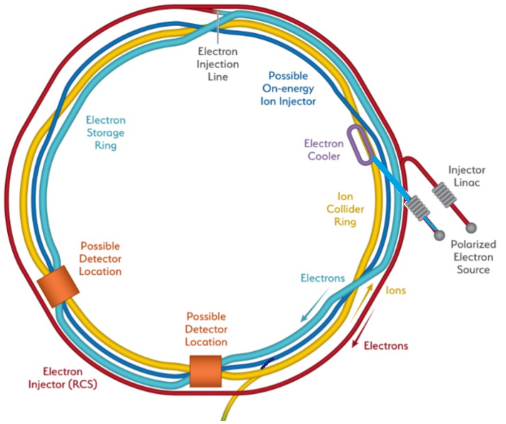
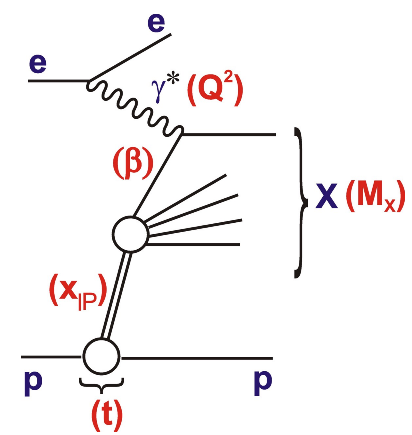
Inclusive Diffraction at the Electron Ion Collider



Paul Newman (Birmingham)

EIC-UG Theory Working Group
Seminar on Diffraction
29 April 2025

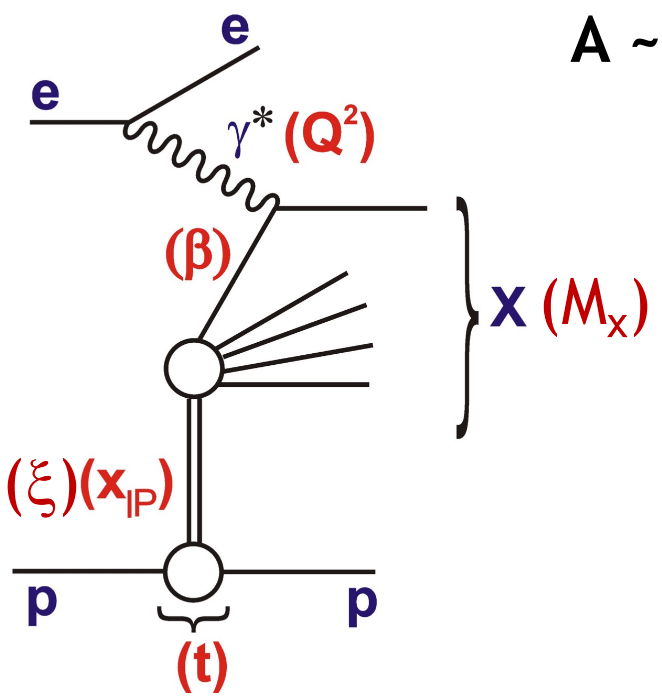


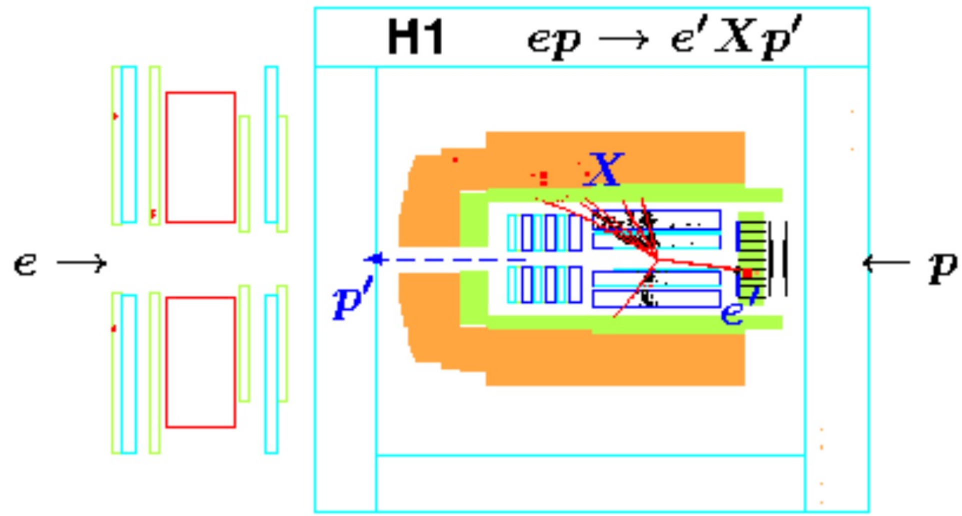
... based largely on work with
Nestor Armesto (Santiago de Compostela),
Anna Stasto (Penn State),
Wojciech Slominski (Jagiellonian, Cracow)

- Diffractive PDFs at LHeC (and EIC)
  Phys Rev D100 (2019) 074022
- Longitudinal Diffractive Structure Function @EIC
  Phys Rev D105 (2022) 074006
- Pomeron v Meson structure at the EIC
  Phys Rev D110 (2024) 054039

Inclusive Diffraction in Deep Inelastic Scattering

A ~10% leading twist contribution to DIS





- Virtual photon dissociation to multi-particle system X (M_X)
- Proton remains intact, losing small energy fraction ($\xi \equiv x_{IP}$)
- Four-momentum transfer squared at proton vertex = t
- Momentum fraction struck quark rel to exchange = β ($x = \beta\xi$)
- More generally, parton momentum fraction = z ($\geq \beta$)

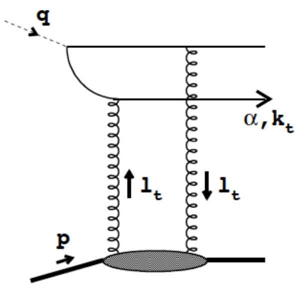
Diffractive DIS & Dipole Models

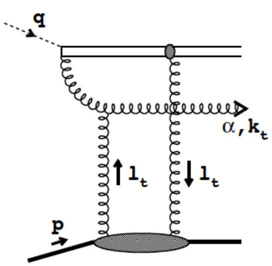
Link to Tobias' talk … BEKW model, Golec-Biernat & Wusthoff, and later evolutions based on dipole model and k_T factorisation

- qqbar dipole sufficient for VM, DVCS

- Inclusive DIS needs qqbar-g terms (and perhaps higher Fock states)

ZEUS data

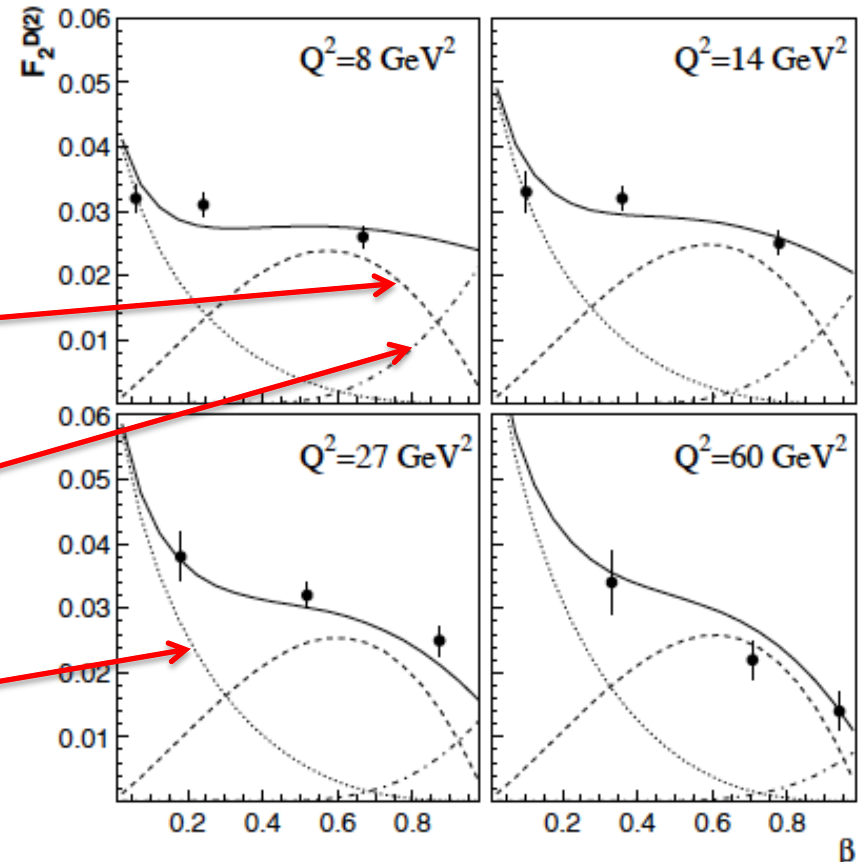




$q\bar{q}_T$ (Leading Twist)

$q\bar{q}_L$ (Higher Twist)

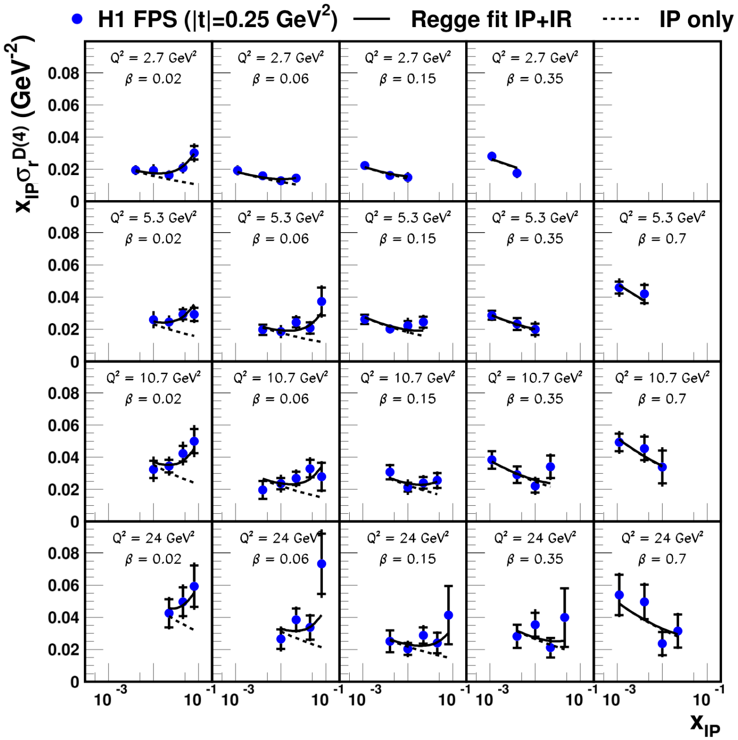
$q\bar{q}g_T$ (Leading Twist)



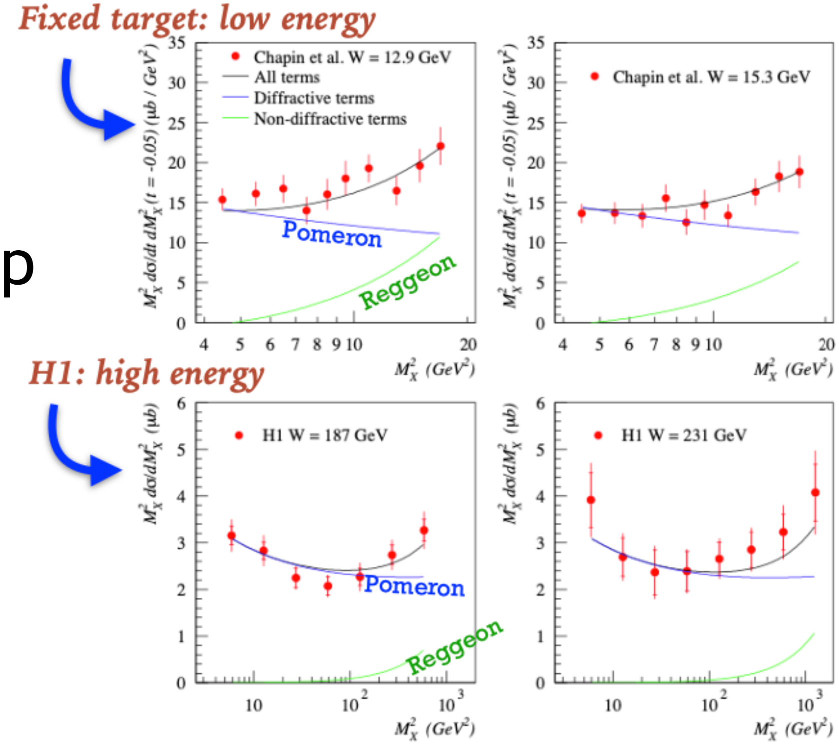
However, the main approach taken at HERA was collinear factorization and Diffractive parton densities → will be explored here …

Example diffractive data from HERA

DIS



γp

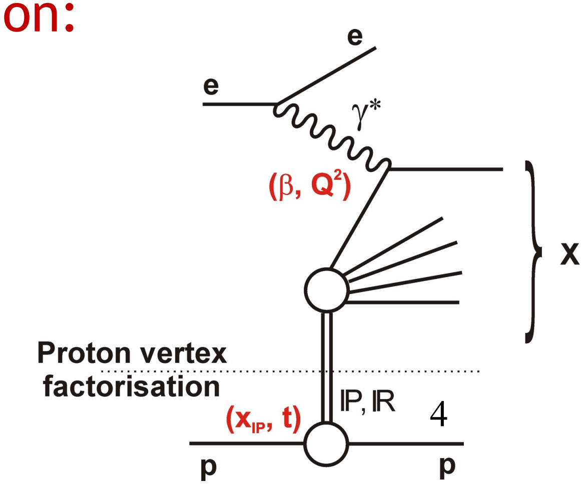


Experimentally motivated 2-component decomposition:

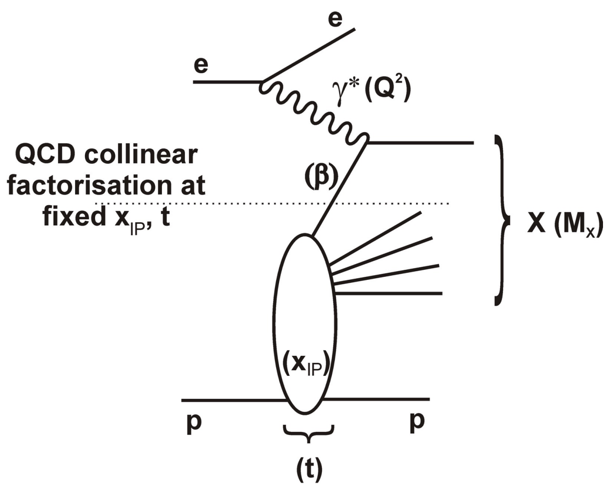
- Leading ‘Pomeron’ (IP) at low ξ
- Sub-leading ‘Reggeon’ or ‘Meson’ (IR) at largest ξ

Sub-leading term poorly constrained

- Isoscalar? – Isovector?
- Combination of multiple exchanges?
- Interference with pomeron part?



