Parton Distributions from High-Precision Collider Data

Juan Rojo
VU Amsterdam & Theory Group, Nikhef

High Energy Physics Seminar
Vrije Universiteit Brussels
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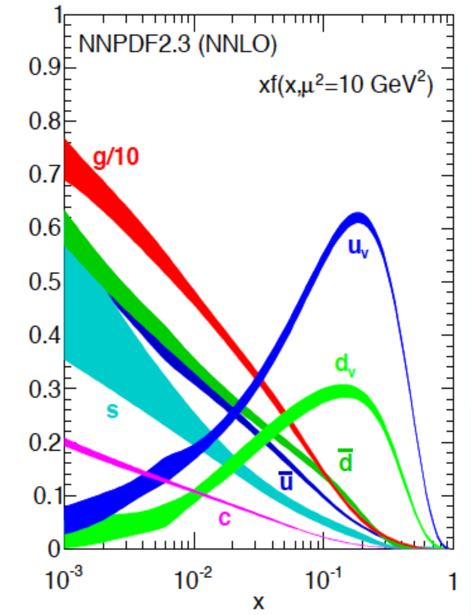
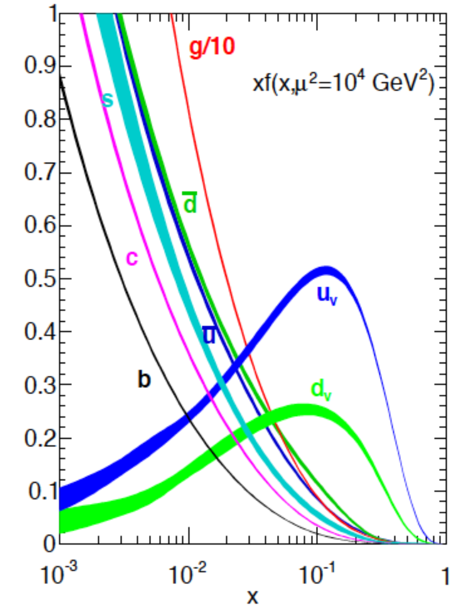
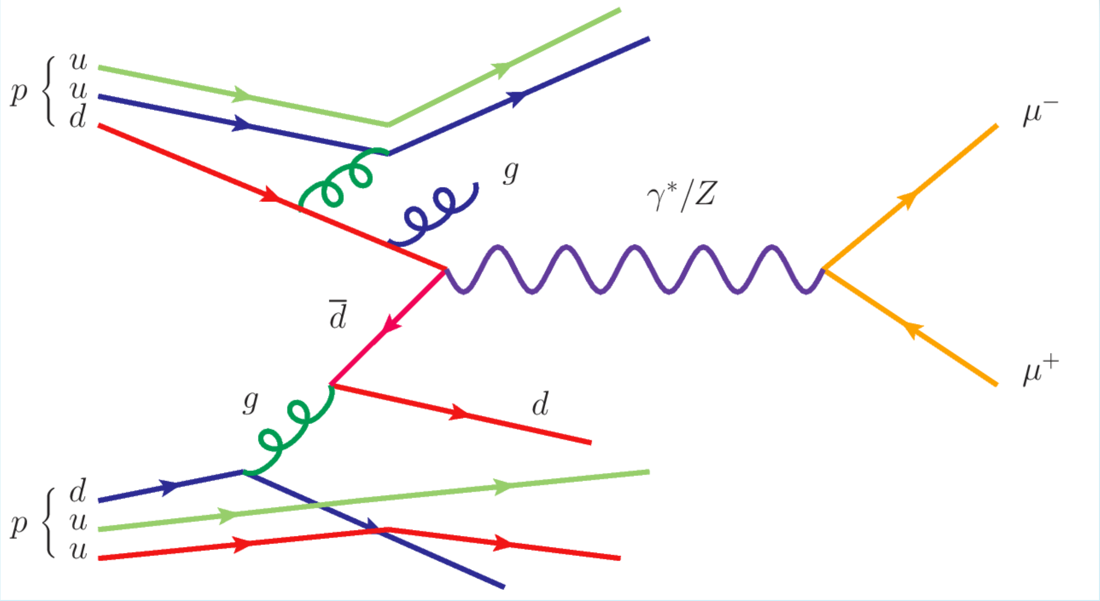


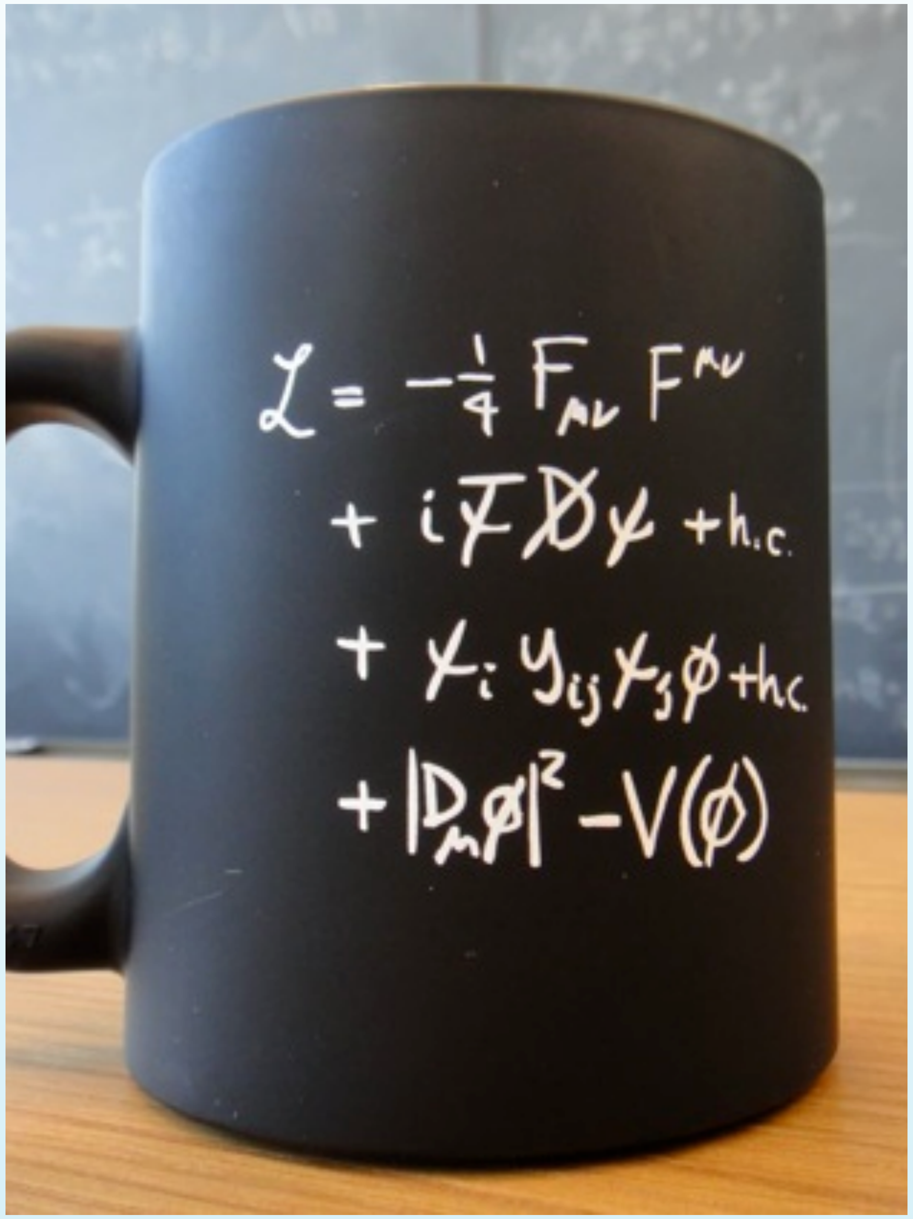


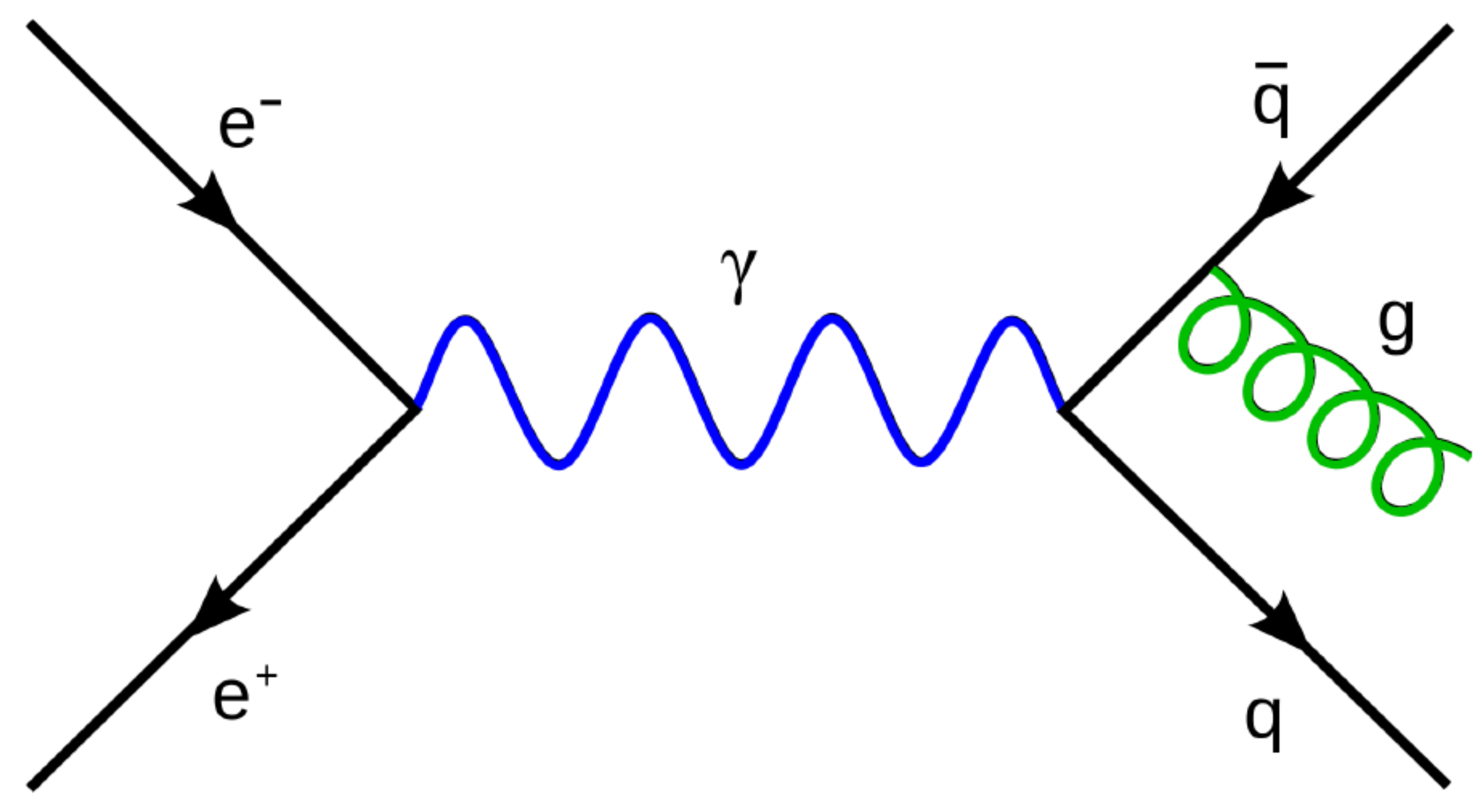
A crash course on parton distributions



Lepton vs Hadron Colliders

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

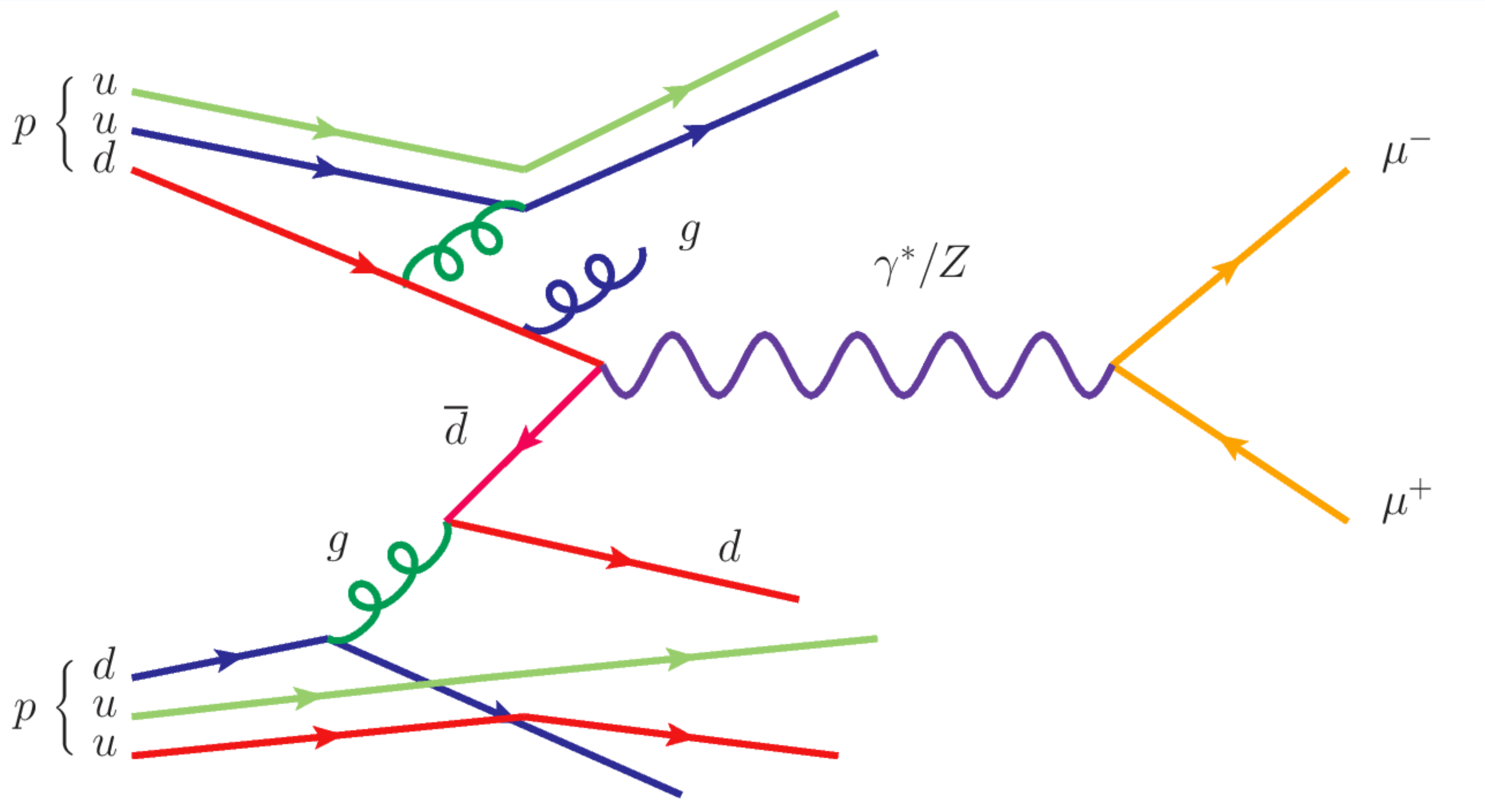




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

Lepton vs Hadron Colliders

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



Lepton vs Hadron Colliders

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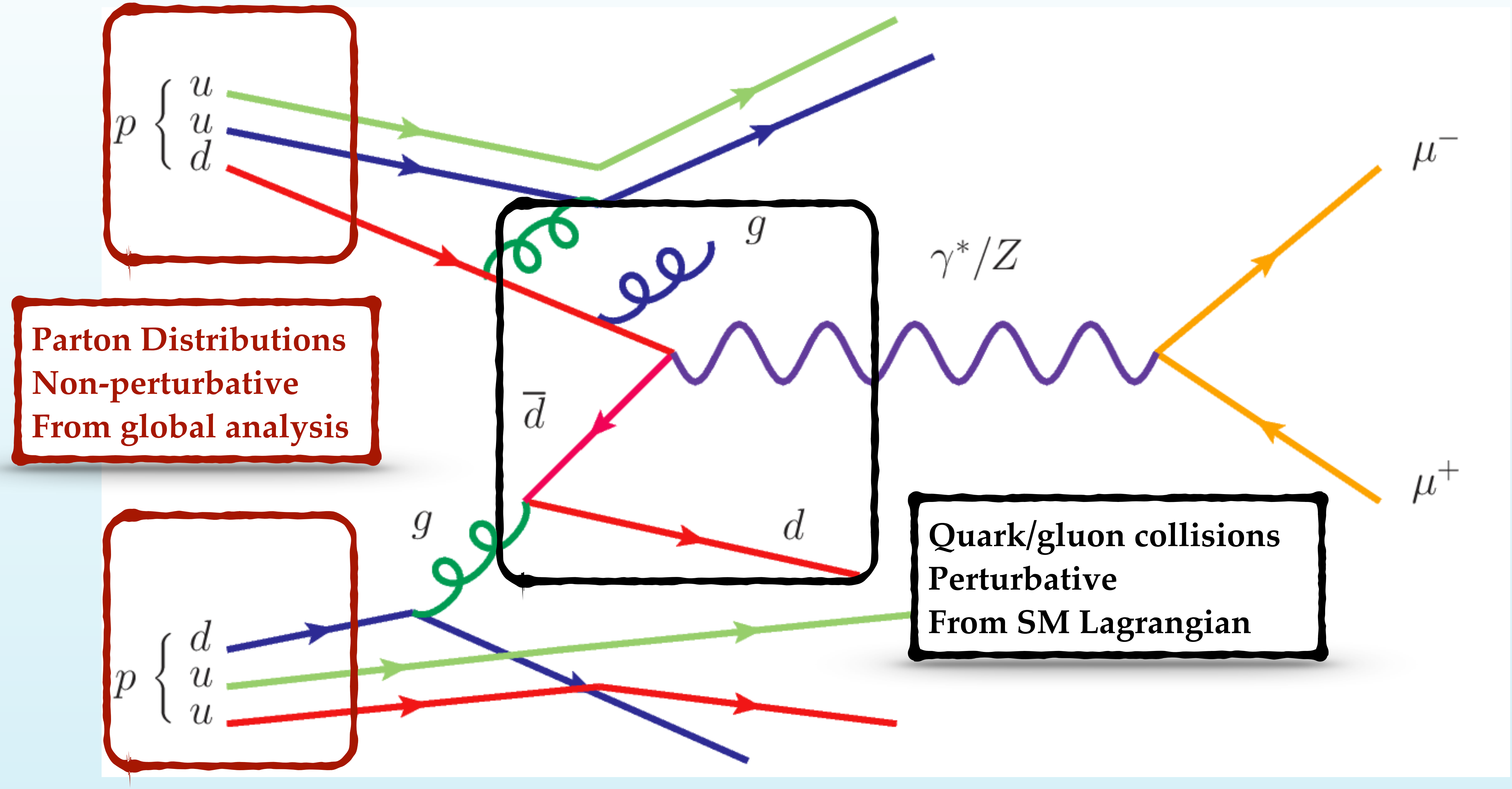


Parton Distributions
Non-perturbative
From global analysis

Quark/gluon collisions
Perturbative
From SM Lagrangian

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

Initial state: 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

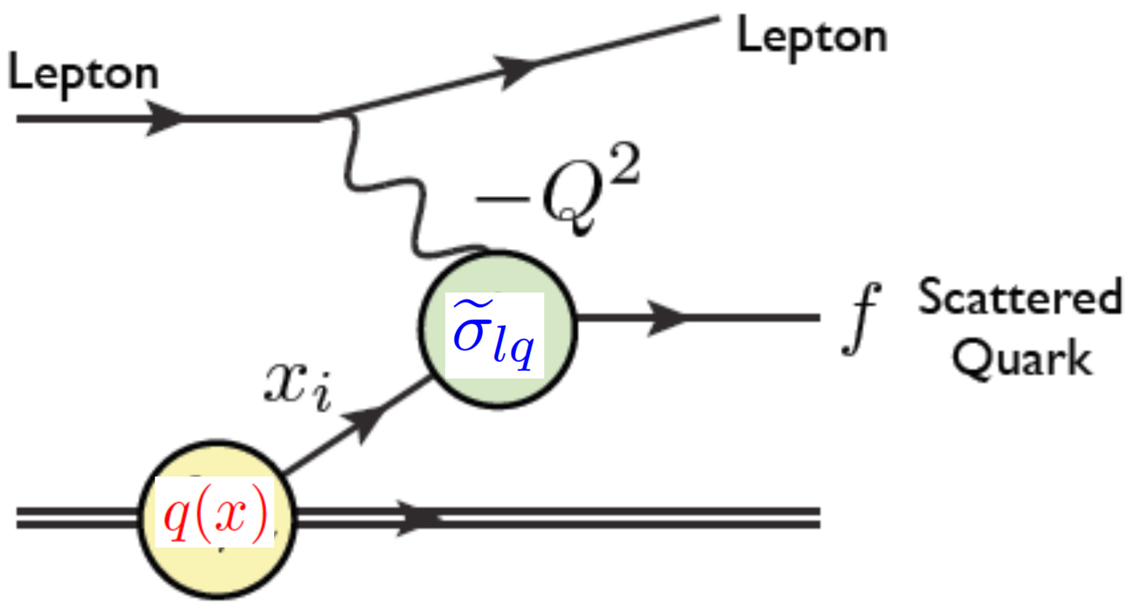
g(x,Q): **Probability** of **finding a gluon inside a proton**, carrying a fraction *x* of the proton momentum, when probed with energy *Q*

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

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

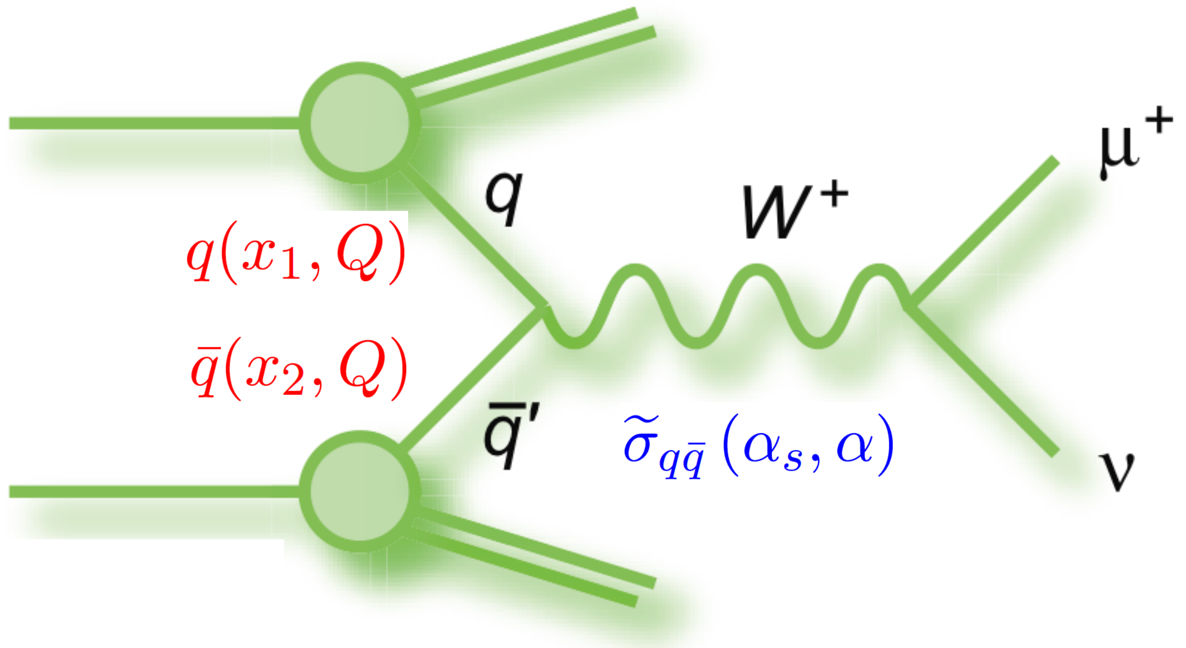
Extract from experimental data within a ***global analysis***

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



Extract PDFs from lepton-proton collisions

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



Use PDFs to predict proton-proton cross-sections

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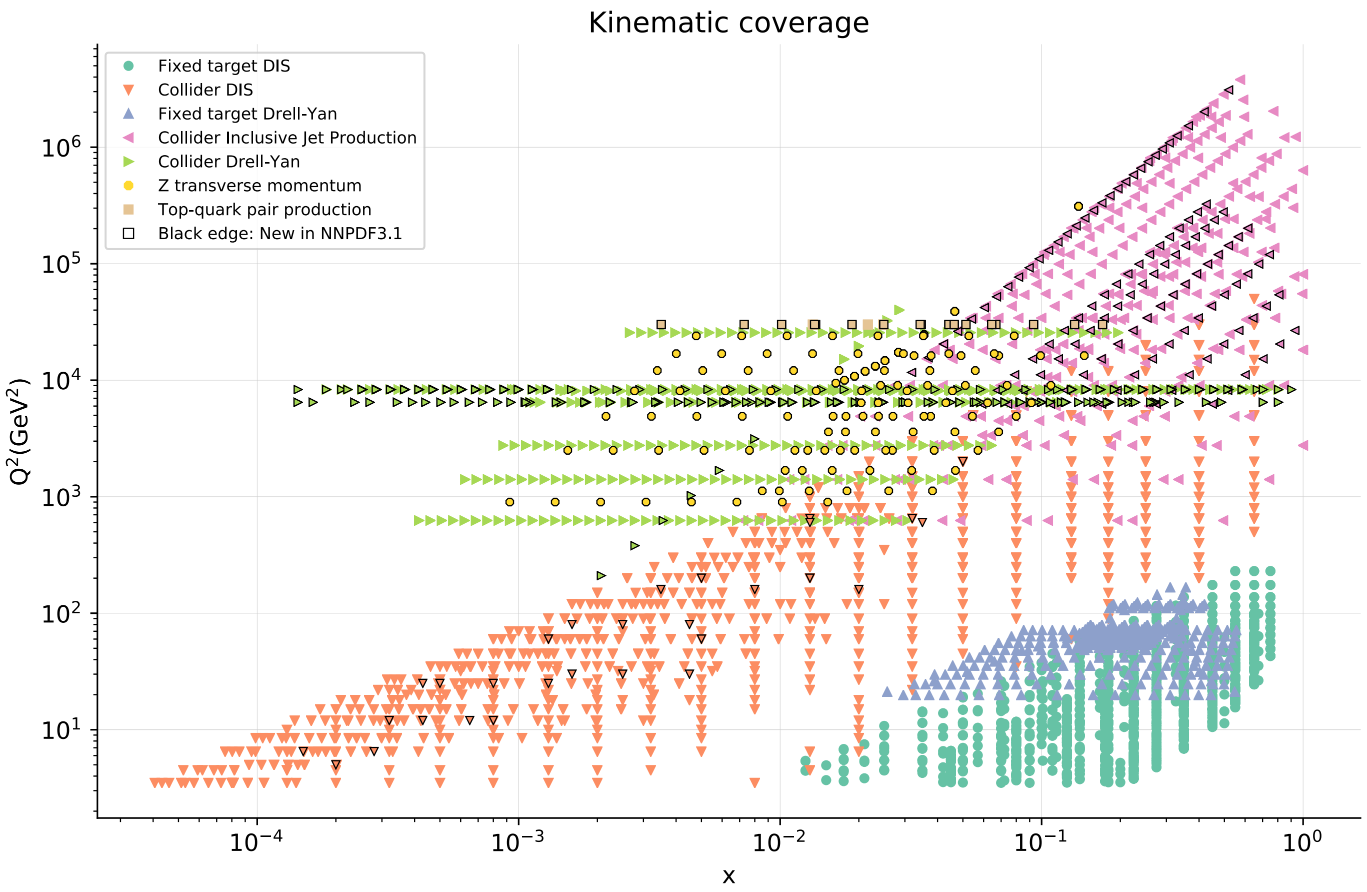
PDFs** determined by **non-perturbative QCD dynamics

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

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

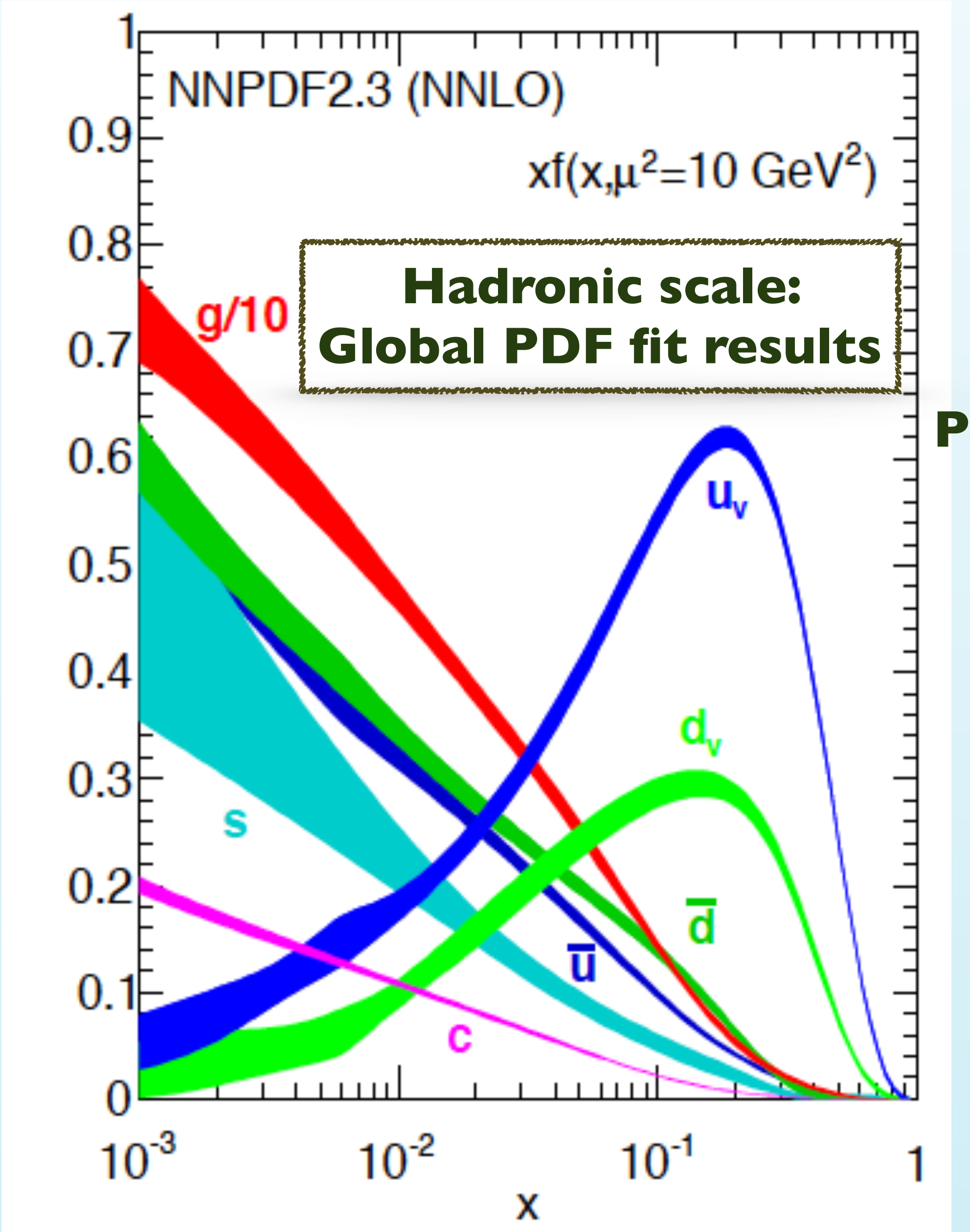
- Including **O(5000) data** points ,
- from **O(40) experiments**,
- some of them with ≈**1% errors**,

