Parton distributions with small-x resummation: unravelling BFKL dynamics at the LHeC

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Theory motivation: beyond DGLAP

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a wealth of data from proton-proton and electron-proton collisions

- There are theoretical reasons that eventually we need to go beyond DGLAP: at very small-x, **logarithmically enhanced terms in 1/x become dominant** and need to be resummed to all orders

- **BFKL/high-energy/small-x resummation** can be matched to the **DGLAP collinear framework**, and thus can be included into a standard PDF analysis

DGLAP Evolution in Q^2

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(\mu^2)\right) f_j(z,\mu^2),$$

BFKL Evolution in x

$$-x\frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

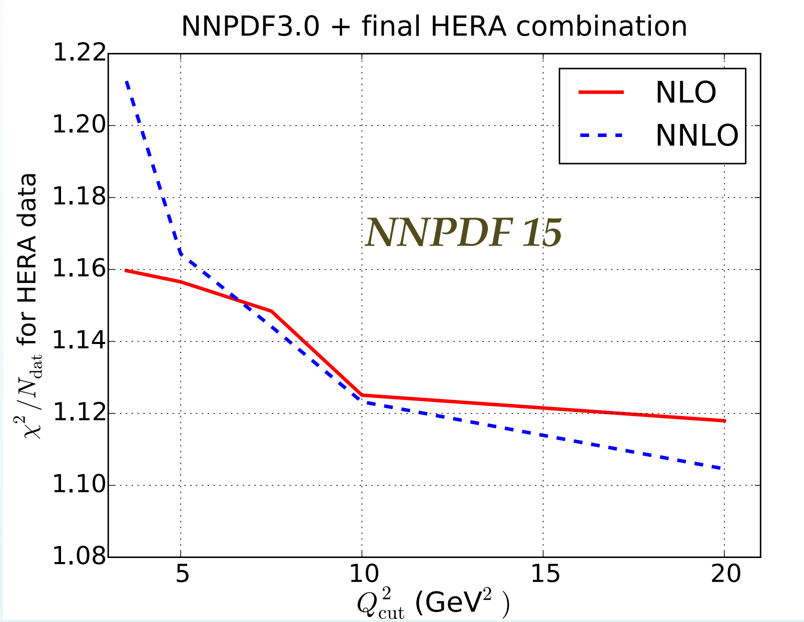
Within small-x resummation, the **N^kLO fixed-order DGLAP splitting functions** are complemented with the **N^hLLx contributions from BKFL**

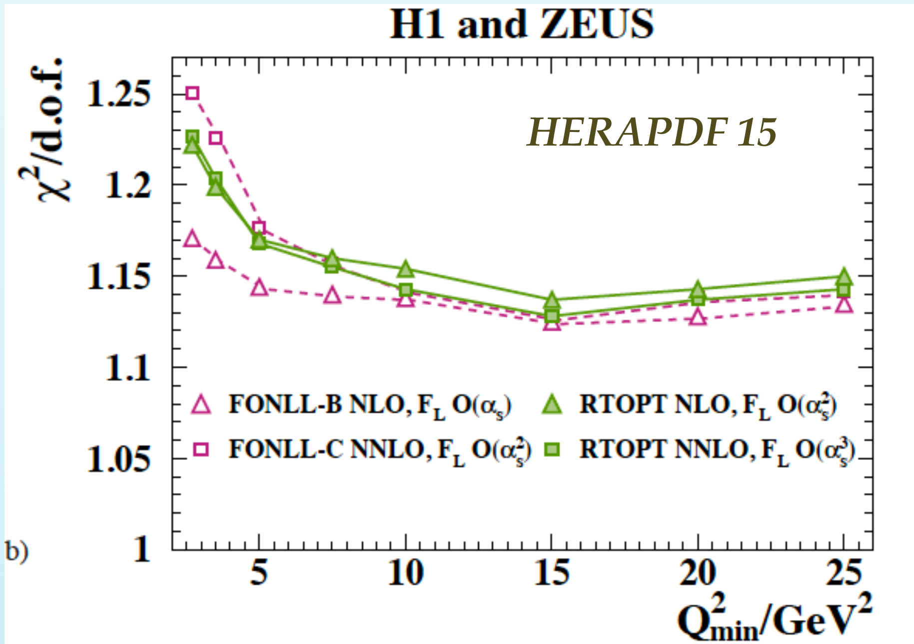
ABF, CCSS, TW + others, 94-08

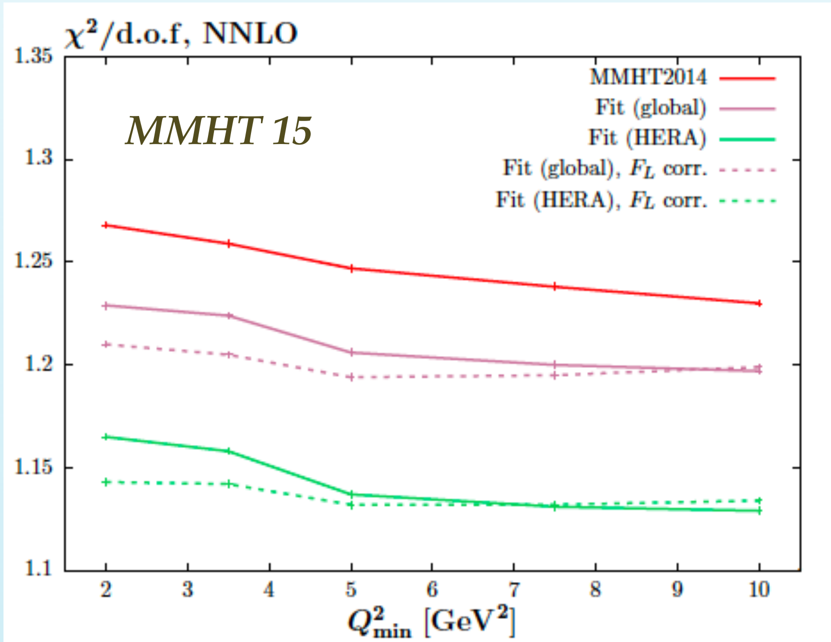
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

Experimental motivation: tensions in HERA data

- Several groups have reported that the **fit quality to the legacy HERA inclusive data** gets worse in the **small-x and small-Q region**
- Typically this trend is **more marked at NNLO**
- Several explanations have been advocated, from **higher twists** (*i.e.* saturation), issues with the **heavy quark schemes**, experimental systematics, …
- What happens if the **PDF fit includes NLLx resummation?**

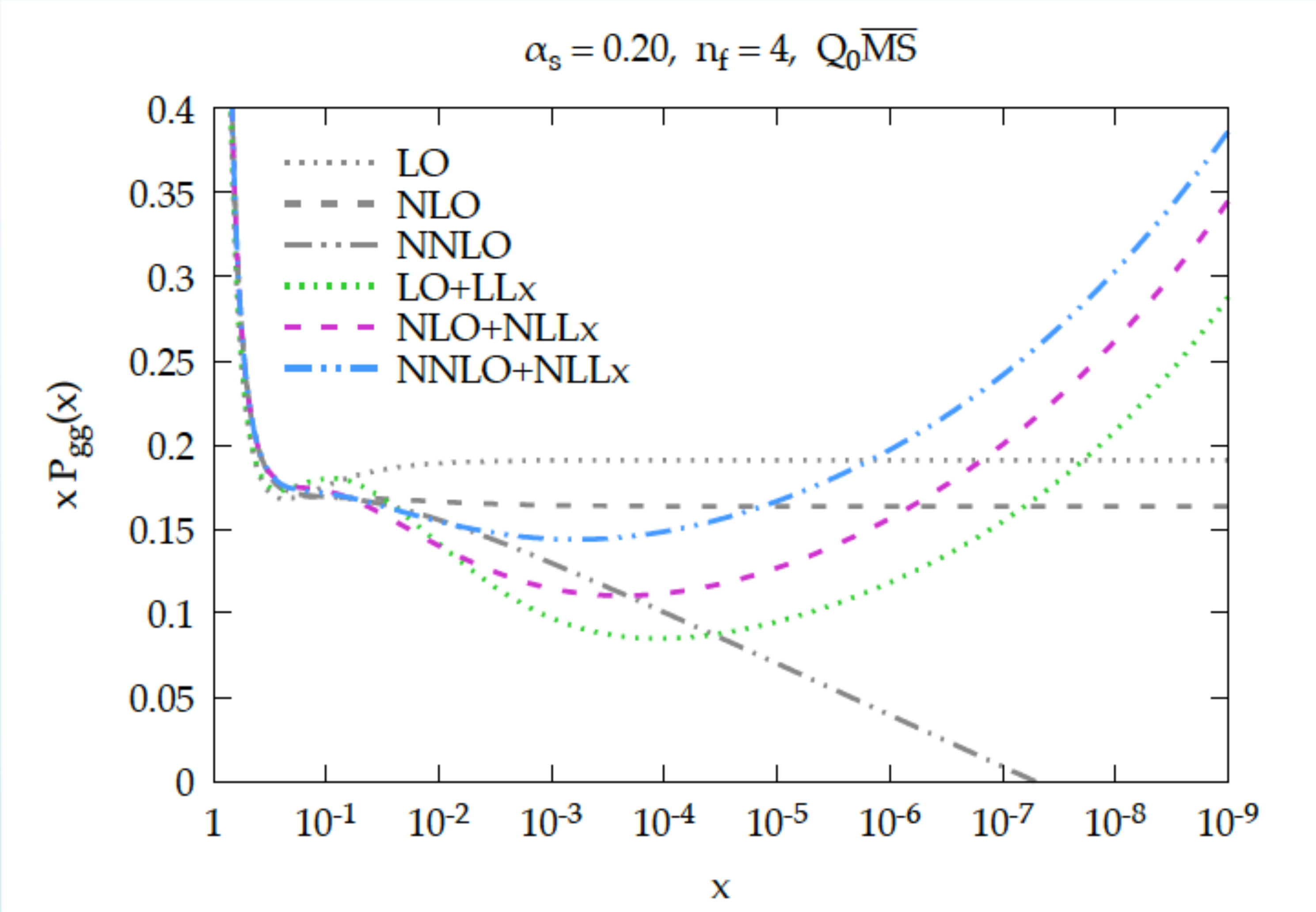






PDFs with small-x resummation

- Ultimately, the need for (or lack of) BKFL resummation in **ep and pp collider data** can only be assessed by performing a **global PDF analysis based on (N)NLO+NLLx theory**
- Theoretical tools are now available: **HELL for NLLx resummation**, interfaced to **APFEL**

