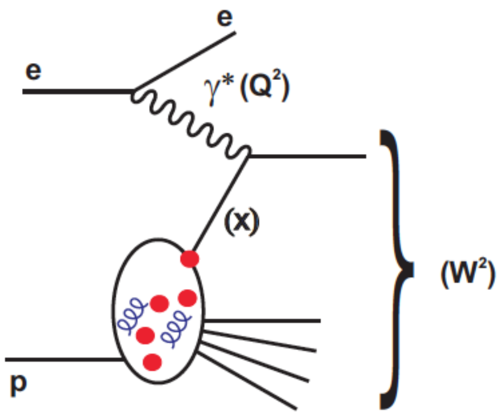
Low x Inclusive and Diffractive DIS: From HERA to Future Facilities

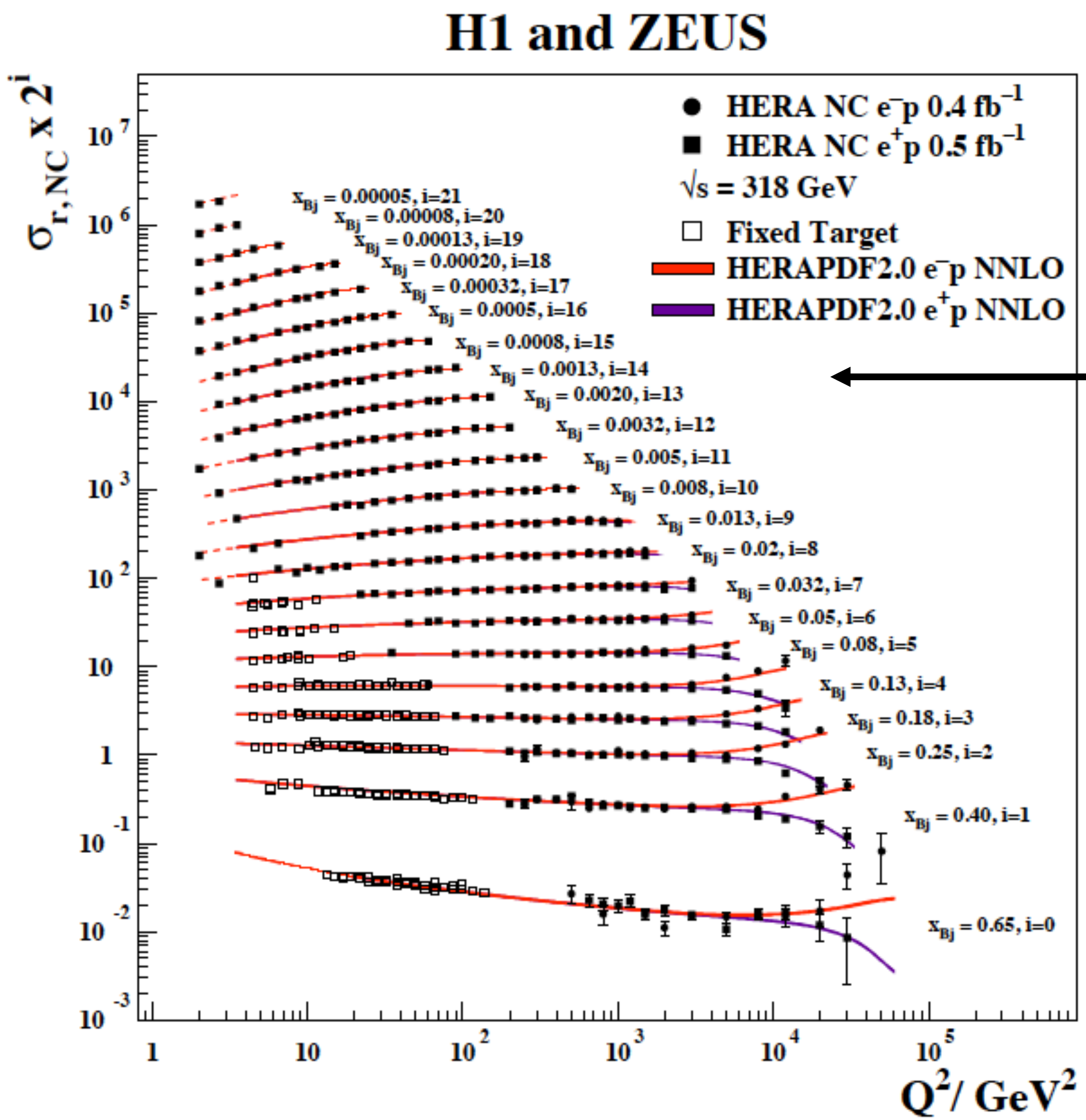
Paul Newman
Birmingham University



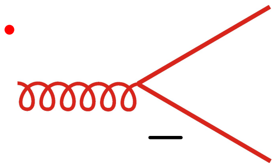
See also plenaries by Raju, Eugenio & Tuomas

Where knowledge of Low x Gluon Comes From

… entirely from inclusive Neutral Current HERA data …



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

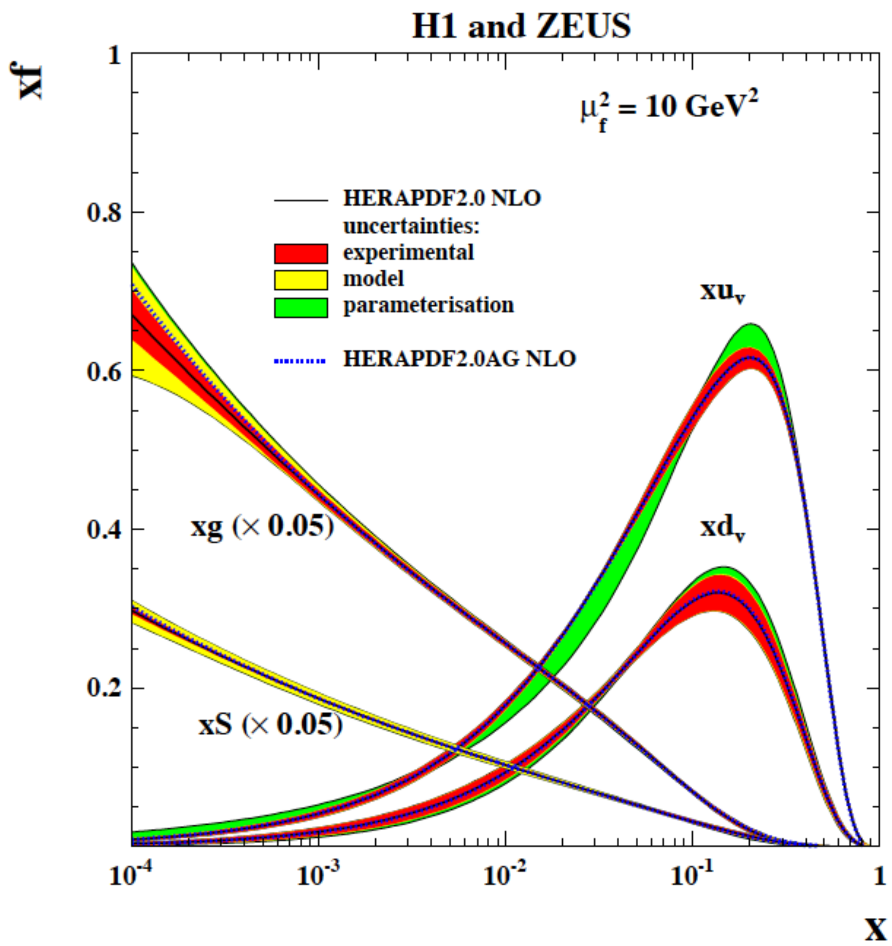


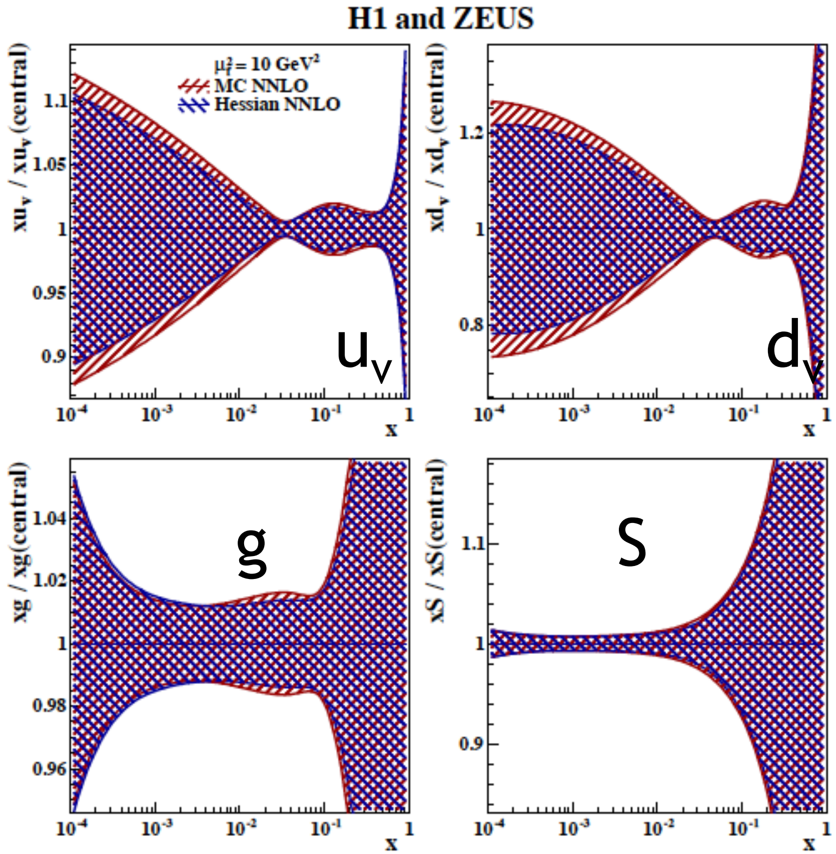
$$g \to q\bar{q}$$

- e.g. Prytz approx: $$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

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

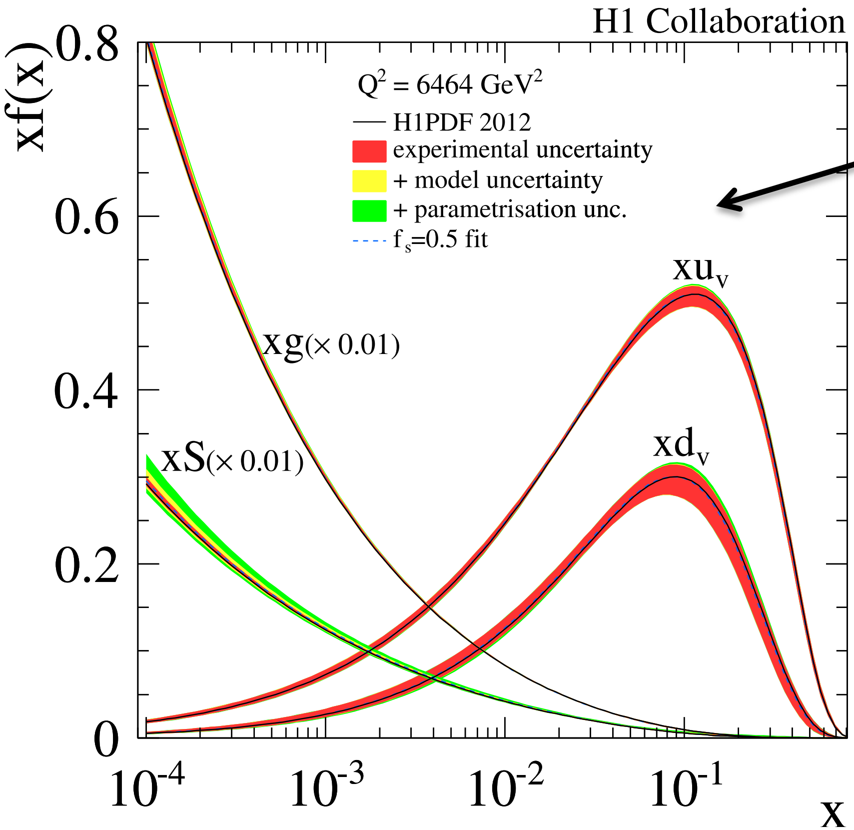
Final HERA Picture of Proton (HERAPDF2.0)





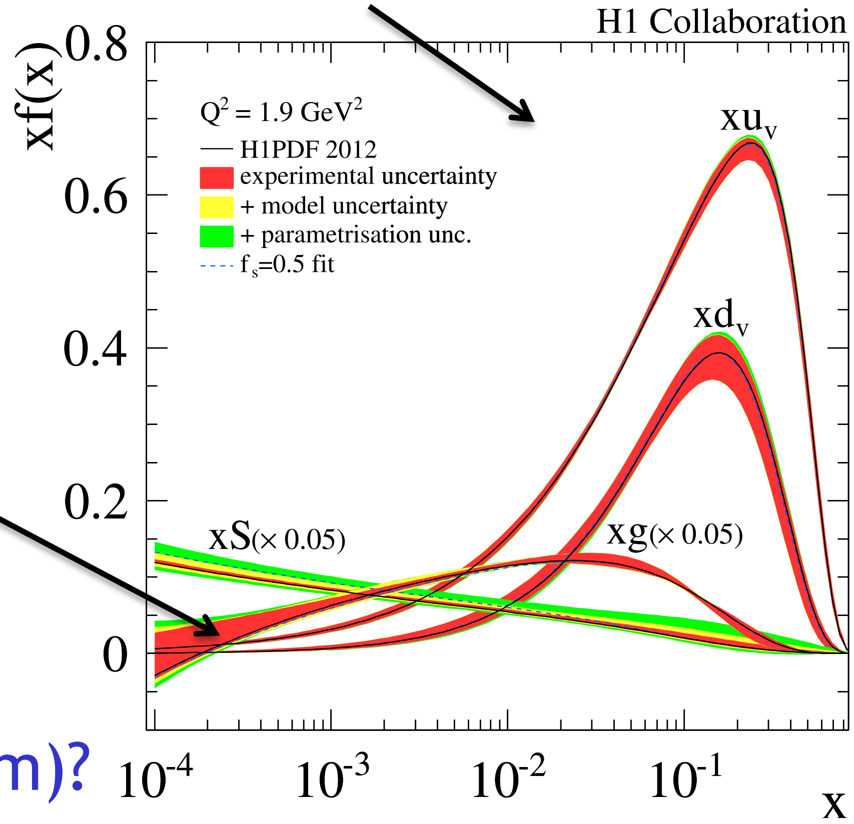
- ~2% precision on gluon over a wide range of x
- Uncertainty explodes towards $x=10^{-4}$
- Gluon itself is rising in a non-sustainable way …
- Note the 'Standard' presentation is at $Q^2 = 10$ GeV^2

The Gluon Density at Other Scales



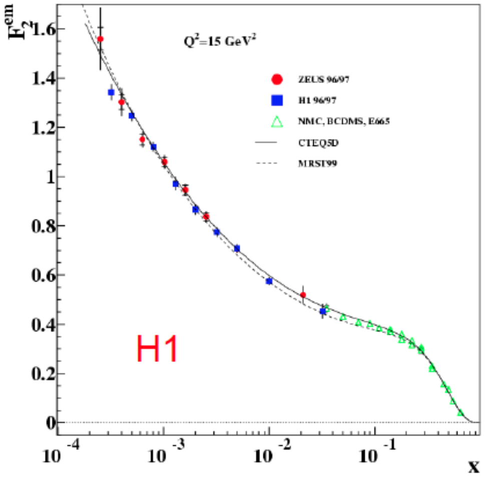
- Electroweak scale ~ M_Z^2 (as relevant to precision LHC physics) … gluon rise gets sharper …

