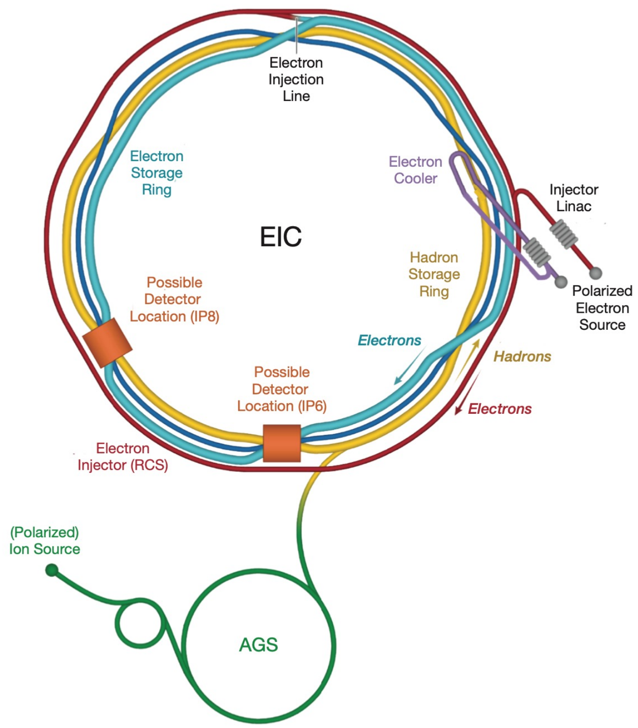

EICUG 2023

Extracting Reggeon exchange at the EIC

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SURGE COLLABORATION

Outline

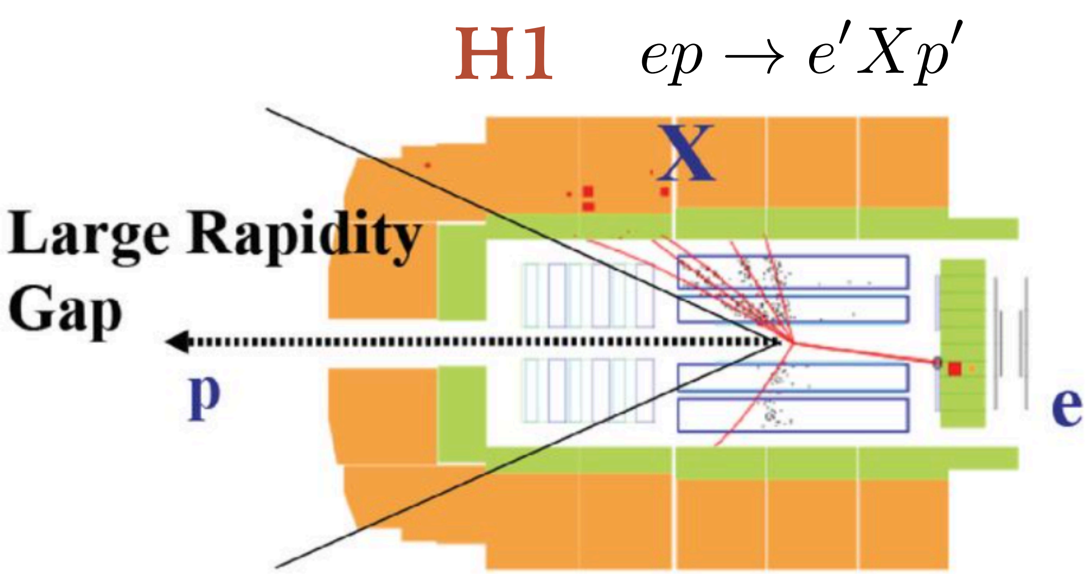
- Inclusive diffraction at HERA
- Description of diffraction: Pomeron and Reggeon components
- EIC pseudodata for diffractive cross section
- Extraction of Pomeron and Reggeon, estimate of uncertainties

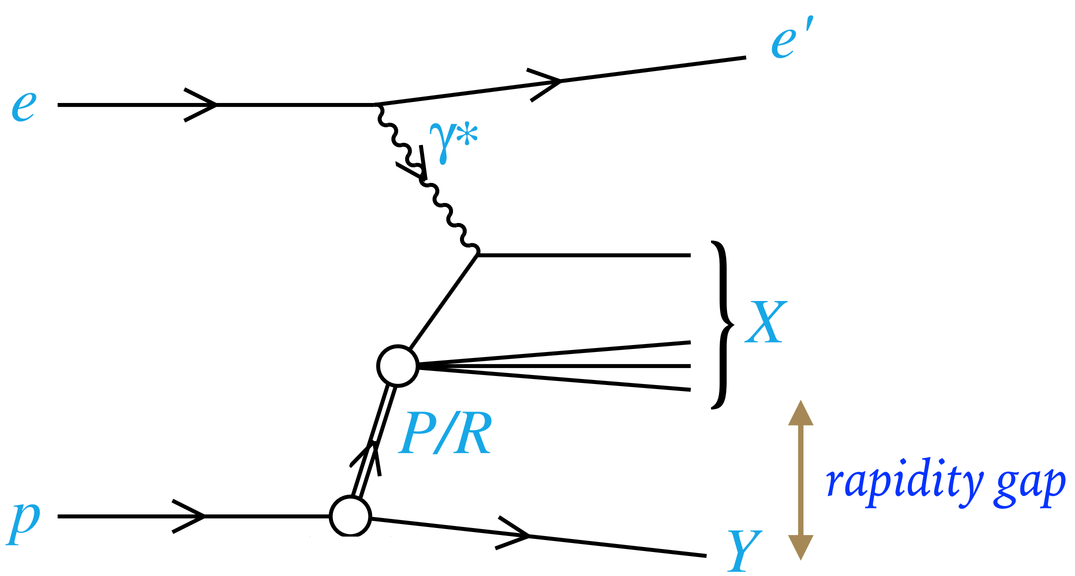
Continuation of series of works on diffraction at ep/eA machines:

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 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**

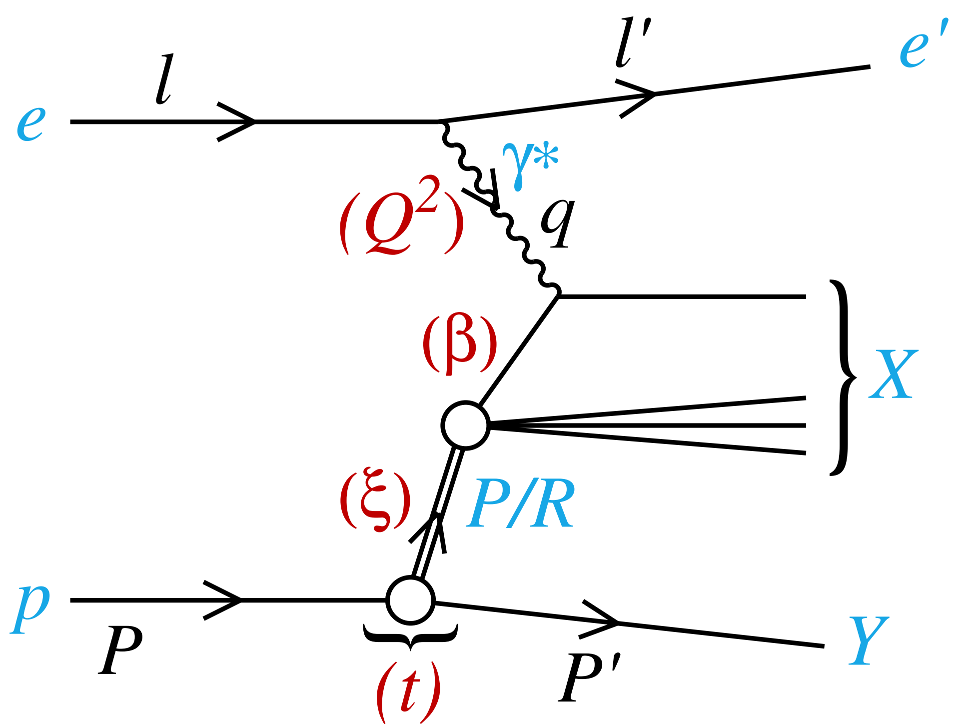




Questions:

- 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:

$$s = (k+p)^2$$

photon-proton cms energy squared:

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

inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x

$$x = \frac{-q^2}{2p \cdot q}$$

(minus) photon virtuality

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

Diffractive DIS variables:

M_X^2 — mass of the diffractive system

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

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

$$z \geq \beta$$

same as above but more generally (at higher orders)

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

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

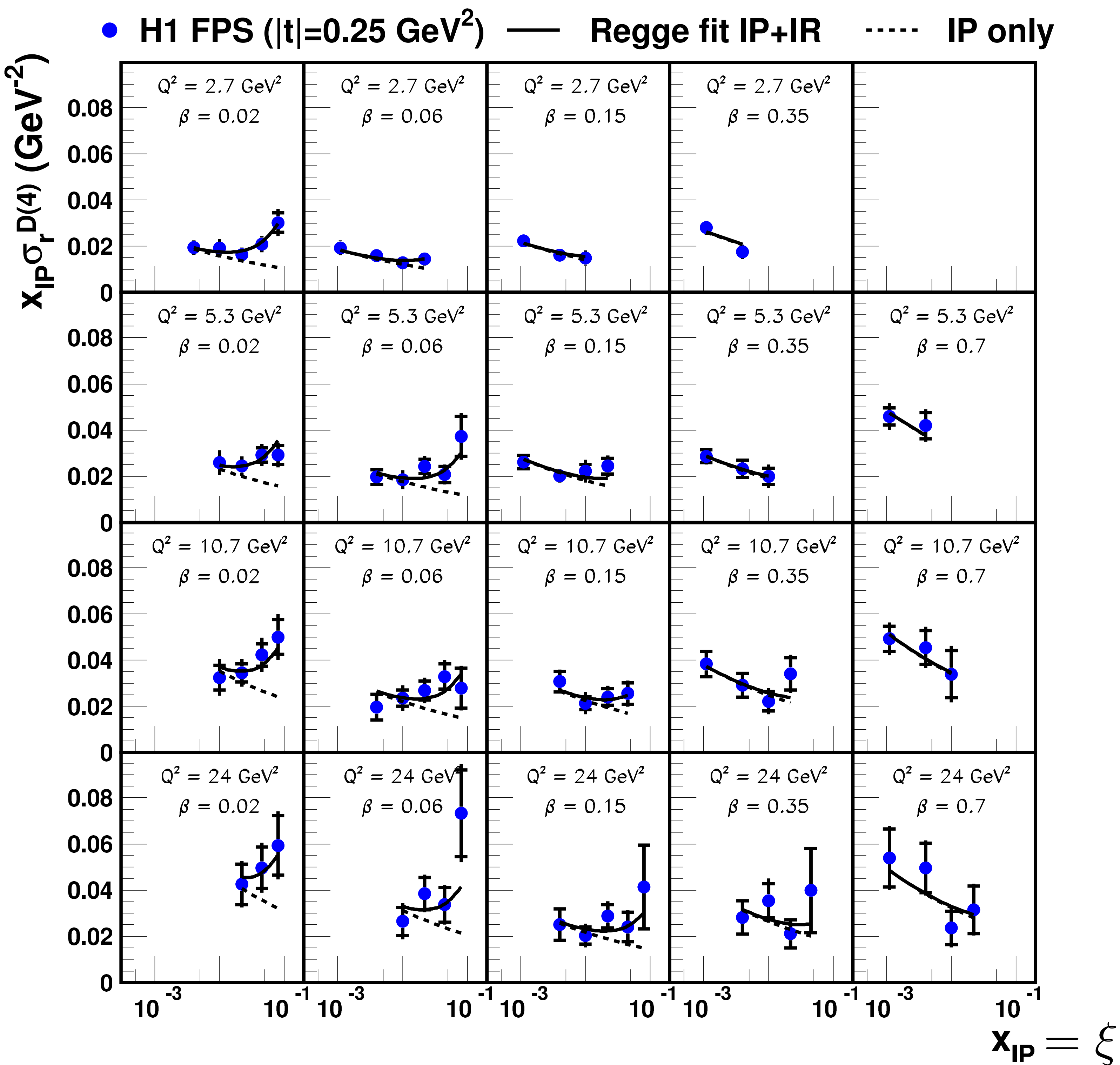
Dimensions:

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

$\sigma_{\rm r}^{\rm D(3)}$ 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 $Q^2 \sim 0$**

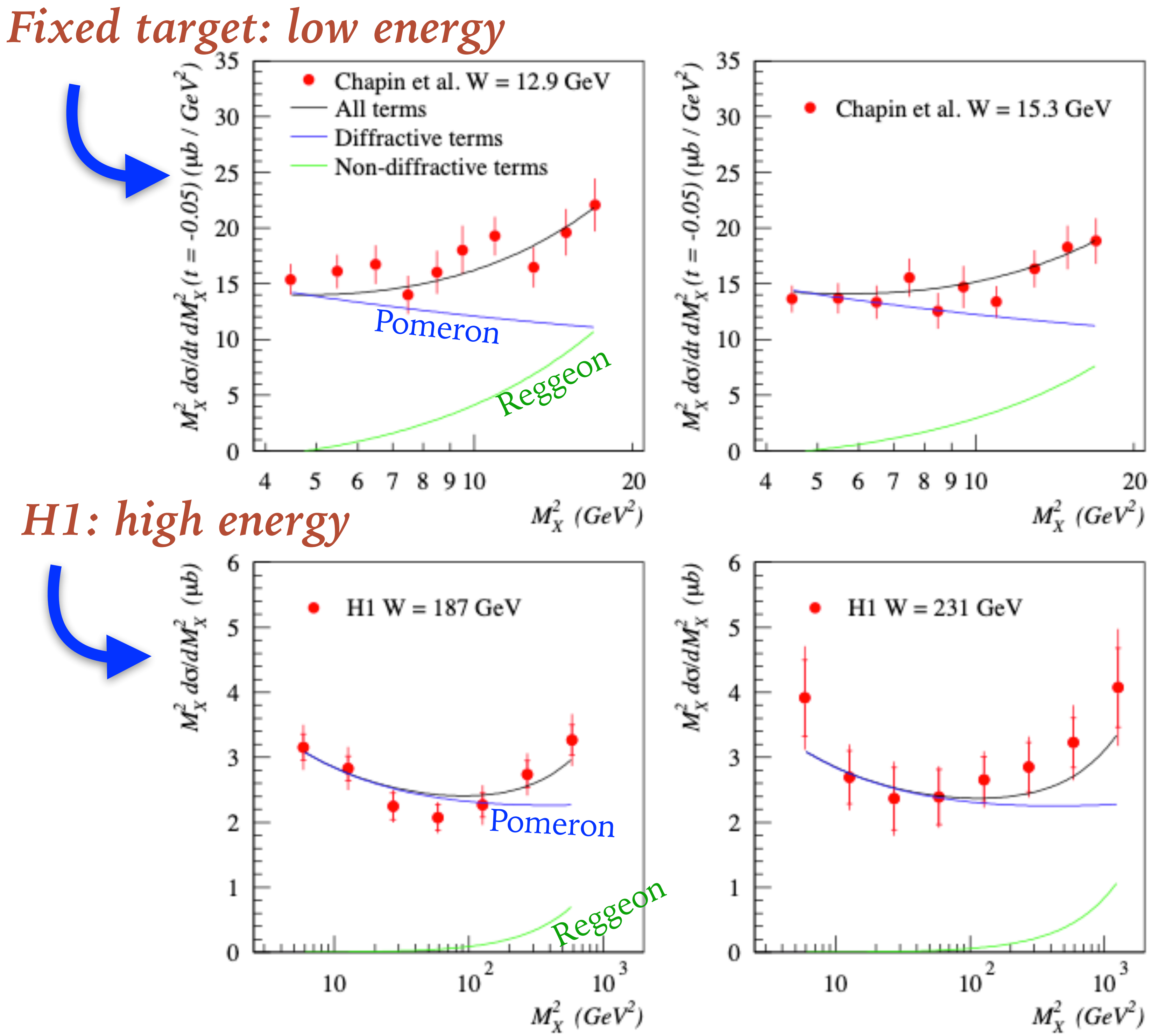
$$\gamma + p \to X + p$$

Fit using **Regge** model

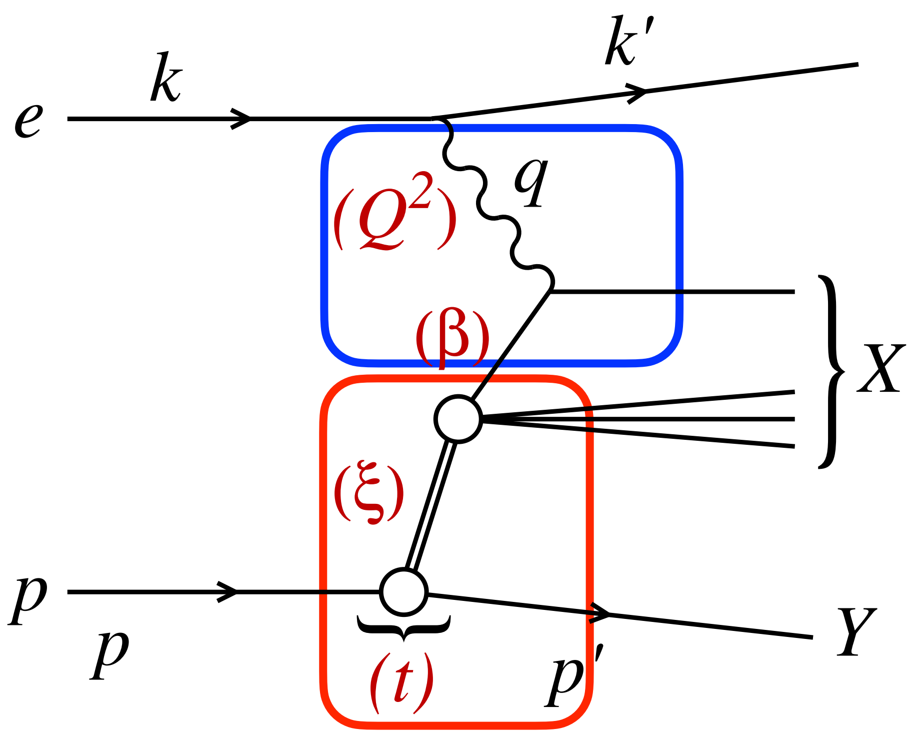
Subleading exchanges present at HERA

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



QCD description of diffraction in DIS



Collins

Collinear factorization in diffractive DIS at $Q^2 \gg 0$

$$d\sigma^D(\beta,\xi,Q^2,t) = \sum_i \int_\beta^1 \frac{dz}{z}\, d\hat{\sigma}(\beta/z,Q^2)\, f_i^D(z,\xi,Q^2,t) + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

- 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 for the inclusive DIS.
- **DPDFs** represent the probability distributions for partons i in the proton under the constraint that the proton is scattered into system Y with a specified 4-momentum.

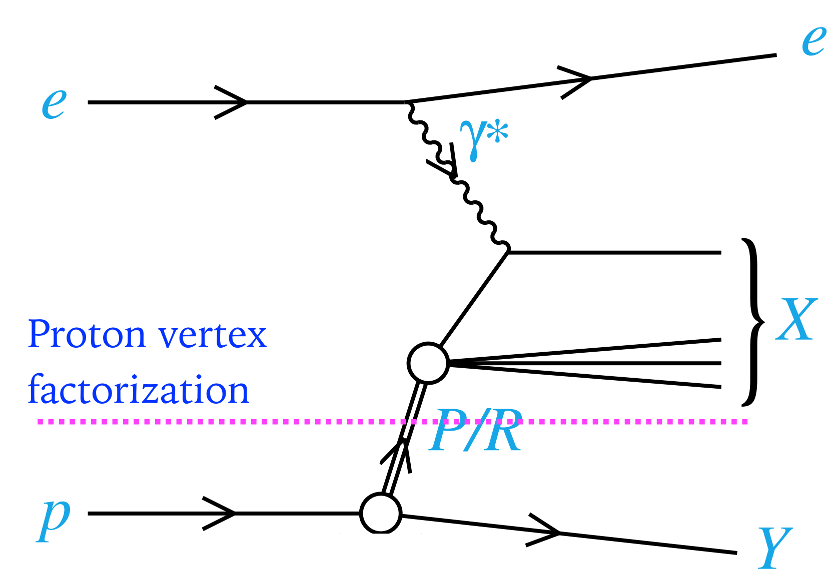
Parametrization of DPDFs

HERA data suggest **Regge factorization** at the proton vertex

$$(z, \xi, Q^2, t) \rightarrow (\xi, t) \times (z, Q^2)$$

Pomeron and **Reggeon** contribution need to be included

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



Regge type flux:

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

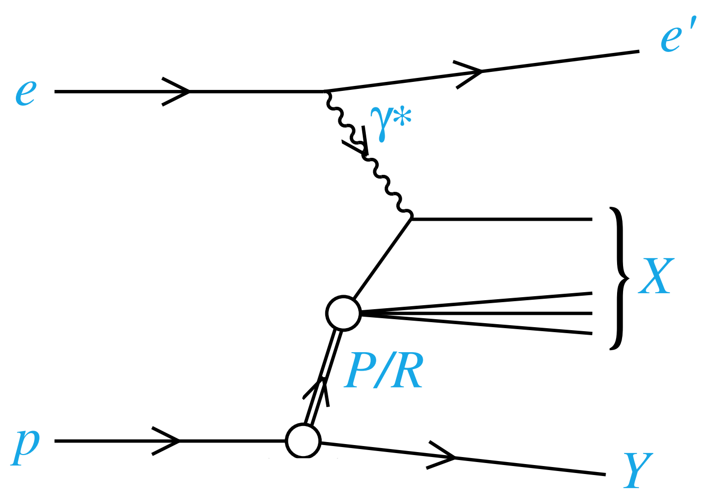
Trajectory:

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

Pomeron PDFs $f_i^{I\!P}$ obtained via NLO DGLAP evolution starting at initial scale $\mu_0^2 = 1.8\ \mathrm{GeV}^2$

Reggeon PDFs $f_i^{I\!R}$ taken from the parametrization of pion structure function

Extraction of DPDF from HERA data

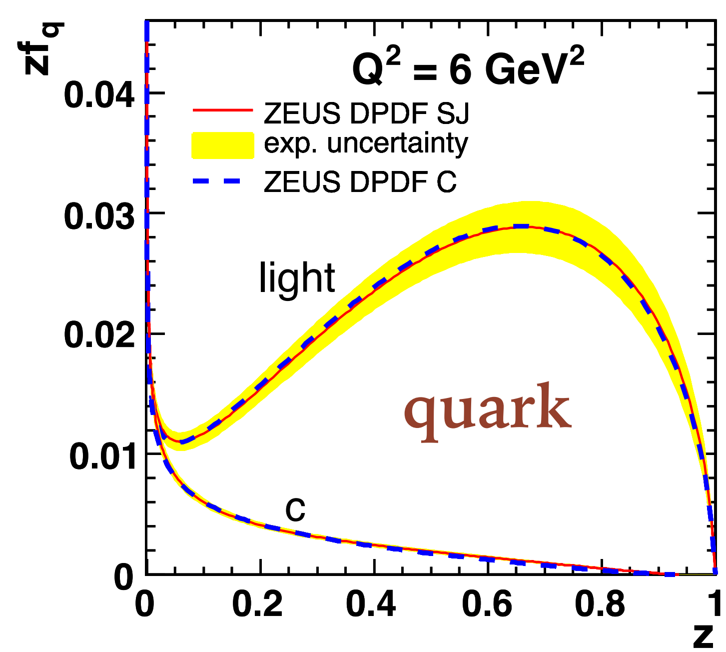


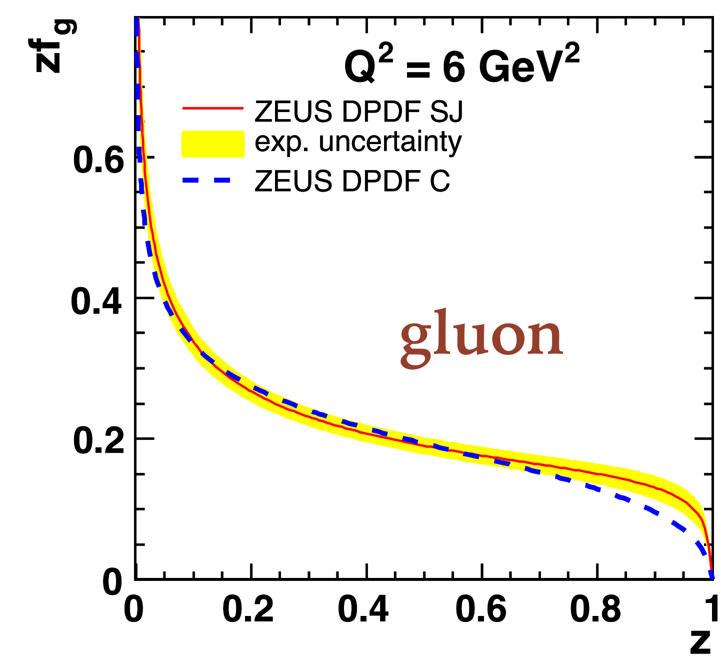
Example of DPDFs extracted from the ZEUS data

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

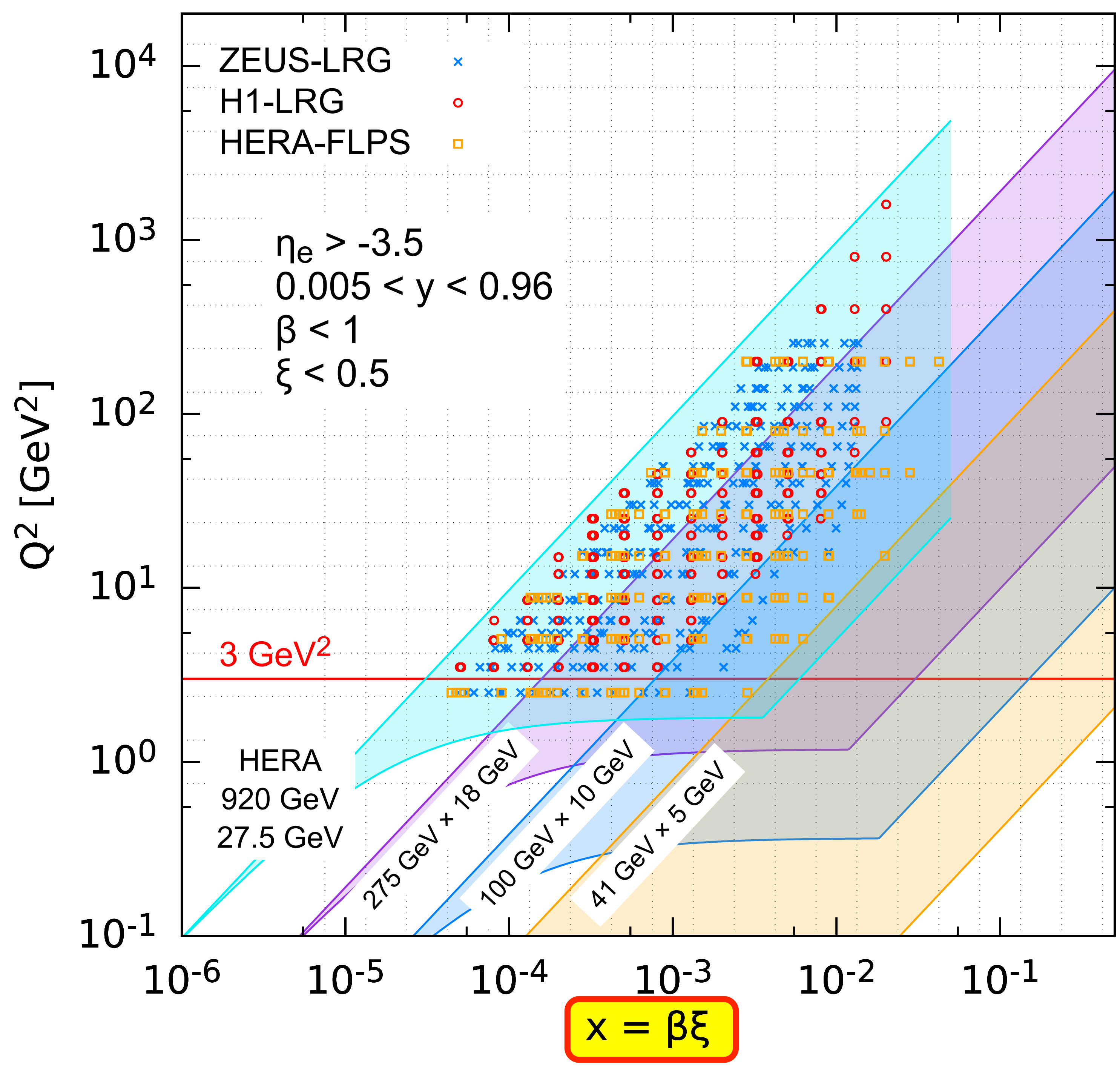
EIC 3 scenarios - HERA

EIC complementarity to HERA

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

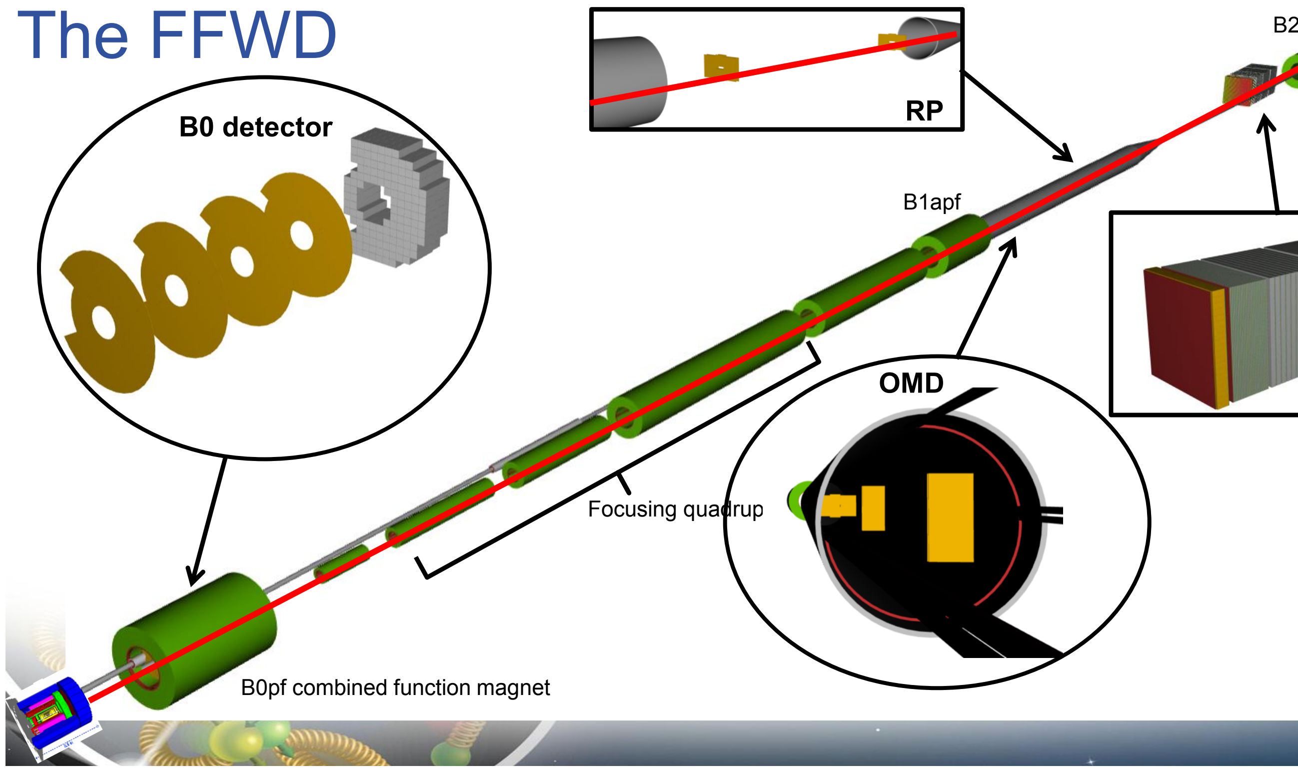
Large $x \rightarrow$ Large β : constraints on large z region of DPDFs