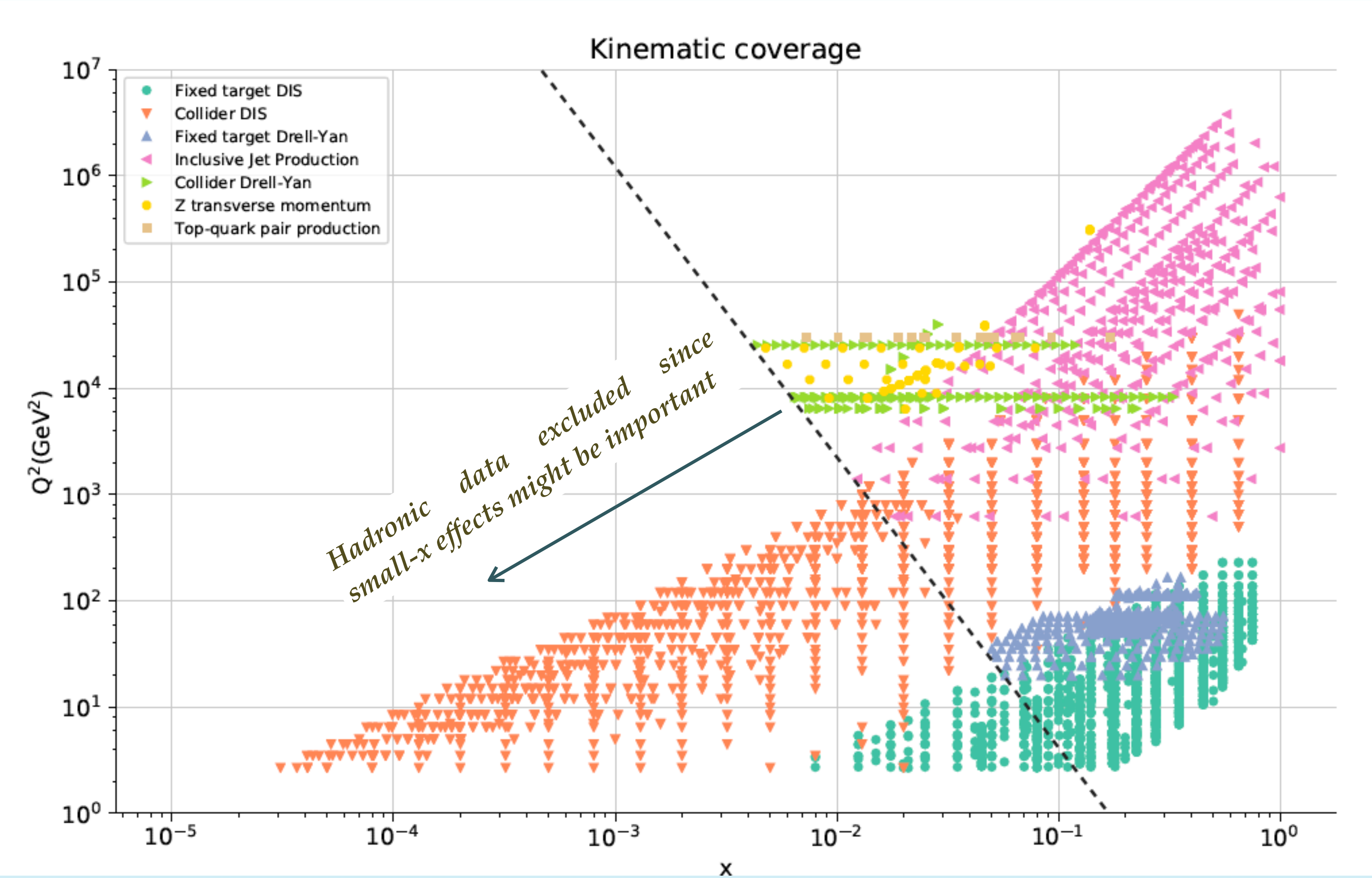


APFEL: Bertone, Carrazza, Rojo 13
https://apfel.hepforge.org/

HELL: Bonvini, Marzani, Peraro, Muselli 16-17
https://www.ge.infn.it/~bonvini/hell/

PDFs with small-x resummation

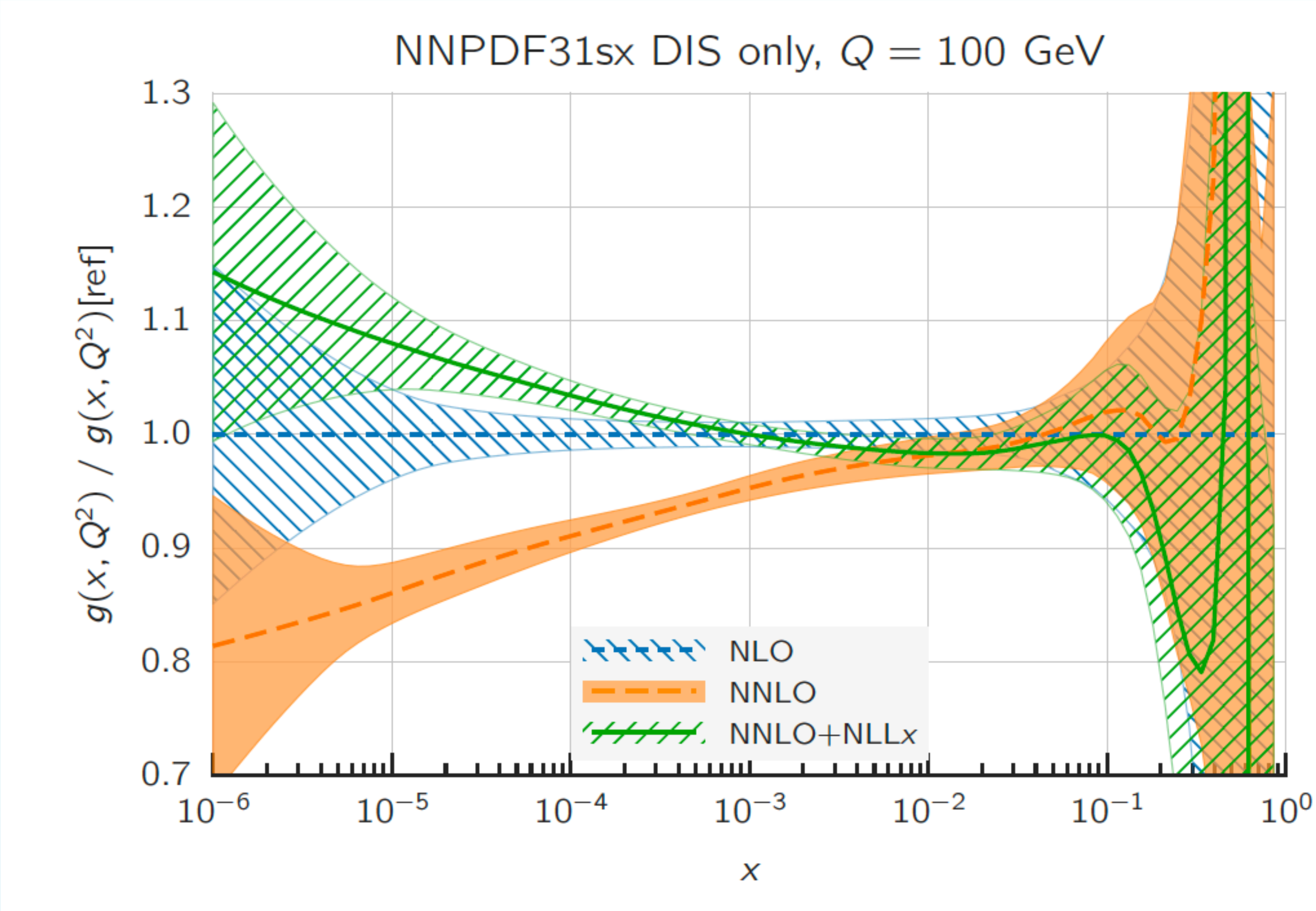
- **NNPDF3.1sx**: Variant of **NNPDF3.1 global fits** using **NLO+NLLx and NNLO+NLL*x* theory**
- Hadronic data treated at NNLO: impose cut to remove region **sensitive to small-x effects**



Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli, 17

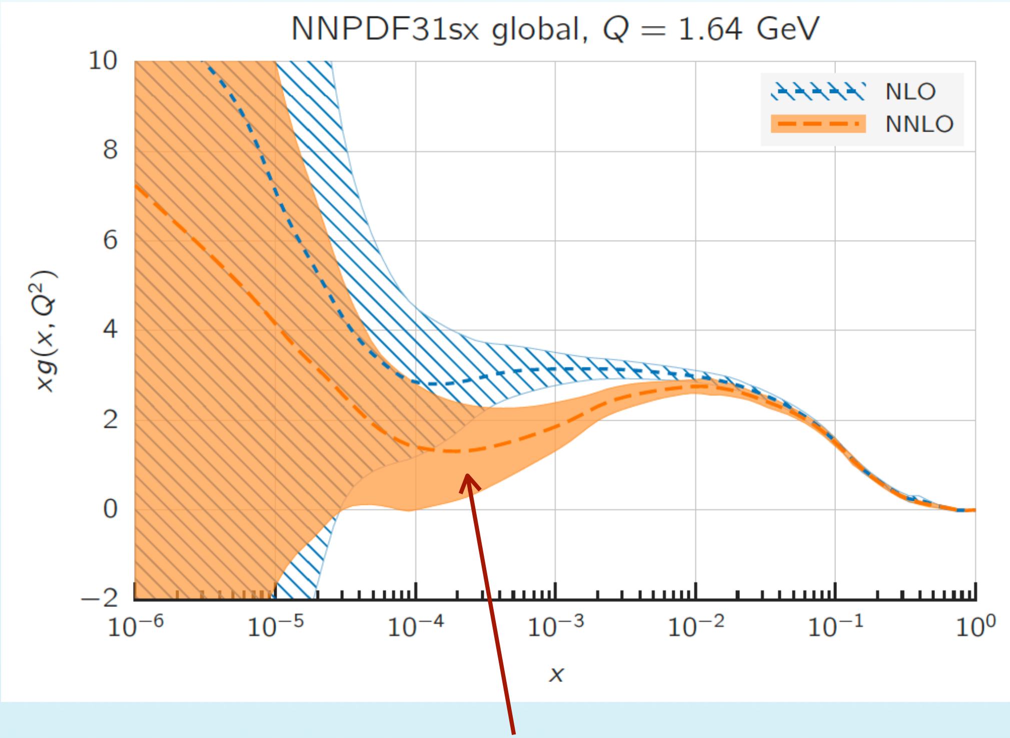
PDFs with small-x resummation

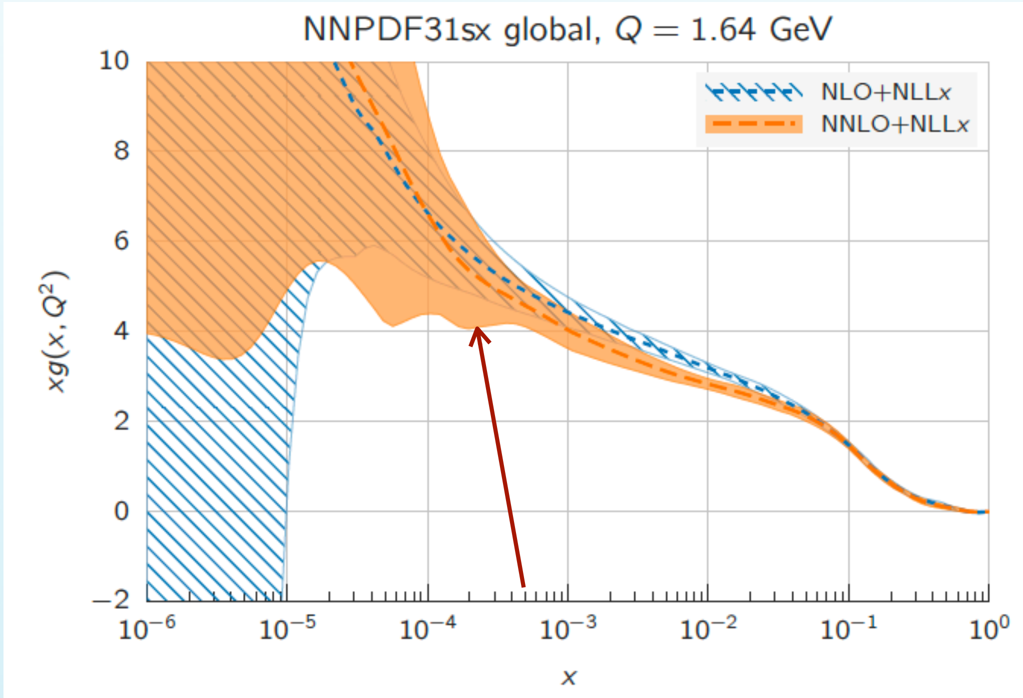
- **NNPDF3.1sx**: Variant of **NNPDF3.1 global fits** using **NLO+NLL*x* and NNLO+NLL*x* theory**
- Using NNLO+NLL*x* theory **stabilises small-x gluon wrt perturbative order**



