Diffractive Lepton-Hadron Scattering

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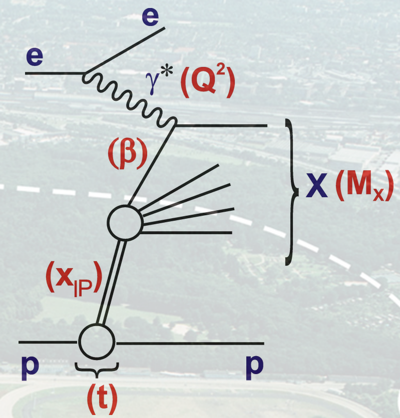
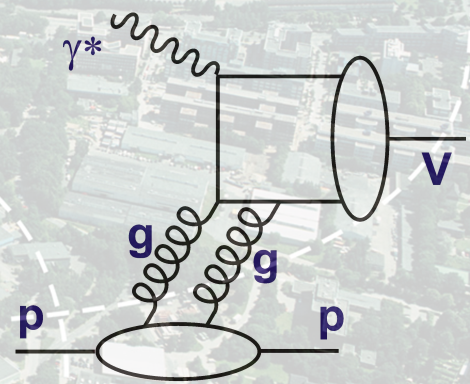


Cracow School of
Theoretical Physics:
'Electron-Ion Collider Physics'

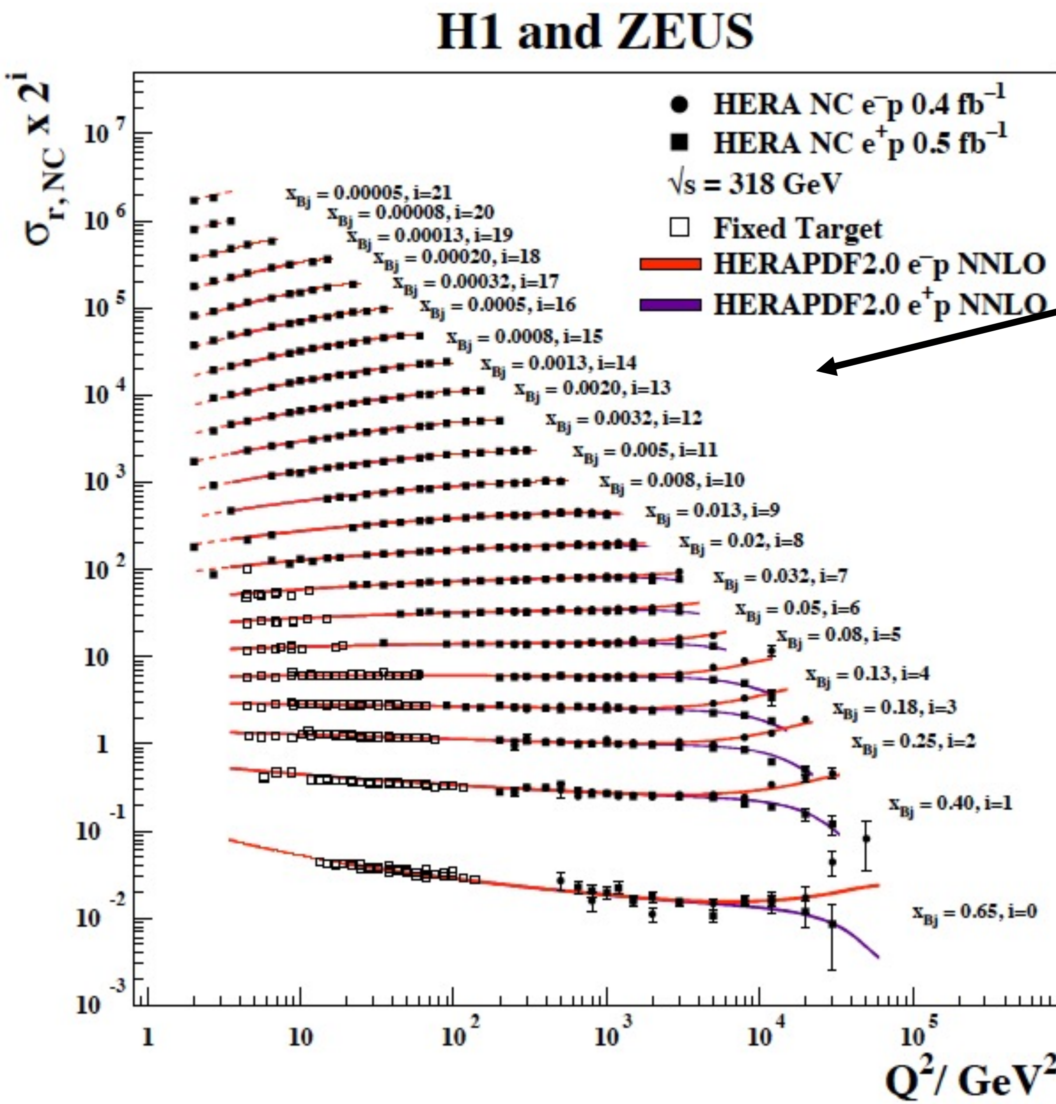


Mon 20 September 2021

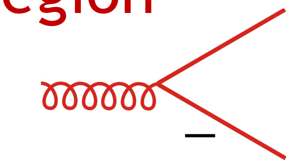
1) Introduction
2) Diffraction at HERA
3) Diffraction at the EIC

Low x Physics: A frontier of Standard Model

… HERA data as discussed by previous lecturer …



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

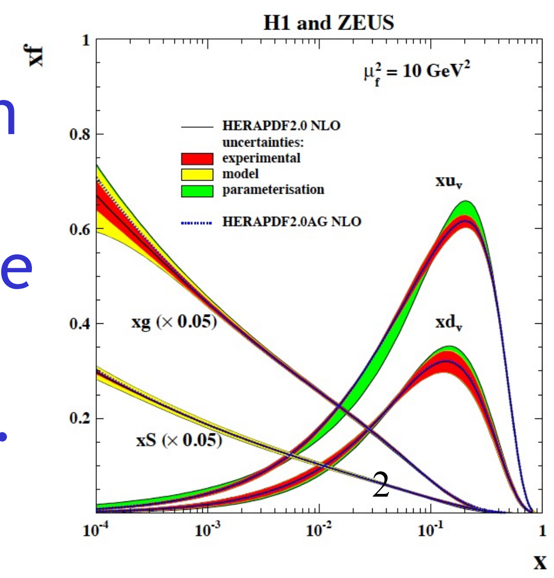


$$g \to q\bar{q}$$

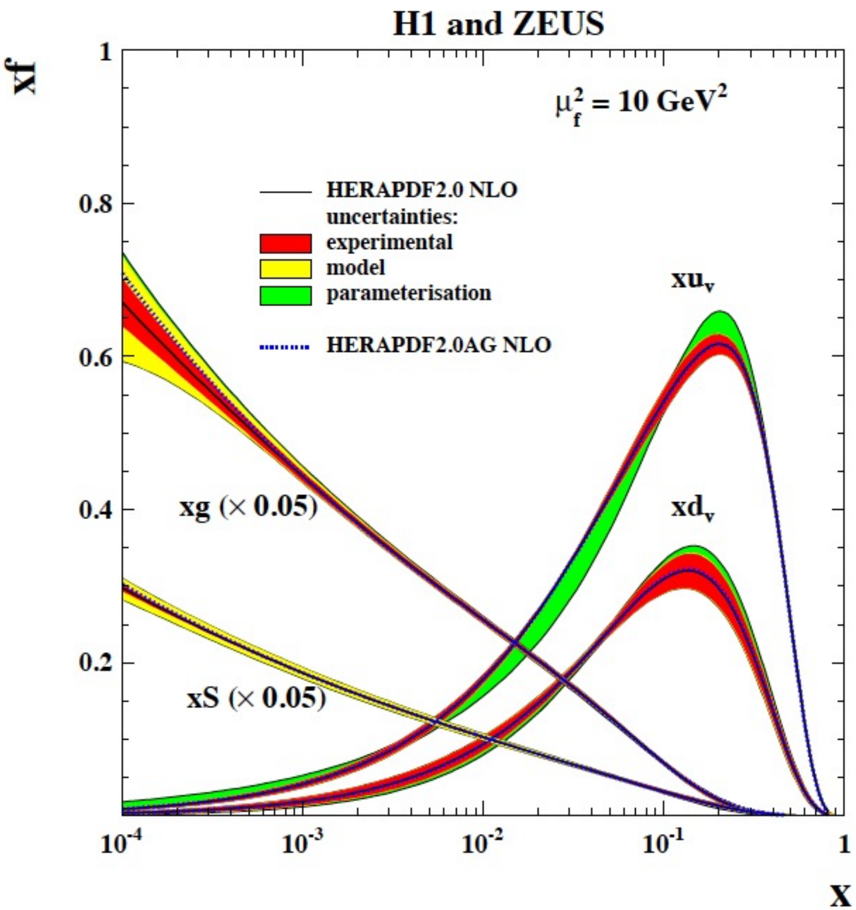
- e.g. Prytz approx:

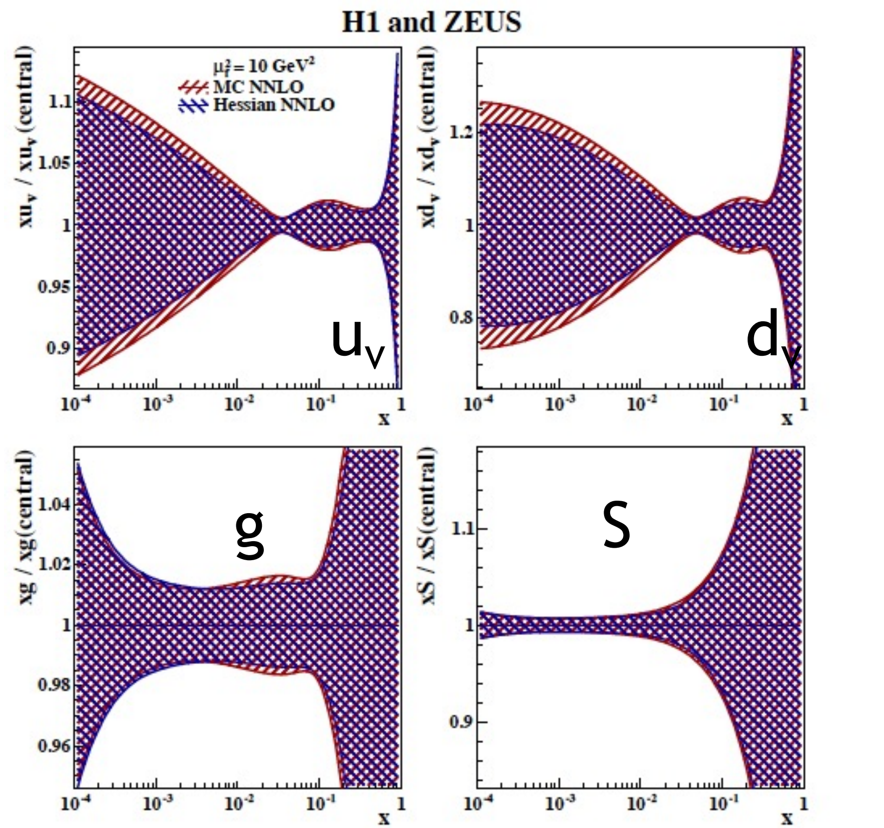
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

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



Final HERA Picture of Proton (HERAPDF2.0)





• ~2% precision on gluon over a wide range of x

• Gluon rises in a non-sustainable way … does it 'saturate'?

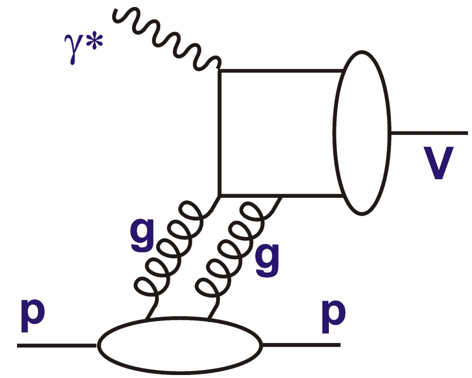
→ emergent phenomena at high parton density & strong coupling

(including diffraction, non-linear evolution, confinement, mass …)

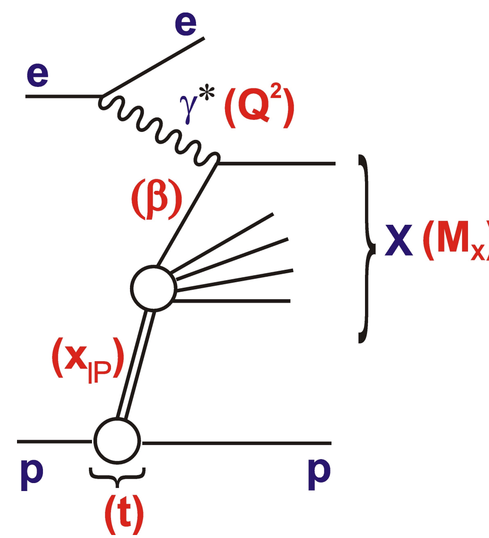
Exclusive / Diffractive Channels

1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to gluon density (at least for exclusives)
2) 2-parton correlations become accessible → 3D imaging!
3) New variable t gives access to impact parameter (b) dependent amplitudes

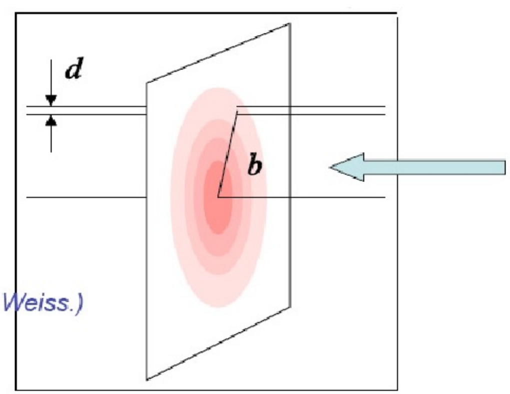
→ Large t (small b) probes densest packed part of proton.



'Exclusive'



'Inclusive'

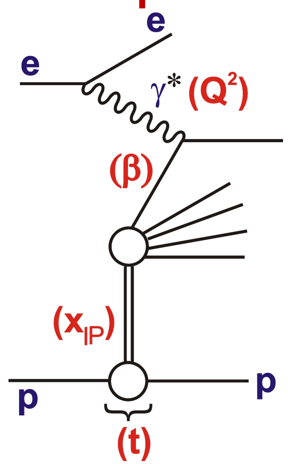


Central black region growing with decrease of x.

(figure from C. Weiss.)