- Starting scale ~ 1.9 GeV^2 (as relevant to future sat'n studies

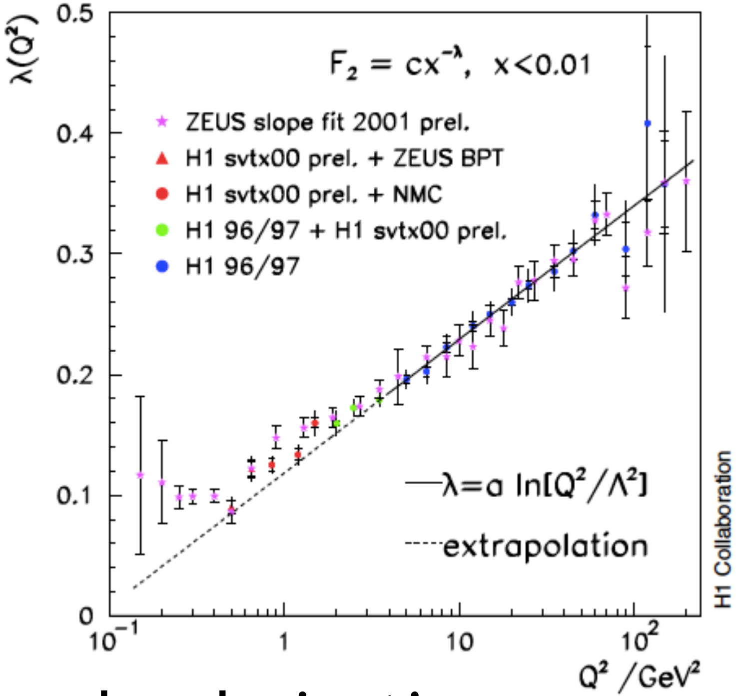


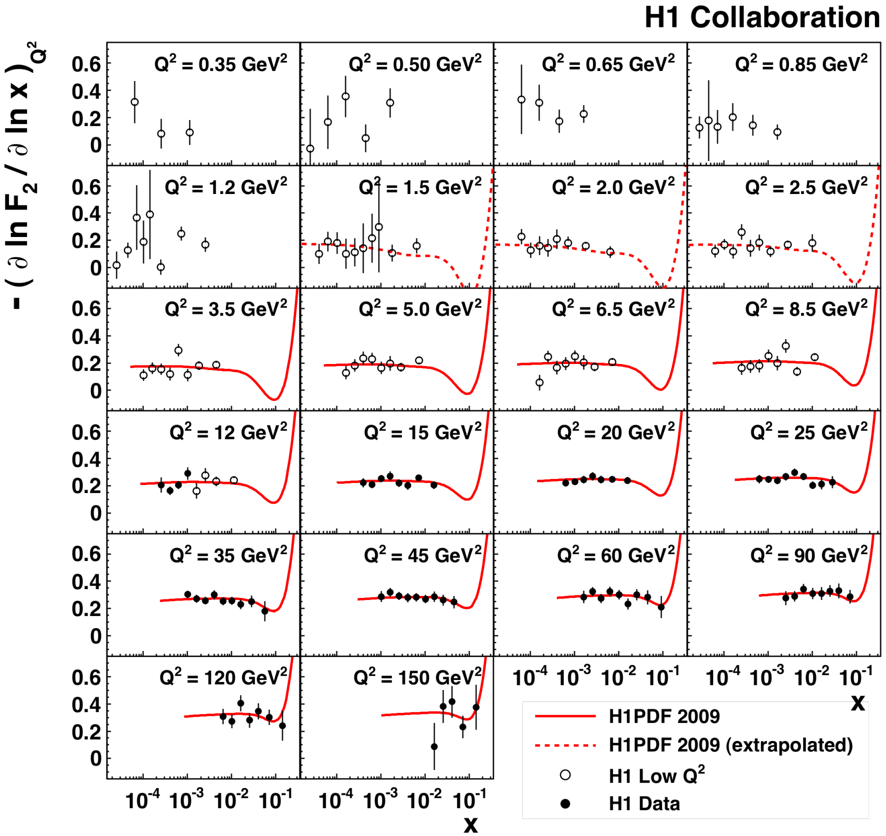
- Gluon close to zero in pure DGLAP approach (and coupling not so weak).
  - Saturating hadrons with a small number of ("large") gluons?
  - Alternative language (dipole models, gluons not degrees of freedom)?

Looking for Saturation in the HERA Data



HERA-I inclusive data well described by $F_2 = Ax^{-\lambda(Q2)}$ with fixed A~0.2 for all Q^2 >~ 1 GeV^2





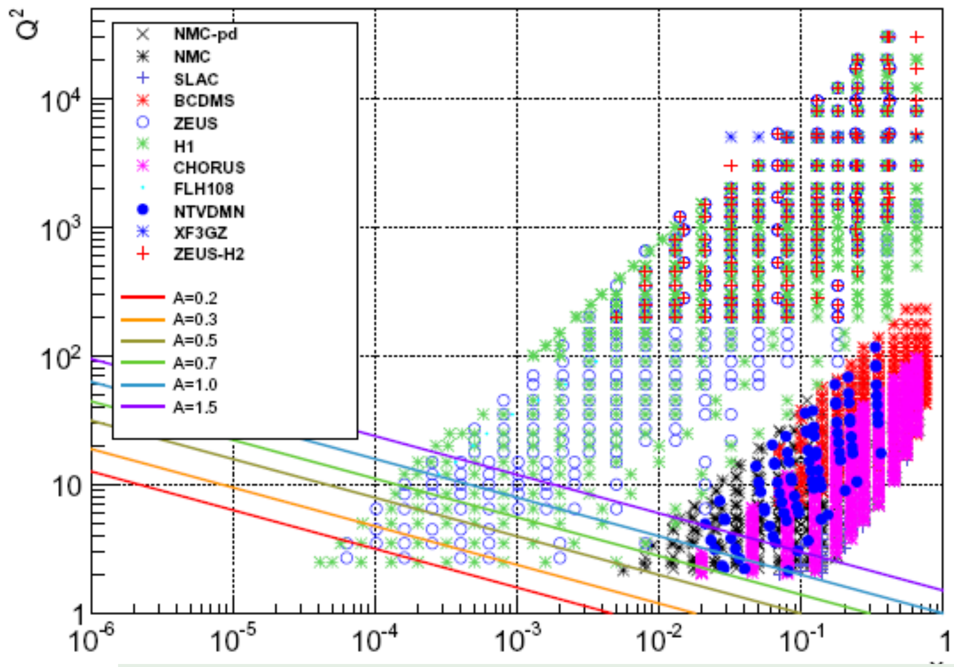
From 2D local x-derivatives:
no evidence here for deviation from monatonic rise of structure functions towards low x in perturbative region.

… but this does not include:

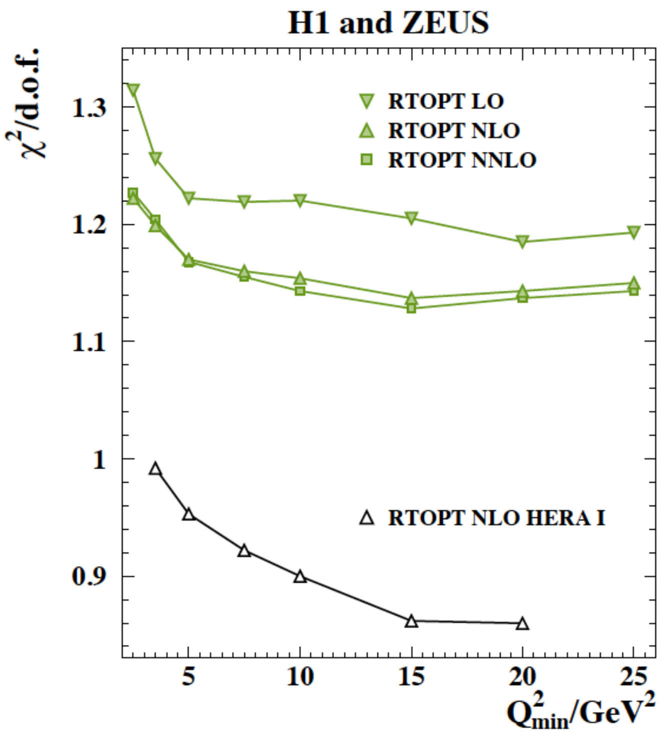
- More precise HERA-II data
- Very low Q^2 data

Different Approaches and improved data in Perturbative region

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.



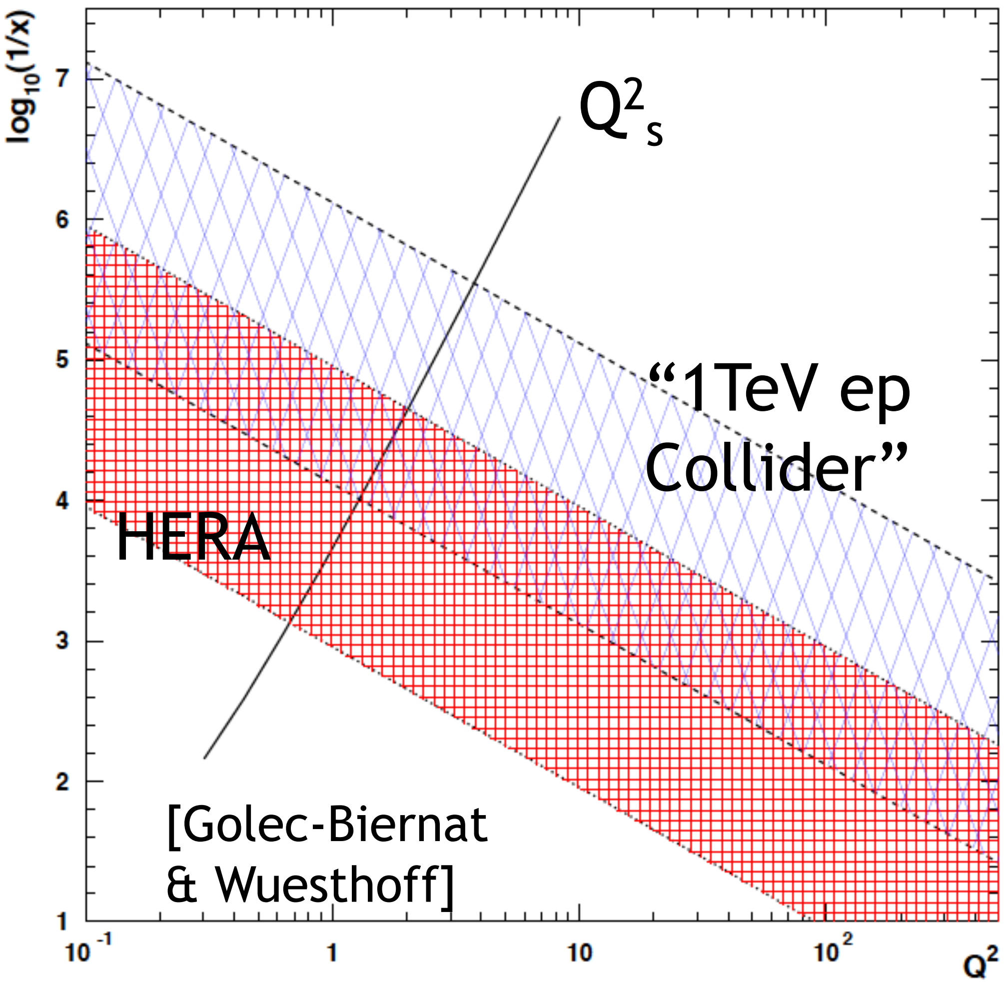
A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	$19.68/25 = 0.79$	$106.22/25 = 4.25$
1.0	$54.41/44 = 1.24$	$138.24/44 = 3.14$
1.5	$62.31/59 = 1.06$	$860.65/59 = 14.6$

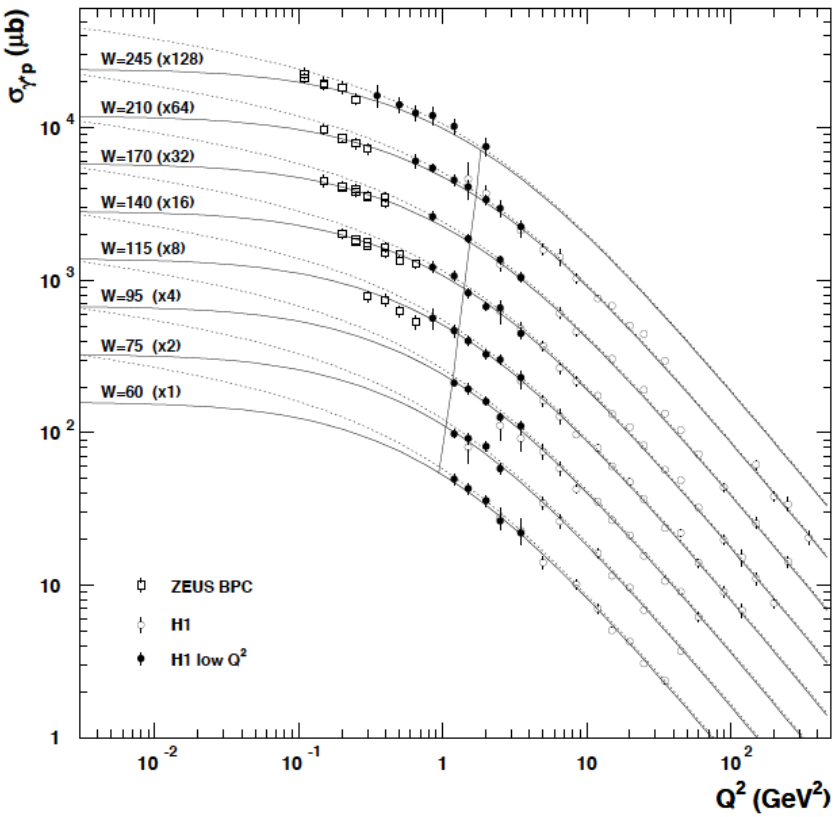


Final HERA-2 Combined PDF Paper:
"some tension in fit between low & medium Q^2 data… not attributable to particular x region" (though kinematic correlation)

… something happens … interpretation?

