Discovering ``*new physics*" within QCD: evidence for BFKL dynamics in HERA data

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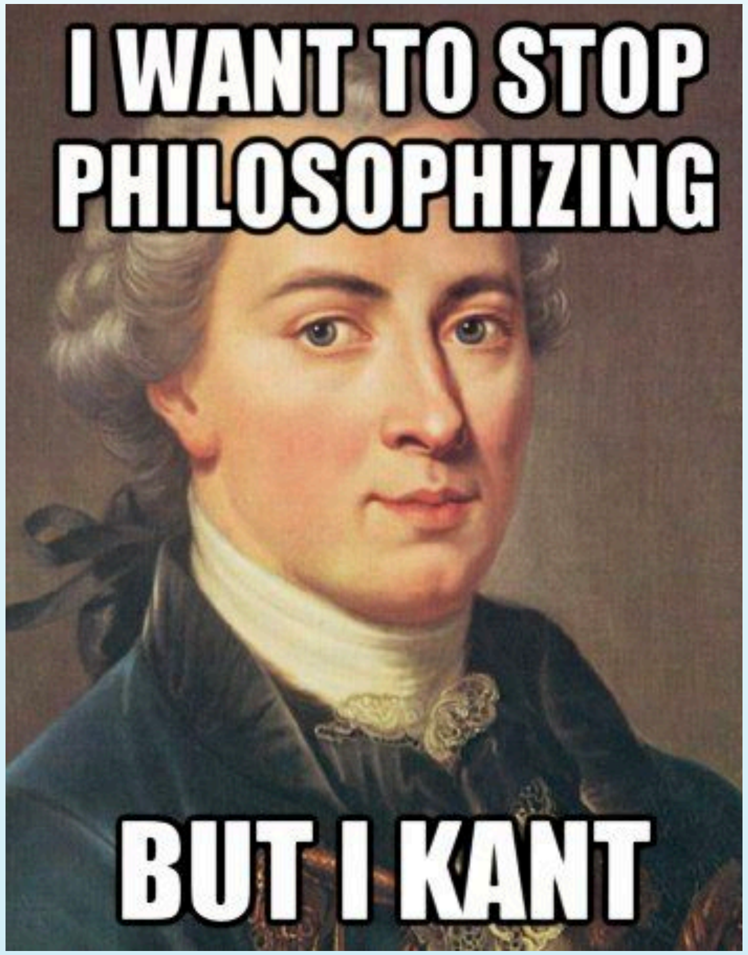
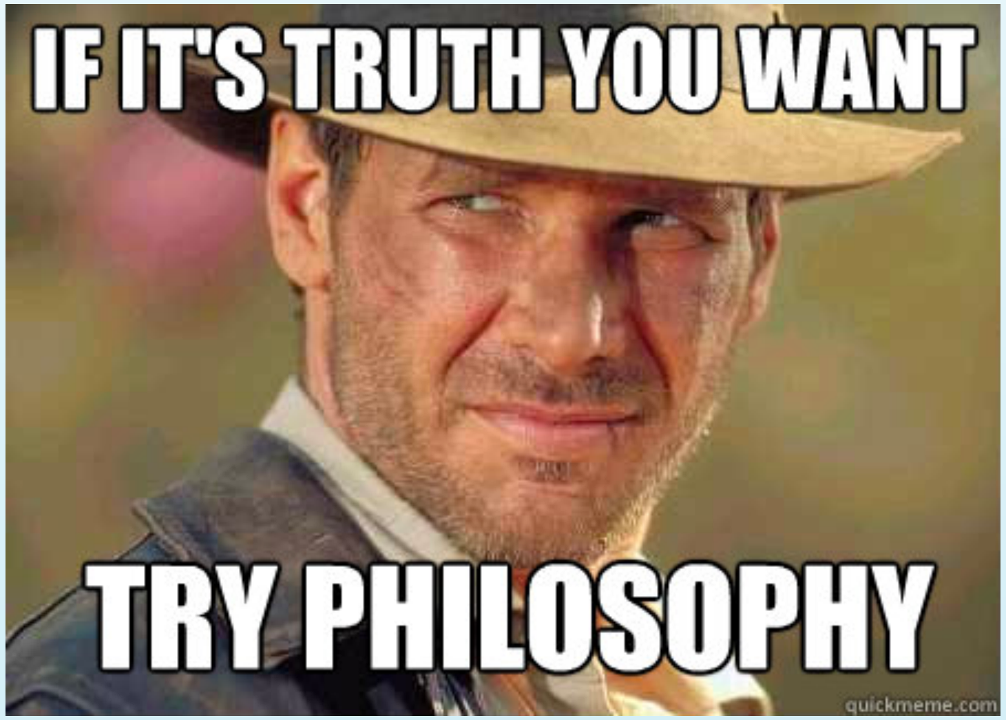
Prologue:
a short philosophical digression





What can we discover?

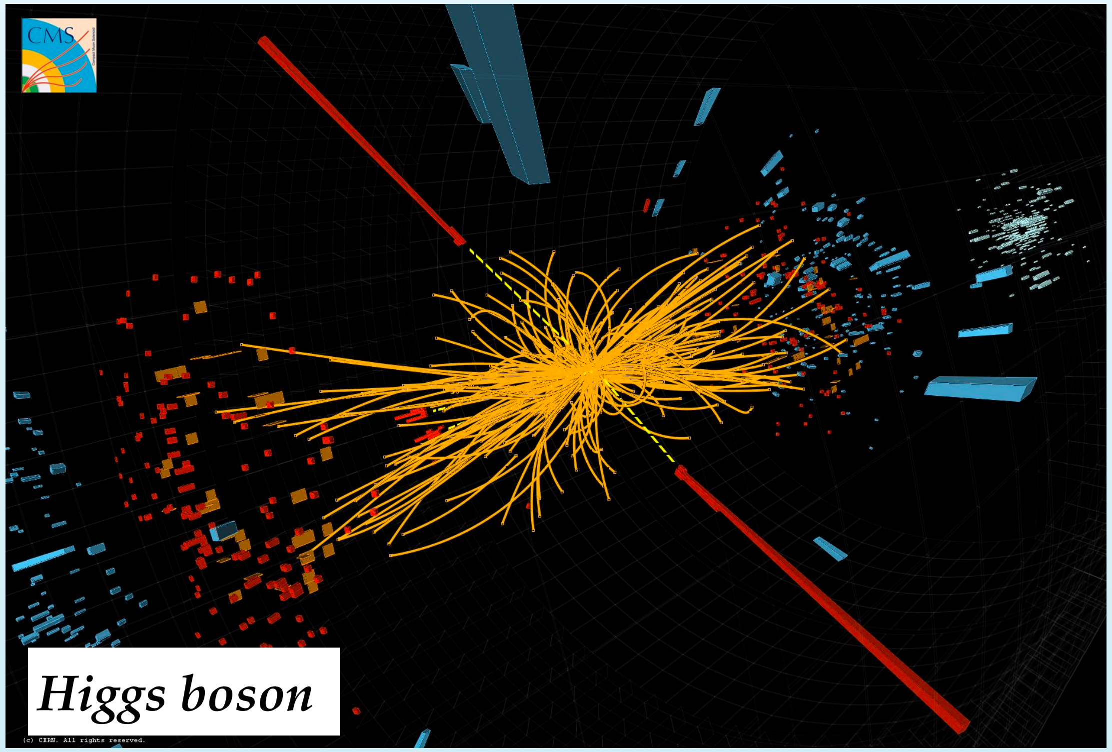
Discovering something **new** or **unexpected** is one of the main thrills of the scientific adventure (as we like to emphasise specially when writing grant applications)

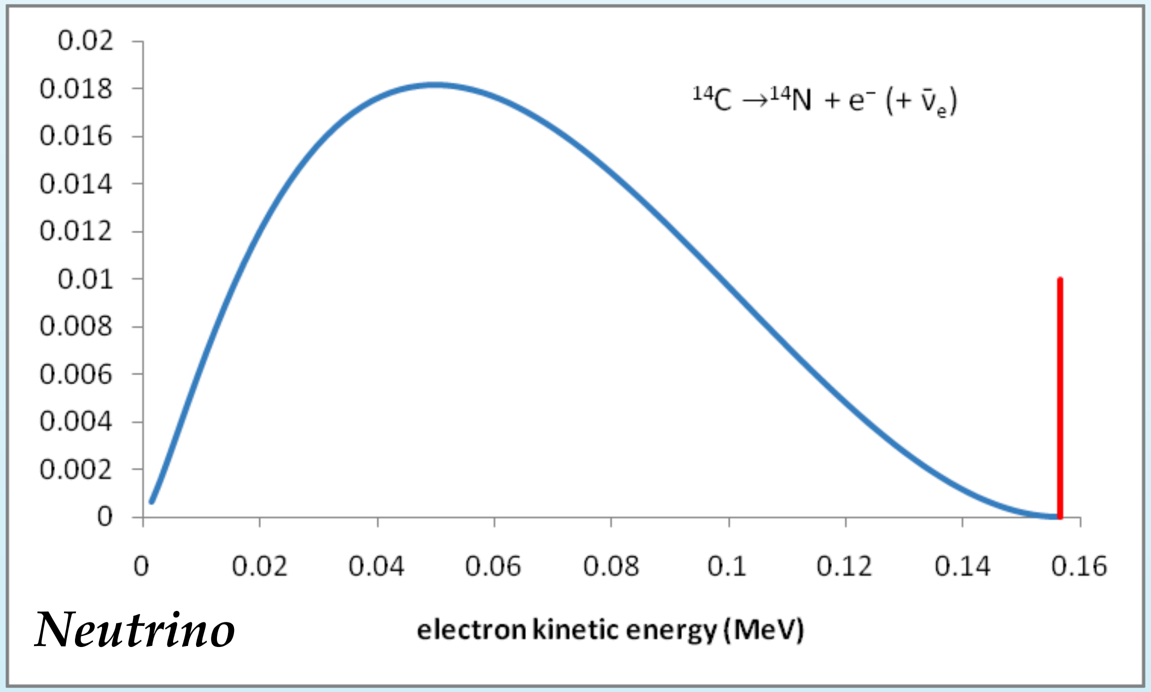
People imply different things when talking about a **discovery** or **new physics,** *i.e.*

A new fundamental particle

i) Expected: confirms pre-existing theory

ii) Unexpected: leads to development of new theory





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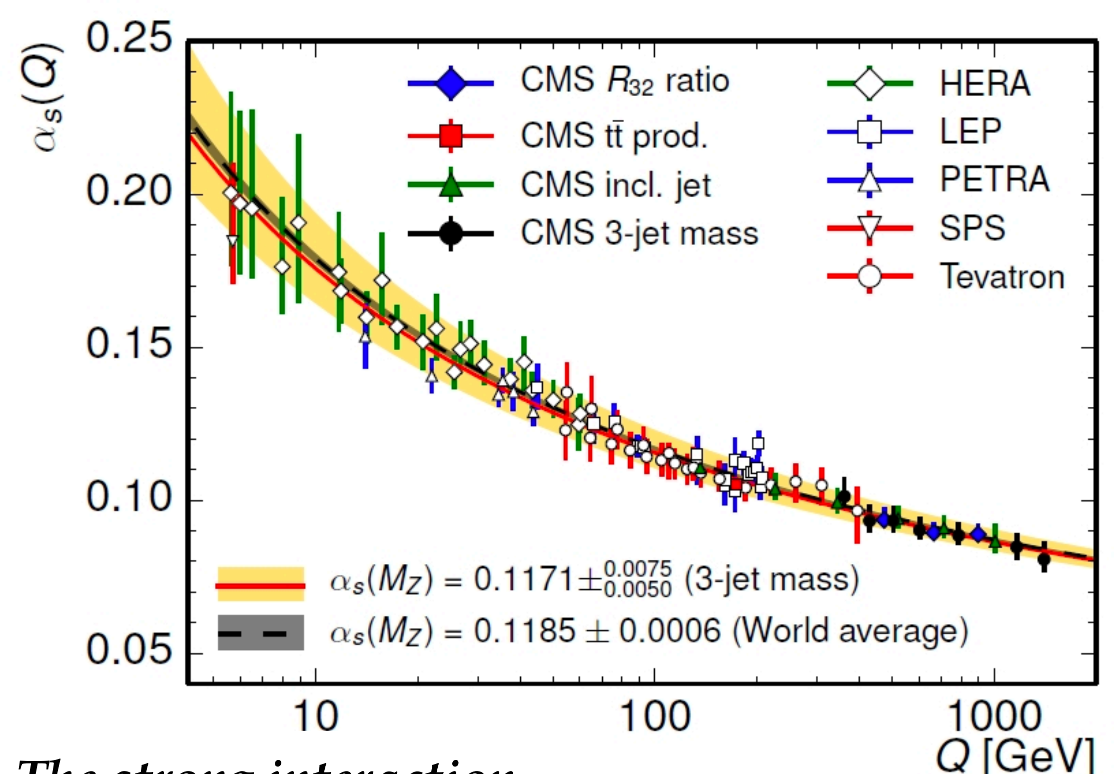
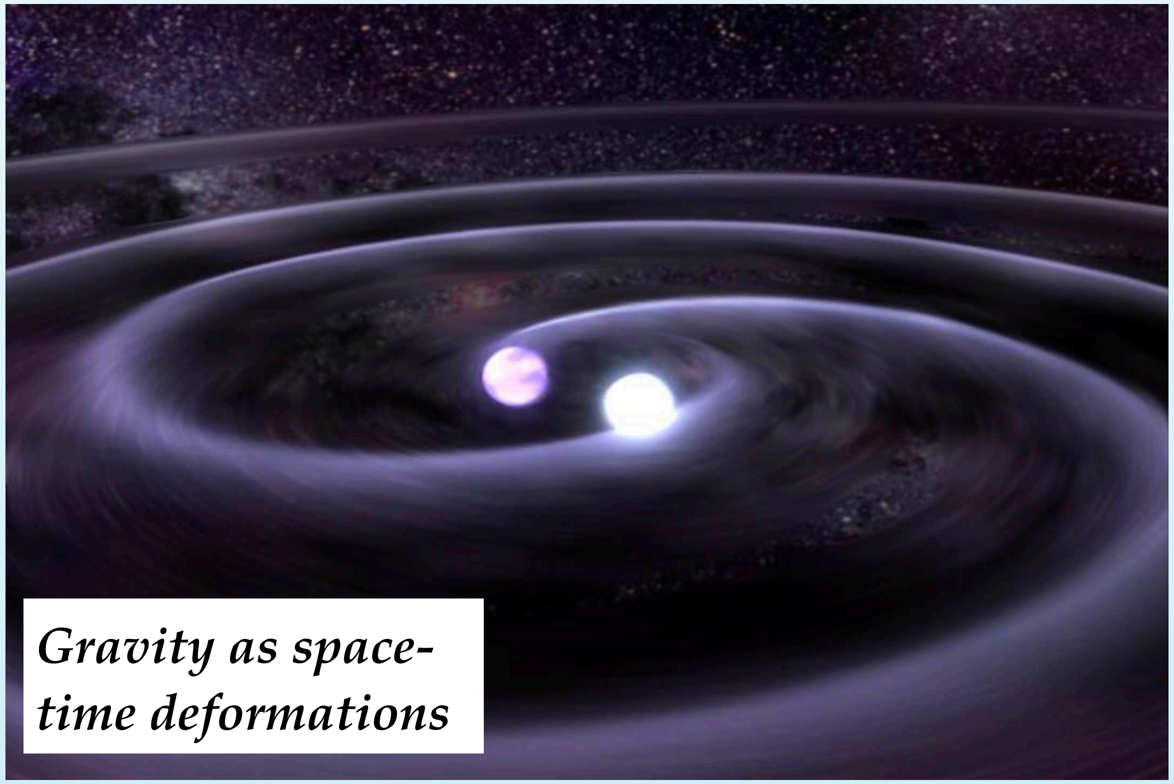
A new understanding of a fundamental interaction

i) Based on known mathematical language

ii) Requires brand-new mathematical language



The strong interaction as a non-abelian QFT



Gravity as space-time deformations

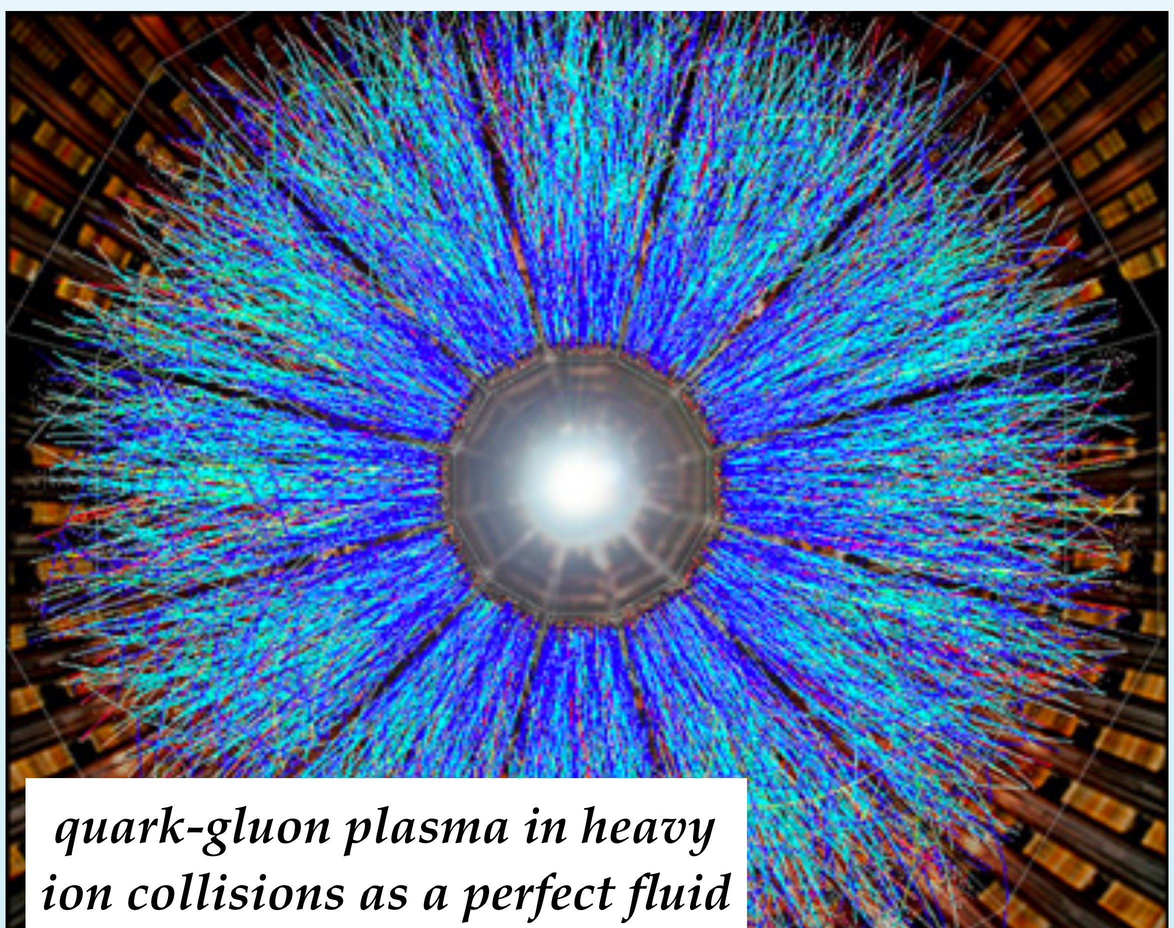
What can we discover?

Except one adopts a extreme **reductionist** point of view, one can meaningfully talk of **discovery** and **new physics** in many other contexts, *i.e.*

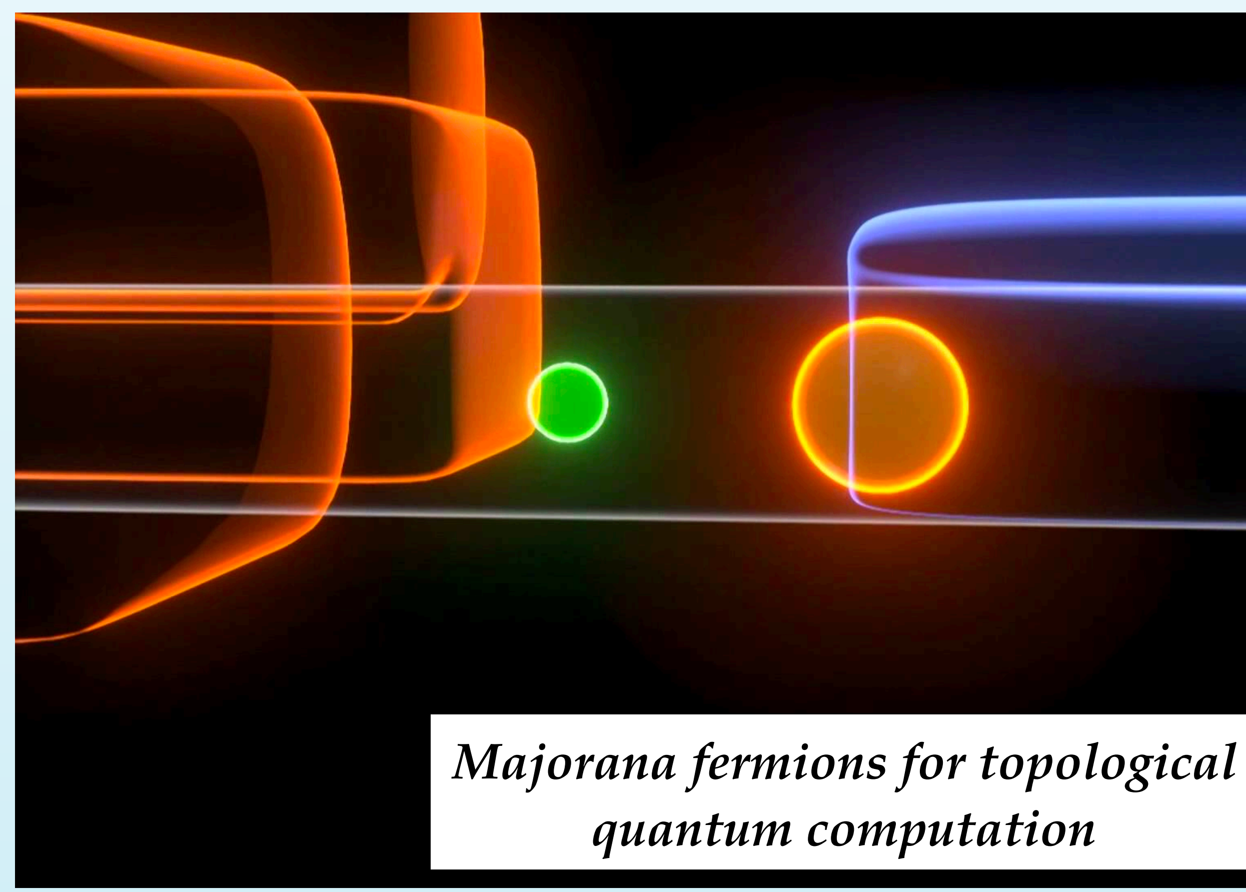
Unexpected emergent phenomena within a known theory

i) Driven by experiment, followed by theory

ii) Driven by theory, confirmed by experiment



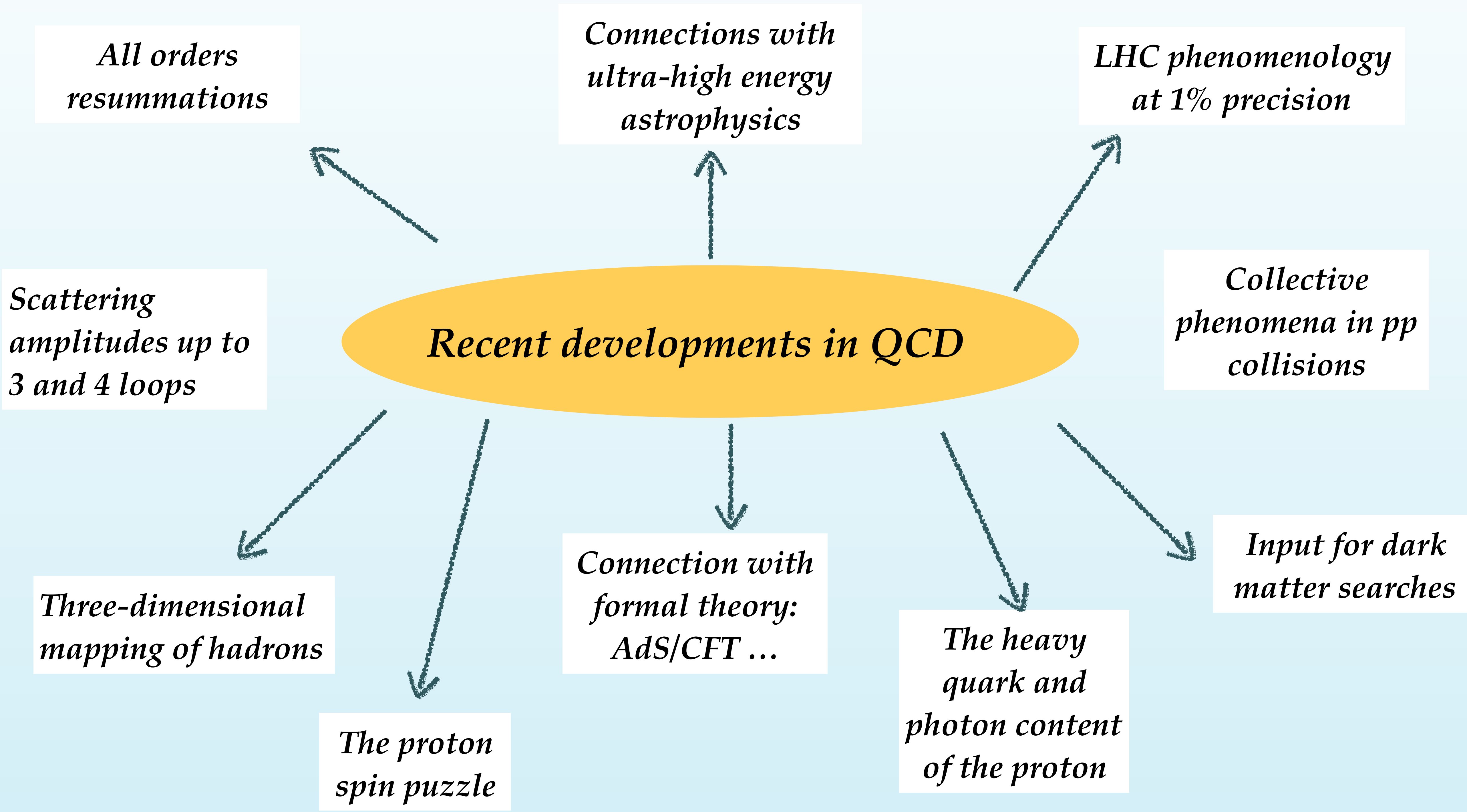
quark-gluon plasma in heavy ion collisions as a perfect fluid



