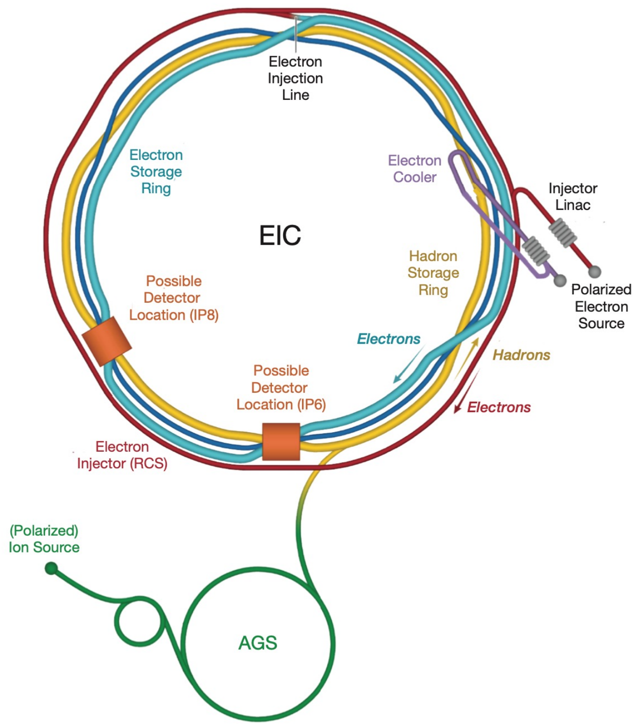

Inclusive diffraction at the EIC

Extracting Reggeon contribution

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Penn State University

collaboration with **Néstor Armesto, Paul Newman** and **Wojciech Słomiński**

Outline

- Inclusive diffraction at HERA
- Description of diffraction: Pomeron and Reggeon components
- EIC pseudodata for diffractive cross section
- Extraction of Pomeron and Reggeon, estimate of uncertainties

Extracting the partonic structure of colorless exchanges at the Electron Ion Collider e-Print: 2406.02227

Continuation of series of works on diffraction at ep/eA machines:

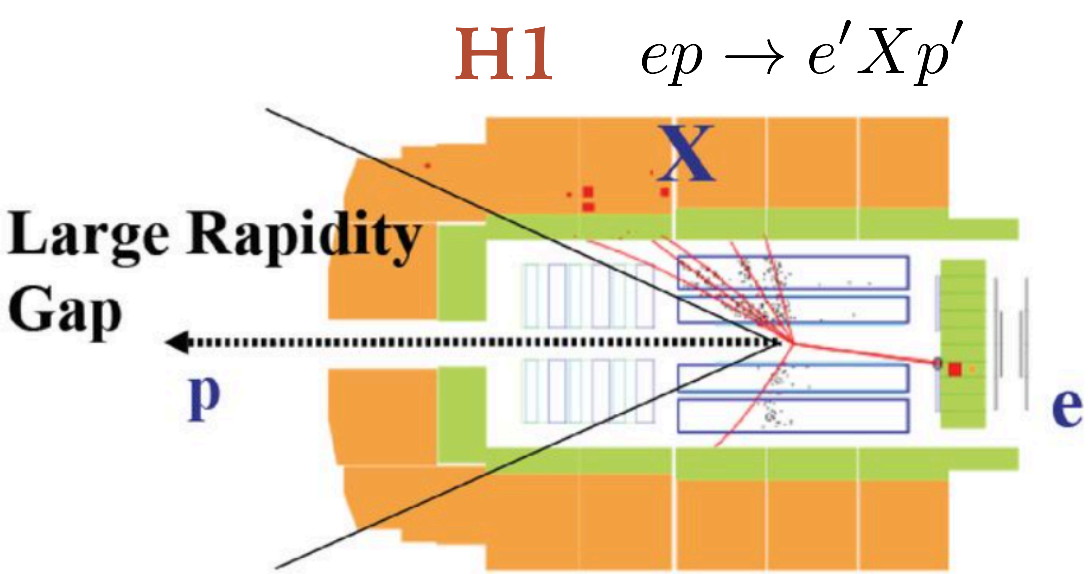
Inclusive diffraction in future electron-proton and electron-ion colliders e-Print: 1901.09076

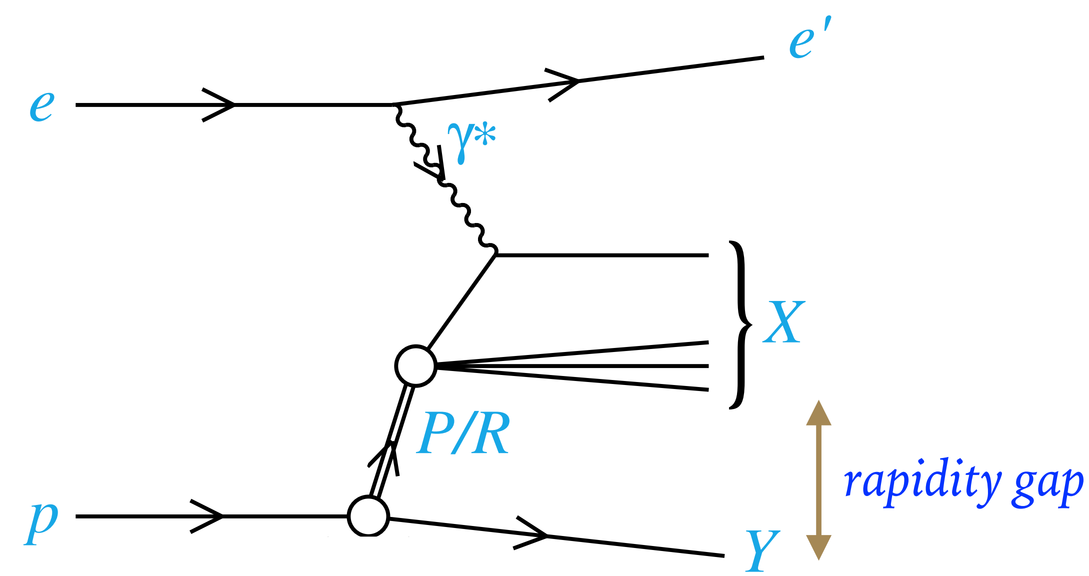
Diffractive longitudinal structure function at Electron Ion Collider e-Print: 2112.06839

also EIC Yellow Report, Sec. 7.1.6, 8.5.7

Diffraction in DIS

- Diffractive characterized by the **rapidity gap**: no activity in part of the detector
- At HERA in electron-proton collisions: about 10% events diffractive
- Interpretation of diffraction : need **colorless exchange**

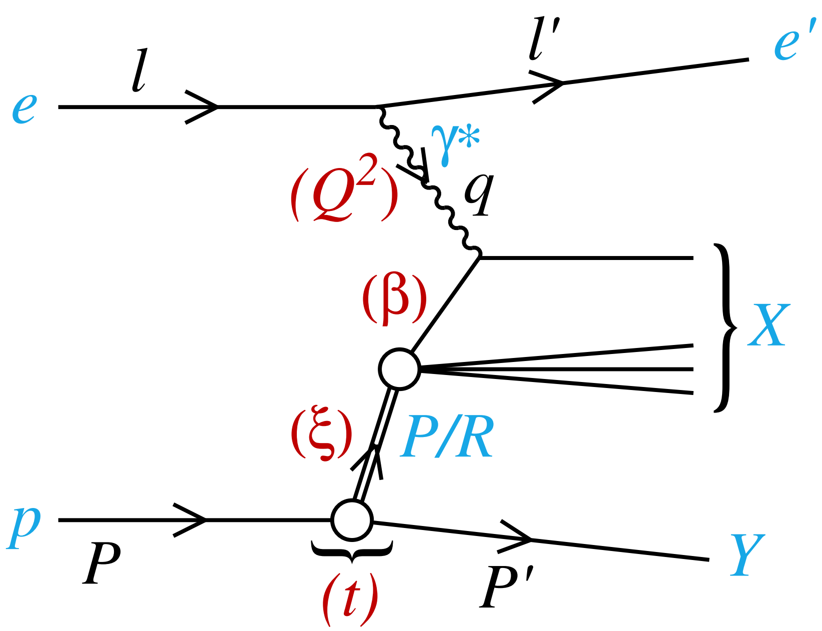




Questions:

- What is the nature of this exchange ?   Partonic composition ?
- One, two, or more exchanges ? Pomeron $I\!P$, Reggeon $I\!R$?
- Energy, momentum transfer dependence ?

Diffractive kinematics in DIS



$$x = \xi\beta$$

Standard DIS variables:

electron-proton
cms energy squared:

$$s = (l + P)^2$$

photon-proton
cms energy squared:

$$W^2 = (q + P)^2$$

inelasticity

$$y = \frac{P \cdot q}{P \cdot l}$$

Bjorken x

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{ys} = \frac{Q^2}{Q^2 + W^2}$$

(minus) photon virtuality

$$Q^2 = -q^2$$

Diffractive DIS variables:

$$\xi = x_{IP} = \frac{x}{\beta} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

$$\beta = \frac{Q^2}{2(P - P') \cdot q} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of parton w.r.t Pomeron

$$t = (P' - P)^2$$

4-momentum transfer squared

Diffractive cross section, structure functions

Diffractive cross section depends on 4 variables (ξ, β, Q^2, t) :

$$\frac{d^4\sigma^D}{d\xi d\beta dQ^2 dt} = \frac{2\pi\alpha_{\rm em}^2}{\beta Q^4} Y_+ \, \sigma_{\rm r}^{\rm D(4)}(\xi,\beta,Q^2,t)$$

$$Y_+ = 1 + (1-y)^2$$

Reduced cross section depends on two **structure functions:**

4-D: $$\sigma_{\rm r}^{\rm D(4)}(\xi,\beta,Q^2,t) = F_2^{\rm D(4)}(\xi,\beta,Q^2,t) - \frac{y^2}{Y_+} F_L^{\rm D(4)}(\xi,\beta,Q^2,t)$$

Upon integration over t:

3-D: $$F_{2,L}^{\rm D(3)}(\xi,\beta,Q^2) = \int_{-\infty}^{0} dt \, F_{2,L}^{\rm D(4)}(\xi,\beta,Q^2,t)$$

Dimensions:

$[\sigma_{\rm r}^{\rm D(4)}] = {\rm GeV}^{-2}$

$\sigma_{\rm r}^{\rm D(3)}$ Dimensionless

Diffraction at HERA: importance of 'Reggeon'

$\xi\sigma_r^{D(4)} \simeq \xi F_2^{D(4)}$ vs ξ for fixed $|t| = 0.25\,\mathrm{GeV}^2$ in bins of β, Q^2

Described by two contributions:

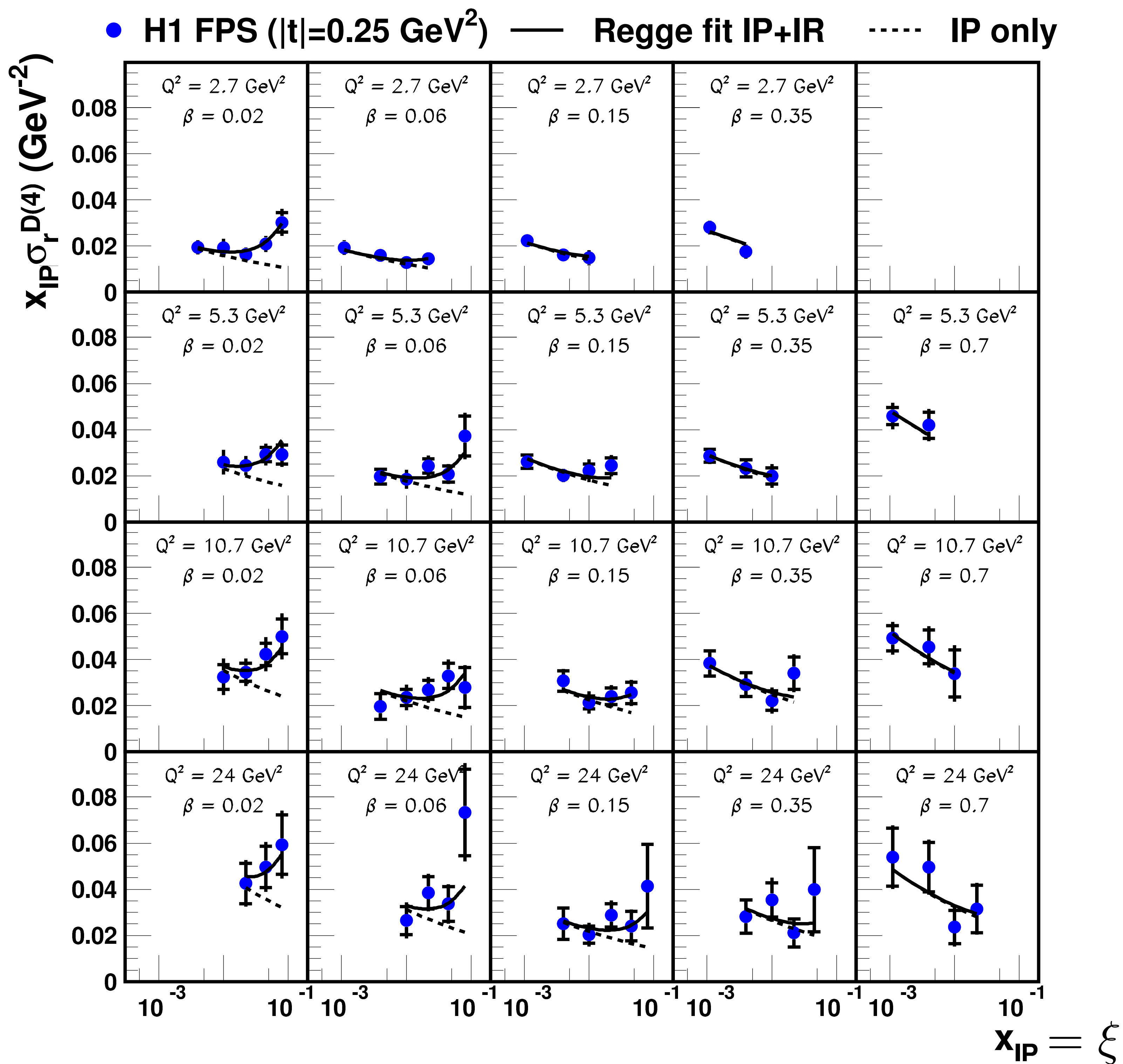
Leading 'Pomeron' at low ξ

$\xi f_{I\!P} \sim \xi^{-0.22}$

Subleading 'Reggeon' at high ξ

$\xi f_{I\!R} \sim \xi^{1.0}$

Subleading terms poorly constrained



Reggeon in photoproduction data

Similar observation in **photoproduction** $Q^2 \sim 0$

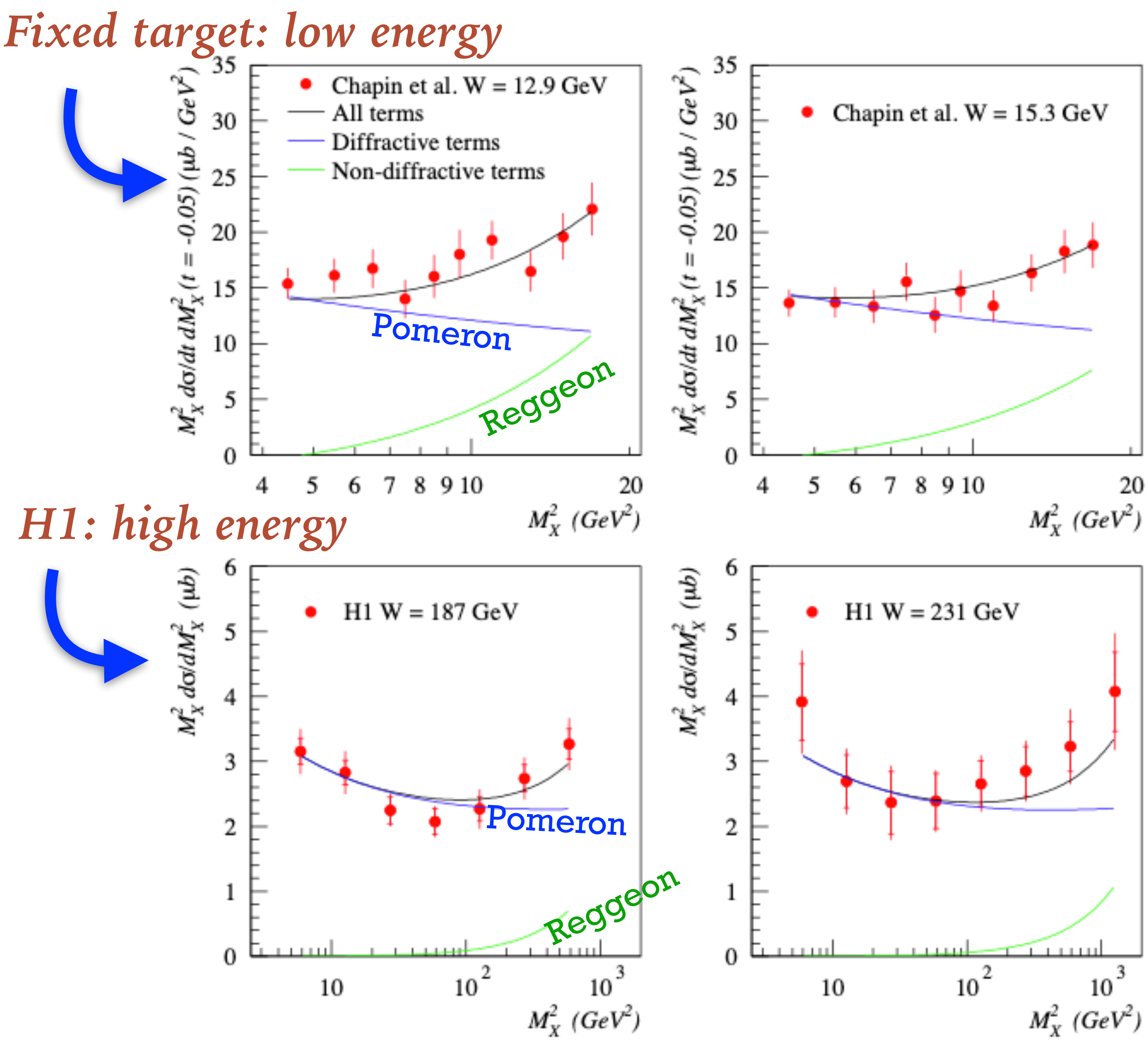
$$\gamma + p \to X + p$$

Fit using **Regge** model

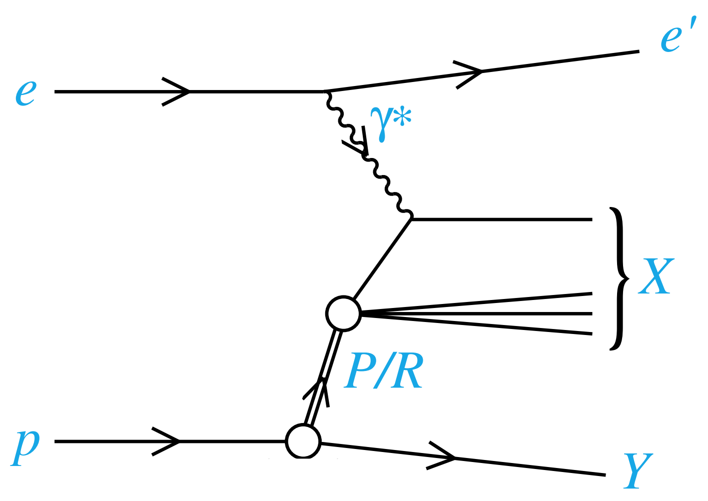
Subleading exchanges present at HERA

More dominant at **lower energies**

EIC (esp. with varying beam energies) has great potential to explore the nature of these exchanges and transition between them