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



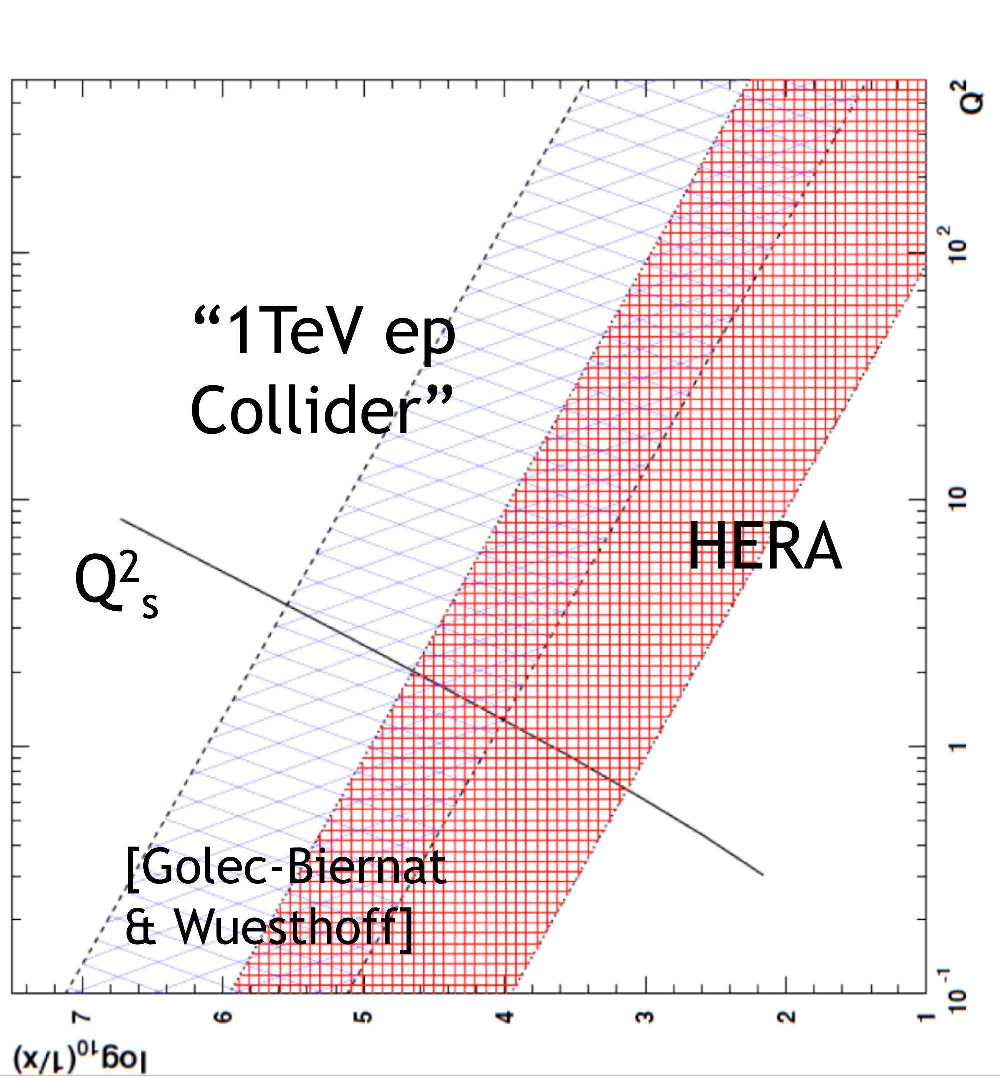


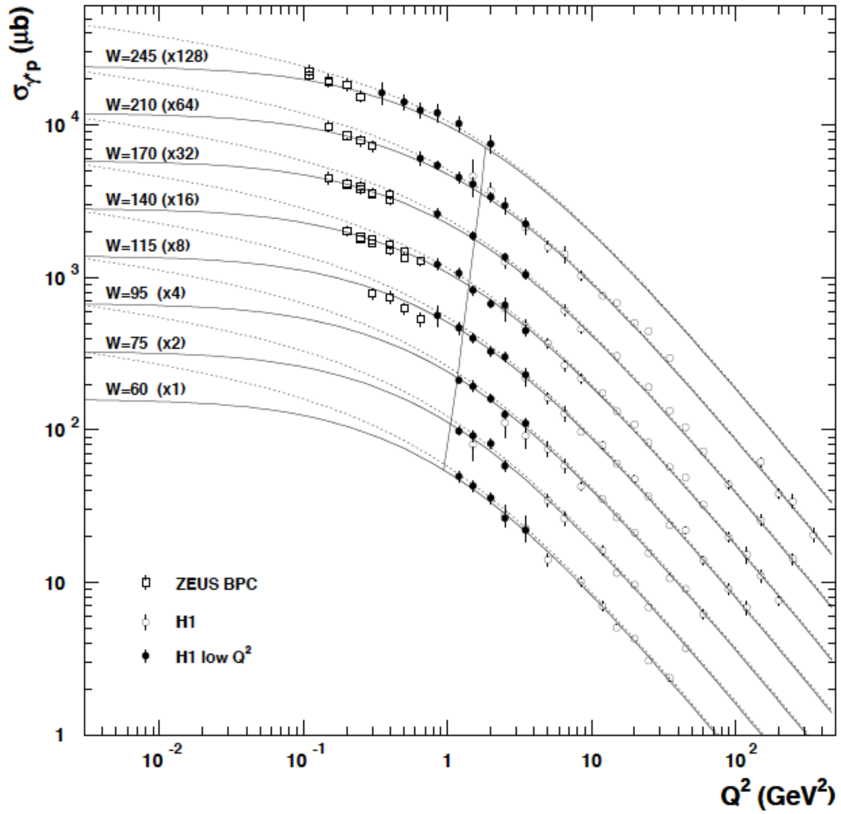
All data (Q^2 >~ 0.05 GeV^2) are well fitted in (dipole) models that include saturation effects

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

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

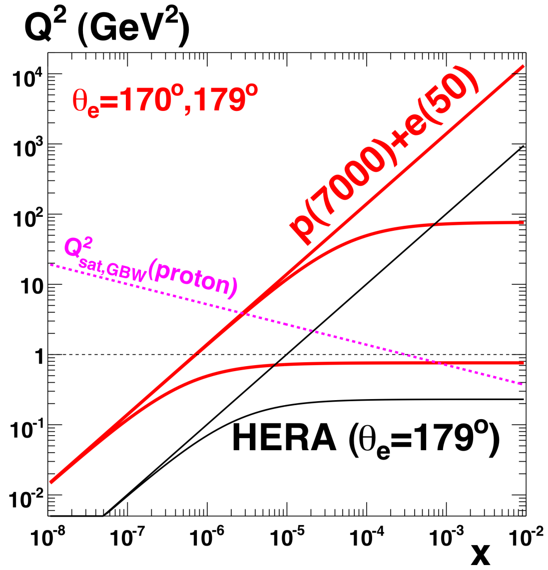
Introducing $Q^2 < 1$ GeV^2 data … and a Dipole Model with Saturation





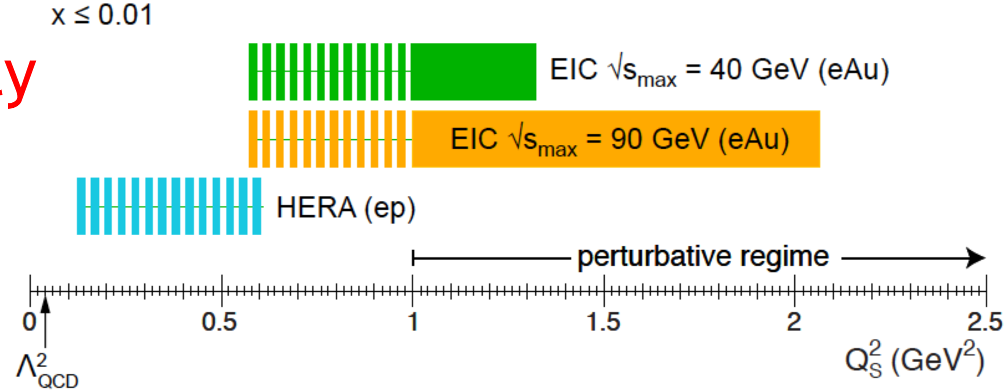
… at HERA, Q^2_s doesn't get above about 0.5 GeV^2
→Saturation may have been observed at HERA … well described by CGC+dipoles
→***Gluon*** sat^n not observed?
(and may not be in inclusive ep in foreseeable future)

How to Access Saturation at Future Lepton-Hadron Facilities

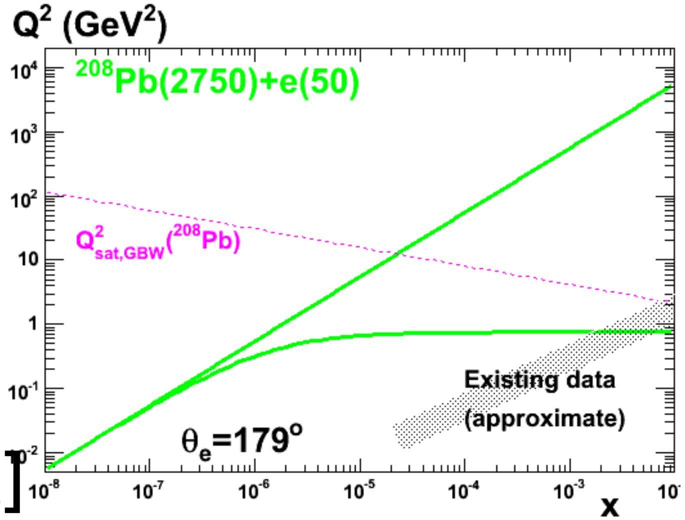


1) Increase √s - Probing lower x at fixed Q^2 in ep [clean evolution of single source → LHeC gets Q^2_s ~ few GeV^2]

2) Use nuclear target - Overlap many sources to enhance density ~ $A^{1/3}$ ~ 6 for Au … [EIC gets to Q^2_s ~ 2 GeV^2, challenge is to disentangle nuclear effects]



3) Non-inclusive observables (diffraction)



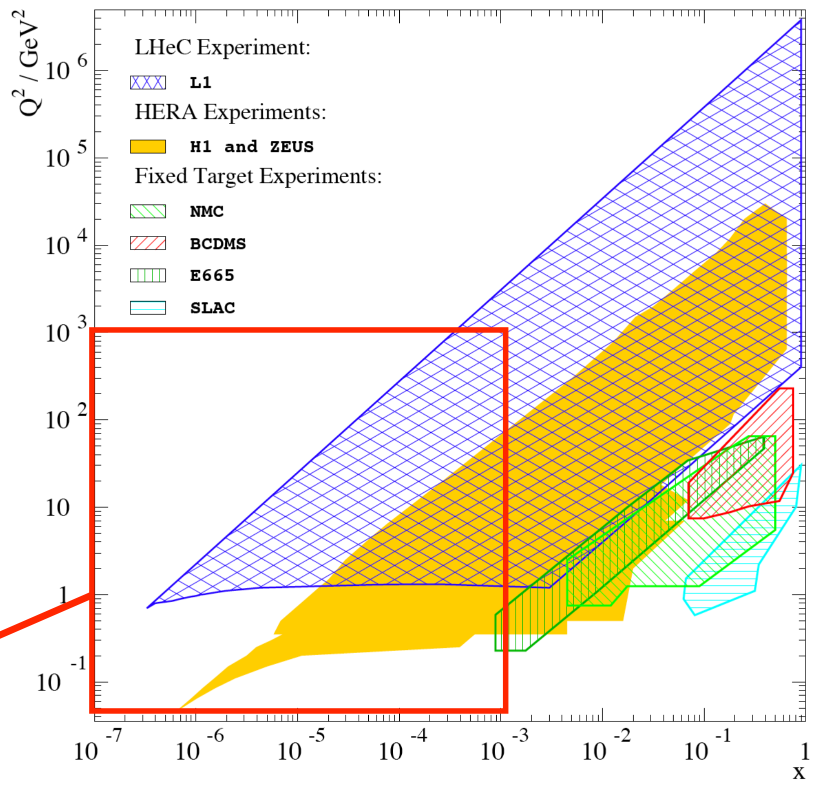
At least two of these at once is needed for a convincing picture … →

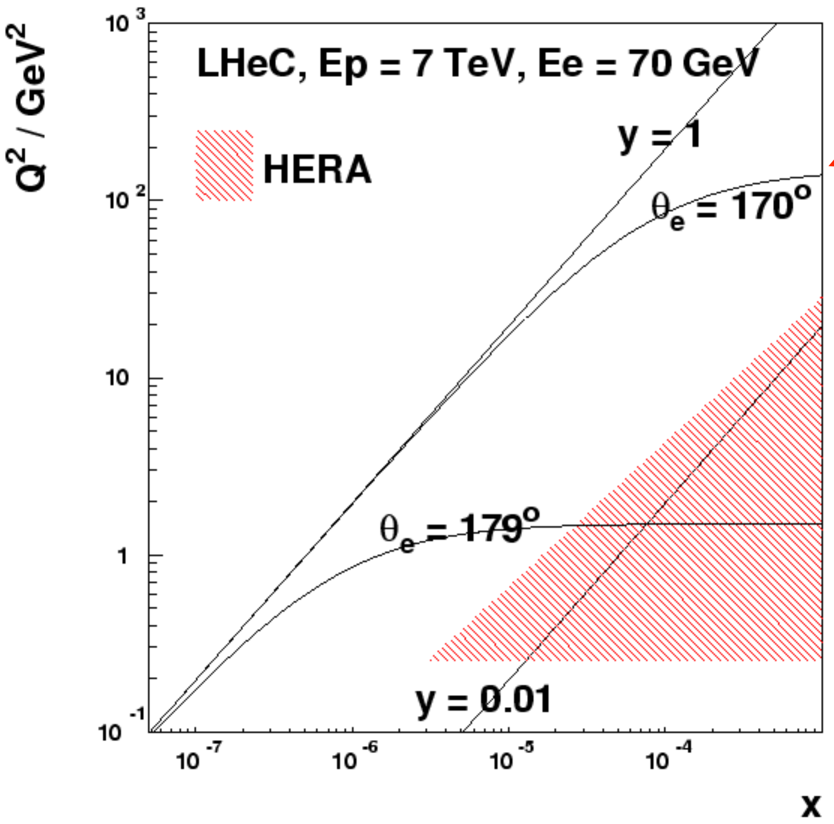
4) Go to LHC [Lacks detailed understanding]

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°



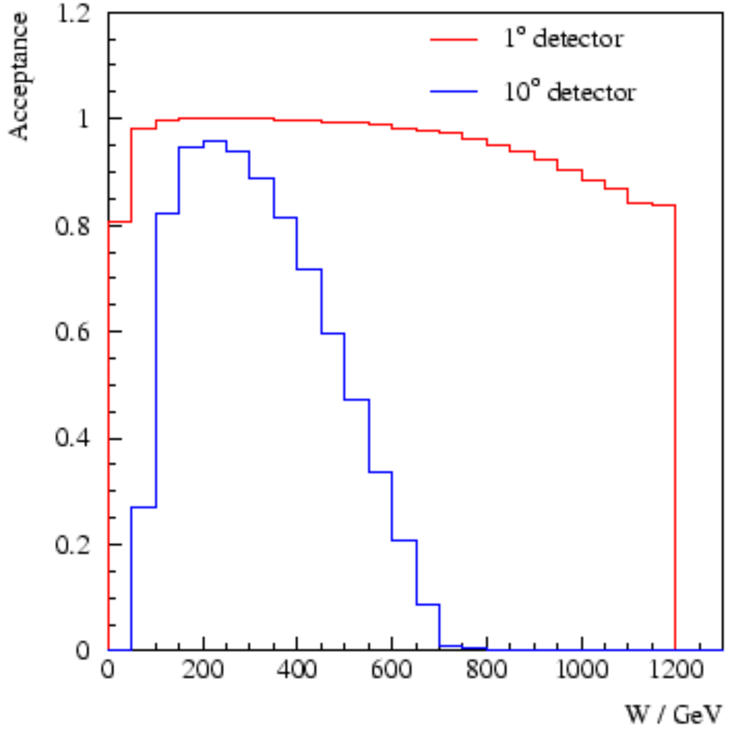


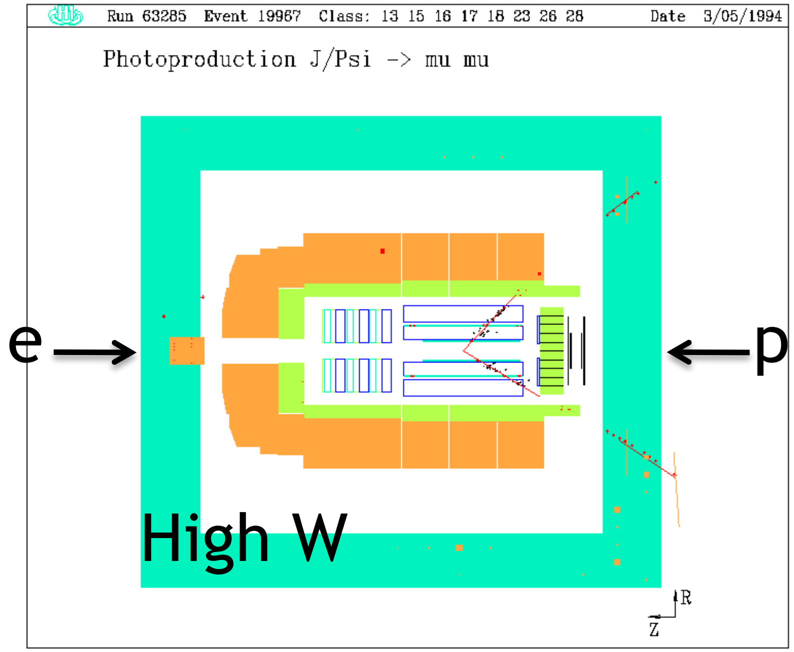
Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, Mueller-Navelet jets, maximise acceptance for new massive particles …

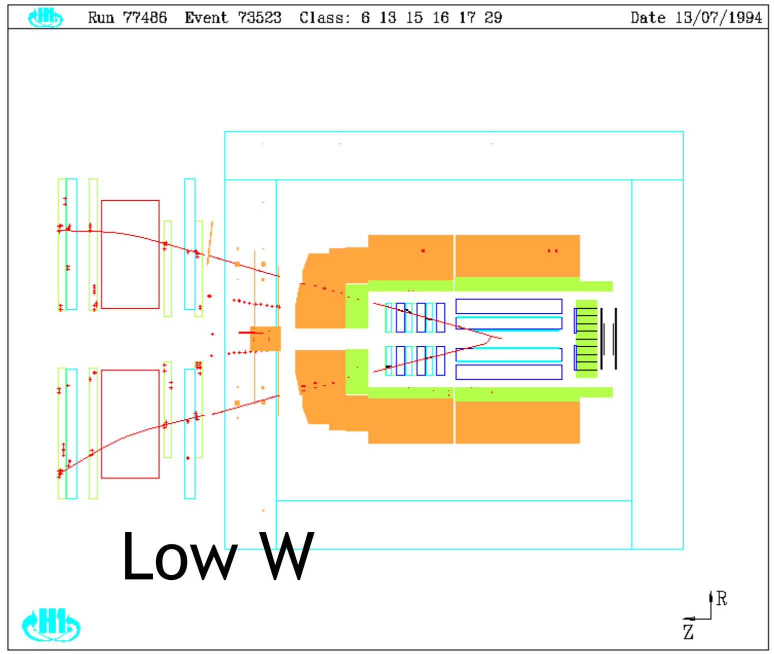
Elastic J/Ψ Kinematics (example from LHeC)