Majorana fermions for topological quantum computation

Pushing the boundaries of QCD

Quantum Chromodynamics is a **extremely rich and complex theory** which keeps fascinating us >40 years after its mathematical formulation as a non-abelian QFT



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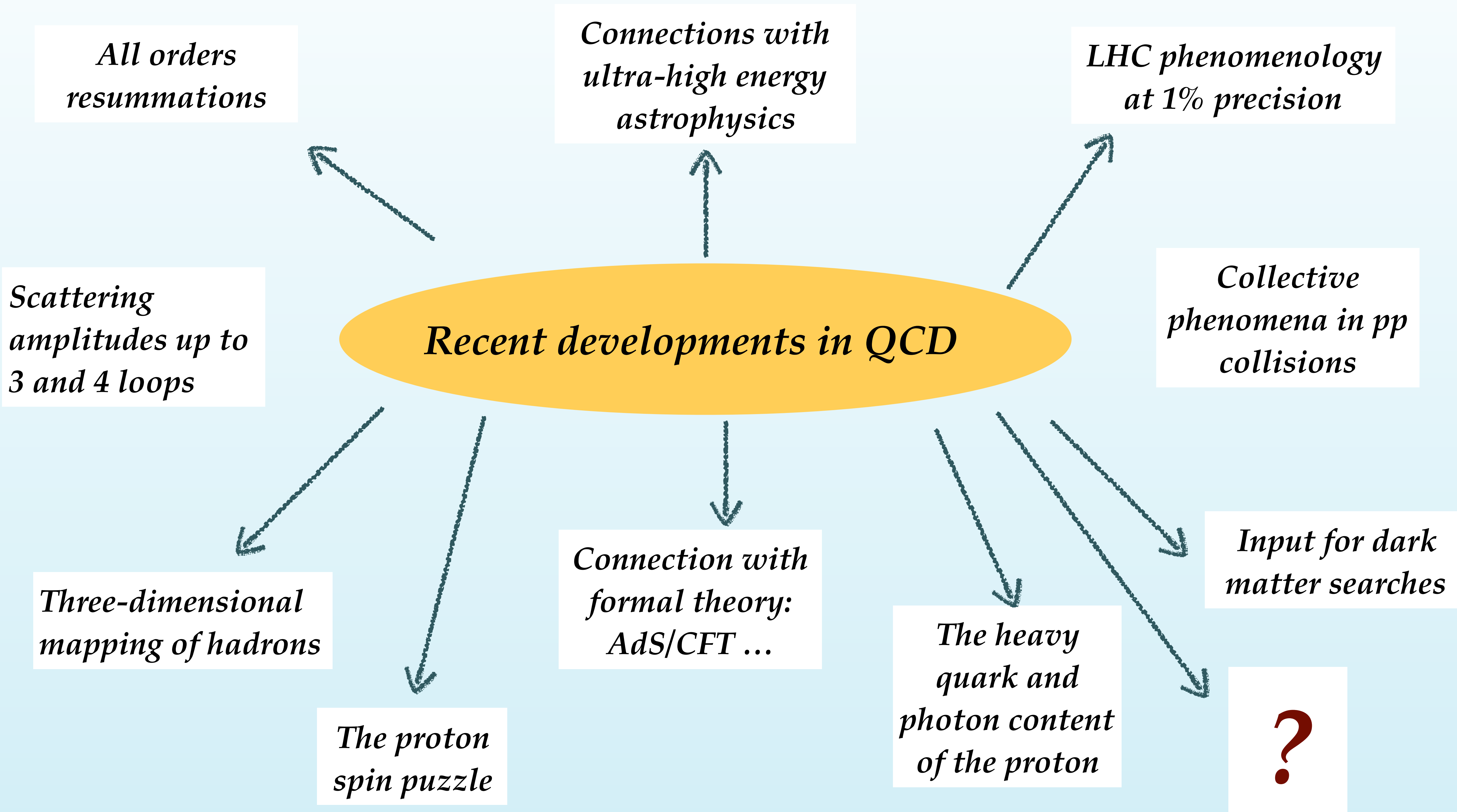
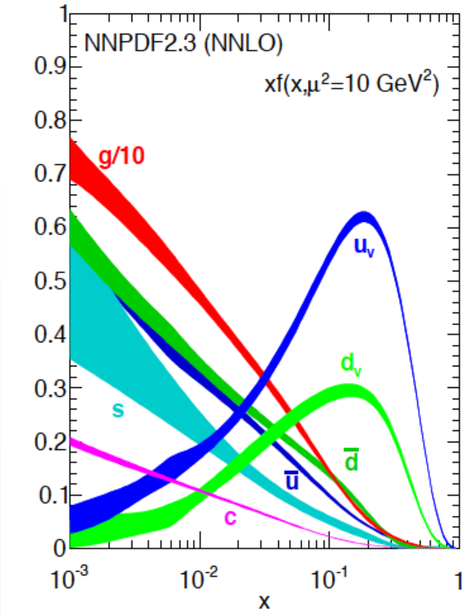
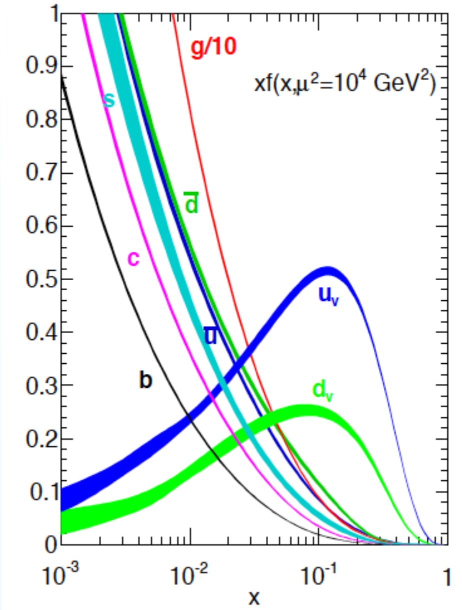
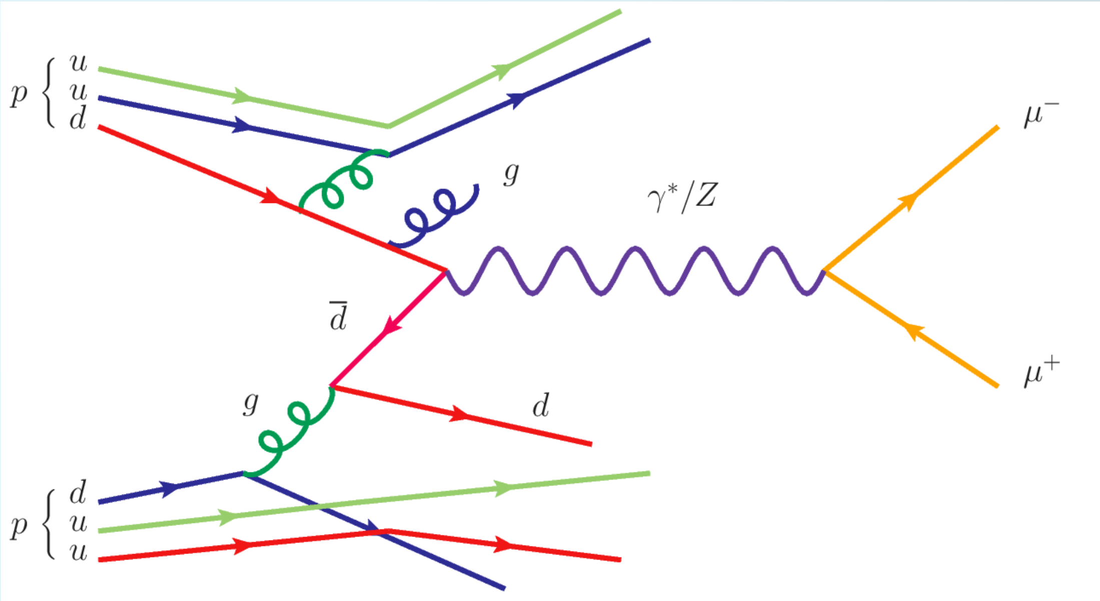




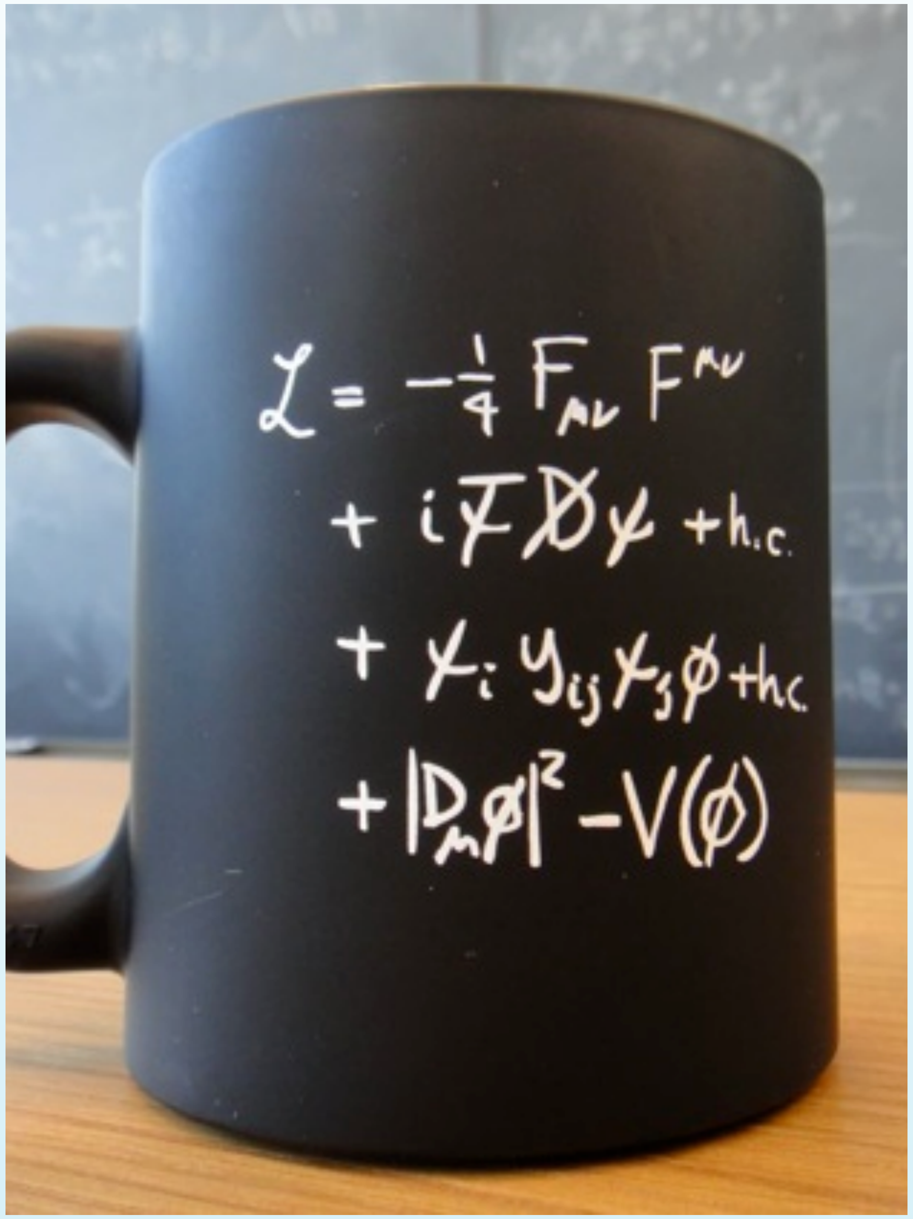


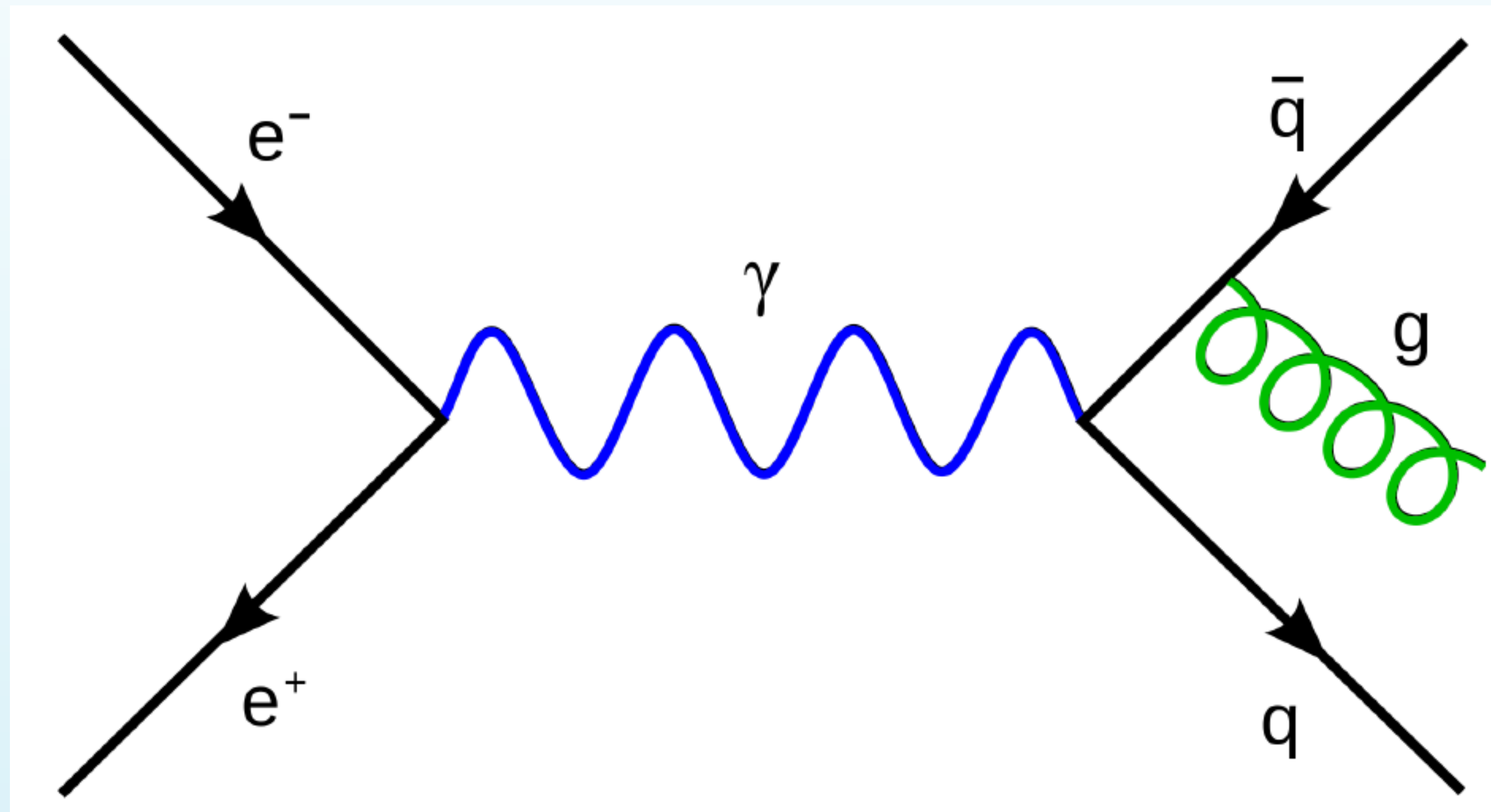
A crash course on parton distributions



QCD in hadronic collisions

In high-energy **lepton colliders**, such as the **Large Electron-Positron Collider** (LEP) at CERN, the collisions involve **elementary particles** without substructure

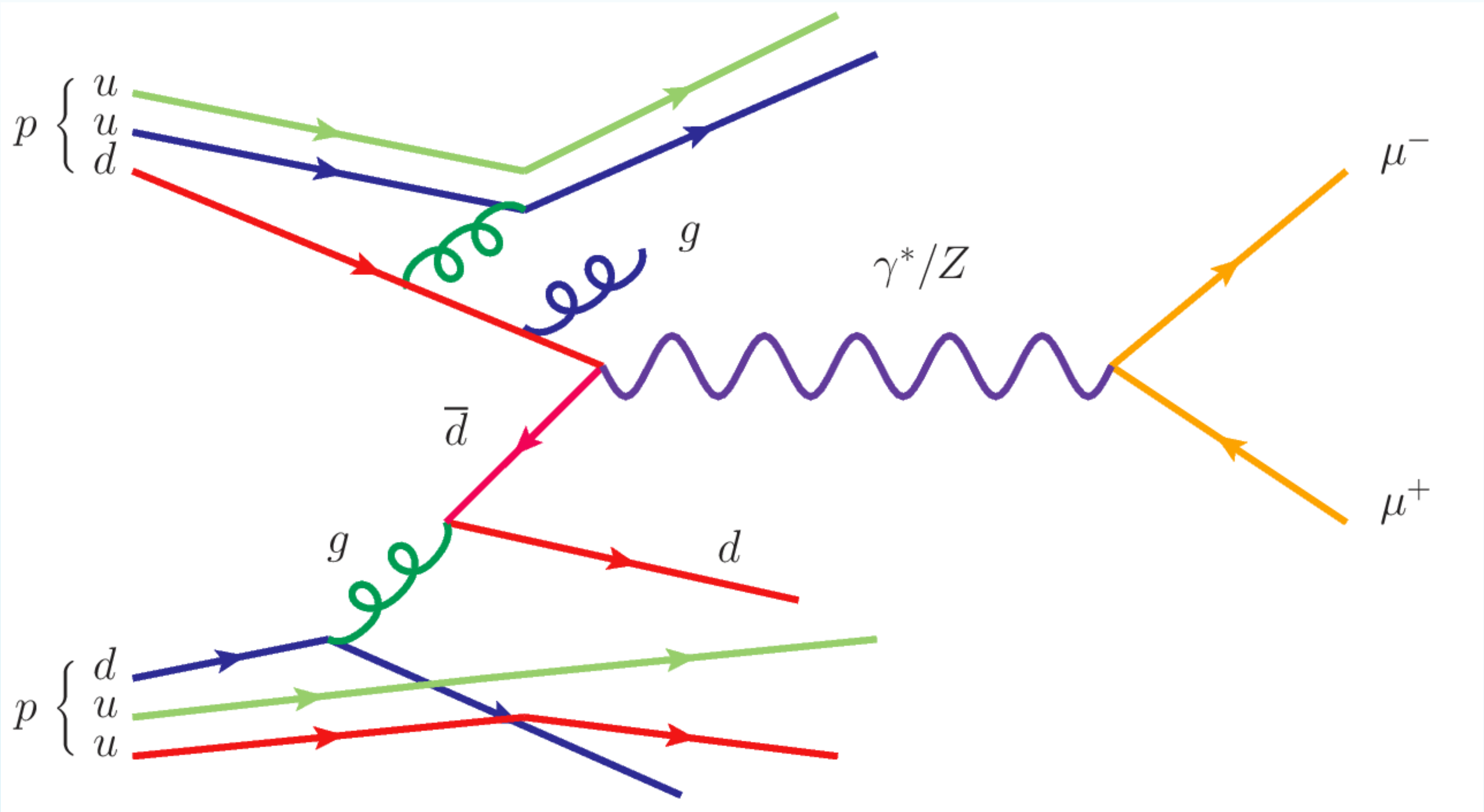




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

QCD in hadronic collisions

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with internal structure (quarks and gluons)



QCD in hadronic collisions

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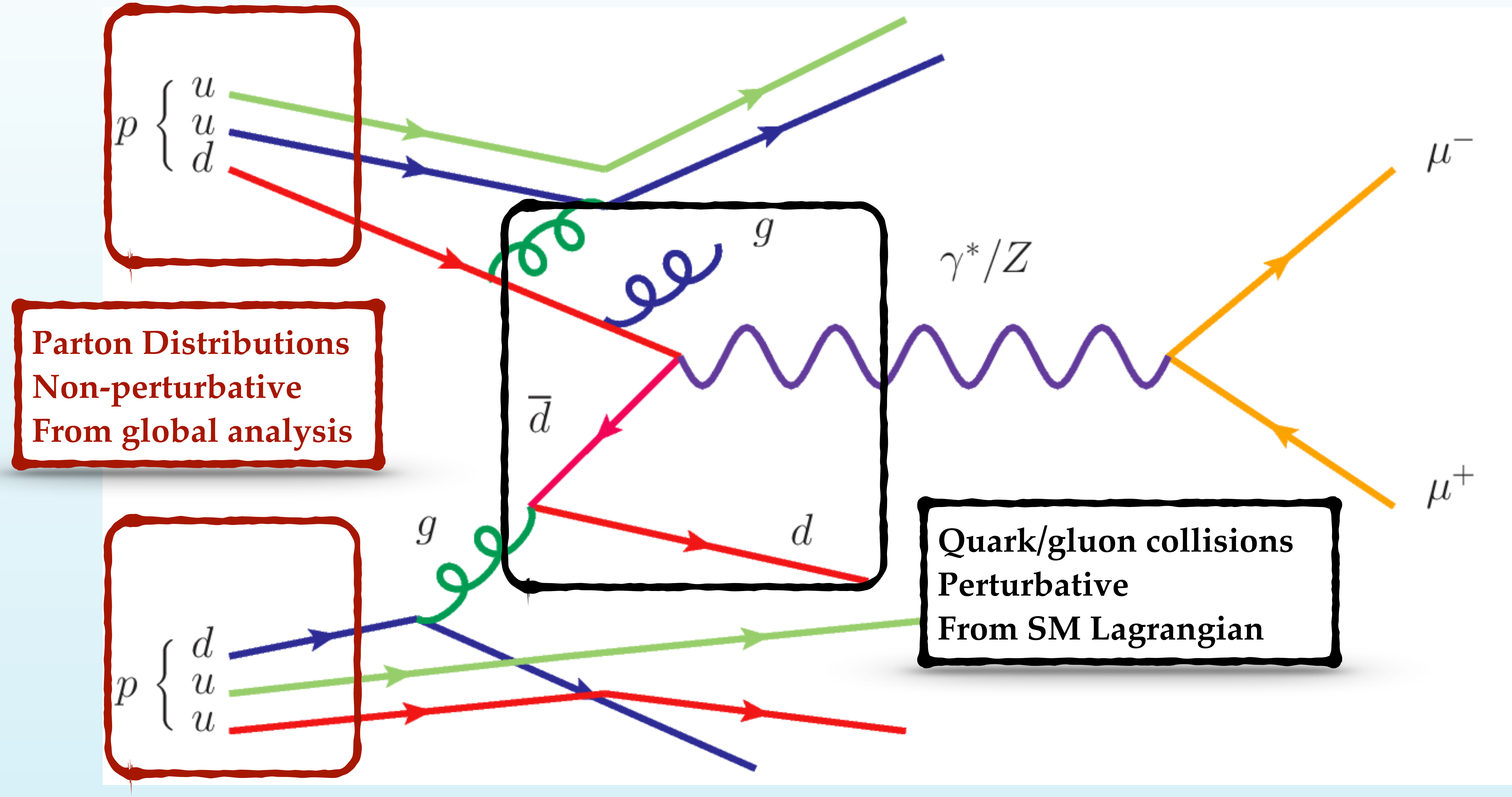