Only selected energy scenarios at EIC shown



Forward instrumentation at EIC and acceptance

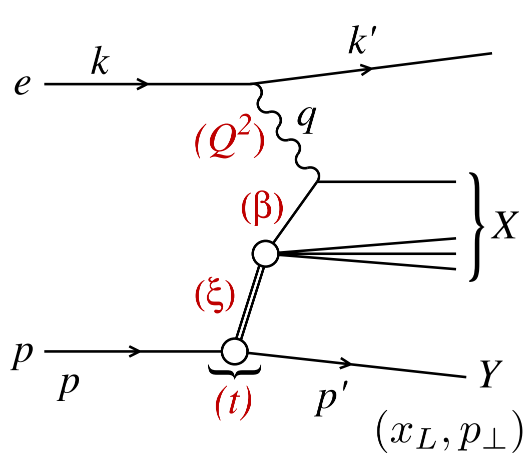
The FFWD

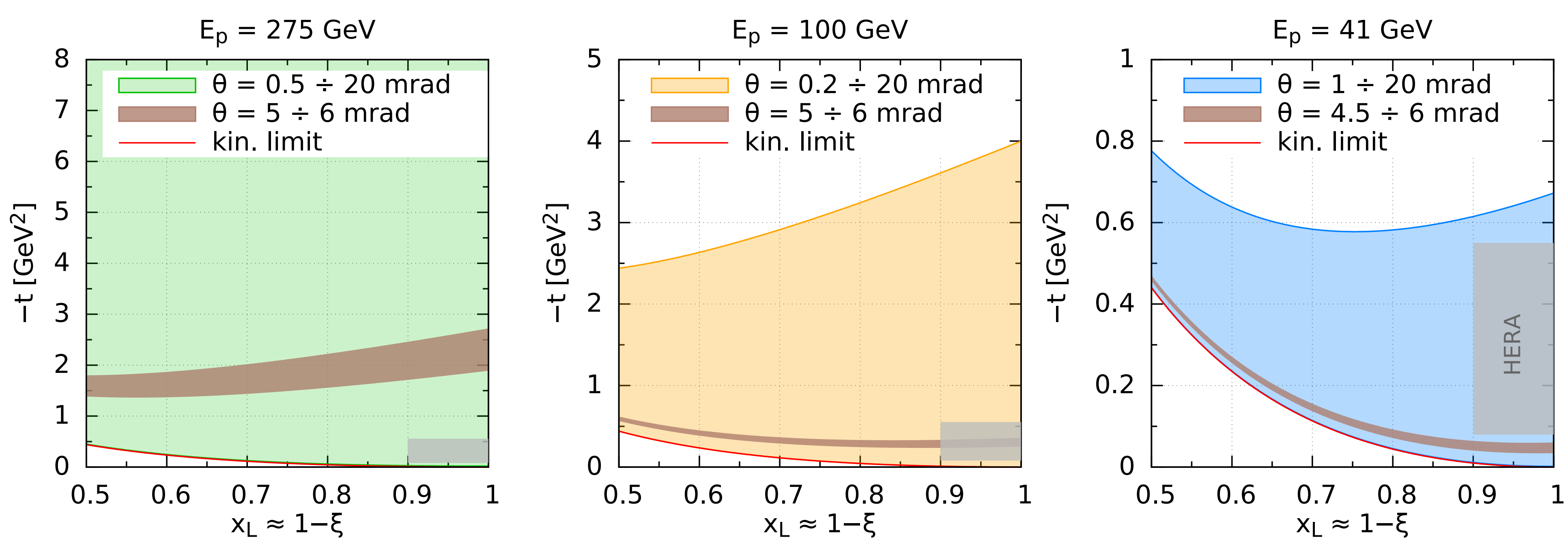


talk by Michael Pitt

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 ($4.6 < \eta < 5.9$)

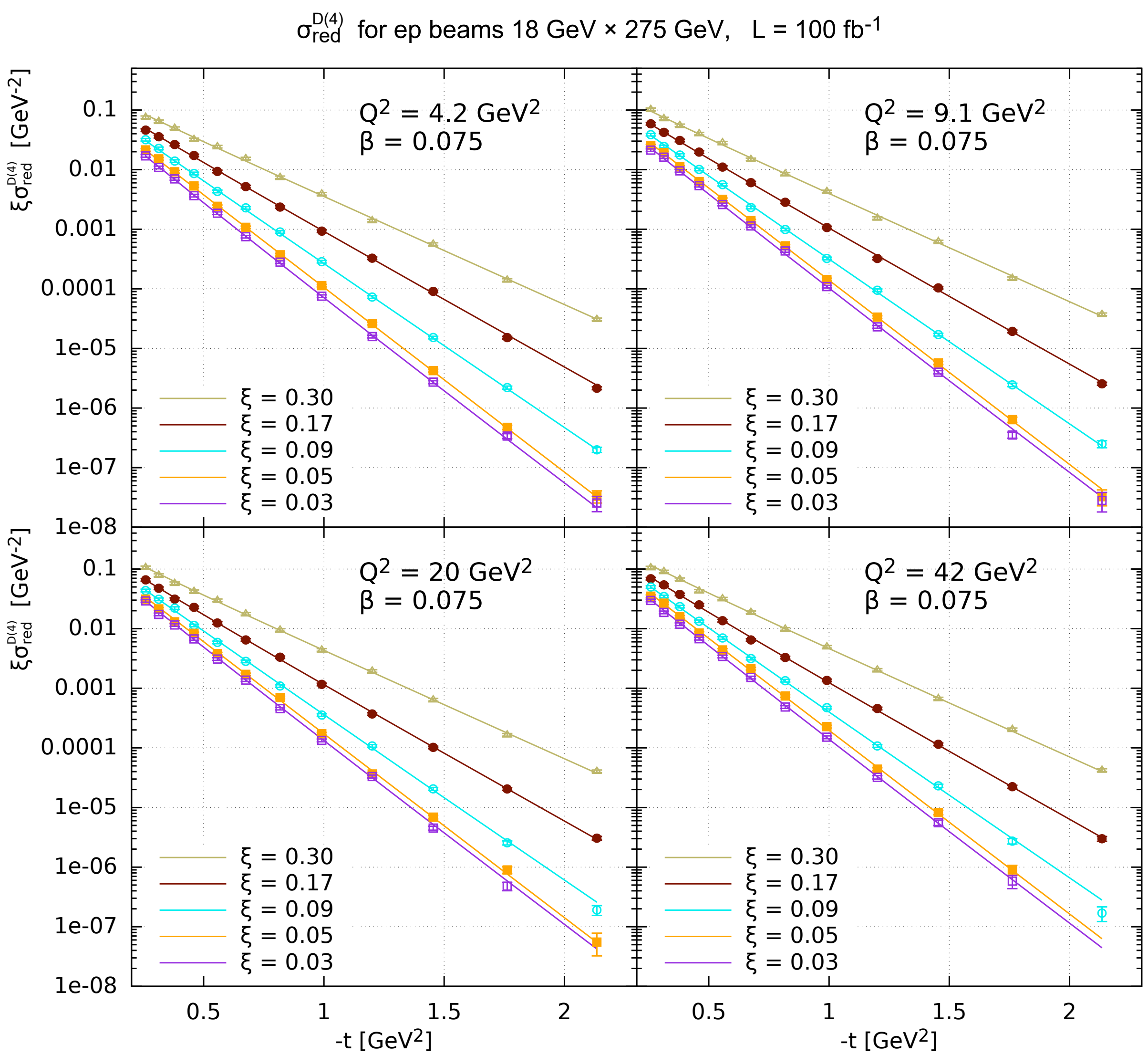




EIC pseudodata

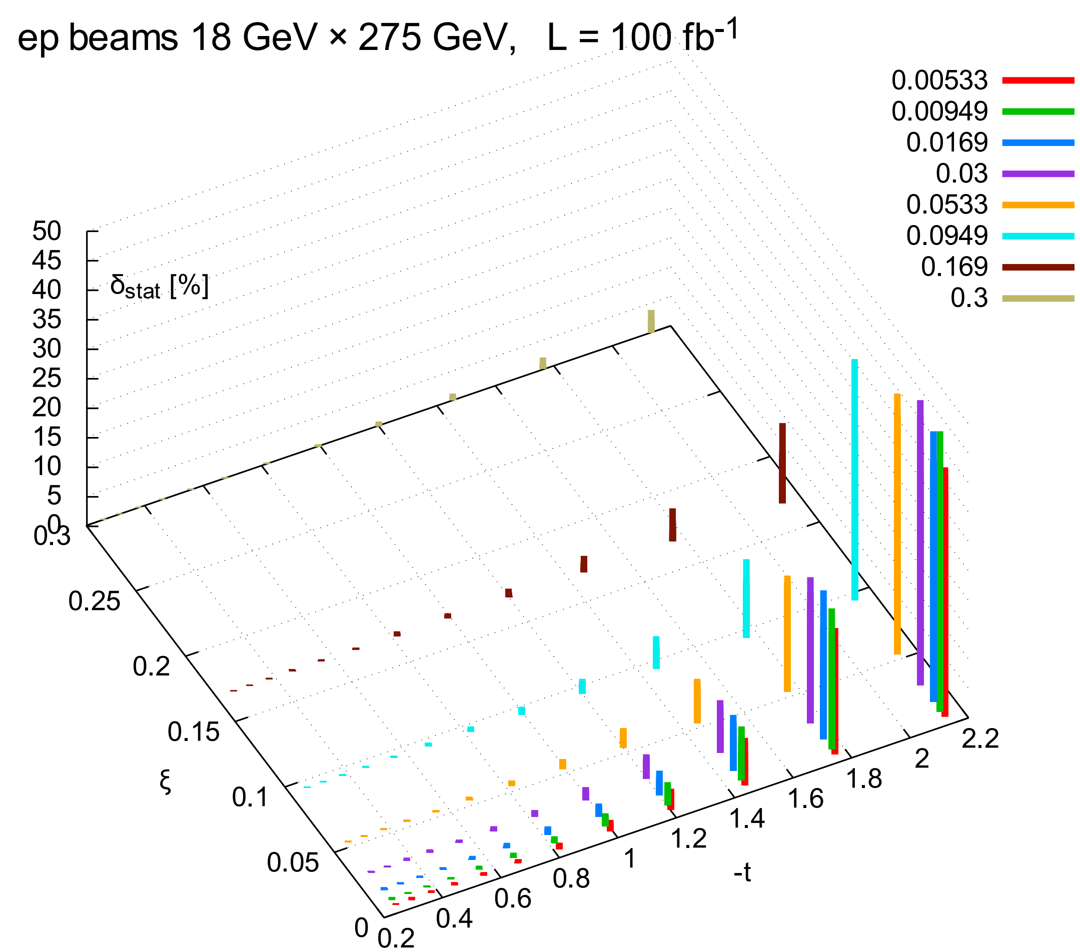
- Based on the HERA 2-component (Pomeron+Reggeon) fit with the GRV pion structure function for the Reggeon
- Use NC simulations for EIC (no HERA nor CC yet)
- Integrated luminosity of $\mathscr{L} = 100\,\mathrm{fb}^{-1}$ at single $\sqrt{s}$ (275 x 18 GeV)
- Require $0.005 < y < 0.96$
- 5% uncorrelated systematics
- Randomly fluctuate each data point according to the uncertainties

