Extracting the partonic structure of colorless exchanges in diffraction at the EIC

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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

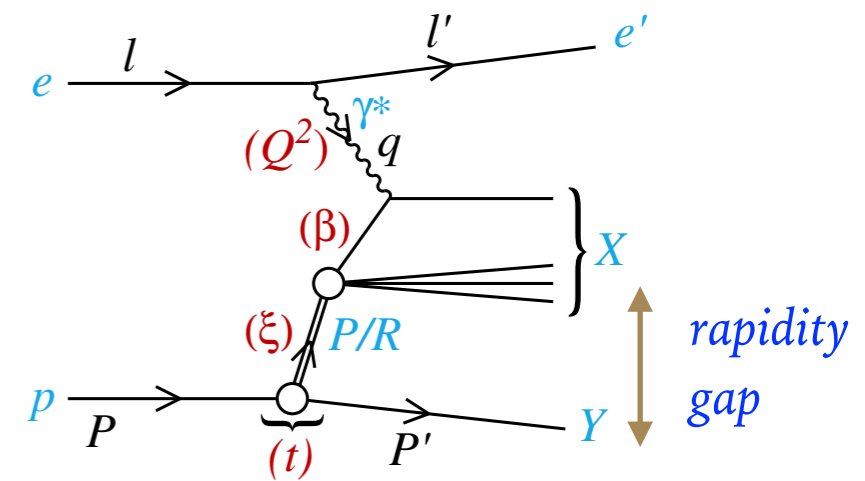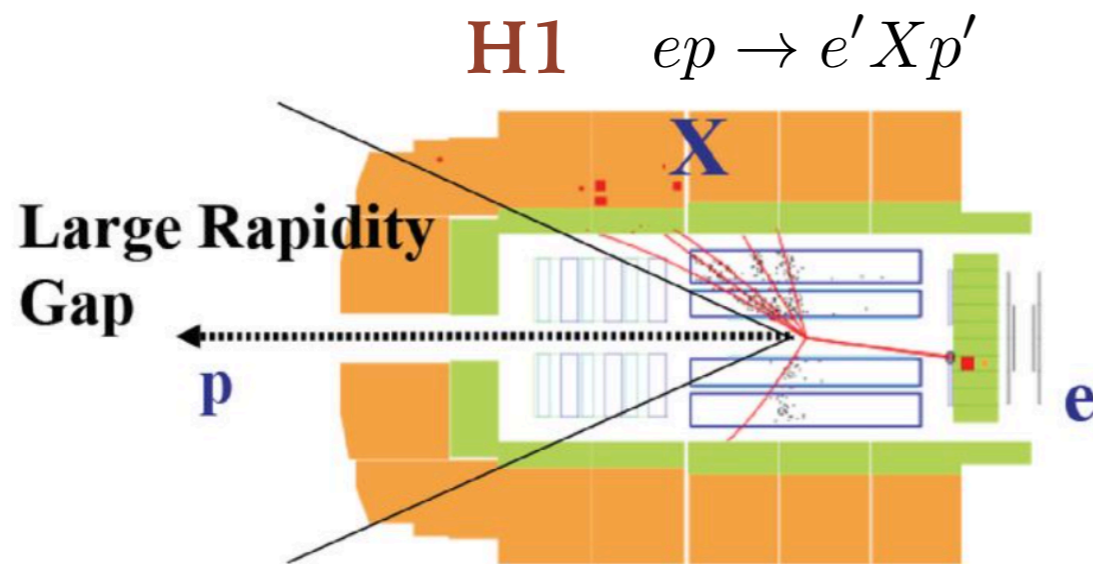Continuation of series of works on diffraction at ep/eA machines:

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 events 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**

H1 $ep \to e'Xp'$

$$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$ momentum fraction of the diffractive exchange w.r.t hadron

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$ momentum fraction of parton w.r.t diffractive exchange

$$z \geq \beta$$

$$t = (p - p')^2$$ 4-momentum transfer squared

$$\boxed{x = \xi \beta}$$

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 ?

Diffraction at HERA: importance of 'Reggeon'

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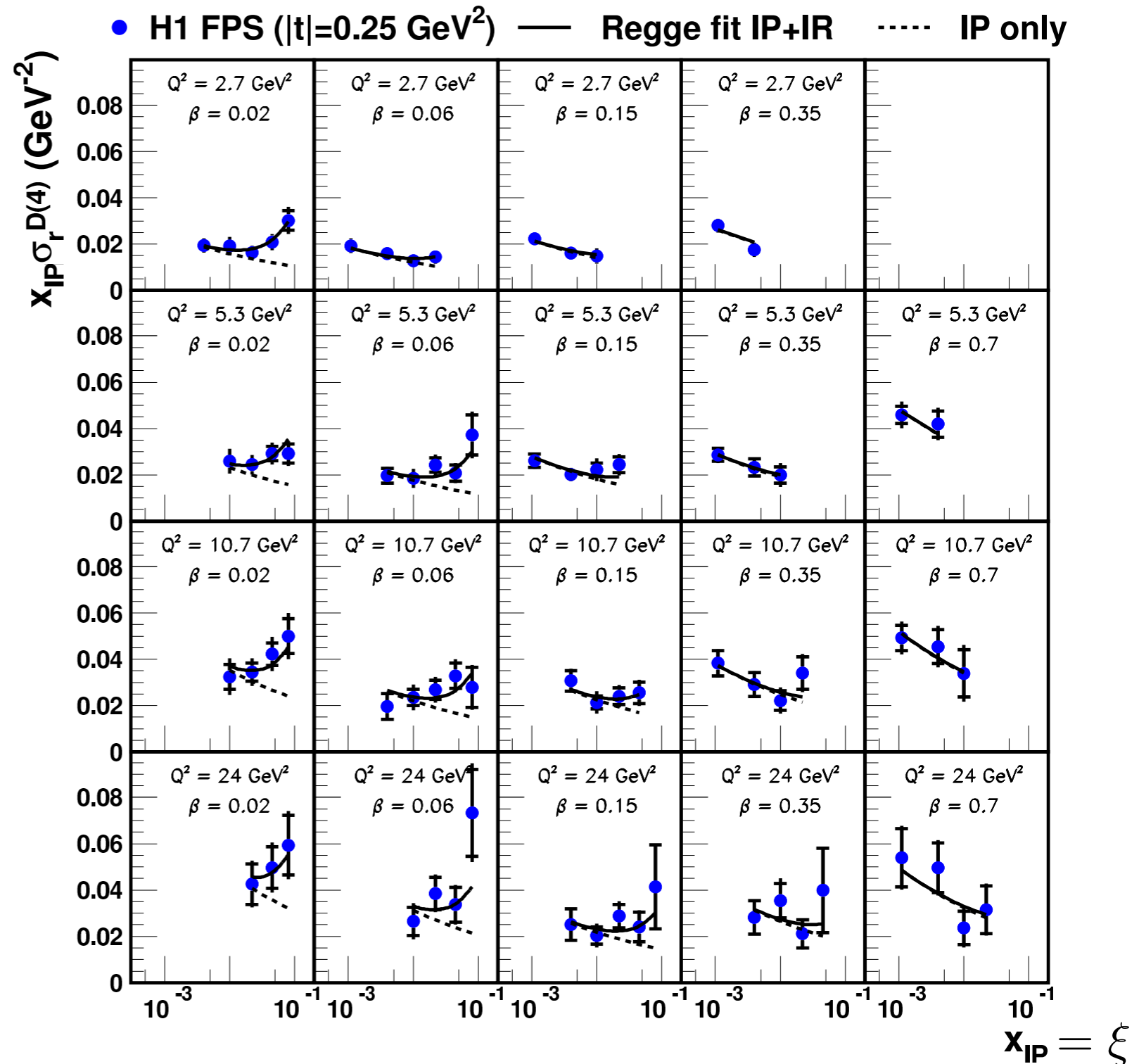
Described by two contributions:

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....
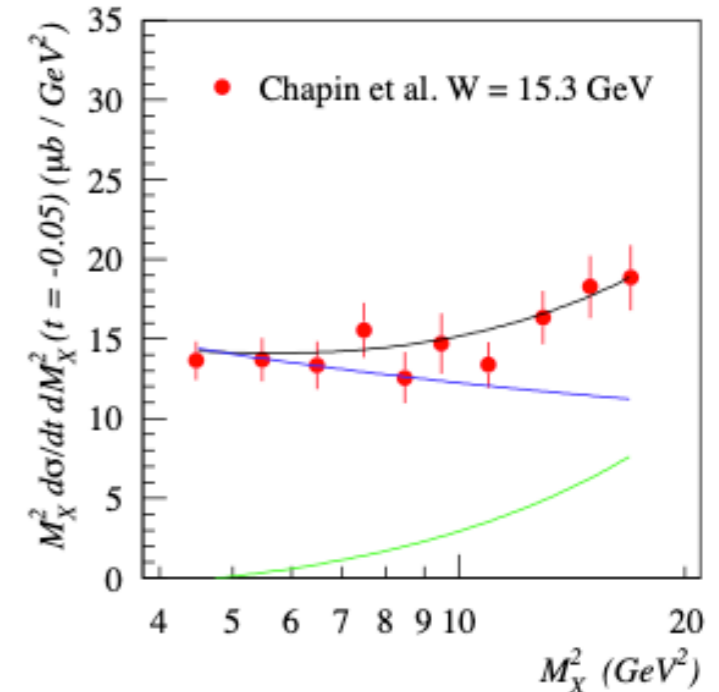
photoproduction $Q^2 \sim 0$
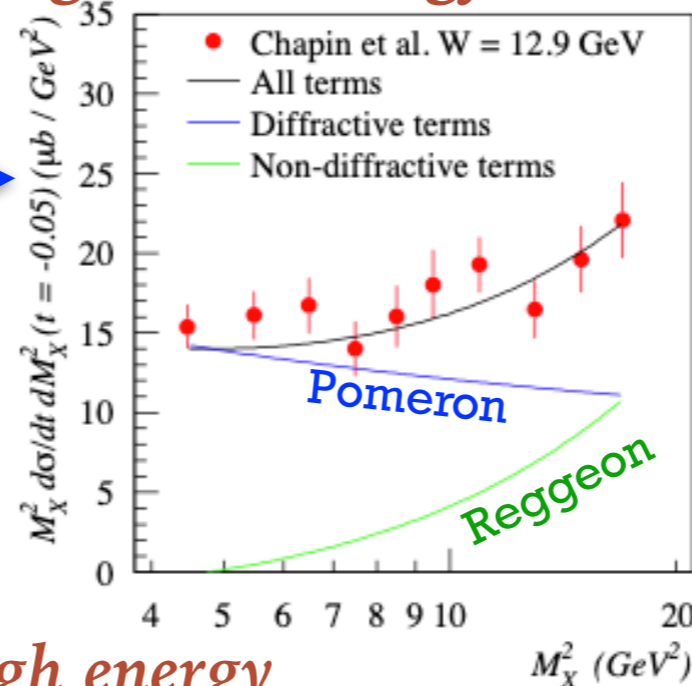
$$\gamma + p \to X + p$$

Fit using **Regge** model
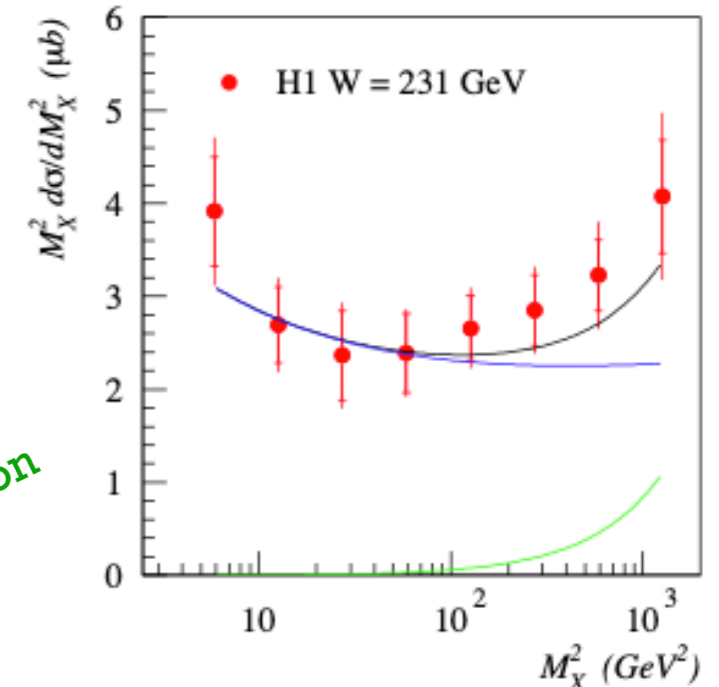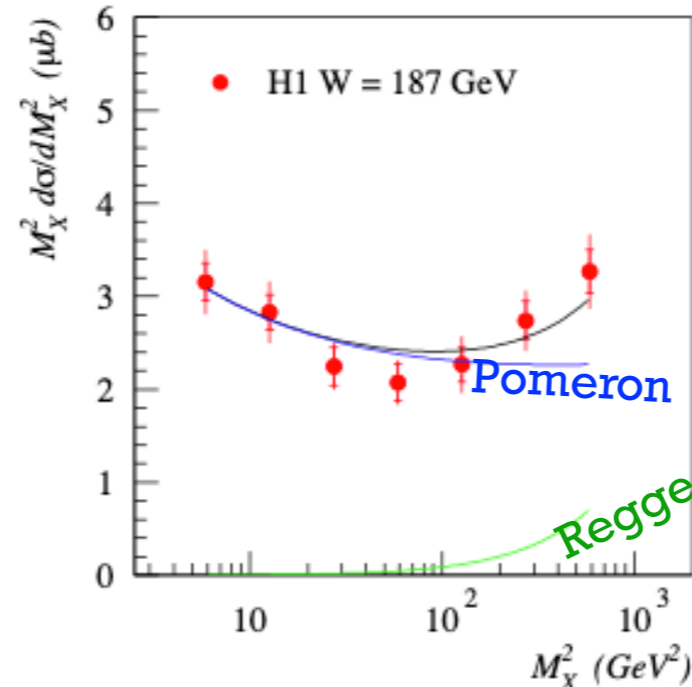
Subleading exchanges present at HERA