Calculations of **cross-sections** in hadron collisions require the combination of **perturbative, quark/gluon-initiated processes**, and **non-perturbative, parton distributions**, information

Parton Distributions

Distribution of energy that **quarks and gluons carry inside proton** quantified by **Parton Distributions**

$$g(x, Q)$$

Q: **Energy of the quark/gluon collision**
Inverse of the resolution length

$g(x,Q)$: **Probability** of **finding a gluon inside a proton**, carrying a fraction x of the proton momentum, when probed with energy Q

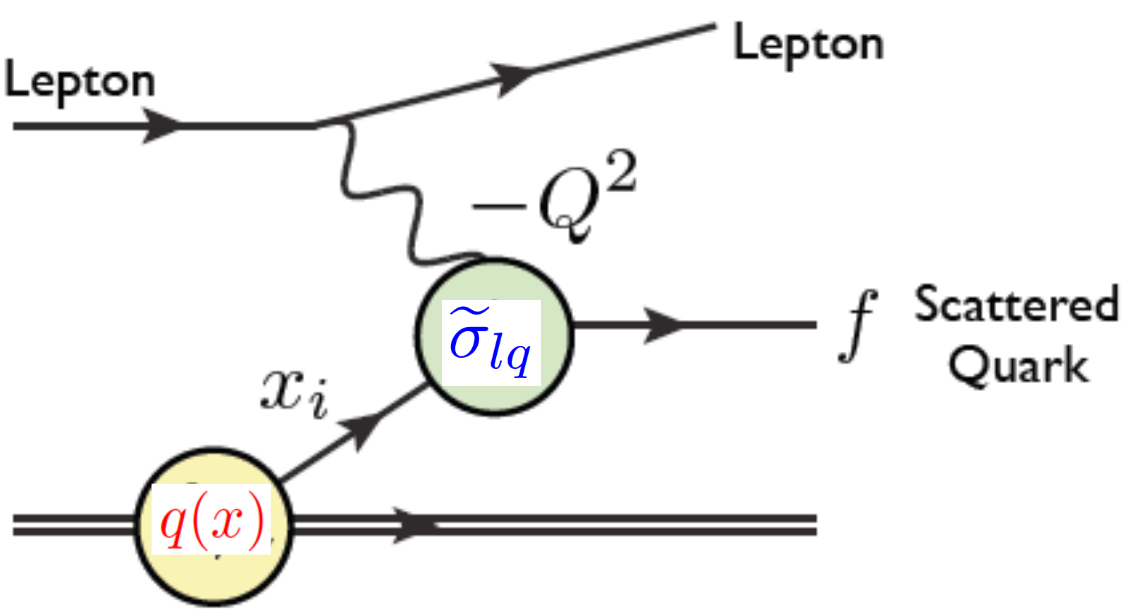
x: **Fraction of the proton's momentum**

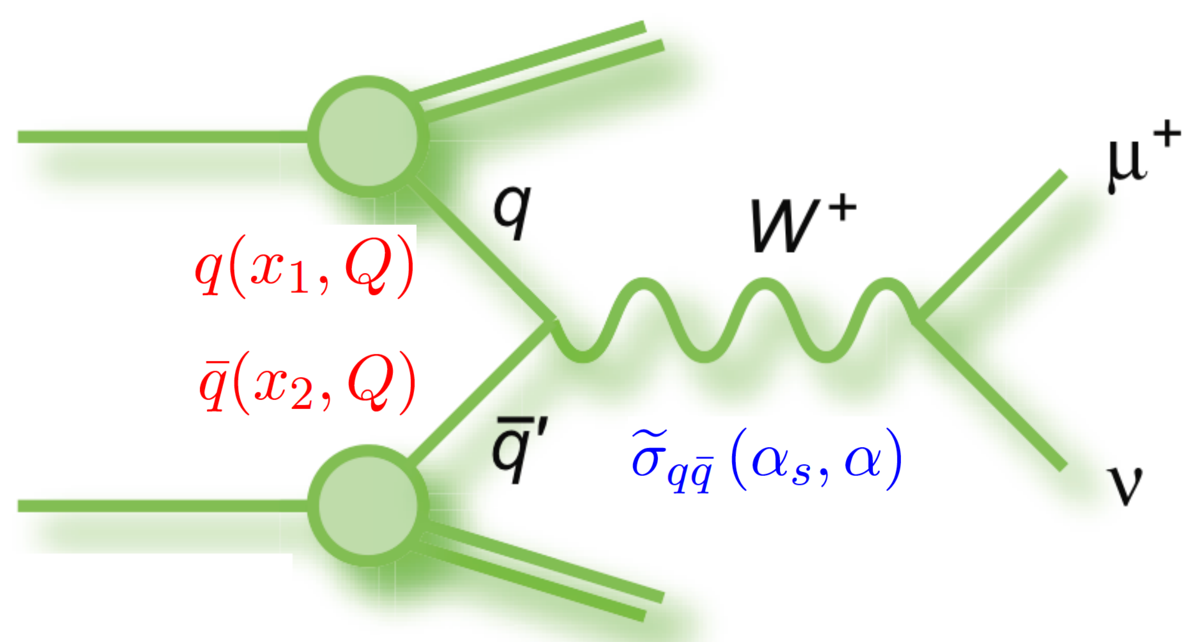
PDFs *determined by* ***non-perturbative QCD dynamics***

Extract from experimental data within a ***global analysis***

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}(\alpha_s, \alpha) \otimes q(x, Q)$$

$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}(\alpha_s, \alpha) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$





Extract PDFs from lepton-proton collisions

Use PDFs to predict proton-proton cross-sections

Parton Distributions

Distribution of energy that **quarks and gluons carry inside proton** quantified by **Parton Distributions**

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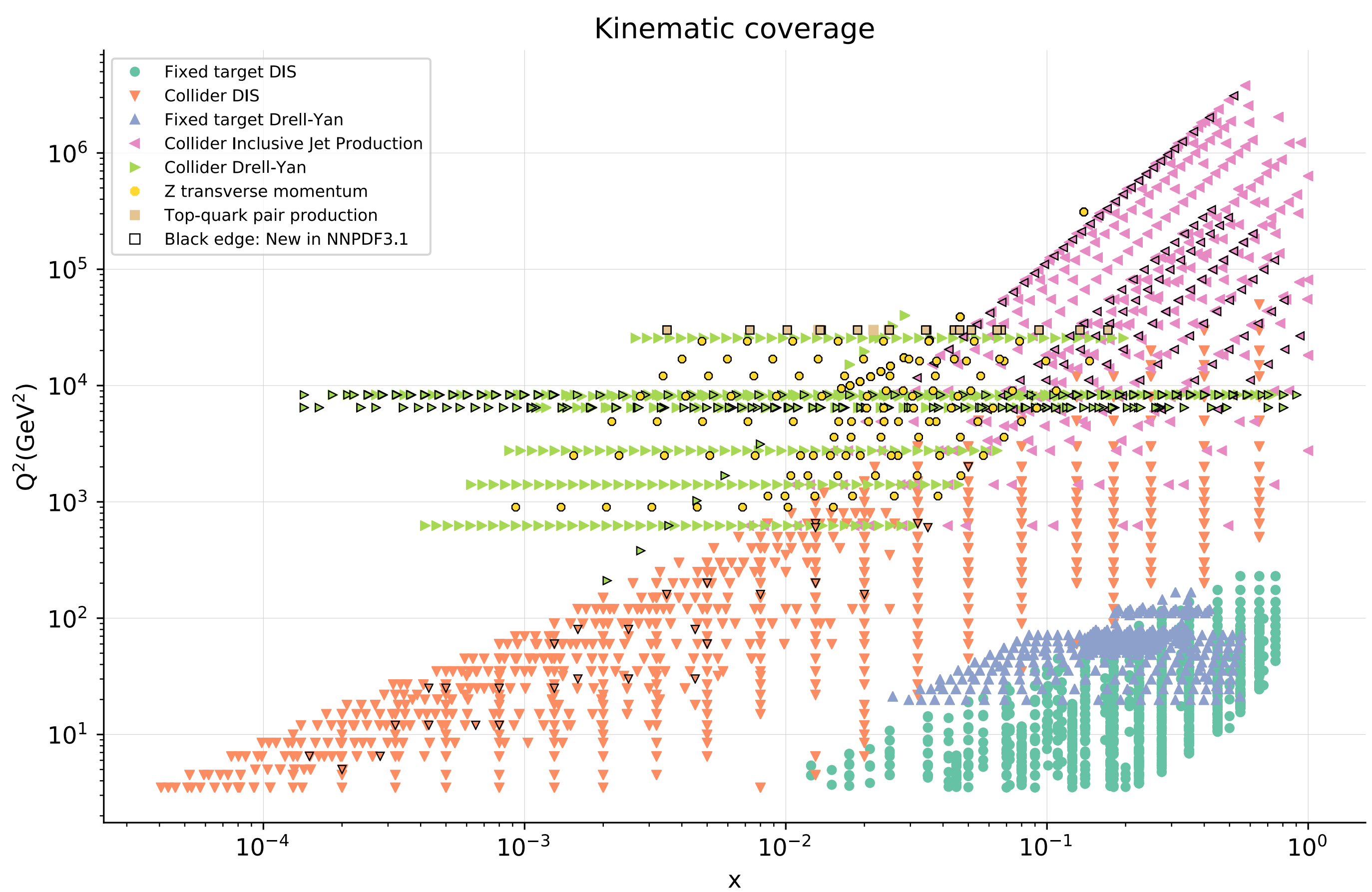
PDFs** determined by **non-perturbative QCD dynamics

*Extract from experimental data within a **global analysis***

Highly non-trivial validation of the **QCD factorisation framework**:

- Including **O(5000) data** points ,
- from **O(40) experiments**,
- some of them with ≈**1%** **errors**,

yet still $\chi^2/N_{dat} \approx 1$!



The global PDF analysis

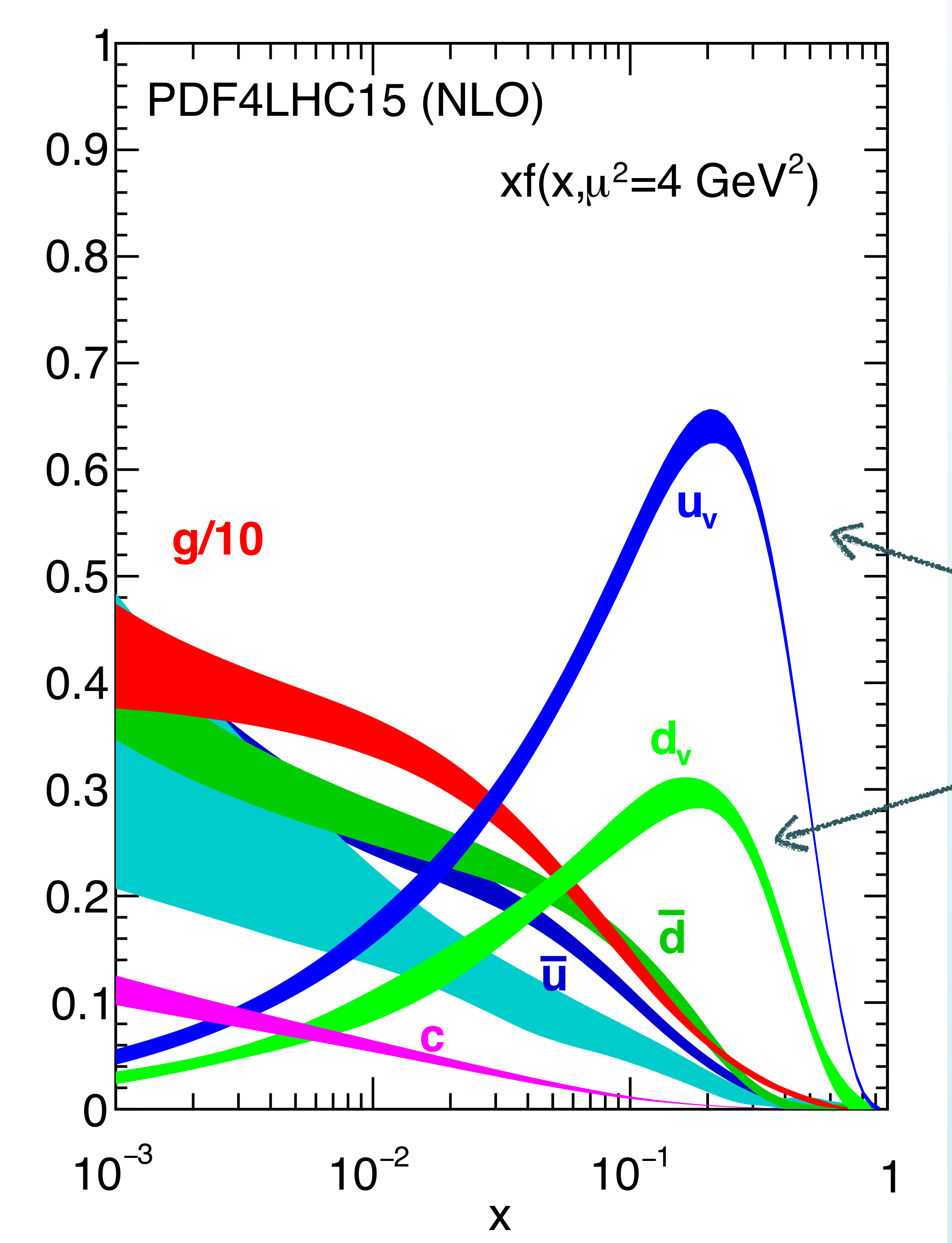
- Combine **state-of-the-art theory calculations,** the **constraints from PDF-sensitive measurements** from different processes and colliders, and a **statistically robust fitting methodology**
- **Extract Parton Distributions** at hadronic scales of **a few GeV,** where non-perturbative QCD sets in

Gluon PDF

Dominates small-x region

Sea PDFs

Combination of intrinsic and perturbative input



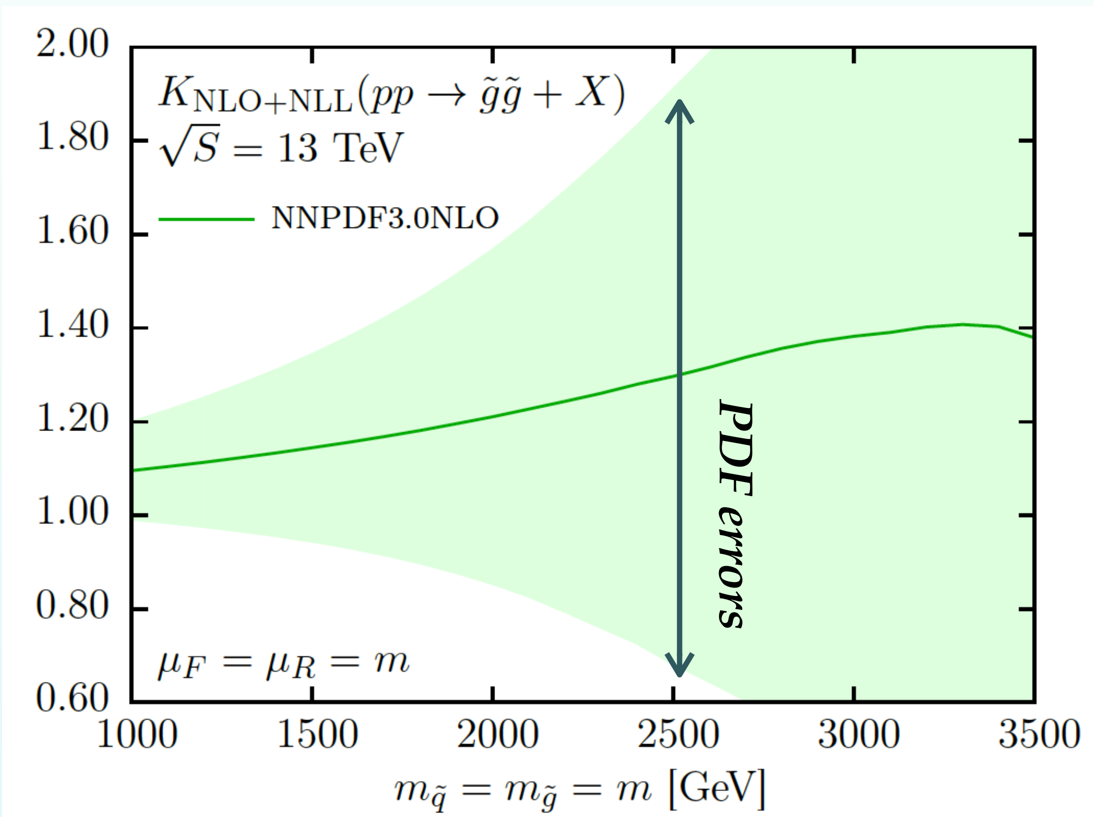
Valence PDFs

Normalisation fixed by valence sum rules

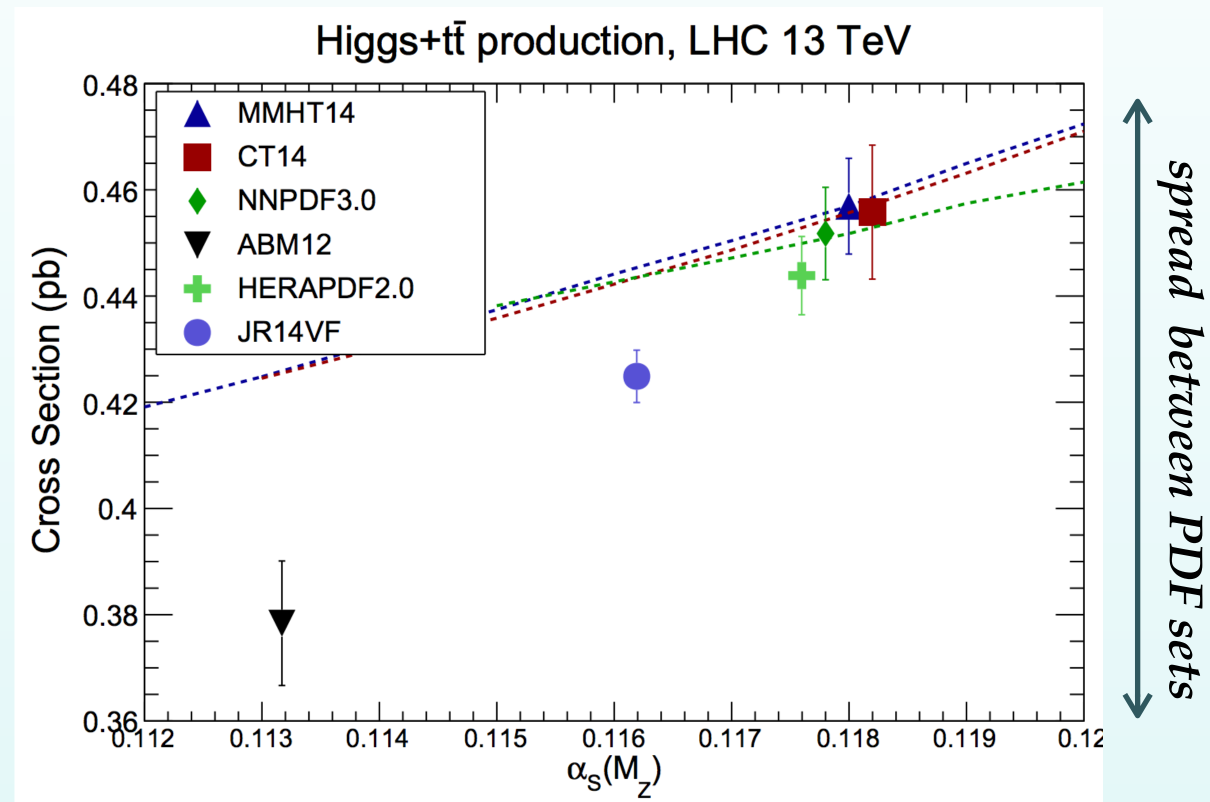
Why precision PDFs?