Example of the pseudodata: t slope



Fixed $\beta = 0.075$

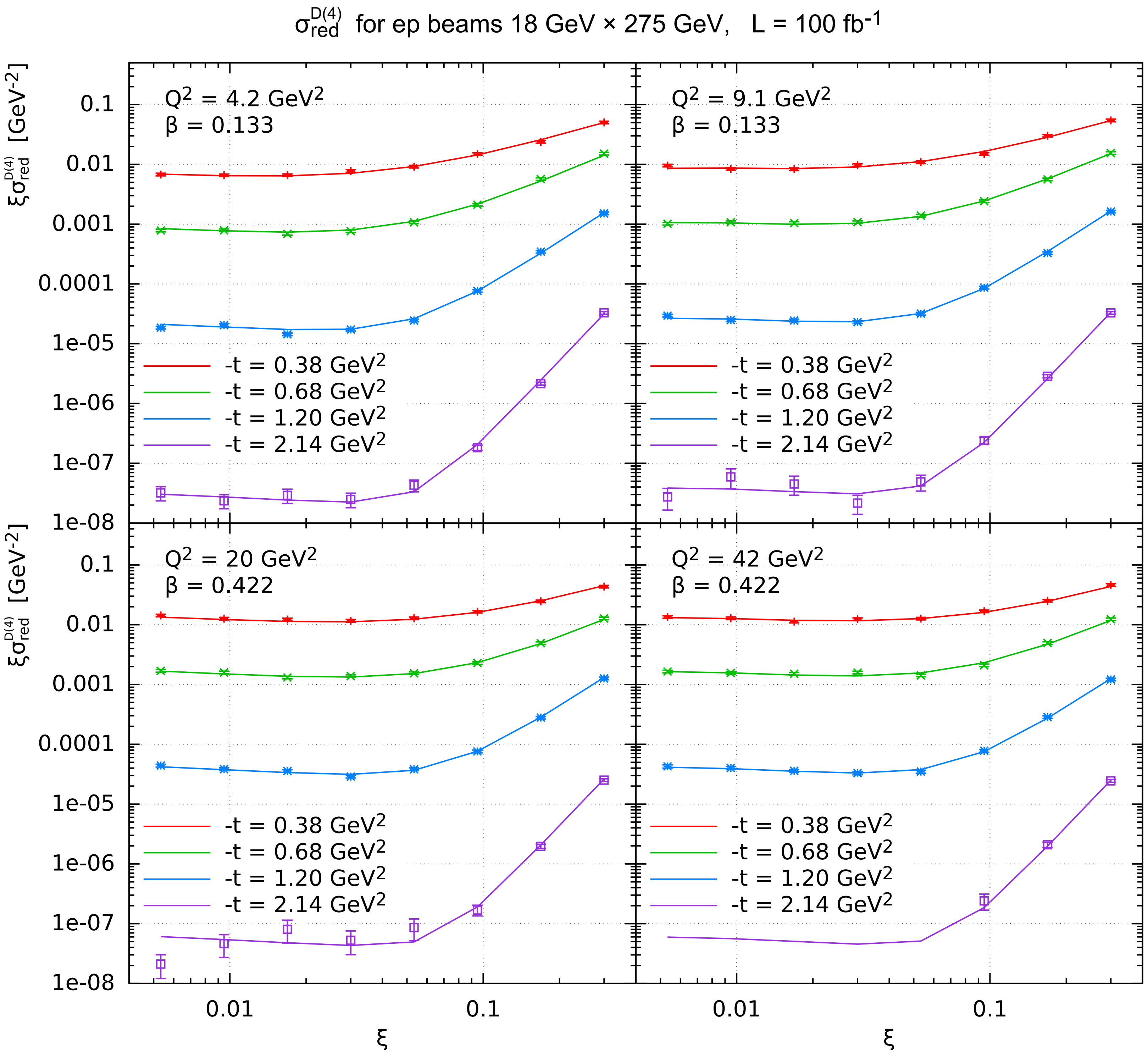
Statistical errors



Changing slope as transitioning from Pomeron to Regeon dominated region

Statistical errors remain manageable up to $|t| \sim 2\,\mathrm{GeV}^2$

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 for the sum of quarks
- Generic parametrization at $Q_0^2 = 1.8\ \mathrm{GeV}^2$:

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

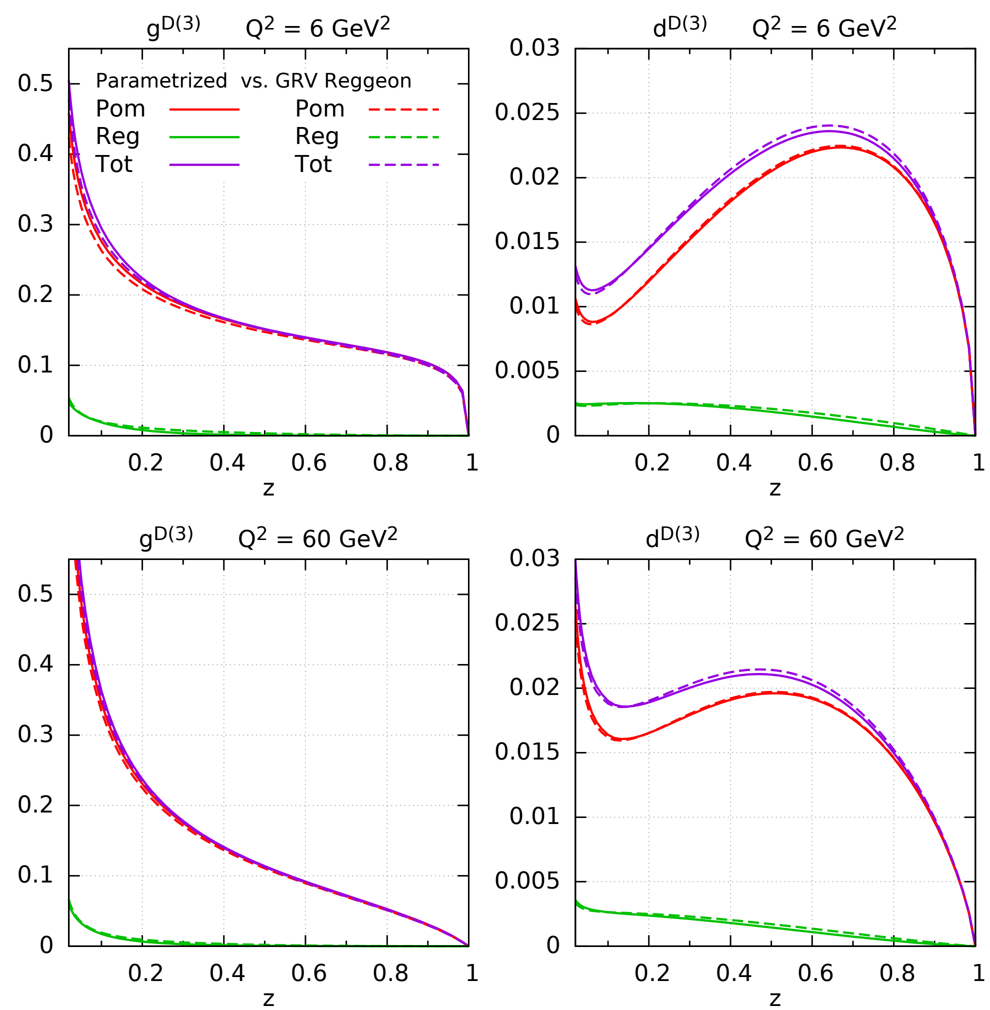
where $k = q, g$ and $m = I\!P, I\!R$

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

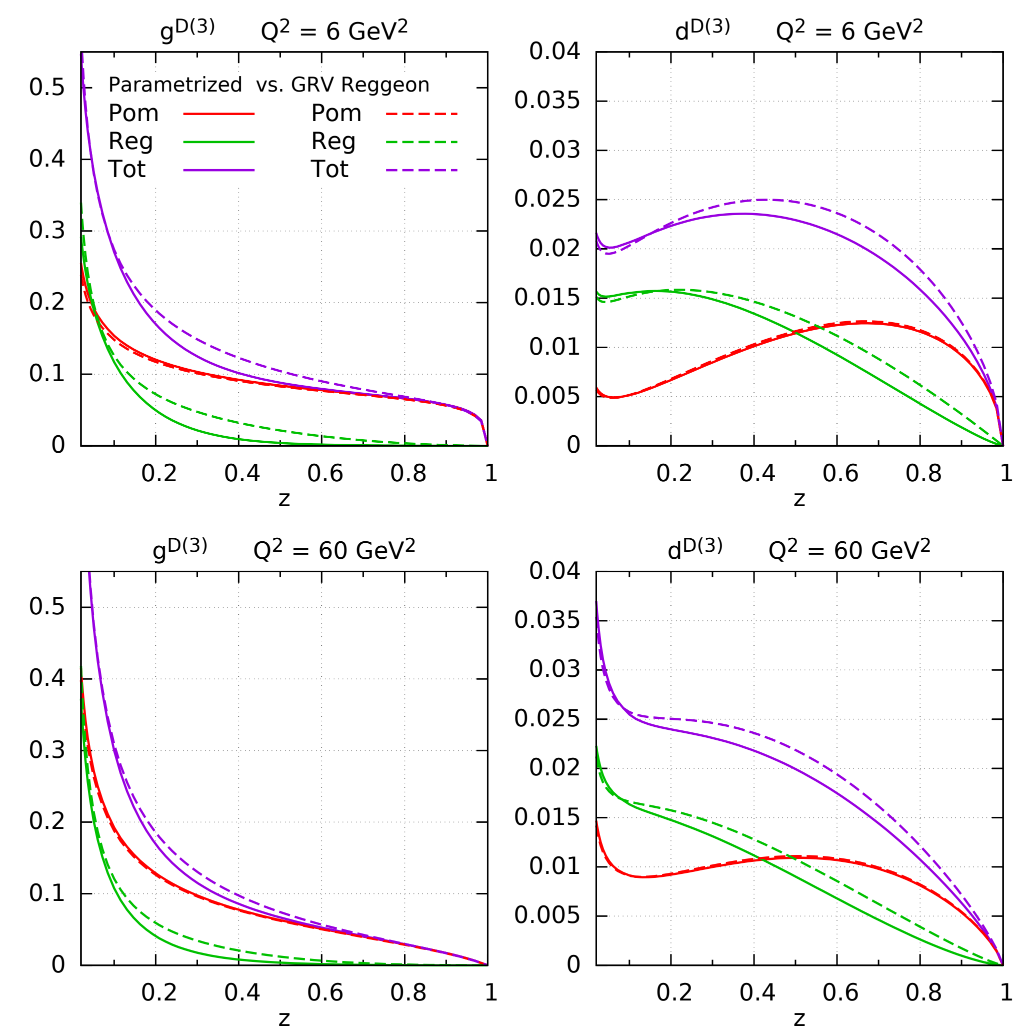
$$\frac{e^{B^{(m)} t}}{\xi^{2\alpha^{(m)}(t)-1}} \qquad \alpha^{(m)}(t) = \alpha^{(m)}(0) + \alpha'^{(m)} t$$

Recovering the Pomeron and Reggeon inputs

gluon ξ = 0.01 quark



gluon ξ = 0.1 quark



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

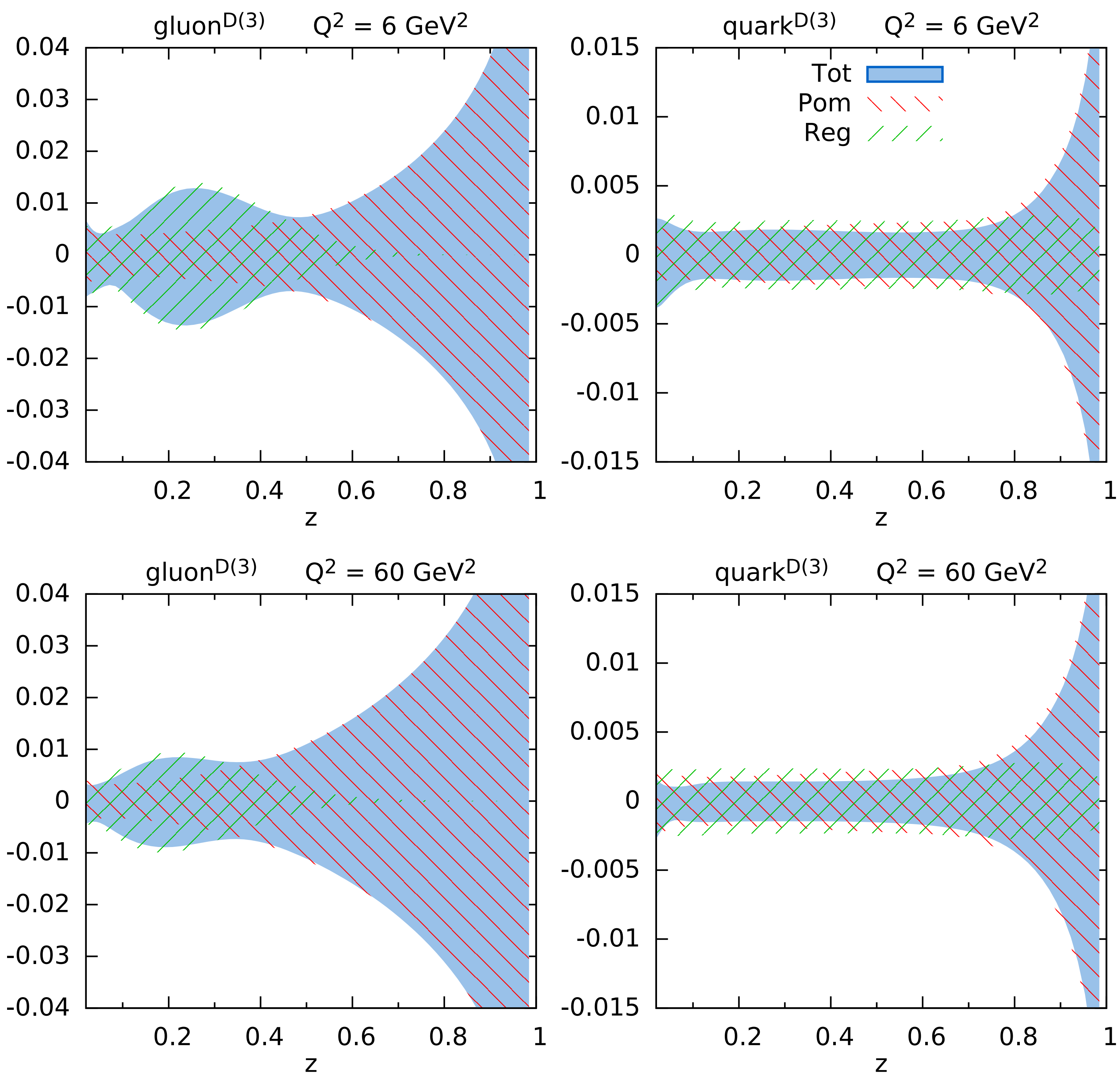
Reggeon reproduced reasonably well

Pomeron reproduced almost perfectly

Uncertainties of diffractive PDFs: large ξ

$$x_{I\!P} \equiv \xi = 0.1$$

linear horizontal scale
note different vertical scale for gluons and quarks



Relative errors obtained as ratio of P,R or Total to the total DPDF

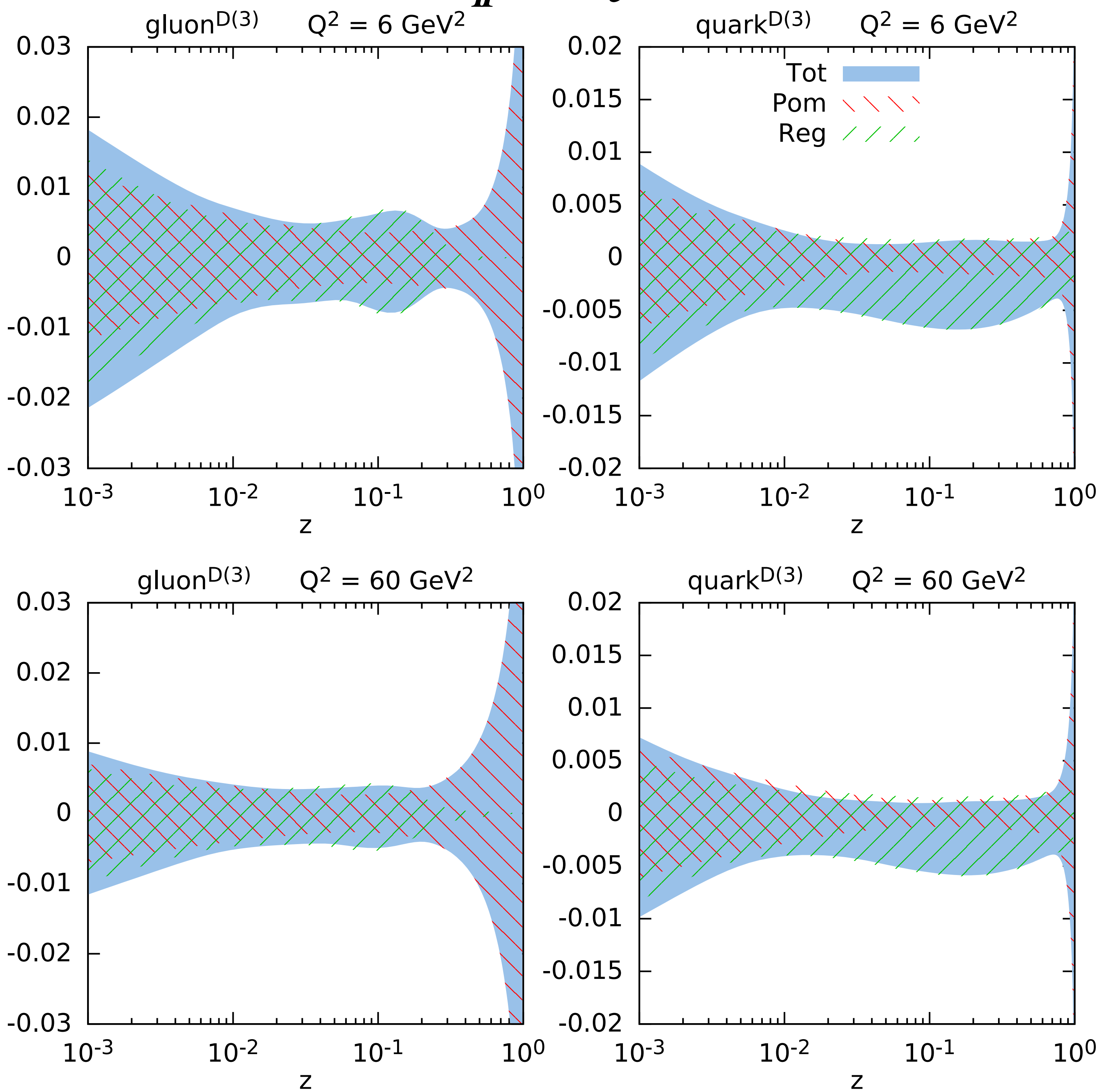
<1% or better for gluon in some region
<0.5% or better for quarks in some regions