PDFs with small-x resummation

- **NNPDF3.1sx**: Variant of **NNPDF3.1 global fits** using **NLO+NLLx and NNLO+NLL*x* theory**
- With resummation, the NNLO gluon at low scales **is not negative anymore**
- **Positivity of physical observables**, such as $F_L(x,Q)$, automatically guaranteed





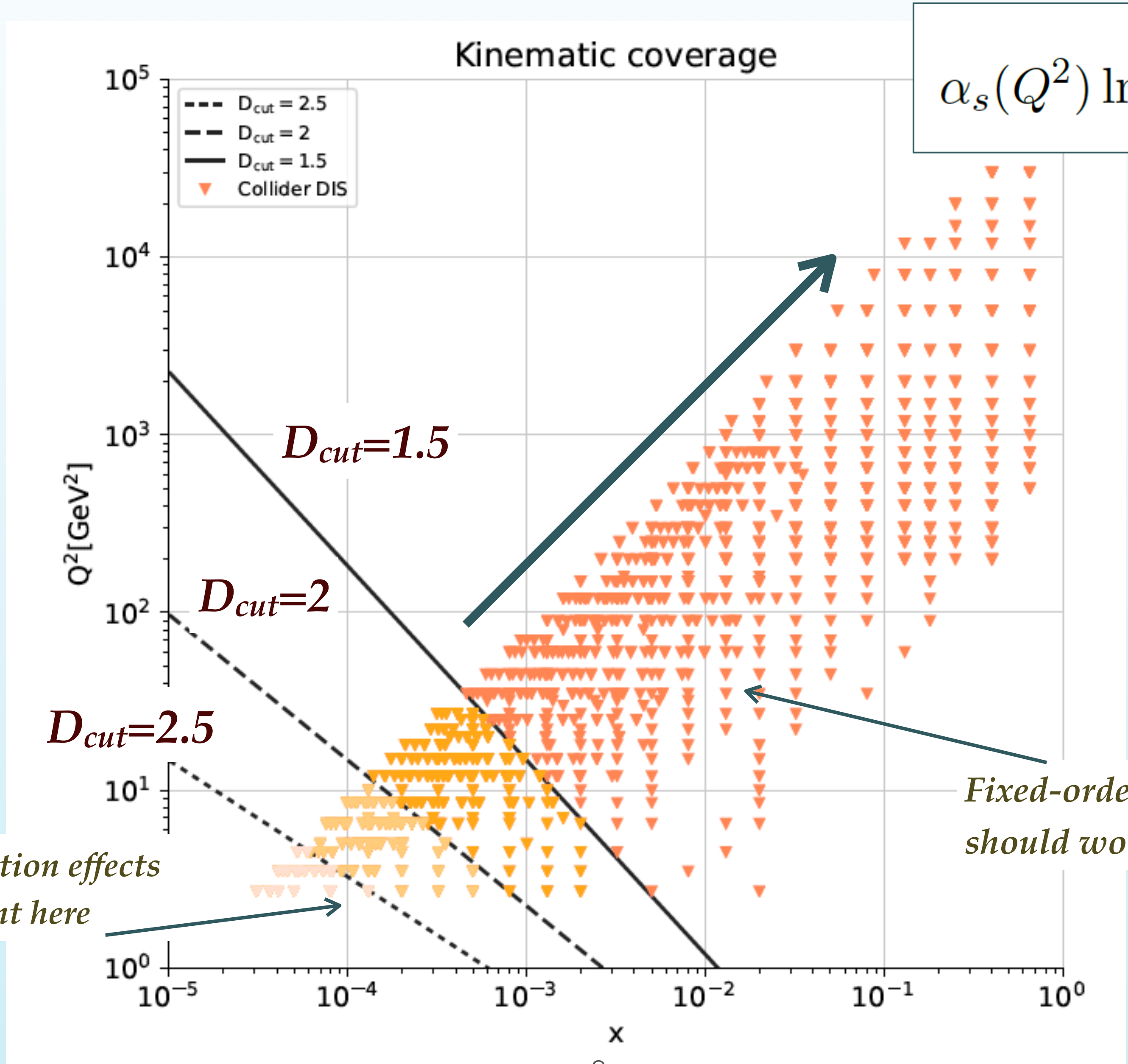
PDFs with small-x resummation

	$\chi^2/N_{\rm dat}$ NLO	$\chi^2/N_{\rm dat}$ NLO+NLLx	$\Delta\chi^2$	$\chi^2/N_{\rm dat}$ NNLO	$\chi^2/N_{\rm dat}$ NNLO+NLLx	$\Delta\chi^2$
NMC	1.35	1.35	+1	1.30	1.33	+9
SLAC	1.16	1.14	−1	0.92	0.95	+2
BCDMS	1.13	1.15	+12	1.18	1.18	+3
CHORUS	1.07	1.10	+20	1.07	1.07	−2
NuTeV dimuon	0.90	0.84	−5	0.97	0.88	−7
HERA I+II incl. NC	1.12	1.12	-2	1.17	1.11	−62
HERA I+II incl. CC	1.24	1.24	-	1.25	1.24	−1
HERA $\sigma_c^{\rm NC}$	1.21	1.19	−1	2.33	1.14	−56
HERA F_2^b	1.07	1.16	+3	1.11	1.17	+2
DY E866 $\sigma^d_{\rm DY}/\sigma^p_{\rm DY}$	0.37	0.37	-	0.32	0.30	-
DY E886 σ^p	1.06	1.10	+3	1.31	1.32	-
DY E605 σ^p	0.89	0.92	+3	1.10	1.10	-
CDF Z rap	1.28	1.30	-	1.24	1.23	-
CDF Run II k_t jets	0.89	0.87	−2	0.85	0.80	−4
D0 Z rap	0.54	0.53	-	0.54	0.53	-
D0 $W \to e\nu$ asy	1.45	1.47	-	3.00	3.10	+1
D0 $W \to \mu\nu$ asy	1.46	1.42	-	1.59	1.56	-
ATLAS total	1.18	1.16	−7	0.99	0.98	−2
ATLAS W, Z 7 TeV 2010	1.52	1.47	-	1.36	1.21	−1
ATLAS HM DY 7 TeV	2.02	1.99	-	1.70	1.70	-
ATLAS W, Z 7 TeV 2011	3.80	3.73	−1	1.43	1.29	−1
ATLAS jets 2010 7 TeV	0.92	0.87	−4	0.86	0.83	−2
ATLAS jets 2.76 TeV	1.07	0.96	−6	0.96	0.96	-
ATLAS jets 2011 7 TeV	1.17	1.18	-	1.10	1.09	−1
ATLAS Z p_T 8 TeV (p_T^{ll}, M_{ll})	1.21	1.24	+2	0.94	0.98	+2
ATLAS Z p_T 8 TeV (p_T^{ll}, y_{ll})	3.89	4.26	+2	0.79	1.07	+2
ATLAS σ_{tt}^{tot}	2.11	2.79	+2	0.85	1.15	+1
ATLAS $t\bar{t}$ rap	1.48	1.49	-	1.61	1.64	-
CMS total	0.97	0.92	−13	0.86	0.85	−3
CMS Drell-Yan 2D 2011	0.77	0.77	-	0.58	0.57	-
CMS jets 7 TeV 2011	0.88	0.82	−9	0.84	0.81	−3
CMS jets 2.76 TeV	1.07	0.98	−7	1.00	1.00	-
CMS Z p_T 8 TeV (p_T^{ll}, y_{ll})	1.49	1.57	+1	0.73	0.77	-
CMS σ_{tt}^{tot}	0.74	1.28	+2	0.23	0.24	-
CMS $t\bar{t}$ rap	1.16	1.19	-	1.08	1.10	-
Total	**1.117**	**1.120**	+11	**1.130**	**1.100**	−121

PDFs with small-x resummation

In order to assess the impact of small-x resummation for the description of the small-x and Q^2 HERA data, compute the χ^2 **removing data points in the region where resummation effects are expected**

$$\alpha_s(Q^2)\ln\frac{1}{x} \geq D_{\rm cut}$$



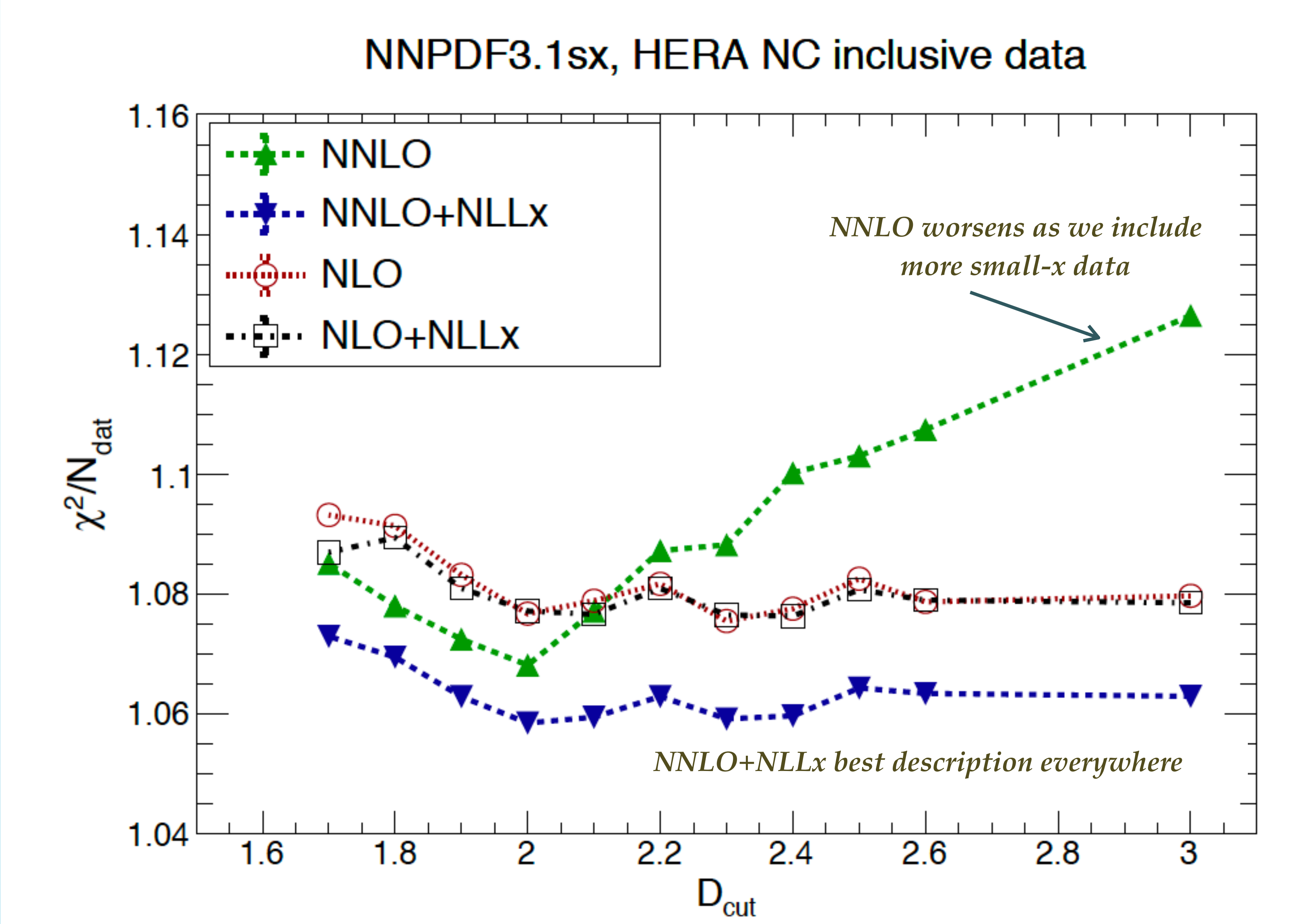
Small-x resummation effects could be important here

