Recent Progress on PDFs and N3LO PDFs

Ringberg 2024

Tommaso Giani 9/05/2024

α_s from Z pT

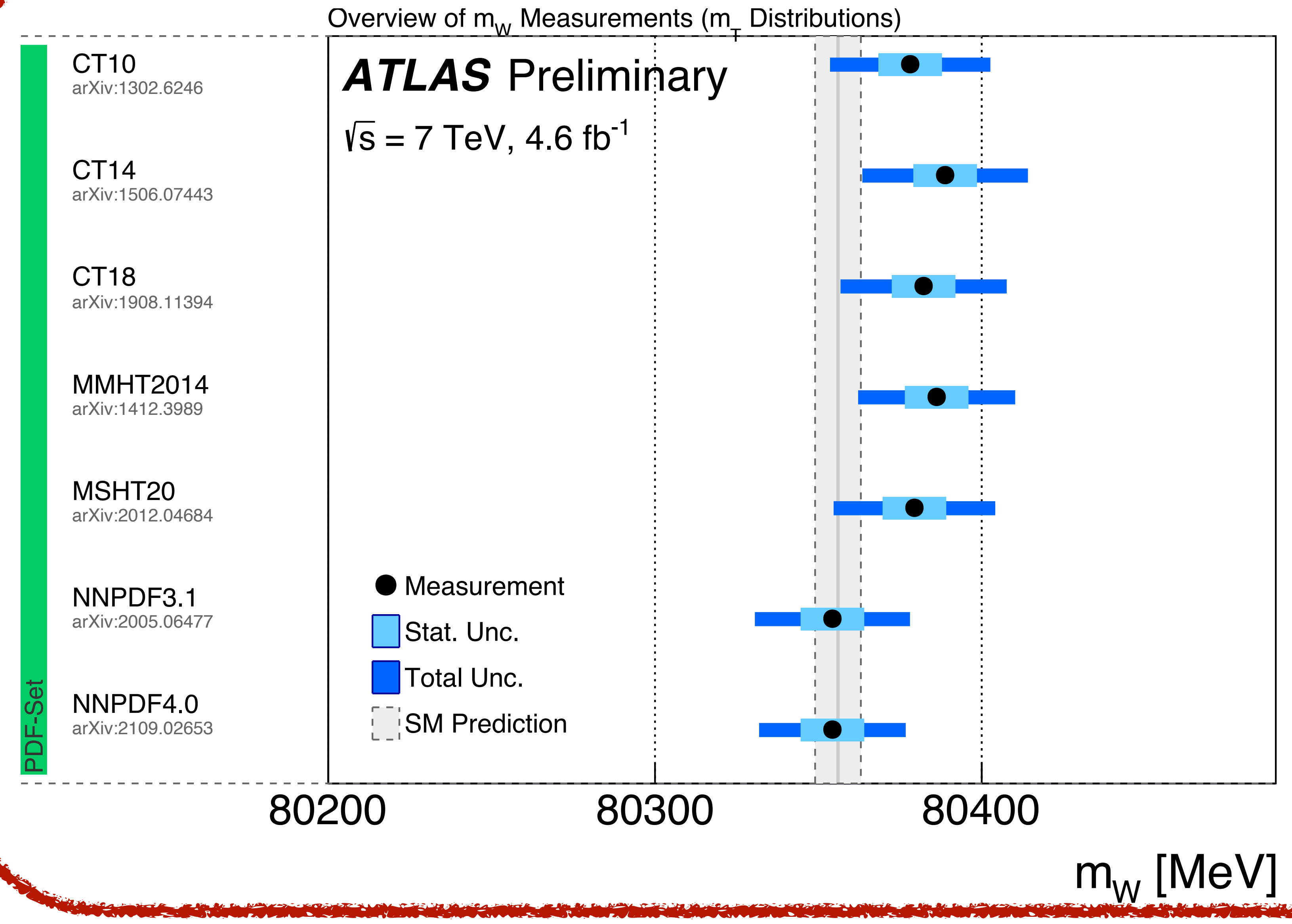
arXiv:2309.12986

$$\alpha_s(m_Z) = 0.11847 + 0.00091 - 0.00088$$

$\sim 0.76\,\%$

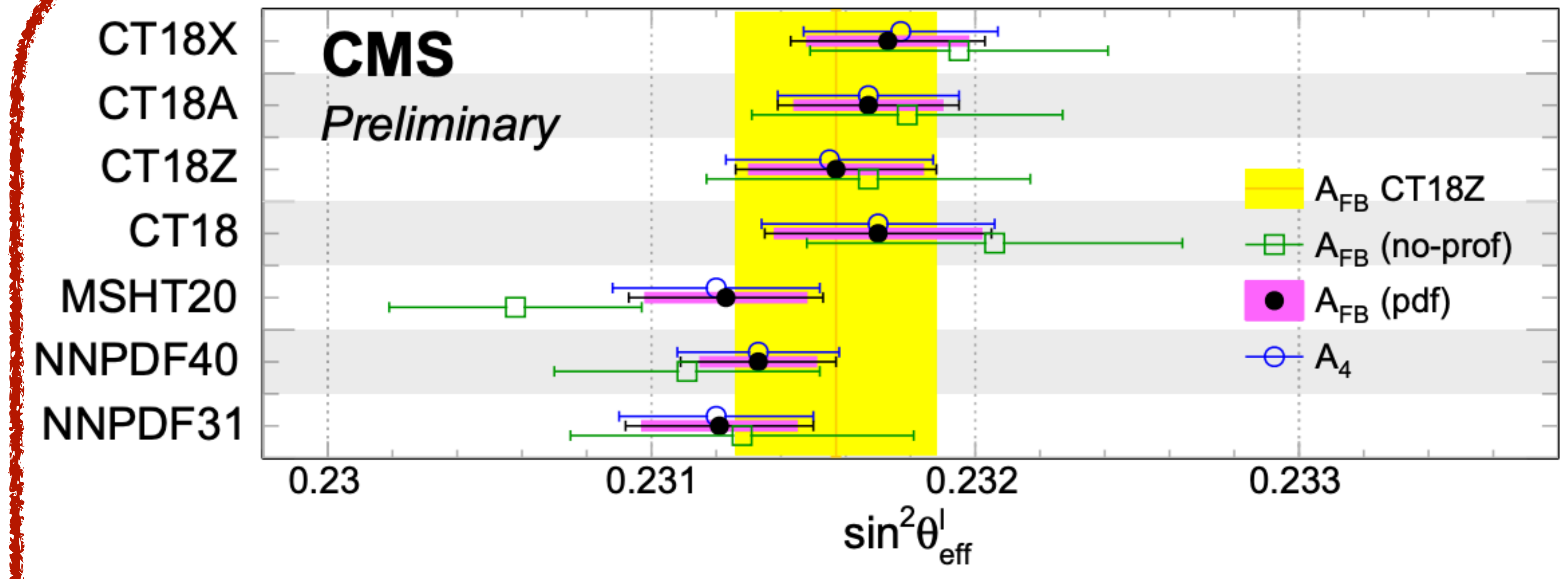
PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g $[GeV^2]$	q $[GeV^4]$
MSHT20 [37]	0.11839	0.00040	0.44	−0.07
NNPDF4.0 [84]	0.11779	0.00024	0.50	−0.08
CT18A [29]	0.11982	0.00050	0.36	−0.03
HERAPDF2.0 [65]	0.11890	0.00027	0.40	−0.04

$\sim 1.7\,\%$



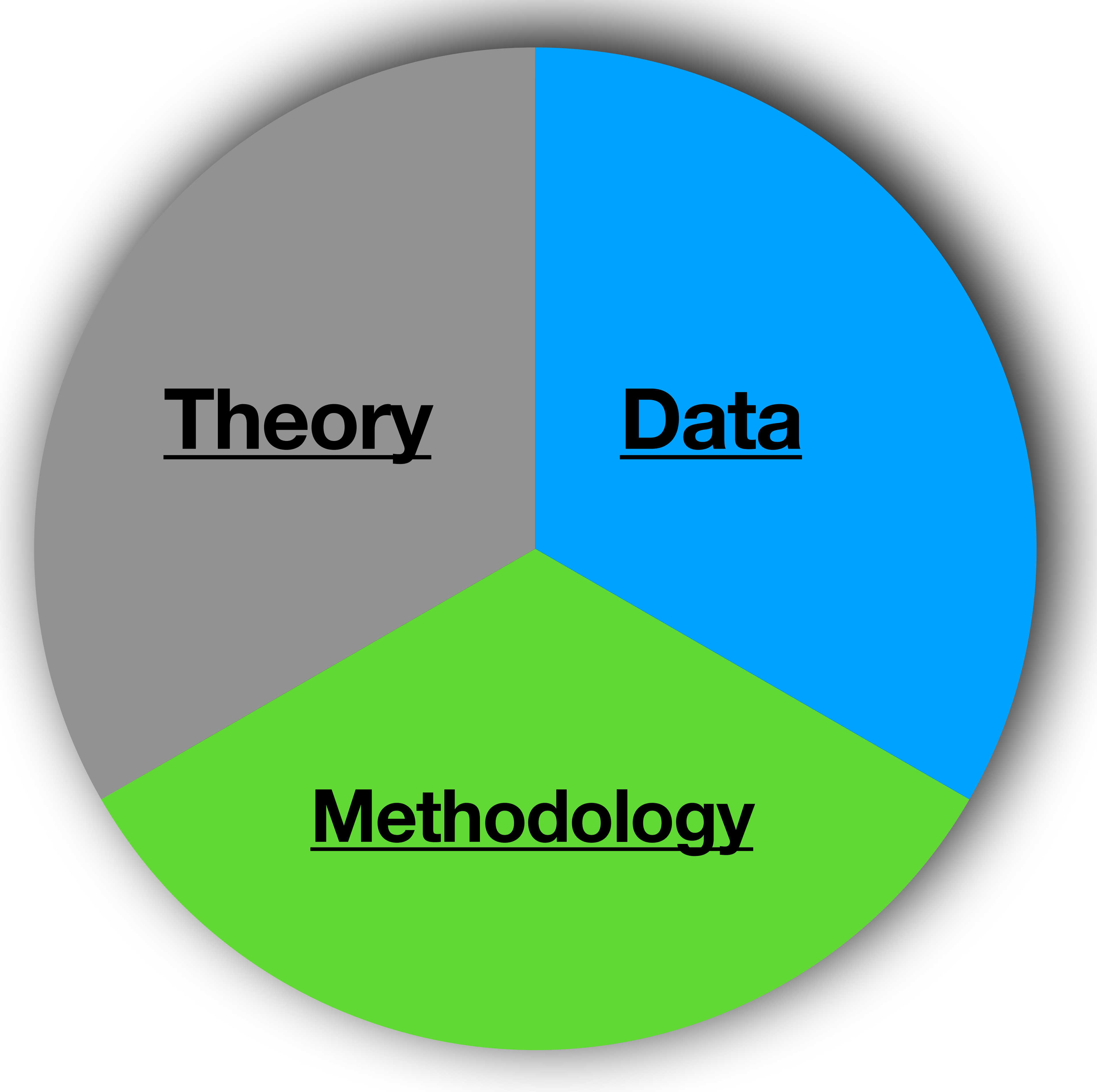
W mass determination

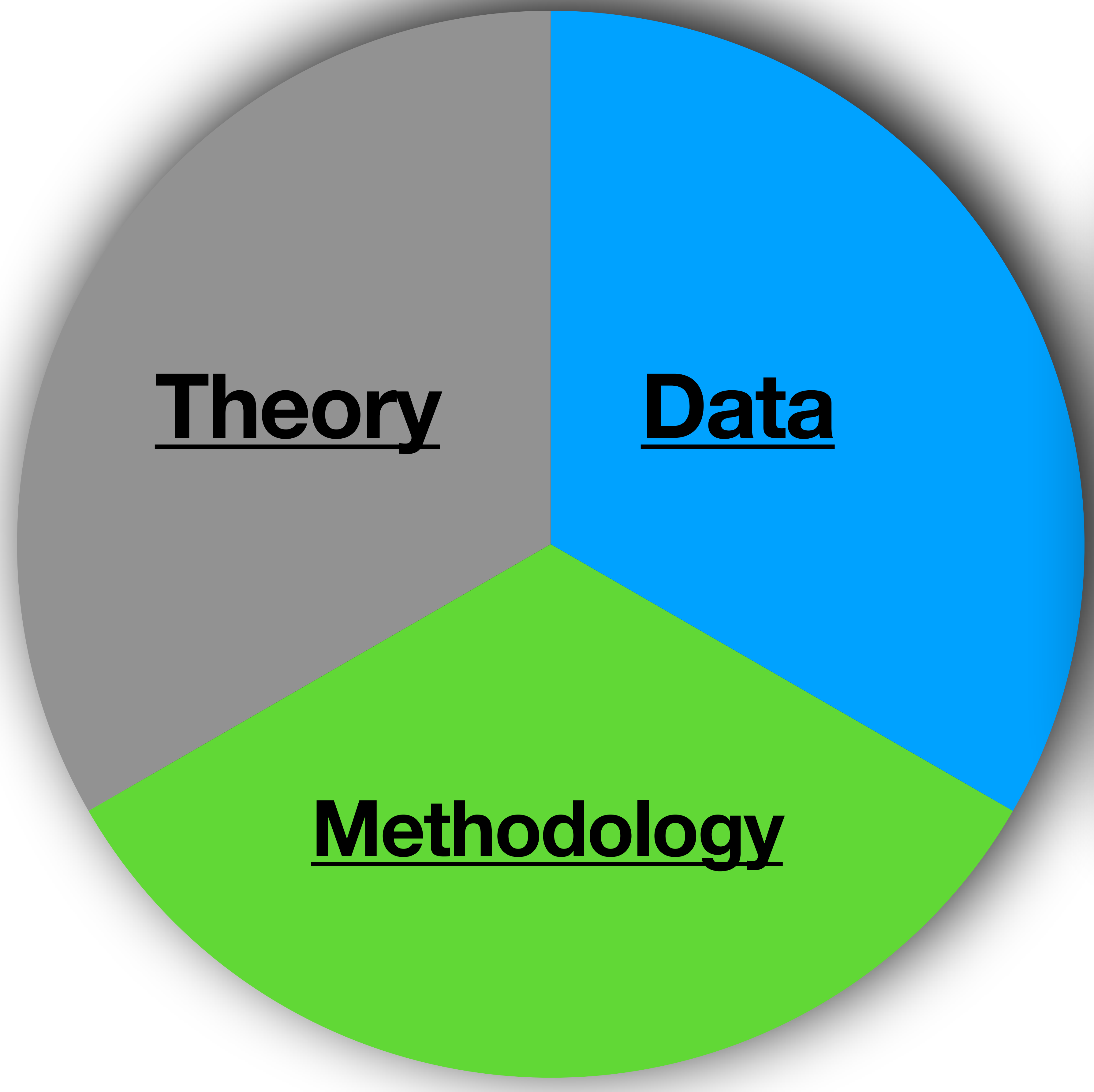
ATLAS-CONF-2023-004



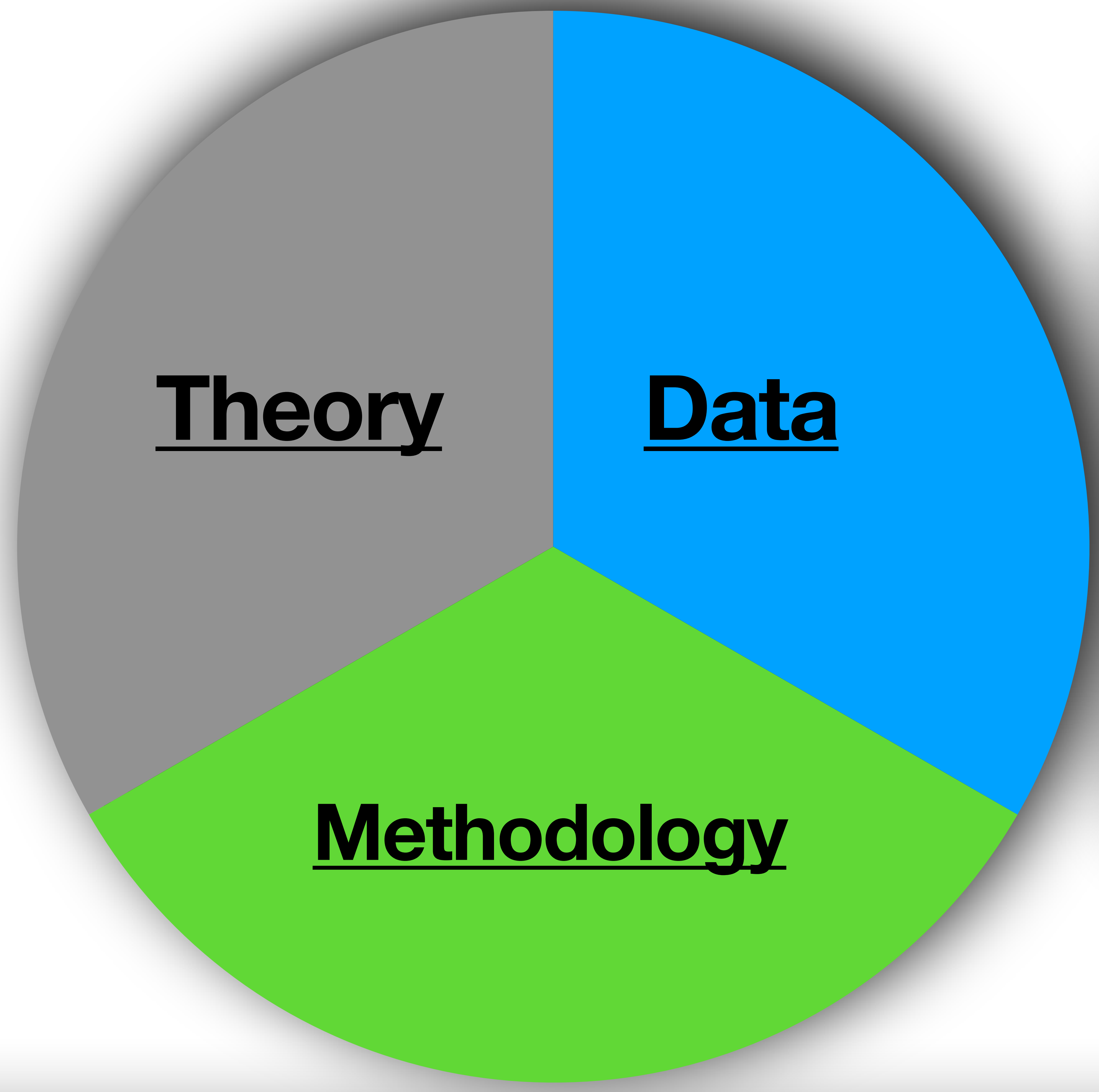
weak mixing angle at 13 TeV

CMS-PAS-SMP-22-010


Theory
Data
Methodology



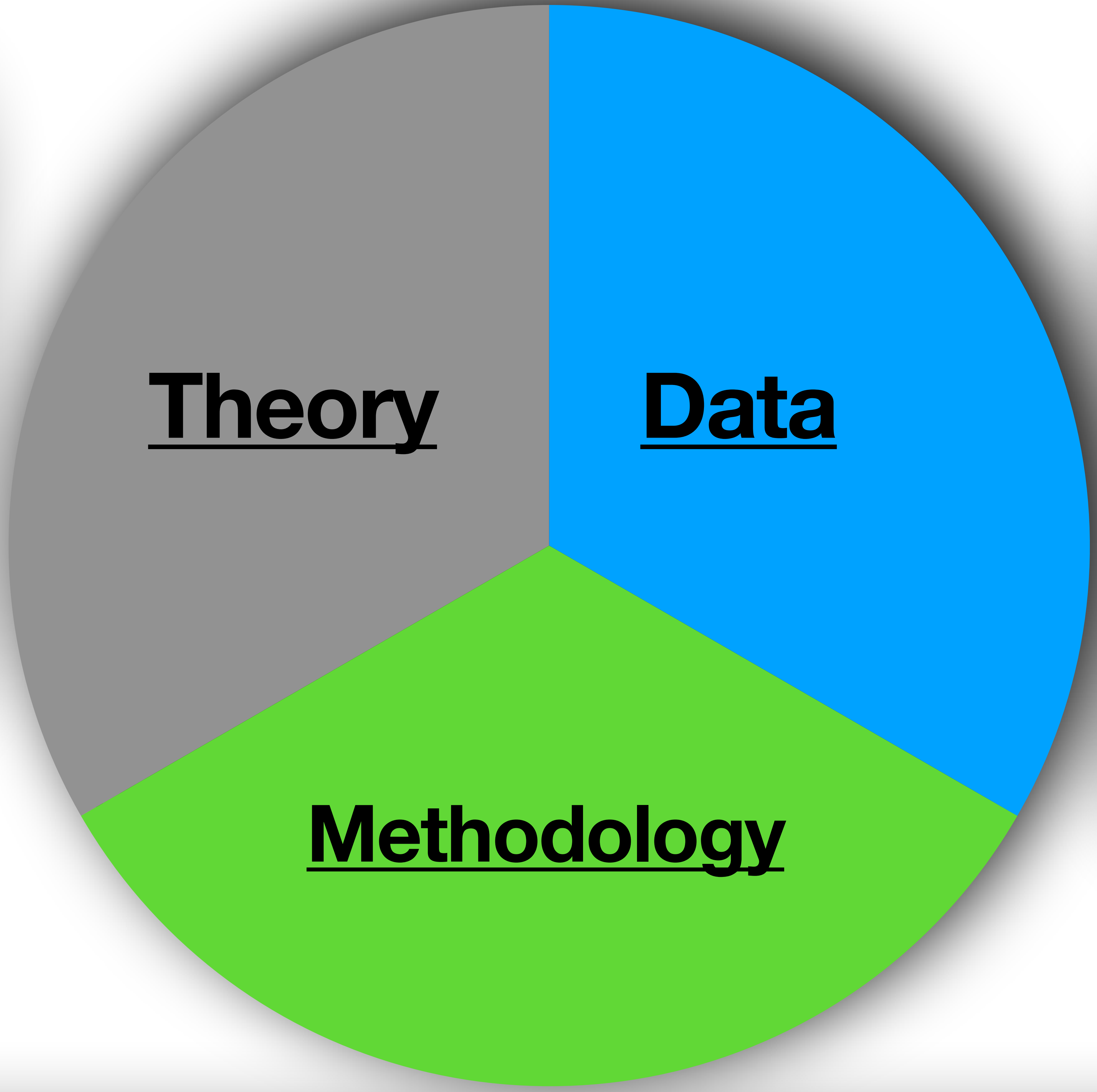
- Impact of jets vs diets at N3LO [arXiv:2312.12505]
- Impact of 13 TeV $t\bar{t}$ data [PRD 109 (2024)]
- Impact of future data (HL-LHC [Eur. Phys. J. C (2018) 78], EIC [PRD 103 (2021) 096005], FPF [arXiv:2309.09581])



- Impact of jets vs diets at N3LO [arXiv:2312.12505]
- Impact of 13 TeV $t\bar{t}$ data [PRD 109 (2024)]
- Impact of future data (HL-LHC [Eur. Phys. J. C (2018) 78], EIC [PRD 103 (2021) 096005], FPF [arXiv:2309.09581])

- Nonparametric regression [arXiv:2404.02964]
- Closure test [EPJC 82 (2022) 4, Talk by Lucian Harland-Lang, DIS2024]

- aN3LO [EPJC 83, arXiv:2402.18635]
- MHOU [arXiv:2401.10319]
- QED [arXiv:2401.08749]
- QED + aN3LO [arXiv:2404.02964]