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



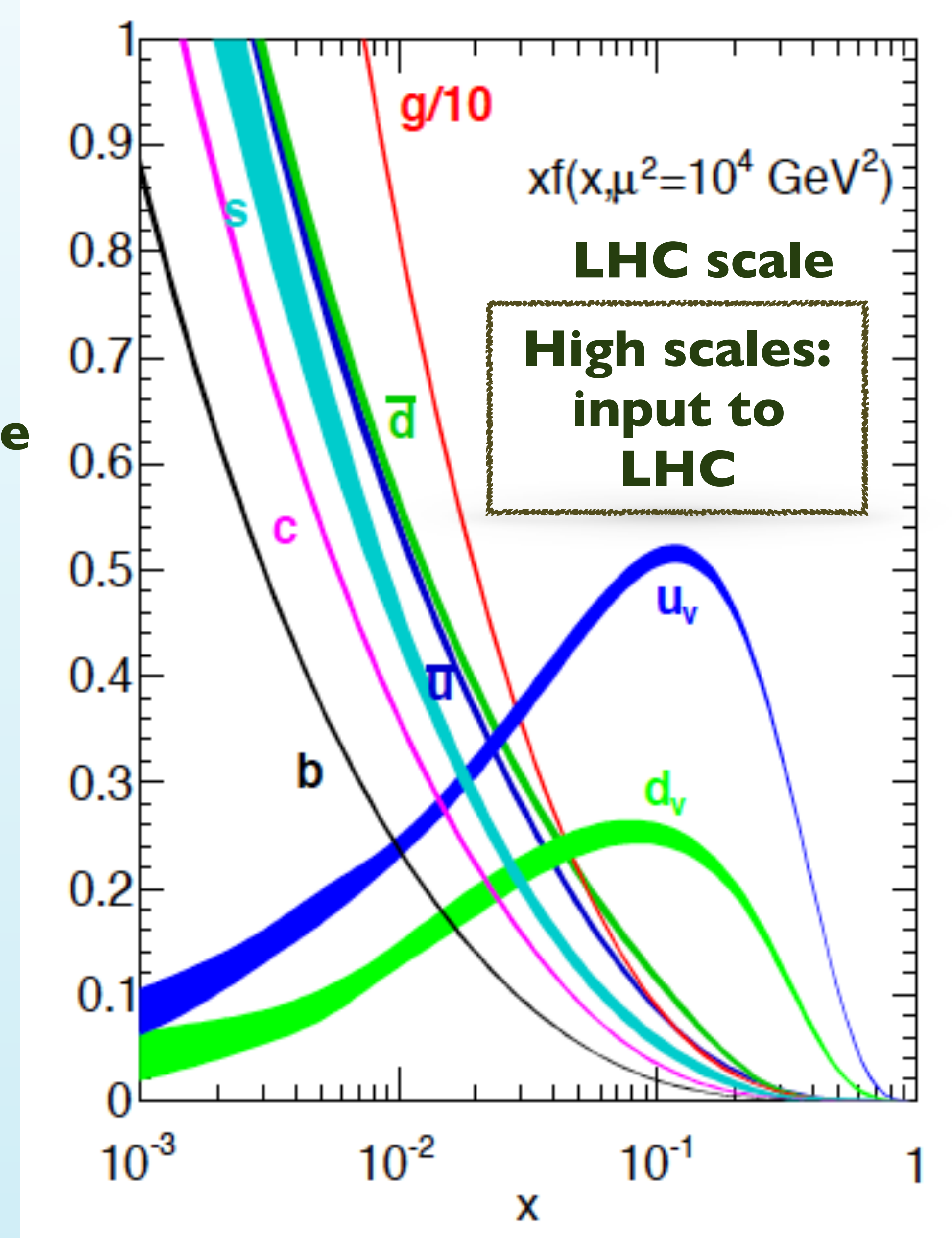
The global PDF analysis

- 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
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**



Hadronic scale: Global PDF fit results

Perturbative Evolution



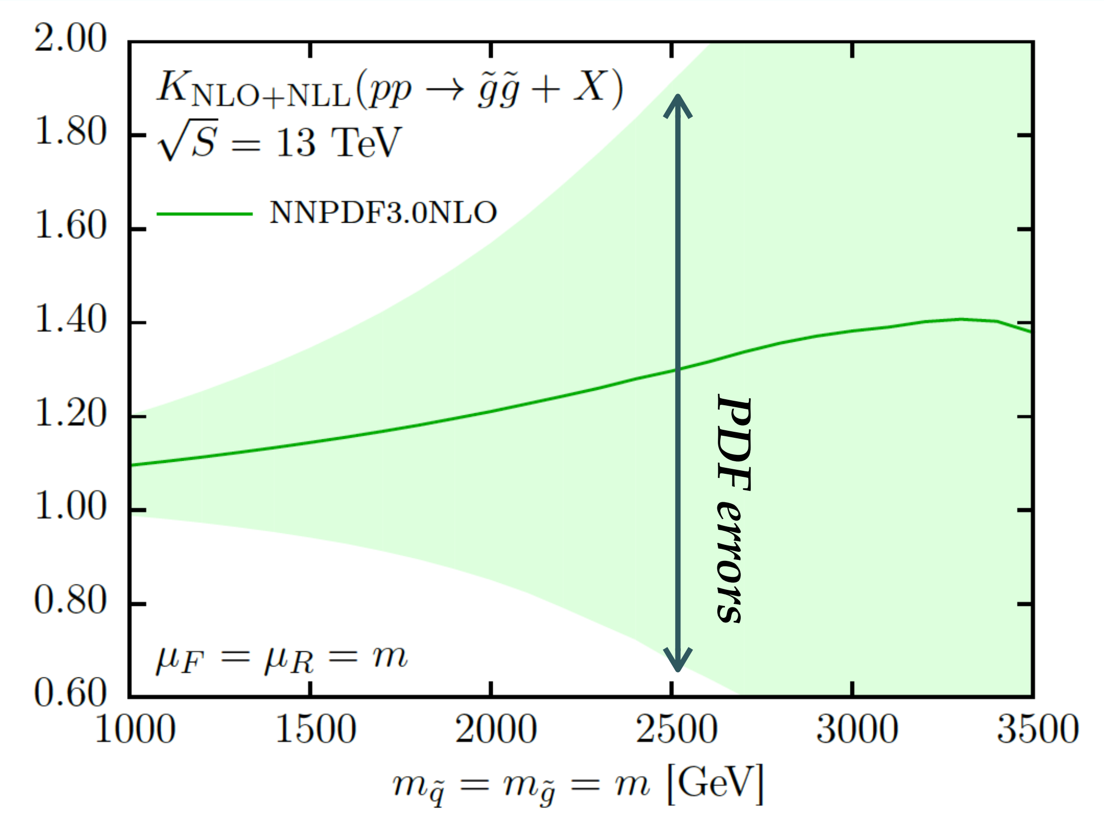
LHC scale

High scales: input to LHC

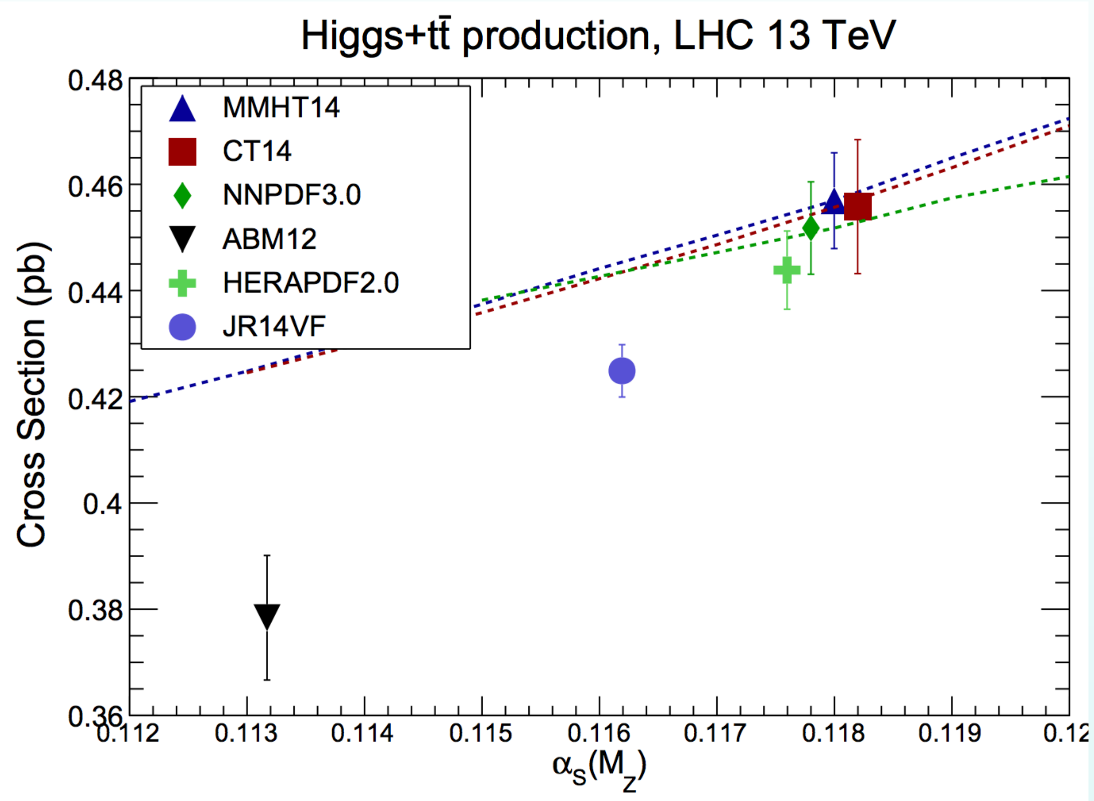
Why precision PDFs?

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

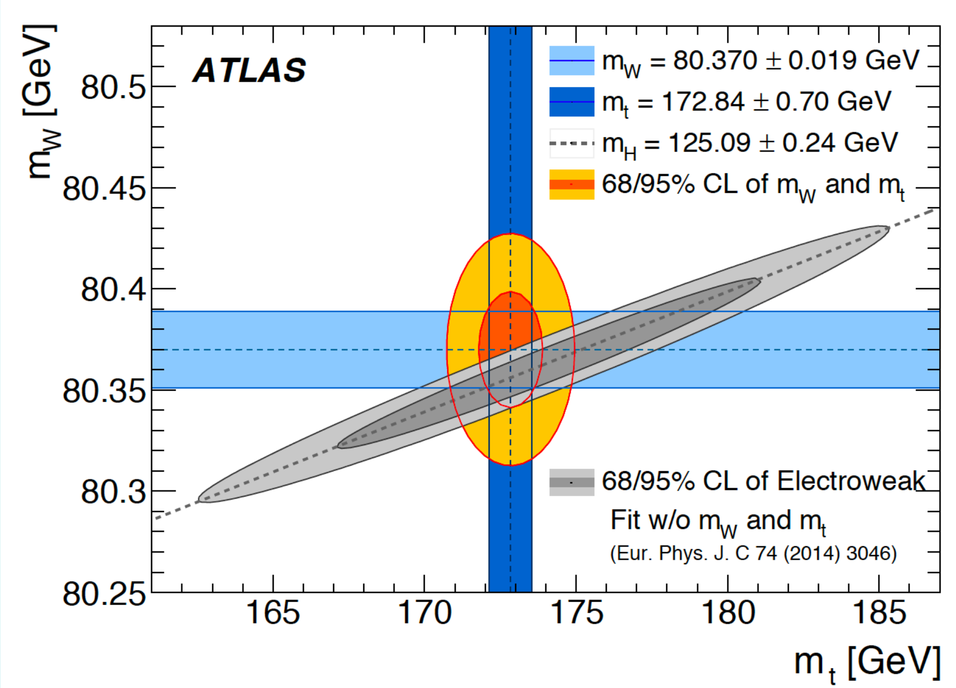
heavy SUSY particle production



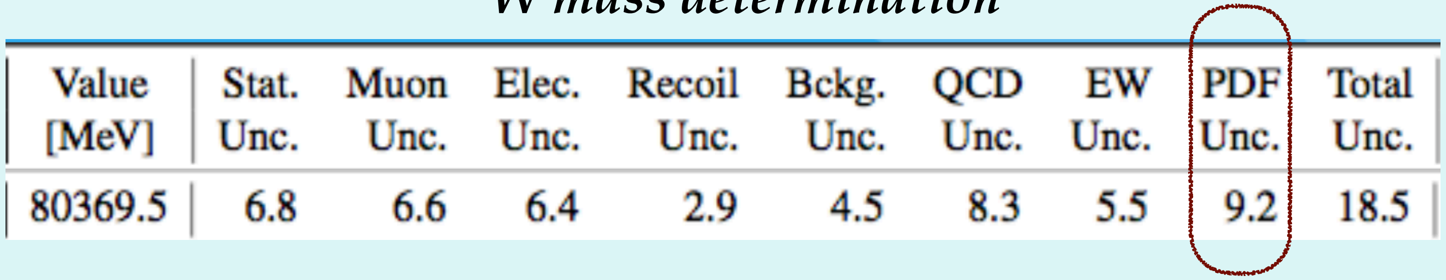
Higgs couplings



spread between PDF sets



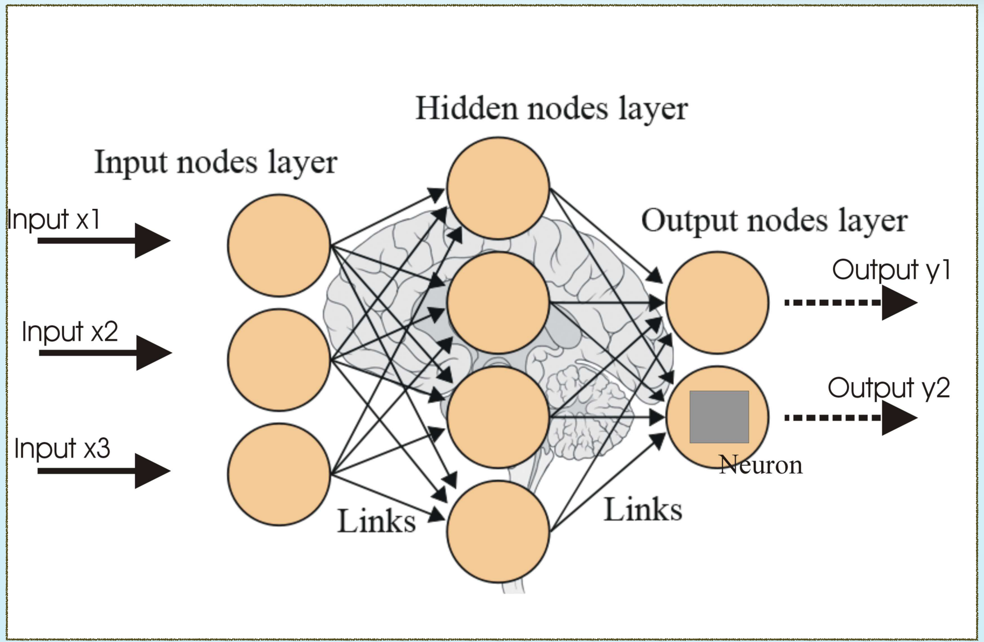
W mass determination



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]

Machine Learning and Artificial Neural Networks

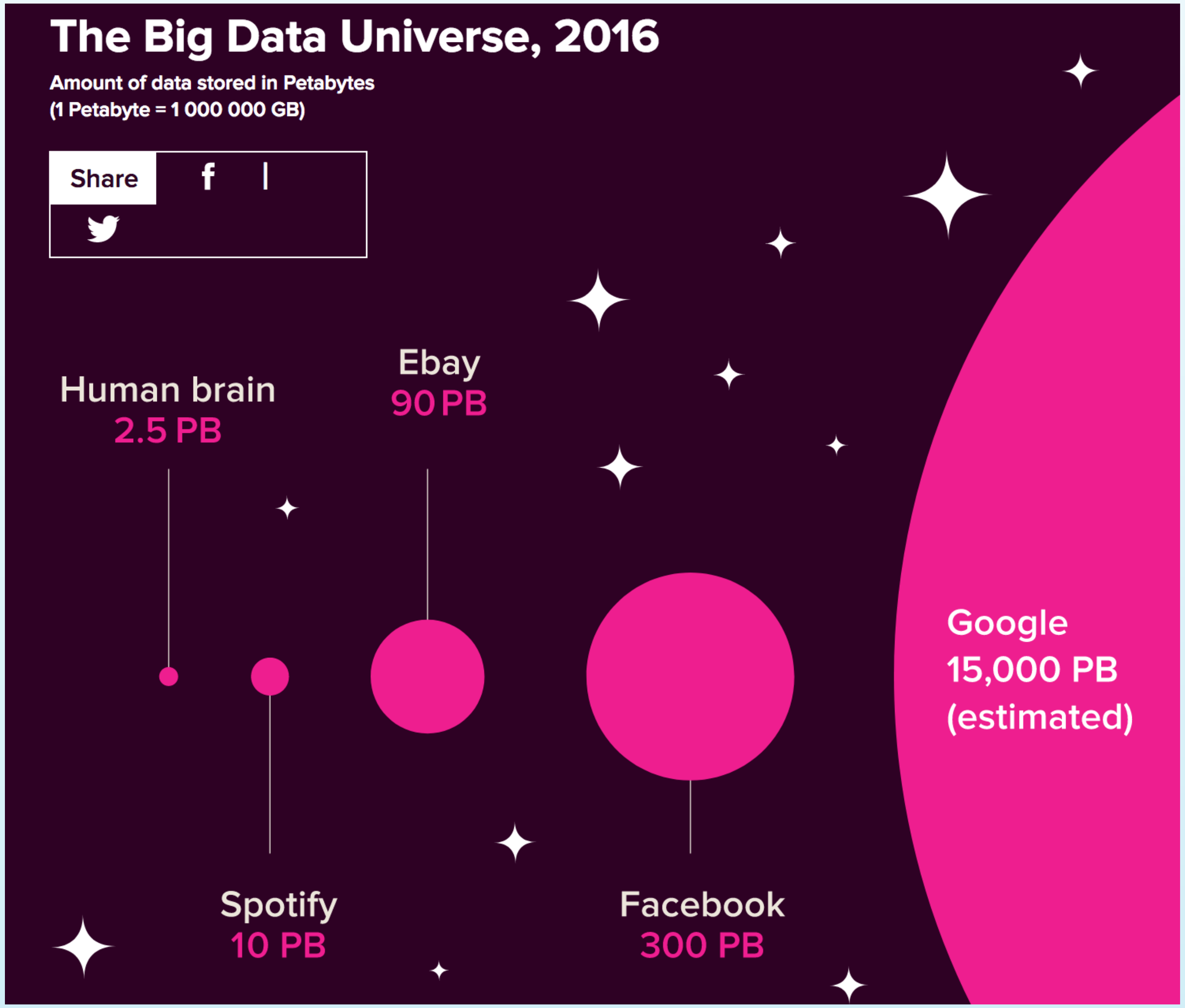


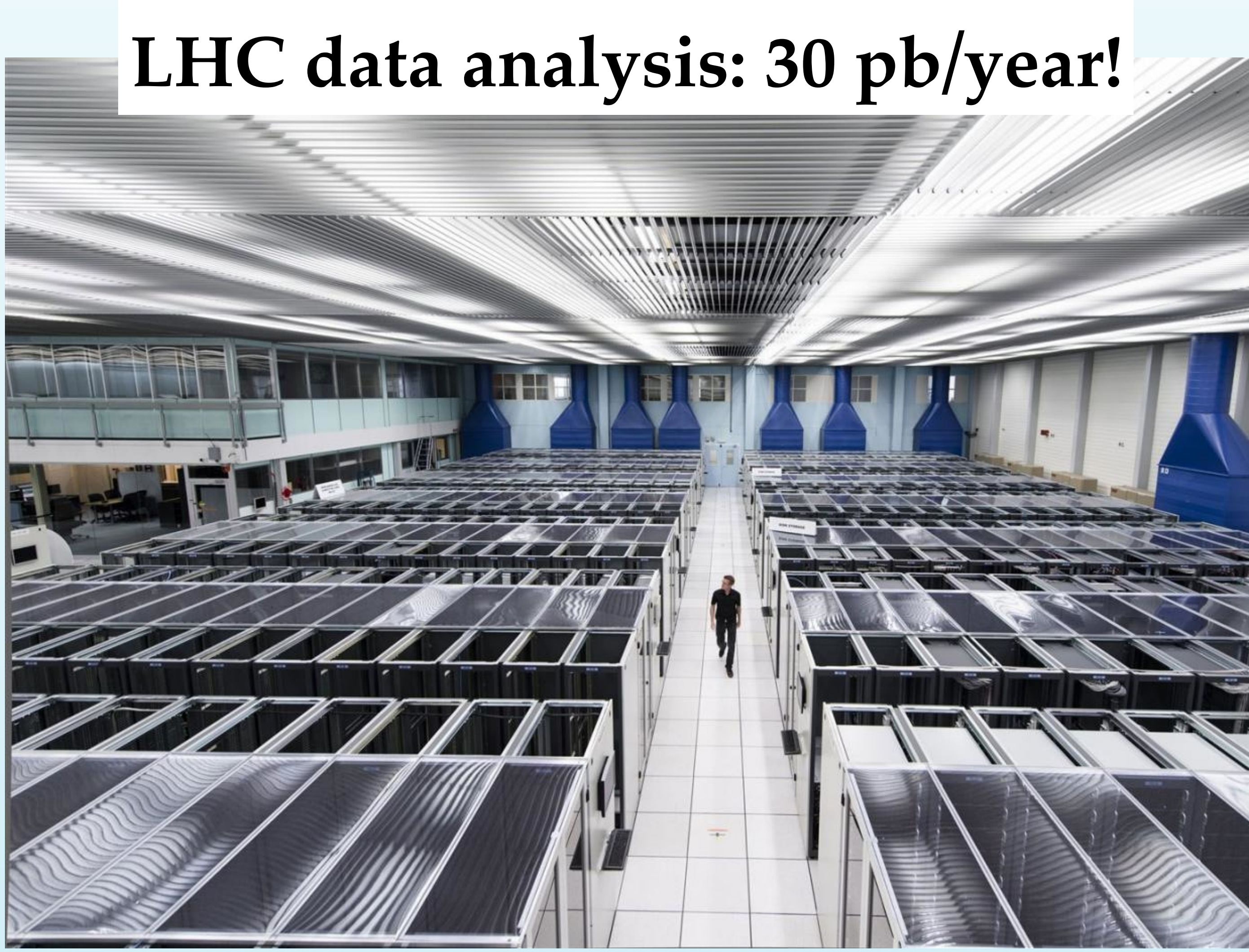
What is machine learning?

THE ROYAL SOCIETY

Machine Learning at the LHC

- By **Machine Learning** we usually denote those families of computer algorithms that **learn how to excel on a task** based on a **large sample of examples**, rather than on some a priori fixed rules
- ML algorithms are nowadays ubiquitous, from **driverless cars** to **Amazon's purchase suggestions**, to **automated medical imaging recognition** to beating the words best players at Go and chess
- ML tools rely on the **efficient exploitation of immense datasets**. And the **LHC** has a lot of data!



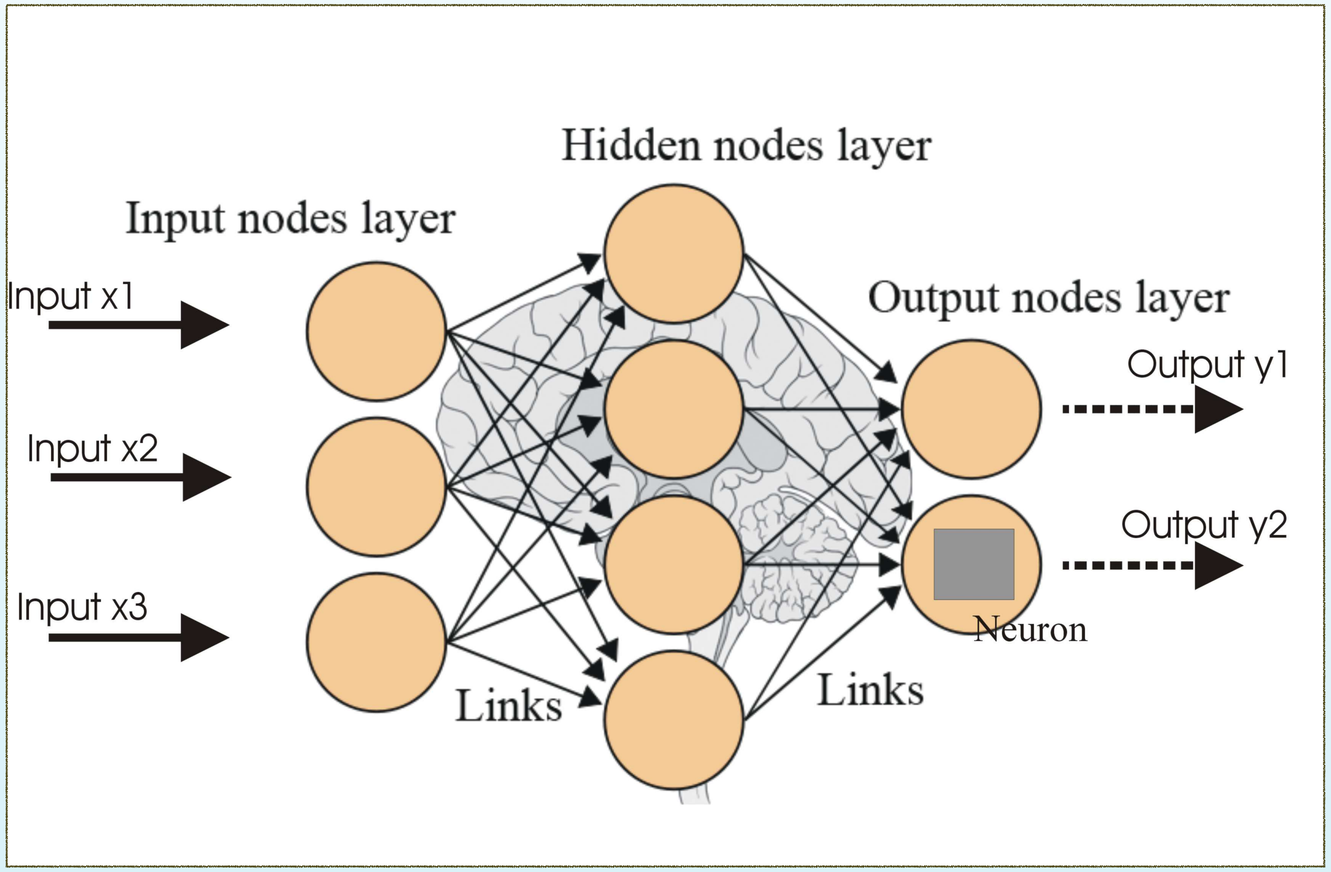


LHC data analysis: 30 pb/year!