Fixed-order theory should work fine here

PDFs with small-x resummation

Using **NNLO+NLLx theory, the NNLO instability of the χ^2 disappears**

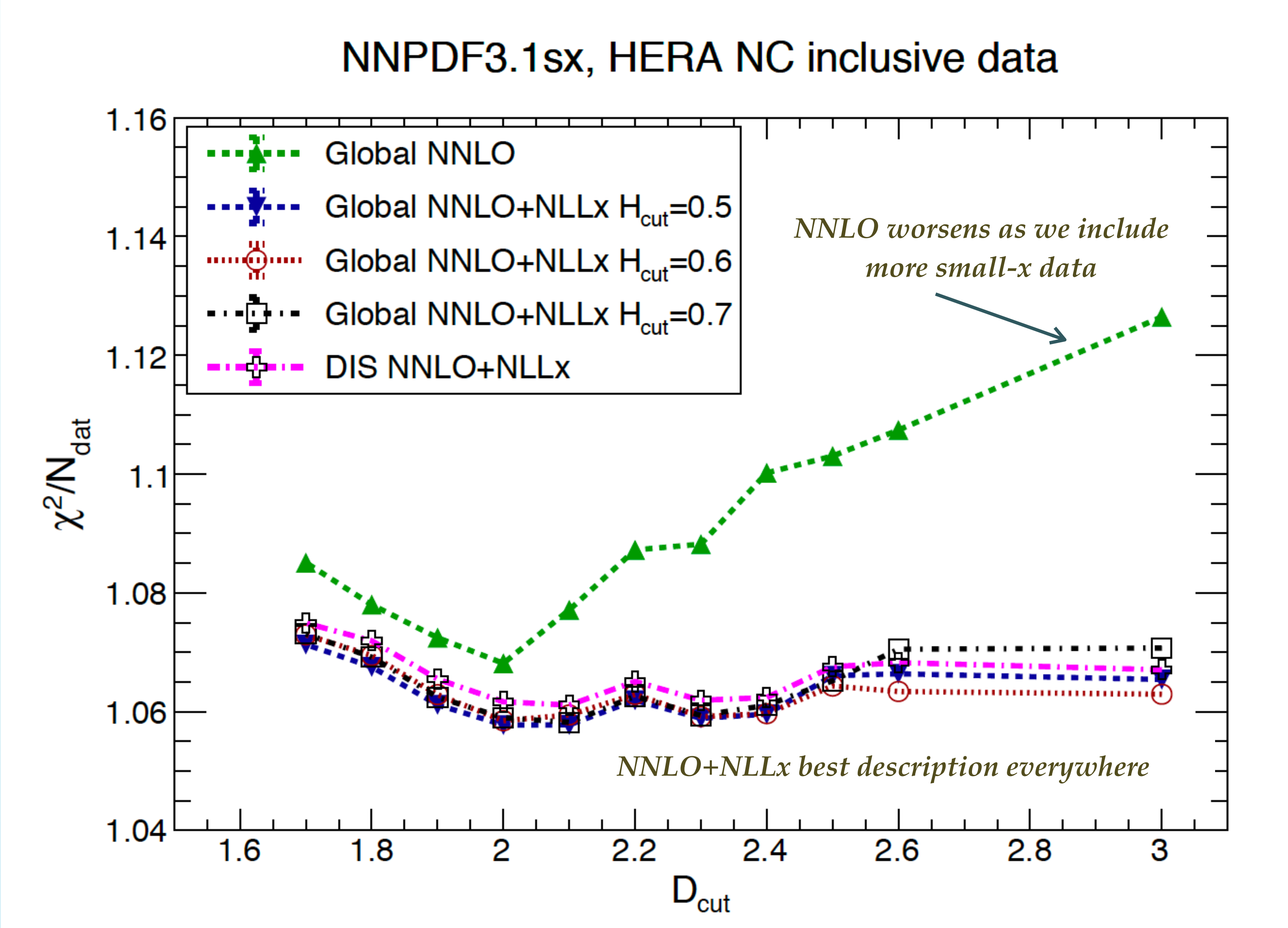
Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire (x,Q^2) region**



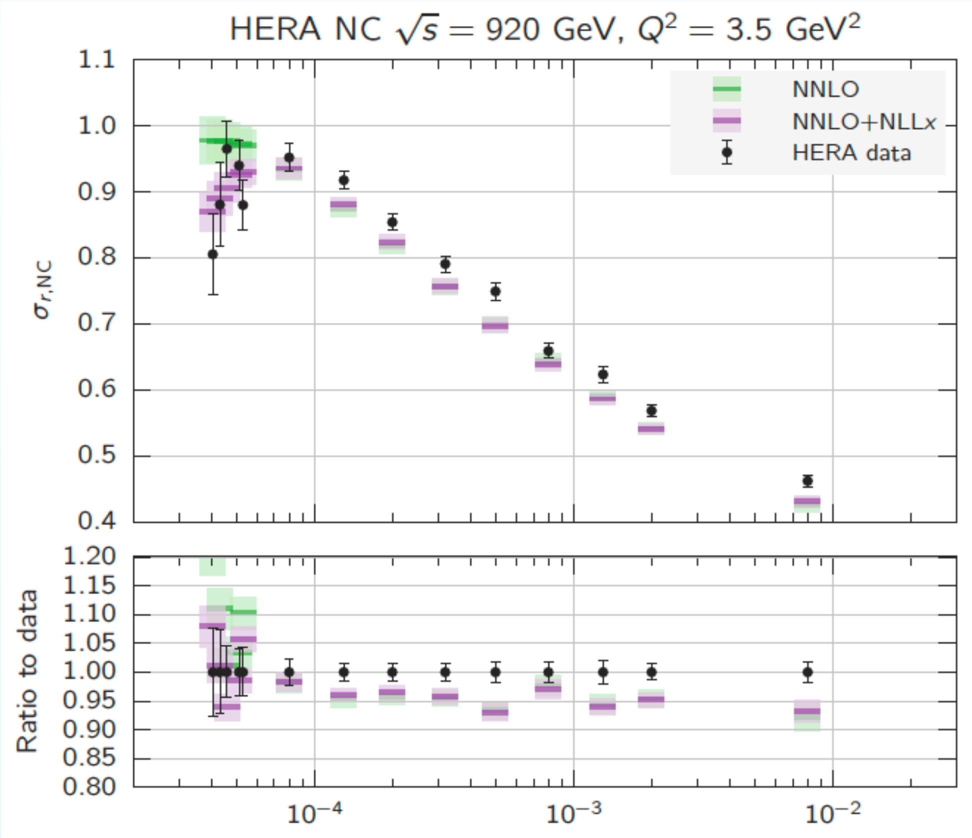
PDFs with small-x resummation

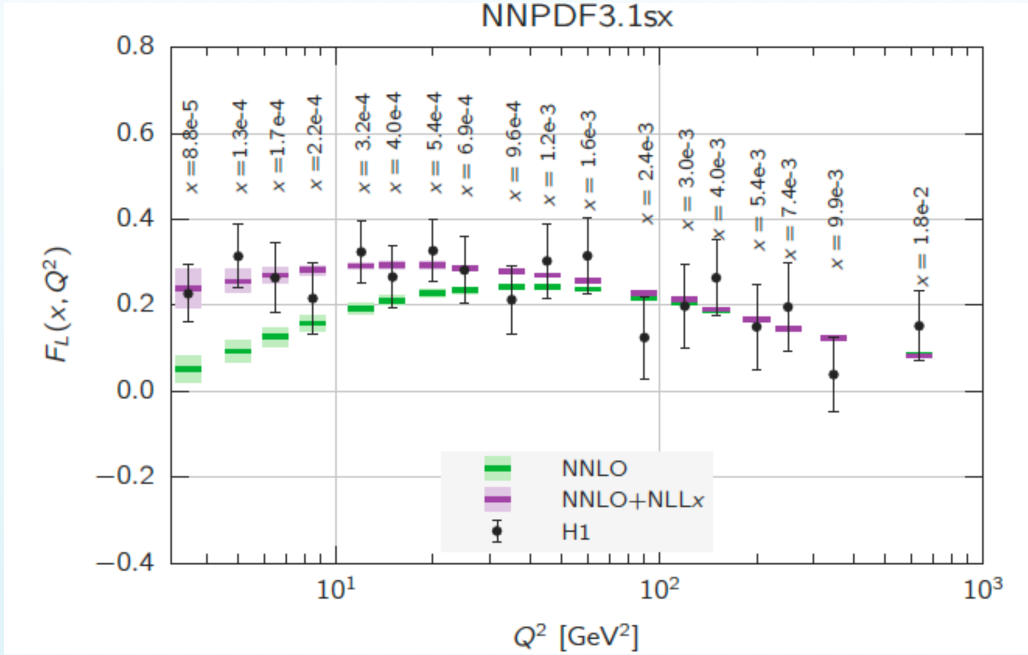
Using **NNLO+NLL*x* theory, the NNLO instability of the χ^2 disappears**

Results stable with respect to the specific **treatment of hadronic data**: genuine DIS small-x phenomenon



Comparison with HERA data





Using **NNLO+NLL*x* theory,** improved description of the **small-x NC cross-sections**, in particular of the **change of slope** (related to differences in F_L)