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
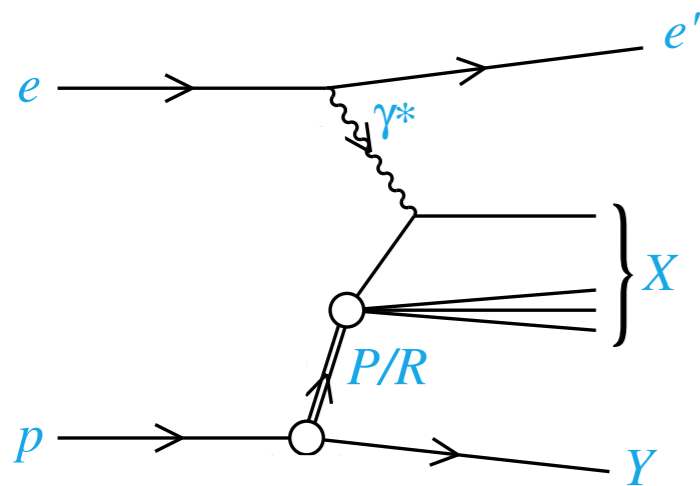

Fixed target: low energy

H1: high energy
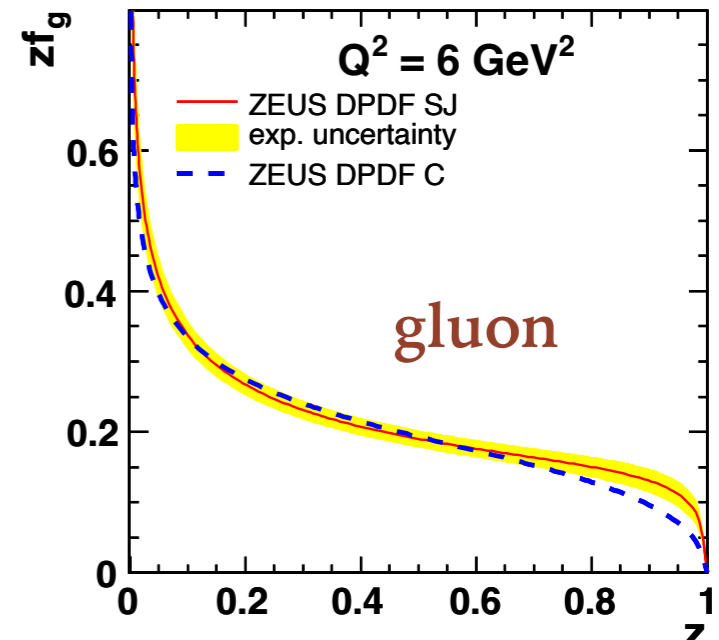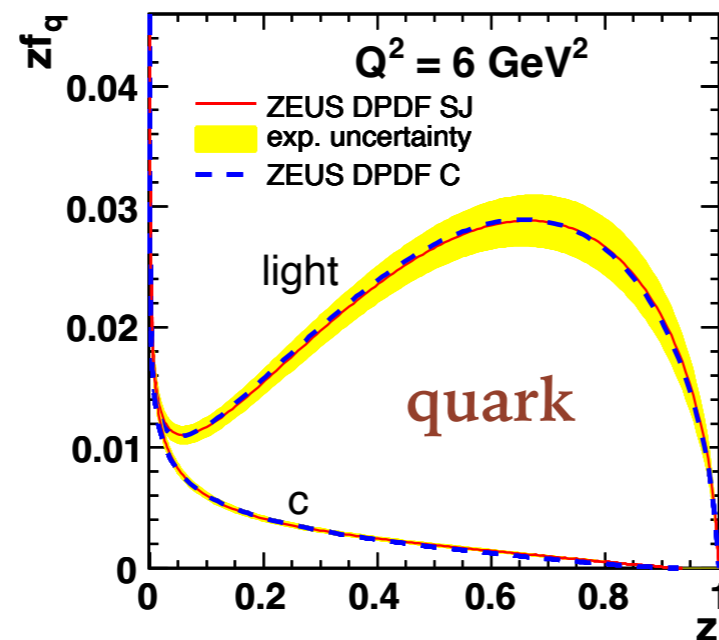
Extraction of DPDF from HERA data

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
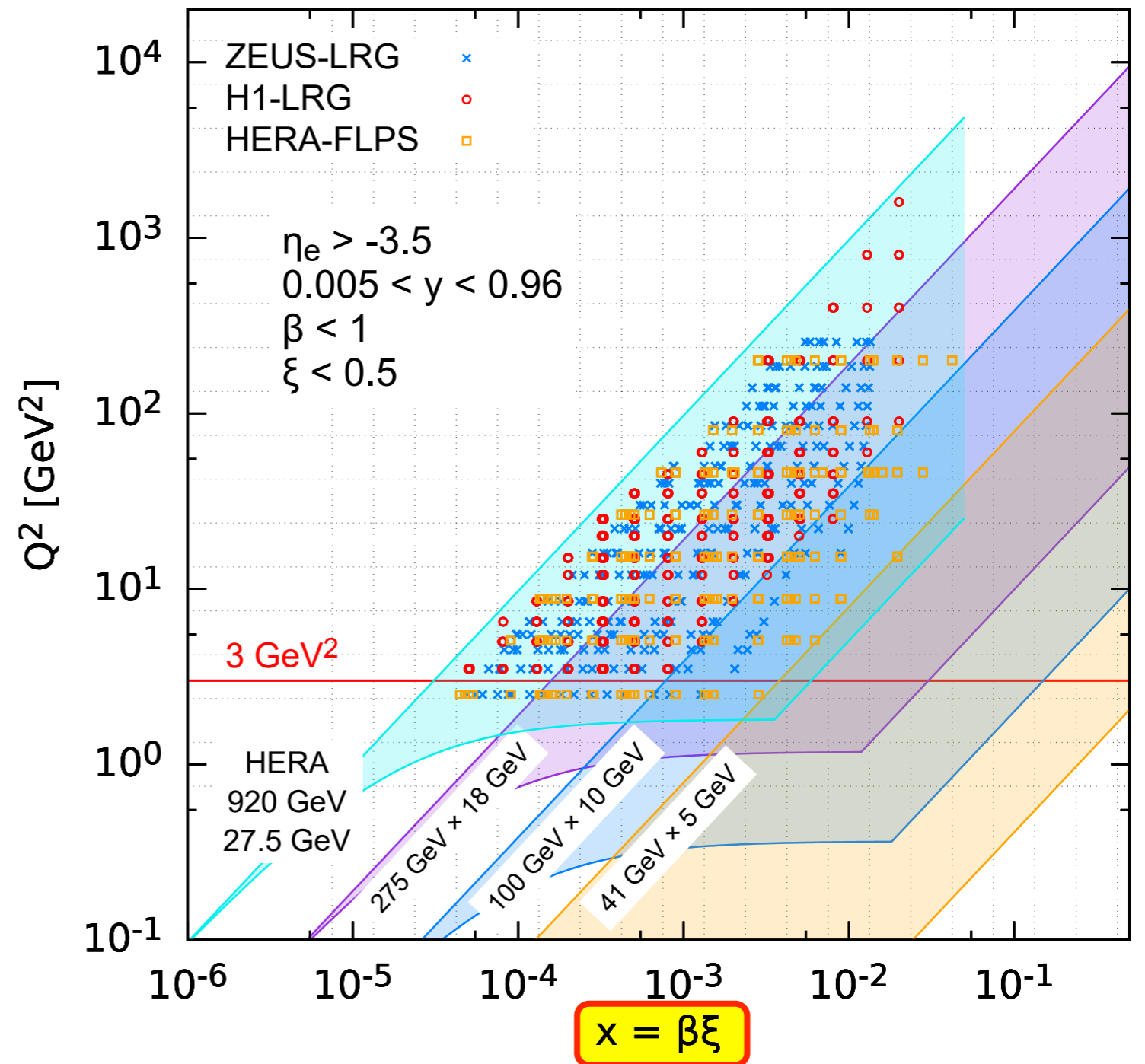
Diffraction at EIC