Extraction of DPDF from HERA data

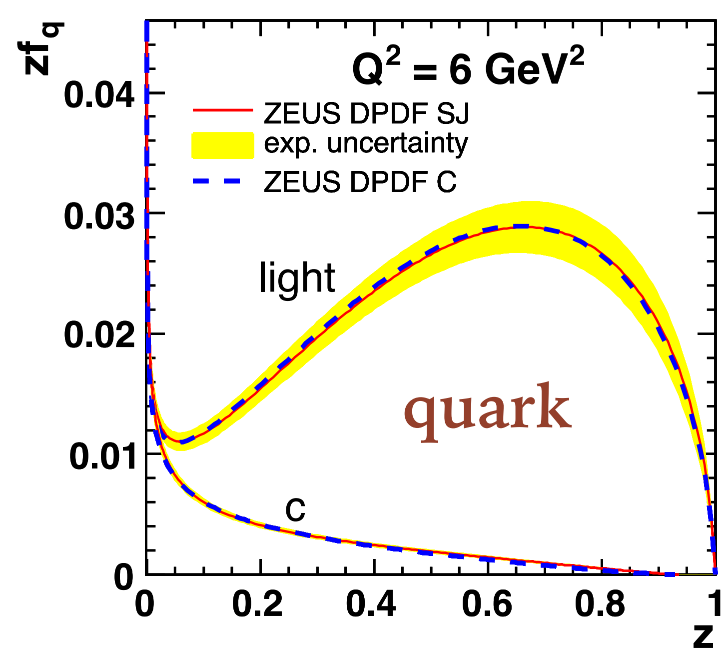


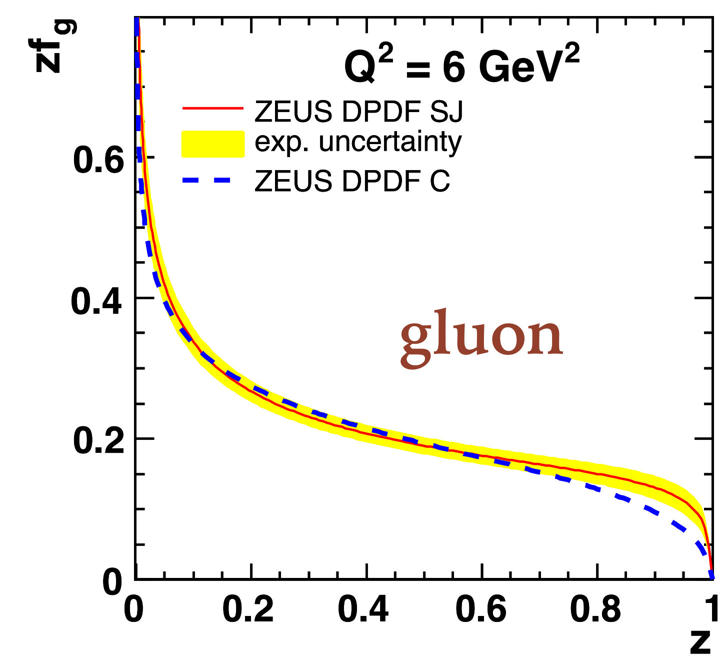
Example of DPDFs extracted from the ZEUS data

QCD analysis at NLO

Partonic content of the Pomeron contribution extracted

Dominated by the gluon density





Successfully used to describe the diffractive data from HERA

but

Large z gluon not very well constrained (need dijet data)

Only Pomeron extracted, Reggeon parametrized using GRV pion

Diffraction at EIC

EIC complementarity to HERA

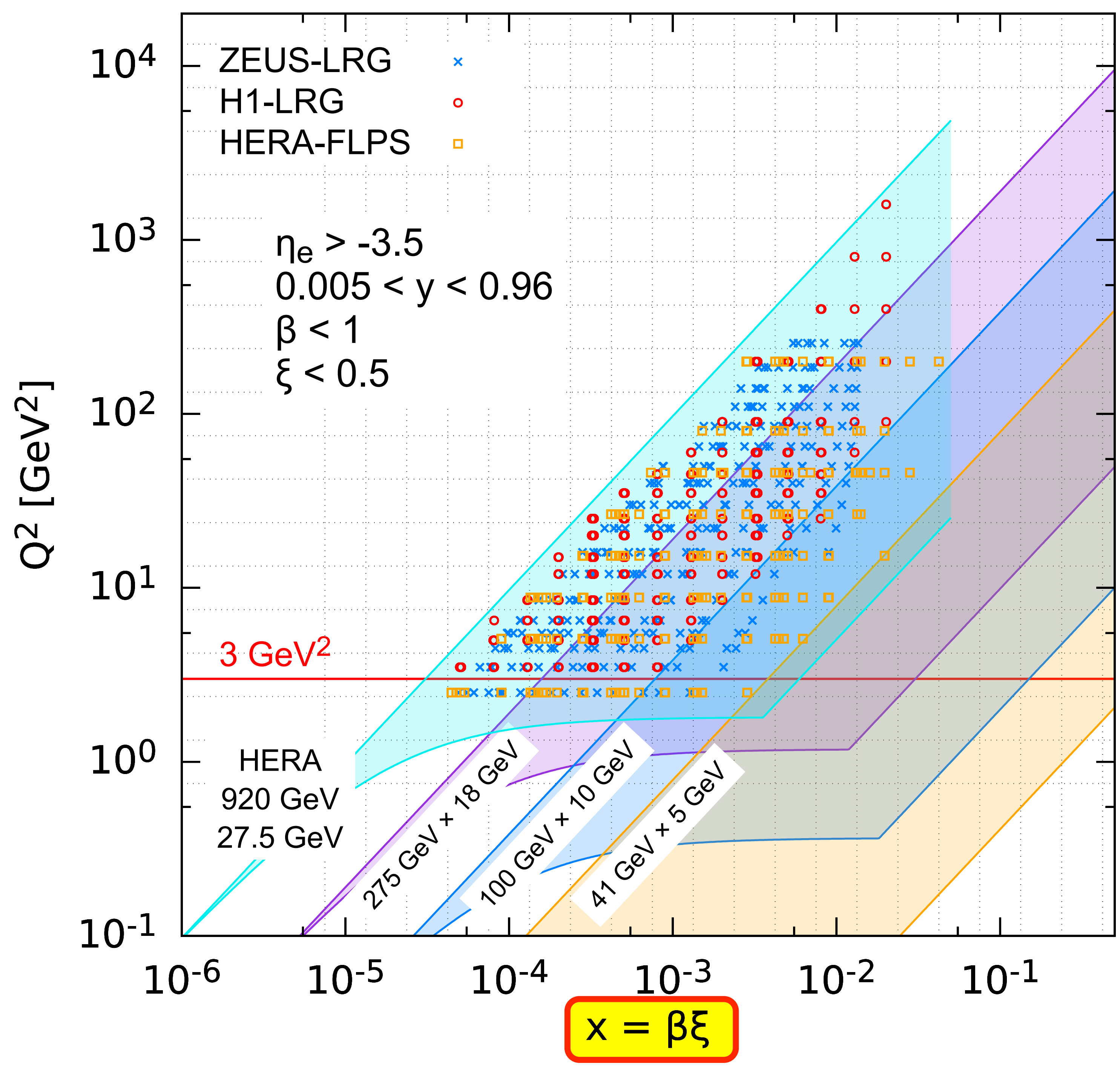
Large $x \to$ Large ξ : constraints on subleading (Reggeon) exchange

Large $x \to$ Large β : constraints on large z region of DPDFs

At EIC use **forward tagging** instrumentation to detect forward protons and study diffraction

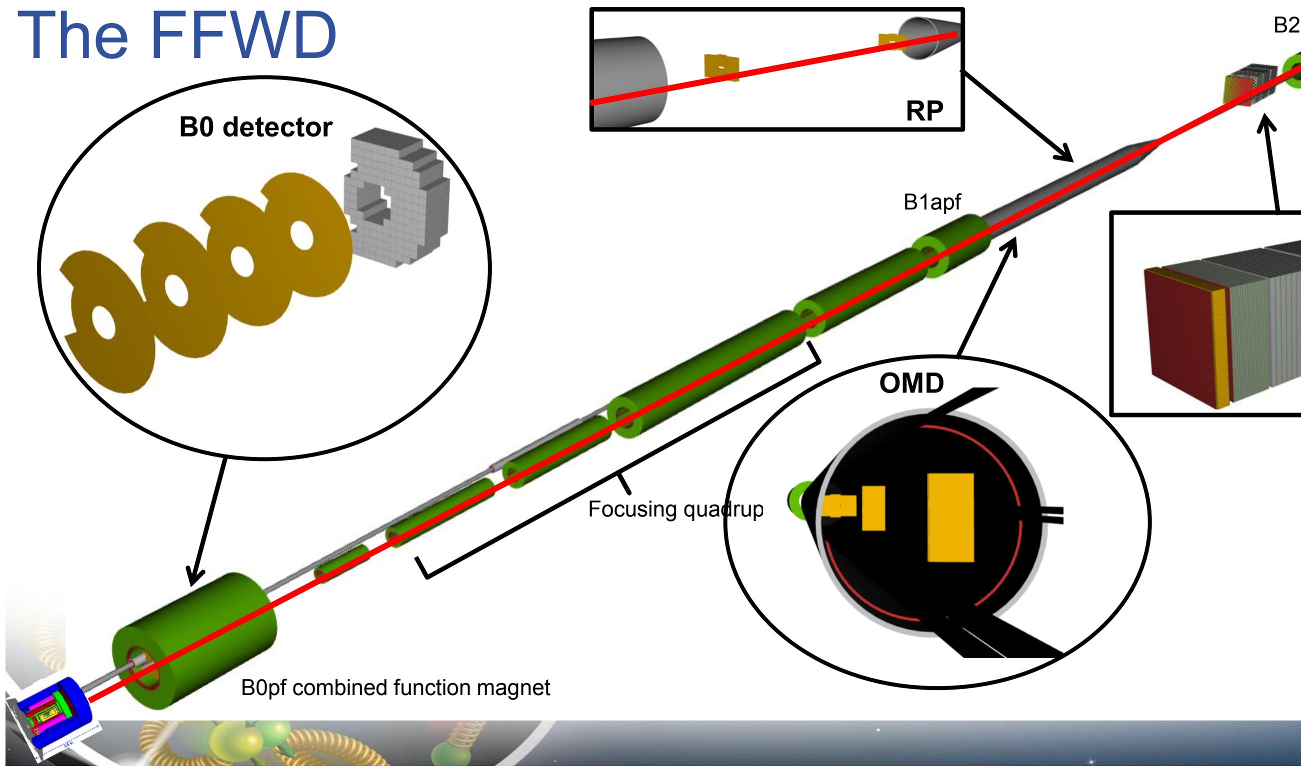
Only selected energy scenarios at EIC shown

EIC 3 scenarios - HERA



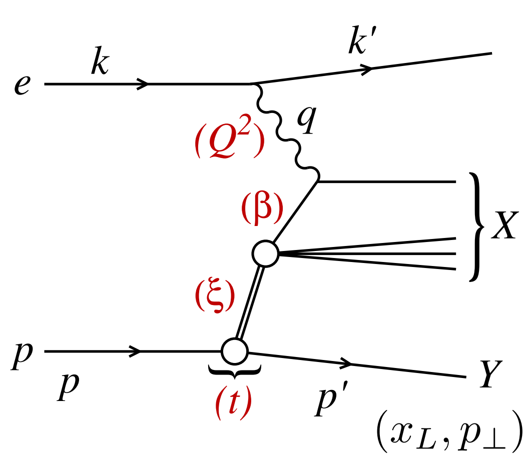
Forward instrumentation at EIC and acceptance