Semi-Inclusive QCD Factorisation (Proven for DIS)



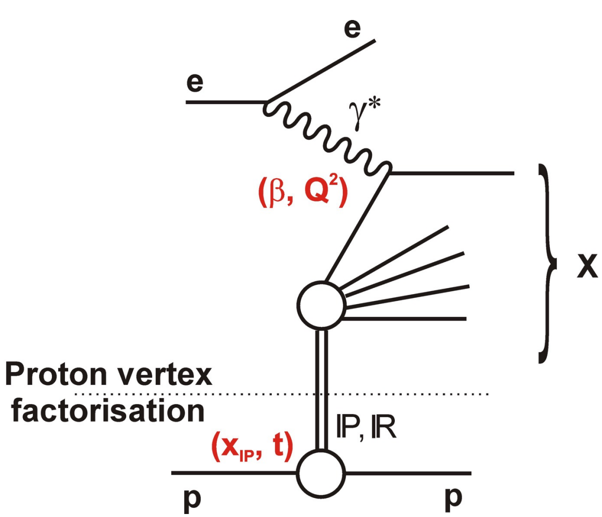
Can define

diffractive PDFs (DPDFs), f_i^D

$$d\sigma_{\text{parton } i}(ep \to eXY) = f_i^D(x, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^{ei}(x, Q^2)$$

At fixed (x_{IP} , t), DPDF Q^2 evolution obeys DGLAP in same way as proton PDFs

'Proton Vertex Factorisation' (Phenomenological)



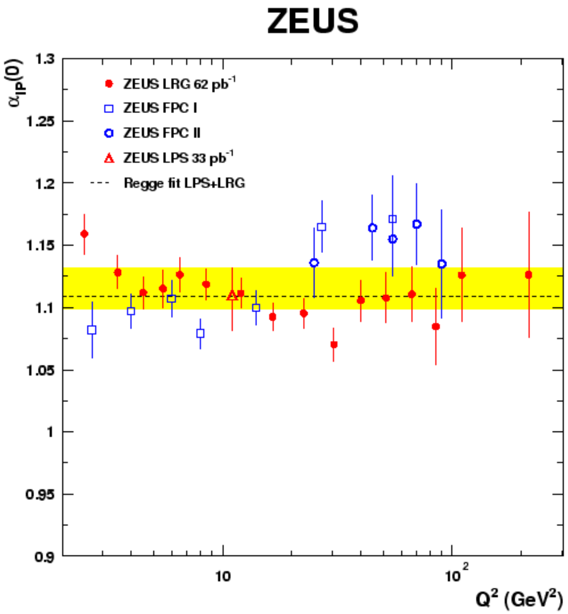
… completely separate (x_{IP} , t) from (β, Q^2) dependences ('Ingelman-Schlein model')

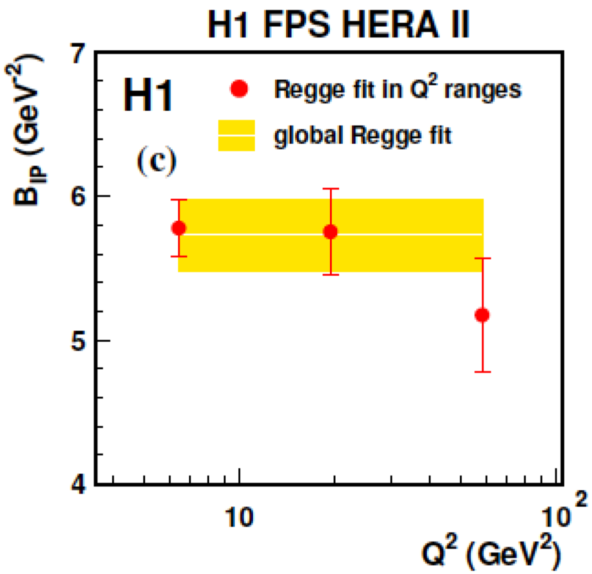
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}(\beta = x / x_{IP}, Q^2)$$

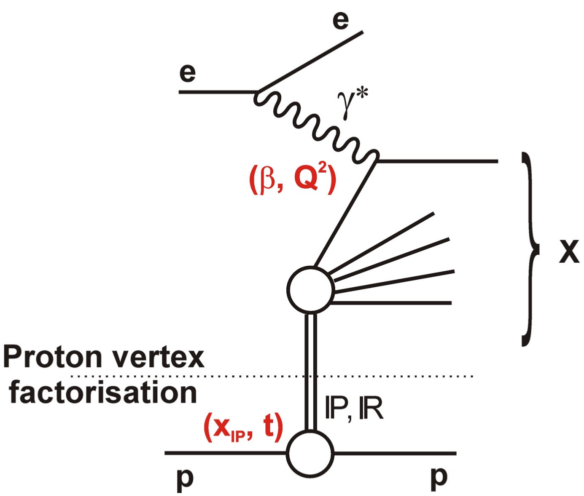
DPDFs f_i^{IP} measure partonic structure of the exchanged system ('pomeron', IP)

Flux factors $f_{IP/p}$ from Regge theory based on pomeron trajectory, $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} t$

Proton Vertex Factorisation & the Effective Pomeron of Diffractive DIS







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

e.g. From H1 FPS data:

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

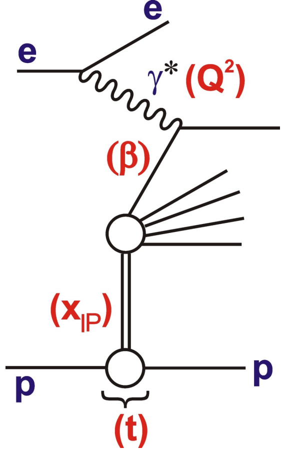
$$\alpha'_{IP} = 0.04 \pm 0.02\ (\text{exp.}) \pm 0.07\ (\text{model})\ \text{GeV}^{-2}$$

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

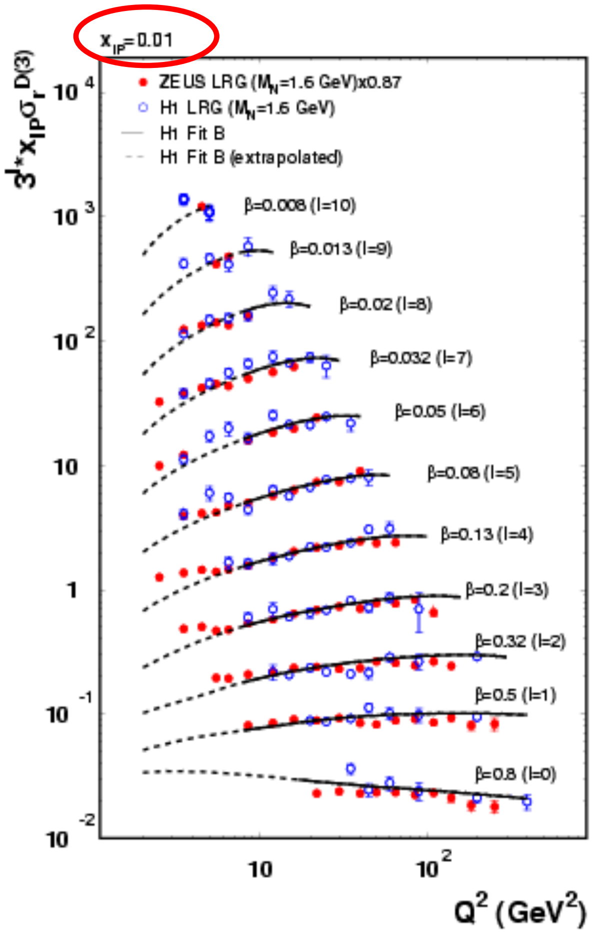
$\alpha_{IP}(0)$ consistent with soft IP → Dominantly soft exchange

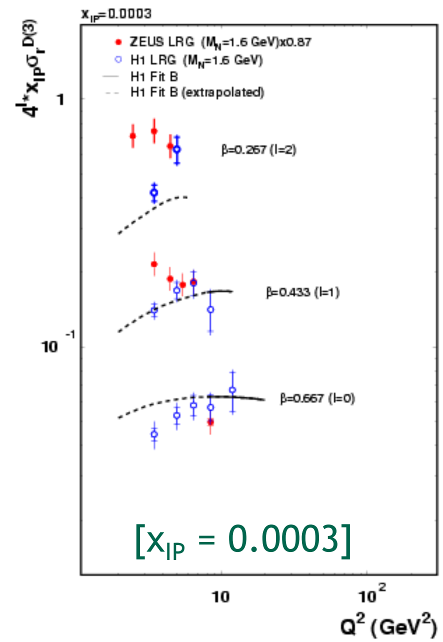
α_{IP}' smaller than soft IP → Absorptive effects?

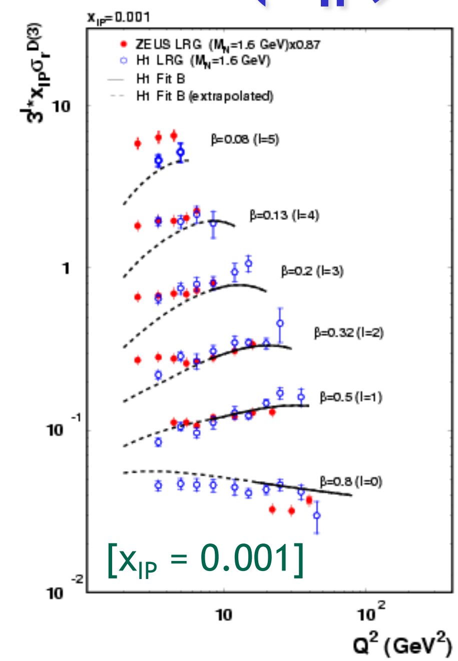
(β, Q^2) Dependences at fixed (x_{IP}, t)

