Diffractive longitudinal structure function at the Electron Ion Collider

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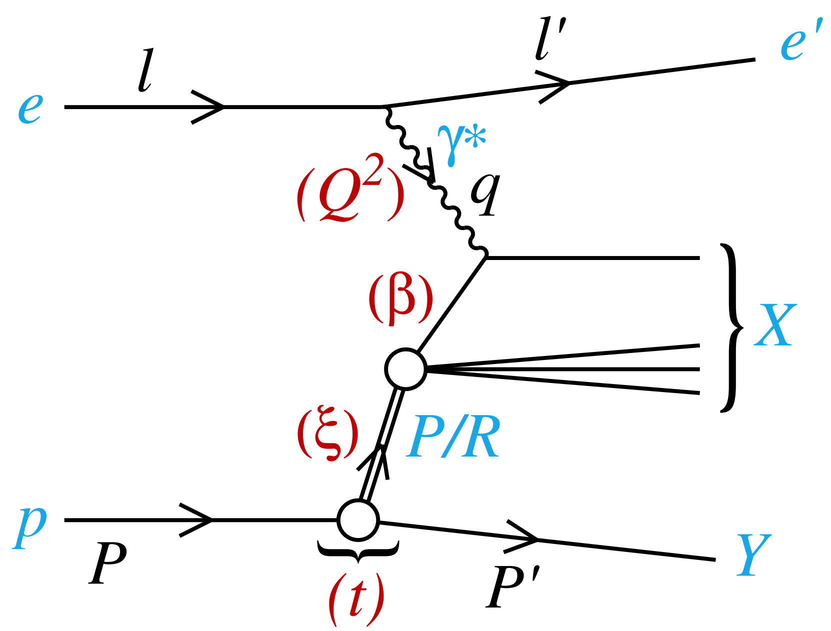
Outline

- $F_L^{D(3)}$
    - Motivation: why is $F_L^{D(3)}$ interesting ?
    - H1 measurement
    - Proton tagging as a method for diffraction at EIC
    - Pseudodata simulation, energy beam scenarios
    - Extraction by linear fit. Kinematic range and precision
    - $F_L^{D(3)}$ and R ratio of longitudinal to transverse cross section

*Nestor Armesto, Paul Newman, **Wojciech Słomiński,** A.S., 2112.06839*
also EIC Yellow Report

Diffractive kinematics in DIS



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

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:

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

momentum fraction of the Pomeron w.r.t hadron

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

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):

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

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

Reduced cross section depends on two structure functions:

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

Upon integration over t:

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

Dimensions:

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

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

When $y \ll 1$

$$\sigma_{\mathrm{r}}^{\mathrm{D}(4,3)} \simeq F_2^{\mathrm{D}(4,3)}$$

Why $F_L^{D(3)}$ is interesting? $F_L^{D(3)}$ at HERA

Why F_L^D is interesting?

F_L^D vanishes in the parton model

Gets non-vanishing contributions in QCD

As in inclusive case, particularly sensitive to the diffractive **gluon density**

Expected large **higher twists**, provides test of the **non-linear, saturation** phenomena

Experimentally challenging…

Measurement requires several beam energies

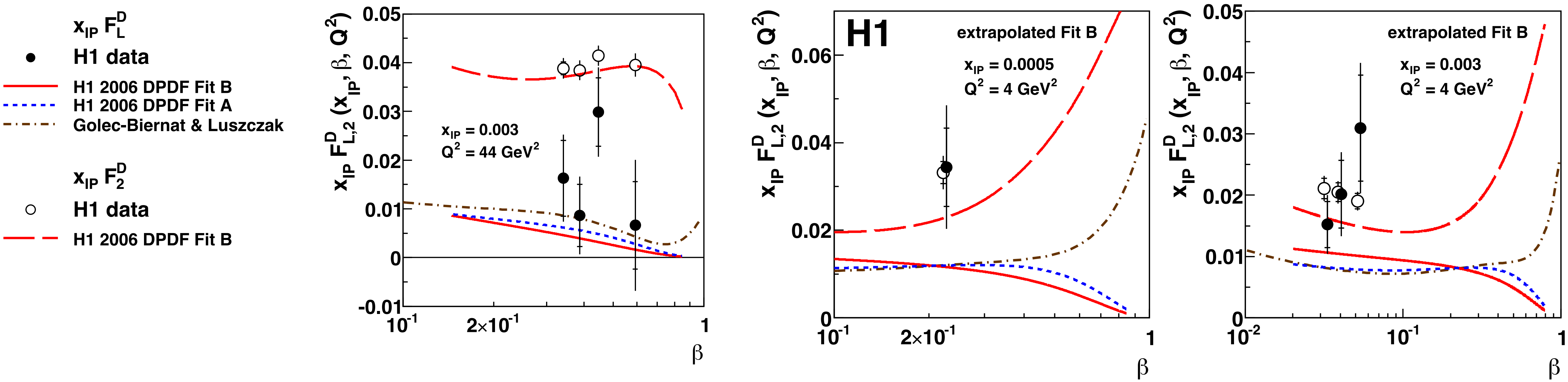
F_L^D strongest when $y \to 1$. Low electron energies

H1 measurement: 4 energies, E_p=920, 820, 575, 460 GeV, electron beam E_e=27.6 GeV

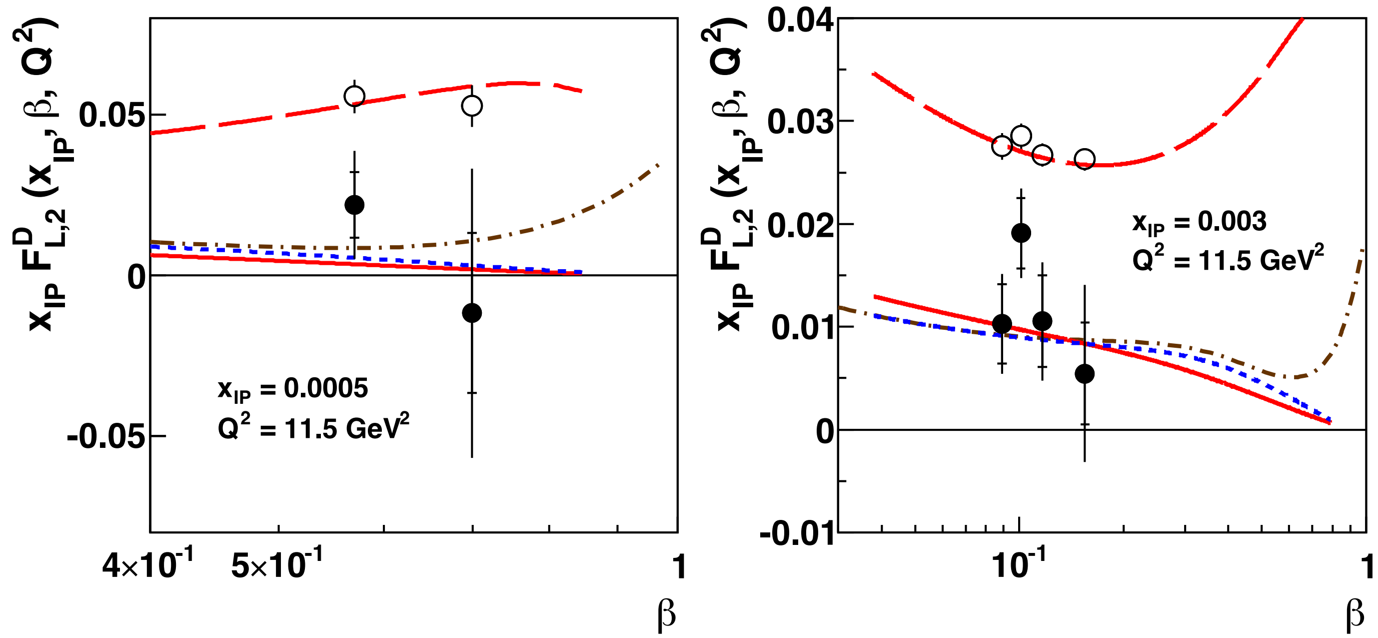
Large errors, limited by statistics at HERA

Careful evaluation of systematics. Best precision 4%, with uncorrelated sources as low as 2%

$F_L^{D(3)}$ at HERA



Measurements of σ_r^D consistent with predictions from the models



Extracted F_L^D has a tendency to be higher than the predictions, though compatible with model predictions within errors