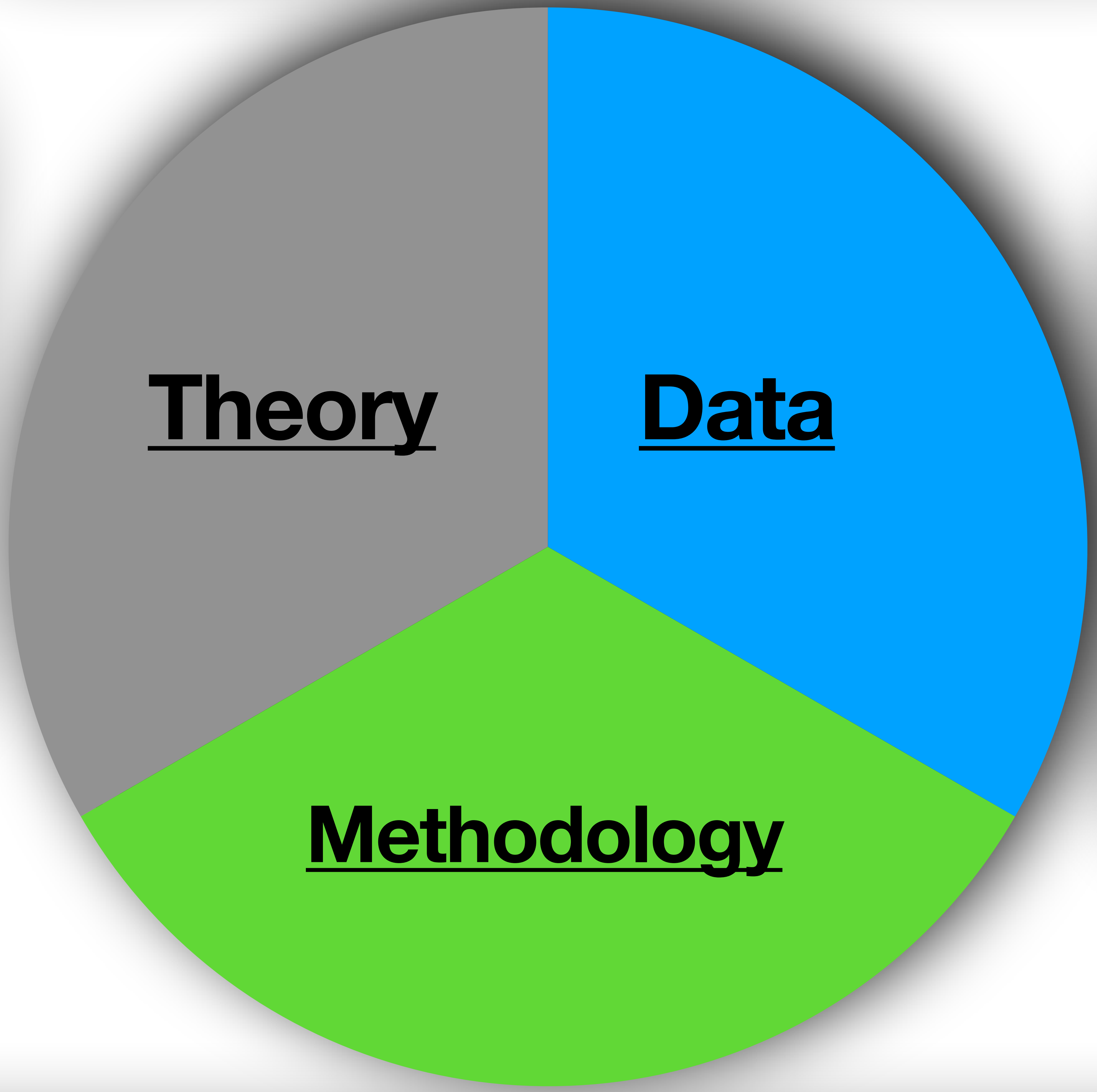


- Impact of jets vs diets at N3LO [arXiv:2312.12505]
- Impact of 13 TeV $t\bar{t}$ data [PRD 109 (2024)]
- Impact of future data (HL-LHC [Eur. Phys. J. C (2018) 78], EIC [PRD 103 (2021) 096005], FPF [arXiv:2309.09581])

- Nonparametric regression [arXiv:2404.02964]
- Closure test [EPJC 82 (2022) 4, Talk by Lucian Harland-Lang, DIS2024]

- α_s+ PDF @ N3LO [arXiv:2404.02964]
- Intrinsic charm valence PDF [arXiv:2311.00743]

- aN3LO [EPJC 83, arXiv:2402.18635]
- MHOU [arXiv:2401.10319]
- QED [arXiv:2401.08749]
- QED + aN3LO [arXiv:2404.02964]

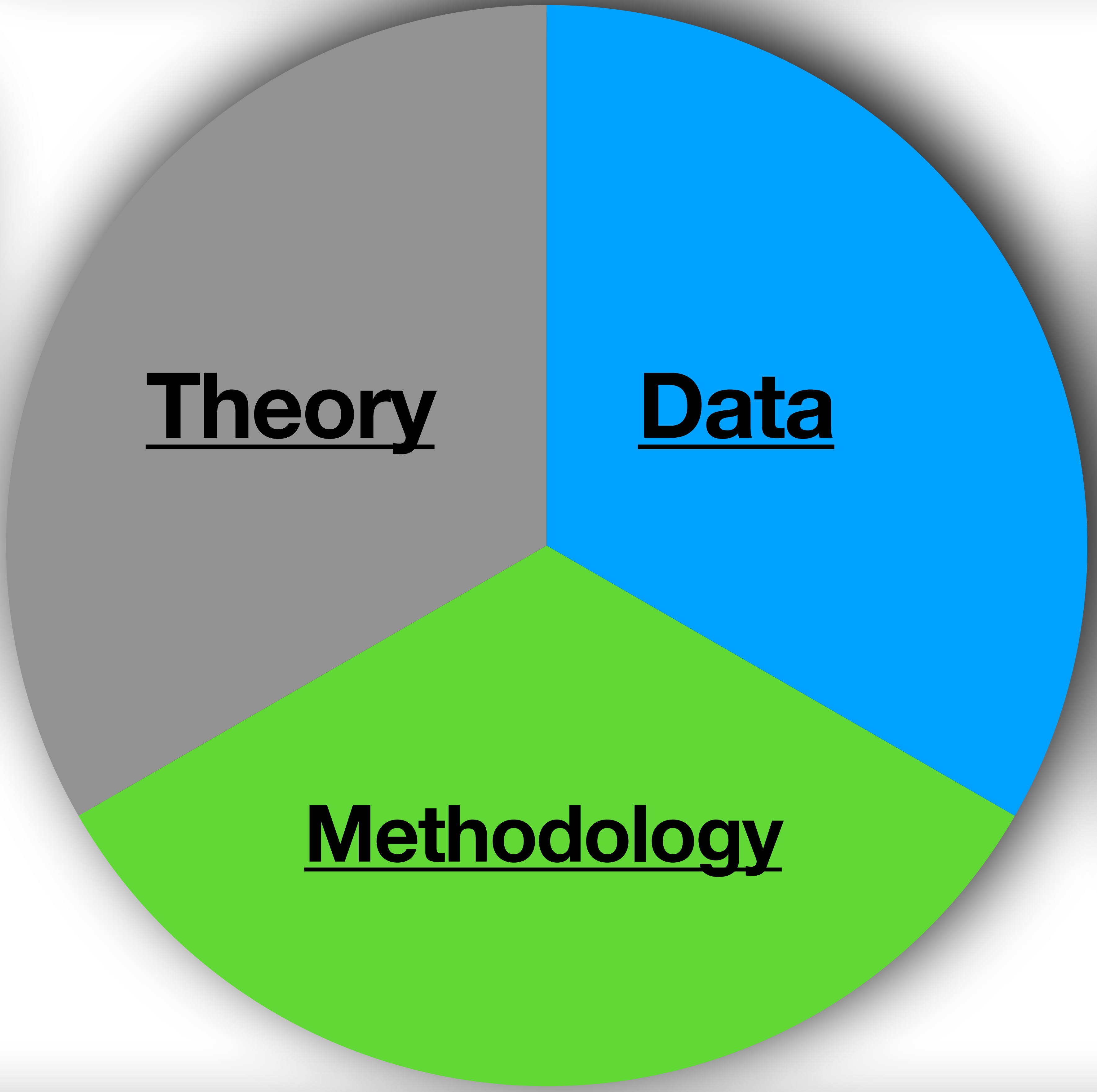


- Impact of jets vs diets at N3LO [arXiv:2312.12505]
- Impact of 13 TeV $t\bar{t}$ data [PRD 109 (2024)]
- Impact of future data (HL-LHC [Eur. Phys. J. C (2018) 78], EIC [PRD 103 (2021) 096005], FPF [arXiv:2309.09581])

- Nonparametric regression [arXiv:2404.02964]
- Closure test [EPJC 82 (2022) 4, Talk by Lucian Harland-Lang, DIS2024]

- α_s+ PDF @ N3LO [arXiv:2404.02964]
- Intrinsic charm valence PDF [arXiv:2311.00743]

- aN3LO [EPJC 83, arXiv:2402.18635]
- MHOU [arXiv:2401.10319]
- QED [arXiv:2401.08749]
- QED + aN3LO [arXiv:2404.02964]



- Impact of jets vs diets at N3LO [arXiv:2312.12505]
- Impact of 13 TeV $t\bar{t}$ data [PRD 109 (2024)]
- Impact of future data (HL-LHC [Eur. Phys. J. C (2018) 78], EIC [PRD 103 (2021) 096005], FPF [arXiv:2309.09581])

- Nonparametric regression [arXiv:2404.02964]
- Closure test [EPJC 82 (2022) 4, Talk by Lucian Harland-Lang, DIS2024]

approximated N3LO PDFs (aN3LO)

Eur. Phys. J. C (2023) 83:185
https://doi.org/10.1140/epjc/s10052-023-11236-0

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

Approximate N^{3}LO parton distribution functions with theoretical uncertainties: MSHT20aN^{3}LO PDFs

J. McGowan[1,a], T. Cridge[1], L. A. Harland-Lang[2], R. S. Thorne[1]

[1] Department of Physics and Astronomy, University College London, London WC1E 6BT, UK
[2] Rudolf Peierls Centre, Beecroft Building, Parks Road, Oxford OX1 3PU, UK

Received: 8 August 2022 / Accepted: 19 January 2023

Abstract We present the first global analysis of parton distribution functions (PDFs) at approximate N^{3}LO in the strong coupling constant α_s, extending beyond the current highest NNLO achieved in PDF fits. To achieve this, we present a general formalism for the inclusion of theoretical uncertainties associated with the perturbative expansion in the strong coupling. We demonstrate how using the currently available knowledge surrounding the next highest order (N^{3}LO) in α_s can provide consistent, justifiable and explainable approximate N^{3}LO (aN^{3}LO) PDFs. This includes estimates for uncertainties due the currently unknown N^{3}LO ingredients,

The Path to N^{3}LO Parton Distributions

The NNPDF Collaboration:

Richard D. Ball[1], Andrea Barontini[2], Alessandro Candido[2,3], Stefano Carrazza[2], Juan Cruz-Martinez[3], Luigi Del Debbio[1], Stefano Forte[2], Tommaso Giani[4,5], Felix Hekhorn[2,6,7], Zahari Kassabov[8], Niccolò Laurenti,[2] Giacomo Magni[4,5], Emanuele R. Nocera[9], Tanjona R. Rabemananjara[4,5], Juan Rojo[4,5], Christopher Schwan[10], Roy Stegeman[1], and Maria Ubiali[8]

[1] *The Higgs Centre for Theoretical Physics, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland*
[2] *Tif Lab, Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*
[3] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[4] *Department of Physics and Astronomy, Vrije Universiteit, NL-1081 HV Amsterdam*
[5] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[6] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*
[7] *Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*
[8] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom*
[9] *Dipartimento di Fisica, Università degli Studi di Torino and INFN, Sezione di Torino, Via Pietro Giuria 1, I-10125 Torino, Italy*
[10] *Universität Würzburg, Institut für Theoretische Physik und Astrophysik, 97074 Würzburg, Germany*

arXiv:2402.18635v1 [hep-ph] 28 Feb 2024

This paper is dedicated to the memory of Stefano Catani, Grand Master of QCD, great scientist and human being

Abstract

We extend the existing leading (LO), next-to-leading (NLO), and next-to-next-to-leading order (NNLO) NNPDF4.0 sets of parton distribution functions (PDFs) to approximate next-to-next-to-next-to-leading order (aN^{3}LO). We construct an approximation to the N^{3}LO splitting functions that includes all available partial information from both fixed-order computations and from small and large x resummation, and estimate the uncertainty on this approximation by varying the set of basis functions used to construct the approximation. We include known N^{3}LO corrections to deep-inelastic scattering structure functions and extend the FONLL general-mass scheme to $\mathcal{O}(\alpha_s^3)$ accuracy. We determine a set of aN^{3}LO PDFs by accounting both for the uncertainty on splitting functions due to the incomplete knowledge of N^{3}LO terms,

N3LO PDFs : what do we need

- Splitting functions

$$\mu^2 \frac{df_i}{d\mu^2} = P_{ij}\left(\mu^2\right) \otimes f_i\left(\mu^2\right)$$

- VFNS matching conditions

$$f_i^{(n_f+1)}\left(x, \mu^2\right) = A_{ij}\left(x, \alpha_s\right) \otimes f_i^{(n_f)}\left(x, \mu^2\right)$$

- DIS **massless** partonic coefficients

  DIS **massive** partonic coefficients

$$F_i\left(x, Q^2\right) = \sum_k C_{i,k} \otimes f_i\left(x, Q^2\right)$$

- Hadronic coefficients at N3LO

N3LO PDFs : what do we need

- Splitting functions ✗

$$\mu^2 \frac{df_i}{d\mu^2} = P_{ij}\left(\mu^2\right) \otimes f_i\left(\mu^2\right)$$

- VFNS matching conditions ✓

$$f_i^{(n_f+1)}\left(x,\mu^2\right) = A_{ij}\left(x,\alpha_s\right) \otimes f_i^{(n_f)}\left(x,\mu^2\right)$$

- DIS **massless** partonic coefficients ✓

  DIS **massive** partonic coefficients ✗

$$F_i\left(x,Q^2\right) = \sum_k C_{i,k} \otimes f_i\left(x,Q^2\right)$$

- Hadronic coefficients at N3LO ✗

Full N3LO info not currently available

- Construct approximation for what is missing
- Estimate theory uncertainty →

Missing Higher Order Uncertainty (MHOU):
missing higher order terms

Incomplete Higher Order Uncertainty (IHOU):
incomplete higher (N3LO) order terms

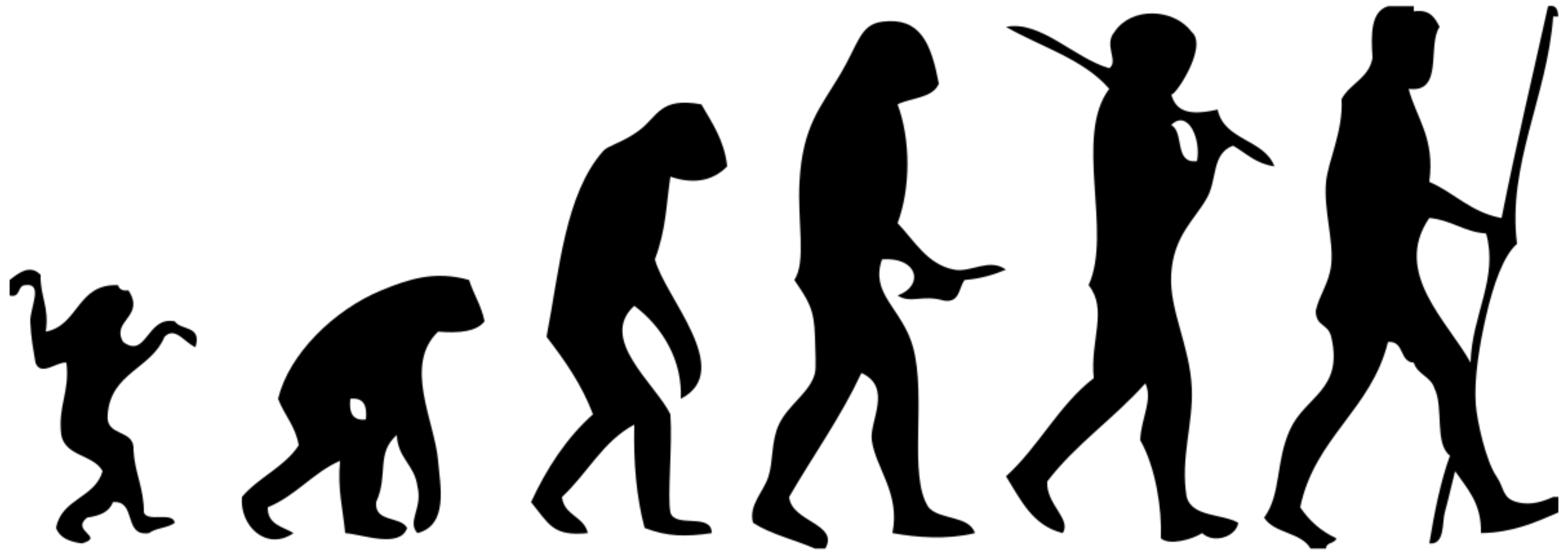
Splitting functions

Nonsinglet

$$\mu^2 \frac{dV}{d\mu^2} = P_{NS,v} \otimes V$$

Singlet

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} g \\ \Sigma \end{pmatrix} = \begin{pmatrix} P_{gg} & P_{gq} \\ P_{qg} & P_{qq} \end{pmatrix} \otimes \begin{pmatrix} g \\ \Sigma \end{pmatrix}$$



Singlet

$P^{(3)}_{qq,ps}$ $P^{(3)}_{qg}$

$P^{(3)}_{gq}$ $P^{(3)}_{gg}$

What we know

- 5 (10) lowest Mellin moments [Phys.Lett.B 825 (2022), Phys.Lett.B 825 (2022), Phys.Lett.B 842 (2023), Phys.Lett.B 849 (2024)]
- Small-x limit [JHEP 06 (2018) 145]
- Large-x limit [JHEP 09 (2022) 155, JHEP 04 (2020) 018, Nucl.Phys.B 832 (2010)]
- large-n_f limit, i.e. $\mathcal{O}(n_f^2)$, $\mathcal{O}(n_f^3)$ [Nucl. Phys. B 915 (2017) 335–362, Phys. Lett. B 848 (2024), JHEP 01 (2024) 029]

Our approximation

$$\gamma^{(3)}_{ij}(N) = \gamma^{(3)}_{ij,n_f}(N) + \gamma^{(3)}_{ij,N\to\infty}(N) + \gamma^{(3)}_{ij,N\to 0}(N) + \gamma^{(3)}_{ij,N\to 1}(N) + \tilde{\gamma}^{(3)}_{ij}(N)$$

large-n_f limit | large-x limit | small-x limit | remainder

- Expanded on a set of basis function
- Coefficients of the expansion determined by known moments
- Reproduce leading and subleading N-space poles with unknown coefficients

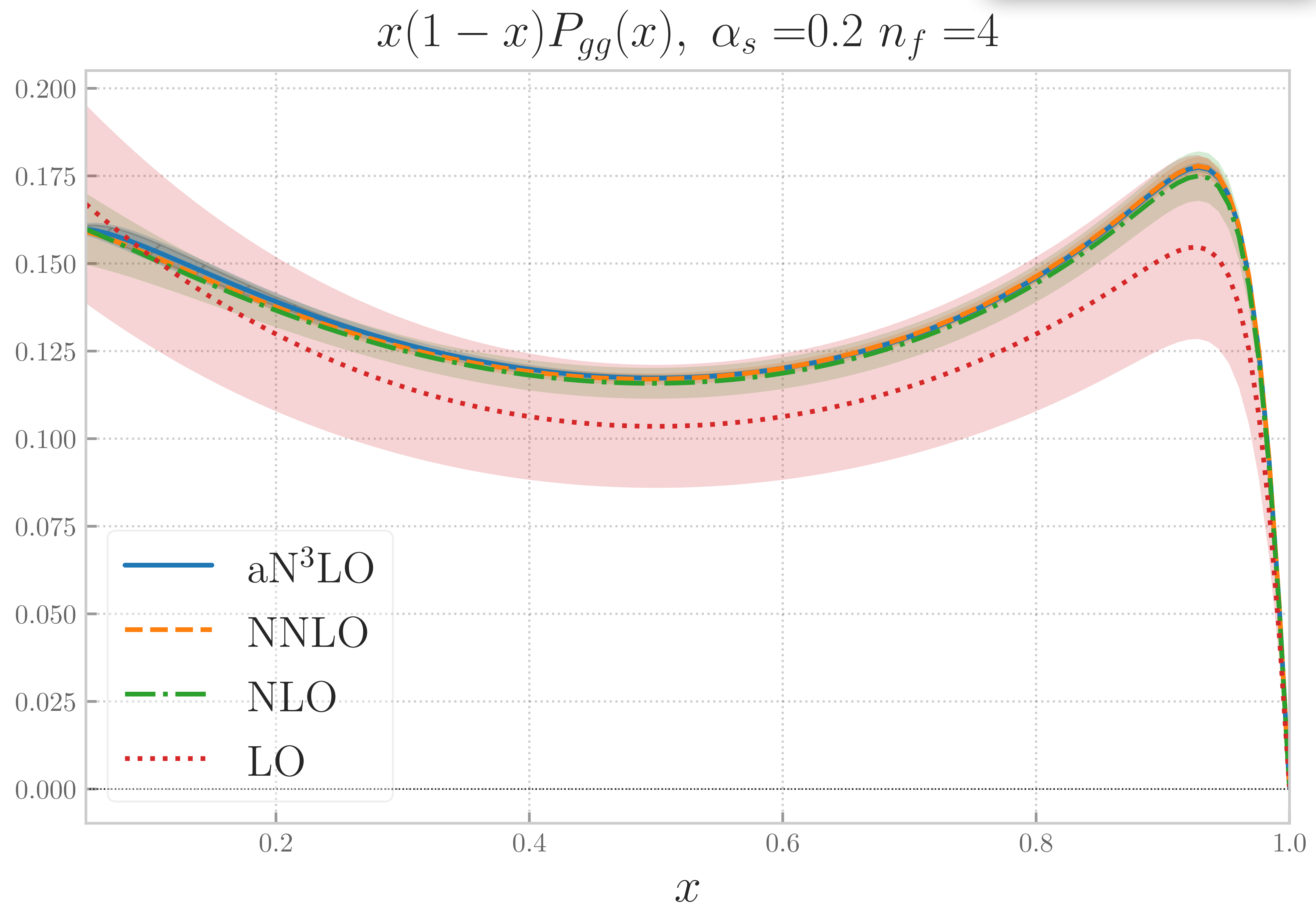
$\gamma^{(3)}_{gg}(N)$	$G^{gg}_1(N)$	$\mathcal{M}[(1-x)\ln^3(1-x)](N)$
	$G^{gg}_2(N)$	$\frac{1}{(N-1)^2}$
	$G^{gg}_3(N)$	$\frac{1}{N-1}$
	$\{H^{gg}_1(N),\ H^{gg}_2(N)\}$	$\frac{1}{N^4},\ \frac{1}{N^3},\ \frac{1}{N^2},\ \frac{1}{N+1},\ \frac{1}{N+2},\ \mathcal{M}[(1-x)\ln^2(1-x)](N),\ \mathcal{M}[(1-x)\ln(1-x)](N)$