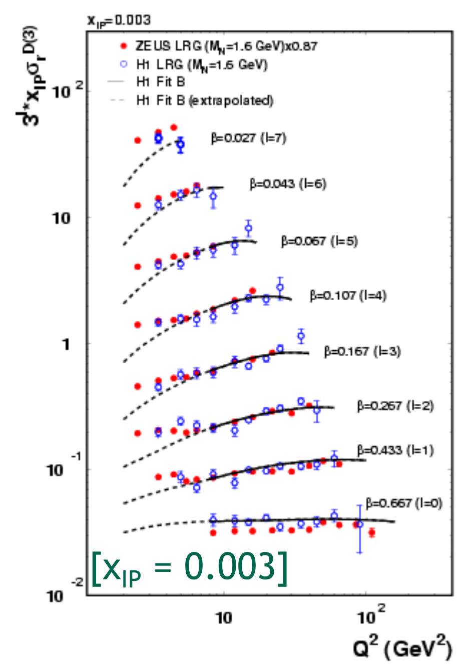


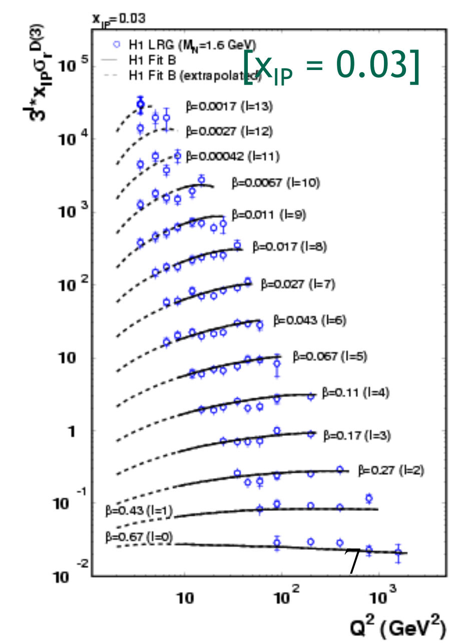
Leading twist and ~10% of total x-sec

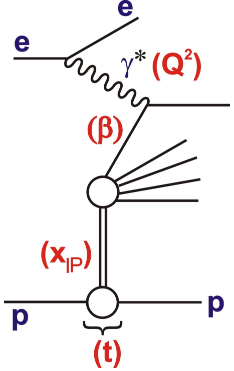






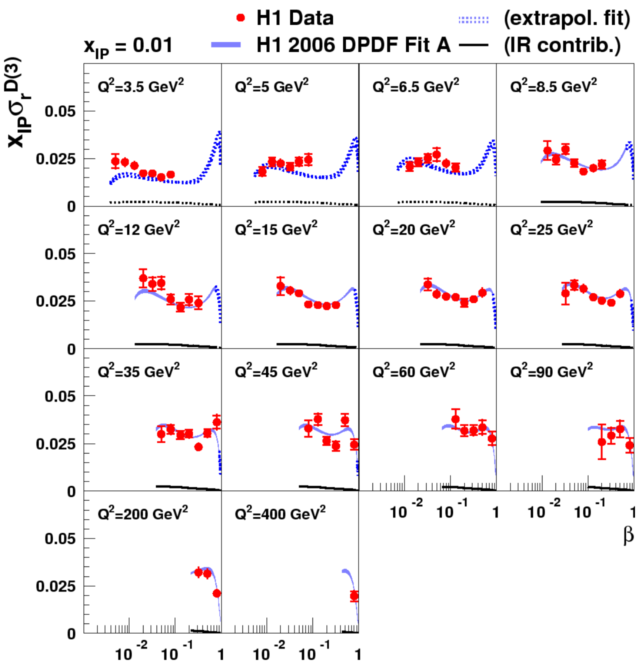


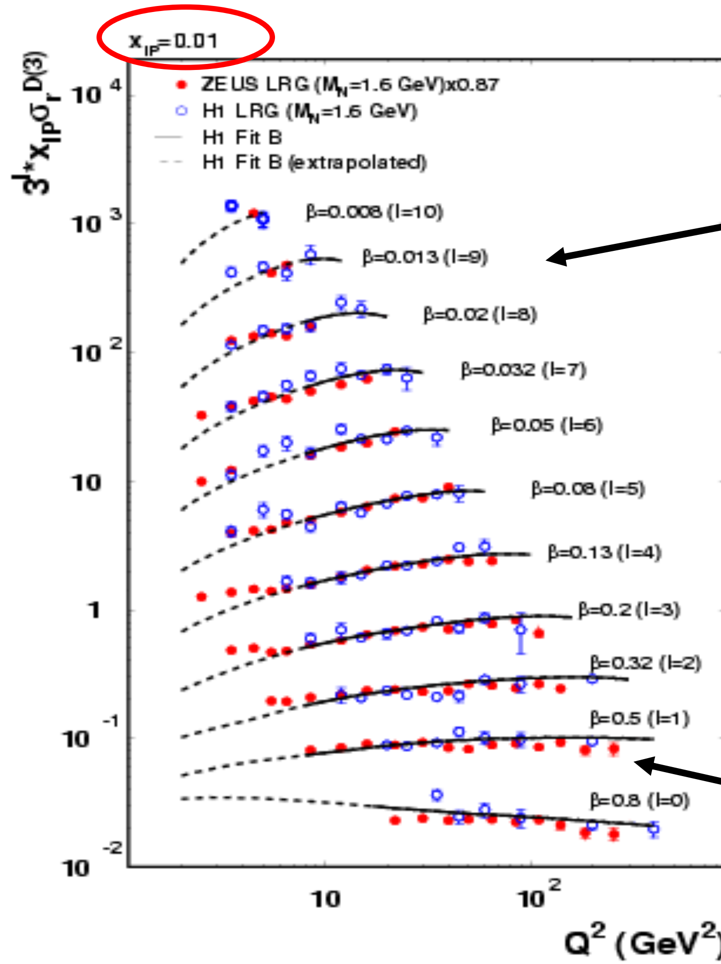


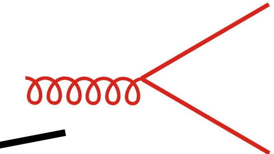


Sensitivity to Diffractive Quarks & Gluons

Similarly to Inclusive DIS …



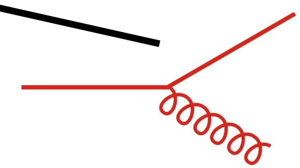




Q^2 dependence tells us gluon density via DGLAP eqns

…

except at highest β

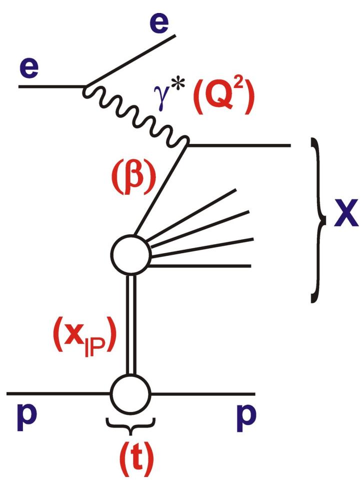


Diffractive cross section measures quark density

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

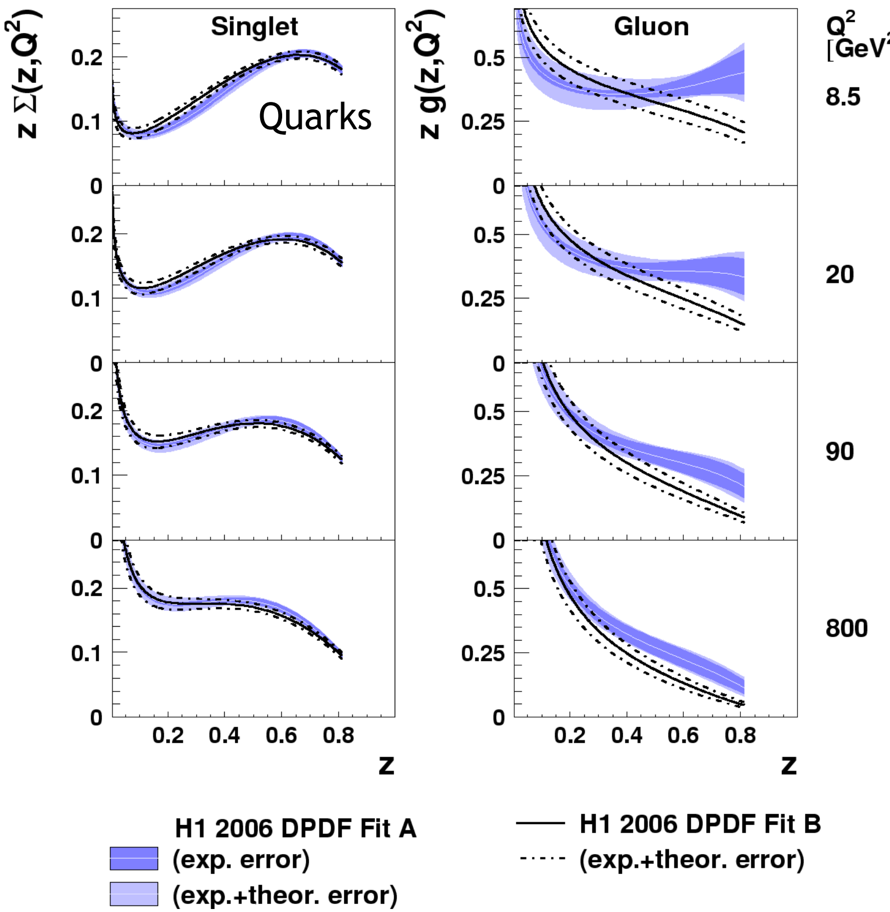
$$\frac{d\sigma_r^D}{d \ln Q^2} \sim \frac{\alpha_s}{2\pi} \left[P_{qg} \otimes g + P_{qq} \otimes q \right]$$

Diffractive Parton Densities (DPDFs)



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

e.g. H1



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

→ Widely used in model-building

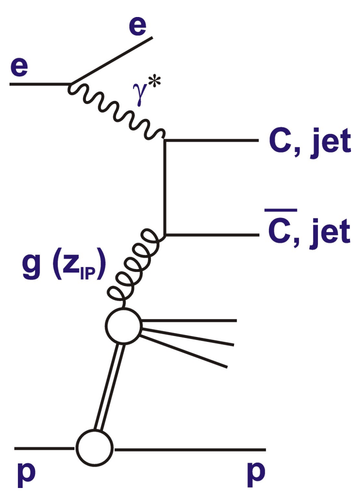
BUT

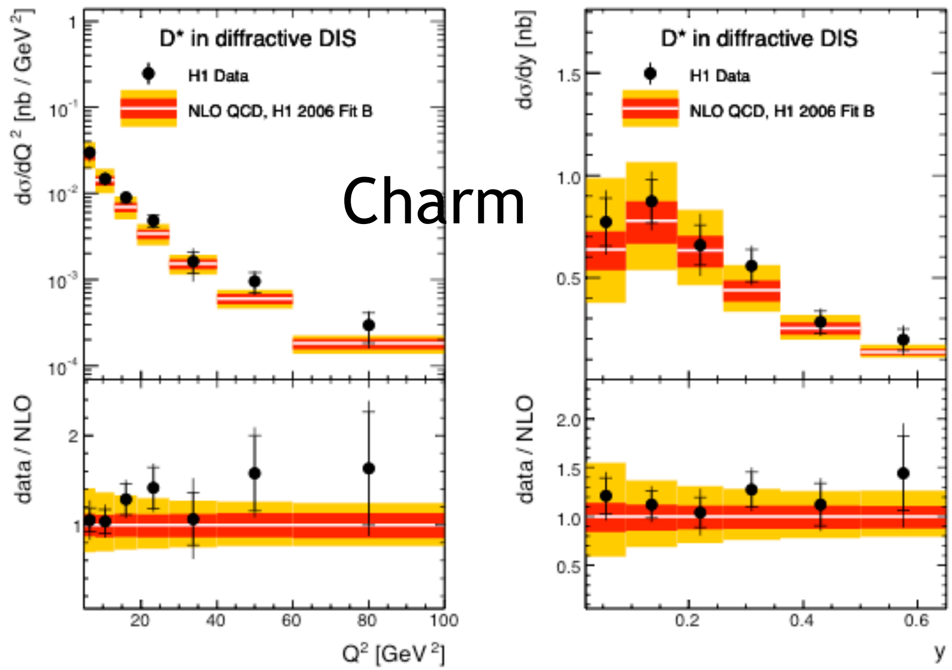
… High z region poorly constrained, particularly for gluon

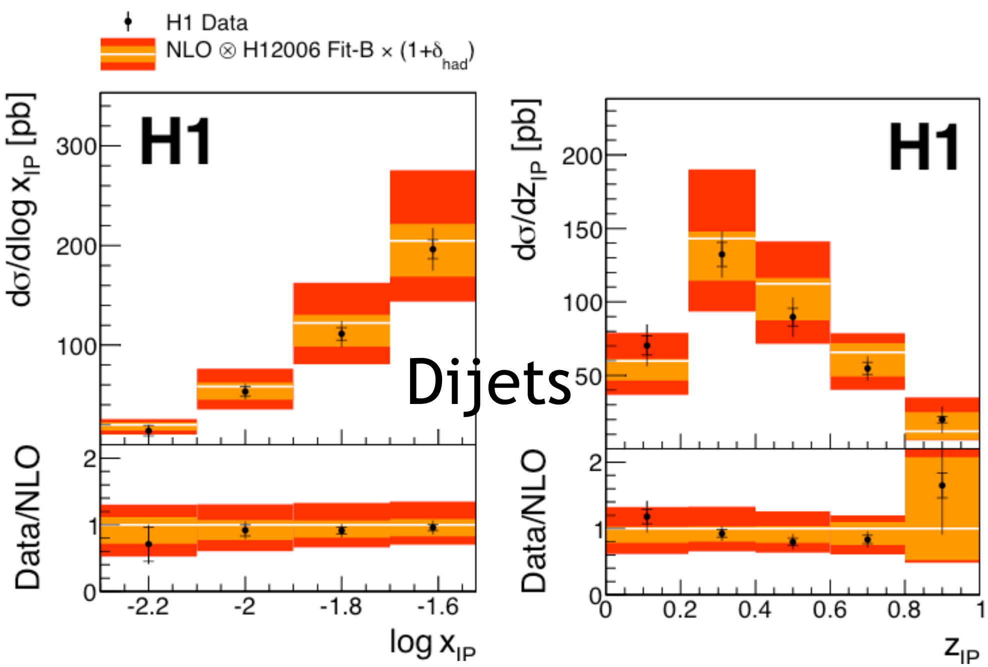
… Model for the Reggeon completely ad hoc (Always GRV π^0)