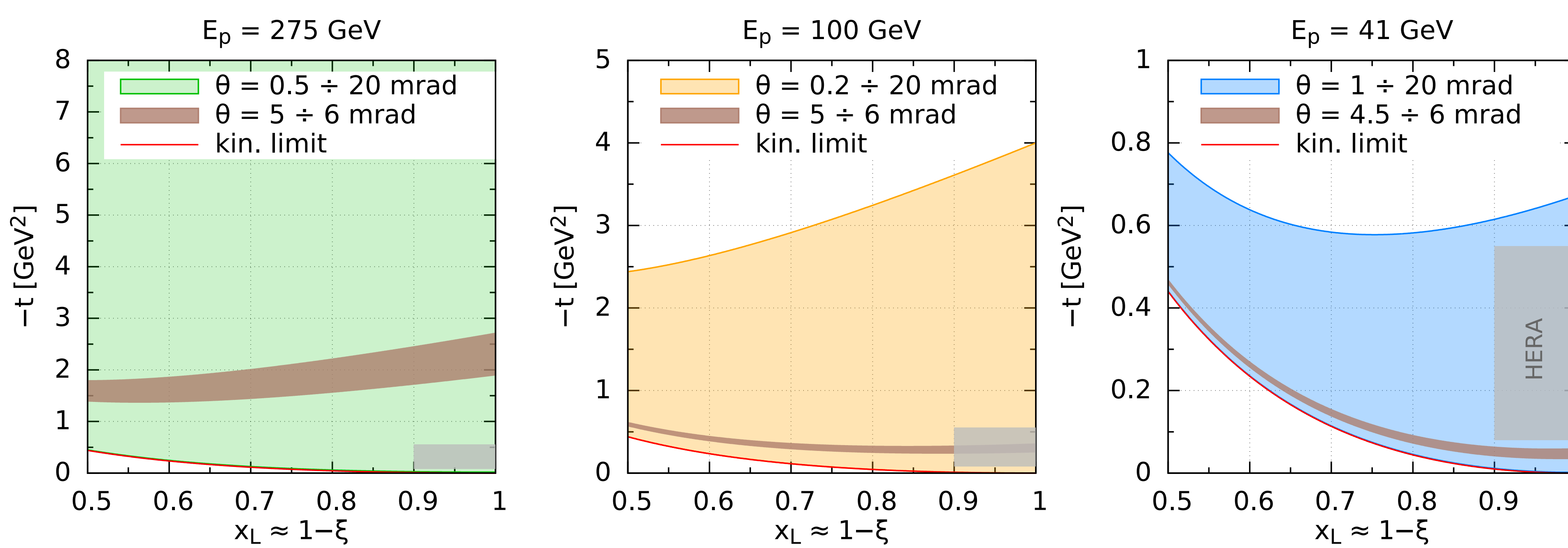
The FFWD



Forward detectors have wide acceptance in ξ and t for detecting protons

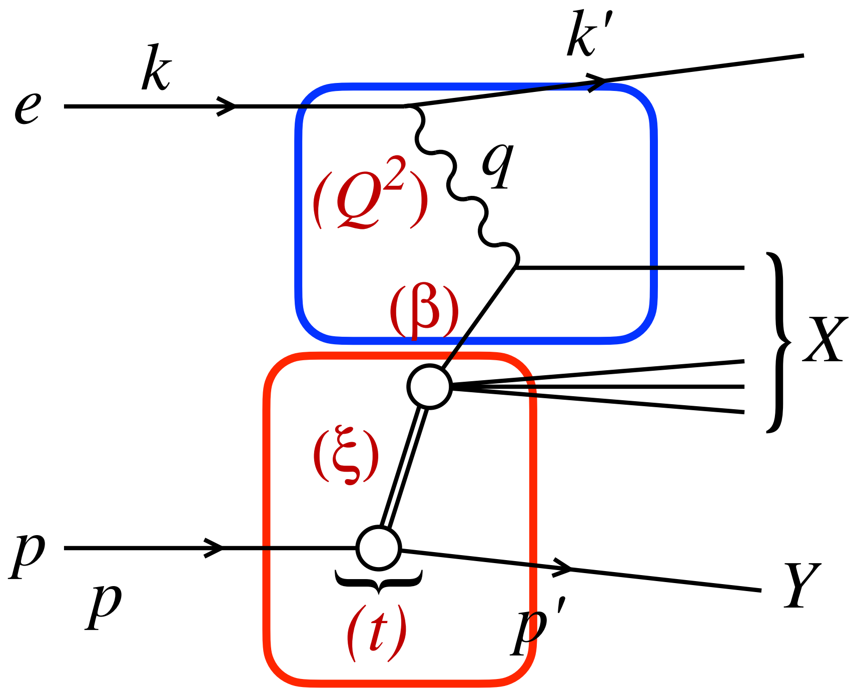
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0^* < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \boldsymbol{\theta} < 20$ mrad ($4.6 < \eta < 5.9$)





Pseudodata generation: collinear factorization for diffraction

Use the collinear factorization for the description of HERA and pseudodata simulation



Collins

Collinear factorization in diffractive DIS

$$F_{2/L}^{D(4)}(\beta,\xi,Q^2,t) \;=\; \sum_i \int_\beta^1 \frac{dz}{z}\, C_{2/L,i}\left(\frac{\beta}{z},Q^2\right)\, f_i^{\mathrm{D}}(z,\xi,Q^2,t)$$

- Diffractive cross section can be factorized into the convolution of the perturbatively calculable **partonic cross sections** and **diffractive parton distributions (DPDFs)**
- Partonic cross sections are the **same as in the inclusive DIS**
- The DPDFs are non-perturbative objects, but evolved perturbatively with **DGLAP**

EIC pseudodata generation: model

Use ZEUS $I\!P + I\!R$ fit with the GRV pion structure function for the $I\!R$

Pseudodata generated in all 4-variables : $(\beta = z, \xi, Q^2, t)$

Diffractive PDF:

$$f_k^{D(4)}(z, Q^2, \xi, t) = \phi_{I\!P}(\xi, t)\, f_k^{I\!P}(z, Q^2) + \phi_{I\!R}(\xi, t)\, f_k^{I\!R}(z, Q^2)$$

Fluxes:

$$\phi_{\mathbb{M}}(\xi, t) = \frac{e^{B_{\mathbb{M}} t}}{\xi^{2\alpha_{\mathbb{M}}(t)-1}}$$

Trajectories:

$$\alpha_{\mathbb{M}}(t) = \alpha_{\mathbb{M}}(0) + \alpha'_{\mathbb{M}}\, t \qquad \mathbb{M} = I\!P, I\!R$$

Reduced cross section:

$$\sigma_{\rm red}^{D(4)} = \phi_{I\!P}(\xi, t)\, \mathcal{F}_2^{I\!P}(\beta, Q^2) + \phi_{I\!R}(\xi, t)\, \mathcal{F}_2^{I\!R}(\beta, Q^2)$$
$$- \frac{y^2}{Y_+} \left[\phi_{I\!P}(\xi, t)\, \mathcal{F}_L^{I\!P}(\beta, Q^2) + \phi_{I\!R}(\xi, t)\, \mathcal{F}_L^{I\!R}(\beta, Q^2)\right]$$

Flux parameters:

$$\xi \phi_{I\!P}(\xi, t) \propto \xi^{-0.22}\, e^{-7|t|}$$

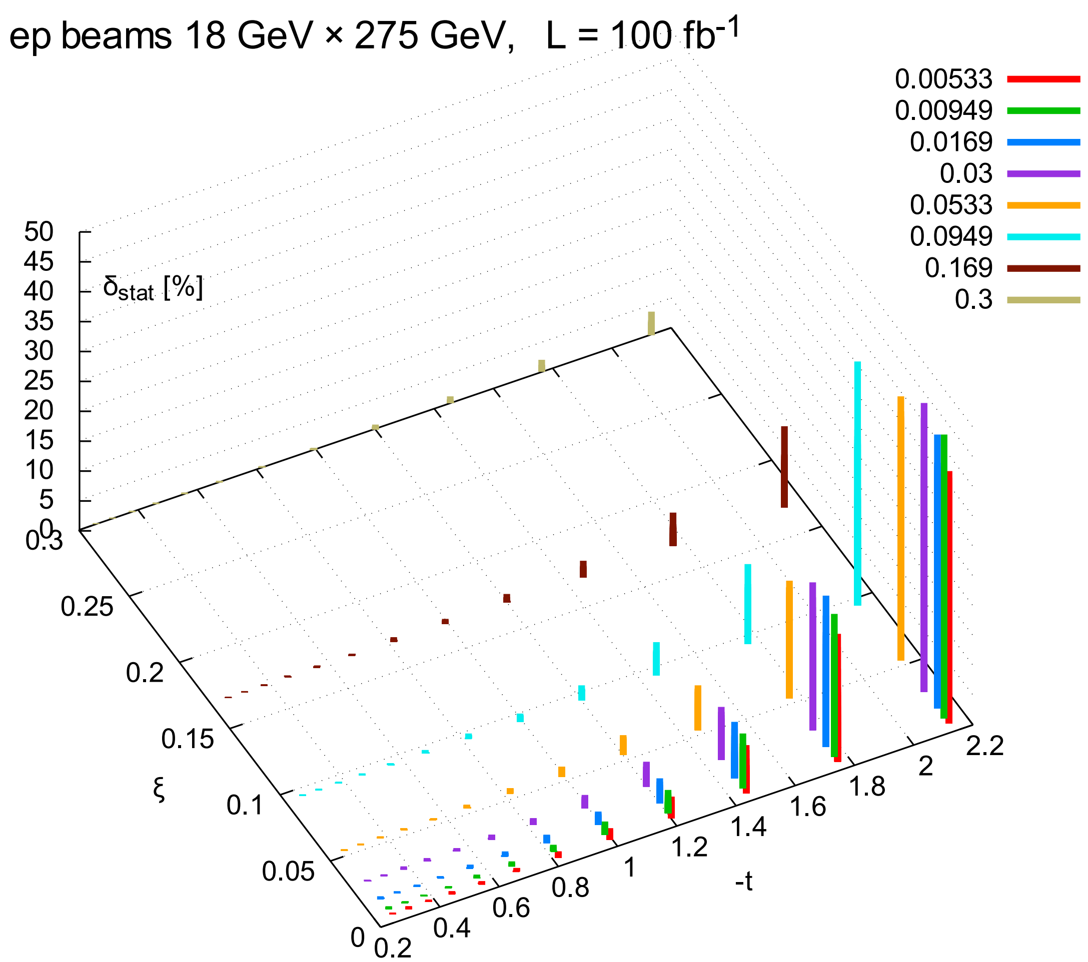
ZEUS fit parameters

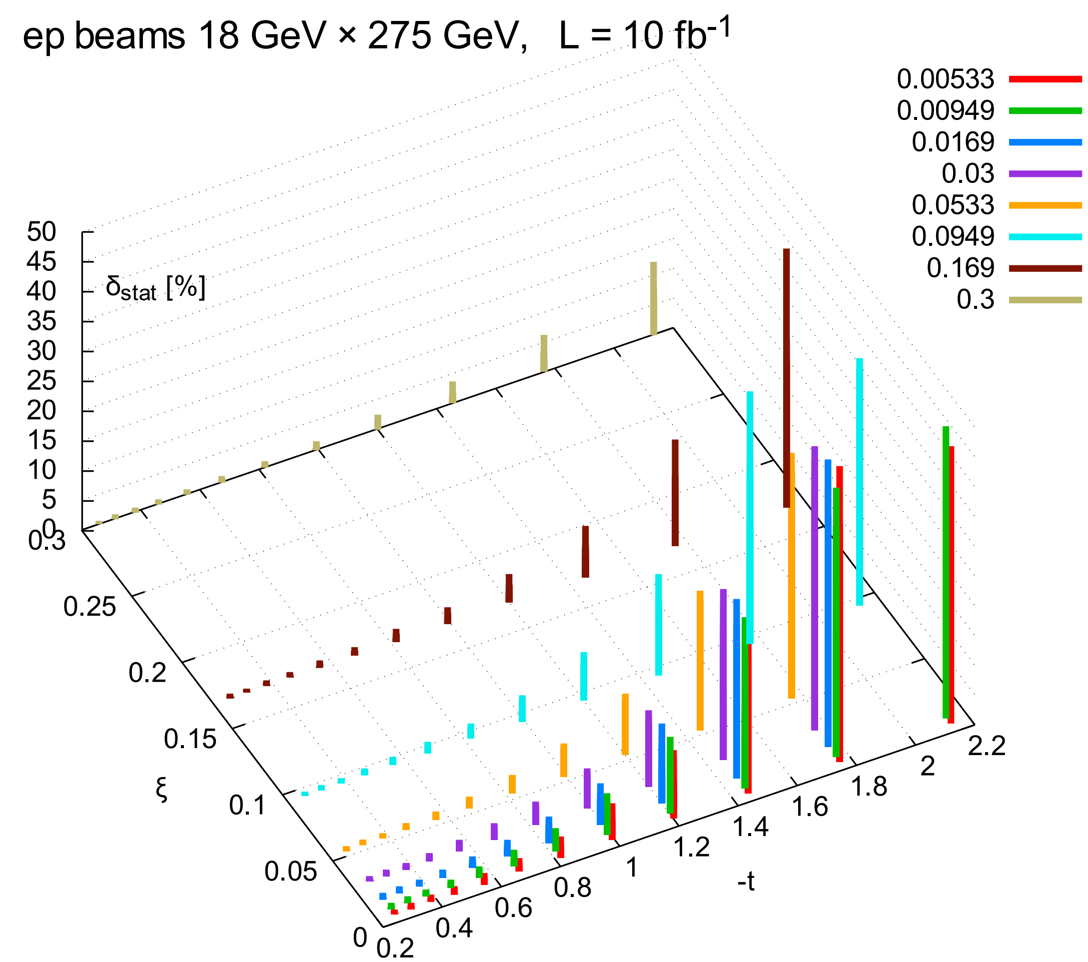
$$\xi \phi_{I\!R}(\xi, t) \propto \xi^{0.6+1.8|t|}\, e^{-2|t|} = \xi^{0.6}\, e^{(-2+1.8\ln\xi)\,|t|}$$

EIC pseudodata generation: lumi, energy, errors

- Use NC simulations for EIC (no HERA nor CC yet)
- Three scenarios for integrated luminosity and energy :
  - $\mathscr{L} = 100\,\mathrm{fb}^{-1}$ at high energy $E_e = 18\,\mathrm{GeV} \times E_p = 275\,\mathrm{GeV}$
  - $\mathscr{L} = 10\,\mathrm{fb}^{-1}$ at high energy $E_e = 18\,\mathrm{GeV} \times E_p = 275\,\mathrm{GeV}$
  - $\mathscr{L} = 10\,\mathrm{fb}^{-1}$ at low energy $E_e = 5\,\mathrm{GeV} \times E_p = 41\,\mathrm{GeV}$
- Require $0.005 < y < 0.96$
- Sparse and dense binning scenarios
- 5% uncorrelated systematics, 2% normalization error on top
- Randomly fluctuate each data point according to the uncertainties

Pseudodata: statistical errors



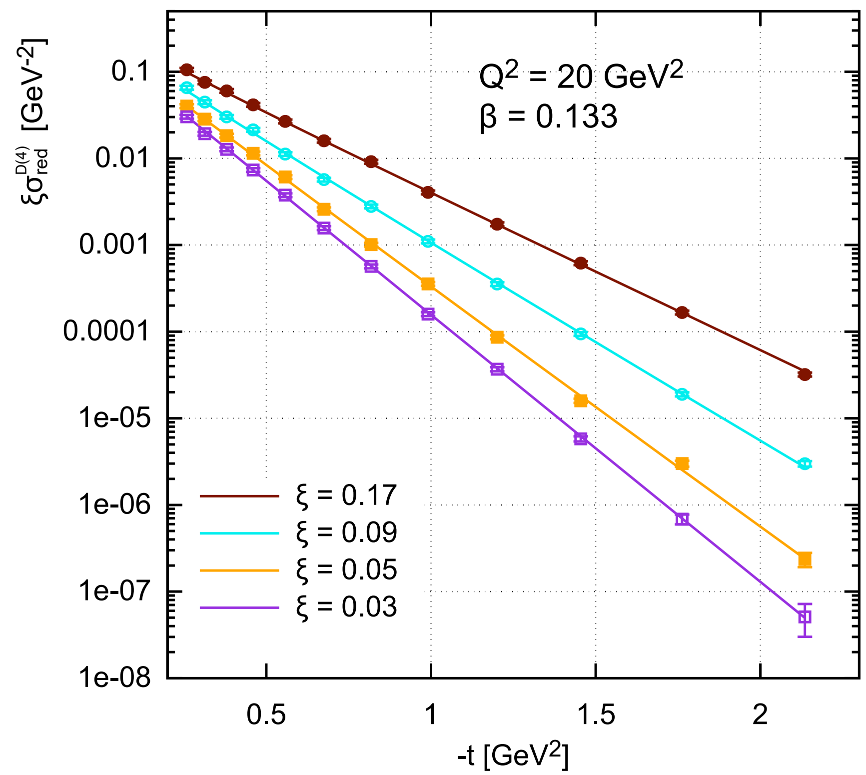


For $Q^2 < 50\,\mathrm{GeV}^2$ and $|t| < 1.2\,\mathrm{GeV}^2$

$\mathscr{L} = 10\,\mathrm{fb}^{-1}$: less than 4% data points have $\delta_{\mathrm{stat}} > 5\,\%$

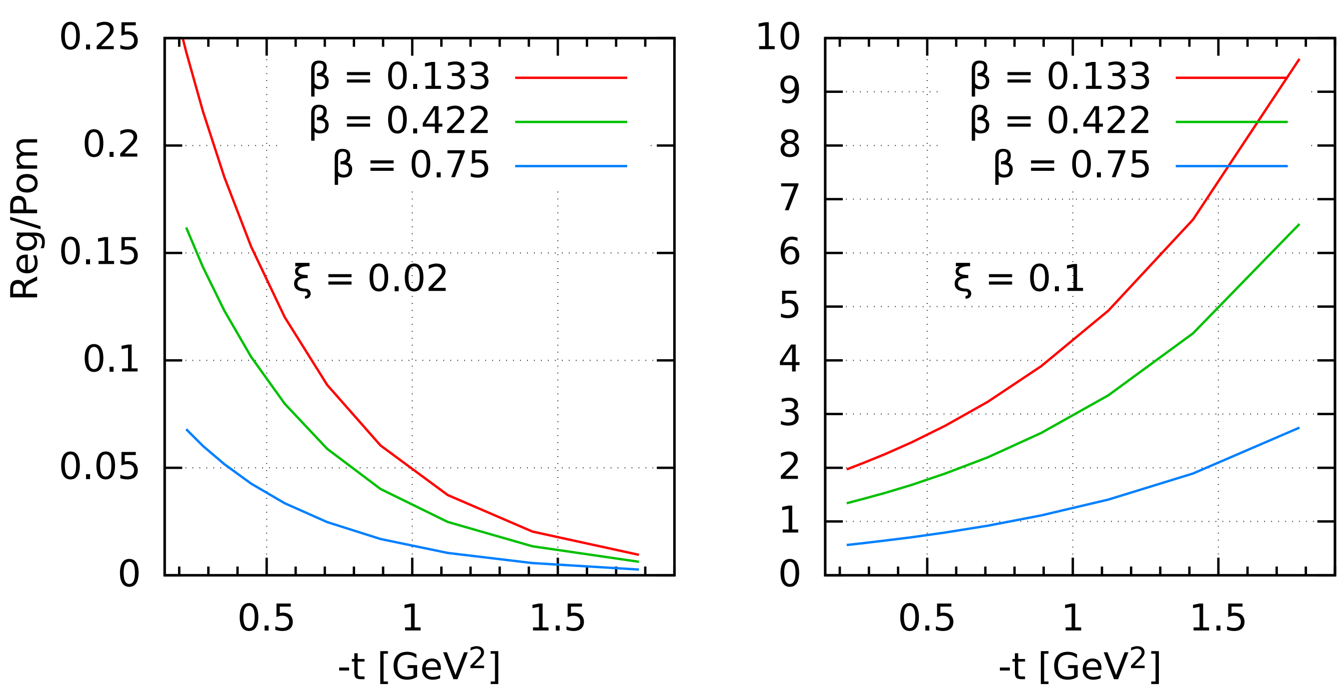
$\mathscr{L} = 100\,\mathrm{fb}^{-1}$: all data points have $\delta_{\mathrm{stat}} < 4.3\,\%$

