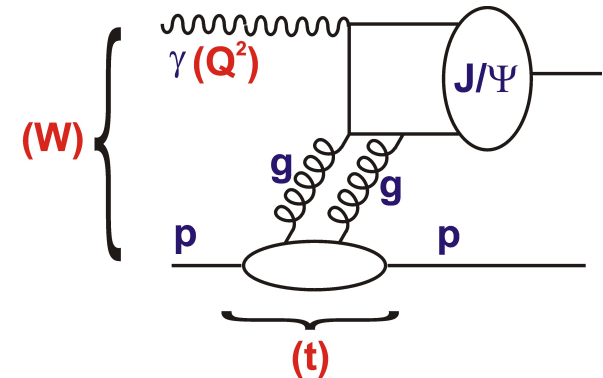
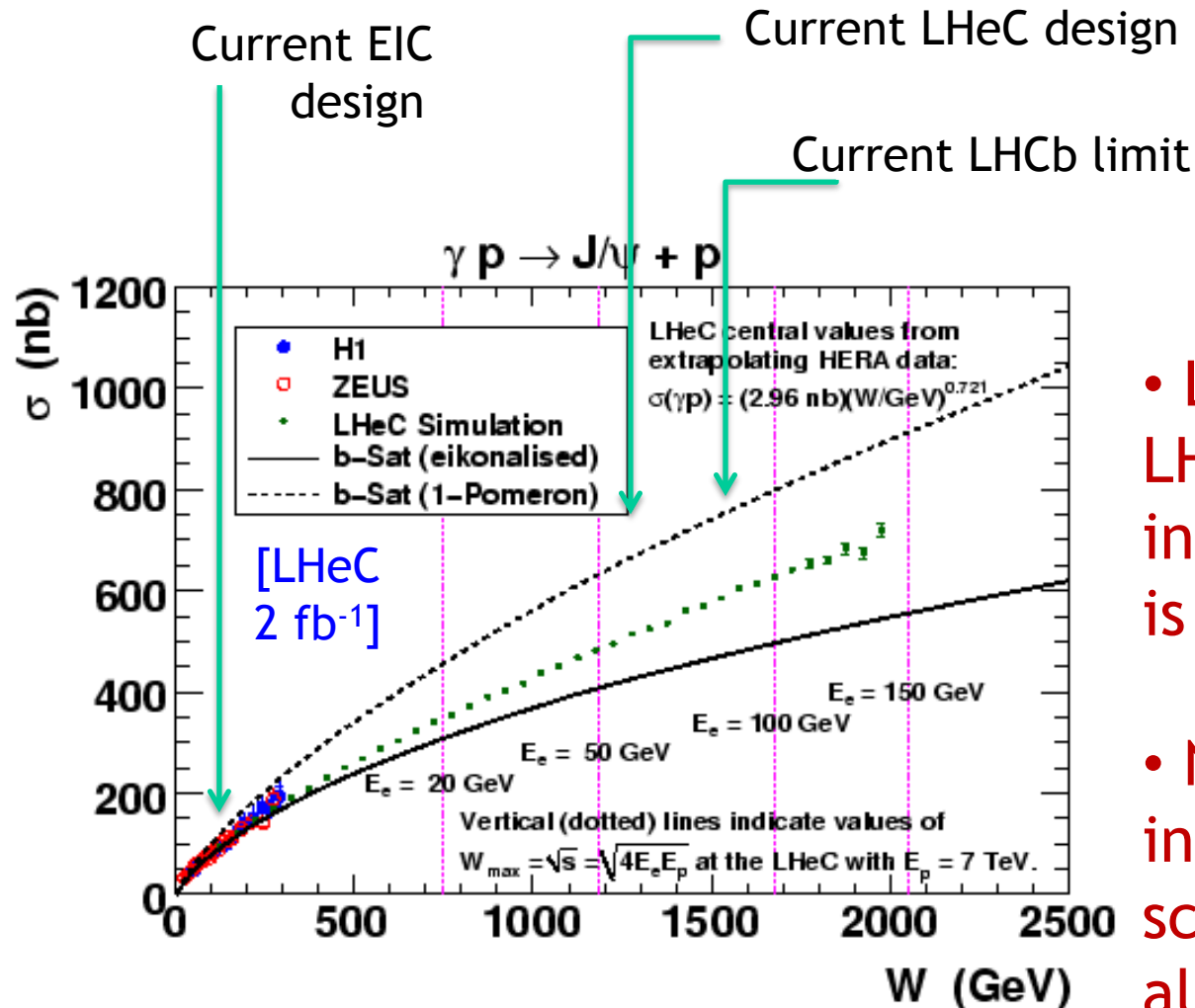


• Significant non-linear effects expected in LHeC kinematic range

... ‘smoking gun’?...

J/Ψ from future ep v Dipole model Predictions

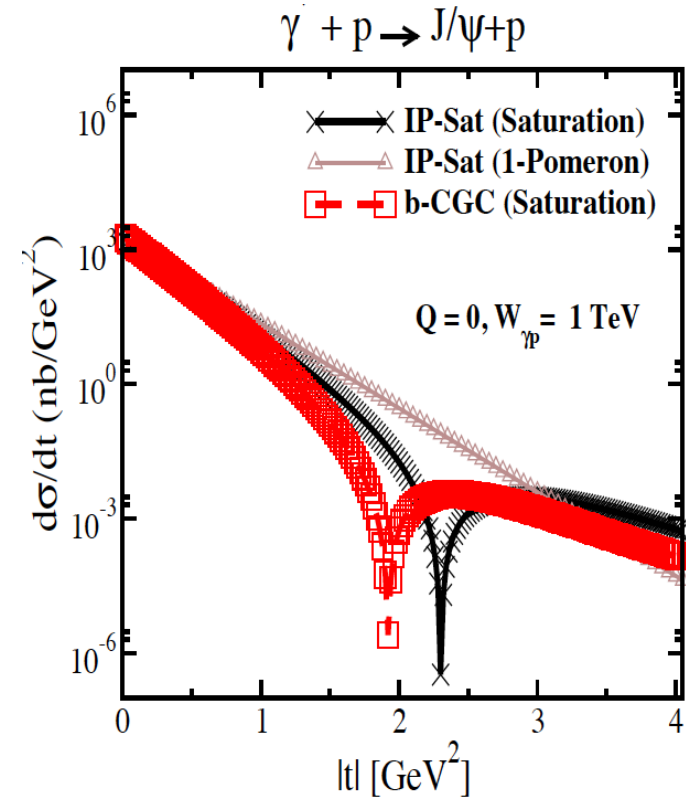
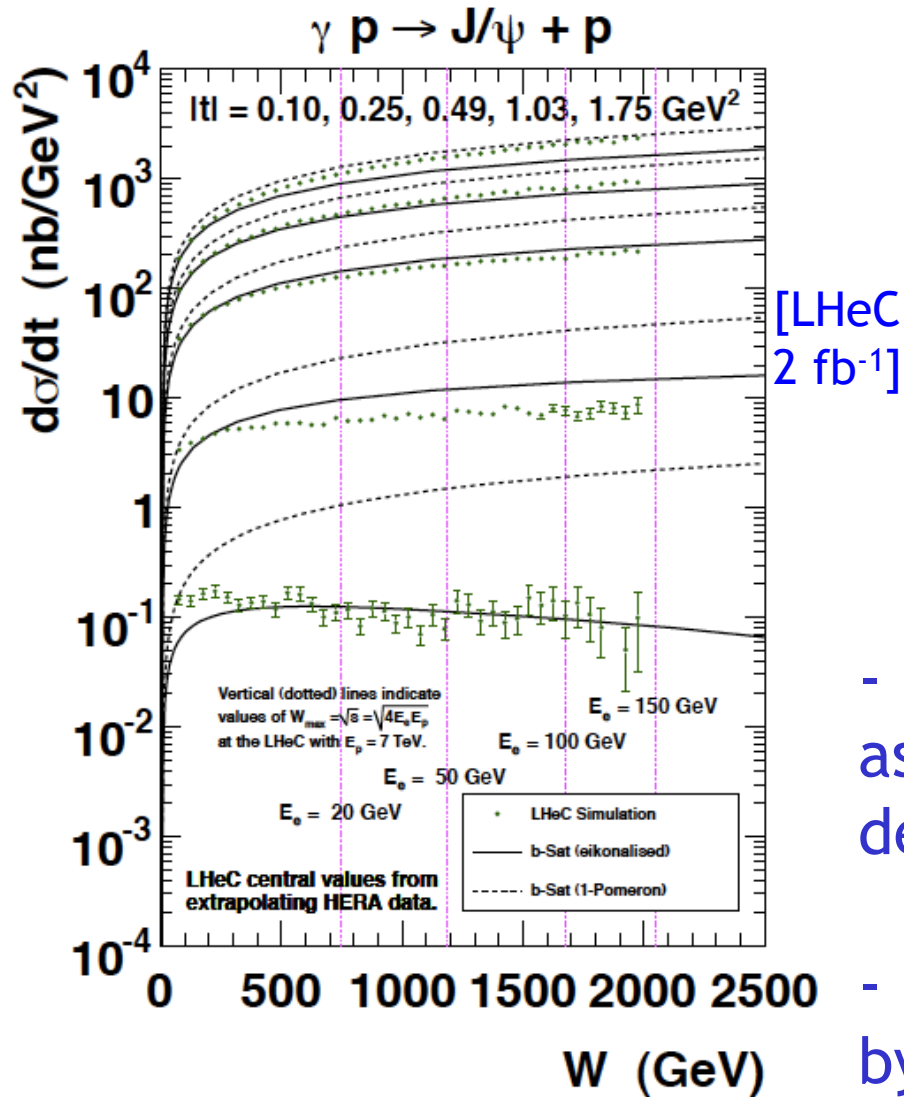
“beware unrealistic non-saturation straw men” [T. Lappi]