Diffraction and HERA

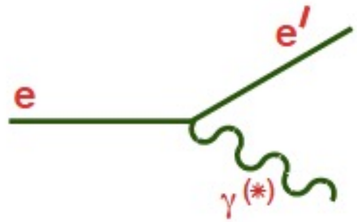
ep collisions
at √s ~ 300 GeV
1992-2007
~ 0.5 fb^{-1} per expt.



e.g. H1 publications on diffraction (similar numbers in ZEUS):

- Inclusive diffractive cross sections: 15 papers
- Diffractive final states: 18 papers
- Quasi-elastic cross sections: 22 papers
- Total γp cross sections / decomposition: 2 papers

Diffractive Lepton-Hadron Scattering: Basics



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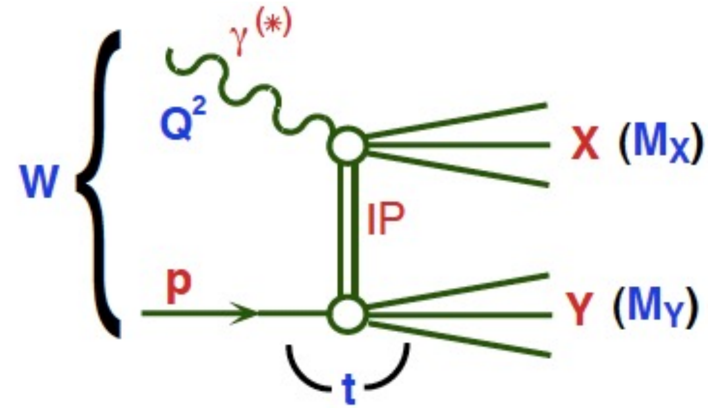


Diffractive γ(*)p processes …

- HERA (and EIC) have favourable kinematics to study X system (photon dissociation)

- By varying Q^2, the process can be smoothly changed
  … from a soft process (real photon, $Q^2 \rightarrow 0$)
  … to a deep inelastic process (highly virtual photon, large Q^2, resolving partons and probing QCD structure)

- I will focus on cases where t is small

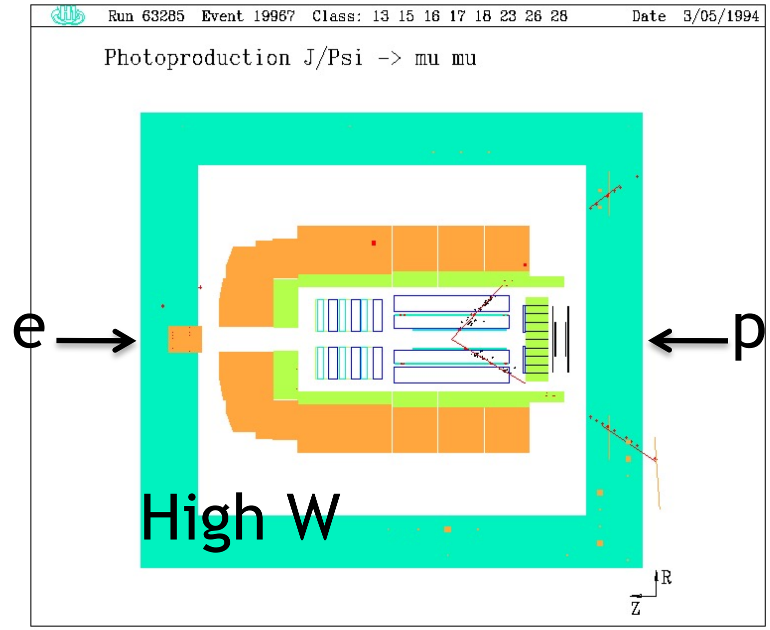
Exclusive Vector Meson Production

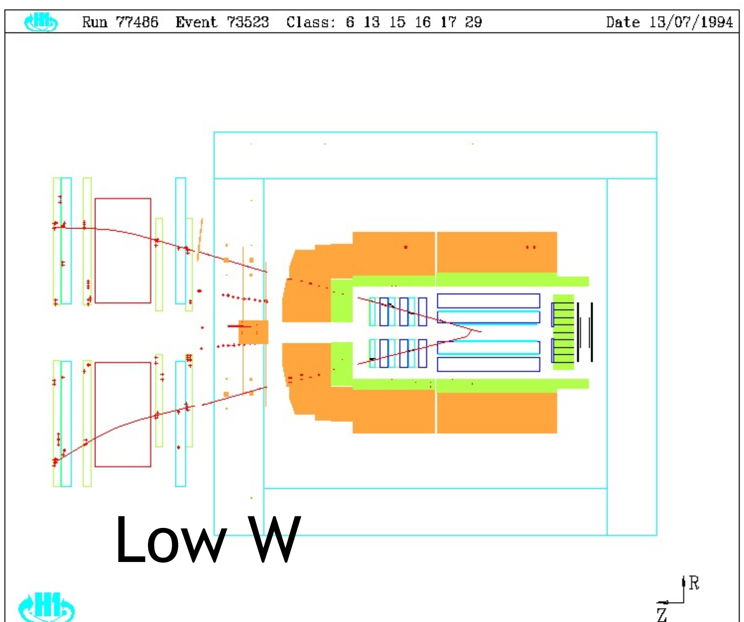
Experimental Selection (examples from H1 - Elastic J/Ψ → μμ)

2-prong decays give beautifully clean events.

→ Select by requiring otherwise empty detector

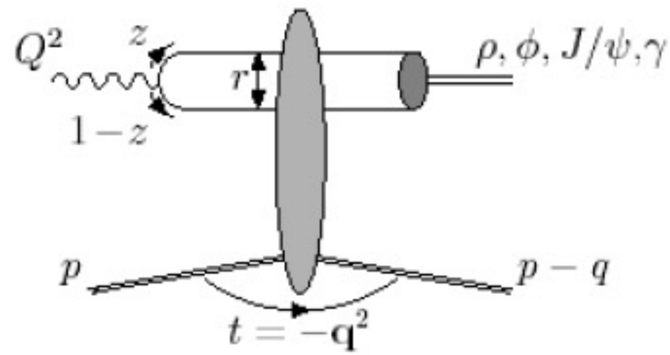
→ Decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$





Describing Vector Mesons in terms of Partons

Factorisation theorem



Dipole Models

step 1. γ fluctuation into $q\bar{q}$ dipole

step 2. dipole – proton interaction $A = \int dr^2\, dz\, \Psi_\gamma\, \sigma(dip-p)\, \Psi_V$

step 3. pair recombination into VM

1. γ wave function

well known : $\Psi(z, k_t)$

however : large $|t|$ studies -> chiral odd contributions

- Basically known

3. pair recombination into VM

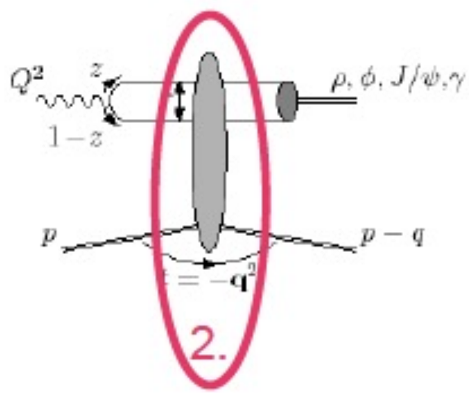
- VM wave function description ?

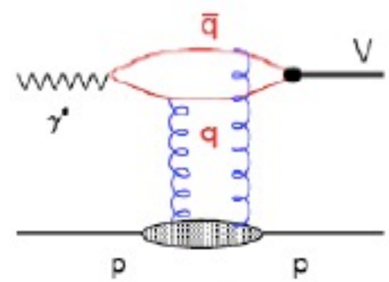
- role on σ_L / σ_T and helicity amplitudes

- Limits theoretical precision

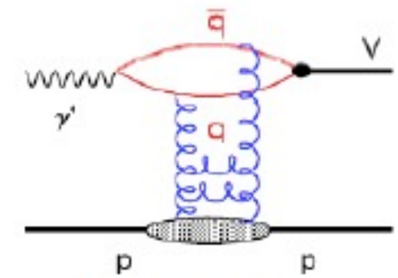
The Dipole-Proton Interaction

2. dipole – proton interaction - The interesting physics





LO 2 gluons



LL1/x ladder

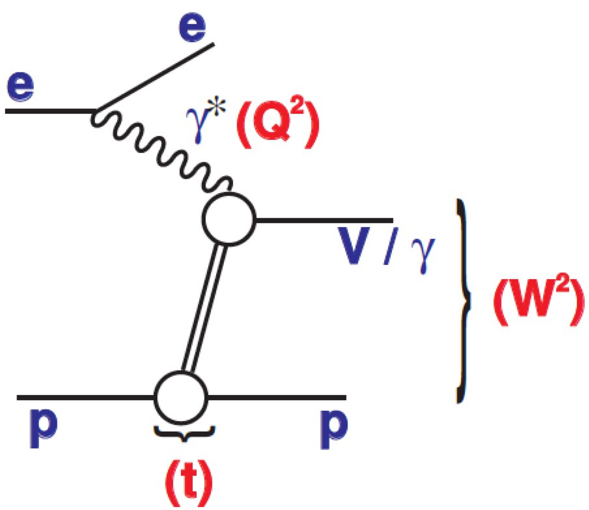
VM production is a promising candidate to learn about the gluon distribution in hadrons and the correlations among gluons

Many models on the details of $\sigma(r)$ (see later talks)

What is the relevant scale?... r depends on Q^2 and $M_V{}^2$

$$Q^2_{eff} = z\,(1-z)\,(Q^2+M_V{}^2) \sim (Q^2+M_V{}^2)\ /\ 4$$ [MRT...]

Vector Mesons & the Soft → Hard Transition



Behaviour usually parameterised in Regge-theory motivated form

$$\frac{d\sigma_{el}}{dt} \sim \left(\frac{W^2}{W_0^2}\right)^{2\alpha(t)-2} e^{bt}$$

– $\alpha(t)=\alpha(0)+\alpha' t$ is the 'effective pomeron trajectory'
'Universal' description of soft physics: $\alpha(t) \sim 1.08 + 0.25t$

- e^{bt} empirically motivated – Fourier transform of spatial distribution of interaction
$b = b_{dipole} + b_{proton} \rightarrow b_{proton}$ as dipole size → 0

- Signatures for 'hard' behaviour include increase in $\alpha(0)$ and decrease in b

Photoproduction of Light v Heavy VM

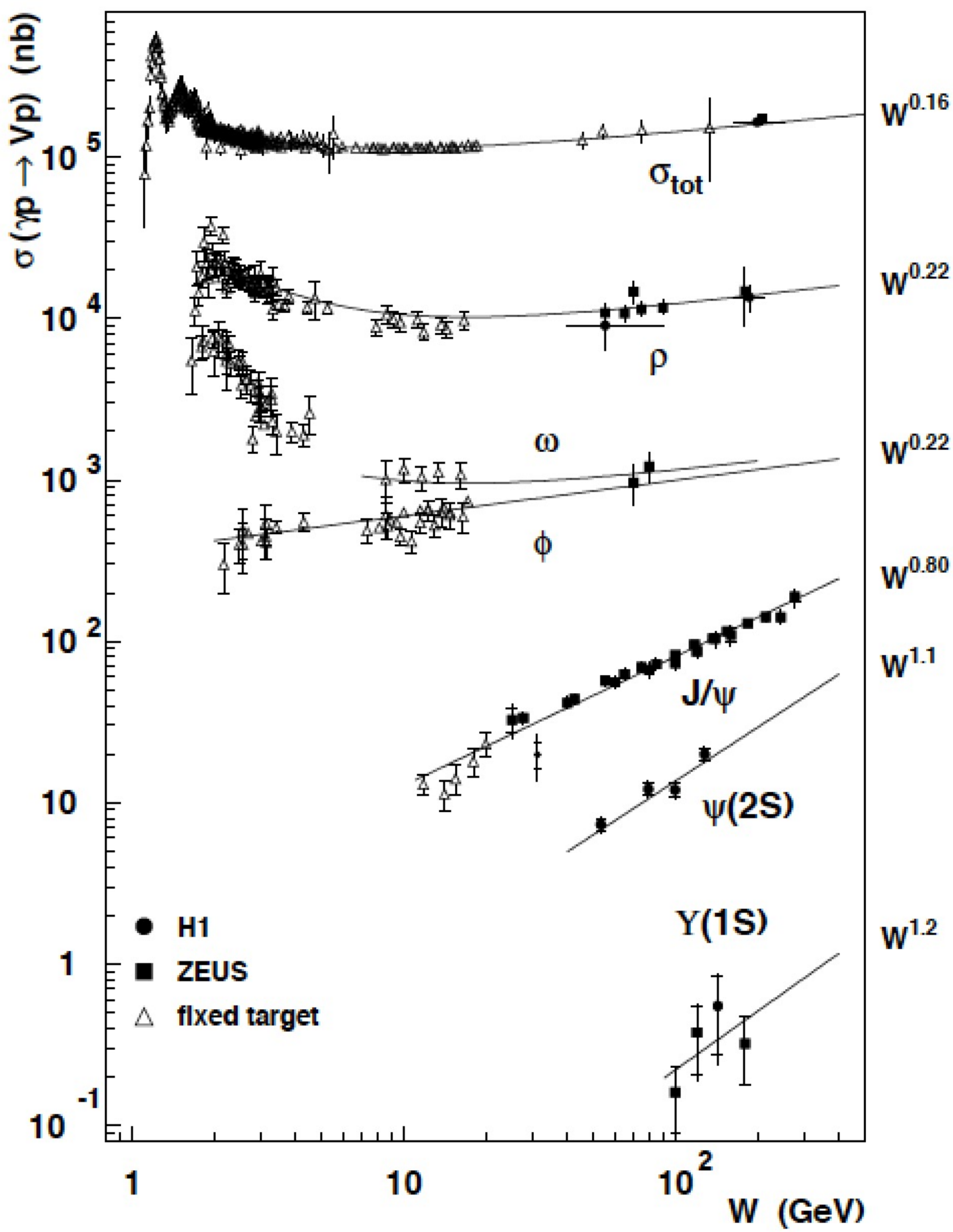
Increasing M_V leads to harder energy dependences

$\sigma \propto W^{\delta}$ with $\delta = 4\alpha(<t>) - 4$

- Consistent with soft pomeron for light vector mesons

- For J/Ψ, effective
$\alpha(t) \sim 1.20 + 0.13t$

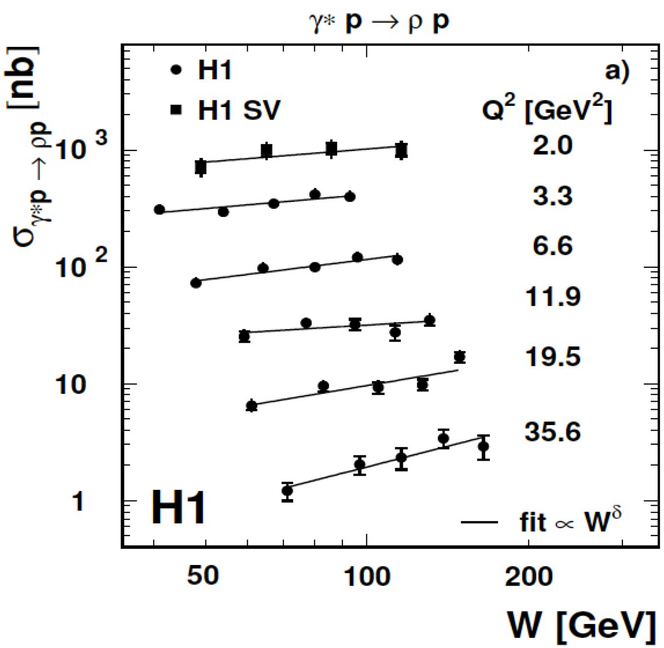
… c, b mass implies pQCD already valid for J/Ψ, Υ at $Q^2 = 0$

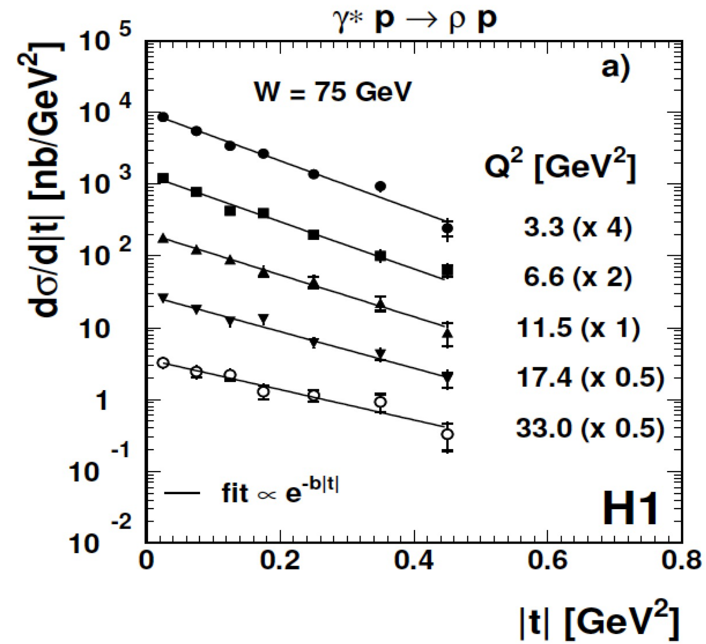


Turning the Q^2 Handle

-J/Ψ: W & t dependences ~ unchanged - already hard @ Q^2=0

- Light vector meson behaviour evolves from soft to hard (eg ρ^0)

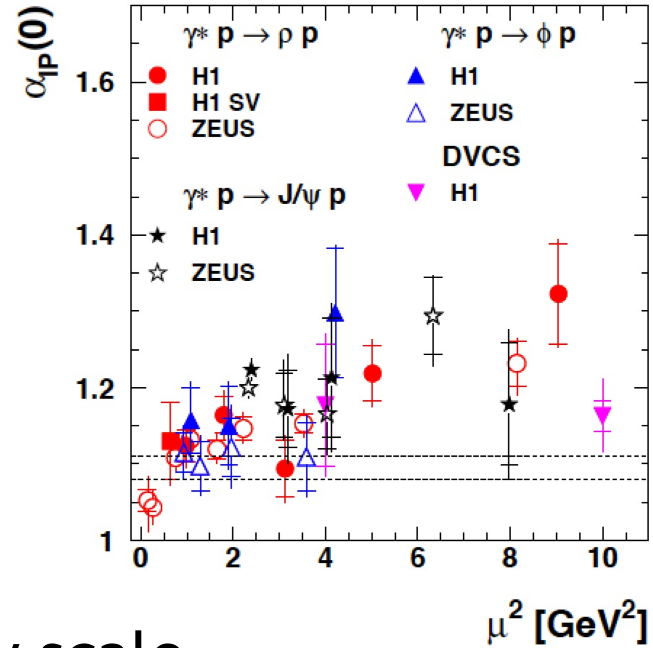




- Vector mesons produced from longitudinal and transverse polarised photons behave slightly differently
- Fast reduction in cross section with Q^2 illustrates higher twist nature of process: $\sigma_L \sim 1/(Q^2+M_V^2)^{2.1}$, $\sigma_T \sim 1/(Q^2+M_V^2)^{2.9}$