Testing Factorisation; eg HERA Jets & Charm

At level of precision achieved … good description of all variables in Diffractive DIS over a wide kinematic range



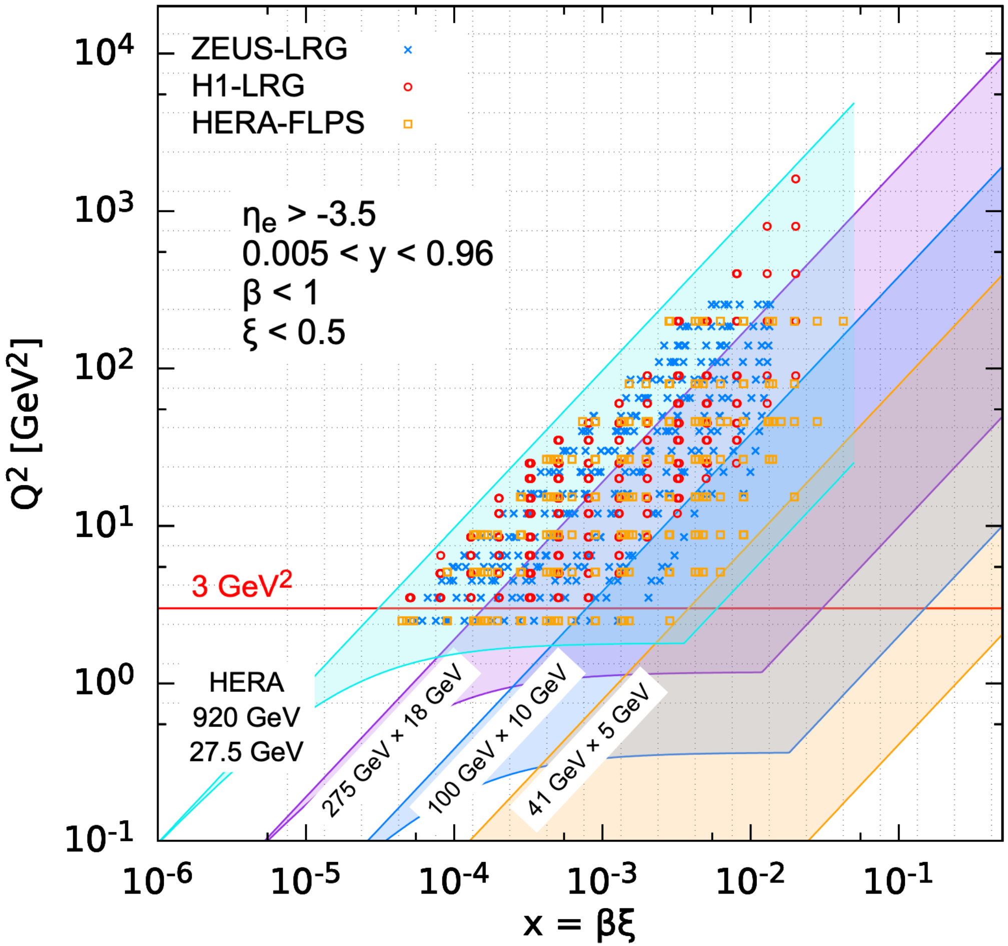




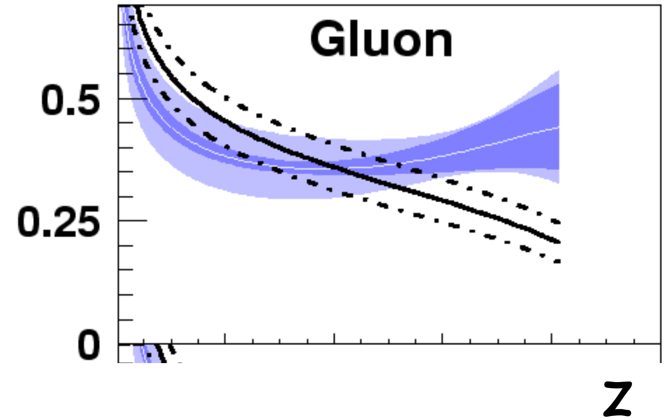
HERA conclusion:

DIS from universal(ish) soft colourless target … sometimes referred to as a `pomeron' with DPDFs that factorise … and should thus be applicable at EIC

Inclusive Diffraction at EIC



In the absence of fixed target DDIS data, EIC fills in the currently unknown high x (=βξ), low Q^2 region

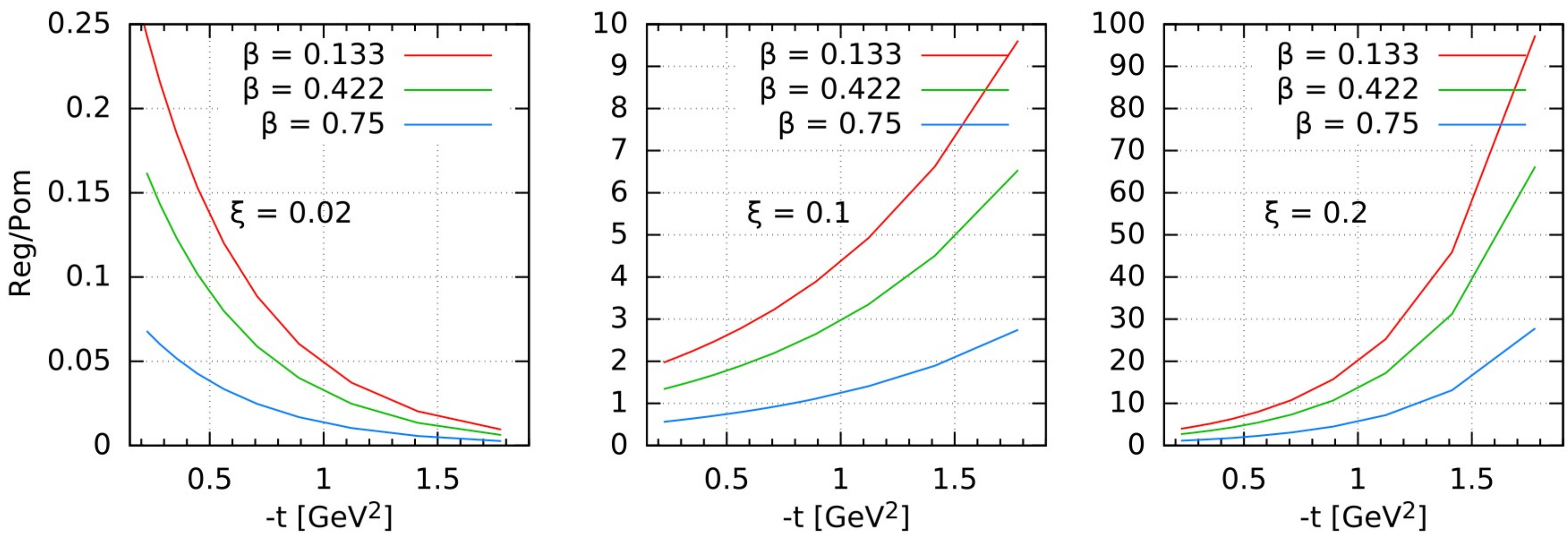


EIC complementarity to HERA:

- Large x → large β → constrains the DPDFs at large z
- Large x → large ξ → region of sensitivity to Reggeon (IR)

Expected Reggeon Contribution at EIC

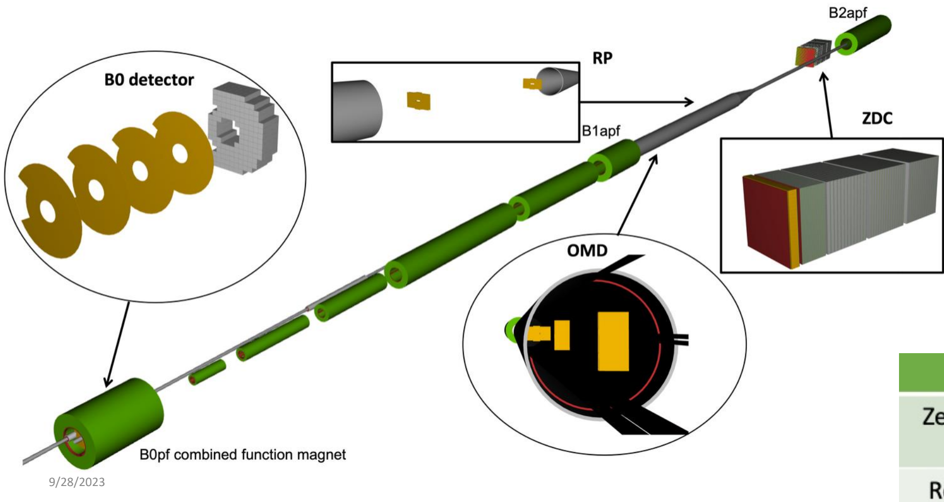
Ratio of IR / IP assuming HERA model



$\sigma_{red}^{D(4)}$ Reg/Pom for ep beams 18 GeV × 275 GeV
$Q^2 = 20$ GeV^2

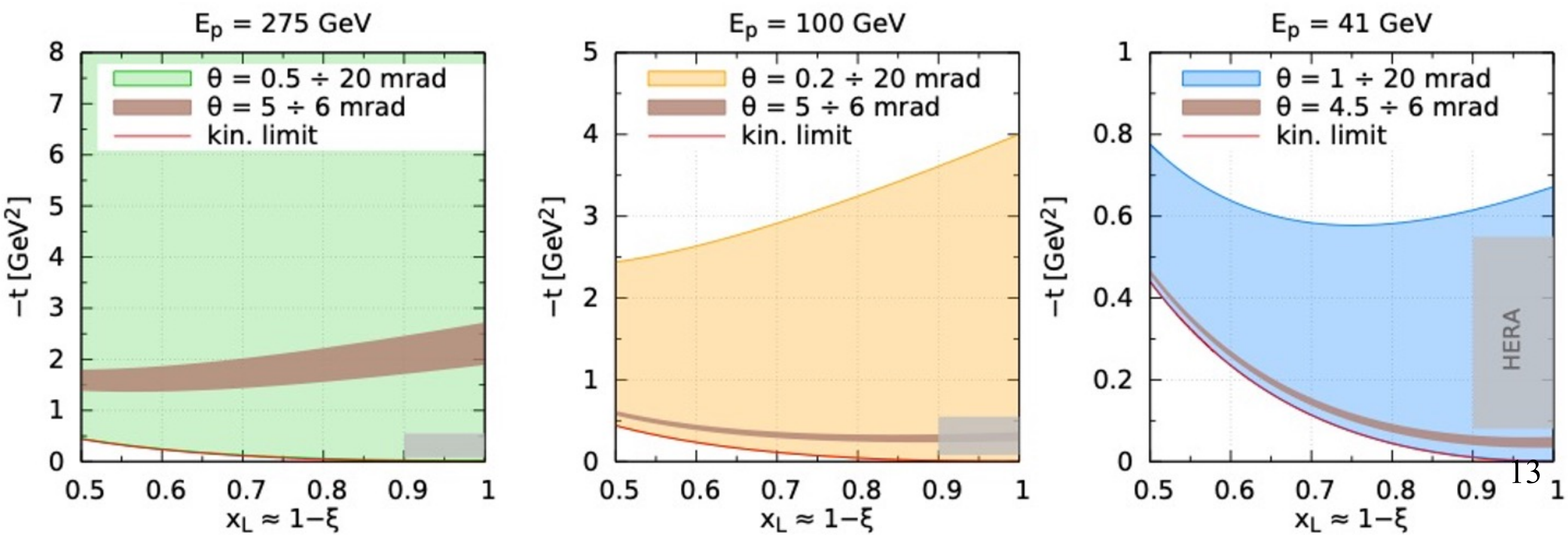
- Reggeon grows fast relative to Pomeron with ξ
- Also a t dependence to the ratio (generated by α', more model dependent)
- Approximate Q^2 independence
- Reggeon even more dominant at lower energies (~1/s suppressed)

Instrumentation and Acceptance at EIC

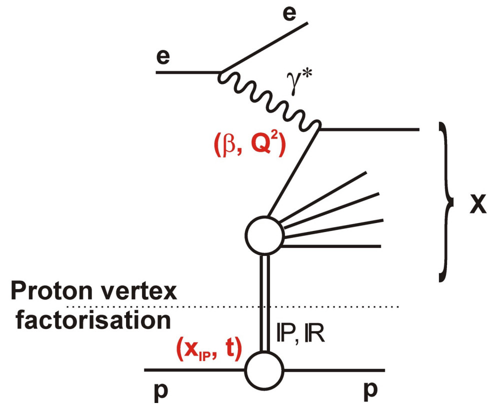


Hermetic beamline detectors have wide acceptance in ξ and t for scattered protons
… improved precision over Large Rapidity Gap method used at HERA