- Lack of satⁿ 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 Q²).

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

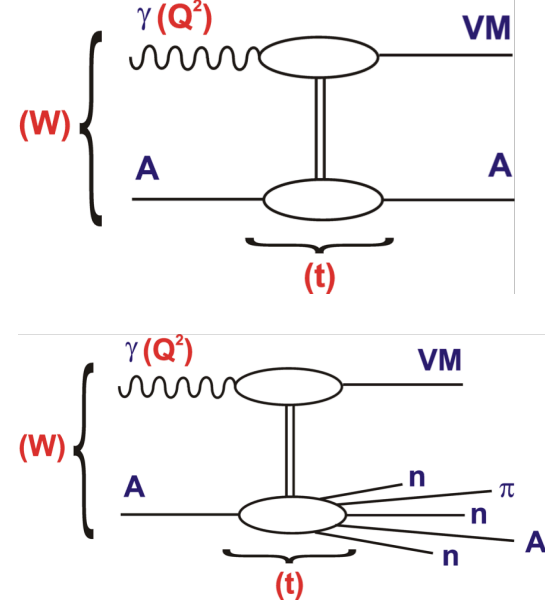
- Precise measurement from decay μ tracks extends to large $|t|$



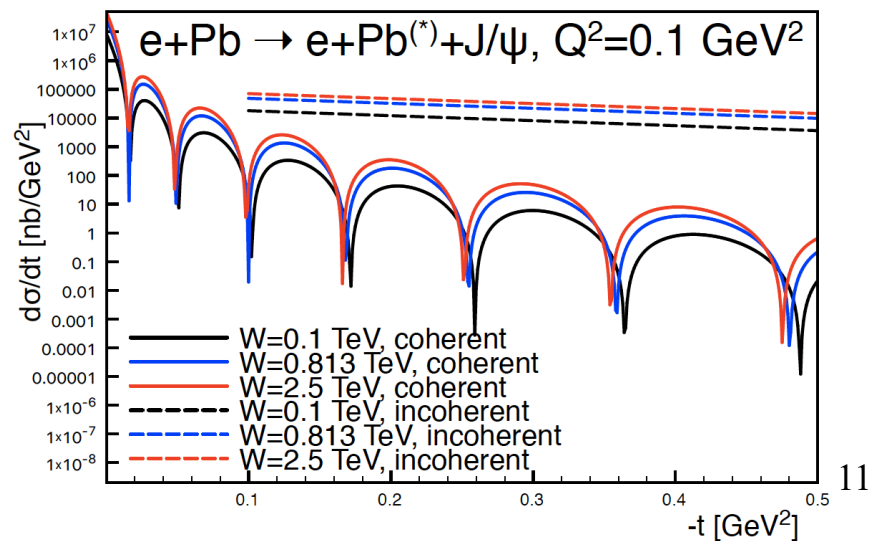
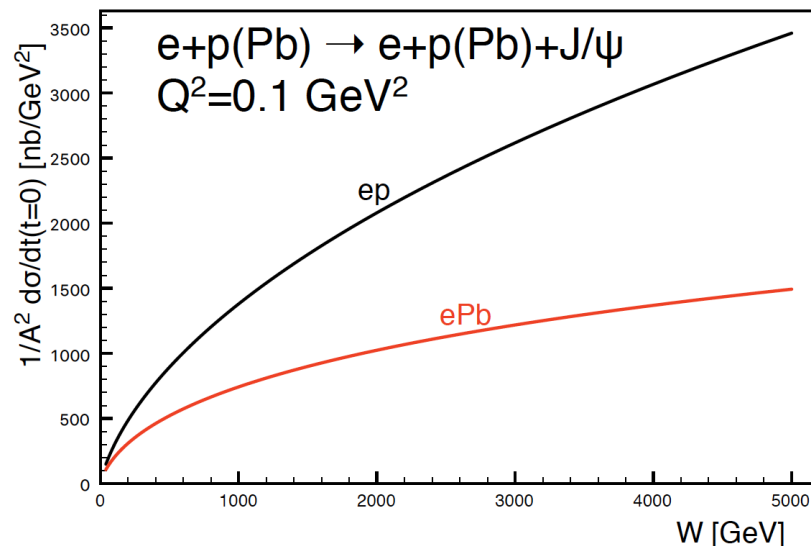
- Dips in t distribution proposed as (model dependent) signature of departure from linear evolution
- Requires large samples / lumi by HERA standards, but not LHeC

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 ($eA \rightarrow eVA$)
- Experimental challenge is to separate coherent from incoherent