Large-N and small-N most leading contributions

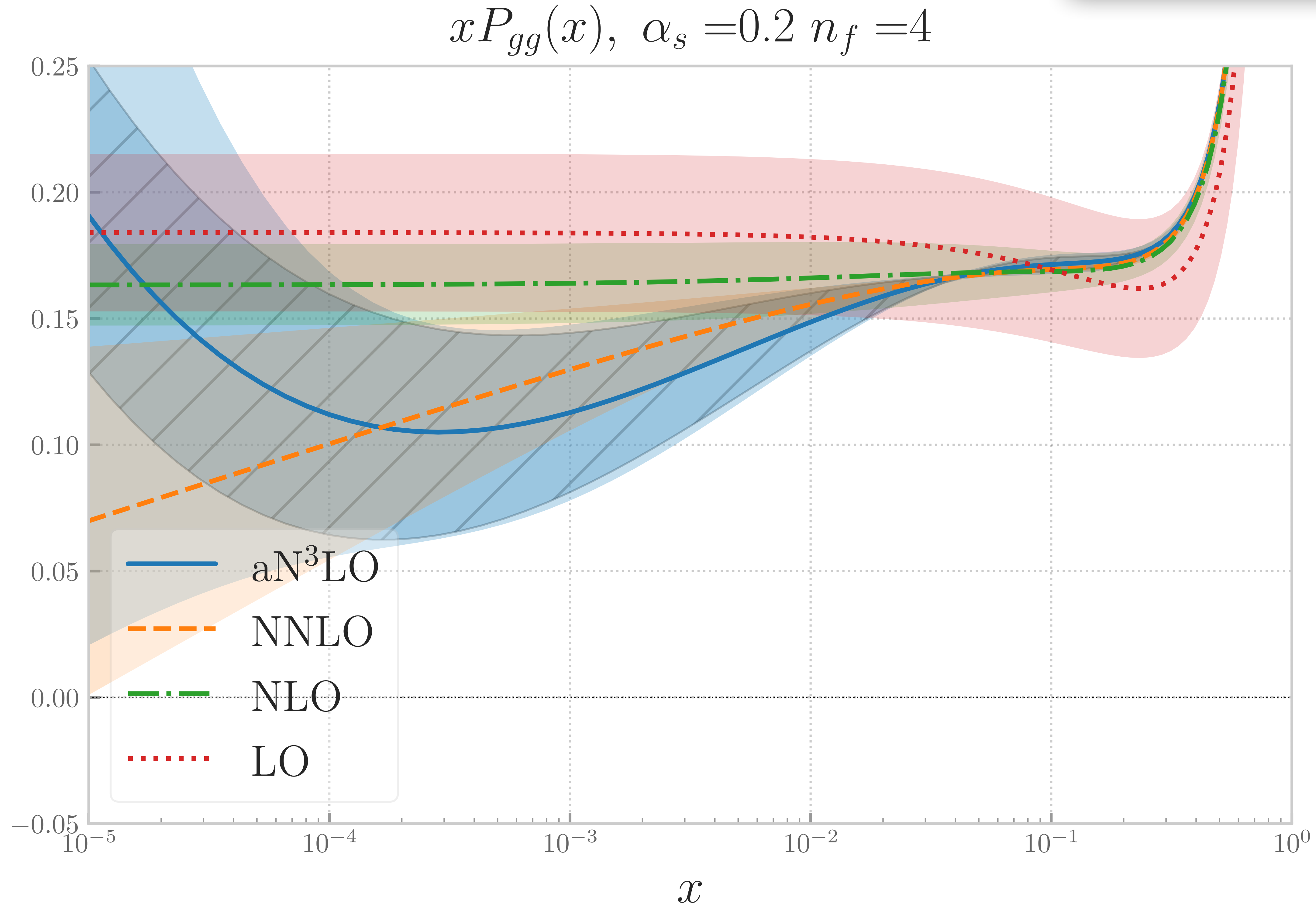
Further subleading terms

P_{gg}

Large-x



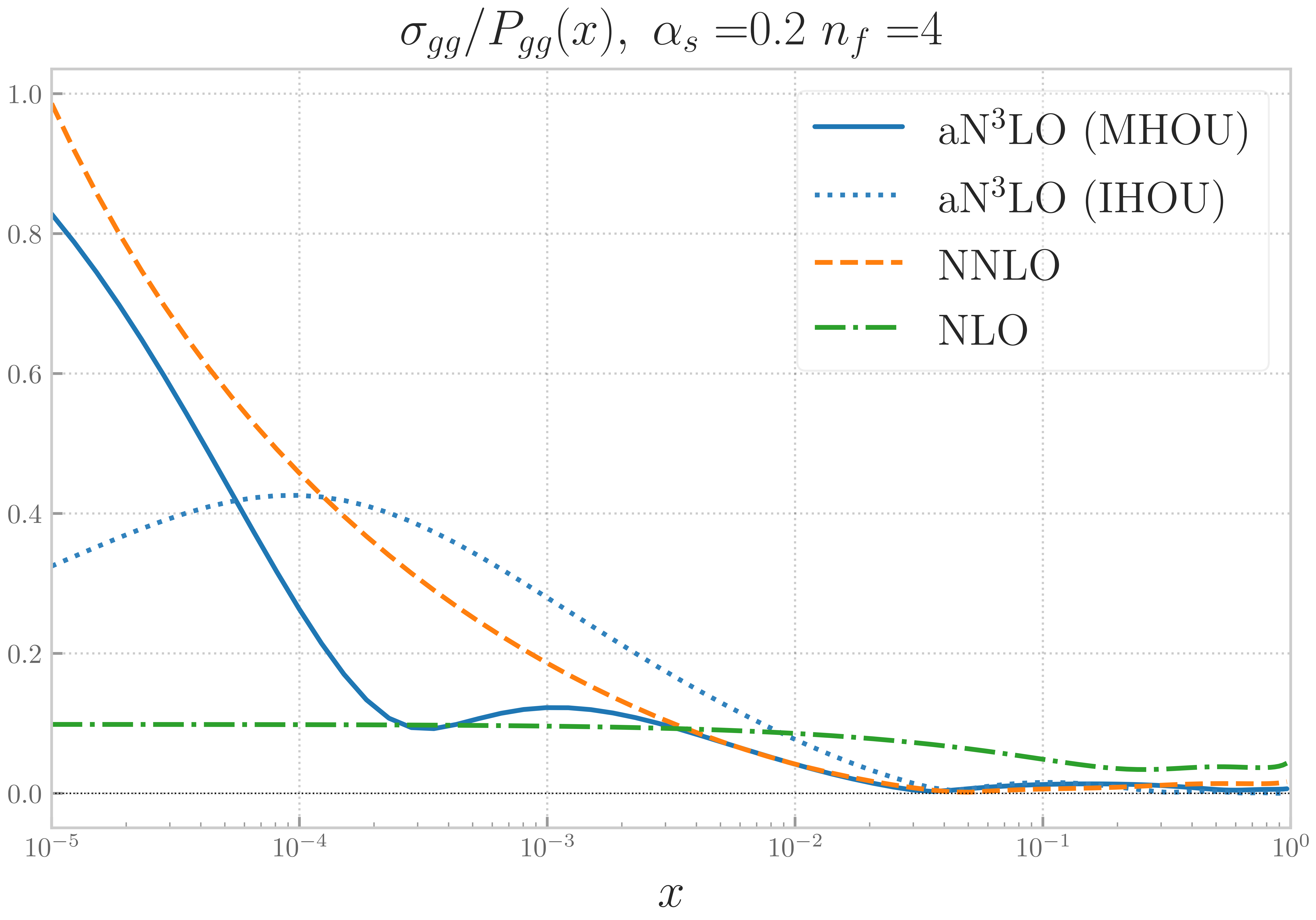
small-x



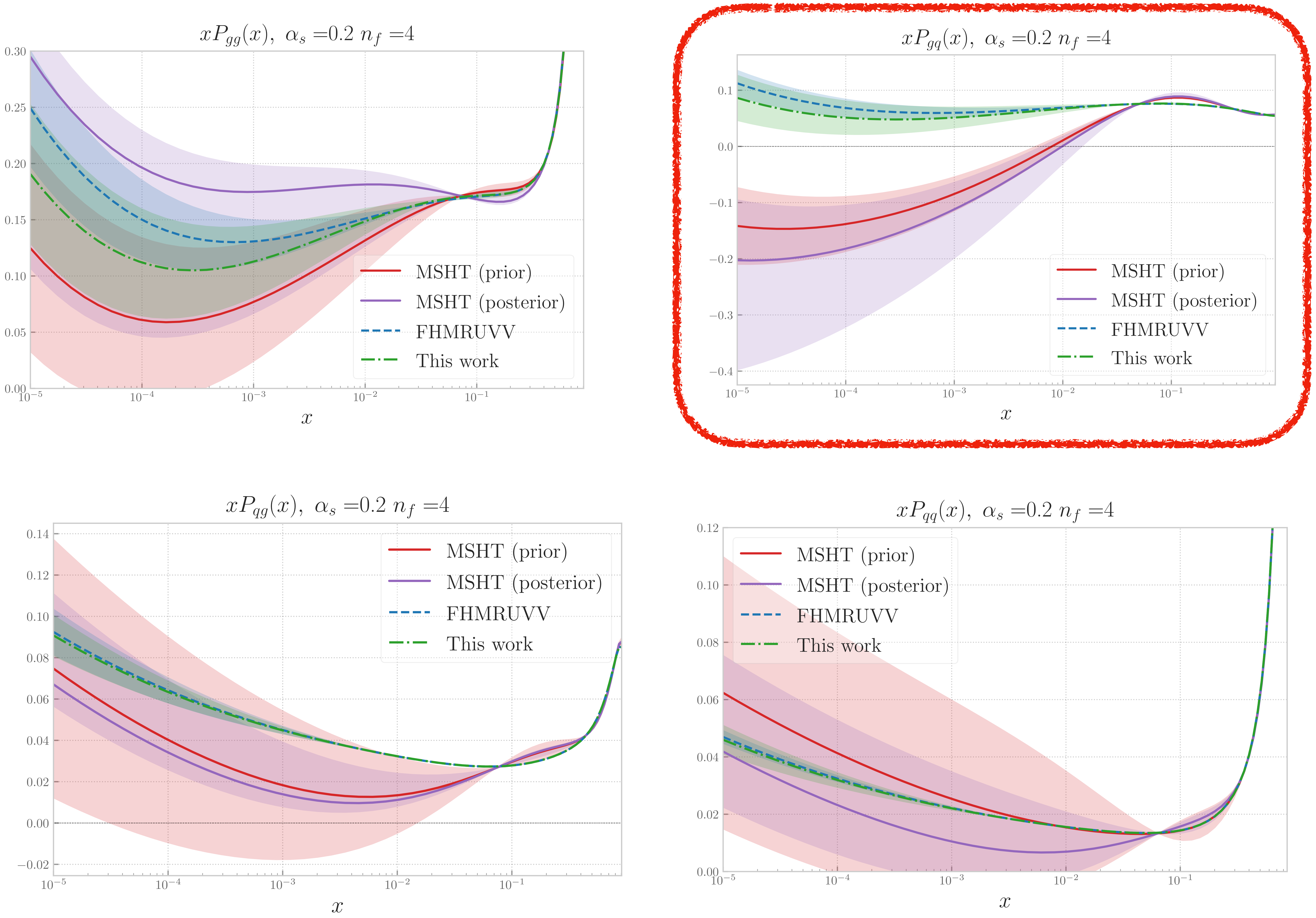
- Good perturbative convergence
- IHOU and MHOU are both negligible

- aN3LO and NNLO result agree within uncertainties
- aN3LO uncertainties are sizeable
- IHOU dominate the gluon sector

singlet: small-x



Comparison to MSHT aN3LO splitting function



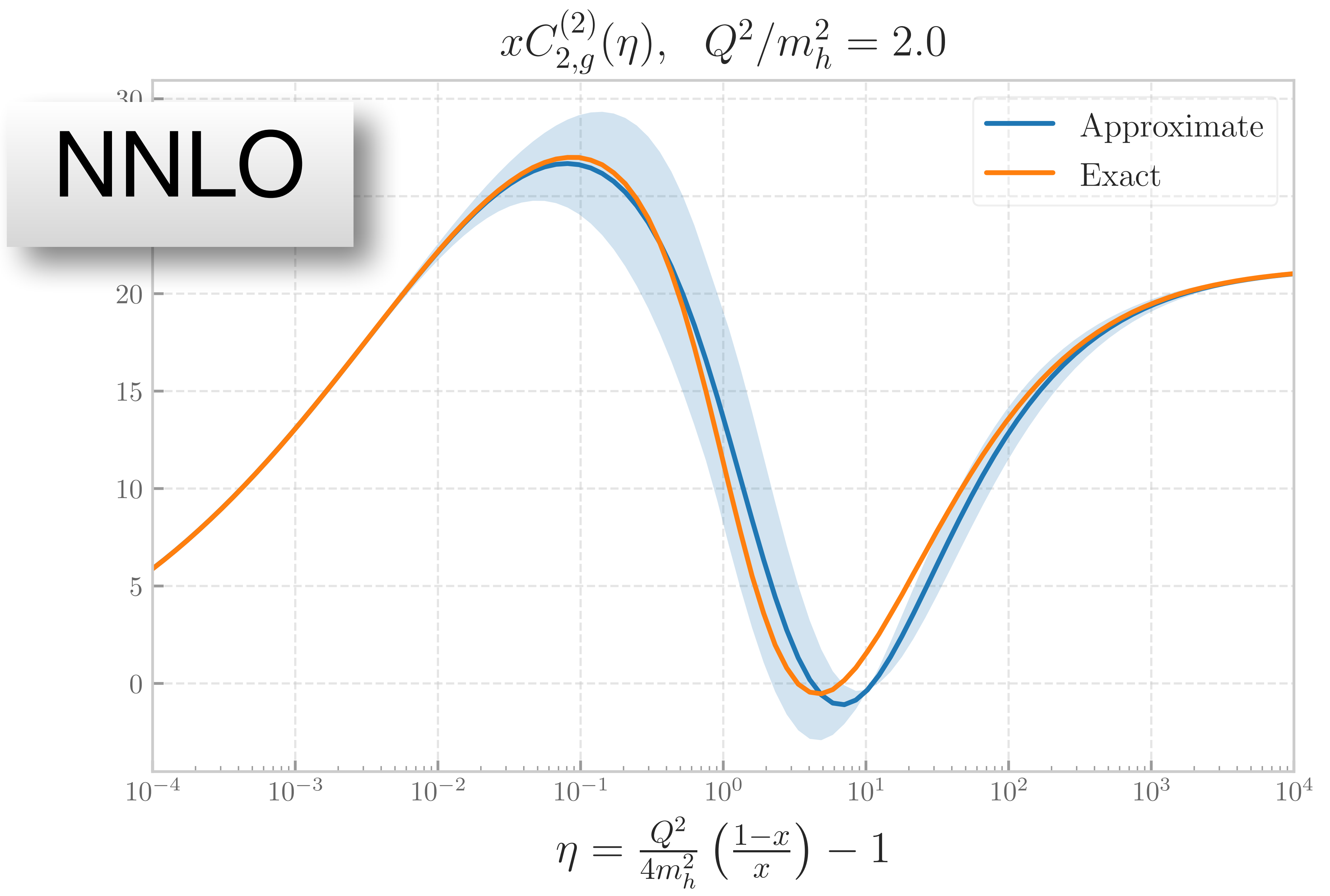
- MSHT: to estimate IHOU additional nuisance parameters which are fitted to the data
- Nuisance params are taken as a prior and by looking at the data they determine posterior
- Biggest difference for P_{qg} where MSHT is very different from both NNPDF and previous approximation FHMRUVV [JHEP 10 (2017) 041]

Partonic cross-sections

DIS

- DIS structure functions F_2, F_L, F_3 known at N3LO in the massless limit
  DIS NC [arxiv:9605317, arxiv:0411112, arxiv:0504242]
  DIS CC [arxiv:0812.4168, arxiv:1606.08907]

- DIS massive structure functions can be approximated from known limits and interpolation functions [arXiv:2401.12139, Barontini, Bonvini, Laurenti, in preparation]



$$C^{(3)}_{i,k}\left(x, m_h^2/Q^2\right) = C^{(3),thr}_{i,k} f_1(x) + C^{(3),asy}_{i,k} f_2(x)$$

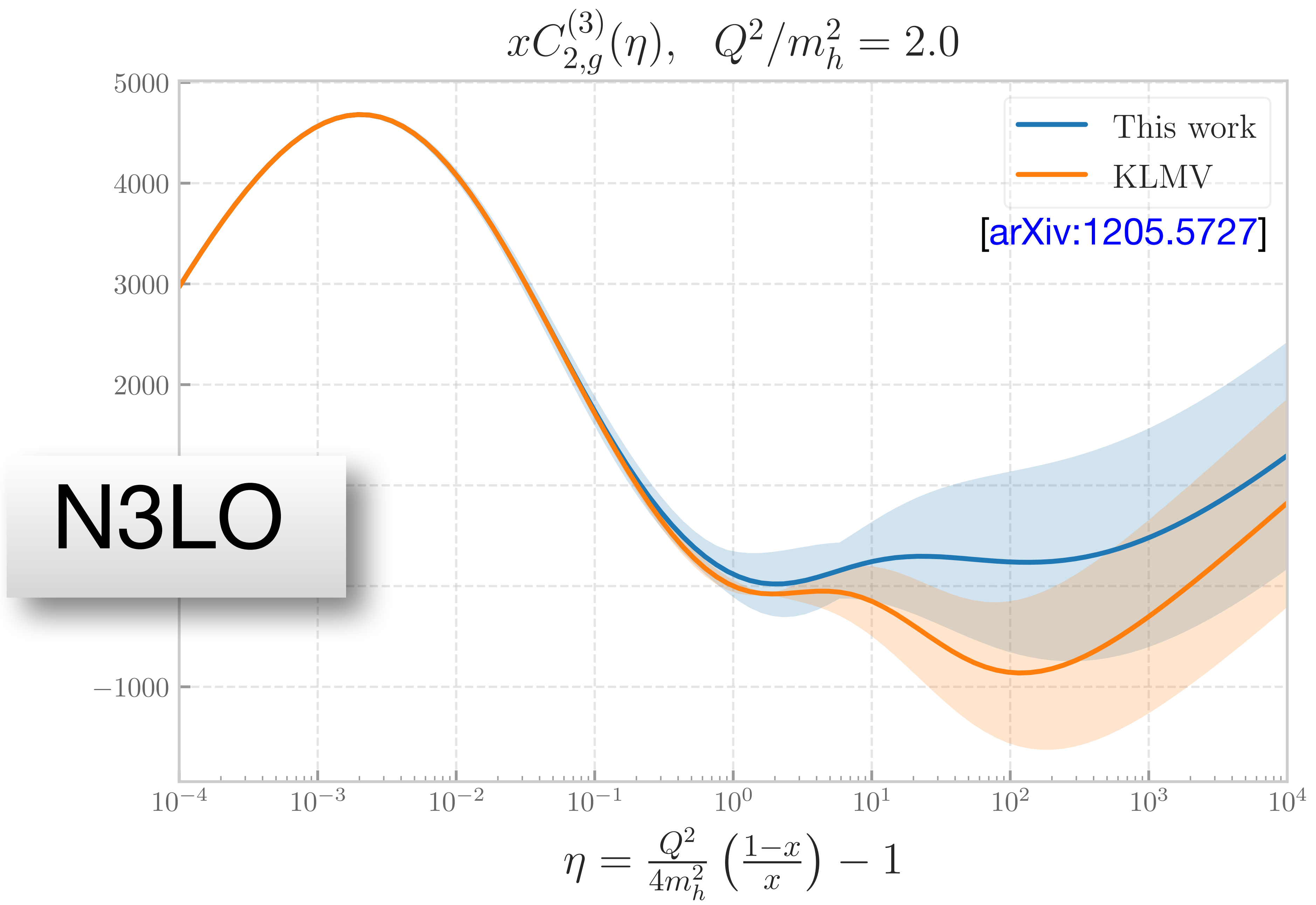
Threshold limit

$$x \to x_{max} = \frac{Q^2}{4m_h^2 + Q^2}$$

High energy limit $x \to 0$

Asymptotic limit $Q^2 \gg m_h^2$

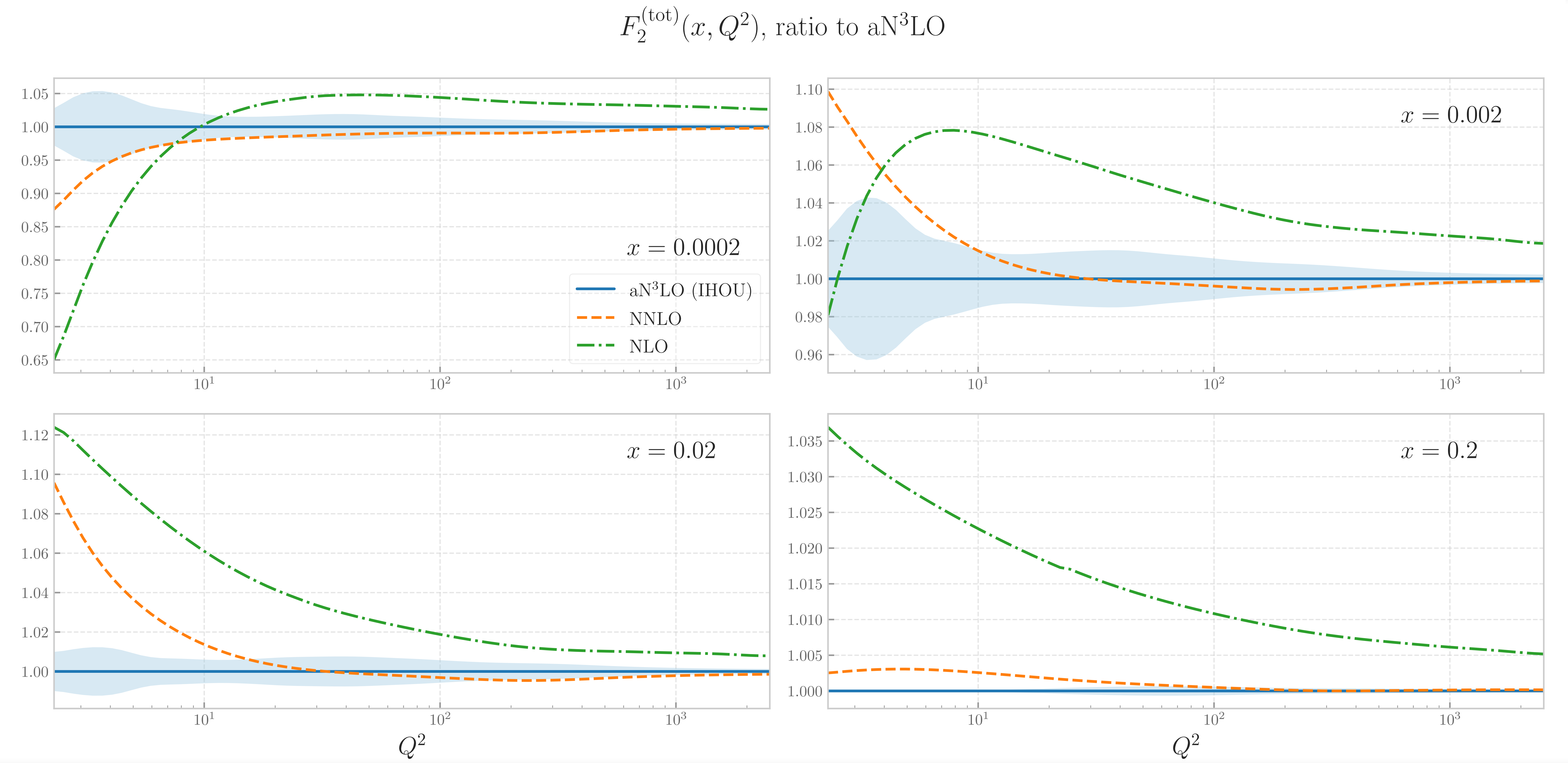
Uncertainty of the approximate coefficient function is built by varying interpolating functions



FONLL

Extension to FONLL accounting for both massive and massless contributions at $\mathcal{O}(\alpha_s^3)$ (FONLL-E)

$$F_i^{FONLL} = F_i^{(n)}(x, Q^2, m_h^2) + F_i^{(n+1)}(x, Q^2) - F_i^{(n,0)}(x, \ln(Q^2/m_h^2))$$



- aN3LO corrections to NNLO lower than 2% for $Q^2 > 10\,GeV^2$ and at most 10% around charm mass
- aN3LO corrections larger than IHOU in a significant region

Hadronic processes

N3LO corrections are not included

Hadronic processes

- N3LO corrections pub available for inclusive NC and CC DY (differential distribution at the level of leptonic observables also computed but not available) ✓
- No N3LO calculations available for other data of NNPDF4.0 ✗
- Rapidity dependence of K factors ✗

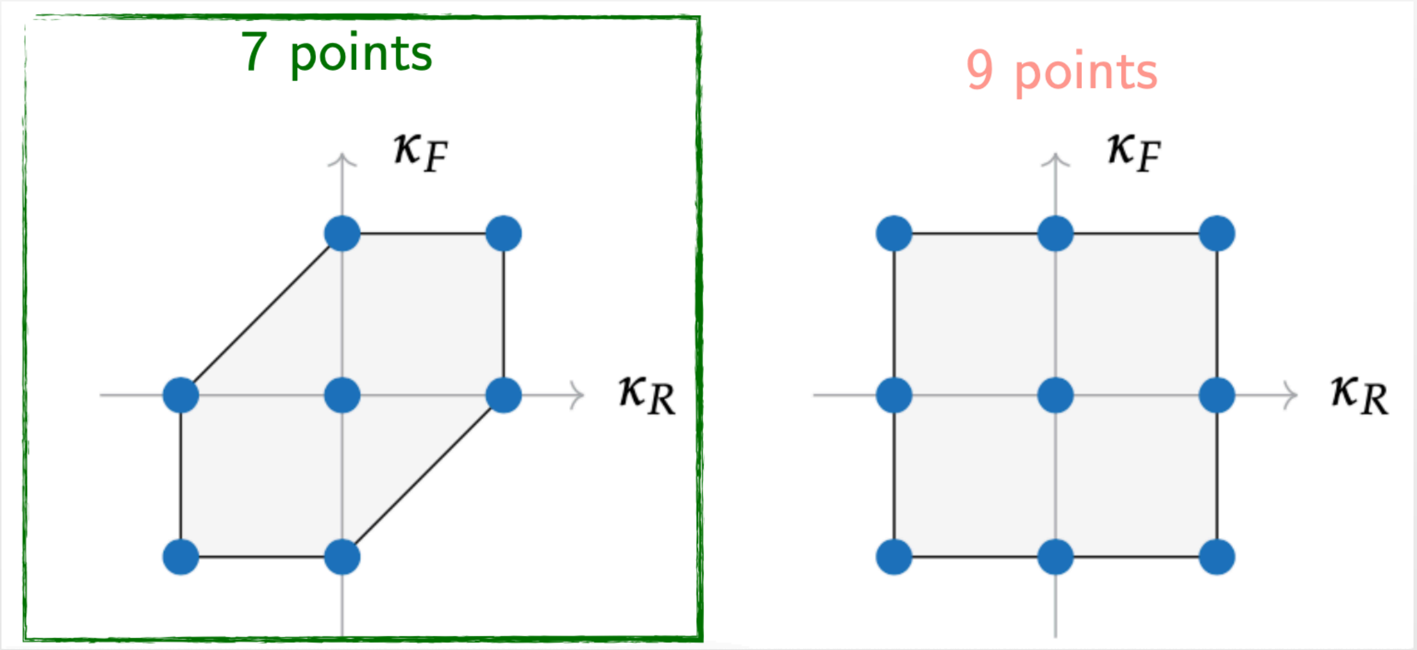
→ **No inclusion of hadronic data in default set.**

dedicated variant to assess the impact of available data/computations (backup)

Dataset	Ref.	$n_{\rm dat}$	Kin$_1$	Kin$_2$ [GeV]	C-factor N^{3}LO/NNLO
ATLAS high-mass DY 7 TeV	[103]	13	$\lvert\eta_\ell\rvert \leq 2.1$	$116 \leq m_{\ell\ell} \leq 1500$	$\mathrm{d}\sigma/dm_{\ell\ell}$
ATLAS Z 7 TeV ($\mathcal{L} = 35$ pb^{-1})	[104]	8	$\lvert\eta_\ell, y_Z\rvert \leq 3.2$	$Q = m_Z$	$\mathrm{d}\sigma/dm_{\ell\ell}$ $(66 < m_{\ell\ell} < 150)$
ATLAS Z 7 TeV ($\mathcal{L} = 4.6$ fb^{-1}) CC	[105]	24	$\lvert\eta_\ell, y_Z\rvert \leq 2.5, 3.6$	$Q = m_Z$	$\mathrm{d}\sigma/dm_{\ell\ell}$ $(46 < m_{\ell\ell} < 116)$
ATLAS $\sigma^{\rm tot}_{W,Z}$ 13 TeV	[106]	3	—	$Q = m_W, m_Z$	σ