Detector	Acceptance	Particles
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5\ mrad$	Neutrons, photons
Roman Pots (2 stations)	$0^* < \theta < 5.0\ mrad$ (*10σ beam cut)	Protons, light nuclei
Off-Momentum Detectors (2 stations)	$0 < \theta < 5.0\ mrad$	Charged particles
B0 Detector	$5.5 < \theta < 20\ mrad$	Charged particles, tagged photons



Producing EIC Pseudodata



$$F_2^{D(4)} = f_{I\!P}(x_{I\!P}, t) F_{I\!P}(\beta, Q^2) + n_{I\!R} \cdot f_{I\!R}(x_{I\!P}, t) F_{I\!R}(\beta, Q^2)$$

- F_{IP} and f_{IP} from fitted results from ZEUS at HERA
- F_{IR} from GRV pion, f_{IR} from educated guesswork

$$f_{I\!P}(x_{I\!P}, t) = A_{I\!P} \cdot \frac{e^{B_{I\!P} t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}} \quad ; \quad f_{I\!R}(x_{I\!P}, t) = A_{I\!R} \cdot \frac{e^{B_{I\!R} t}}{x_{I\!P}^{2\alpha_{I\!R}(t)-1}}$$

(HERA "Standard Model")

Considering scenarios with: E_px E_e = 275 GeV x 18 GeV (100 fb^{-1} or 10 fb^{-1})

E_px E_e = 41 GeV x 5 GeV (10 fb^{-1})

Logarithmically spaced binning in two different schemes (results not very sensitive

'Dense':

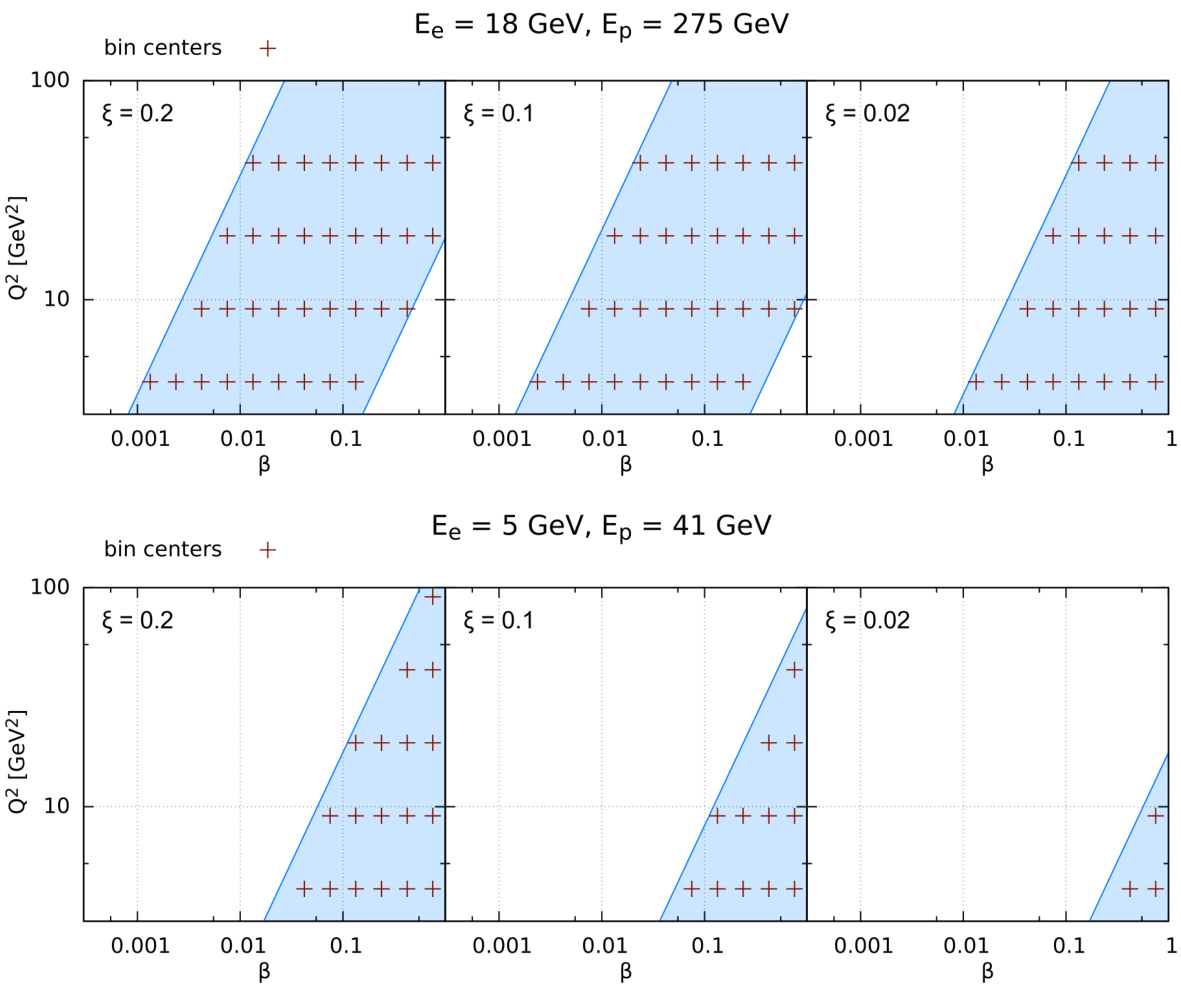
$-t \in [0.01, 2]$ GeV^2 (23 bins);
$\xi \in [0.0004, 0.4]$ (24 bins);
$\beta \in [0.001, 1]$ (12 bins);
$Q^2 \in [3, 62]$ GeV^2 (4 bins).

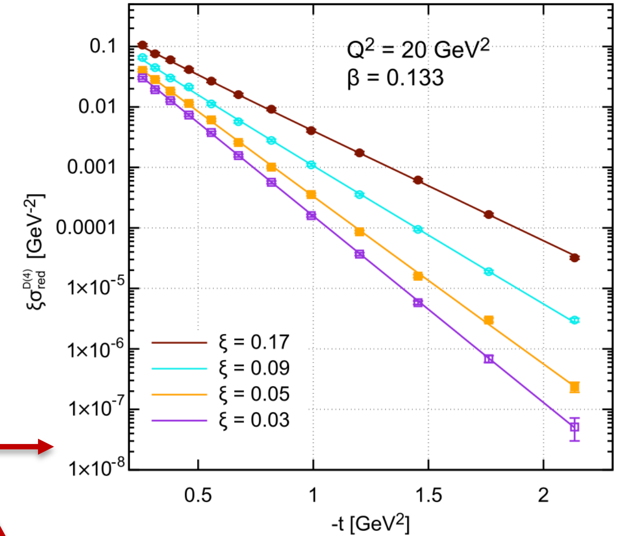
'Sparse':

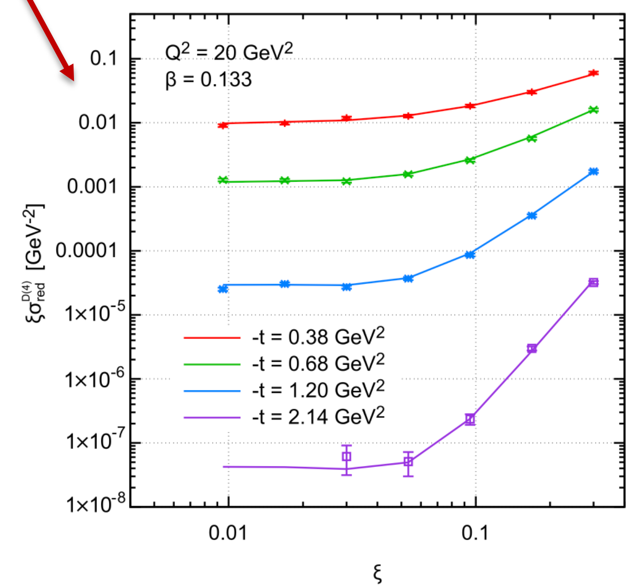
$-t \in [0.01, 2]$ GeV^2 (14 bins);
$\xi \in [0.0004, 0.4]$ (18 bins);
$\beta \in [0.001, 1]$ (12 bins);
$Q^2 \in [3, 130]$ GeV^2 (5 bins).

Uncertainties taken to be 5% (uncorrelated) ⊕ 2% normalisation

Pseudodata Coverage







- Statistical uncertainties remain manageable up to $|t|\sim 2$ GeV^2 even for 10fb^{-1}

- Kinematic coverage in $x<10^{-2}$ 'pure IP' region limited at lower $\sqrt{s}$ values

Parameterisation for Fitting Pseudodata

- Treat IP and IR contributions as symmetrically as possible …

- Light quark flavour separation not possible in inclusive NC fits.
  … for both IP and IR, fit for gluon and for sum of quarks

- Generic PDF parameterisation at starting scale, $Q_0^2 = 1.8$ GeV^2:

$$f_k^m(x, Q_0^2) = A_k \; x^{B_k} \, (1-x)^{C_k} \, (1 + D_k \,) \qquad [m = IP, IR, \;\; k = q, g]$$

- Following sensitivity studies, a suitable choice is …
  - f_q^{IP} has A, B and C params
  - f_g^{IP} has A, B and C params
  - f_q^{IR} has A, B, C and D params
  - f_g^{IR} has A, B and C params

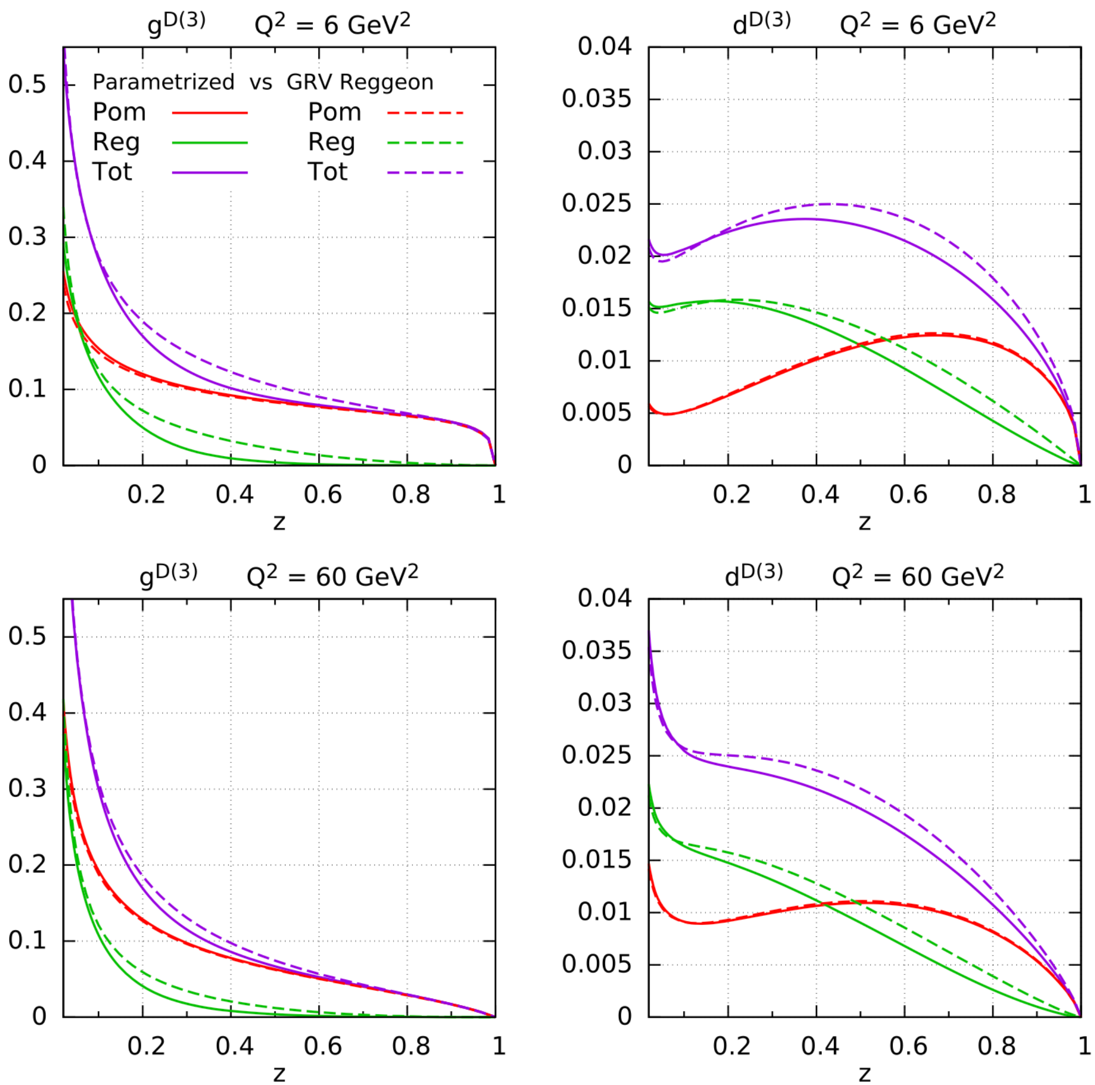
- In addition, fit for $\alpha(0), \alpha', B$ parameters from pomeron and meson flux factors

$$\frac{e^{B_m t}}{\xi^{2\alpha_m(t)-1}}$$

where $\alpha_m(t) = \alpha_m(0) + \alpha'_m \, t$

Recovering Pomeron & Reggeon Inputs

[High energy, high luminosity scenario]



