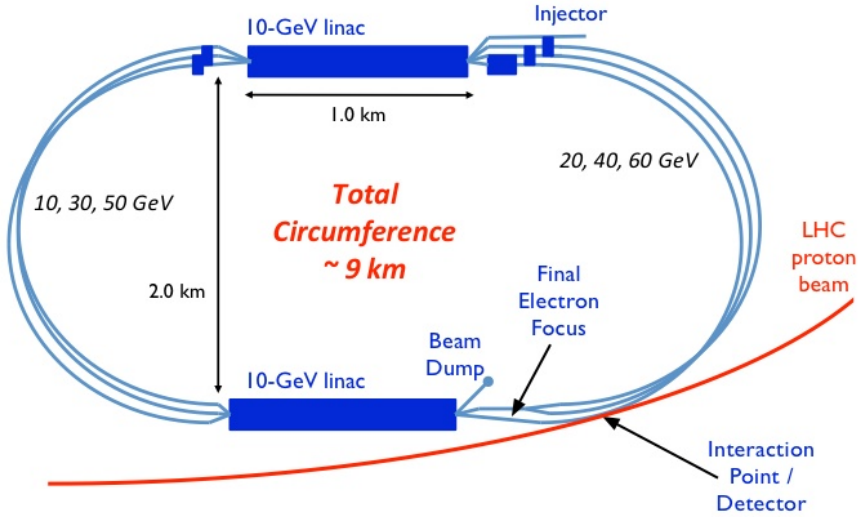
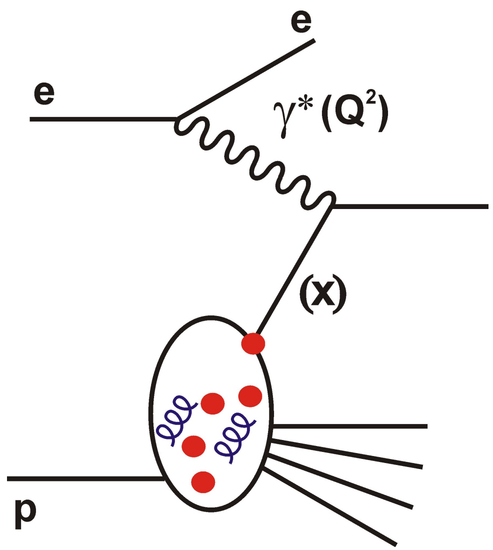
Low x LHeC and FCC-eh Studies

Paul Newman
Birmingham University



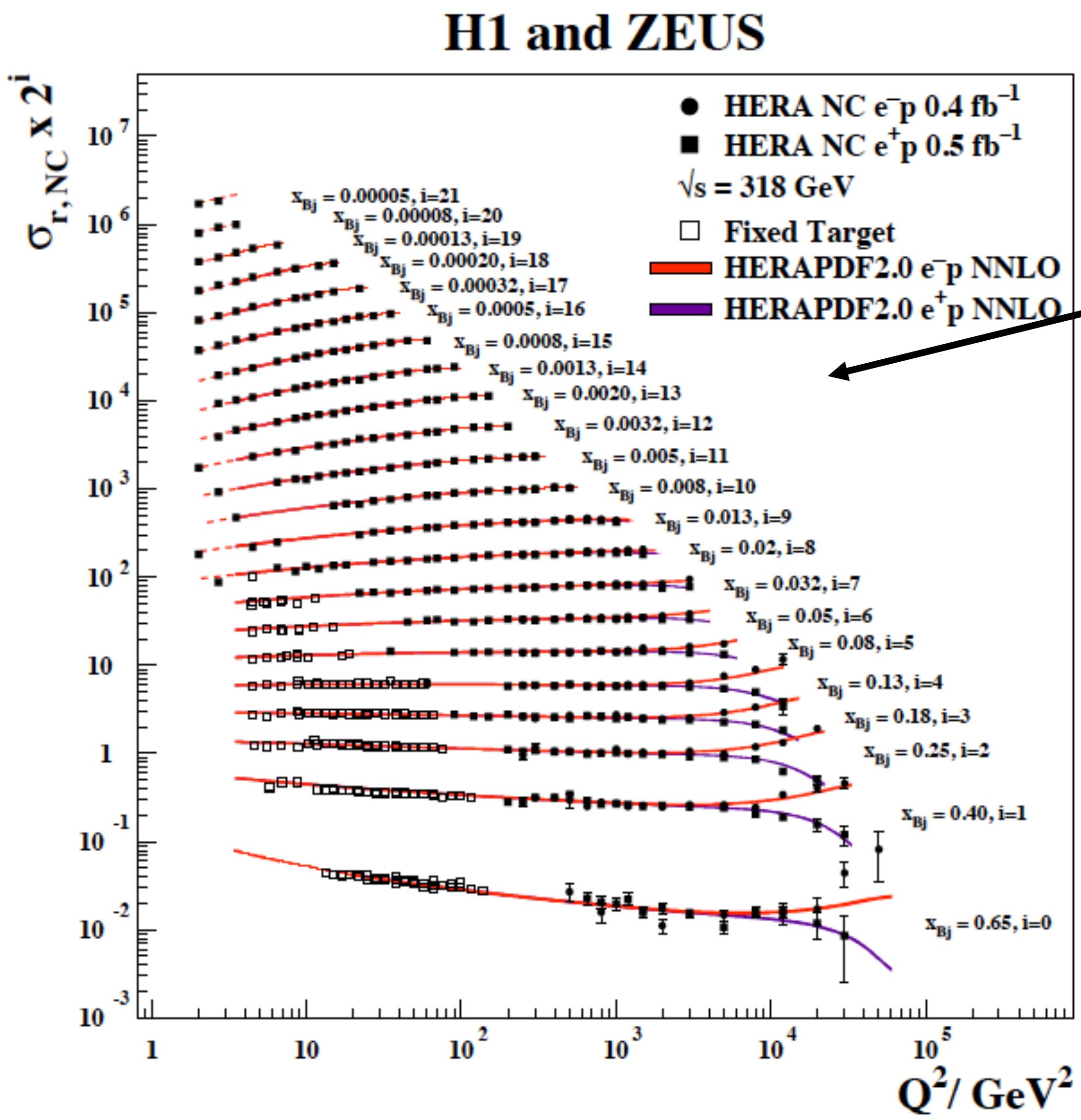


LHeC and FCC-eh Workshop

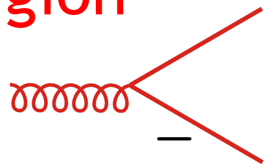
11-13 September 2017
CERN

Low x Physics is Driven by the Gluon

… knowledge comes entirely from inclusive NC HERA data …



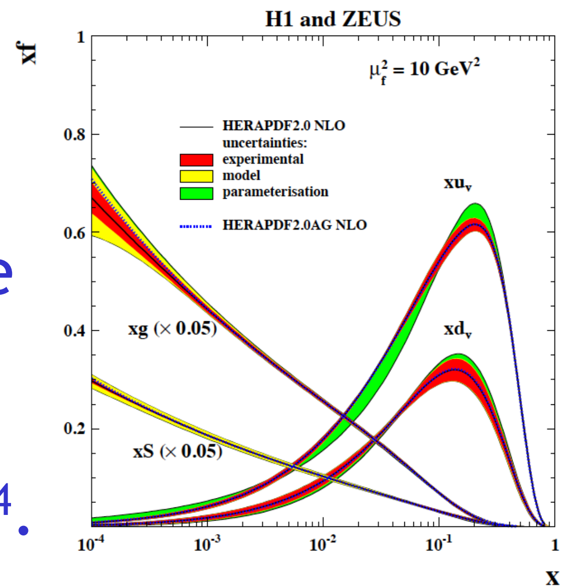
- NC Q^2 dependence in perturbative region driven by …



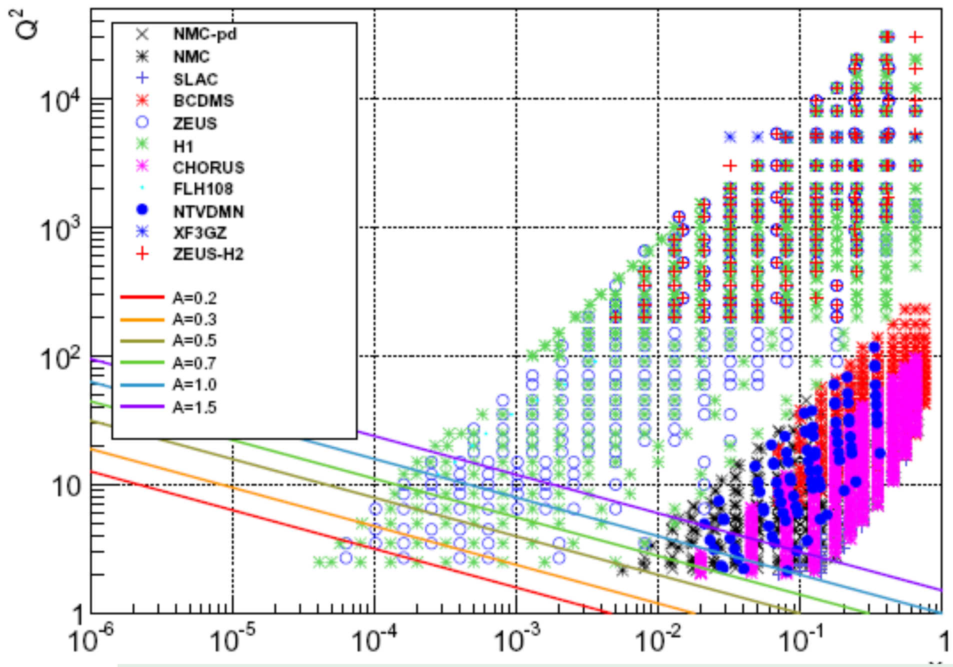
$g \rightarrow q\bar{q}$

- 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 only to $x \sim 10^{-3}/10^{-4}$.

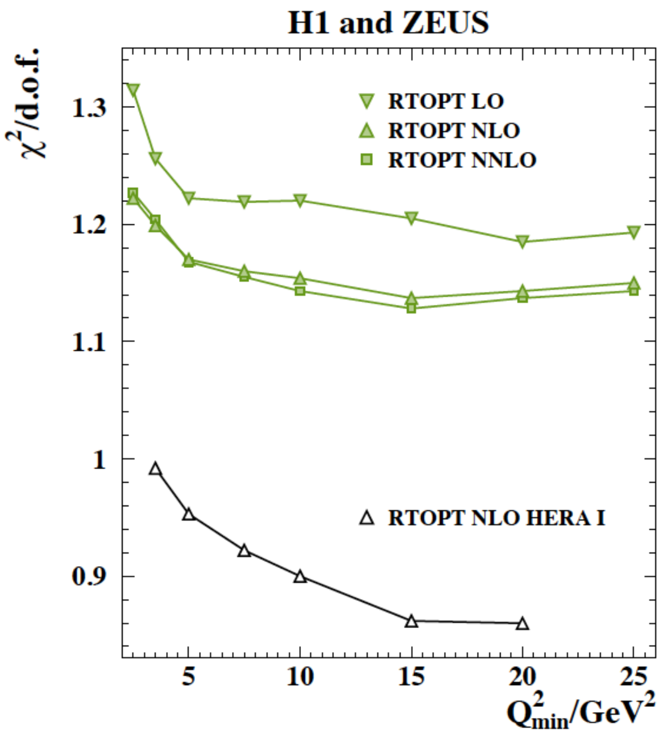


Are there Saturation Effects in low x HERA data?



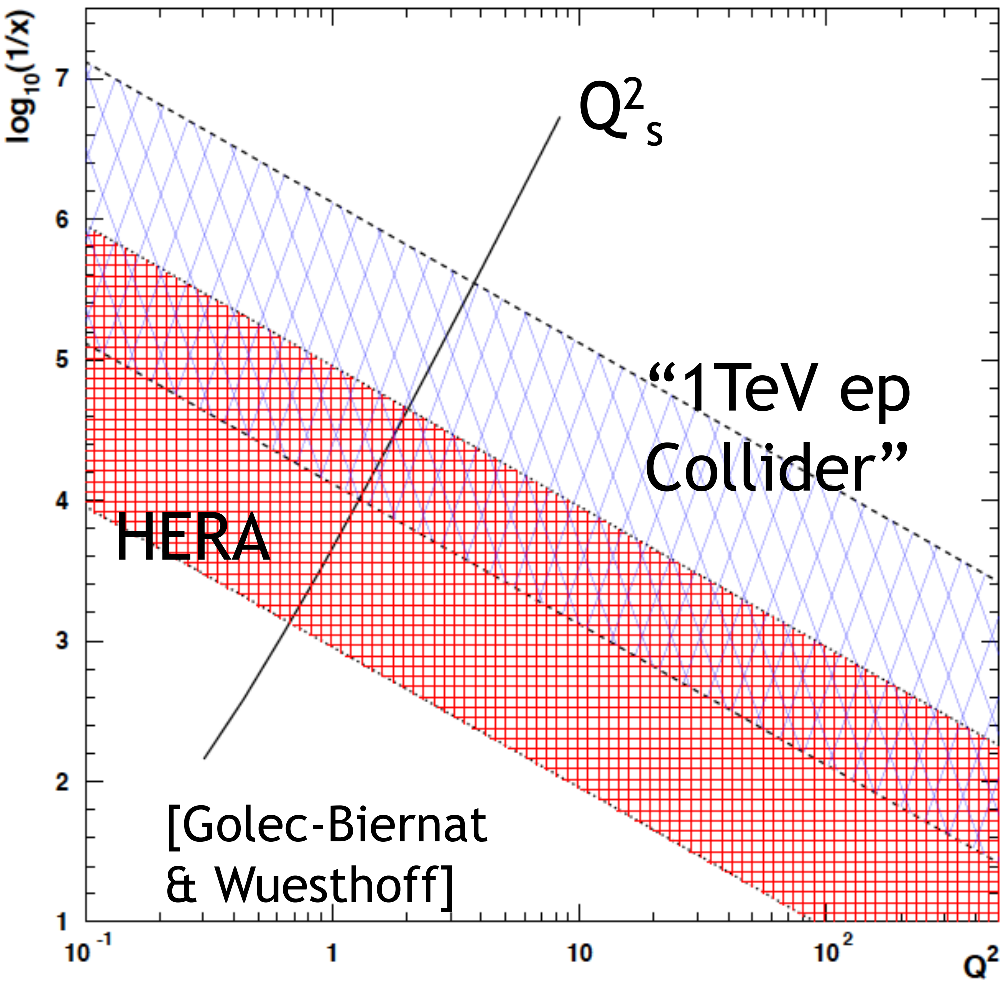
e.g. NNPDF: NLO DGLAP description deteriorates when adding data in lines $Q^2 > Ax^{-0.3}$ parallel to 'saturation' curve in x/Q^2.

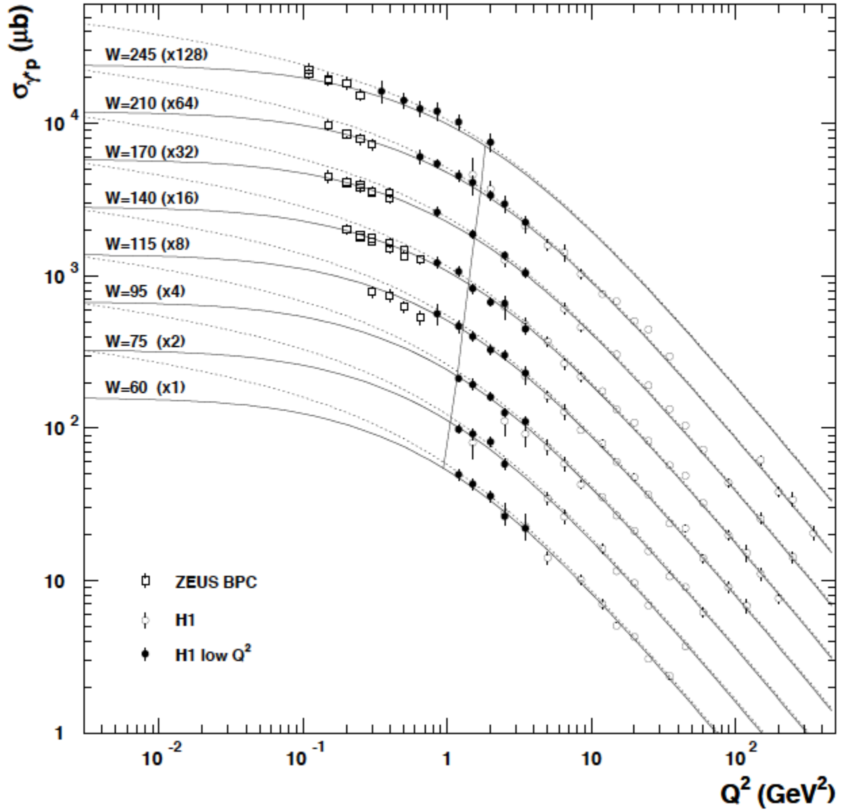
A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	19.68/25 = 0.79	106.22/25 = 4.25
1.0	54.41/44 = 1.24	138.24/44 = 3.14
1.5	62.31/59 = 1.06	860.65/59 = 14.6



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 probably happens, but subtle … interpretation?**

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



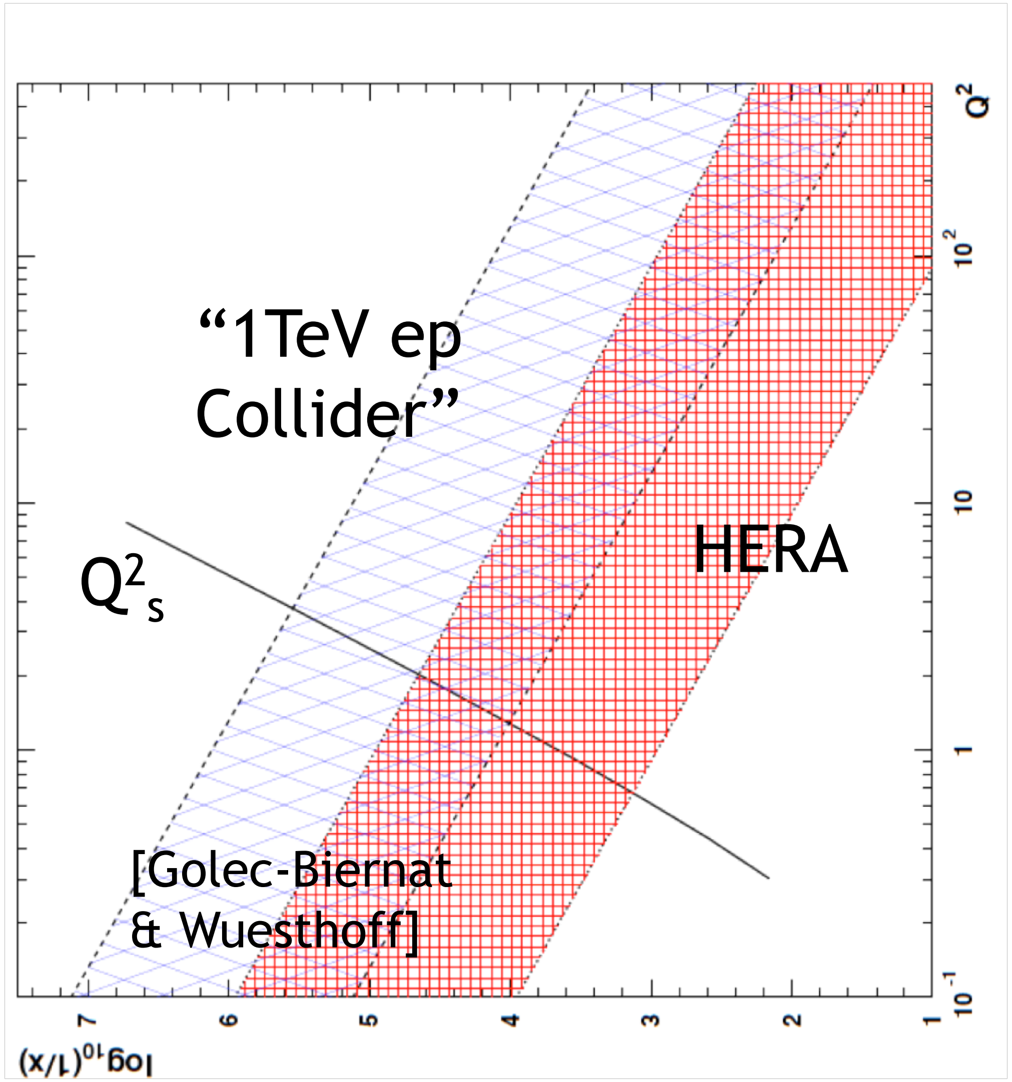


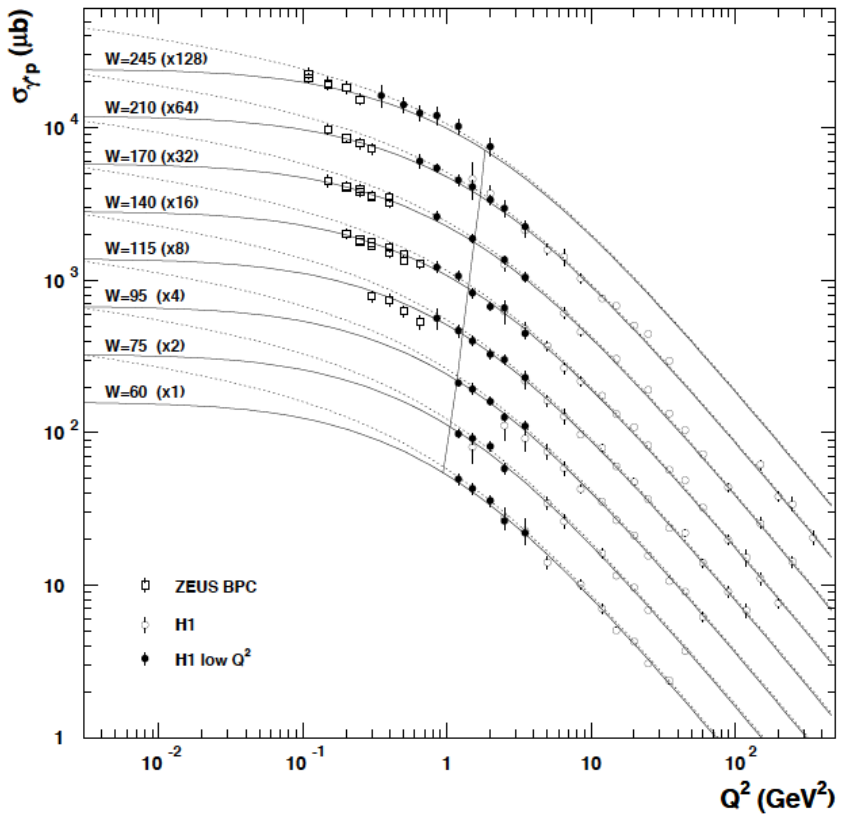
All data (Q^2 >~ 0.05 GeV^2) are well fitted in (dipole) models that include saturation effects

- 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



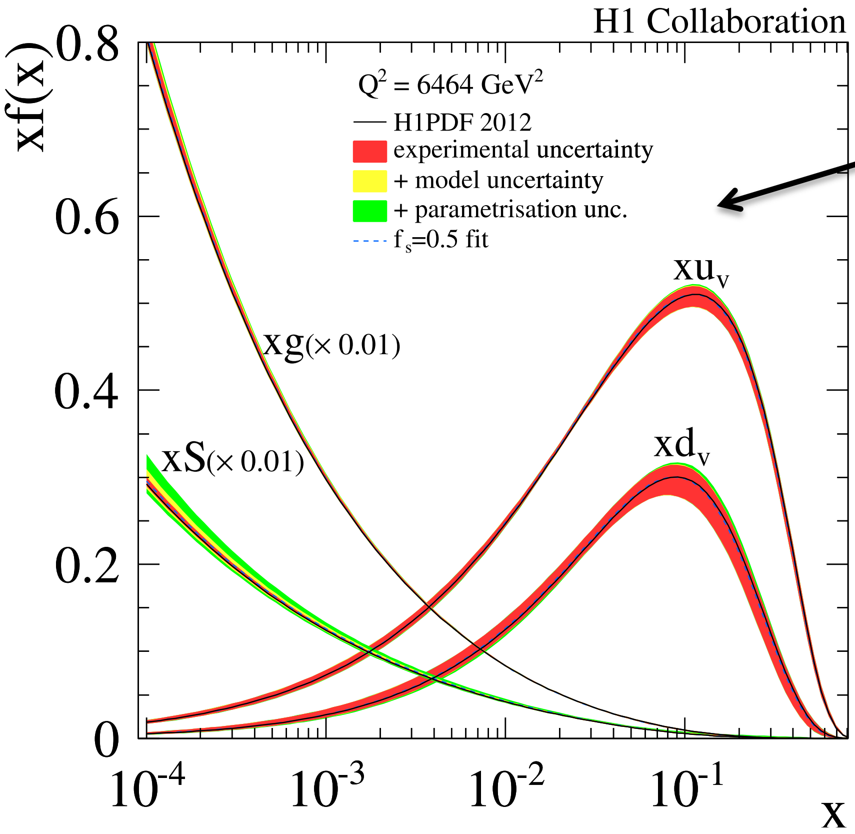


… at HERA, Q^2_s doesn't get above about 0.5 GeV^2

→Saturation may have been observed at HERA … well described by CGC+dipoles

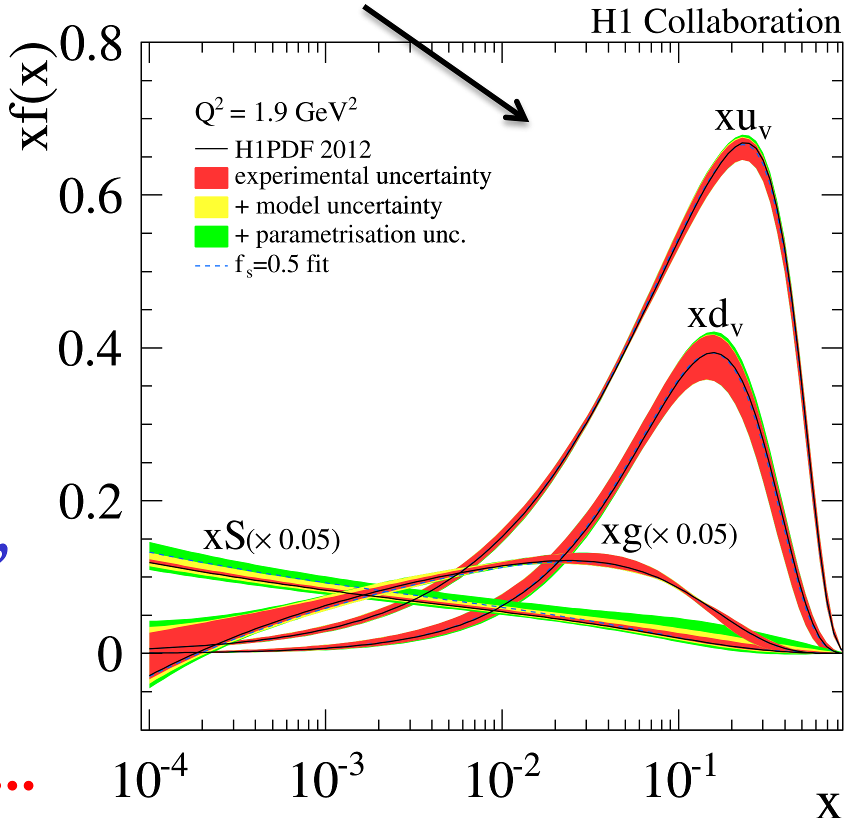
→***Gluon*** sat^n not observed (and may not be in inclusive ep in foreseeable future)

The Gluon Density at Scales other than 10GeV^2



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

- Starting scale ~ 1.9 GeV^2 (gluon close to 0 in pure DGLAP approach … and coupling not so weak!)