EIC complementarity to HERA

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

Large $x \rightarrow$ 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

Legend:
- ZEUS-LRG (blue ×)
- H1-LRG (red ○)
- HERA-FLPS (orange □)

$\eta_e > -3.5$
$0.005 < y < 0.96$
$\beta < 1$
$\xi < 0.5$

3 GeV²

HERA 920 GeV 27.5 GeV

275 GeV × 18 GeV
100 GeV × 10 GeV
41 GeV × 5 GeV

Q^2 [GeV²]

$x = \beta\xi$

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:

$$\sigma_{\mathrm{red}}^{D(4)} = \phi_{I\!\!P}(\xi, t)\, \mathcal{F}_2^{I\!\!P}(\beta, Q^2) + \phi_{I\!\!R}(\xi, t)\, \mathcal{F}_2^{I\!\!R}(\beta, Q^2)$$

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

Flux parameters:

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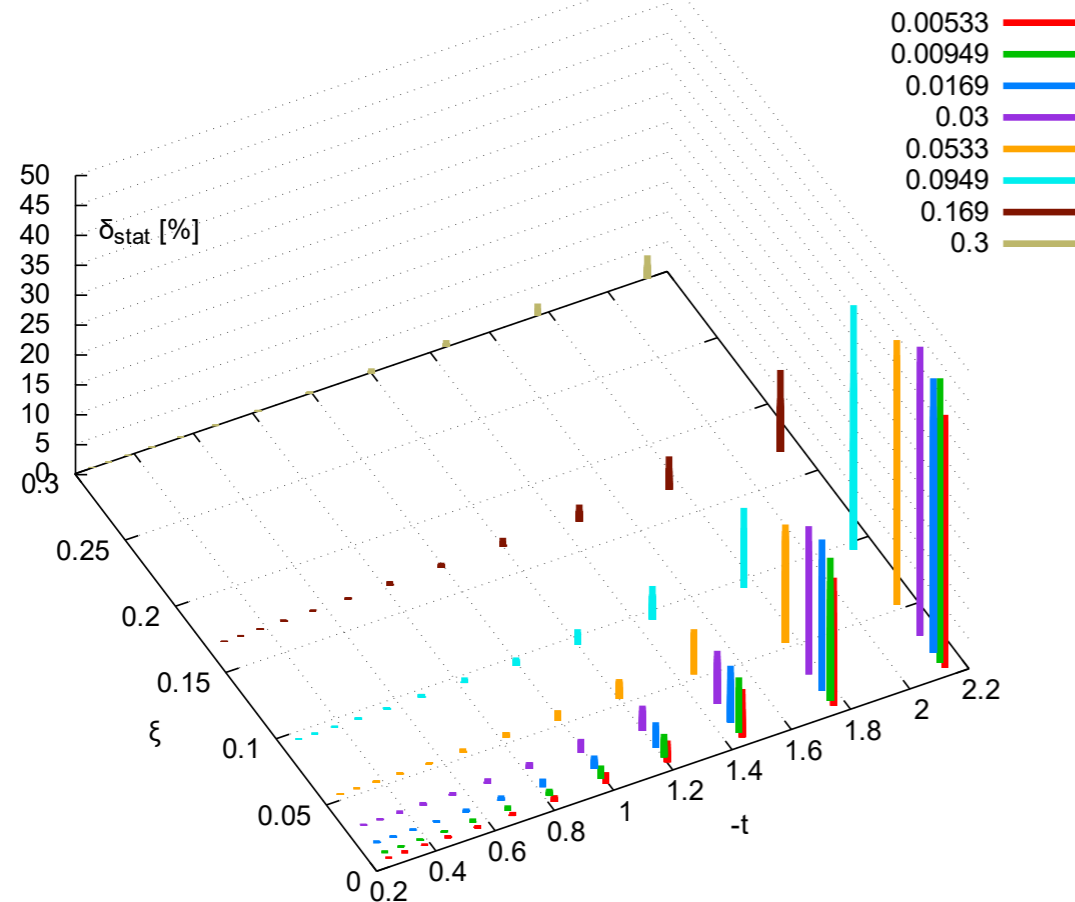
ZEUS fit parameters