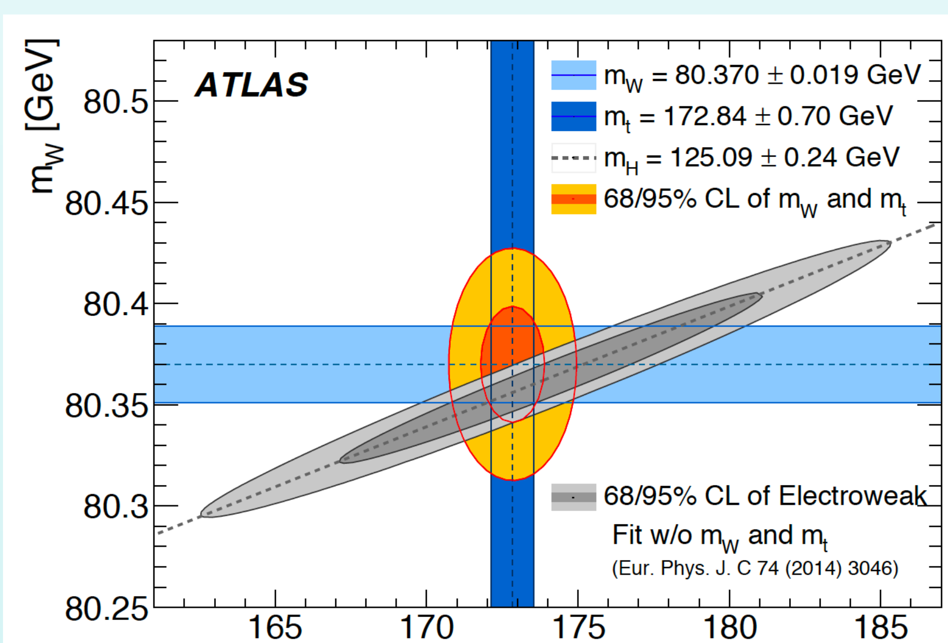
Ultimate accuracy of LHC calculations limited by **knowledge of proton structure**

heavy SUSY particle production



Higgs couplings





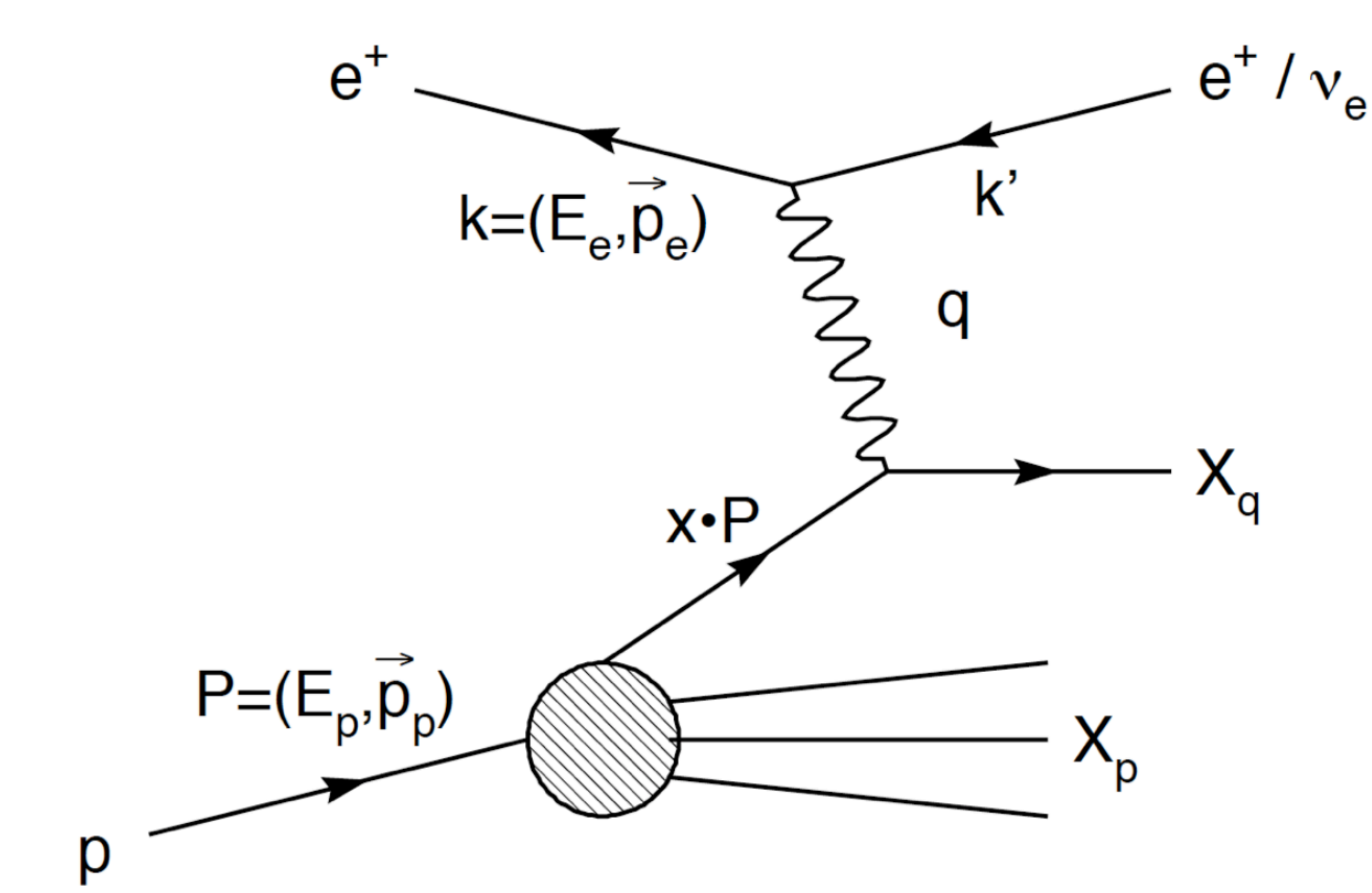
W mass determination

Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

[HL-LHC forecast]

PDF evolution

- Let us review how parton distributions acquire **scale dependence**
- Try to compute the **deep-inelastic lepton-proton scattering cross-section** at one-loop



Scale-independent PDFs

QED partonic cross-section

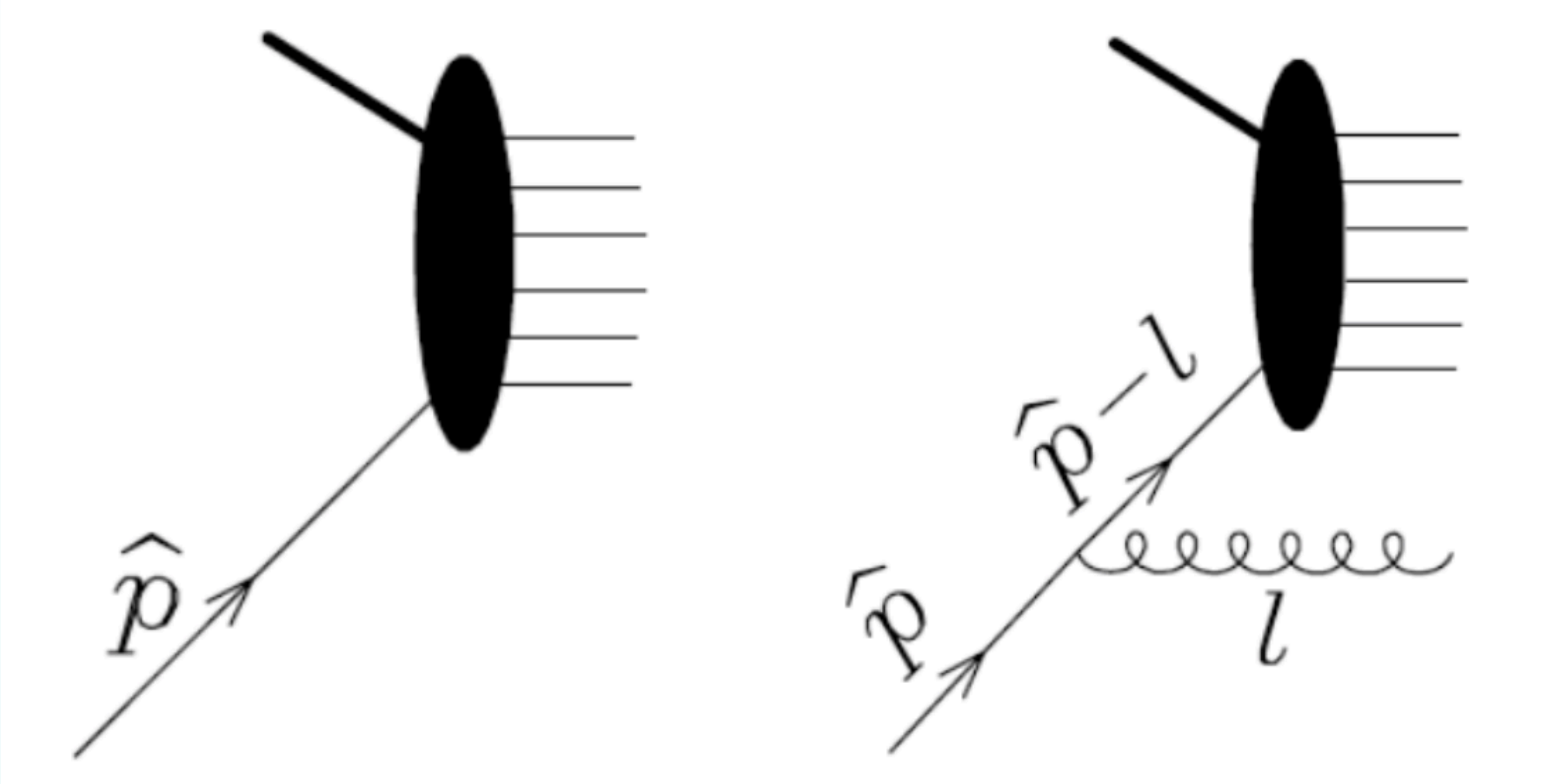
The Born cross-section is obtained via a QED calculation:

$$\frac{Q^4 x}{2\pi\alpha^2_{\rm QED}\left(1+(1-y)^2\right)}\frac{d^2\sigma^{\rm DIS}}{dx dQ^2} = F_2(x) = \sum_{\rm q,\bar{q}} \int_x^1 \frac{dz}{z} f_q(z)\widehat{\sigma}_{q\gamma^*\to X}\left(\frac{x}{z}\right)$$

PDF evolution

Now let's include QCD corrections, starting from the **real emission off the incoming quark leg**

Born *NLO corrections: real radiation*



(1-z): fraction of longitudinal momentum carried by gluon

$l_\perp$: transverse momentum carried by gluon

NLO partonic cross-section — *From real emission* — *From virtual diagrams* — *Soft singularity* — *Collinear singularity*

$$\hat{\sigma}^{(1)} = \frac{\alpha_S C_F}{2\pi} \int \left[\sigma^{(0)}(z\hat{p}) - \sigma^{(0)}(\hat{p})\right] \frac{1+z^2}{1-z} \frac{dl_\perp^2}{l_\perp^2} dz \,,$$

Collinear singularities do not cancel in the NLO partonic cross-section!

PDF evolution

- However initial-state collinear divergences are unphysical, and will be eventually **screened by infrared dynamics** such as finite quark masses and non-perturbative QCD effects
- They can be absorbed into a **redefinition of the proton's parton distributions**
- Introduction the **factorisation scale μ** that separates **low-scale from high-scale dynamics**

λ : infrared regulator

$$\hat{\sigma}^{\rm NLO} = \left(\mathbb{1} + \frac{\alpha_s C_F}{2\pi} \ln \frac{\mu^2}{\lambda^2} P_{qq}\right) \otimes \left(\mathbb{1} + \frac{\alpha_s C_F}{2\pi} \ln \frac{Q^2}{\mu^2} P_{qq}\right) \sigma^{(0)}(\hat{p})$$

Encodes IR sensitivity

no dependance on IR physics

$$\sigma^{\rm DIS}(p) = f_q\, \hat{\sigma}^{\rm NLO}(\hat{p}) \equiv \tilde{f}_q(\mu)\tilde{\sigma}(p,\mu)$$

$$\tilde{f}(\mu) \equiv f \otimes \left(\mathbb{1} + \frac{\alpha_s C_F}{2\pi} \ln \frac{\mu^2}{\lambda^2} P_{qq}\right)$$

$$\tilde{\sigma}(p,\mu) \equiv \left(\mathbb{1} + \frac{\alpha_s C_F}{2\pi} \ln \frac{Q^2}{\mu^2} P_{qq}\right) \hat{\sigma}^{(0)}(\hat{p})$$

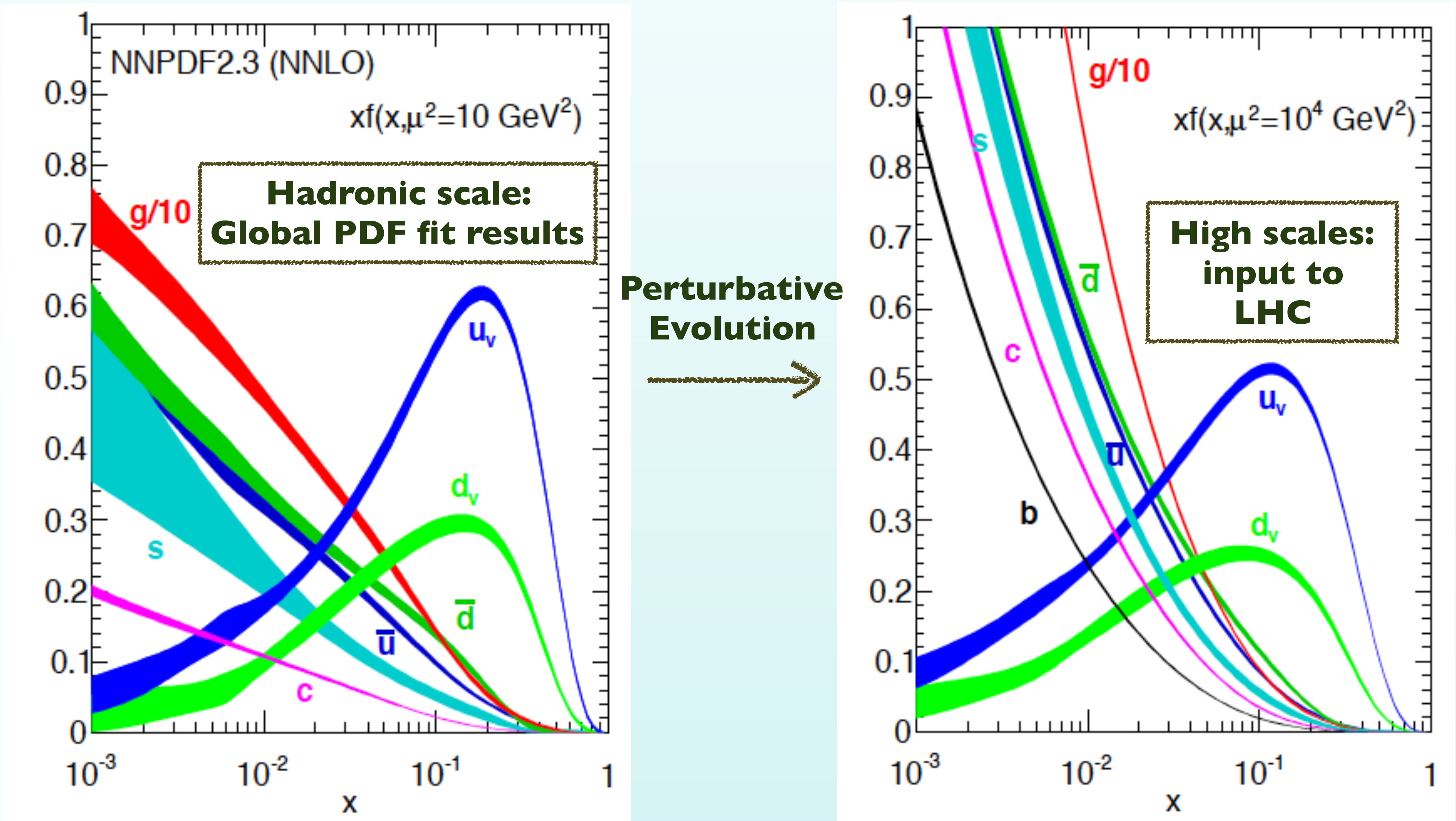
The DIS NLO cross-section is now finite!

All IR sensitivity absorbed into the PDFs, which are determined from data anyway

PDF evolution

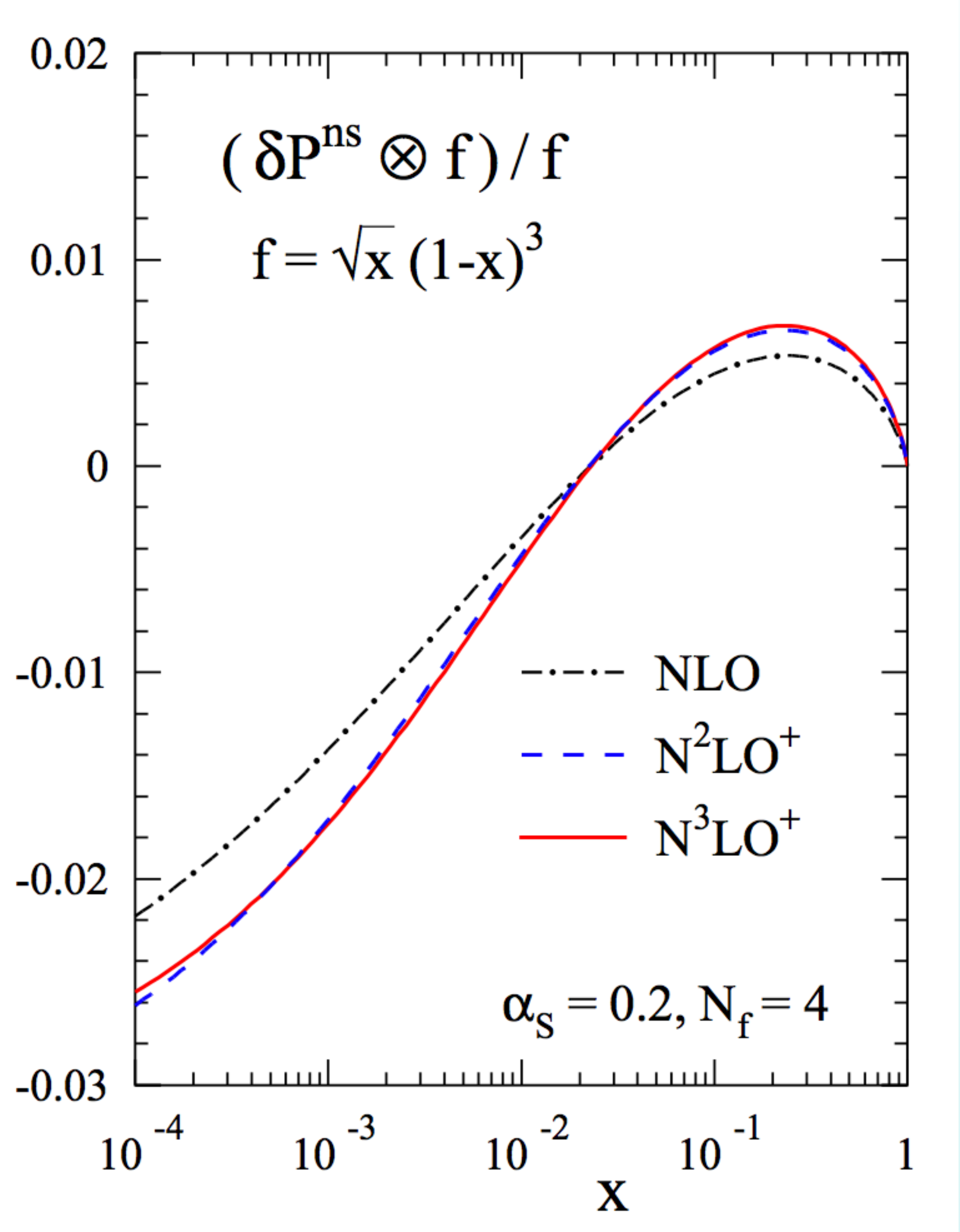
- The NLO cross-section **cannot depend** on the unphysical factorization scale (up to NNLO terms)
- This restriction fully specifies the **scale dependence of the PDFs:** the **DGLAP evolution equations**

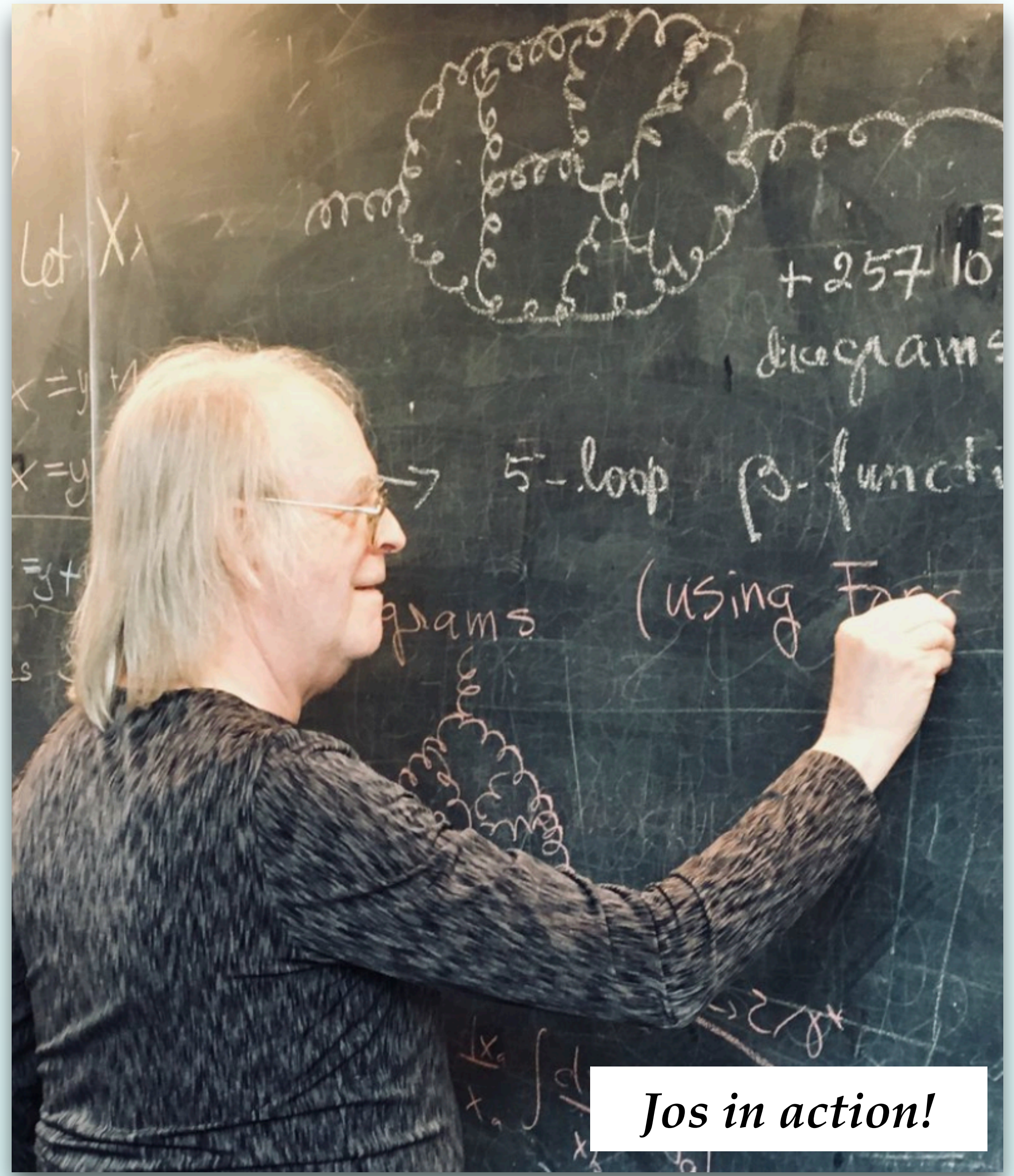
$$\mu^2 \frac{\partial f_q(x,\mu^2)}{\partial \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dz}{z} P_{qq}(z) f_q\left(\frac{x}{z}, \mu^2\right)$$



Loops and more loops

First results on the **4-loop QCD splitting functions** computed by Jos Vermaseren and collaborations

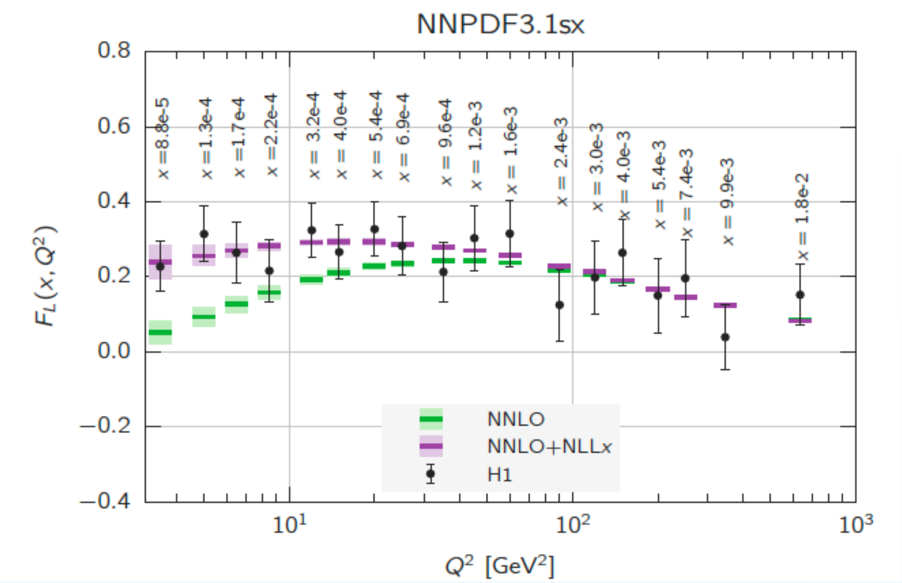




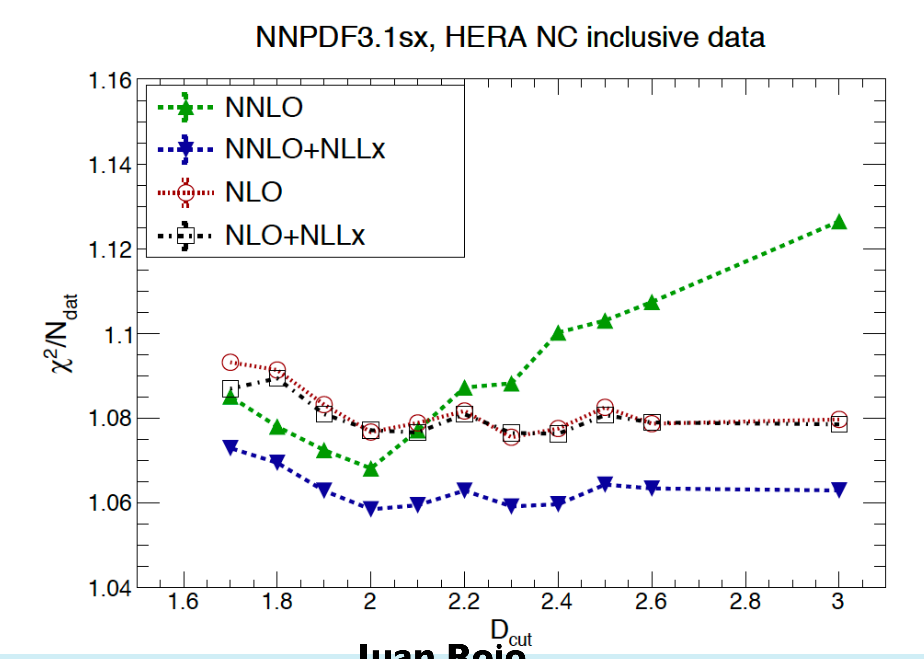
Jos in action!