MHOU

Uncertainties due to perturbative truncation of partonic cross sections and anomalous dimensions [arXiv:1905.04311, arXiv:1906.10698, arXiv:2401.10319]



Process categories
DIS NC
DIS CC
DY NC
DY CC
Top pair
Single top
Single inclusive jets
Prompt photon
Dijets

- **Splitting functions (N4LO)**
- **DIS partonic coefficients (N4LO)**
- **Hadronic partonic xsec (N3LO)**

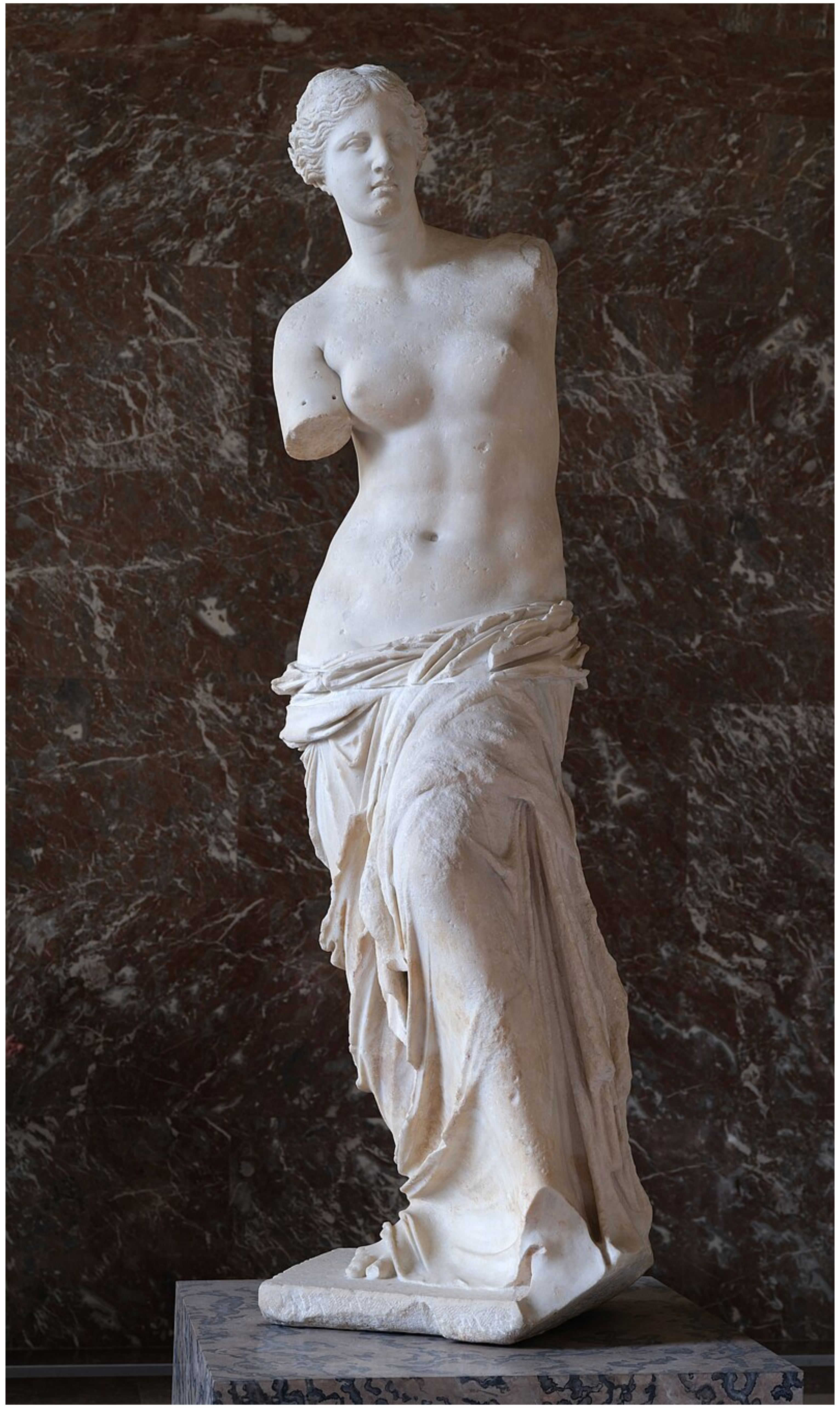
IHOU

Uncertainties due to incomplete knowledge of N3LO corrections

- **Splitting functions**
- **DIS partonic coefficients**

$$\text{cov}^{tot} = \text{cov}^{exp} + \text{cov}^{MHOU} + \text{cov}^{IHOU}$$

aN3LO PDFs



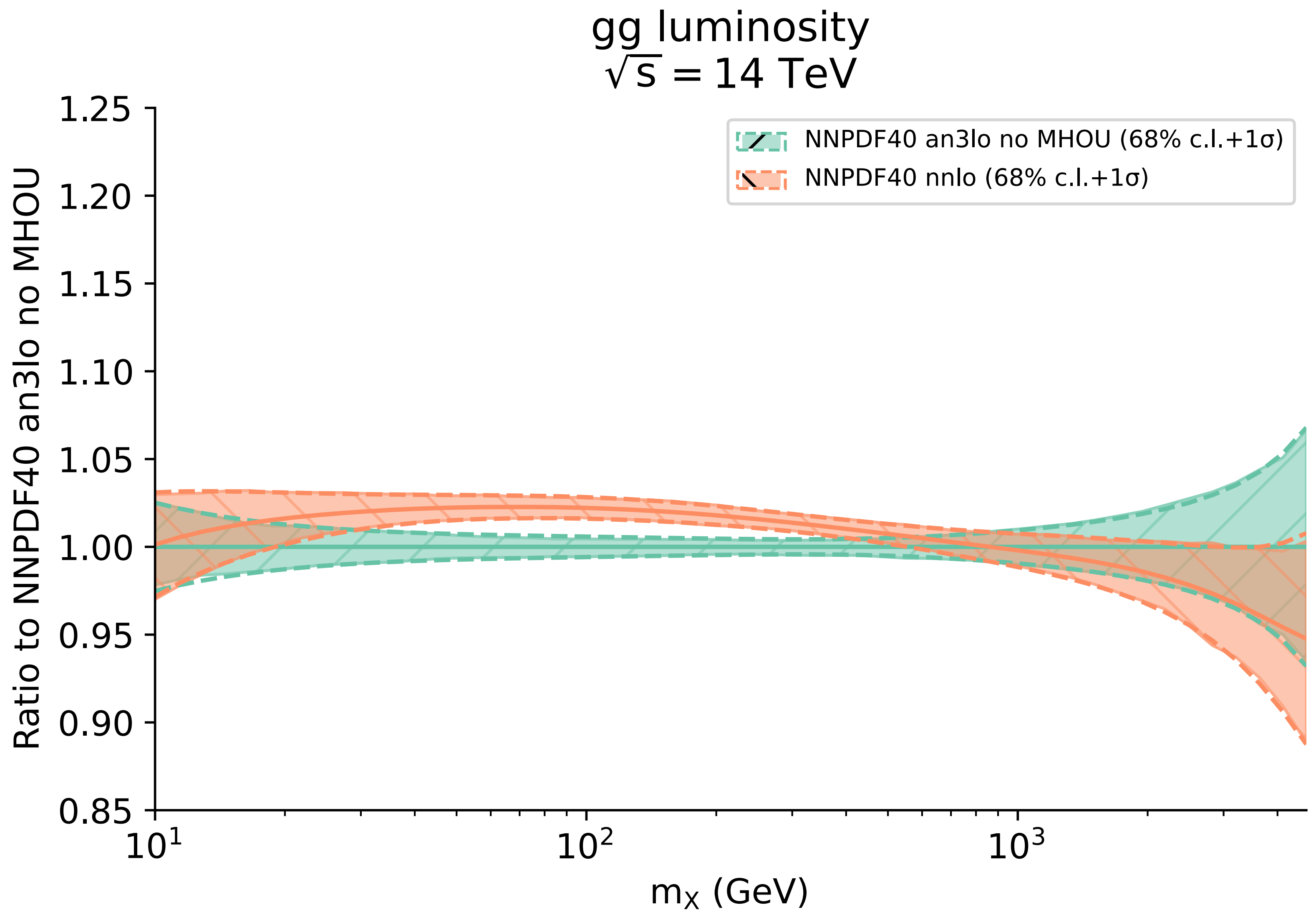
aN3LO default sets

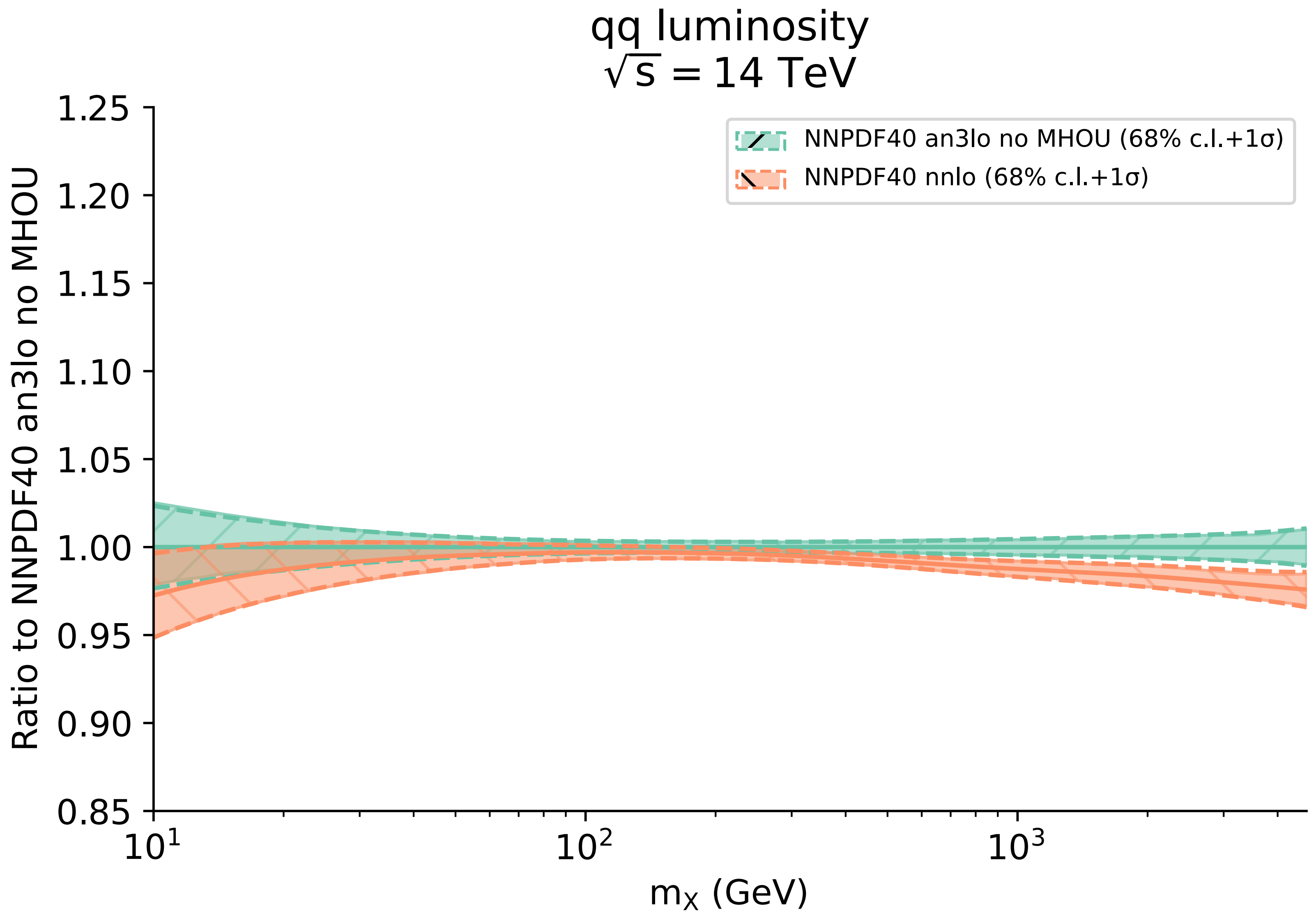
	aN3LO splitting functions	N3LO massless DIS + aN3LO massive	N3LO corrections on hadronic data	MHOU on hadronic data	MHOU on DIS data	MHOU on anomalous dimension
NNPDF40 aN3LO	✓	✓	✗	✓	✗	✗
NNPDF40 aN3LO MHOU	✓	✓	✗	✓	✓	✓

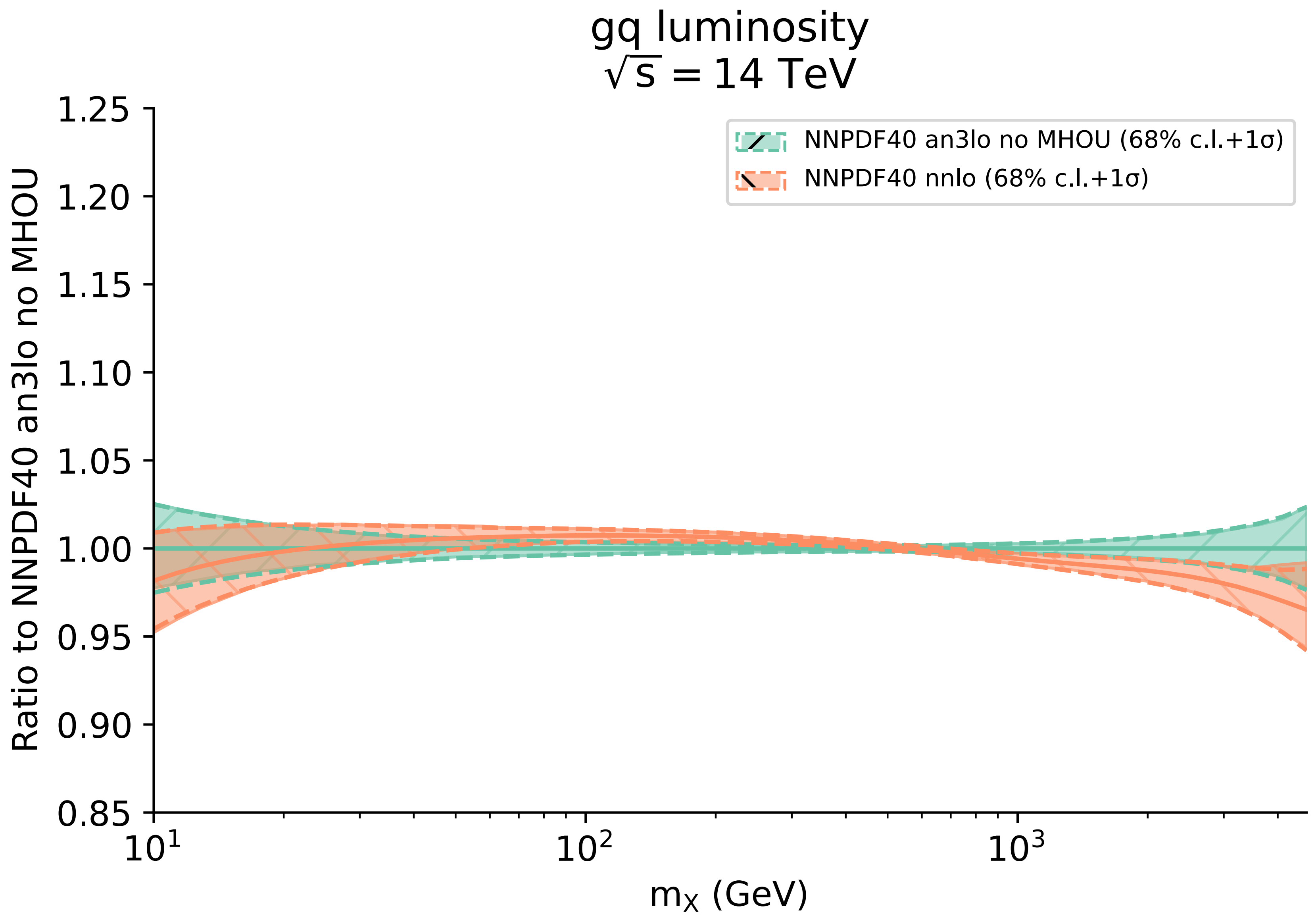
- Same dataset and methodology used for NNPDF4.0
- Results provided both with and without MHOU
- Impact of the available hadronic data is assessed in variant fits (backup slides)

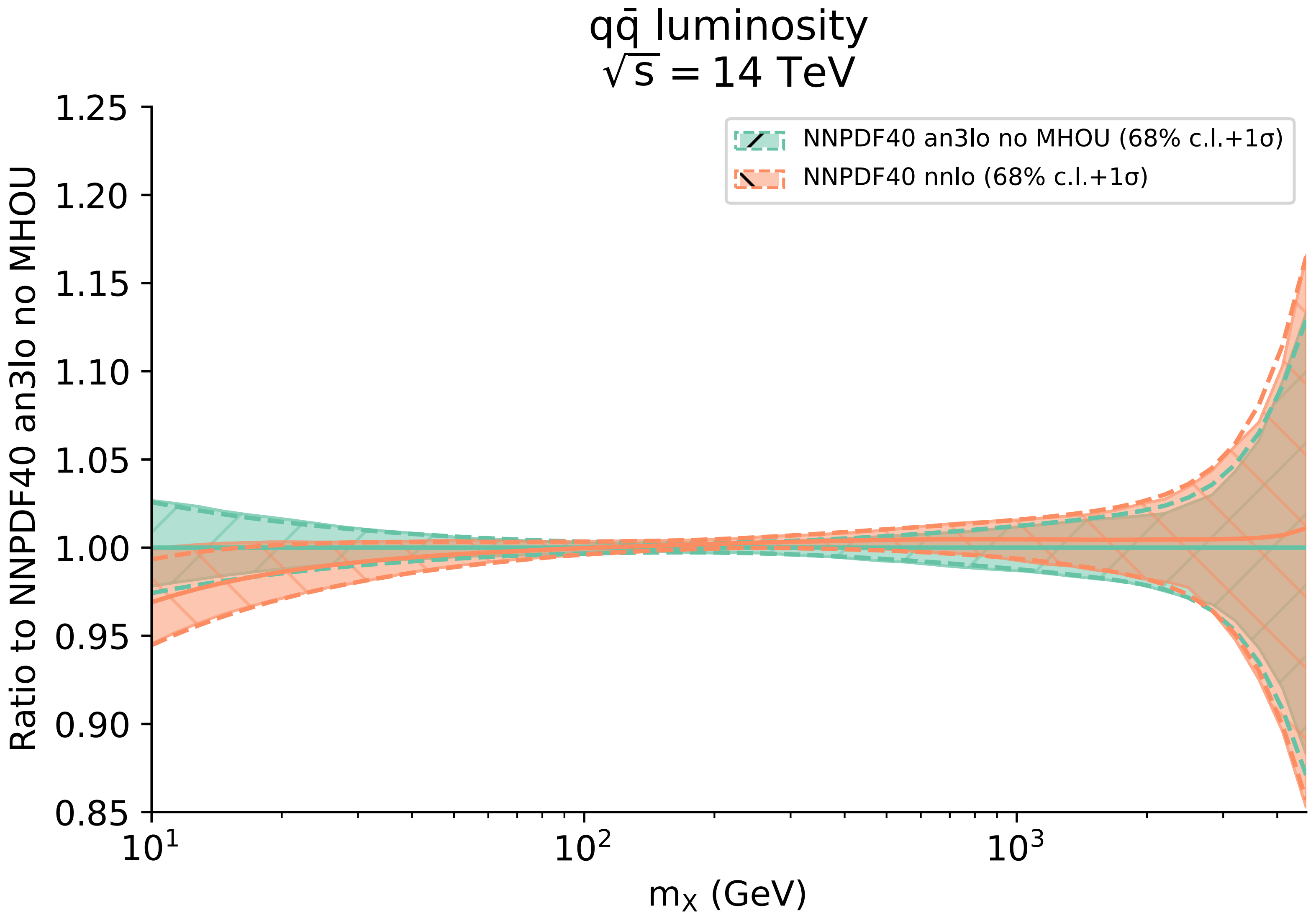
aN3LO partonic luminosity (NNPDF)

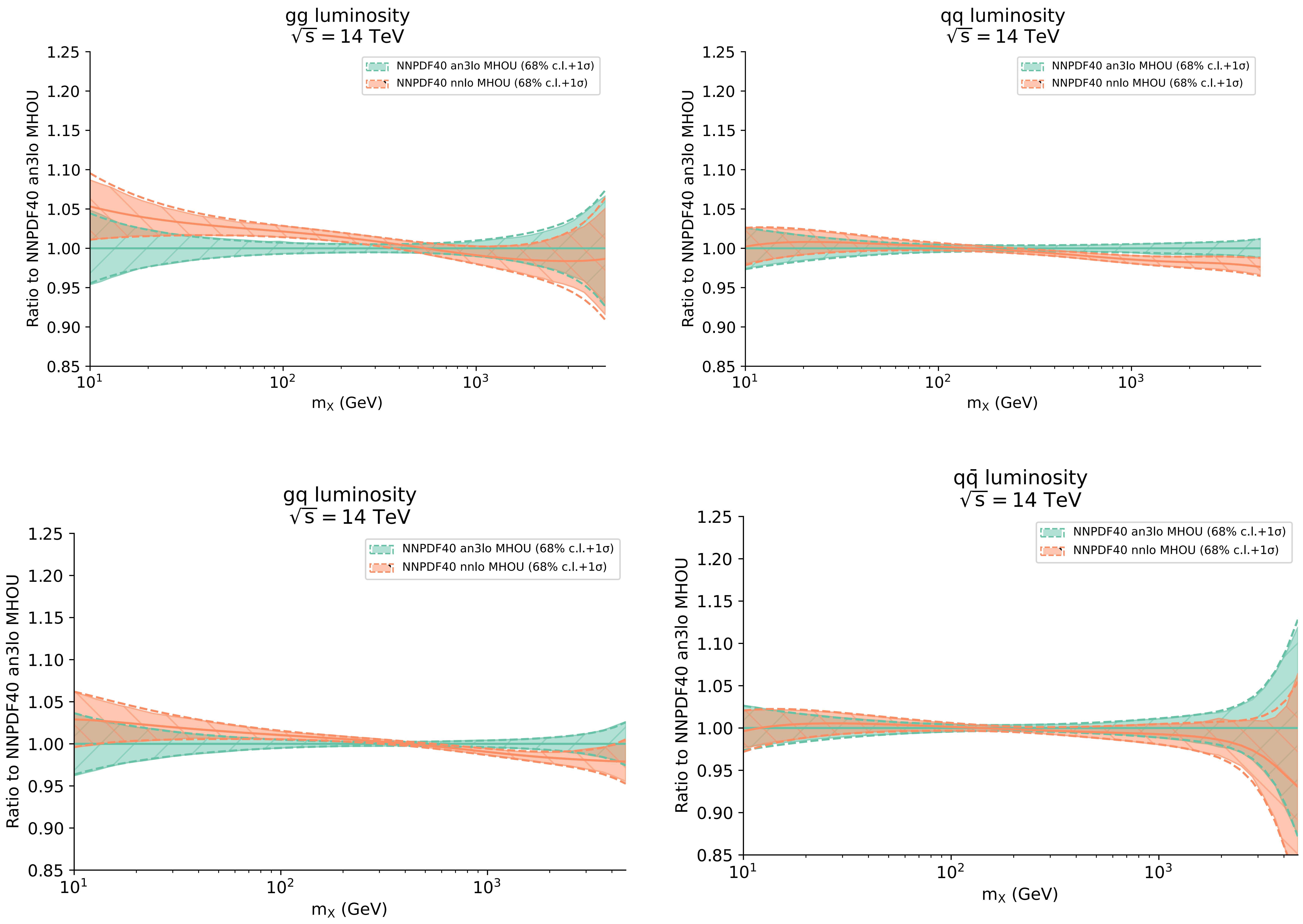
$$\mathscr{L}_{ij}(m_x, \sqrt{s}) = \frac{1}{s}\int_\tau^1 \frac{dx}{x} f_i\left(x, m_x\right) f_j\left(\frac{\tau}{x}, m_x\right)$$