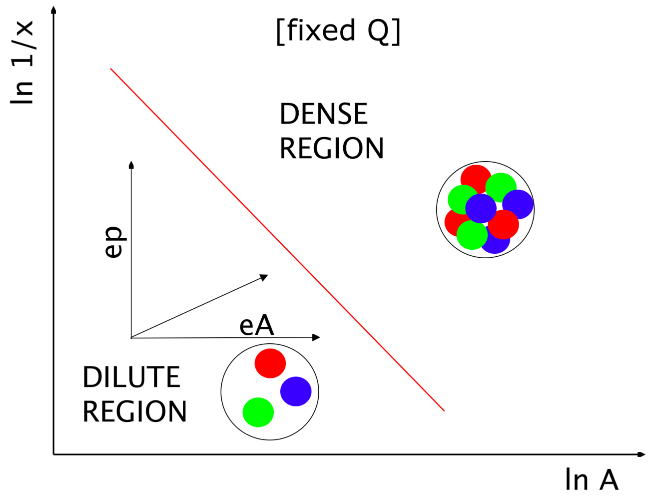


- Saturating hadrons with a small number of ("large") gluons?
- Alternative language (dipole models, gluons not degrees of freedom)?

… Phase space is vital for a clean partonic investigation of saturation …

LHeC: Accessing saturation region at large Q^2

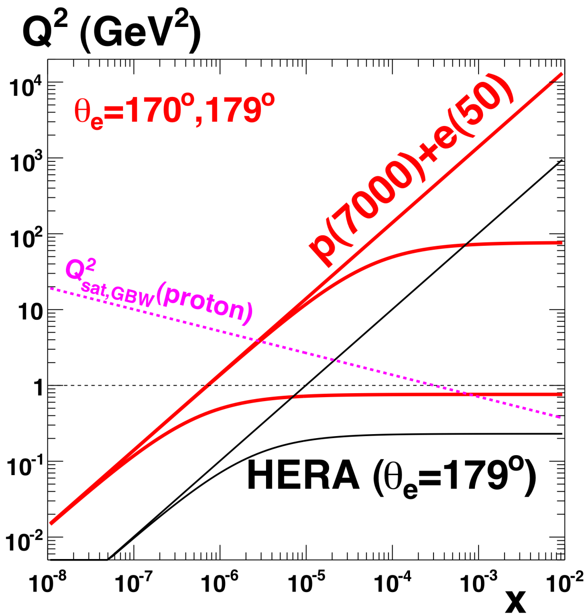
LHeC delivers a 2-pronged approach:

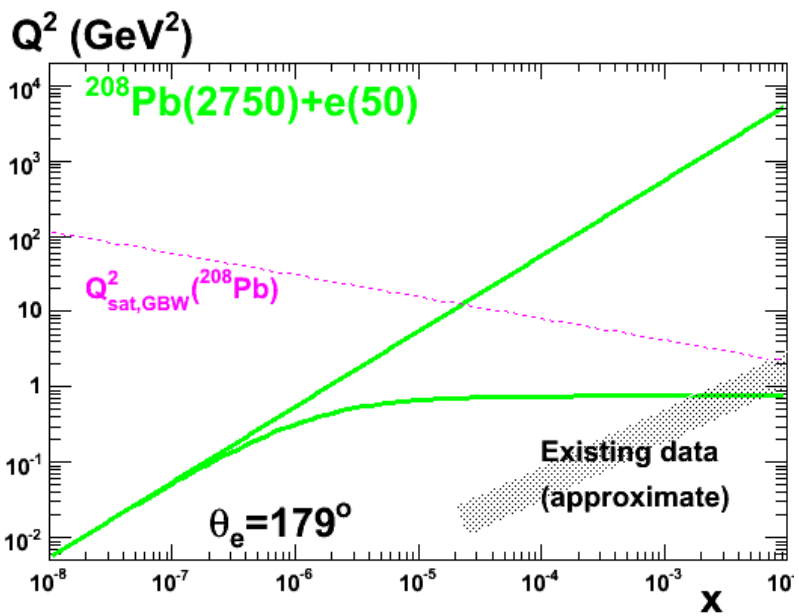


Enhance target `blackness' by:

1) Probing lower x at fixed Q^2 in ep
   [evolution of a single source]

2) Increasing target matter in eA
   [overlapping many sources at fixed kinematics …
   Density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in x]



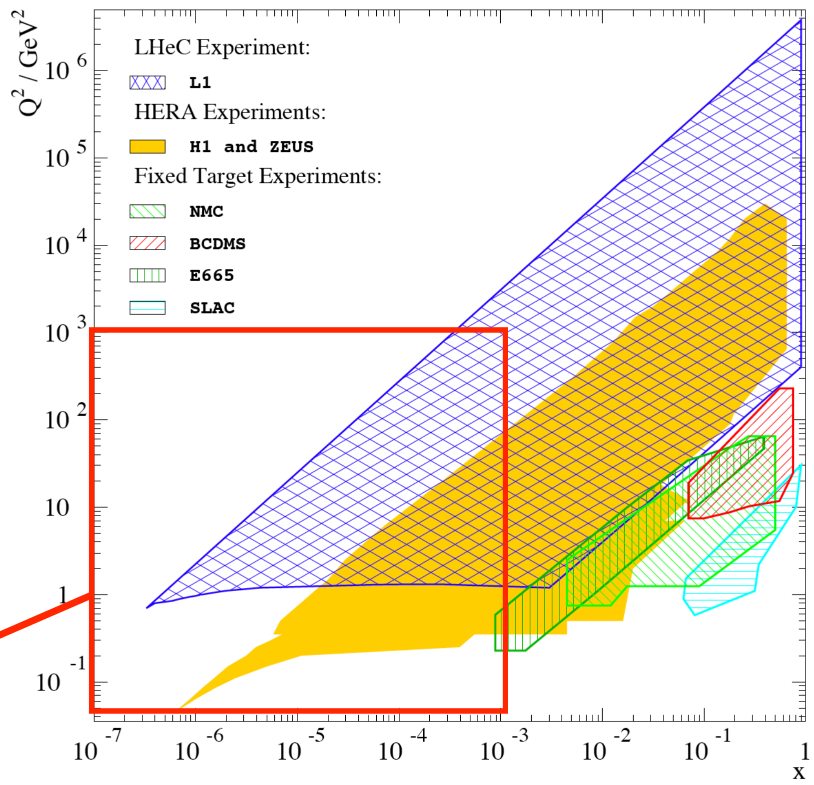


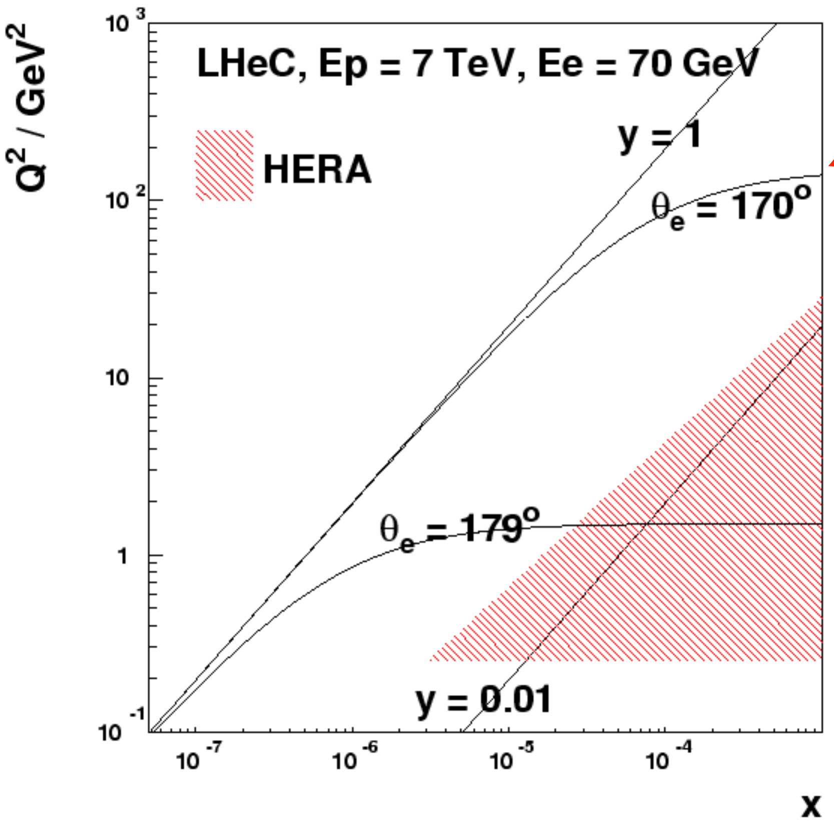
… Reaches saturated region in both ep & eA inclusive data according to models

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°



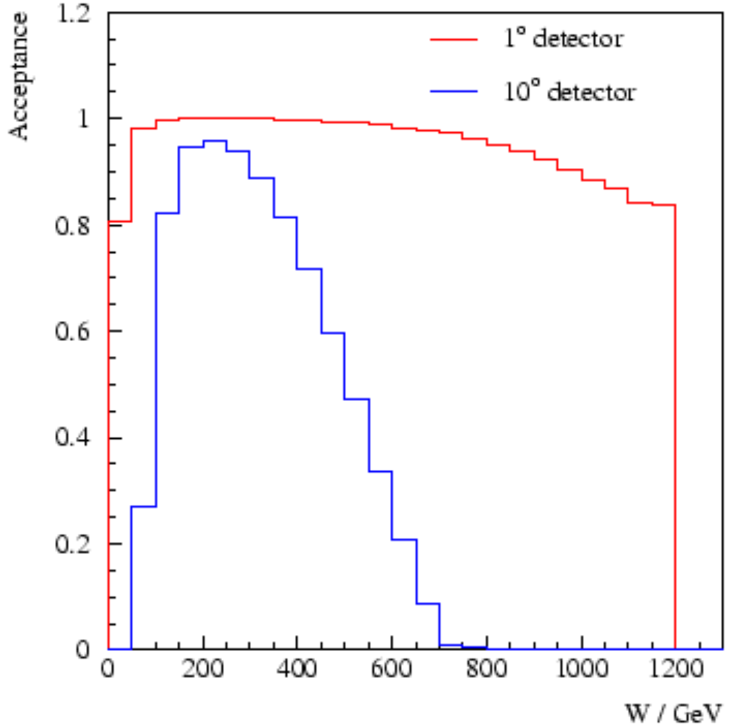


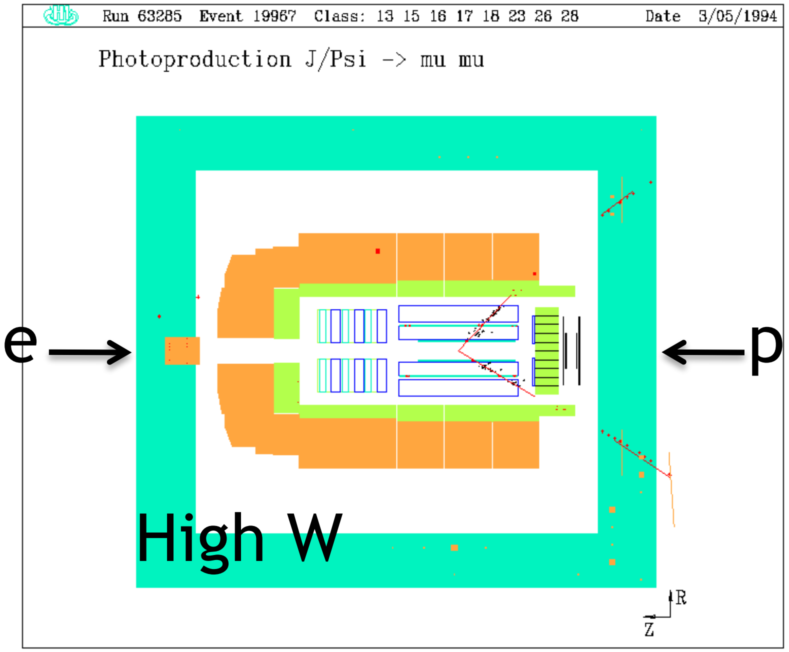
Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, Mueller-Navelet jets, maximise acceptance for new massive particles …

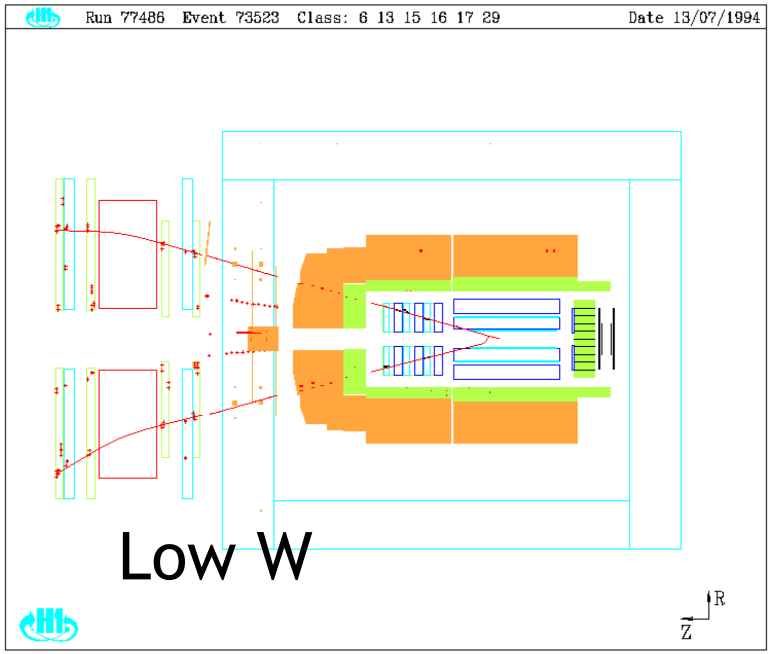
Elastic J/Ψ Kinematics (example from LHeC)

- 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



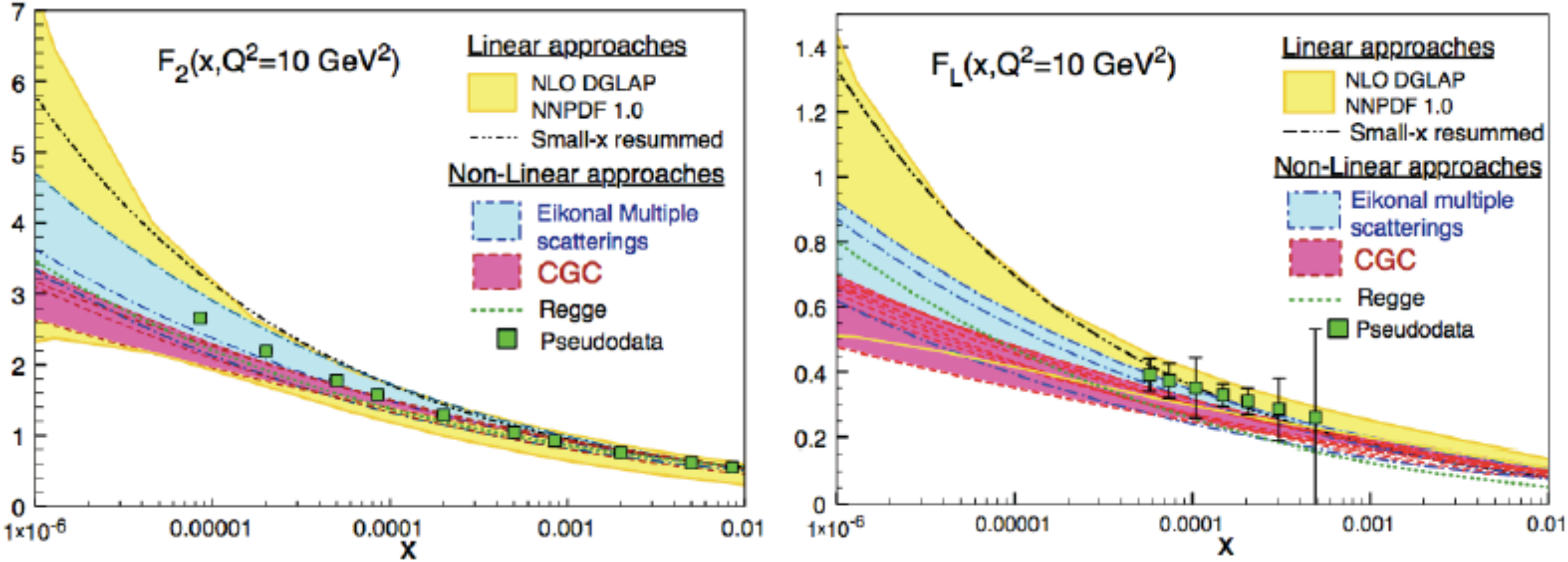




LHeC Sensitivity to Different Saturation Models

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

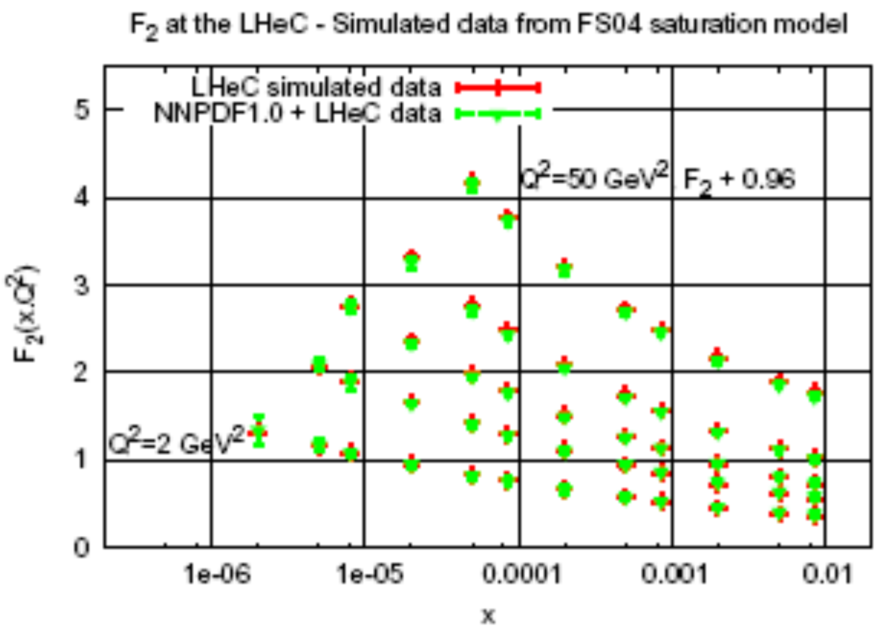


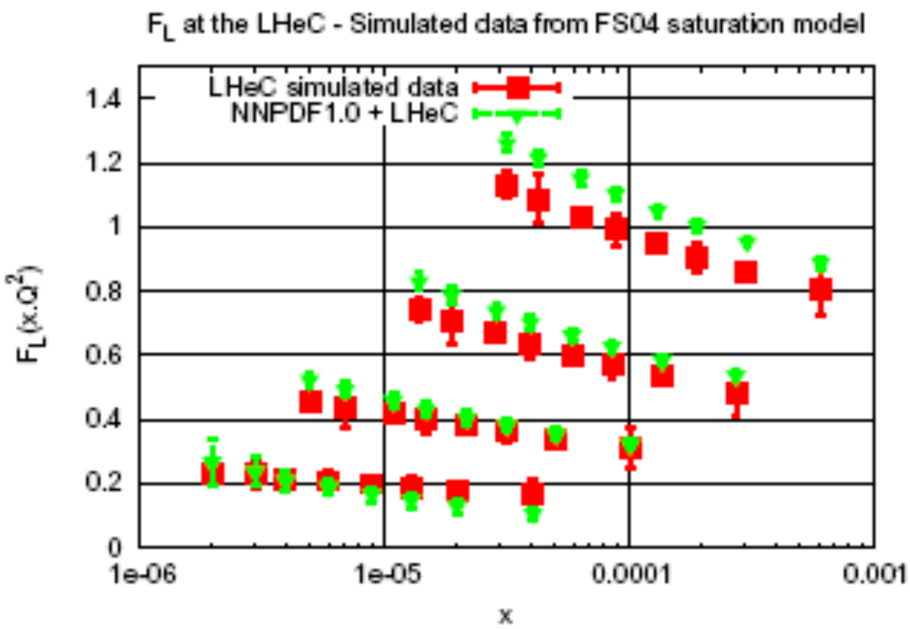
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

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

Can Parton 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





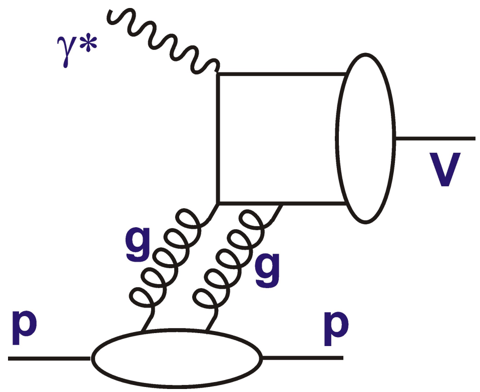
• Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

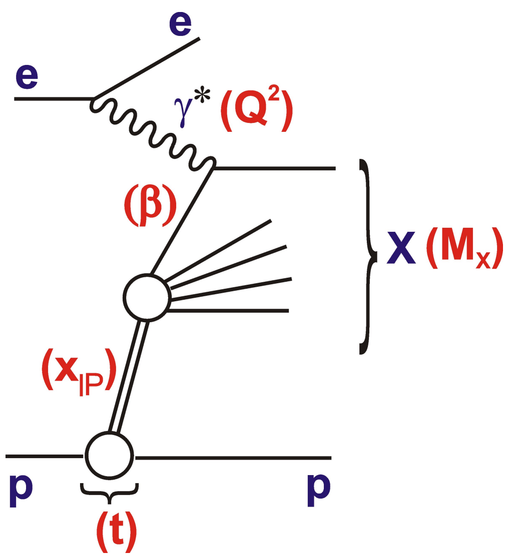
Exclusive / Diffractive Channels and Saturation

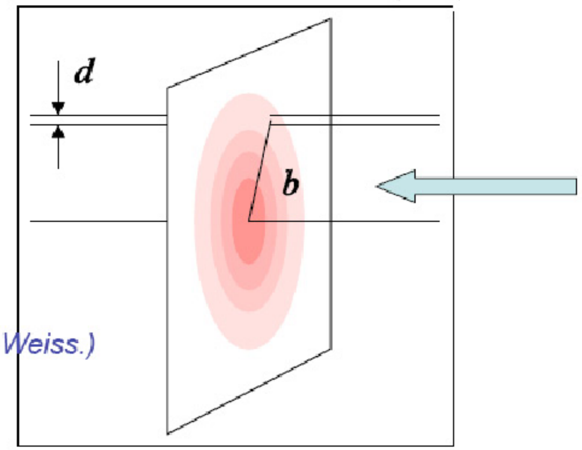
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)

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

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







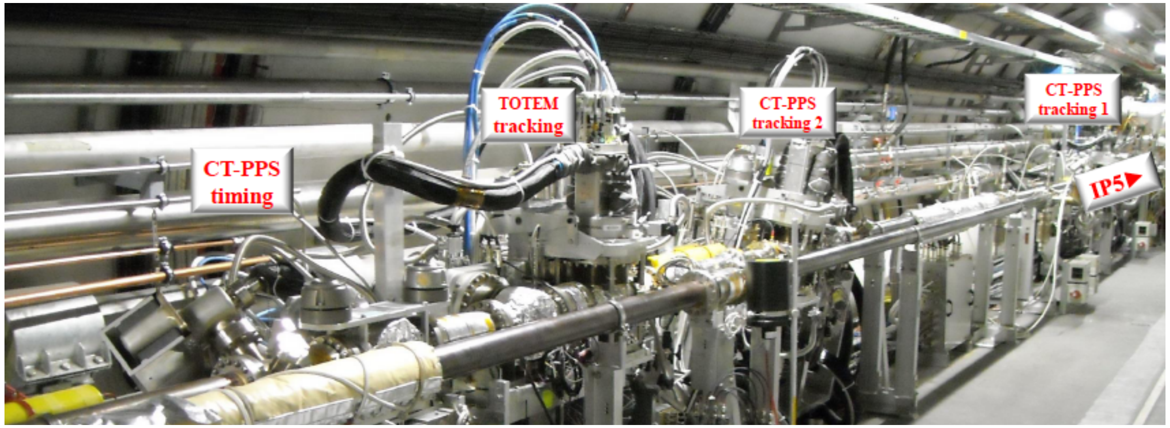
(figure from C. Weiss.)

