News from NNPDF: QED, small-x, and α_S fits

Juan Rojo
VU Amsterdam & Theory group, Nikhef

on behalf of the NNPDF Collaboration

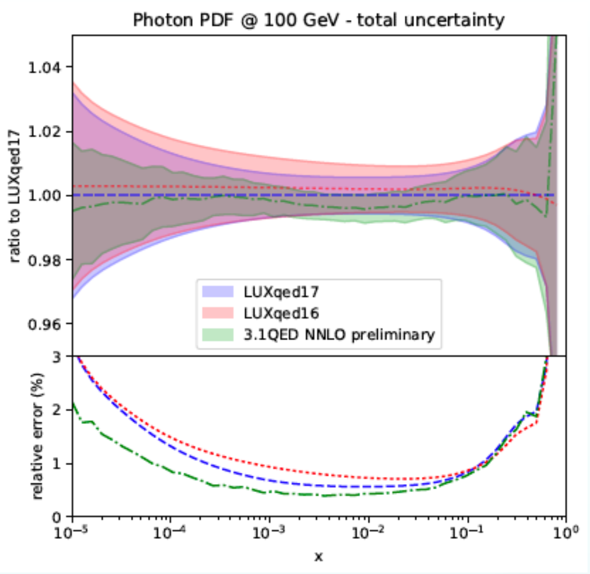
Outline

The **NNPDF3.1 global analysis** was released in June 2017 (*arxiv:1706.00482, EPJC in press*).

Since then, most of our efforts have been focused on **three spin-offs of the NNPDF3.1 fits:**

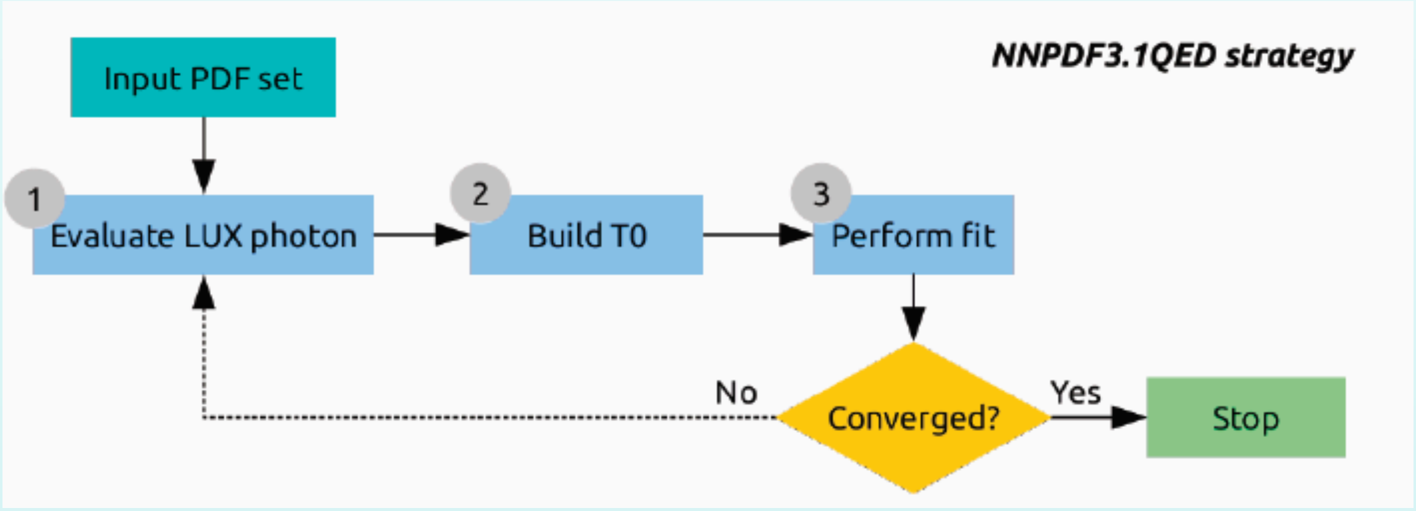
- ☑ **NNPDF3.1QED** and the photon PDF using the **LUXqed formalism**
- ☑ NNPDF3.1 fits with **small-x (BFKL) resummation**
- ☑ A **determination of $\alpha_S(m_Z)$** based on the NNPDF3.1 analysis

In this talk we report on the progress in these three topics



Photon PDF @ 100 GeV - total uncertainty
ratio to LUXqed17
relative error (%)
LUXqed17
LUXqed16
3.1QED NNLO preliminary
x

NNPDF3.1QED



NNPDF3.1QED strategy
Input PDF set
1
Evaluate LUX photon
2
Build T0
3
Perform fit
Converged?
No
Yes
Stop

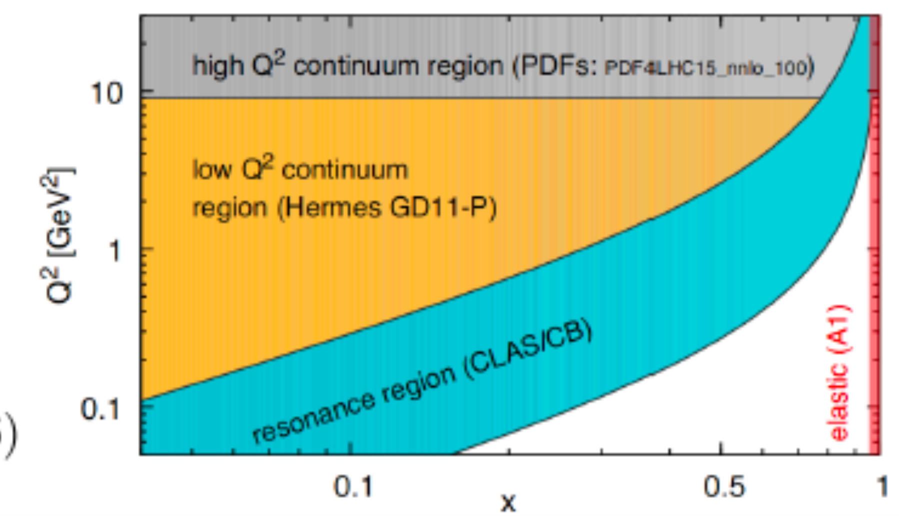
Motivation

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

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



Where the structure functions are decomposed in 3 parts:

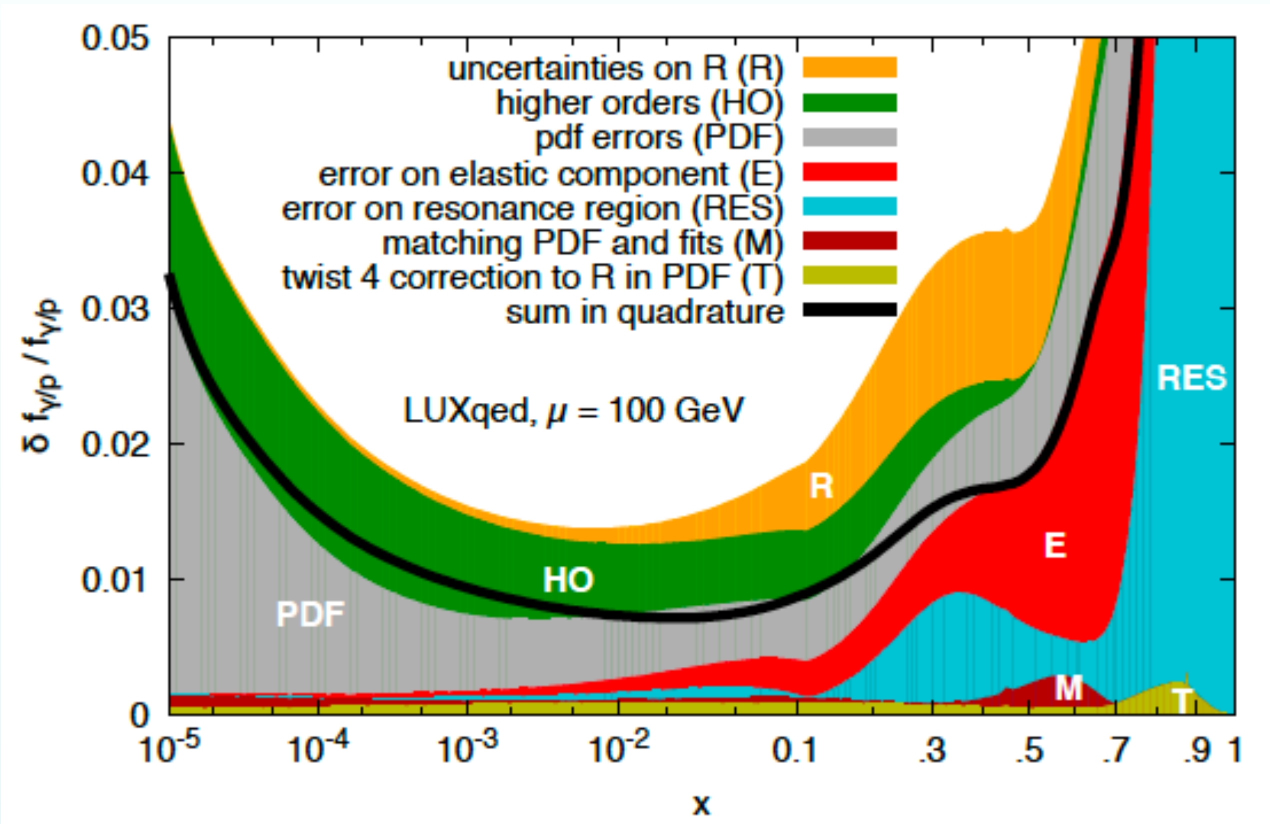
$$F_2(x,Q) = F_2^{\text{elastic}}(x,Q) + F_2^{\text{inelastic}}(x,Q) + F_2^{\overline{\text{MS}}}(x,Q)$$

Manohar, Nason, Salam, Zanderighi 16, 17

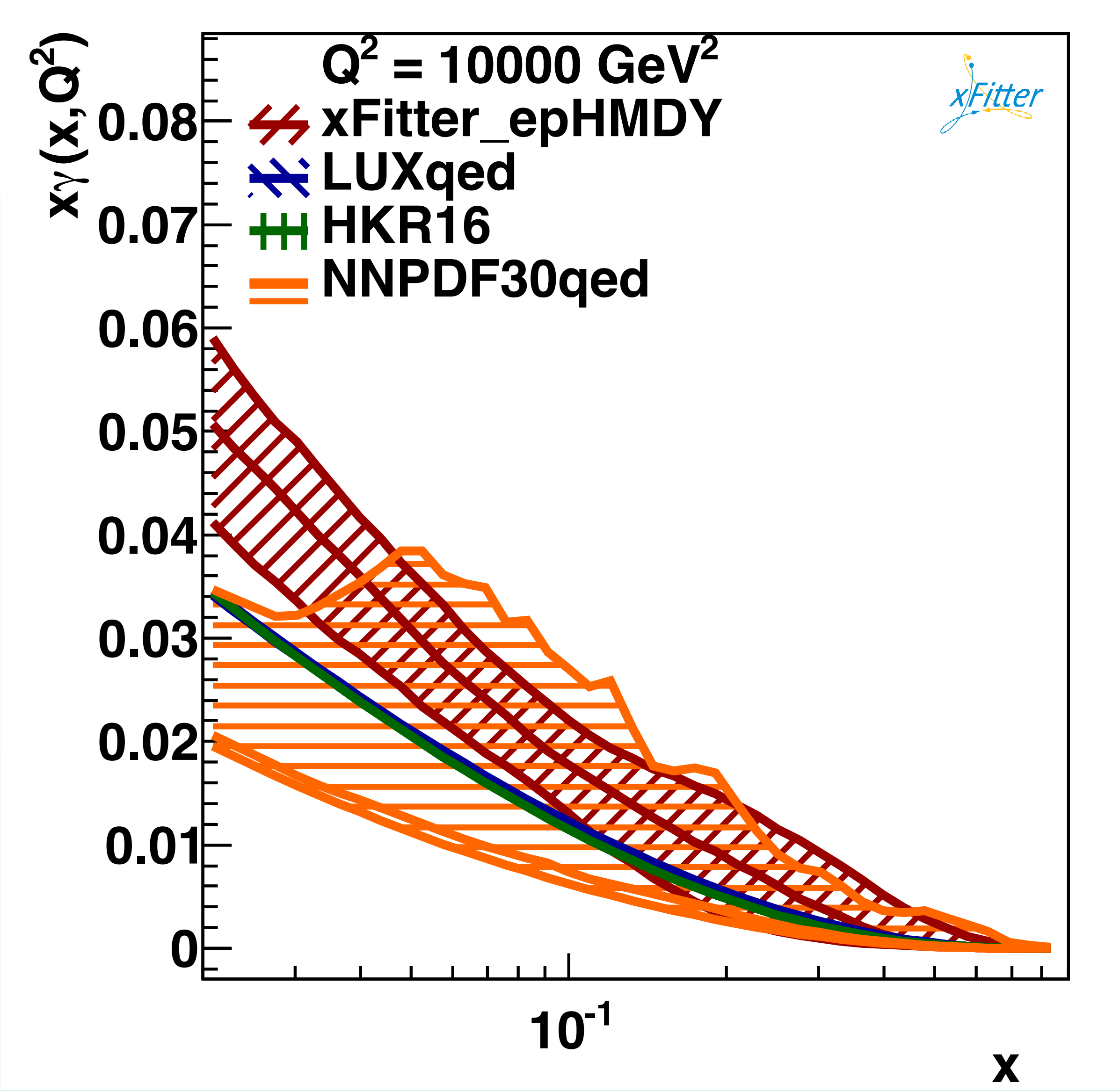
It is clearly more advantageous to **perform a QED fit imposing the LUXqed theory constraints** on the photon PDF **ɣ(x,Q)**, rather than extracting it from experimental measurements

Motivation

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

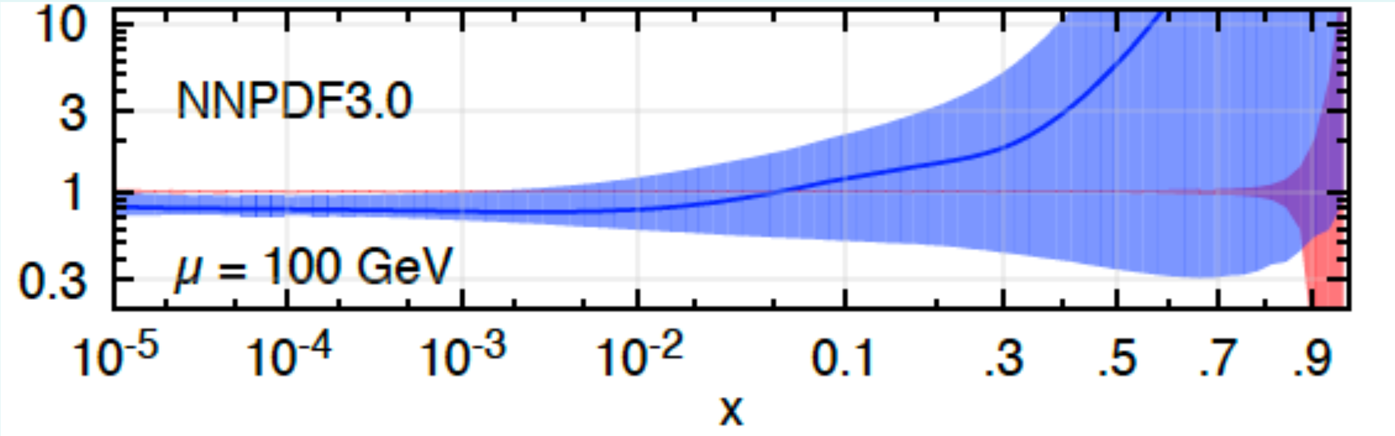


Even using one of the most sensitive processes to photon-initiated contributions, **high-mass DY at 8 TeV**, uncertainties in **γ(x,Q)** still at the **30% level**



xFitter Developer's Team 17

Agreement within errors with NNPDF3.0QED



NNPDF3.1QED: strategy

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

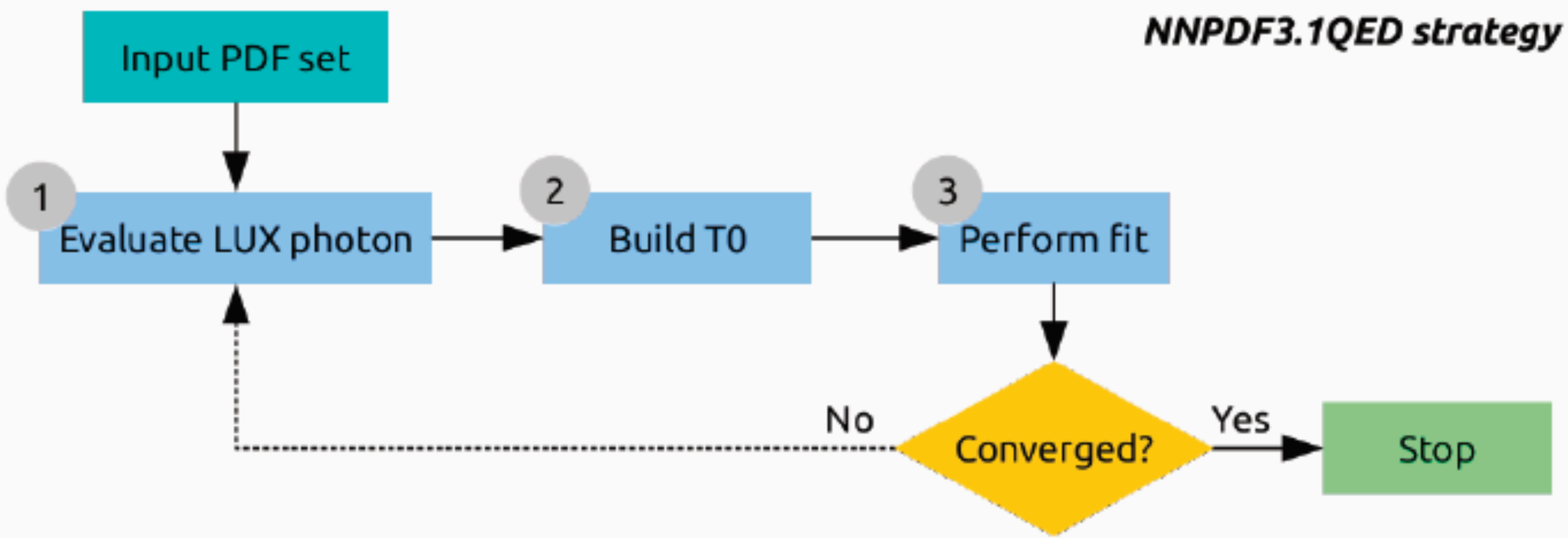
We base our approach in 4 steps:

``FiatLUX", Carrazza in preparation

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

NNPDF3.1QED strategy



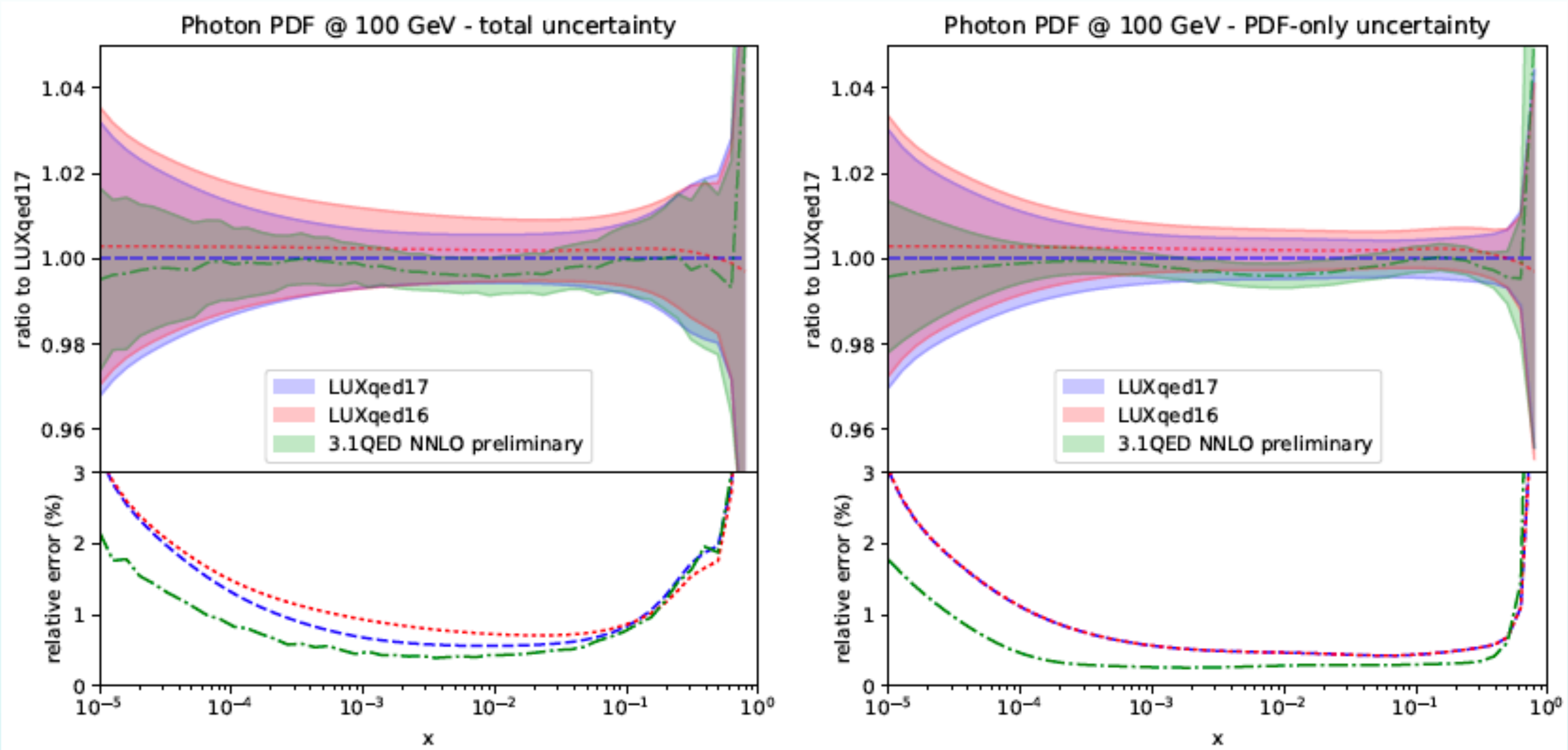
Another important update in the NNPDF3.1QED fits is the use of **NLO QED theory** both in **splitting functions** and in the **DIS coefficient functions**, implemented in the **APFEL code**

Bertone, Carrazza, Rojo 13

Preliminary results

PDF + LUXqed systematic uncertainties

PDF-only uncertainties

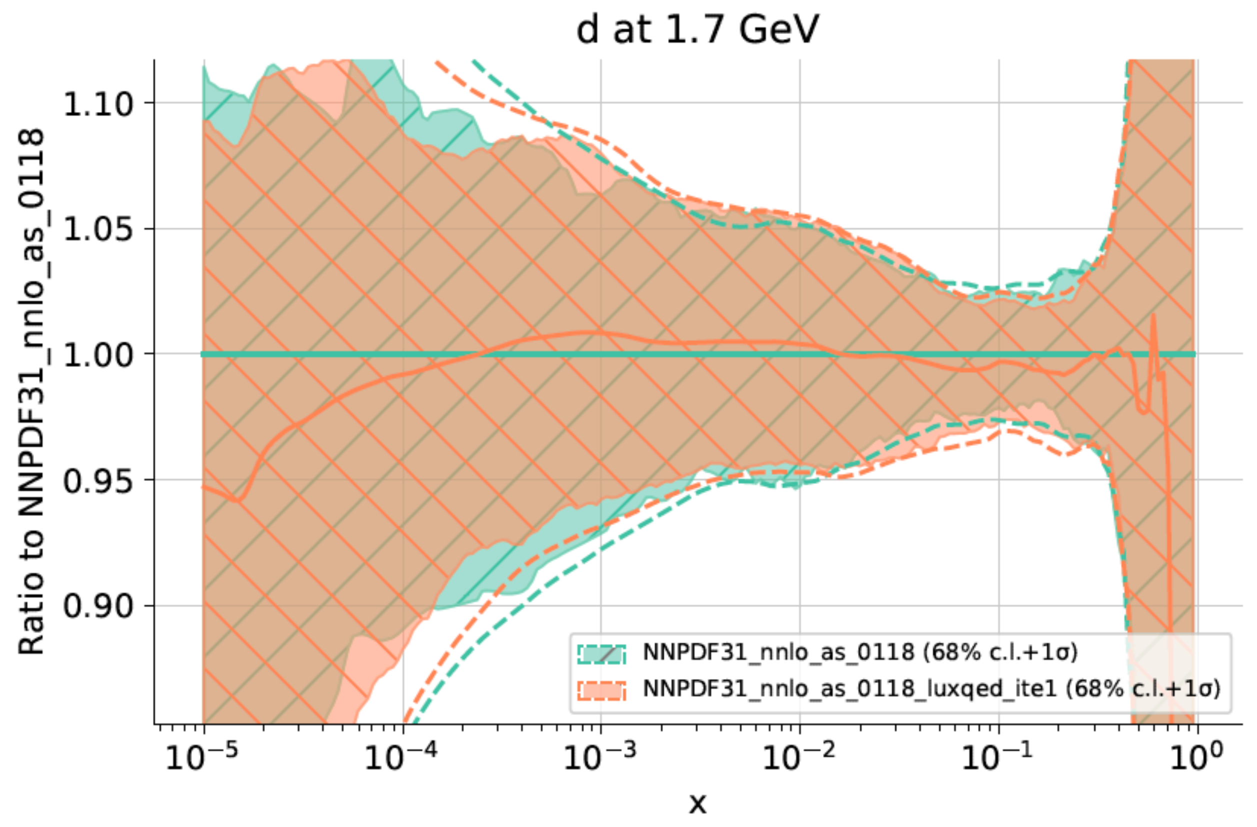


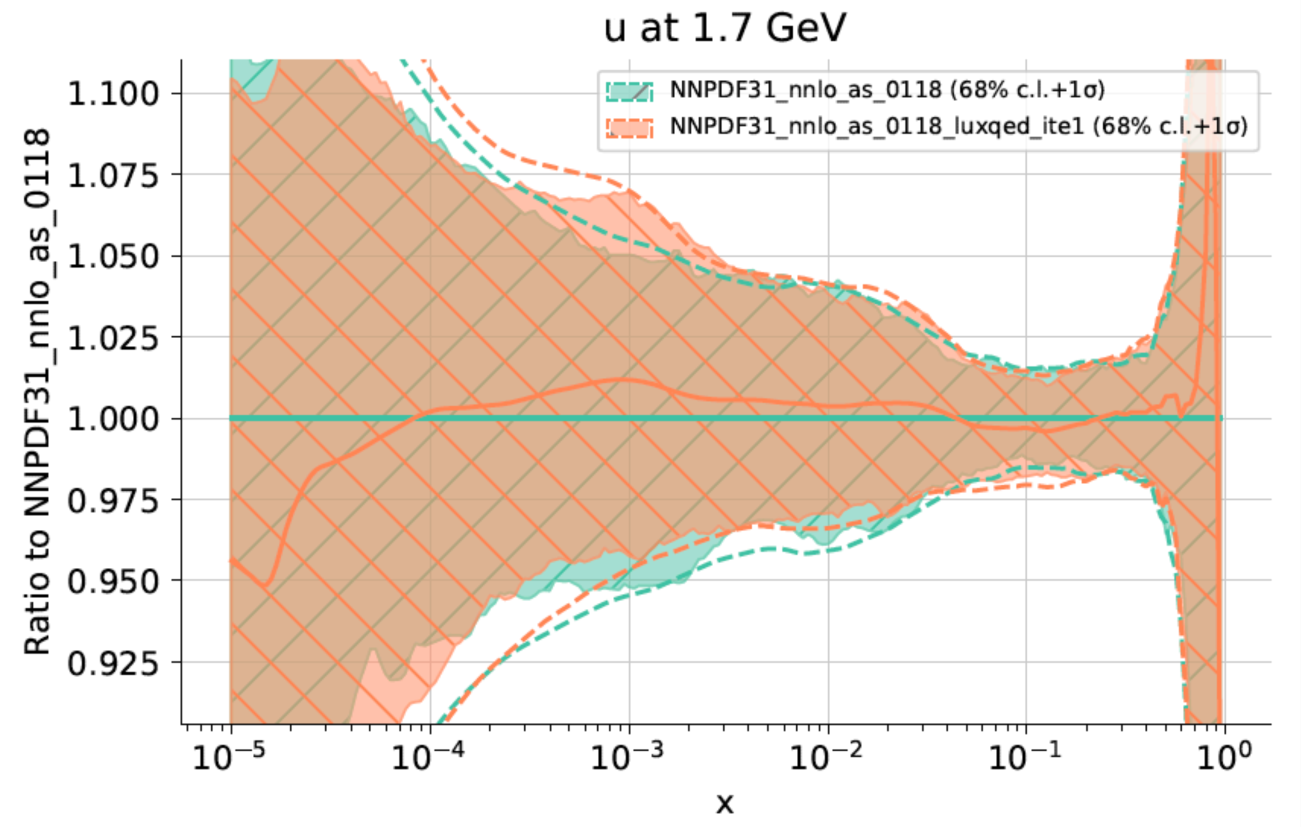
Good agreement between **NNPDF3.1QED and the LUXqed photon PDF**

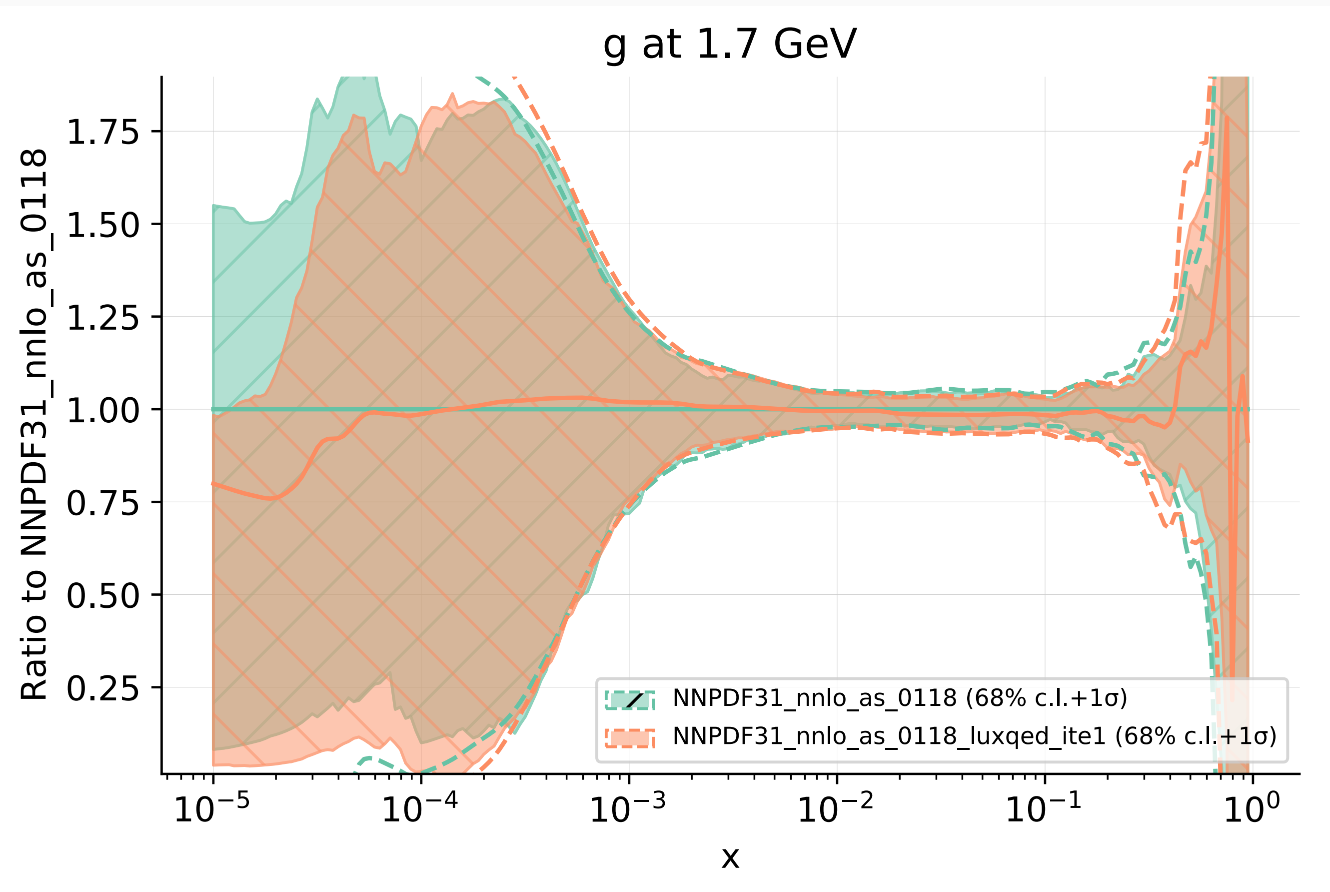
The LUXqed systematic uncertainties on **γ(x,Q)** are included as **extra Gaussian fluctuations**

$$\gamma^k_{\mathrm{unc}}(x,Q) = \gamma^k(x,Q) + \sum_{j=1}^{N_{\mathrm{sys}}} \delta\sigma_j^{\mathrm{LUX17}} \mathcal{N}(0,1)$$