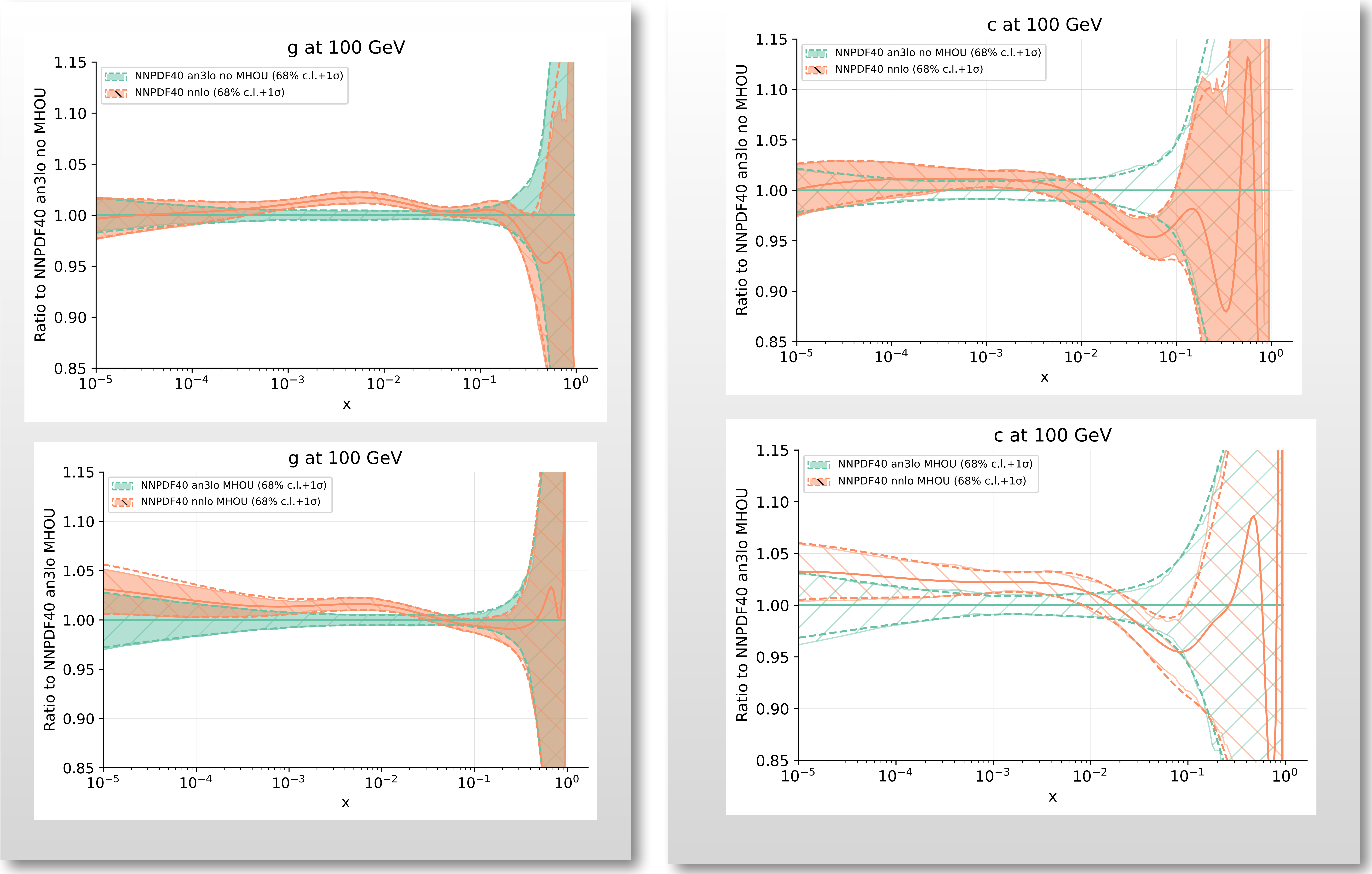








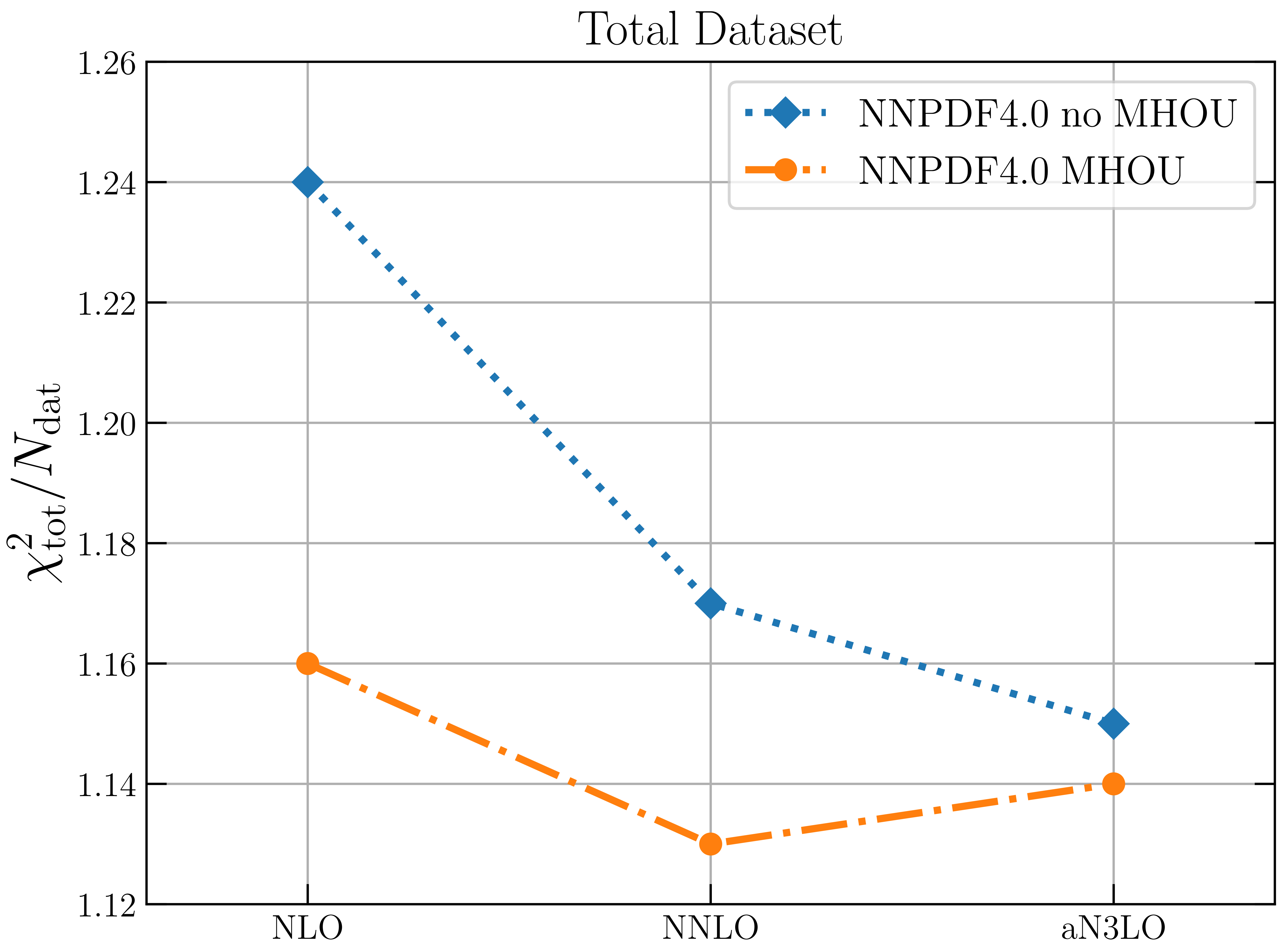
- Suppression of gg luminosity
- Enhancement of qq luminosity
- Inclusion of MHOU improve agreement (increase in uncertainties of $\sim 1\% - 2\,\%$)


g at 100 GeV
NNPDF40 an3lo no MHOU (68% c.l.+1σ)
NNPDF40 nnlo (68% c.l.+1σ)
Ratio to NNPDF40 an3lo no MHOU
x
g at 100 GeV
NNPDF40 an3lo MHOU (68% c.l.+1σ)
NNPDF40 nnlo MHOU (68% c.l.+1σ)
Ratio to NNPDF40 an3lo MHOU
x
c at 100 GeV
NNPDF40 an3lo no MHOU (68% c.l.+1σ)
NNPDF40 nnlo (68% c.l.+1σ)
Ratio to NNPDF40 an3lo no MHOU
x
c at 100 GeV
NNPDF40 an3lo MHOU (68% c.l.+1σ)
NNPDF40 nnlo MHOU (68% c.l.+1σ)
Ratio to NNPDF40 an3lo MHOU
x

no MHOU

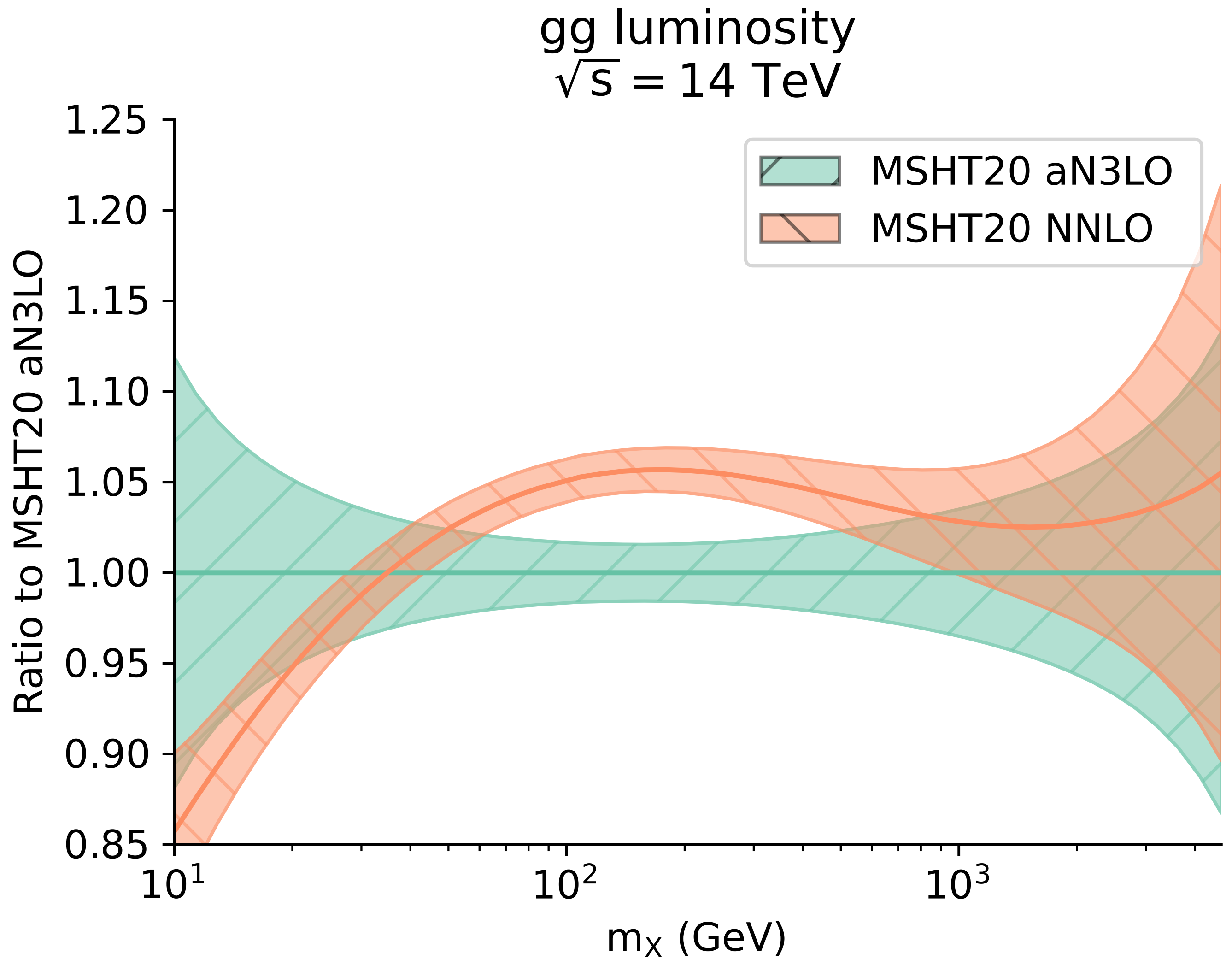
MHOU

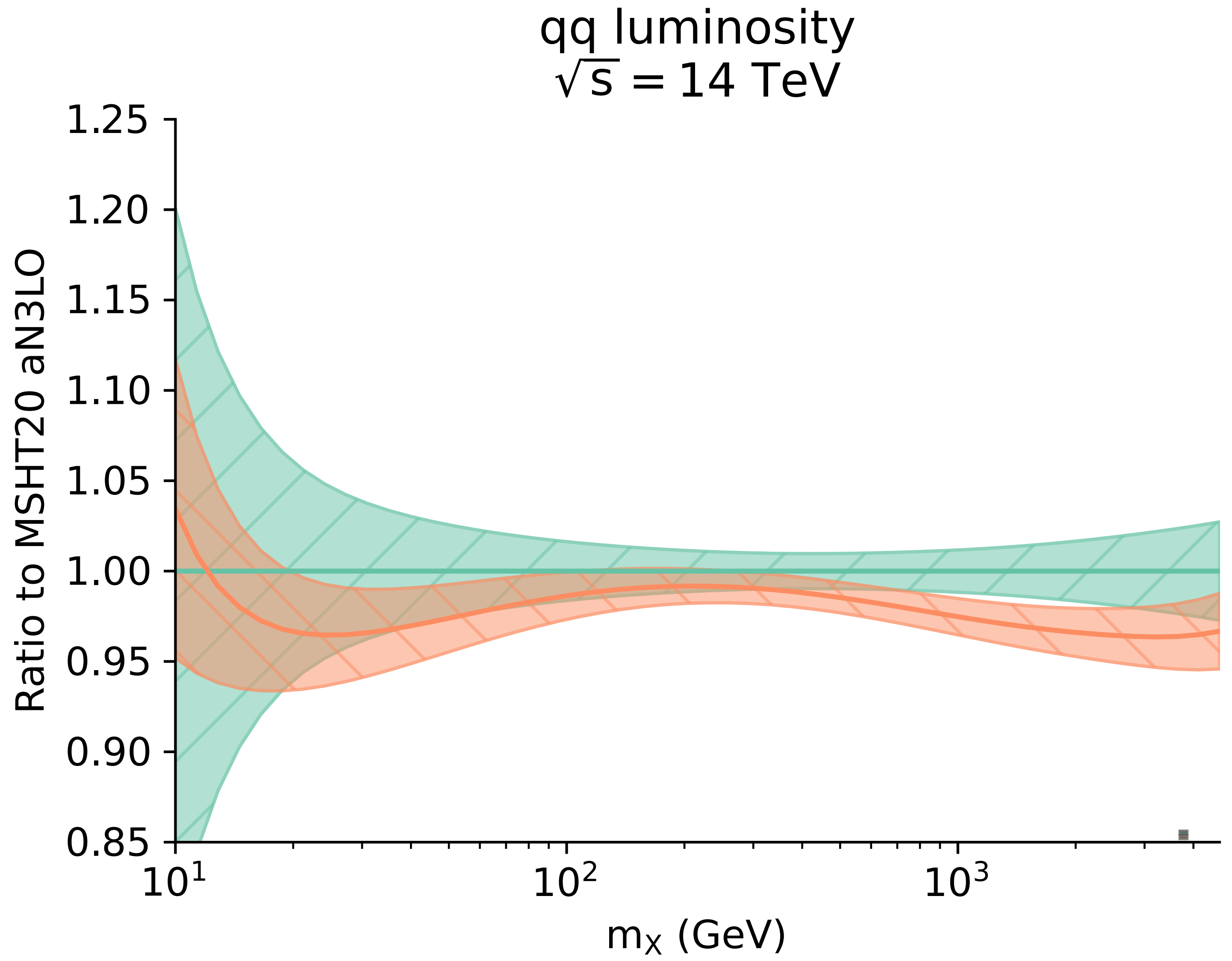
Fit quality

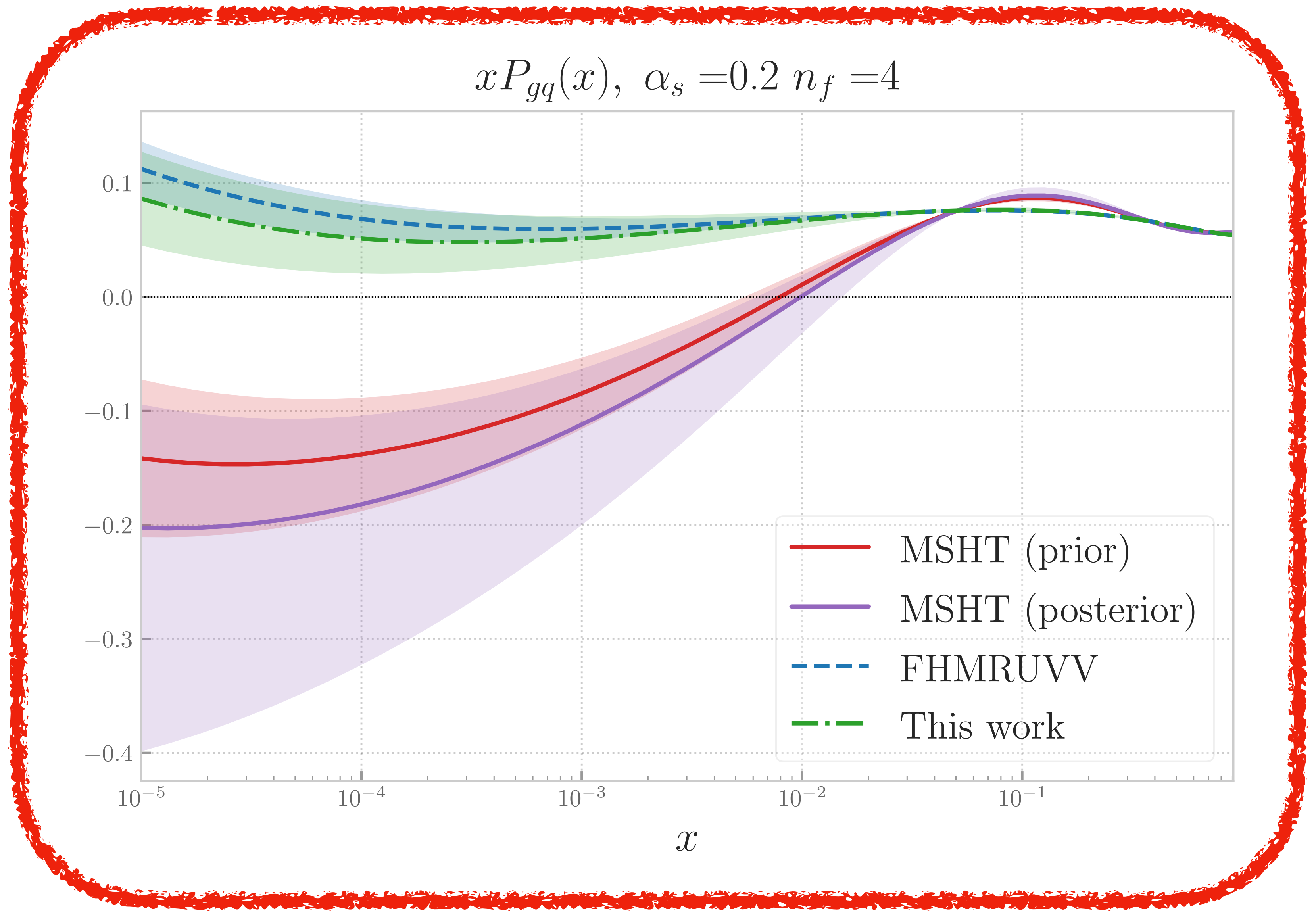


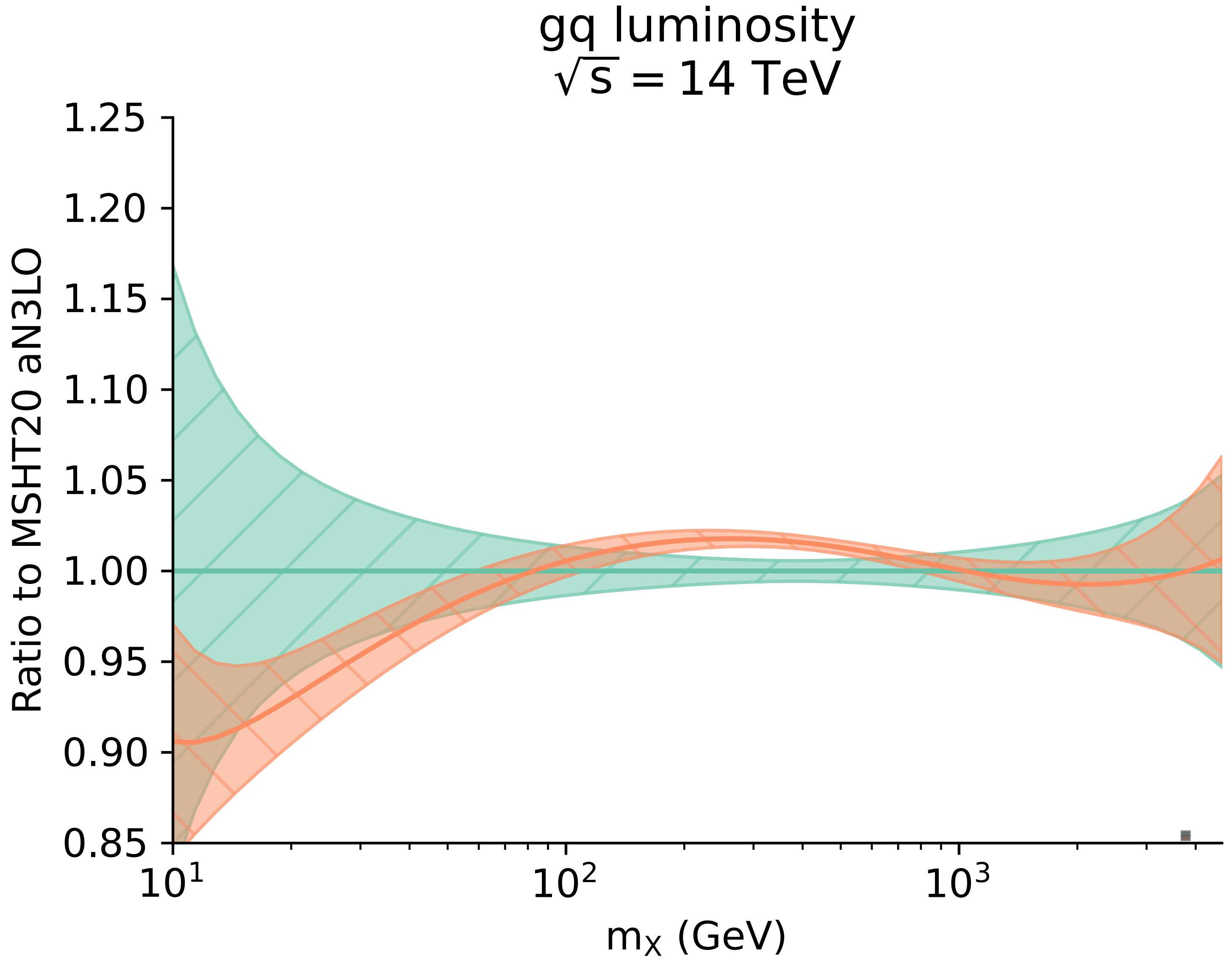
- Without MHOU fit quality improves as perturbative order improves
- With MHOU fit quality is independent on perturbative order within χ^2 uncertainties
  $N_{dat} = 4462, \quad \sigma_{\chi^2} = 0.03$

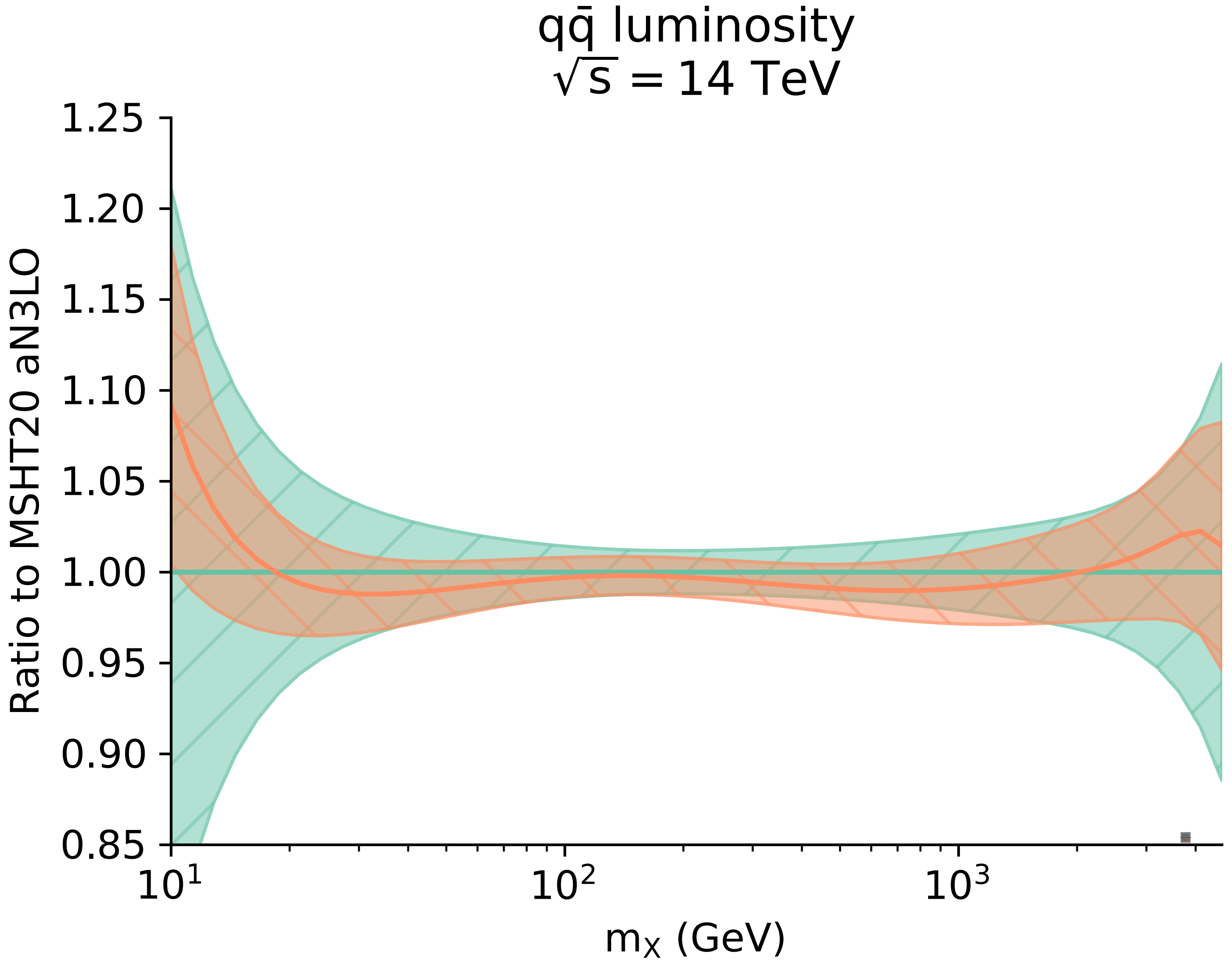
aN3LO partonic luminosity (MSHT)