… reasonably well described by dipole (2 gluon) models

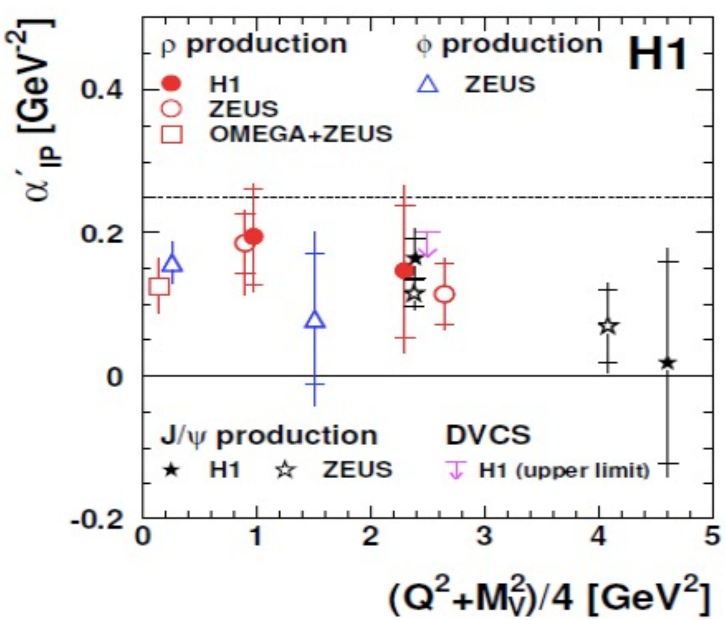
VM Overall Characterisation Summary

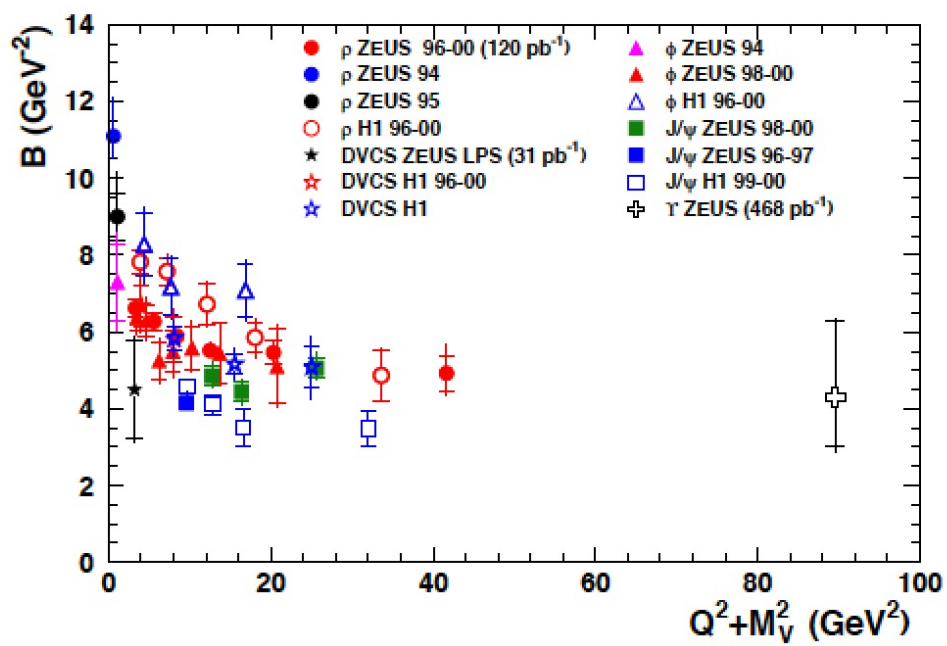


- Approximate scaling between different meson species in $(Q^2 + M_V^2)/4$

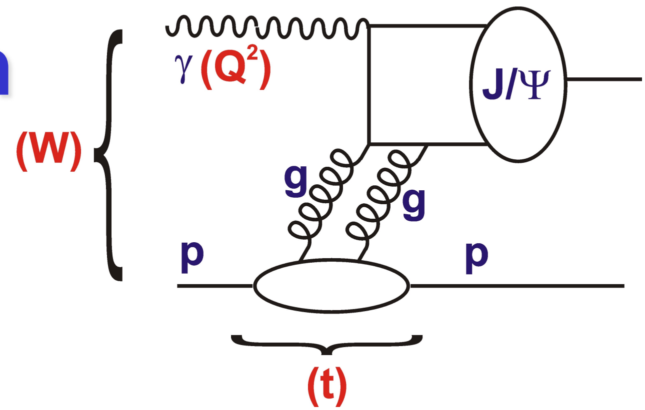
-t-slope approaches B~ 4-5 GeV^{-2} ~ 0.6fm … slightly smaller than EM size of proton?

– α' shows no significant variation with any scale.





Exclusive J/Ψ Photoproduction



Maybe the ideal place to look for gluon saturation in ep, eA …

Advantages

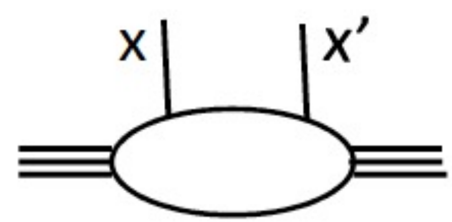
- Clean 2 lepton experimental signature

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

Possible clear saturation signature: energy (W) dependence flattening in a manner dependent on t or in eA as A grows

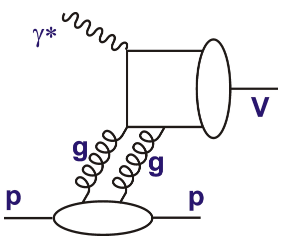
Complications

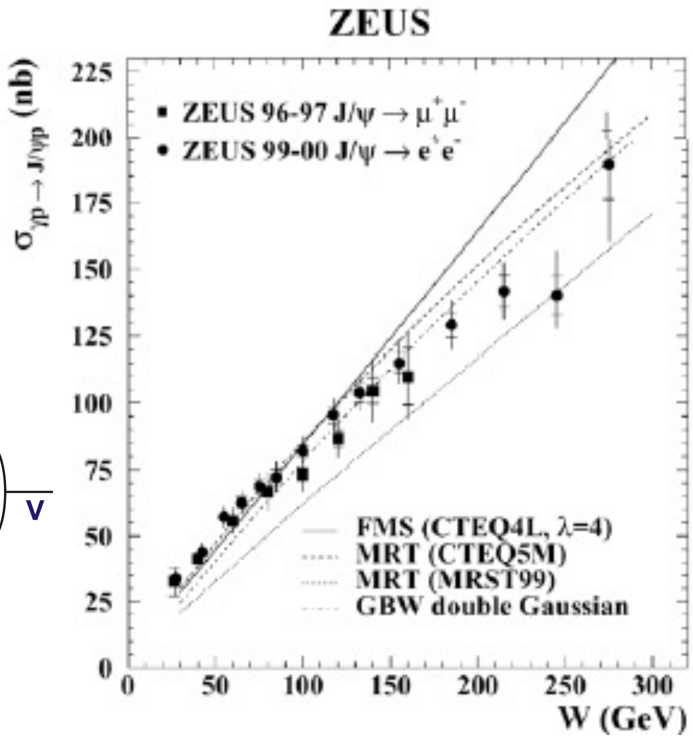
- Vector meson wavefunction

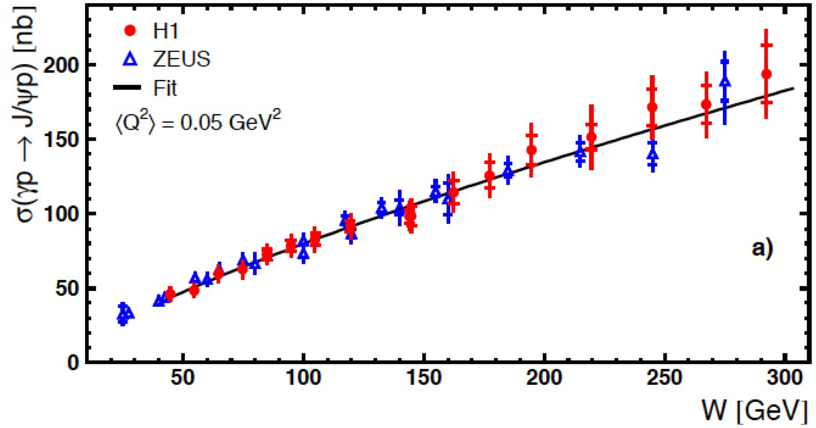


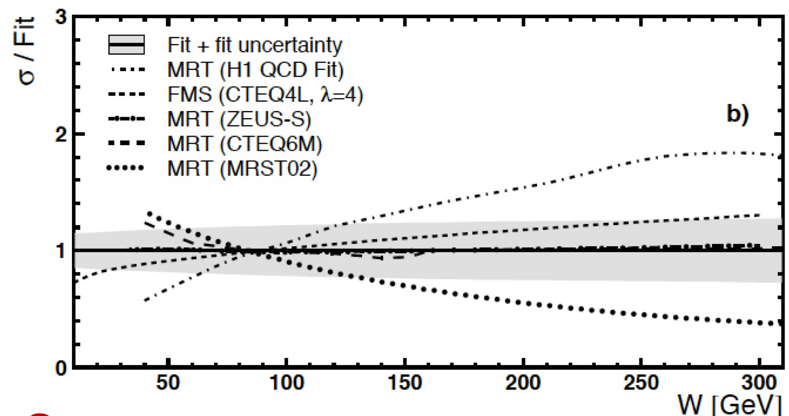
- Difficulties in collinear factorization theory → large scale uncertainties (NLO v LO convergence)

HERA Photoproduction of J/Ψ and the Gluon









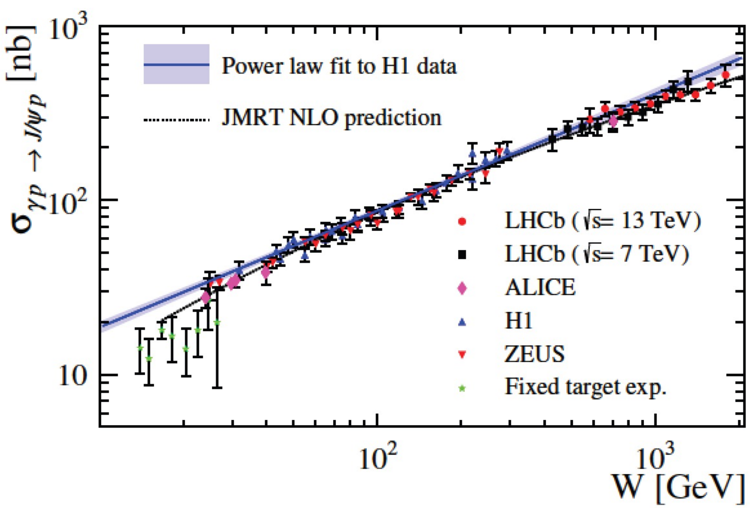
- QCD models based on 2-gluon exchange describe HERA data well & suggest power to discriminate between PDFs

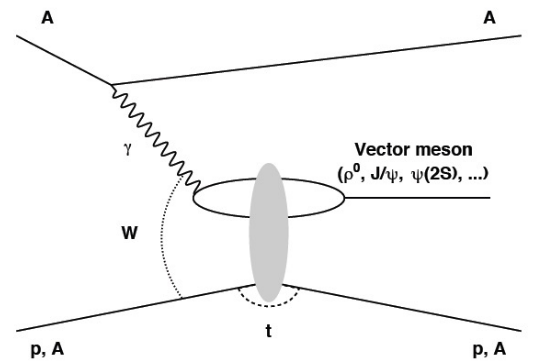
- Sensitivity limited by theory uncertainties

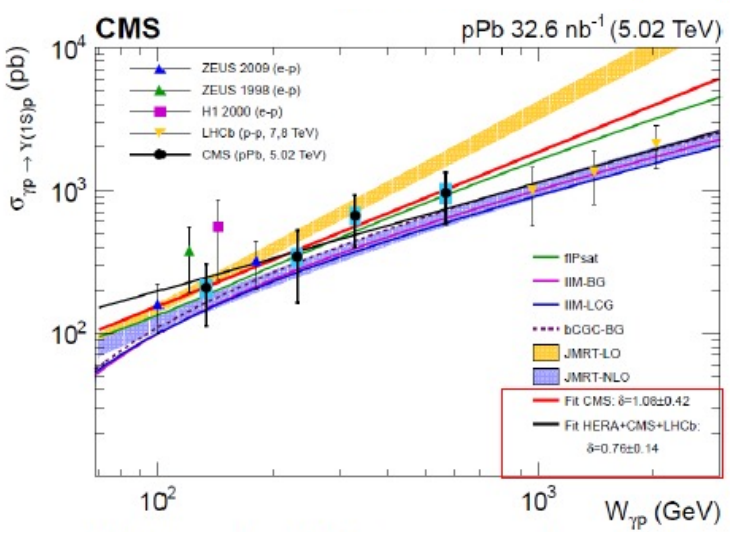
- No evidence for saturation phenomena in HERA data (all ep)

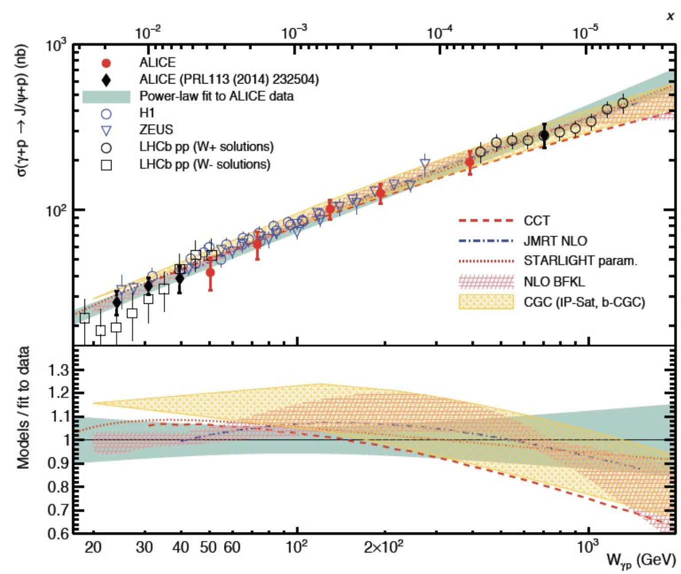
Exclusive J/Ψ Data from the LHC

J/Ψ Photoproduction also studied (at higher energy) in Ultraperipheral Collisions at LHC









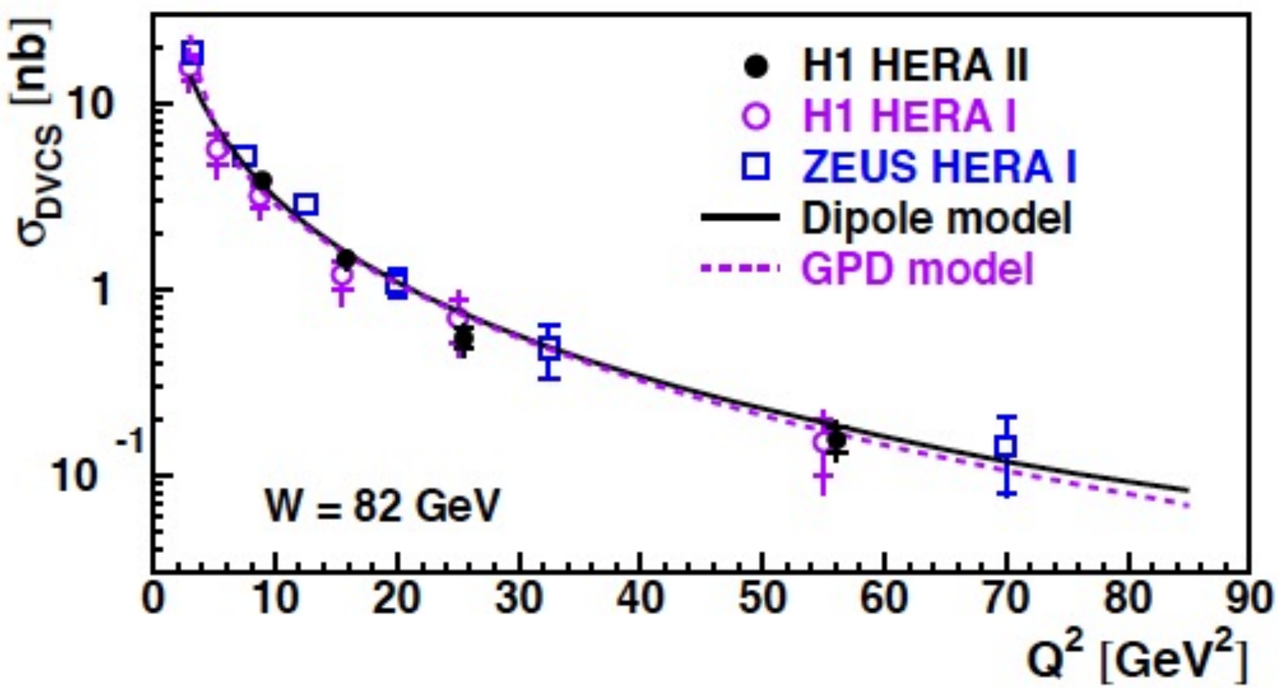
- No sign of deviation from simple power law behaviour (yet)
- More subtle signatures may exist in t dependences and eA/ep