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** are **mathematical algorithms** widely used in a wide range of applications, from **HEP** to **targeted marketing** and **finance forecasting**

From Biological to Artificial Neural Networks



Artificial neural networks aim to excel where domains as their **evolution-driven counterparts outperforms traditional algorithms in tasks such as pattern recognition, forecasting, classification**, …

Neural Networks demystified

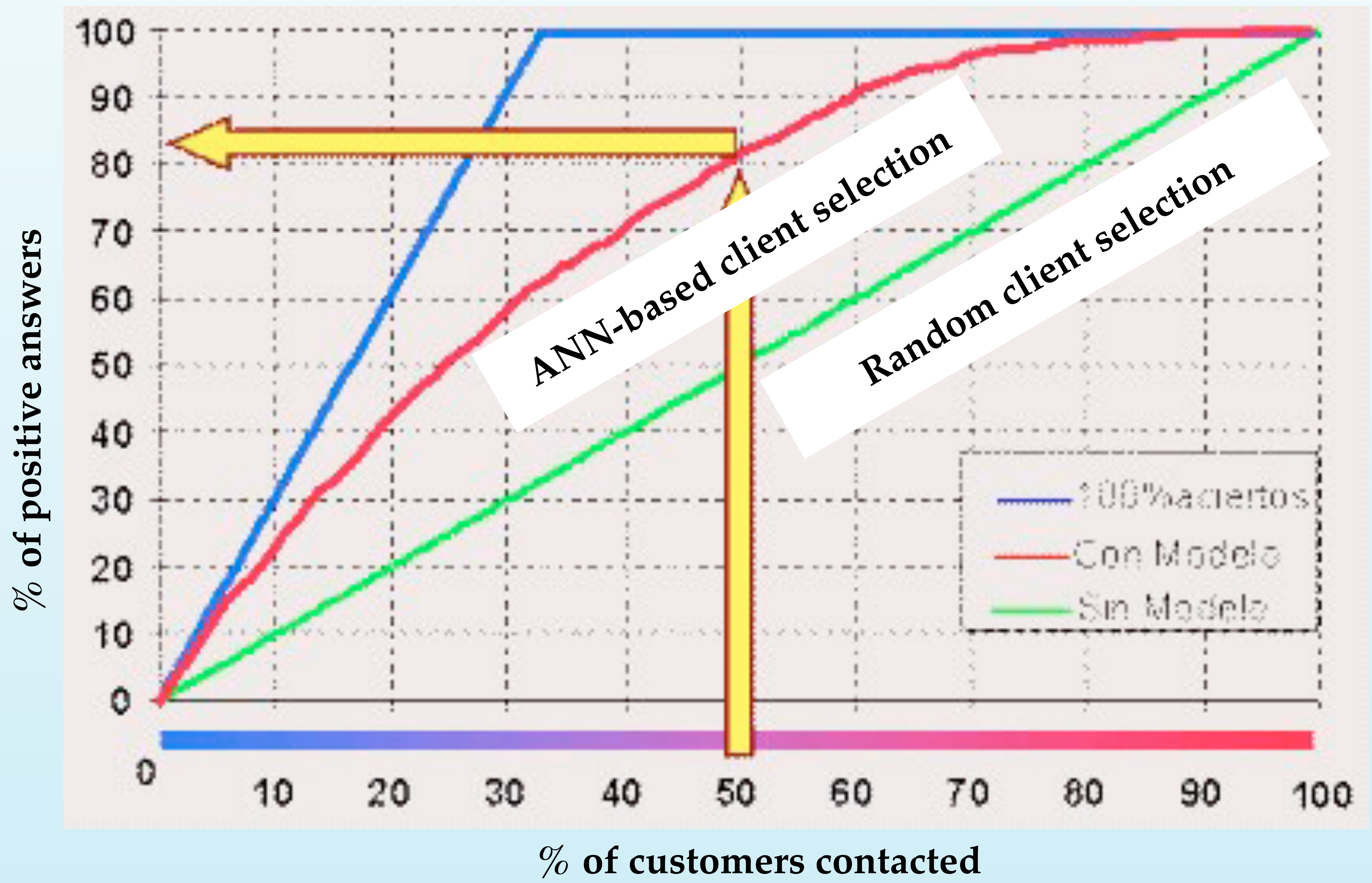
[*https://www.youtube.com/watch?v=bxe2T-V8XRs*](https://www.youtube.com/watch?v=bxe2T-V8XRs)

ANNs - a marketing example

A bank wants to offer a new credit card to their clients. Two possible strategies:

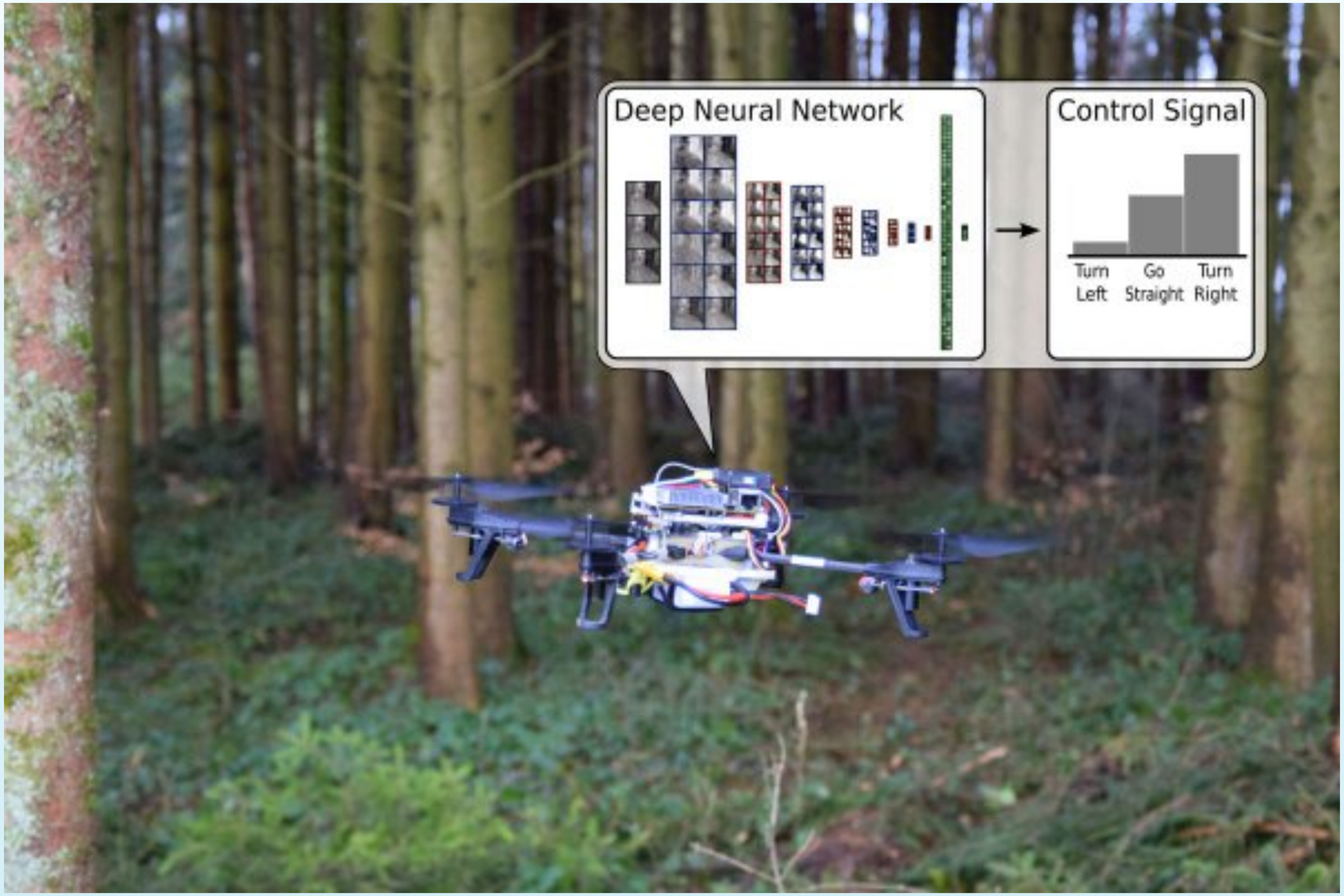
- **Contact all customers**: slow and costly
- Contact **5%** of the customers, **train a ANN with their input** (gender, income, loans) and **their output** (yes/no) and use the information to **contact only clients likely to accept the product**

Cost-effective method to improve marketing performance!



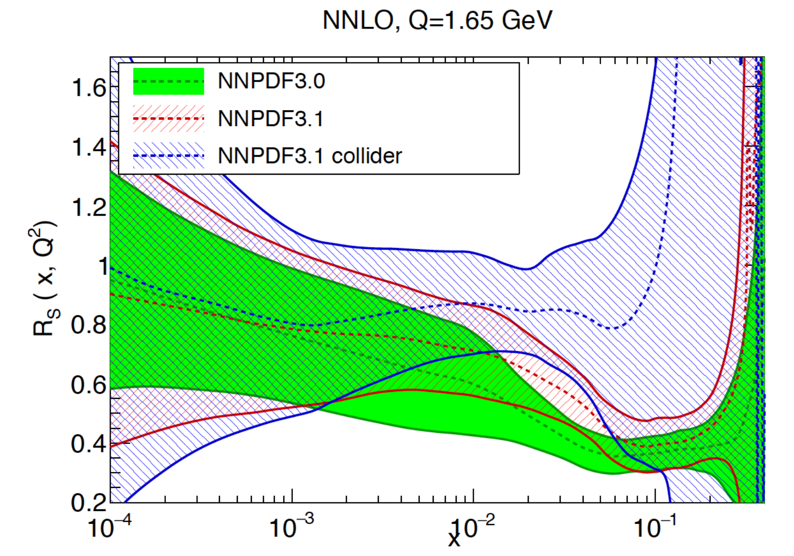
ANNs and pattern recognition

- ANNs can enable an **autonomous vision-control drone** to recognize and follow forest trails
- Image classifier operates directly on **pixel-level image intensities**
- If a trail is visible, the **software steers the drone** in the corresponding direction

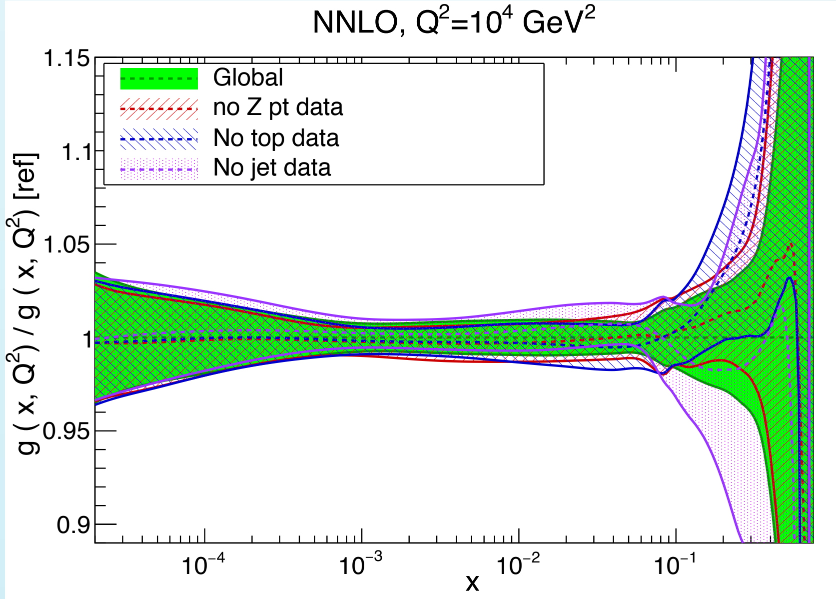


Giusti et al, IEEE Robotics and Automation Letters, 2016

Similar algorithms at work in self-driving cars!



The NNPDF way



The NNPDF approach

A **novel approach to PDF determination**, improving the limitations of the traditional PDF fitting methods with the use of **advanced statistical techniques** such as **machine learning** and **multivariate analysis**

Non-perturbative PDF parametrization

- **Traditional approach**: based on **restrictive functional forms** leading to strong theoretical bias
- **NNPDF solution**: use **Artificial Neural Networks** as universal unbiased interpolants

PDF uncertainties and propagation to LHC calculations

- **Traditional approach**: limited to Gaussian/linear approximation
- **NNPDF solution**: based on the **Monte Carlo replica method** to create a probability distribution in the space of PDFs. Specially critical in **extrapolation regions** (**i.e.** high-x) for New Physics searches

Fitting technique

- **Traditional approach**: deterministic minimization of χ^2, **flat directions** problem
- **NNPDF solution**: **Genetic Algorithms** to explore efficiently the vast parameter space, with **cross-validation** to avoid fitting stat fluctuations

ANNs as universal unbiased interpolants

ANNs provide **universal unbiased interpolants** to parametrize the non-perturbative dynamics that determines the **size and shape of the PDFs** from experimental data

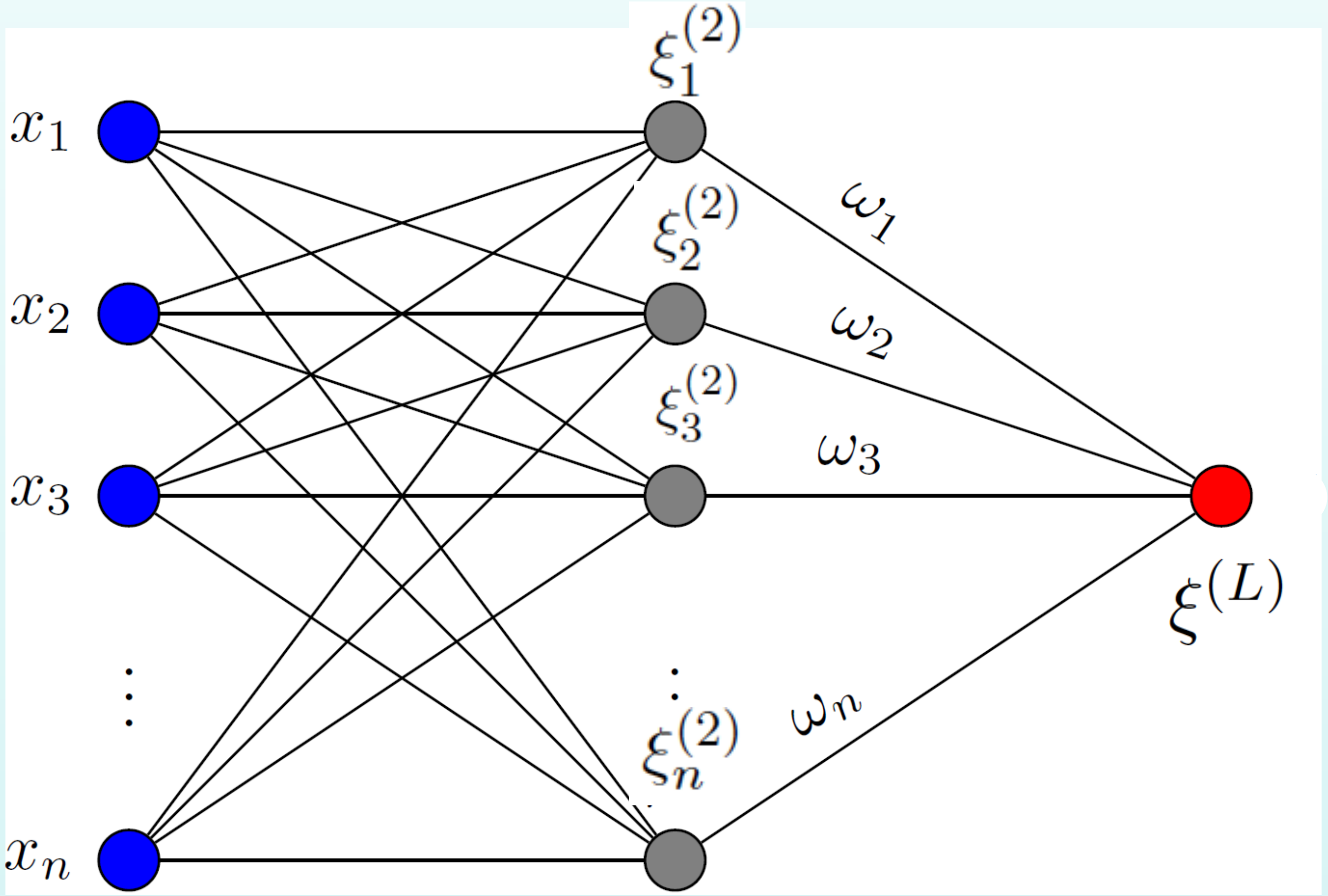
not from QCD!

Traditional approach

$$g(x,Q_0) = A_g(1-x)^{a_g}x^{-b_g}\left(1+c_g\sqrt{s}+d_gx+\ldots\right)$$

NNPDF approach

$$g(x,Q_0) = A_g\mathrm{ANN}_g(x)$$



$$\mathrm{ANN}_g(x) = \xi^{(L)} = \mathcal{F}\left[\xi^{(1)},\{\omega_{ij}^{(l)}\},\{\theta_i^{(l)}\}\right]$$

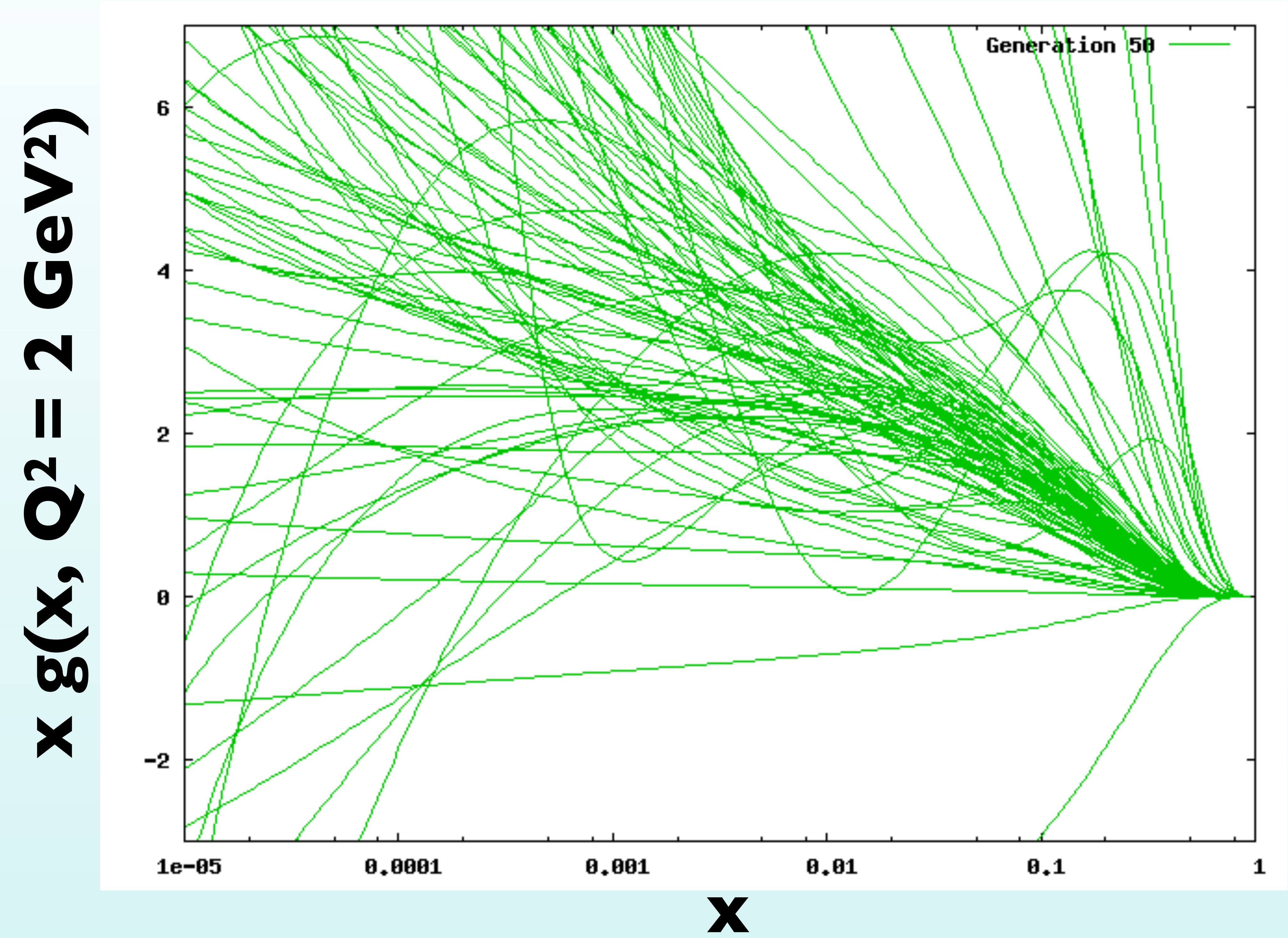
$$\xi_i^{(l)} = g\left(\sum_{j=1}^{n_{l-1}}\omega_{ij}^{(l-1)}\xi_j^{(l-1)}-\theta_i^{(l)}\right)$$

- ANNs eliminate **theory bias** introduced in PDF fits from choice of *ad-hoc* functional forms
- NNPDF fits used **O(400) free parameters**, to be compared with O(10-20) in traditional PDFs. Results stable if **O(4000) parameters used!**

PDF Replica Neural Network Learning

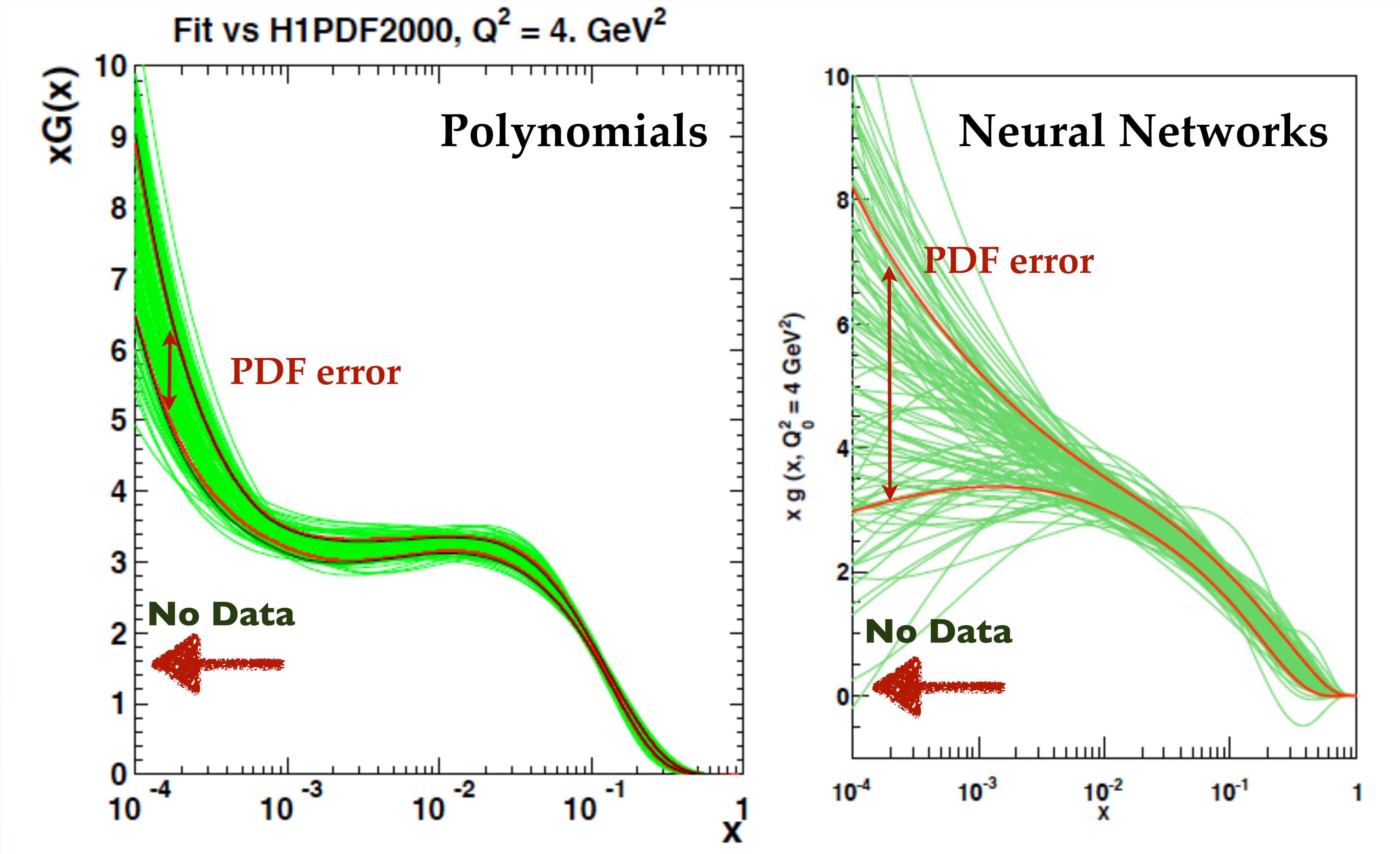
The minimisation of the **data vs theory χ^2** is performed using **Genetic Algorithms**

Each **green curve** corresponds to a **gluon PDF Monte Carlo** replica



Artificial Neural Networks vs Polynomials

- Compare a **benchmark PDF analysis** where **the same dataset** is fitted with **Artificial Neural Networks** and with **standard polynomials,** other settings identical)
- **ANNs** avoid biasing the PDFs, **faithful extrapolation at small-x** (very few data, thus error blow up)



The NNPDF3.1 global analysis

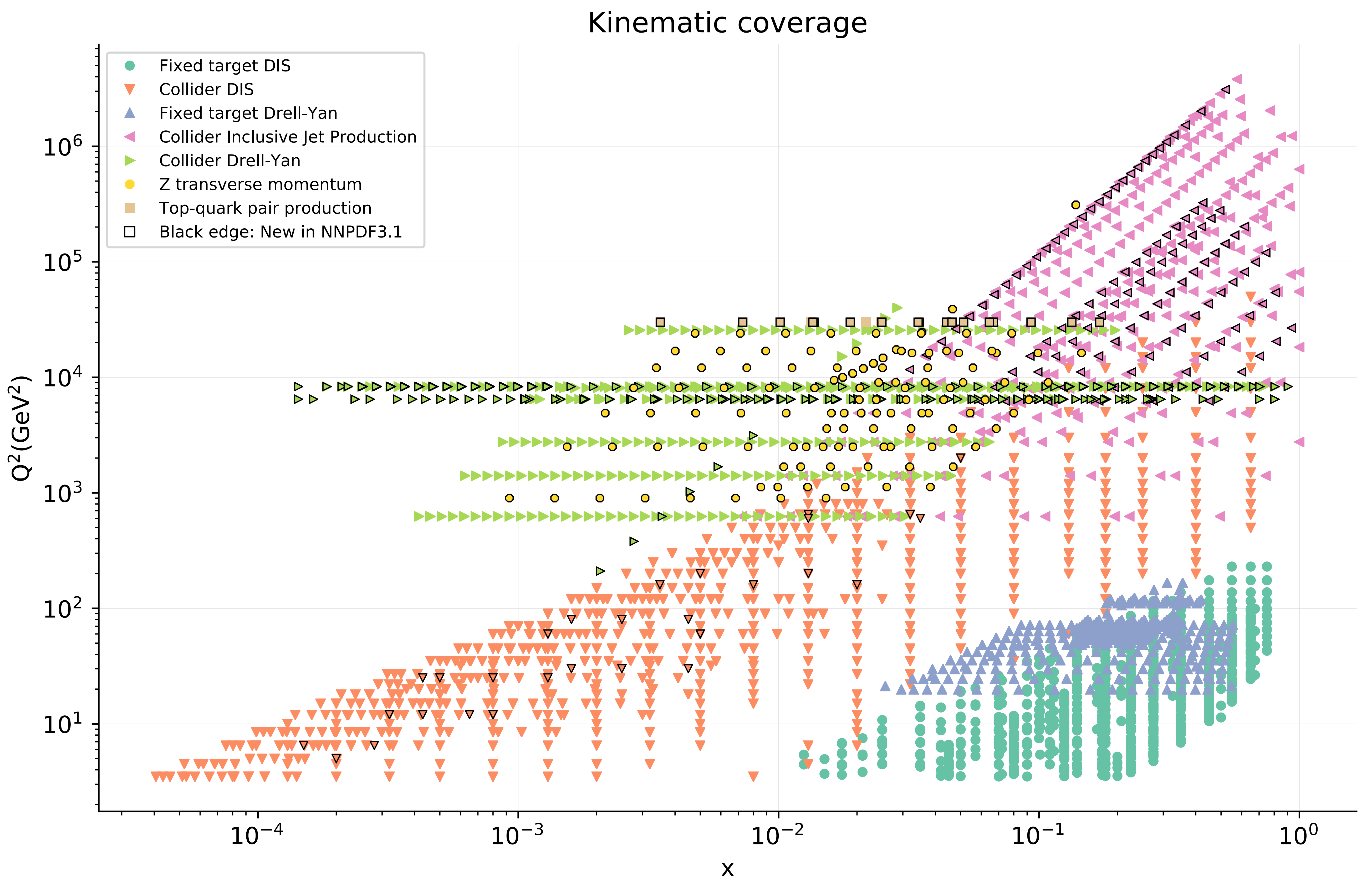
An **update of the NNPDF global analysis** is motivated by:

☑ The availability of a wealth of **high-precision PDF-sensitive measurements** from the Tevatron, ATLAS, CMS and LHCb, including processes such as the **Z p_T** and **differential distributions in top-quark production** that have never been used before in a PDF fit

☑ The striking **recent progress in NNLO QCD calculations**, which allows to include the majority of PDF-sensitive collider measurements into a **fully consistent NNLO global analysis**

☑ The recent realisation that **fitting the charm PDF** has several advantages in the global QCD fit (beyond comparison with non-perturbative models), in particular **stabilise the dependence with m_{charm}** and improve the **data/theory agreement** for some of the most precise collider observables.