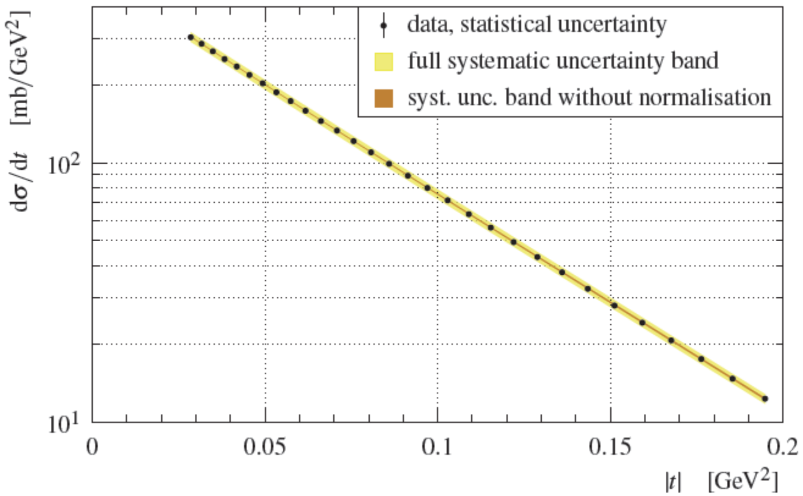
Central black region growing with decrease of x.

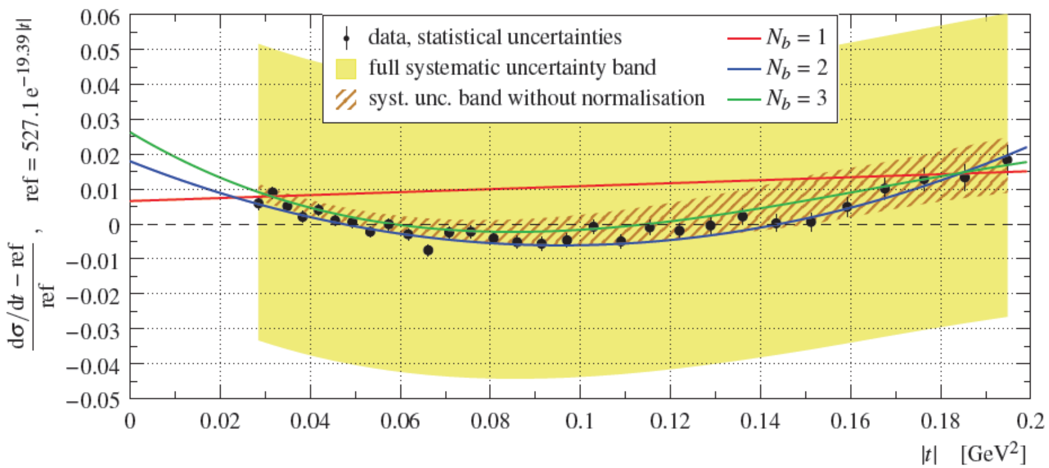
Proton Spectrometers Come of Age

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

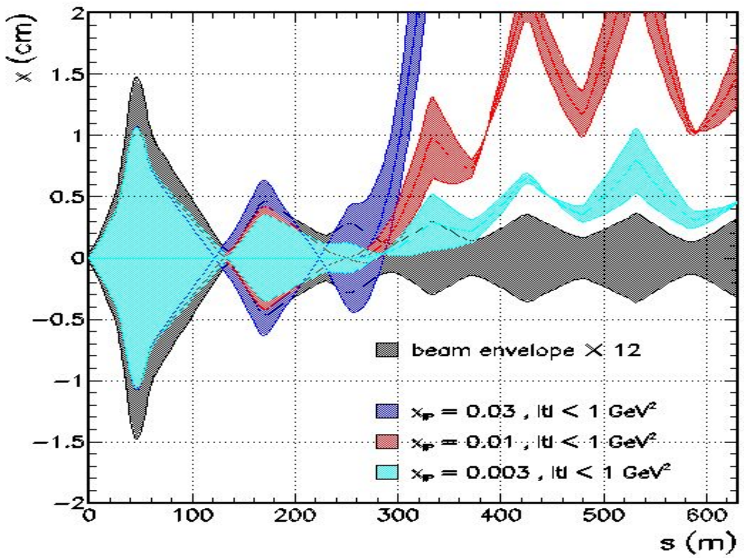
e.g. TOTEM operates 14(?) pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential term in elastic t dependence …





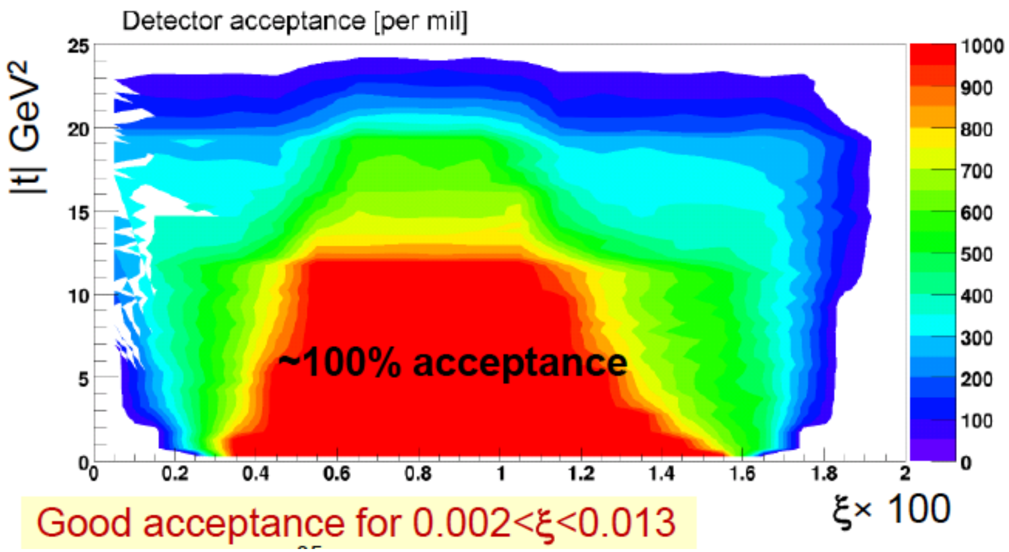


Design for LHeC Forward Proton Spectrometers

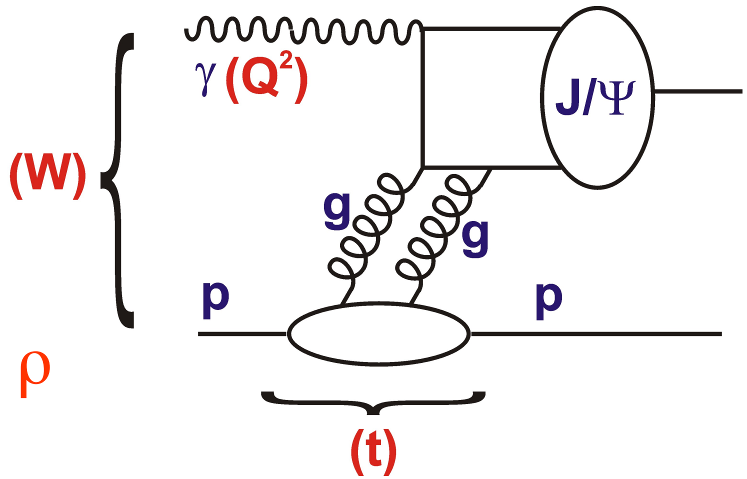


We should ensure full acceptance Roman pot forward detector systems are integrated into our future facility designs from outset

- 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



Test Case: Elastic 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)

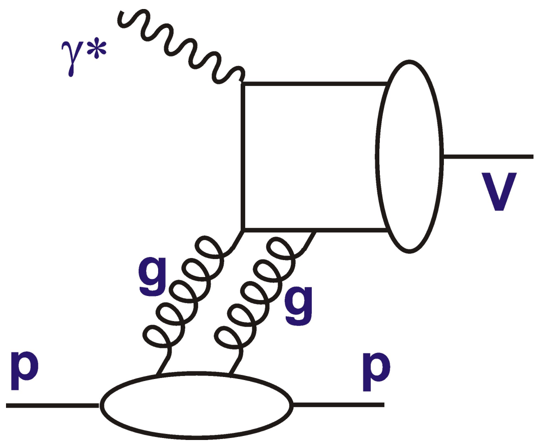
• Scale $\overline{Q^2} \sim (Q^2 + M_V^2) / 4 \ >\sim 3\ \text{GeV}^2$ ideally suited to reaching lowest possible x whilst remaining in perturbative regime

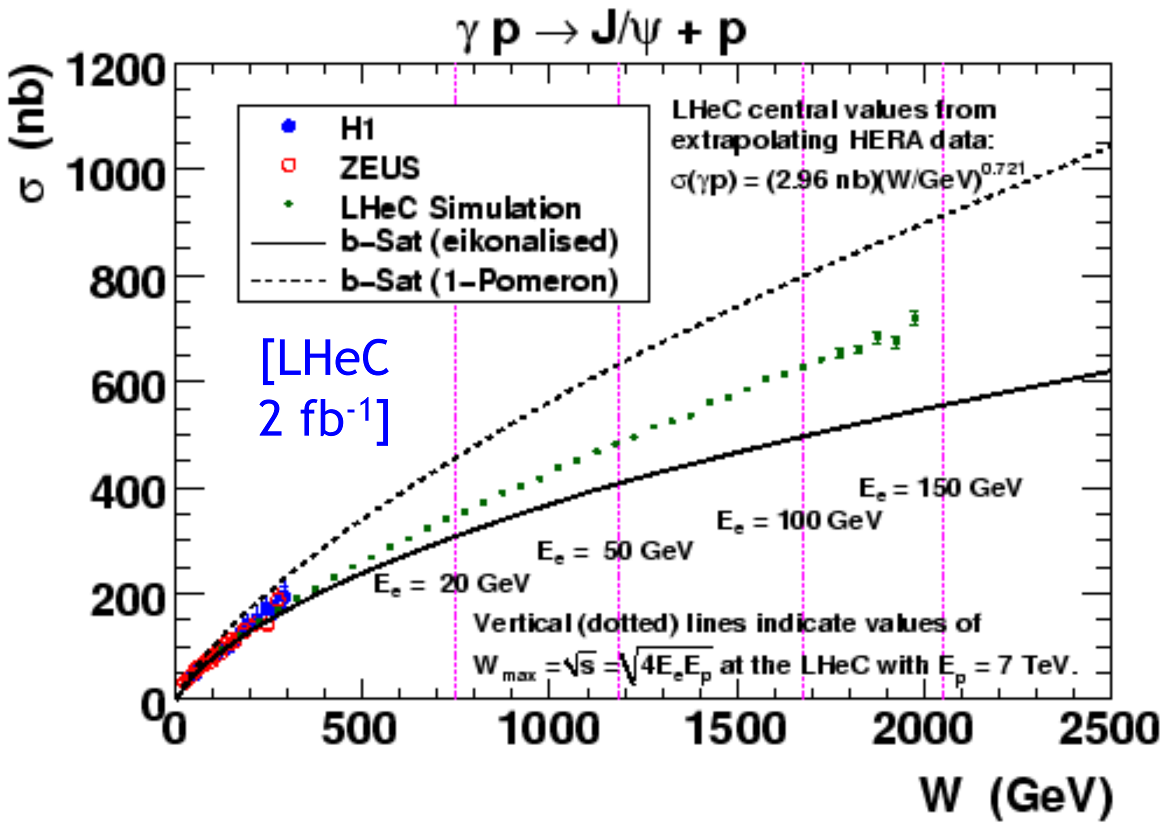
… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

• Simulations (DIFFVM) of elastic J/Ψ → μμ photoproduction
→ scattered electron untagged, 1° acceptance for muons
(similar method to H1 and ZEUS)

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



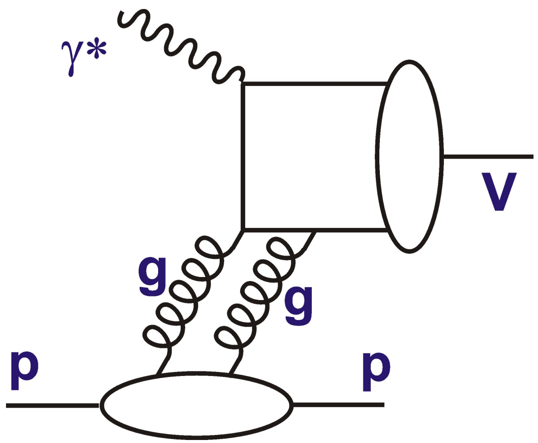


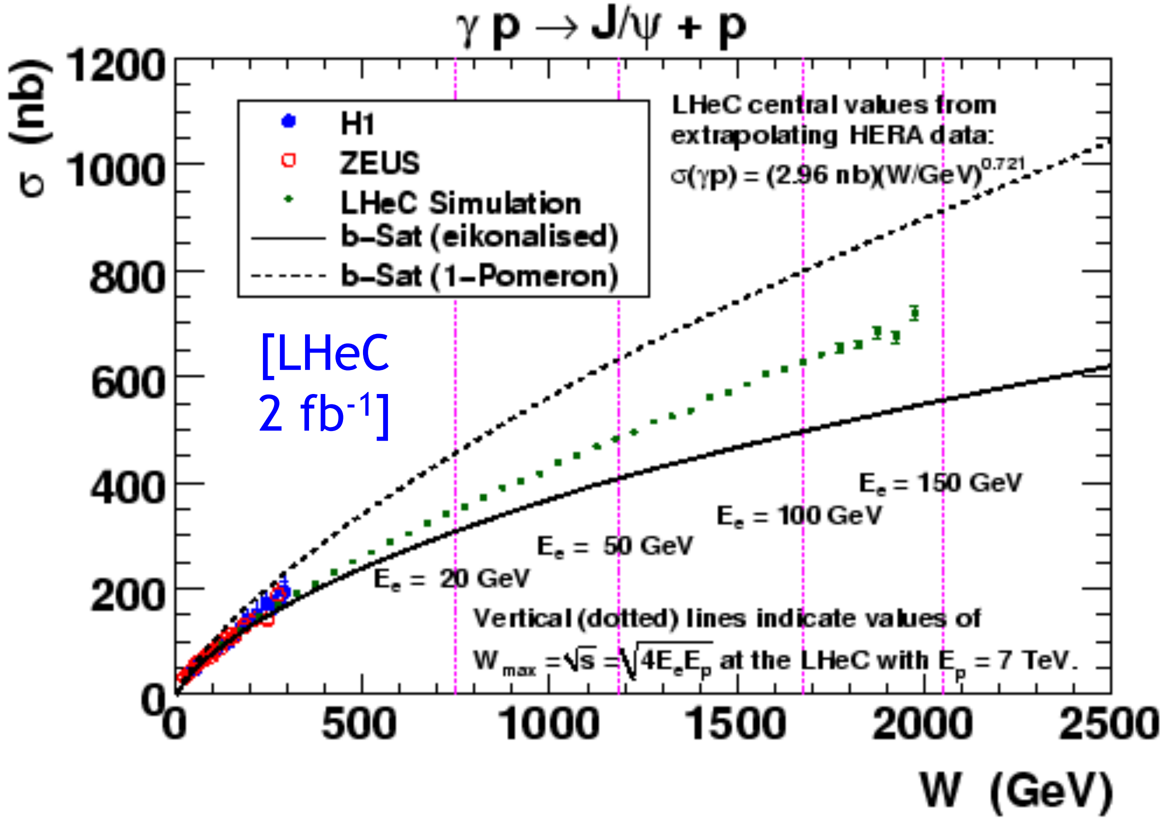
- Significant non-linear effects expected in LHeC kinematic range

… 'smoking gun'?…

J/Ψ from future ep v Dipole model Predictions

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





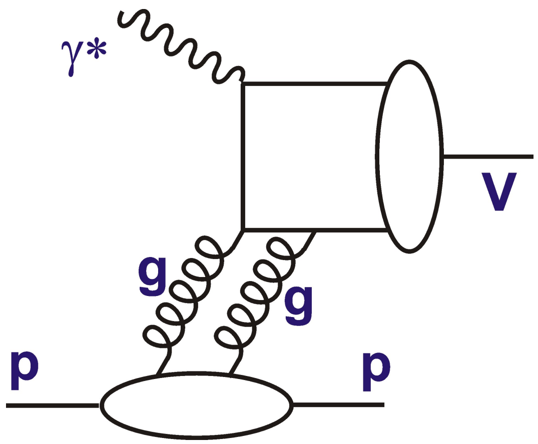
[LHeC 2 fb^{-1}]

- Significant non-linear effects expected in LHeC kinematic range

… 'smoking gun'?...

J/Ψ from future ep v Dipole model Predictions

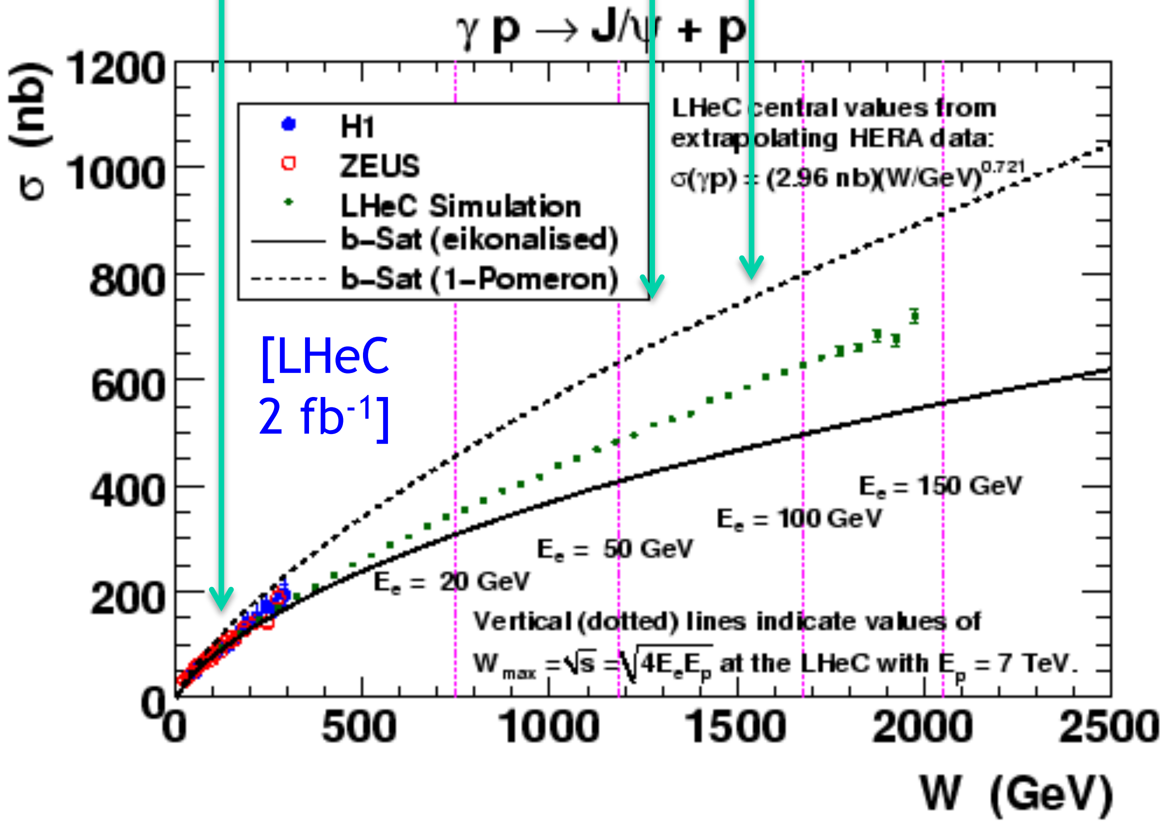
"beware unrealistic non-saturation straw men" [T. Lappi]



Current EIC design

Current LHeC design

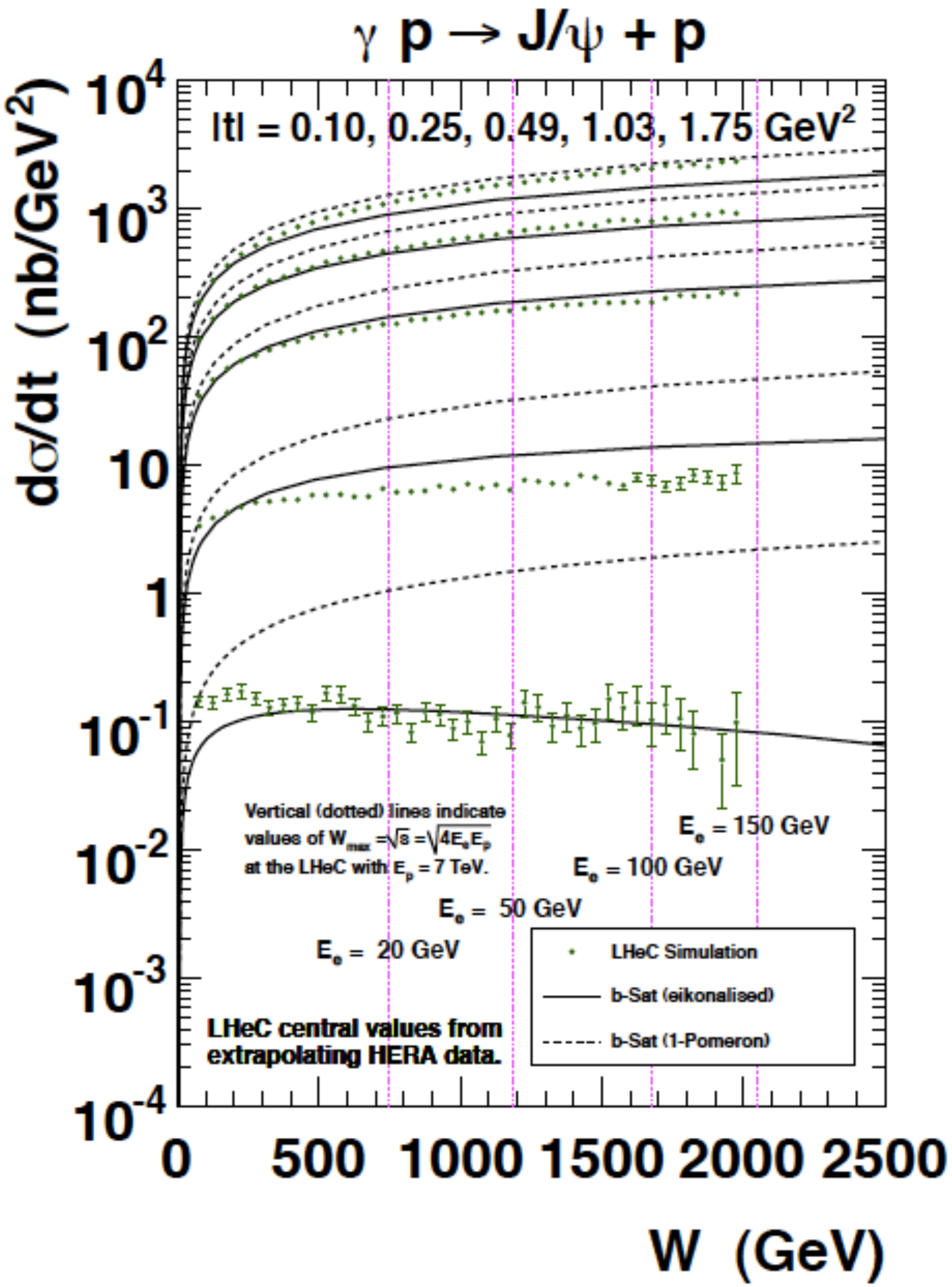
Current LHCb limit



- 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

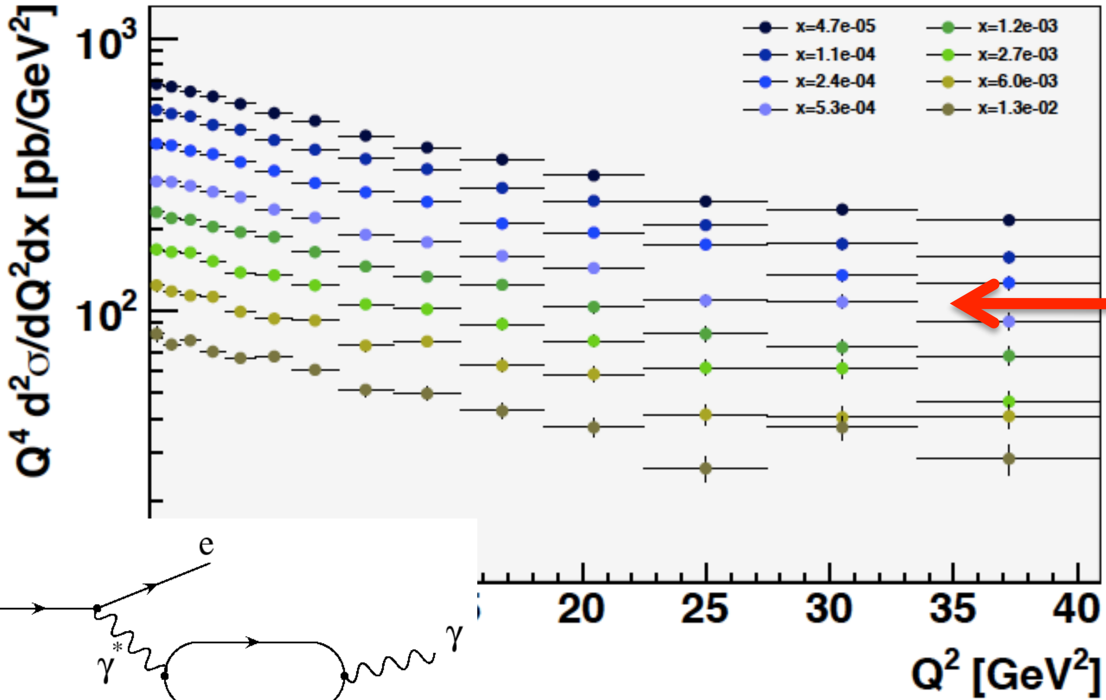


- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV^2 and enhances sensitivity to saturation effects