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

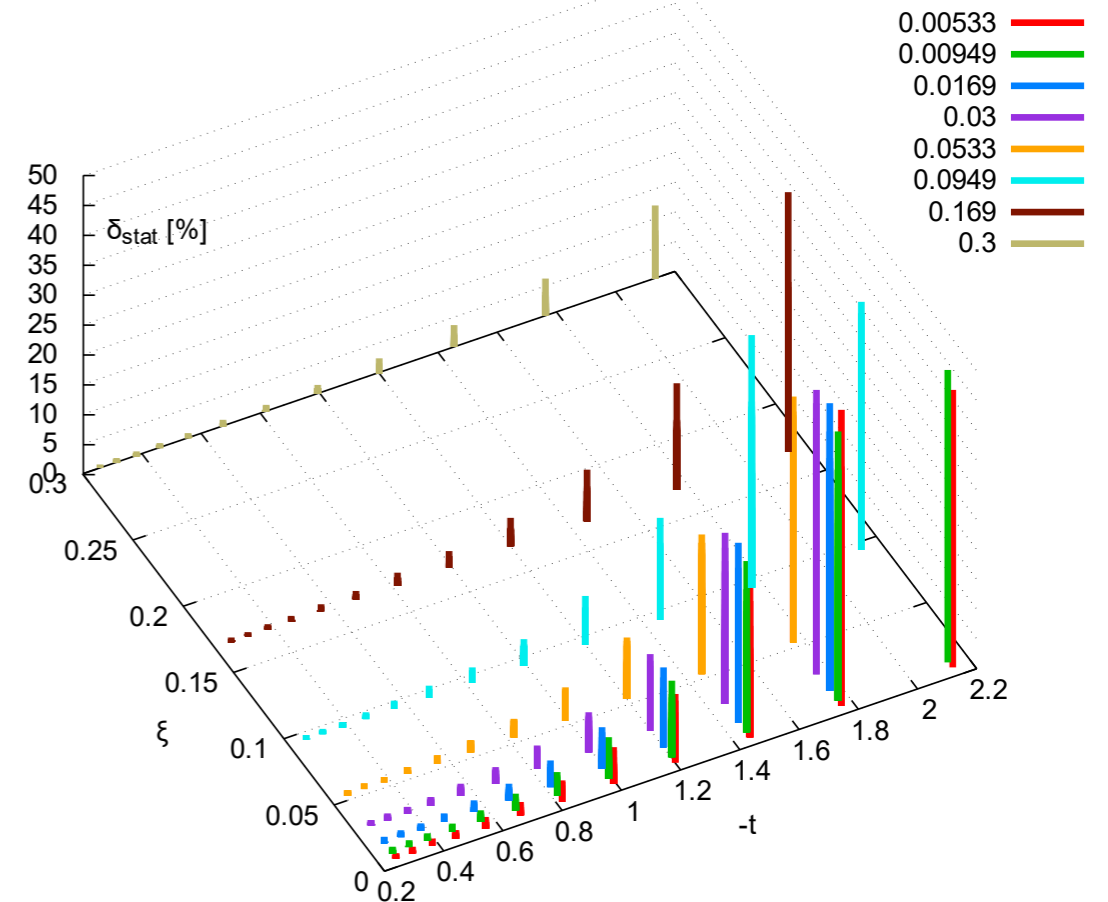# EIC pseudodata generation: lumi, energy, errors

- Use NC simulations for EIC (no HERA nor CC yet)

- Three scenarios for integrated luminosity and energy :

  - $\mathscr{L} = 100 \, \text{fb}^{-1}$ at high energy $E_e = 18 \, \text{GeV} \times E_p = 275 \, \text{GeV}$

  - $\mathscr{L} = 10 \, \text{fb}^{-1}$ at high energy $E_e = 18 \, \text{GeV} \times E_p = 275 \, \text{GeV}$

  - $\mathscr{L} = 10 \, \text{fb}^{-1}$ at low energy $E_e = 5 \, \text{GeV} \times E_p = 41 \, \text{GeV}$

- 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

ep beams 18 GeV × 275 GeV, L = 100 fb⁻¹

ep beams 18 GeV × 275 GeV, L = 10 fb⁻¹

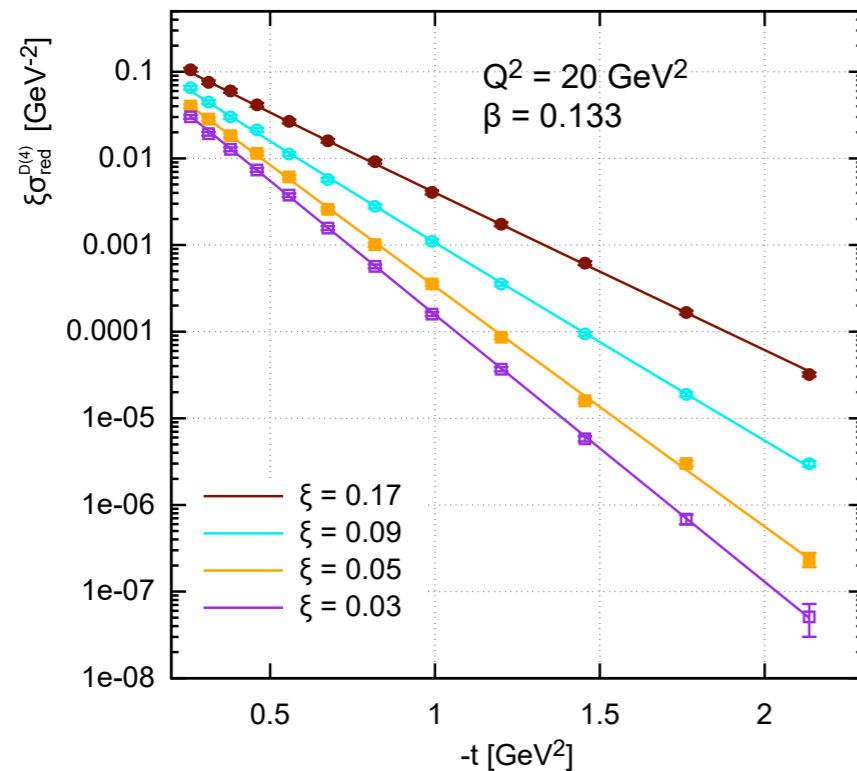For $Q^2 < 50\,\mathrm{GeV}^2$ and $|t| < 1.2\,\mathrm{GeV}^2$