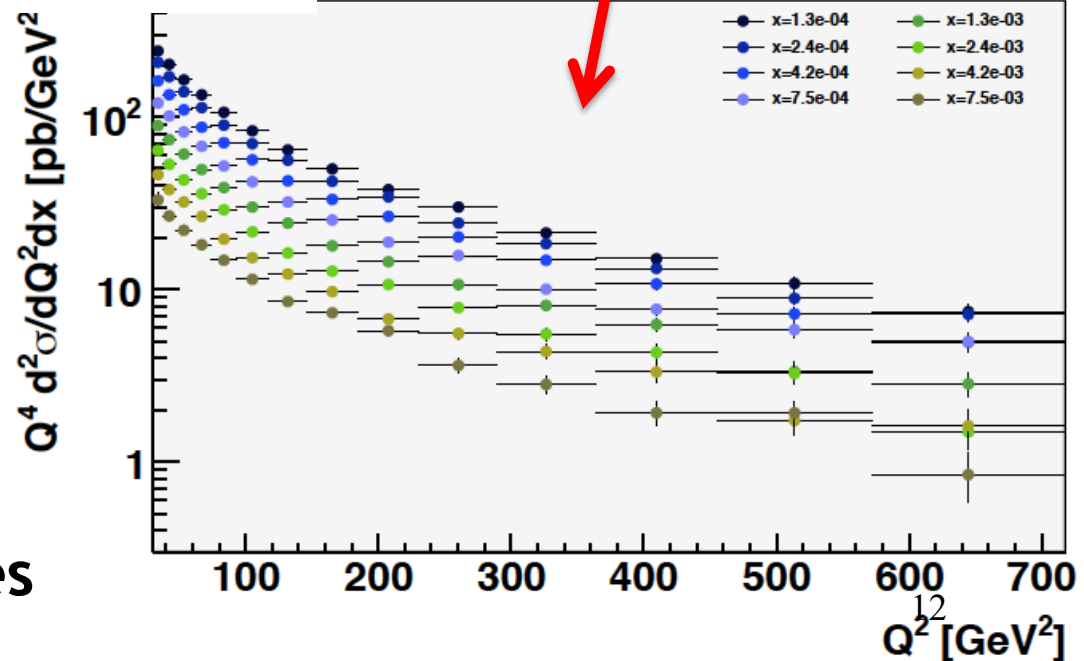
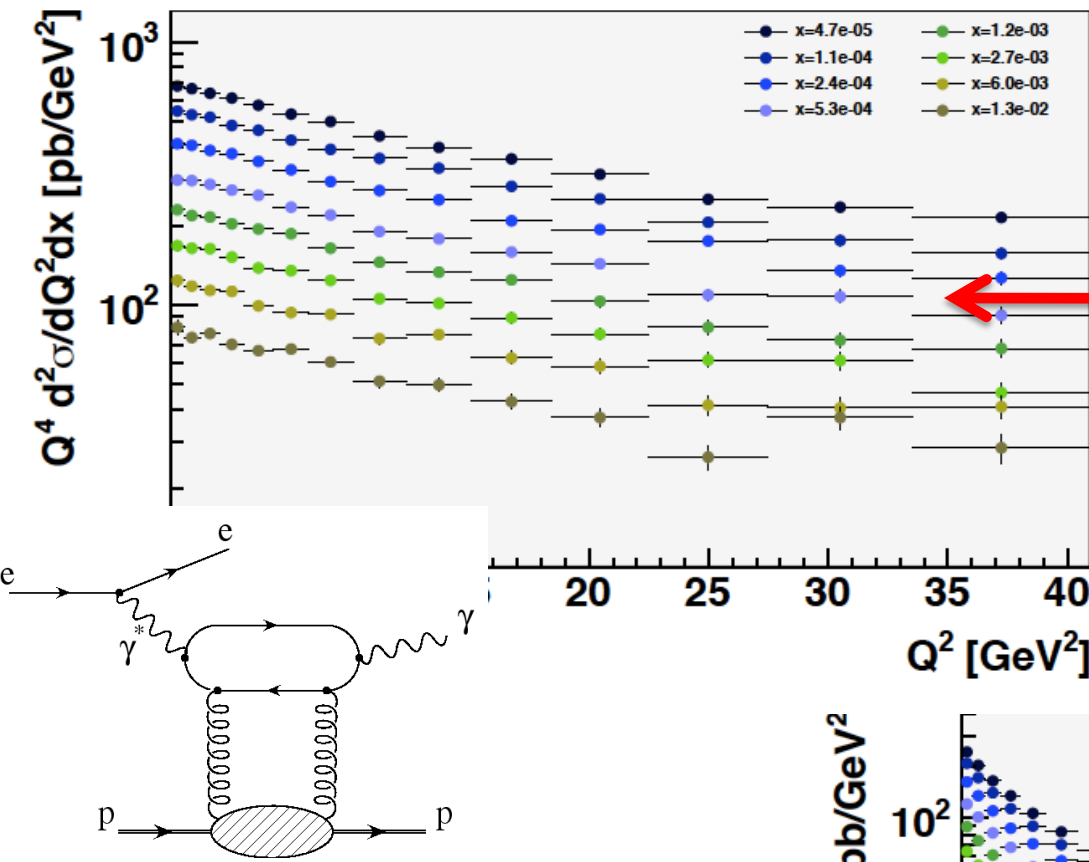
- Roman pots to tag nuclei impractical - tiny scattering angles
- Separation of incoherent diffraction based mainly on neutrons in ZDC ... some theoretical uncertainty



(OLD) DVCS simulation (MILOU)

1 fb⁻¹, E_e = 50 GeV,
1° acc'nce, p_T^γ > 2 GeV

100 fb⁻¹, E_e = 50 GeV,
10° acc'nce, p_T^γ > 5 GeV

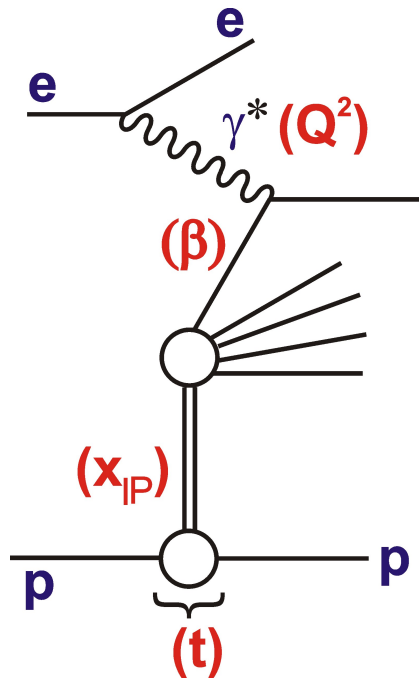


Precise data with
W → 1 TeV, Q² → 700 GeV²,
x → 5.10⁻⁵

Still to do:

- Beam charge asymmetries
- Sensitivity to GPDs

Inclusive Diffraction and Semi-Inclusive (Diffractive) PDFs

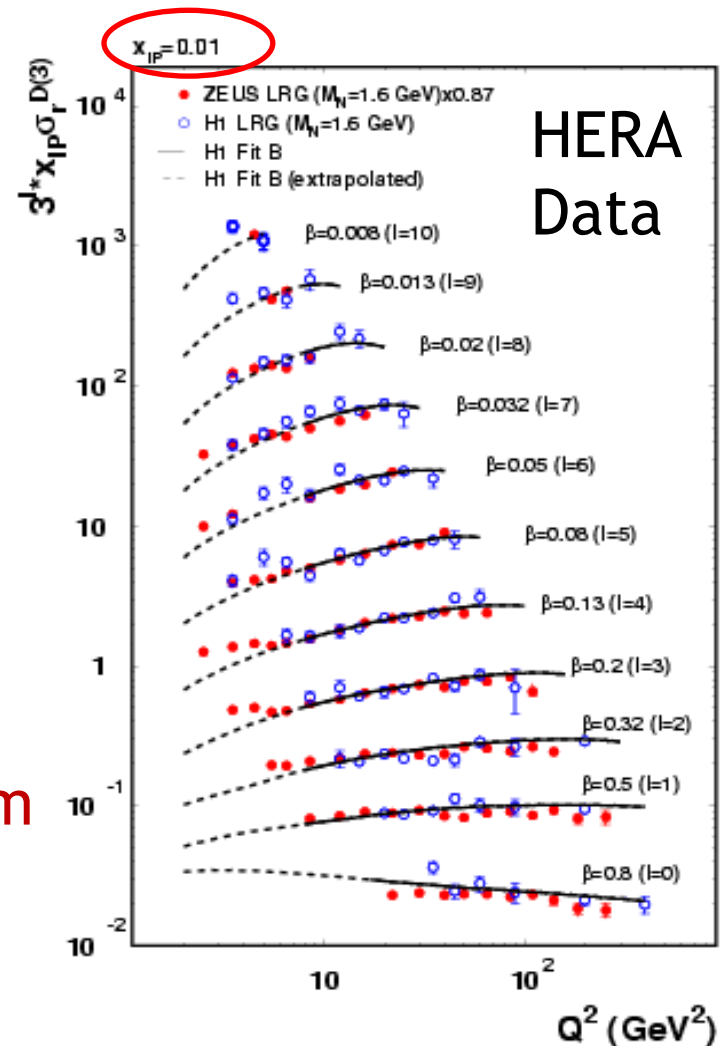


$$x_{IP} \equiv \xi = x_{IP}/p$$

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

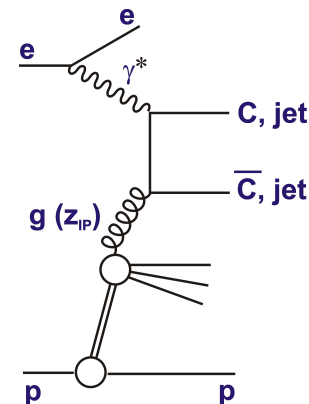
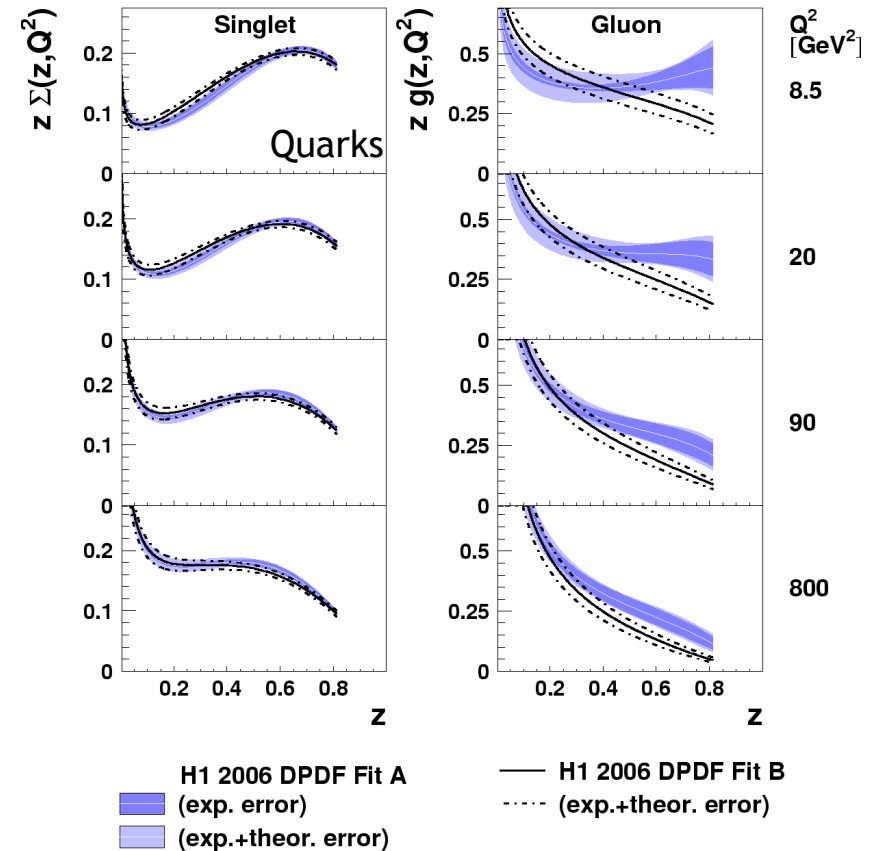
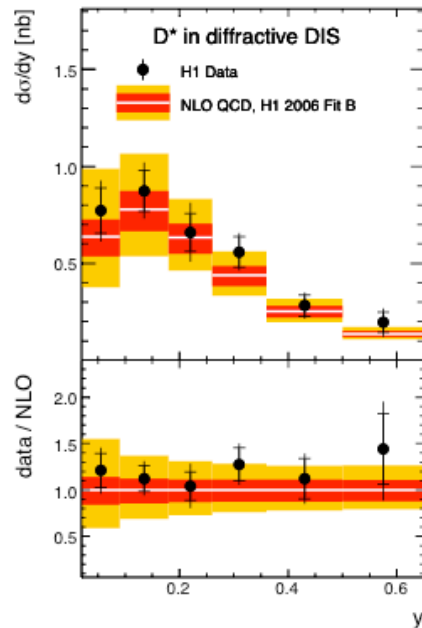
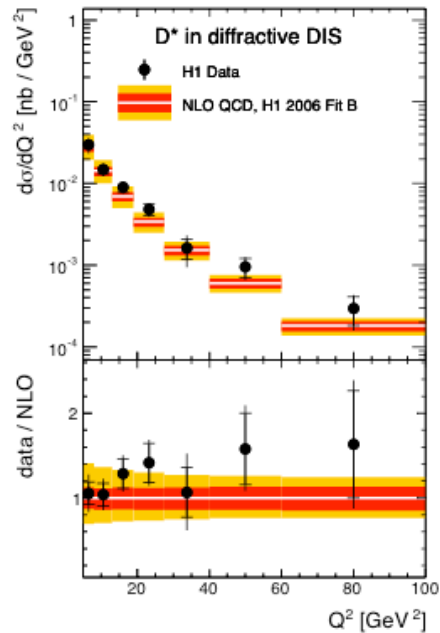
- $ep \rightarrow eXp$ with proton 4-momentum barely changed has a leading twist contribution at $\sim 10\%$ of total x-sec

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



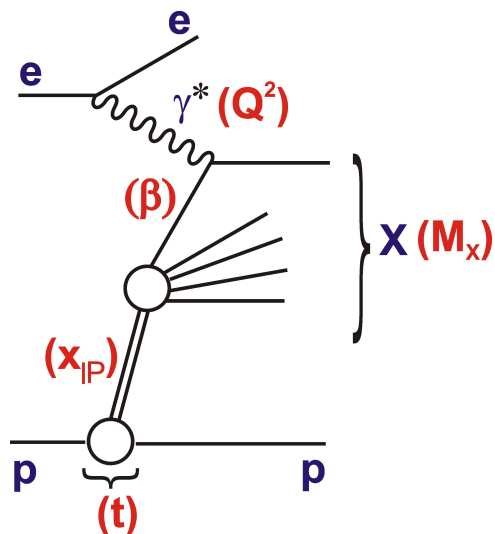
Diffractive Parton Densities (DPDFs) at HERA

- 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)



→ 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 ...

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

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

Néstor Armesto¹, Paul R. Newman², Wojciech Słomiński³ and Anna M. Staśto⁴

¹*Instituto Galego de Física de Altas Enerxías IGFAE, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia-Spain*

²*School of Physics and Astronomy, University of Birmingham, B15 2TT, United Kingdom*

³*Institute of Physics, Jagiellonian University, 30-348 Krakow, Poland*

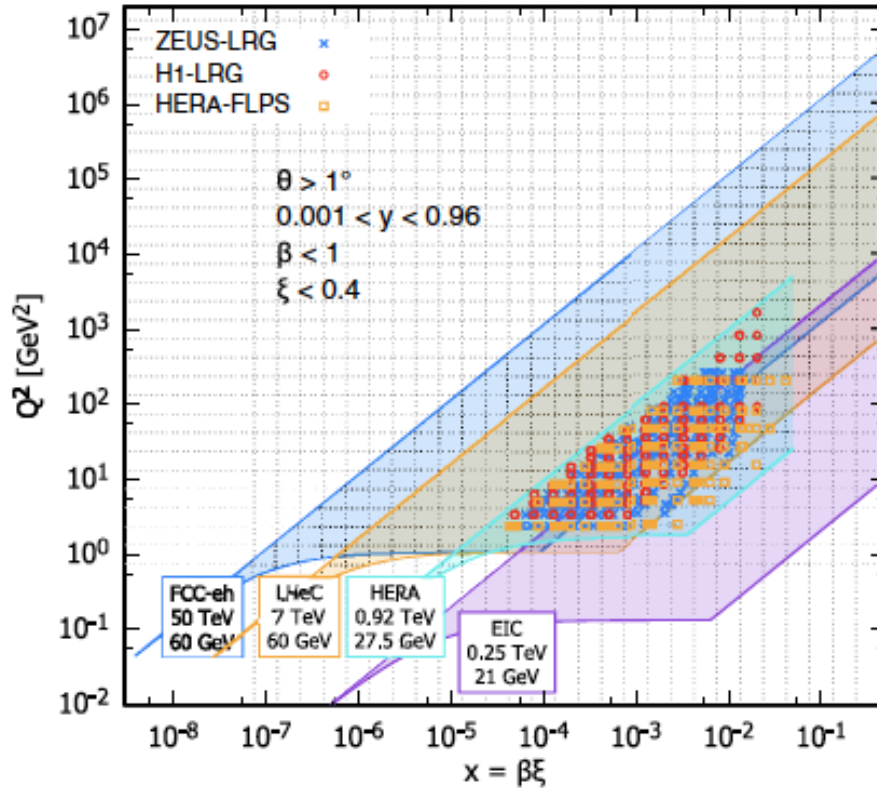
⁴*Department of Physics, Penn State University, University Park, Pennsylvania 16802, USA*

(Received 29 August 2019; published 21 October 2019)

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 .