Overall: $0 < F_L^D < F_2^D$

Phase space (x,Q^2) EIC-HERA

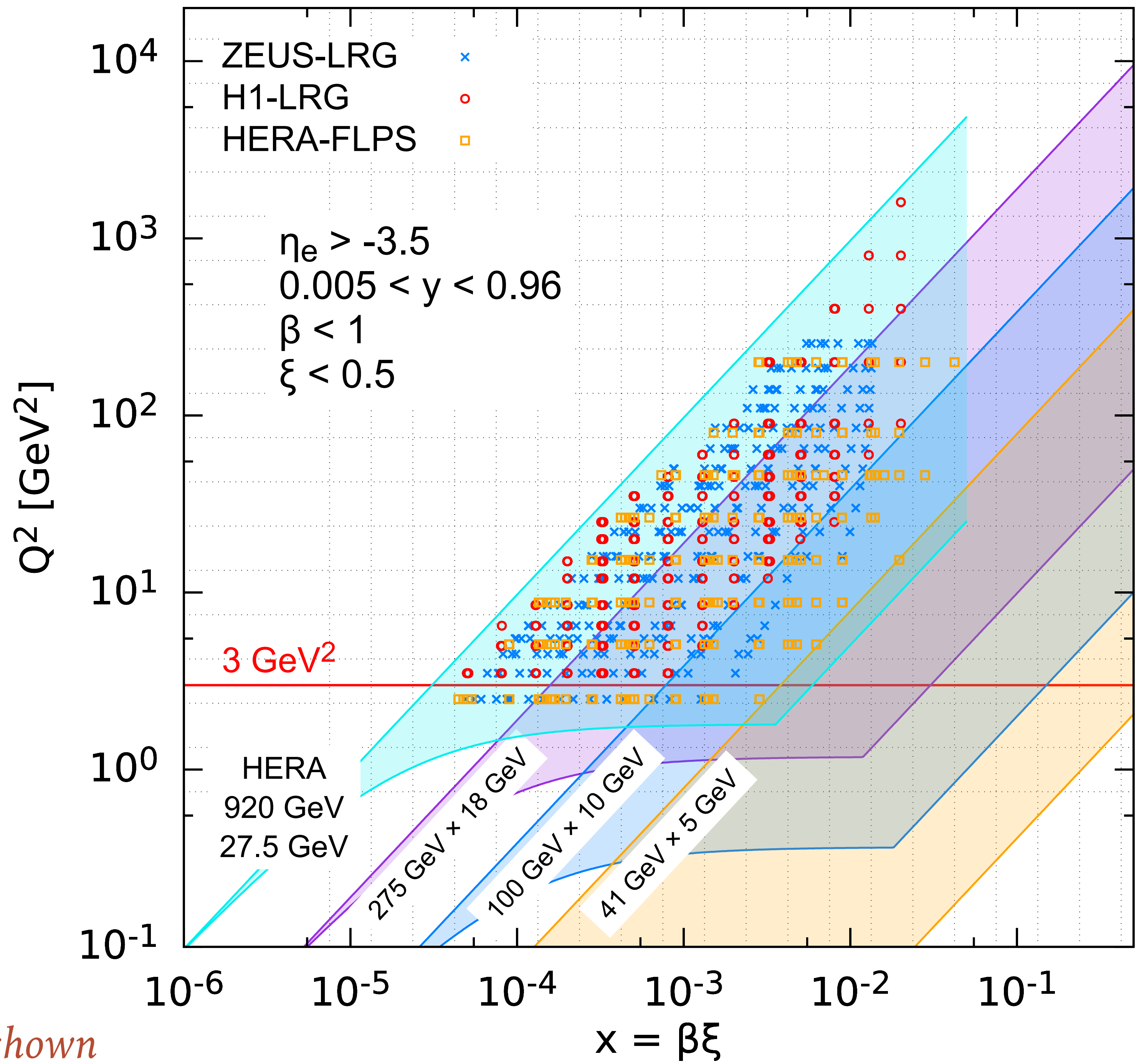
EIC can operate at various energy combinations

Can cover wide range of x

Large instantaneous luminosity

Statistics should not be a limiting factor

EIC 3 scenarios - HERA

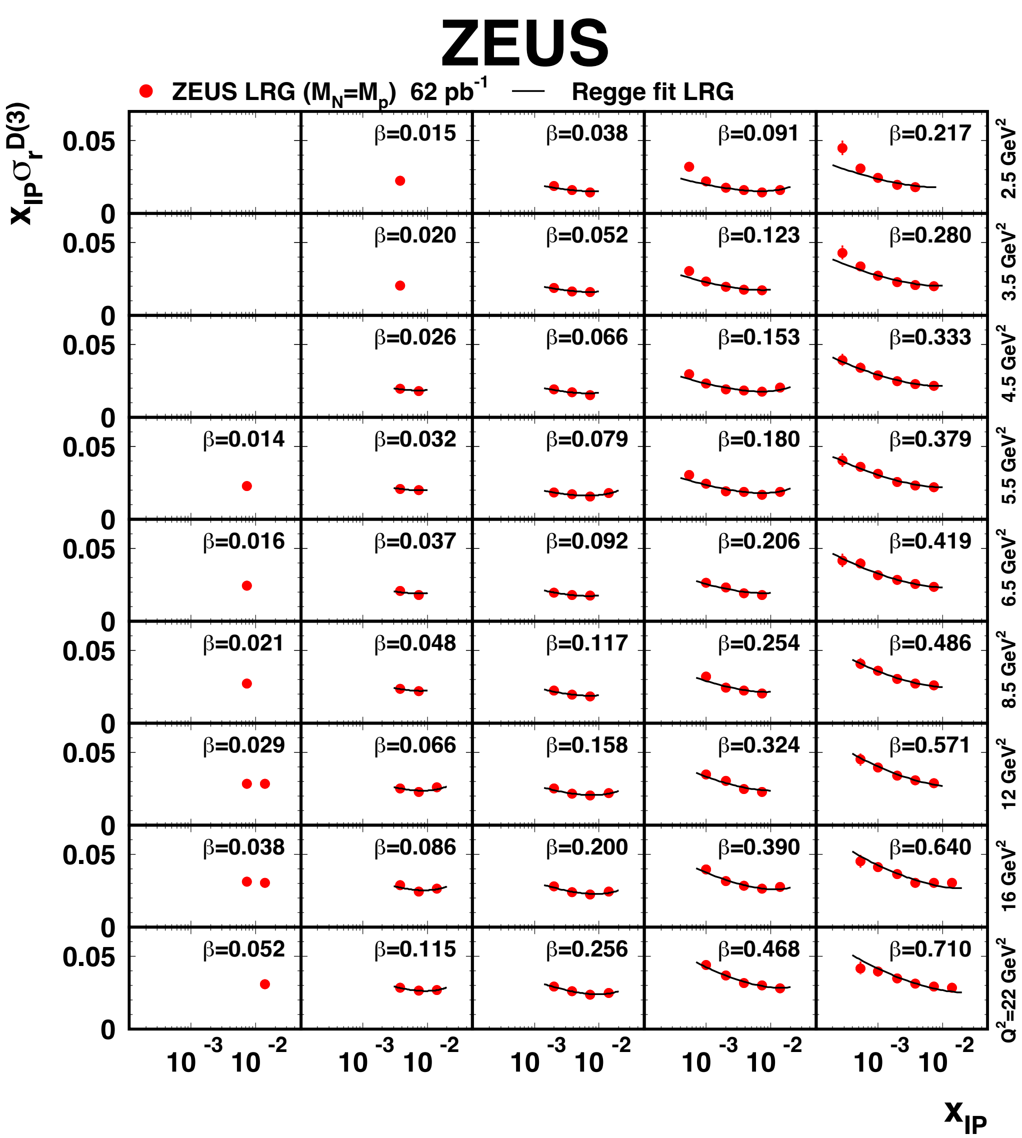


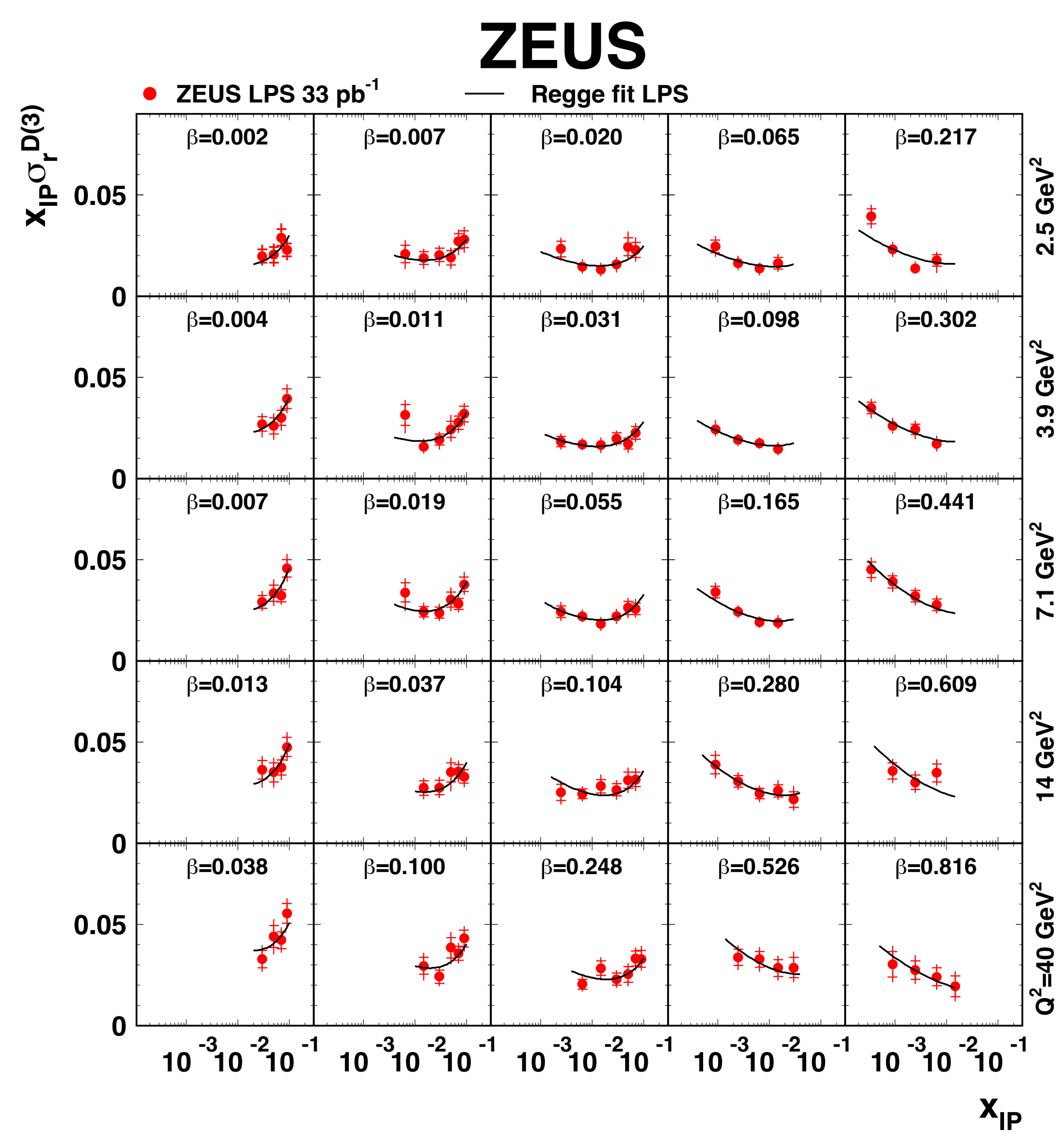
Only selected energy scenarios at EIC shown