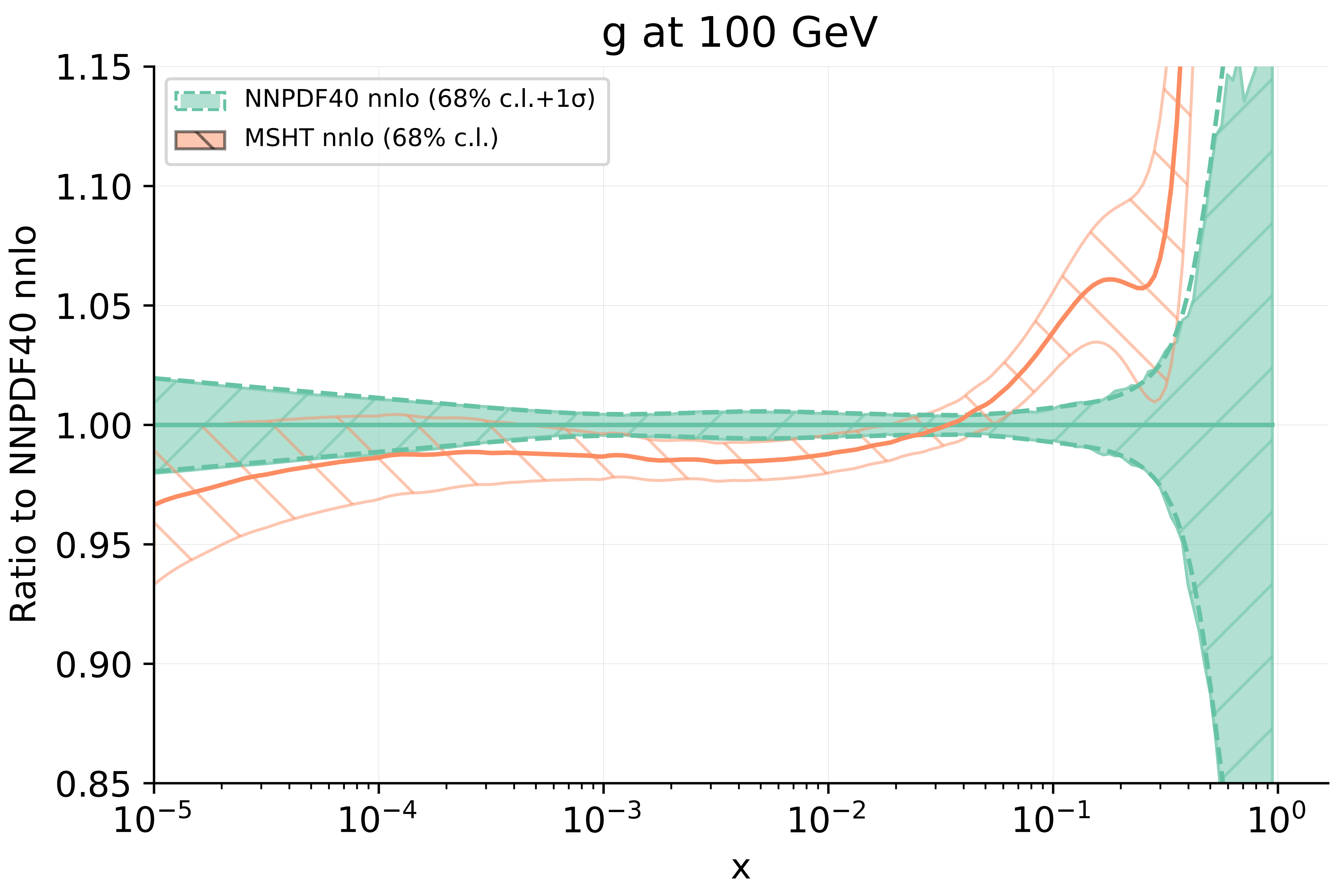




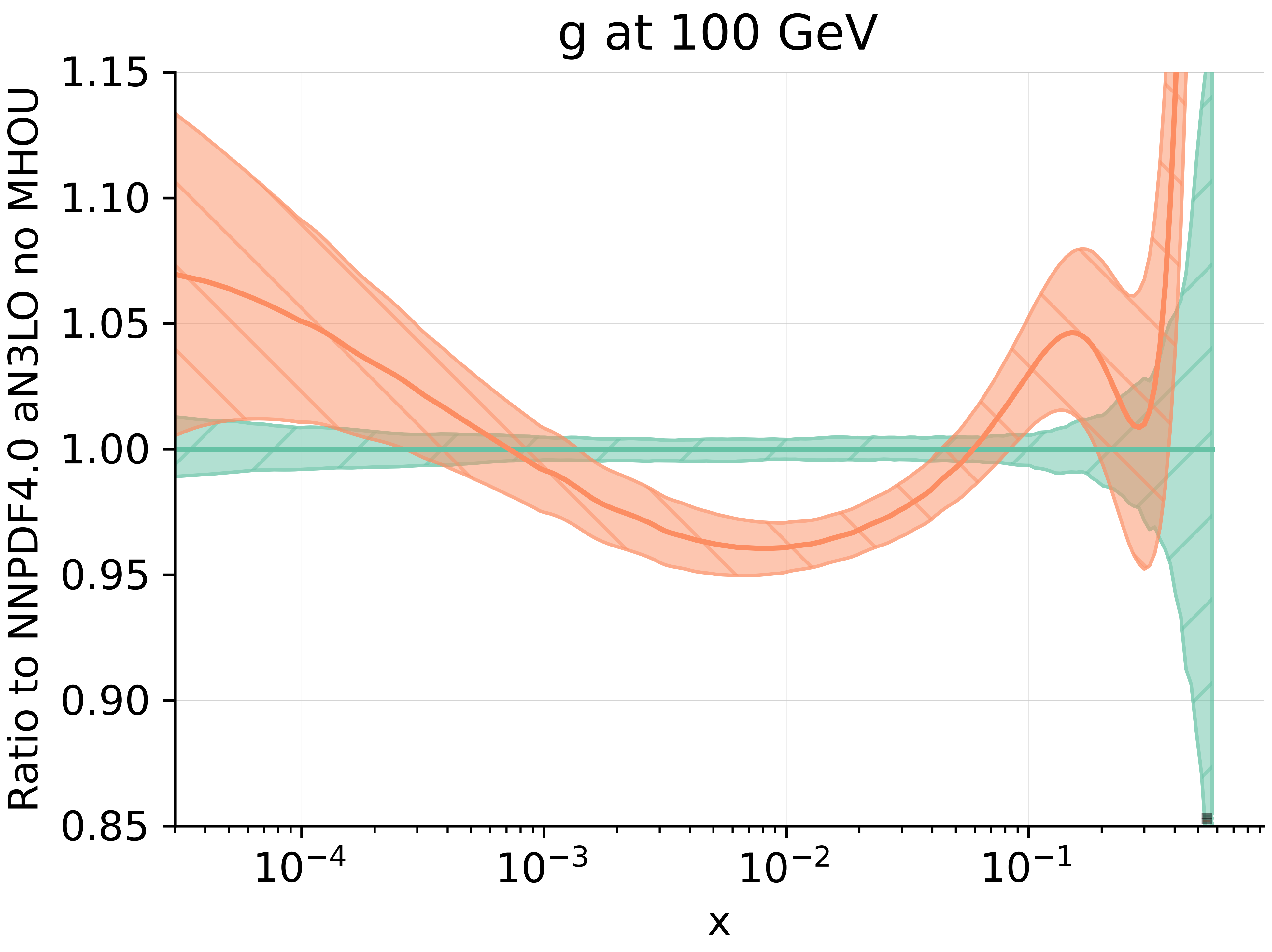


Comparison with MSHT

- Differences similar to those observed at NNLO
- At aN3LO differences in the gluon become bigger
- Most likely due to the differences in P_{gq}



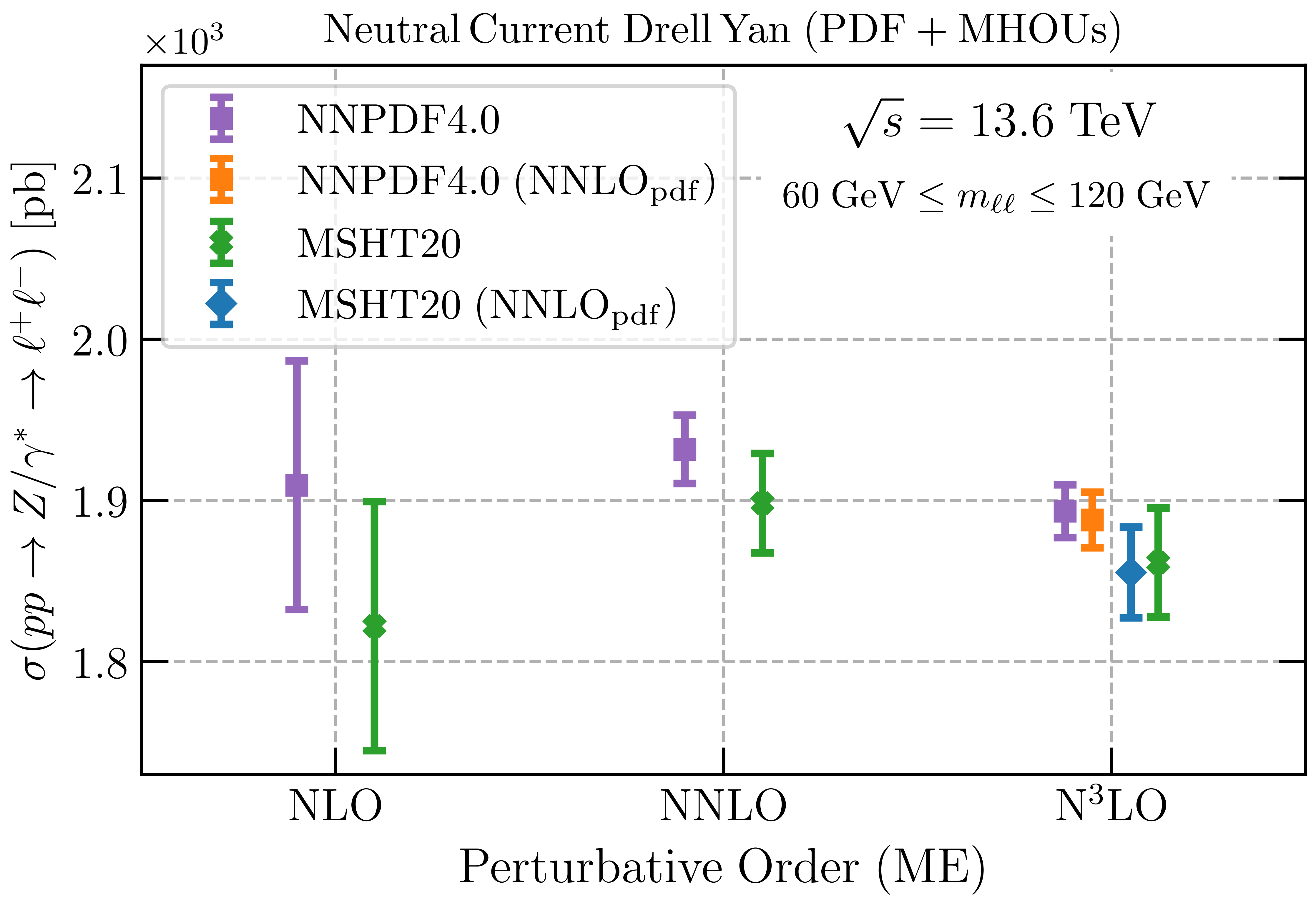
NNLO



aN3LO

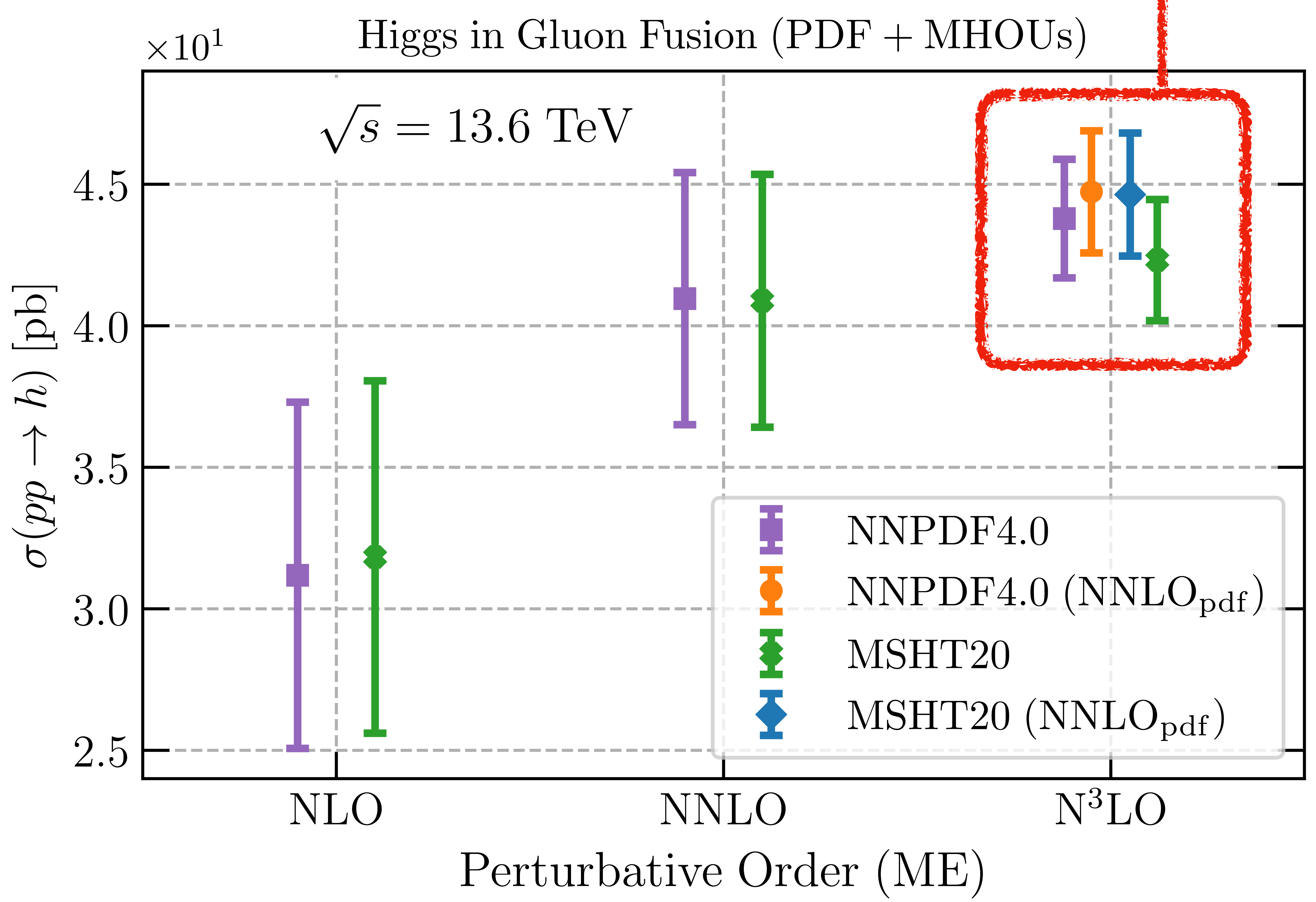
Some pheno

n3loxs [arXiv:2209.06138]

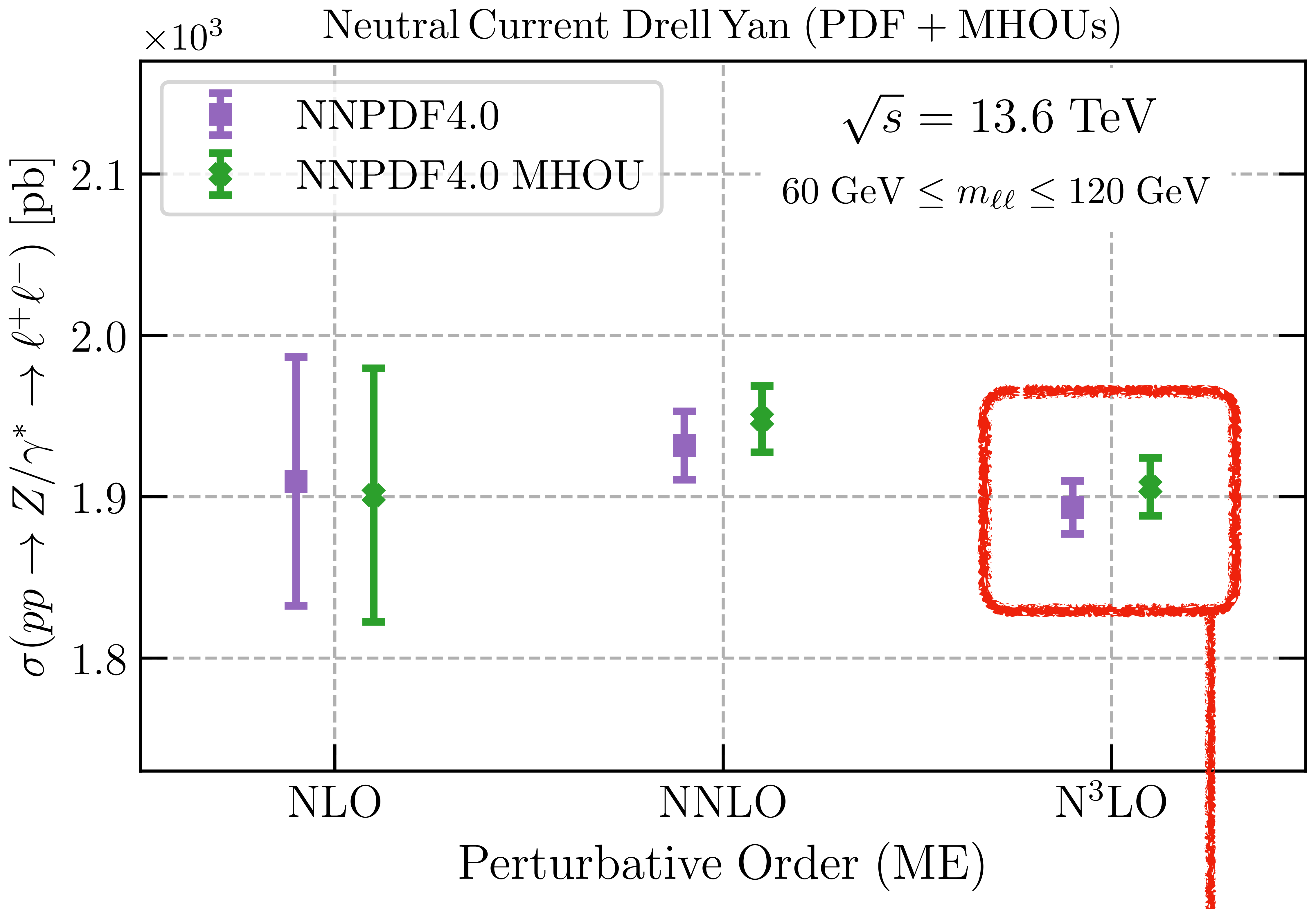


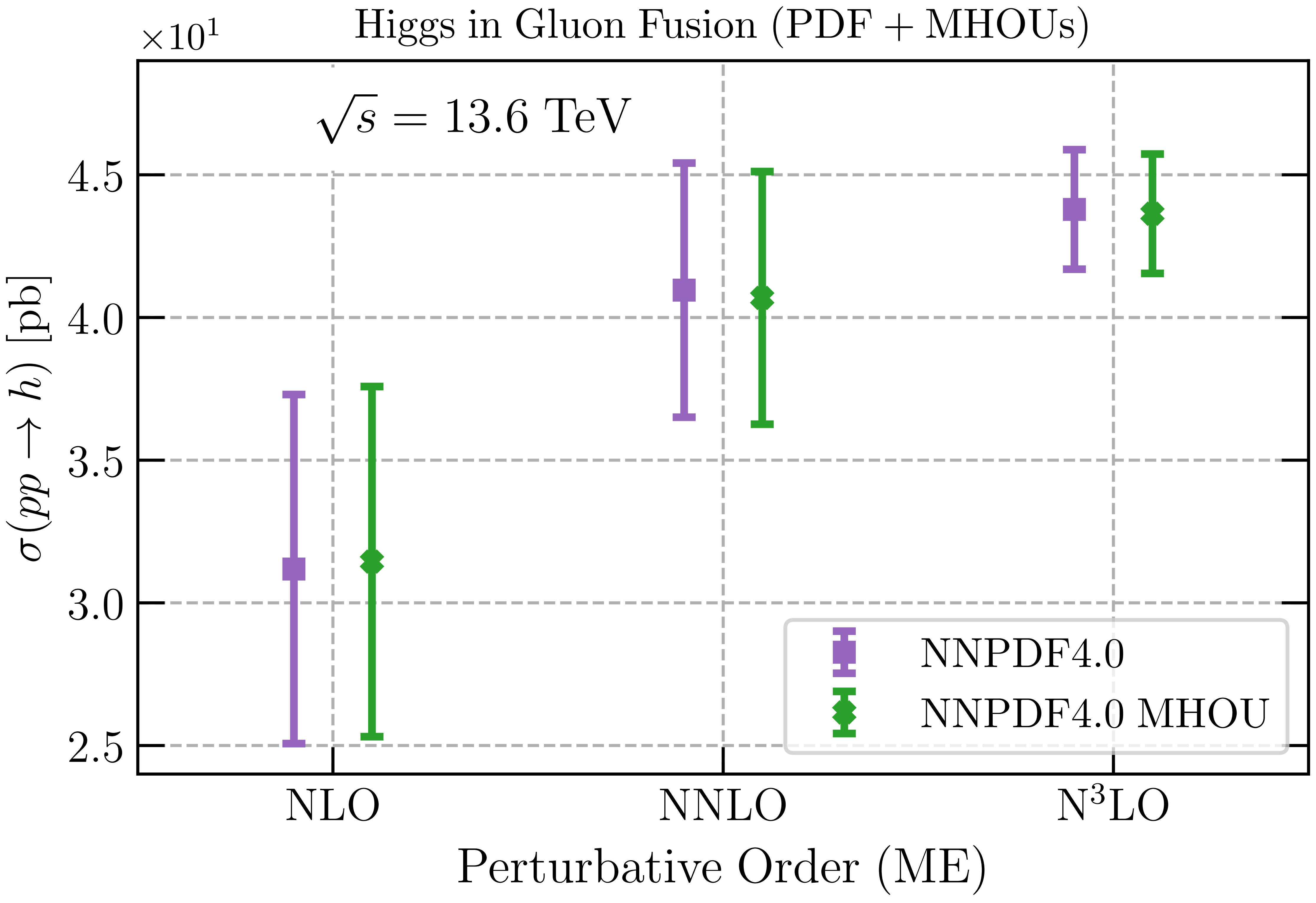
ggHiggs [arXiv:1404.3204]

Suppression of aN3lo gluon



- Th predictions based on NNPDF4.0 and MSHT20 compatible within uncertainties (agreement improves at N3LO for DY)
- Using correctly aN3LO PDF in N3LO prediction rather than NNLO PDF reducer difference wrt NNLO result

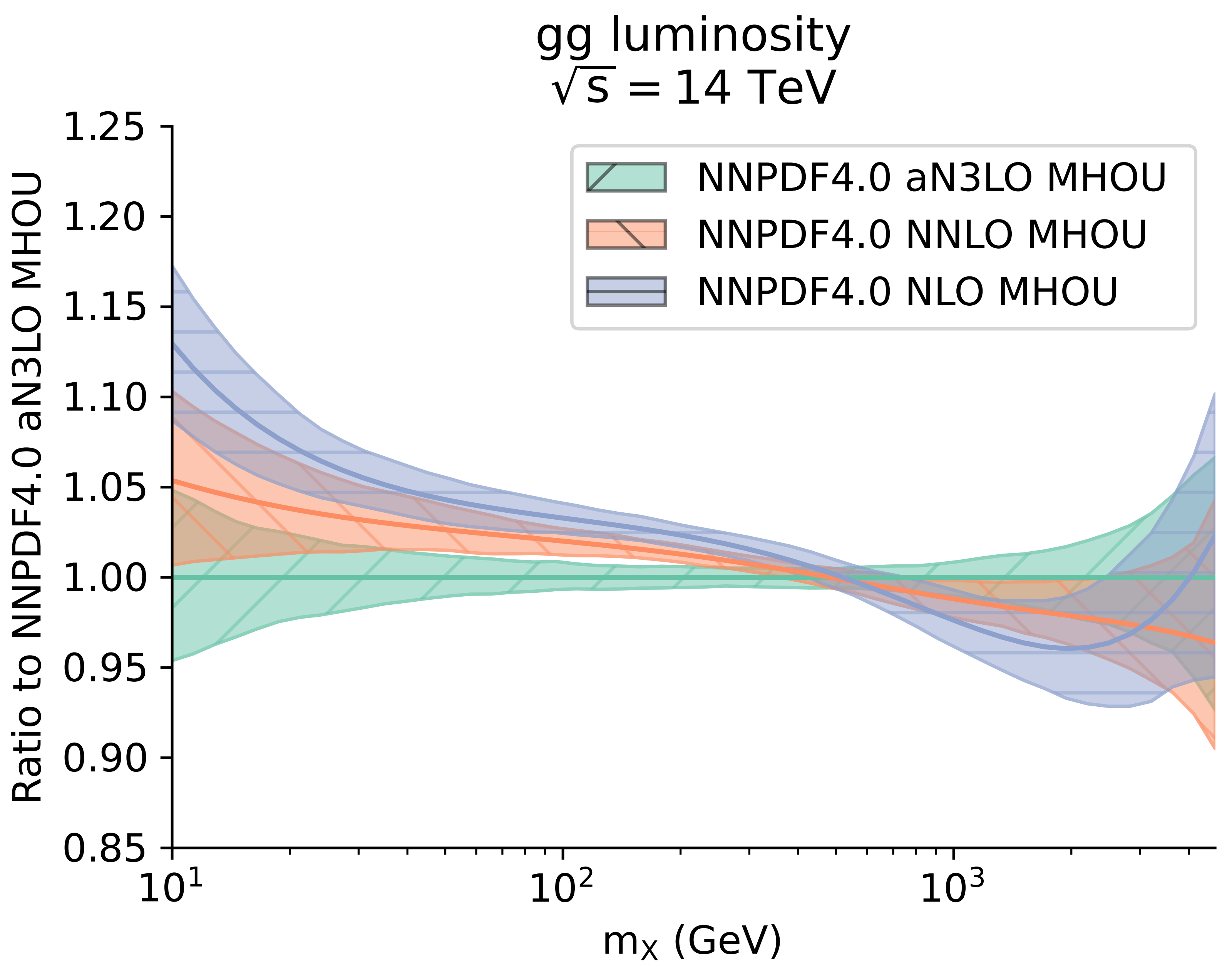




When considering MHOU in the fit the differences are small but compared to the total uncertainty (DY)

Summary

- **Two aN3LO PDF sets** are now available (MSHT and NNPDF)
- NNPDF4.0 aN3LO released **both with and without MHOU**
- **IHOU** are estimated and included in the analysis (different approaches followed by NNPDF and MSHT)
- **Impact of N3LO corrections** found by MSHT and NNPDF seems consistent, with differences which can be traced back to different input splitting functions
- Biggest differences when going from NNLO to aN3LO are observed in the **gluon**



Thank you!