Reggeon and Pomeron component in cross section at EIC



4D cross section pseudodata

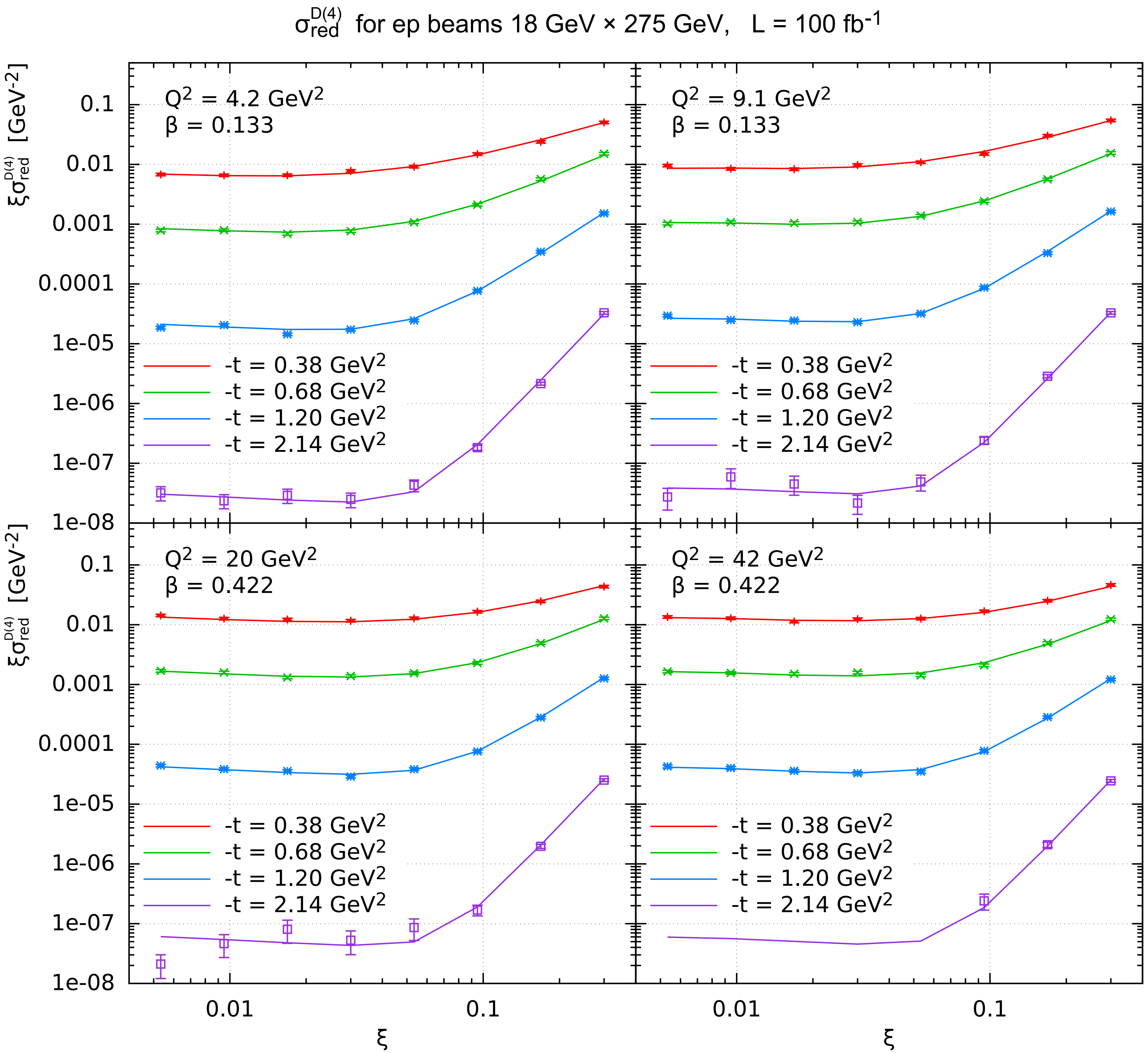
- Changing t slope as transitioning from Pomeron to Reggeon dominated region
- σ_r^D slowly varying with Q^2



$I\!R/I\!P$ ratio vs $-t$ for $\xi = 0.01, 0.1$

- Change of ratio for small vs large ξ as a function of $-t$: different slope
- $I\!R/I\!P < 1$ for small $\xi \sim 0.02$
- $I\!R/I\!P > 1$ for larger $\xi \geq 0.1$: not accessible at HERA

Example of the pseudodata: ξ dependence



σ_r^D slowly varying with Q^2

Transition between $I\!P/I\!R$ clearly visible

Need to measure $\xi \geq 0.1$

Parametrisation for fitting the pseudodata

- Treat the Pomeron and Reggeon contributions as symmetrically as possible
- Light quark separation not possible with only inclusive NC fits
- For both $I\!P$ and $I\!R$ fit the gluon and the sum of quarks
- Generic parametrization at $Q_0^2 = 1.8$ GeV^2 :

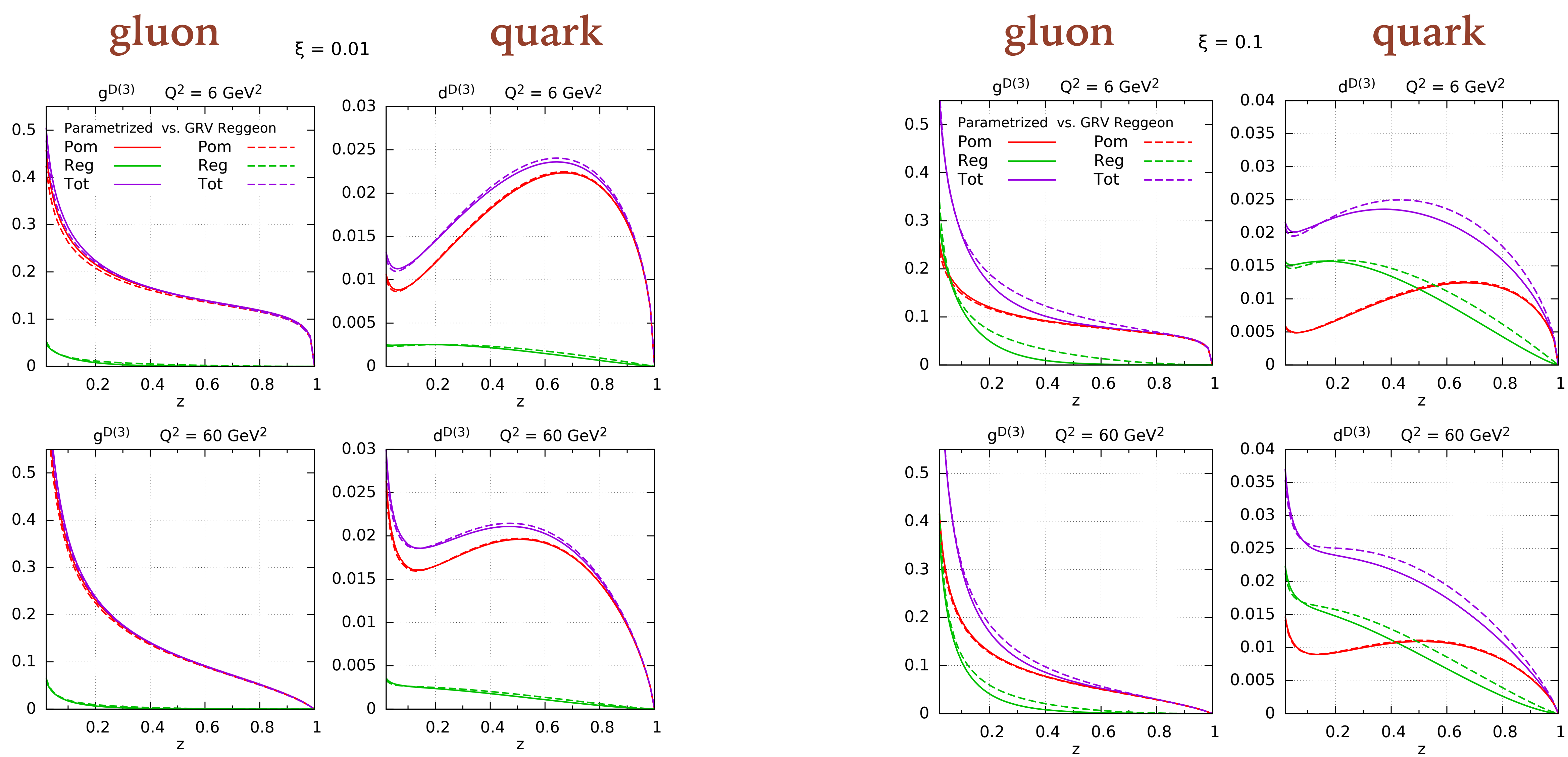
$$f_k^{(m)}(x, Q_0^2) = A_k^{(m)}\, x^{B_k^{(m)}} (1-x)^{C_k^{(m)}} (1 + D_k^{(m)}\, x^{E_k^{(m)}})$$

where $k = q, g$ and $m = I\!P, I\!R$

- Following sensitivity studies a suitable choice is:
  - $f_q^{I\!P}$ has A,B,C parameters
  - $f_g^{I\!P}$ has A,B,C parameters
  - $f_q^{I\!R}$ has A,B,C,D parameters
  - $f_g^{I\!R}$ has A,B,C parameters
- In addition fit for the parameters of the fluxes for $I\!P$ and $I\!R$: $\alpha(0), \alpha', B$

$$\frac{e^{B^{(m)}t}}{\xi^{2\alpha^{(m)}(t)-1}} \qquad \alpha^{(m)}(t) = \alpha^{(m)}(0) + \alpha'^{(m)} t$$

Recovering the Pomeron and Reggeon inputs



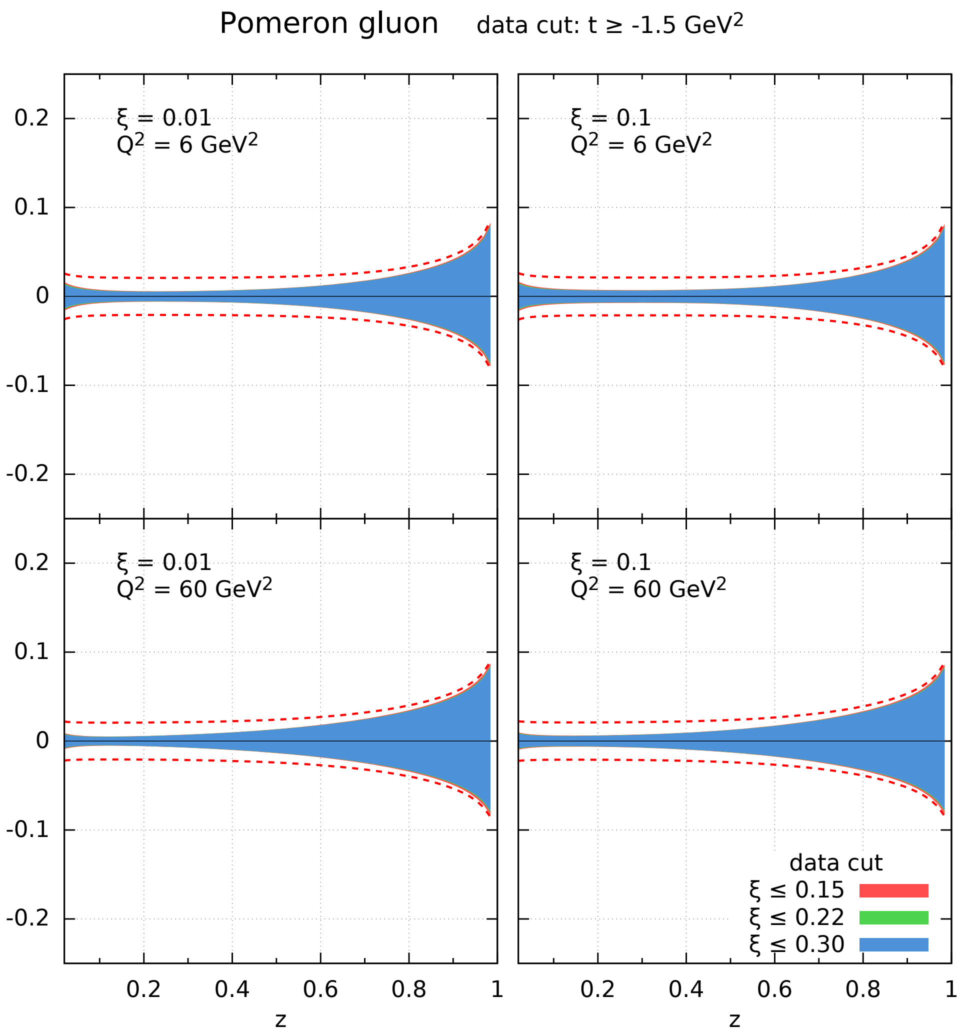
Fit results with free Reggeon parametrization (solid) made to the pseudodata based on the GRV pion structure function (dashed)