Measurement methods: LRG vs LP

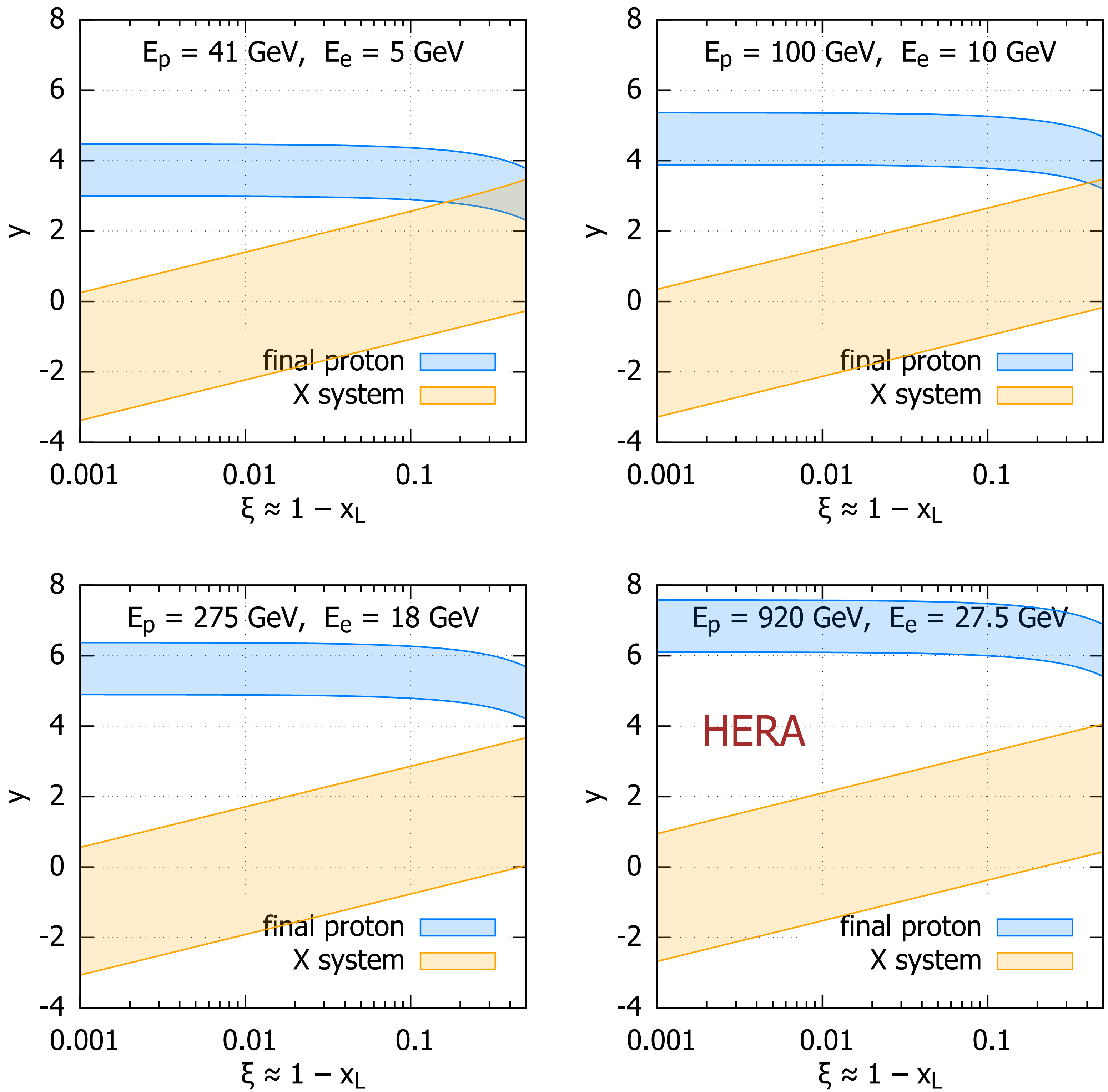
Large Rapidity Gap method:
request a large rapidity gap (ex. ZEUS 2009 $\xi<0.02$)

Proton Tagging (Leading Proton) method:
detection of a leading proton (ex. Leading Proton Spectrometer in ZEUS, Forward Proton Spectrometer in H1, can go to higher $\xi<0.1$)





Rapidity range at EIC in diffraction



Rapidity range of proton and undecayed diffractive system X

$p_T^{proton} < 4\,\mathrm{GeV}$

$0.1 < \beta < 0.9$

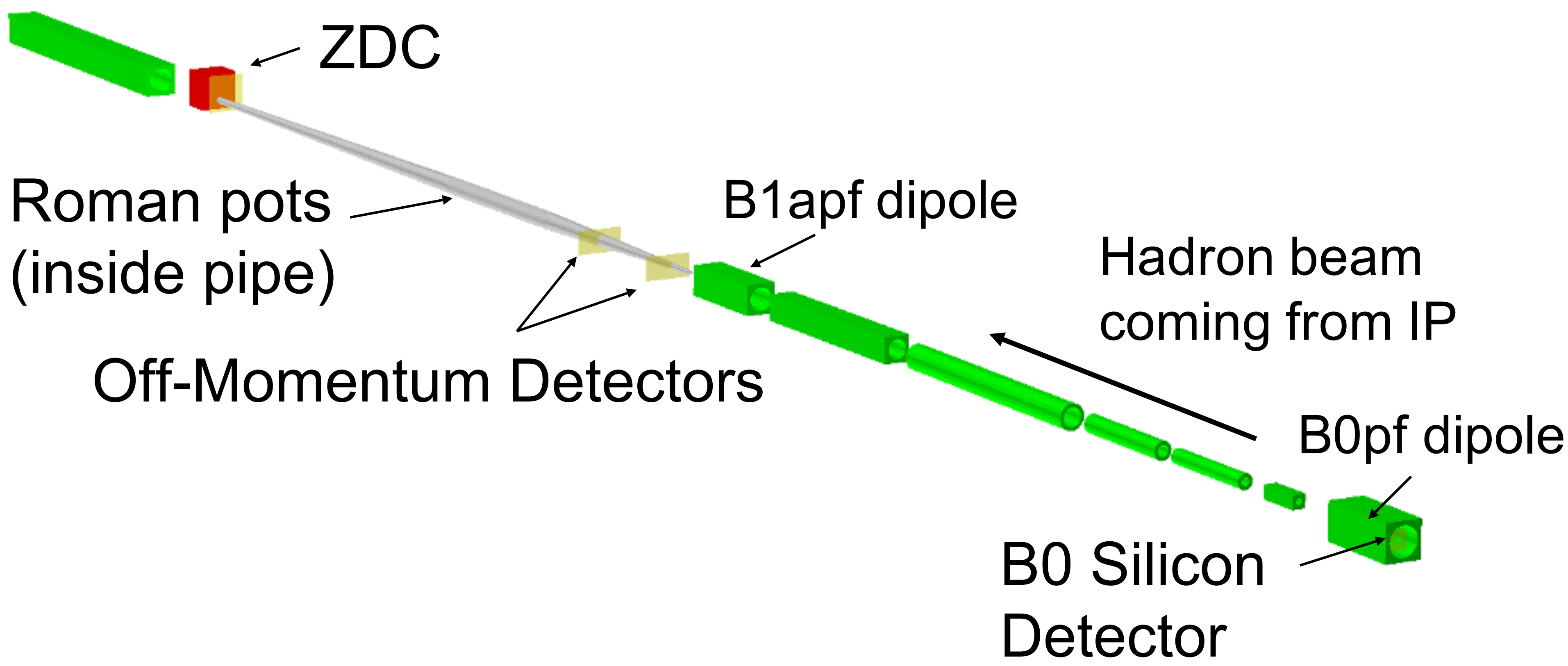
$0.005 < y < 0.96$

HERA: LRG method reliable for gaps > 3 units of rapidity

EIC: fairly large gaps ($\Delta\eta \geq 4$) exist for smallest ξ and largest s

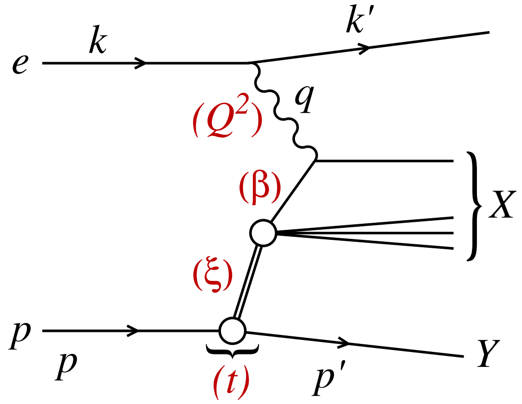
However, through most region LRG method may be challenging at EIC

Far forward detectors at EIC



Detector	Angle	Position [m]
ZDC	θ<5.5 mrad	37.5
Roman Pots	0.5<θ<5.0 mrad	26.0, 28.0
Off-momentum detectors	θ<5.0 mrad	22.5, 25.5
B0	6.0<θ<20.0 mrad	5.4<z<6.4