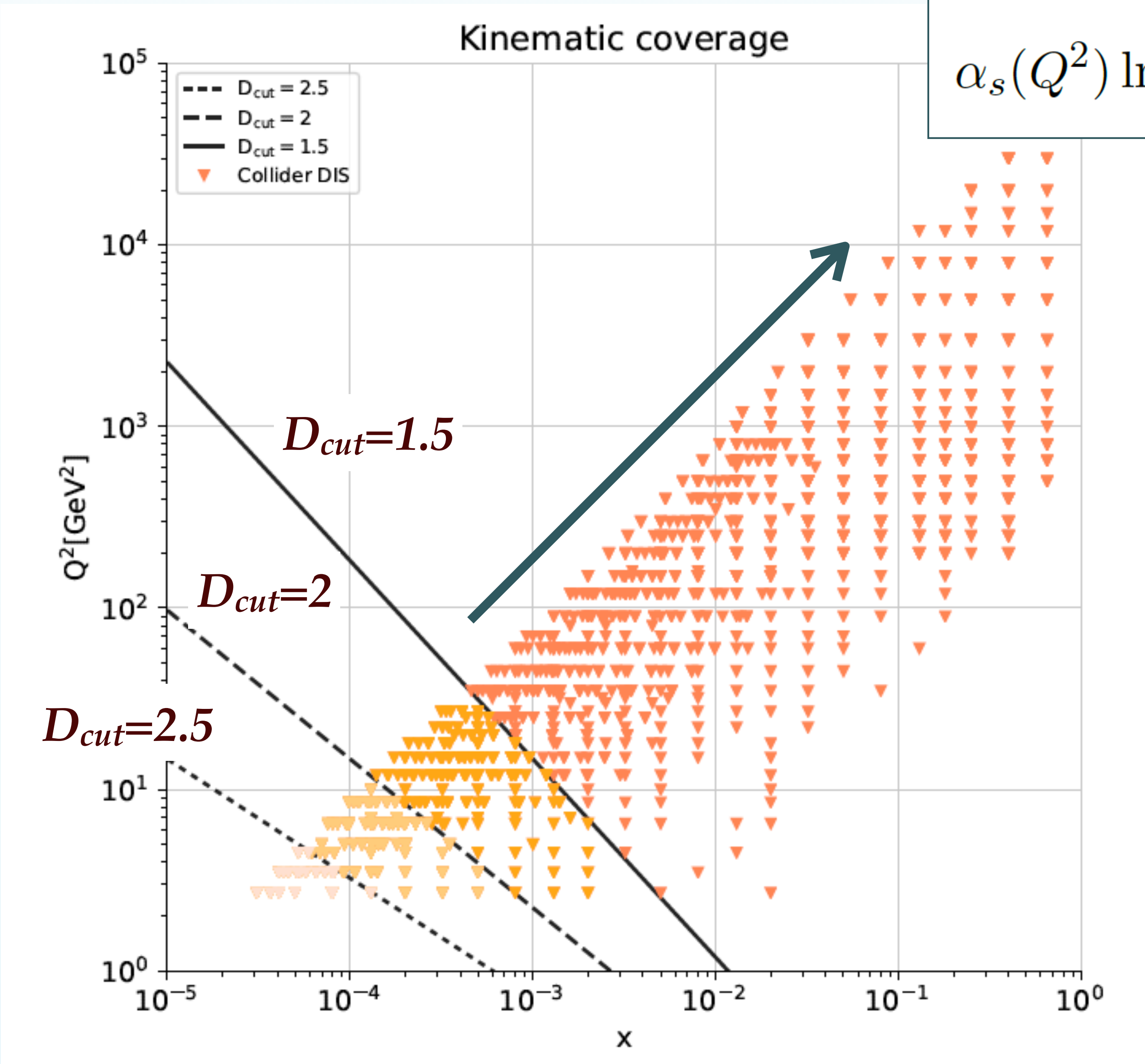
Also **improved description of F_L,** which moreover remains markedly **positive** down to the smallest values of x and Q probed

Implications for fixed-order fits

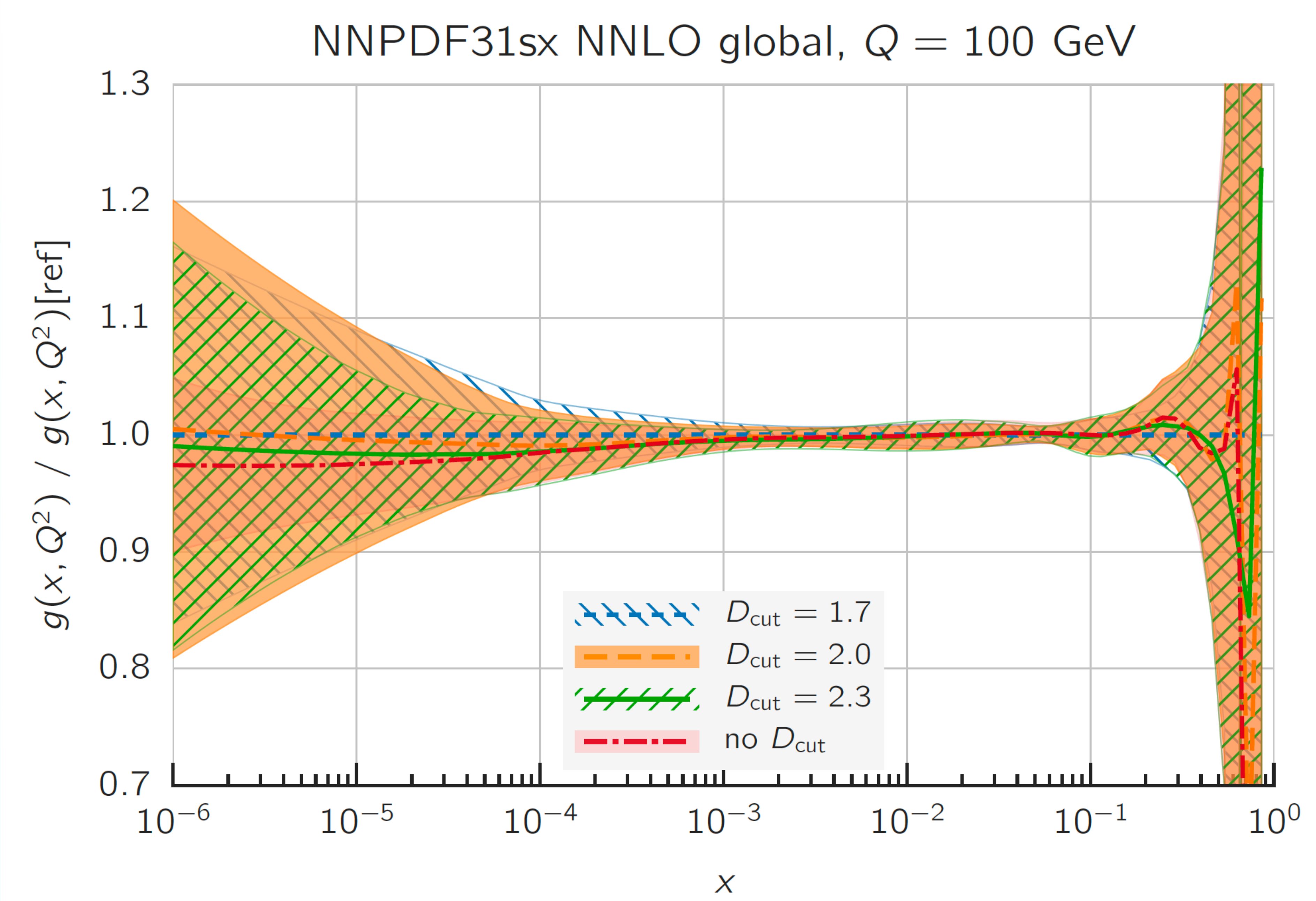
Do these results imply at existing NNLO fits are **biased?** What are implications for LHC pheno?

Study **stability of NNLO fits** as the HERA data at small x and Q is cut away

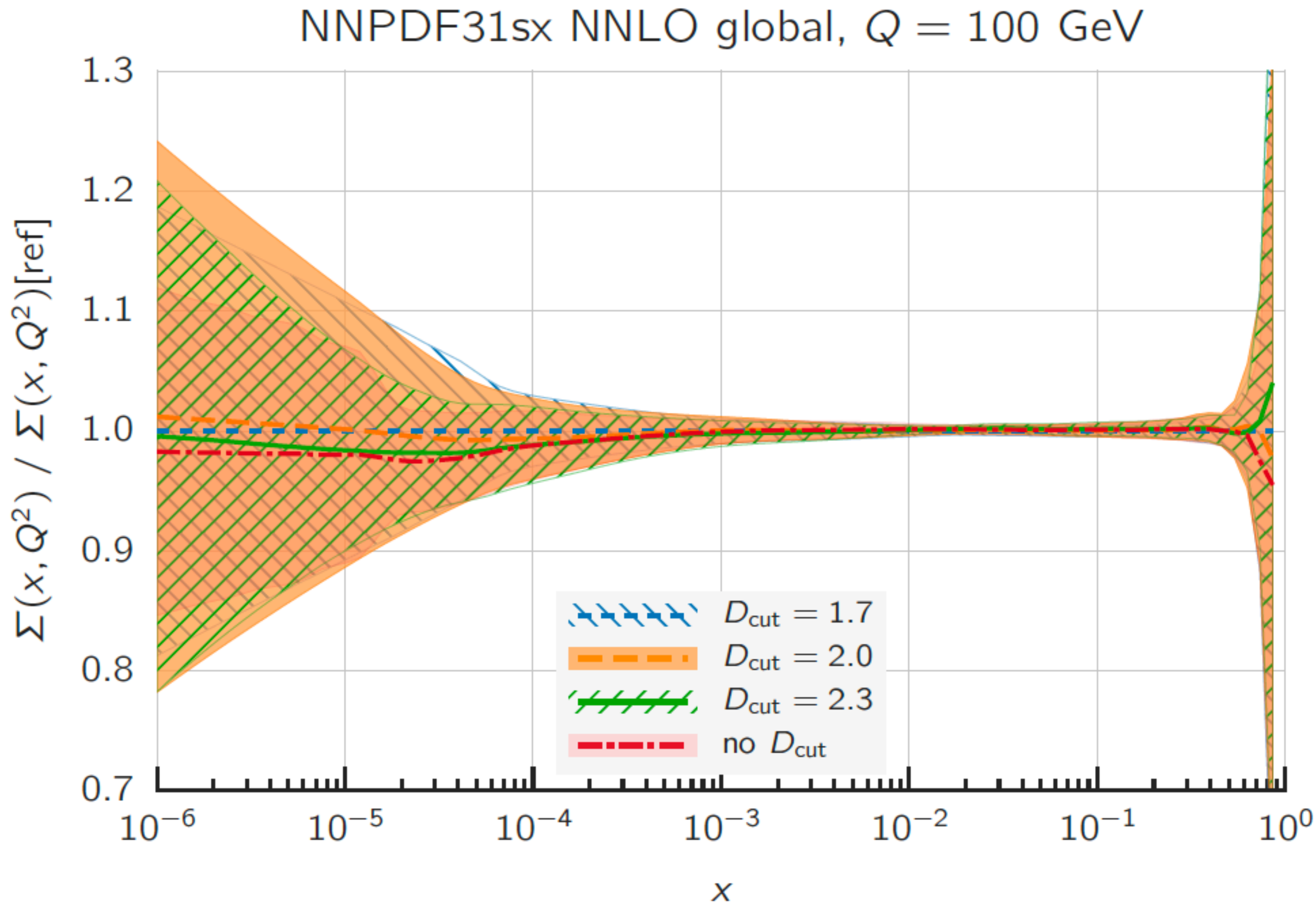
$$\alpha_s(Q^2)\ln\frac{1}{x} \geq D_{\rm cut}$$