- 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



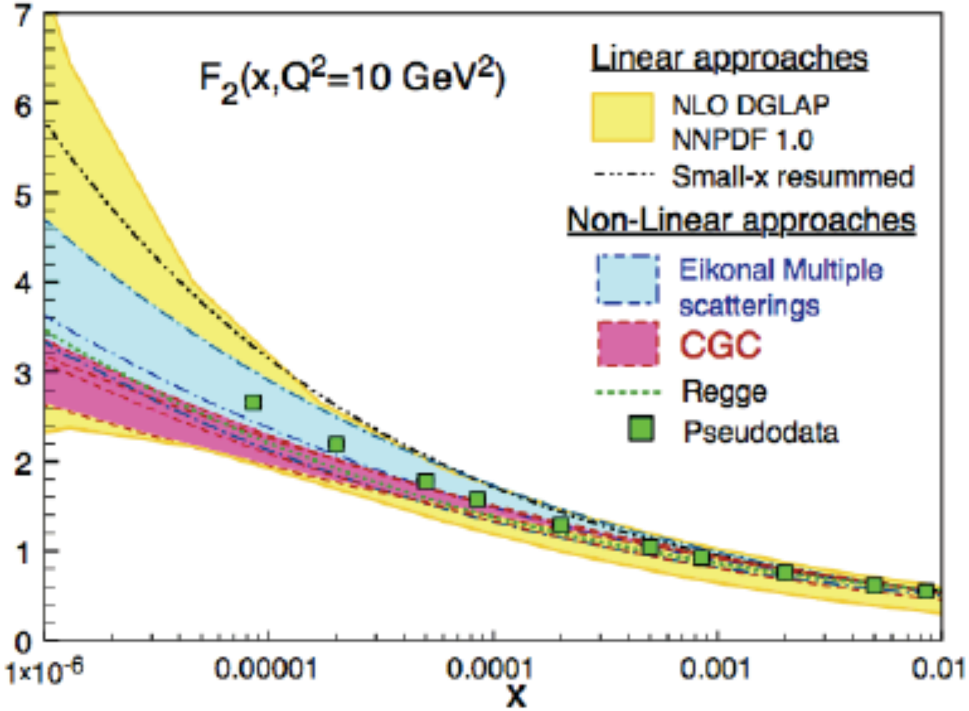


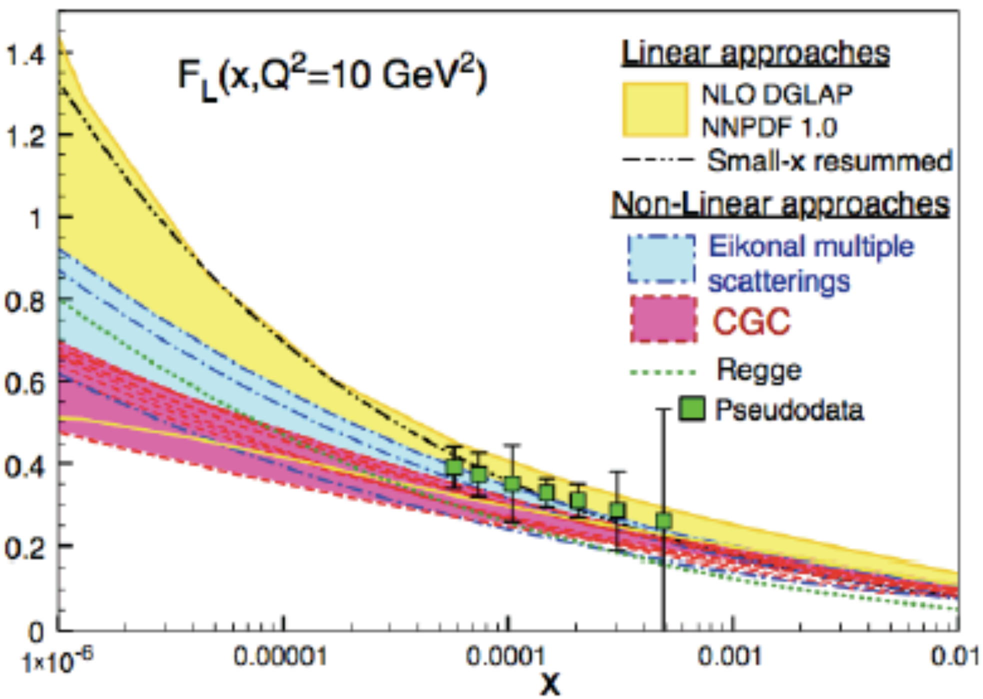


Inclusive DIS in ep at LHeC ep and Saturation

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





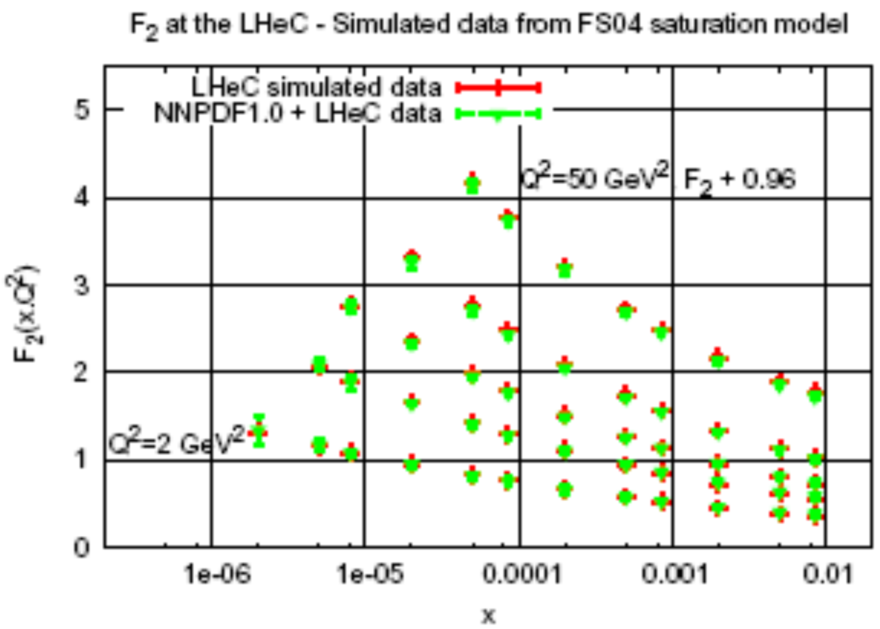
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

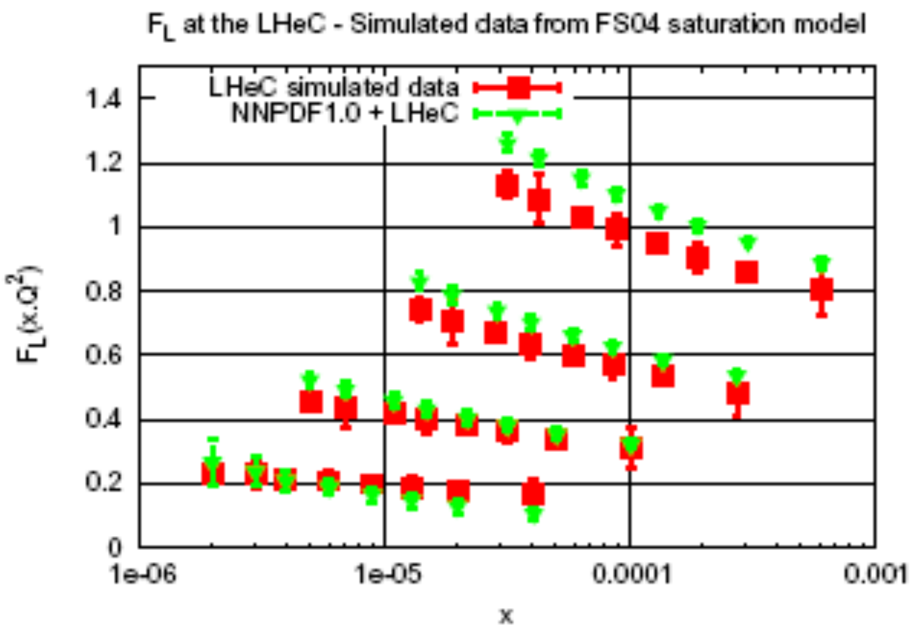
… but can sat^n effects hide in standard fit parameterisations?

Can 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





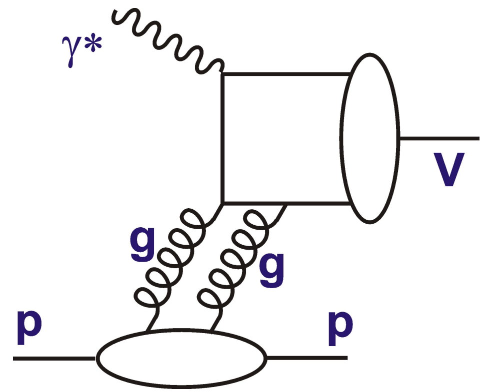
• Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

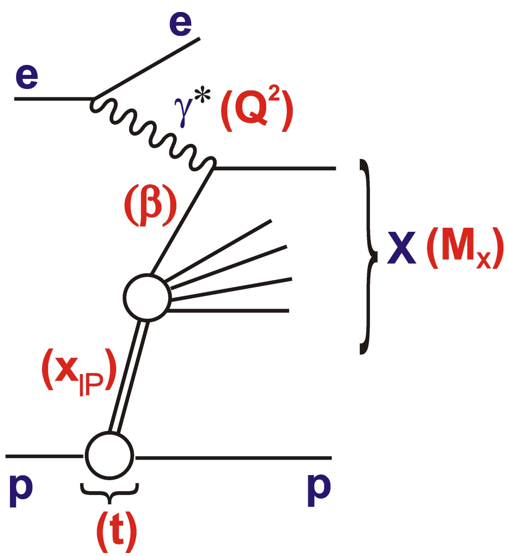
Exclusive / Diffractive Channels and Saturation

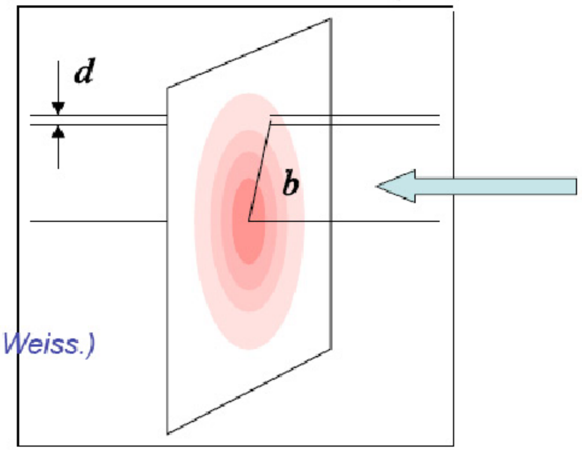
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)

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

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



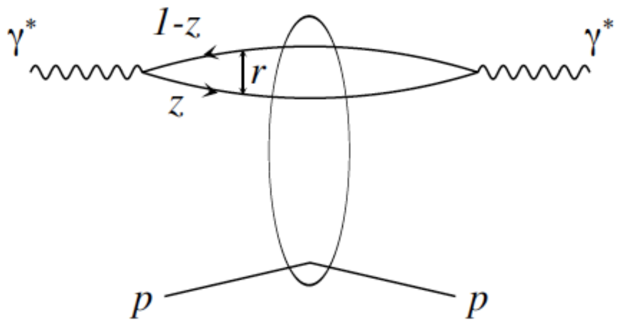




(figure from C. Weiss.)

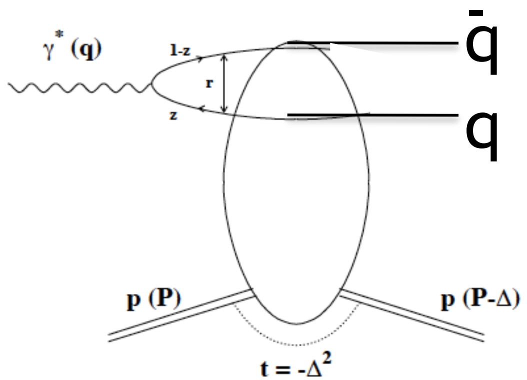
Central black region growing with decrease of x.

Advantage of Diffractive DIS: Dipole Language



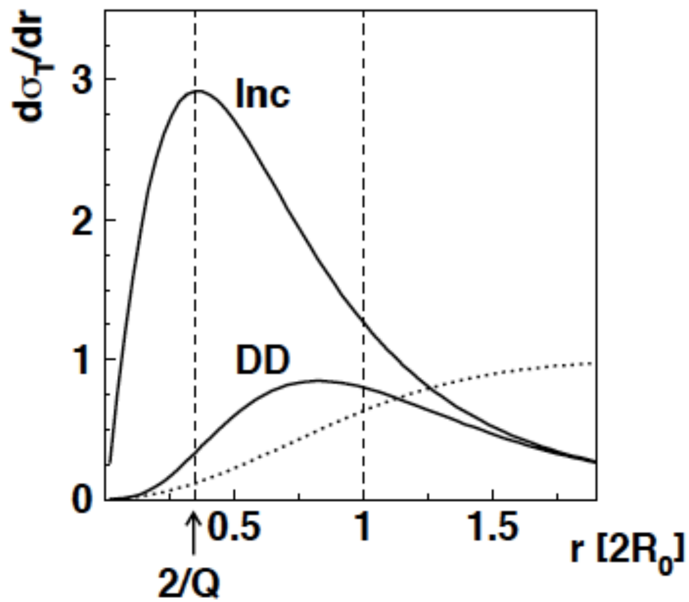
Inclusive Cross Section

$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 d\alpha \, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}(x,r^2)$$



Diffractive DIS

$$\left.\frac{d\sigma^D_{T,L}}{dt}\right|_{t=0} = \frac{1}{16\pi} \int d^2\mathbf{r} \int_0^1 d\alpha \, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}^2(x,r^2)$$

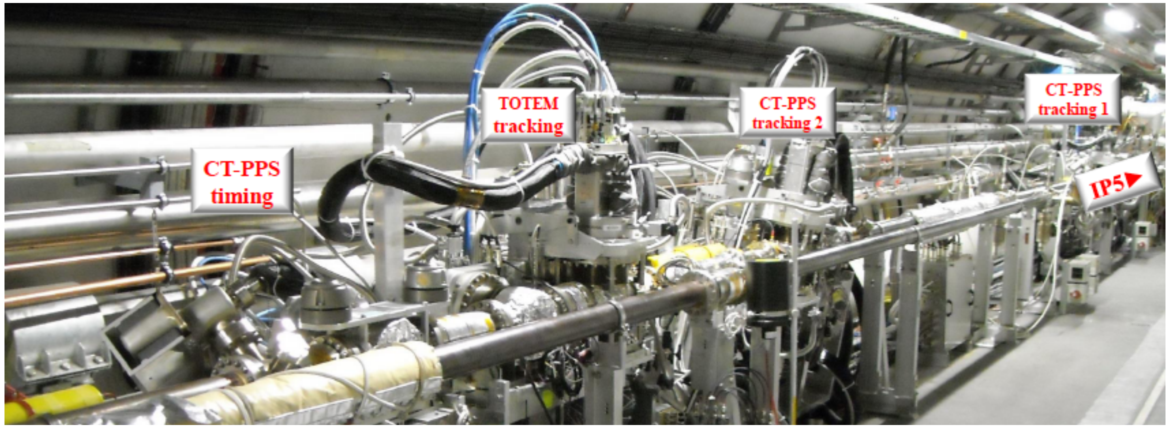


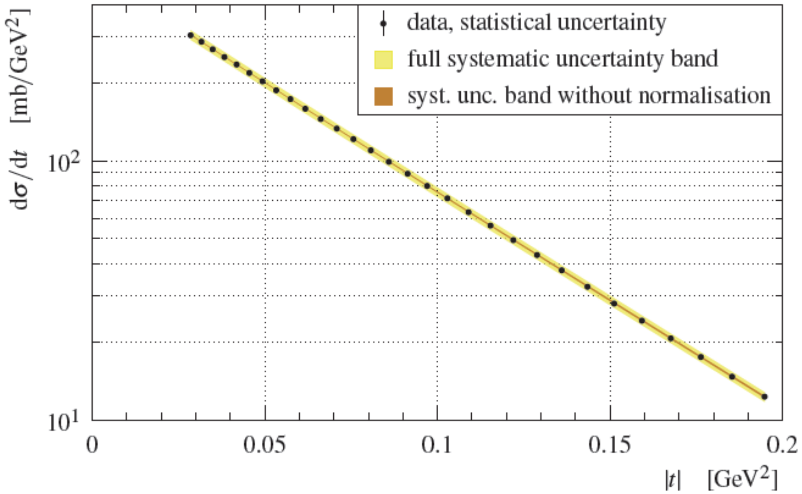
3) Extra factor of dipole cross section weights DDIS cross section towards larger dipole sizes → enhanced sensitivity to saturation effects.