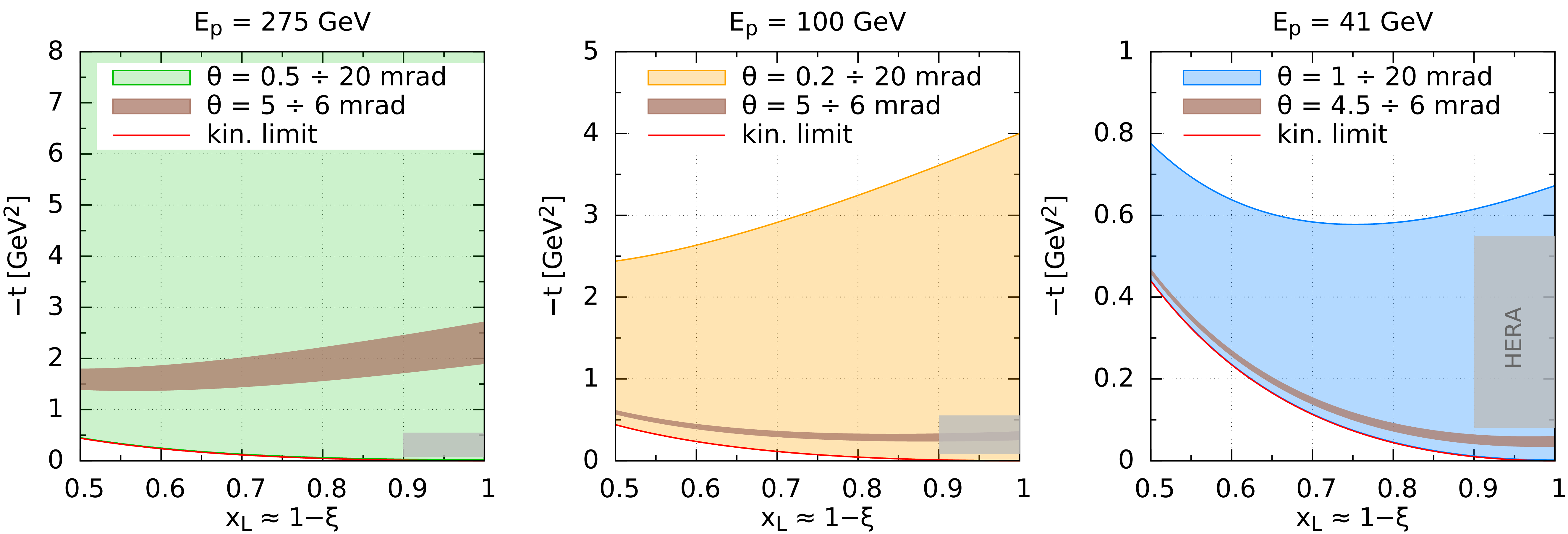
Final proton tagging



$(x_L, p_\perp)$

Small angle acceptance i.e. Roman pots

$(x_L, p_\perp, \theta)$ measured in LAB, collinear (e,p) frame



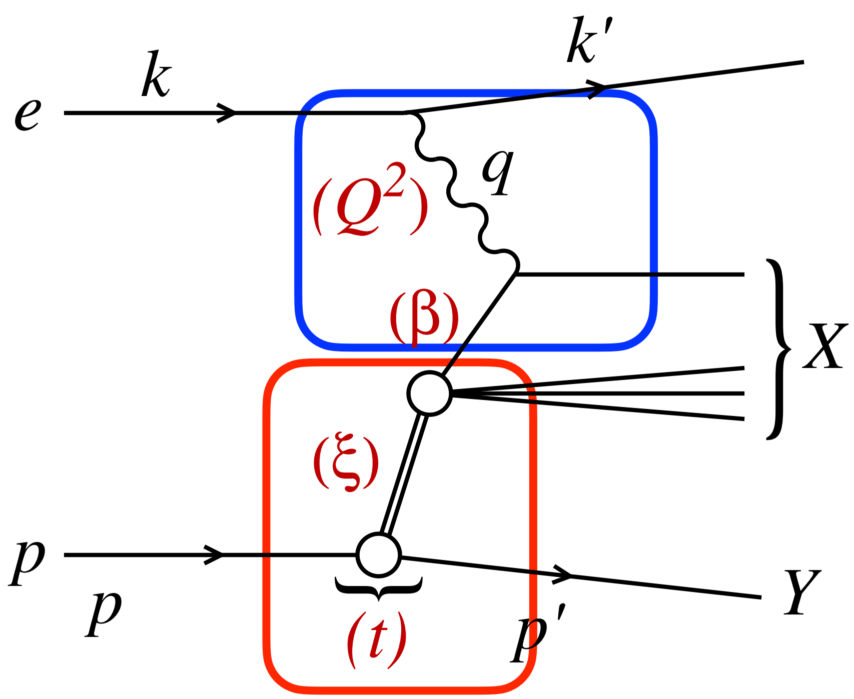
Much better than at HERA

Best way to select diffractive events through proton tagging

$$t = -\frac{p_\perp^2}{x_L} - \frac{(1-x_L)^2}{x_L} m_p^2$$

Pseudodata generation: collinear factorization for diffraction

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



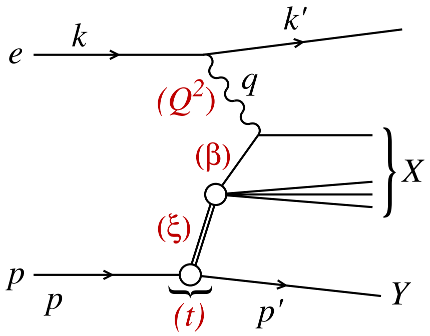
Collins

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).
- The DPDFs are non-perturbative objects, but evolved perturbatively with DGLAP

Pseudodata generation: model for diffractive structure functions



Regge factorization with Pomeron terms works for small ξ<0.01

At higher ξ additional exchanges `Reggeons' need to be included

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

Pomeron *Reggeon*

Regge type flux:

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

Trajectory:

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

For t-integrated case

$$f_i^{\mathrm{D}(3)}(z,\xi,Q^2) = \phi^p_{I\!P}(\xi)\, f_i^{I\!P}(z,Q^2) + \phi^p_{I\!R}(\xi)\, f_i^{I\!R}(z,Q^2)$$

Integrated flux:

$$\phi^p_{I\!P,I\!R}(\xi) = \int dt\; f^p_{I\!P,I\!R}(\xi,t)$$

Pomeron PDFs obtained via NLO DGLAP evolution starting at initial scale μ_0^2=1.8 GeV^2

$$z f_i(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i} \qquad i=q,g$$

Pseudodata generation: energy choice

$$\sigma_{\rm red}^{\rm D(3)} = F_2^{\rm D(3)}(\beta,\xi,Q^2) - Y_{\rm L}\, F_{\rm L}^{\rm D(3)}(\beta,\xi,Q^2)$$

Integrated over t-momentum transfer

$$Y_{\rm L} = \frac{y^2}{Y_+} = \frac{y^2}{1+(1-y)^2}$$

Can disentangle $F_2^{D(3)}$ from $F_L^{D(3)}$ by varying energy and performing the linear fit.

$$y = \frac{Q^2}{xs} = \frac{Q^2}{\beta\xi s}$$

Need to vary the energy $\sqrt{s}$ to change y for fixed (β,ξ,Q²)

EIC energies for electron and proton:

$E_e = 5{,}10{,}18$ GeV

$E_p = 41{,}100{,}120{,}165{,}180{,}275$ GeV

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-17 all 17 combinations

S-9 9 - bold red

S-5 5 - green (EIC preferred)

Pseudodata generation

Binning and cuts

Uniform logarithmic binning, 4 bins per order of magnitude in each β, Q^2, ξ

Bins in (ξ, β, Q^2), common to at least four beam setups

$Q^2 > 3$ GeV^2 both H1 and ZEUS fits indicate deterioration of fits for low Q^2

$0.96>y>0.005$ expected coverage of the experiment

Simulations

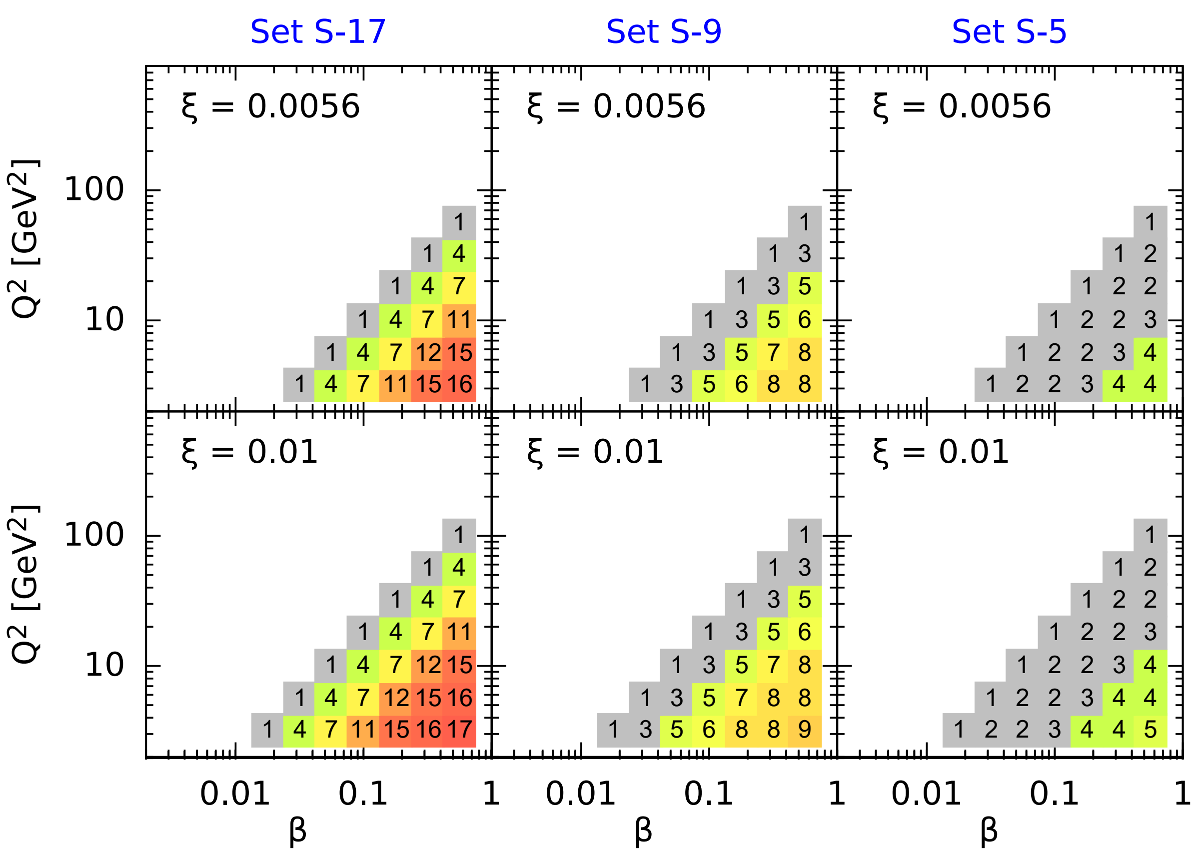
Cross section generation from ZEUS-SJ diffractive PDFs evolved with DGLAP