- Measurements also possible in multiple Q^2 bins

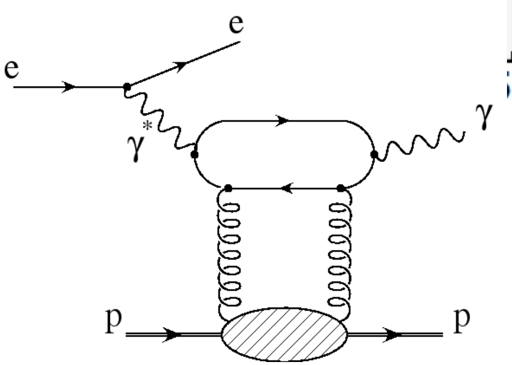
… see also eA (later talks)

DVCS (MILOU simulation)

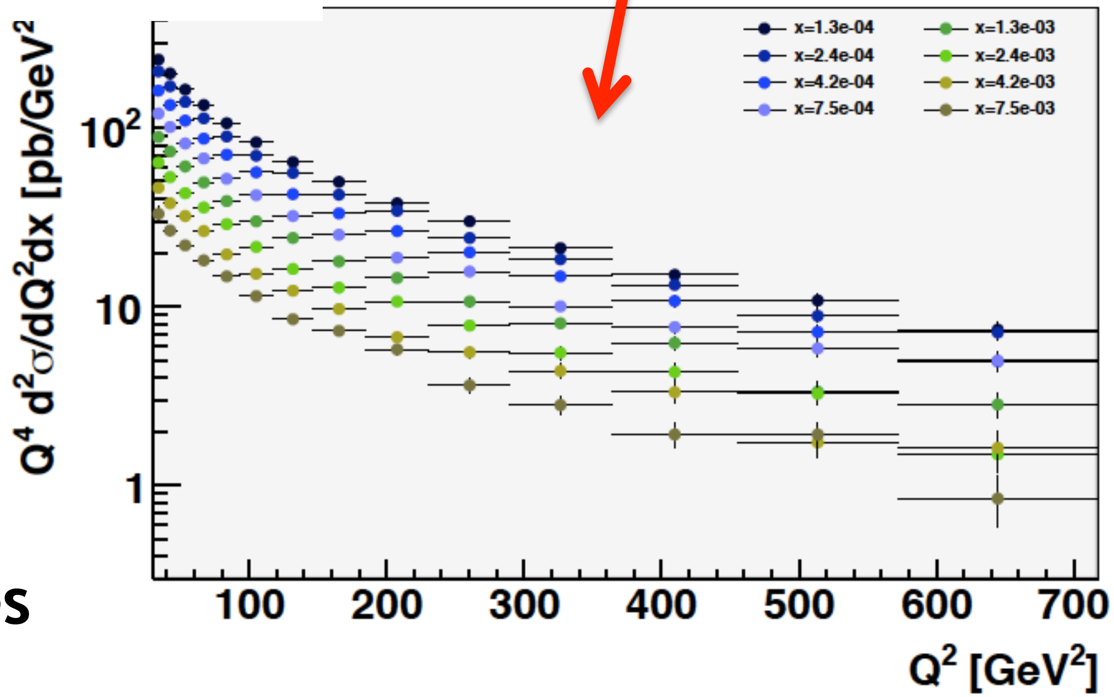


$1\ fb^{-1}$, $E_e = 50$ GeV,
1° acc'nce, $p_T^{\gamma} > 2$ GeV

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

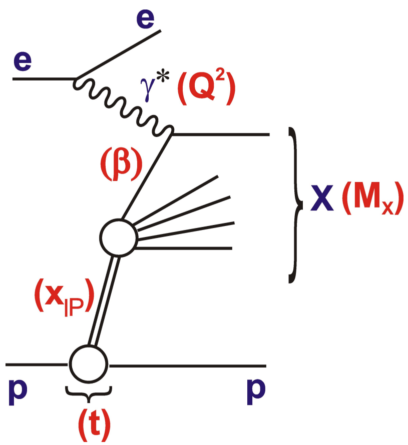


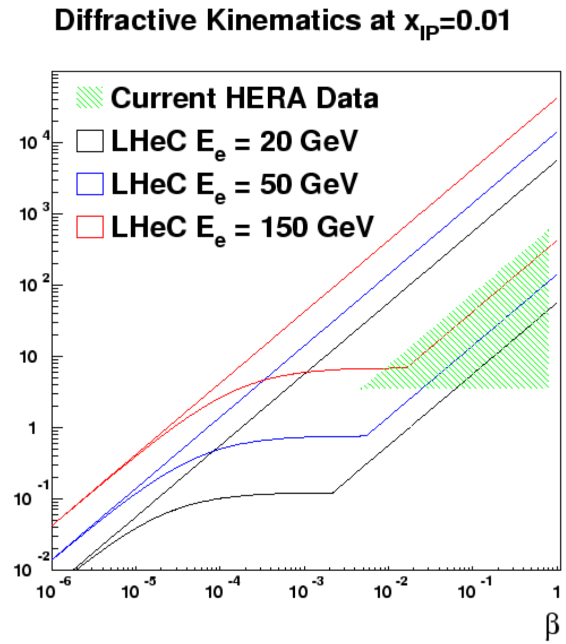
Precise data with
W → 1 TeV, Q^2 → 700 GeV^2,
x → 5.10^{-5}



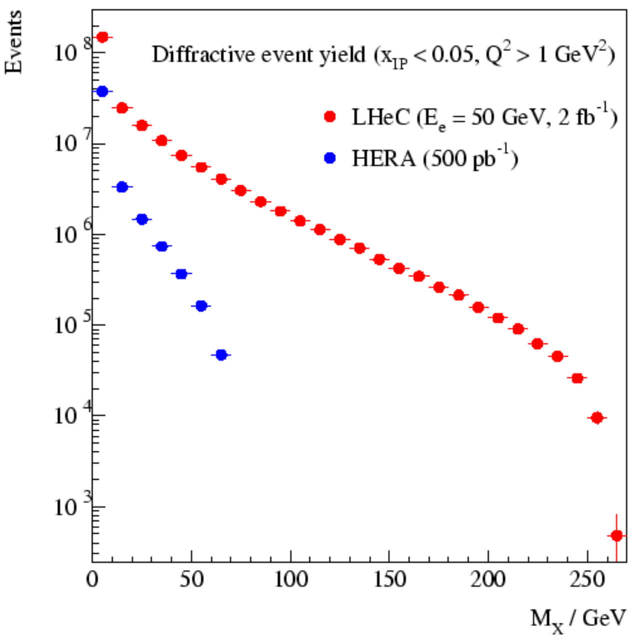
Still to do:
- Beam charge asymmetries
- Sensitivity to GPDs

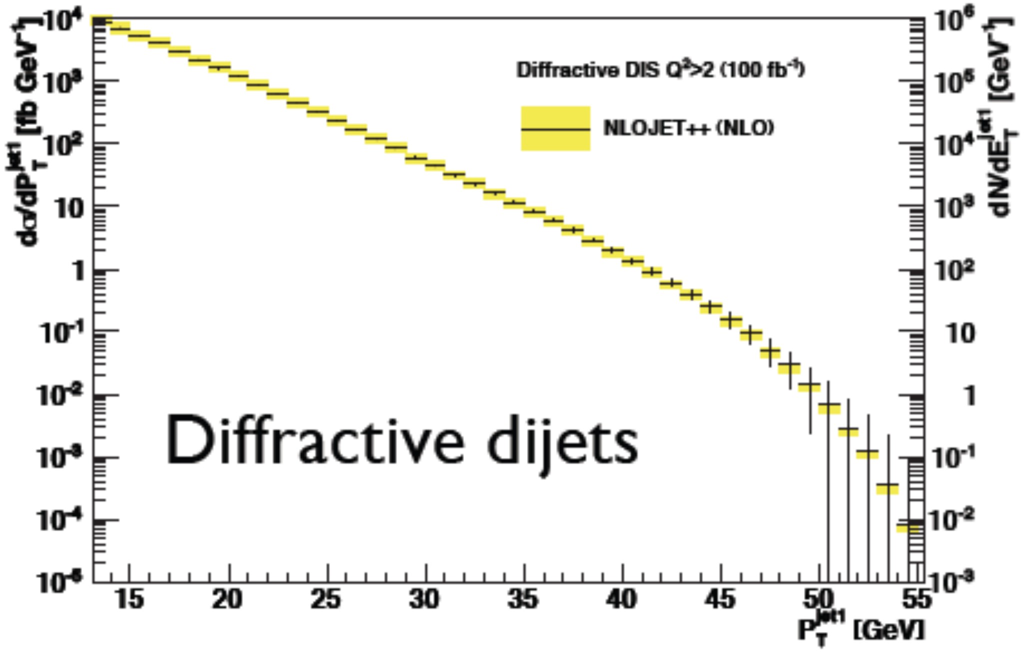
Inclusive Diffraction at LHeC





- 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 …





New Study (Wojtek Slominski)

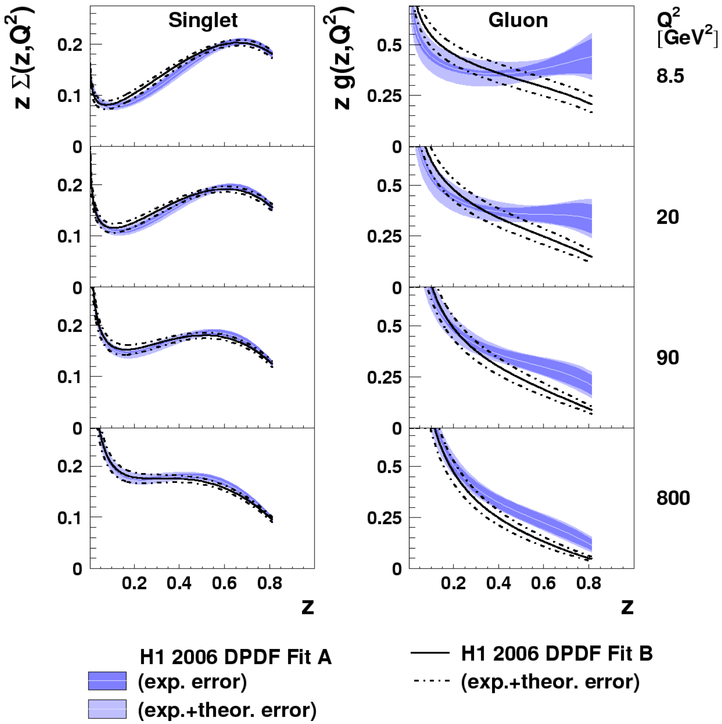
Investigate LHeC potential for diffractive parton densities

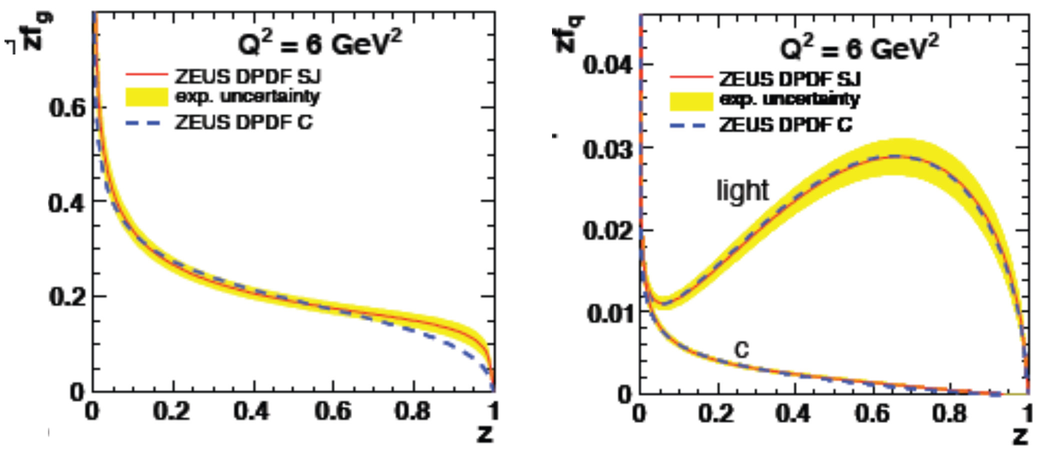
- So far using same framework as at HERA (ZEUS version) with factorising x_{IP} dependence (IP) and (β, Q^2) dependence from NLO DGLAP fit

$$f_k = A_k x^{B_k} (1-x)^{C_k}$$

k=g,d and A_k, B_k, C_k free

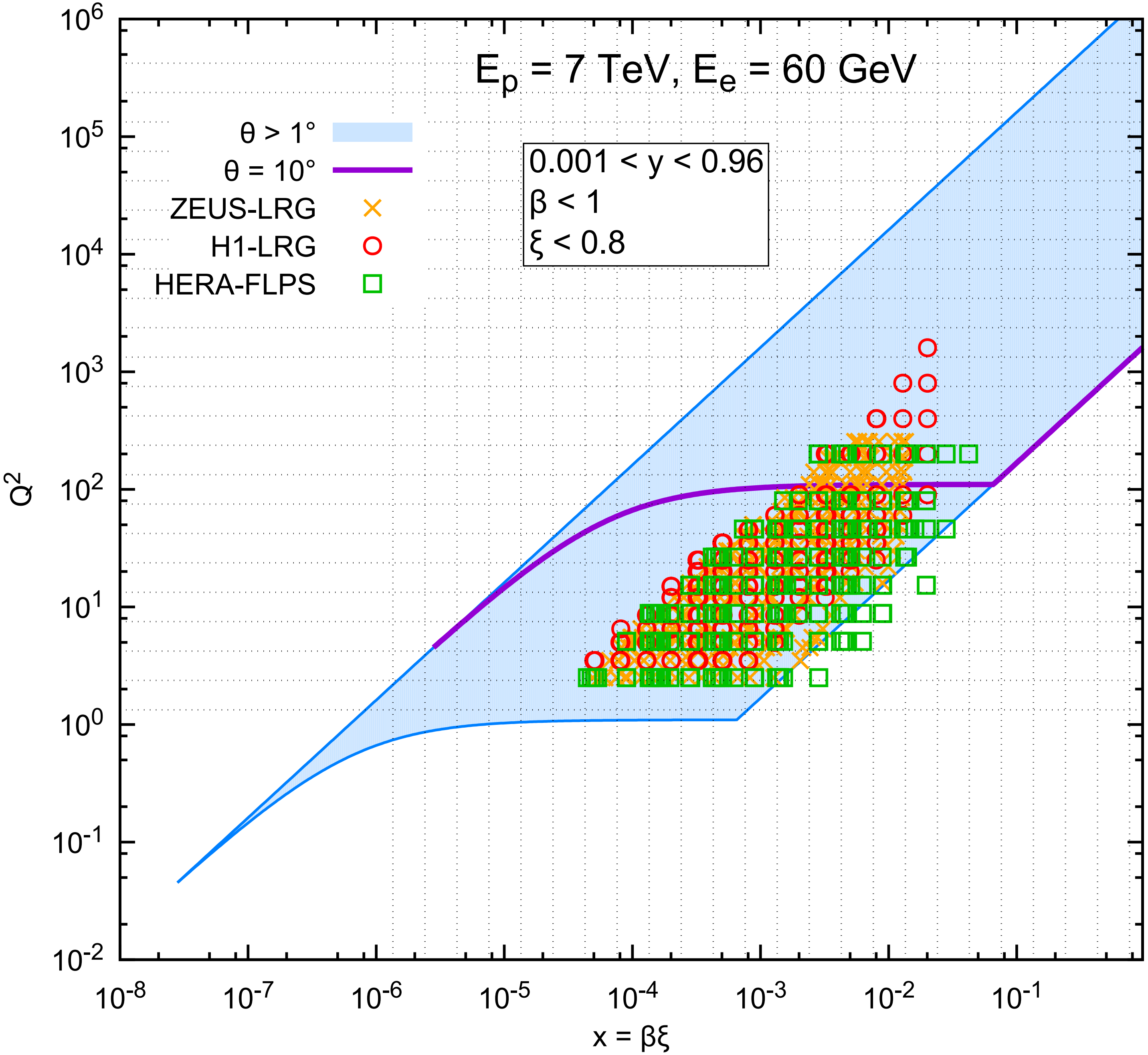
d = u = s = dbar= ubar = sbar



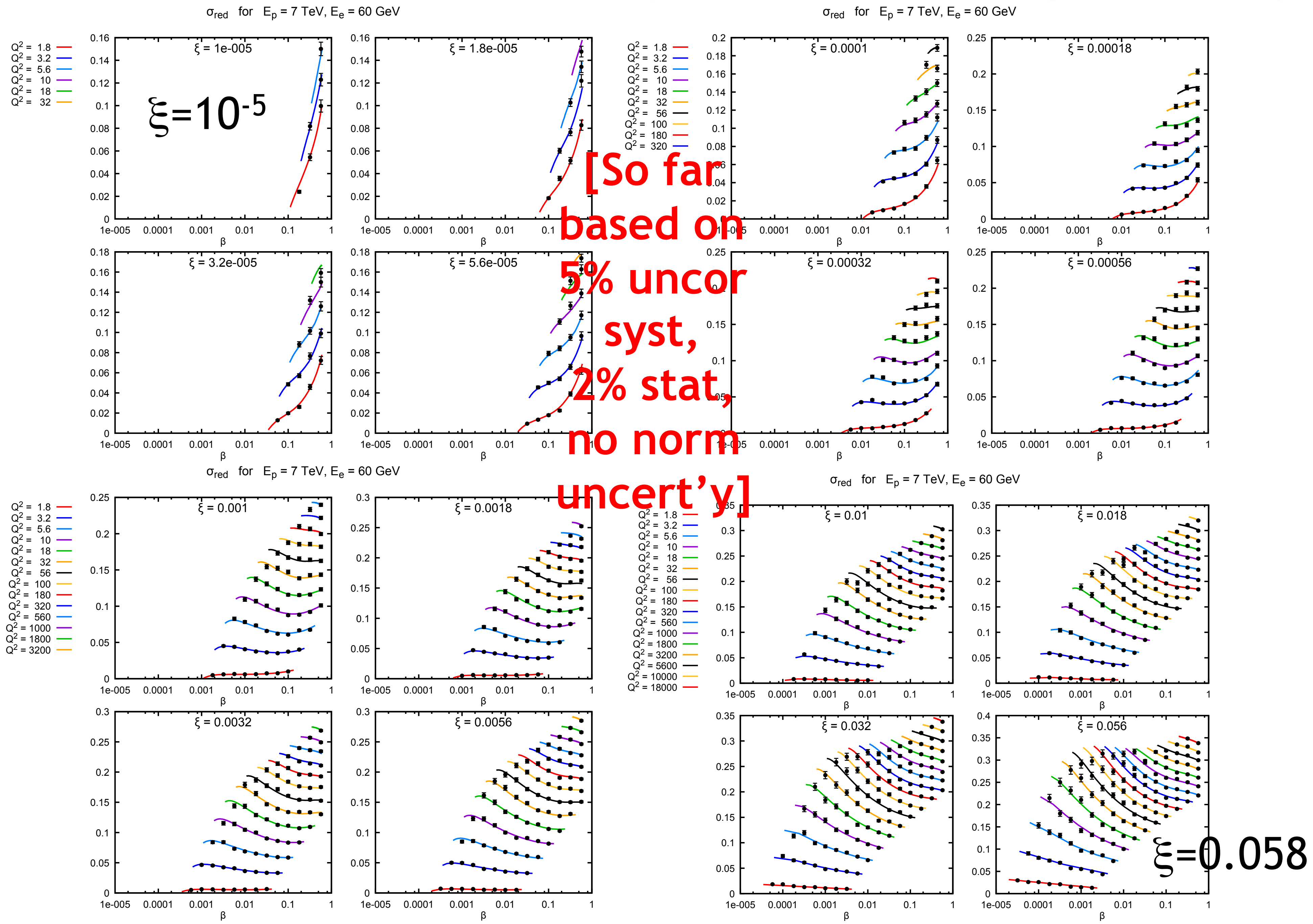


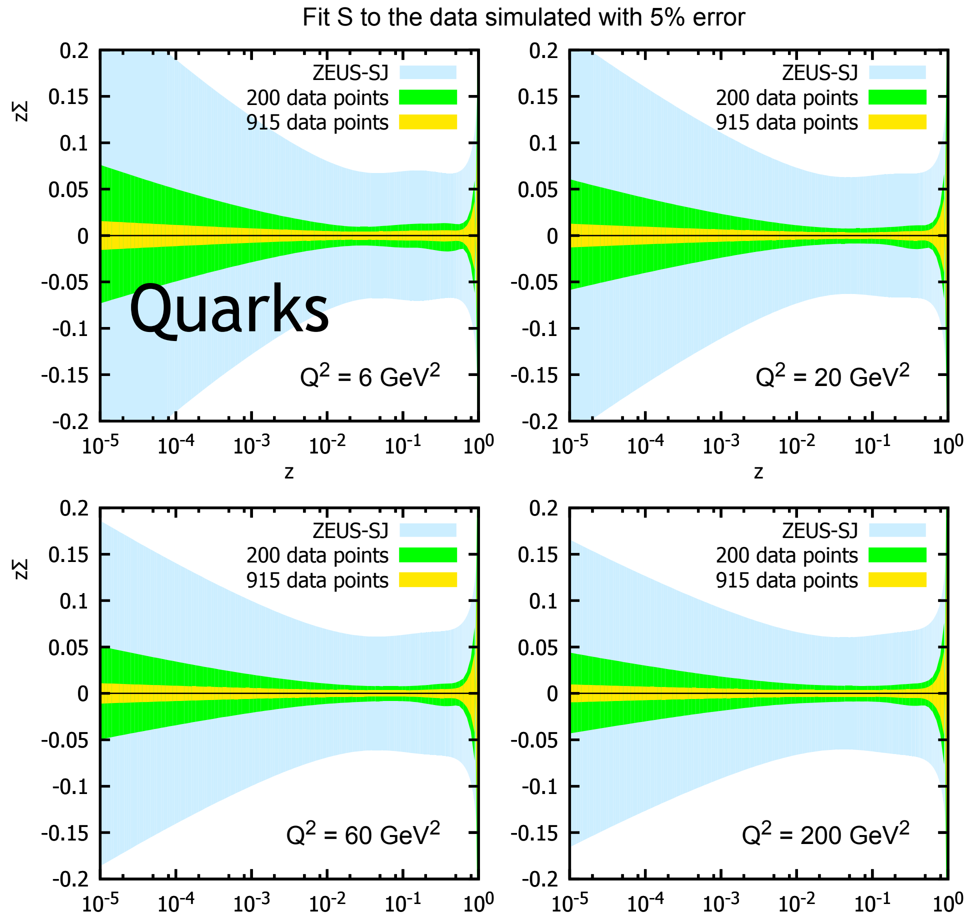
- Small sub-leading (IR) exchange required at largest x_{IP}

HERA Data v LHeC Phase Space

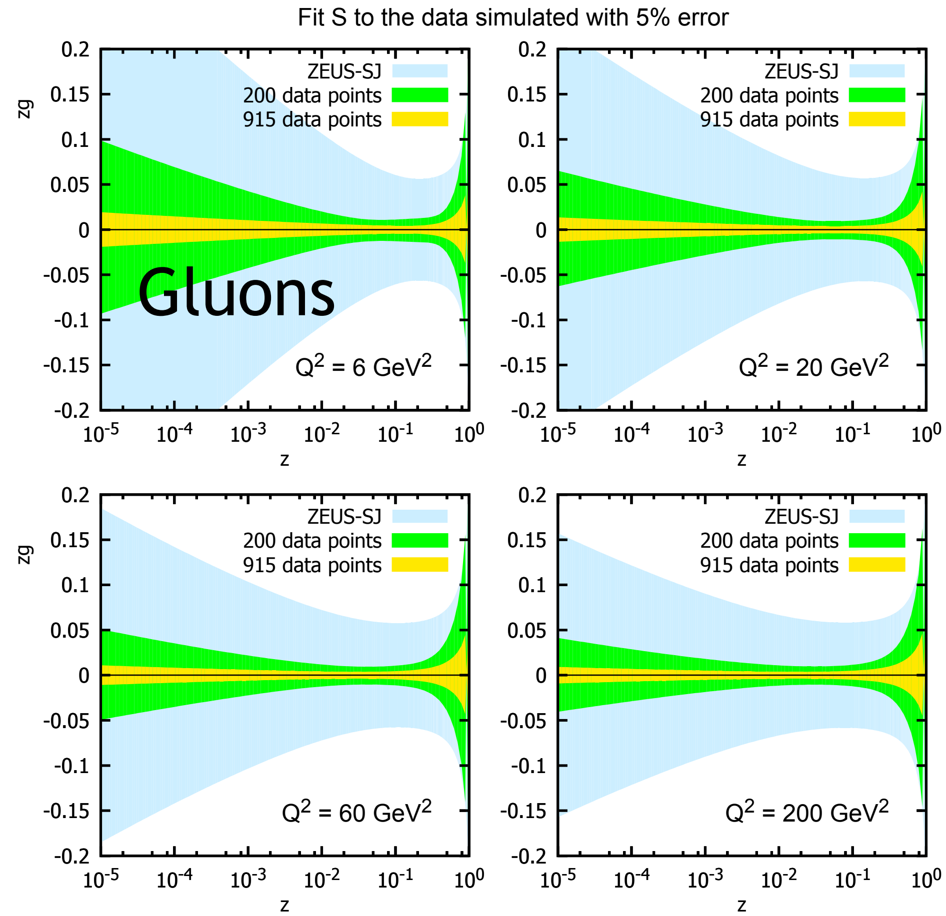


LHeC Simulated Data (ZEUS-SJ extrapolation)