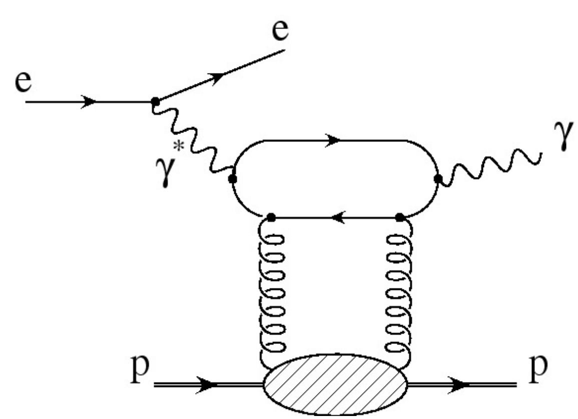
Deeply Virtual Compton Scattering (ep → eγp)

- DVCS is the classic exclusive process to investigate hadron transverse structure and correlations via Generalised Parton Densities

… BUT …

- HERA measurements were luminosity-limited (lower cross sections than Vector Mesons due to γ coupling)
- HERA did not have polarised proton beams



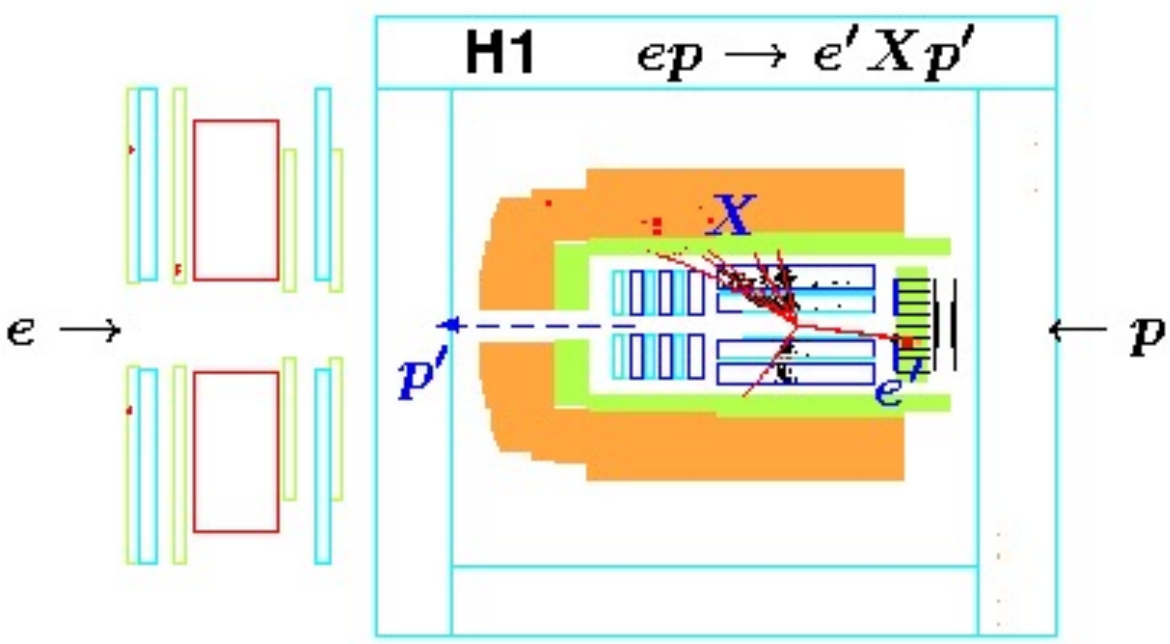


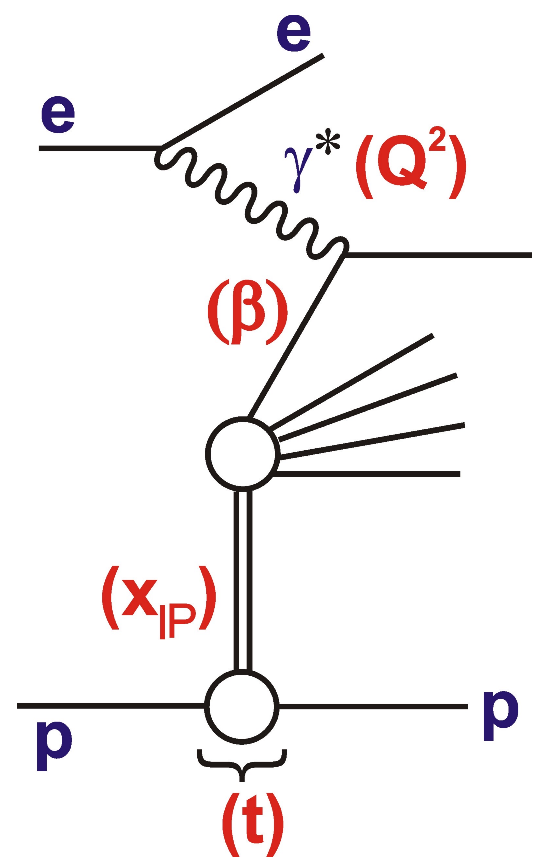
Inclusive Diffraction in Deep Inelastic Scattering

Diffractive DIS

Vector meson production is a 'higher twist' (Q^2 suppressed) process

There are 'leading twist' diffractive processes with same Q^2 dependence as the bulk DIS cross section …





~10% of DIS events have no forward energy flow

Kinematics

Standard DIS variables …

x = momentum fraction q/p
Q^2 = |γ^* 4-momentum squared|

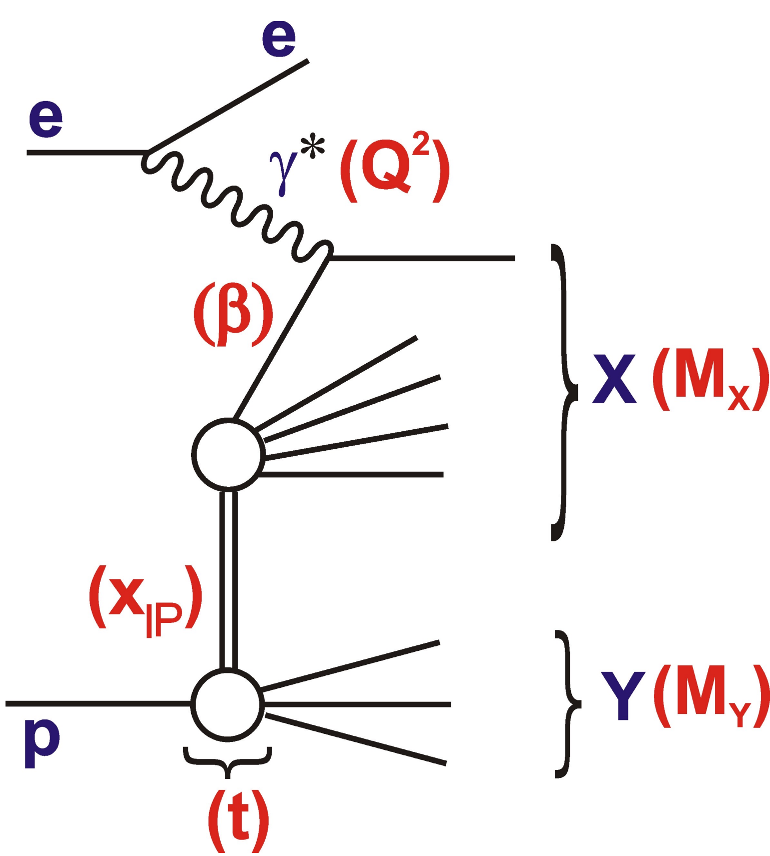
Additional variables for diffraction …

t = squared 4-momentum transfer at proton vertex

x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

β = x / x_{IP} (momentum fraction q / IP)

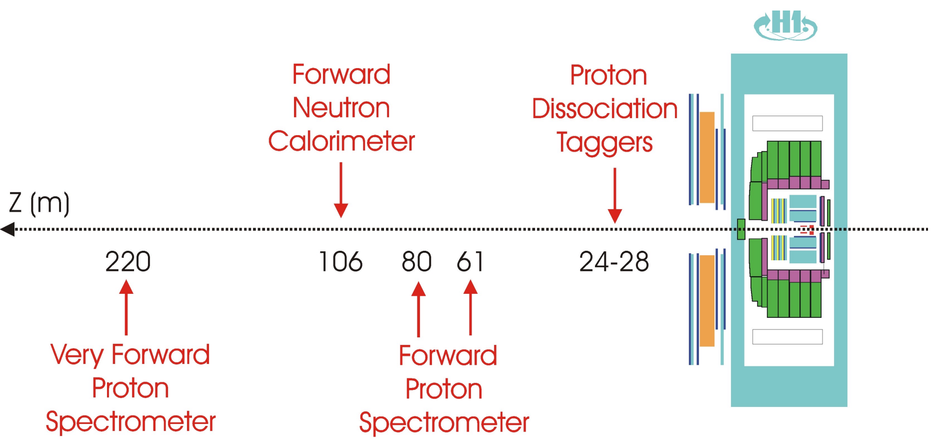
Most generally ep→eXY …



In most cases here, Y=p, (small admixture of low mass excitations)

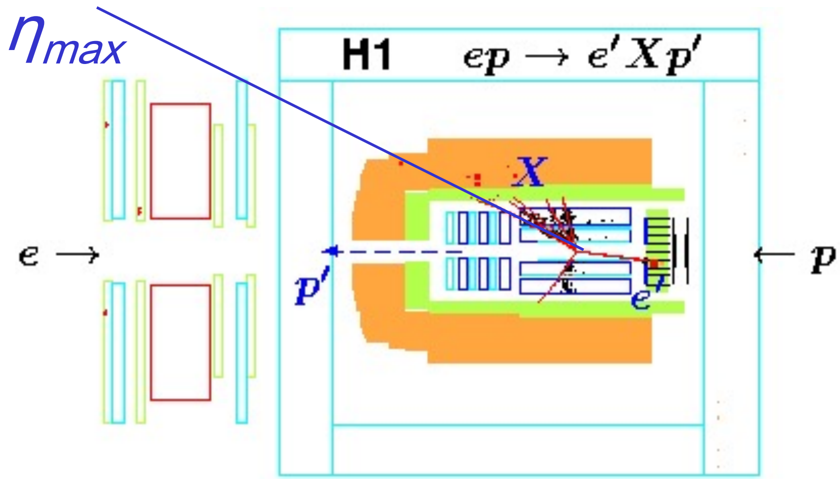
Signatures and Selection Methods

Scattered proton in Leading Proton Spectrometers **(LPS)**



Limited by statistics and p-tagging systematics

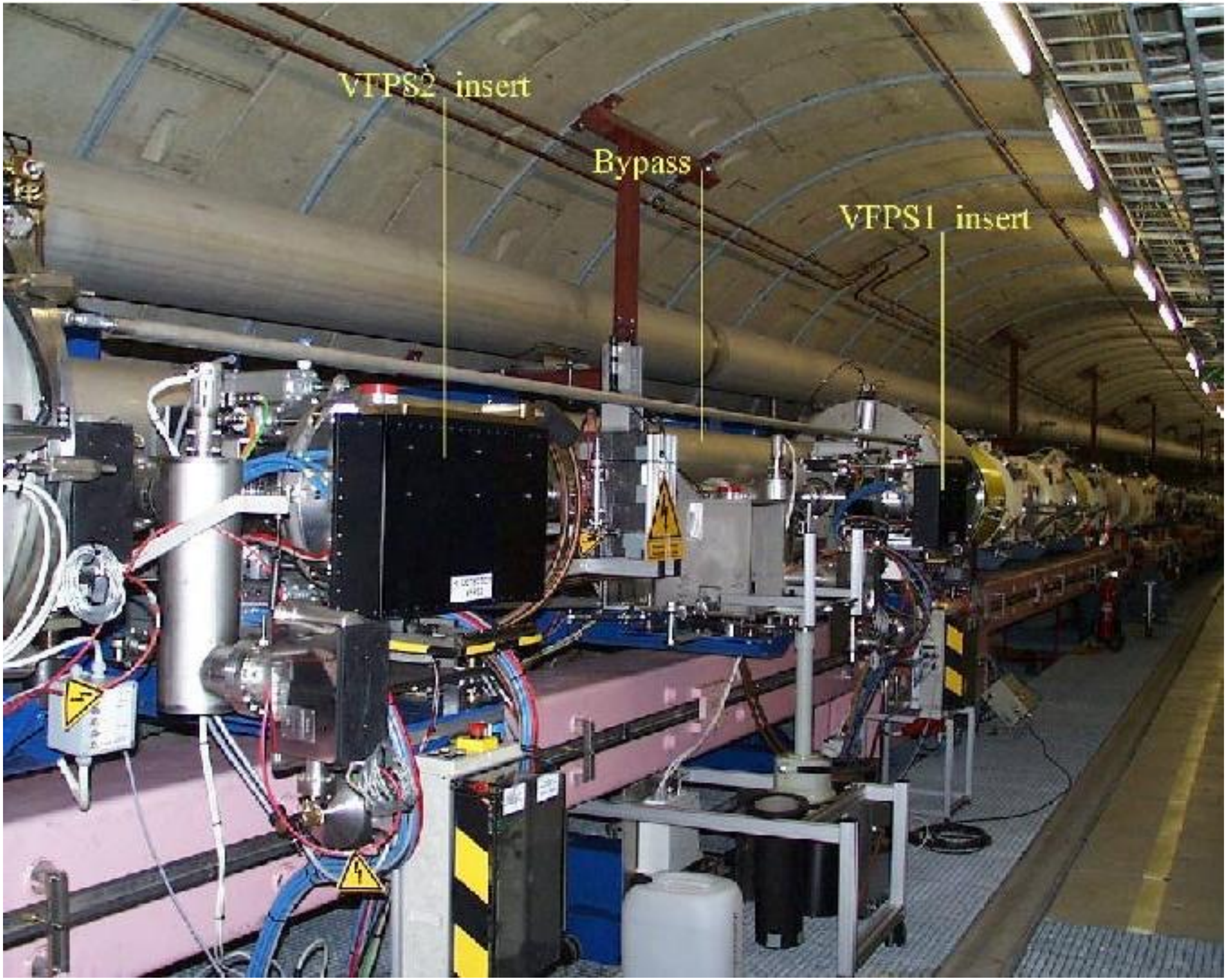
\`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton



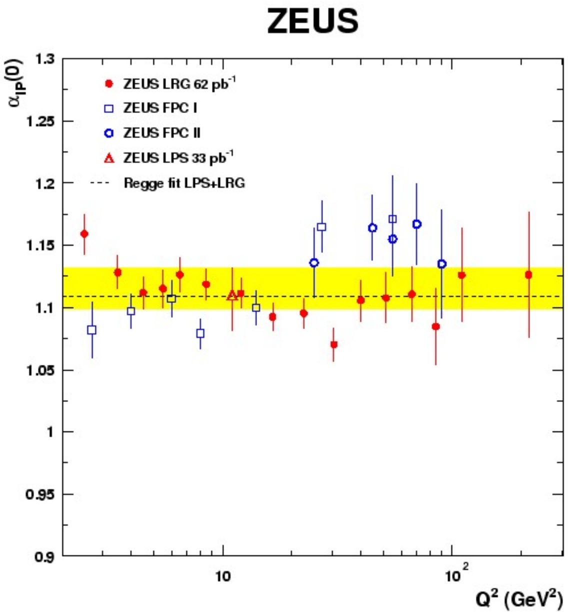
Limited by p-diss systematics

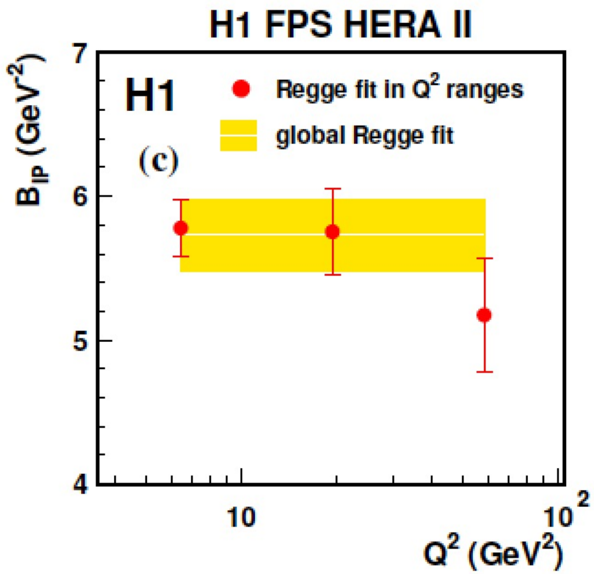
- The 2 methods have very different systematics
- LRG was the main method used at HERA
- At EIC it is more likely to be LPS (technologies improved!)