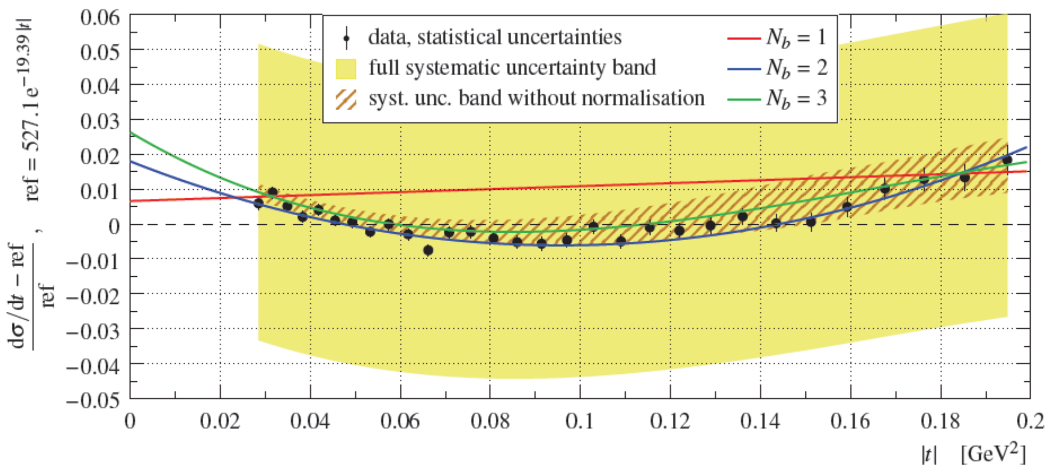
Proton Spectrometers Come of Age

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

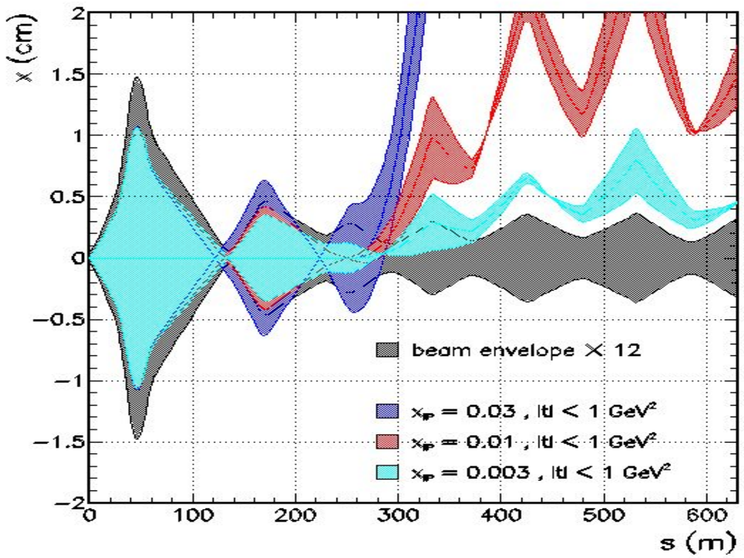
e.g. TOTEM operates 14(?) pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential term in elastic t dependence …





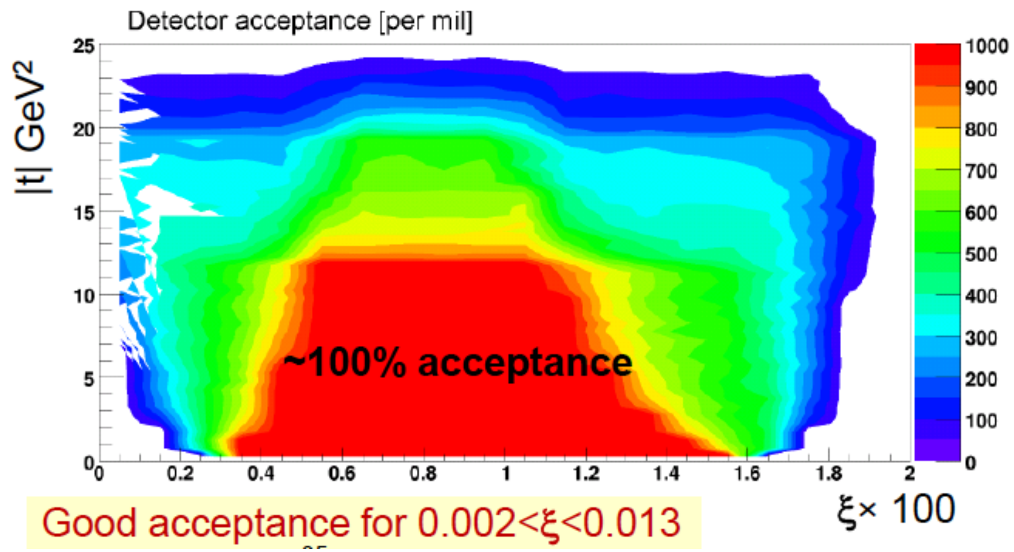


Future DIS Forward Proton Spectrometers



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

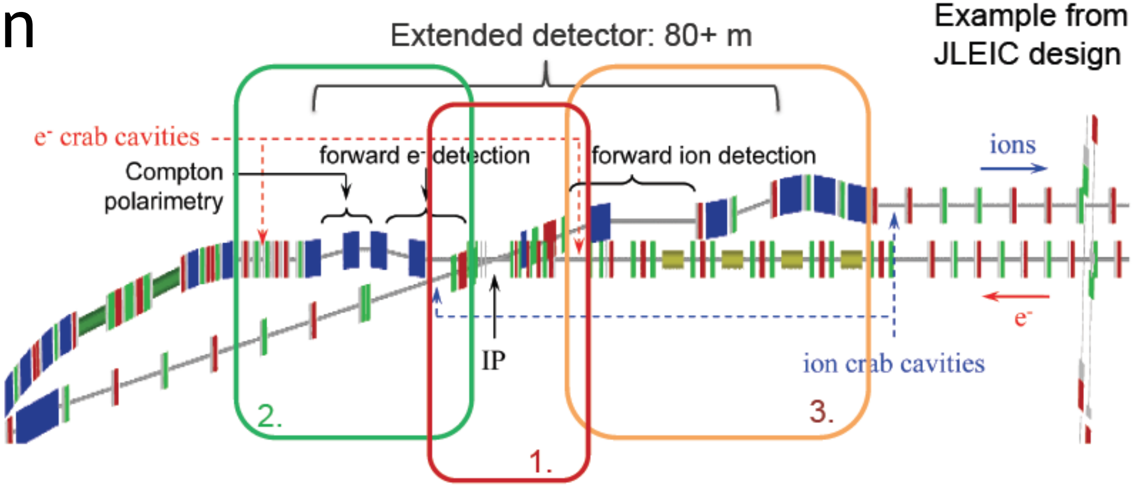
- eg LHeC Proton spectrometer uses outcomes of FP420 project (proposal for low ξ Roman pots at ATLAS / CMS – not yet adopted)
- Tags elastically scattered protons with high acceptance over a wide

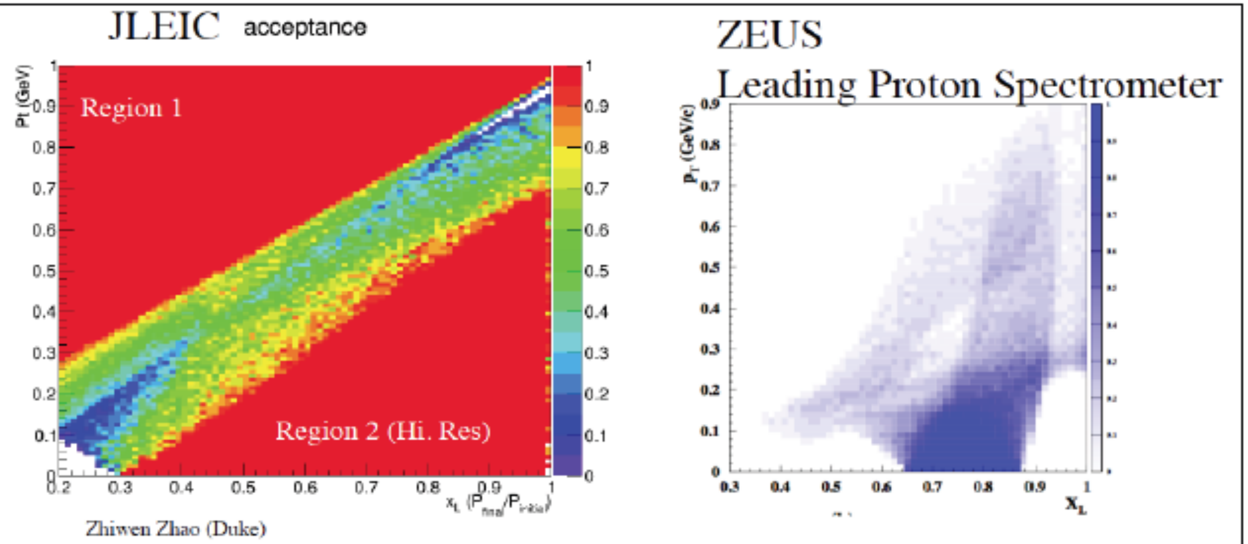


EIC Forward Proton Spectrometer

- Beamline instrumentation intrinsic to e-RHIC and JLEIC designs from outset
- e.g JLEIC version with access points at 12m – 45m from IP…

Example from JLEIC design



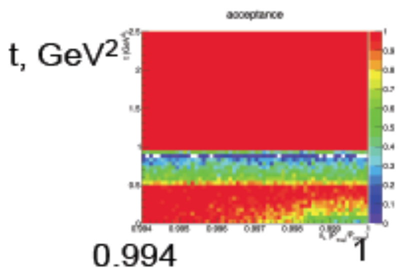


Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

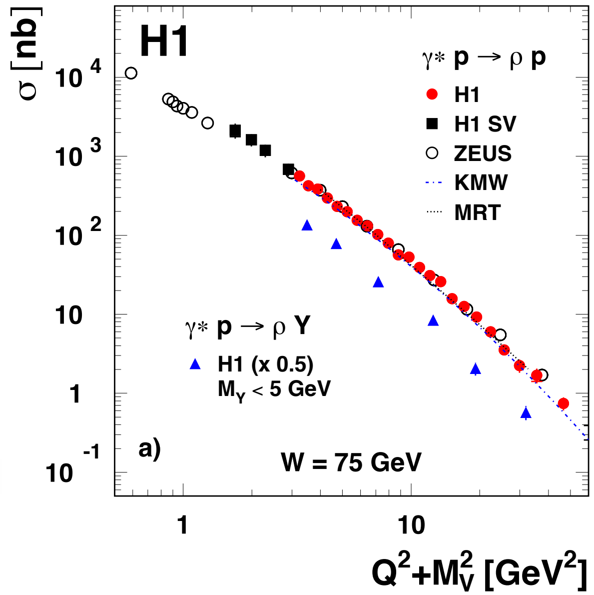
JLEIC: ~100% (also covers much higher X_L than ZEUS)

[Rik Yoshida]



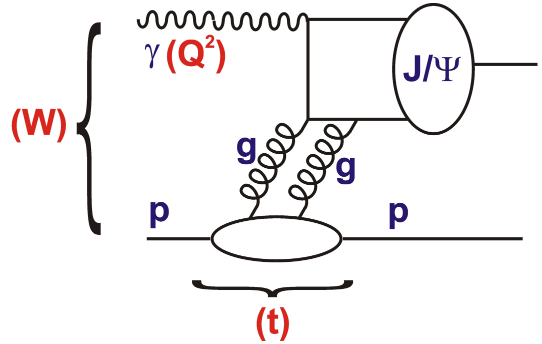
Exclusive Vector Mesons

• Huge database of measurements from HERA, Ψ, J/Ψ, φ, ρ, ρ', DVCS … mapping soft-hard transition, unfolding σ_T, σ_L …



Test Case: 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

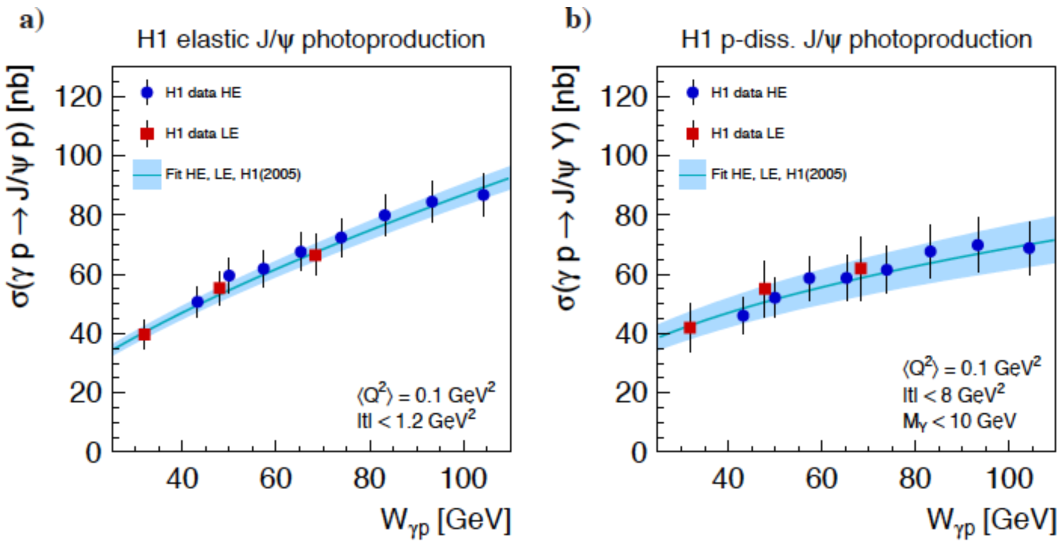
• Clean experimental signature (just 2 leptons)

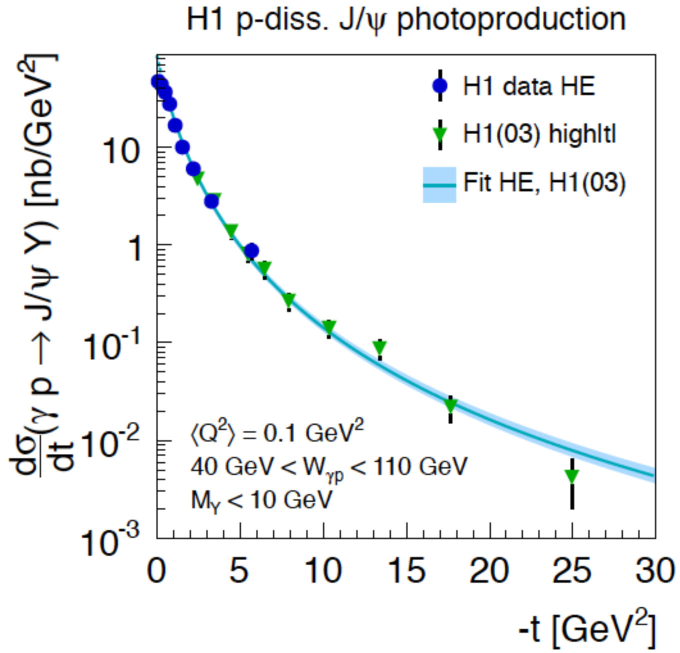
• Scale $\overline{Q^2} \sim (Q^2 + M_V^2) / 4 \;>\sim 3$ GeV^2 ideally suited to reaching Lowest possible x whilst remaining in perturbative regime

… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

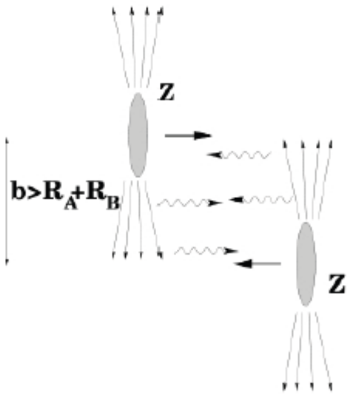
Existing Diffractive J/Ψ Photoproduction Data

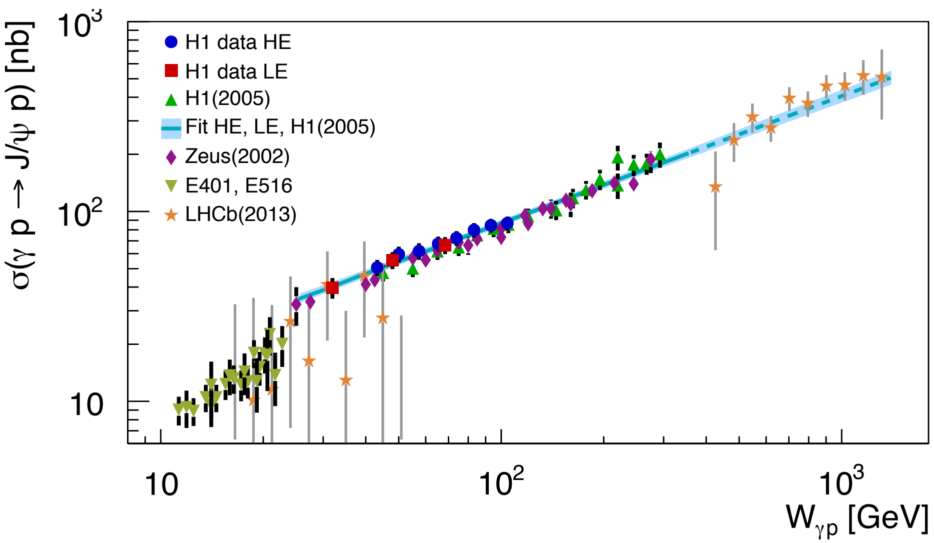
… HERA: $\gamma p \rightarrow J/\Psi p$, $\gamma p \rightarrow J/\Psi\ Y$:





… Adding Ultraperipheral Collisions at LHC:

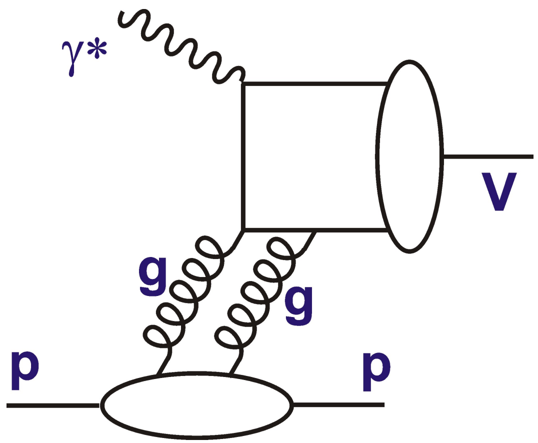


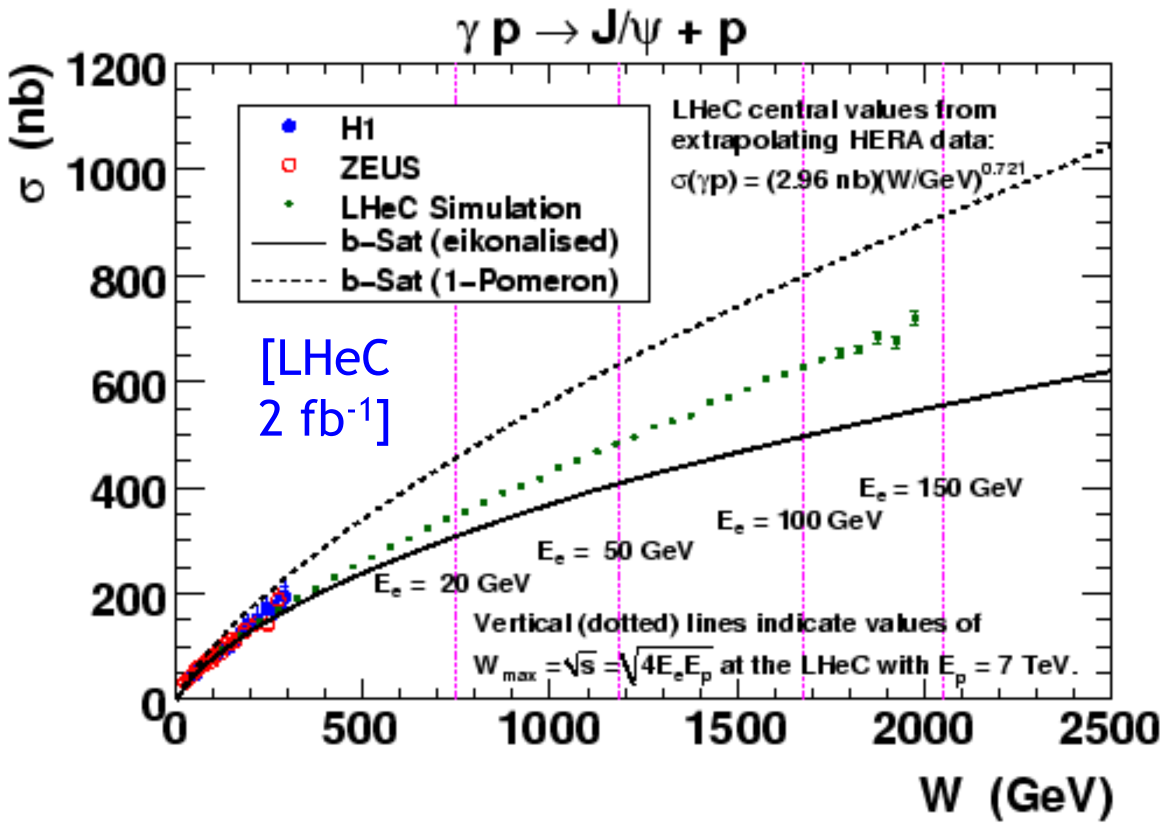


- No evidence for deviation from monatomic rise with increasing W (decreasing x).
- See also pPb, PbPb results

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

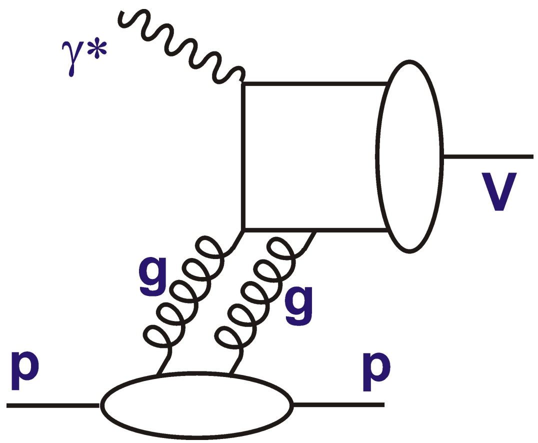




- Significant non-linear effects expected in LHeC kinematic range

"beware unrealistic non-sat Straw men" [T. Lappi]

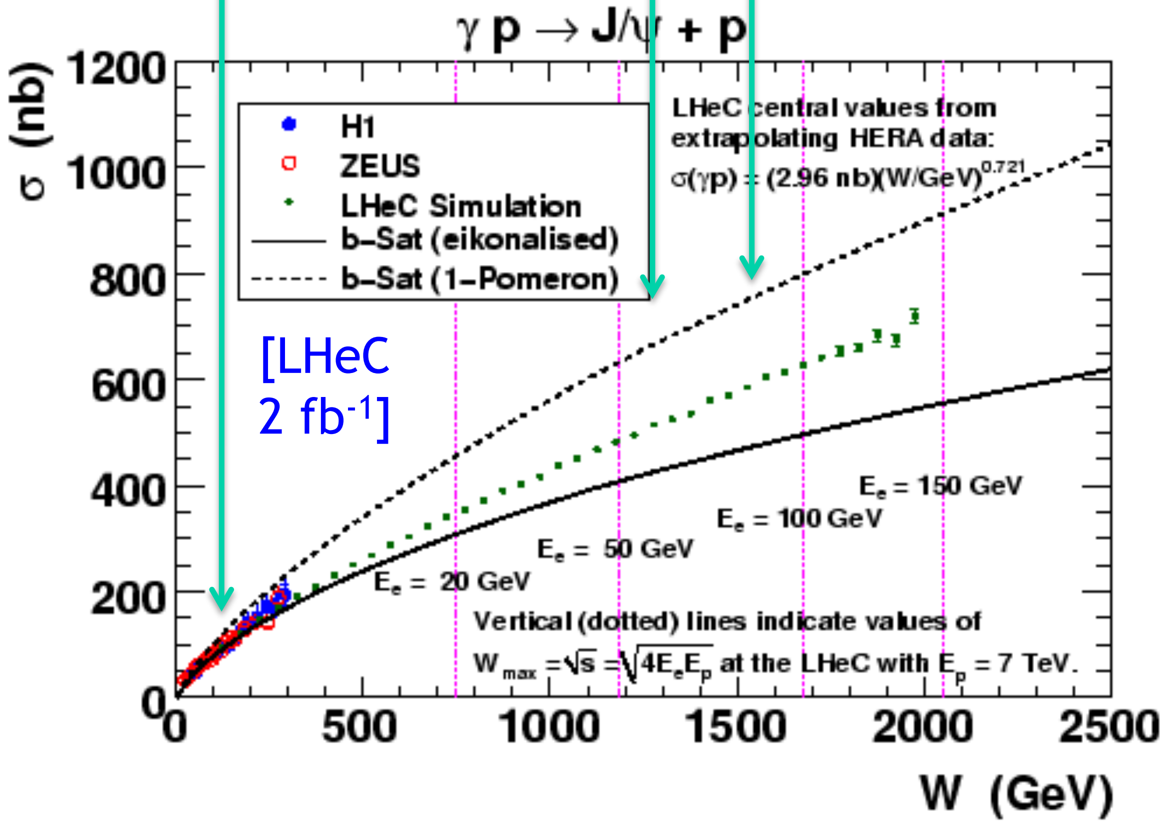
J/Ψ from future ep v Dipole model Predictions



Current EIC design

Current LHeC design

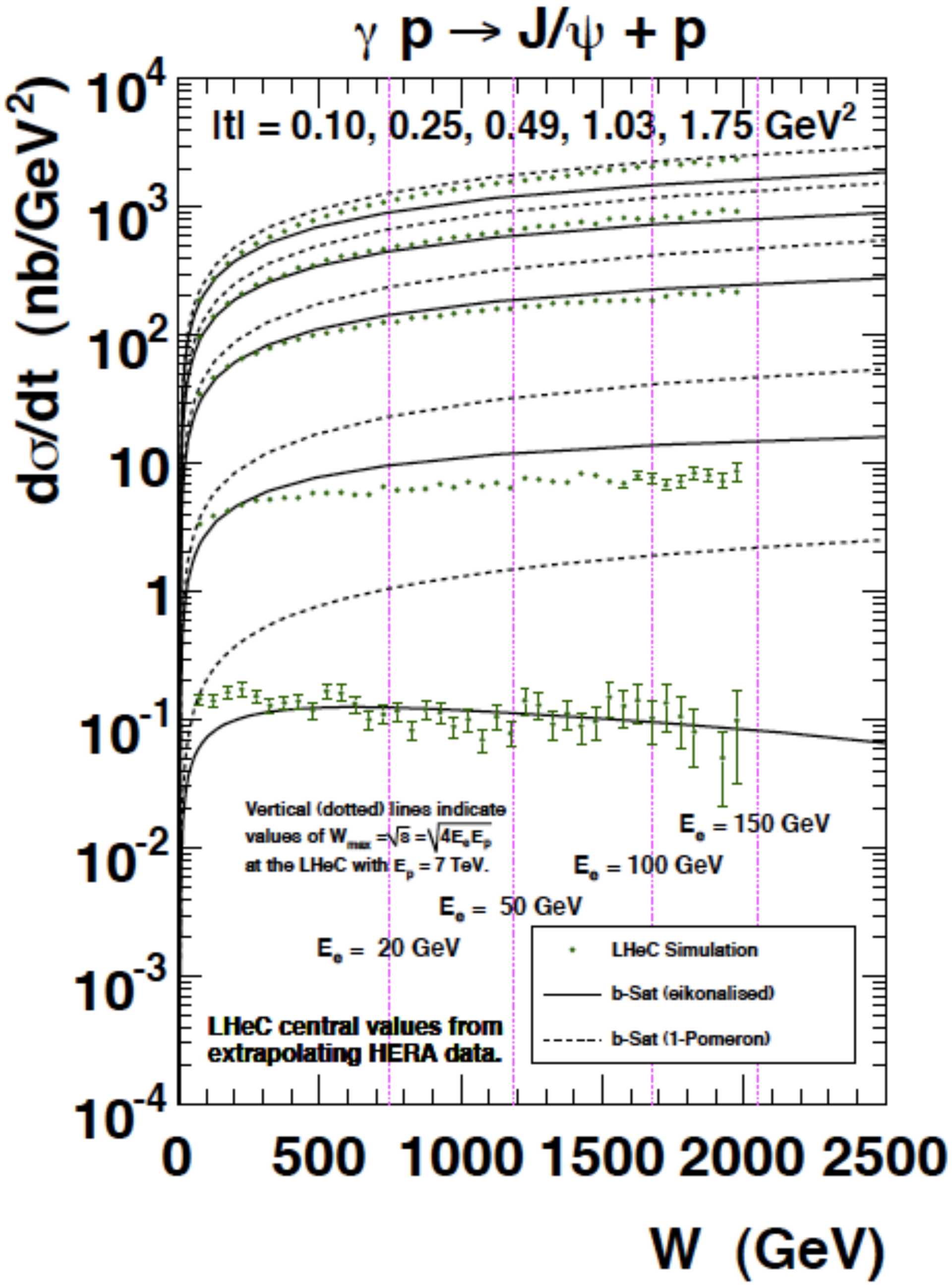
Current LHCb limit



- 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

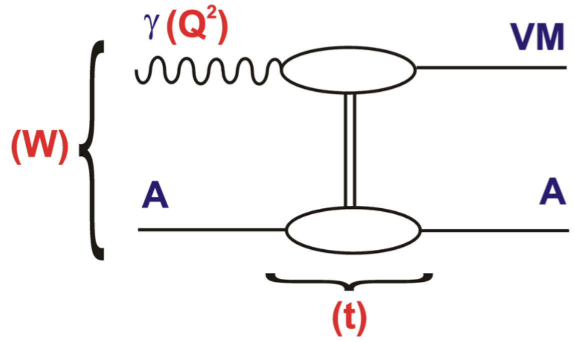


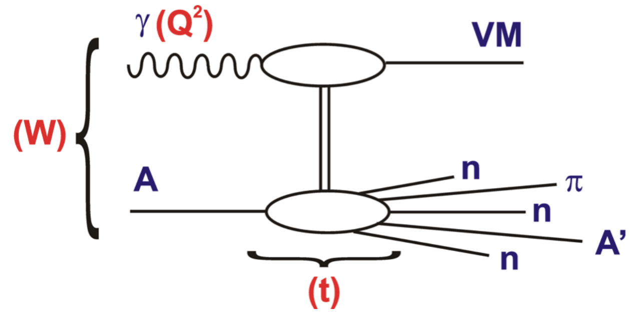
- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV² and enhances sensitivity to saturation effects