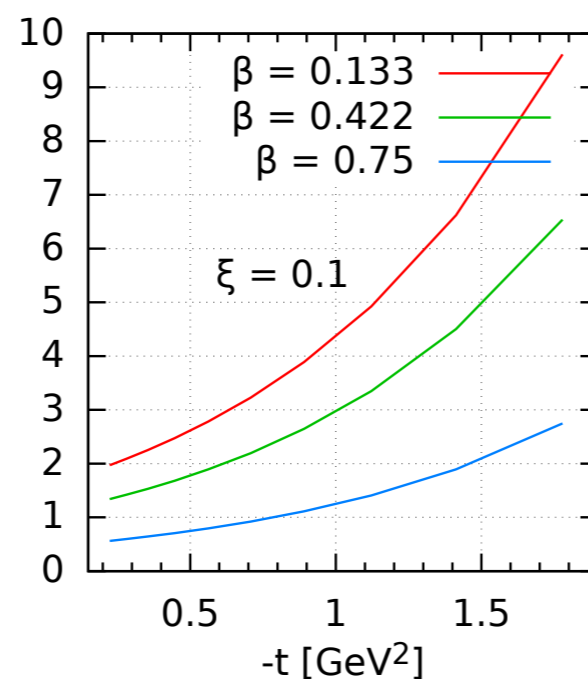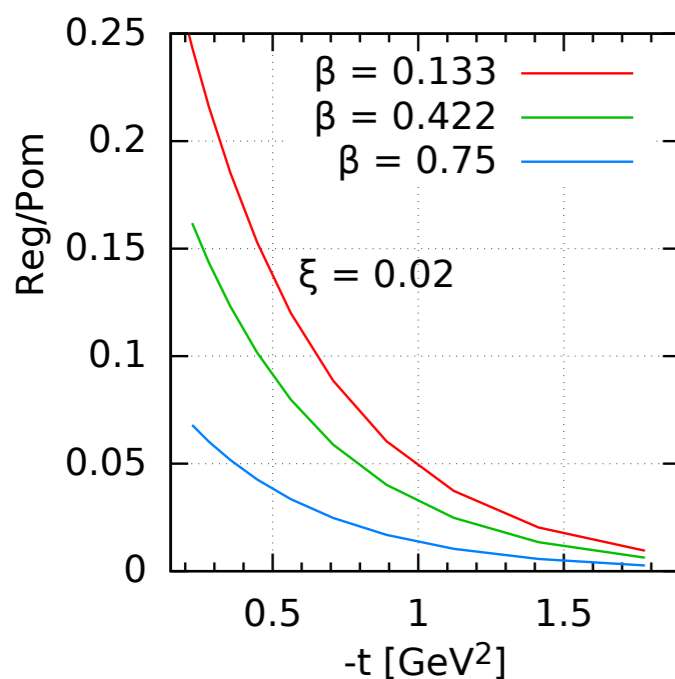$\mathscr{L} = 10\,\mathrm{fb}^{-1}$: less than 4% data points have $\delta_{\mathrm{stat}} > 5\,\%$

$\mathscr{L} = 100\,\mathrm{fb}^{-1}$: 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

$\mathbb{R}/\mathbb{P}$ ratio vs $-t$ for $\xi = 0.01, 0.1$

- Change of ratio for small vs large ξ as a function of $-t$: different slope

- $\mathbb{R}/\mathbb{P} < 1$ for small $\xi \sim 0.02$

- $\mathbb{R}/\mathbb{P} > 1$ for larger $\xi \geq 0.1$: not accessible at HERA

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
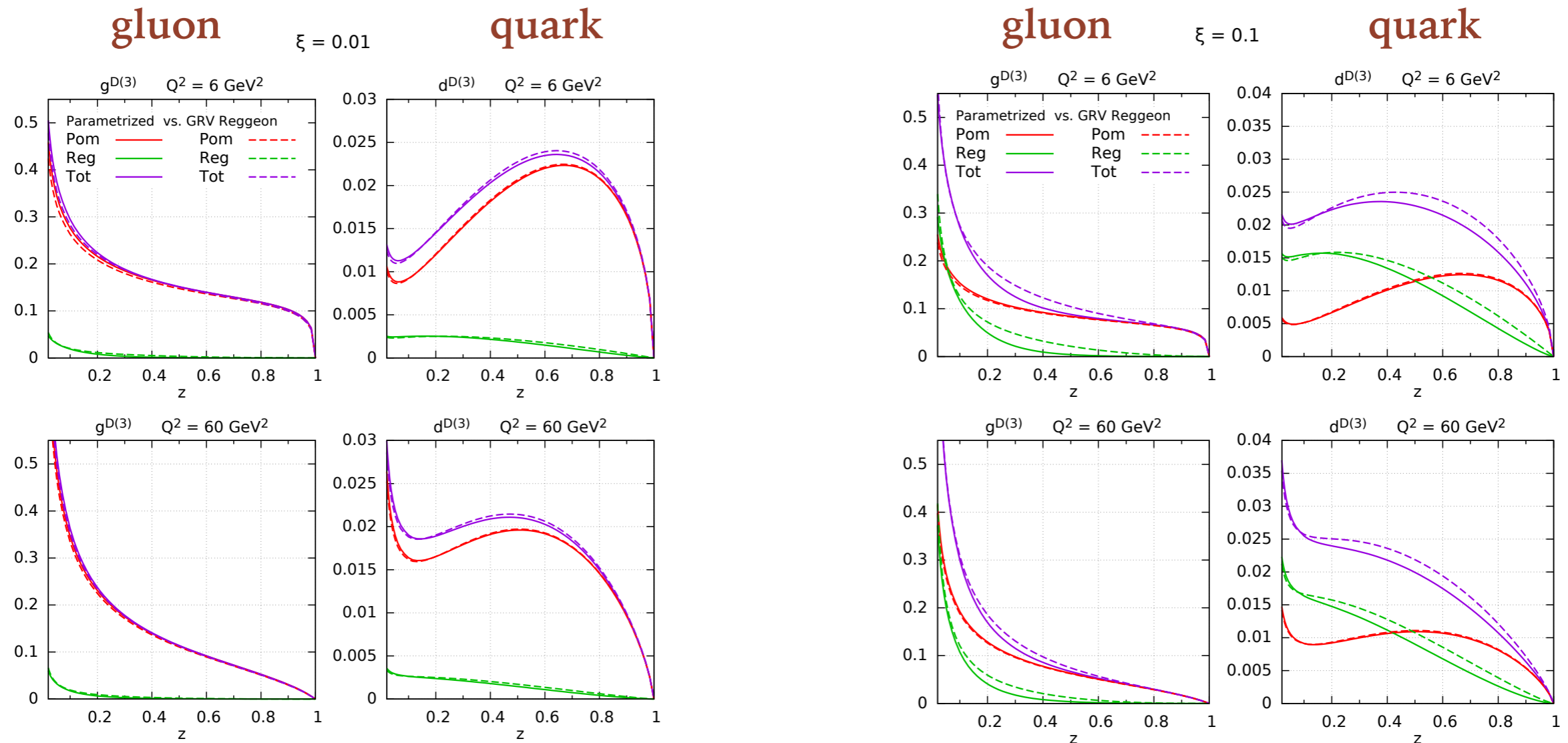- Generic parametrization at $Q_0^2 = 1.8 \text{ GeV}^2$:

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

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 $I\!\!R$: $\alpha(0), \alpha', B$