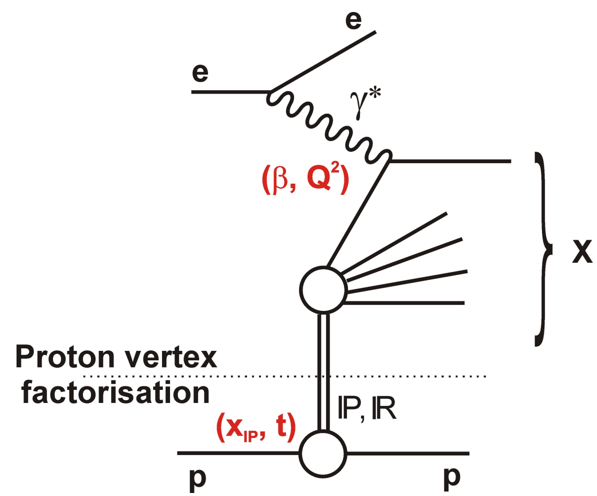
Example Roman Pots (H1 VFPS @ ~200m)



Proton Vertex Factorisation & the Effective Pomeron of Diffractive DIS







- x_{IP} (via $\alpha_{IP}(0)$) and t (via b slope) dependence invariant with Q^2 and β !

e.g. From H1 FPS data:

$$\alpha_{IP}(0) = 1.10 \pm 0.02 \text{ (exp.)} \pm 0.03 \text{ (model)}$$

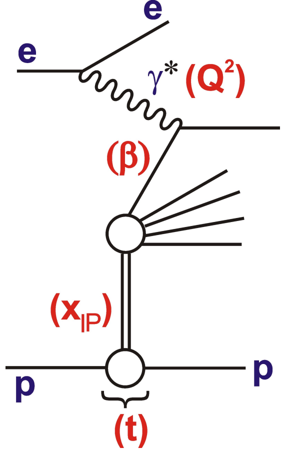
$$\alpha'_{IP} = 0.04 \pm 0.02 \text{ (exp.)} \pm 0.07 \text{ (model) GeV}^{-2}$$

$$B_{IP} = 5.7 \pm 0.3 \text{ (exp.)} \pm 0.9 \text{ (model) GeV}^{-2}$$

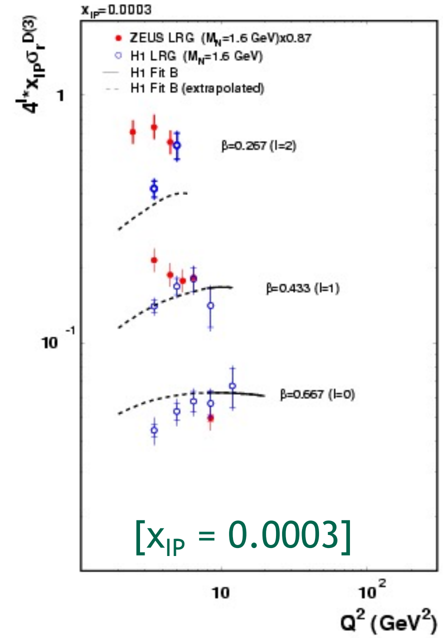
$\alpha_{IP}(0)$ consistent with soft IP → Dominantly soft exchange

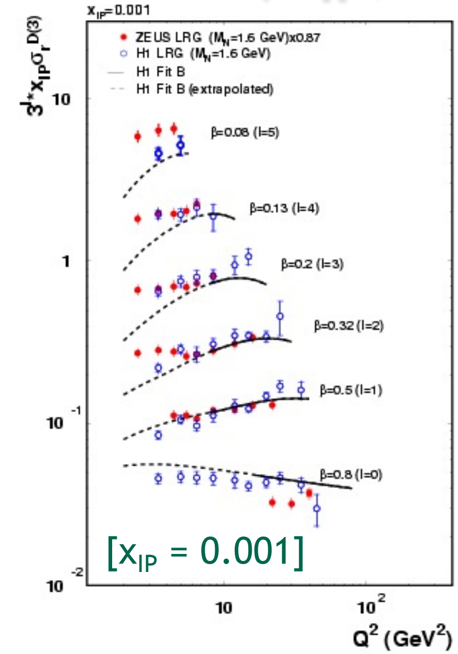
α_{IP}' smaller than soft IP → Absorptive effects?...

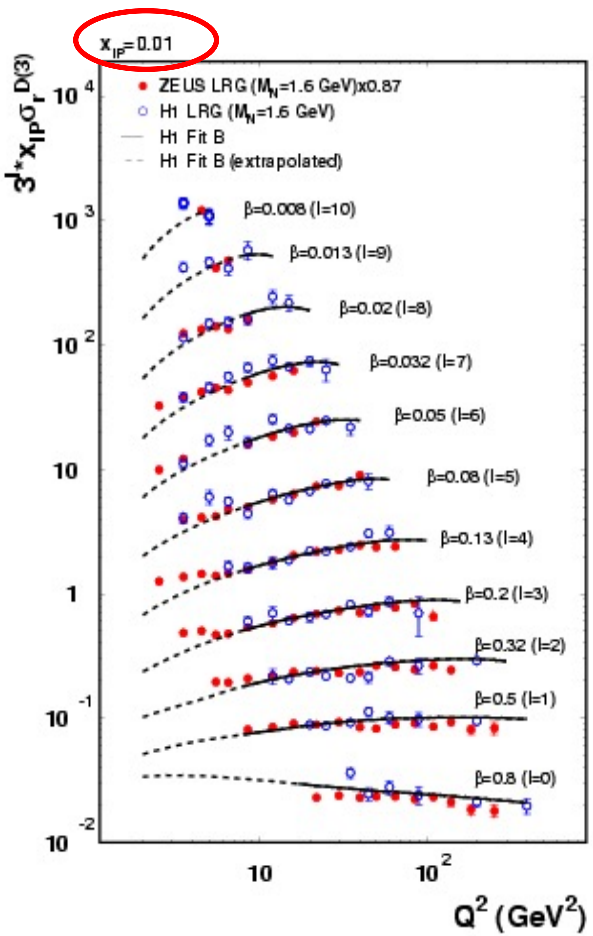
(β, Q^2) Dependences at fixed (x_{IP}, t)

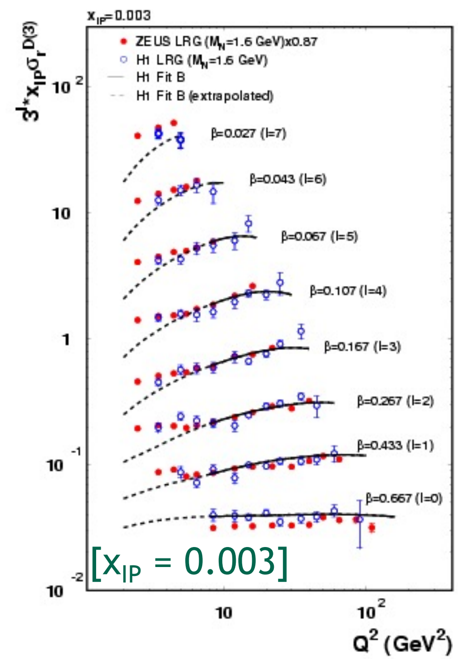


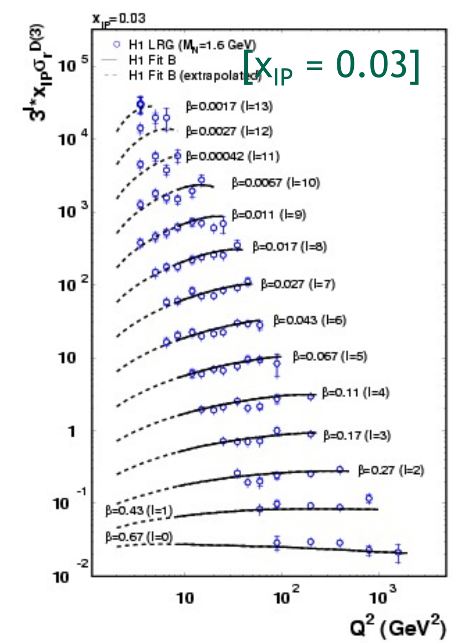
Leading twist and ~10% of total x-sec

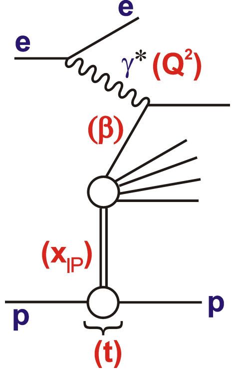






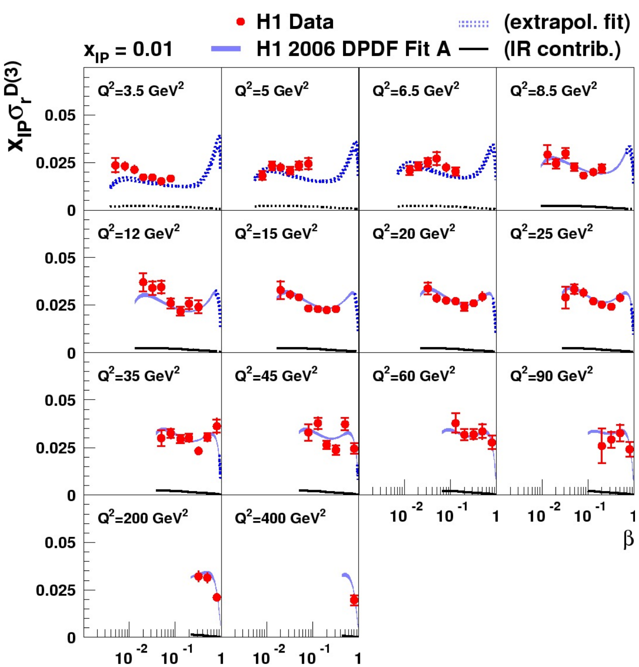


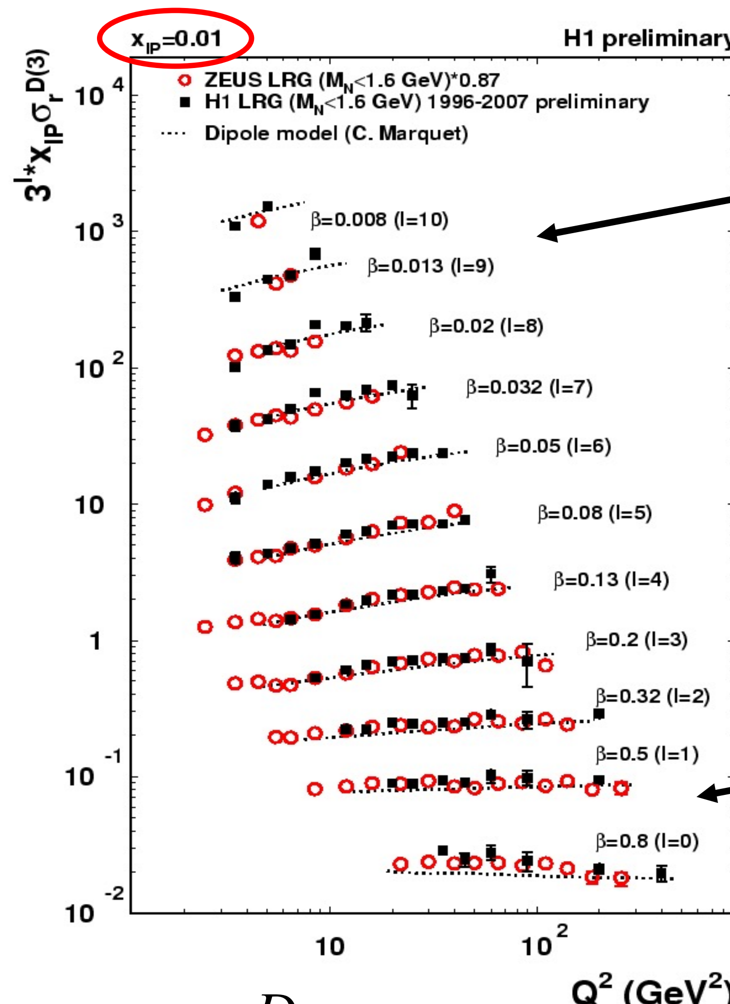


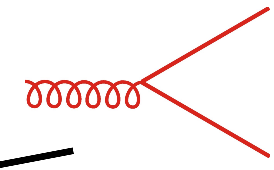


Sensitivity to Diffractive Quarks & Gluons

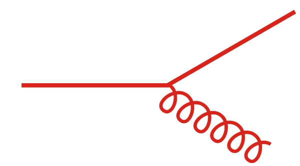
Similarly to Inclusive DIS …







Q^2 dependence tells us gluon density via DGLAP eqns

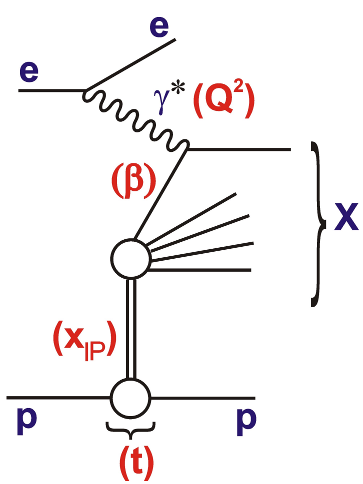


Diffractive cross section measures quark density

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

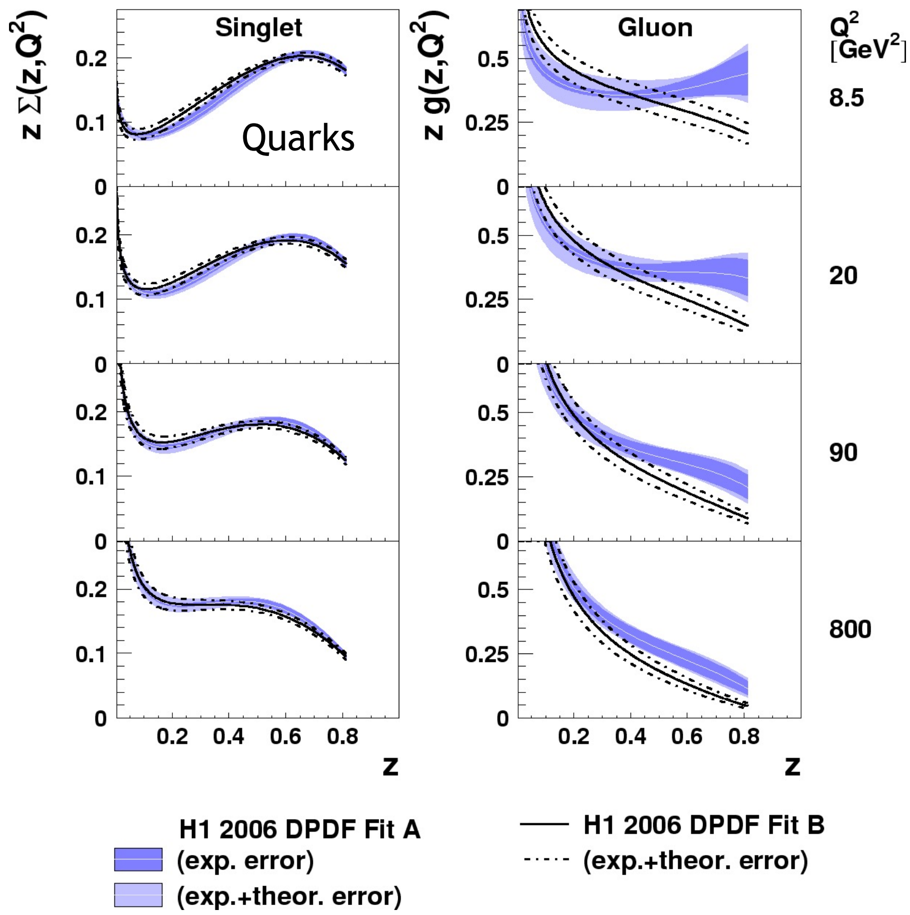
$$\frac{d\sigma_r^D}{d \ln Q^2} \sim \frac{\alpha_s}{2\pi} \left[P_{qg} \otimes g + P_{qq} \otimes q \right]$$

Diffractive Parton Densities (DPDFs)