New datasets in NNPDF3.1



Fit quality: χ^2

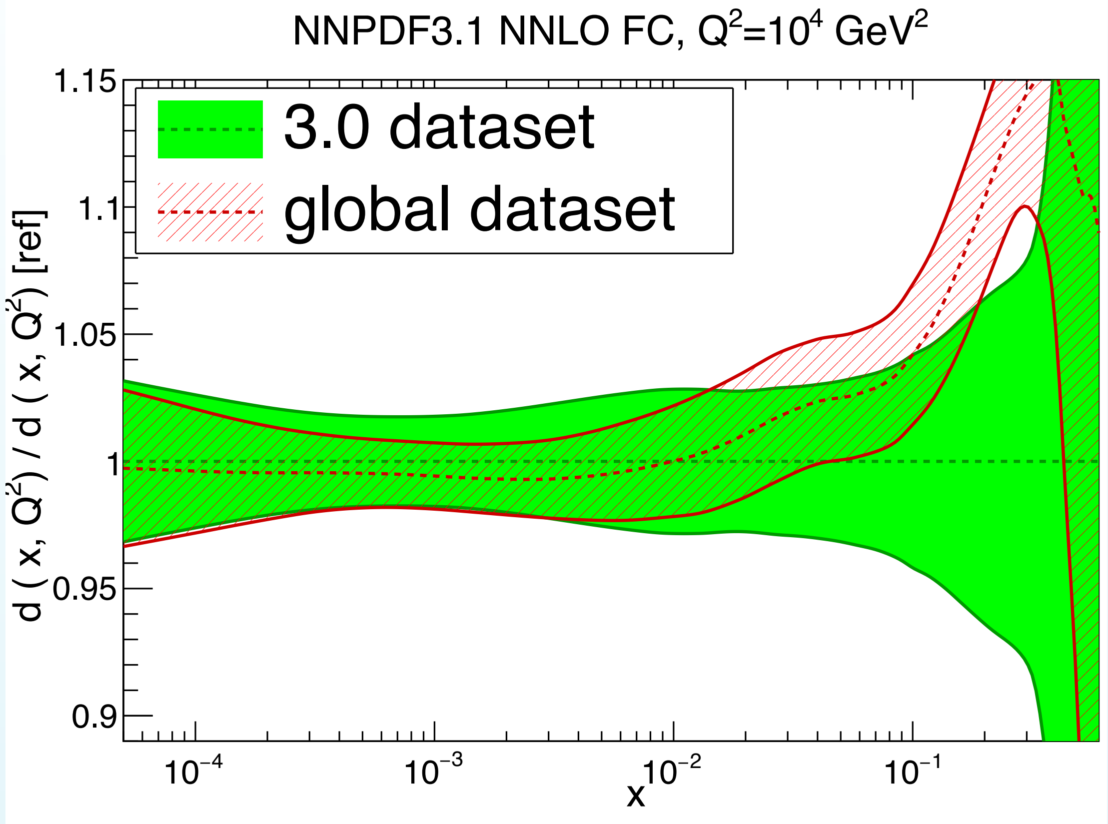
	NNLO FittedCharm	NNLO PertCharm	NLO FittedCharm	NLO PertCharm
HERA	1.16	1.21	1.14	1.15
ATLAS	1.09	1.17	1.37	1.45
CMS	1.06	1.09	1.20	1.21
LHCb	1.47	1.48	1.61	1.77
TOTAL	1.148	1.187	1.168	1.197

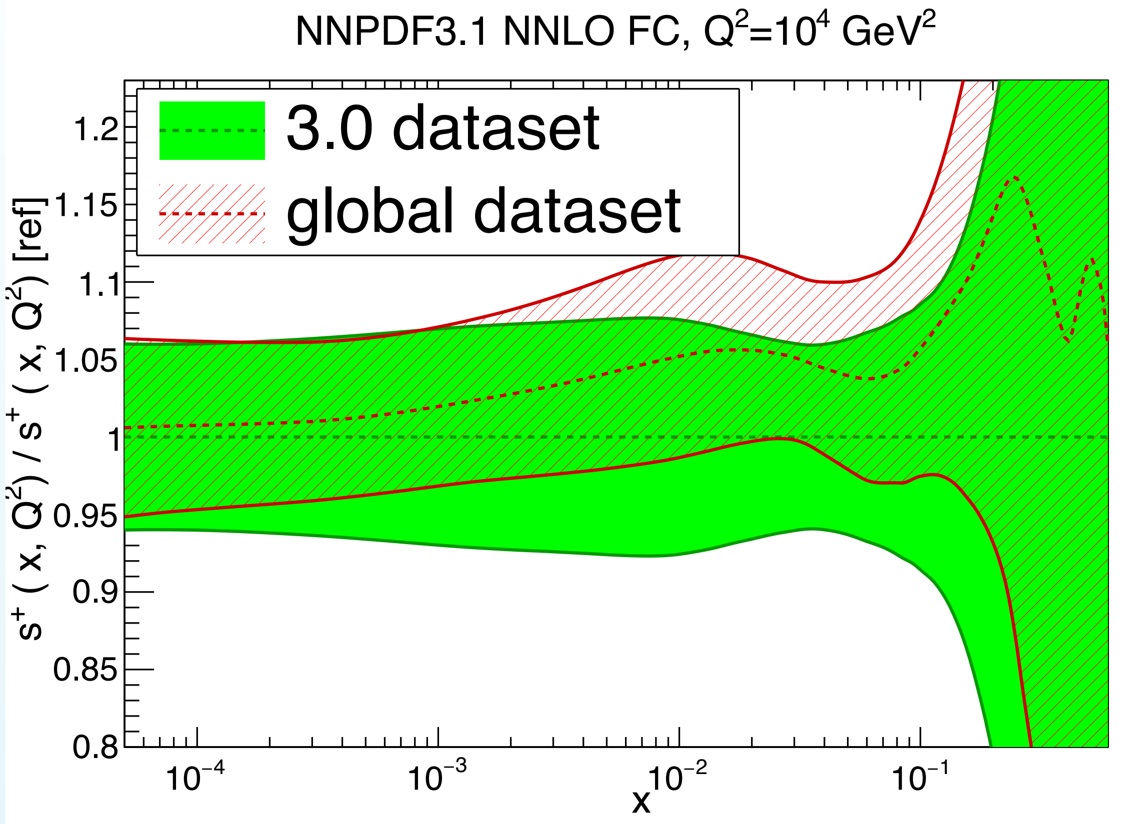
- For collider data, **NNLO theory** leads to a markedly better fit quality that than **NLO** (since the new data included has small experimental uncertainties, and NNLO corrections mandatory)

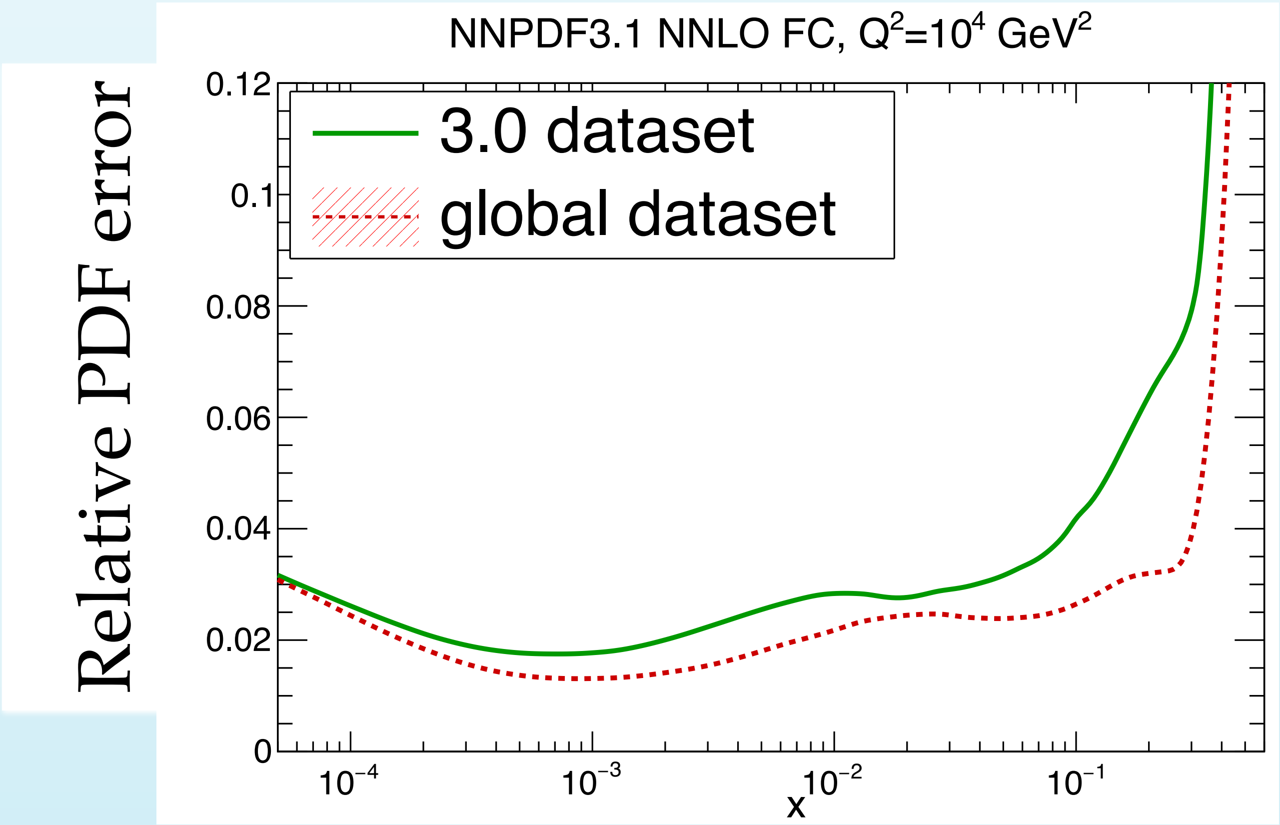
- The global PDF analysis where the charm PDF is fitted leads to a **slightly superior fit quality** than assuming a perturbatively generated charm PDF

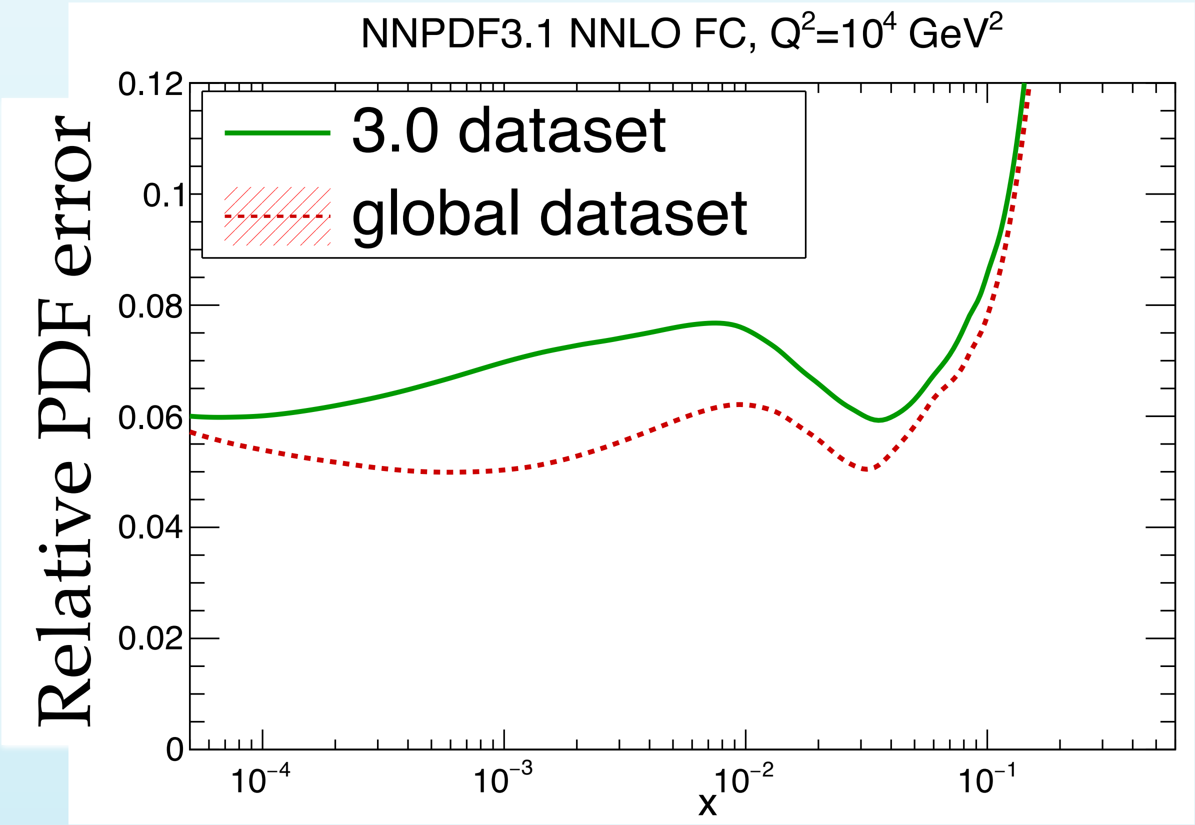
- In general **good description of all the new collider measurements** included in NNPDF3.1

Impact of new data









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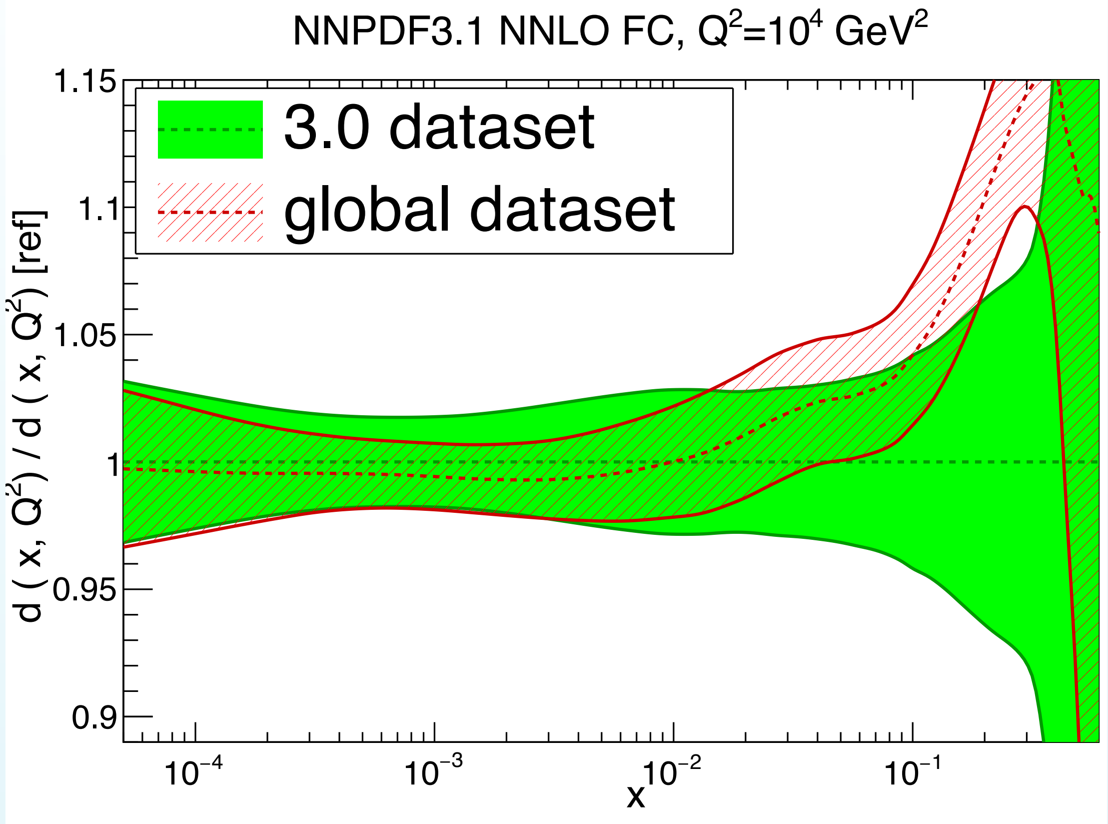
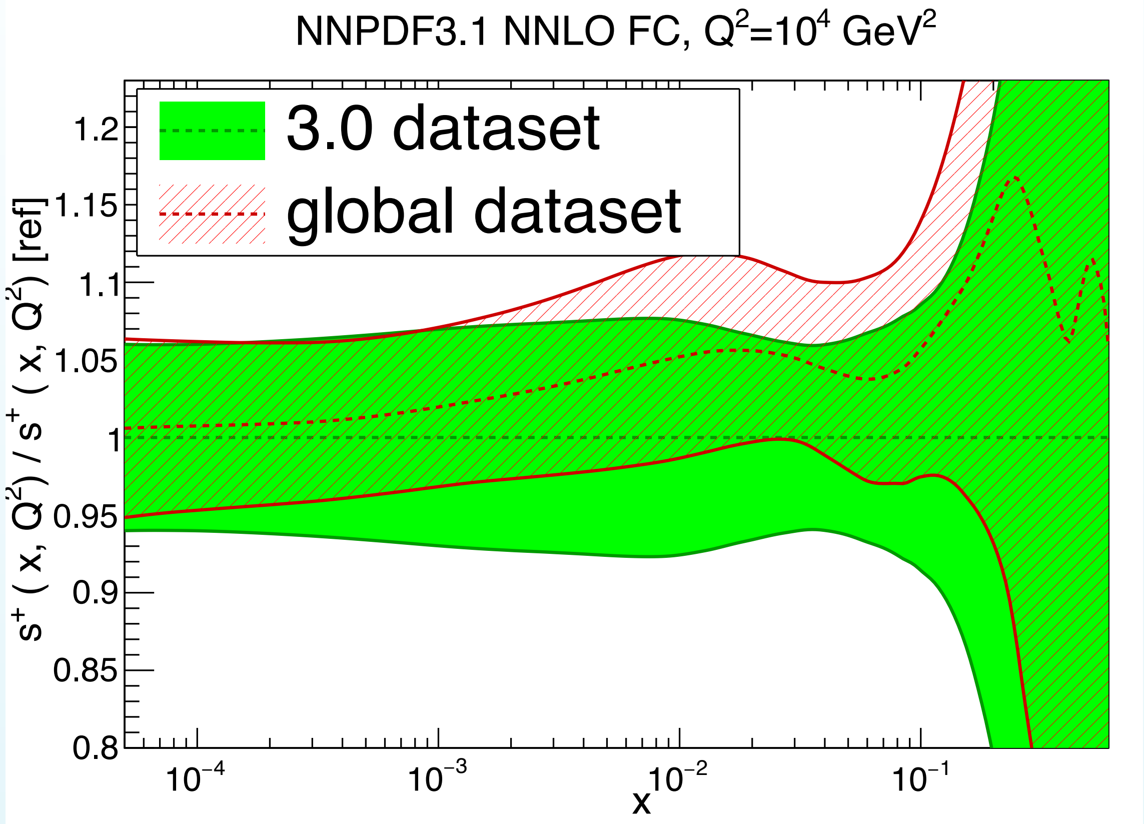
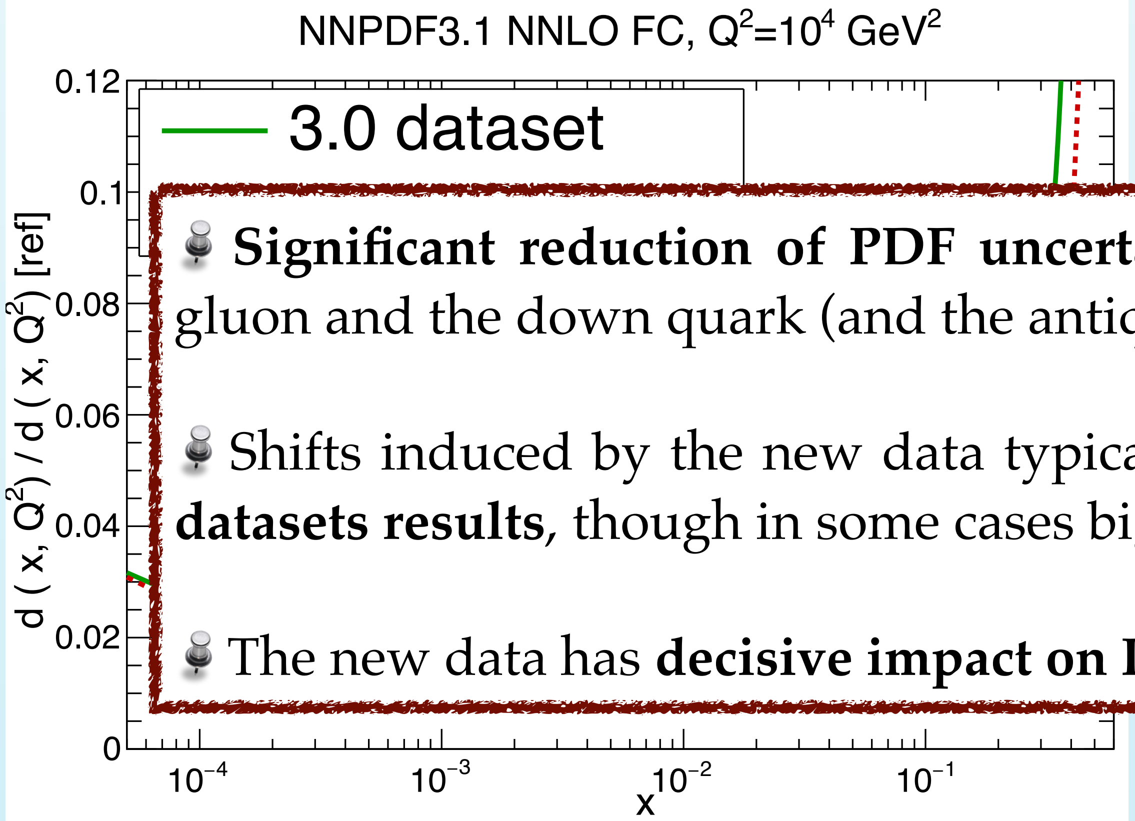
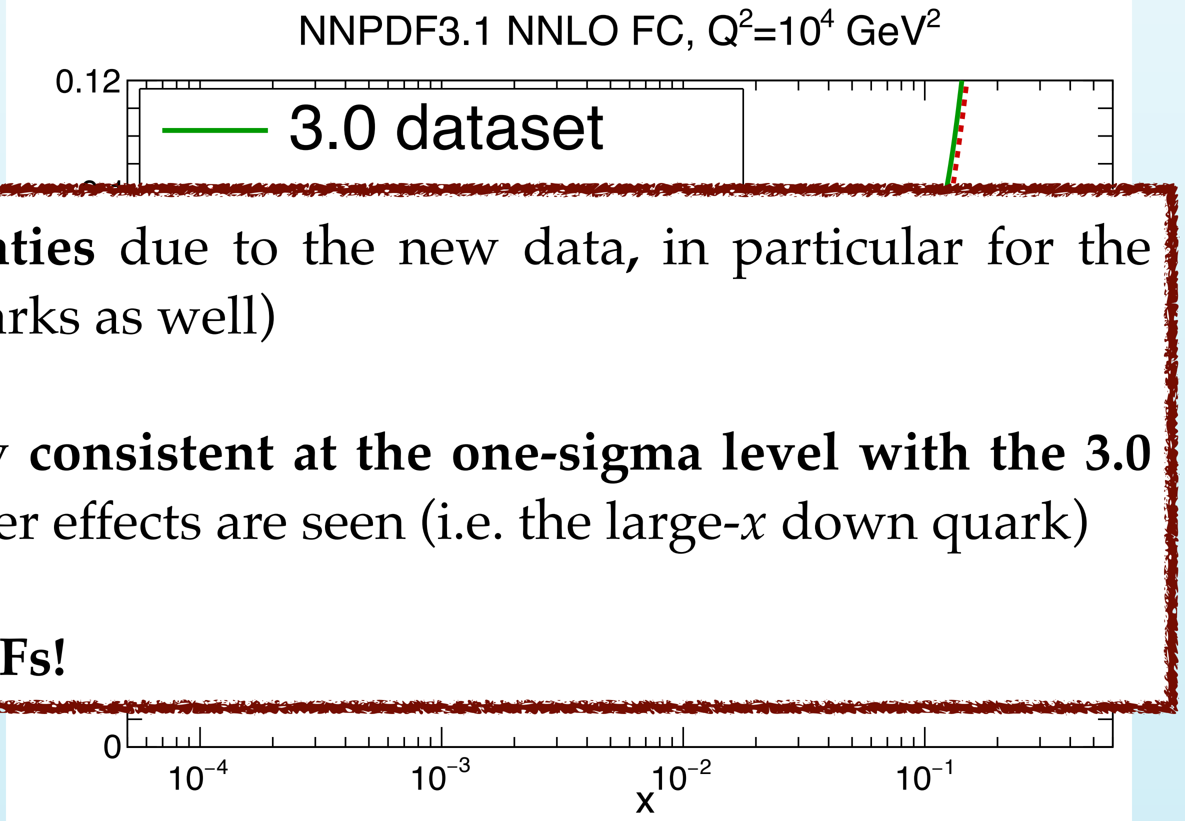








- **Significant reduction of PDF uncertainties** due to the new data, in particular for the gluon and the down quark (and the antiquarks as well)

- Shifts induced by the new data typically **consistent at the one-sigma level with the 3.0 datasets results**, though in some cases bigger effects are seen (i.e. the large-*x* down quark)

- The new data has **decisive impact on PDFs!**

The large-x gluon from top-quark production

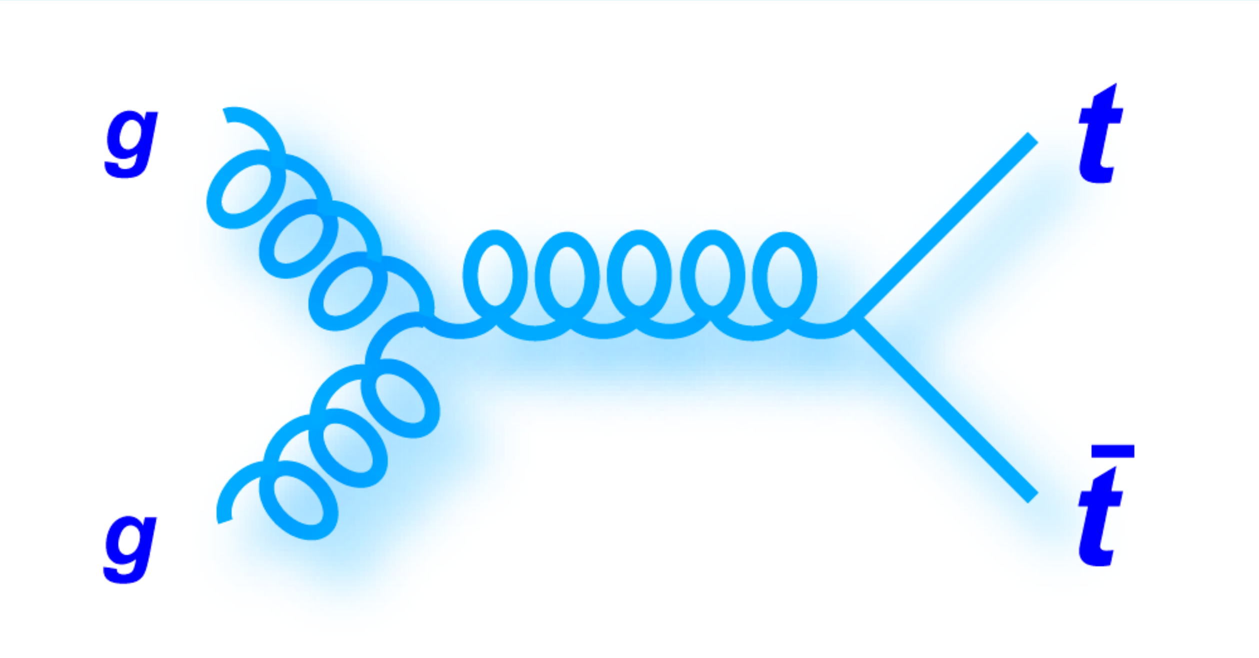
- Top-quark pair production driven by the **gluon-gluon luminosity**

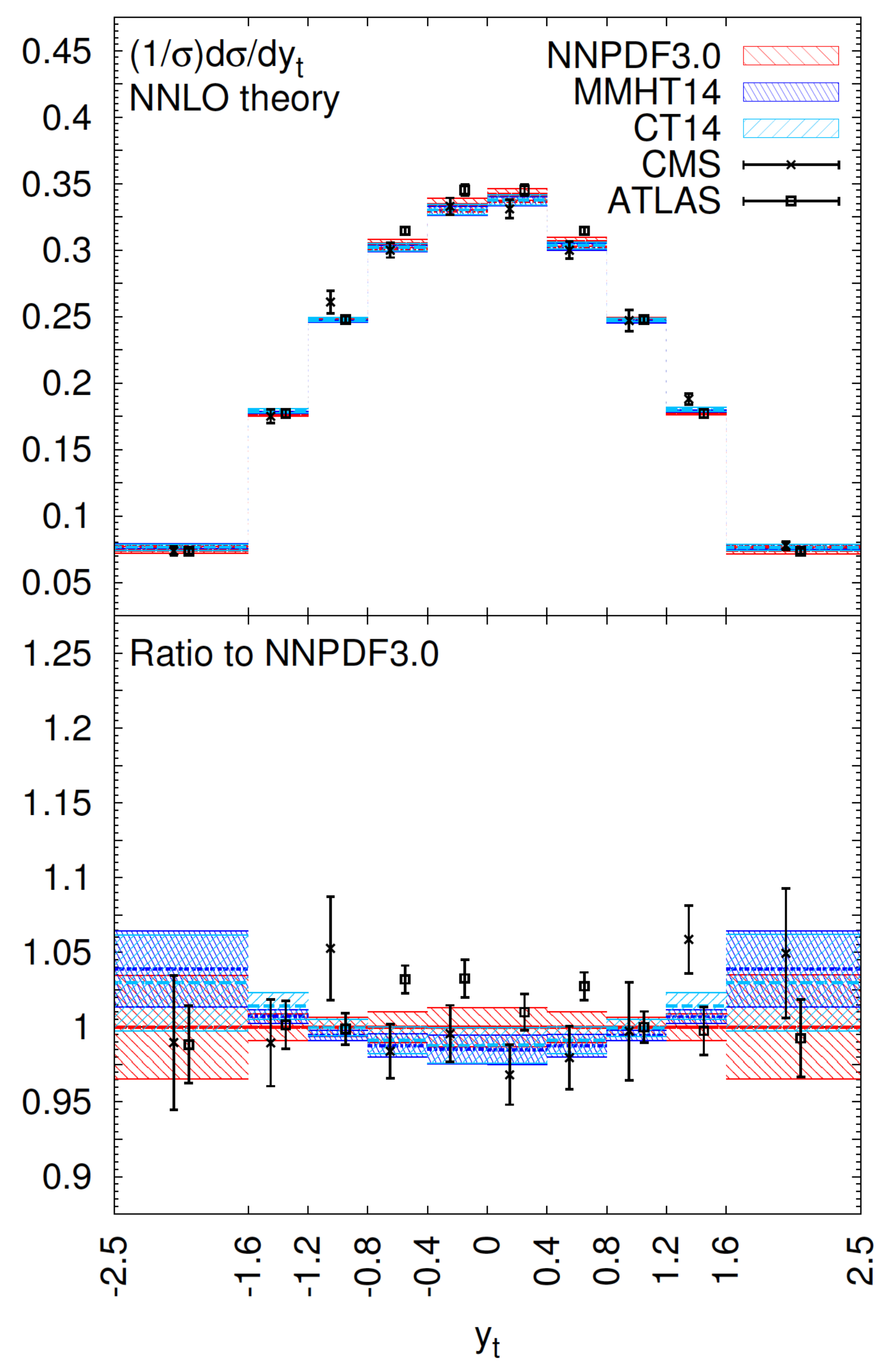
- **NNLO calculations for stable top quarks** available (with decays in the pipeline)

- Recent **precision data from ATLAS and CMS at 8 TeV** with full breakdown of statistical and systematic uncertainties

- For the first time, included ATLAS+CMS 8 TeV differential top measurements into the **global PDF fit**