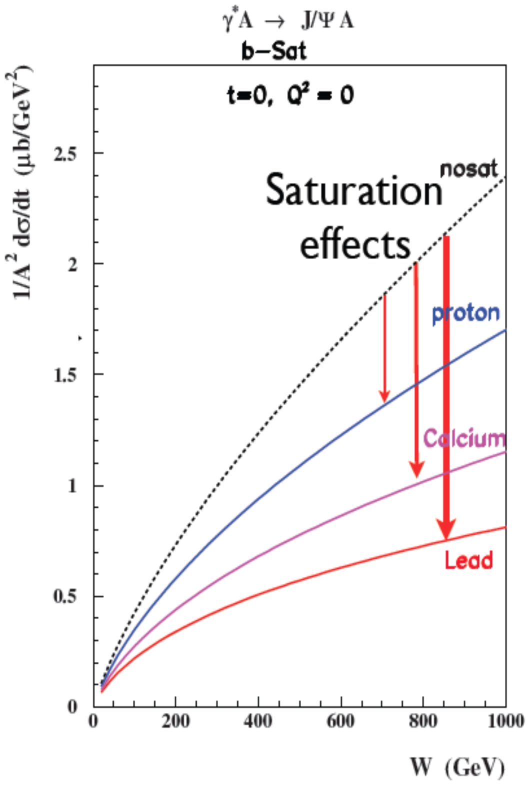
- Measurements also possible in multiple Q^2 bins

Exclusive Diffraction in eA

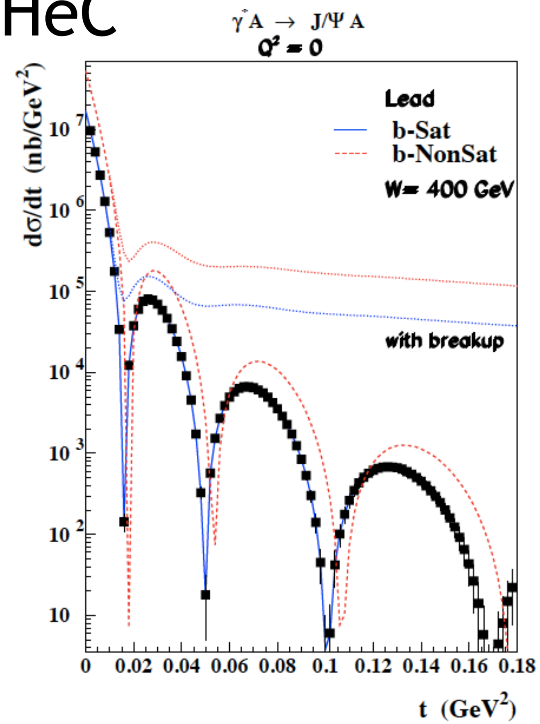
- Separation of coherent / incoherent can be done based on ZDC
- Large saturation effects predicted at LHeC in coherent case (eA → eVA)
- Smaller saturation effects at EIC → cleaner opportunity to image structure via conjugate variables b

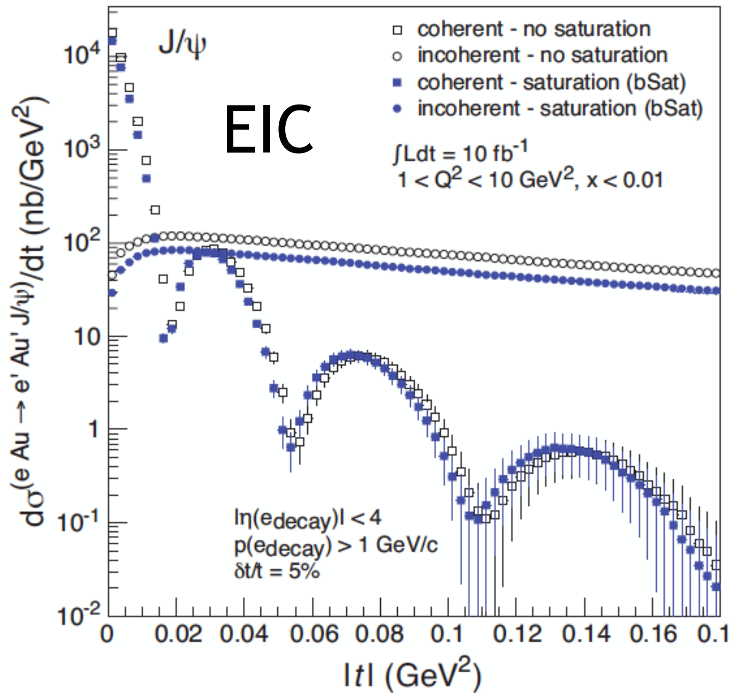




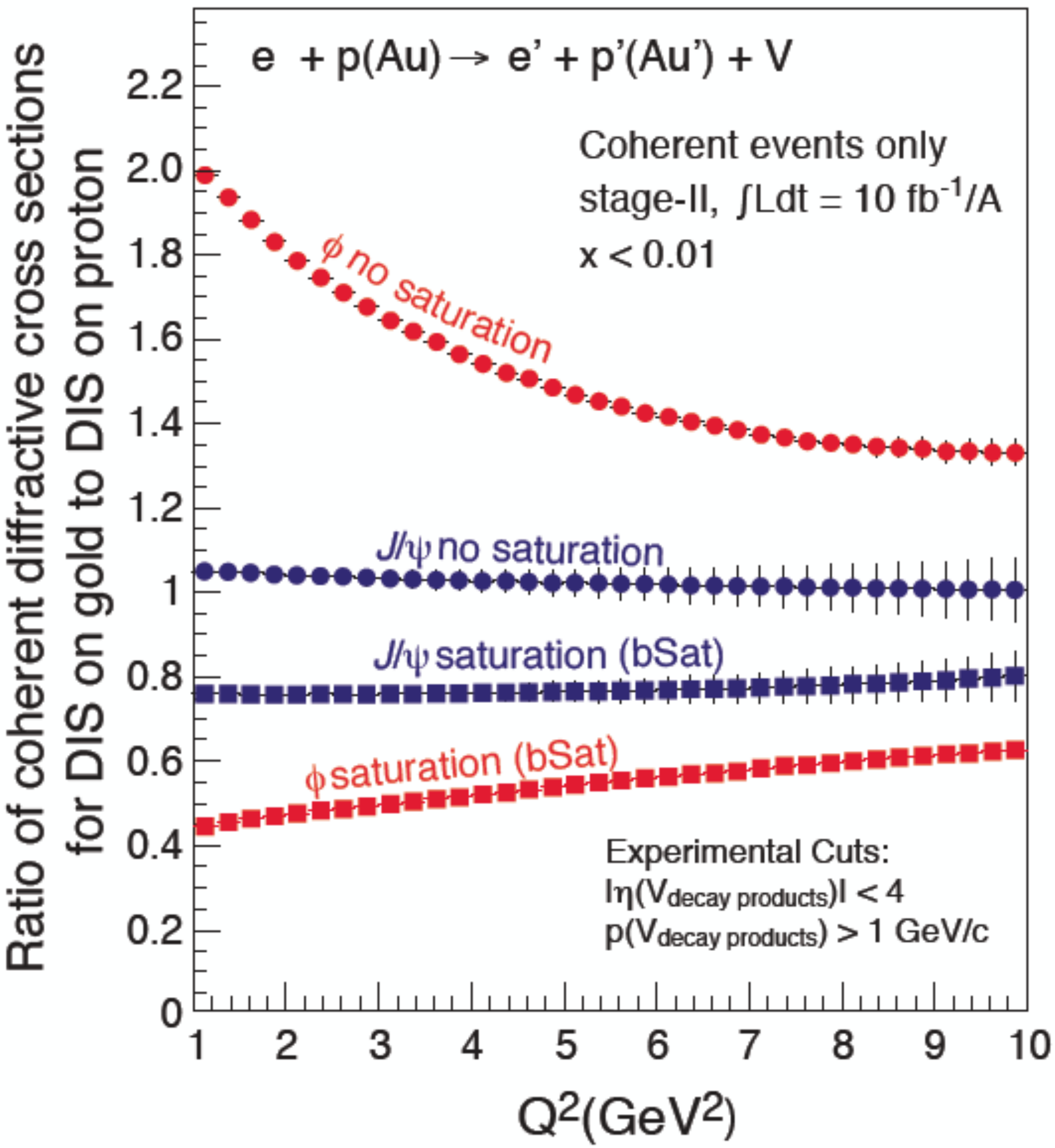


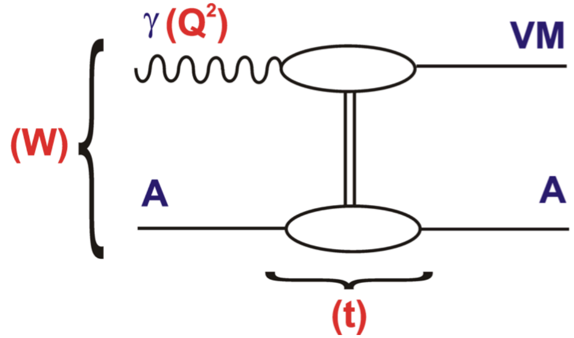
LHeC





Light Vector Mesons in eA / ep at EIC

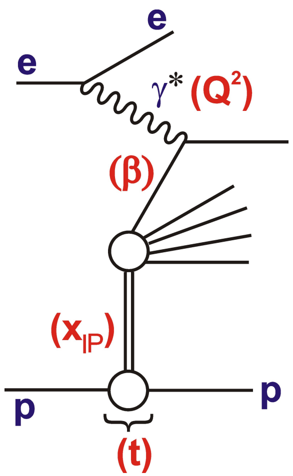




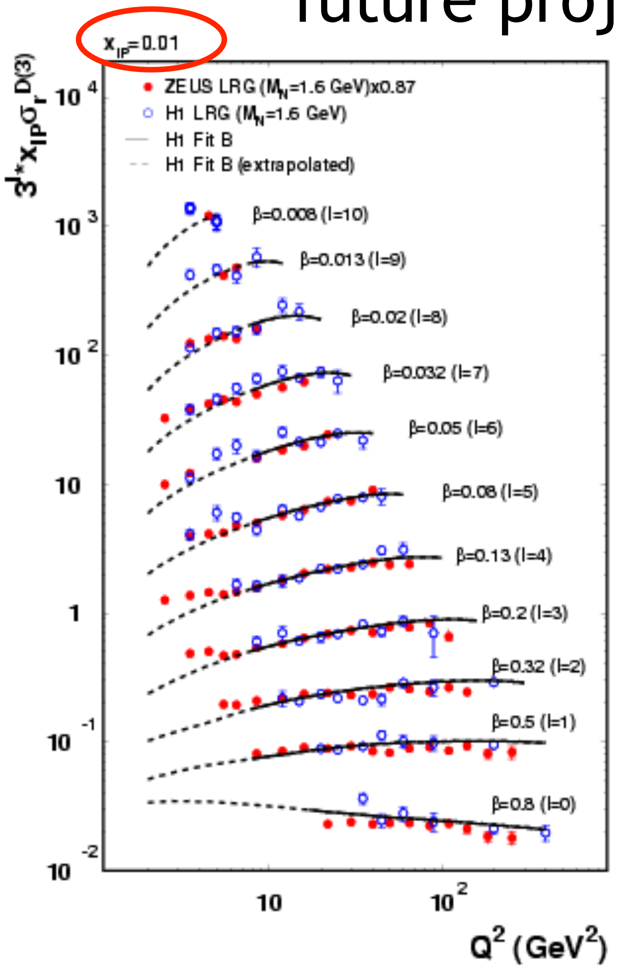
- bSat saturation model predicts big saturation effects from comparisons of eA with ep for elastic ρ, ϕ.

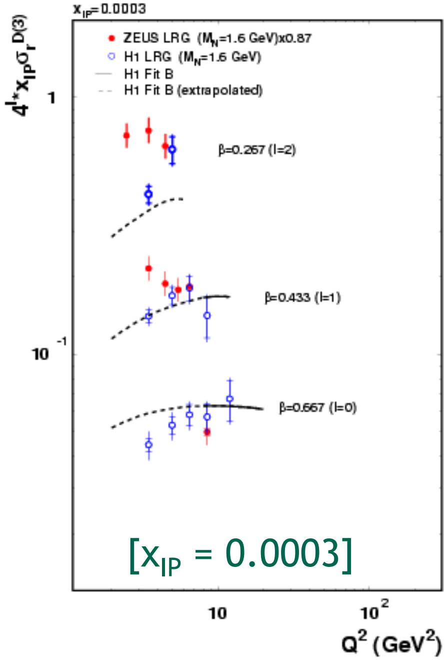
- Effects for ϕ larger than for J/Ψ due to lower scale.

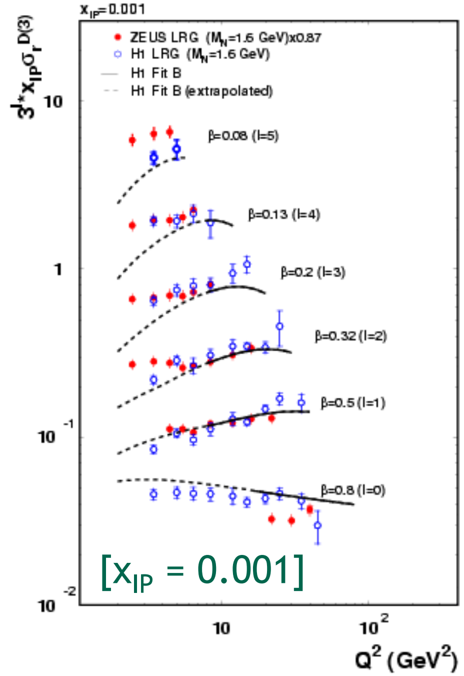
Inclusive Diffraction at HERA

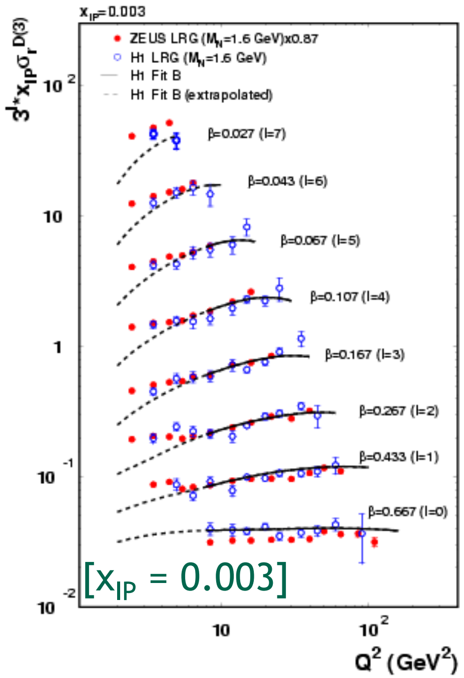


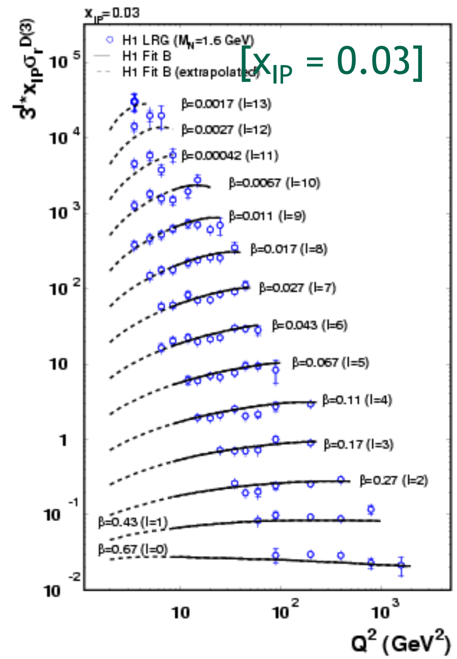
-Huge topic with rich outputs
- Not yet fully explored for future projects