Moch et al 17

Towards PDF evolution with per-mille theoretical uncertainties



Unravelling BFKL dynamics from HERA data



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

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

$$P_{gg} \sim \frac{1}{x} \sum_n \alpha_s^n \ln^{n-1} \frac{1}{x}$$

- **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 Q²

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

BFKL Evolution in x

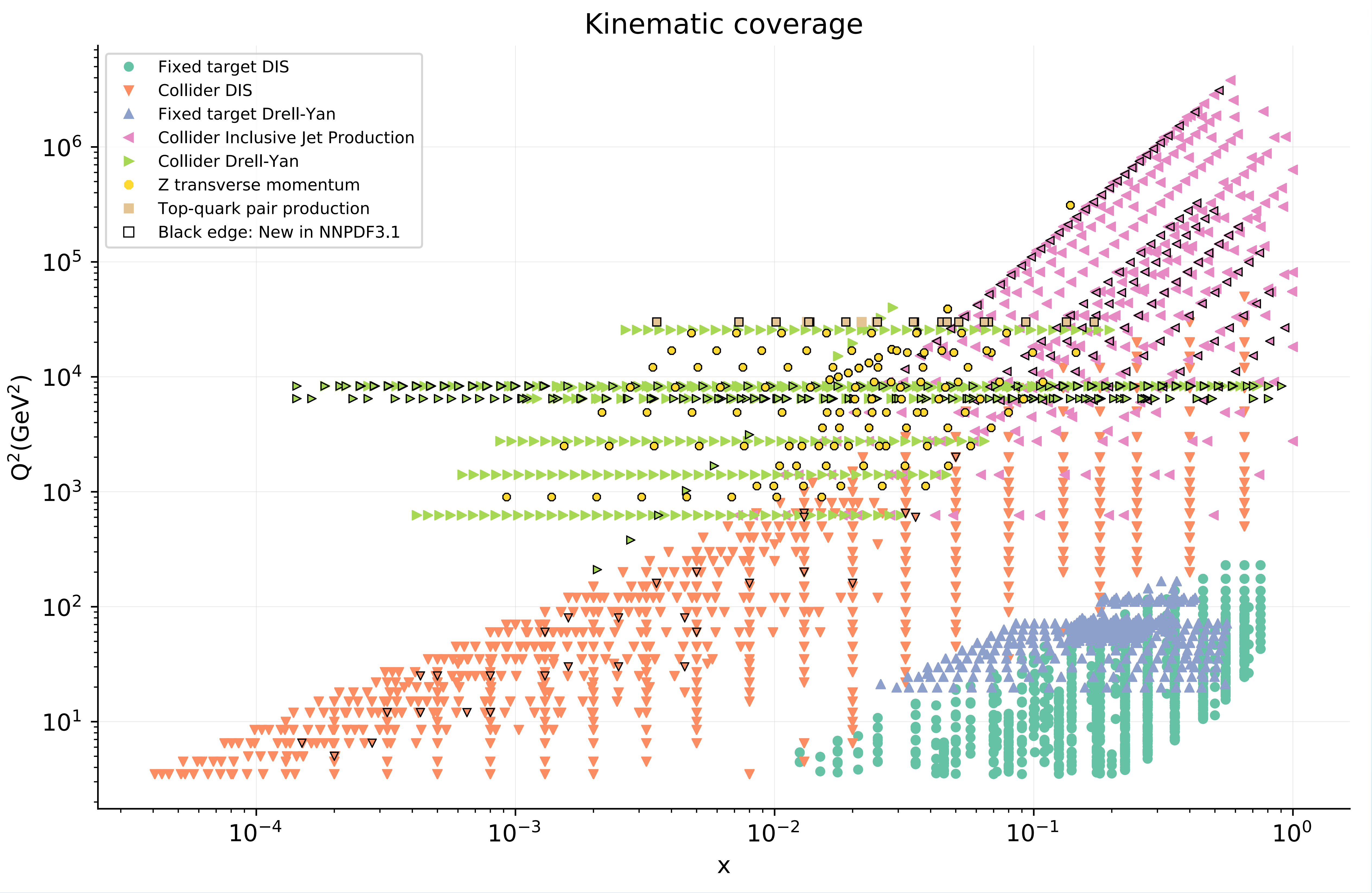
$$-x \frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

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

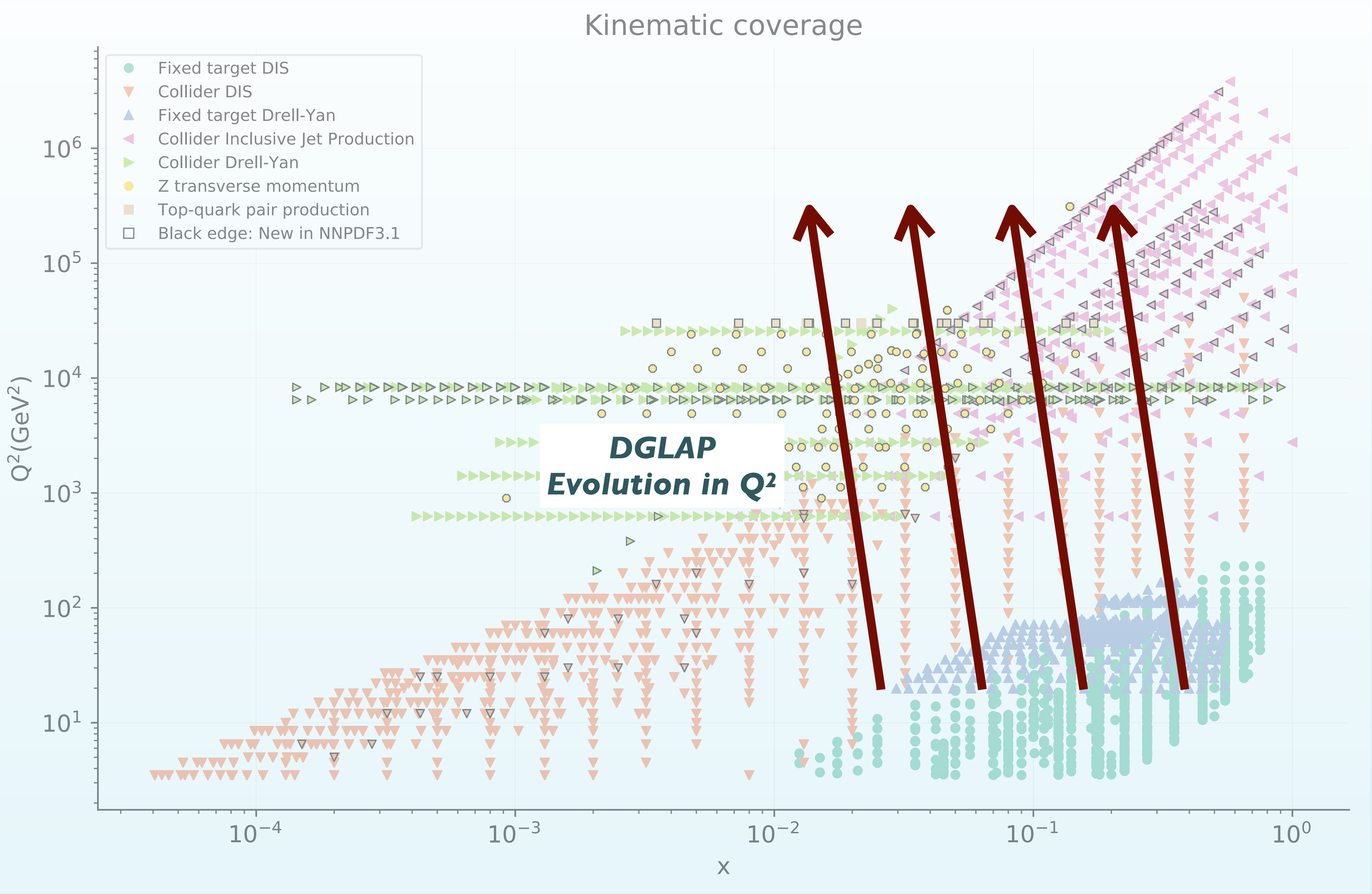
ABF, CCSS, TW + others, 94-08

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

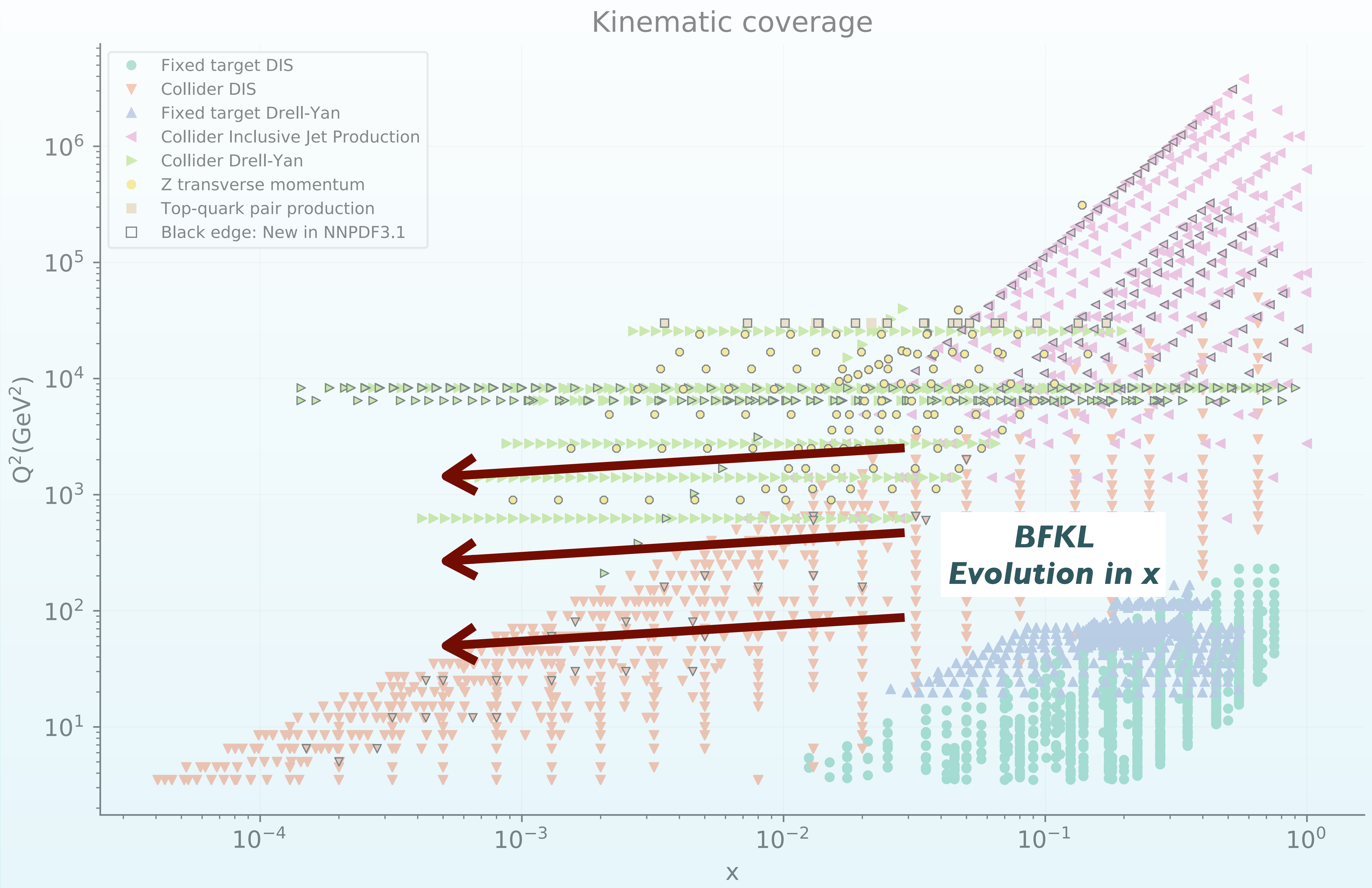
Theory motivation: beyond DGLAP



Theory motivation: beyond DGLAP

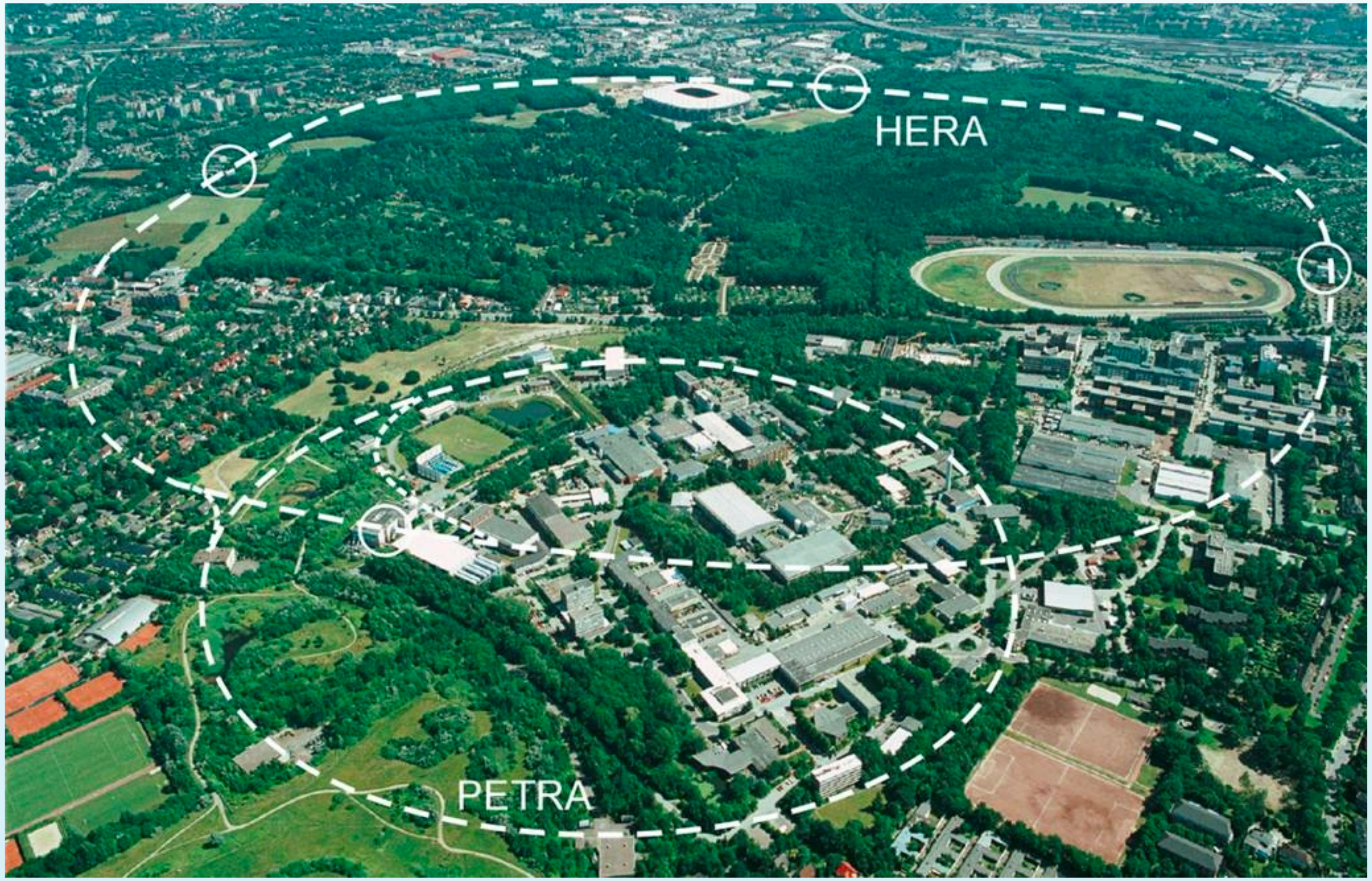


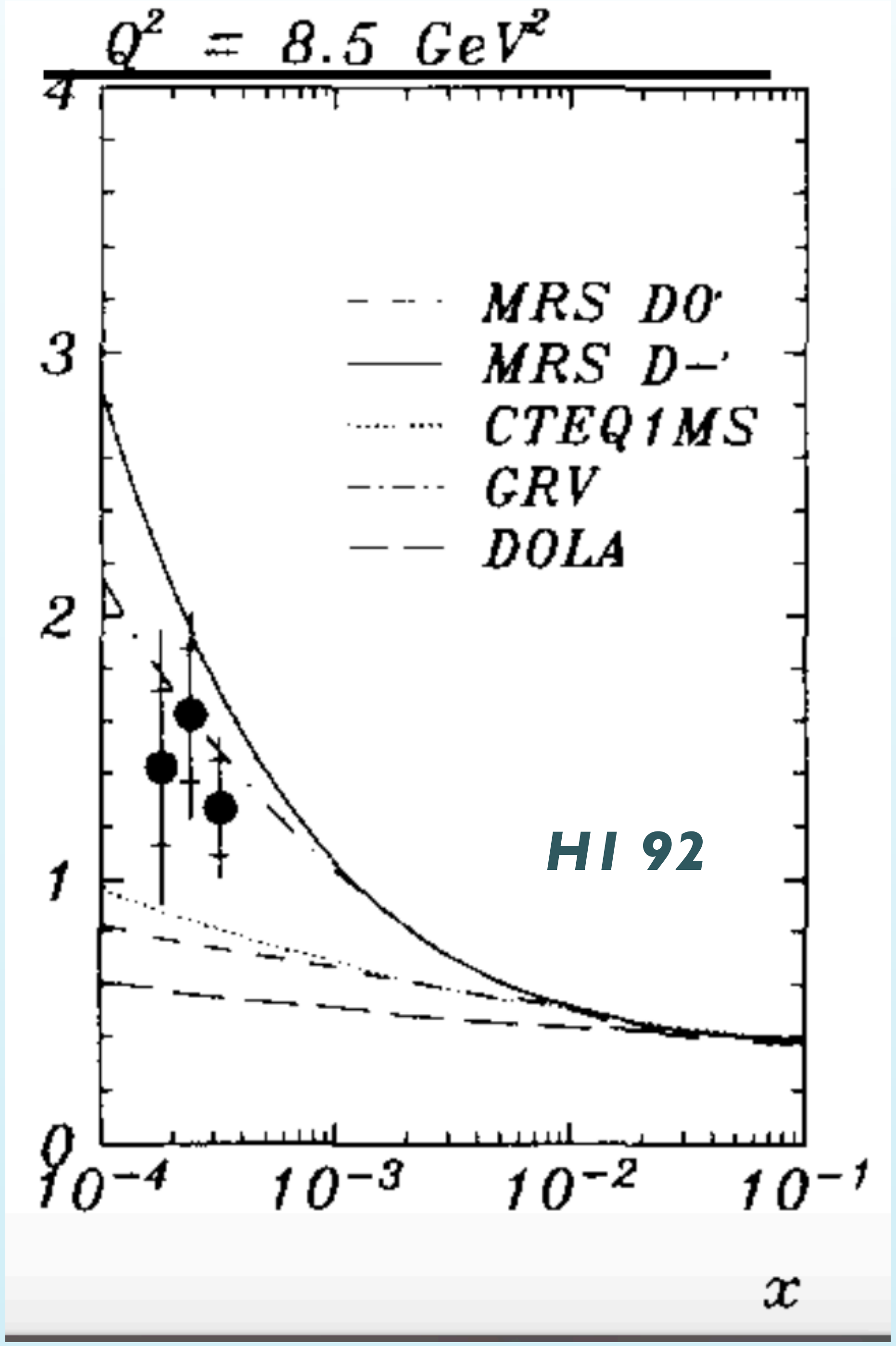
Theory motivation: beyond DGLAP



Experimental motivation: tensions in HERA data

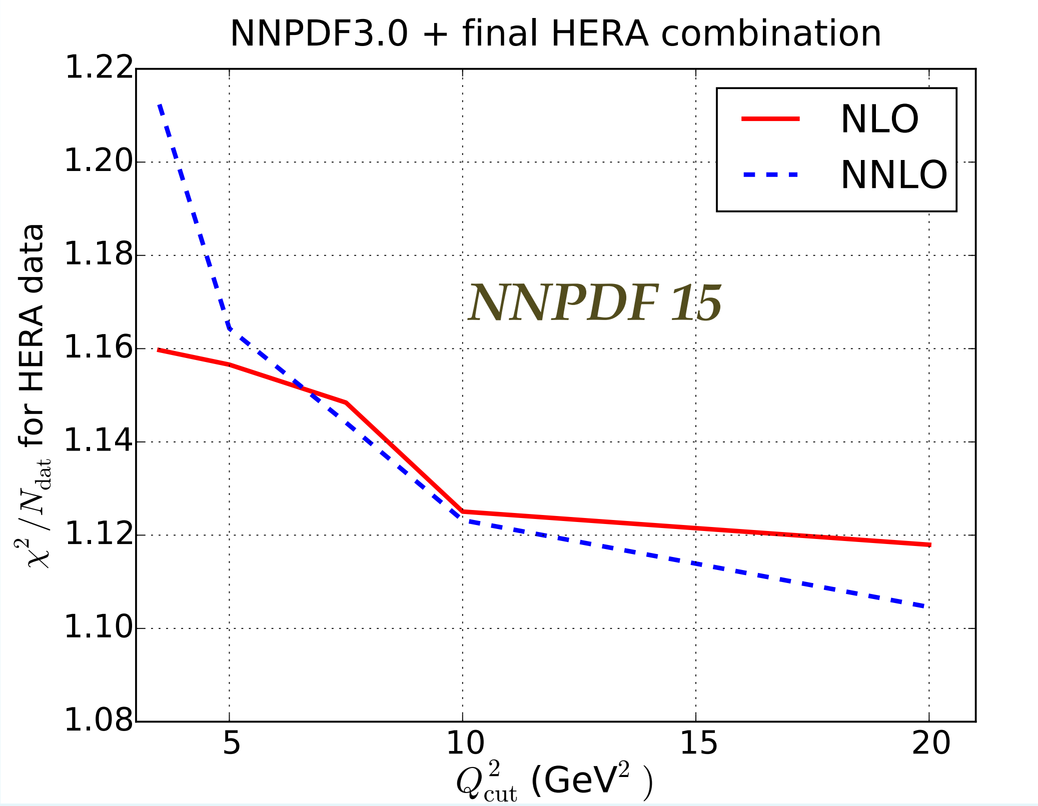
- HERA was the first (and only) **lepton-proton collider**, operating in DESY between 1992 and 2007
- HERA measurements provide the **backbone of all global PDF analyses**
- Evidence for BFKL (small-x) dynamics **searched for > 25 years**, without success