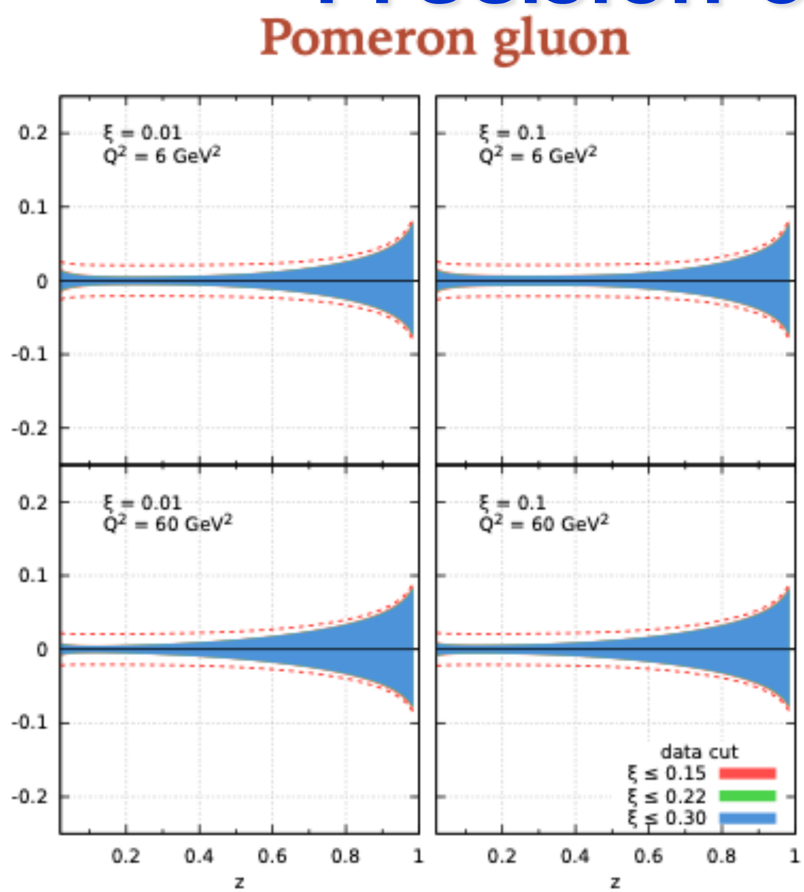
Fit results with free Reggeon parameterisation (solid) made to pseudodata based on GRV pion (dashed)

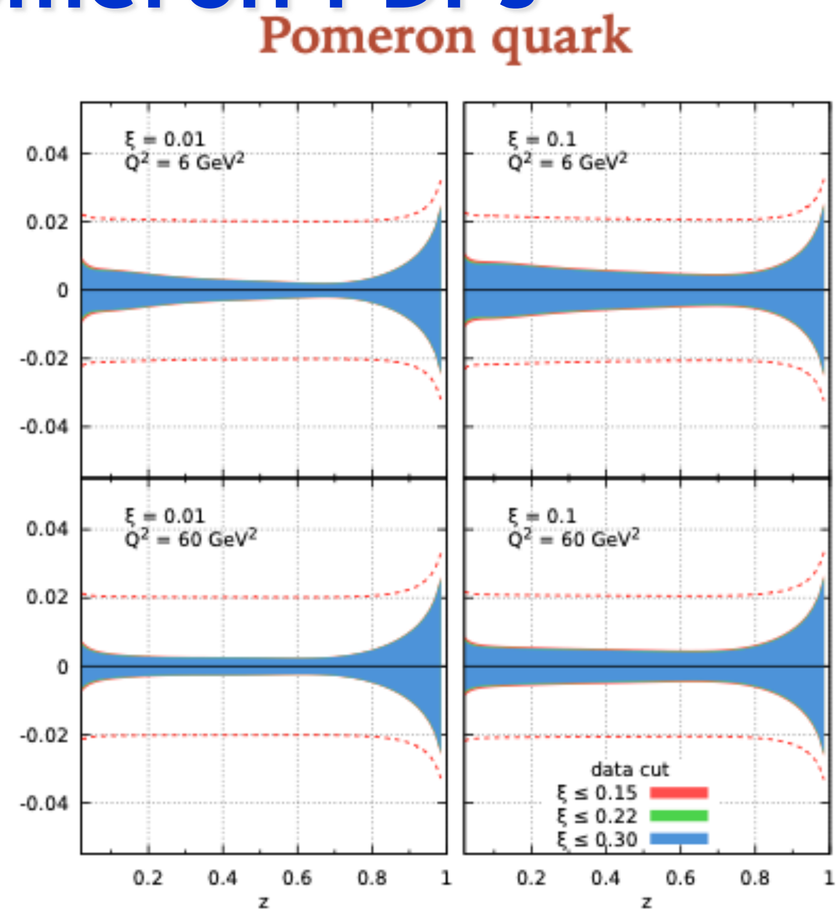
...

Reasonable reproduction of Reggeon input

Pomeron reproduced essentially perfectly (by construction)

Precision on Pomeron PDFs

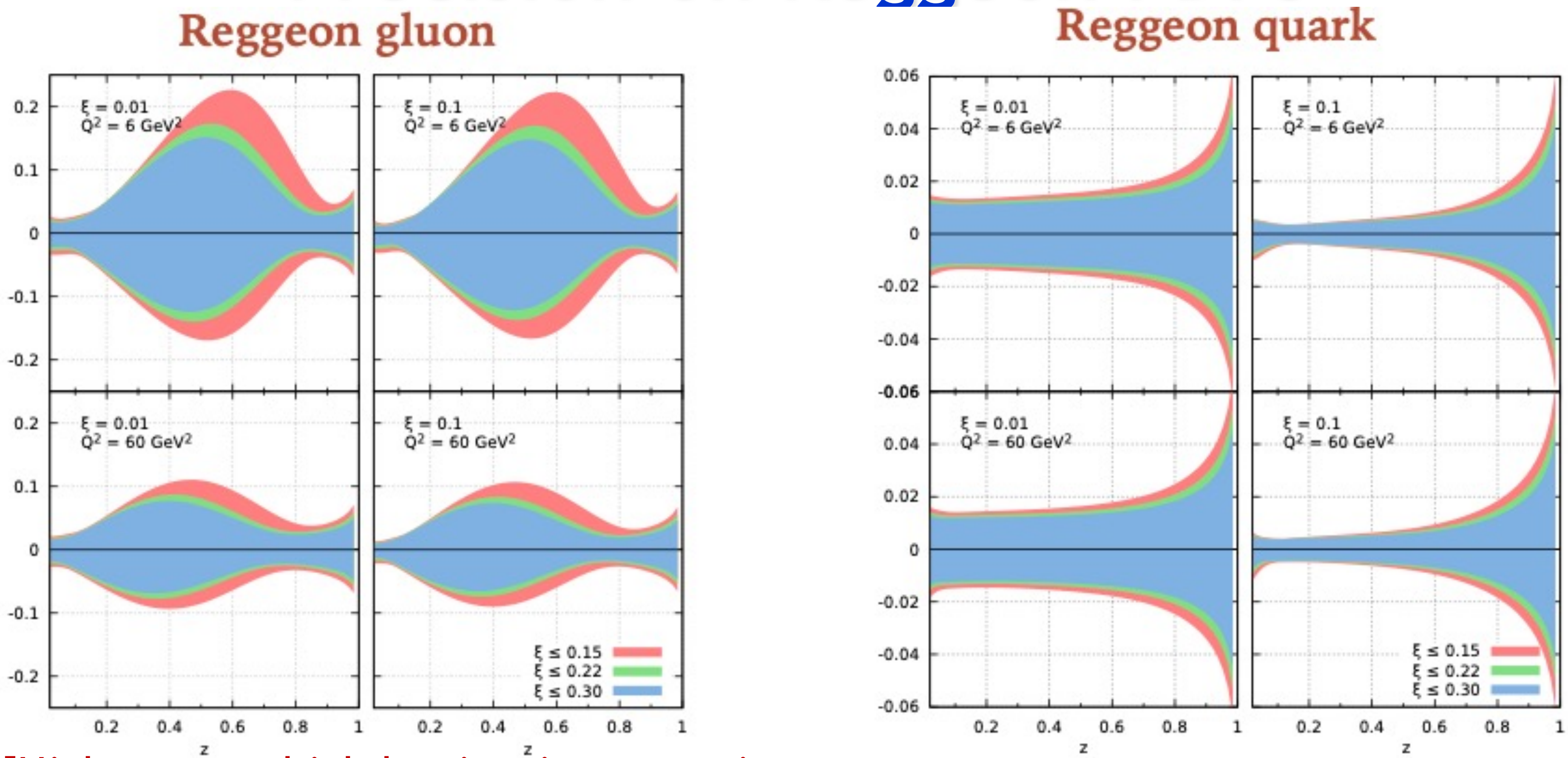




[High energy, high luminosity scenario.
Note linear z scale and different vertical scales for q and g]

- Within this model, statistical / uncorrelated systematic uncertainties are ~0.5% for quarks across wide range, ~1% for gluons
- Normalisation uncertainty on data propagates directly (dashed lines)
- Model and parameterization uncertainties not evaluated, but significant

Precision on Reggeon PDFs



[High energy, high luminosity scenario.
Note linear z scale and different vertical scales for q and g]

- Within this model, Reggeon uncertainties reduced to <2% for quarks, ~10% for gluons (note that Reggeon gluon is much smaller than Pomeron)
- Reggeon precision more dependent on ξ range, especially for gluon
- Highly model-dependent.

Precision on Flux Parameters

$$f_{I\!P}(x_{I\!P}, t) = A_{I\!P} \cdot \frac{e^{B_{I\!P} t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}} \quad ; \quad f_{I\!R}(x_{I\!P}, t) = A_{I\!R} \cdot \frac{e^{B_{I\!R} t}}{x_{I\!P}^{2\alpha_{I\!R}(t)-1}}$$

Sensitivity to 3 free parameters for each flux factor.
Example fit …

Input		Fit returns
	$\alpha_{IP}(0) = 1.11$,	1.1119 ± 0.0007
	$\alpha'_{IP} = 0$,	-0.0024 ± 0.0010
	$B_{IP} = 7$ GeV^{-2},	7.033 ± 0.010
	$\alpha_{IR}(0) = 0.70$,	0.7014 ± 0.0018
	$\alpha'_{IR} = 0.90$,	-0.8957 ± 0.0021
	$B_{IR} = 2$ GeV^{-2},	2.020 ± 0.073

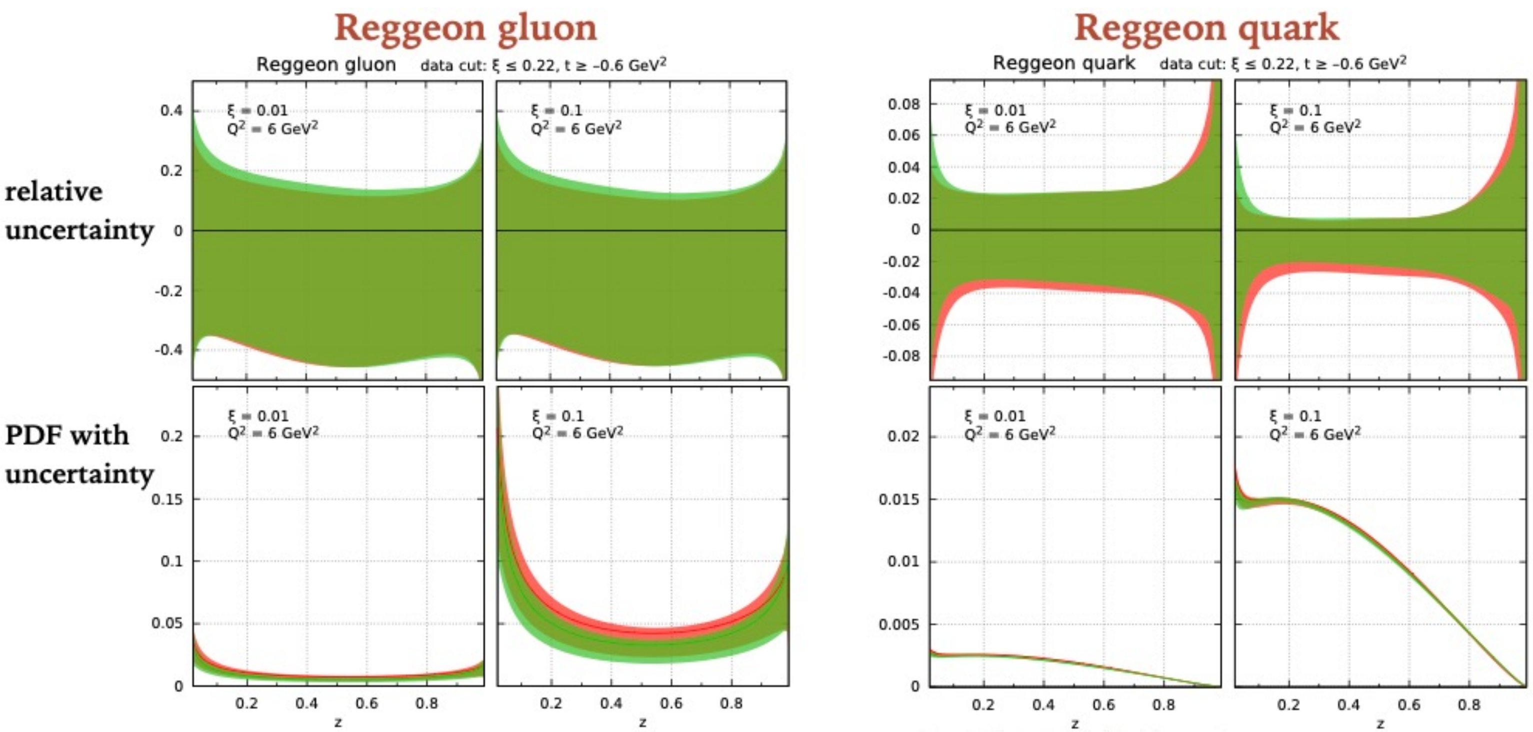
- Input values recovered at ~2-3σ level (no major biases).
- Precision looks attractive (at least within model)
- Some strong correlations between variables.