Czakon, Hartland, Mitov, Nocera, Rojo 16





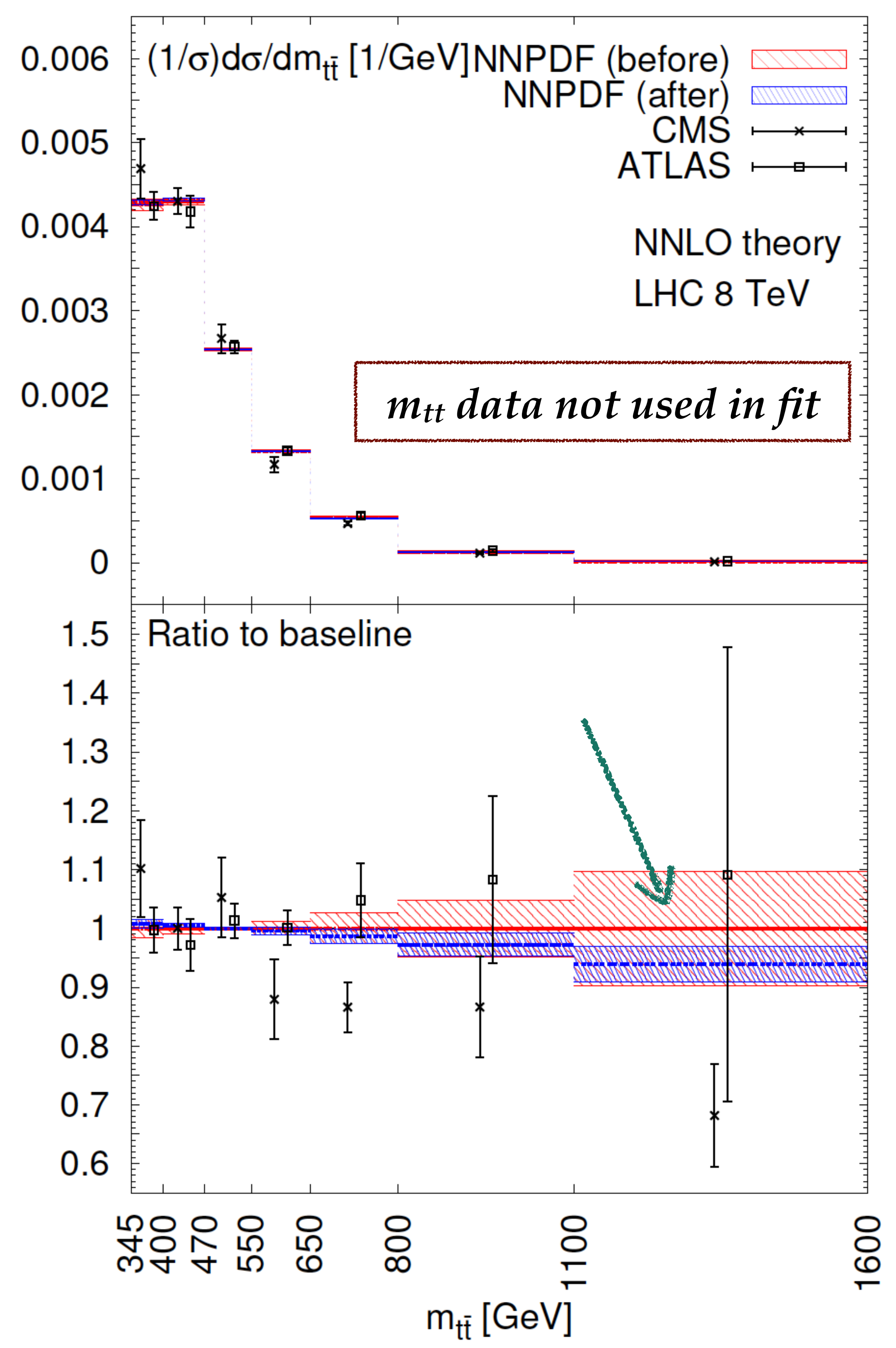
The large-x gluon from top-quark production

- PDF uncertainties reduced by more than a factor two for **$m_{tt} \gtrsim$ 500 GeV**

- Our choice of fitted distributions, **y_t** and **y_{tt}**, reduces the **risk of *BSM contamination*** (kinematical suppression of resonances), which might show up instead in **m_{tt}** and **p^t_T**, where PDF uncertainties are now much smaller

- Self-consistent program to **use top data to provide better theory predictions**

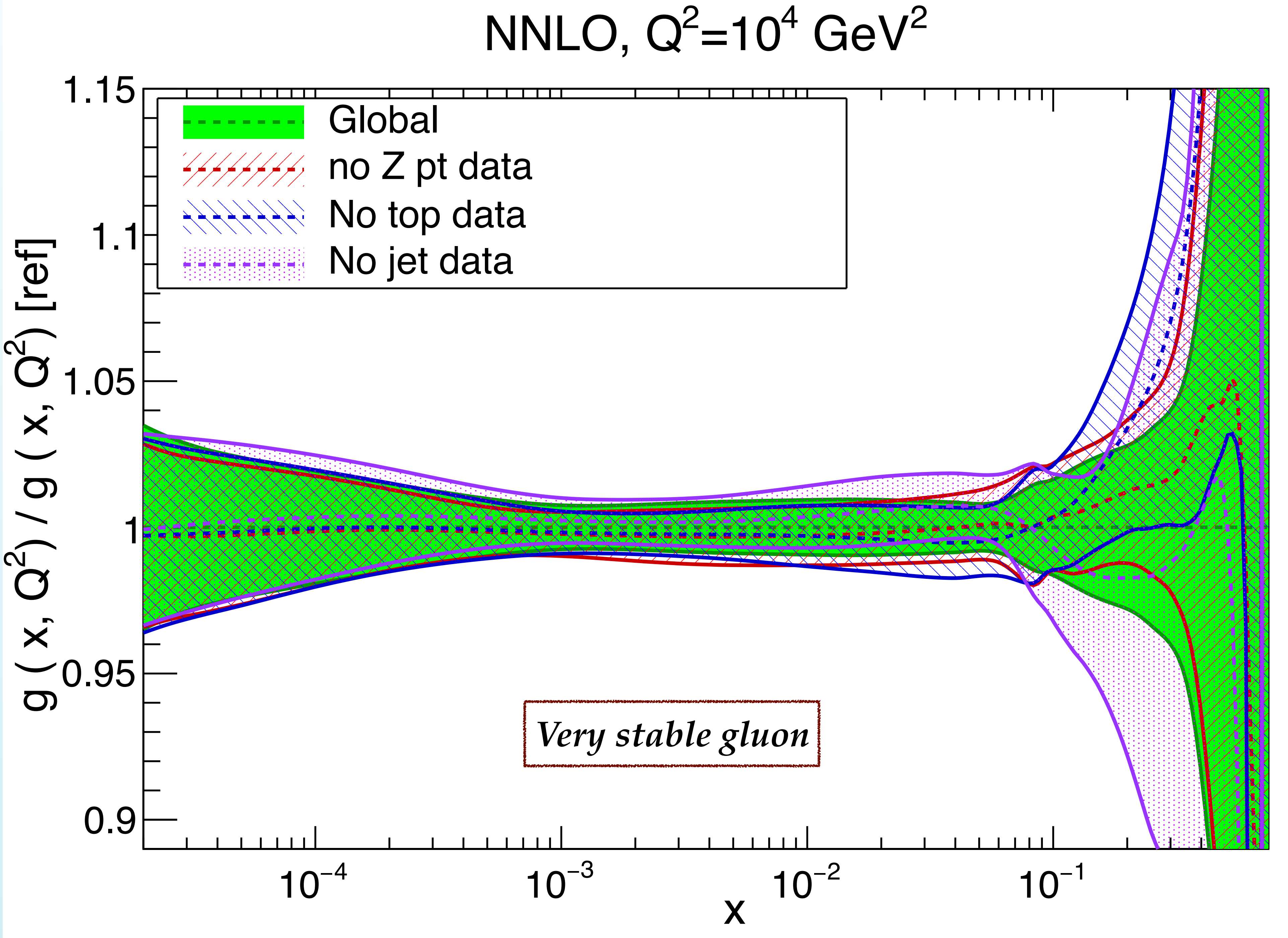
Improved sensitivity to BSM dynamics with top-quark final states

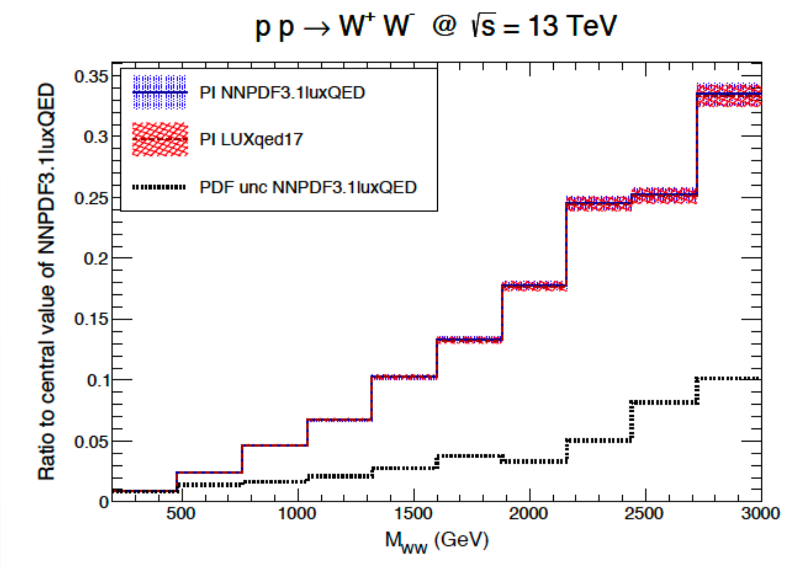


m_{tt} data not used in fit

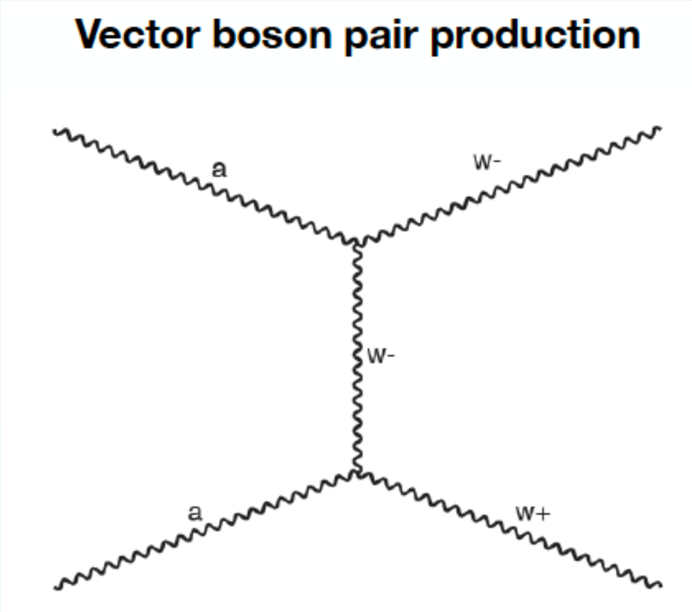
Impact on the gluon

- In NNPDF3.1 we have three groups of processes that provide **direct information on the gluon**: inclusive jets, top pair differential, and the Z transverse momentum
- Are the constraints from each of these groups **consistent among them?** Yes!





Illuminating the photon content of the proton within a global PDF fit


Vector boson pair production

Bertone, Carrazza, Harland, Rojo, in preparation

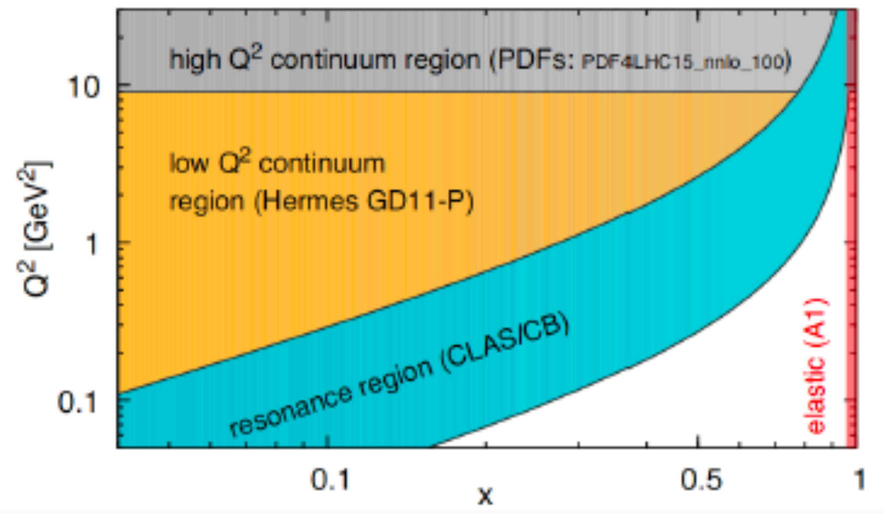
Motivation

The **NNPDF2.3/3.0QED fits** were data-driven determinations of the **photon PDF ɣ(x,Q)**, freely parametrised in terms of an ANN, and the constrained by **LHC Drell-Yan measurements**

NNPDF 13, Bertone and Carrazza 15

Data-driven QED fits are not competitive anymore with the **semi-analytical calculation of the photon PDF using the LUXqed formalism** in terms of the inclusive structure functions

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \Bigg\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \Bigg\}, \quad (6)$$



Where the structure functions are decomposed in 3 parts:

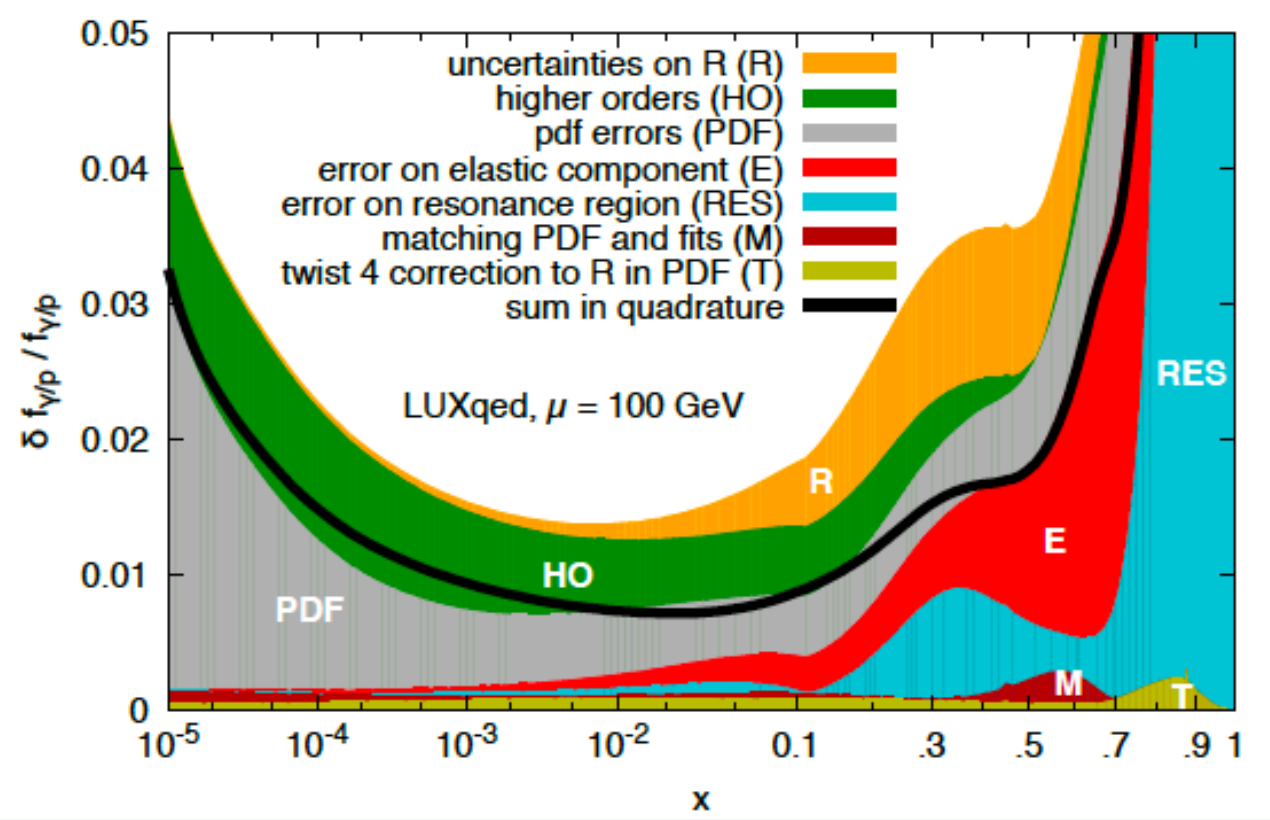
$$F_2(x,Q) = F_2^{\text{elastic}}(x,Q) + F_2^{\text{inelastic}}(x,Q) + F_2^{\overline{\text{MS}}}(x,Q)$$

Manohar, Nason, Salam, Zanderighi 16, 17

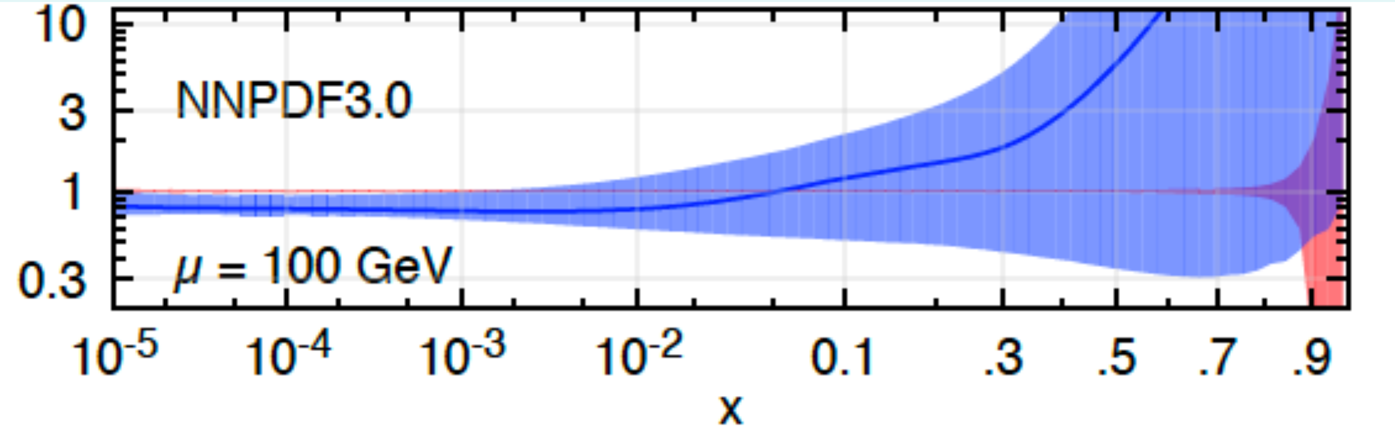
It is clearly more advantageous to **perform a QED fit imposing the LUXqed theory constraints** on the photon PDF **ɣ(x,Q)**, rather than extracting it from experimental measurements

Motivation

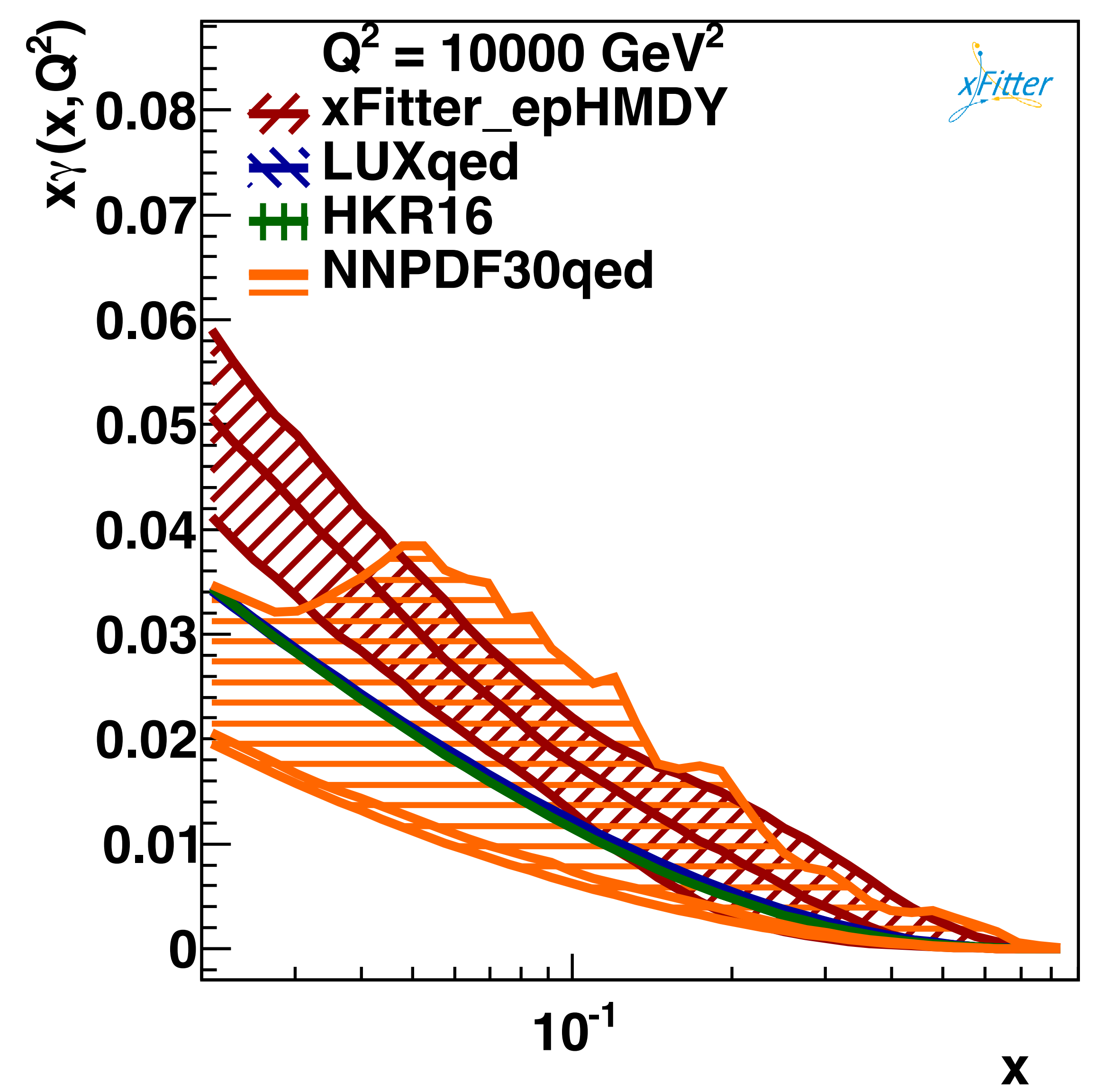
Few-percent PDF uncertainties on **γ(x,Q)**



Agreement within errors with NNPDF3.0QED



Even using one of the most sensitive processes to photon-initiated contributions, **high-mass DY at 8 TeV**, uncertainties in **γ(x,Q)** still at the **30% level**



xFitter Developer's Team 17

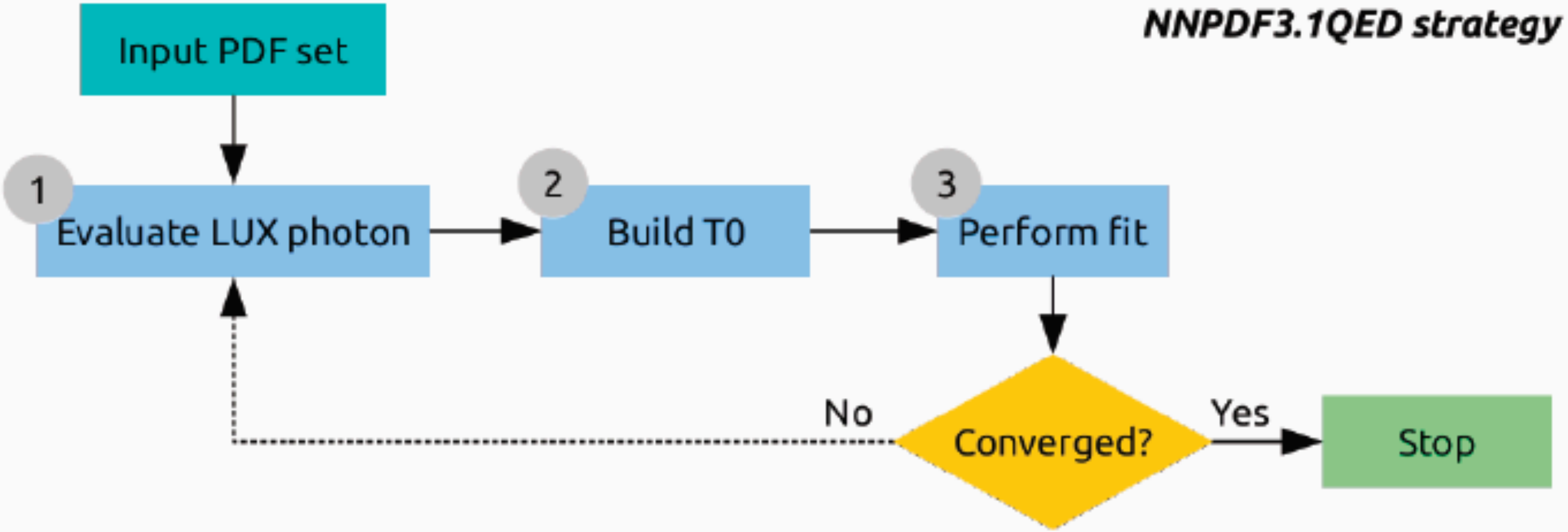
NNPDF3.1QED: strategy

The **NNPDF3.1QED fits** will impose the **LUXqed formalism** as an external theoretical constrain:

We base our approach in 4 steps:

1. build a **public library** for the evaluation of the LUX photon
2. convert (1) to a **T0 set of PDFs**
3. perform **fit** with **QED** corrections (DGLAP, data) and **T0** from (2)
4. iterate until convergence $\rightarrow$ stable quarks/gluons

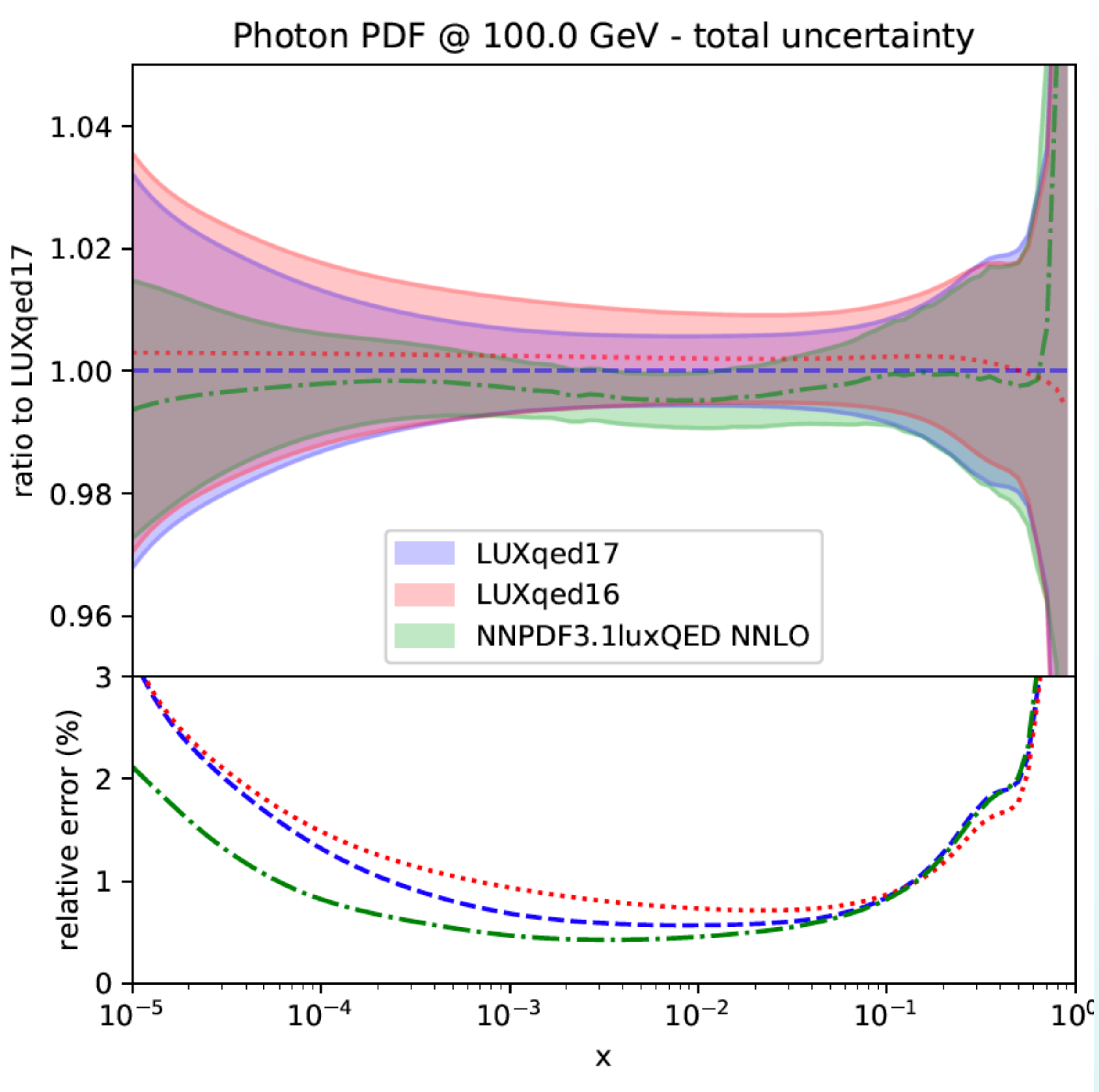
i.e. generate N_{rep} photon PDFs $\gamma^{(k)}(x,Q)$ from the N_{rep} NNPDF3.1 quarks and gluons

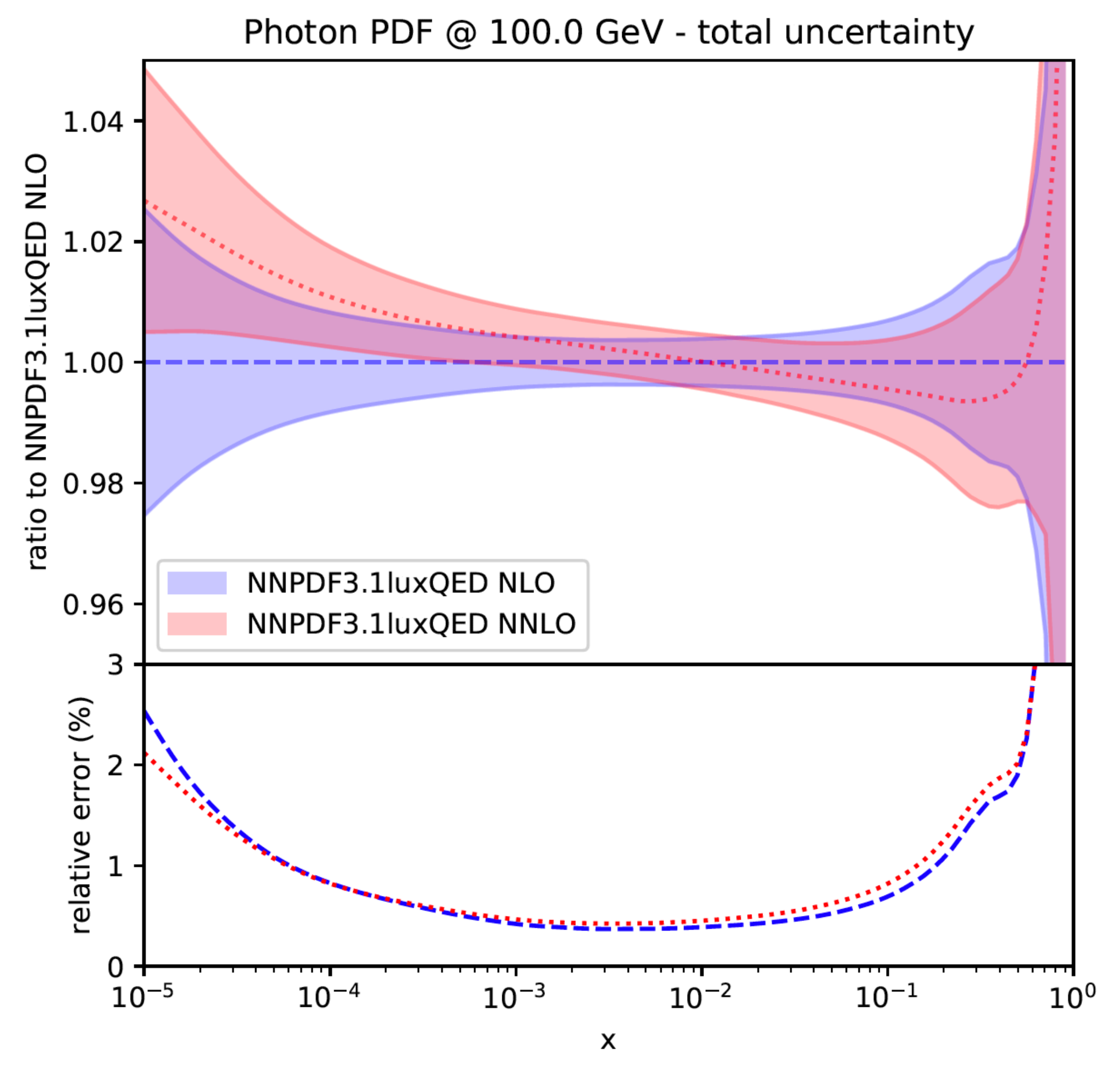


Another important update in the NNPDF3.1QED fits is the use of **NLO QED theory** both in **splitting functions** and in the **DIS coefficient functions**, implemented in the **APFEL code**