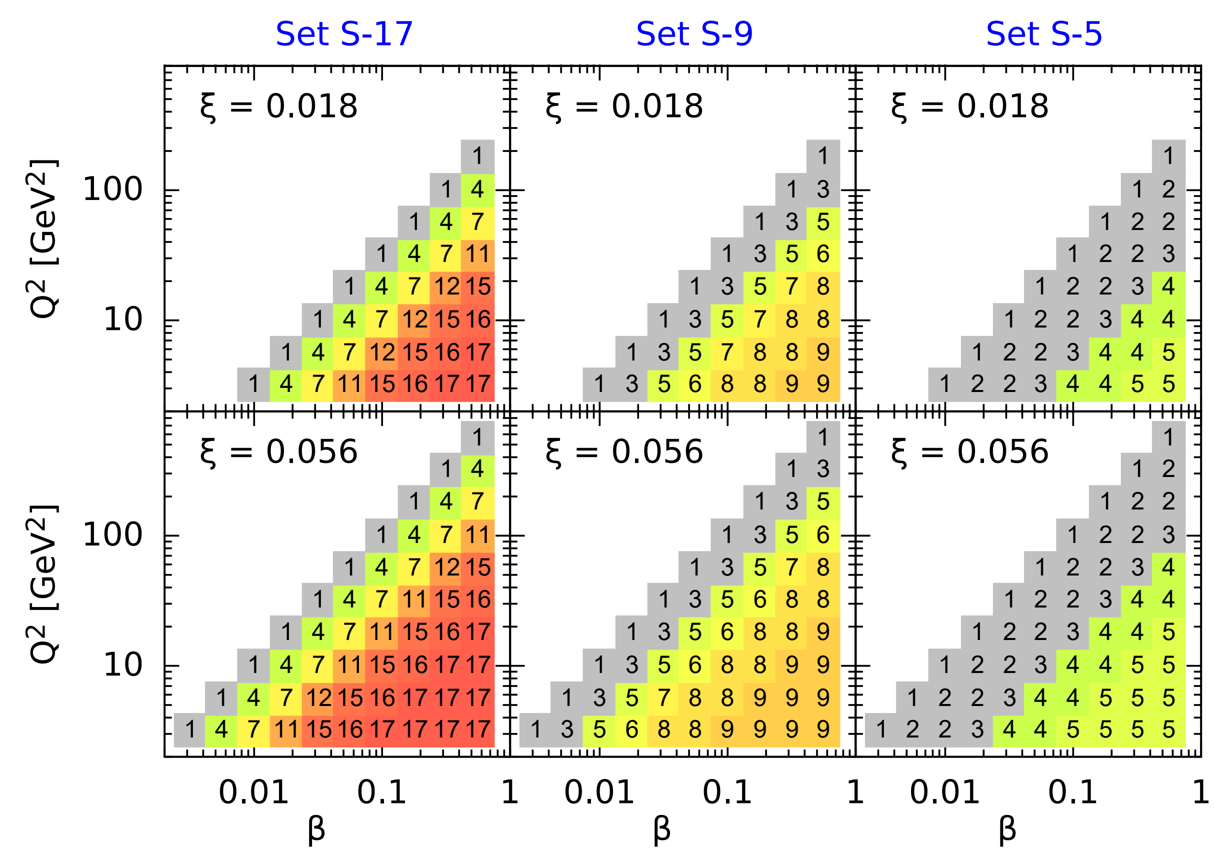
Assumed $\delta_{sys}=1$-2%, extrapolated from HERA 2% uncorrelated systematics; normalization/correlated systematics negligible effect on extraction of F_L^D

δ_{stat} from 10 fb^{-1} integrated luminosity

Several random samples are generated

Kinematic range and number of points





Count of different beam energy combinations for S-17, S-9, S-5

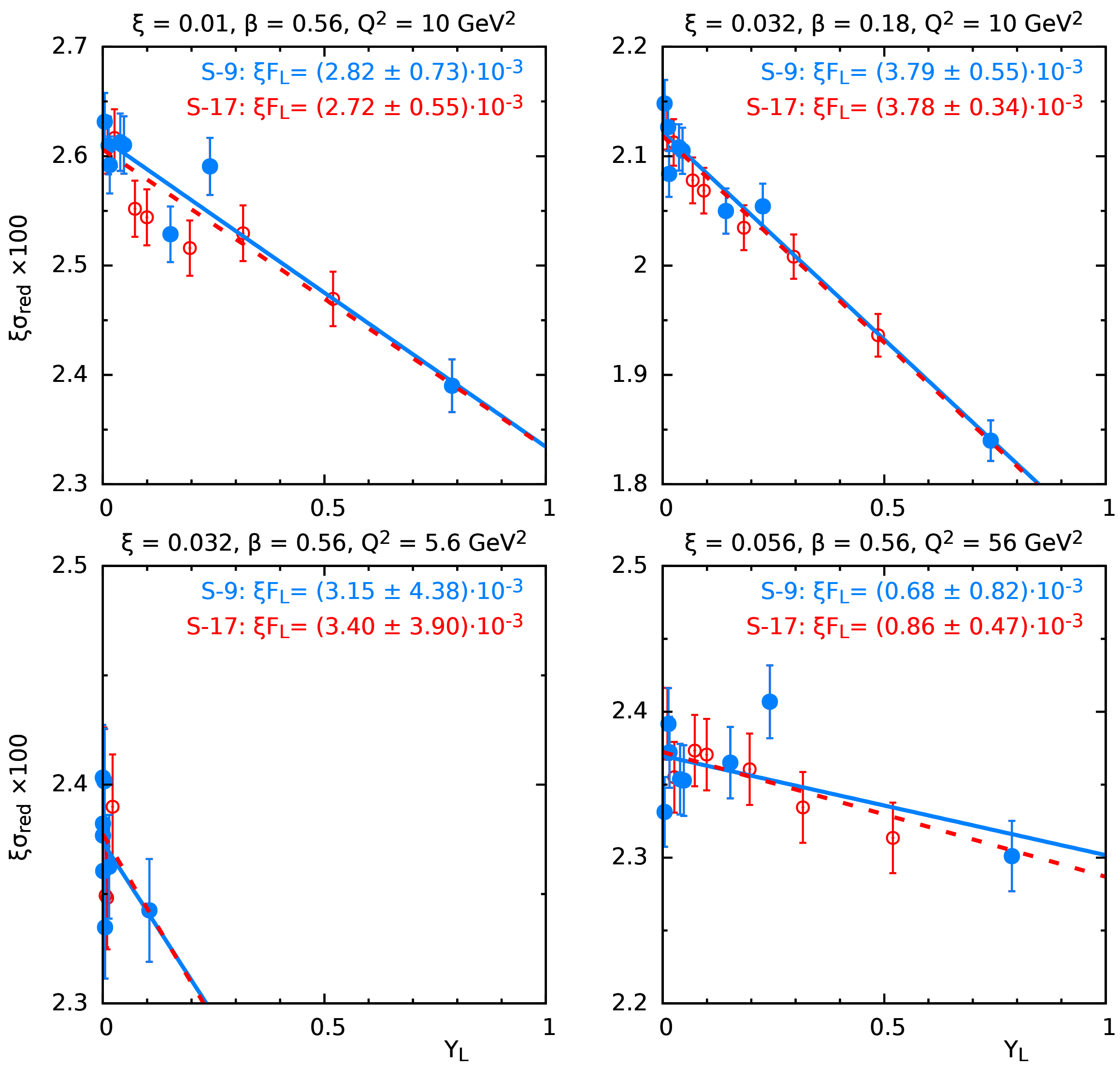
Only points with more than 4 combinations are taken for F_L extraction

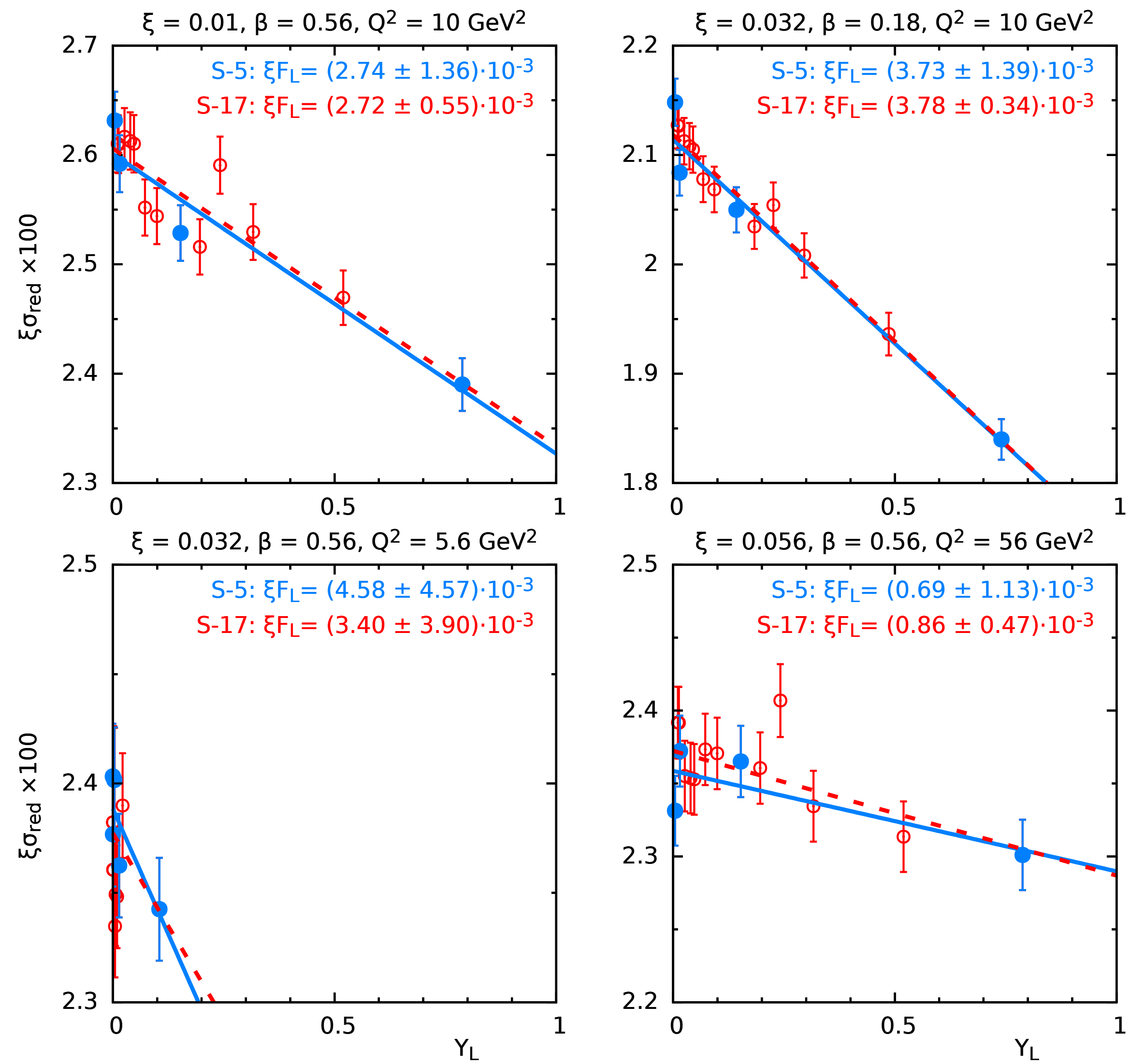
Set-17: 364, set-9: 285, set-5: 160 values of F_L