Model, parametrization uncertainties still to be studied

EIC can constrain Reggeon at similar level of precision as the Pomeron

Uncertainties of diffractive PDFs: large ξ

$$x_{I\!P} \equiv \xi = 0.1$$



logarithmic horizontal scale
note different vertical scale for gluons and quarks

Relative errors obtained as ratio of P,R or Total to the total DPDF

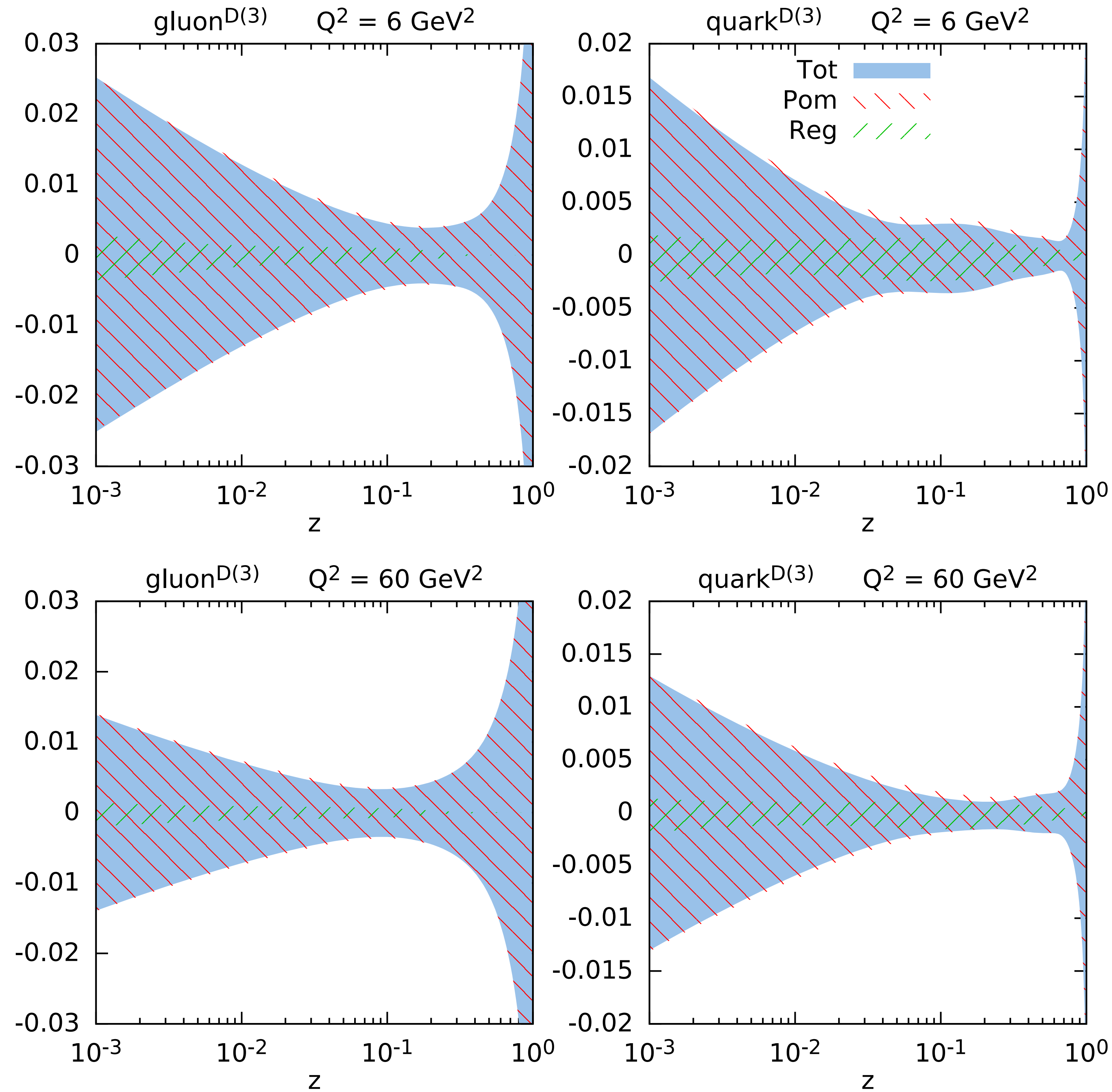
<1% or better for gluon in some region
<0.5% or better for quarks in some regions

Model, parametrization uncertainties still to be studied

EIC can constrain Reggeon at similar level of precision as the Pomeron

Uncertainties of diffractive PDFs: small ξ

$$x_{\mathbb{P}} \equiv \xi = 0.01$$



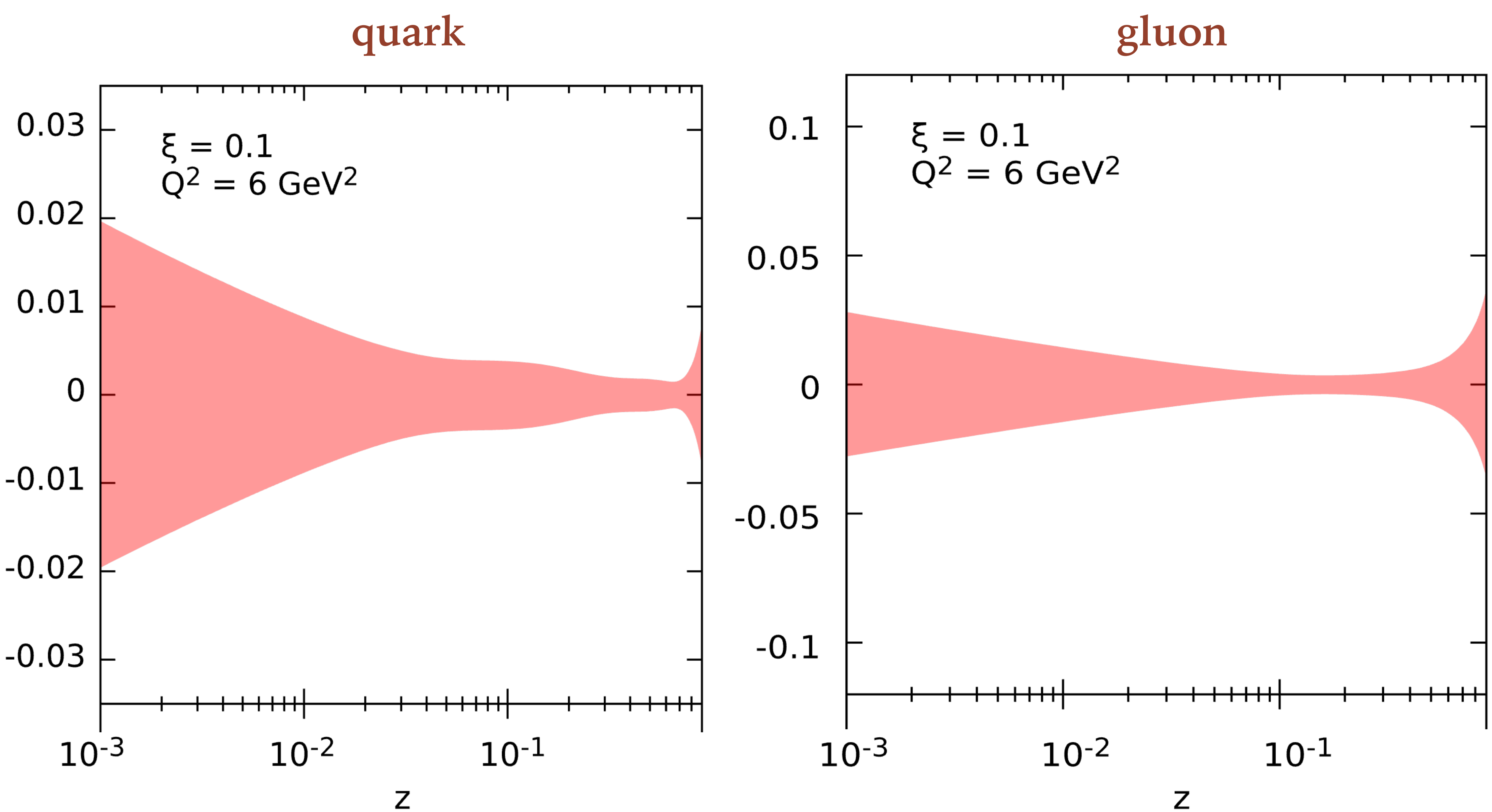
logarithmic horizontal scale
note different vertical scale for gluons and quarks