Backup slides

Nonsinglet $P^{(3)}_{ns,\pm}$ $P^{(3)}_{ns,s}$

Nonsinglet splitting functions can be determined with high accuracy

What we know

- 8 moments [JHEP 10 (2017) 041]
- Small-x limit [JHEP 08 (2022) 135]
- Large-x limit [JHEP 10 (2017) 041]
- large-n_f limit, i.e. $\mathcal{O}(n_f^2)$, $\mathcal{O}(n_f^3)$ [Nucl. Phys. B 915 (2017) 335–362]

Our approximation

$$\gamma_{ij}^{(3,0)} + n_f \gamma_{ij}^{(3,1)} + n_f^2 \gamma_{ij}^{(3,2)} + n_f^3 \gamma_{ij}^{(3,3)}$$

$$\gamma_{ij}^{(3)}(N) = \gamma_{ij,n_f}^{(3)}(N) + \gamma_{ij,N\to\infty}^{(3)}(N) + \gamma_{ij,N\to 0}^{(3)}(N) + \tilde{\gamma}_{ij}^{(3)}(N)$$

large-n_f limit — large-x limit — small-x limit — remainder

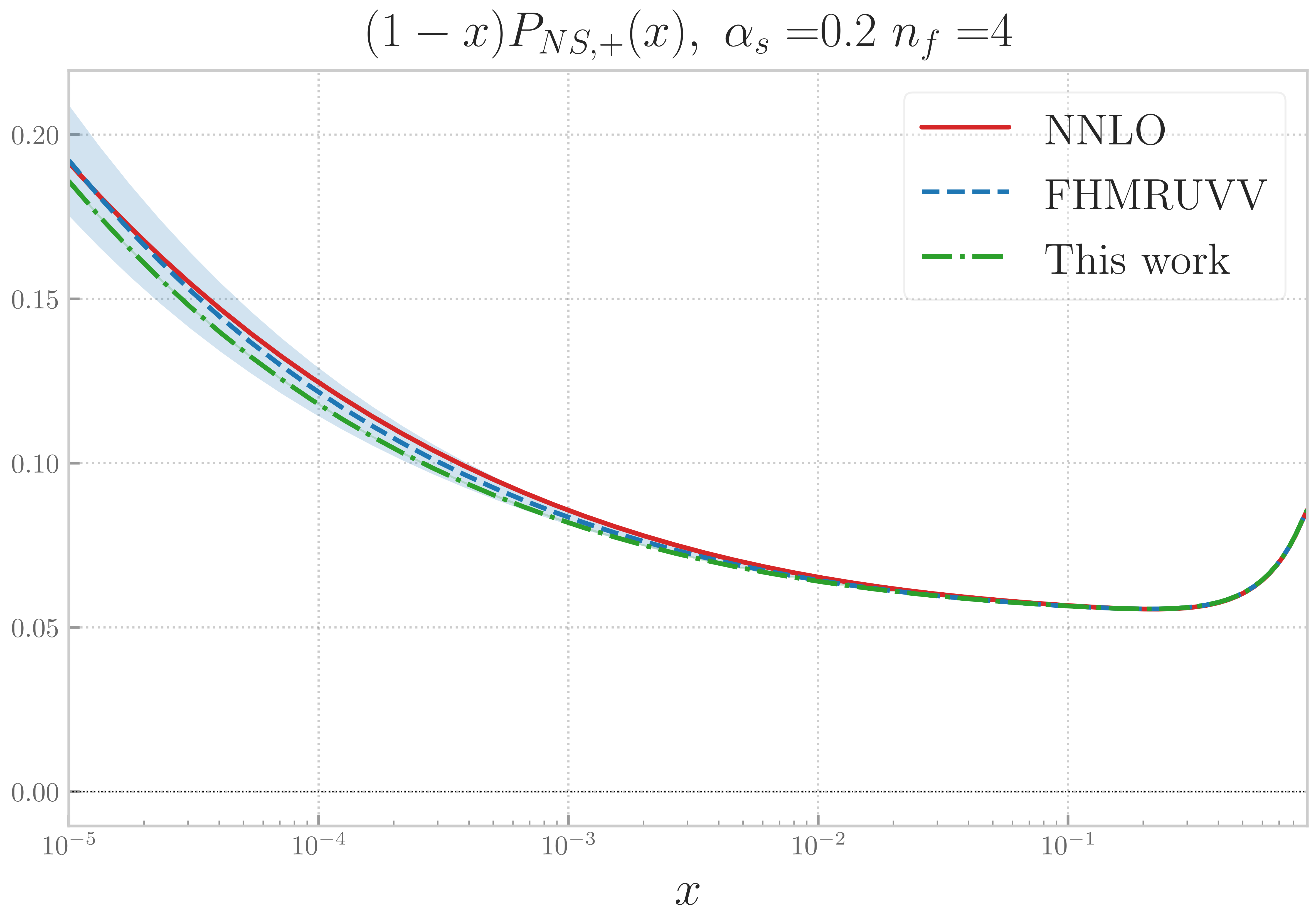
$$A_4 S_1(N) + B_4 + C_4 \frac{S_1(N)}{N} + D_4 \frac{1}{N}$$

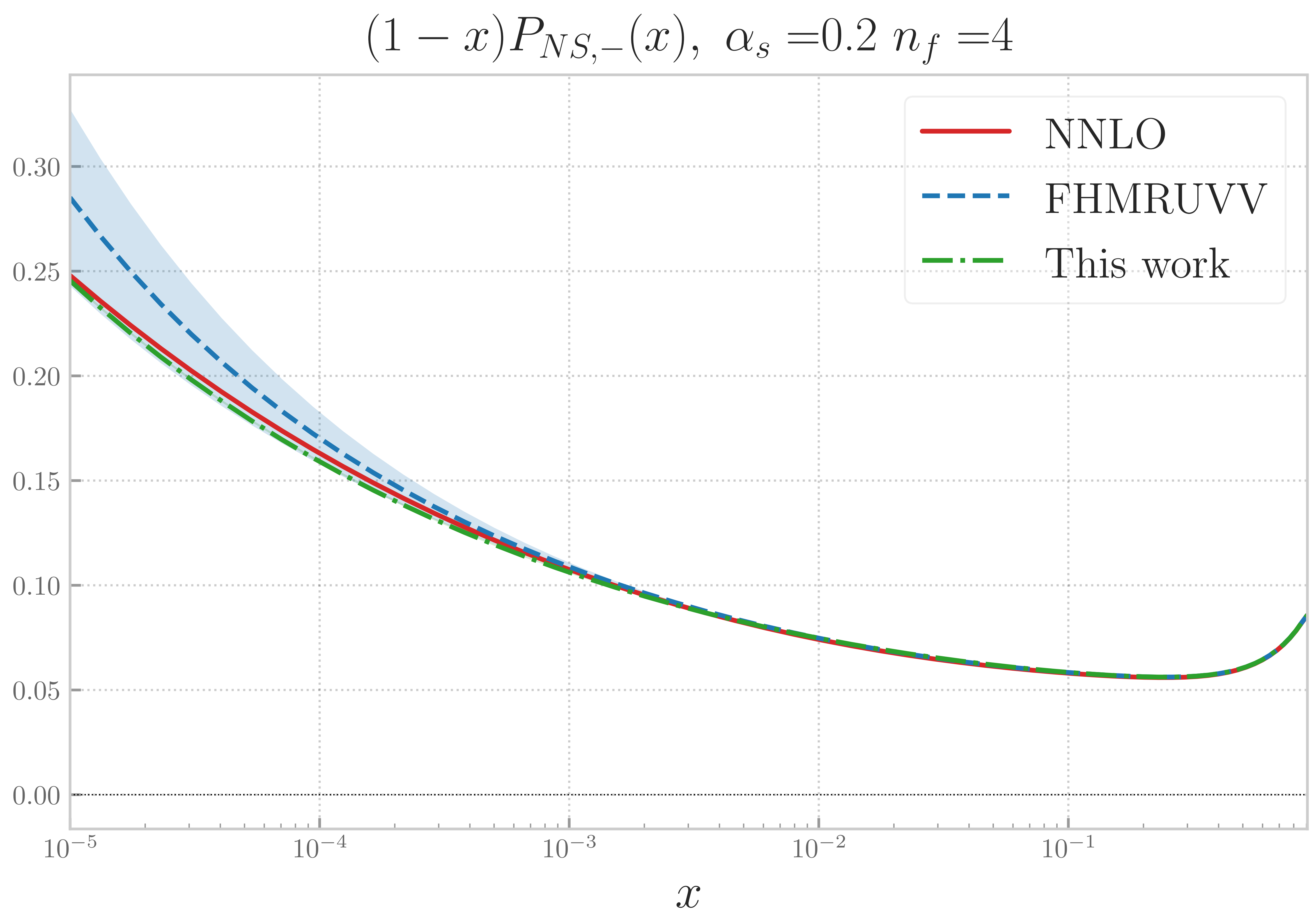
$$\sum_{k=1}^{6} c_{ns}^{k} (-1)^k \frac{k!}{N^{k+1}}$$

Leading unknown contributions (small-N and large-N)

$G_1^{ns,\pm}(N)$	1
$G_2^{ns,\pm}(N)$	$\mathcal{M}[(1-x)\ln(1-x)](N)$
$G_3^{ns,\pm}(N)$	$\mathcal{M}[(1-x)\ln^2(1-x)](N)$
$G_4^{ns,\pm}(N)$	$\mathcal{M}[(1-x)\ln^3(1-x)](N)$
$G_5^{ns,\pm}(N)$	$\frac{S_1(N)}{N^2}$
$G_6^{ns,\pm}(N)$	$\frac{1}{(N+1)^2}$
$G_7^{ns,\pm}(N)$	$\frac{1}{(N+1)^3}$
$G_8^{ns,+}(N)$, $G_8^{ns,-}(N)$	$\frac{1}{(N+2)}$, $\frac{1}{(N+3)}$

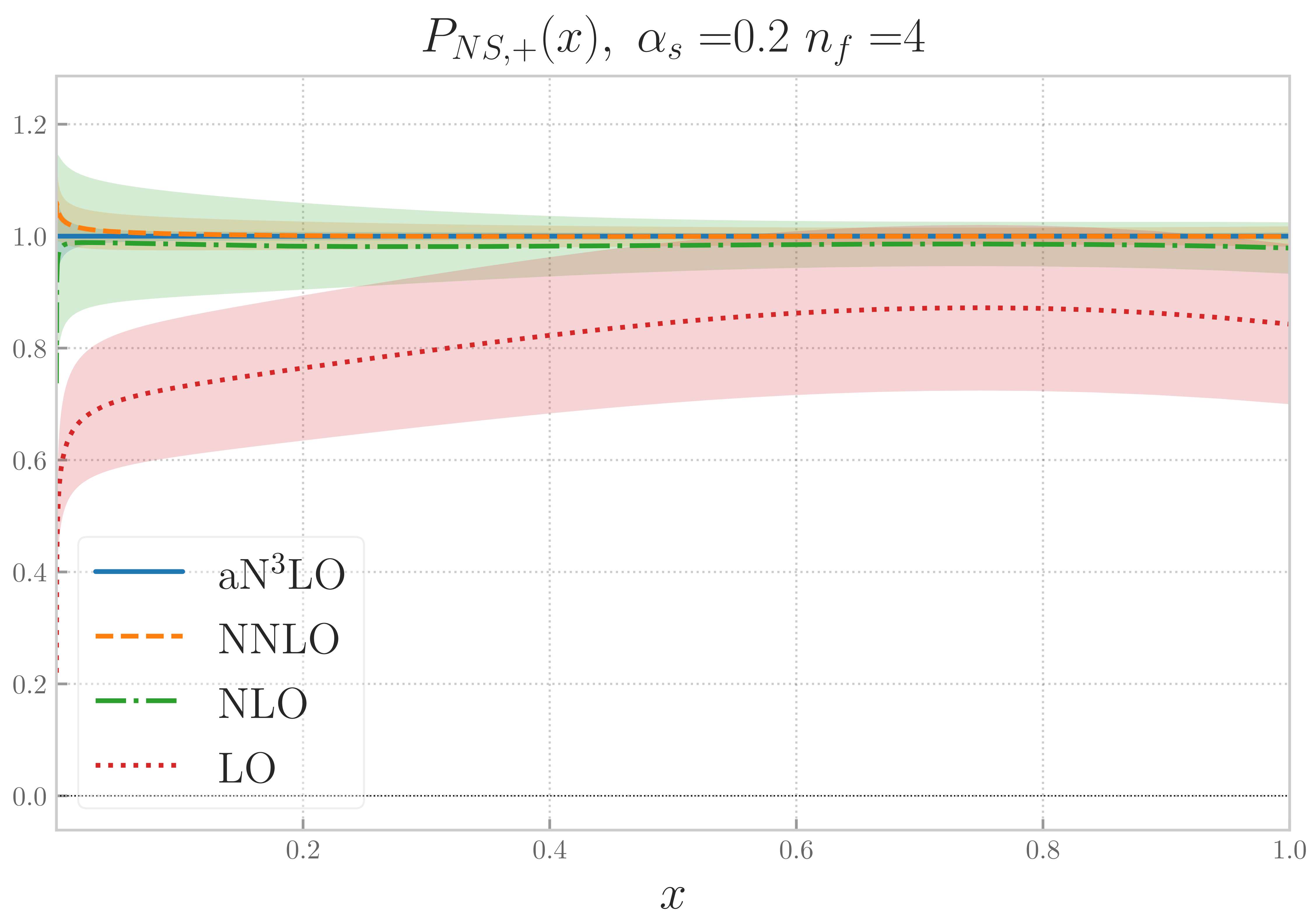
Nonsinglet: comparison to previous approximation

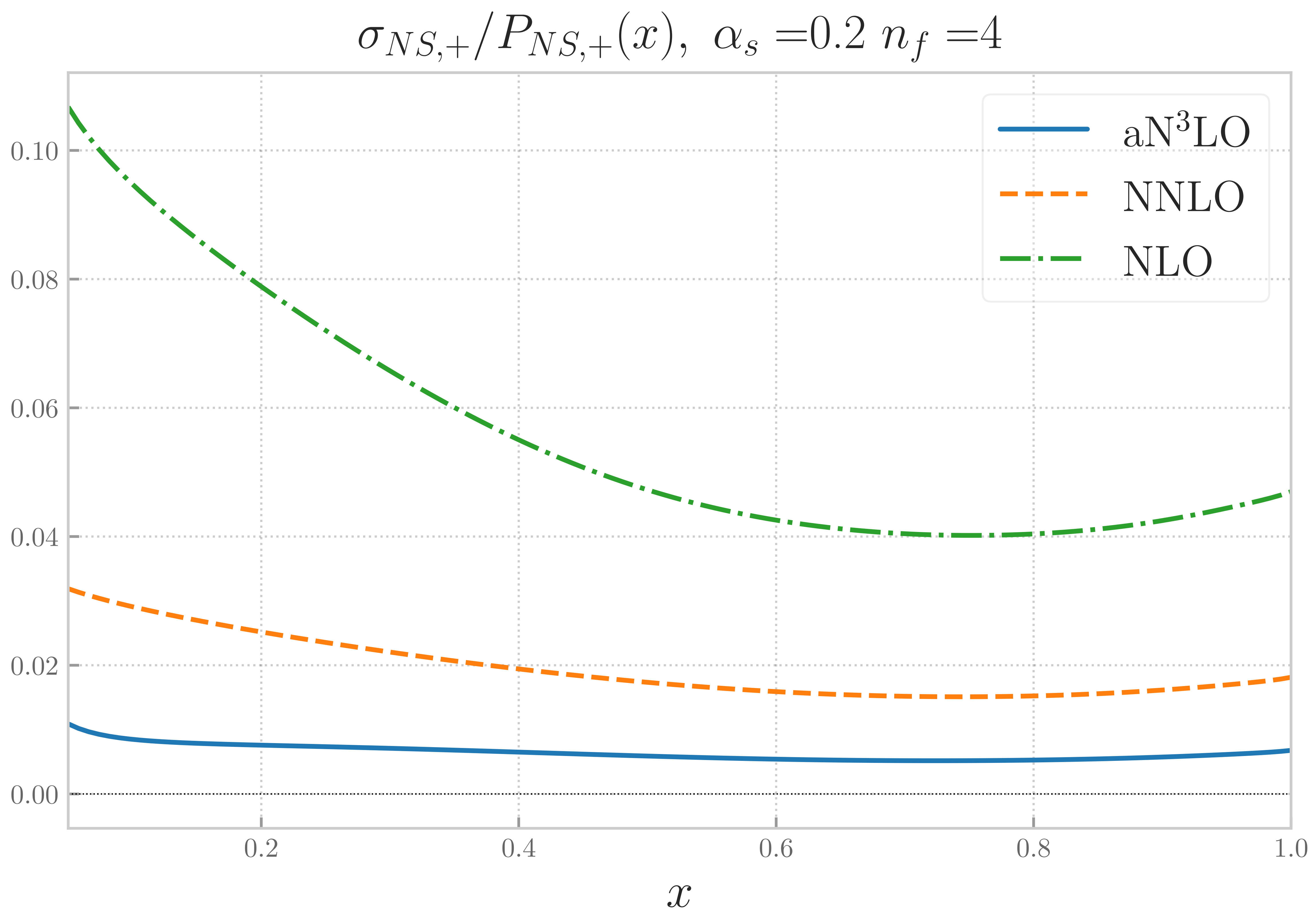




- Compatibility with previous approximation FHMRUVV [JHEP 10 (2017) 041]
- Additional small-x info included in current approximation

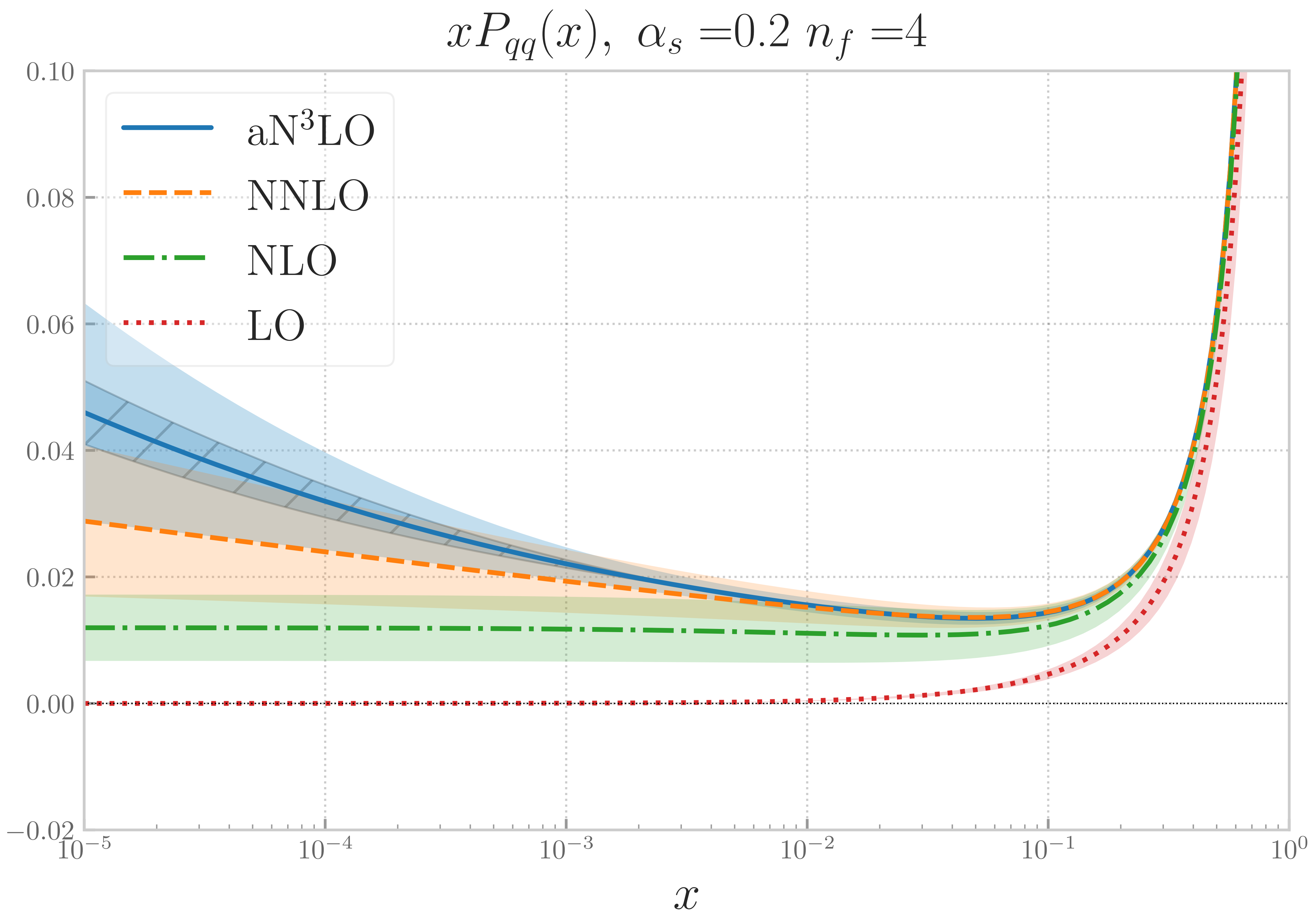
Nonsinglet: LO, NLO, NNLO, aN3LO with MHOU