Preliminary results





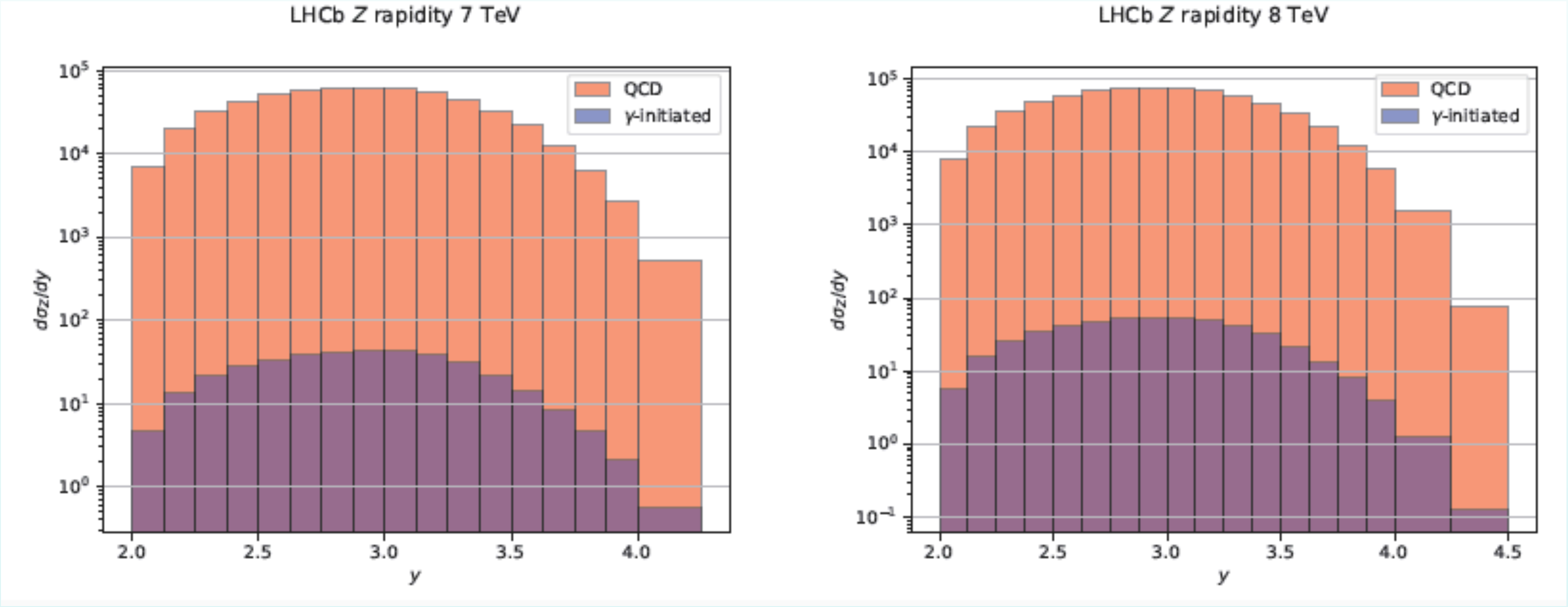


- The iterative procedure **converges very fast** (within 2 iterations at most)

- At the level of **quarks and gluons**, the **differences between the NNPDF3.1 QCD and QCD+QED fits** are minimal

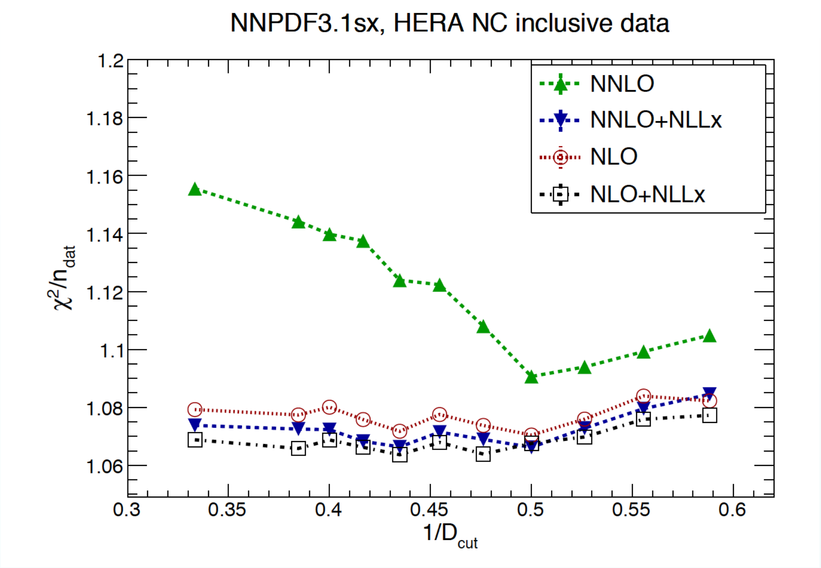
Fits with photon-initiated contributions

- 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

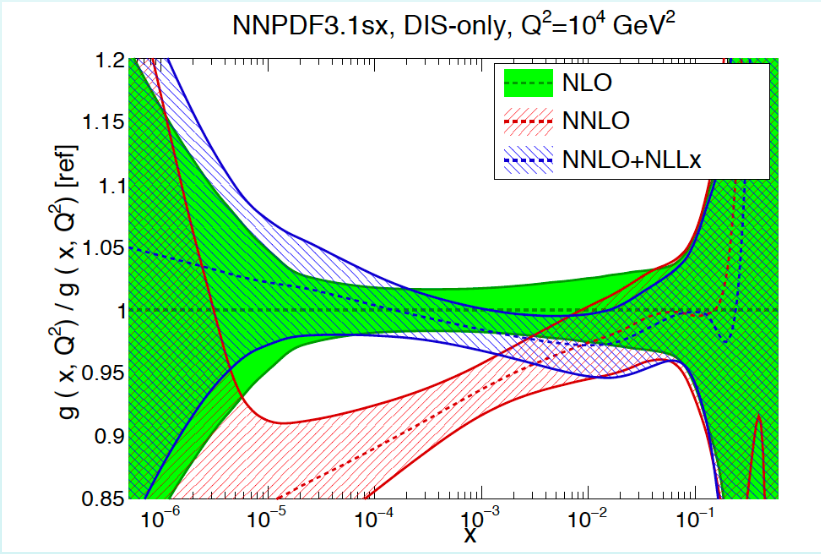


The fits are mostly **insensitive to the inclusion of PI effects in the LHCb cross-sections**

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



Parton Distributions with Small-x Resummation



Motivation I: beyond fixed-order DGLAP

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a wealth of data from proton-proton and electron-proton collisions
- However, there are theoretical indications that eventually we might 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: **small-x/high-energy/BFKL resummation** formalism.
  - The **steep rise in the small-x gluon** will eventually trigger **non-linear** recombinations: **gluon saturation**, BK/JIMWLK equations …..
- **BFKL resummation** can be matched to the **DGLAP collinear framework**, and thus can in principle 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

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

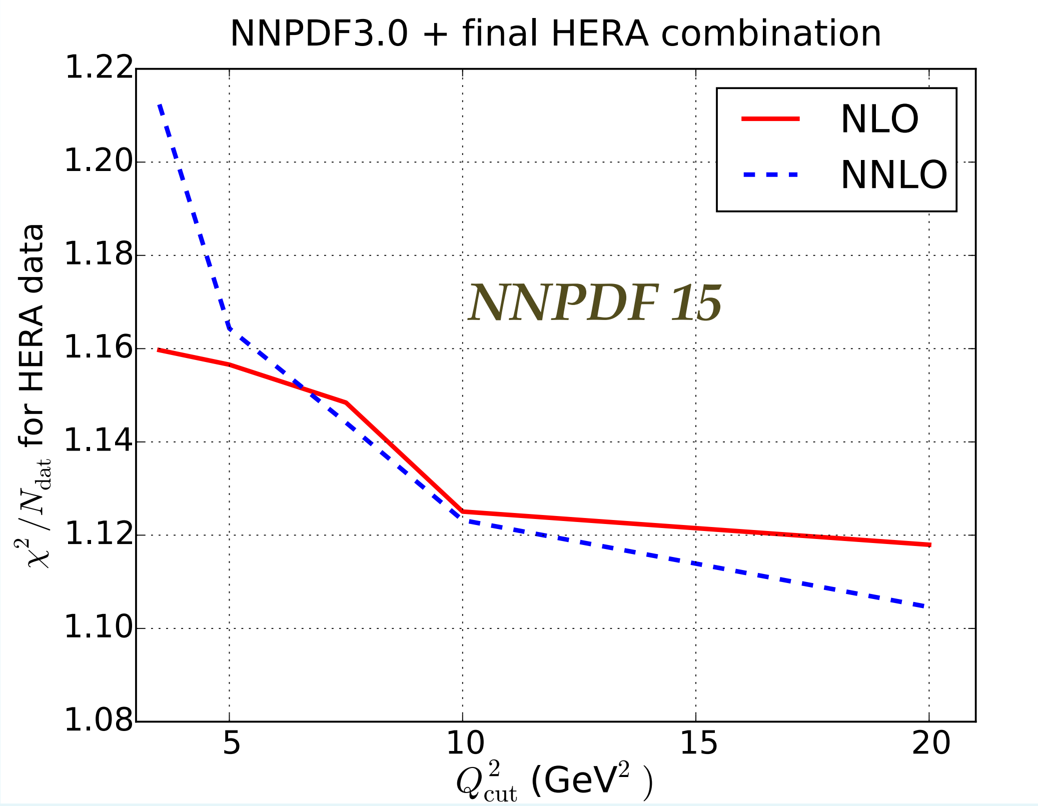
Altarelli, Ball, Forte 08
Ciafalini, Colferai, Salam, Stasto 07
Thorne and White 07
+ others

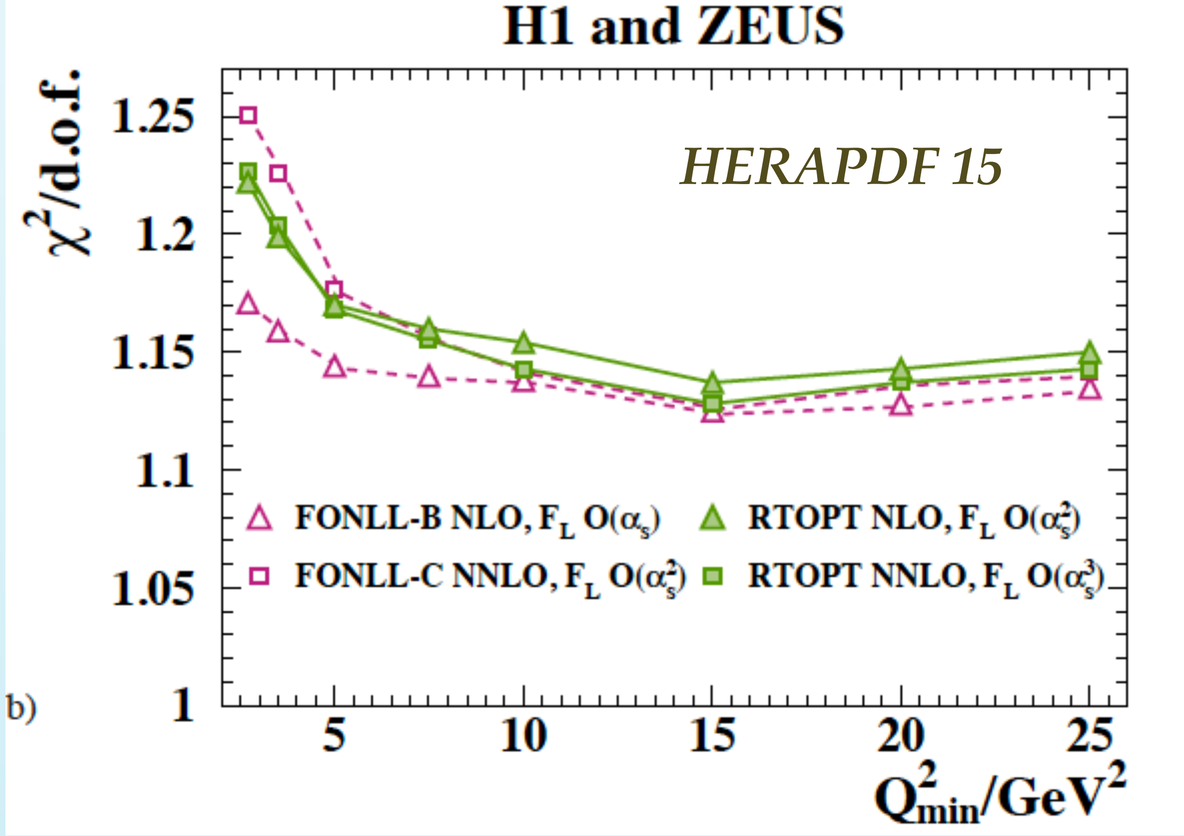
Within small-x resummation, the **N^kLO fixed-order DGLAP splitting functions** are complemented with the **N^hLLx contributions from BKFL**

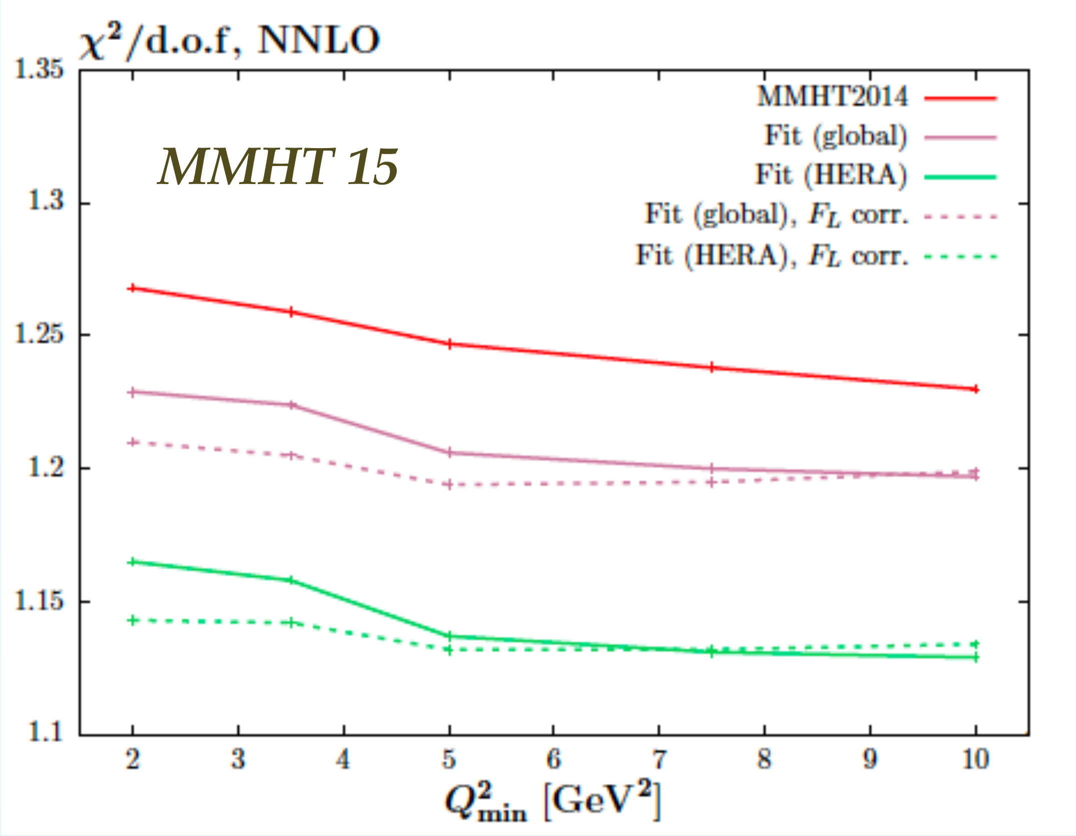
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

Motivation II: tensions in inclusive 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?**