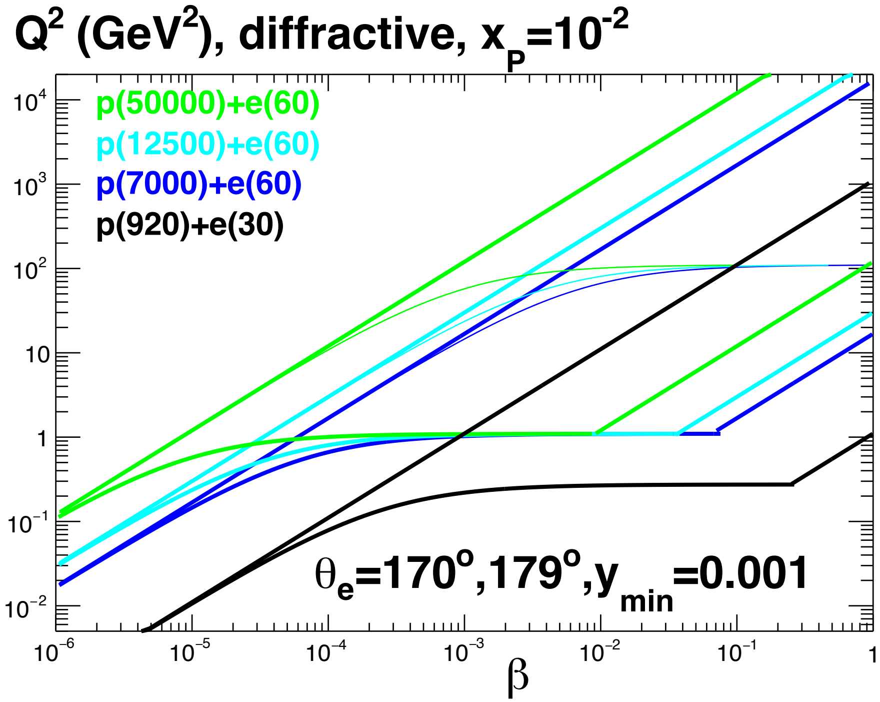
Simulated DPDF Precision (work in progress)



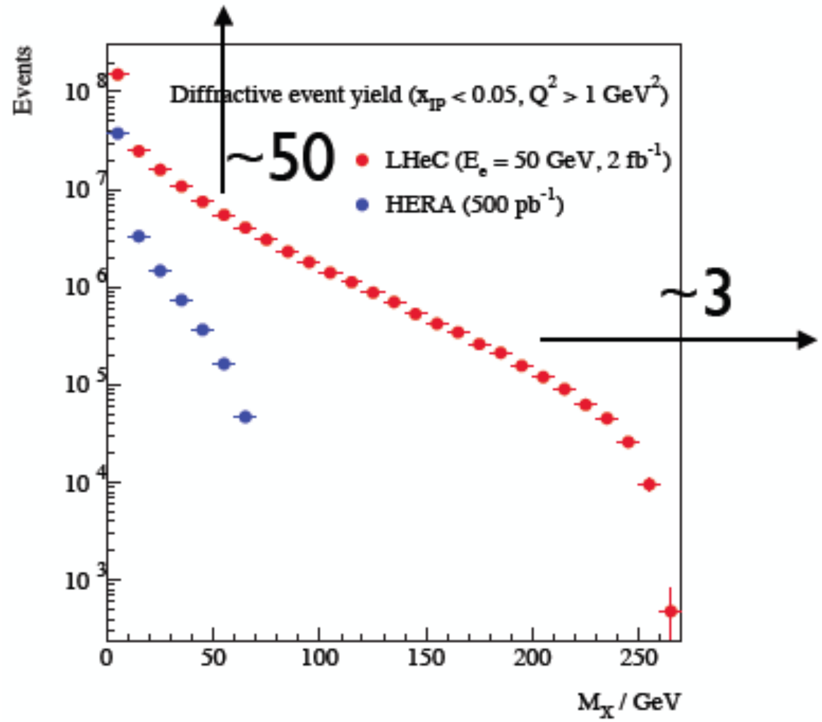
Next steps:

- Normalisation uncertainties
- Parameterisation bias etc?
- Optimise binning
- Sensitivity to flavour decomp
- Sensitivity to deviations from pure DGLAP

Diffraction at FCC-eh in 1 slide



FCC-eh kinematics sensitive to diffractive structure in larger (β,Q^2) range than (x,Q^2) range sampled for the proton @ HERA!



- Similarly for masses and transverse momenta of jets.

- W range for VMs → multi-TeV

Summary

- Low x QCD is a frontier of future → emergent phenomena at high density, strong coupling (saturation, confinement, mass)

- LHeC / FCC-eh addresses this physics better than any other future facility

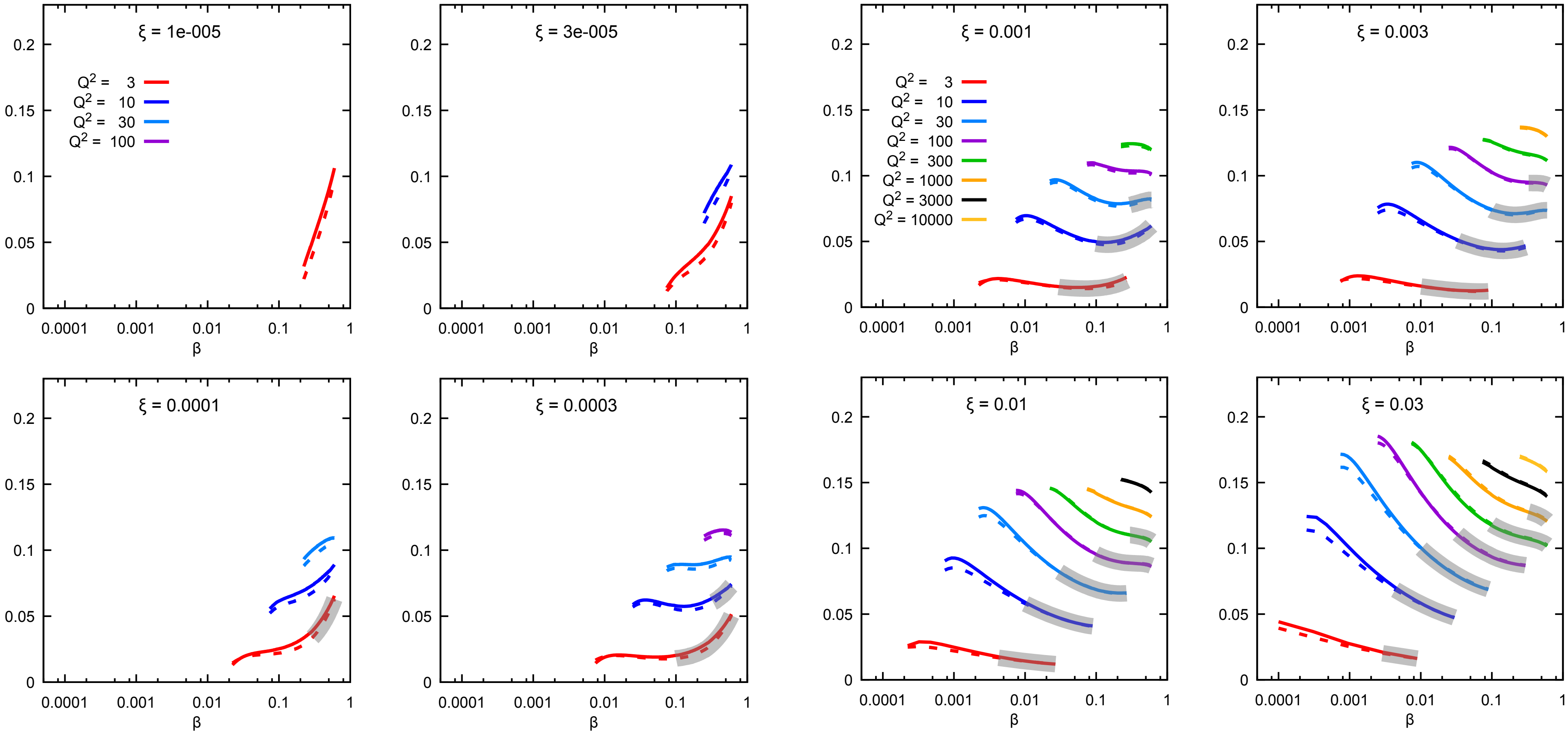
- Recent progress in sensitivity to diffractive PDFs

- Still plenty more to do … wish list
    - → DVCS and GPD / TMD sensitivity
    - → Lots of FCC-eh simulations
    - → Any simulations with real attempts at systematics
    - → More detailed forward instrumentation design
    - → …

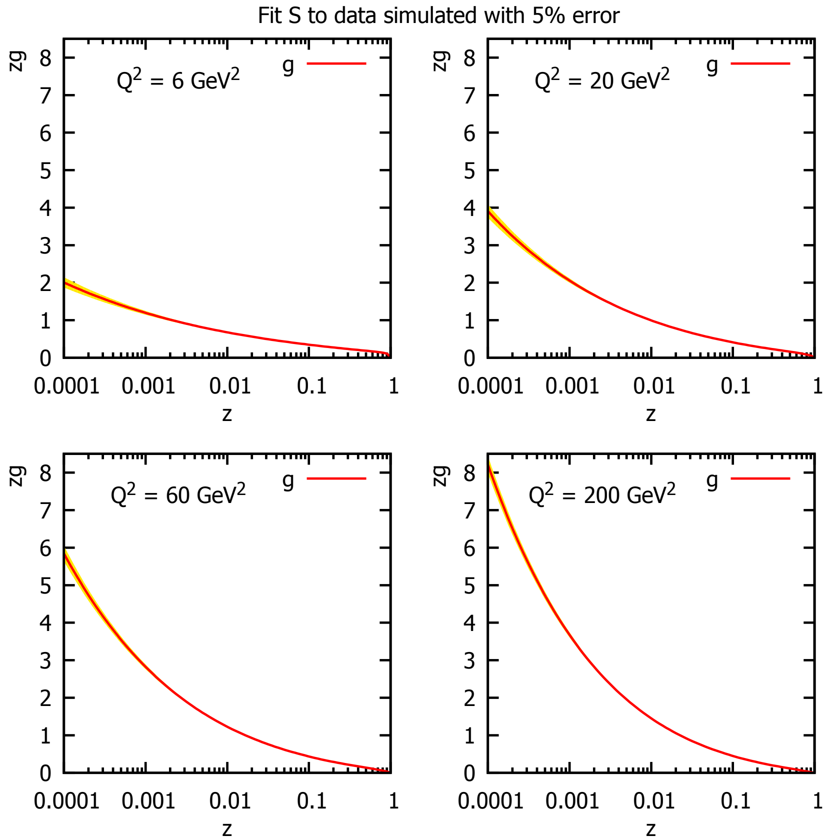
[Thanks: Nestor Armesto, Anna Stasto, Wojtek Slominski …]

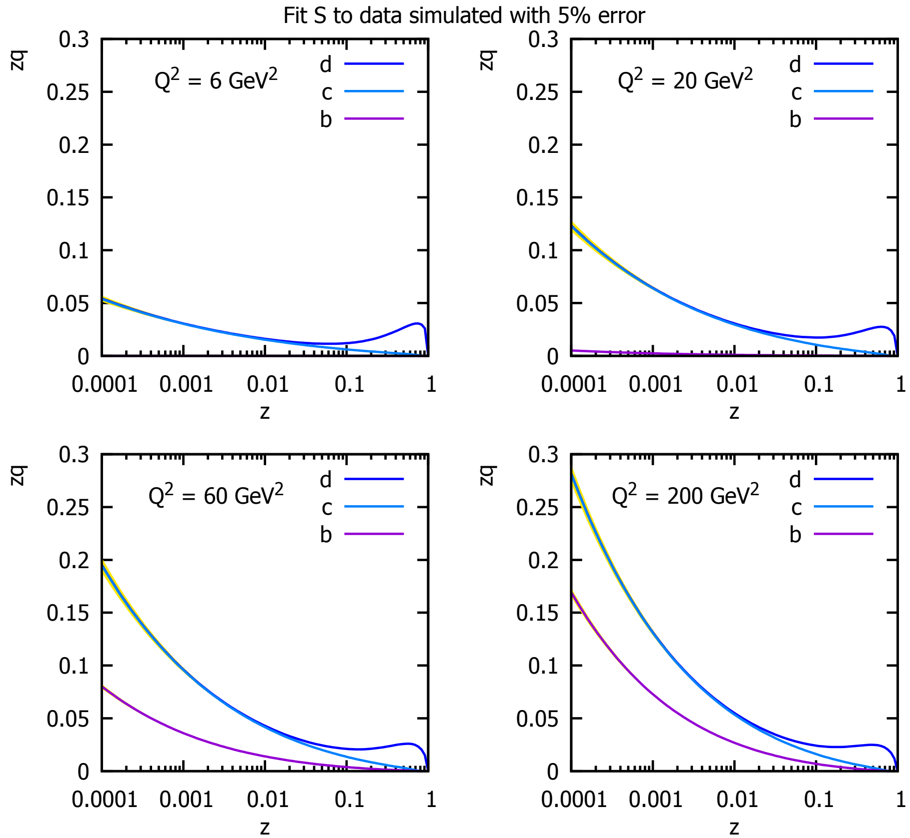
Back-Ups Follow

New Study: Wojtek Slominski

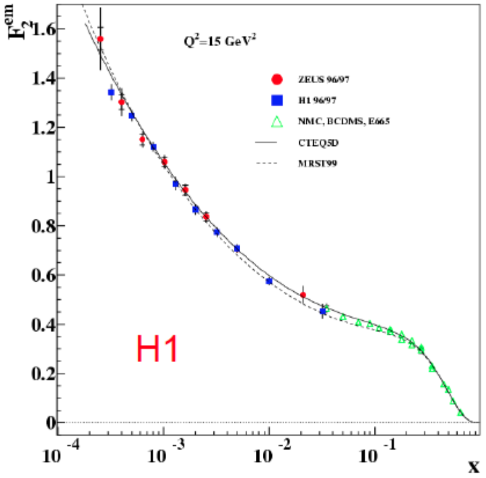


New Study: Wojtek Slominski

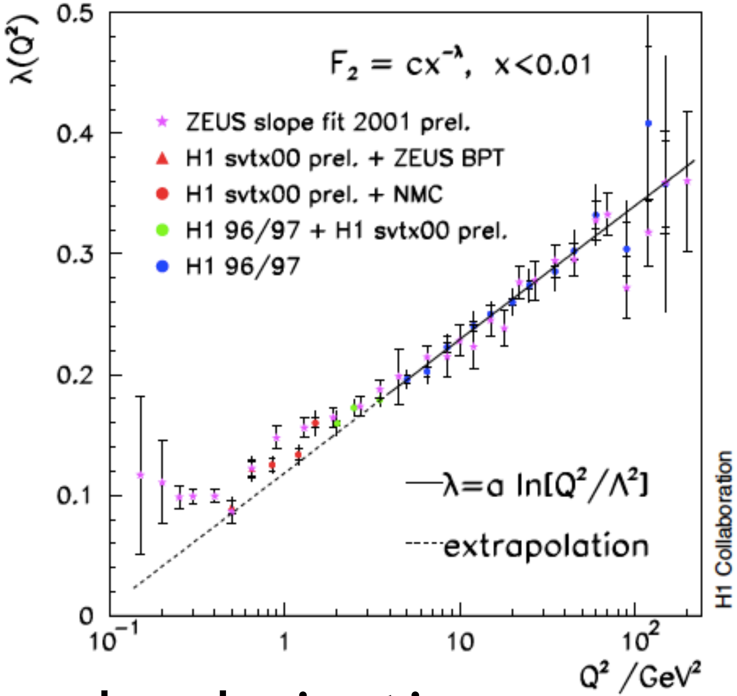


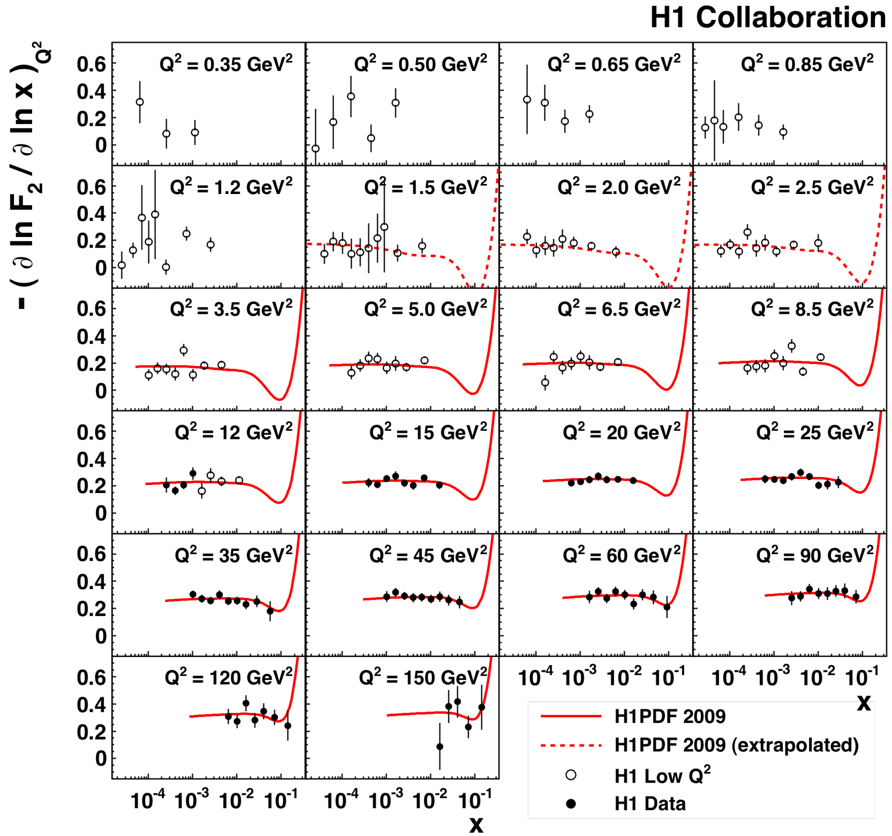


Looking for Saturation in the HERA Data



HERA-I inclusive data well described by $\mathbf{F_2 = Ax^{-\lambda(Q2)}}$ 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

(NEW) DGLAP PDF Fits to LHeC Pseudo-Data

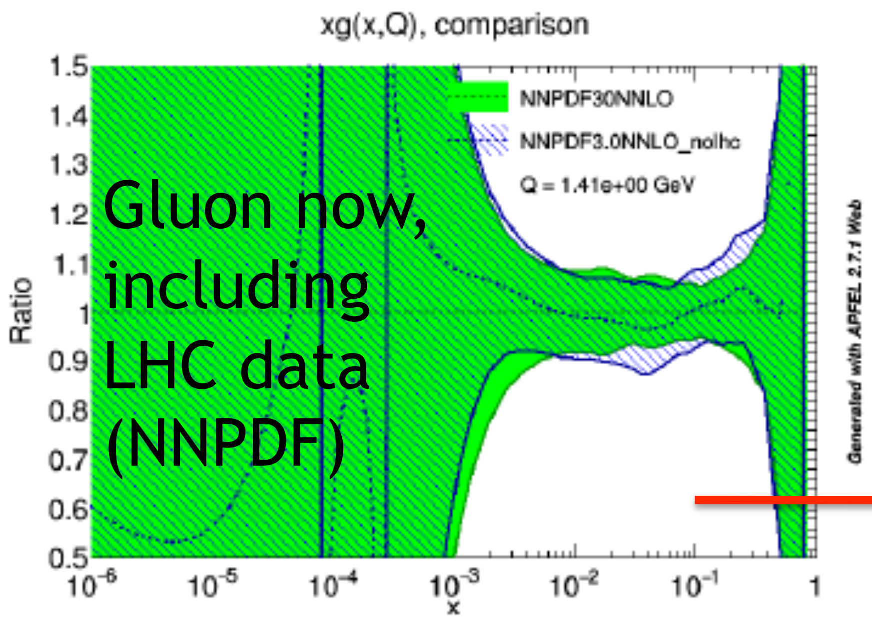
-Simulated NC, CC `pseudo-data' with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

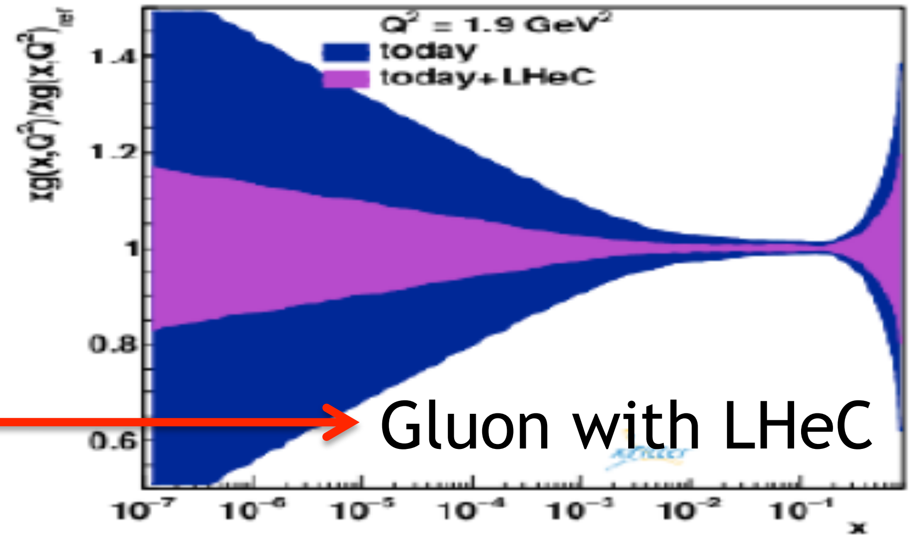
- NEW: Luminosity increased since CDR → up to 1ab^{-1}
- NEW: Fitting framework → as for HERAPDF 2.0 at NLO

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E_e'/E_e'$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.3%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

- NLO DGLAP fit using HERAPDF2.0, including:
  - LHeC NC and CC e^+p and e^-p cross sections
  - NEW: HERA-1 and HERA-2 final combined H1+ZEUS data
  - Fixed target BCDMS data with W>15 GeV
  - NEW: HERA jet and various Tevatron / LHC data

Low x Gluon with LHC, with and without LHeC

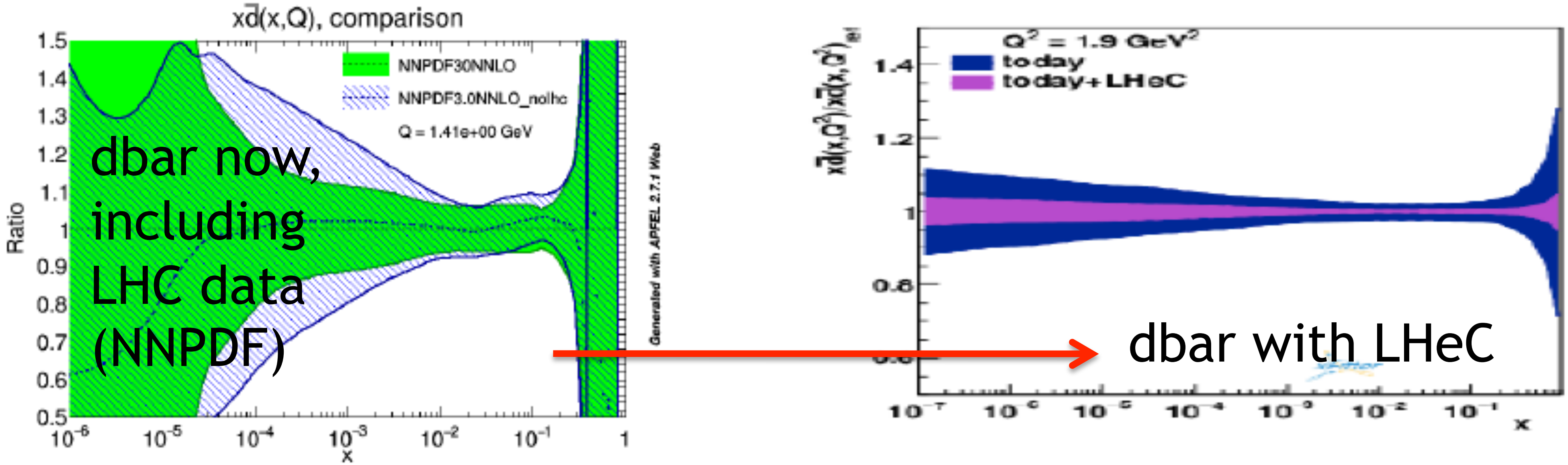




Standard LHC channels do not help much:

- ATLAS and CMS constraints as currently included in PDF fits (jets, top) don't extend below $x \sim 10^{-3}$.
- Other channels may help if theoretical issues can be overcome (LHCb c,b, maybe even exclusive J/Ψ)
- Current knowledge basically comes from HERA: stops at $x \sim 5.10^{-4}$
- LHeC gives constraints to $x \sim 10^{-6}$ from scaling violations and F_L

Low x Sea with LHC, with and without LHeC



LHC channels help, but not on same level as LHeC:

- ATLAS and CMS low mass Drell-Yan data have an impact
- Also potentially LHCb Drell-Yan
- Other channels may help (see eg ALICE direct photon / FOCAL)
- LHeC goes to $x\sim10^{-6}$, directly from F_2

… this is what DIS does best …

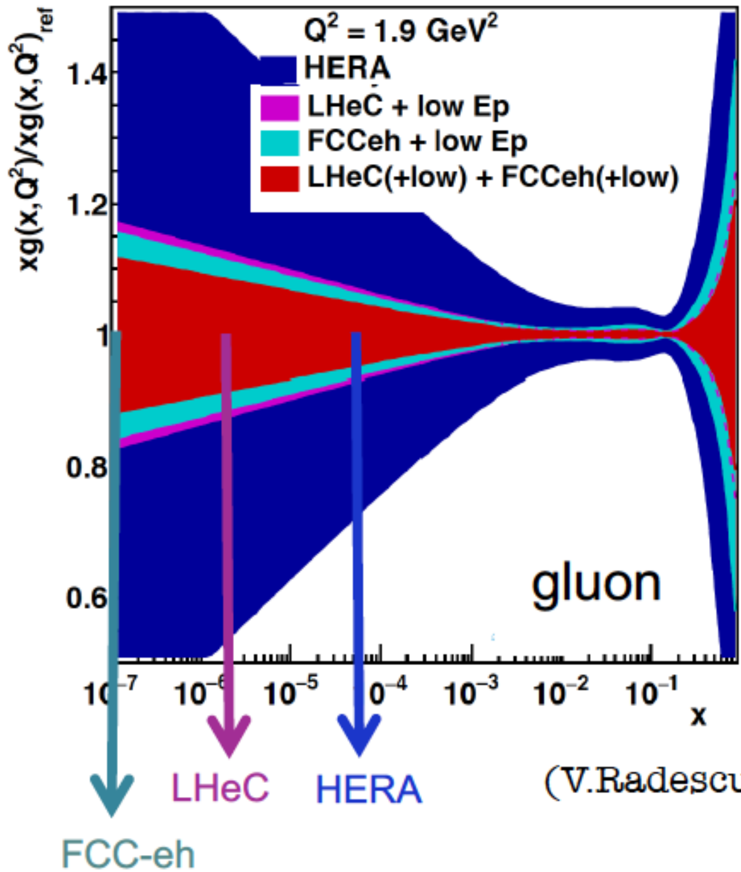
FCC-eh Data have also been included

NC/CC	E_e [GeV]	E_p [TeV]	P(e)	charge	lumi. [fb^{-1}]	
NC	60 (60)	50 (7)	−0.8	−1	1000	e−, neg. pol.
CC	60 (60)	50 (7)	−0.8	−1	1000	
NC	60 (60)	50 (7)	+0.8	−1	300	e−, pos. pol.
CC	60 (60)	50 (7)	+0.8	−1	300	
NC	60 (60)	50 (7)	0	+1	100	e+, unpol.
CC	60 (60)	50 (7)	0	+1	100	
NC	20 (60)	7 (1)	0	−1	100	low energy
CC	20 (60)	7 (1)	0	−1	100	

* second and third columns show FCC-eh (LHeC)

(M.Klein)

error assumptions:
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; γp at high y: 1%
uncorrelated extra eff. 0.5%



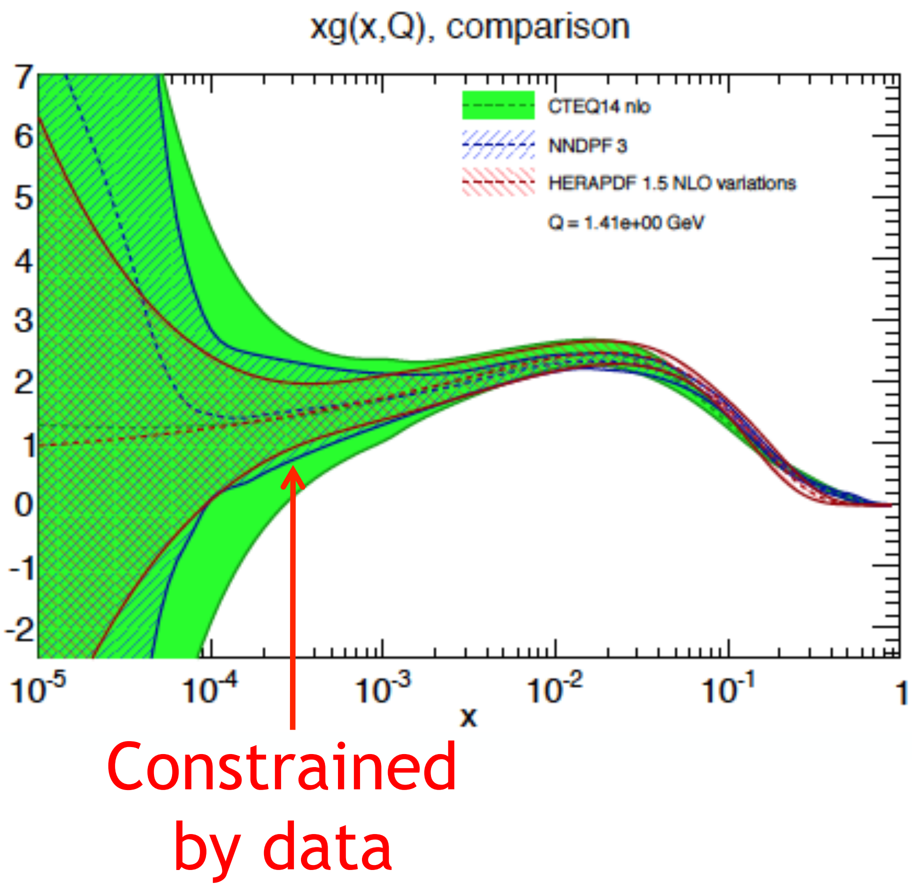
(V.Radescu)

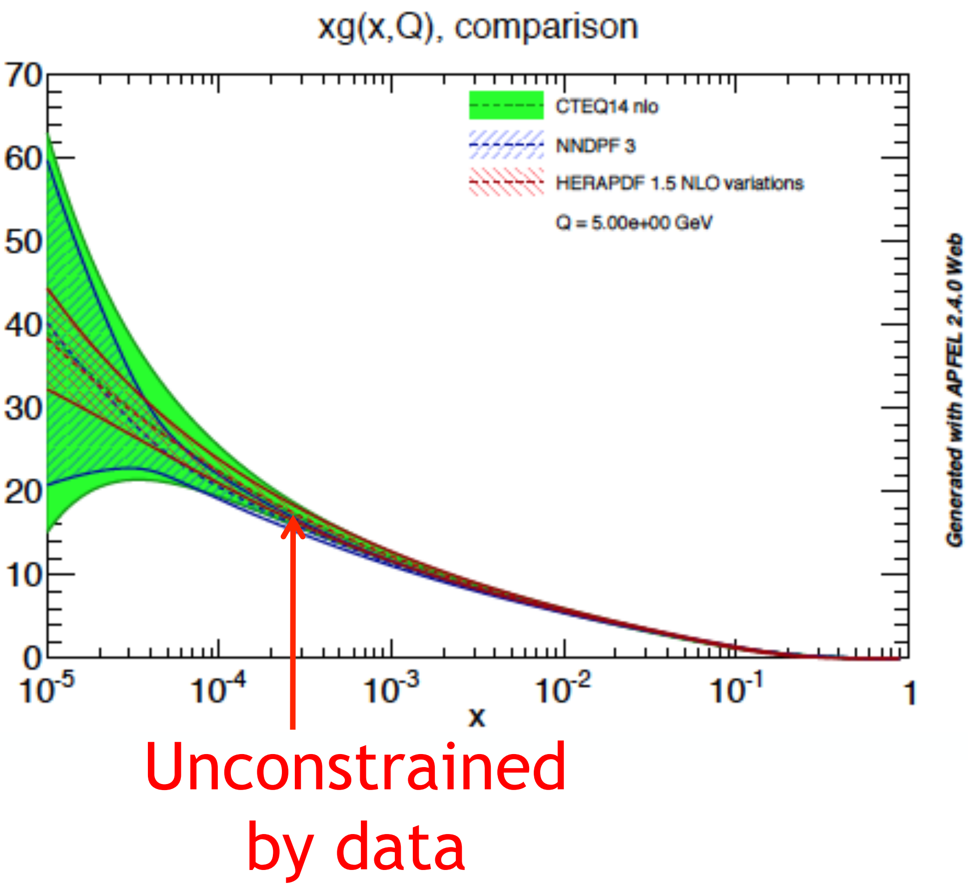
Some improvement in precision

Main impact is direct coverage with data down to $x=10^{-7}$.

Why this is already dangerous at the LHC

- Use of PDFs based purely on DGLAP Q^2 evolution at low(ish) x, high Q^2 at the LHC will give incorrect results if there are saturation effects in the low x, low Q2 data …

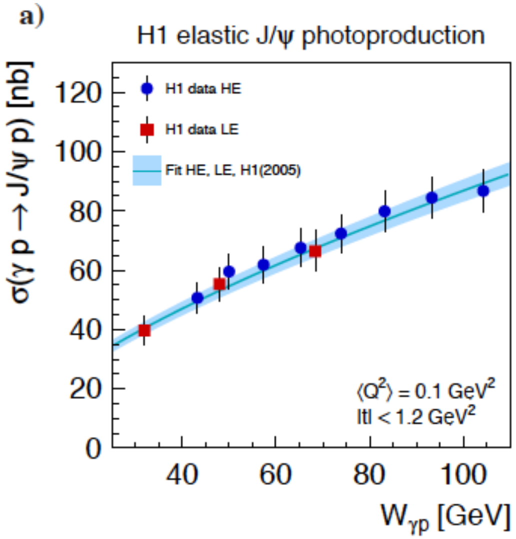


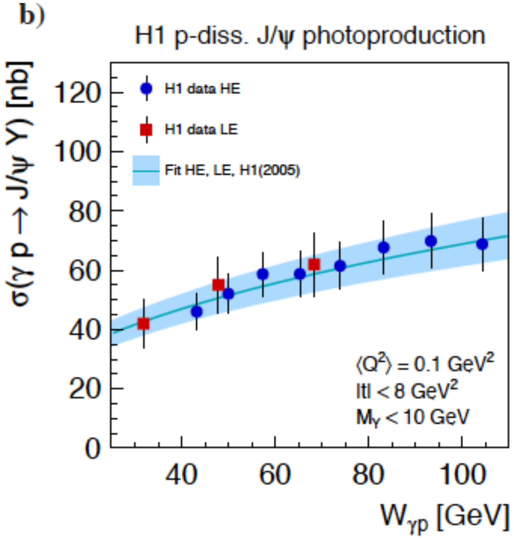


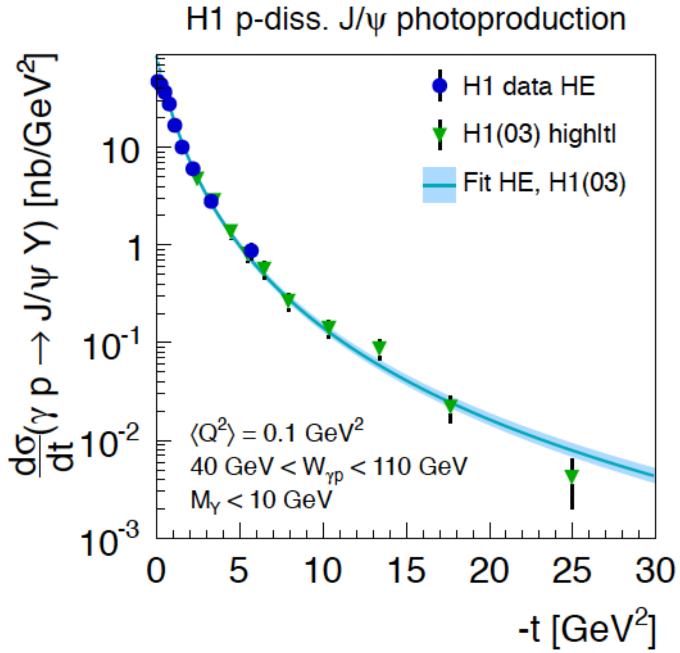
- Convergent solutions after DGLAP evolution can already be misleading at the LHC … worse at lower x → LHeC, FCC-eh …

Existing Diffractive J/Ψ Photoproduction Data

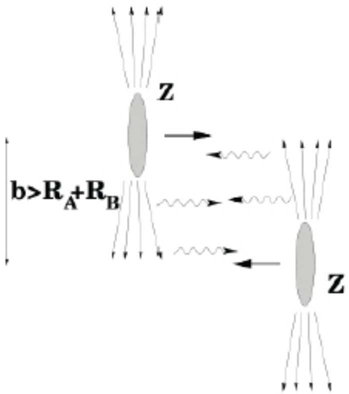
… HERA: $\gamma p \rightarrow J/\Psi p$, $\gamma p \rightarrow J/\Psi\ Y$:

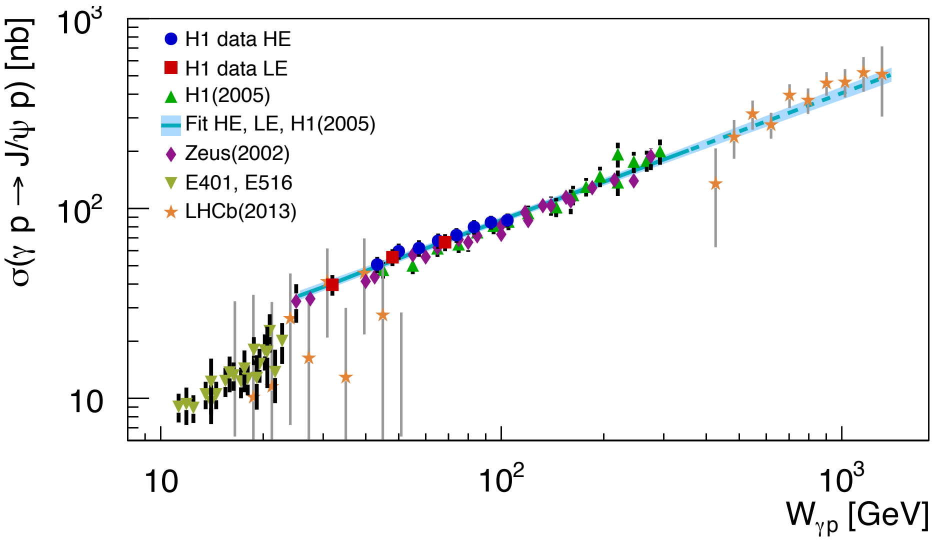






… Adding Ultraperipheral Collisions at LHC:

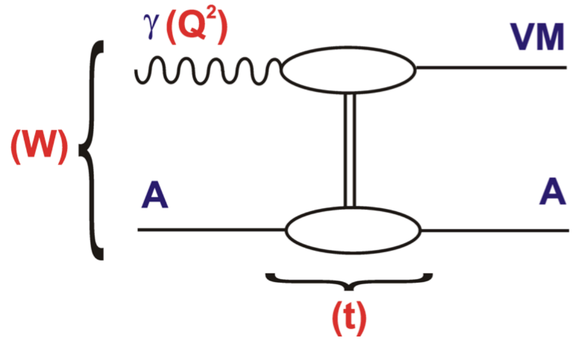


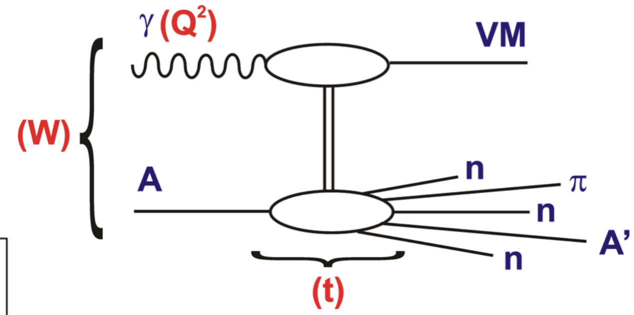


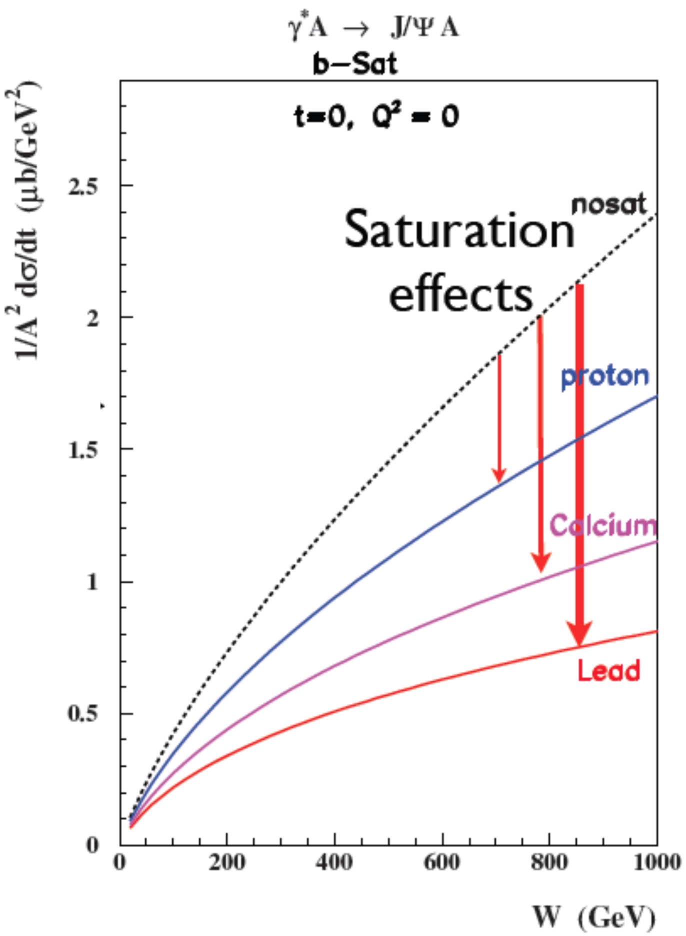
- No evidence for deviation from monatomic rise with increasing W (decreasing x).
- See also pPb, PbPb results

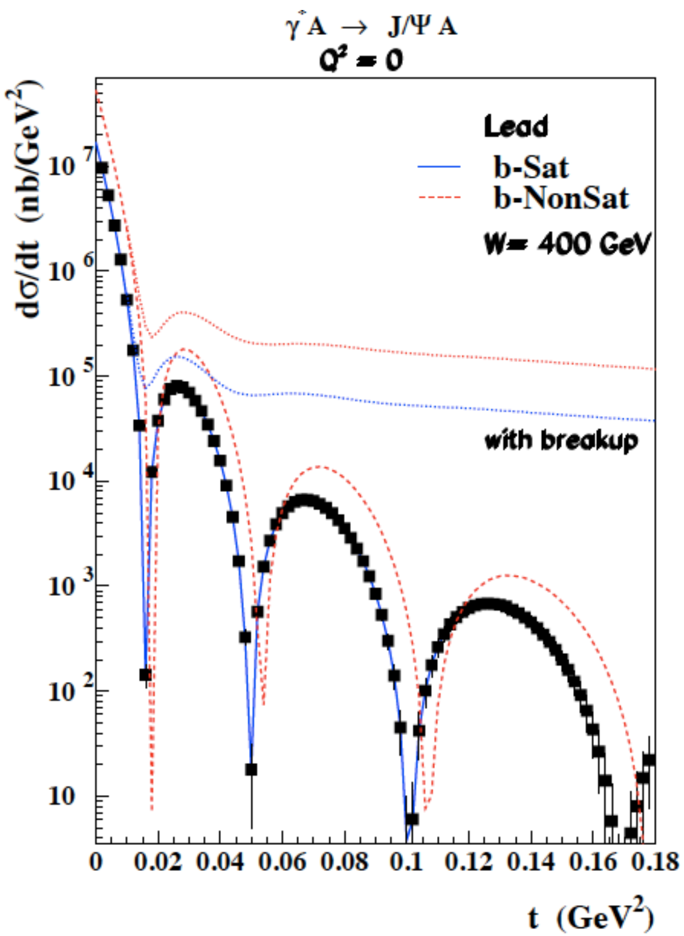
Exclusive Diffraction in eA

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



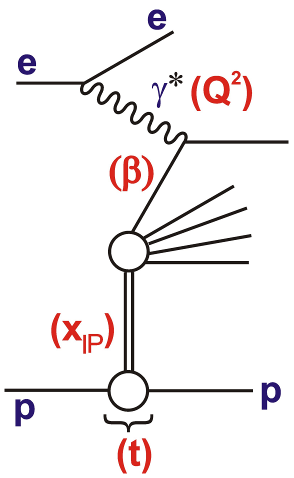




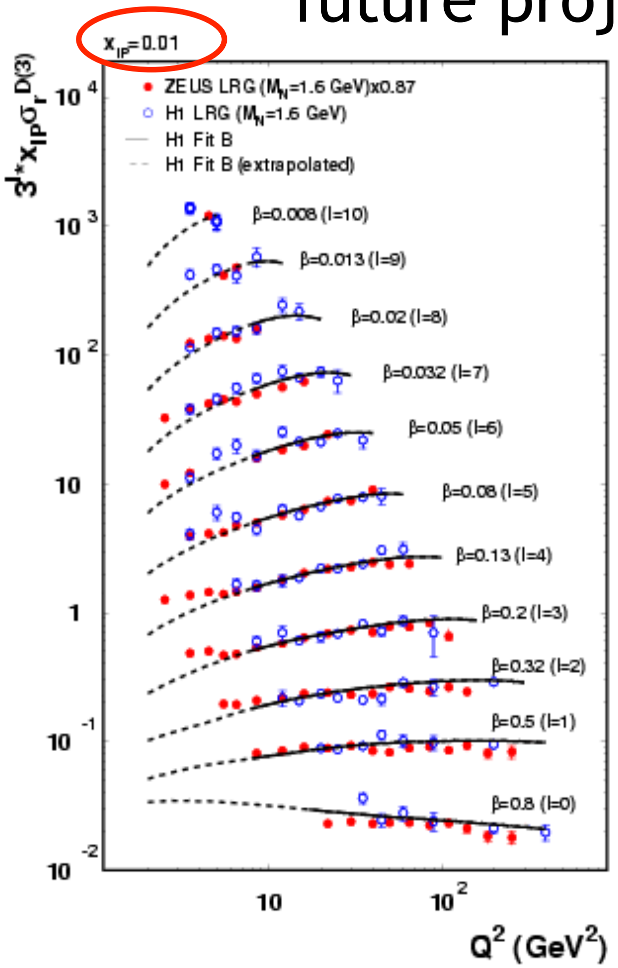


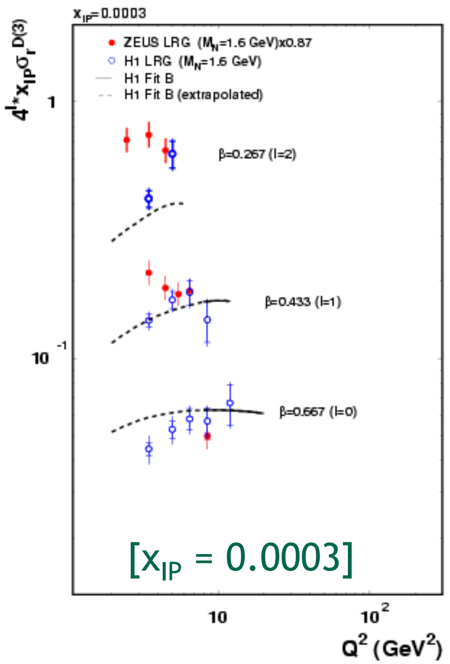
Experimental separation of incoherent diffraction based mainly on ZDC