$F_L^{D(3)}$ extraction

$\sigma_{\rm r} = F_2(\xi,\beta,Q^2) - Y_L F_L(\xi,\beta,Q^2)$ as a function of Y_L

Bins in (ξ,β,Q^2)





Uncorrelated systematics 1%

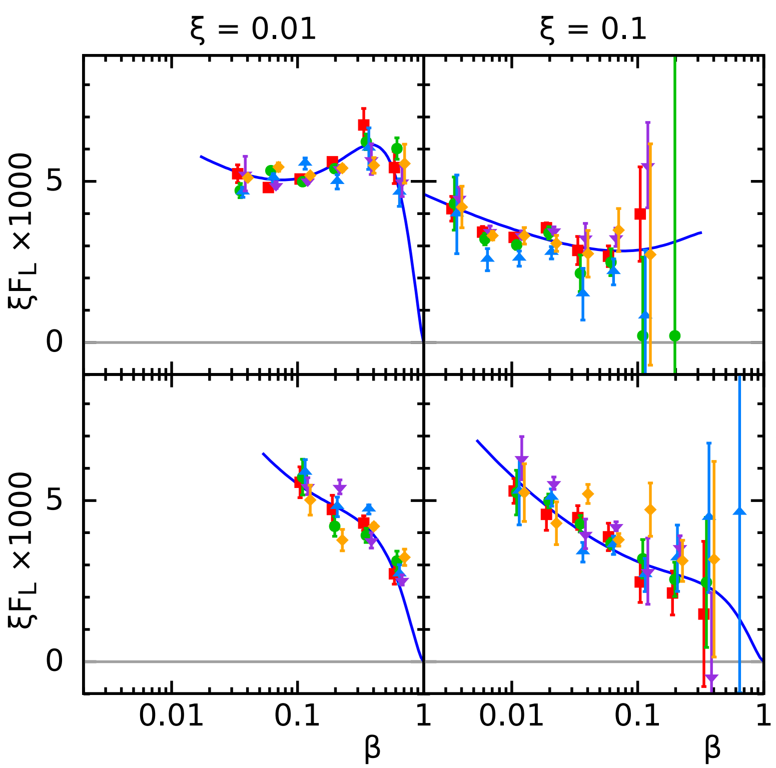
Differences between S-17 and S-9, S-5 small

Increase in error bar on the extraction when smaller number of energy points

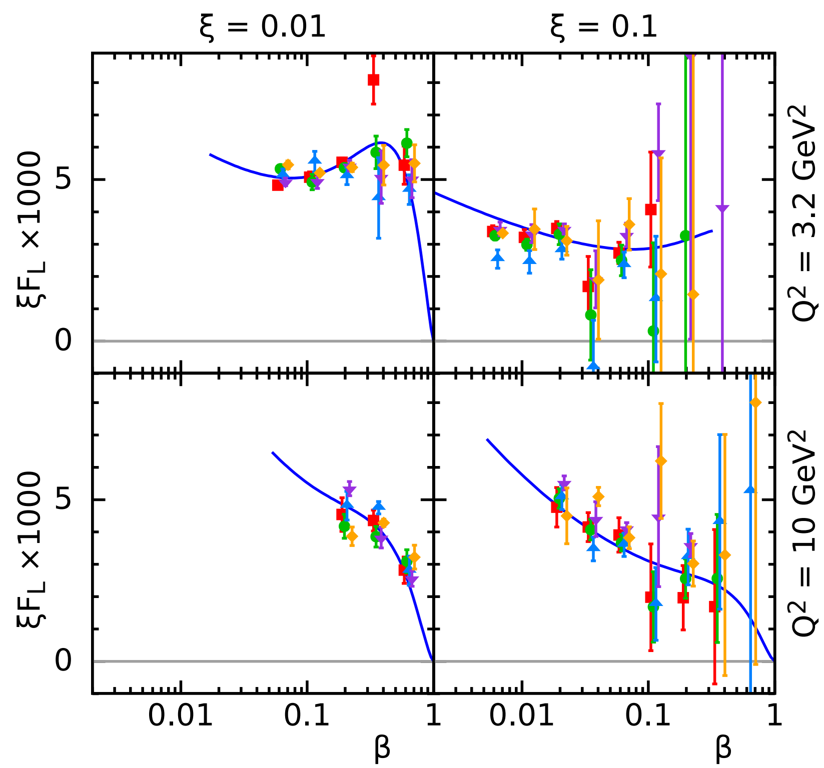
Largest errors for bins with shortest range of Y_L

Simulated measurement of $F_L^{D(3)}$ vs β in bins of (ξ, Q^2)

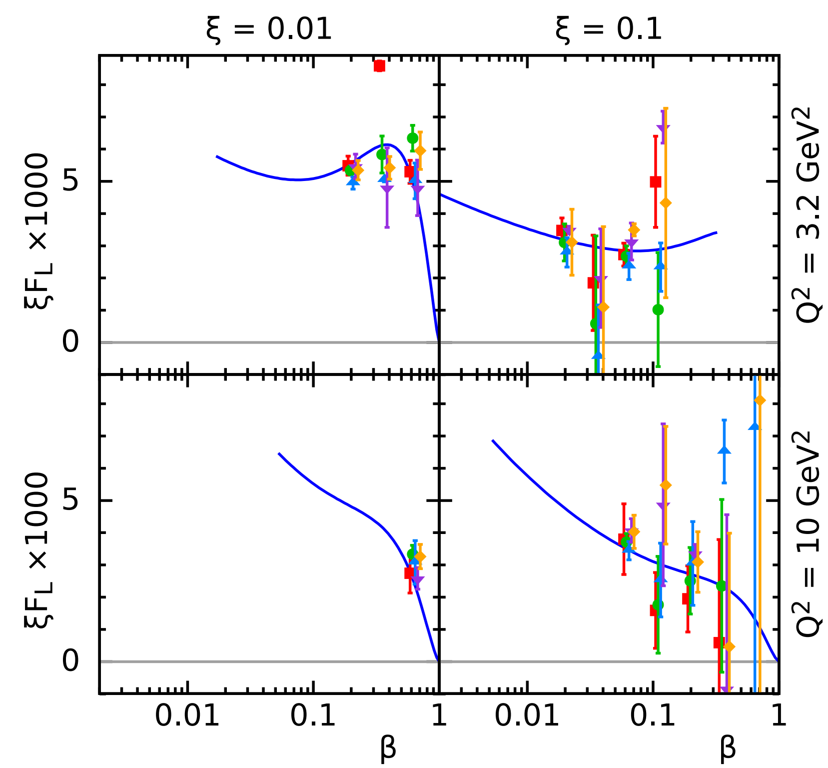
Uncorr. systematic error 1%, 5 MC samples to illustrate fluctuations



17 energies



9 energies



5 energies

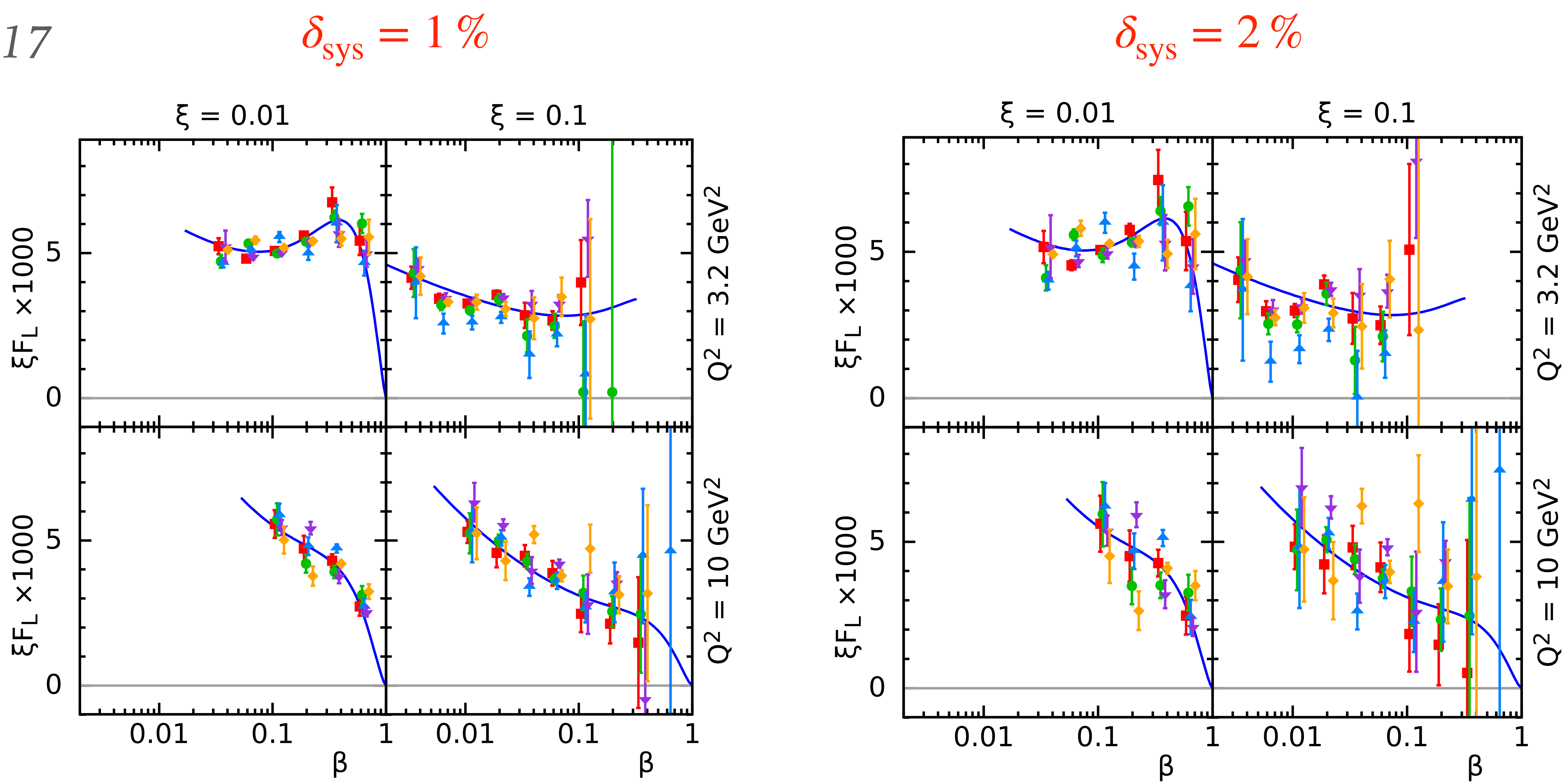
Small differences between S-17 and S-9, small reduction to range and increase in uncertainties.