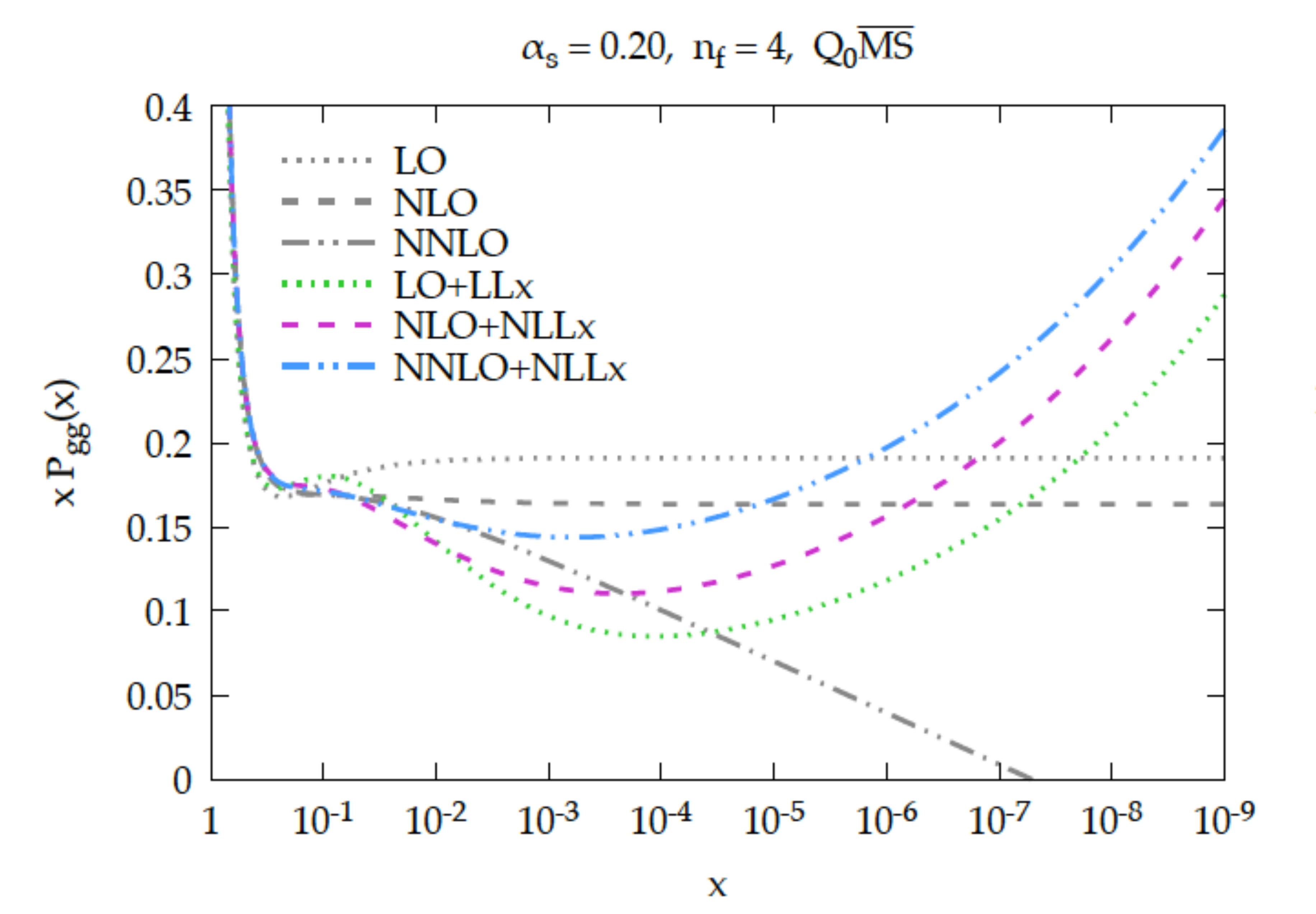






PDFs with BFKL resummation

- Ultimately, the need for (or lack of) BKFL resummation can only be assessed by performing a **global PDF analysis with (N)NLO+NLLx matched theory**
- Theoretical tools are now available: **HELL for NLLx resummation**, interfaced to the public **APFEL** code



Bonvini, Marzani, Peraro 16

Bonvini, Marzani, Muselli 17

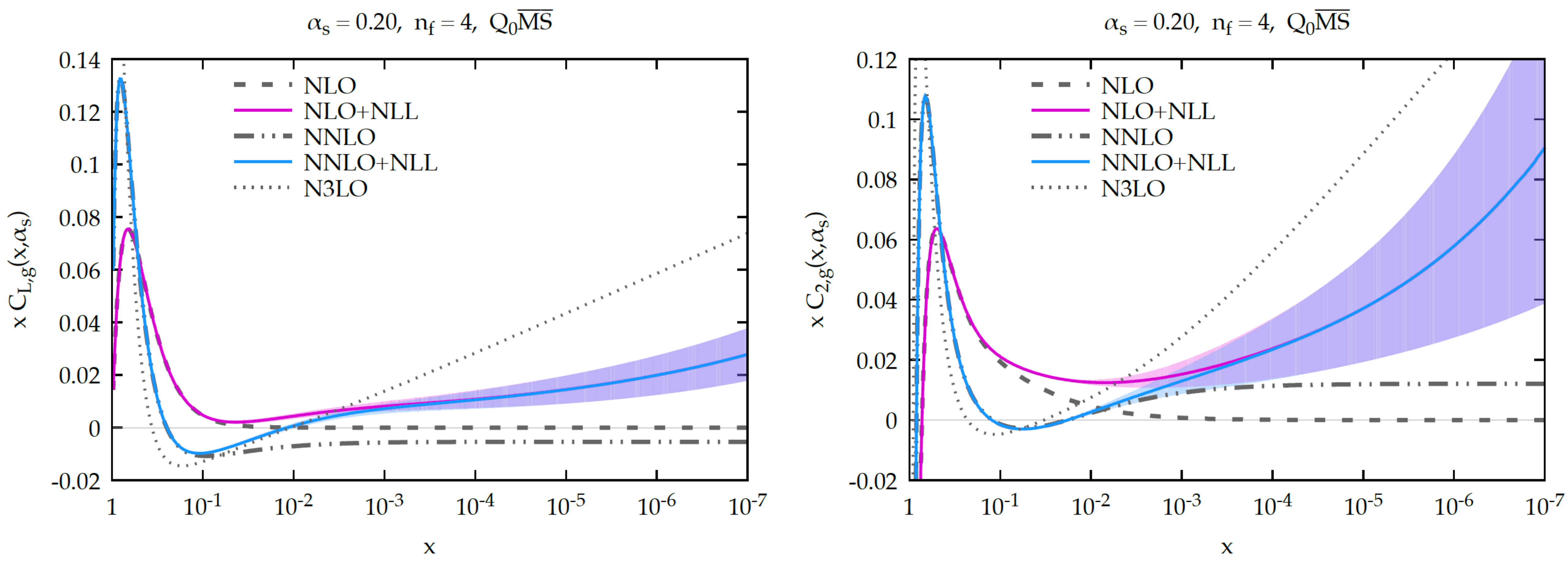
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

https://www.ge.infn.it/~bonvini/hell/

PDFs with BFKL resumation

- Ultimately, the need for (or lack of) BKFL resummation can only be assessed by performing a **global PDF analysis with (N)NLO+NLLx matched theory**
- Theoretical tools are now available: **HELL for NLLx resummation**, interfaced to the public **APFEL** code

At small-x, **NNLO+NNL*x* coefficient functions for DIS structure functions** soften the steep rise of the N3LO result

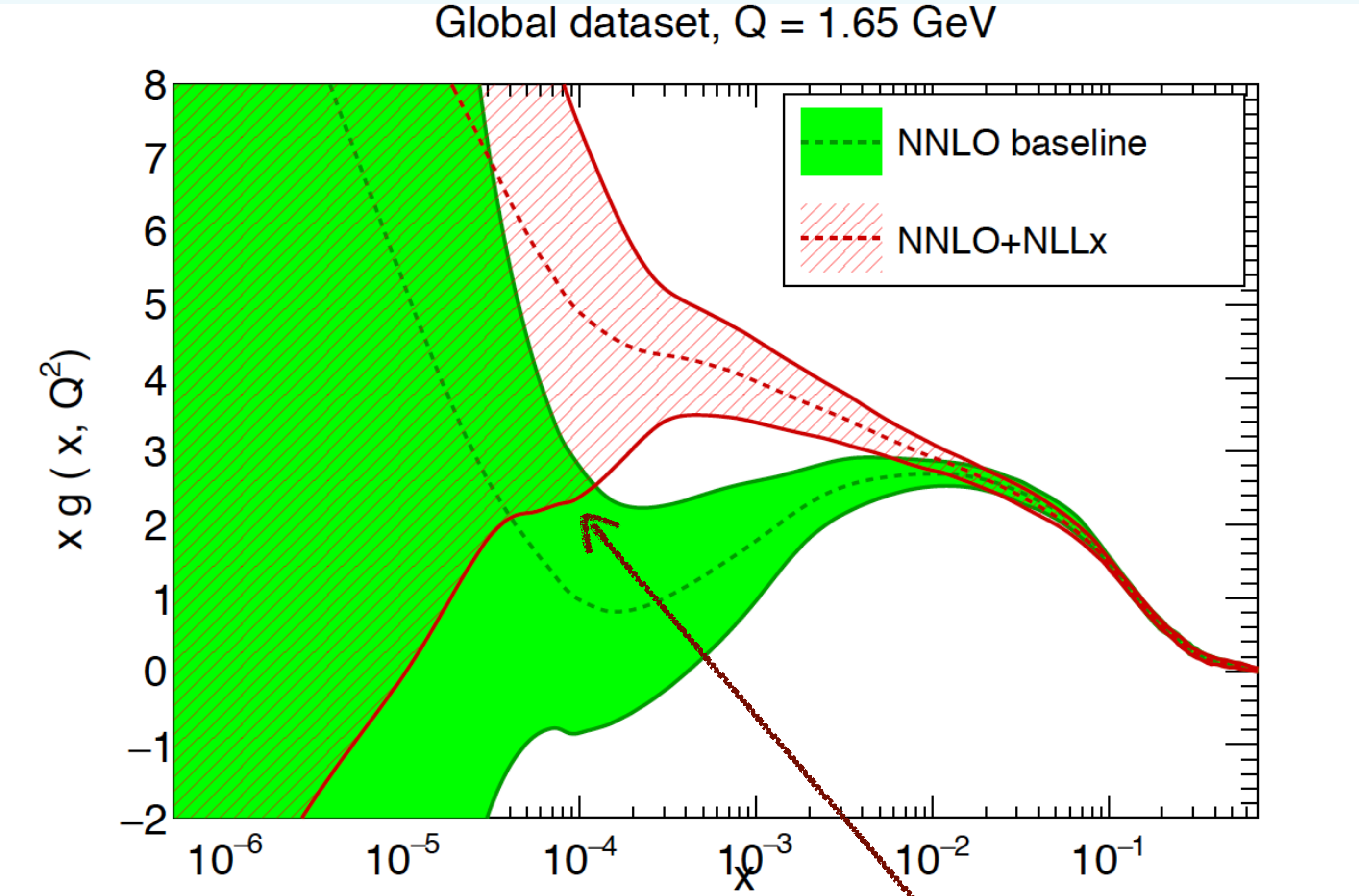


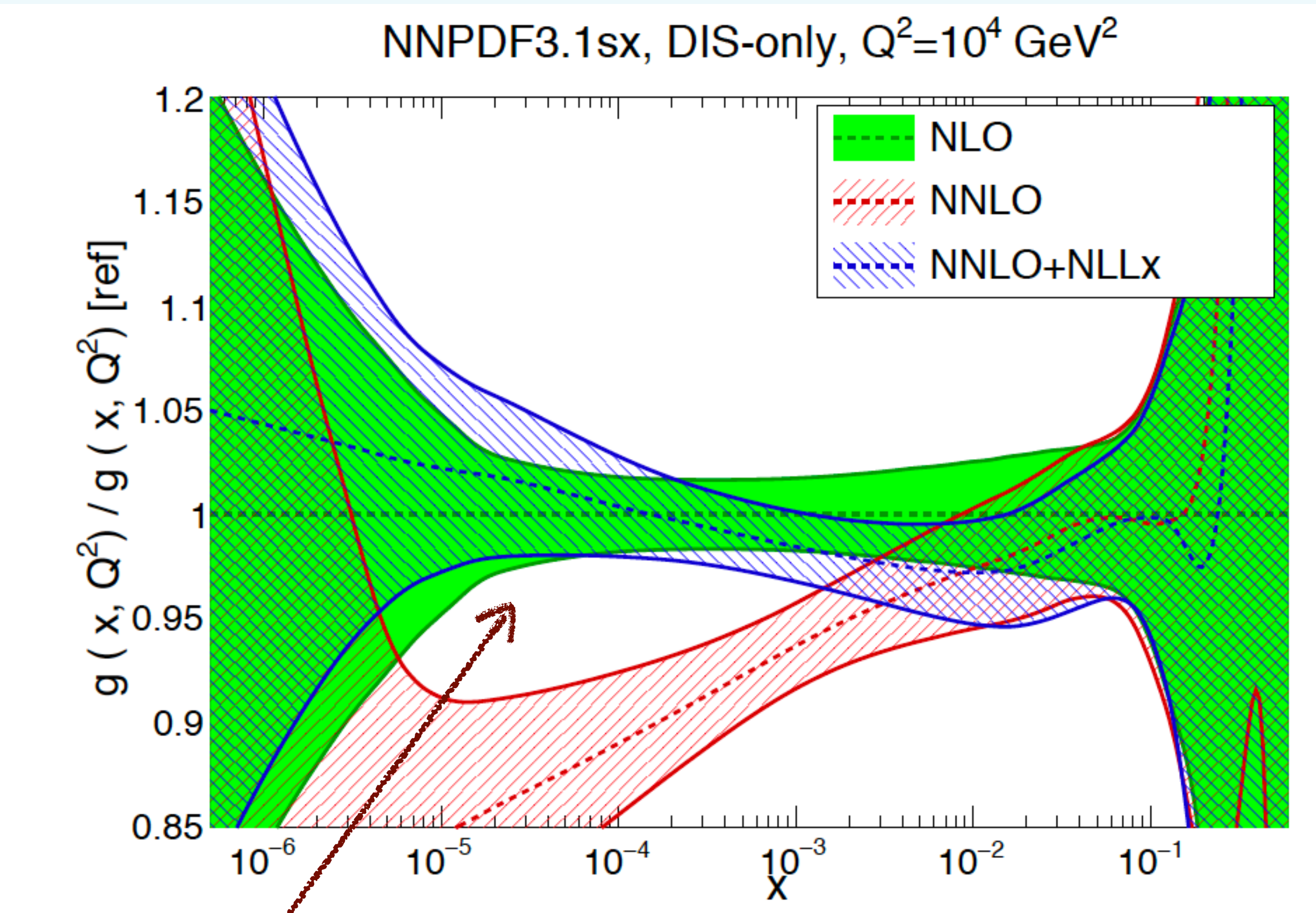
Bonvini, Marzani, Peraro 16

Bonvini, Marzani, Muselli 17

Global PDFs with BFKL resummation

- Performed a variant of the **NNPDF3.1 global fits** using **NLO+NLLx and NNLO+NLL*x* theory**
- Small-x resummation of partonic cross-sections included **only for DIS structure functions**: remove all collider data with potential sensitivity to small-x effects
- Using NNLO+NLL*x* theory **stabilises small-x gluon**, leading to improved agreement with NLO result