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

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)
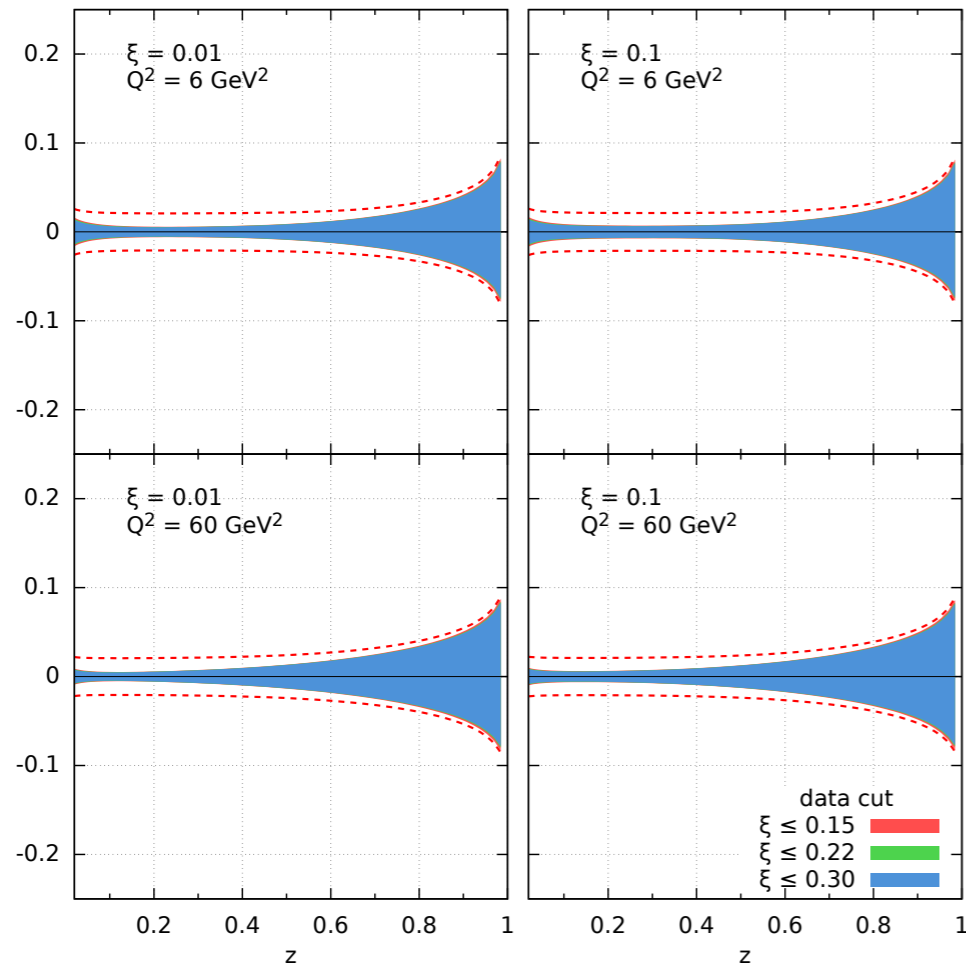
Reggeon reproduced reasonably well