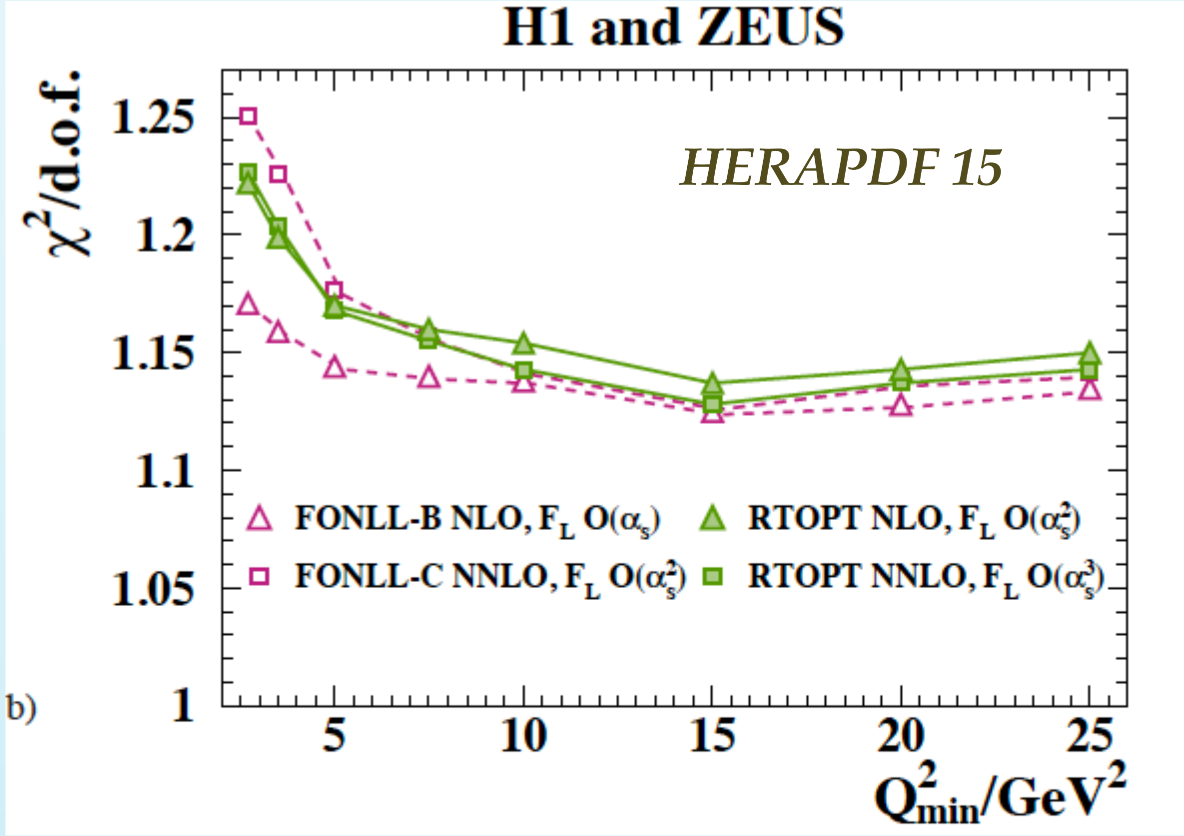


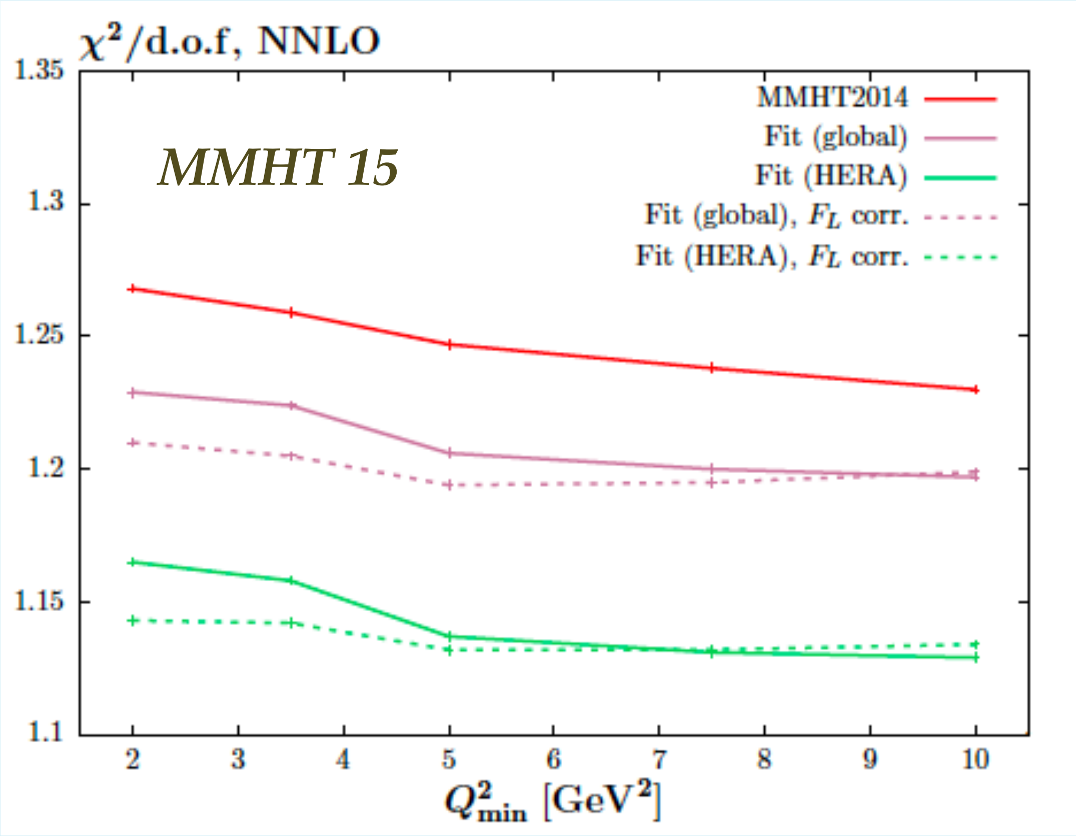


Experimental motivation: tensions in HERA data

- 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?**



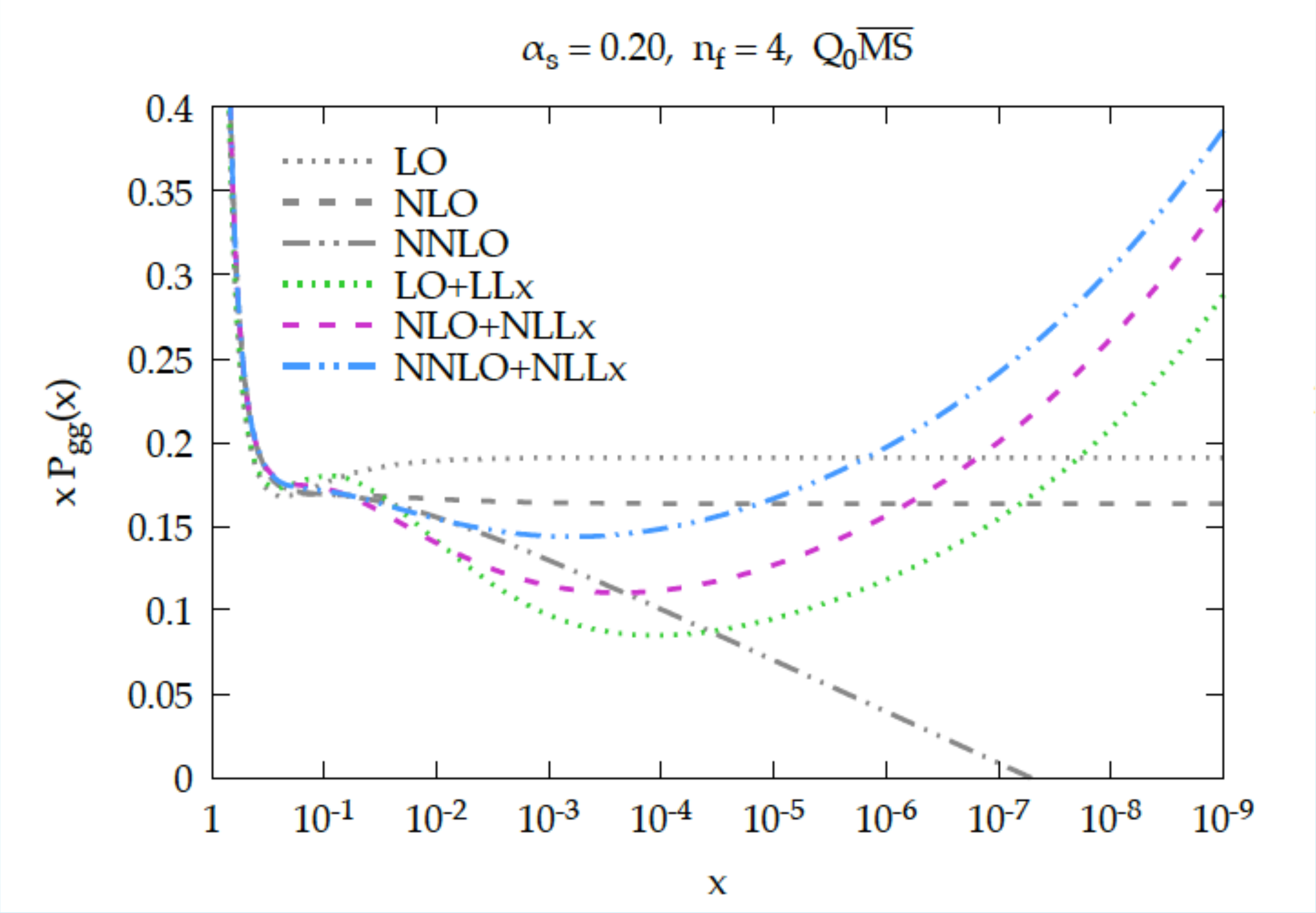




PDFs with small-x resummation

- 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**

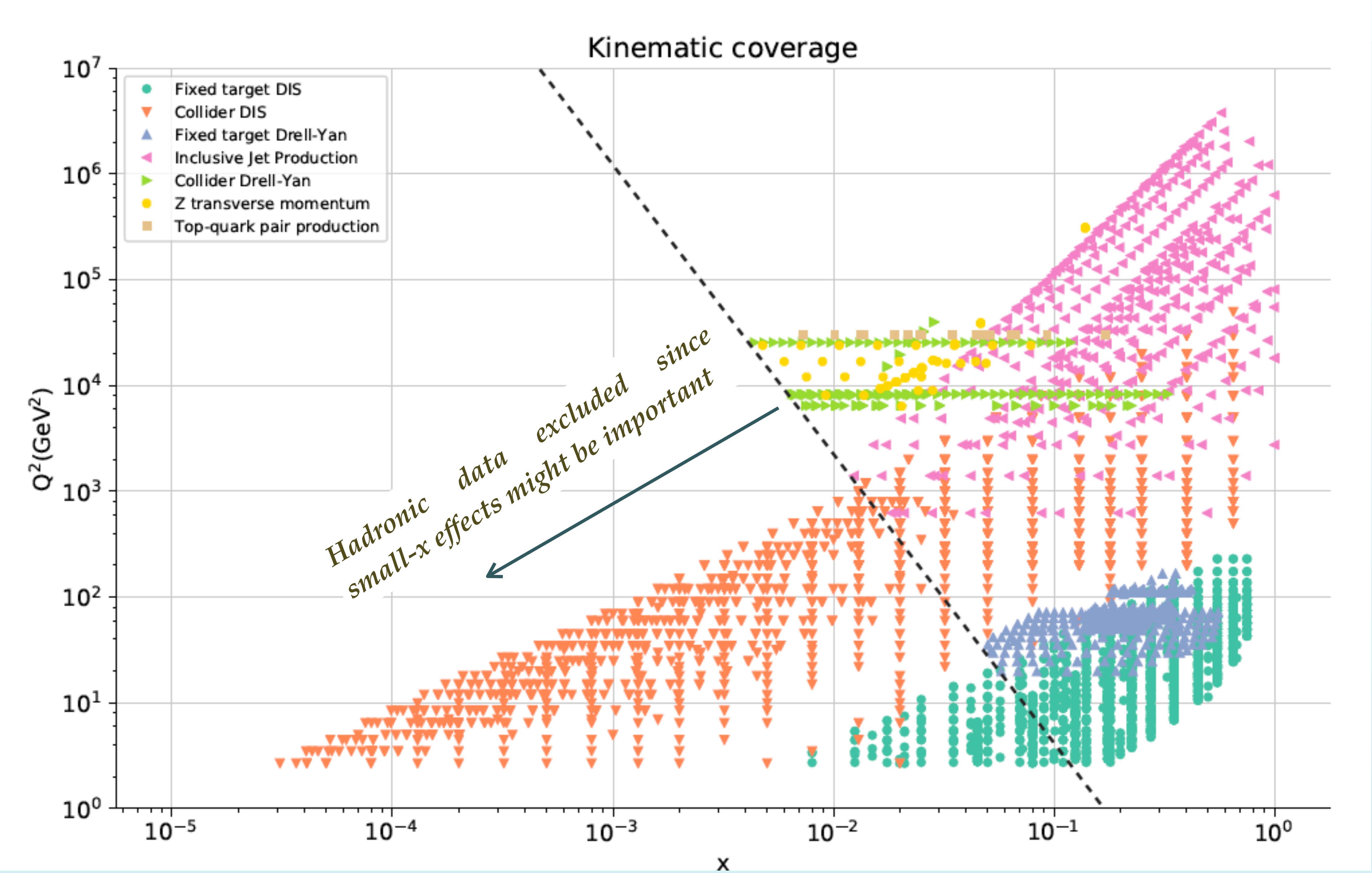


APFEL: Bertone, Carrazza, Rojo 13
https://apfel.hepforge.org/

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

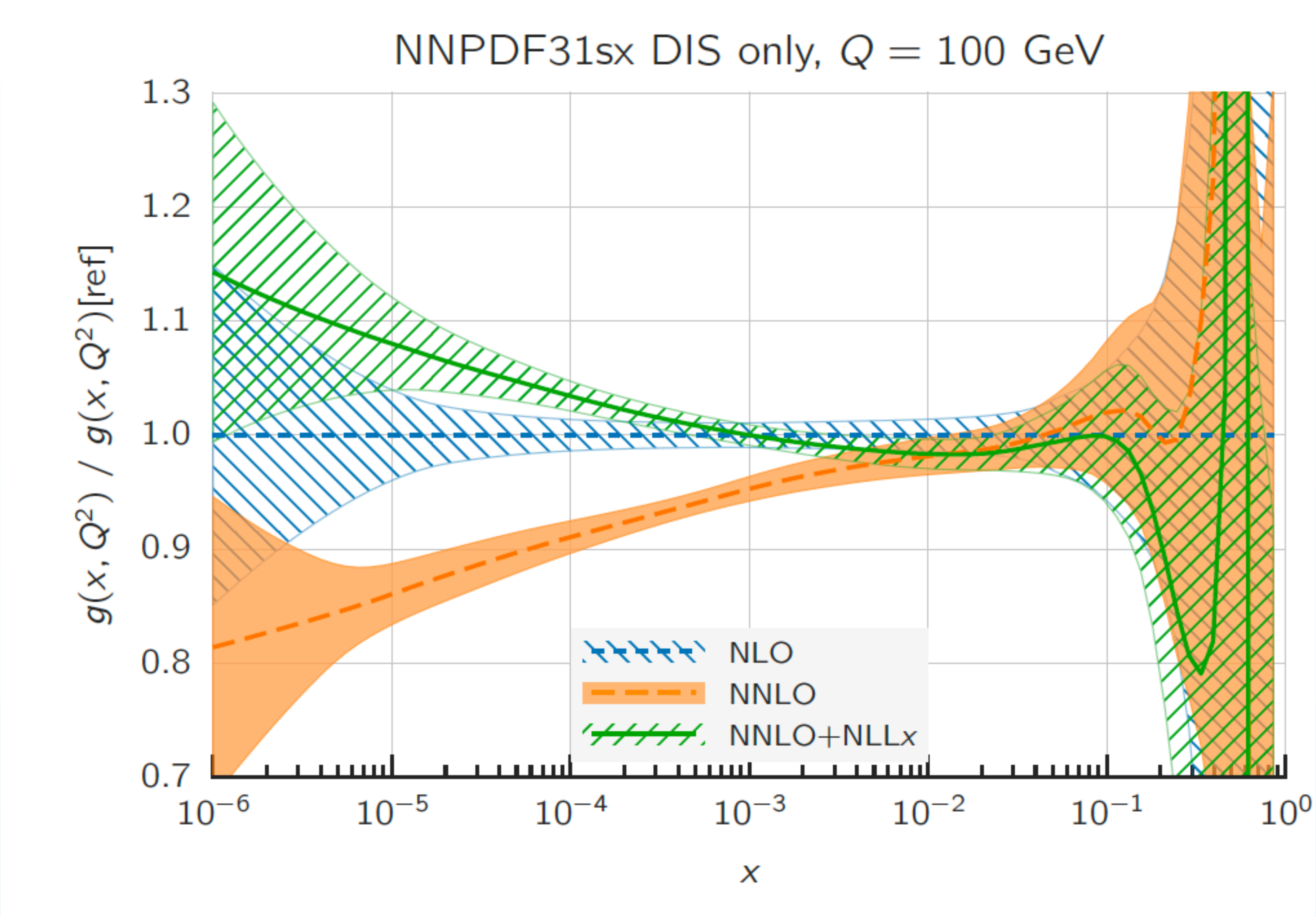
PDFs with small-x resummation

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



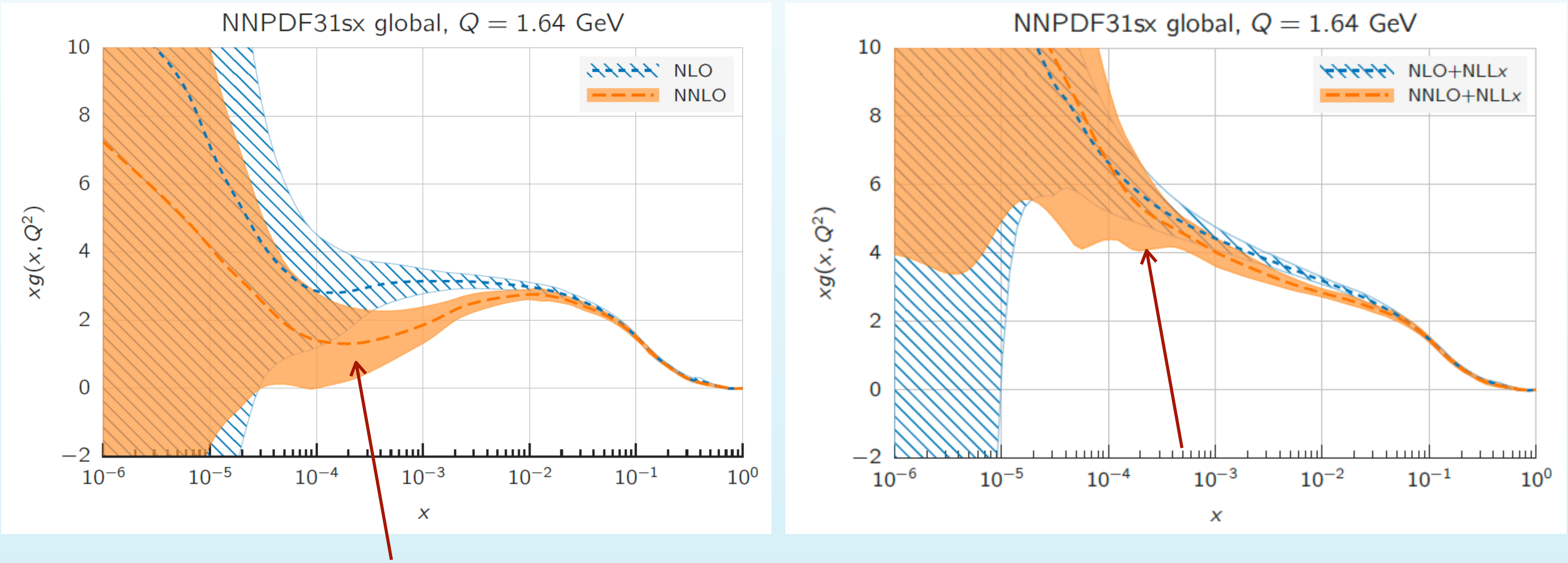
PDFs with small-x resummation

- **NNPDF3.1sx**: Variant of **NNPDF3.1 global fits** using **NLO+NLLx 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