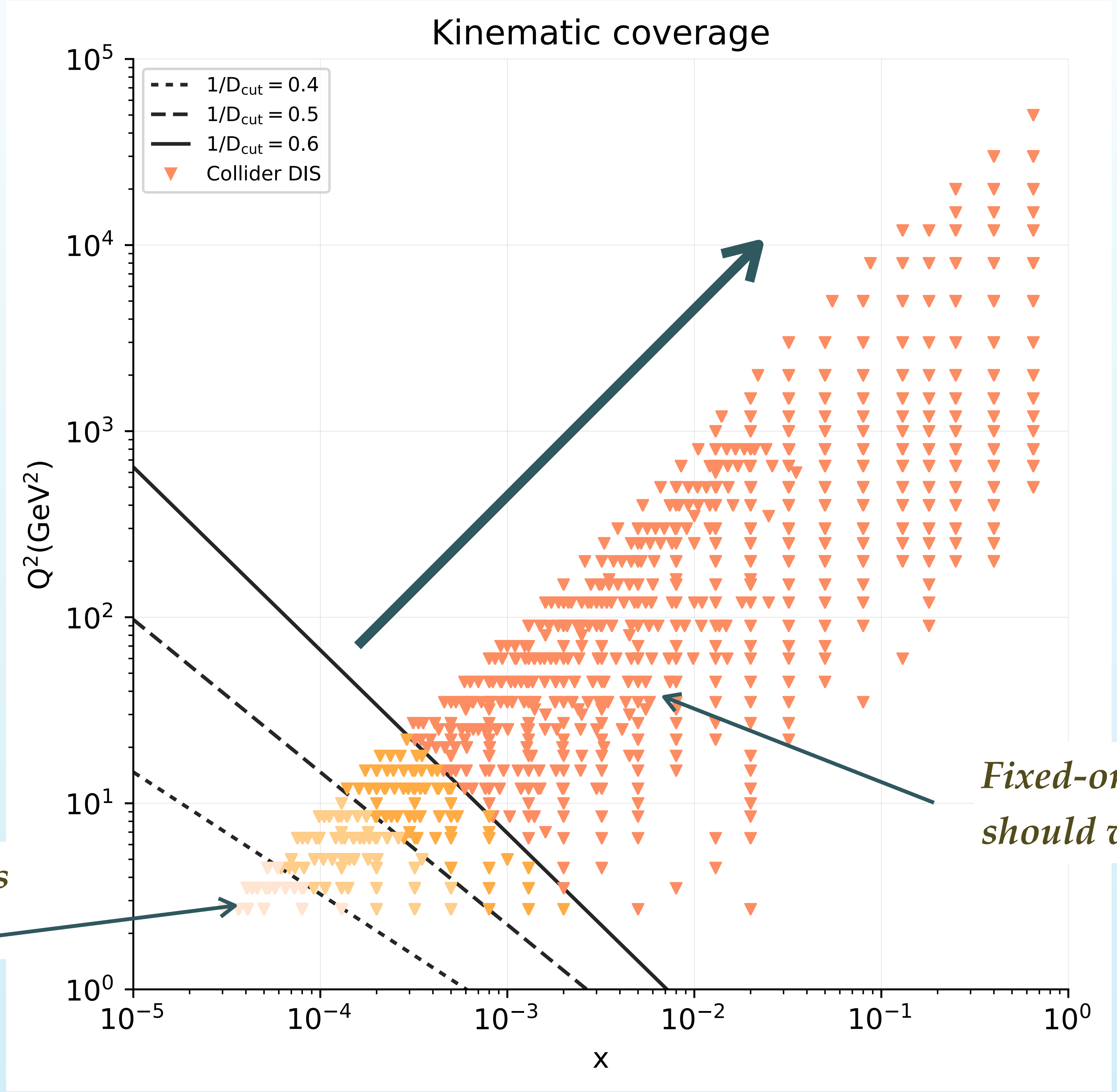




Improved **perturbative convergence of the small-x gluons**

Fit quality at small-x and Q^2

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**



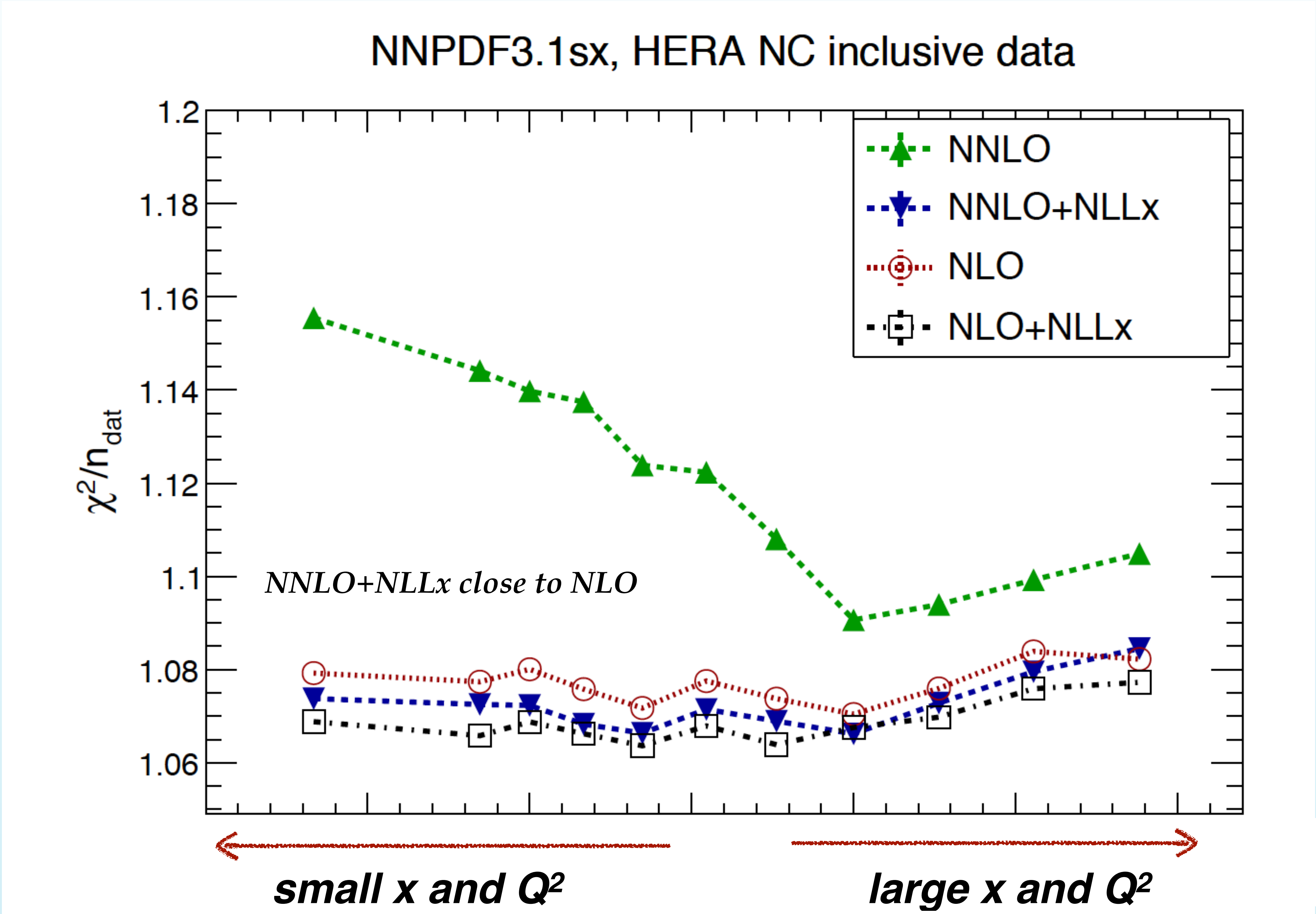
Fixed-order theory should work fine here

Small-x resummation effects could be important here

Fit quality at small-x and Q^2

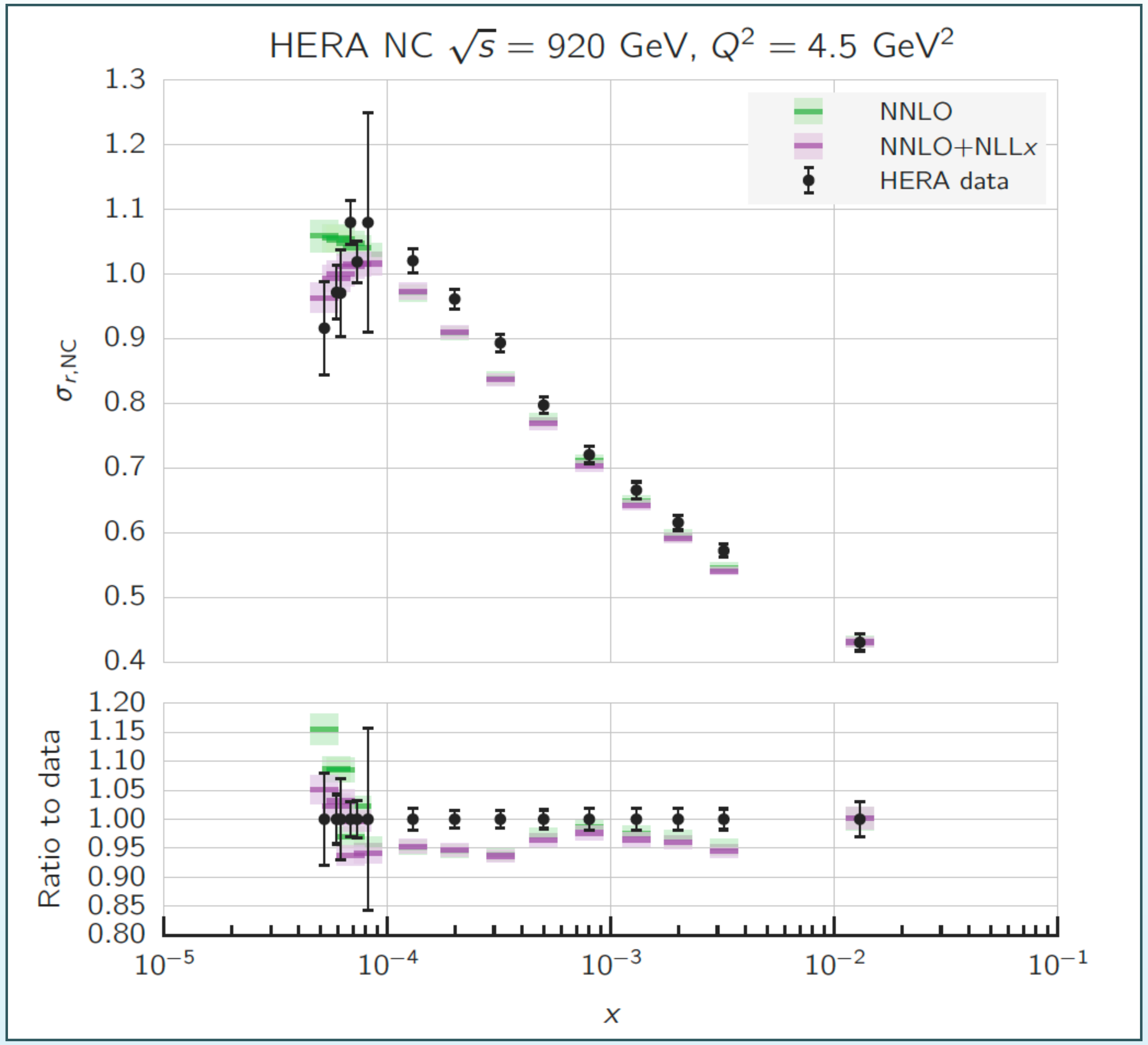
Using **NNLO+NLLx theory, the NNLO instability of the χ^2 disappears**

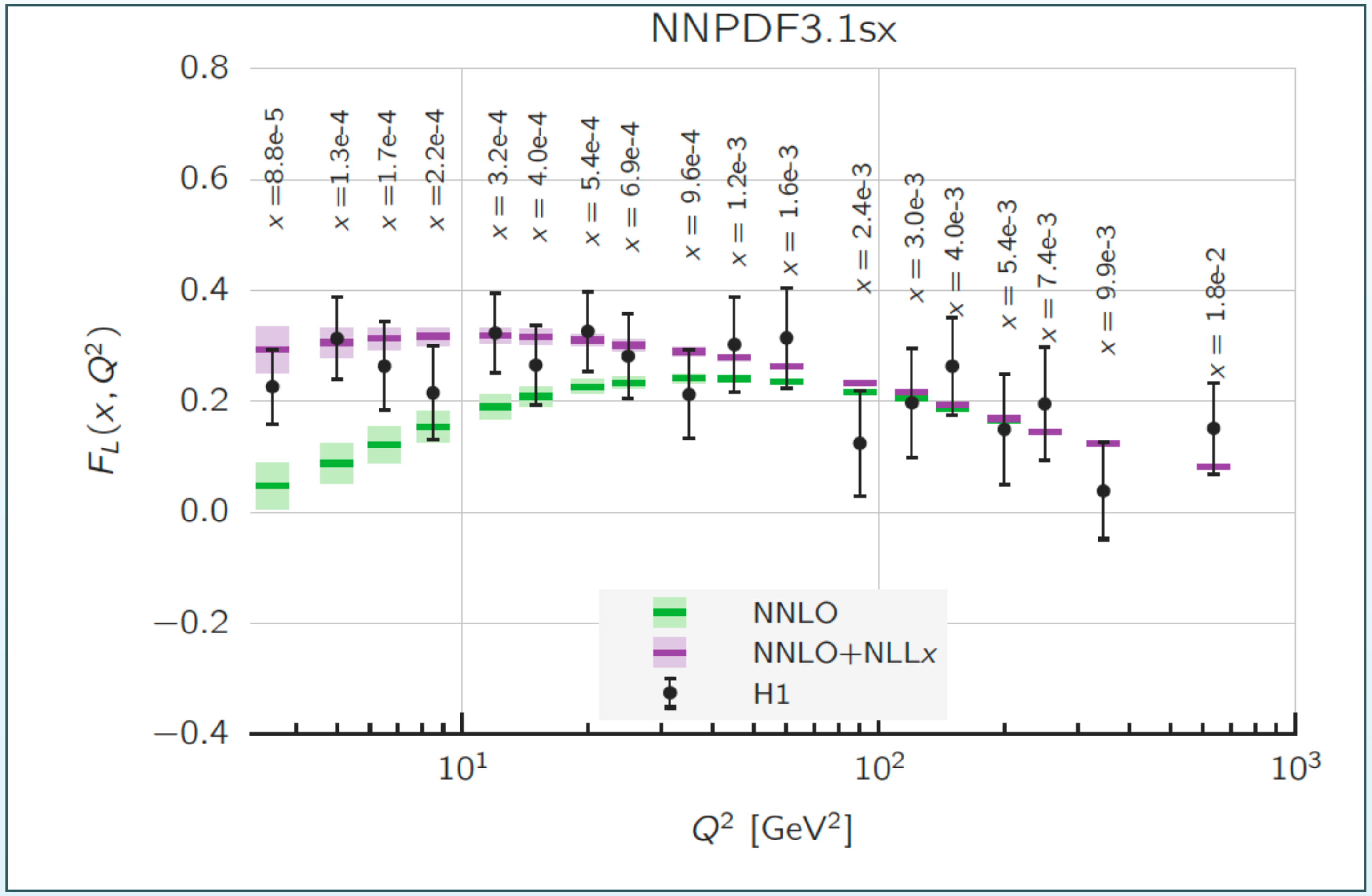
Excellent fit quality to inclusive HERA data achieved in the **entire (x,Q^2) region** accessible experimentally



Cut in small-x and Q HERA data

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

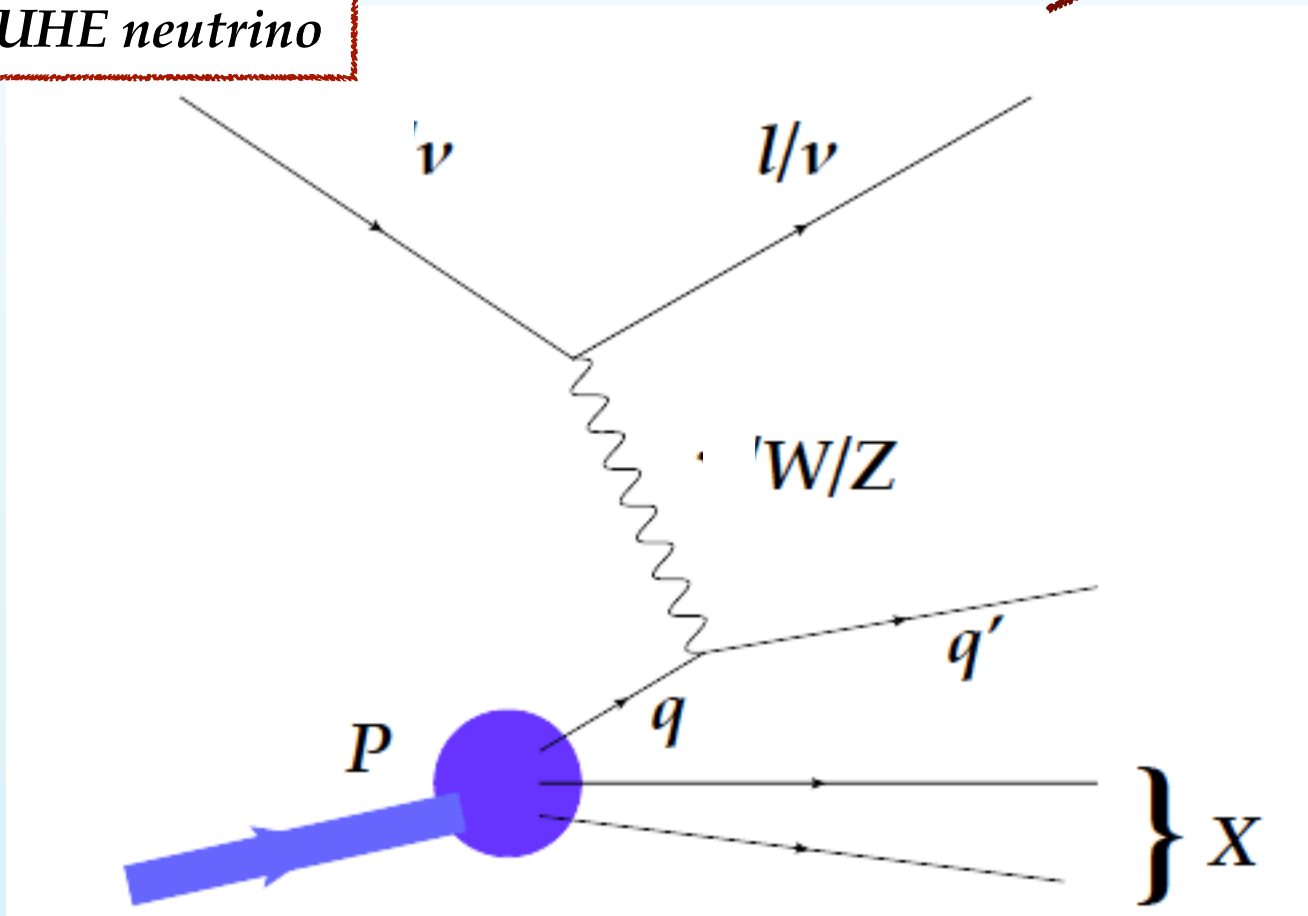
Also **improved description of F$_L$,** which moreover remains markedly **positive** down to the smallest values of *x* and Q probed