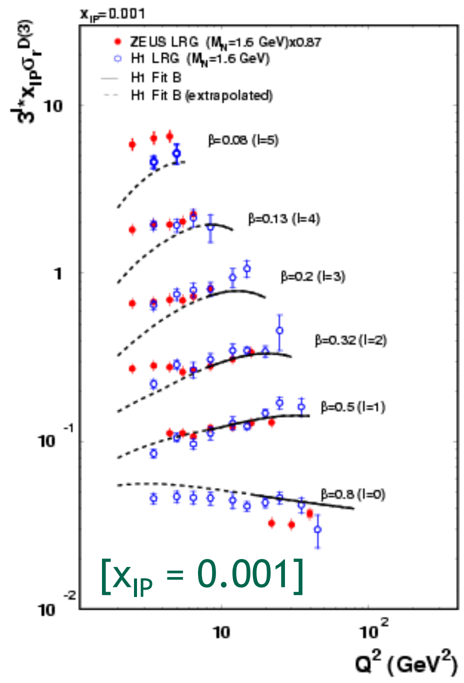
Inclusive Diffraction at HERA

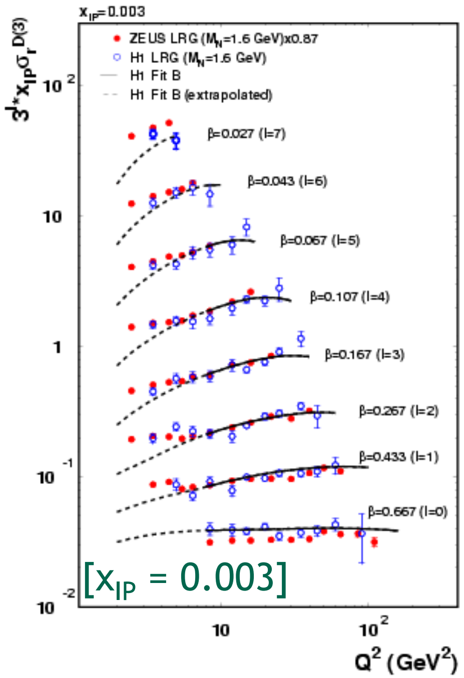


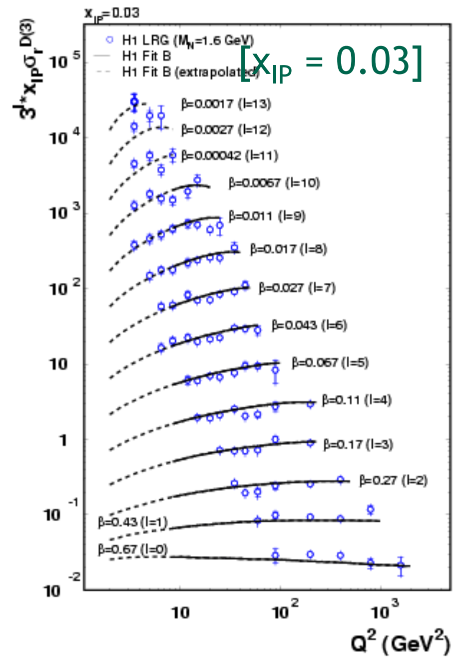
- Huge topic with rich outputs
- Not yet fully explored for future projects



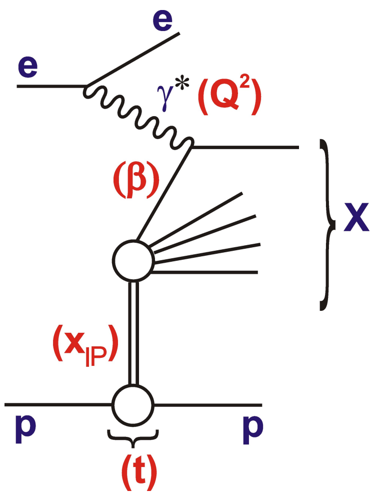


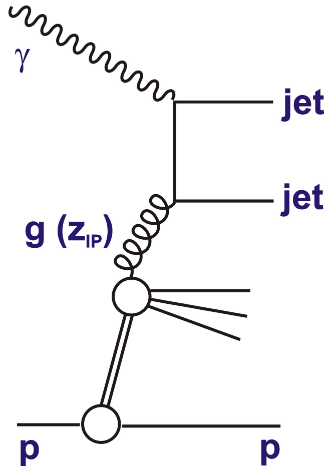


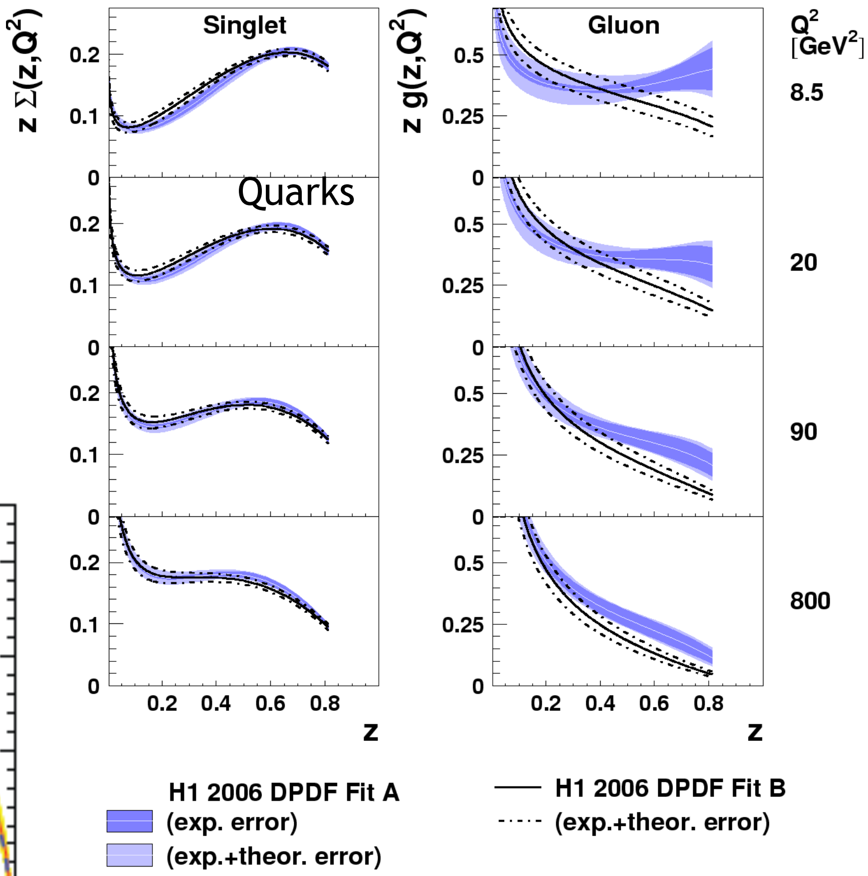


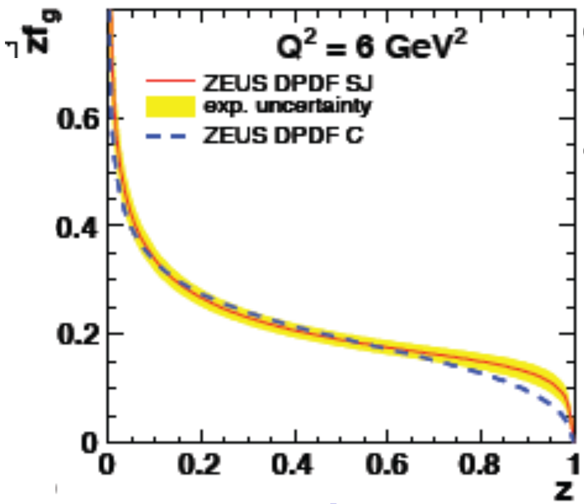


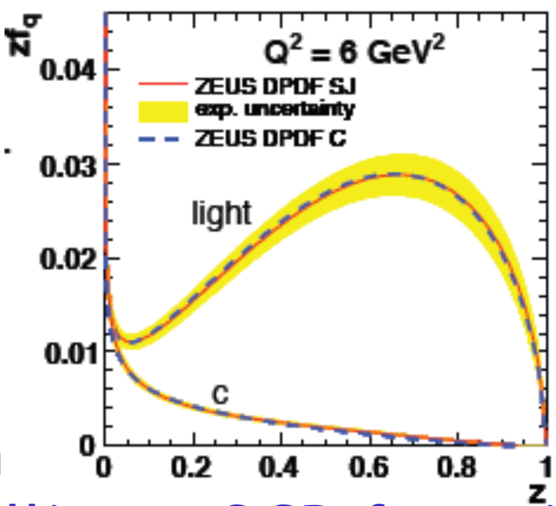
Diffractive Parton Densities (DPDFs)











… semi-inclusive collinear QCD factorisation works!

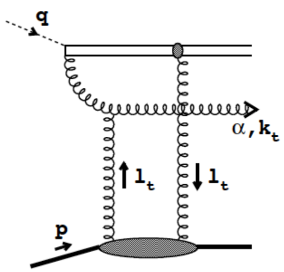
… DPDFs from F_2^D lead to impressive description of all HERA 'hard' diffractive data (not shown here)

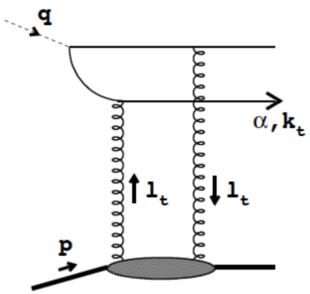
… Failure of diffractive PDF fits to data at lowest Q^2 …

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)

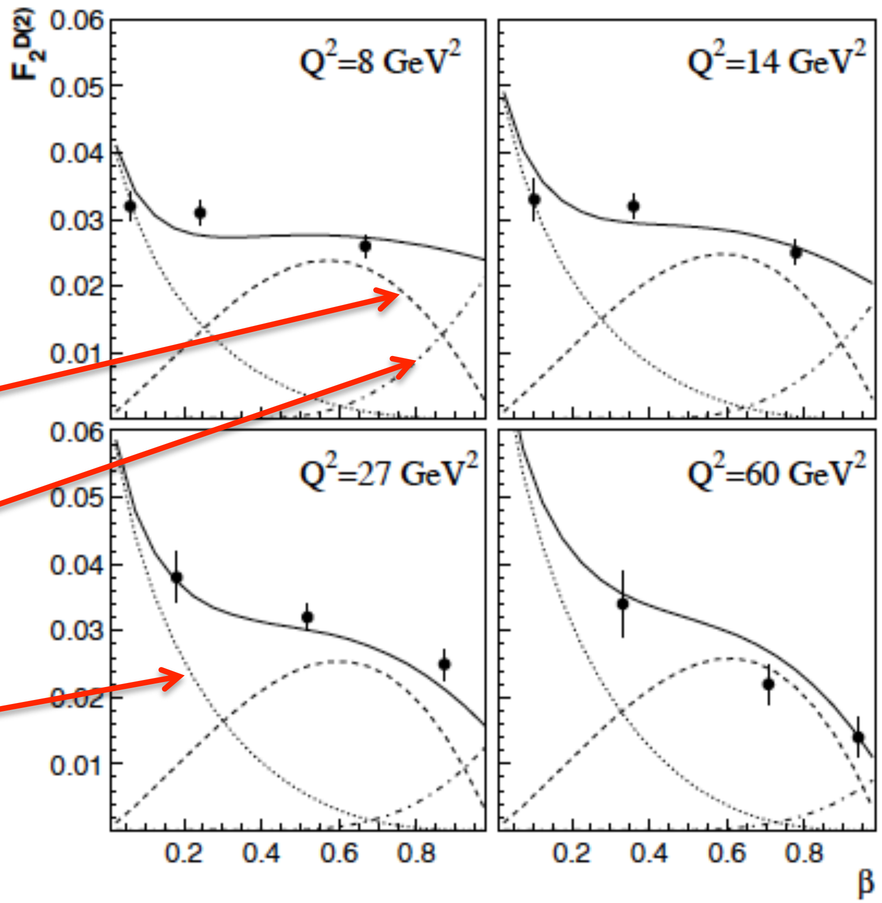




qq_T (Leading Twist)

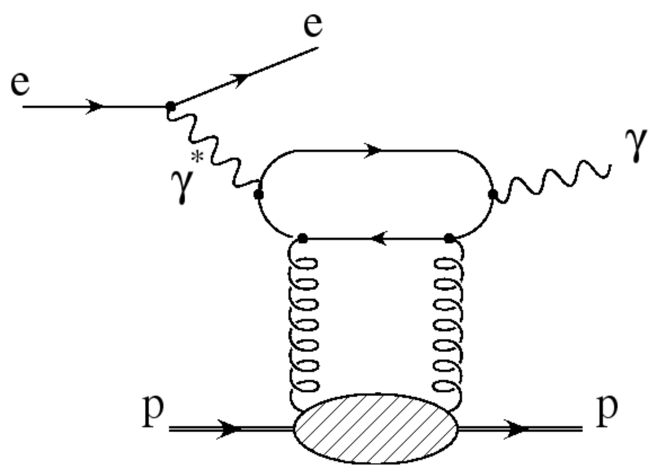
qq_L (Higher Twist)

qqg_T (Leading Twist)



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

Deeply Virtual Compton Scattering



• No vector meson wavefunction complications

• Cross sections suppressed by photon coupling

→ limited precision at HERA

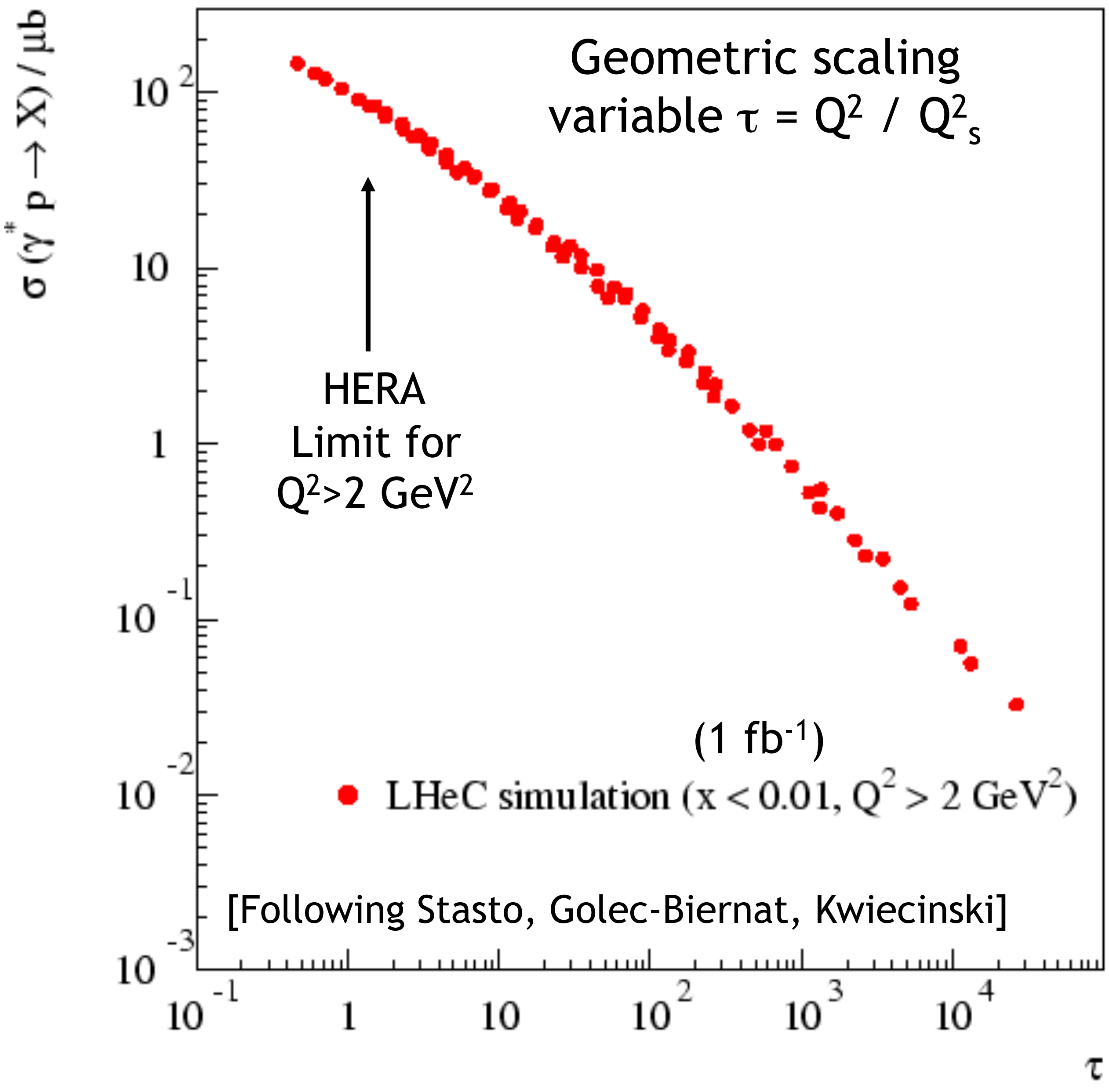
→ would benefit most from high lumi of LHeC and EIC

LHeC Simulations based on FFS model in MILOU generator

→ Double differential distributions in (x, Q^2) with 1^o and 10^o cuts for scattered electron

→Kinematic range determined largely by cut on p_T^γ (relies on ECAL performance / linearity at low energies)

Problem of Inclusive Data in a 1D nutshell: `Geometric Scaling'



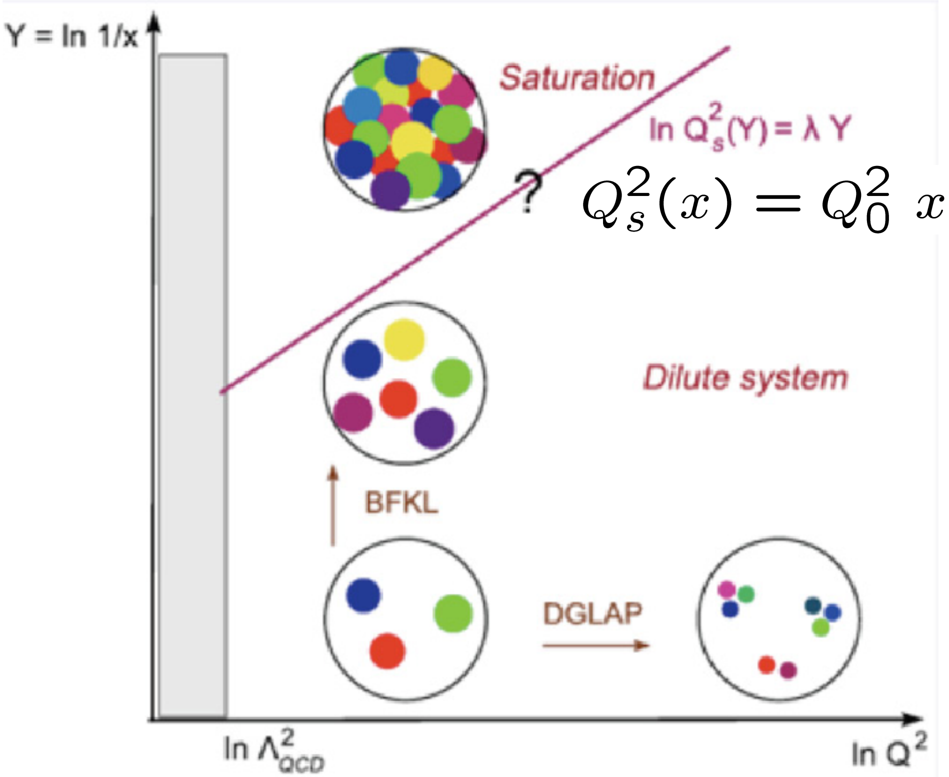
... HERA had very limited aceptance for $\tau<1$ ... **saturation effects depend mainly on data with $0.045 < Q^2 < 1$ GeV^2**

e.g. LHeC reaches $\tau \sim 0.15$ for $Q^2=1$ GeV^2 and $\tau \sim 0.4$ for $Q^2=2$ GeV^2

Can also be enhanced with nuclei.

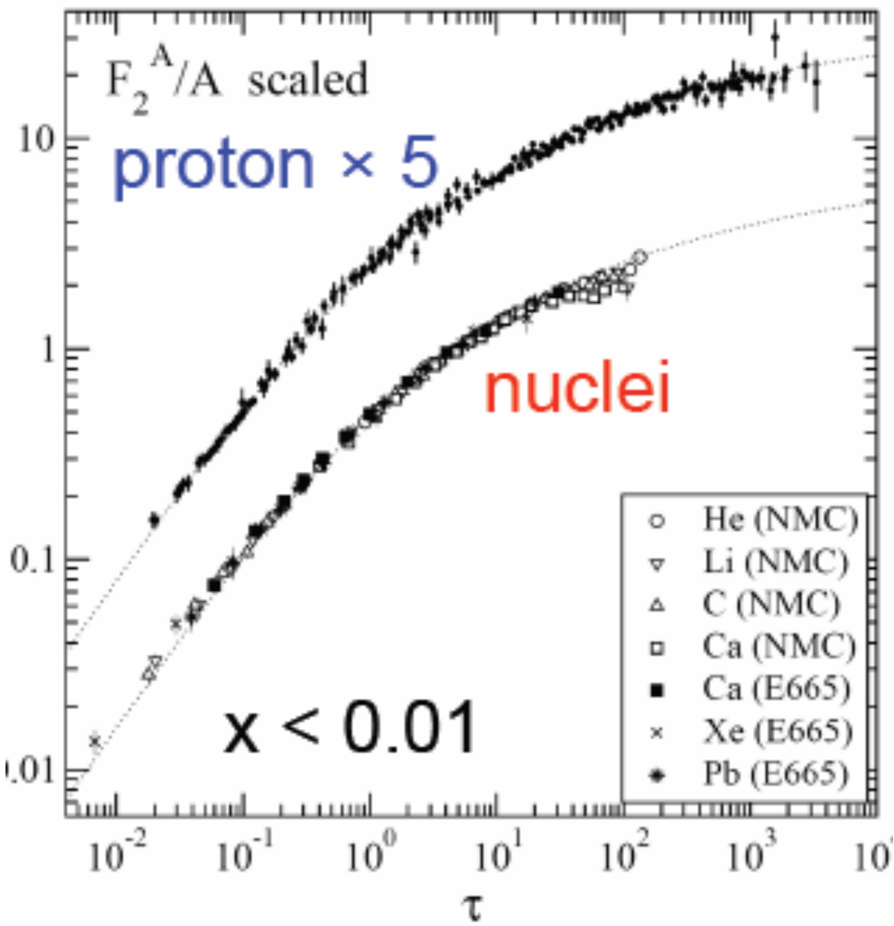
Non-linear effects in HERA and eA Data?

Lines of constant 'blackness' diagonal … scattering cross section appears constant along them … "Geometric Scaling"



$$Q_s^2(x) = Q_0^2 \; x^{-\lambda}$$

$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$



Something appears to happen around $\tau = Q^2/Q^2_s = 1$

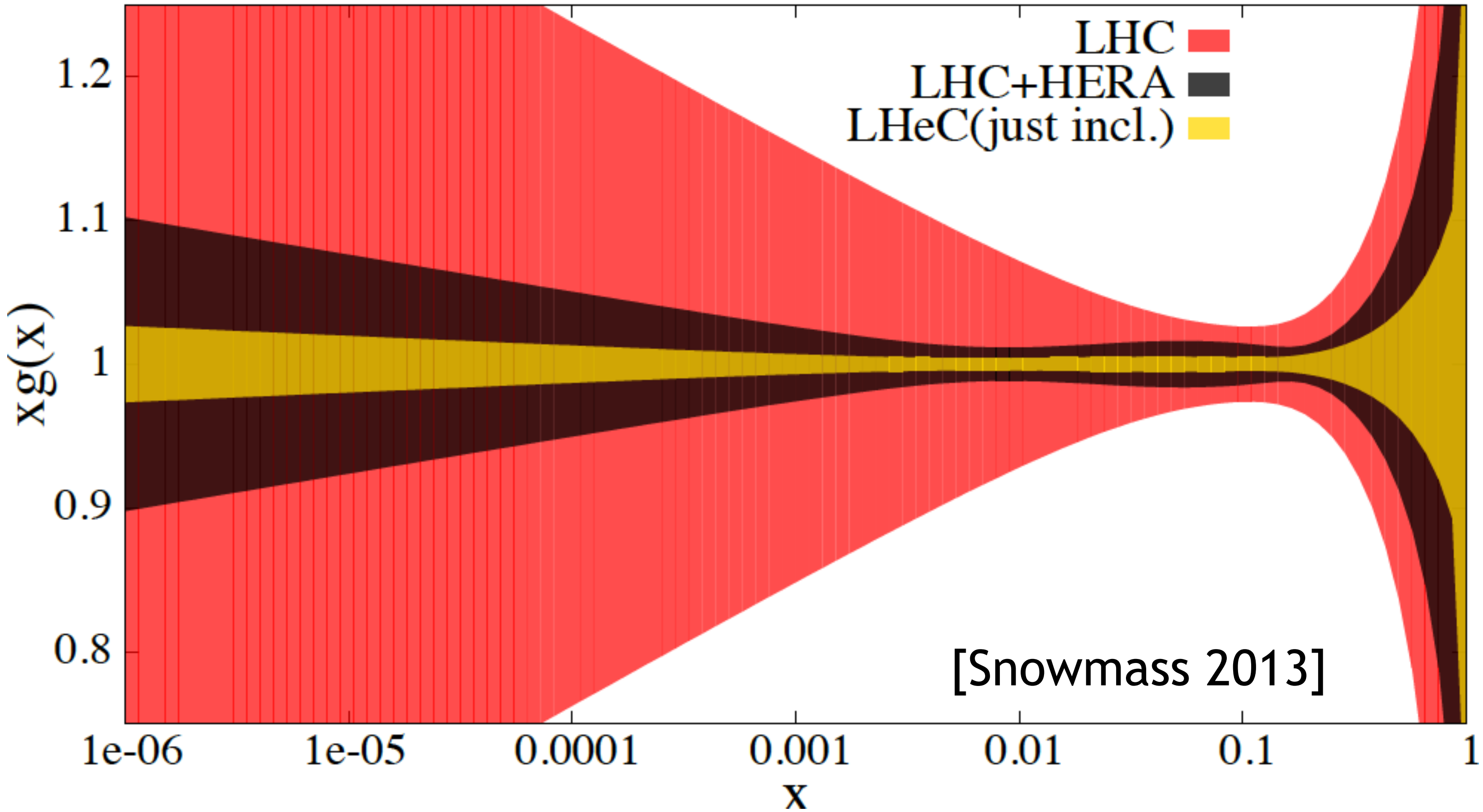
(confirmed in many analyses)

BUT … Q^2 small for τ <~ 1

… not easily interpreted in QCD

What can be done with LHC alone?