DOI: 10.1103/PhysRevD.100.074022

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 , Q^2)

- 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

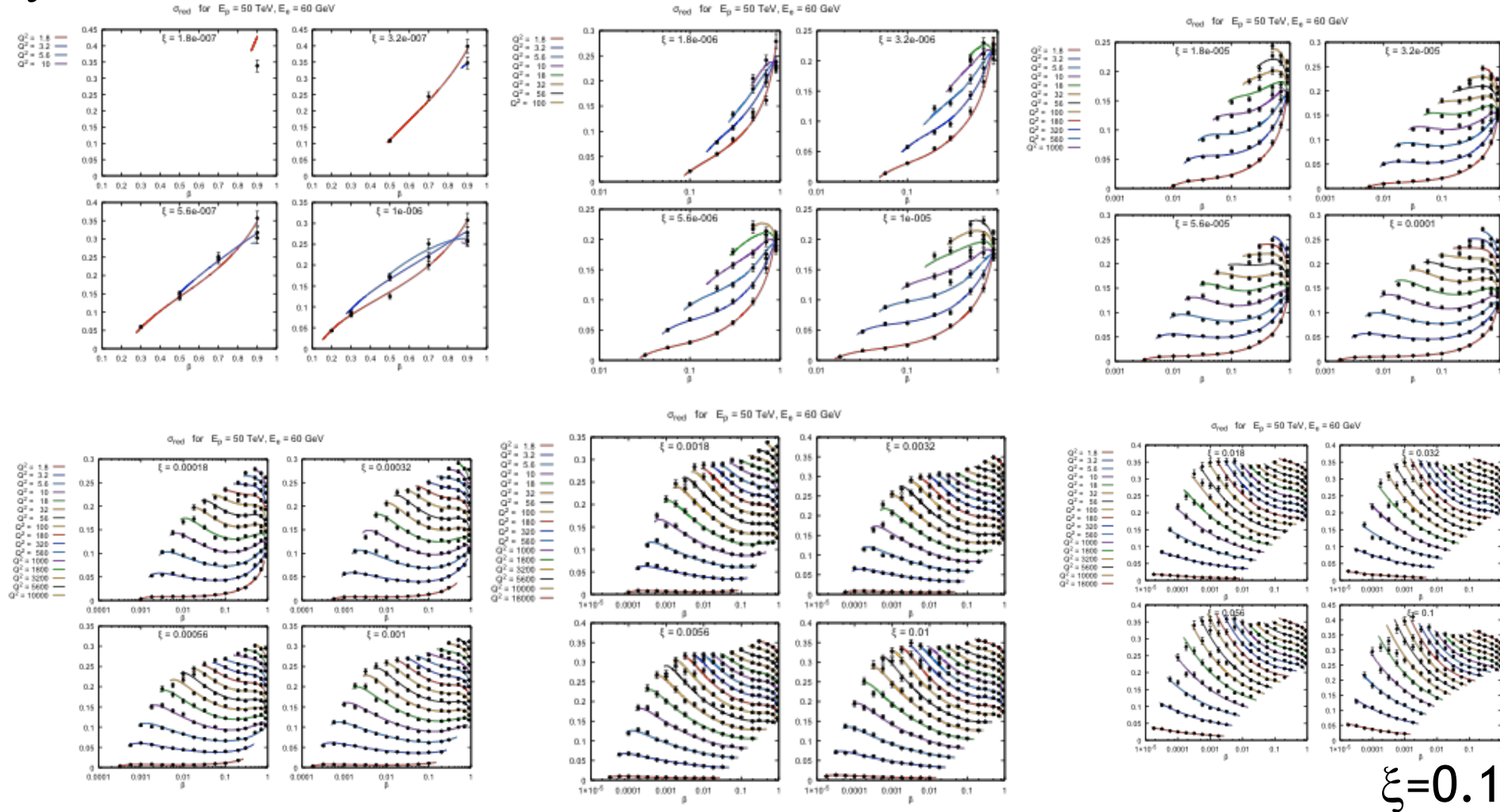
$d = u = s = \text{dbar} = \text{ubar} = \text{sbar}$

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

GM-VFNS heavy flavour scheme

All pseudodata bins at FCC-eh

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



$$\xi = 0.1$$

Data uncertainties:

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

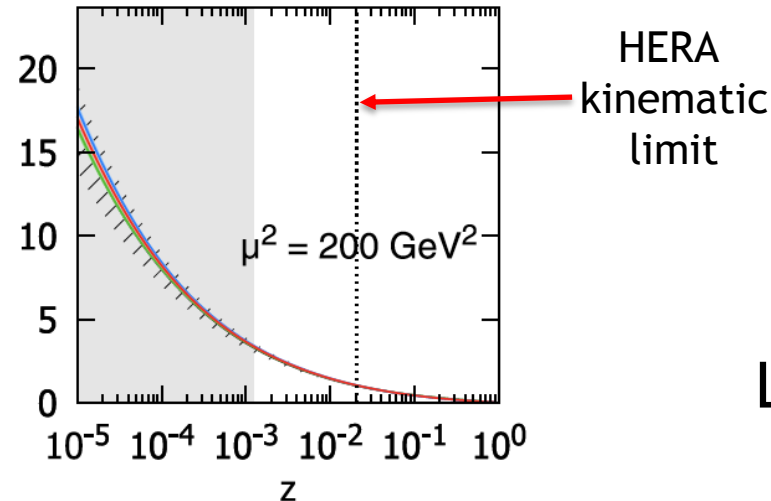
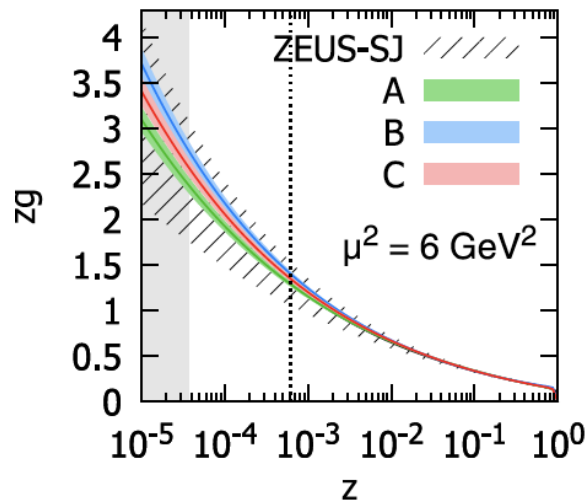
Fit range:

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

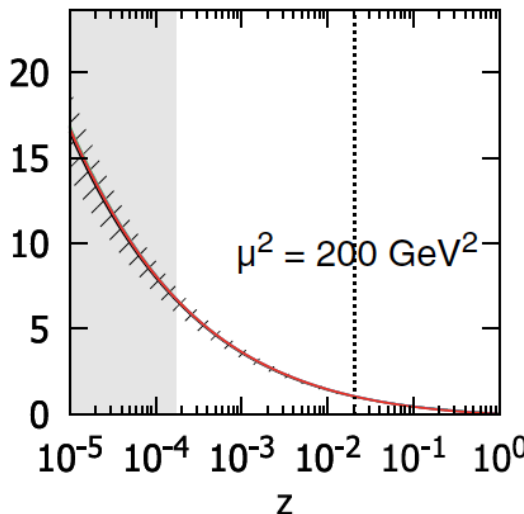
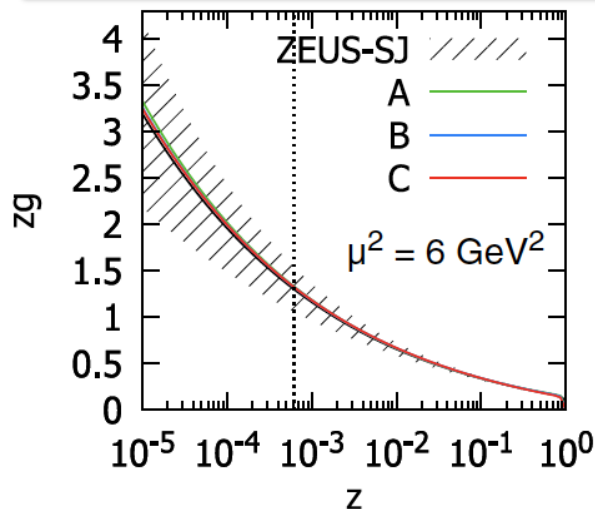
$$\xi_{\max} = 0.1$$

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

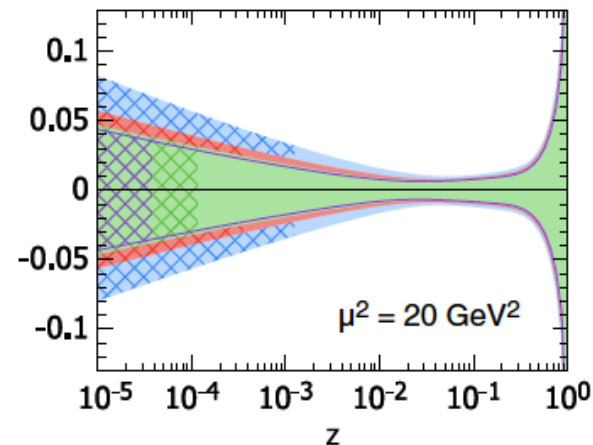
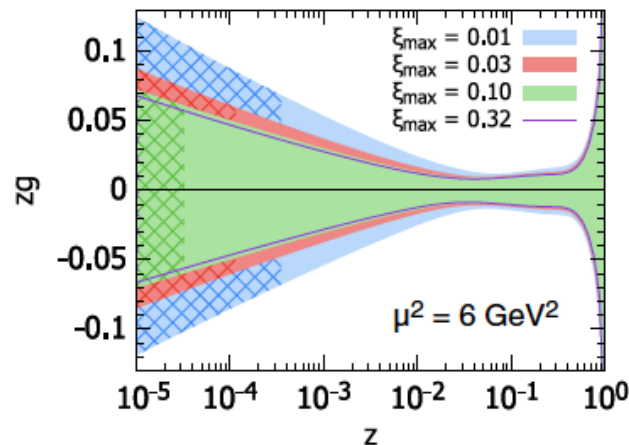


FCC-eh gluon

[Absolute values not very meaningful $\rightarrow$ relative precision]

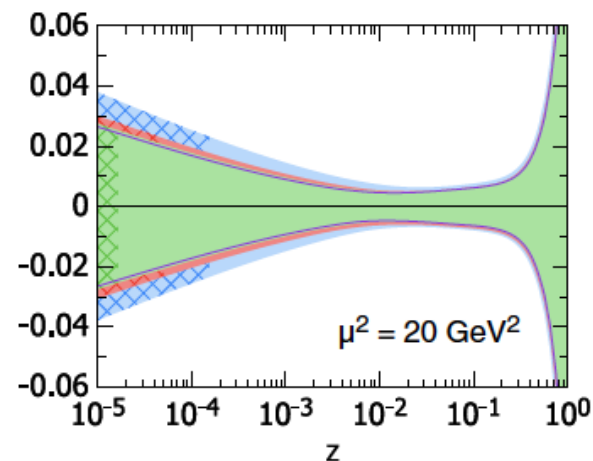
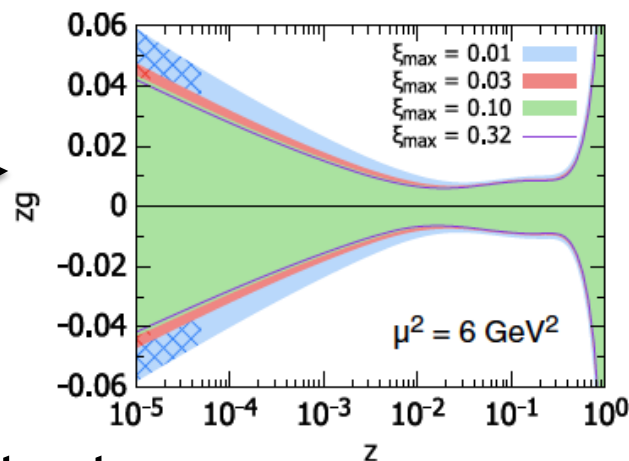
Relative Precision on Diffractive Gluon Density

LHeC $\longrightarrow$



[90% CL bands]

FCC-eh $\longrightarrow$

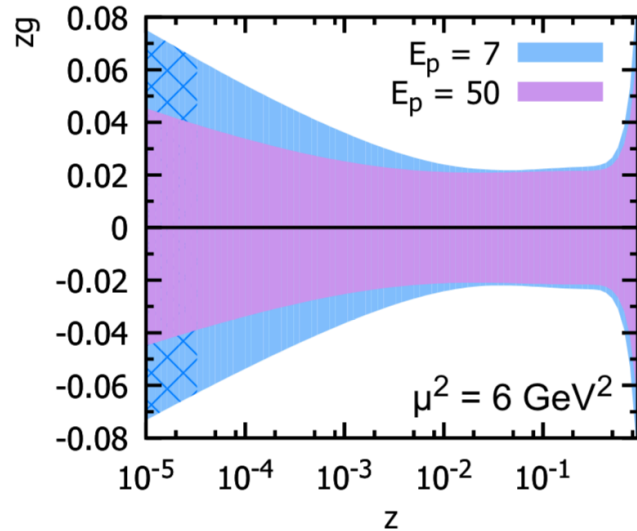


Notes in LHeC context:

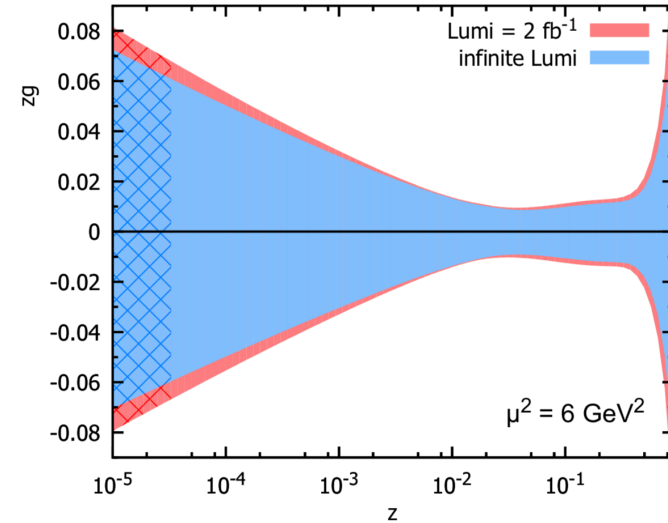
- Well constrained down to β or $z \sim 10^{-4} - 10^{-5}$
- Experimental precision on quarks $< 2\%$ (direct from data)
- Experimental precision on gluons few% (scaling viol's)
- No statement on parameterisation or theory uncertainties