From the LHC to Neutrino Telescopes

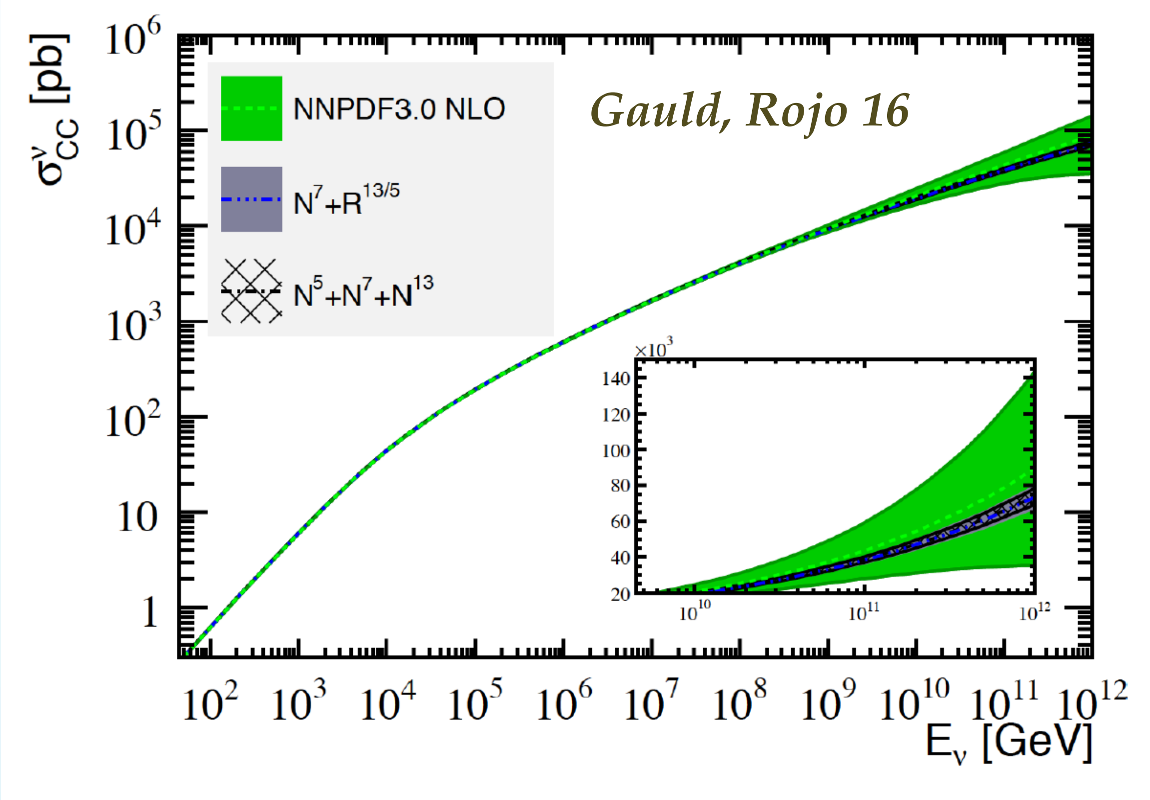
Provide state-of-the-art predictions for the UHE neutrino nucleus cross-sections for neutrino telescopes

Using better data

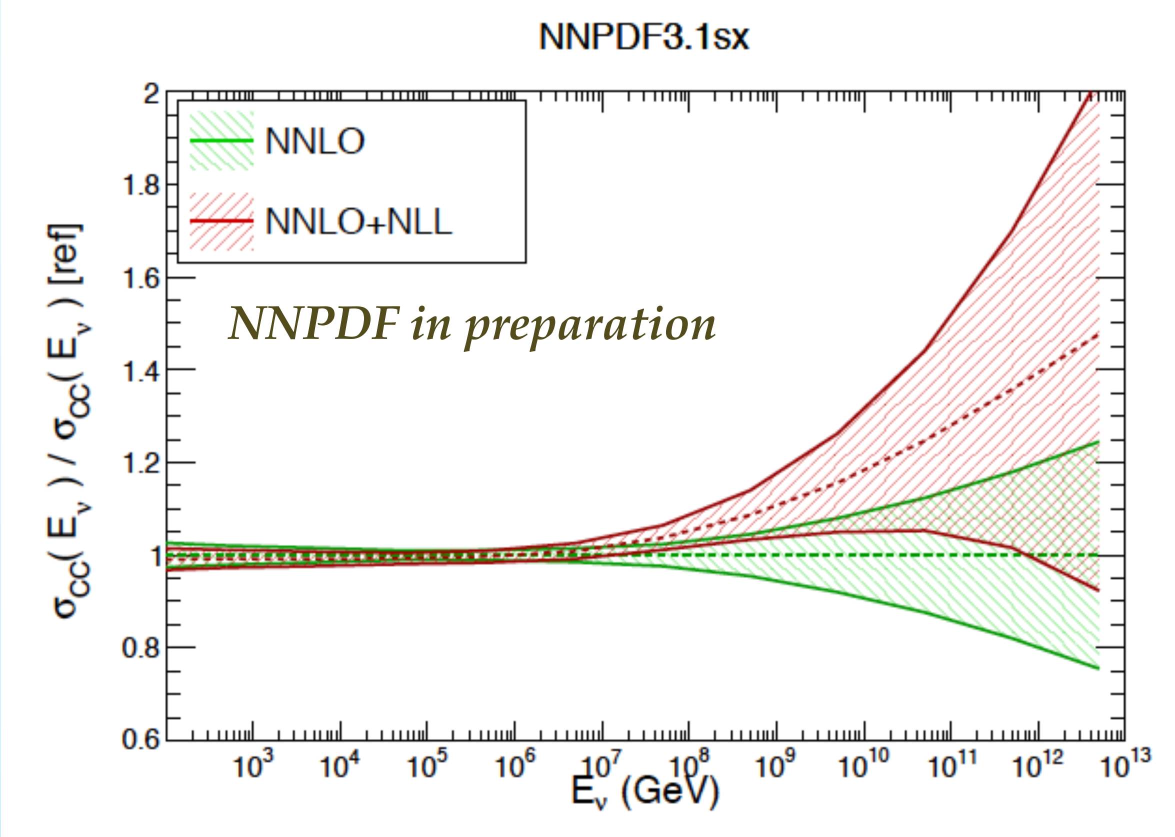
UHE neutrino



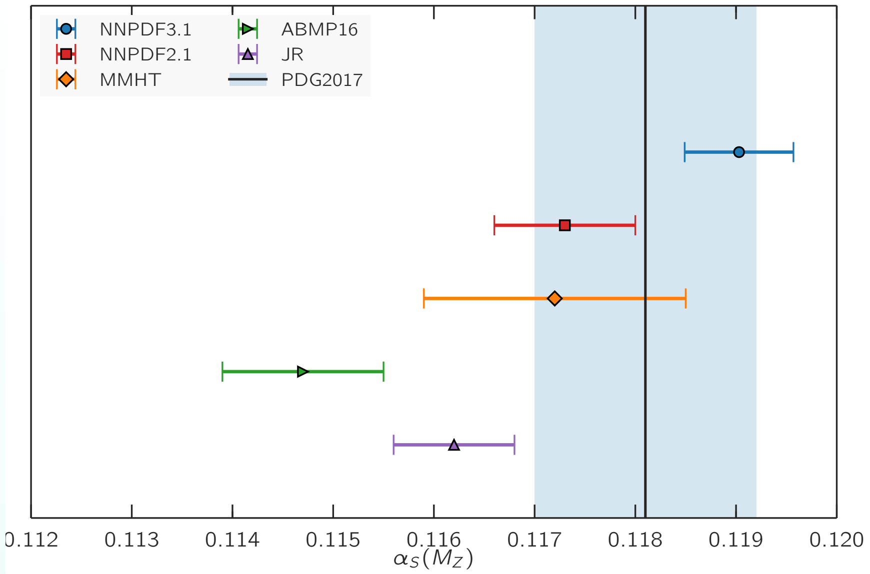
Constraints from LHCb D production



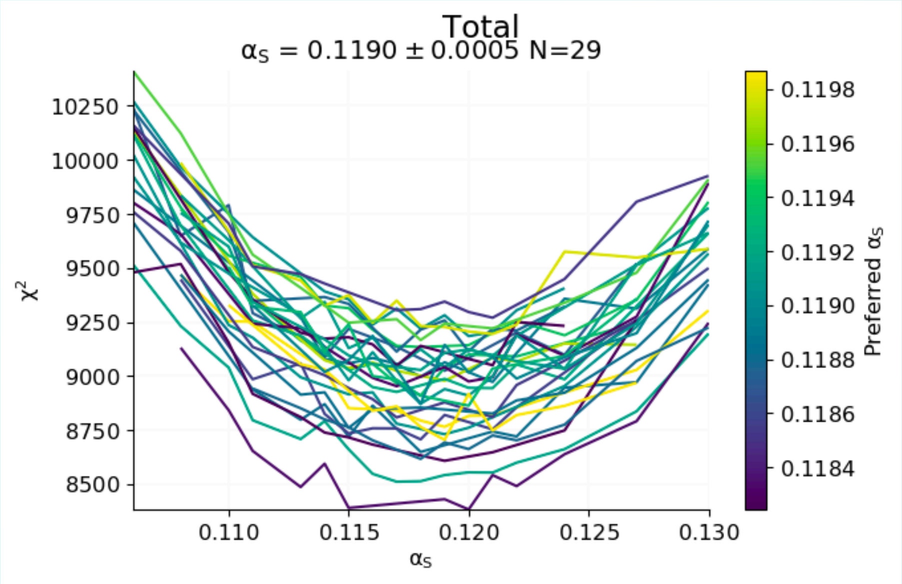
Using better theory



Constraints from BFKL resummation



The strong coupling constant $\alpha_S(m_Z)$ from the NNPDF3.1 analysis



Recap: $\alpha_S(m_Z)$ determination from NNPDF2.1

The last determination of $\alpha_S(m_Z)$ within the NNPDF framework was based on the **NNPDF2.1 fit**

NNPDF 10,11

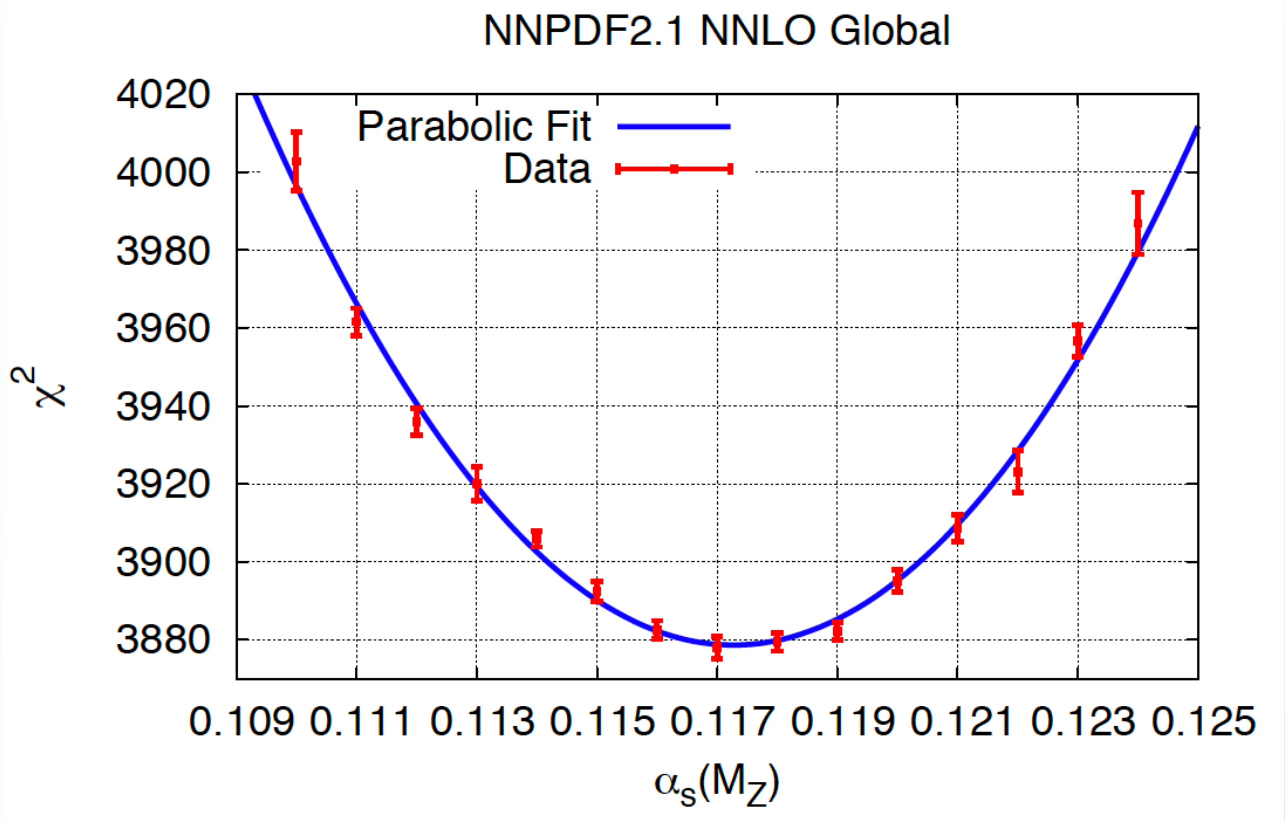
A **large number of MC replicas** (between 1000 and 100) generated for a range in $\alpha_S(m_Z)$, and then a **parabola was fitted to the χ^2 results of the best fit** for each $\alpha_S(m_Z)$ value

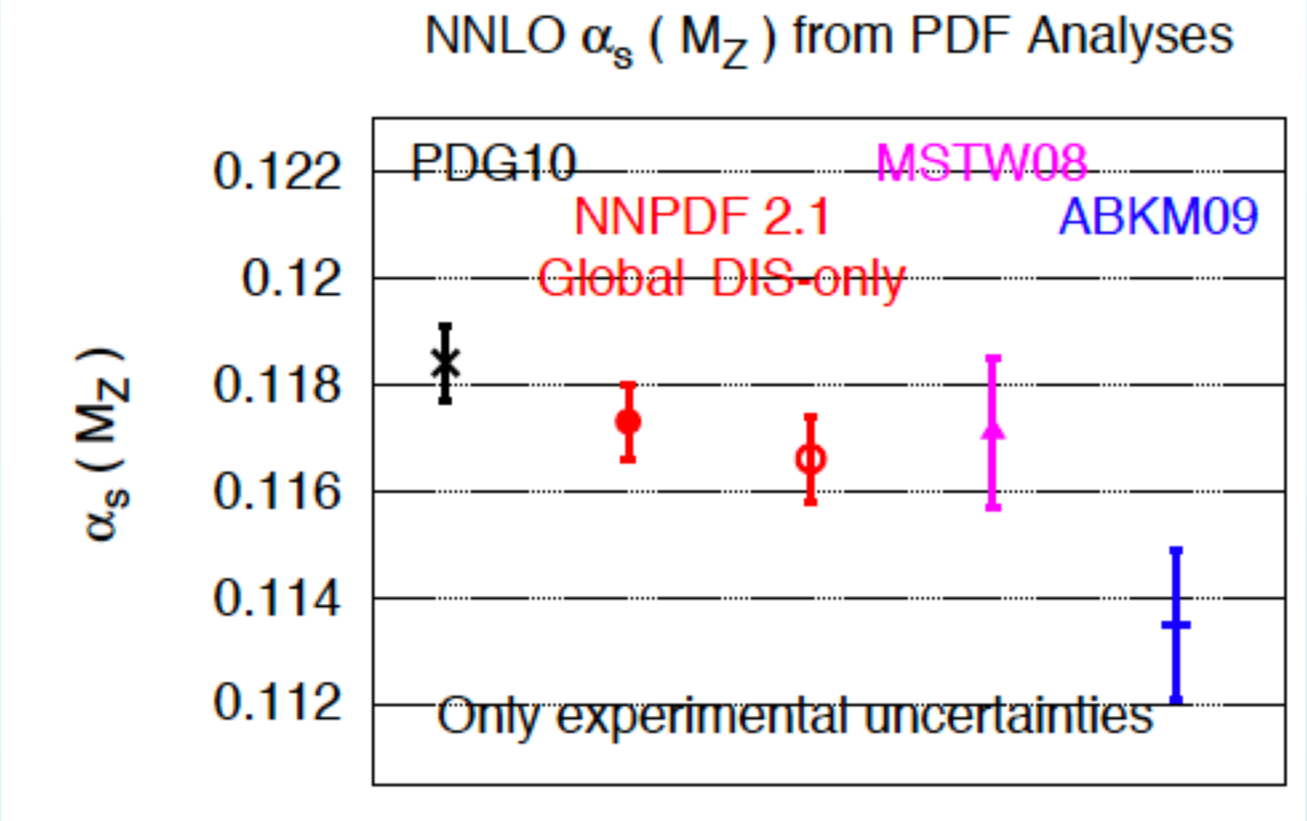
Theoretical uncertainties from MHOU estimated using the **Cacciari-Houdeau method**

Result in good agreement with the **PDG average** and with the **MSTW08 determination**

$$\alpha_S(m_Z) = 0.1173 \pm 0.0007^{\rm PDF} \pm 0.0009^{\rm MHO}$$

NNPDF 11





Motivation for an updated $\alpha_S(m_Z)$ fit

- Several of the new datasets included in NNPDF3.1 **provide a direct handle on α_S(m_Z)**: inclusive jets, top quark pair differential distributions, the Z p_T distribution, …

- **Exact NNLO theory is used for the calculations of all collider cross-sections**, also for **inclusive jet production** (removed the LHC 2.76 TeV jet data from the baseline fit since NNLO calculations not yet available)