Low Energy, Low Luminosity Scenario

- E_p x E_e = 41 GeV x 5 GeV (10 fb^{-1})

  … restricts phase space to $\xi > 0.01$ and $|t| < 0.06$ GeV^2

→ Fix pomeron to results from HERA and investigate sensitivity to reggeon …



Green / Red are separately fluctuated samples … only Small dependence

- Even in this scenario, Reggeon quark is well-constrained (~3%)
- Gluon less so (but also small in absolute terms)
- Model dependence remains to be investigated

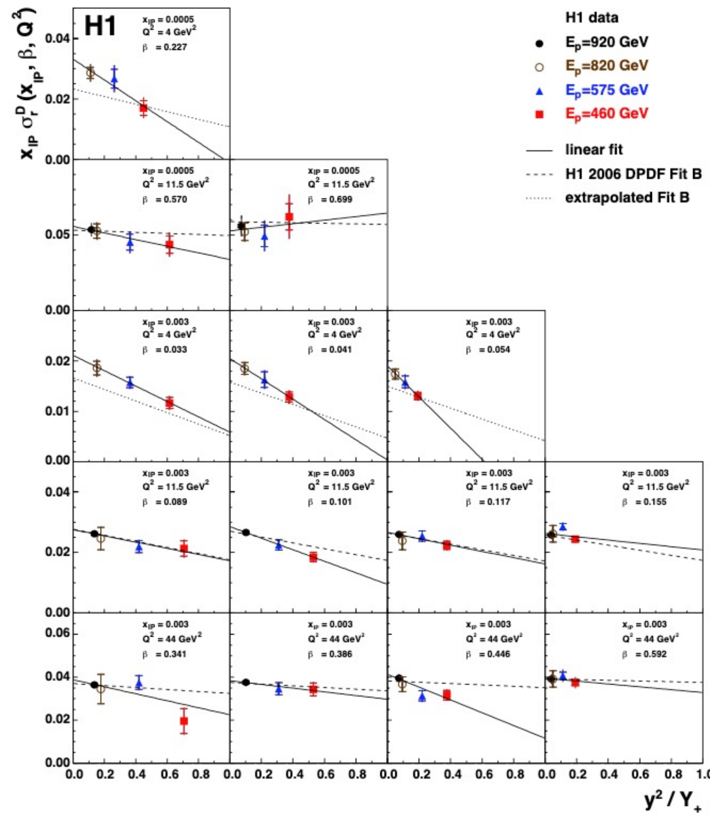
Diffractive longitudinal structure function

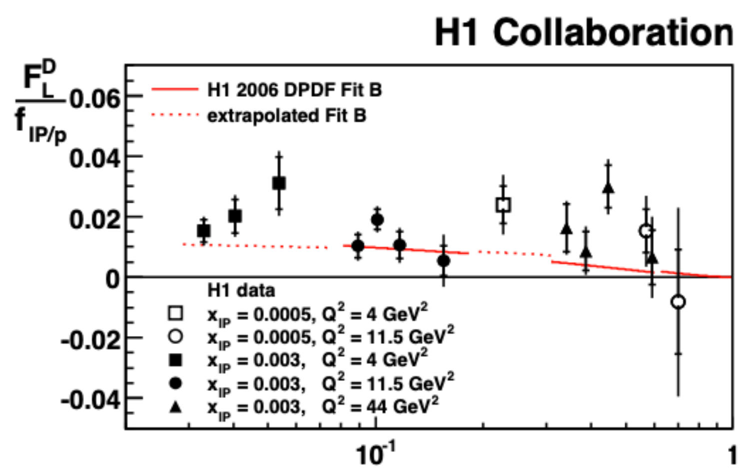
$$\sigma_{\text{red}}^{D} = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

- Cross section measurements at high y are sensitive to F_L^D as well as F_2^D

- F_L^D vanishes in QPM
- Highly sensitive to gluon density in QCD
- Expected large higher twists … tests non-linear / saturation phenomena

- Measurement at same (ξ,t,β,Q^2) and varying $\sqrt{s}$ (hence y) gives sensitivity to F_L^D (Rosenbluth plots)
- Precision strongly dependent on statistical uncertainties and systematics that are uncorrelated between different $\sqrt{s}$





- Experimentally challenging … only one measurement from HERA

Exploiting Multiple $\sqrt{s}$ Values at EIC

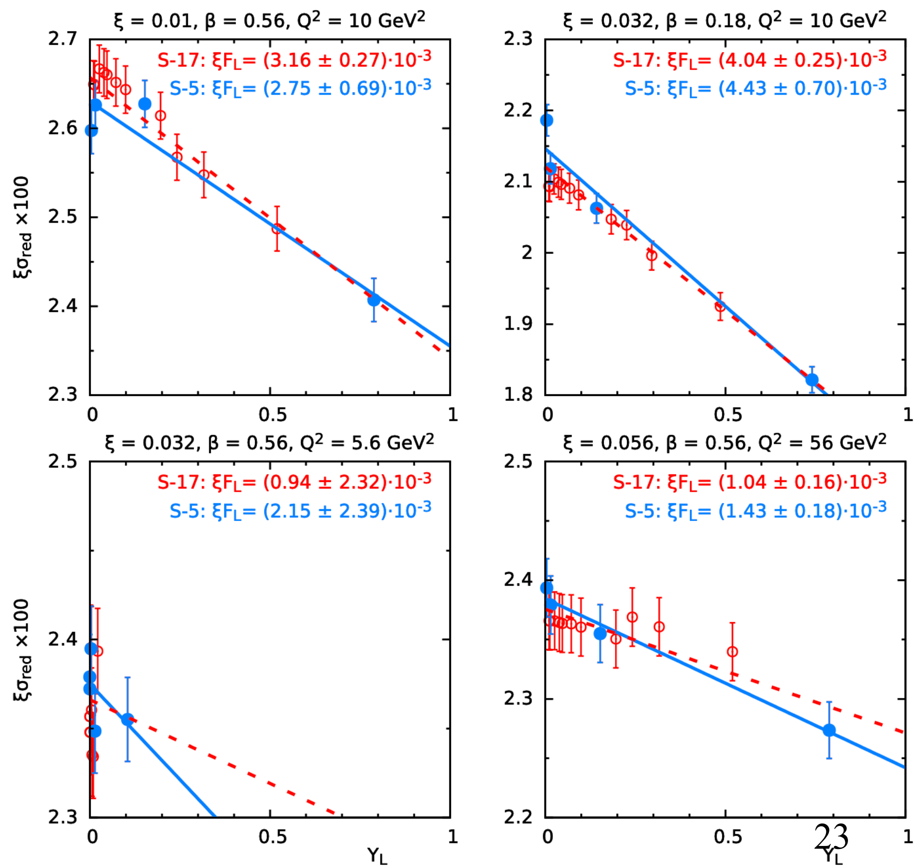
E_e [GeV] \ E_p [GeV]	41	100	120	165	180	275
5	29	45	49	57	60	74
10	40	63	69	81	85	105
18	54	85	93	109	114	141

S-5 = Default combinations (green)
S-9 = Adding selected others (red)
S-17 = All non-energy-degenerate combs

… Multiple randomly fluctuated simulations based on 'HERA SM' with statistical uncertainties based on 10fb^{-1} at each $\sqrt{s}$ and 1% uncorrelated systematics (ambitious!) or 2% (realistic?)

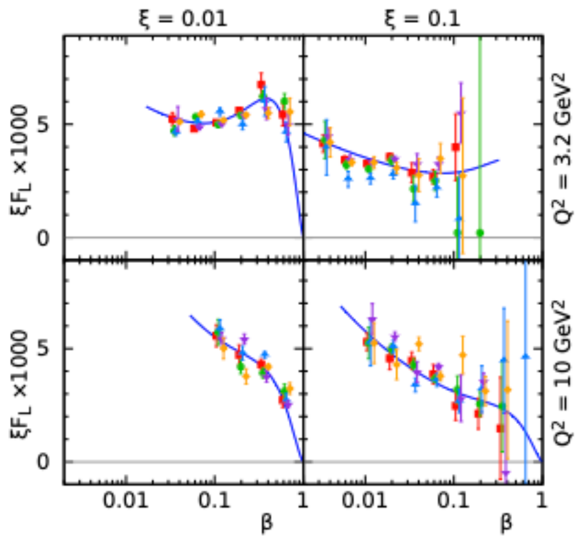
F_L^D precision depends on number of data points and kinematic range

… lever-arm in $Y_L = \frac{y^2}{1+(1-y)^2}$

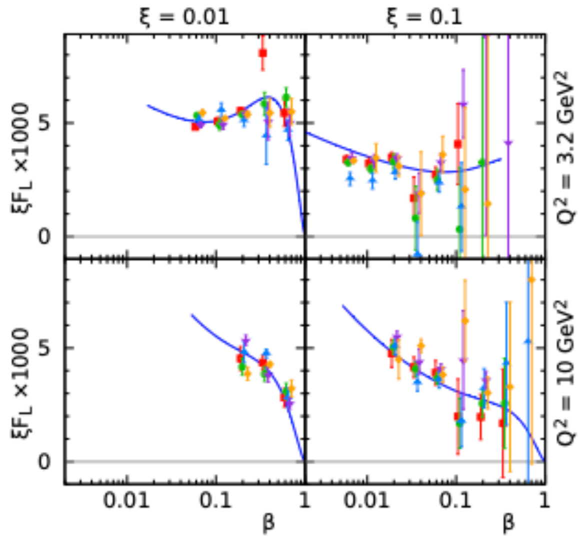


Some Simulations

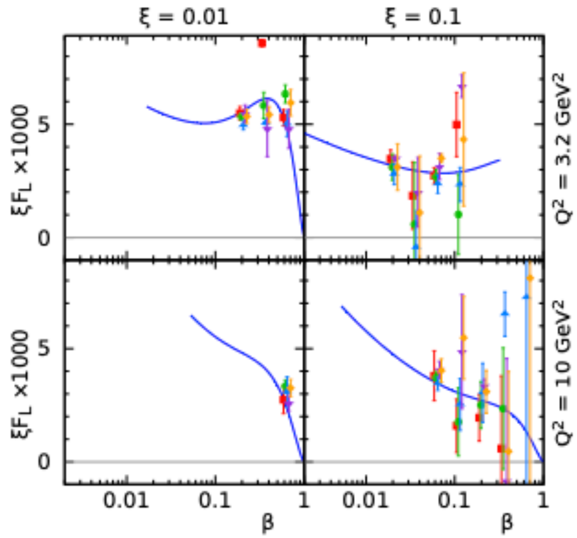
- 5 independent simulations per scenario with 1% uncorrelated systematics