DPDFs extracted through fits to inclusive (& jet) data, assuming NLO/NNLO DGLAP evolution, similarly to inclusive DIS

e.g. H1

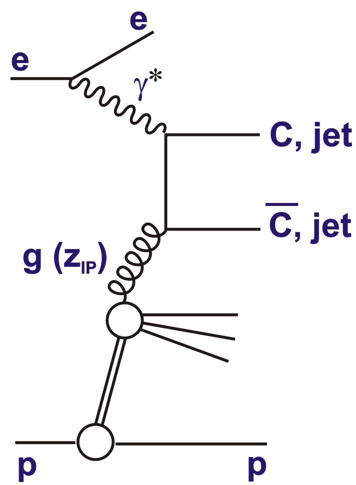


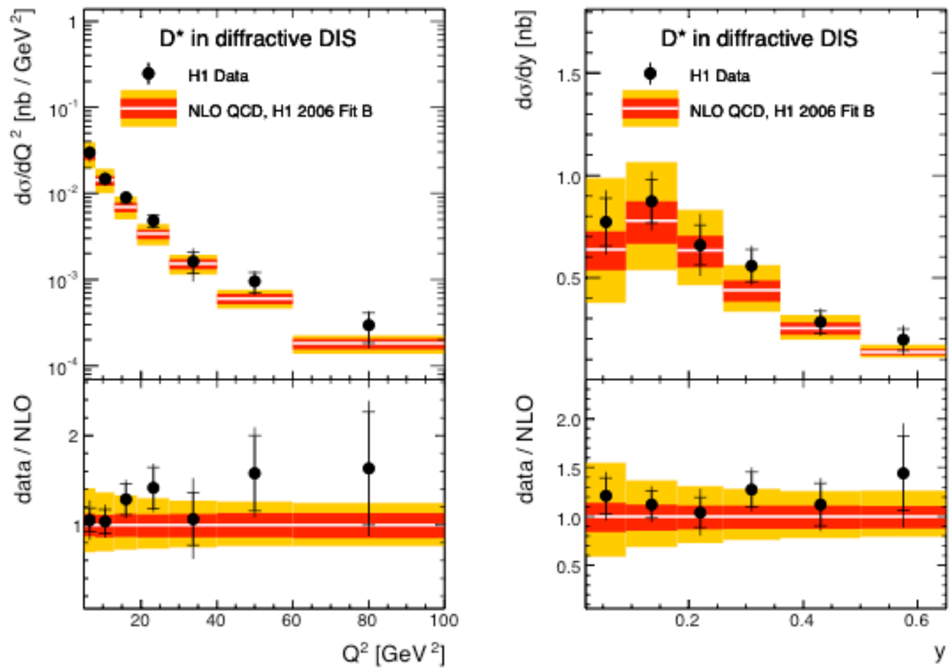
… dominated by gluon density extending to large momentum fractions, z

- NLO DGLAP QCD fits describe data over most of phase space
- Failure of diffractive PDF fits to describe data at lowest Q^2 …

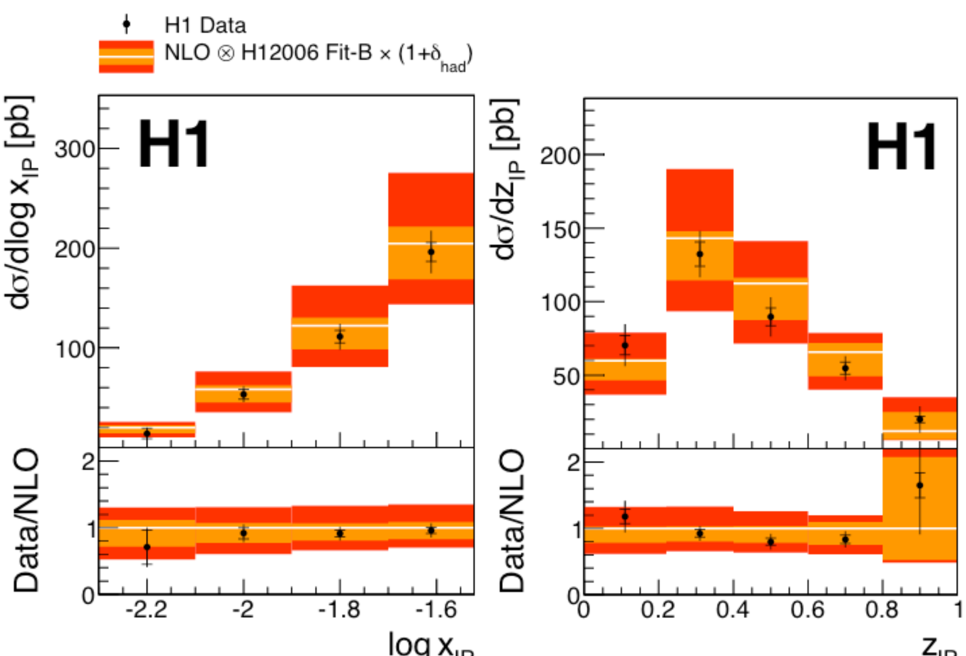
Testing Factorisation; eg HERA Jets & Charm

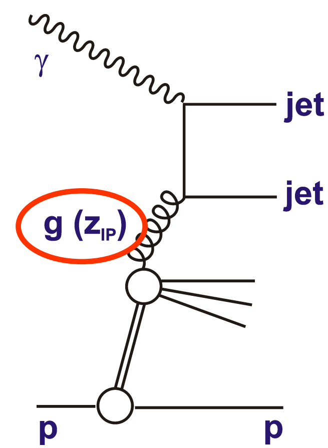
Remarkably good description of all variables in Diffractive DIS over a wide kinematic range





Charm in DIS



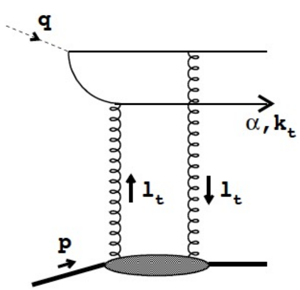


Dijets in DIS

Diffractive DIS & Dipole Models

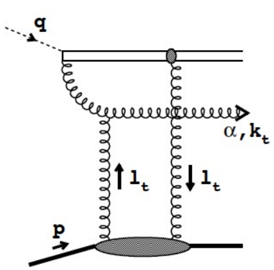
- Quality of H1 & ZEUS DPDF fits degrades at low Q^2 <~ 5 GeV^2
  … low Q^2 breakdown of pure Leading Twist DGLAP approach

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

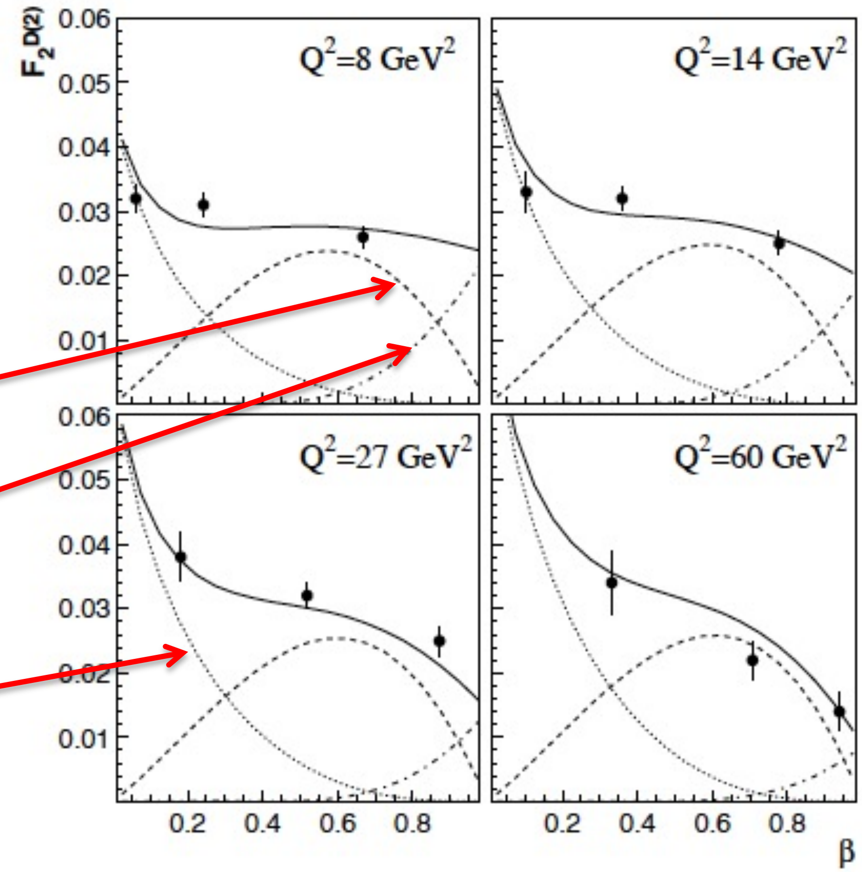


qq_T (Leading Twist)

qq_L (Higher Twist)



qqg_T (Leading Twist)

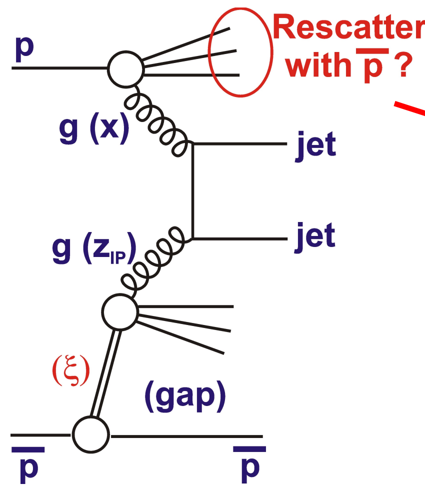


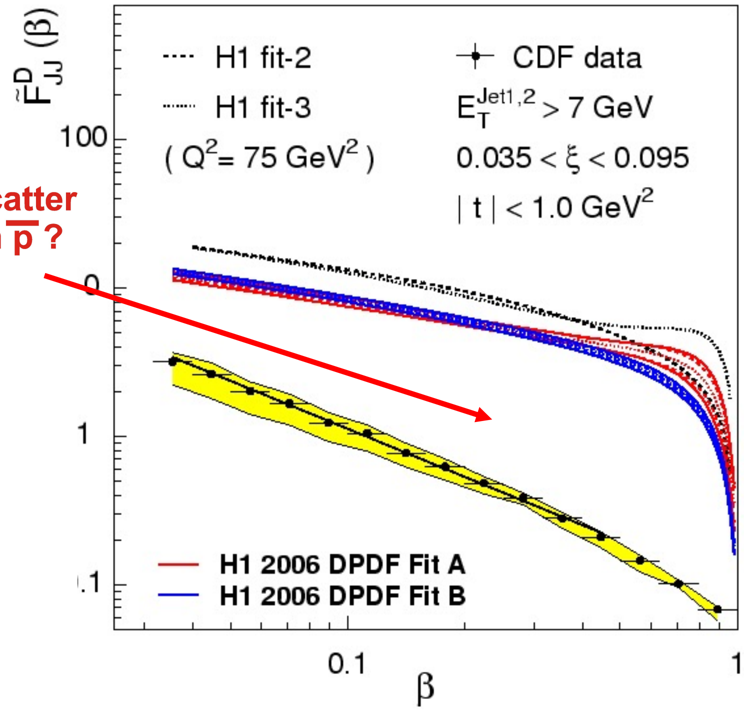
describing fine detail

- See later talks

.. meanwhile in pp(bar) ...

Strong evidence for absorptive effects in comparing Tevatron diffractive dijets with HERA DPDFs ...
`rapidity gap survival probability' $S^2 \sim 0.1$

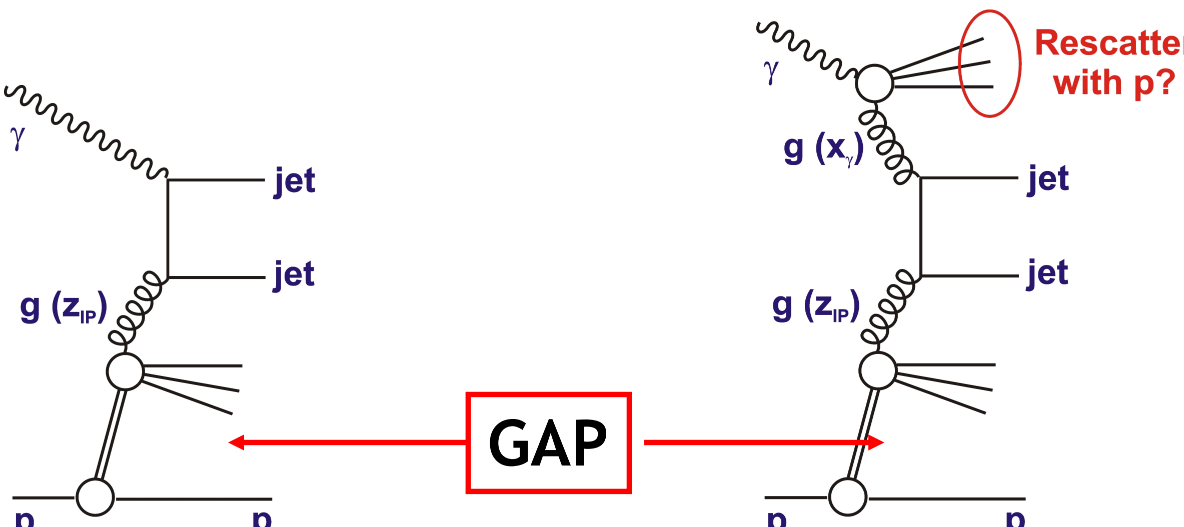




... photoproduction jets as the perfect control experiment?...

"Direct" photon
($x_\gamma \rightarrow 1$)

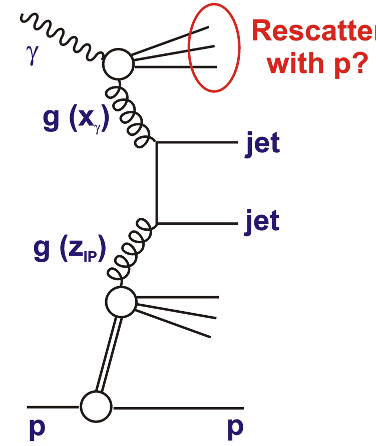
"$S^2 = 1$"

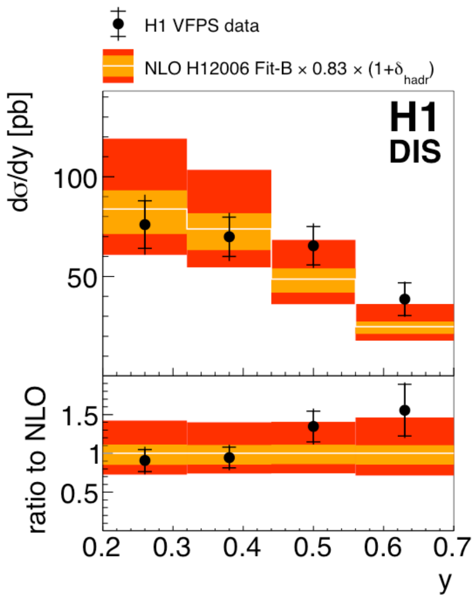


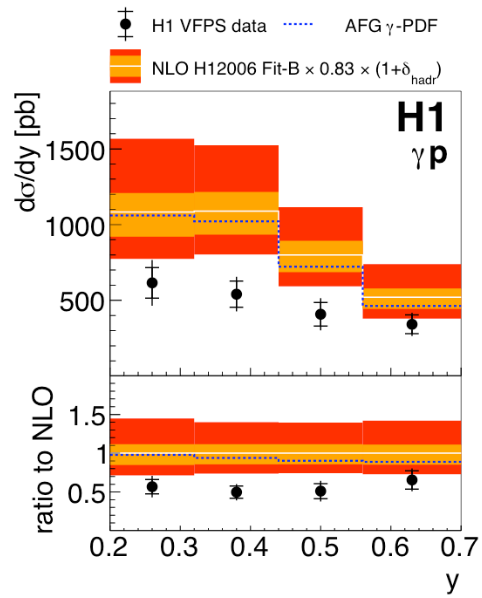
"Resolved" photon
($x_\gamma < 1$)

S^2 ?