Relative errors obtained as ratio of P,R or Total to the total DPDF

Errors expand towards small $z(\beta)$ as ξ is lower

EIC can constrain Reggeon at similar level of precision as the Pomeron

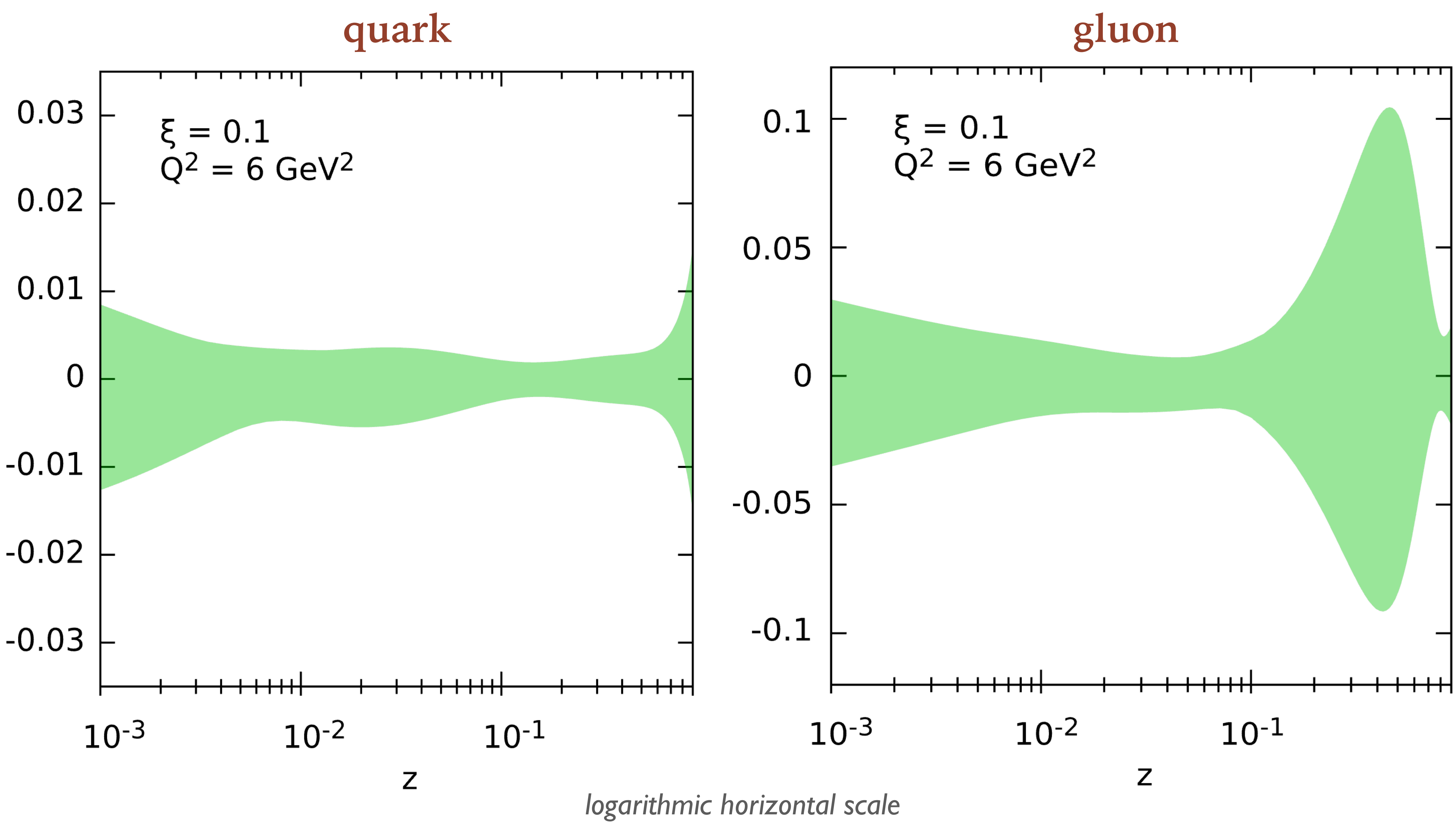
Precision on Pomeron contribution



logarithmic horizontal scale

Precise extraction of Pomeron, especially at large/moderate values of z

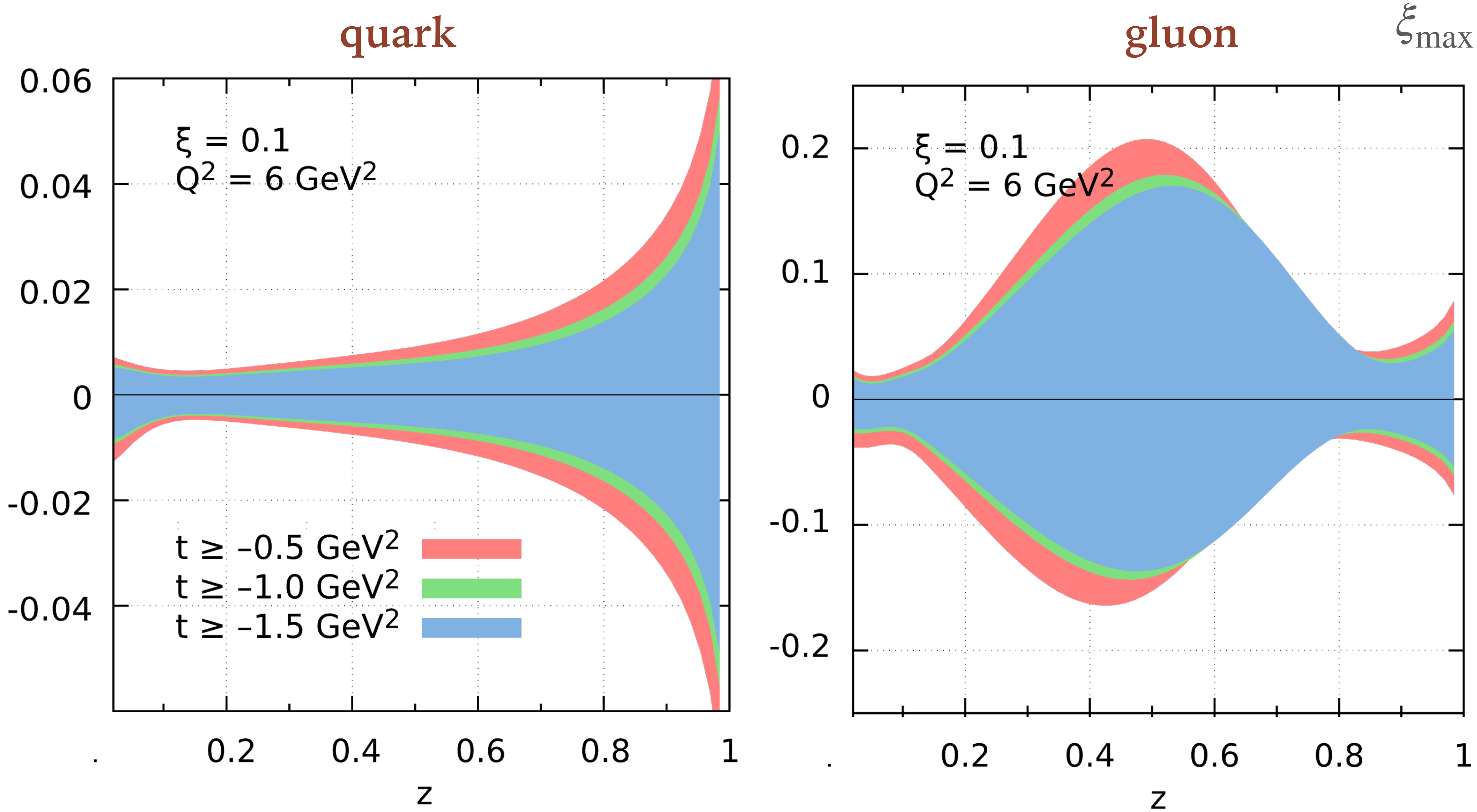
Precision on Reggeon contribution



Novel result from EIC: precise extraction of Reggeon

Dependence of Reggeon on t range

$\xi_{max} = 0.22$



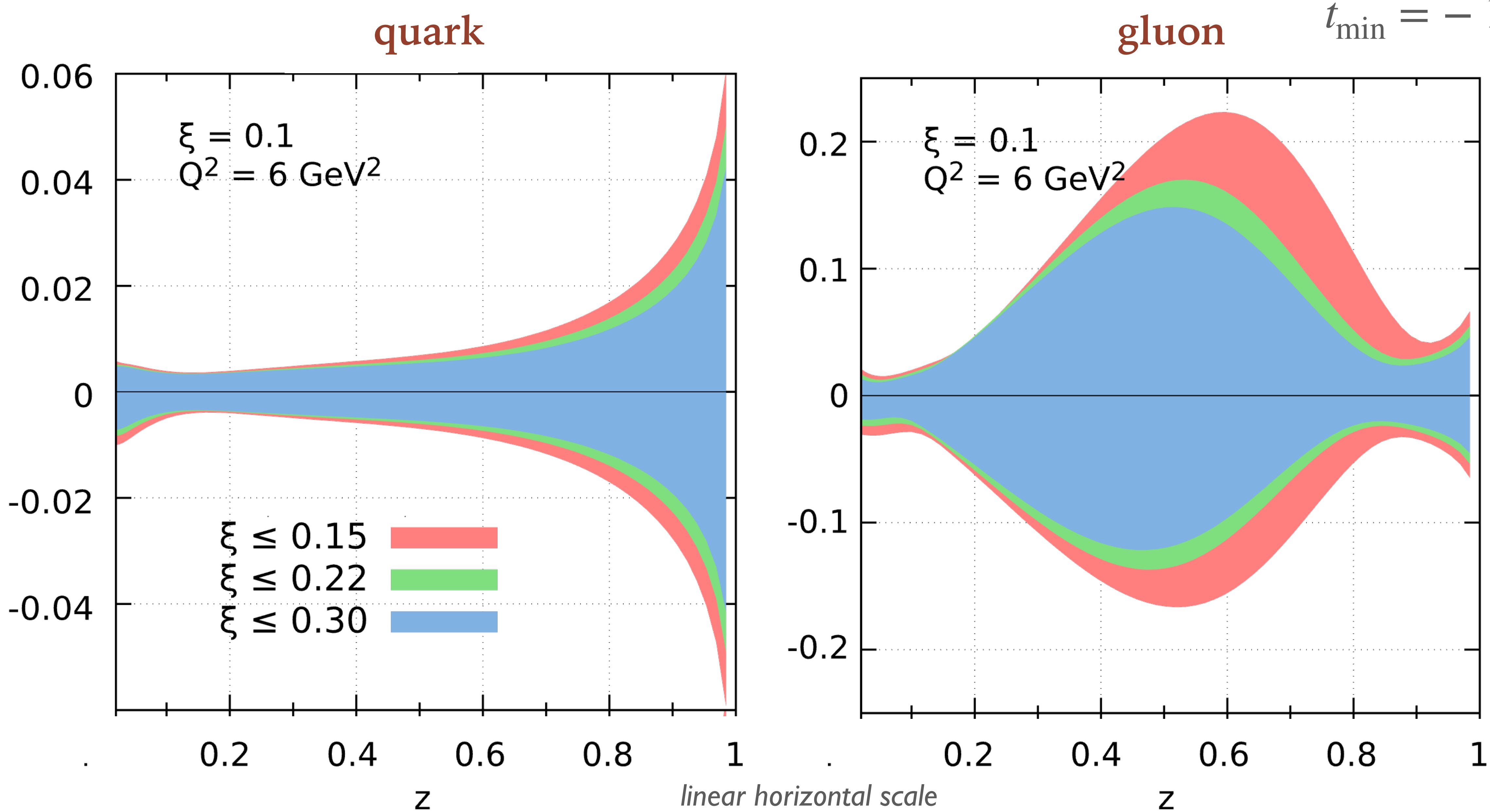
linear horizontal scale

Quality of fit does not change with t_{min}

Errors slightly change, overall result are not very sensitive

Dependence of Reggeon on ξ range

$t_{min} = -1.5\,\mathrm{GeV}^2$



Quality of fit changes slightly with ξ_{max}

Errors do increase with the more restricted ξ range. Large ξ important for Reggeon at large z

Restriction to $\xi < 0.15$ still leaves strong sensitivity

Precision on flux parameters

Regge type flux for Pomeron/Reggeon :

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

Trajectory :

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

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

Input values recovered with very precisely

Some flux parameters get correlated with the PDF parameters

Summary

EIC can extract flux parameters and partonic structure of the subleading 'Reggeon' exchange with similar precision to the leading 'Pomeron' exchange.

More work needed on uncertainties:

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

Ideas for further studies:

- Different EIC beam energies
- Combined HERA and EIC fits
- Charged current contribution