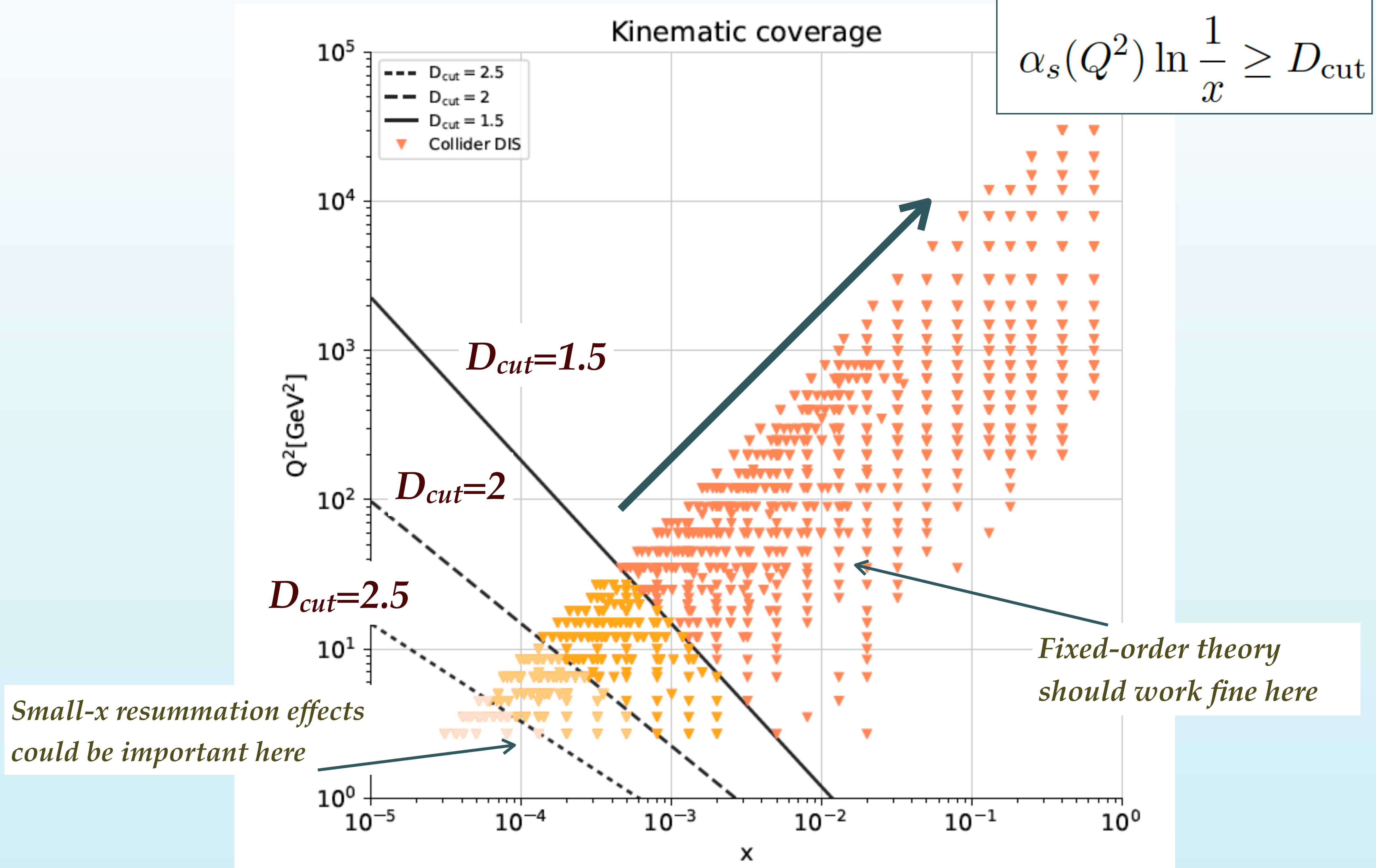
PDFs with small-x resummation

	$\chi^2/N_{\rm dat}$ 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**

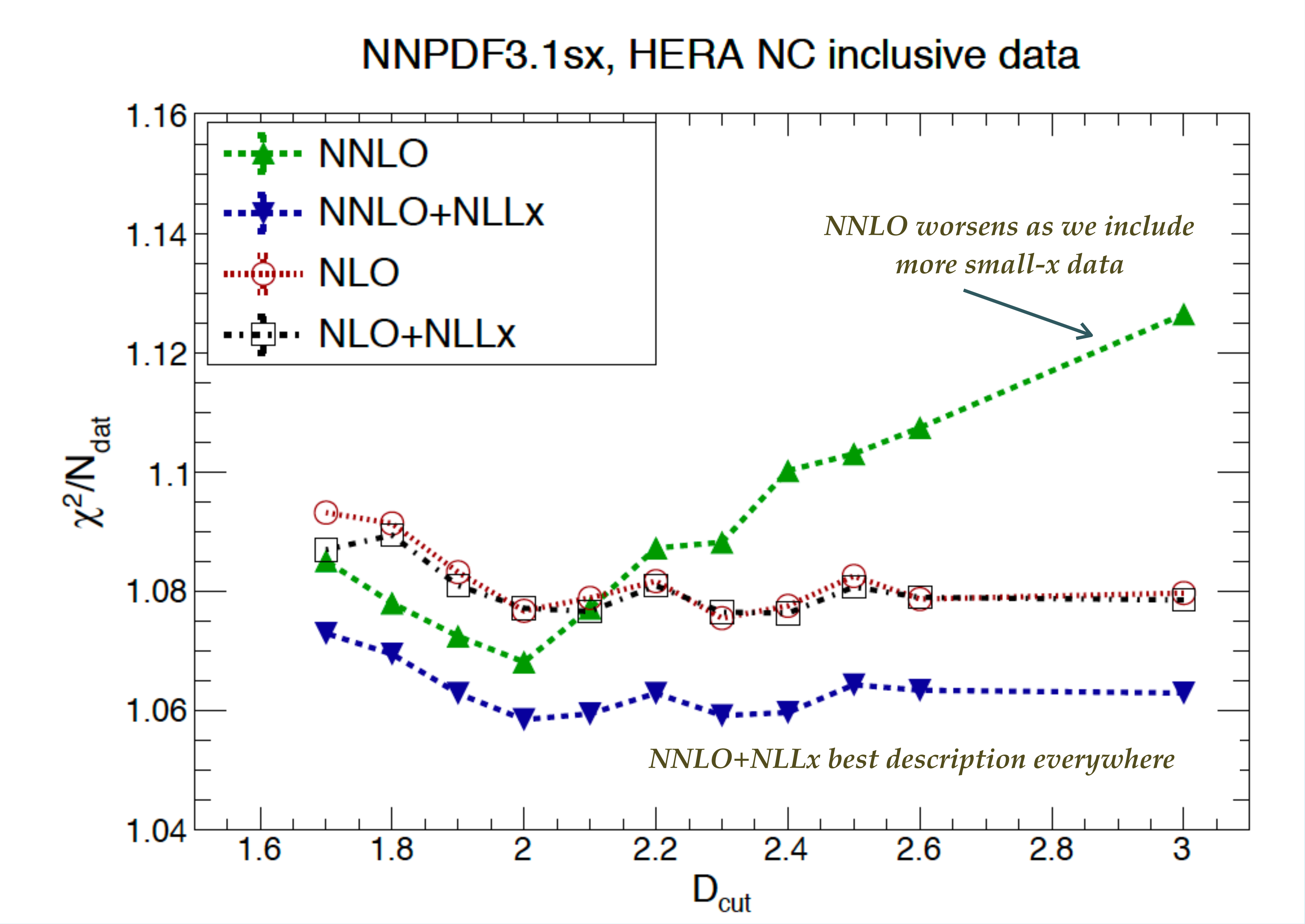
$$\alpha_s(Q^2)\ln\frac{1}{x} \geq D_{\rm cut}$$



PDFs with small-x resummation

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

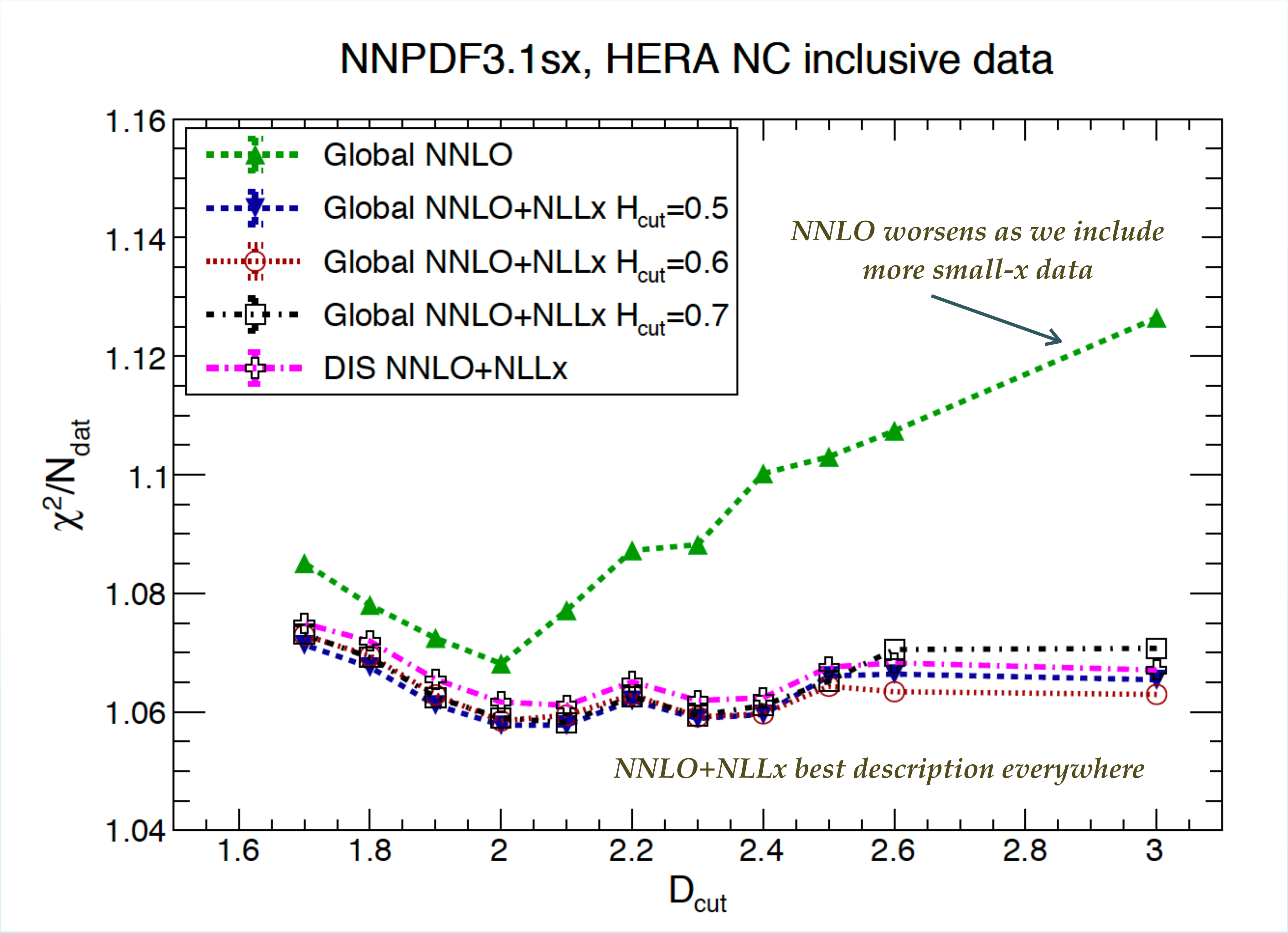
Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire (x,Q²) region**



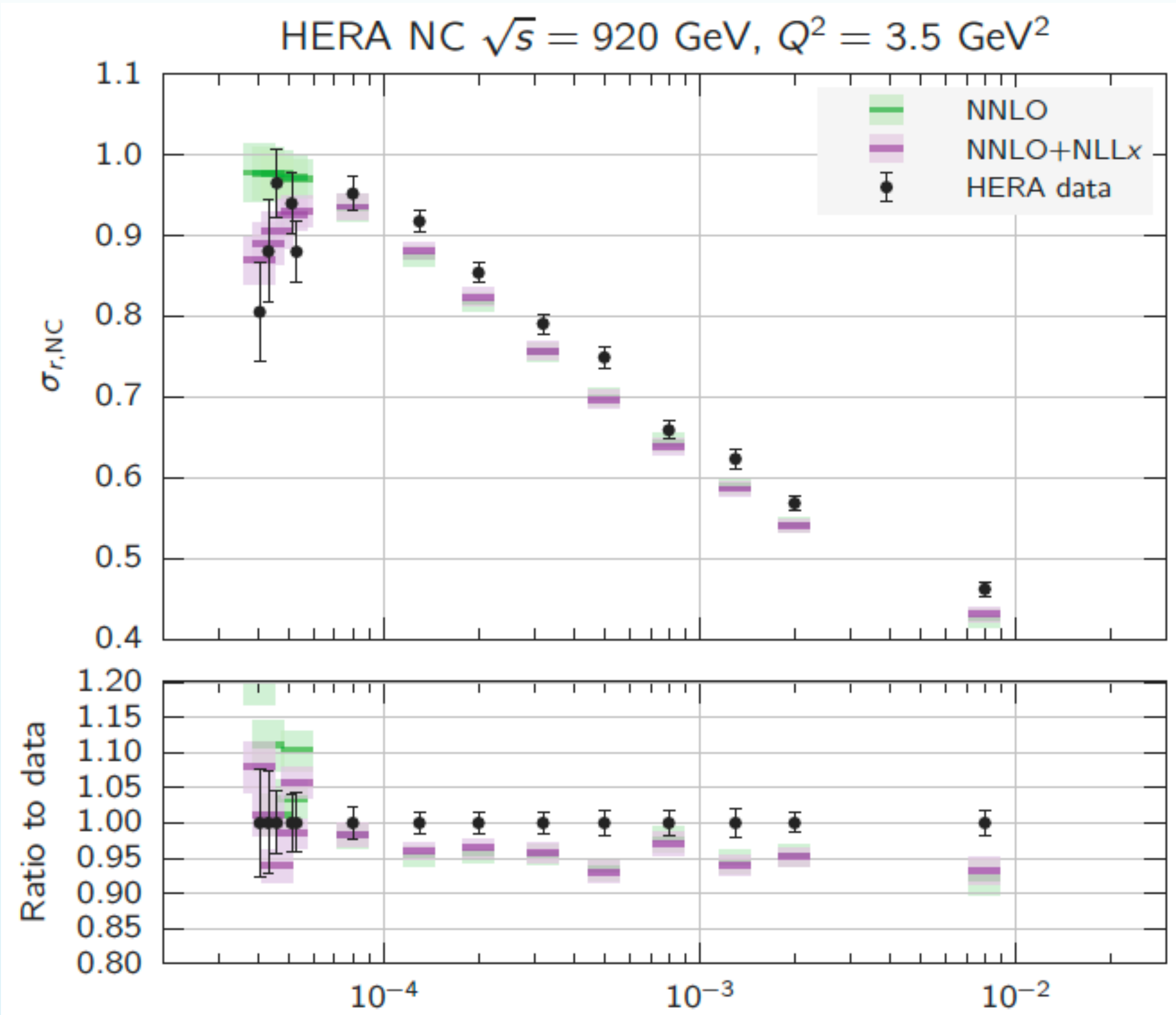
PDFs with small-x resummation

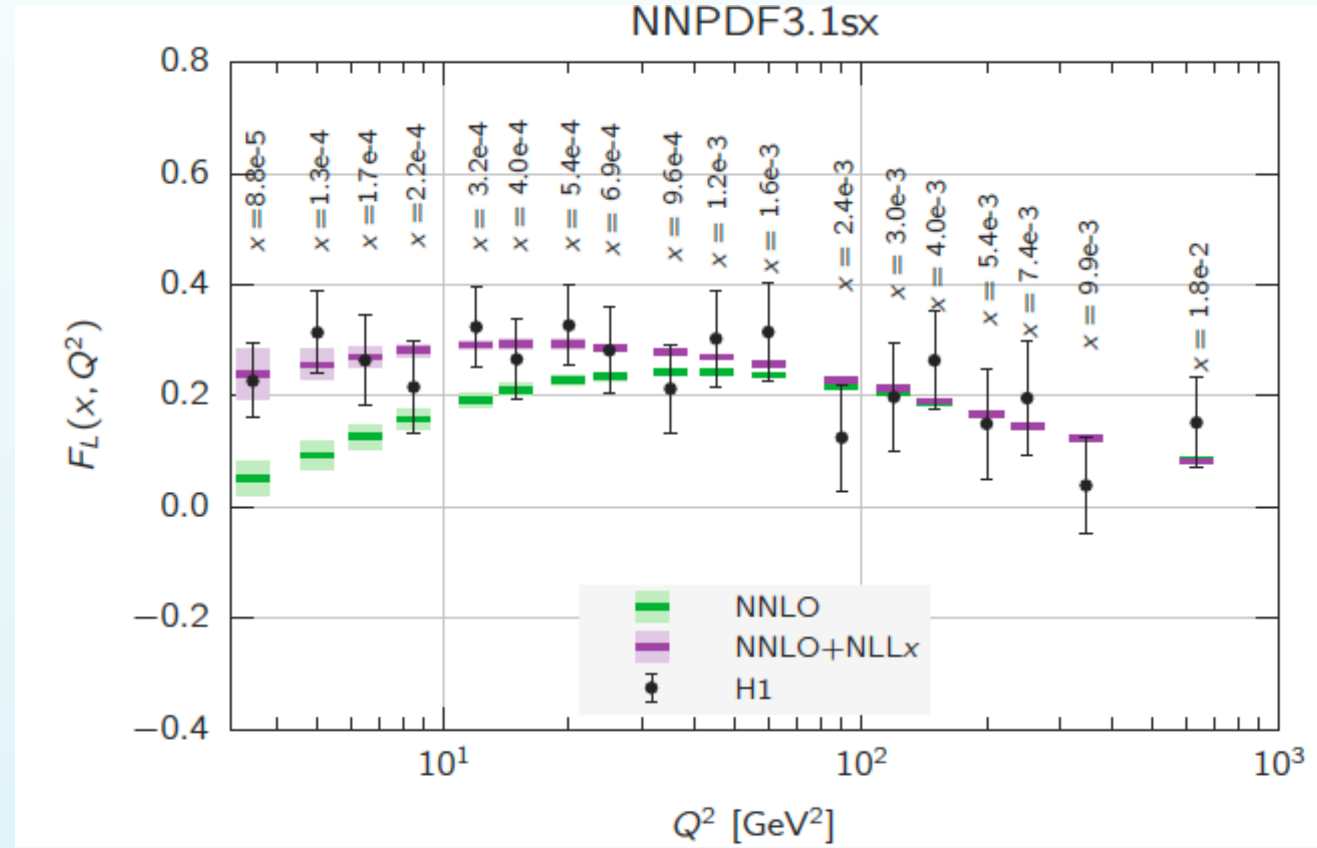
Using **NNLO+NLL*x* theory, the NNLO instability of the χ^2 disappears**

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)

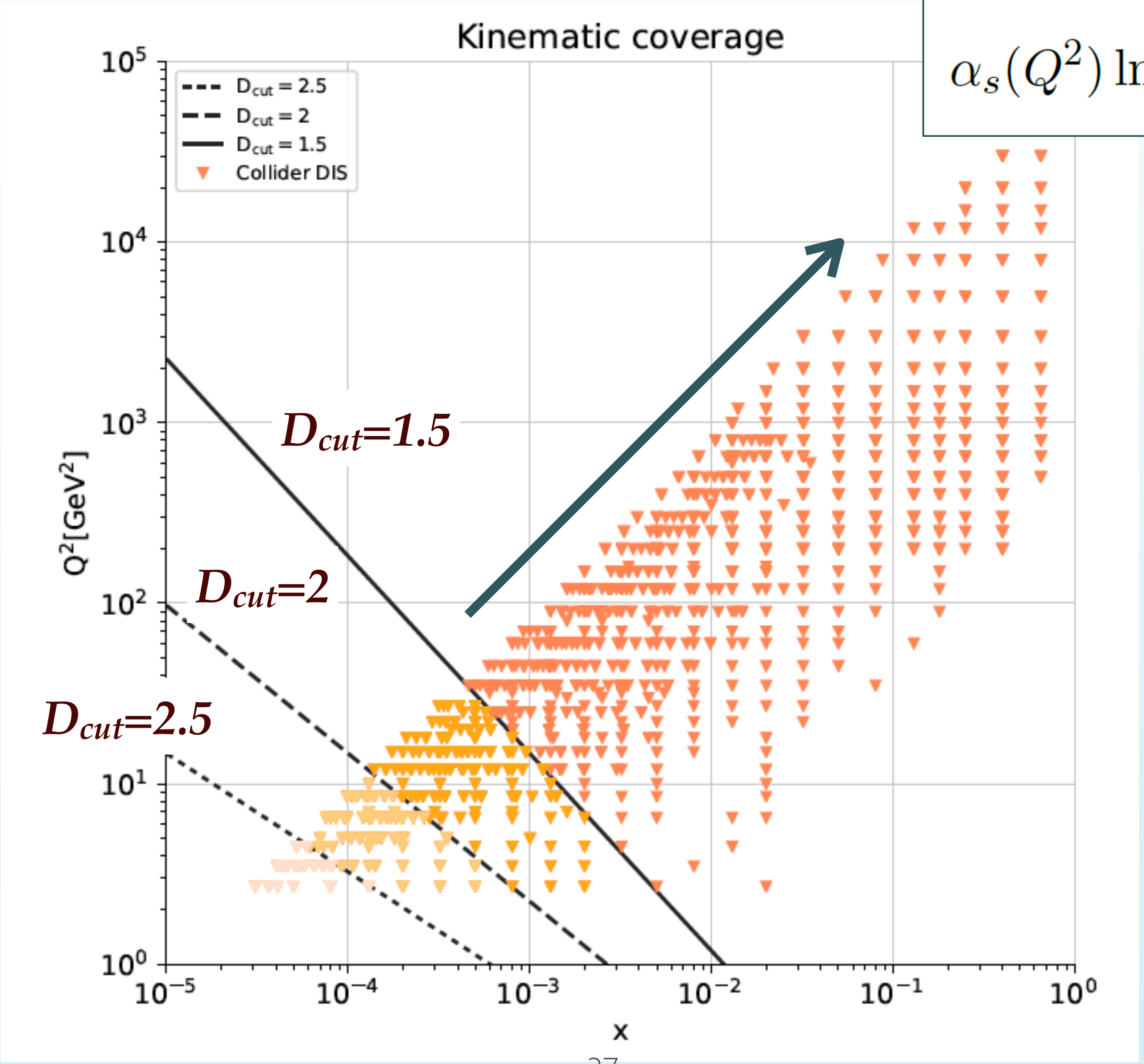
Also **improved description of F_L,** which moreover remains markedly **positive** down to the smallest values of *x* and *Q* probed

Implications for fixed-order fits

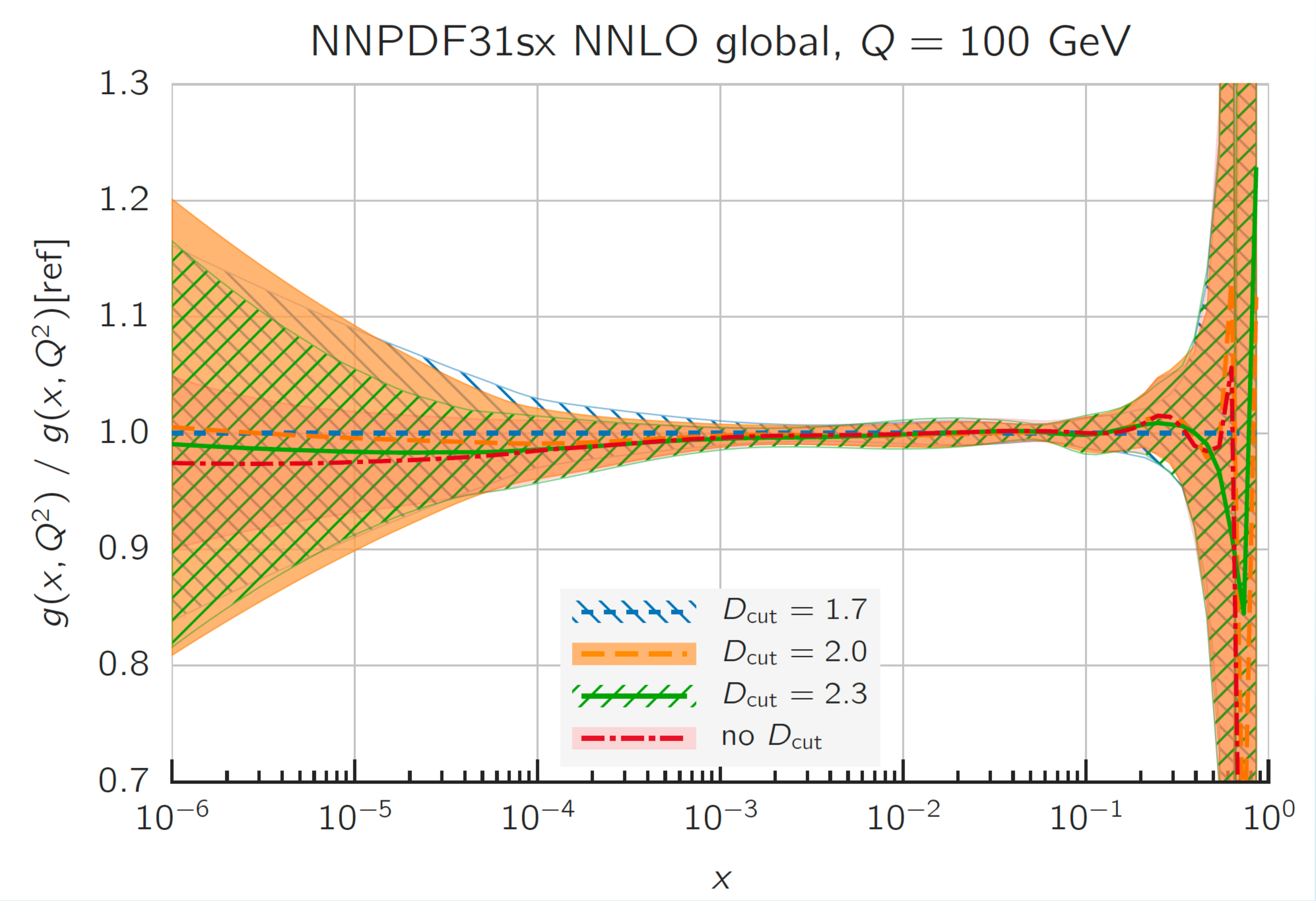
Do these results imply at existing NNLO fits are **biased?** What are implications for LHC pheno?