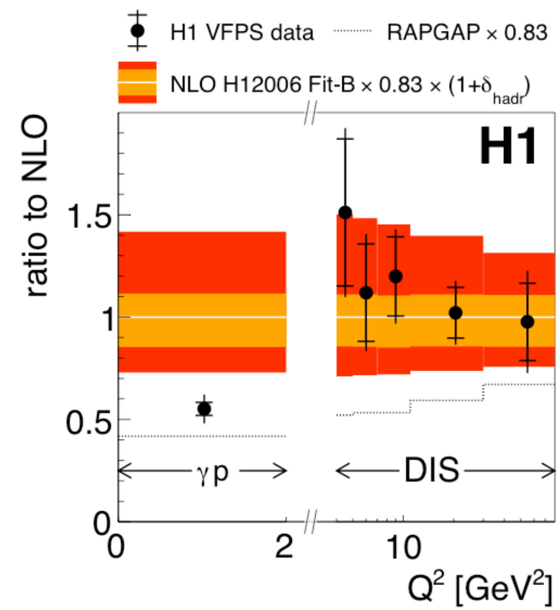
Rapidity Gap Survival Probability in Diffractive Dijet Photoproduction







Data v NLO QCD with H1 2006 Fit B DPDFs



From double ratio:

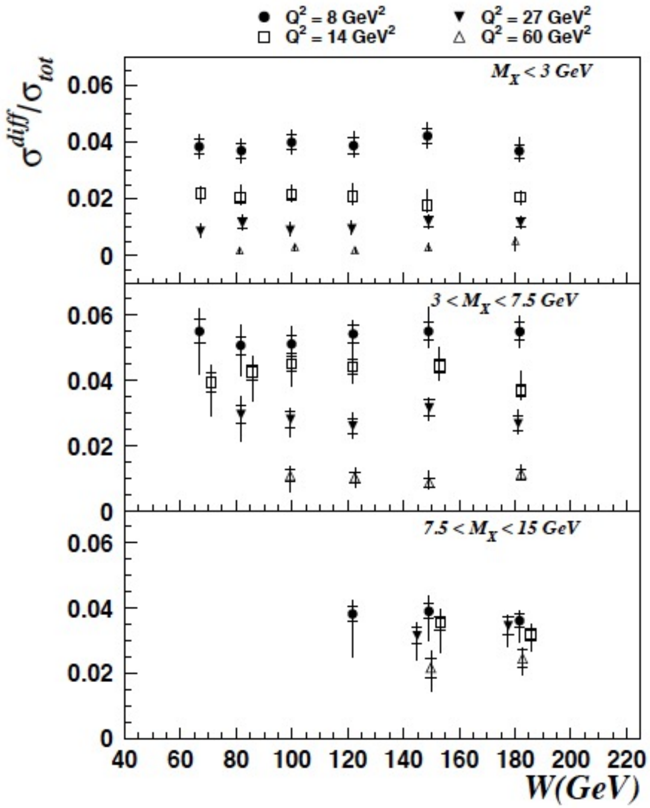
(data/theory) (γp / DIS) = 0.51 ± 0.09

- Gap survival unexpectedly has little dependence on x_γ
- Some inconsistencies between ZEUS and H1
  → mysteries still to be understood

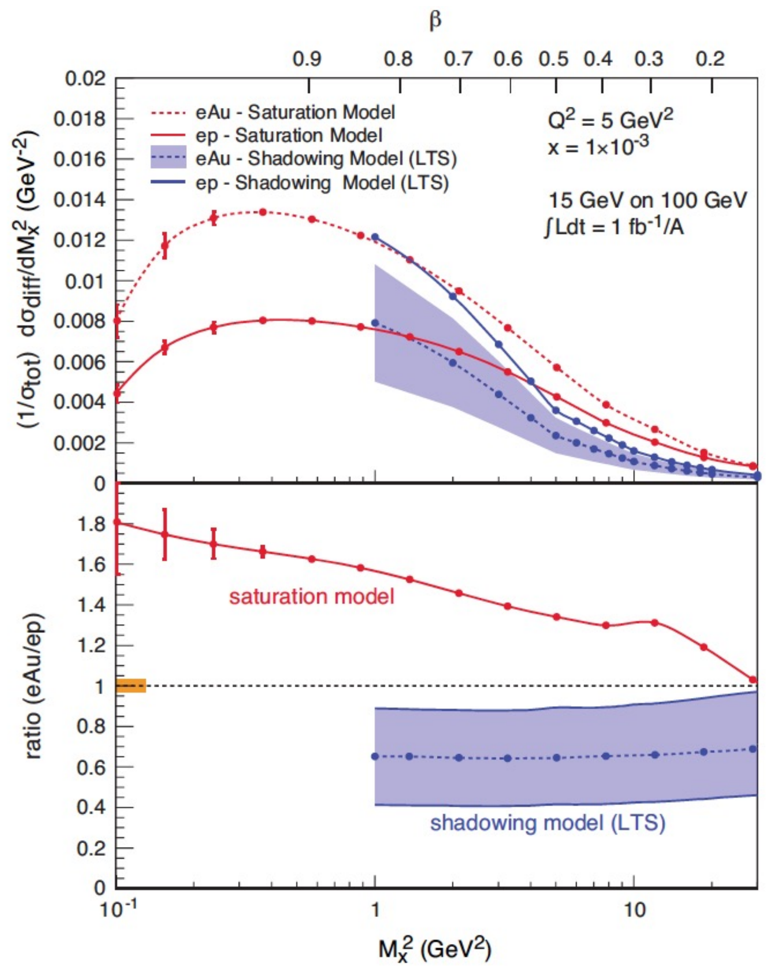
Diffraction and the Electron-Ion Collider

[Examples from some early studies]

‘Day 1’ at EIC: Diffractive / Inclusive Ratio



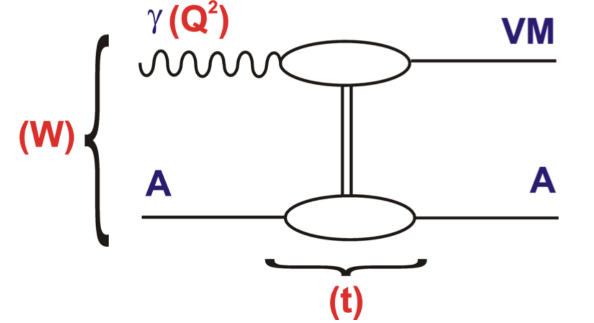
- Famous ZEUS plot … Rather flat diffractive/inclusive ratio v x at fixed Q2, taken as evidence for saturation

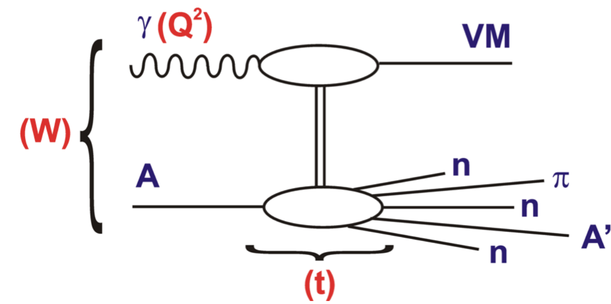


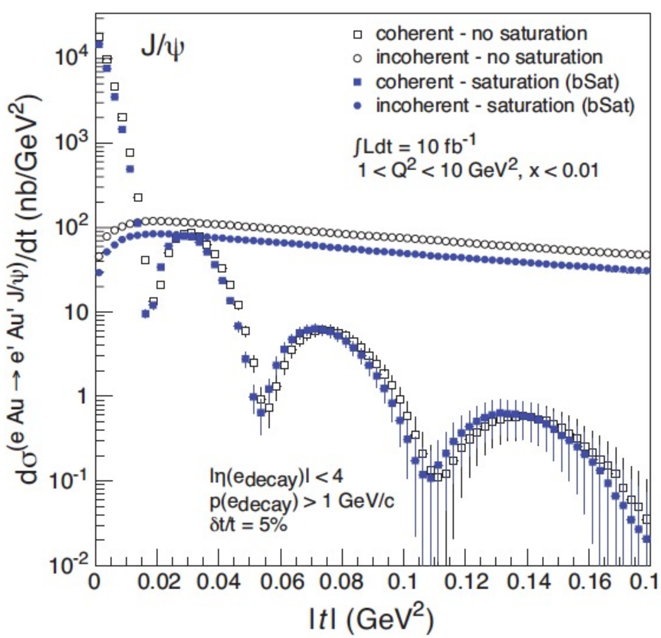
- EIC ‘Day 1’ simulations confirm the importance of this sort of observable to disentangle saturation and shadowing …
… increasing diff/incl ratio with A in saturation case …

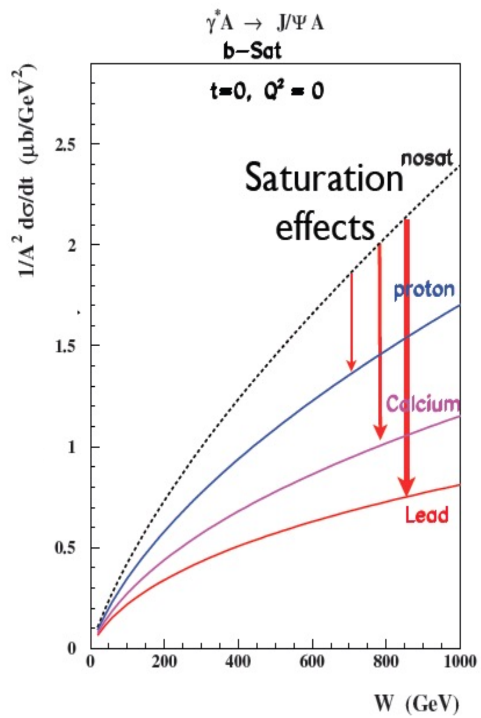
Exclusive Diffraction in eA

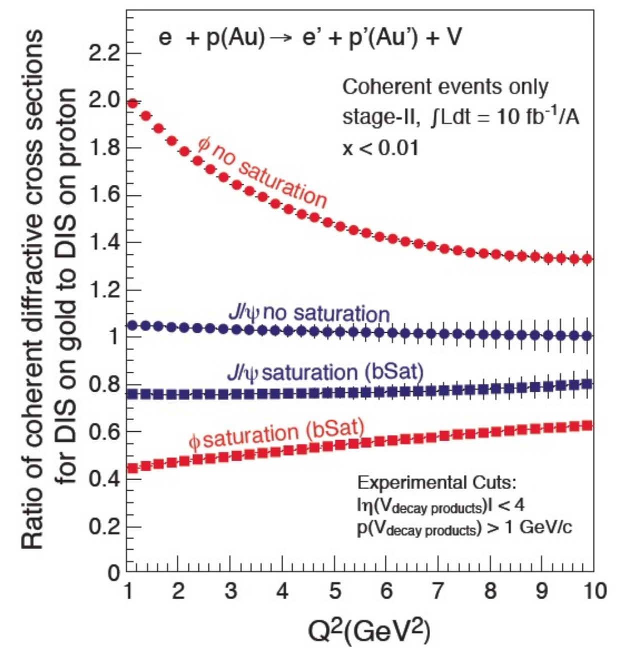
- Separation of coherent / incoherent can be done based on ZDC
- Opportunity to image structure
- Significant saturation effects predicted in coherent case (eA → eVA), visible in total cross sections, A and t dependences
- ϕ mesons may be most sensitive



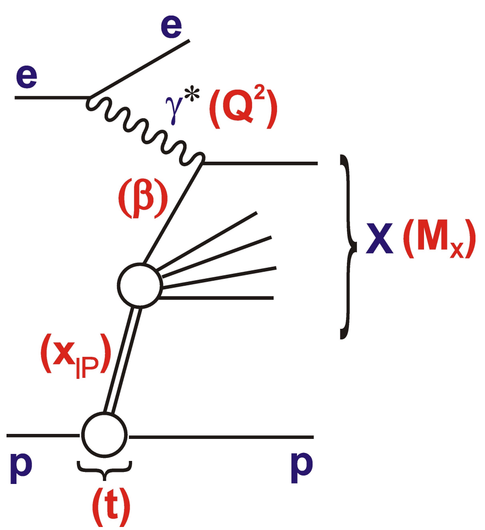


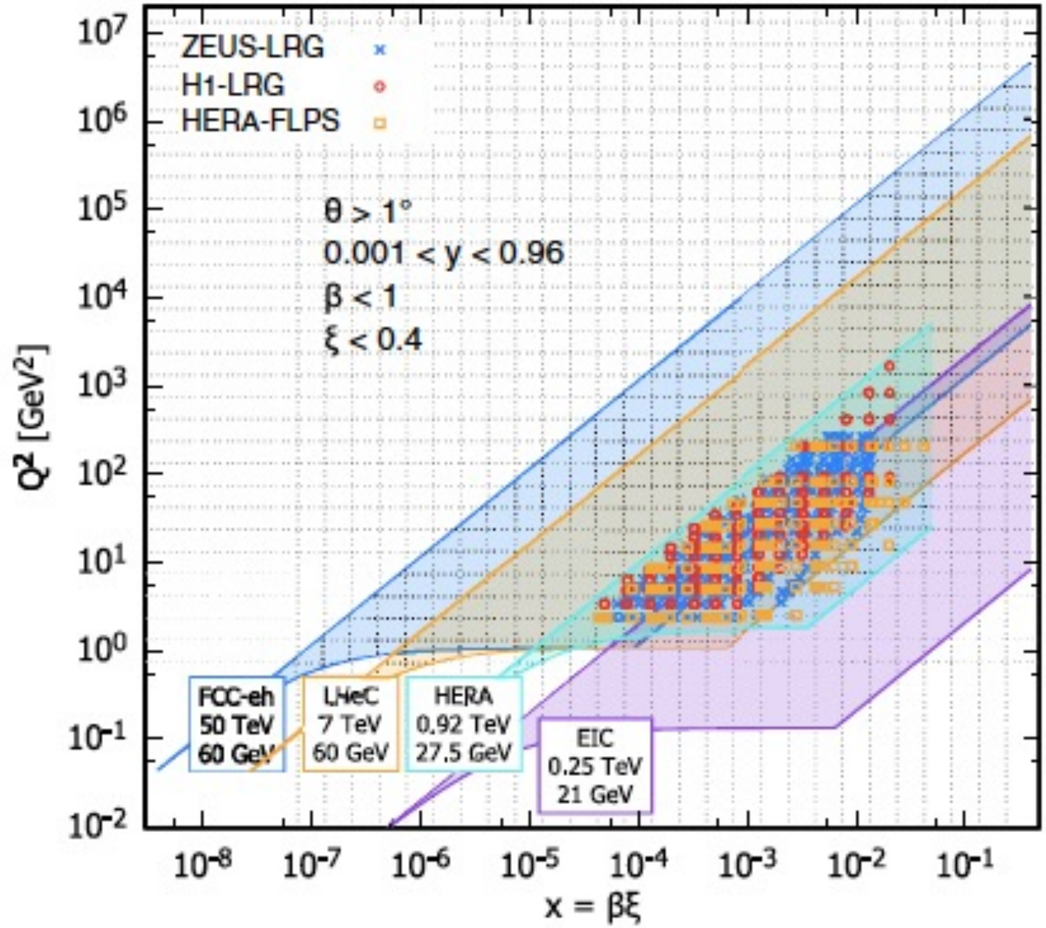






Inclusive Diffraction at EIC

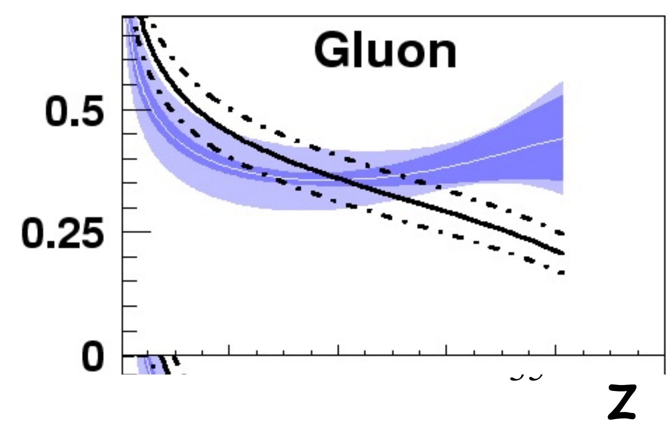




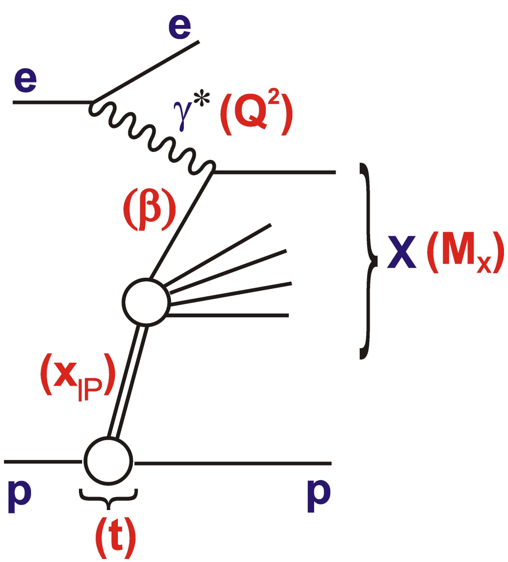
Lower centre of mass energy than HERA, but …

- Fills gap in kinematic plane at large x (there are no fixed target data) → Sensitivity to poorly constrained structure at large momentum fraction (β or z)