Reggeon reproduced reasonably well

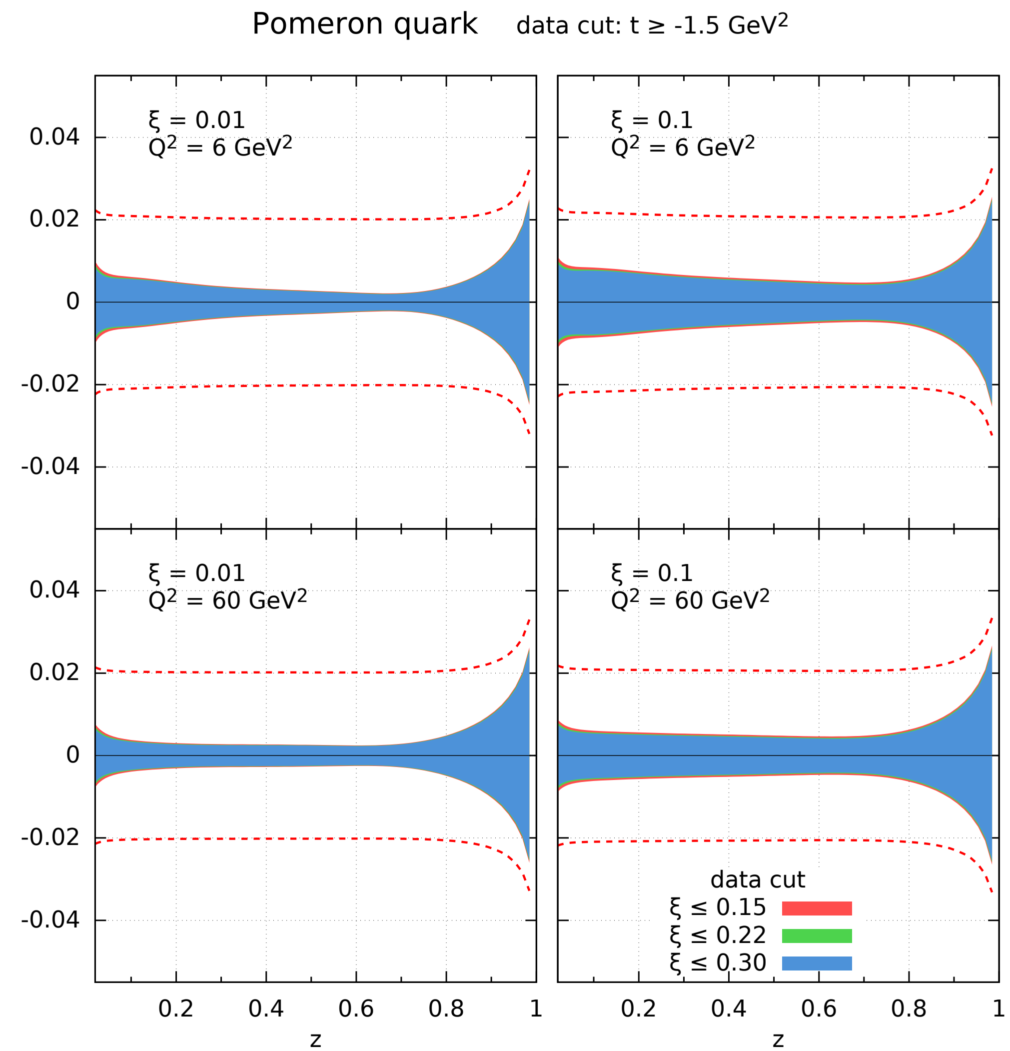
Pomeron reproduced almost perfectly

Uncertainties of diffractive PDFs: Pomeron

Pomeron gluon



Pomeron quark

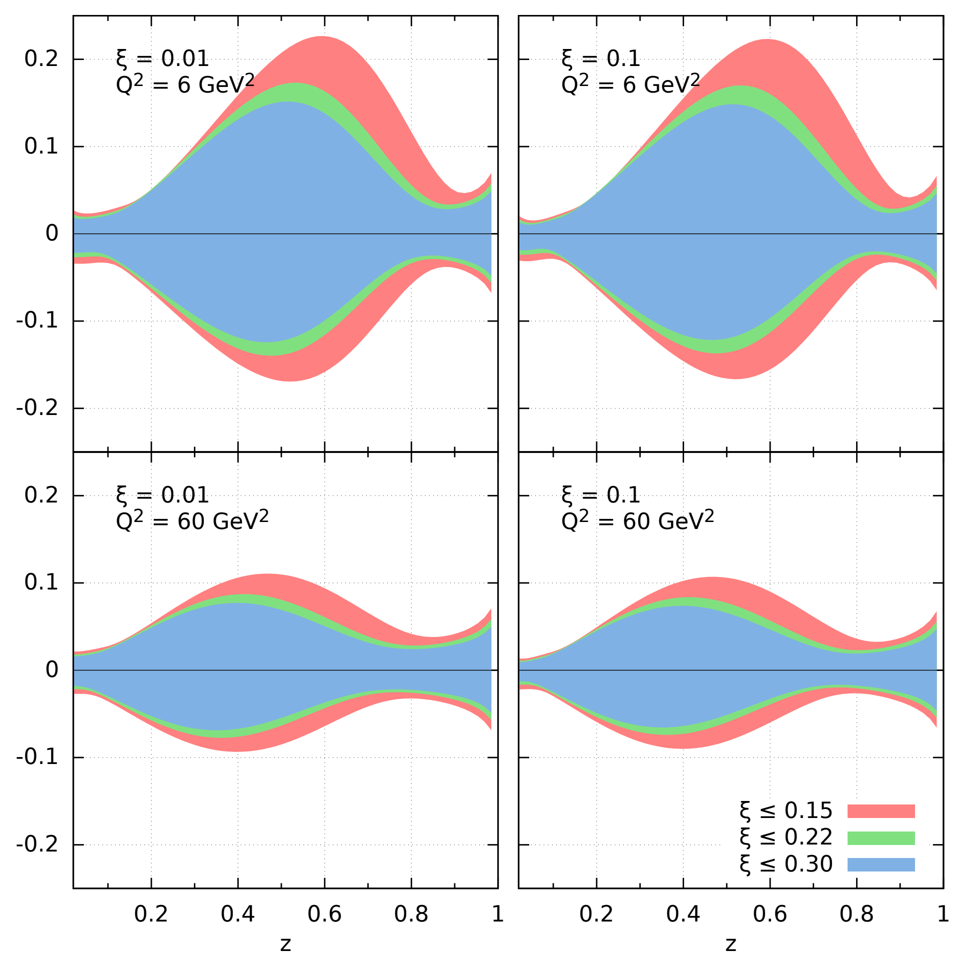


- relative uncertainty
- <few % or better in most regions
- larger uncertainty for gluon at large z (and also small z)
- normalization error at 2% is dominant at most regions (dashed red)

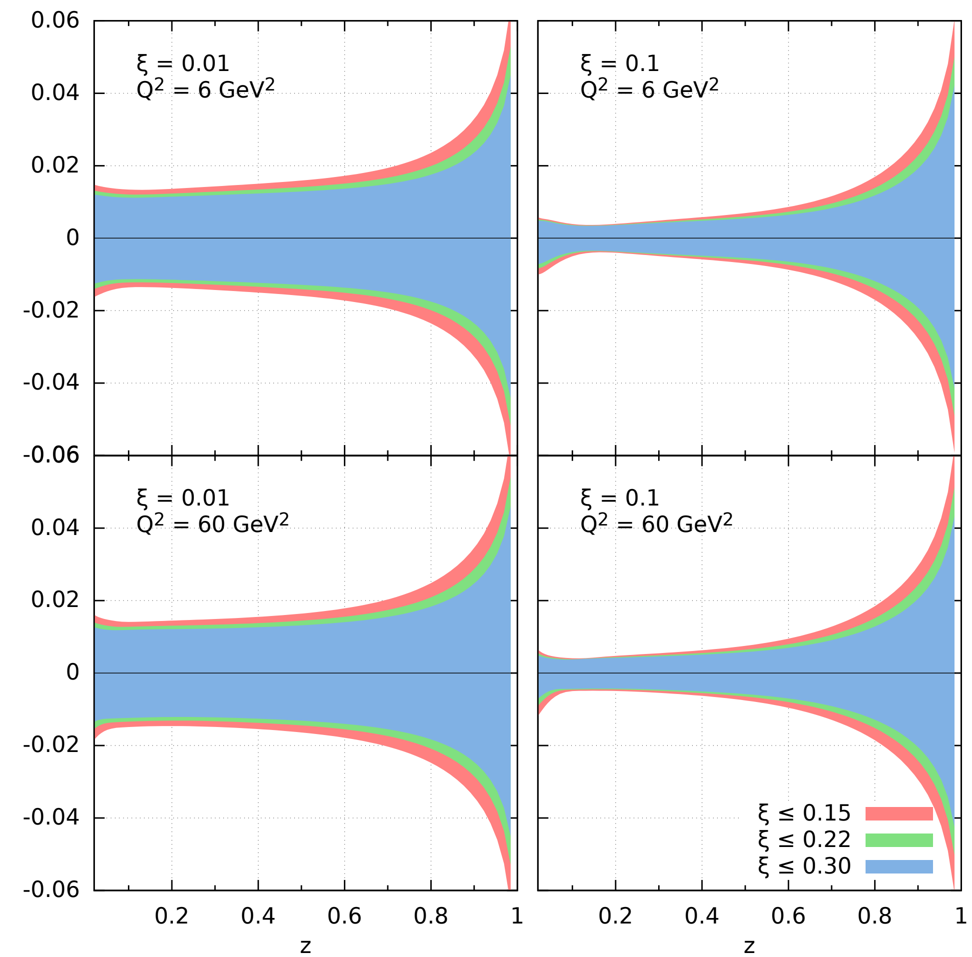
linear horizontal scale
note different vertical scale for gluons and quarks