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

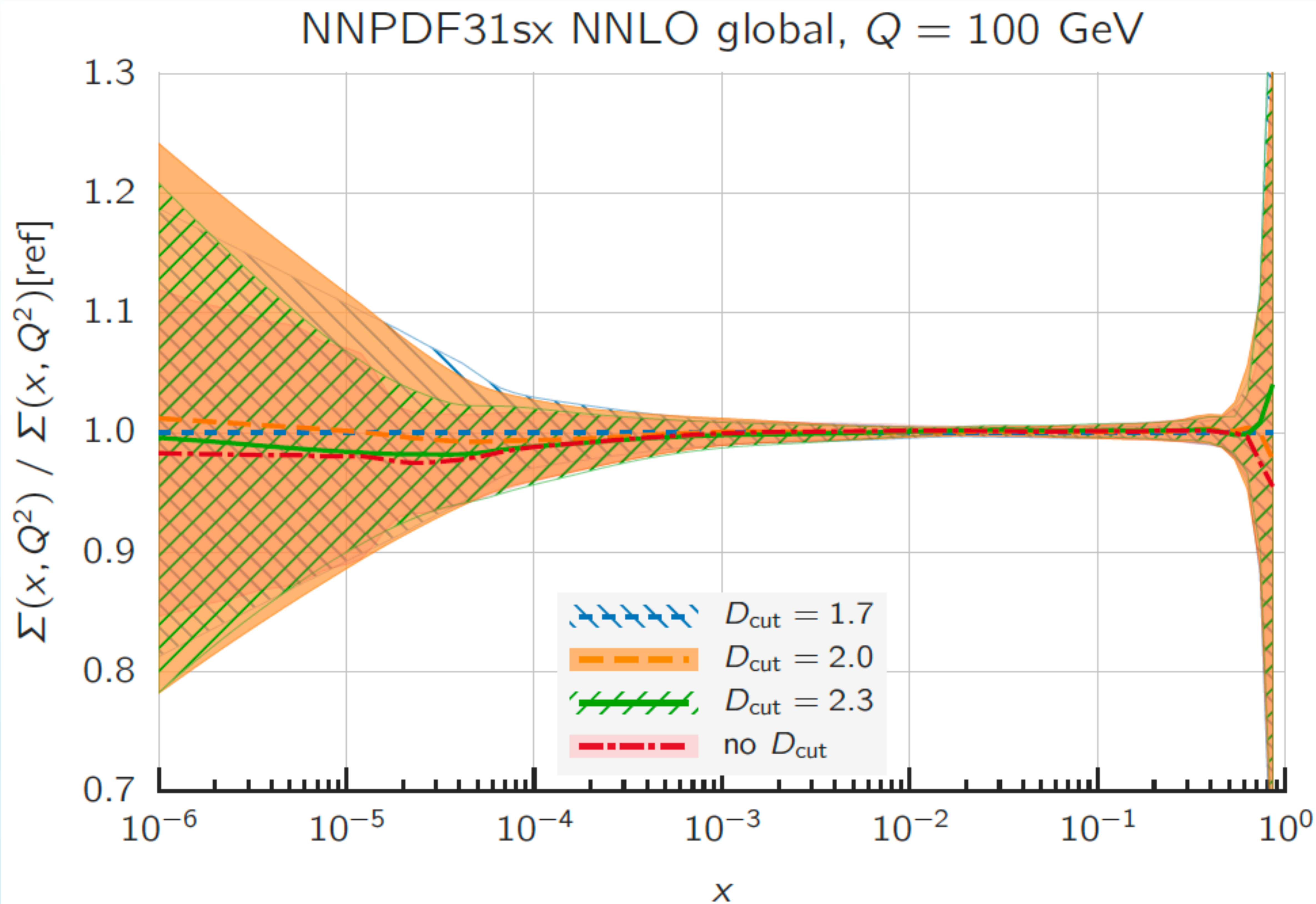
$$\alpha_s(Q^2)\ln\frac{1}{x} \geq D_{\rm cut}$$



Implications for fixed-order fits



Implications for fixed-order fits

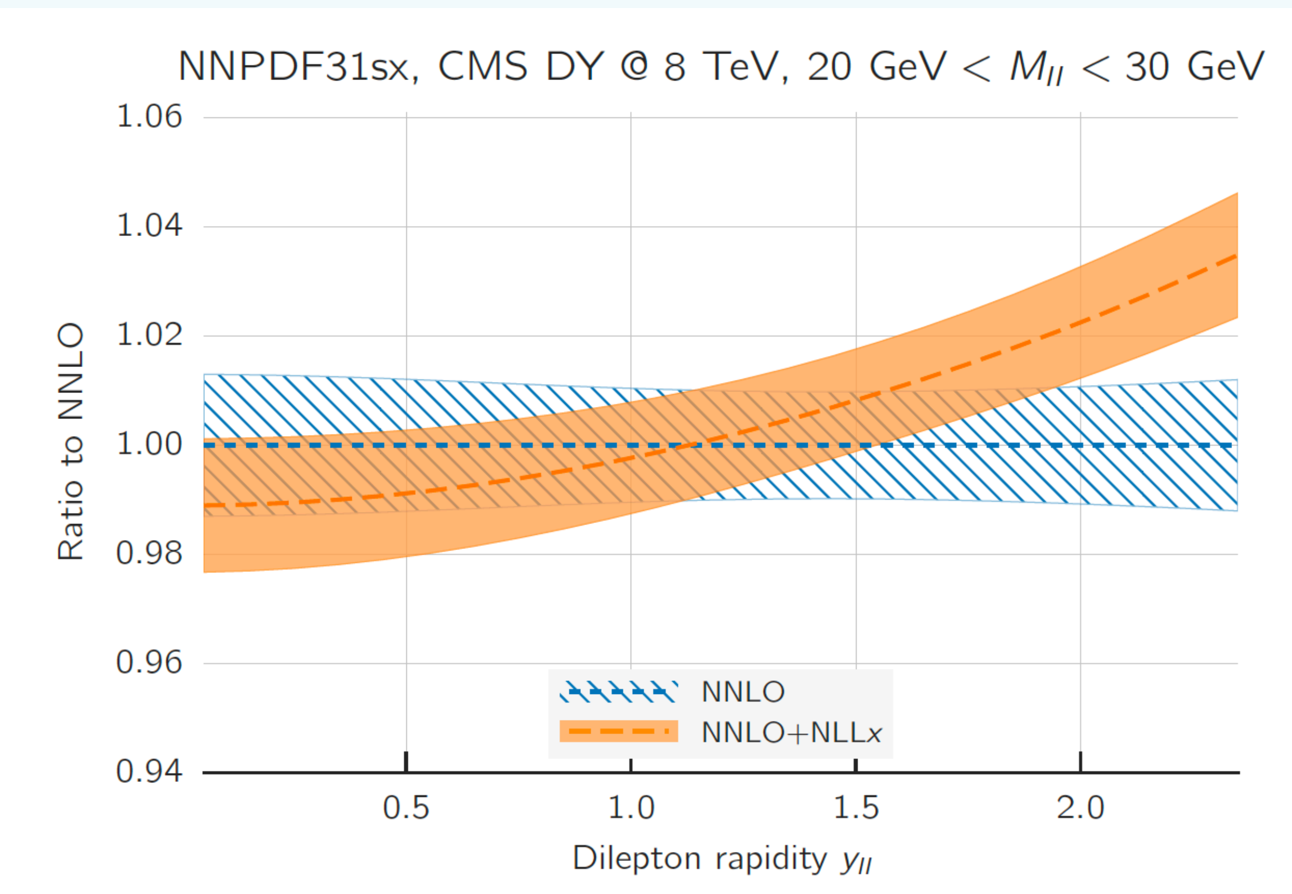


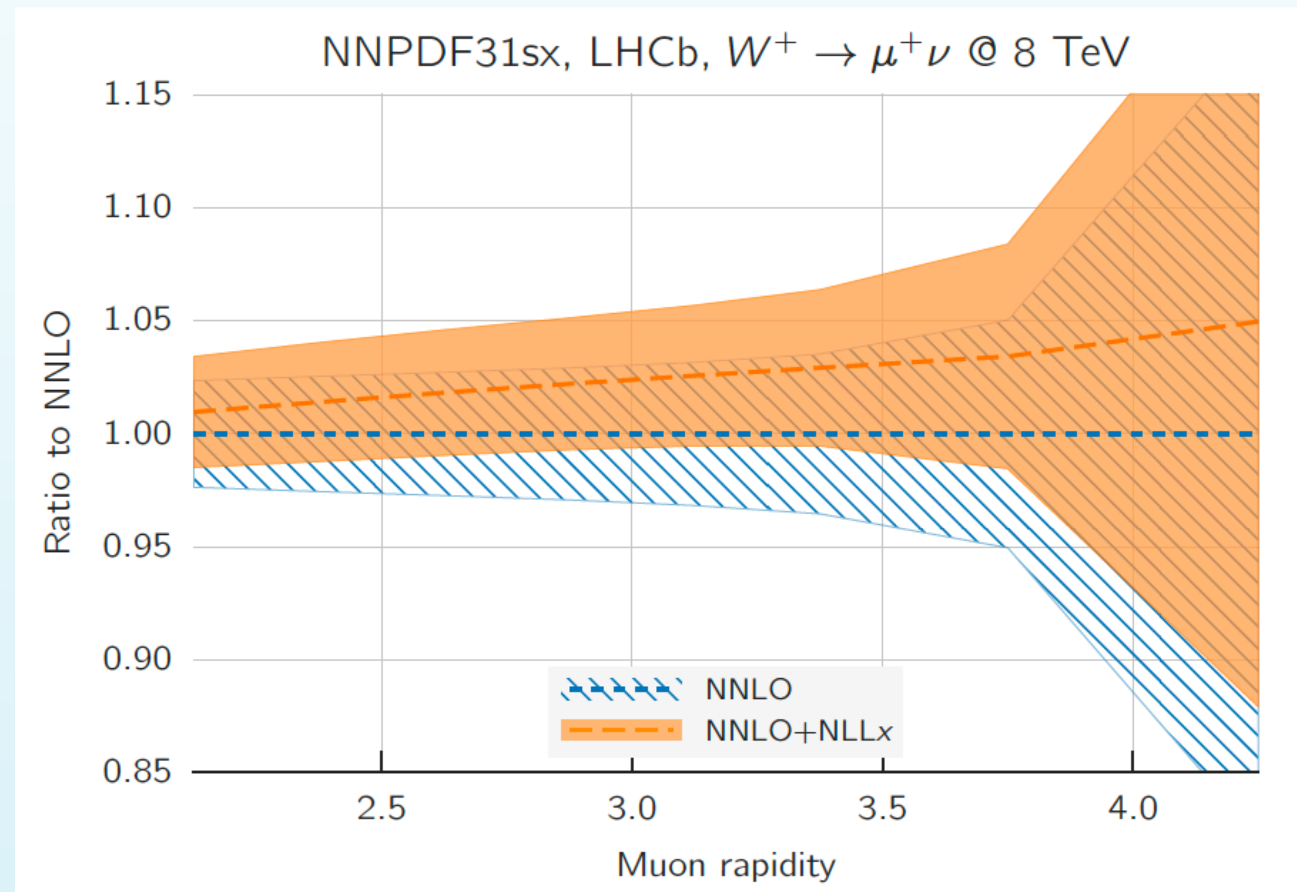
Good stability at medium and large-x: **NNLO global fits perfectly fine for LHC applications**

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





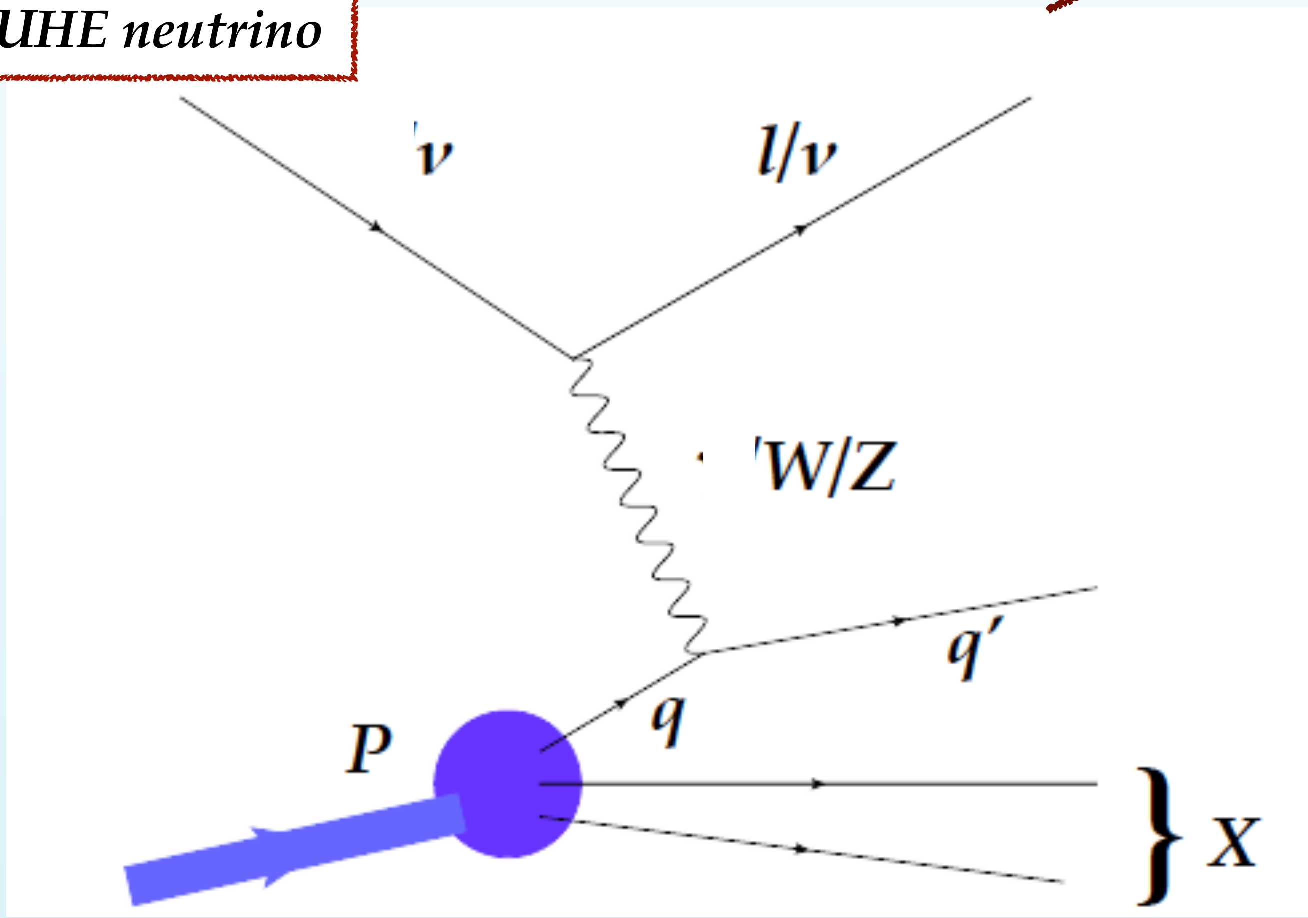
NB none of these exps included in NNPDF3.1sx

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

From the LHC to Neutrino Telescopes

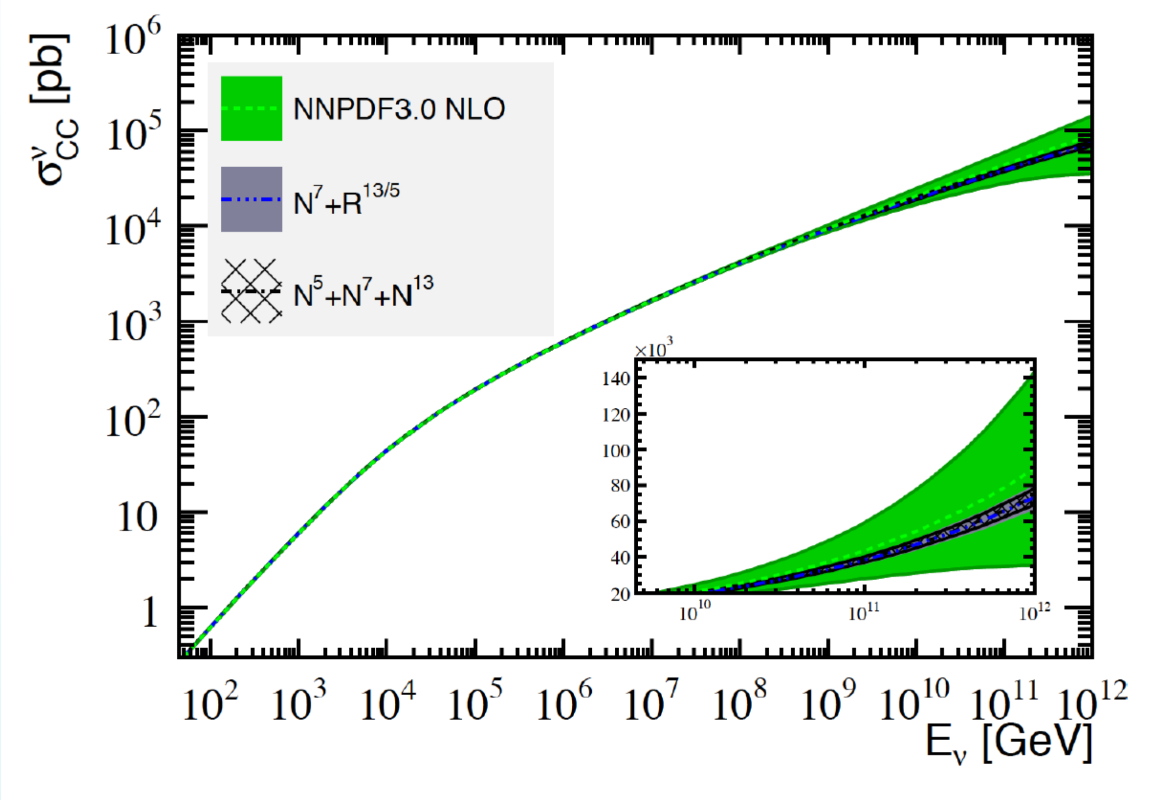
Provide state-of-the-art predictions for the UHE neutrino nucleus cross-sections for neutrino telescopes

UHE neutrino

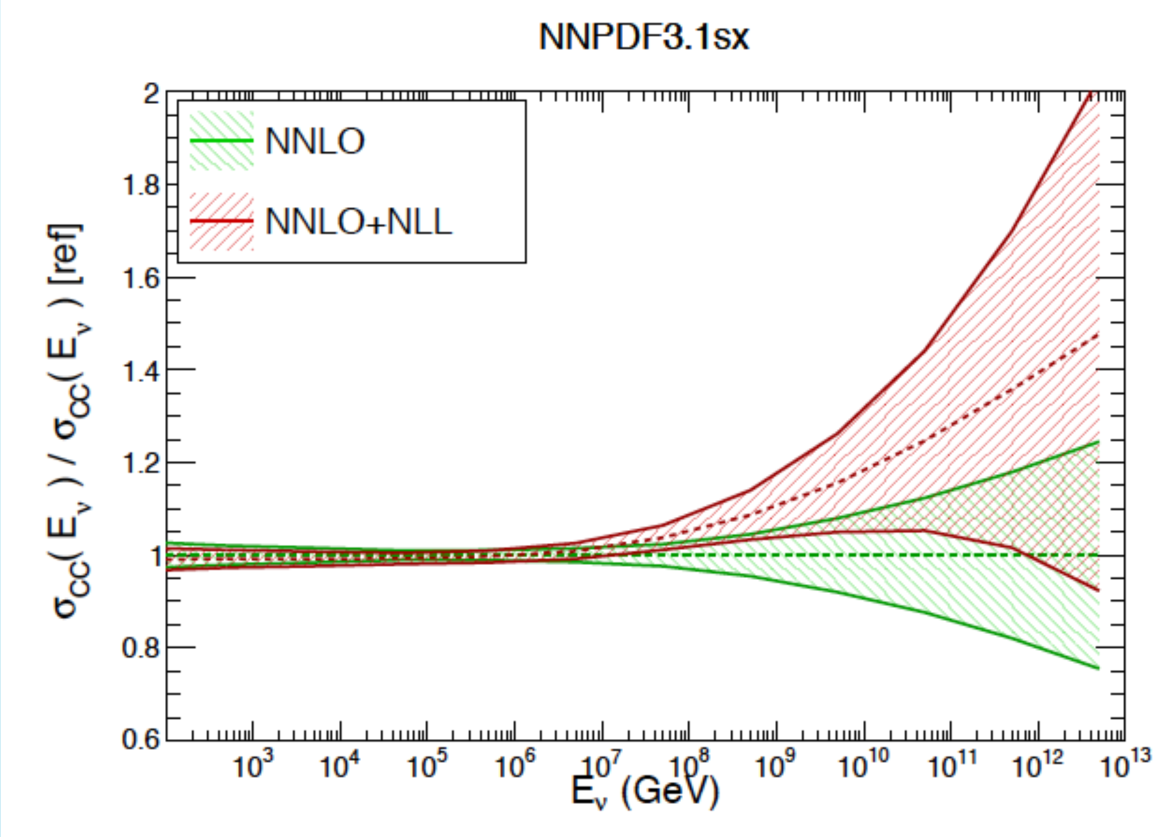


Using better data

Constraints from LHCb D production



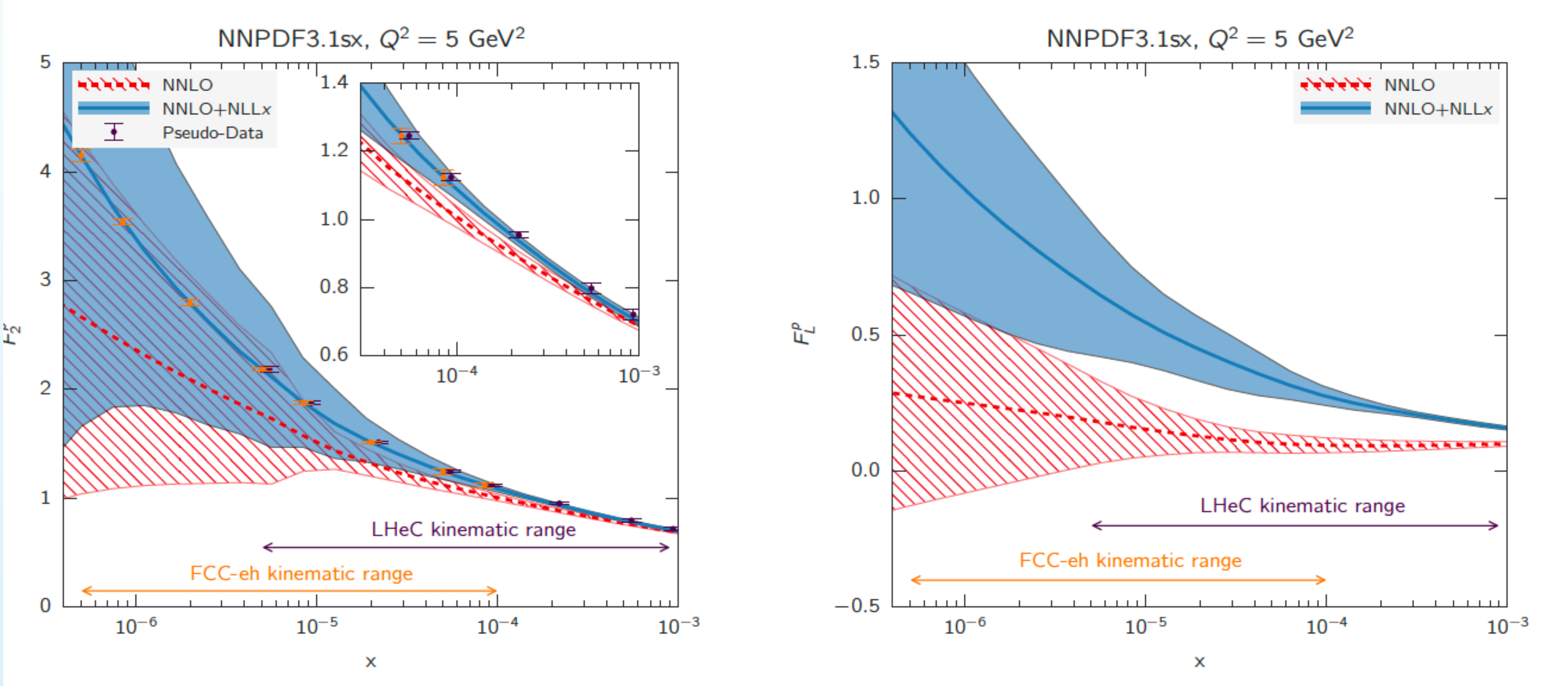
Using better theory



Constraints from BFKL resummation

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

Discovering new physics in QCD

- Quantum Chromodynamics is a extremely rich and complex theory that keeps **delivering many exciting surprises**

- The **QCD evolution equations** allow us to relate physics in different regimes: from low scales to high scales (DGLAP) and from large *x* to small **x** (BFKL)

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

- After > 25 years of searching, we now have **convincing evidence for the onset of BFKL dynamics** in HERA structure function data

- Next step is assessing the implications for **high-precision LHC phenomenology**

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- Next step is assessing the implications for **high-precision LHC phenomenology**

Thanks for your attention!