- Inclusive diffaction has never been studied with nuclear or polarised targets



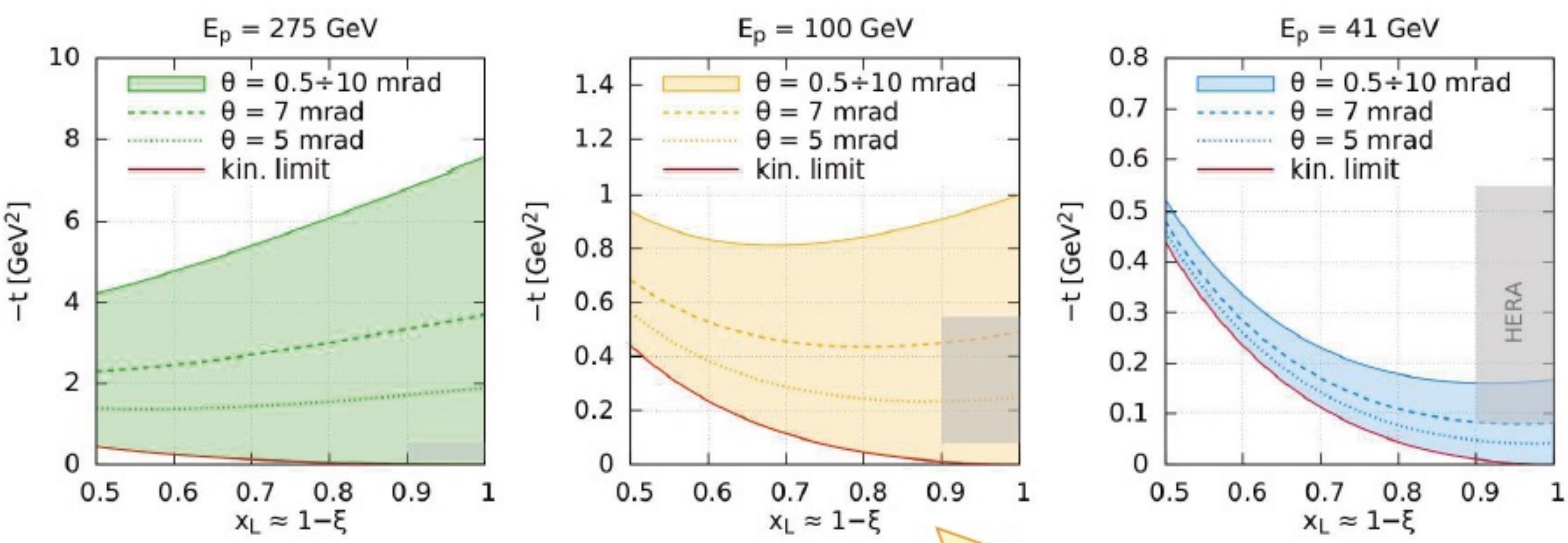
Inclusive Diffraction in ep at EIC: Scattered proton kinematics



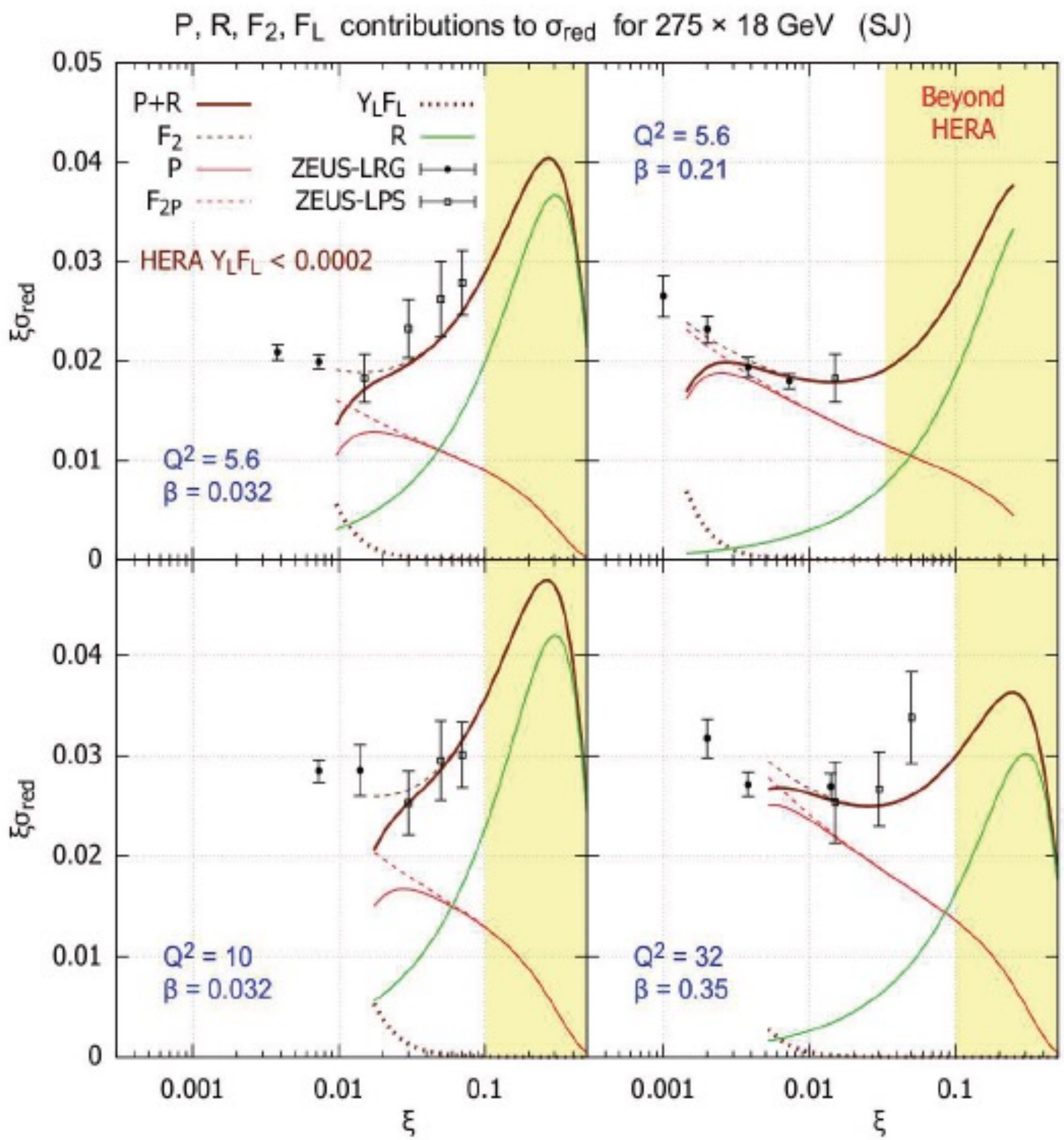
$$t \approx -p_T^2 \qquad x_L = {E'_p}\Big/{E_p} = 1 - x_{\mathrm{IP}}$$

Planned EIC Roman pots provide:

- Good coverage in most interesting large x_L, low |t|, diffractive region for all $\sqrt{s}$
- Interesting coverage at smaller x_L at large $\sqrt{s}$ (sub-leading `Reggeon' exchanges)

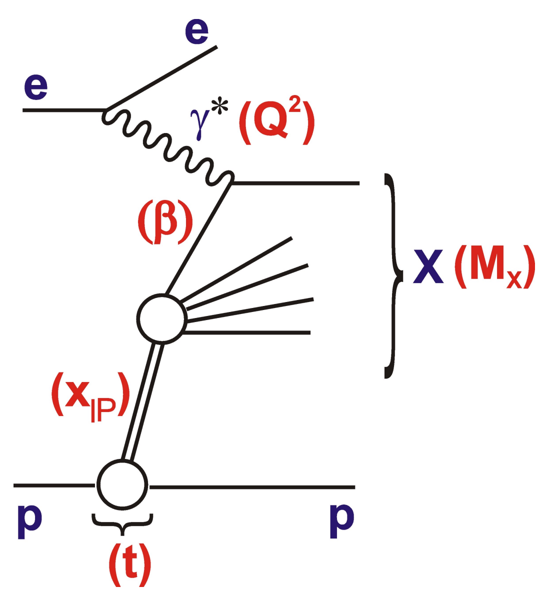


Inclusive Diffraction in ep at EIC: Sensitivity to sub-leading (non-pomeron) exchange



→ Yellow shaded region at large x_L is previously unexplored

→ Opportunity to understand sub-leading Reggeon (meson) exchanges and measure their structure



Inclusive Diffraction in ep at EIC: Sensitivity to diffractive longitudinal structure function

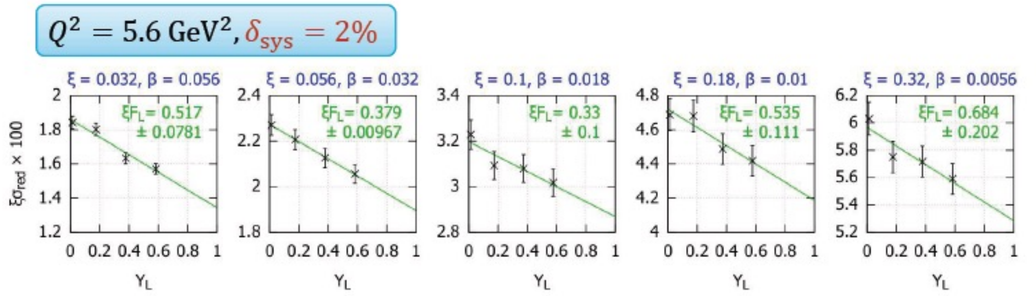
- Longitudinal structure function is proportional to gluon density at lowest order.

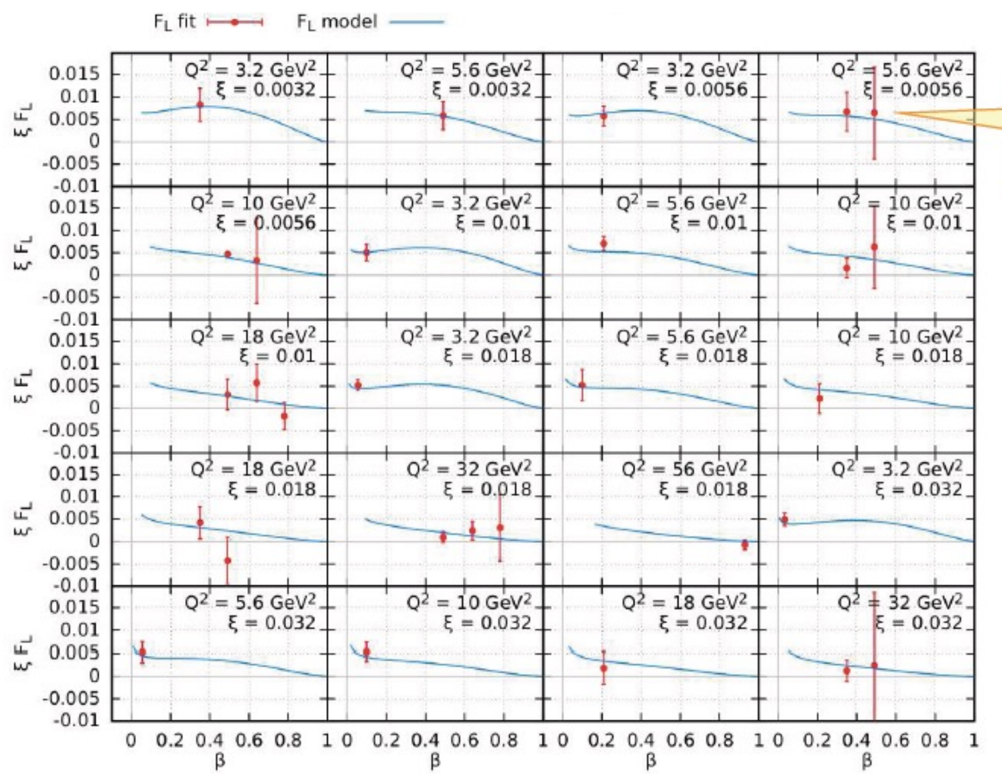
- Measurement at same (ξ,t,β,Q^2) and varying $\sqrt{s}$ (hence y) gives sensitivity to F_L^D (Rosenbluth plots)

$$\sigma_{\rm red}^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

- First simulations look promising

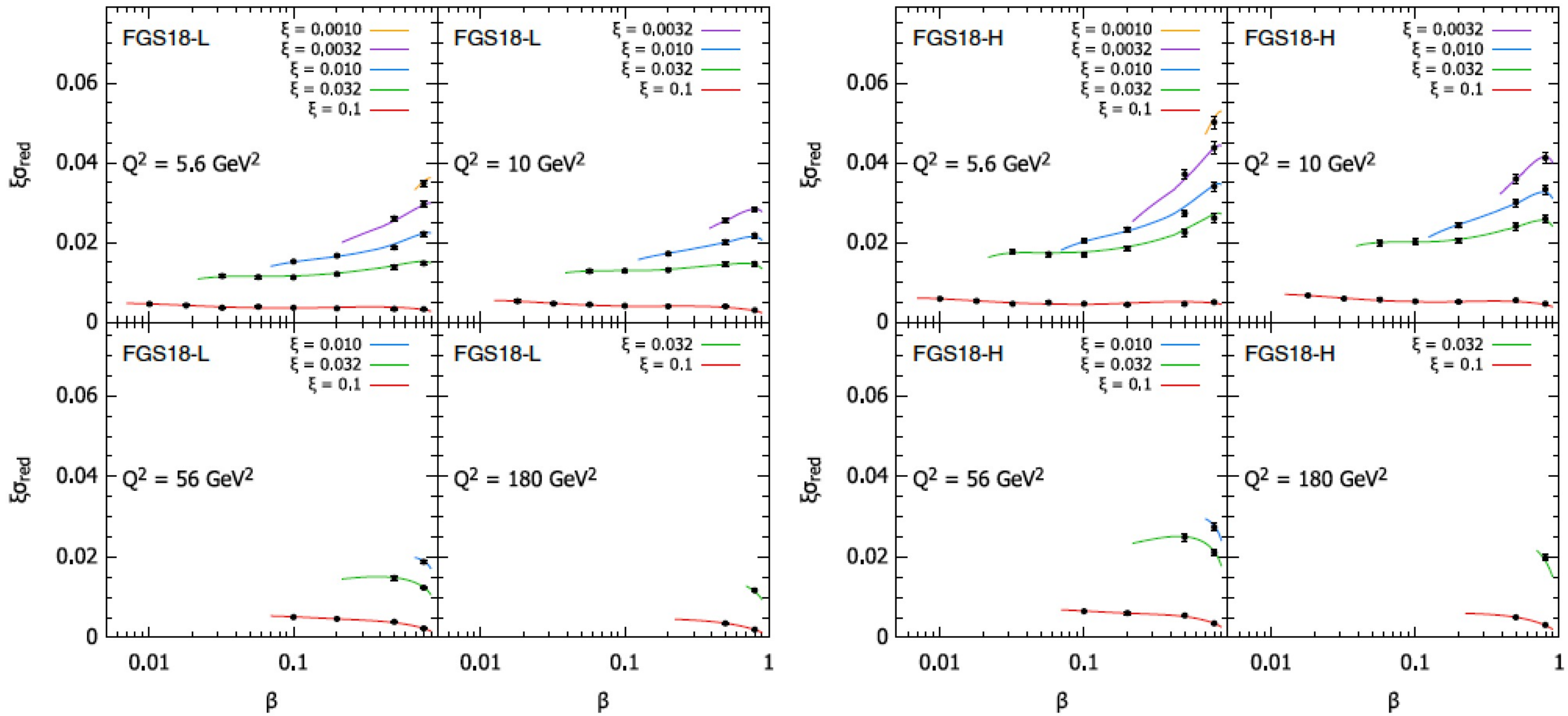
- Precision strongly dependent on correlations between systematics at different $\sqrt{s}$





Inclusive Diffraction from Nuclei at EIC: Selected Simulated Data for e Au → e X Au

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



Simulations based on different versions of FGS model →
- illustrates accessible kinematic range and ability to distinguish between (widely varying) models

Summary

HERA revolutionised our understanding of Diffraction in QCD

Exclusive (vector meson) processes (ep→eVp):

- Turn-on of hard scales mapped for multiple VM species.
- $(Q^2 + M_V^2)/4$ is often a good scale choice for comparisons
- Hard VM production in principle sensitive to proton gluon density / saturation

Inclusive process (ep→eXp):

- Dominant contribution can be viewed as LT DIS off 'soft' colour-singlet exchange: properties similar to the 'soft pomeron'
- Colour Singlet Exchange dominated by gluons carrying large momentum fraction

EIC will go further with improved beamline instrumentation, much larger luminosity, ep/eA comparisons and polarisation

→ 3D imaging **→ High density effects**