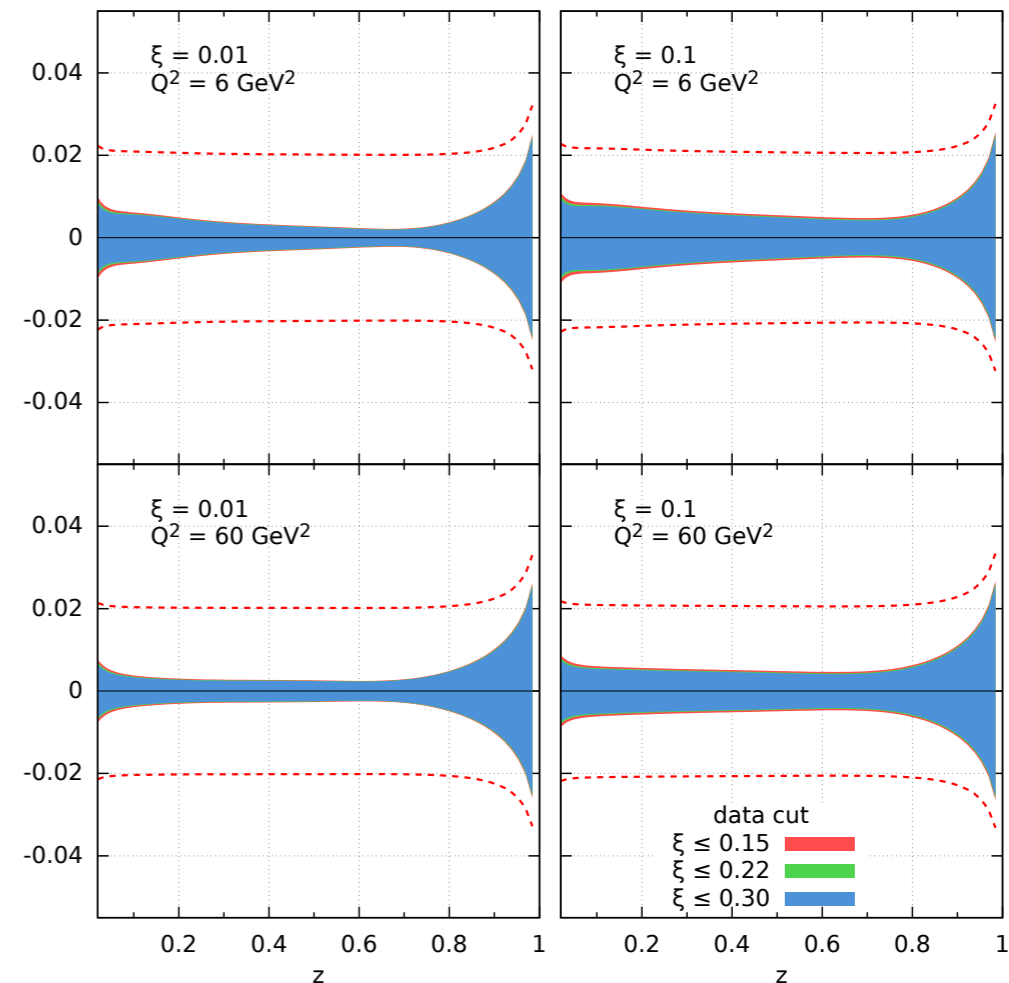**Pomeron** reproduced almost perfectly

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
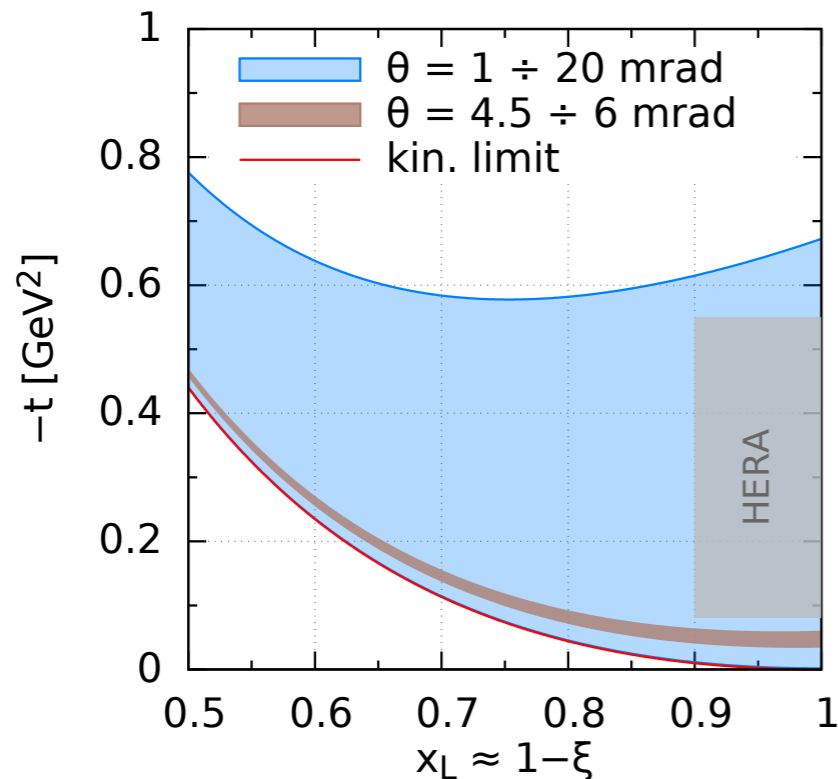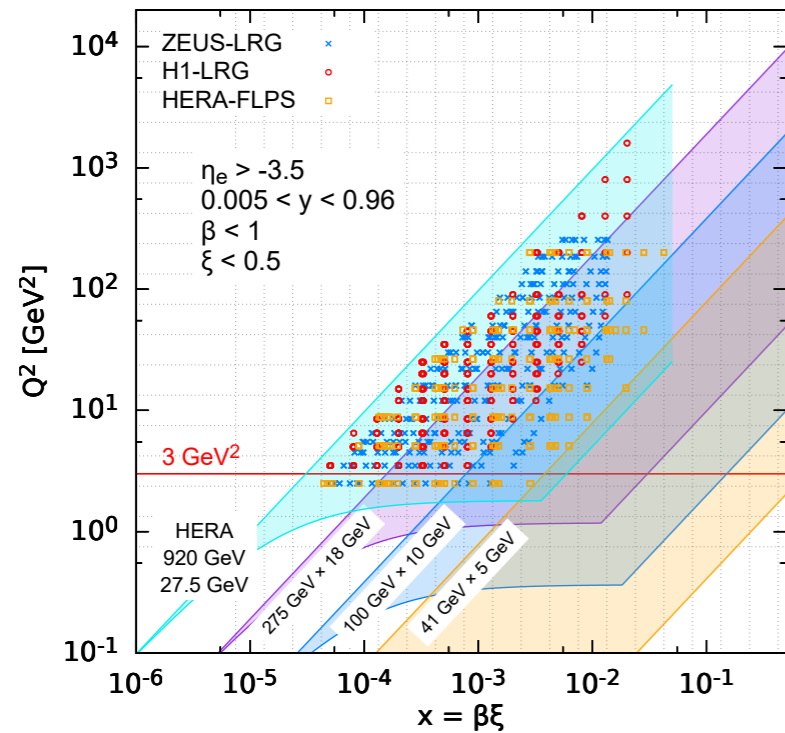*note different vertical scale for gluons and quarks*

Uncertainties of diffractive PDFs: Reggeon

- <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 $\xi_{\max} \simeq 0.15 \div 0.2$

Low energy scenario

- Low energy scenario:
  $$E_e = 5\,\text{GeV} \times E_p = 41\,\text{GeV}$$

- Kinematics restricted:
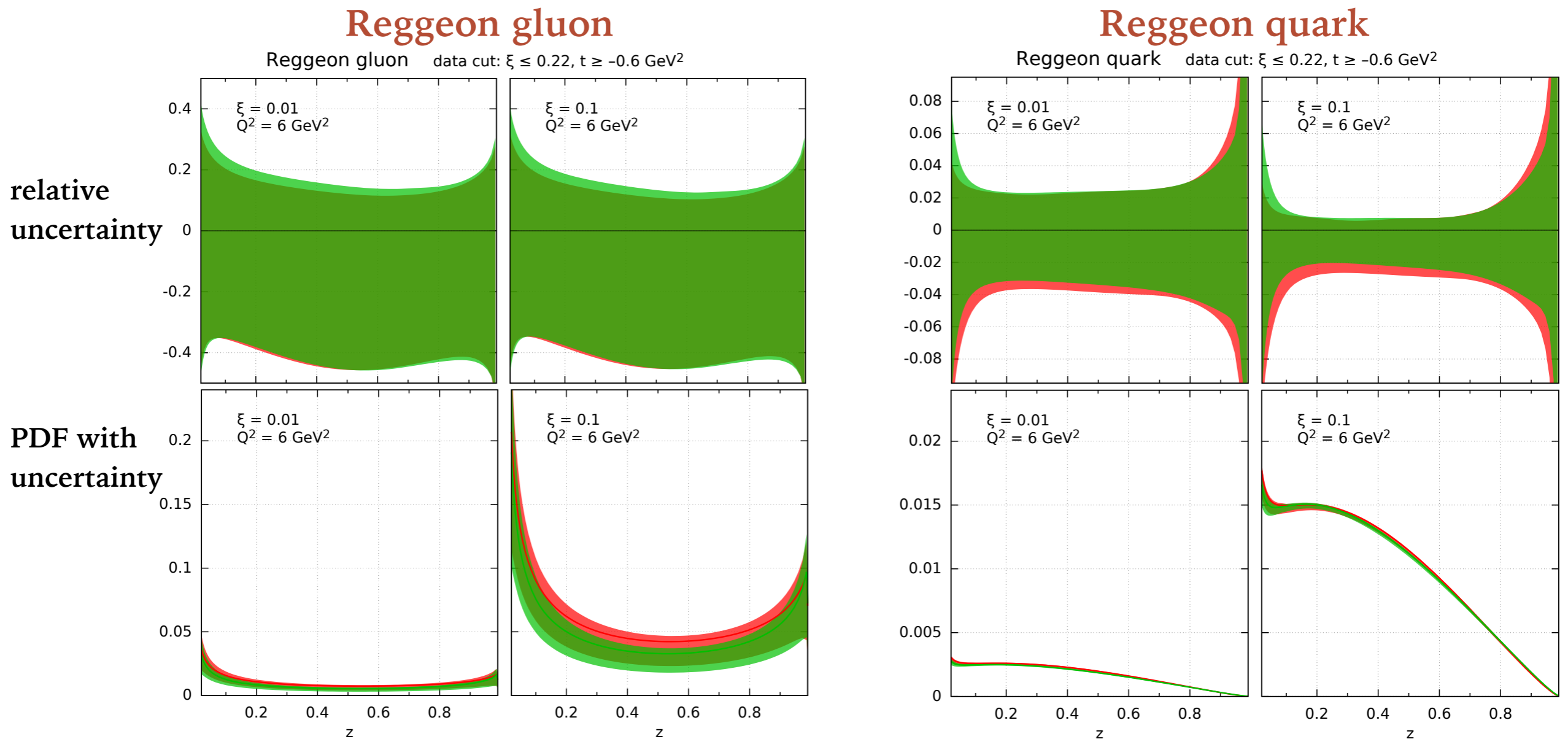
  - $\xi \geq 0.01$, by cms energy

  - $t \geq -0.6\,\text{GeV}^2$, 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 quant

- 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