More Detail (LHeC version, only gluon shown)

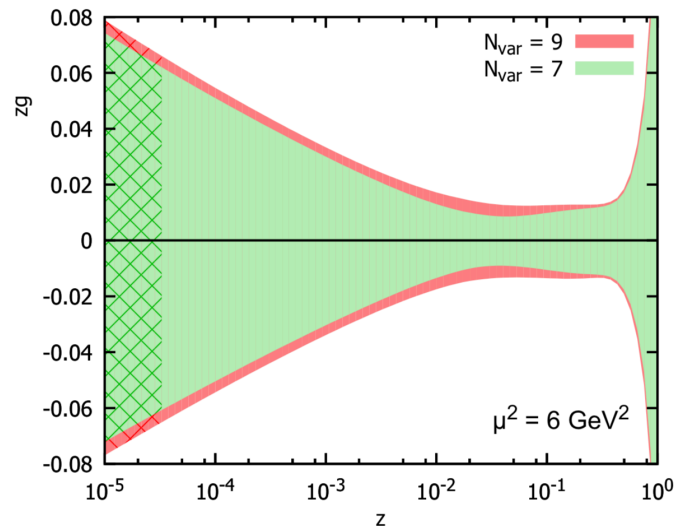
with 2% norm'n uncertainty



2fb^{-1} v infinite lumi



Free IP and IR intercepts



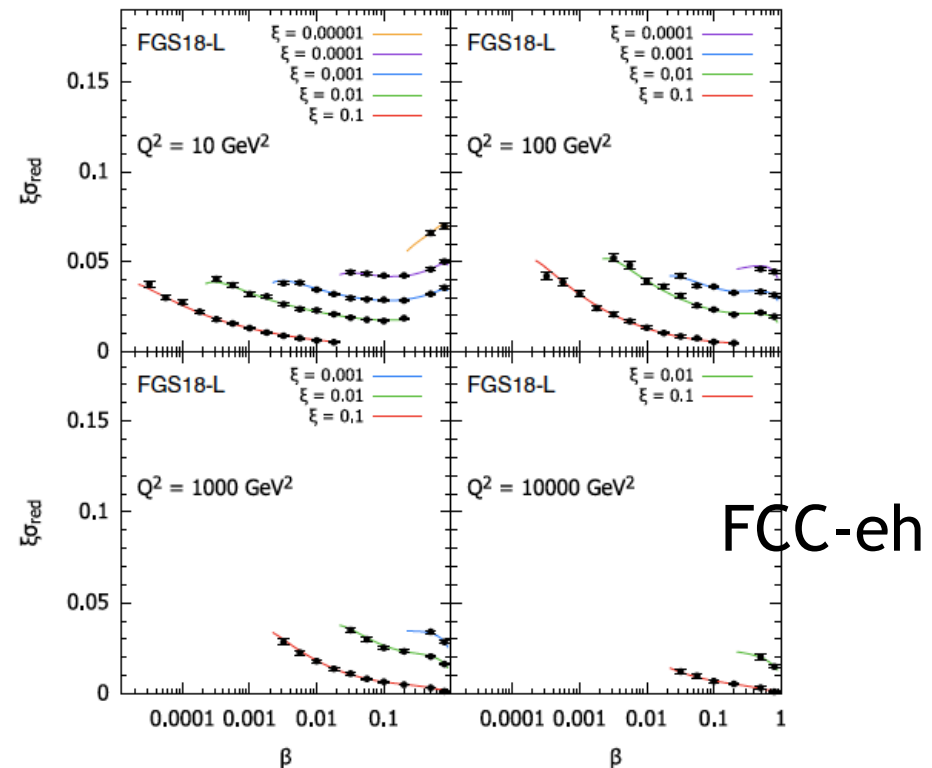
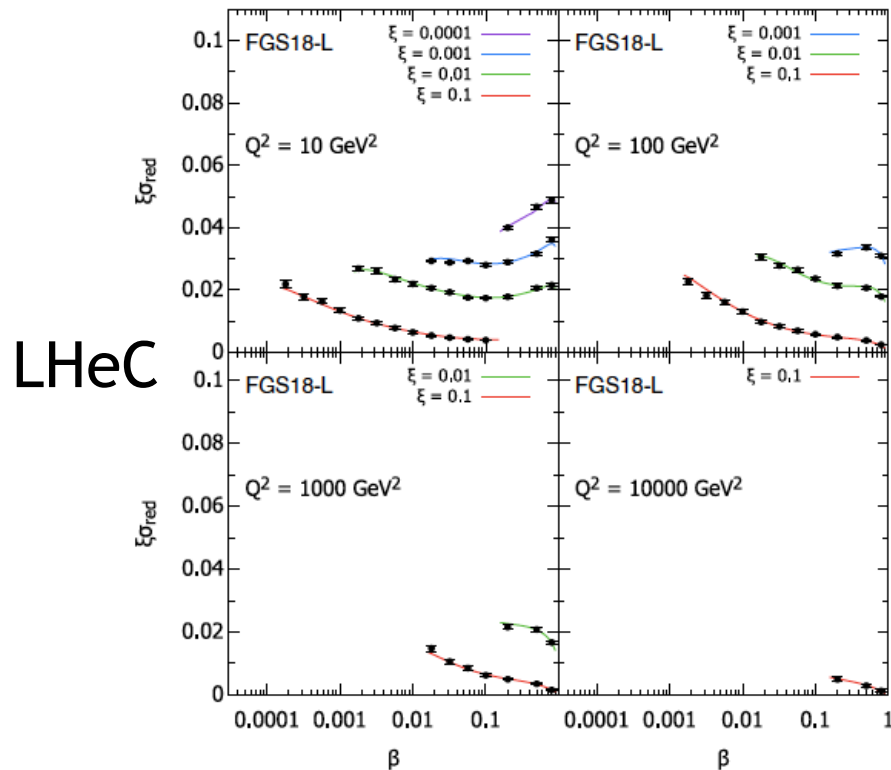
Still open questions:

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

Inclusive Diffraction from Nuclei:

Selected Simulated Data for $e \text{ Pb} \rightarrow e X \text{ Pb}$

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



- Pseudodata (coherent Pb) - based on different versions of FGS model - illustrates accessible kinematic range
- Still to be subjected to DGLAP fits $\rightarrow$ nuclear DPDFs ...

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}

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

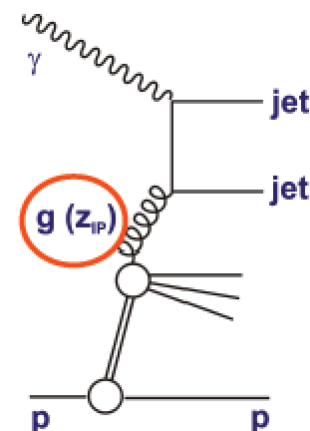
⁴ Theoretical Physics Department, CERN, 1211 Geneva, Switzerland