More pronounced reduction in range and higher uncertainties in S-5.

An extraction of F^D_L possible with EIC-favored set of energy combinations

Simulated measurement of $F_L^{D(3)}$ vs β in bins of (ξ, Q^2)

S-17



Change from 1% to 2% results in roughly twice large error bars

Statistical errors negligible

$F_L^{D(3)}$ fit accuracy

Estimate the accuracy of extraction for $F_L^{D(3)}$

Generate several MC samples of pseudodata and perform fits

Use direct arithmetic averaging

average

$$\bar{v} = \frac{S_1}{N}$$

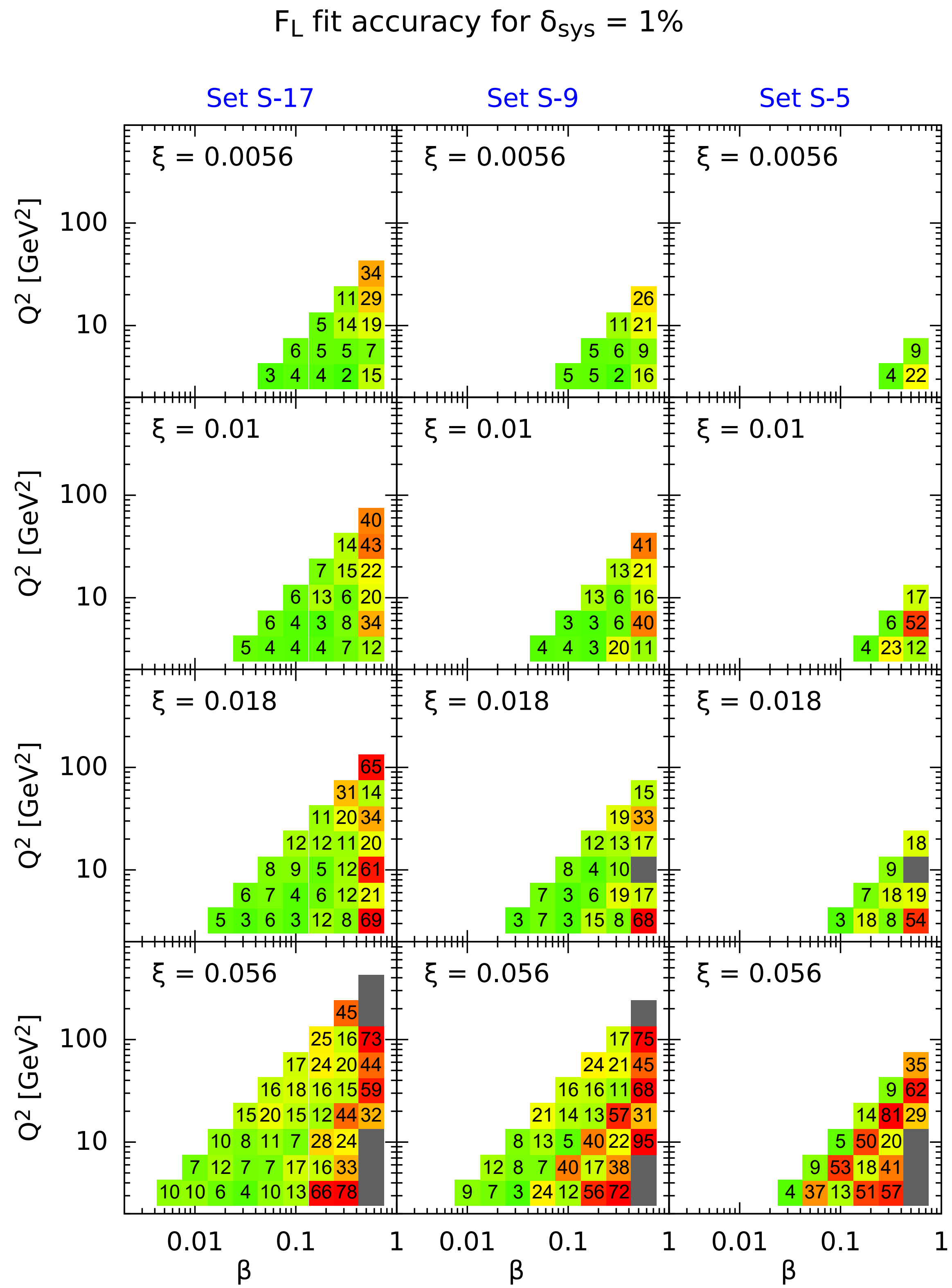
variance

$$(\Delta v)^2 = \frac{S_2 - S_1^2/N}{N-1}$$

$$S_n = \sum_{i=1}^{N} v_i^n$$

Where v_i is the value of F_L^D

in Monte Carlo sample i



$R^D = F_L^D / F_T^D$ ratio of longitudinal to transverse

Ratio of cross section for longitudinally polarized photons to cross sections for transverse polarized photons

$$R^{D(3)} = F_L^{D(3)} / F_T^{D(3)}$$

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

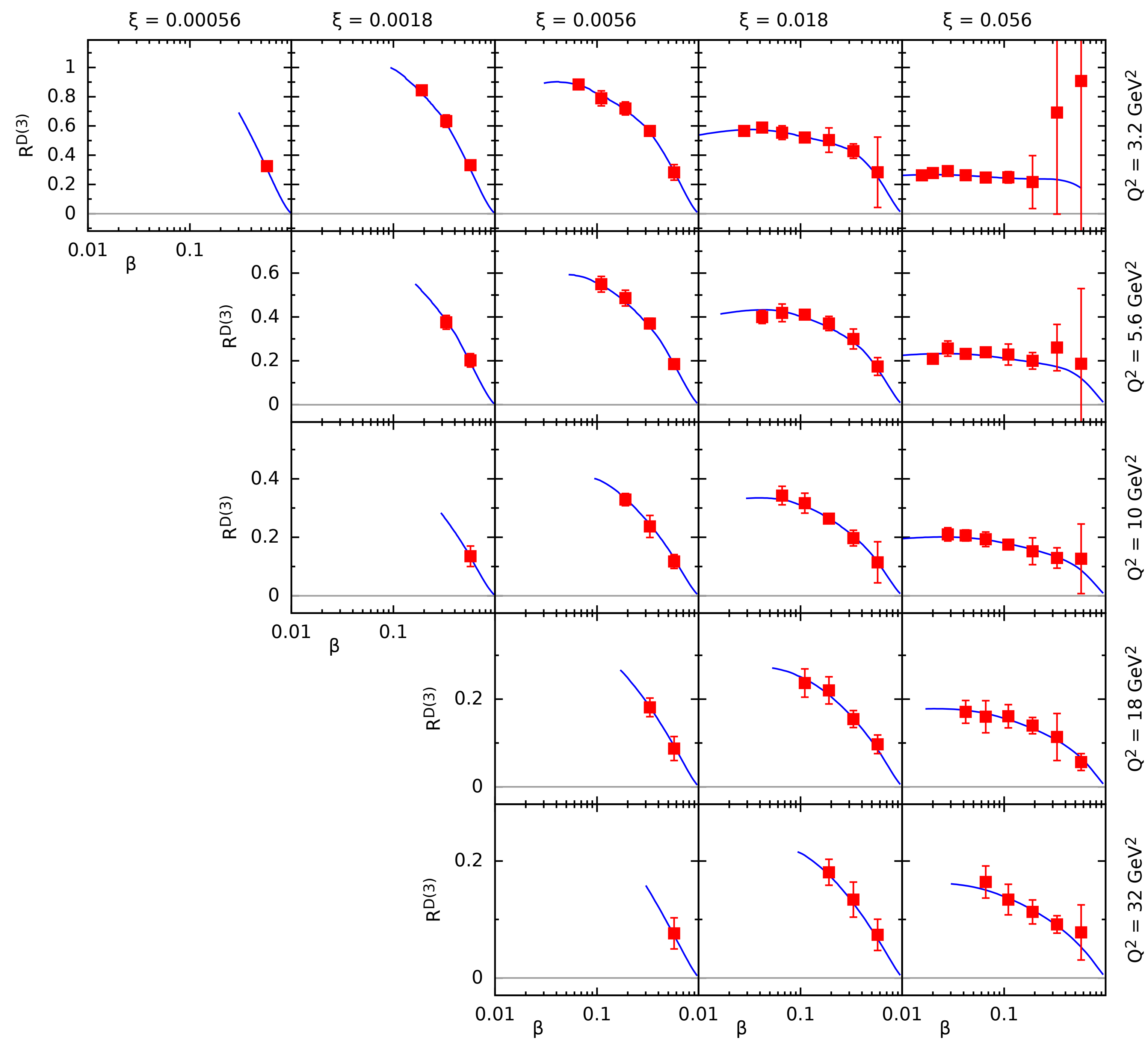
$$\sigma_{\text{red}}^{D(3)} = [1 + (1 - Y_L) R^{D(3)}] F_T^{D(3)}$$

Different form of reduced cross section

Alternative fit has different sensitivities to the uncertainties

Systematics 1%

Averaged over 10 MC samples: reduced fluctuations



Summary and outlook

- Investigated potential of EIC for the longitudinal structure function in diffraction : $F_L^{D(3)}$
- Important quantity, sensitive to diffractive gluon density (saturation, higher twists…). Only one extraction at HERA by H1, large errors. Challenging measurement.
- Three scenarios: 17, 9, 5 energy combinations. Pseudodata from DGLAP, assumed 1-2% systematics, 10 fb^{-1} integrated luminosity. Extraction via linear fit to reduced cross section
- Scenarios S-17 and S-9 do not differ much, S-5 reduced kinematic range
- Precision in a given bin of (Q^2,ξ,β) correlates strongly with range in inelasticity y, dominated by systematics.
- **Overall: good prospects for the measurement of $F_L^{D(3)}$ at EIC even with 5 energy combinations**

- **Outlook:**
- Potential for 4-dim diffractive structure function measurement in large t-range
- Pomeron/Reggeon component separation

Backup

Simulations of $\sigma^{D(4)}$

What can we learn about the t-dependence of the diffractive structure function?