Bertone, Carrazza, Rojo 13

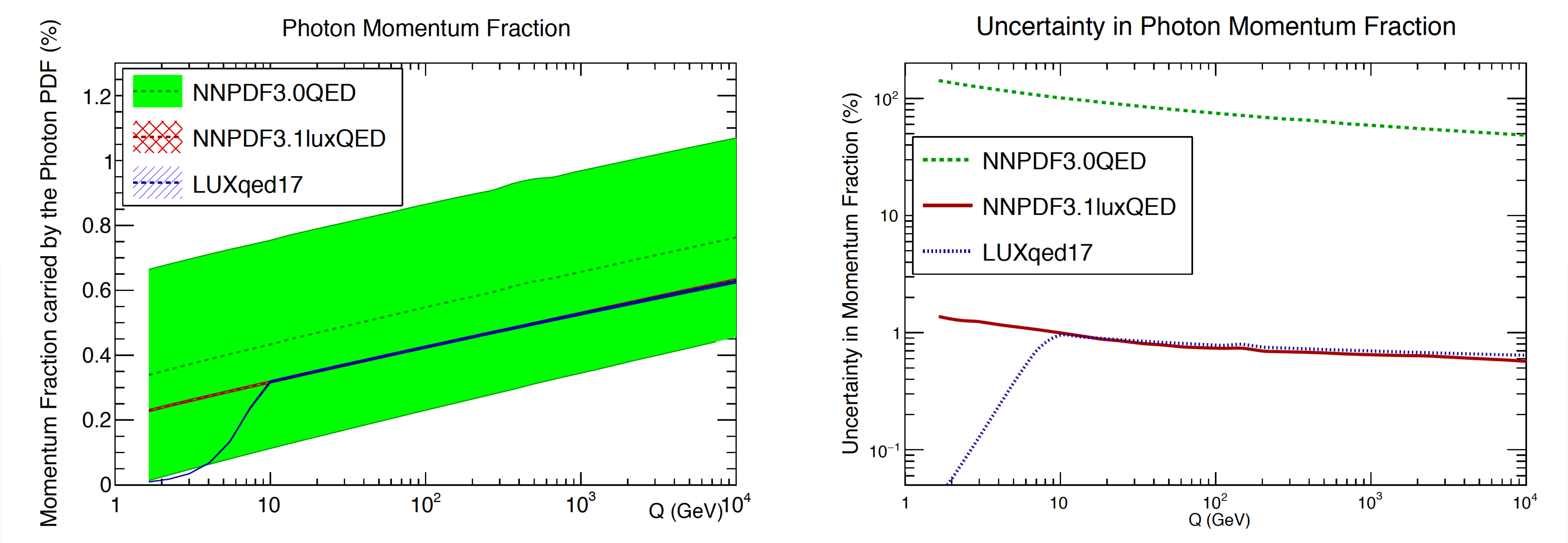
Results

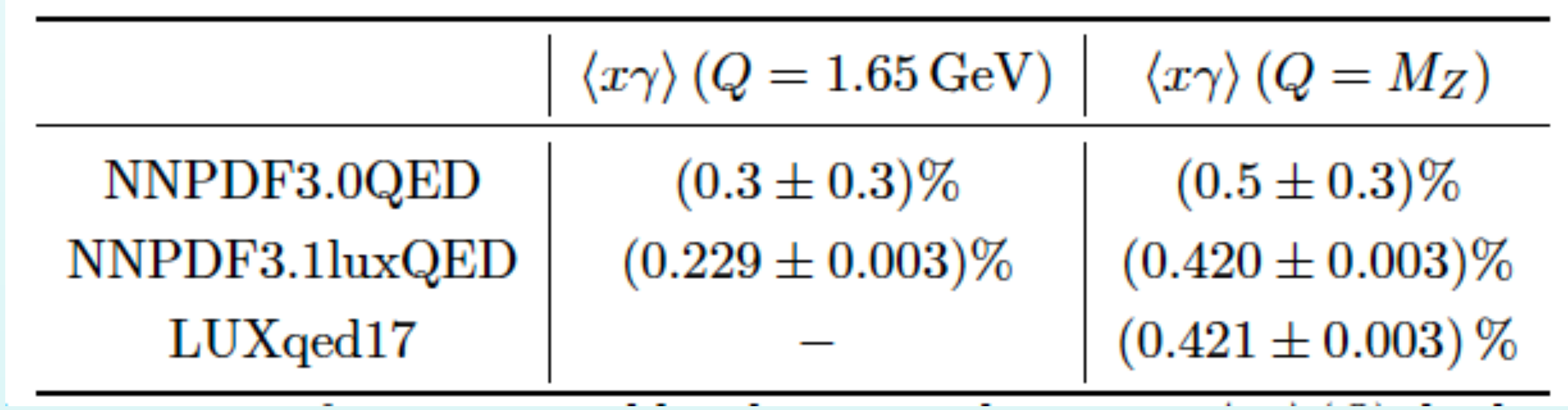




- Agreement with **LUXqed17**, both in terms of central values and of uncertainties
- Good perturbative stability of the photon PDF
- **PDF uncertainties on γ(x,Q) < 3%** in the range relevant for LHC applications

Momentum fraction carried by photons



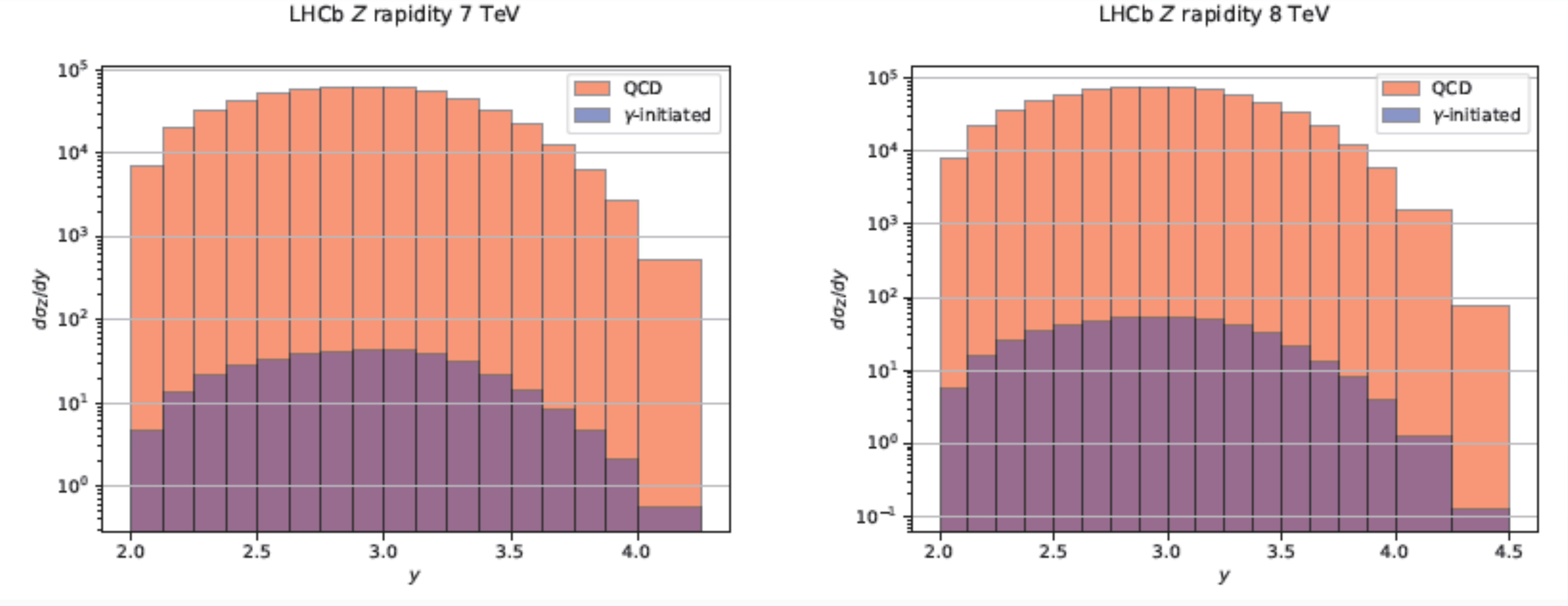


	$\langle x\gamma\rangle\ (Q = 1.65\,\mathrm{GeV})$	$\langle x\gamma\rangle\ (Q = M_Z)$
NNPDF3.0QED	$(0.3 \pm 0.3)\%$	$(0.5 \pm 0.3)\%$
NNPDF3.1luxQED	$(0.229 \pm 0.003)\%$	$(0.420 \pm 0.003)\%$
LUXqed17	–	$(0.421 \pm 0.003)\%$

- Up to **0.5% of the proton momentum** is carried by the photon
- Important to account since this will feed into other PDFs (i.e. the gluon).
- Also QED DGLAP evolution affects indirectly gluon and quarks as compared to QCD-only fit

Fits with photon-initiated contributions

- The previous results are based on fits where the **PI contributions are added only to the DIS SFs**
- In principle one needs to add them to **all hadronic processes**, but this is very cumbersome
- We have checked that NNPDF3.1QED results are stable once **PI contributions added to the LHCb Z production data**, which are directly sensitive to the photon PDF at large *x*



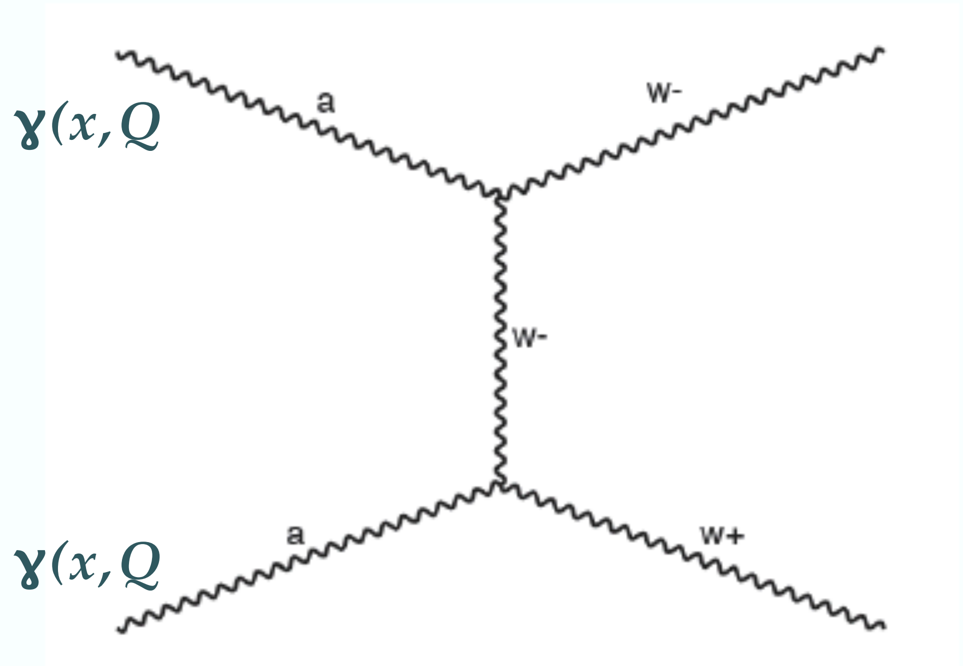
The fits are mostly **insensitive to the inclusion of PI effects in the LHCb cross-sections**

Even smaller effects on **γ(x,Q)** would then arise for the rest of the datasets in NNPDF3.1

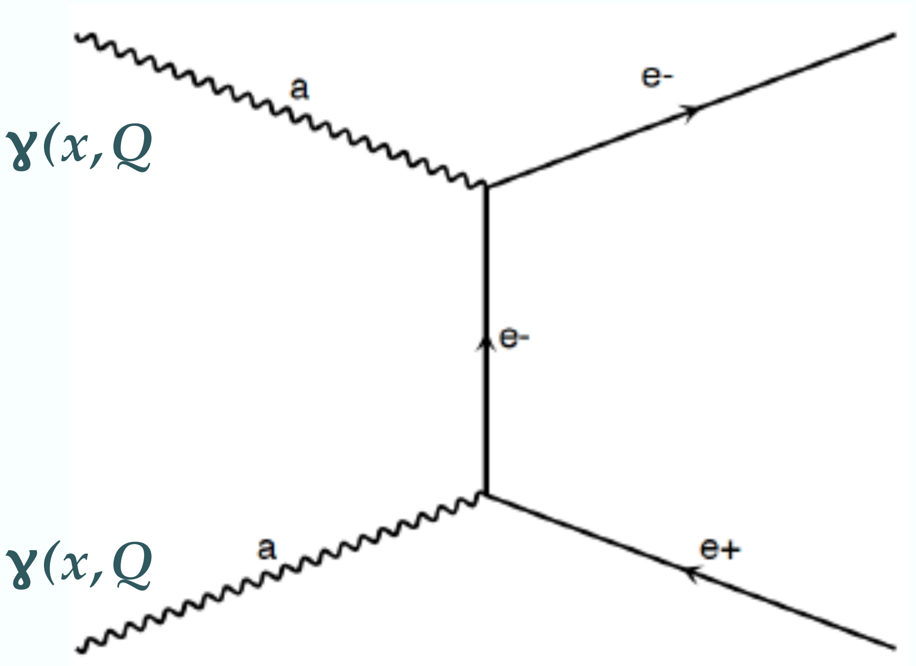
Implications at the LHC

Photon-initiated contributions are relevant for many LHC processes

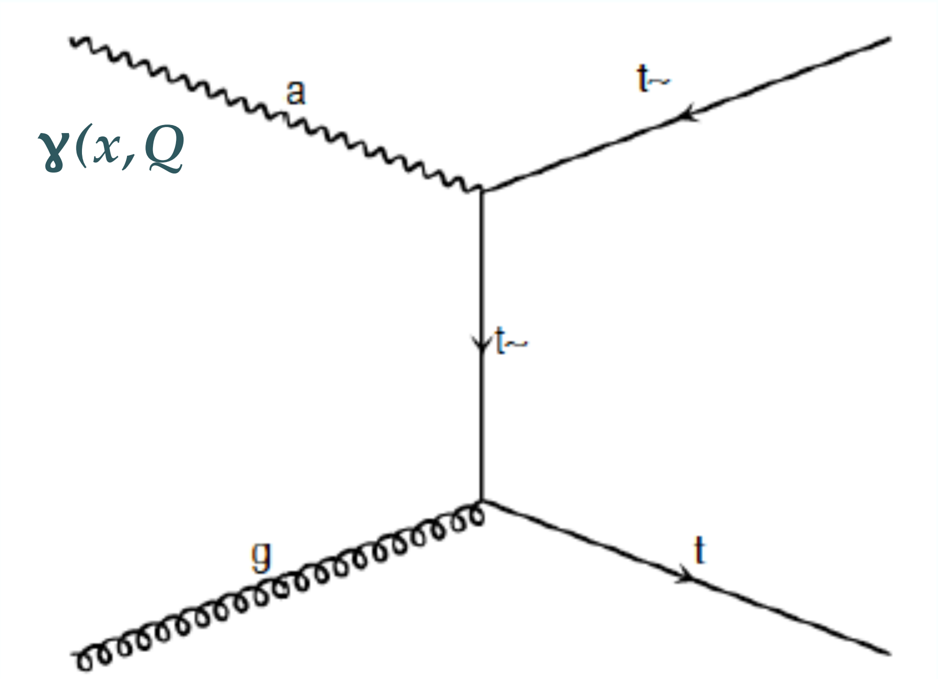
Vector boson pair production



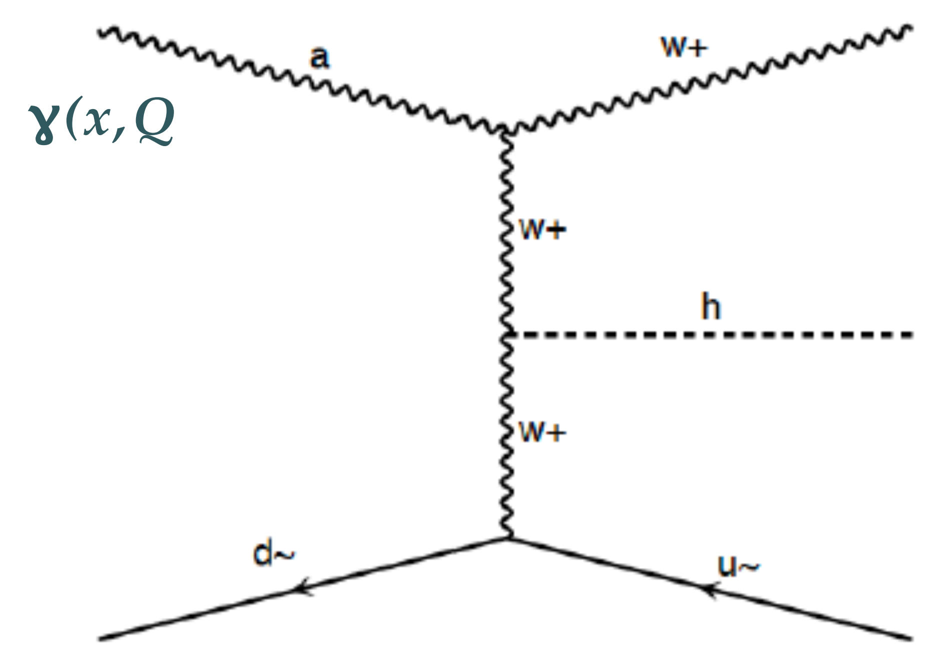
Drell-Yan



Top quark pair production



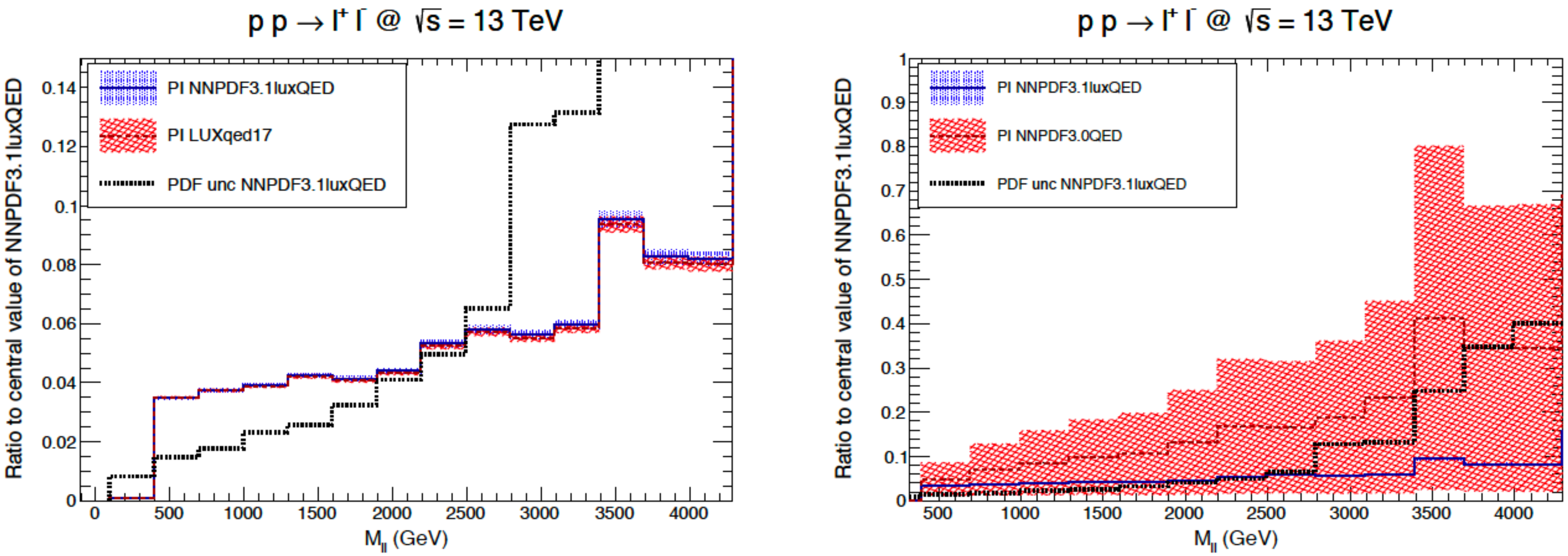
Higgs-W associated production



Similar size, but with opposite sign, as virtual electroweak corrections

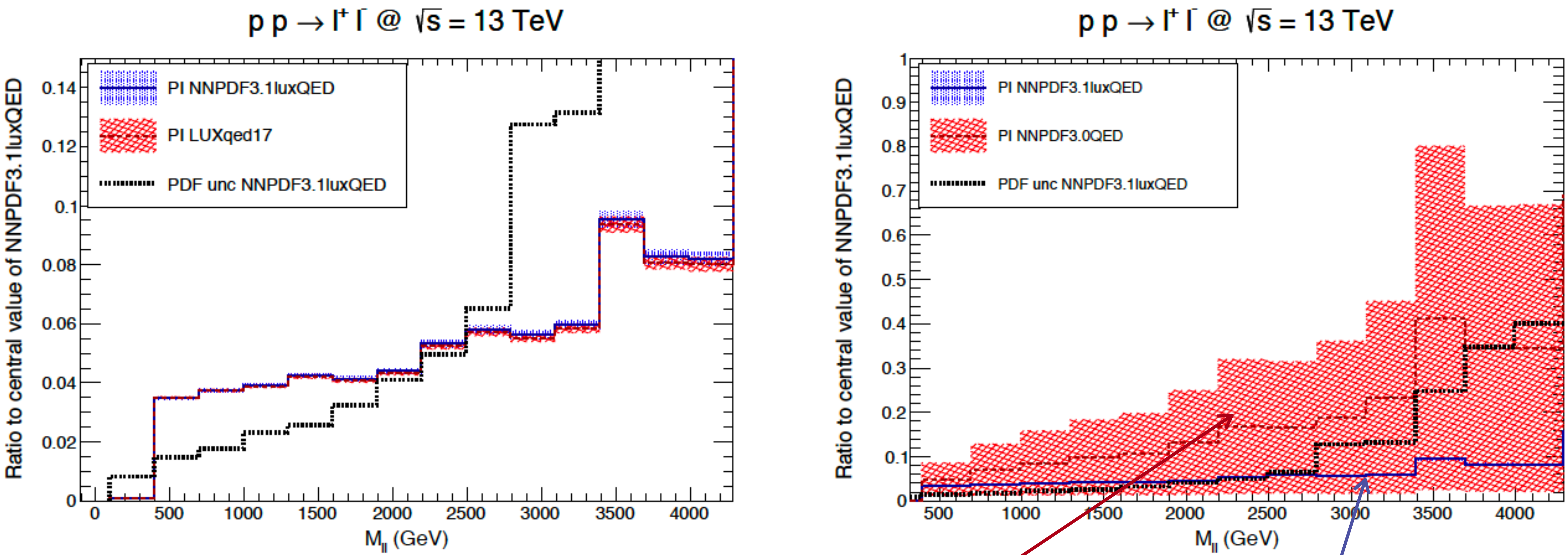
Implications at the LHC

PI contributions to high-mass Drell-Yan production



Implications at the LHC

PI contributions to high-mass Drell-Yan production



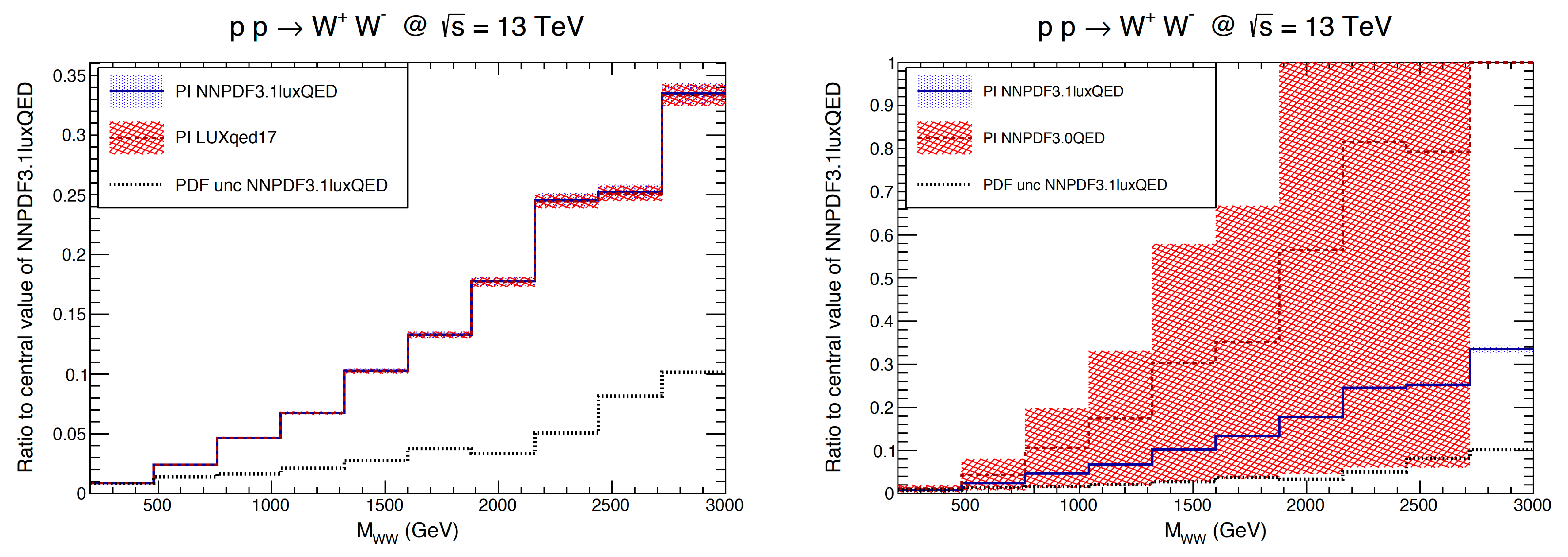
Model-independent determination of γ(x,Q) from data

Imposing LUXqed theoretical constraints

- For high-mass Drell-Yan, **PI contributions much smaller than in NNPDF3.0QED,** but still significant for precision phenomenology (up to 10% at large M_{ll})
- Comparable or larger than PDF uncertainties in most of the relevant kinematic region

Implications at the LHC

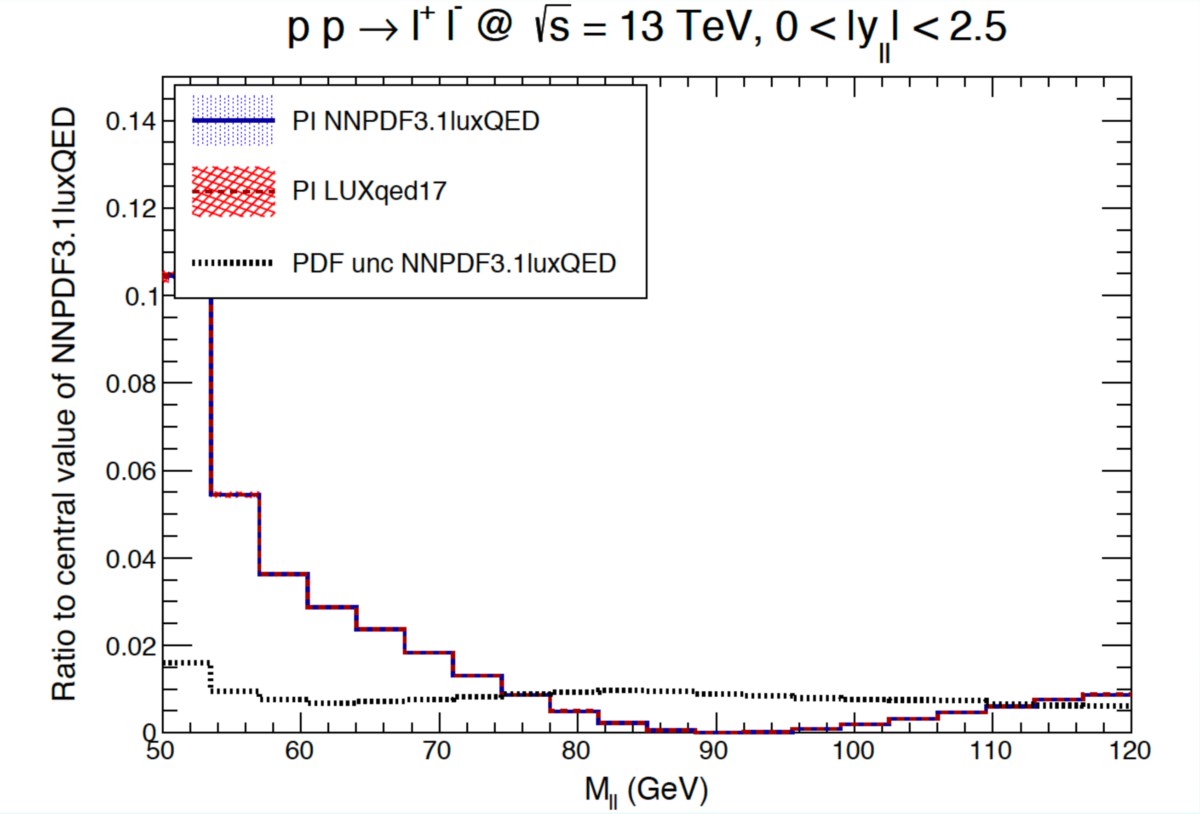
PI contributions to high-mass W pair production