Implications for fixed-order fits



Implications for fixed-order fits

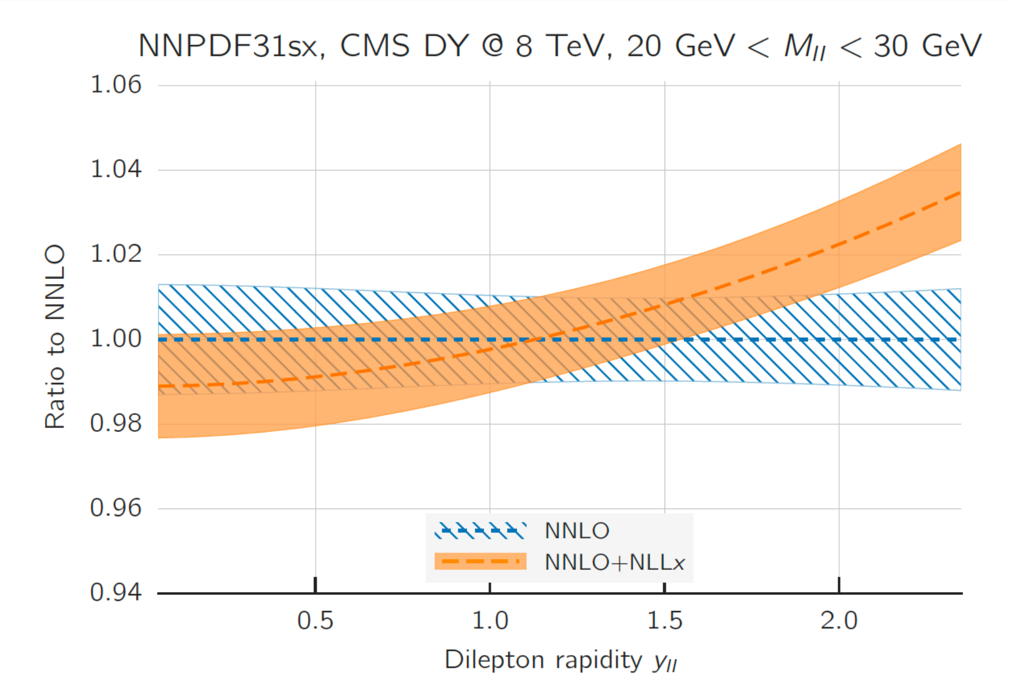


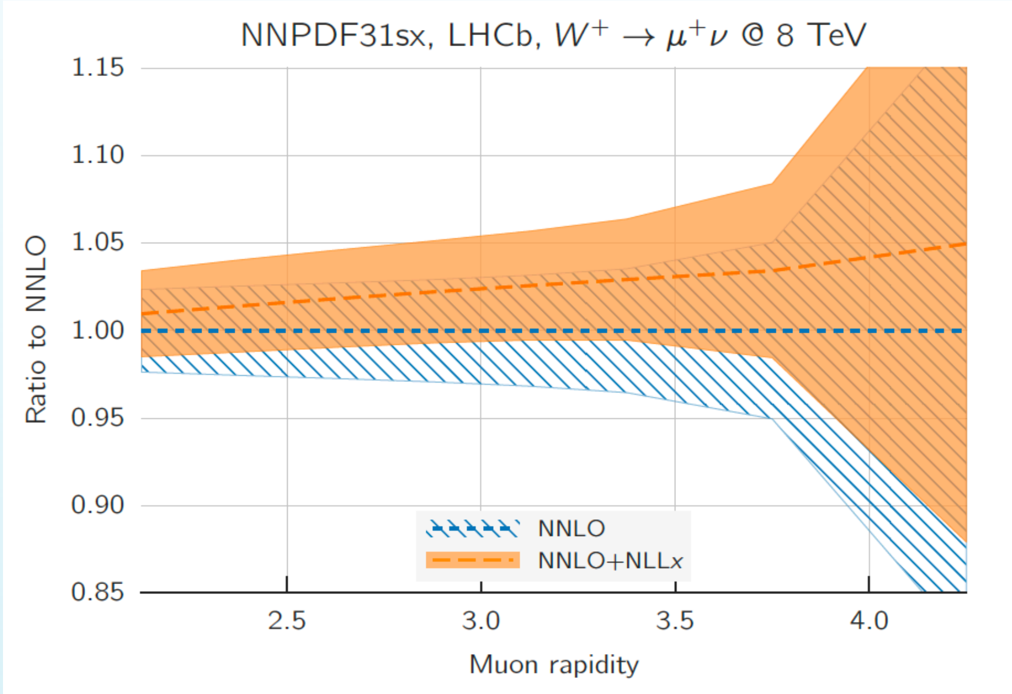
Good stability at medium and large-x: **NNLO global fits perfectly fine for LHC applications**

What next?

Aim to a **consistent NNLO+NLLx global analysis**: need to implement as well resummation of hadronic cross-sections, to being with **Drell-Yan**

A first estimate of expected impact provided by comparing xsecs with **resummation only in PDFs**, not in the partonic matrix elements



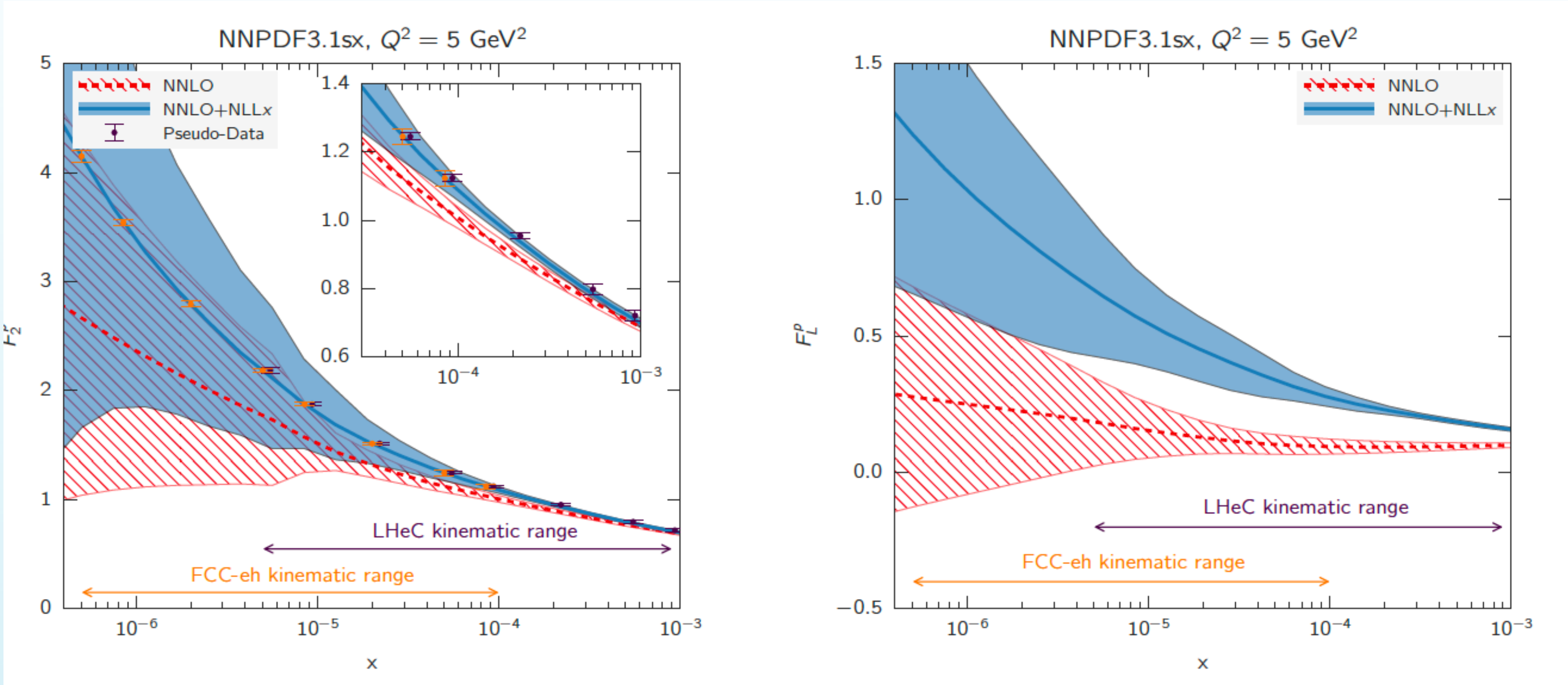


NB none of these exps included in NNPDF3.1sx

Small-x resummed PDFs might be needed to **push the boundaries of precision LHC phenomenology**

BFKL resummation at the LHeC

Small-x resummation will be key aspect of the physics program of **future electron-proton colliders**



In order to quantify sensitivity to BFKL dynamics of LHeC/FCC-eh:

redo the NNPDF3.1sx fits including LHeC/FCC-eh pseudo-data

Pseudo-data fit settings

- **LHeC (FCC-eh) pseudo-data** on 7 TeV + 60 GeV (50 TeV + 60 GeV) collisions used

- Generate pseudo-data for the NC reduced cross-sections assuming **NNPDF3.1 NNLO+NLLx as central value** (``truth'').

- By construction, $\chi^2/N_{dat} \approxeq$ **1 if NNLO+NLLx theory used**

- Add all uncertainties in quadrature (can redo including correlations)

- Identical settings as in the NNPDF3.1sx DIS-only fits. Hadronic data irrelevant to study the small-x region

- Perform fits with **various combinations of LHeC/FCC-eh pseudo-data:** LHeC only, FCC-eh only, and the two experiments at the same time ….