Uncertainties of diffractive PDFs: Reggeon

Reggeon gluon



Reggeon quark



- <2 % or better in most regions for quark except at large z
- Larger uncertainty for Reggeon gluon which is much smaller than Pomeron gluon
- Mild sensitivity to the cut on ξ for gluon, quark less sensitive
- Minimal sensitivity to the cut on t, dense vs sparse binning, lower luminosity $\mathscr{L} = 10\,\mathrm{fb}^{-1}$

EIC can constrain Reggeon at similar level of precision as the Pomeron
even when restricting data to $|t| \leq 0.5\ \mathrm{GeV}^2$ and $\xi_{\mathrm{max}} \simeq 0.15 \div 0.2$

Precision on flux parameters

Regge type flux for Pomeron/Reggeon :

$$f^{p}_{I\!P,I\!R}(\xi,t) = A_{I\!P,I\!R}\frac{e^{B_{I\!P,I\!R}t}}{\xi^{2\alpha_{I\!P,I\!R}(t)-1}}$$

Trajectory :

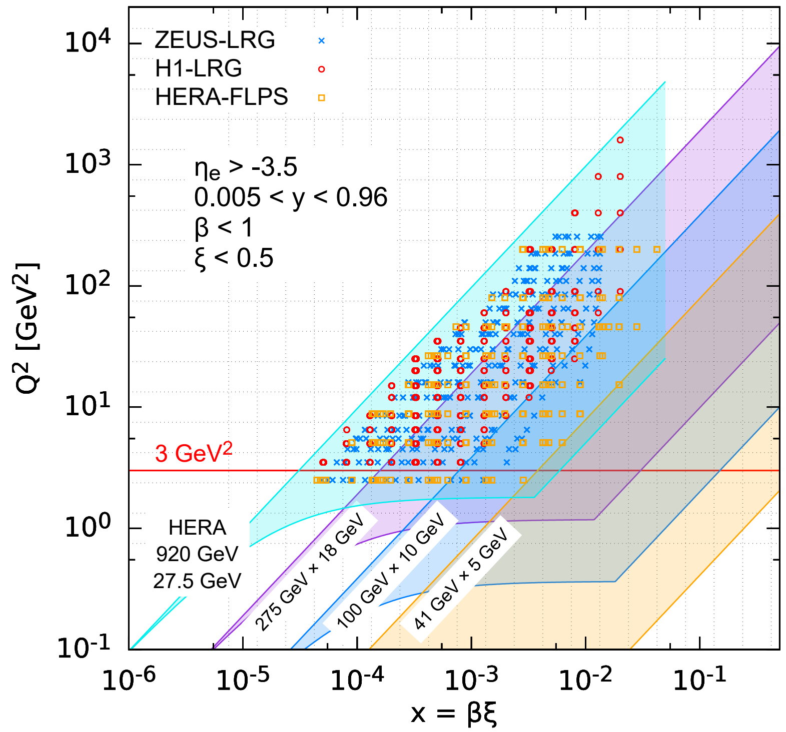
$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}\, t$$

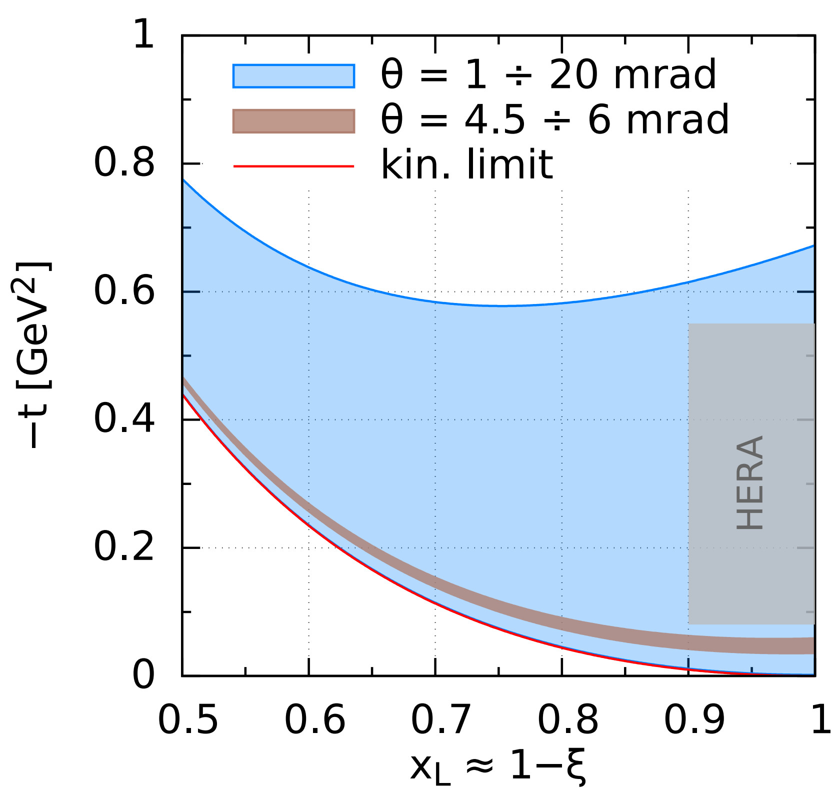
Parameter	Input	Fit
$\alpha_{I\!P}(0)$	1.11	1.1119±0.0007
$\alpha'_{I\!P}$	0	-0.0024±0.0010
$B_{I\!P}\,[\mathrm{GeV}^{-2}]$	7	7.033±0.010
$\alpha_{I\!R}(0)$	0.70	0.7014±0.0018
$\alpha'_{I\!R}$	0.90	0.8957±0.0021
$B_{I\!R}\,[\mathrm{GeV}^{-2}]$	2	2.020 ± 0.073

Input values recovered with very precisely

Some flux parameters get correlated with the PDF parameters

Low energy scenario





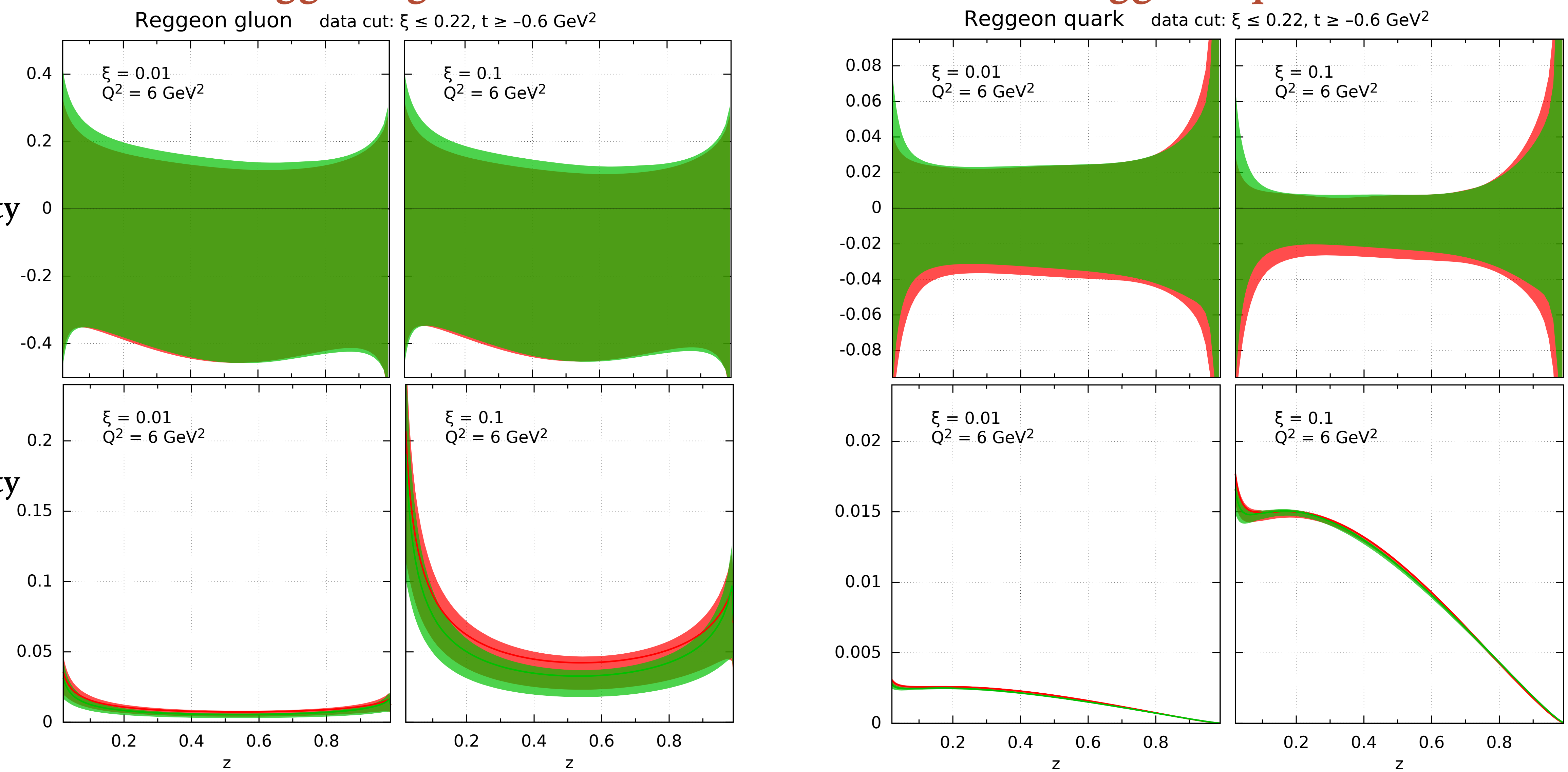
- Low energy scenario: $E_e = 5\,\text{GeV} \times E_p = 41\,\text{GeV}$
- Kinematics restricted:
  - $\xi \geq 0.01$, by cms energy
  - $t \geq -0.6\,\text{GeV}^2$, forward detector acceptance
- Reggeon dominated
- Fix Pomeron from HERA and fit only Reggeon
- Luminosity $\mathscr{L} = 10\,\text{fb}^{-1}$

Low energy: Reggeon DPDFs and uncertainties

Reggeon gluon | **Reggeon quark**

relative uncertainty

PDF with uncertainty



- Quark Reggeon constrained very well
- Larger uncertainty for Reggeon gluon which is much smaller than Pomeron gluon
- Two bands indicate sensitivity to two Monte Carlo samples: small variation

Low energy data at EIC can already determine Reggeon

Summary

- 4-D fit with Pomeron and Reggeon to the diffractive pseudodata
- EIC can extract flux parameters and partonic structure of the subleading 'Reggeon' exchange with similar precision to the leading 'Pomeron' exchange
- Constraints on Reggeon already from low energy run

More work needed on uncertainties:

- Experimental (correlated systematics)
- Theoretical (model dependence, parton parametrization)

Ideas for further studies:

- Combined HERA and EIC fits
- Charged current contribution