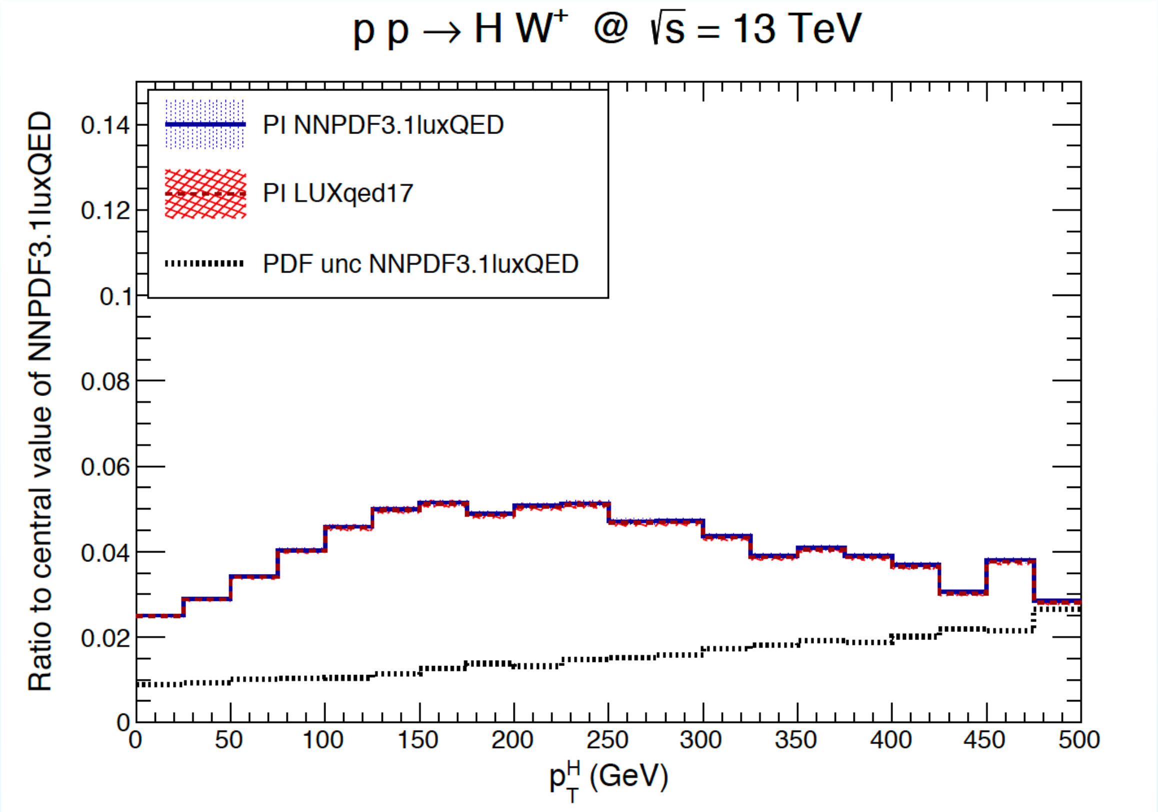
- For high-mass W^+W^- production, **PI contributions** can be as large as to 30% at large M_{WW}
- The production kinematics enhance PI over QCD contributions at large mass M_{WW}

Implications at the LHC

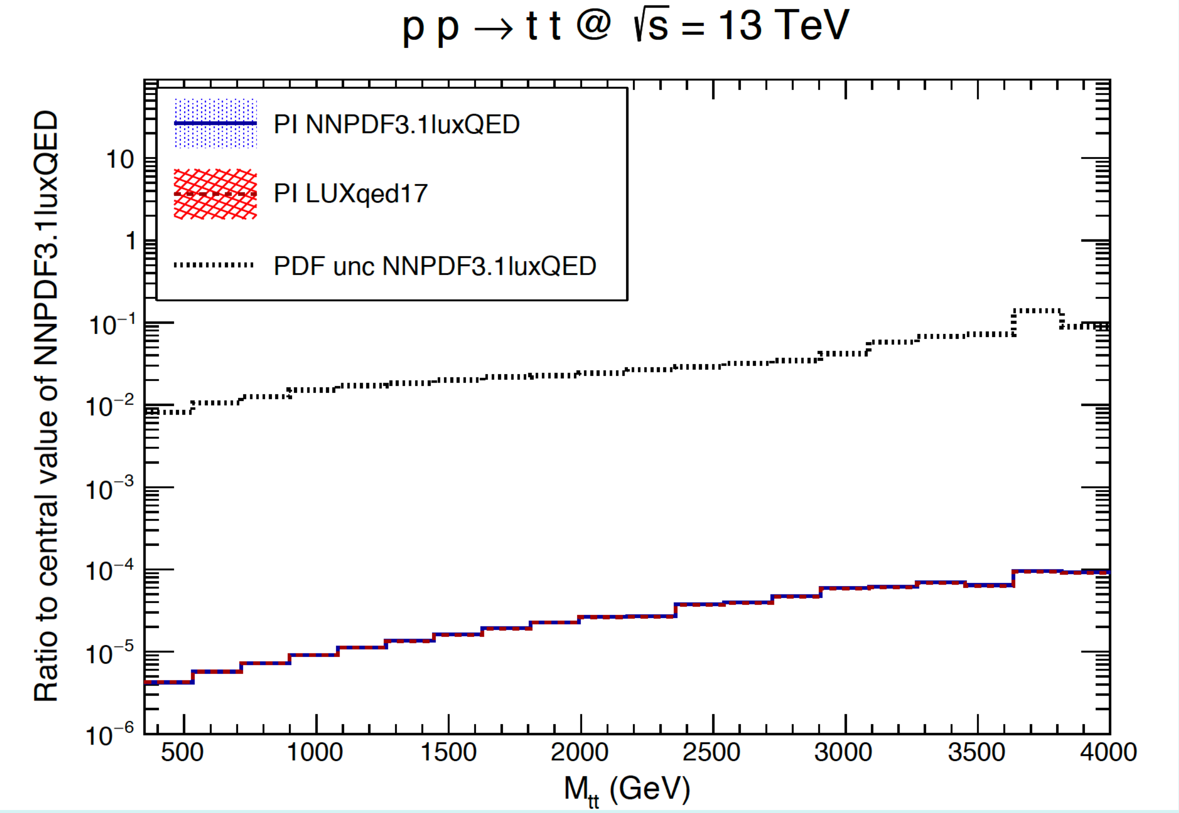
Low-mass Drell-Yan



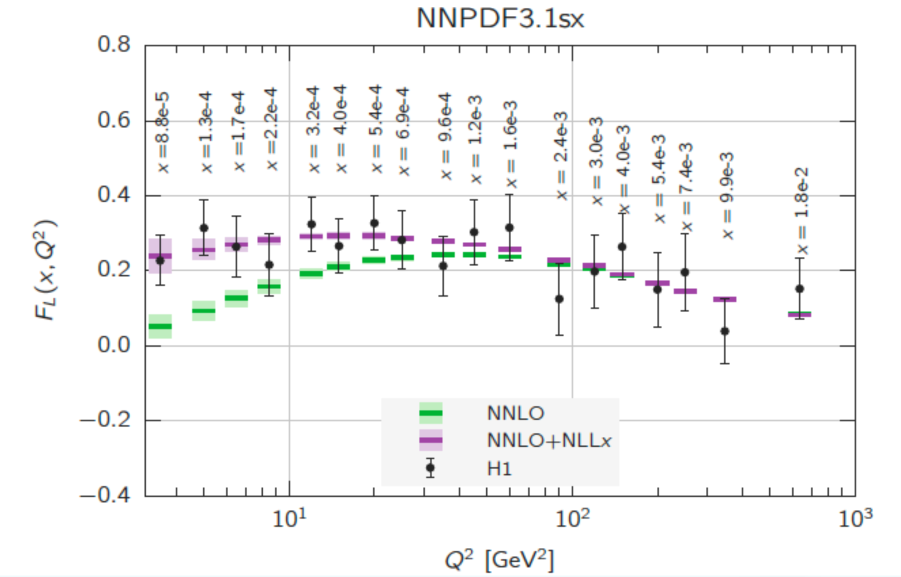
HW associated production



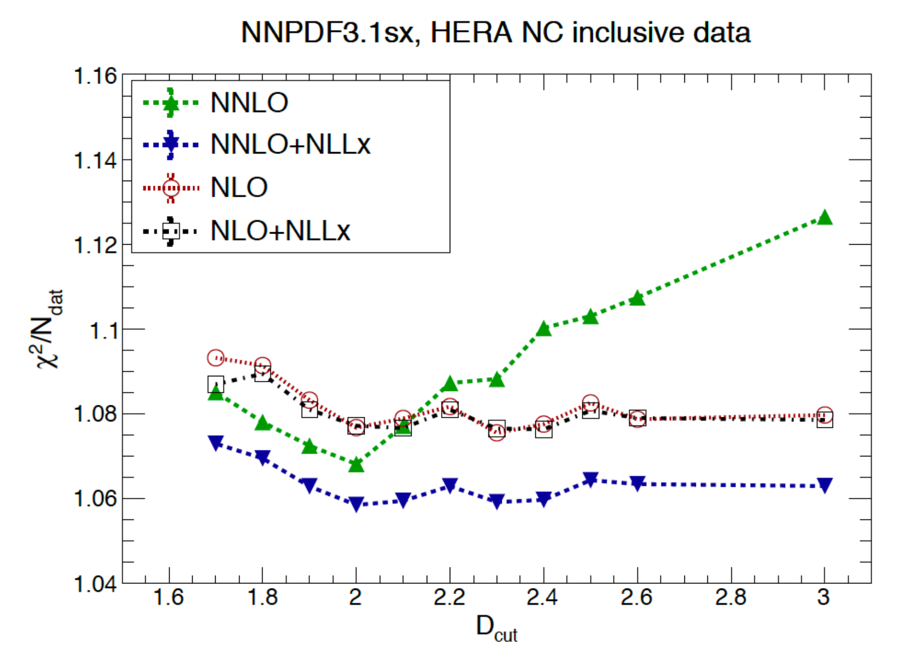
Top-quark pair production



- In electroweak processes, **PI contributions are now determined to high-precision** to be between few % and up to 30%
- Essential to account for them, and include consistently **EW corrections**
- For QCD-initiated processes (top, jets) PI contributions turn out to be **negligible**



Parton Distributions with BFKL resummation



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

- **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

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

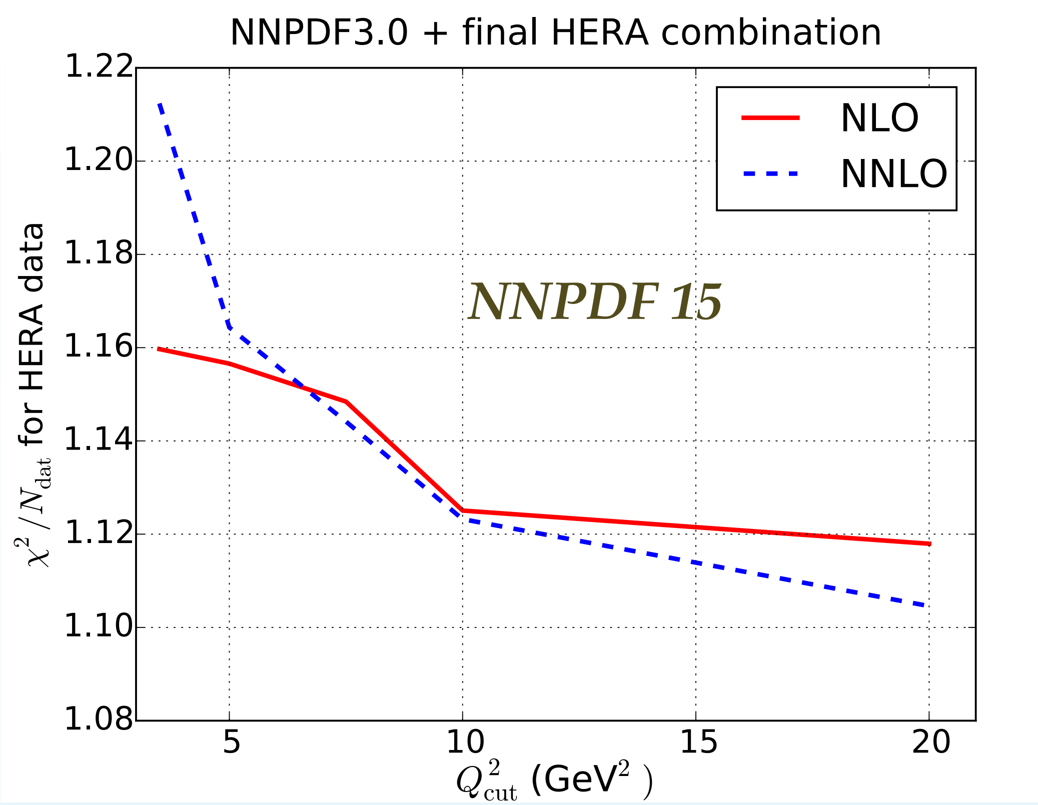
Within small-*x* resummation, the **N^{k}LO fixed-order DGLAP splitting functions** are complemented with the **N^{h}LL*x* contributions from BKFL**

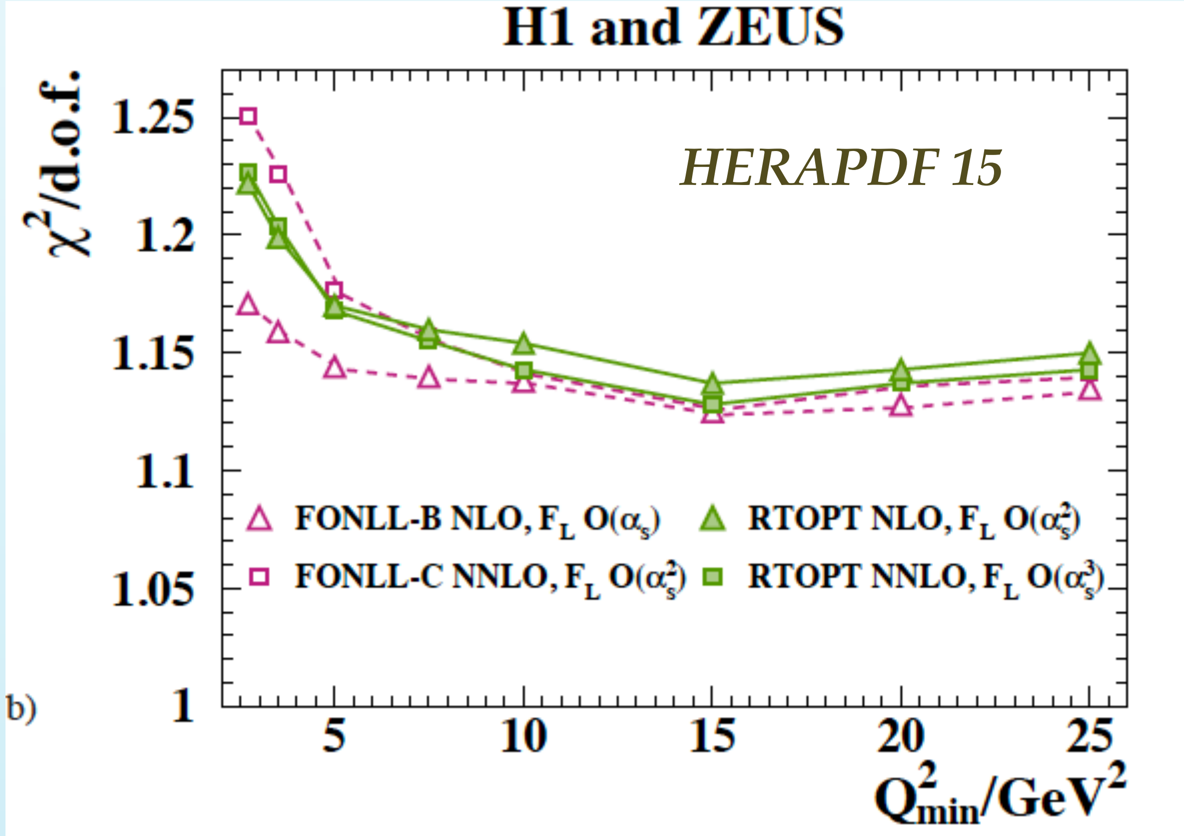
ABF, CCSS, TW + others, 94-08

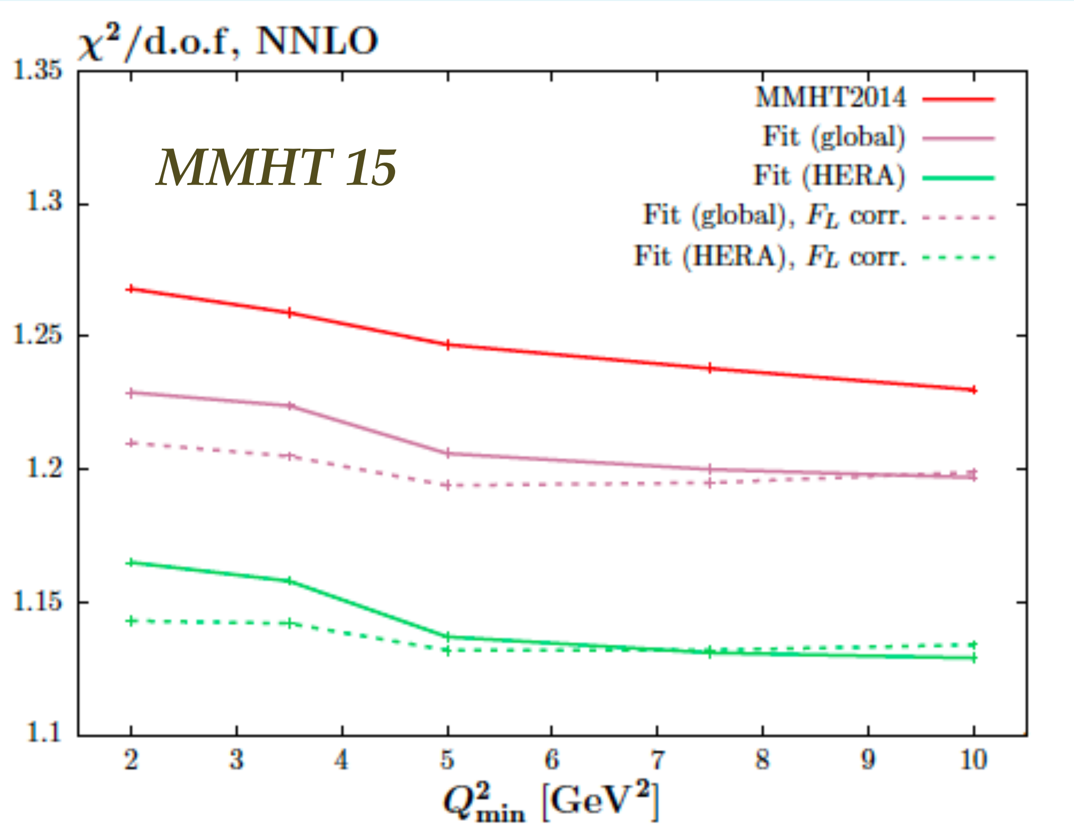
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

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 NLL*x* resummation?**



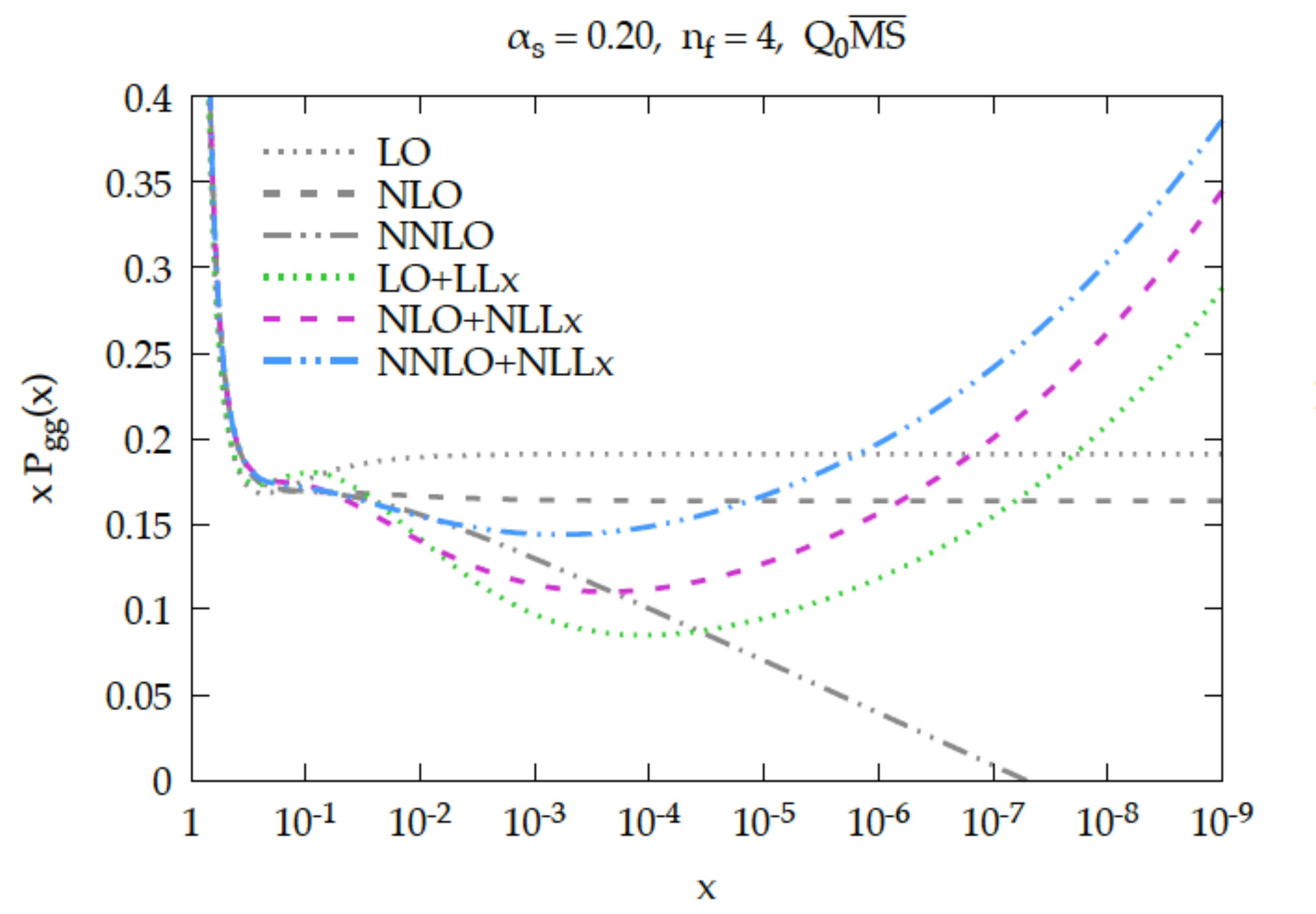




PDFs with small-x resummation

- 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**

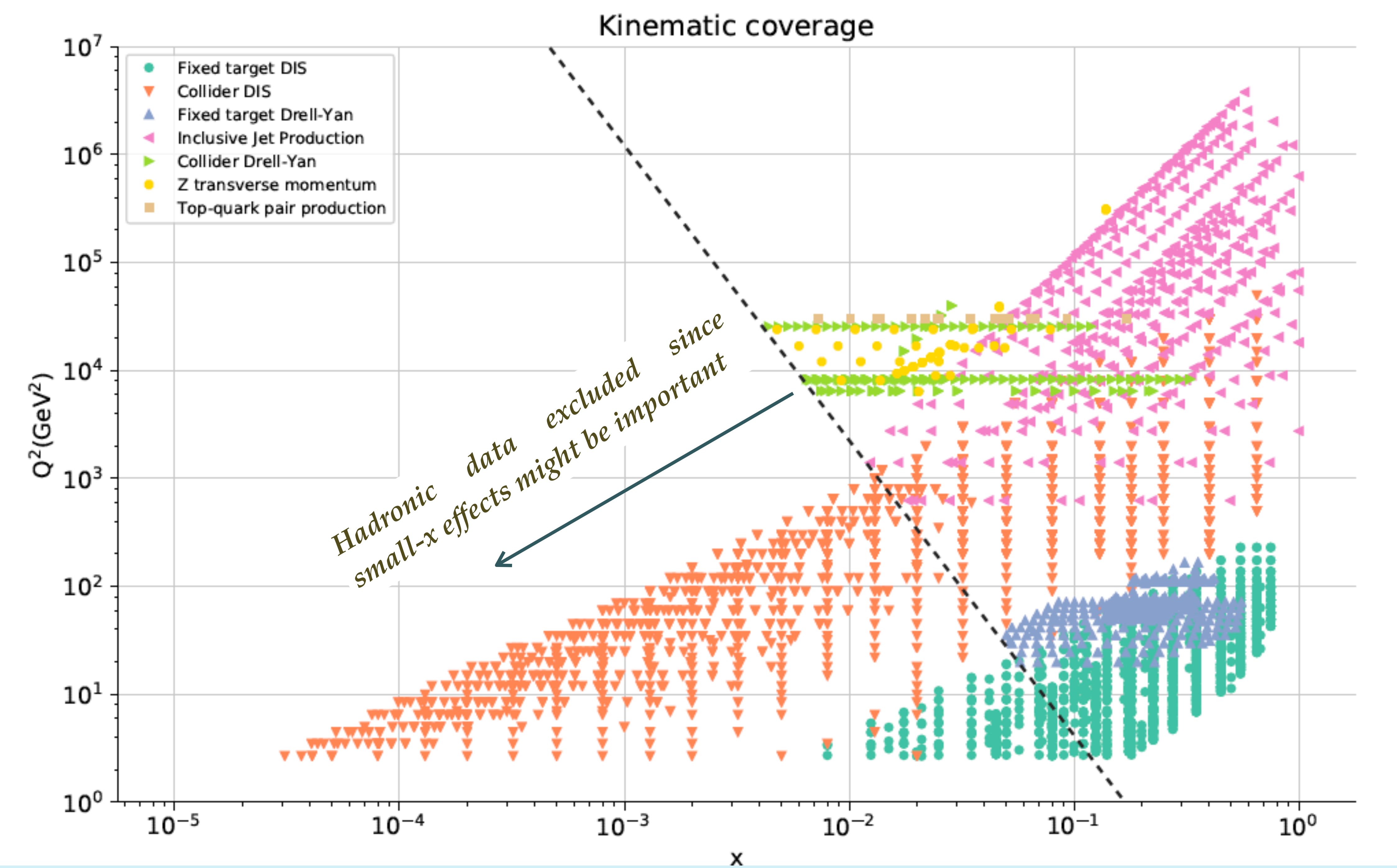


APFEL: Bertone, Carrazza, Rojo 13
https://apfel.hepforge.org/

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**

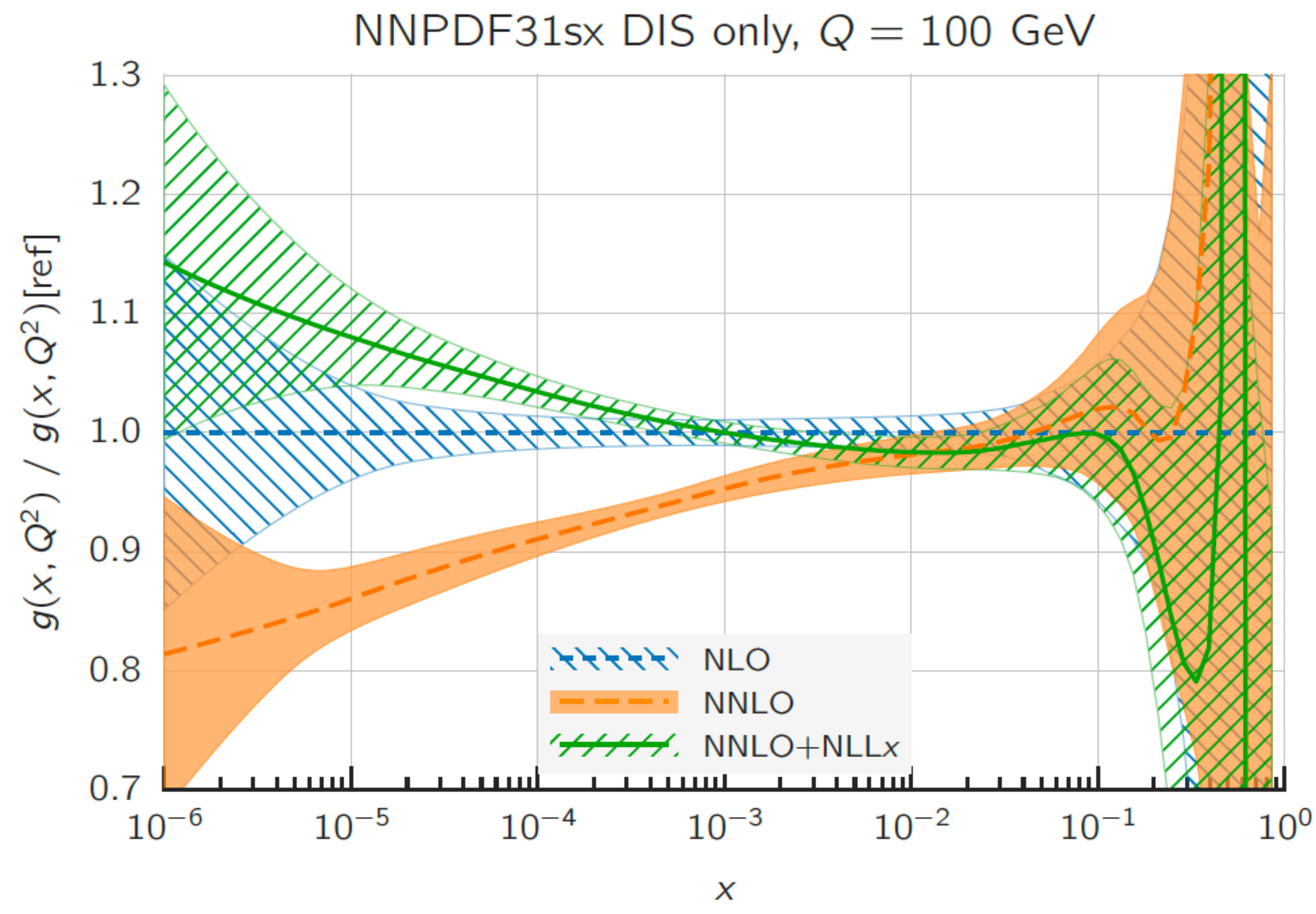


Hadronic data excluded since small-x effects might be important

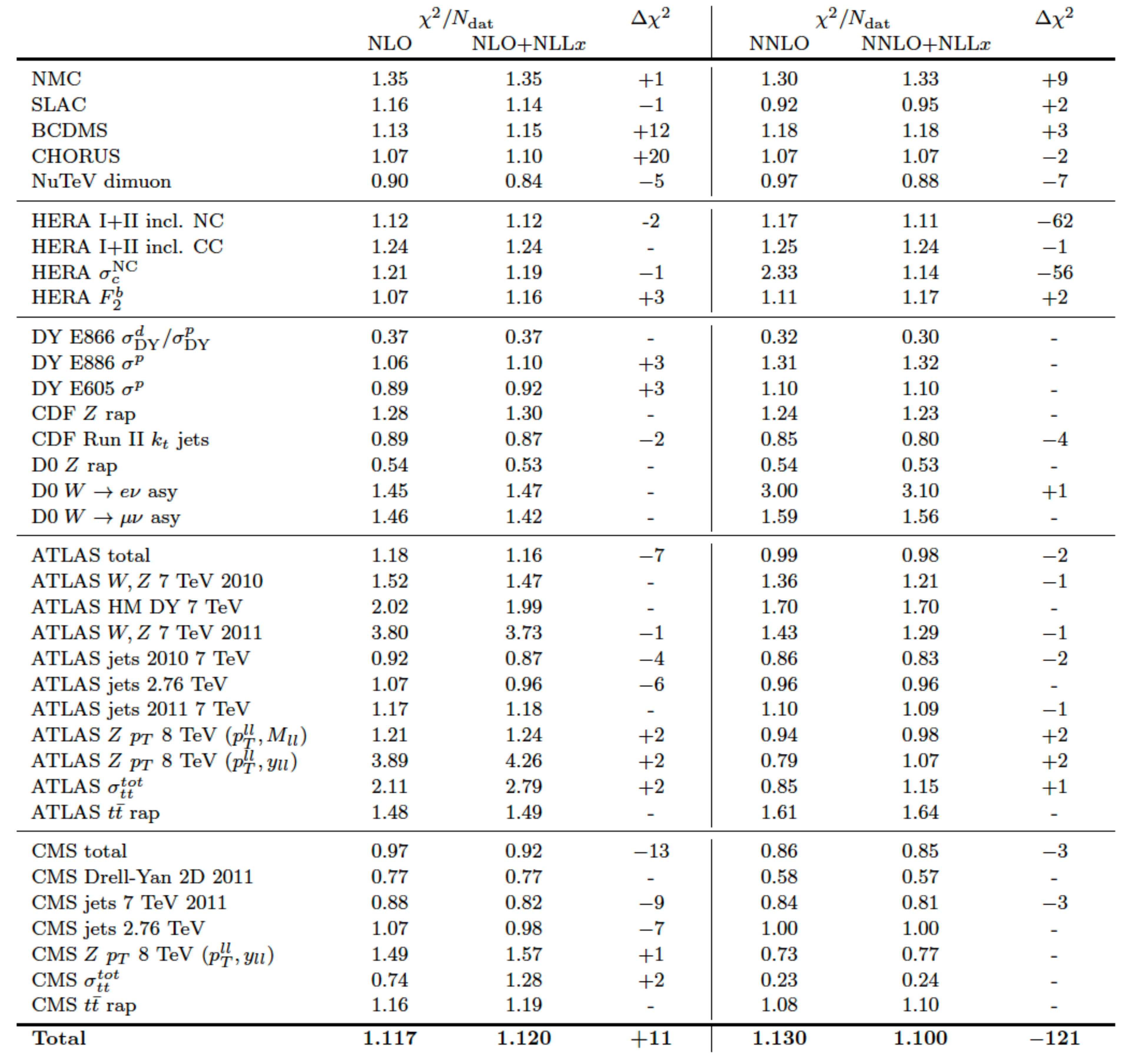
Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli, 17