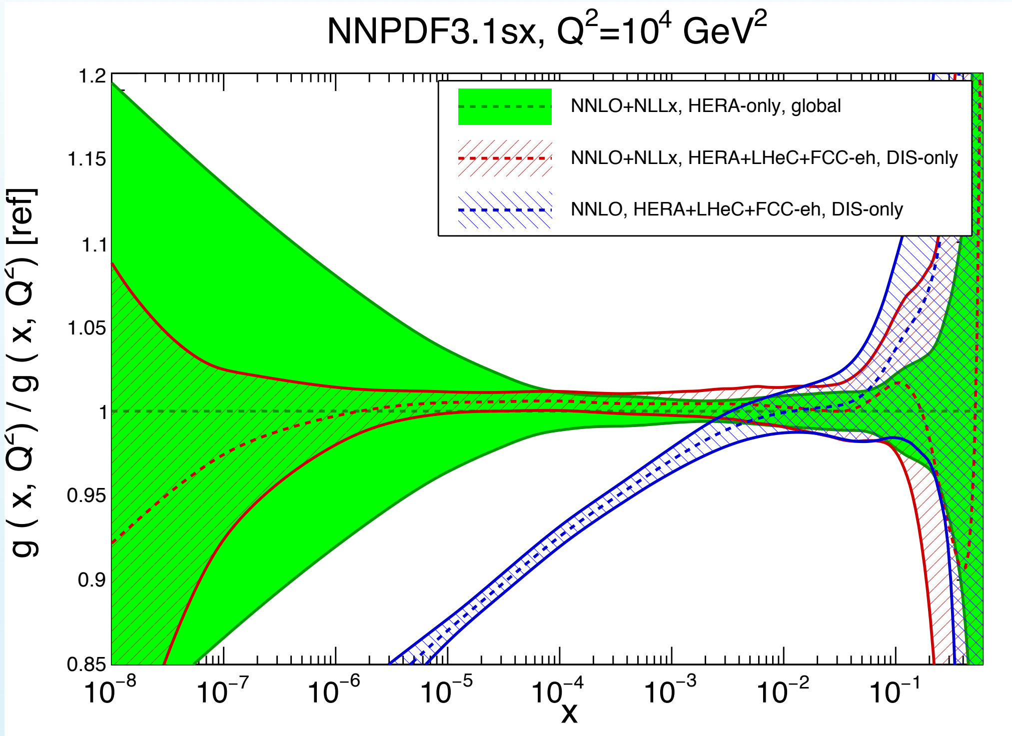
- Redo same statistical tests than in the NNPDF3.1sx paper

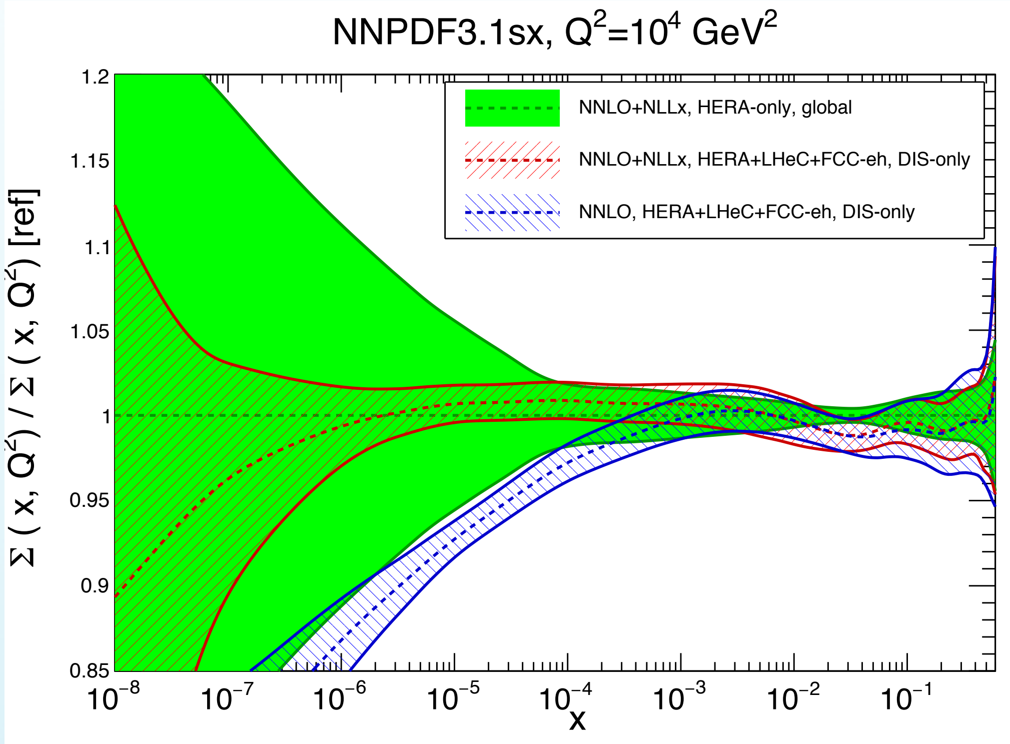
- Here show results of fit including **both** the LHeC and FCC-eh pseudo-data. Fits with other dataset combinations also available

PDF uncertainty reduction at small-x

First of all compare results when ``**correct" NNLO+NNLx theory is used in the fit**

That is, same theory as used to generate the central values of the pseudo-data



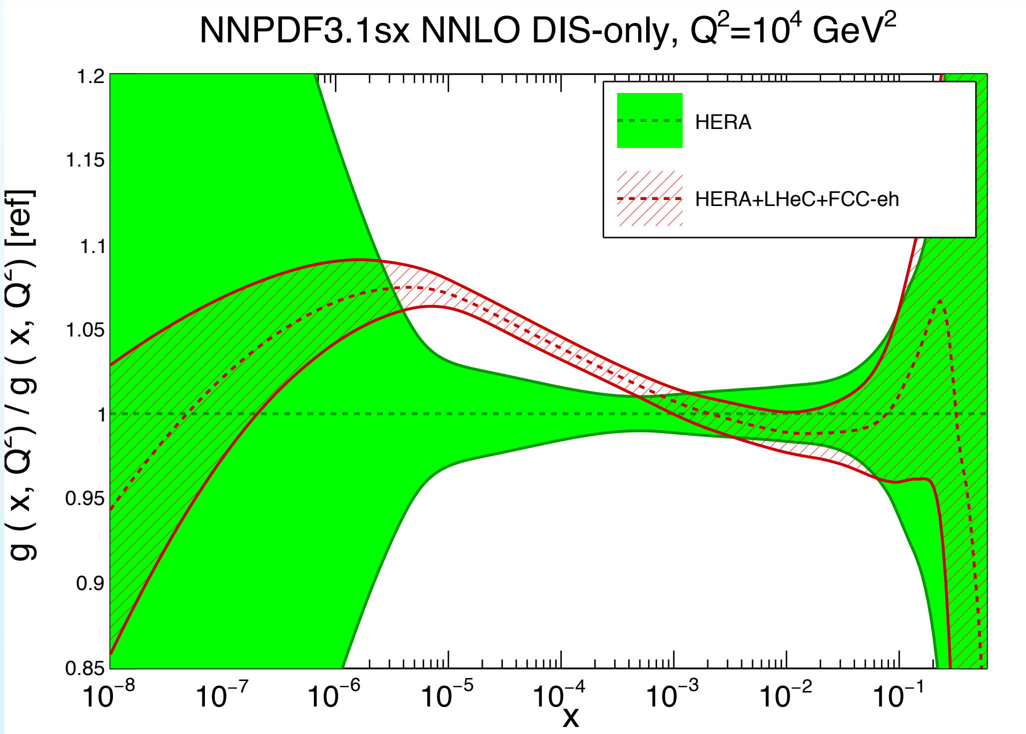


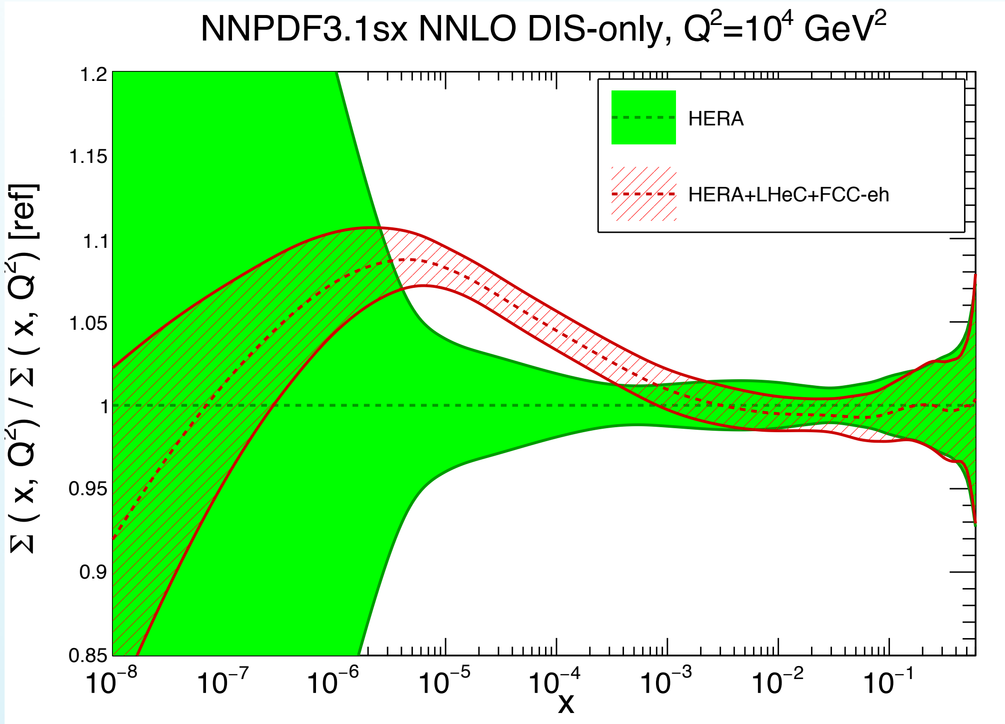
The PDF uncertainties on the gluon and singlet are reduced **down to a few percent even for $x \approx 10^{-7}$**

The gluon PDF is **extremely different** if the ``wrong" theory (NNLO) is used in the fit (difference with the ``truth" at the level of several sigmas in units of the PDF uncertainty)

BFKL resummation at the LHeC

Then compare the results when the **"wrong" theory (NNLO)** is used in the first





Marked distortion on the central values of both the gluon and singlet, arising from the inconsistency between the theories used in the fit and to generate the pseudo-data

Fit quality

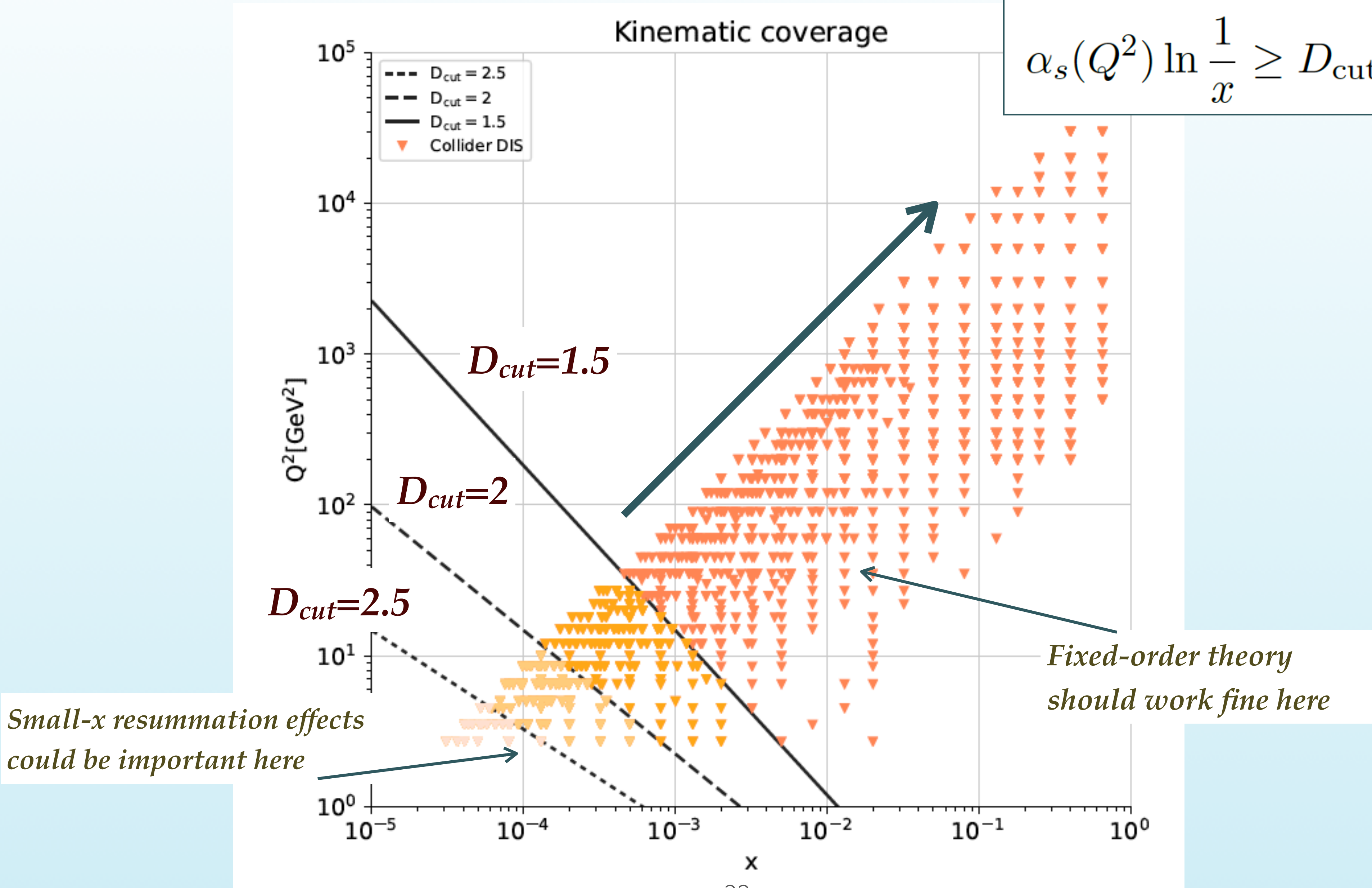
	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ NNLO	NNLO+NLLx	$\Delta\chi^2$
HERA I+II incl. NC	922	1.22	1.07	-138
LHeC 7 TeV + 60 GeV NC incl.	148	1.71	1.22	-73
FCC-eh 50 TeV + 60 GeV NC incl.	98	2.72	1.34	-135
Total	**1168**	**1.407**	**1.110**	**-346**