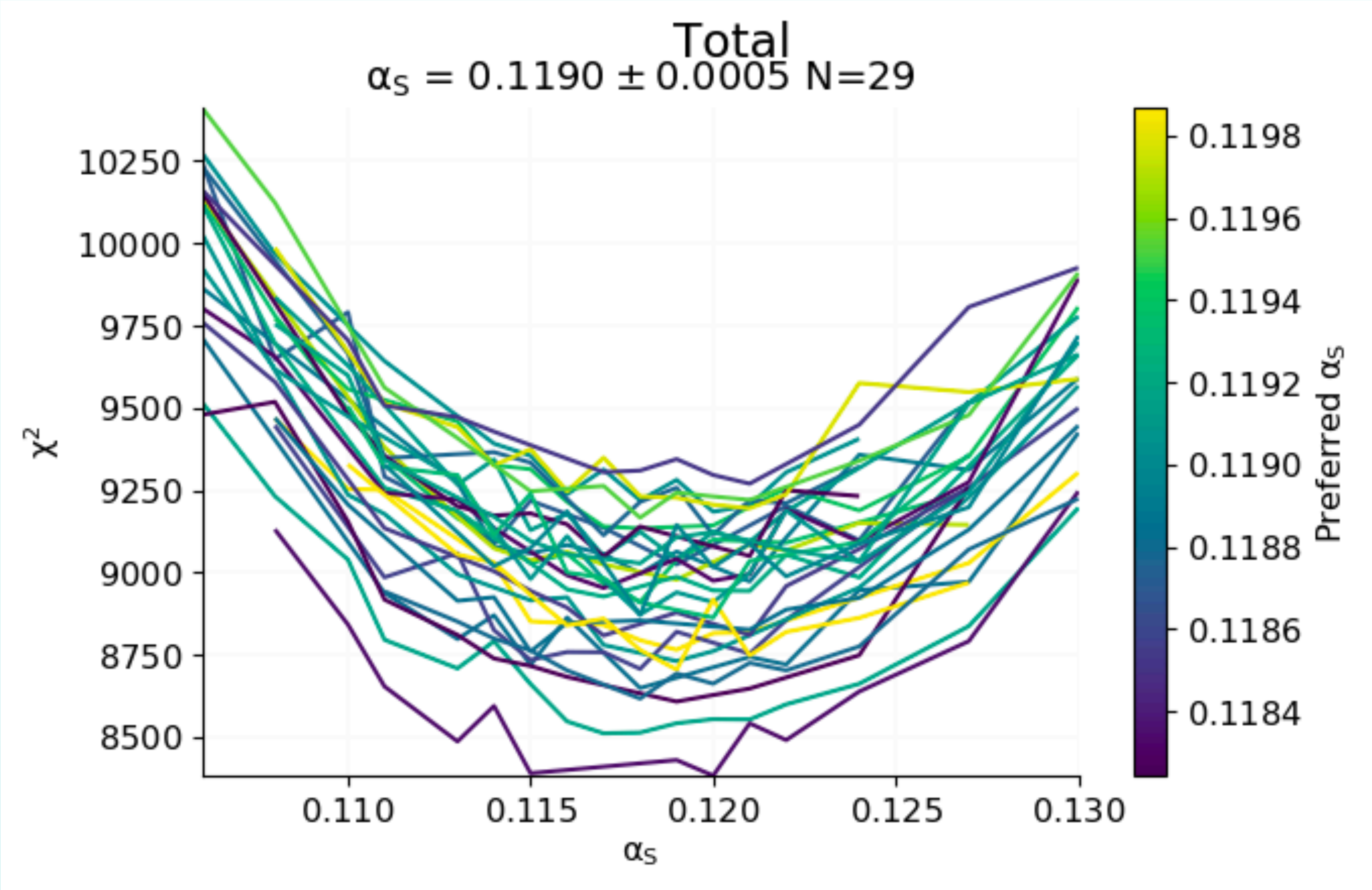
- The wide NNPDF3.1 dataset allows the study in detail of the **interplay between different classes of processes** that constrain the strong coupling constant

- Improved methodology for the α_S**(m_Z)** extraction, based on performing parabolic fits **replica by replica,** keeping the correlations within the generated pseudo-data: this way, α_S**(m_Z) is determined on exactly the same footing as the PDFs themselves**, keeping all PDF-α_S**(m_Z)** correlations

- This bypasses the need of using the **$\Delta\chi^2$=1 criterion** (or any other value for the tolerance), which might not be adequate in the presence of **inconsistent experiments**

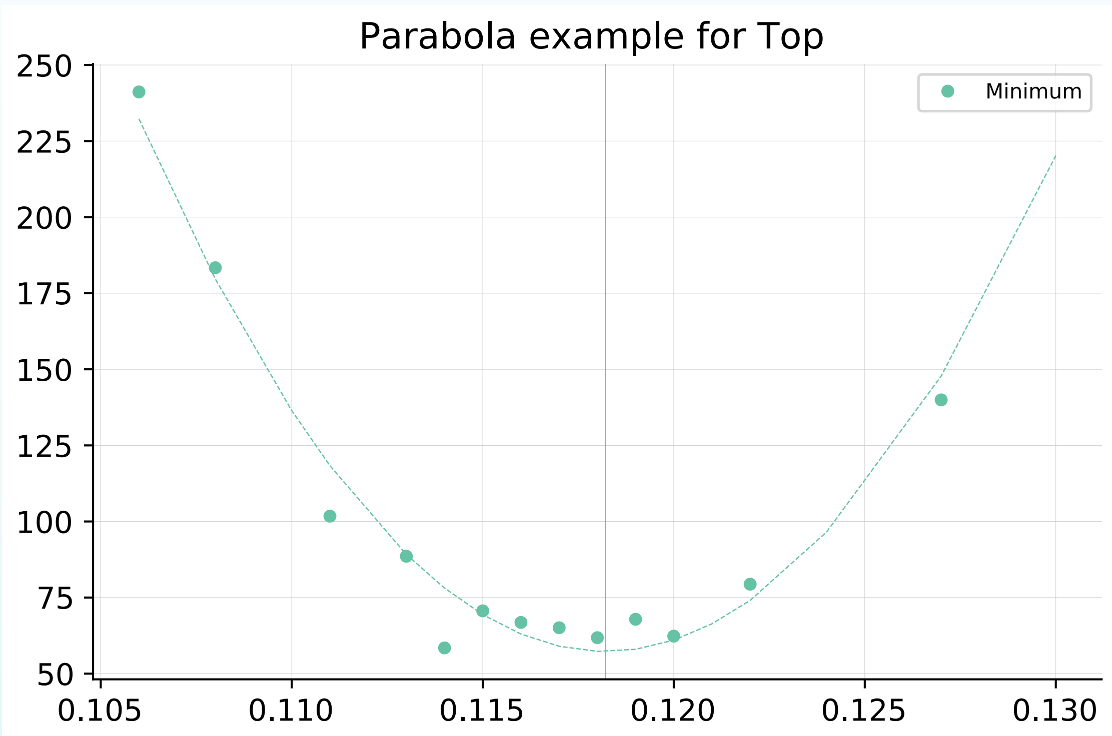
Fitting strategy

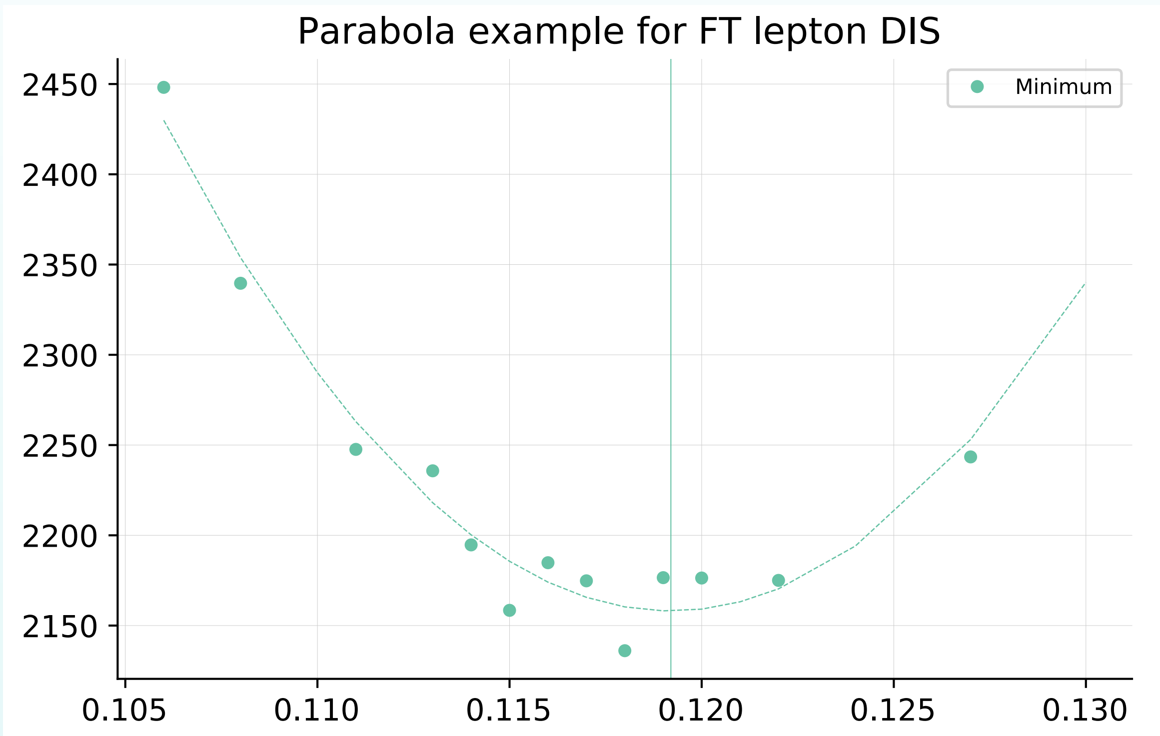
- **Fully correlated pseudo-data replicas** are generated, and then fits with a range of $\alpha_S(m_Z)$ values are performed for each MC replica
- A parabolic fit determines the **preferred value of $\alpha_S(m_Z)$ for each replica** (points that fail to satisfy quality criteria are removed, *i.e.*, fits that have not converged)
- The **mean and variance of the preferred $\alpha_S(m_Z)$ over the replica sample** determines the central value of $\alpha_S(m_Z)$ and the associated 68% CL PDF uncertainty

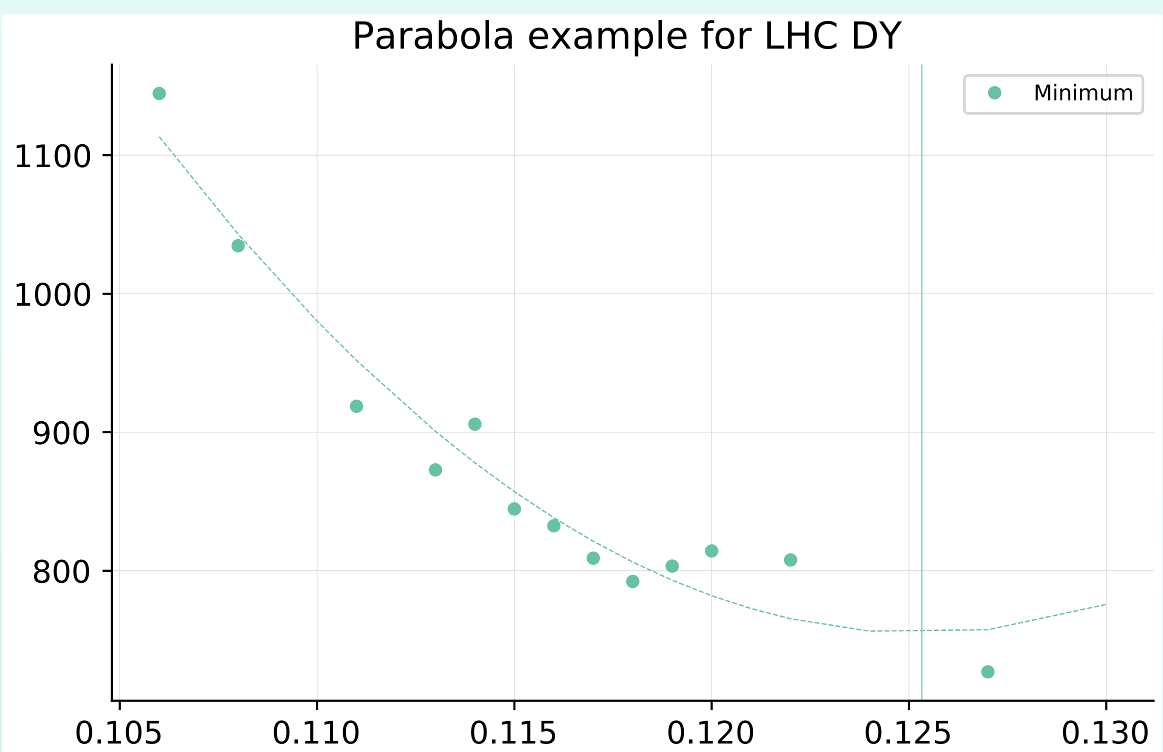


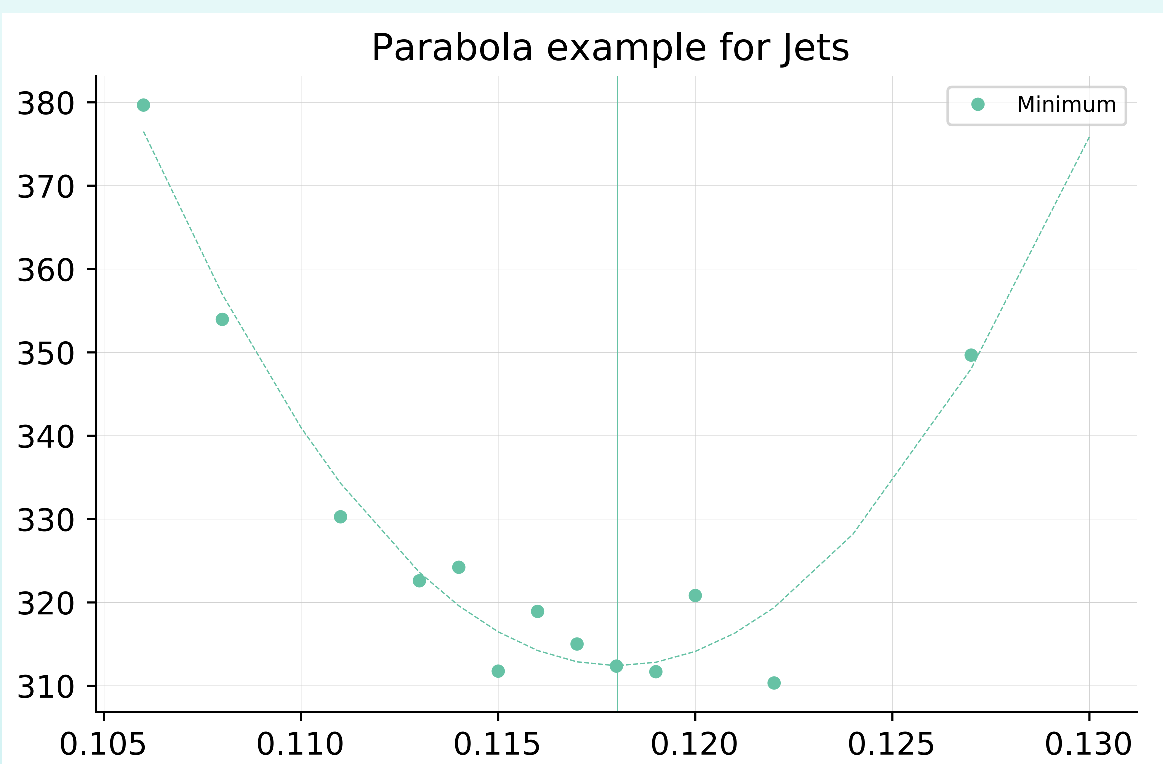
Fitting strategy

- Some processes (jets, top, FT NC DIS, …) lead to **marked parabolas**, illustrating **sensitivity to $\alpha_S(m_Z)$**
- Other processes, such as LHC Drell-Yan, are **less sensitive**, except for very small values of $\alpha_S(m_Z)$