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

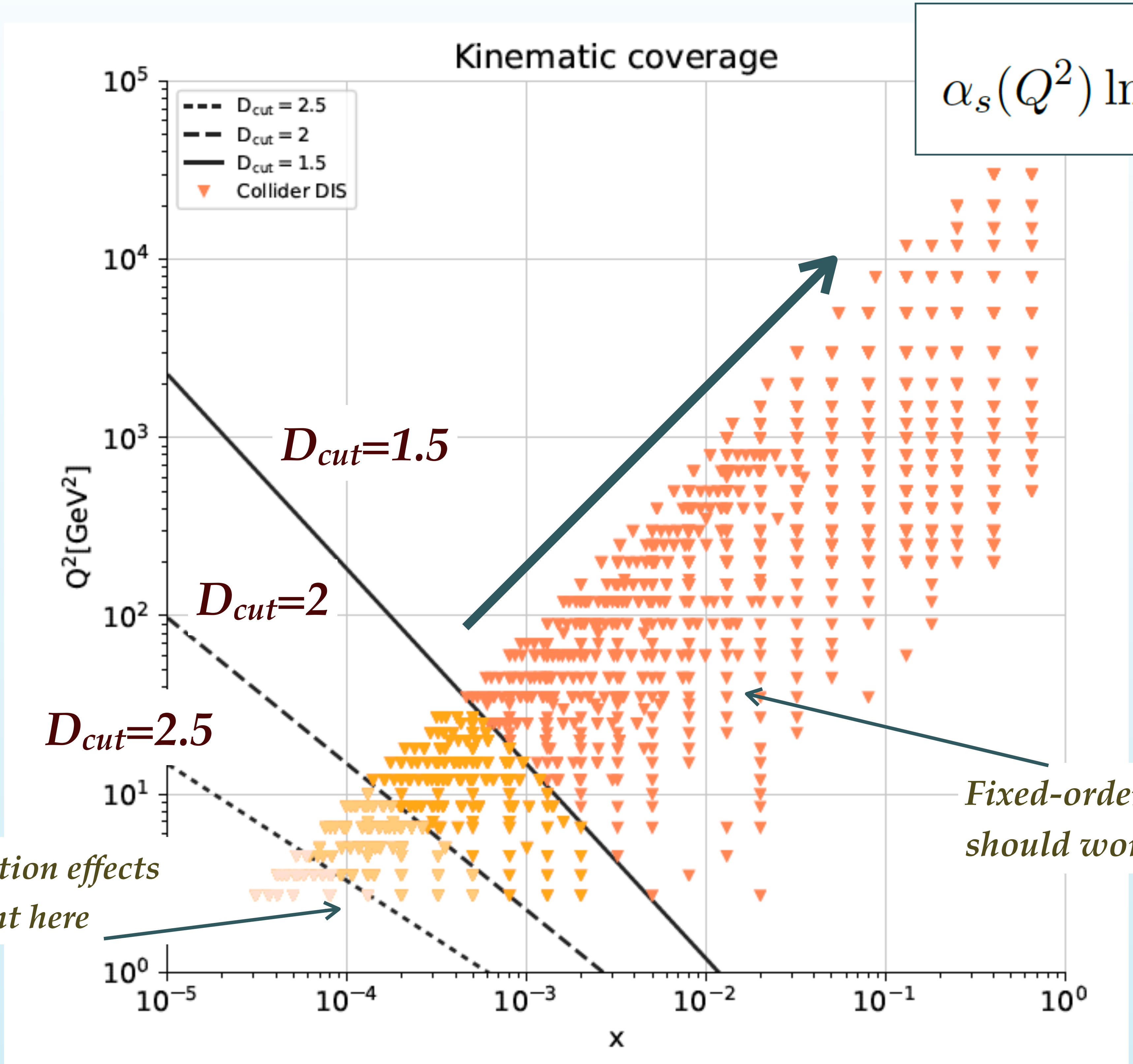


	$\chi^2/N_{\rm dat}$		$\Delta\chi^2$	$\chi^2/N_{\rm dat}$		$\Delta\chi^2$
	NLO	NLO+NLLx		NNLO	NNLO+NLLx	
NMC	1.35	1.35	+1	1.30	1.33	+9
SLAC	1.16	1.14	−1	0.92	0.95	+2
BCDMS	1.13	1.15	+12	1.18	1.18	+3
CHORUS	1.07	1.10	+20	1.07	1.07	−2
NuTeV dimuon	0.90	0.84	−5	0.97	0.88	−7
HERA I+II incl. NC	1.12	1.12	-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**

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



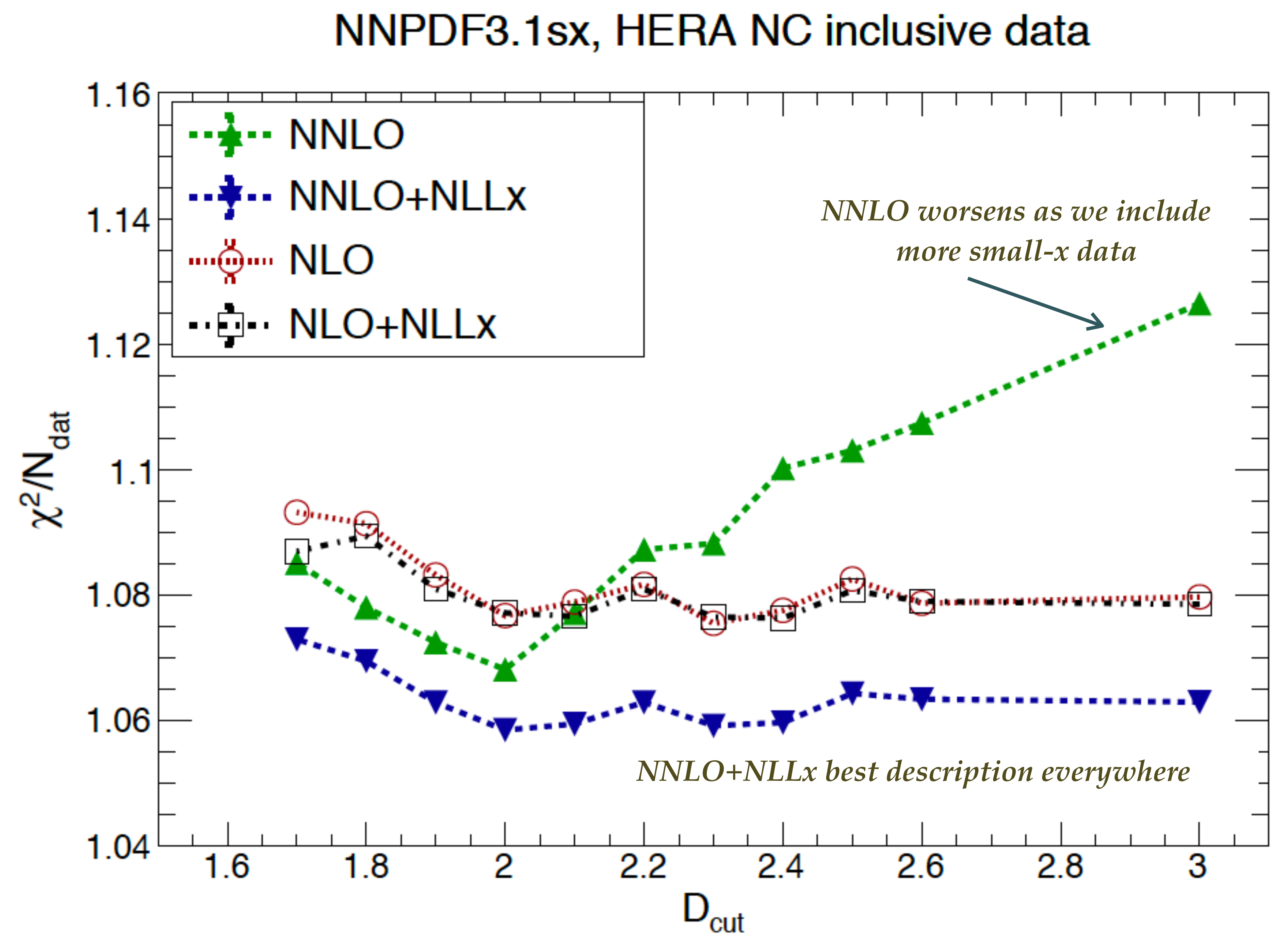
Small-x resummation effects could be important here

Fixed-order theory should work fine here

PDFs with small-x resummation

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

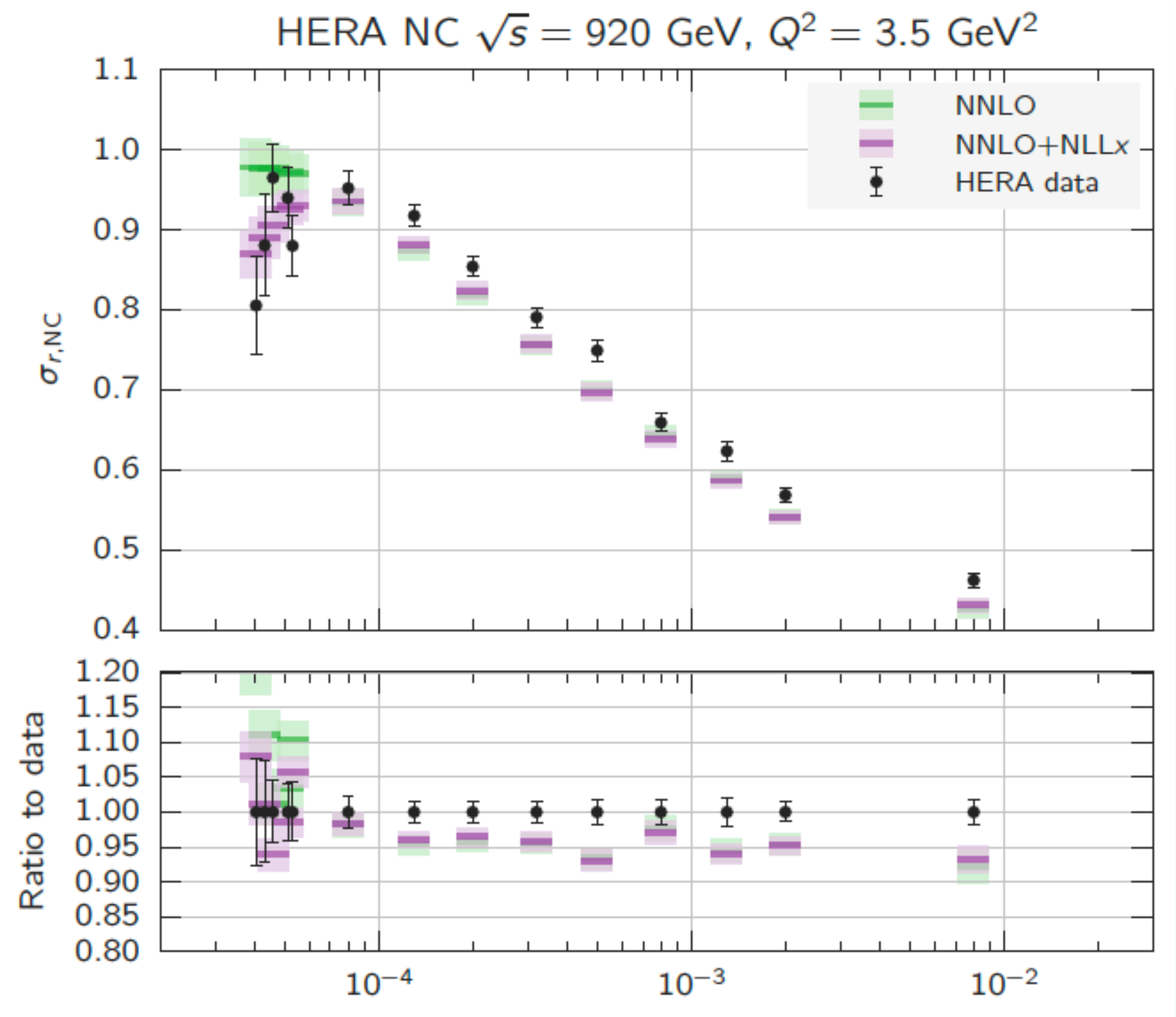
Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire (x,Q²) region**

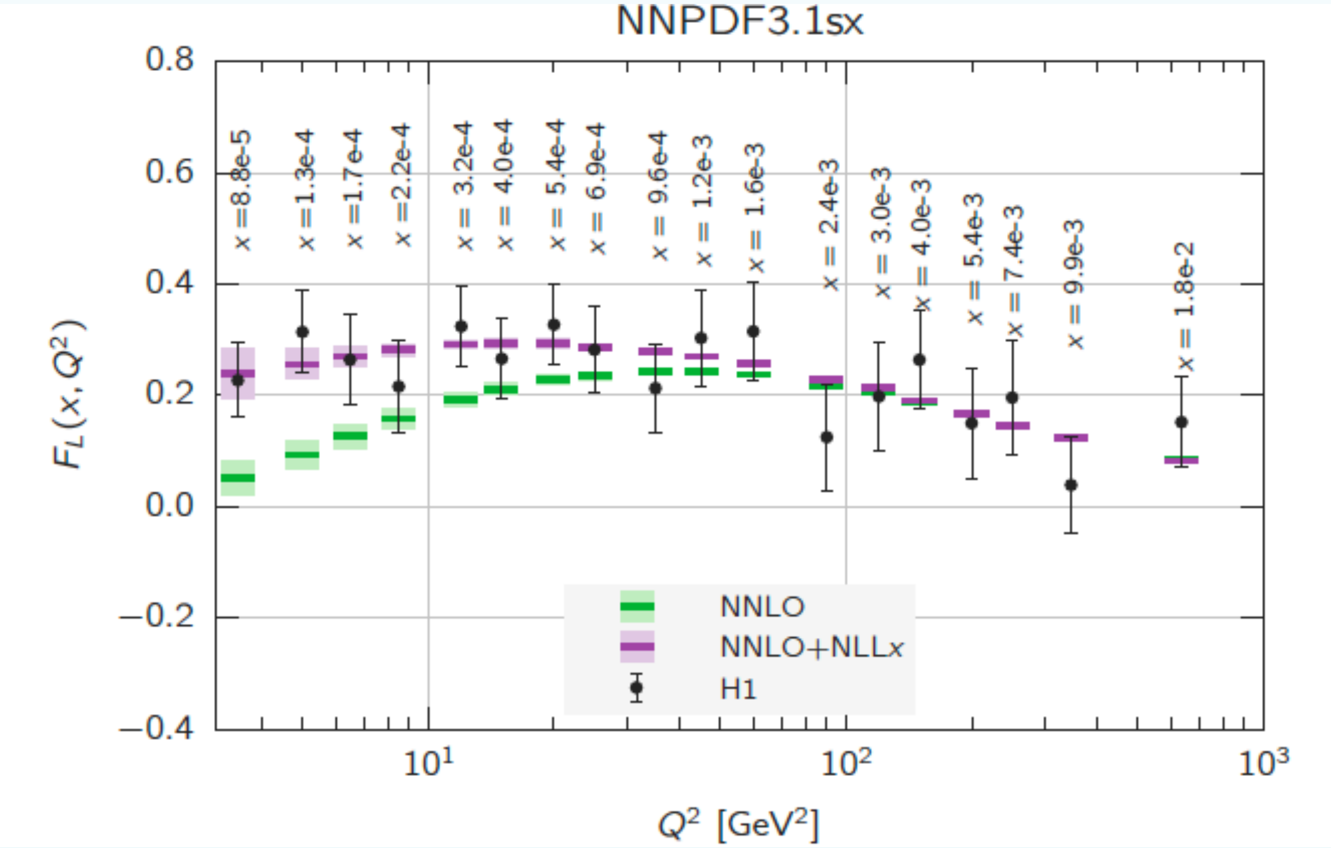


NNLO worsens as we include more small-x data

NNLO+NLLx best description everywhere

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)

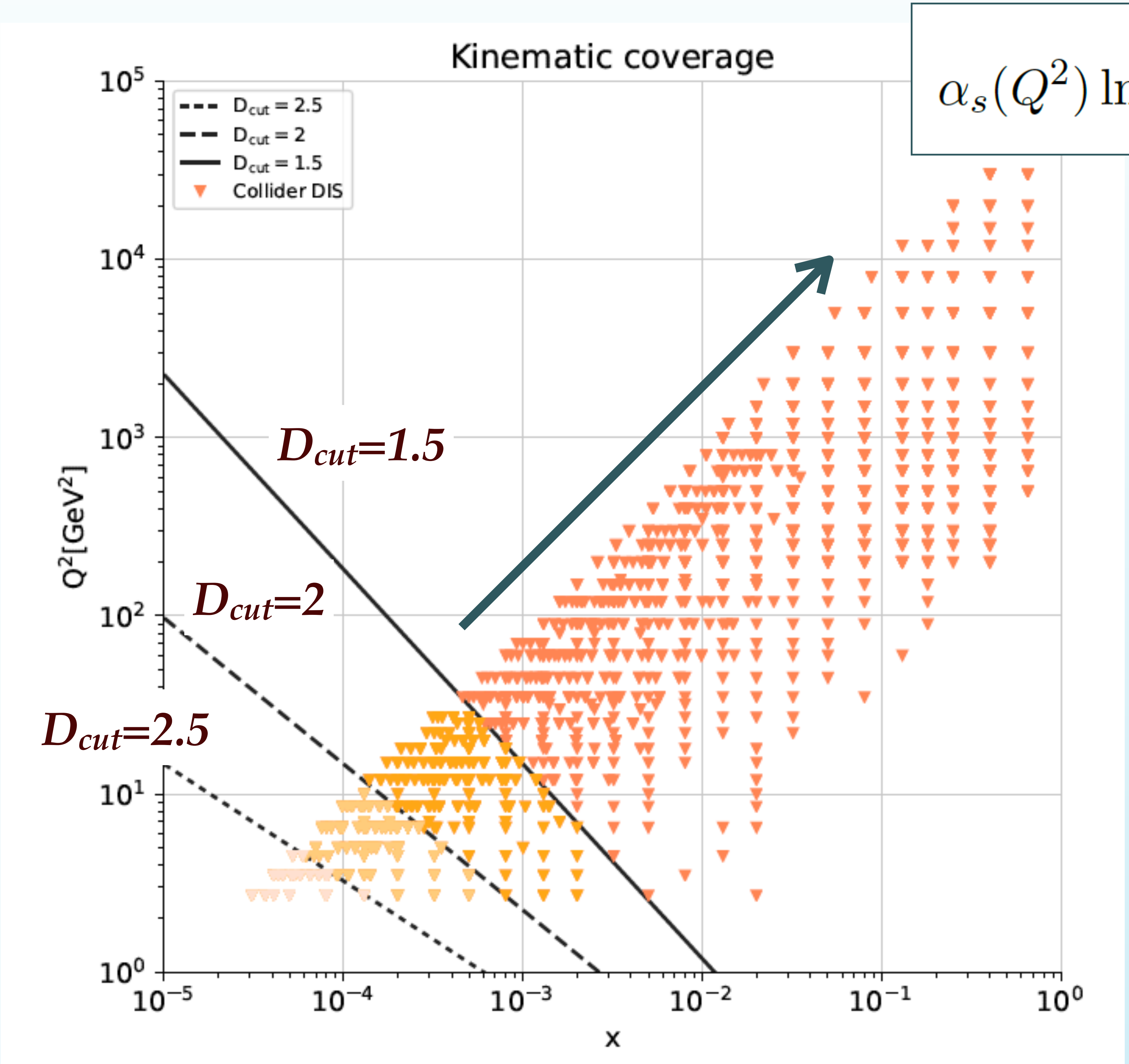
Also **improved description of F_L**, which moreover remains markedly **positive** down to the smallest values of *x* and *Q* probed

Implications for fixed-order fits

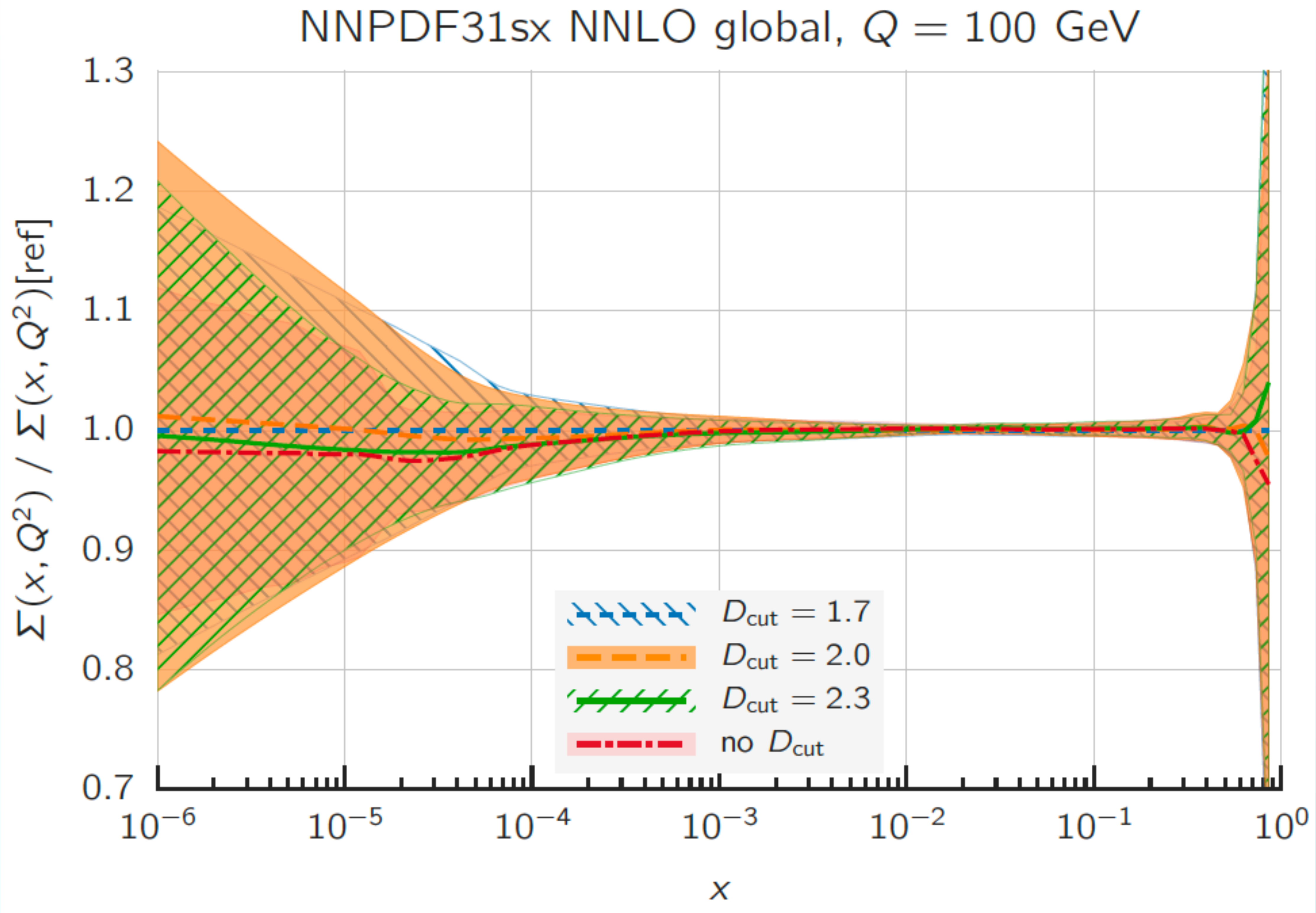
Do these results imply at existing NNLO fits are **biased?** What are implications for LHC pheno?

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

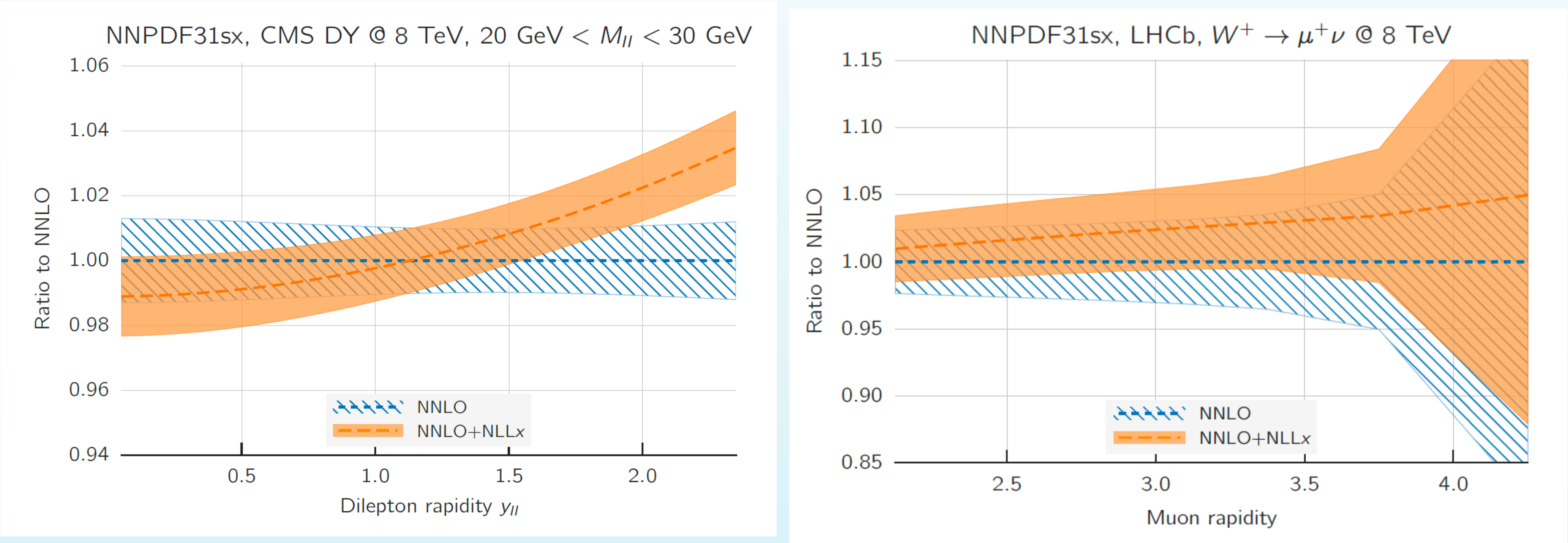


Effects **confined to the small-x region**: global NNLO fits unaffected for (most) LHC applications

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**

Summary and outlook

- **Parton distributions** are a crucial aspect of the **LHC precision phenomenology program**, with direct implications from Higgs characterisation to BSM searches

- **NNPDF3.1** is an state-of-the-art global PDF analysis including a **wealth of precision LHC measurements**, some of them for the first time such as the 8 Z p_T data and top quark production differential distributions

- Thanks to recent theoretical developments, we now have **the photon PDF under good control** with few-percent uncertainties

- **Photon-initiated contributions** are an important component for EW phenomenology at high masses, in particular in combination with **higher-order electroweak corrections**

- The perturbative convergence of small-x QCD can be improved by matching DGLAP to BFKL evolution using **small-x resummation**

- Clear evidence of the **onset of BFKL dynamics** in HERA data: ***New Physics* within QCD!**

Summary and outlook

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Thanks for your attention!