At Q2=1.9 GeV2

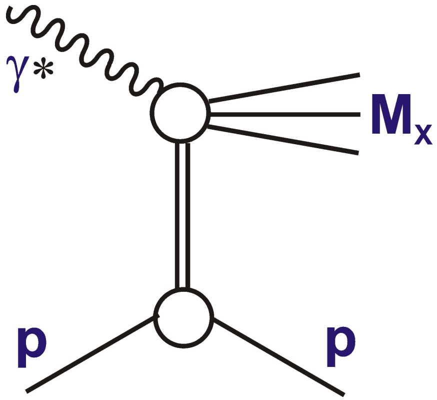


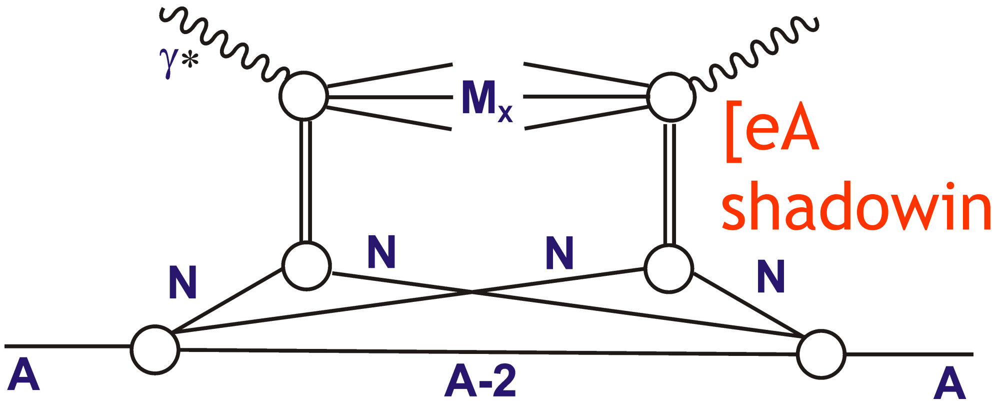
- LHC = current LHC W, Z and jet data
- Remarkable what can be achieved with LHC data alone
- Can we improve substantially? – Often already systs limited

F_2^D and Nuclear Shadowing

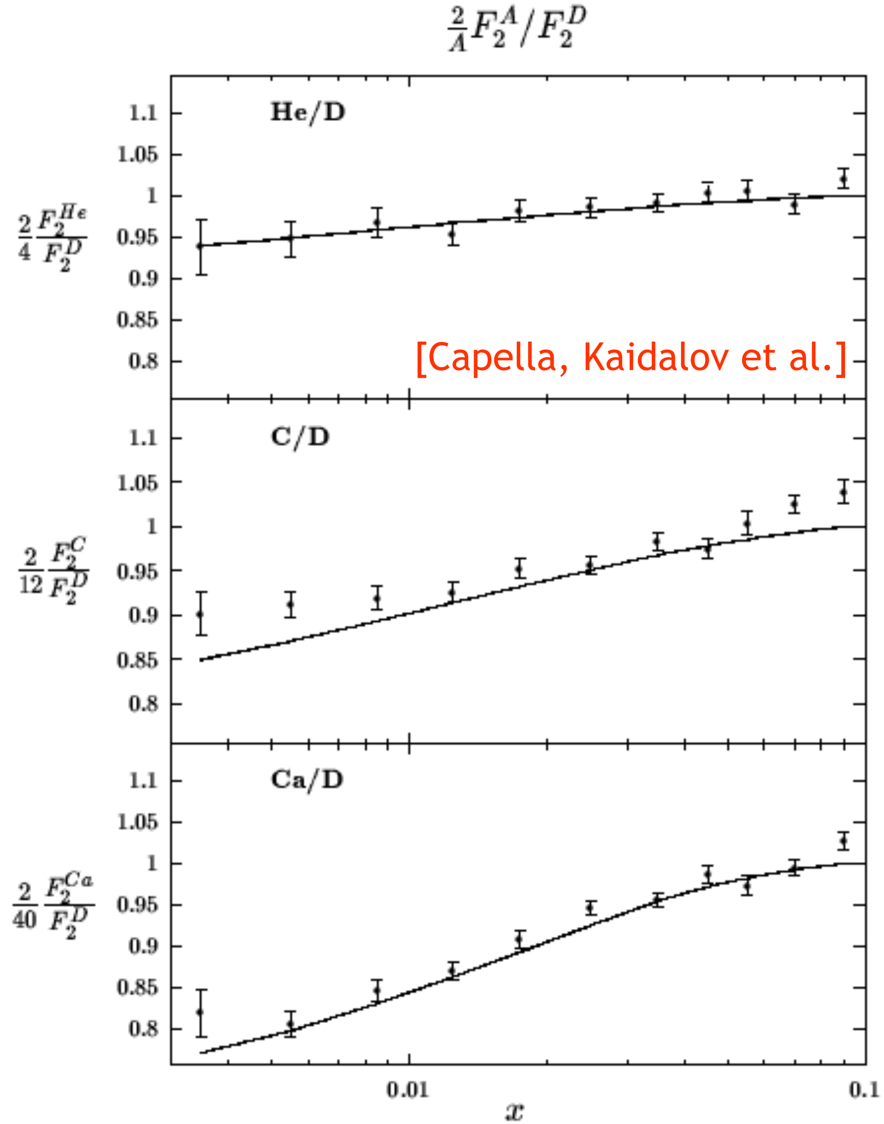
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]





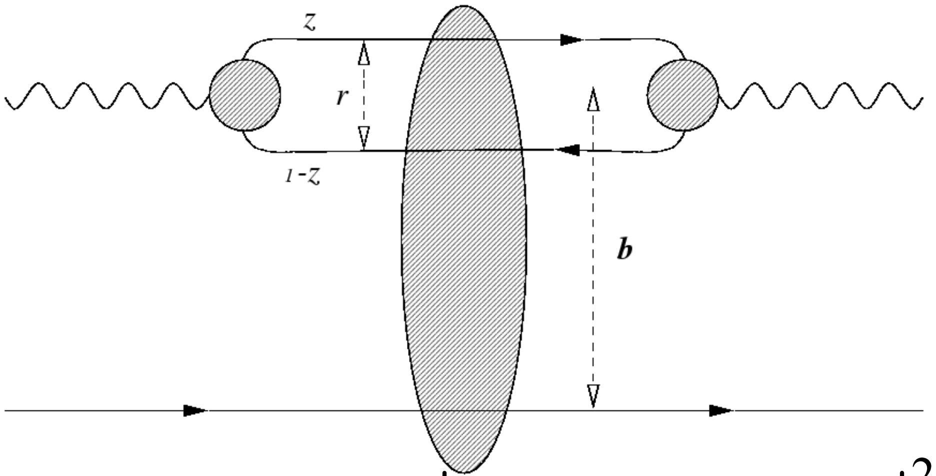
[eA shadowing]



… starting point for extending precision LHeC studies into eA collisions

Reminder : Dipole models

• Unified description of low x region, including region where Q^2 small and partons not appropriate degrees of freedom …



$$\sigma_{\gamma^* p}^{T,L}(x,Q^2) \sim \int dz\, d^2r\, \left|\psi_{\gamma^*}^{T,L}(z,r,Q^2)\right|^2 \sigma_{dipole}(x,r,z)$$

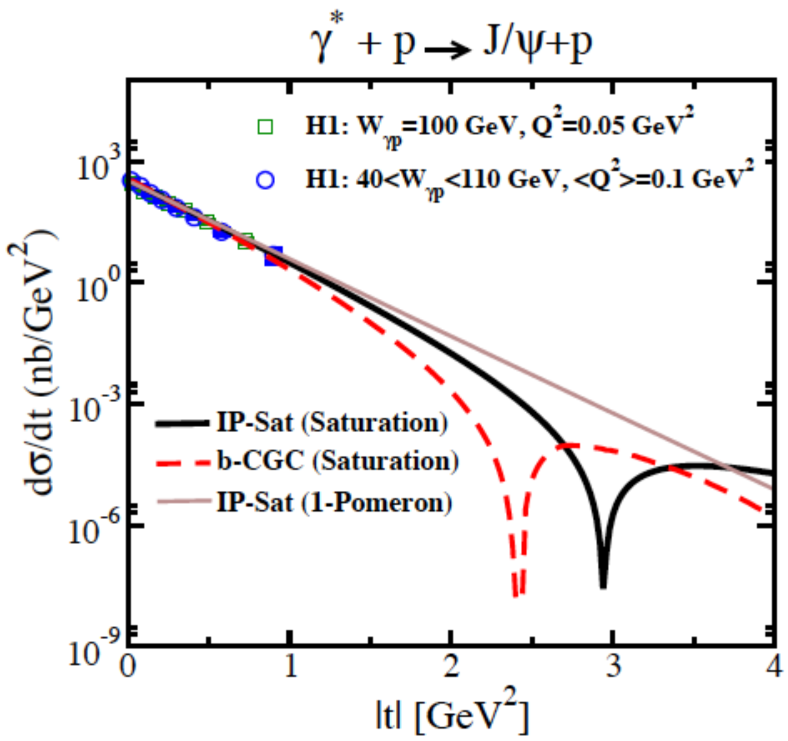
• Simple unified picture of many inclusive and exclusive processes … strong interaction physics in (universal) dipole cross section σ_{dipole}. Process dependence in wavefunction Ψ Factors

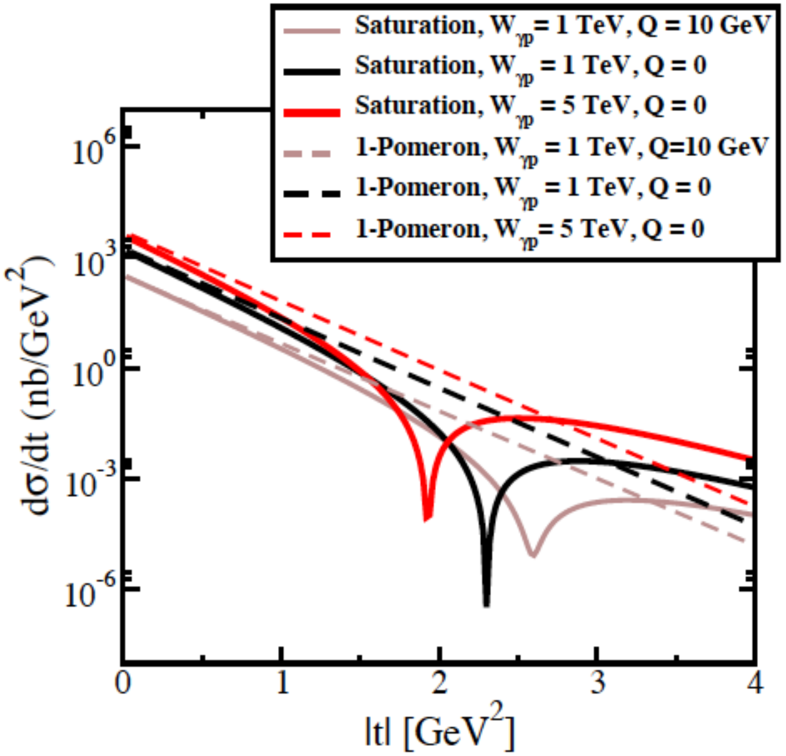
• qqbar-g dipoles also needed to describe inclusive diffraction

Signals in t Dependences: e.g. J/ψ Photoproduction

t dependences measure Fourier transform of impact parameter distribution. → Unusual features can arise from deviations from Gaussian matter distribution

e.g. Characteristic dips in model by Rezaeian et al, (just) within LHeC sensitive t range.





Leading Neutrons

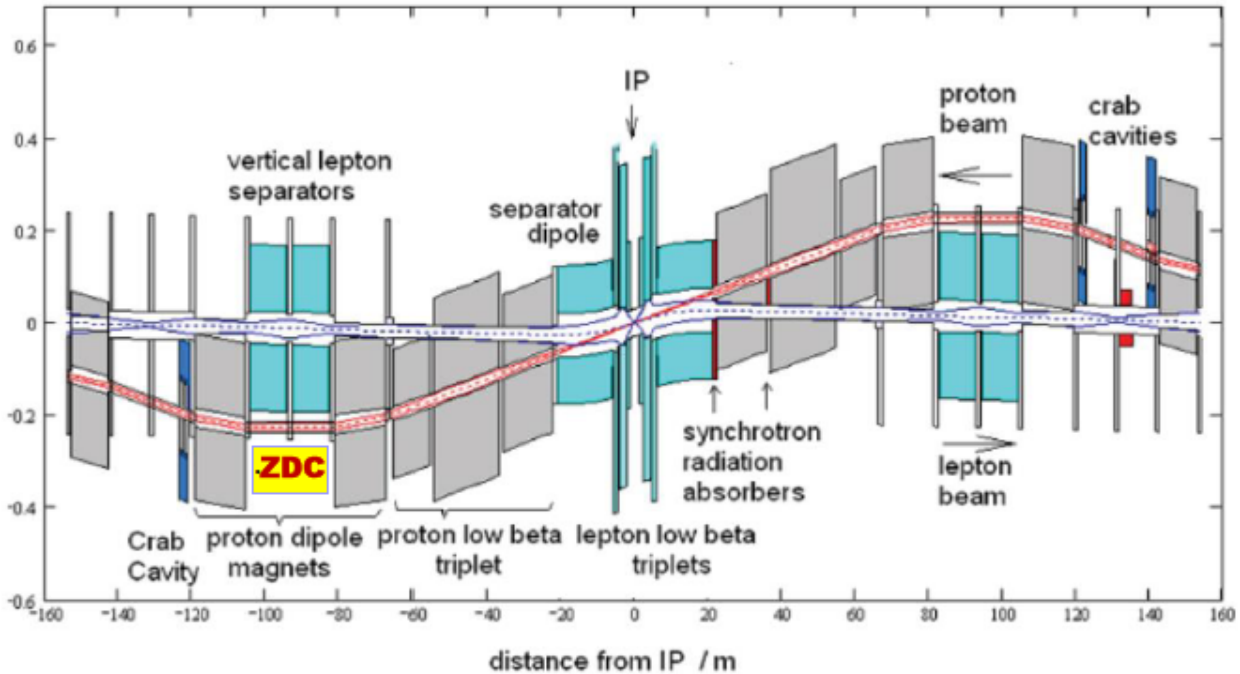
- Crucial in eA, to determine whether nucleus remains intact e.g. to distinguish coherent from incoherent diffraction

- Crucial in ed, to distinguish scattering from p or n

- Forward γ and n cross sections relevant to cosmic ray physics

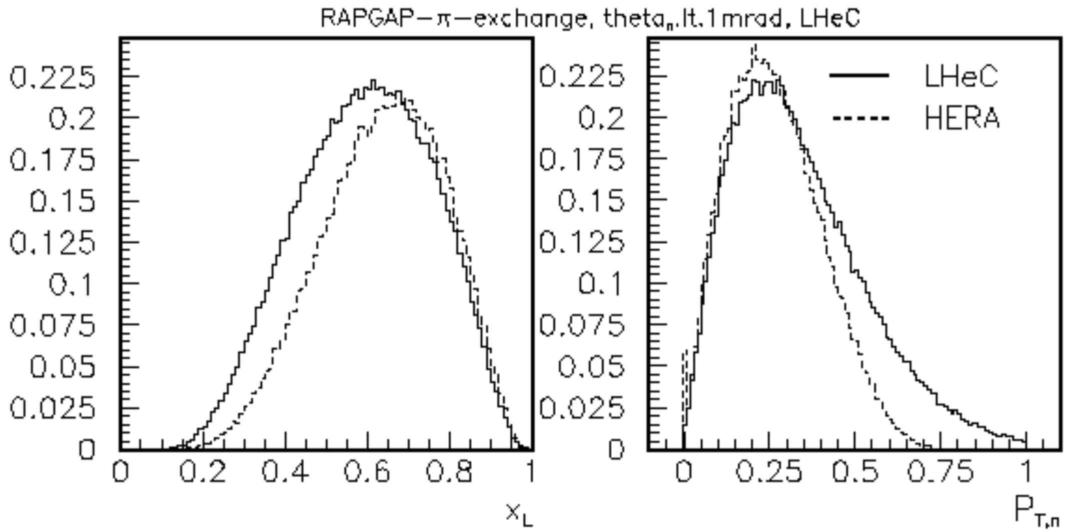
- Has previously been used in ep to study π structure function

Possible space at z ~ 100m (also possibly for proton calorimeter)



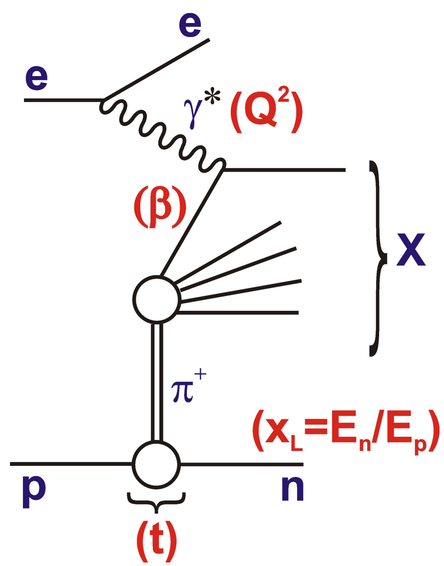
… to be further investigated

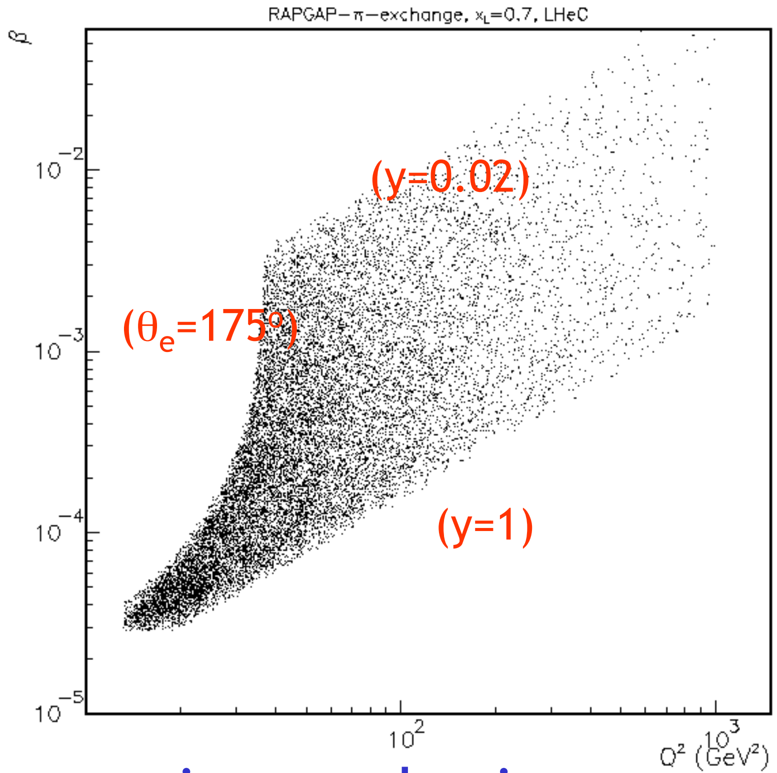
π Structure with Leading Neutrons



[Bunyatyan]

(RAPGAP MC model, E_p=7TeV, E_e=70GeV)



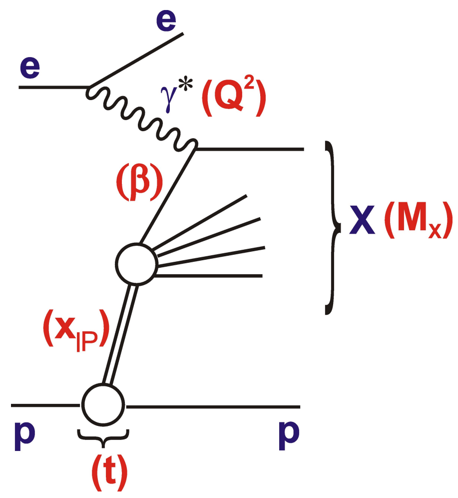


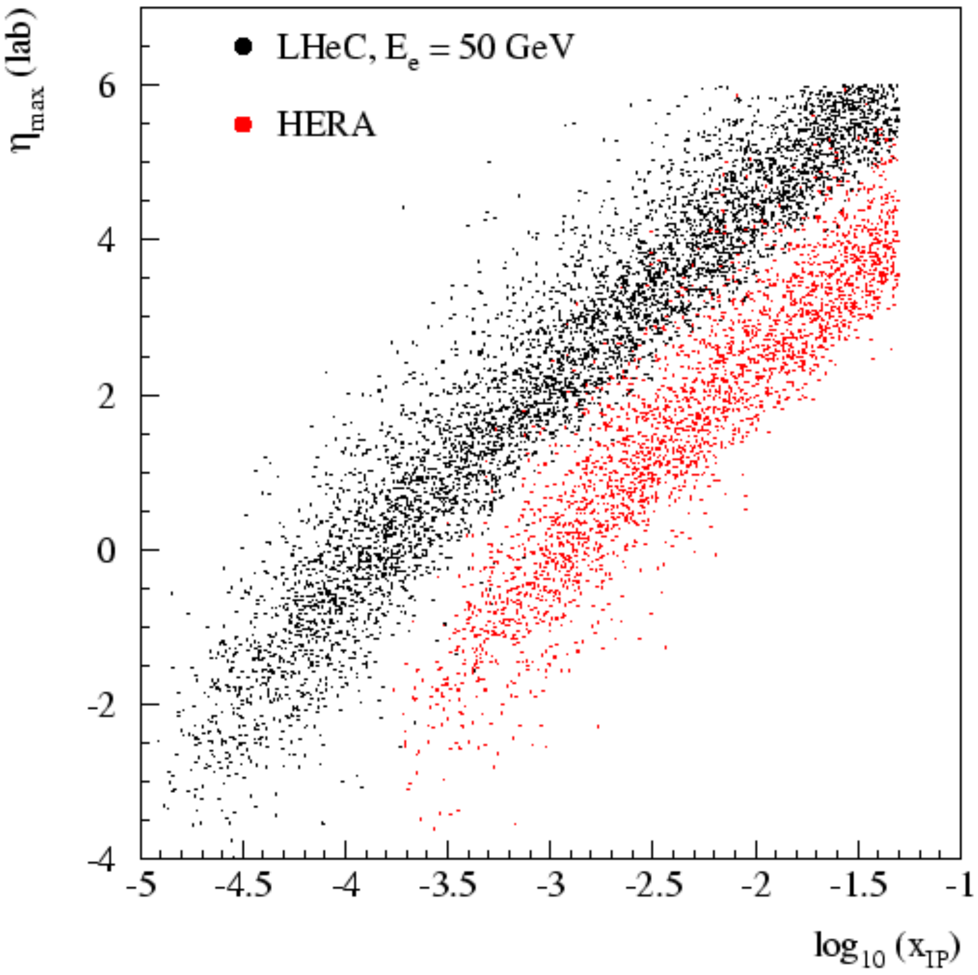
- With θ_n < 1 mrad, similar x_L and p_t ranges to HERA (a bit more p_t lever-arm for π flux).

- Extentions to lower β and higher Q^2 as in leading proton case. → F_2^π At $\beta<5.10^{-5}$ (cf HERA reaches $\beta\sim10^{-3}$)

Also relevant to absorptive corrections, cosmic ray physics …

Rapidity Gap Selection



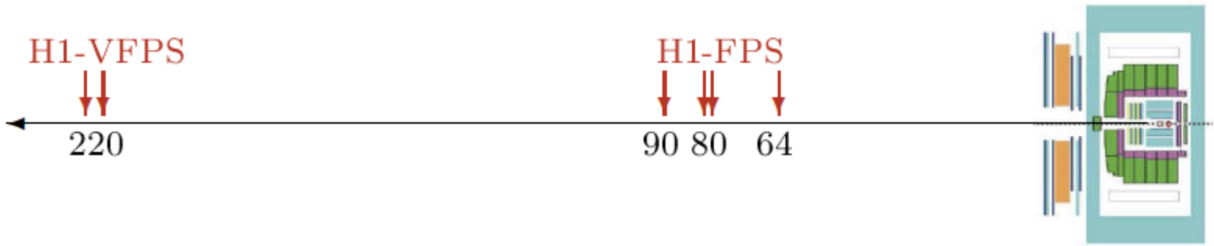


– η_{max} v ξ correlation entirely determined by proton beam energy

- Cut around η_{max} ~ 3 selects events with x_{IP} <~ 10^{-3} at LHeC (cf x_{IP} <~ 10^{-2} at HERA

Intact Proton Selection Methods beyond HERA

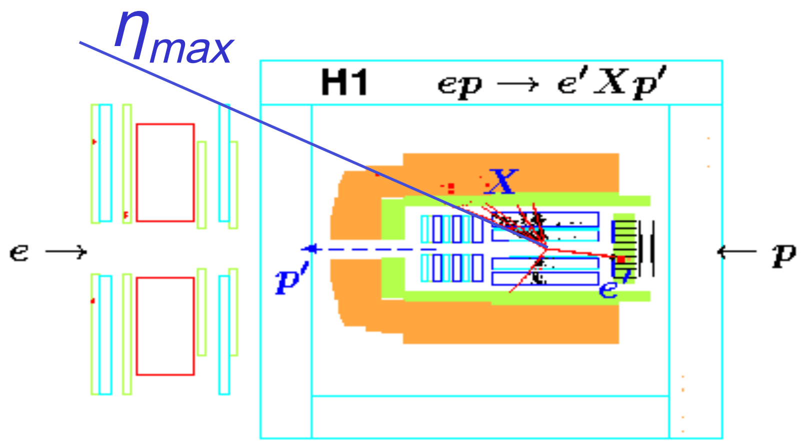
1) Measure scattered Proton in Roman Pots



- Allows t measurement, but limited by stats, p- tagging systs

2) Select Large Rapidity Gaps

-Limited by control over proton dissociation contribution



- Methods have very different systematics → complementary
- In practice, method 2 yielded lasting HERA results, because of statistical and kinematic range limitations of Roman pots
- Roman pots mainly contsrained t distributions
- **LHeC & EIC different → higher lumi + pot design from outset**