⁵ DESY, Notkestraße 85, D-22607 Hamburg, Germany

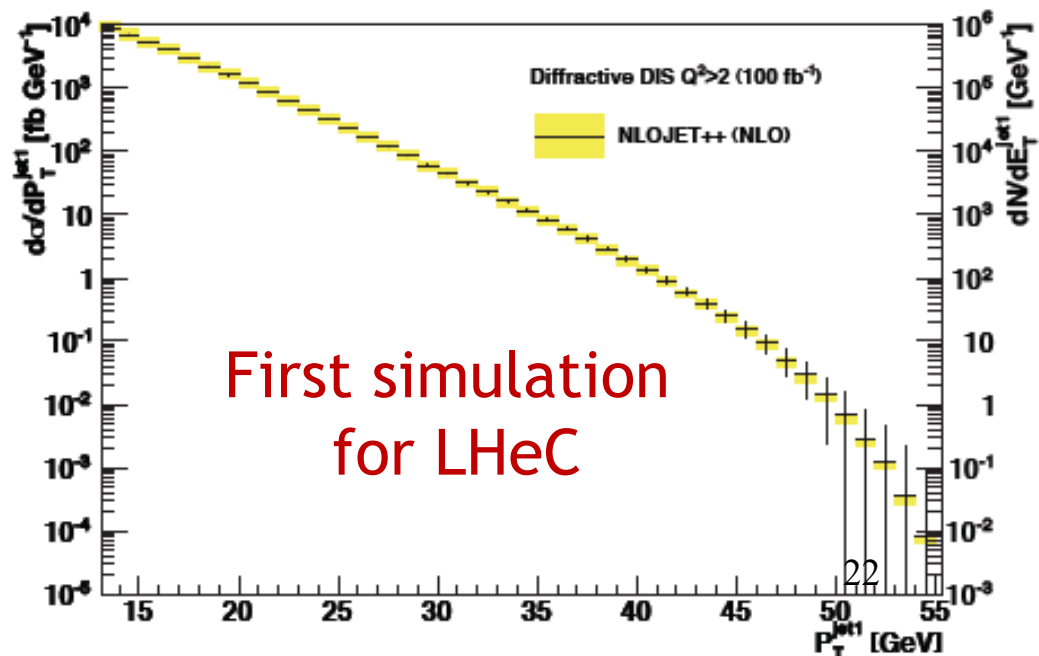
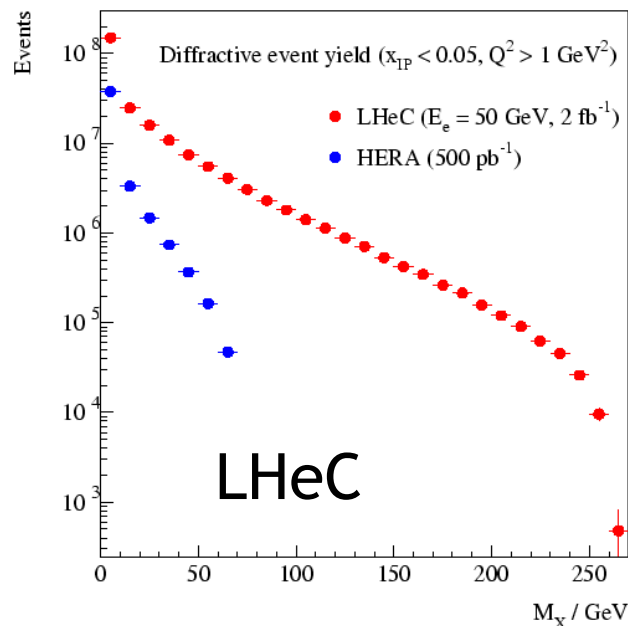
Received: date / Accepted: date

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.

Diffractive DIS Dijets (NEWish)



... precision
theory deserves precision
data!



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},
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¹ Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

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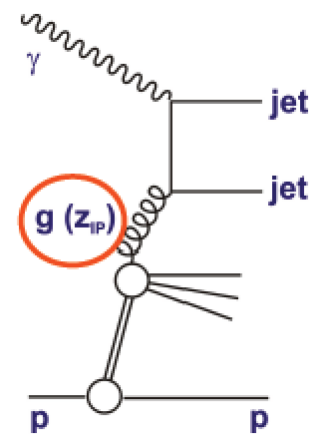
⁴ Theoretical Physics Department, CERN, 1211 Geneva, Switzerland

⁵ DESY, Notkestraße 85, D-22607 Hamburg, Germany

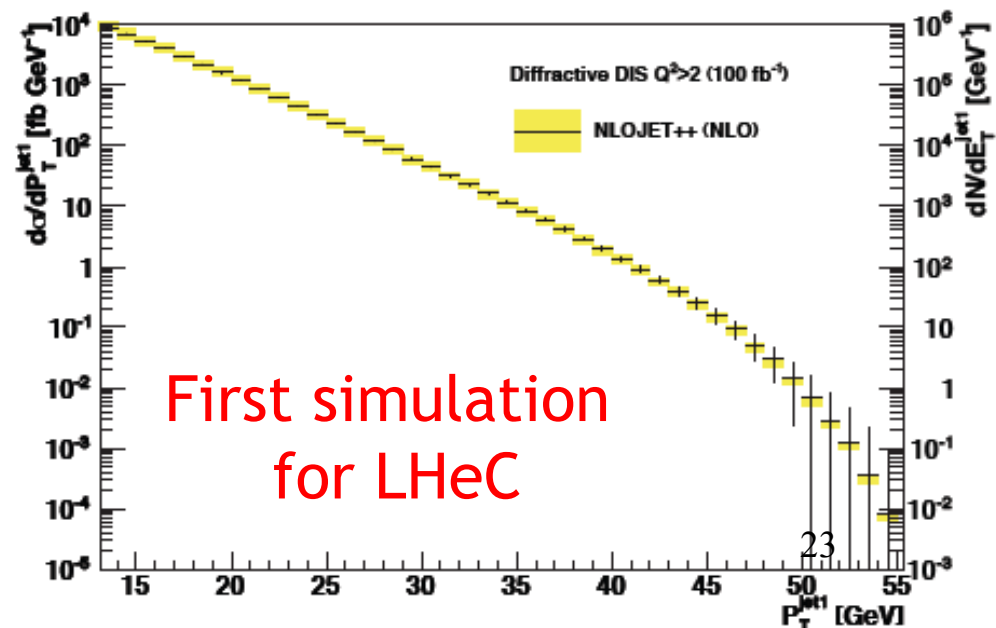
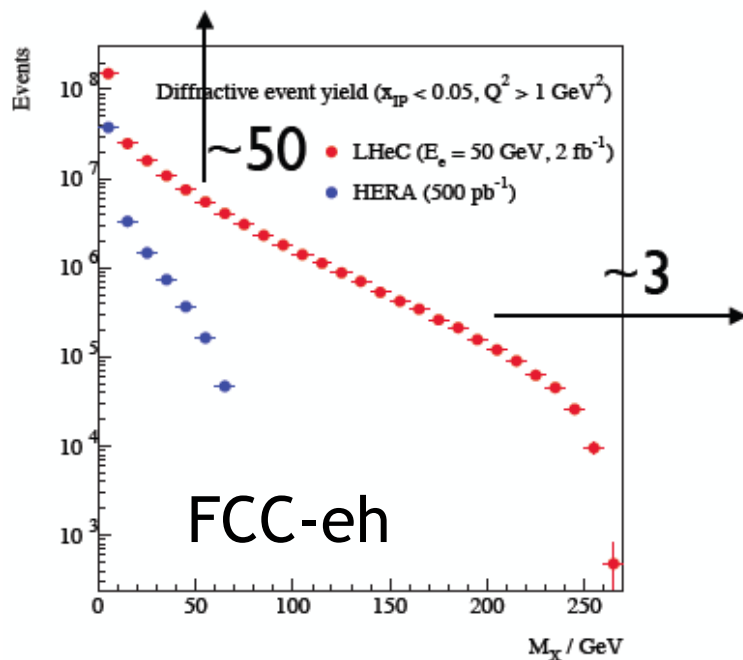
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Abstract Hard processes in diffractive deep-inelastic scattering can be described by a factorisation into parton-level subprocesses and diffractive parton distributions. In this framework, cross sections for inclusive dijet production in diffractive 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.

Diffractive DIS Dijets (NEWish)



... precision
theory deserves precision
data!



Summary

- Low x QCD is a future frontier $\rightarrow$ 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
 - $\rightarrow$ DVCS (and VM) $\rightarrow$ GPD / TMD sensitivity
 - $\rightarrow$ More on jets / HF at NNLO $\rightarrow$ diffractive gluon
 - $\rightarrow$ Interface detector simulations $\rightarrow$ realistic systematics
 - $\rightarrow$ More detailed forward instrumentation design