17 energies

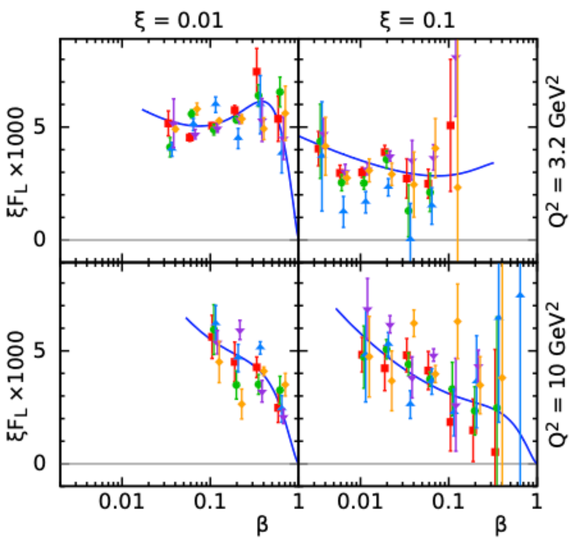


9 energies



5 energies

… and 17 energies, 2%



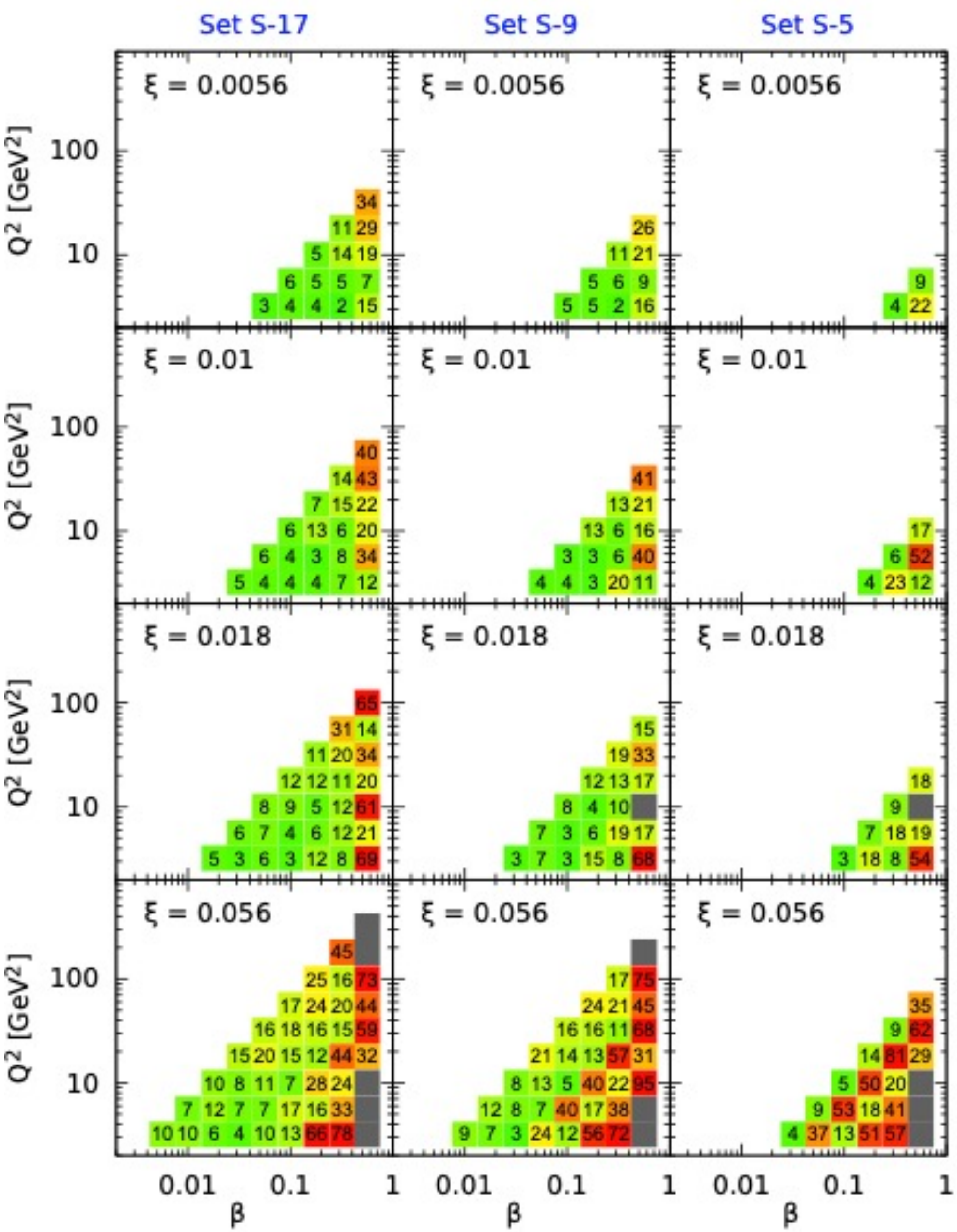
- Extractions possible in all scenarios

- Precision visibly improves with number of $\sqrt{s}$ values

- F_L^D precision scales approximately with uncorrelated systematics

- Statistical uncertainties negligible

Precisions averaged over many simulations



Full set of expected % uncertainties (averaged over 10 independently fluctuated simulations) for 1% uncorrelated systematics

… Few % precision in principle achievable in some regions → challenging theory at a very interesting level

… Motivation for as many beam energy combinations as possible!

Another Projection: Photo-absorption Ratio

Ratio of cross sections for longitudinally v transversely polarised photons.

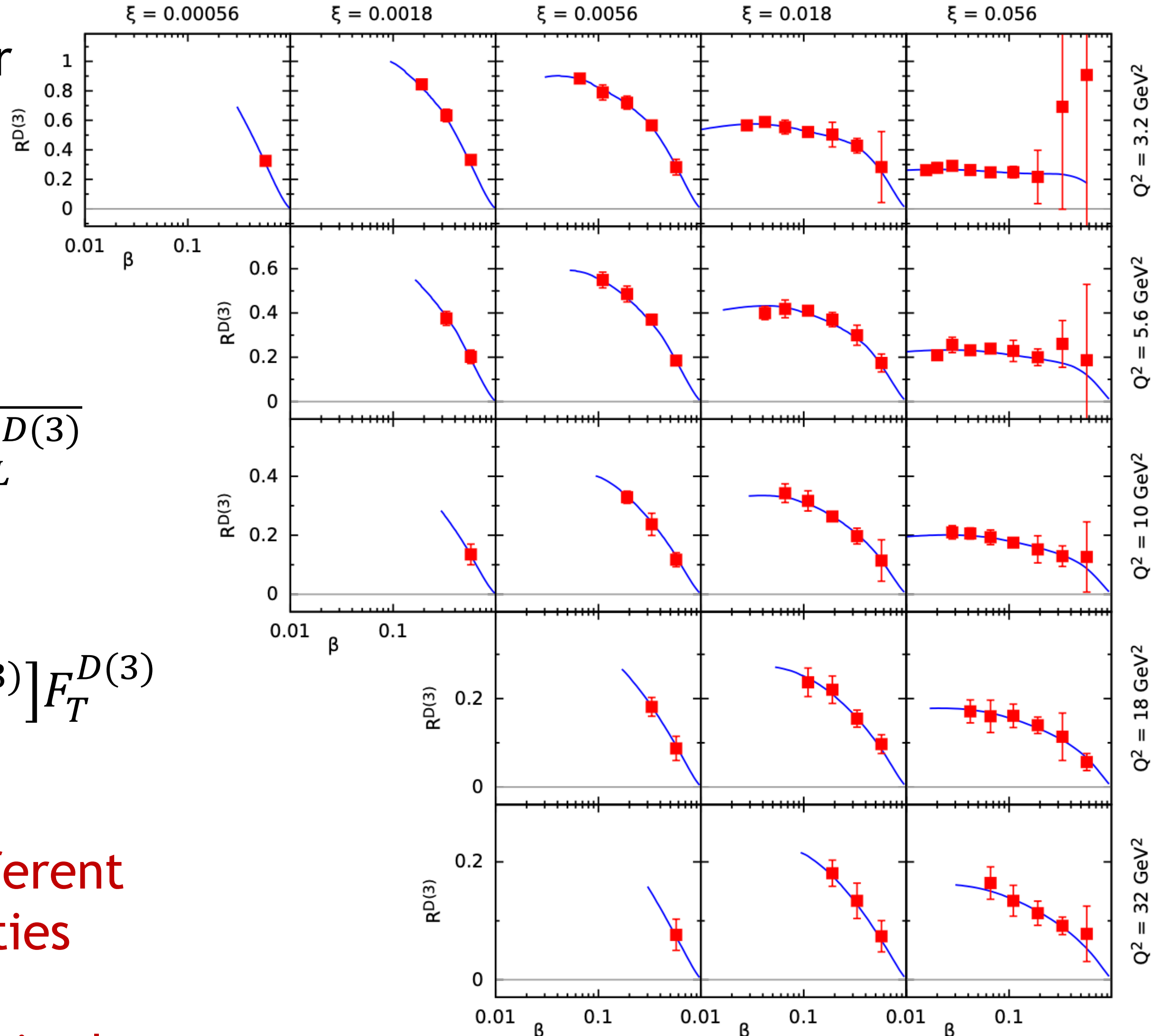
$$R^{D(3)} = \frac{F_L^{D(3)}}{F_T^{D(3)}} = \frac{F_L^{D(3)}}{F_2^{D(3)} - F_L^{D(3)}}$$

… such that …

$$\sigma_r^{D(3)} = \left[1 + (1 - Y_L) R^{D(3)}\right] F_T^{D(3)}$$

- Alternative fit has different sensitivities to uncertainties

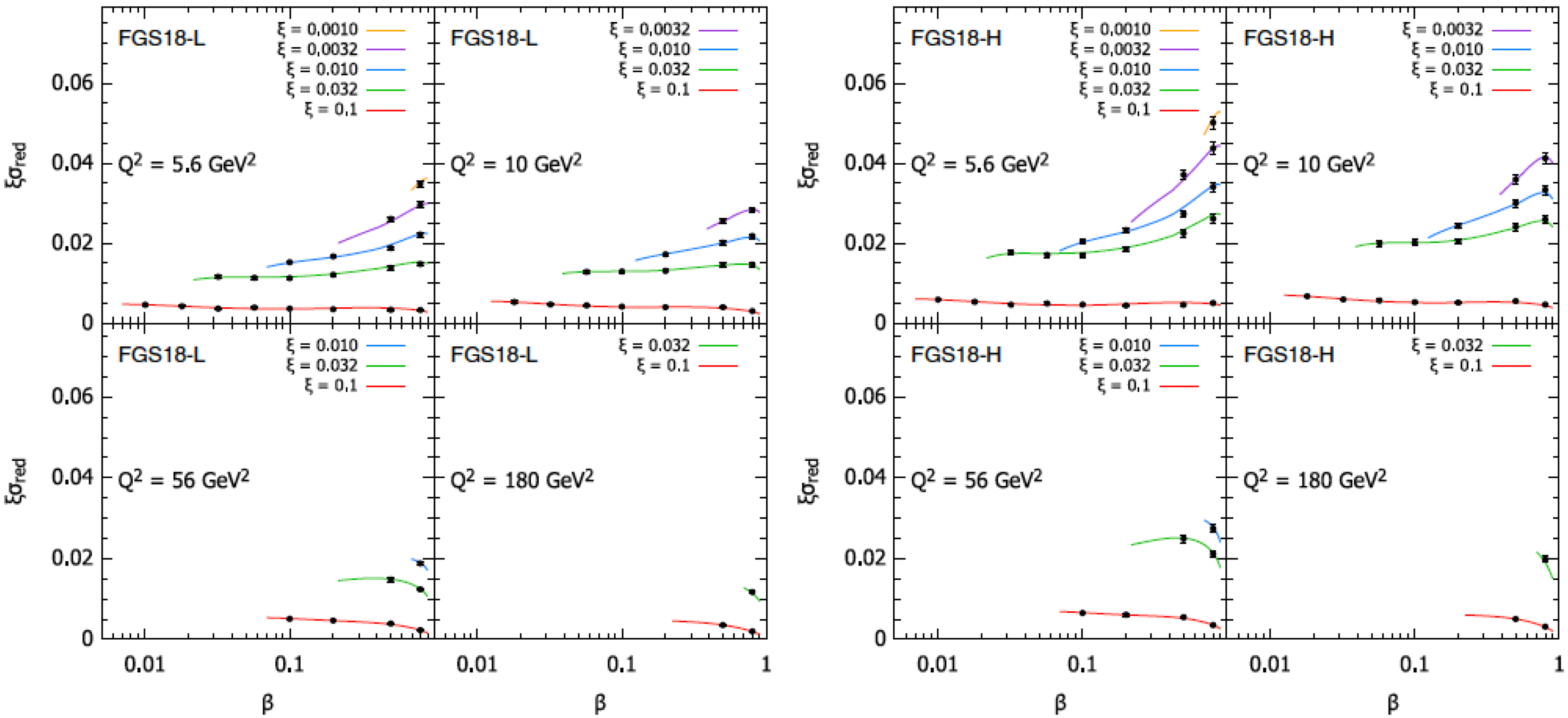
- Few percent precision in the best measured regions



Averaged results over 10 simulations for S-17 at 1% systematics

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 (saturation) dynamics



Simulations based on 2 fb-1, 5% systematics for different versions of FGS model (H, L, with different strength colour fluctuations) → illustrates accessible kinematic range & ability to distinguish widely varying models

Summary

With its high luminosity, variations in beams and hermetic beam-line instrumentation, the EIC can …

- Extract the partonic structure of the pomeron at intermediate-to-large z with unprecedented precision
- Extract the partonic structure of the sub-leading 'Reggeon' exchange with similar precision to Pomeron at HERA
- Extract the diffractive longitudinal structure function with good precision for the first time

(Incomplete list of) things still to be investigated?…

- Full simulations of diffractive events!
- Potential to measure diffractive final states (charm, jets, event shapes, flow & spectra) to test factorization
- Sensitivity of EIC F_2^D and F_L^D to saturation models
- Model dependence in DPDF and flux modelling
- Additional possibilities with polarised beams
- Possibilities in Early Running