Preliminary results

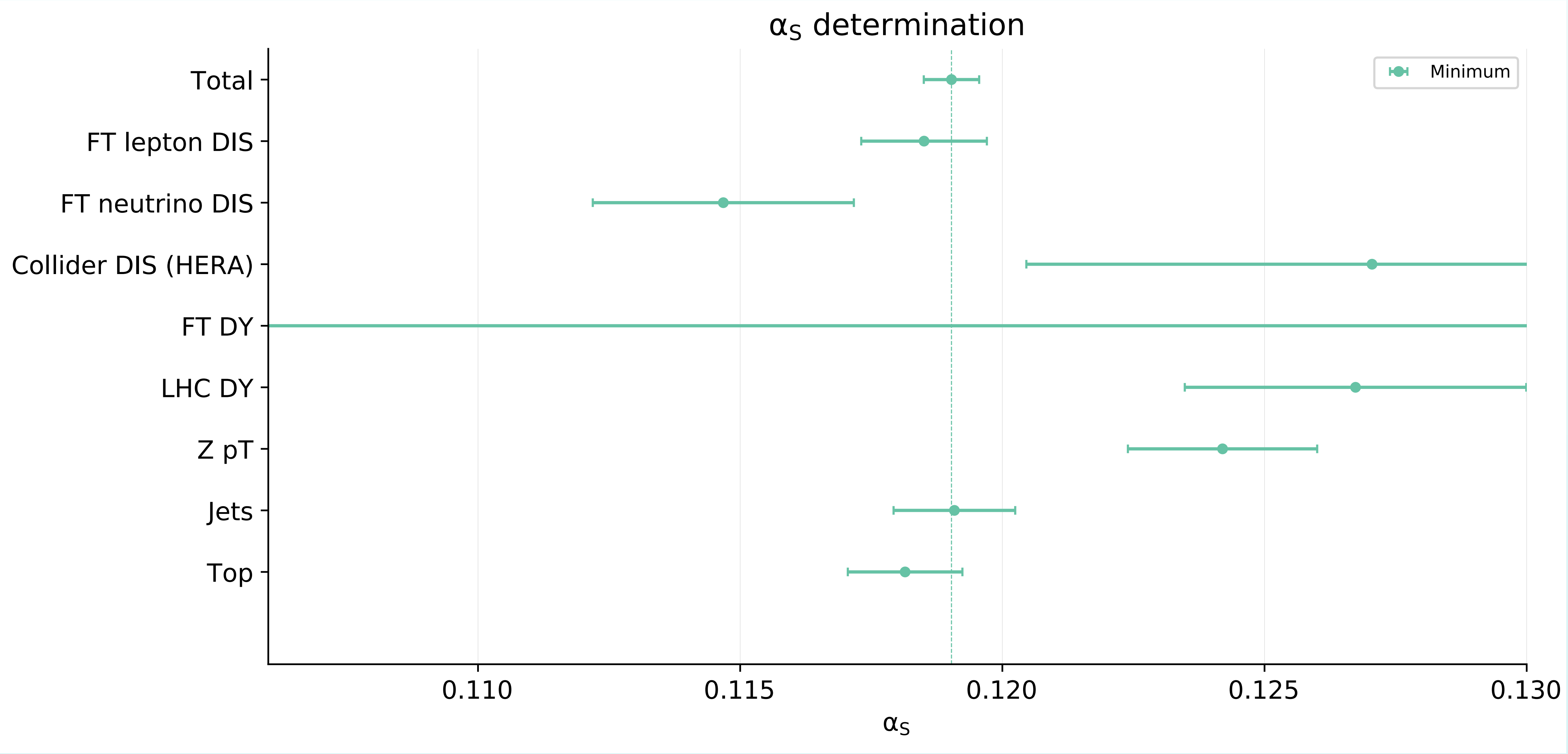
- Using the **correlated replica method**, we find that the NNPDF3.1 global analysis leads to:

  $\alpha_S(m_Z, \text{NNLO}) = 0.1190 \pm 0.0005^{\text{PDF}}$ $\alpha_S(m_Z, \text{NLO}) = 0.1219 \pm 0.0007^{\text{PDF}}$

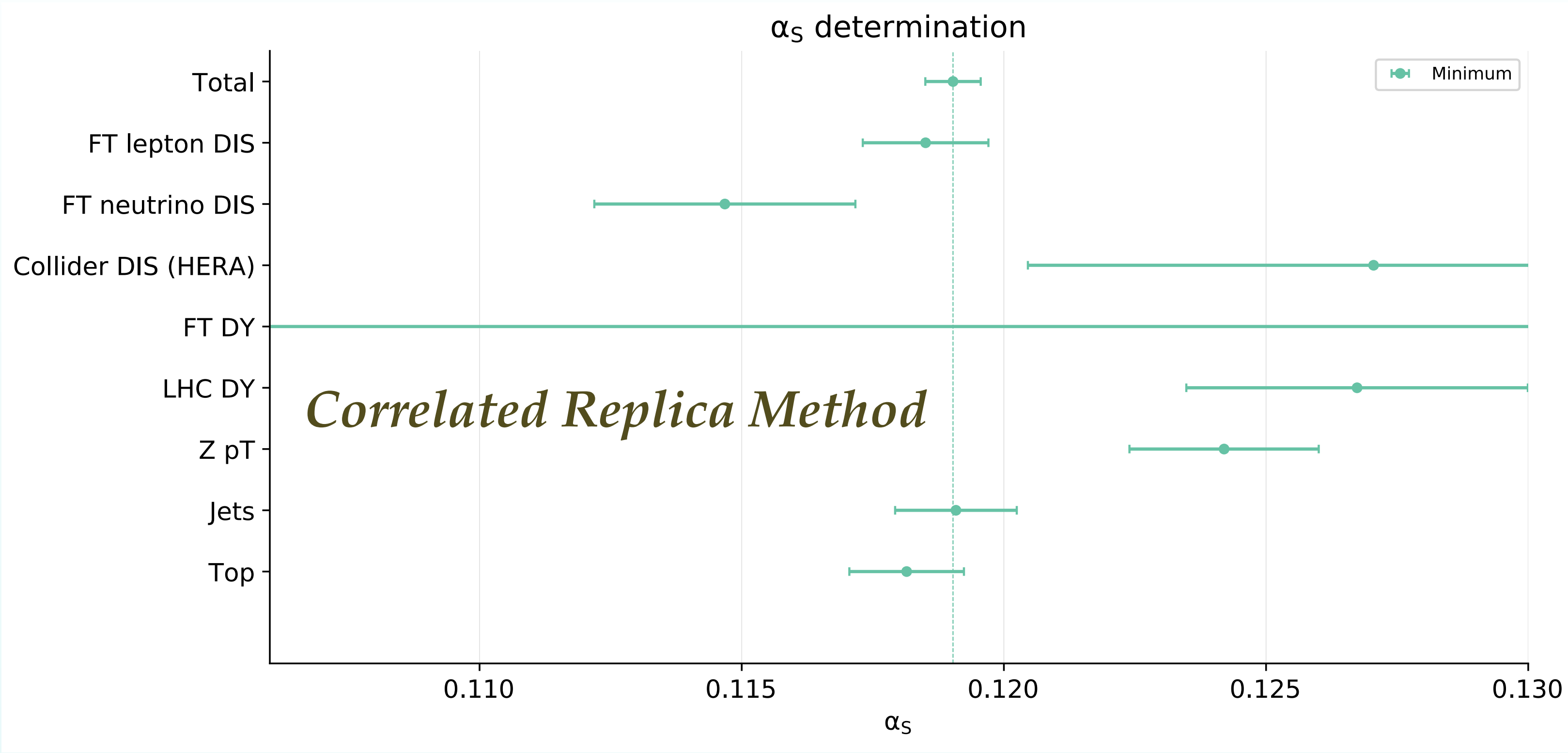
- This is to be compared with the results obtained using the central fits and the **$\Delta\chi^2$=1 criterion:**

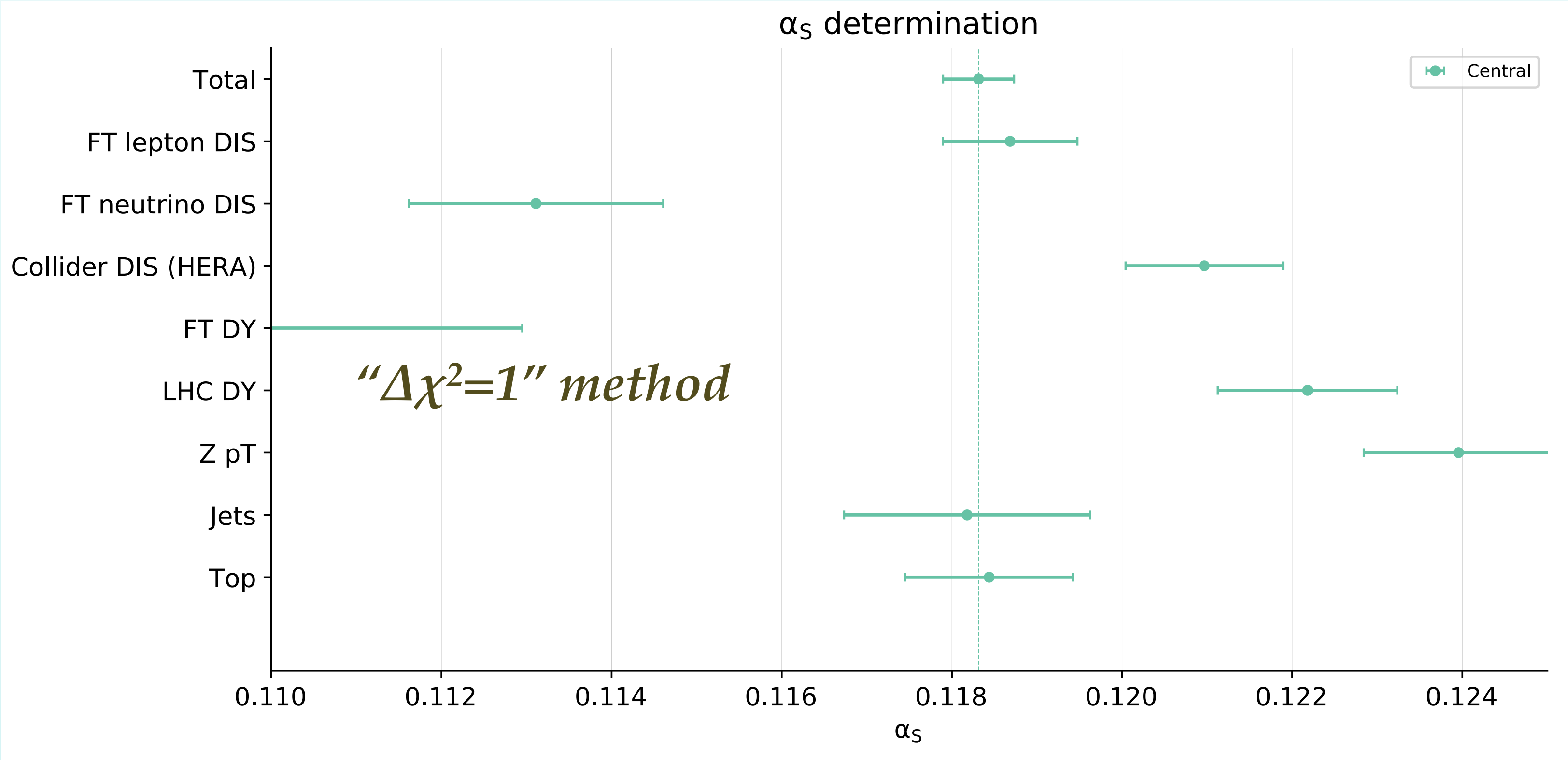
  $\alpha_S(m_Z, \text{NNLO}) = 0.1183 \pm 0.0004^{\text{PDF}}$ $\alpha_S(m_Z, \text{NLO}) = 0.1214 \pm 0.0004^{\text{PDF}}$

- The best-fit $\alpha_S(m_Z)$ value is driven by the **jet, top, and FT NC DIS data**. The higher value of $\alpha_S(m_Z)$ as compared to the NNPDF2.1 fit is partly due to the **LHC DY and Z p_T data.**



Correlated replica method vs “$\Delta\chi^2=1$” method

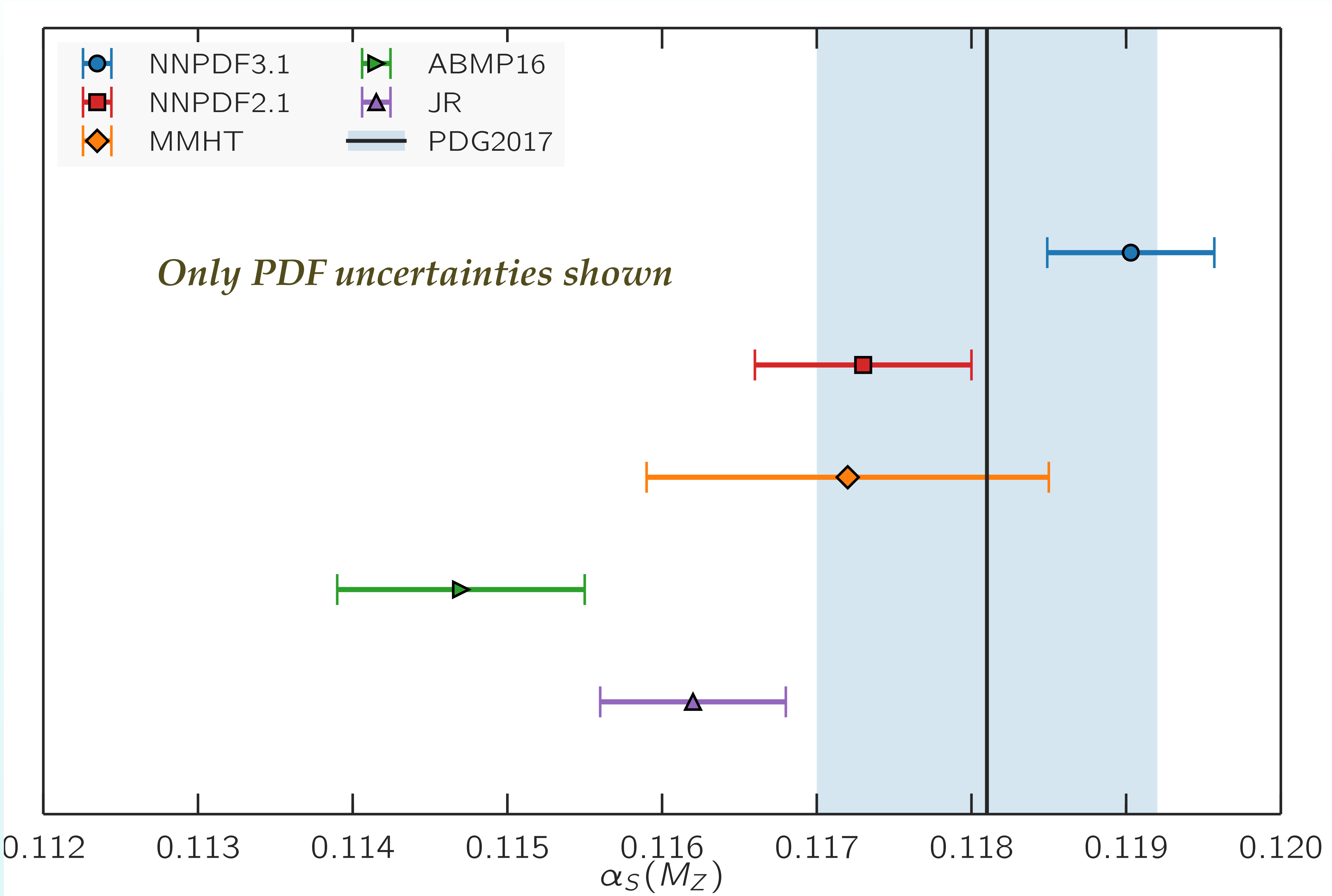




- In general there is reasonable **consistency between the two methods**, highlighting the robustness of the results

- The “$\Delta\chi^2=1$” method can **underestimate the real PDF uncertainties**, by a small amount in some cases (total dataset, jets, top) and by a large amount for those processes with little sensitivity to $\alpha_S(m_Z)$, such as HERA and FT Drell-Yan

Preliminary results



Good agreement with the PDG17 average, and consistent with the MMHT2014 determination

Also repeated the analysis based on a **collider-only dataset:** not competitive with the global fit, presumably because the constraints from the **fixed-target DIS data still important**

$$\alpha_S(m_Z, \text{NNLO, global}) = 0.1190 \pm 0.0005^{\text{PDF}}$$

$$\alpha_S(m_Z, \text{NNLO, collider-only}) = 0.1229 \pm 0.0026^{\text{PDF}}$$

Summary and outlook

- **NNPDF3.1QED** and the photon PDF using the LUXqed formalism
  - Preliminary results presented, **final NNPDF3.1QED NLO and NNLO close to completion**. Good agreement with LUXqed, no changes for quarks and gluons
  - Release of the **public library *FiatLUX*** that implements the LUXqed formalism
  - Study of phenomenological implications at the LHC for PI processes
- NNPDF3.1 fits with **small-x (BFKL) resummation**
  - Using **NNLO+NLL*x* theory** improves the perturbative expansion at small-x, cures the chi2 instability, and the allows a better description of the **inclusive HERA data**
  - Implications for **UHE astrophysics**, as well as for f**uture colliders (LHeC, FCC-hh/eh)**
- A **determination of α_S(m_Z)** based on the NNPDF3.1 analysis
  - New approach developed, based on **correlated MC replicas**
  - The new fit result, **$\alpha_S(m_Z, \mathrm{NNLO}) = 0.1190 \pm 0.0005^{\mathrm{PDF}}$**, is consistent with the PDG average but **higher than other PDF-based determinations**, mostly due to the pull of the recent high-precision LHC data. Collider-only determinations still not competitive
  - Ongoing work towards an estimate of the **theoretical uncertainties from MHO**