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

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

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

$$d\sigma^{ep\to eXY}(\beta,\xi,Q^2,t) \; = \; \sum_i \int_\beta^1 dz \; d\hat{\sigma}^{ei}\left(\frac{\beta}{z},Q^2\right) \; f_i^{\rm D}(z,\xi,Q^2,t)$$

Ansatz for DPDFs:

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

Pomeron *Reggeon*

At HERA Reggeon part could not be extracted precisely.

Is it possible to disentangle Pomeron/Reggeon at EIC ?

Simulations of $\sigma^{D(4)}$

High luminosity and excellent possibility of proton tagging

Prospect of high quality data for $\sigma_{\mathrm{r}}^{D(4)}(\xi, \beta, Q^2, t)$

From the ZEUS-SJ fit

$$\xi \varphi_P(\xi, t) \propto \xi^{-0.22}\, e^{-7|t|}$$

$$\xi \varphi_R(\xi, t) \propto \xi^{0.6+1.8|t|}\, e^{-2|t|}$$

Very different slopes in t for Reggeon and Pomeron

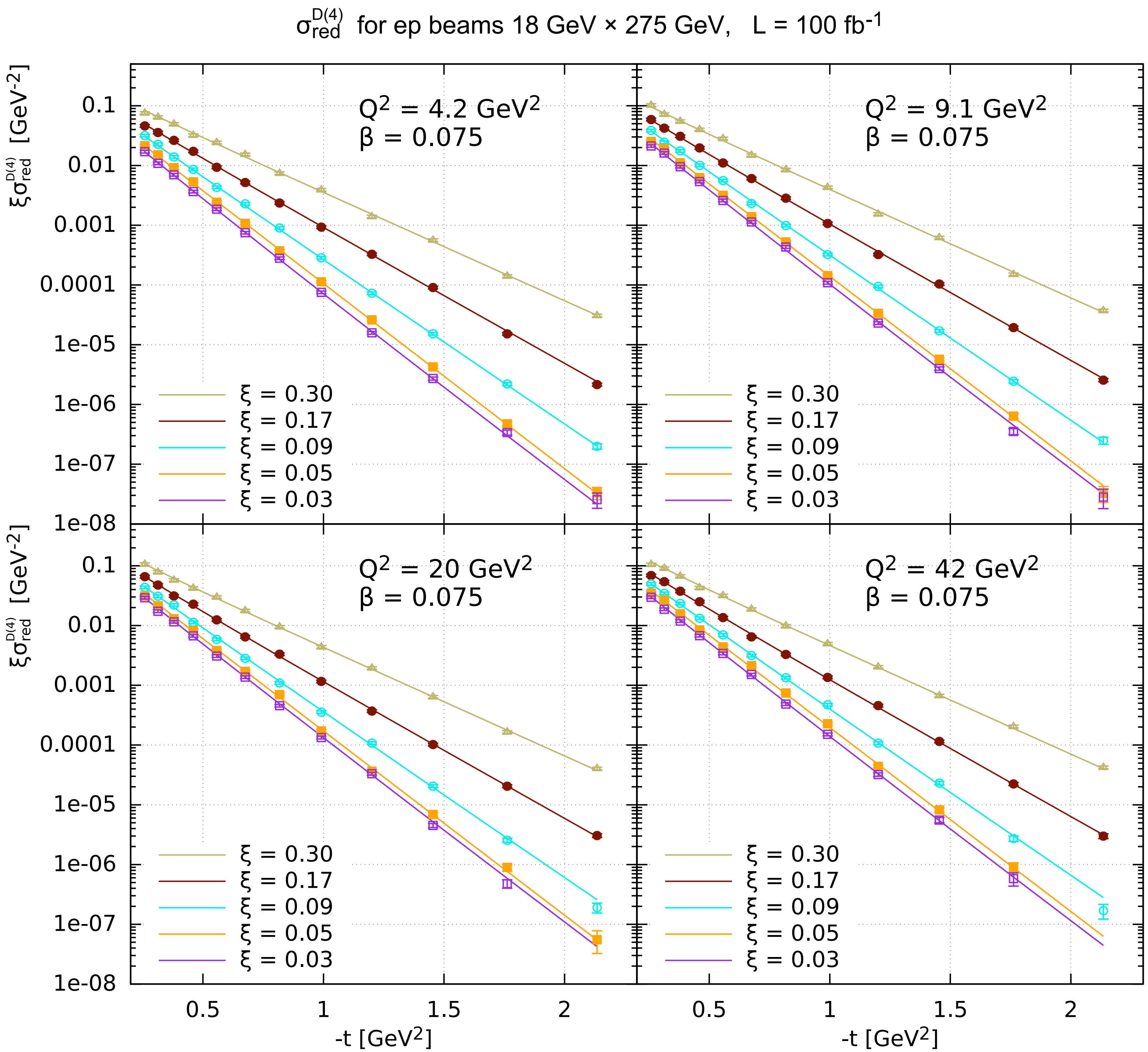
Extrapolation of reduced cross section using ZEUS SJ fit

Random smearing with errors:

Systematic: $\delta_{sys} = 5\ \%$

Statistics: δ_{stat} from integrated luminosity 10 fb^{-1}

$\sigma^{D(4)}$ vs t



$E_e = 18\,\mathrm{GeV}$

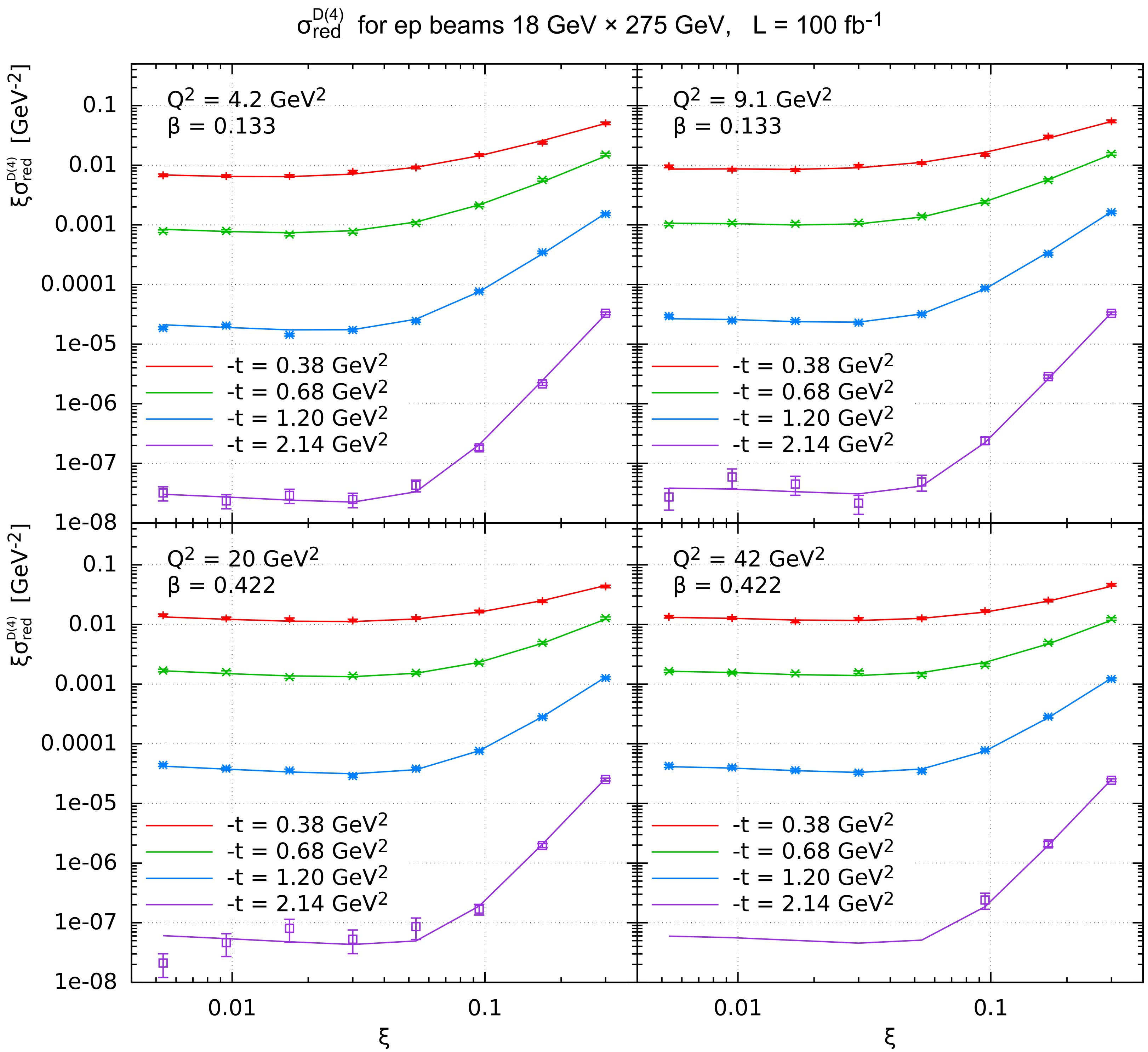
$E_p = 275\,\mathrm{GeV}$

Lines-extrapolation

Points-simulation

Prospects for the very good measurement of the t-slope as a function of ξ

$\sigma^{D(4)}$ vs ξ



$E_e = 18\,\text{GeV}$

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Lines-extrapolation

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Prospects for the very good measurement of the t-slope as a function of ξ

Double-slope structure