- It is **not possible to satisfactory fit the LHeC/FCC-eh pseudo-data** on inclusive cross-sections using NNLO theory assuming that NNLO+NLLx theory is the ``truth''
- The more marked differences are observed for the FCC-eh pseudo-data
- Makes possible **detailed studies of BFKL dynamics** already at the inclusive cross-section level

PDFs with small-x resummation

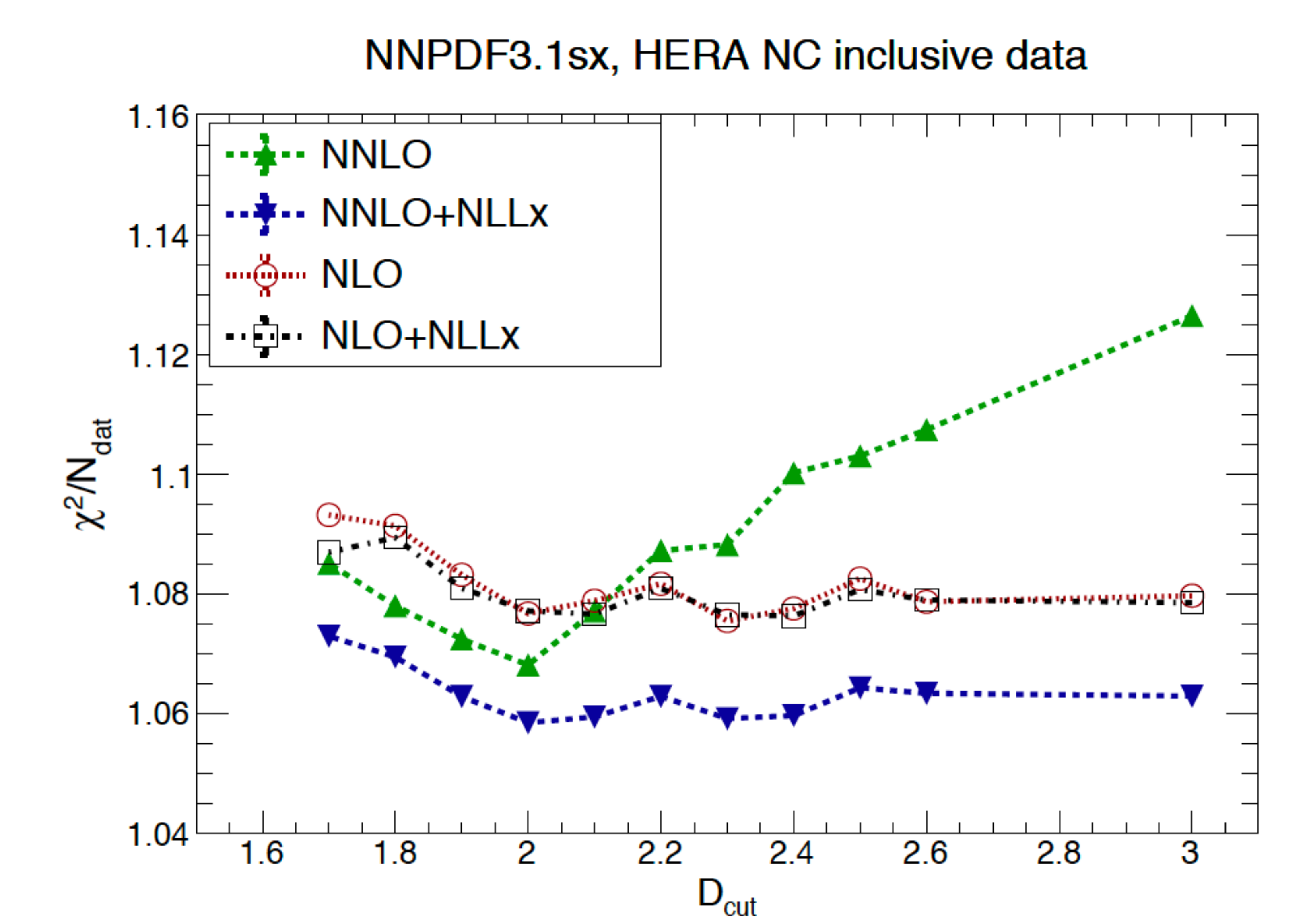
In order to assess the impact of small-x resummation for the description of the small-x and Q^2 HERA data, compute the χ^2 **removing data points in the region where resummation effects are expected**

$$\alpha_s(Q^2)\ln\frac{1}{x} \geq D_{\mathrm{cut}}$$



BFKL resummation at HERA

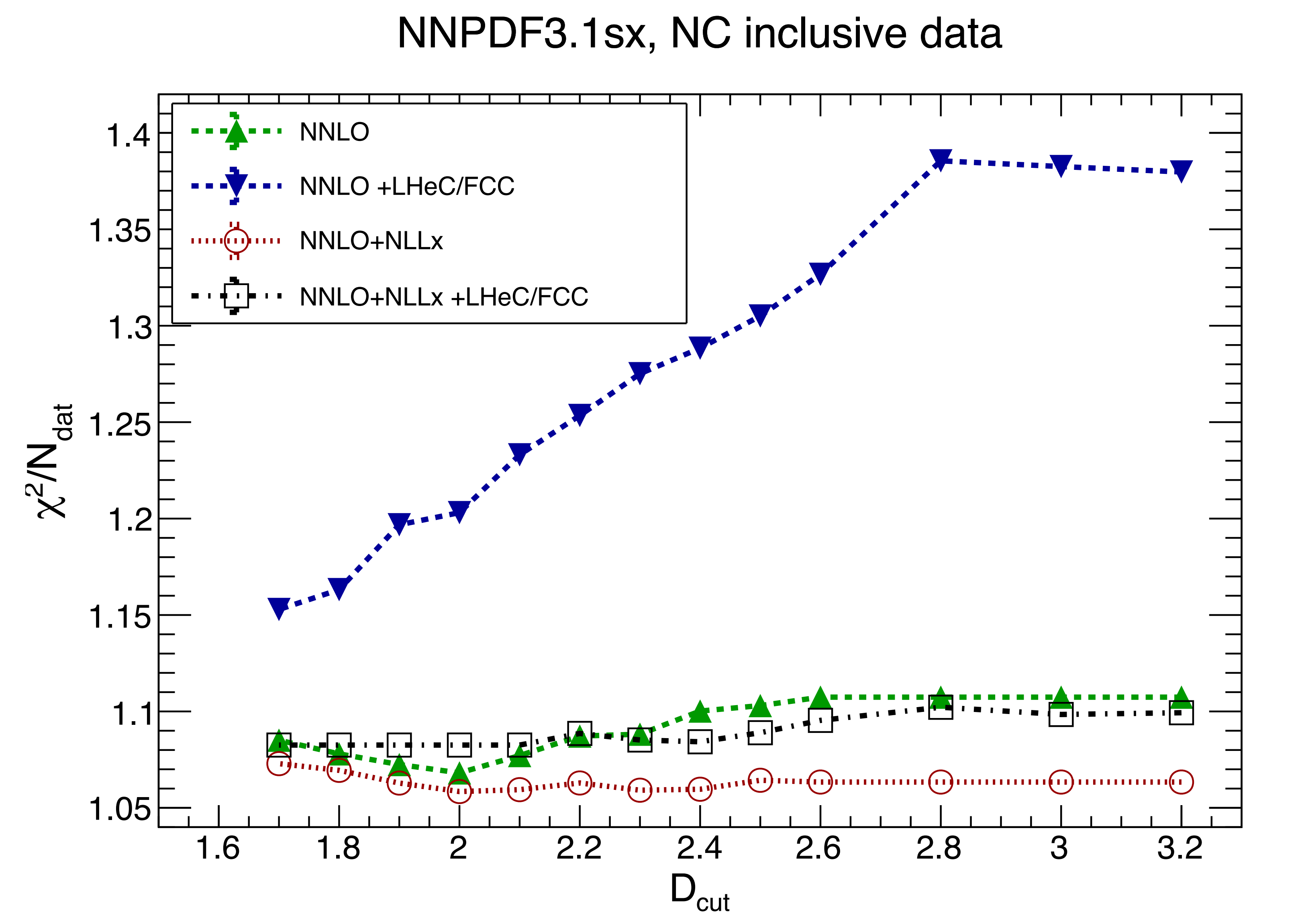
At HERA we have a **subtle but identifiable trend**: NNLO fits degrade as we include more small-x and small-Q data, NNLO+NLLx good fit quality in all kinematic plane



BFKL resummation at the LHeC

Same qualitative trend when including LHeC/FCC-eh pseudo-data

Much more marked at the quantitative level: **increased statistical significance**



BFKL dynamics at the LHeC

- **NNLO+NLL*x* theory** improves the perturbative expansion at small-*x*, curing the χ^2 instability, and allows a better description of the **inclusive and charm HERA data**

- **NNLO fits not affected:** medium and large-x behaviour of the PDFs unaffected by theory used to include the small-x HERA data in the fit

- NNPDF3.1sx fits with LHeC/FCC-eh pseudo-data exhibit the same qualitative trend as the HERA data (by construction!) but with a **greatly increased statistical significance**

- LHeC/FCC-eh pseudo-data **reduce the PDF errors at small-*x*** down to few percent at **$x \approx 10^{-7}$**