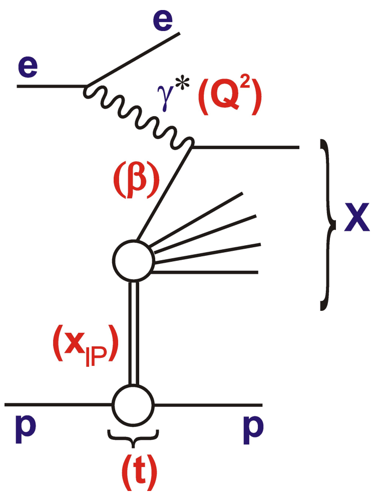


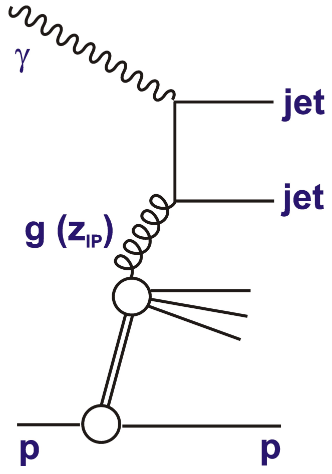


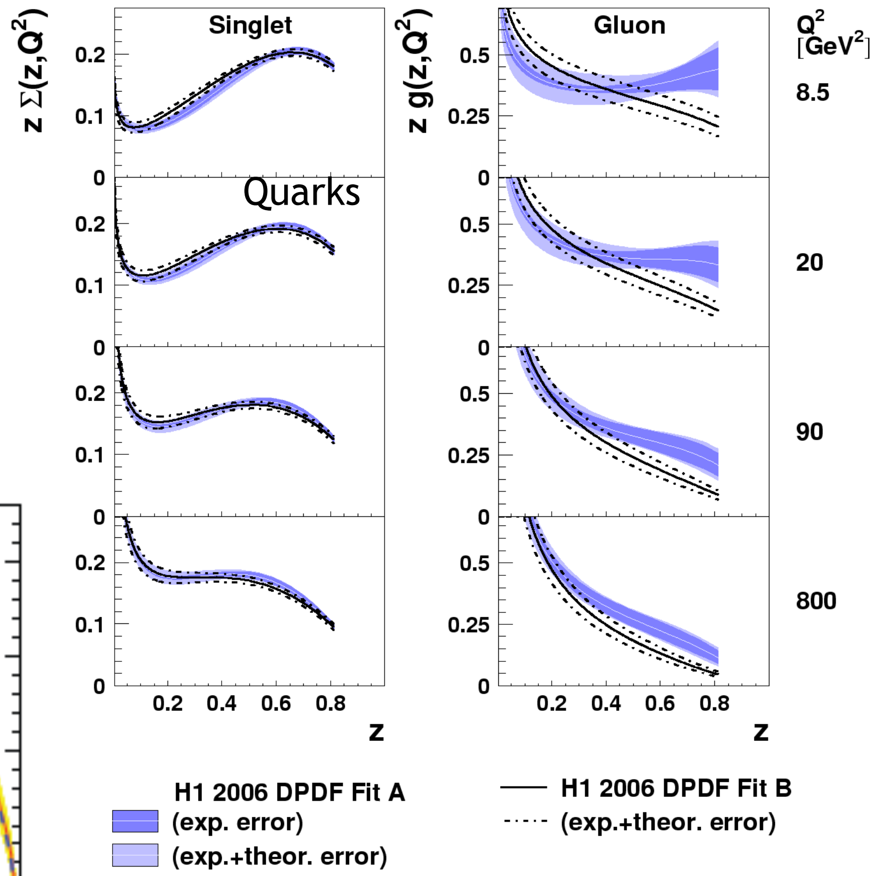


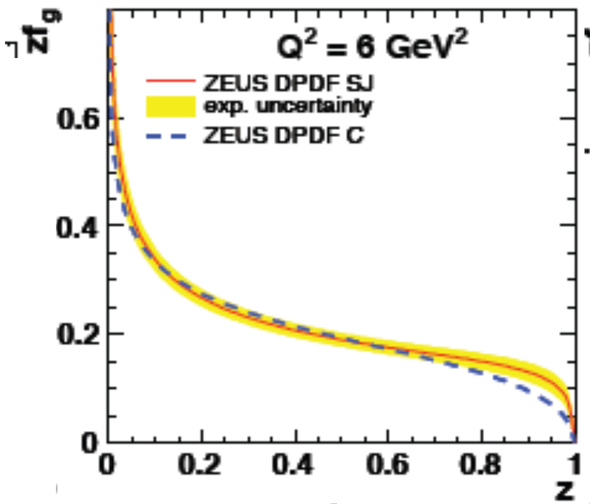


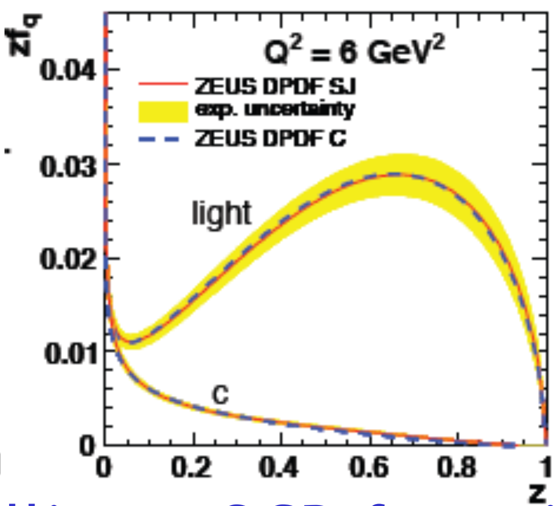
Diffractive Parton Densities (DPDFs)











… semi-inclusive collinear QCD factorisation works!

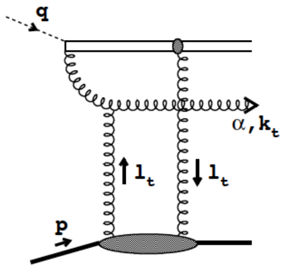
… DPDFs from F_2^D lead to impressive description of all HERA 'hard' diffractive data (not shown here)

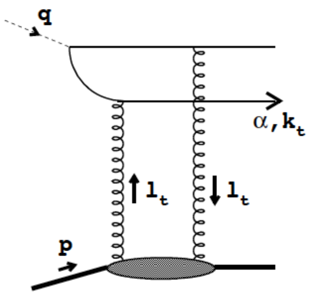
… Failure of diffractive PDF fits to data at lowest Q^2 …

Diffractive DIS & Dipole Models

– χ^2 / ndf increases systematically in H1 DPDF fits when data of Q^2 < 8.5 GeV^2 are included (slightly lower in ZEUS)
… low Q^2 breakdown of pure Leading Twist DGLAP approach

- Dipole models also applied, but need qqbar-g terms (and perhaps higher Fock states)

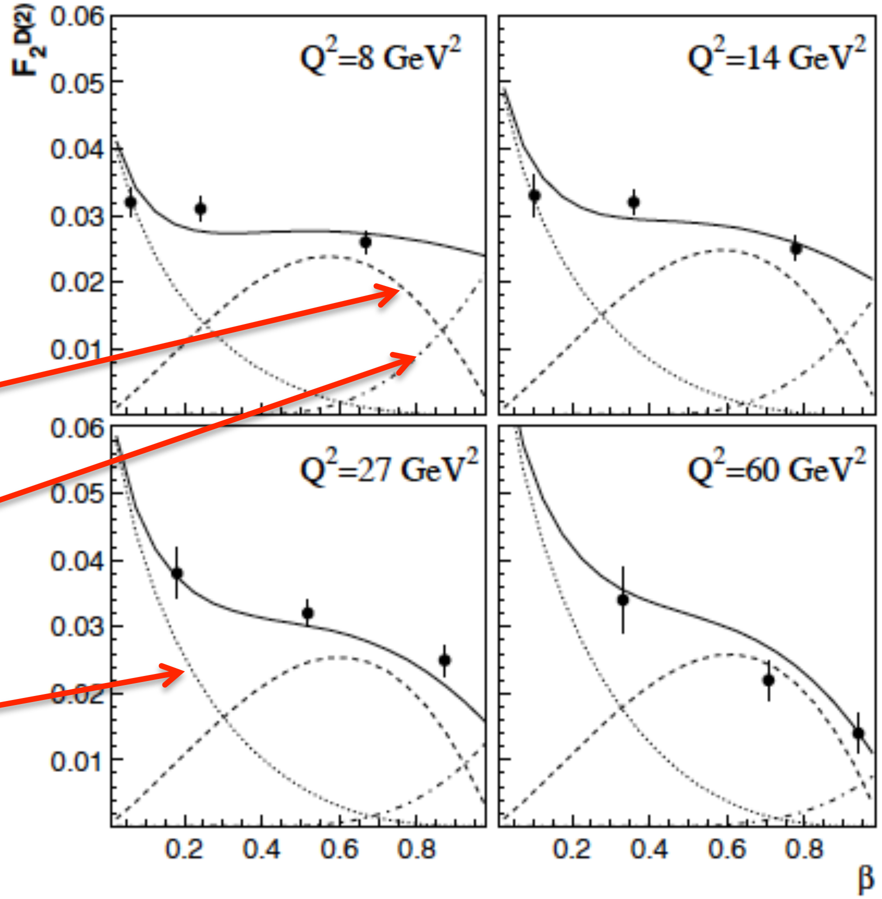




qq_T (Leading Twist)

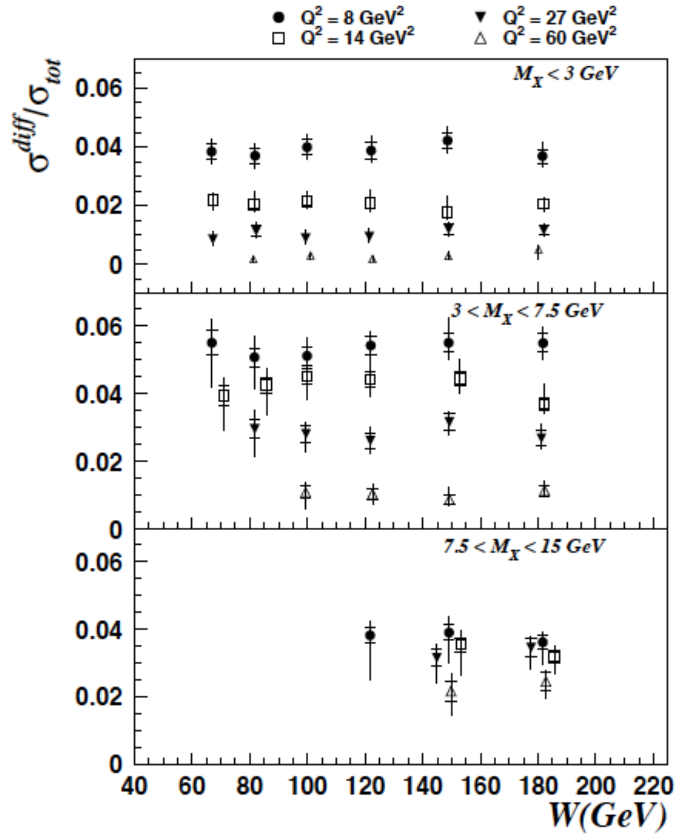
qq_L (Higher Twist)

qqg_T (Leading Twist)

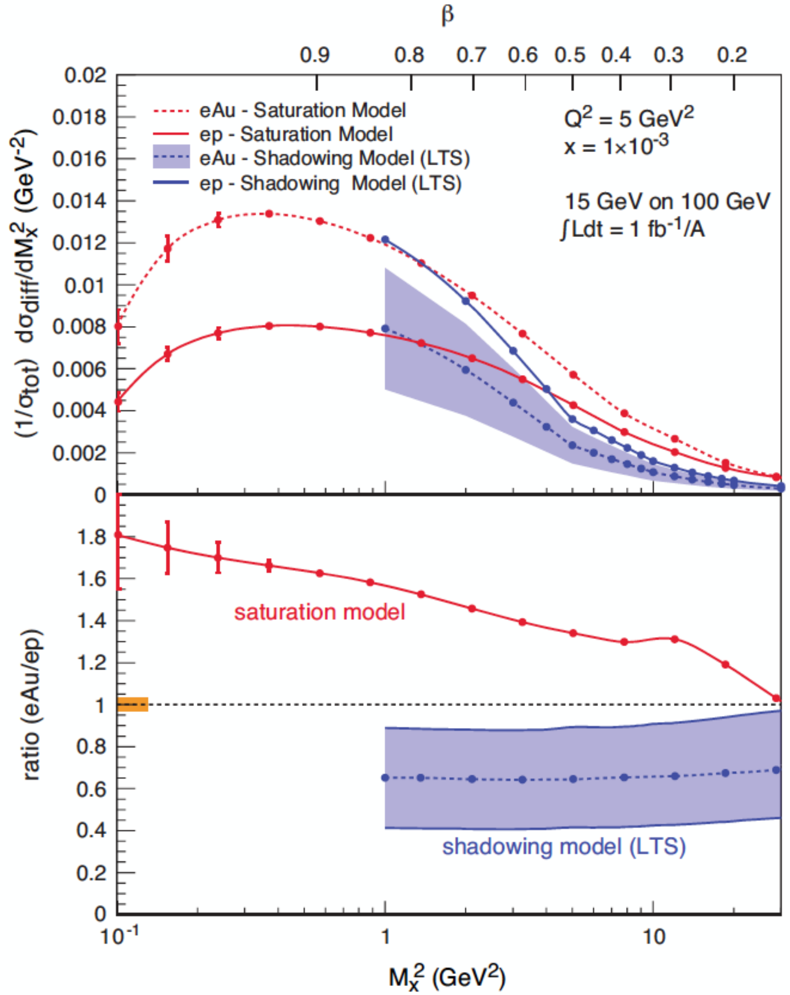


- Not yet describing fine detail
- Unravelling this rich phenomonology can yield big rewards!

Diffractive : Inclusive Ratio



- Famous HERA plot … Rather flat diffractive/inclusive ratio v x at fixed Q2, taken as evidence for saturation

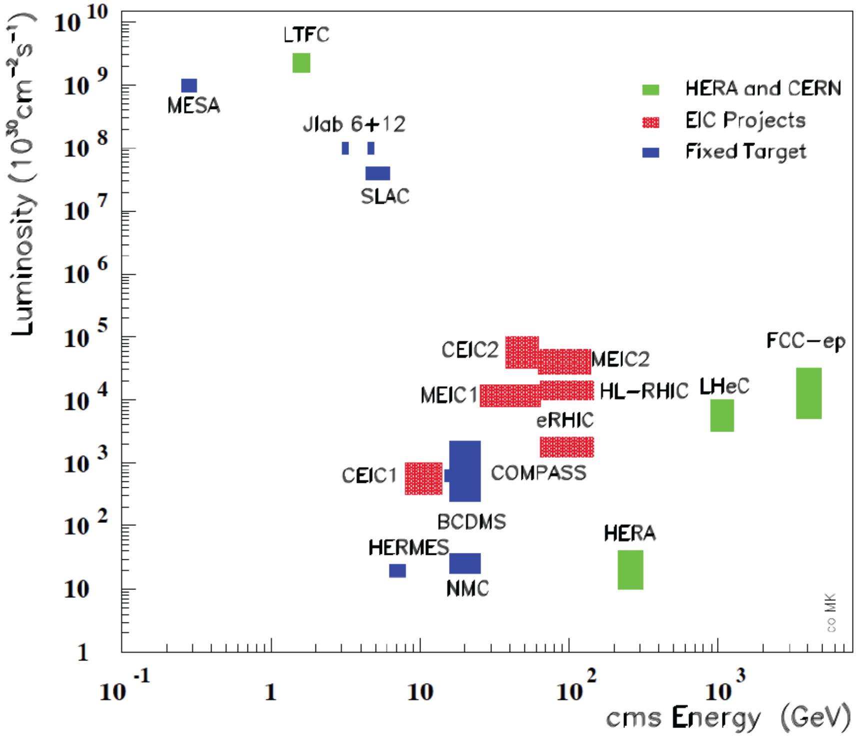


- EIC ‘Day 1’ simulations confirm the importance of this sort of observable to disentangle saturation and shadowing …

… increasing diff/incl ratio with A in saturation case …

Summary

• HERA showed that the closer you look at low x physics, the more surprising it gets and the more it teaches you … and that was with only 0.5fb-1 per experiment (eg DVCS came late and with limited precision)



• Future DIS facilities are vital to fully establish and characterise the dynamics of saturation and precisely map its onset

• Extrapolating and interpolating from HERA and including LHC suggests studies at future DIS facilities will need to include non-perturbative region and a multi-observable approach … ep and eA inclusive, diffractive, semi-inclusive over a range of energies