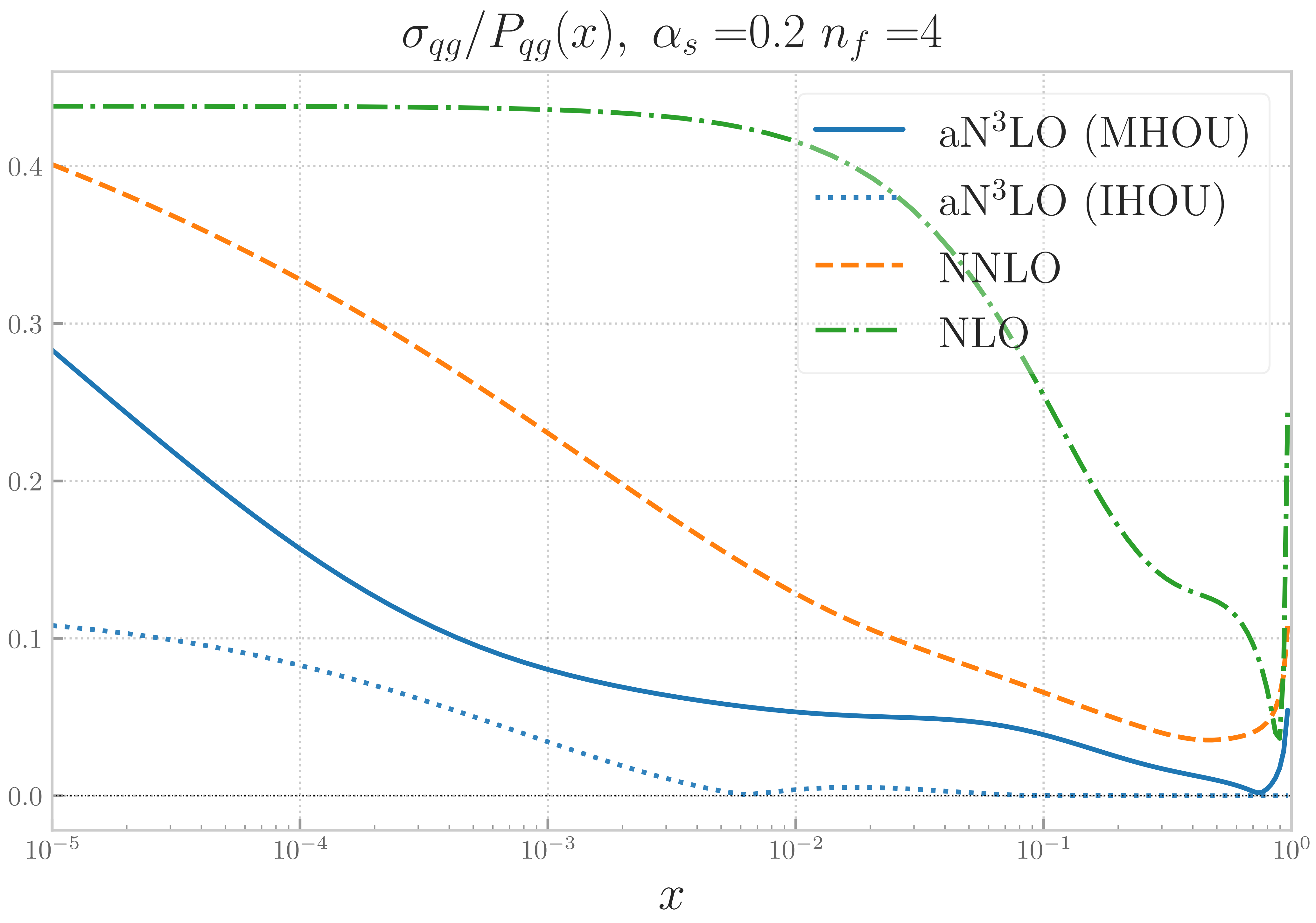




- Good perturbative convergence
- Except at small-x (where nonsiglet sector is subdominant anyway) N3LO corrections are negligible
- Current approximation can be considered exact (no IHOU) with negligible MHOU

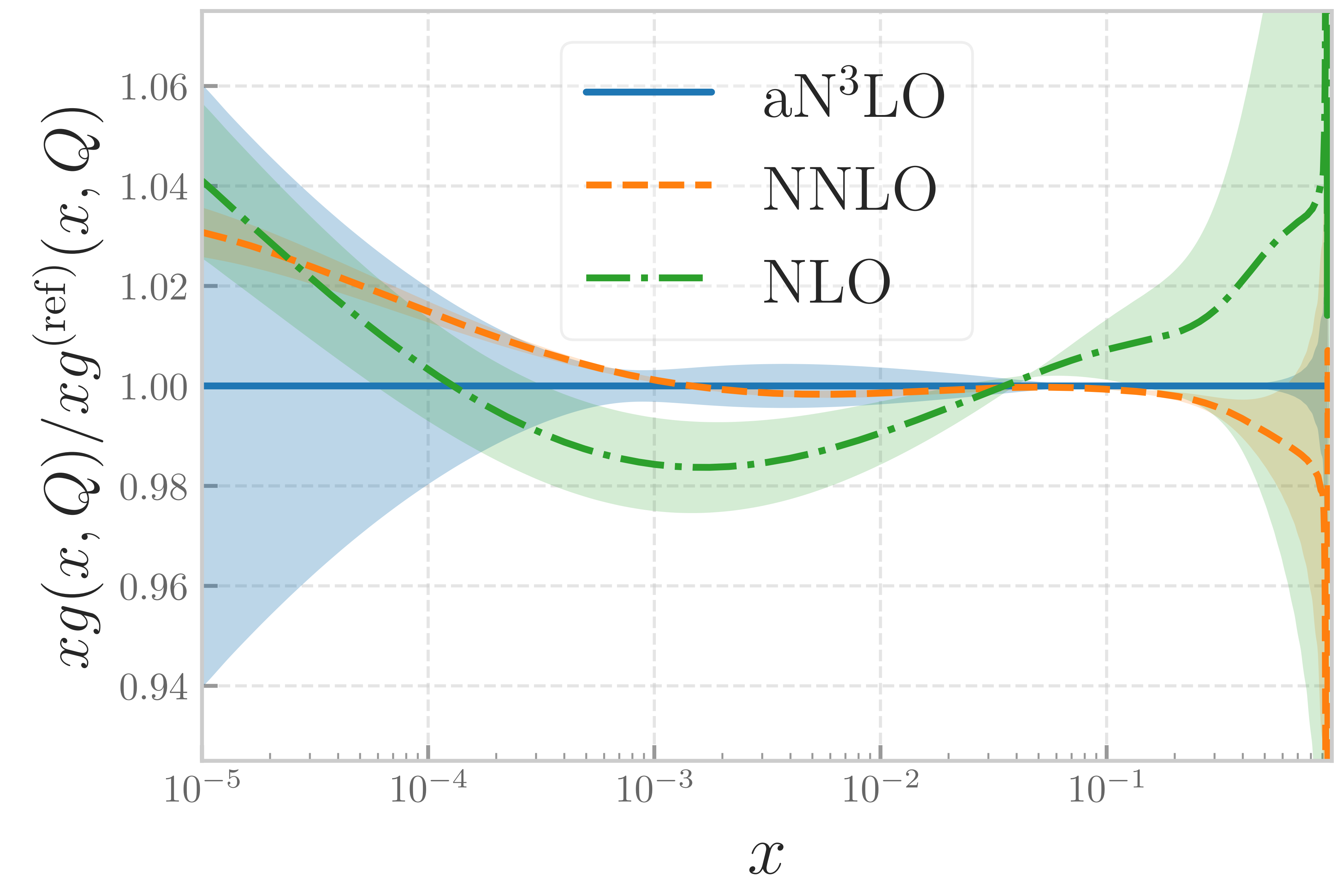
singlet: small-x

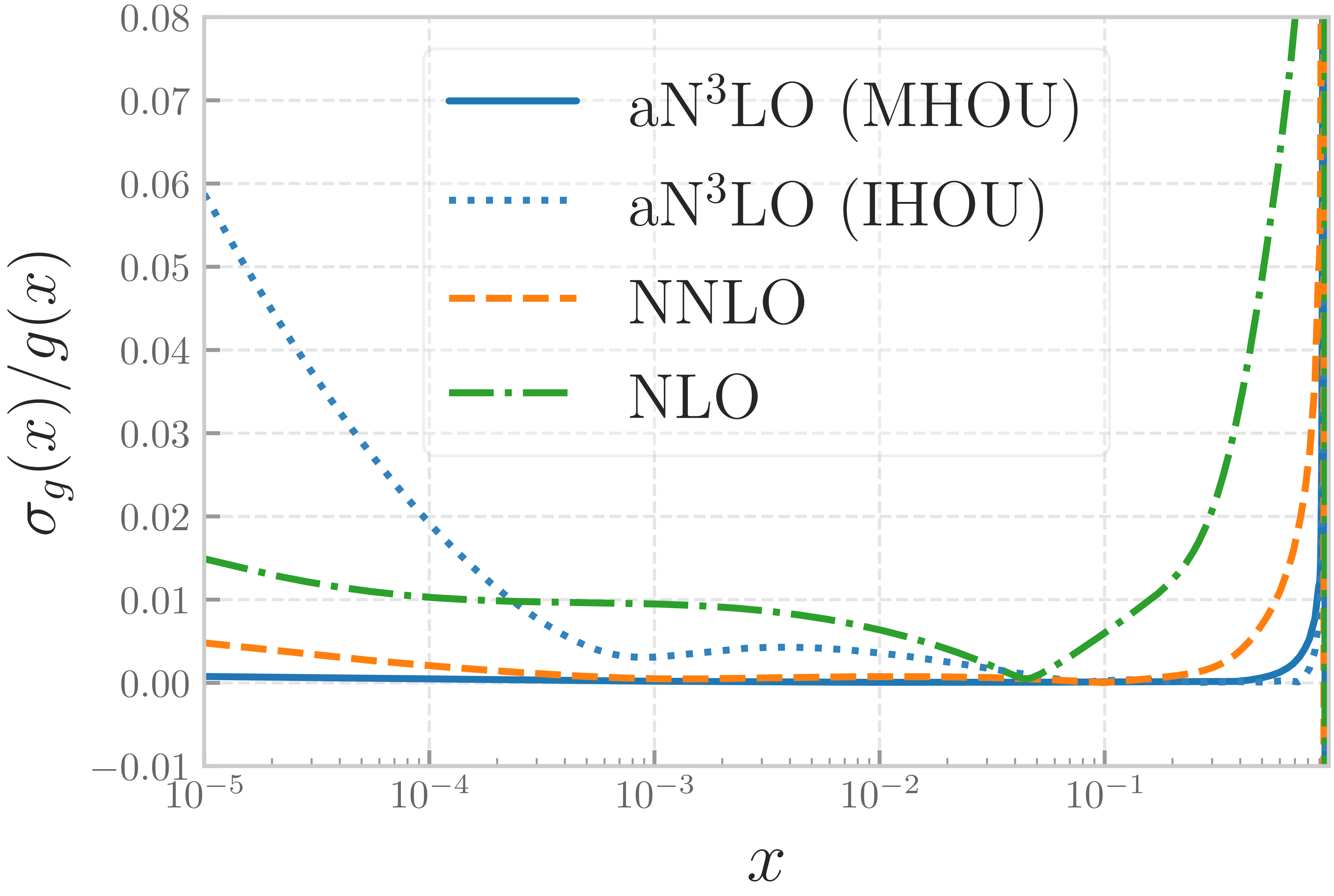




- aN3LO and NNLO result agree within uncertainties
- aN3LO uncertainties are sizeable
- MHOU (IHOU) dominate the quark (gluon) sector

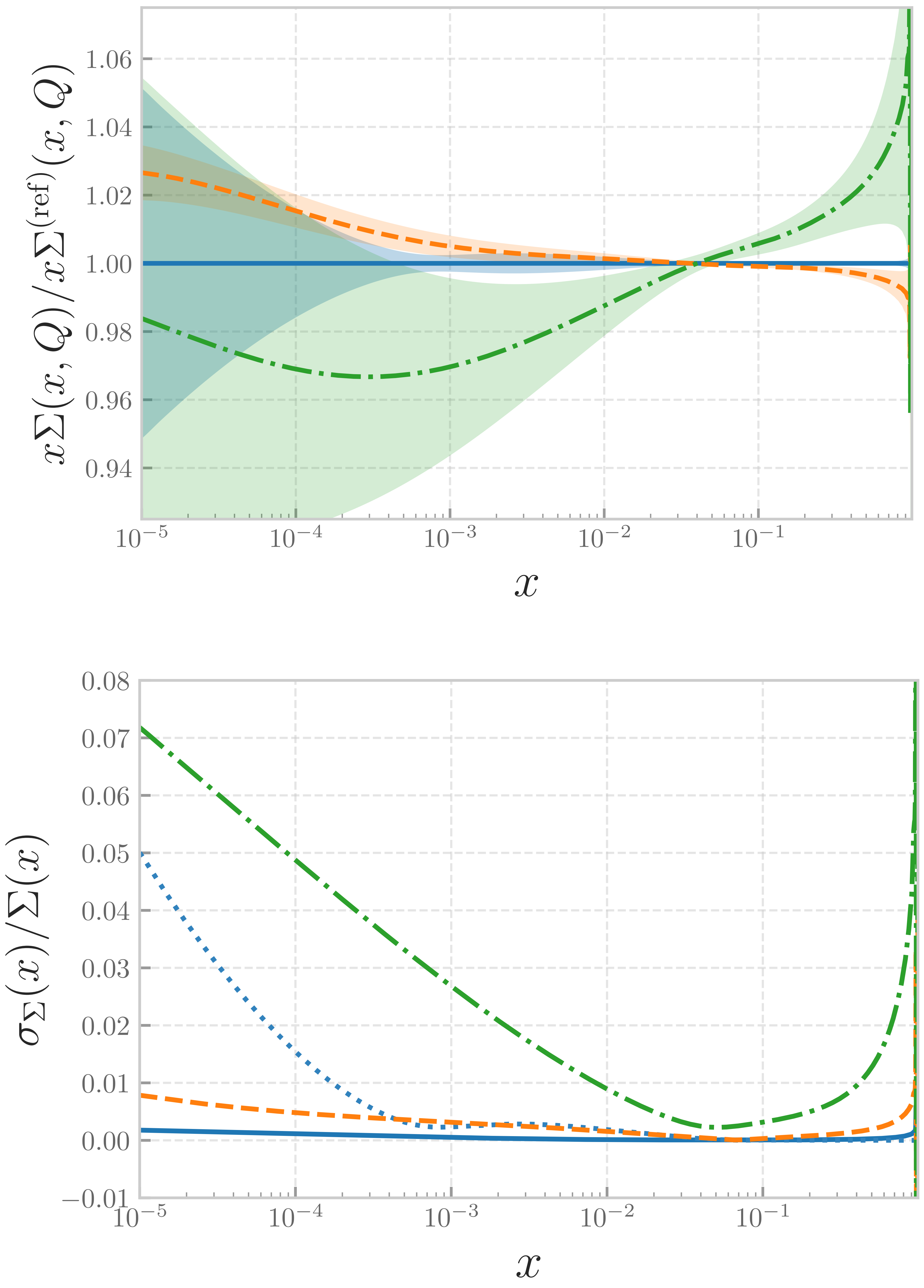
aN3LO evolution





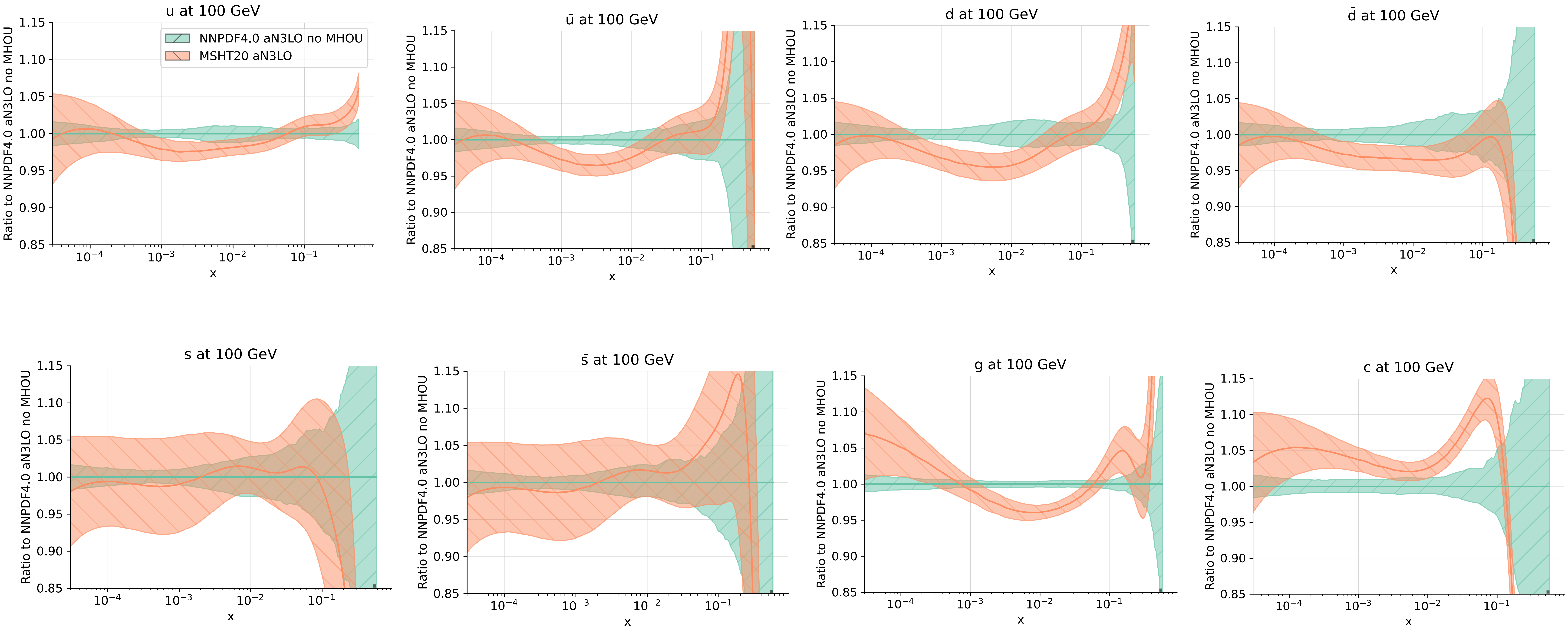
- comparison between NLO, NNLO and aN3lO evolution starting from NNPDF4.0 NNLO at 1.65 GeV and evolving up to 100 Gev
- Almost no difference between aN3LO and NNLO for nonsinglet PDFs
- For $x < 10^{-3}$ singlet evolution is weaker at aN3LO

aN3LO evolution



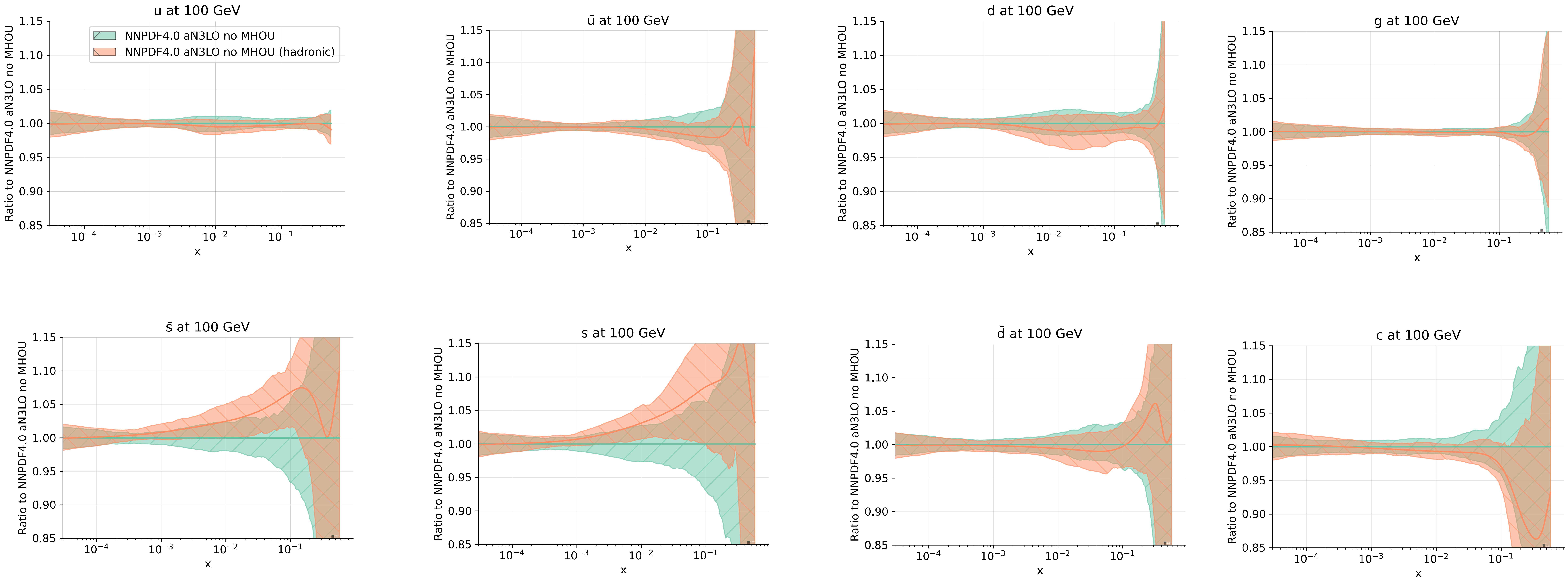
- comparison between NLO, NNLO and aN3lO evolution starting from NNPDF4.0 NNLO at 1.65 GeV and evolving up to 100 Gev
- Almost no difference between aN3LO and NNLO for nonsinglet PDFs
- For $x < 10^{-3}$ singlet evolution is weaker at aN3LO

Comparison with MSHT



- Differences similar to those observed at NNLO
- Biggest differences between charm and gluon

Impact of available N3LO corrections for hadronic data



Photons in the proton

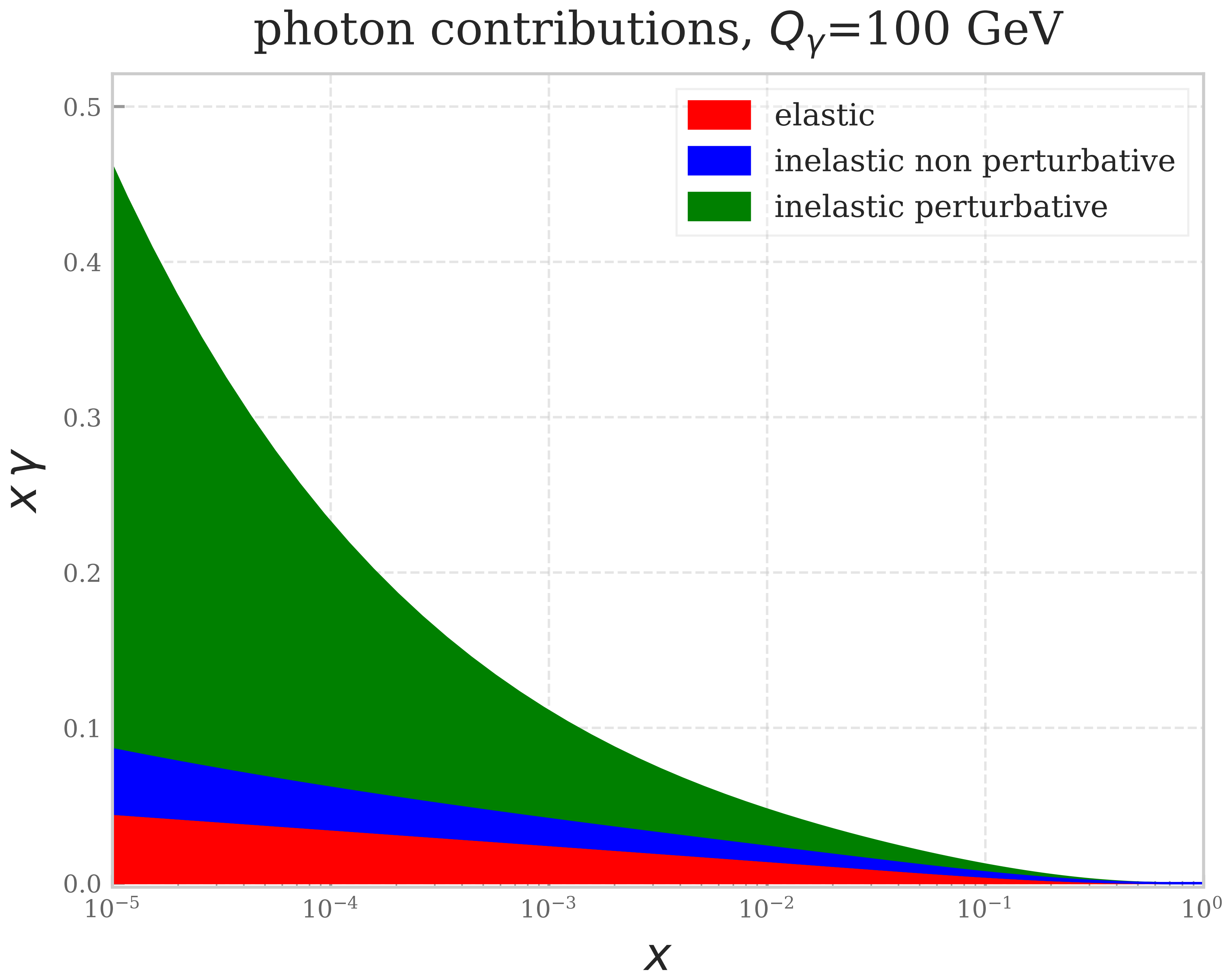
- New NLO and NNLO sets supplementing with a photon PDF the pure QCD PDF set

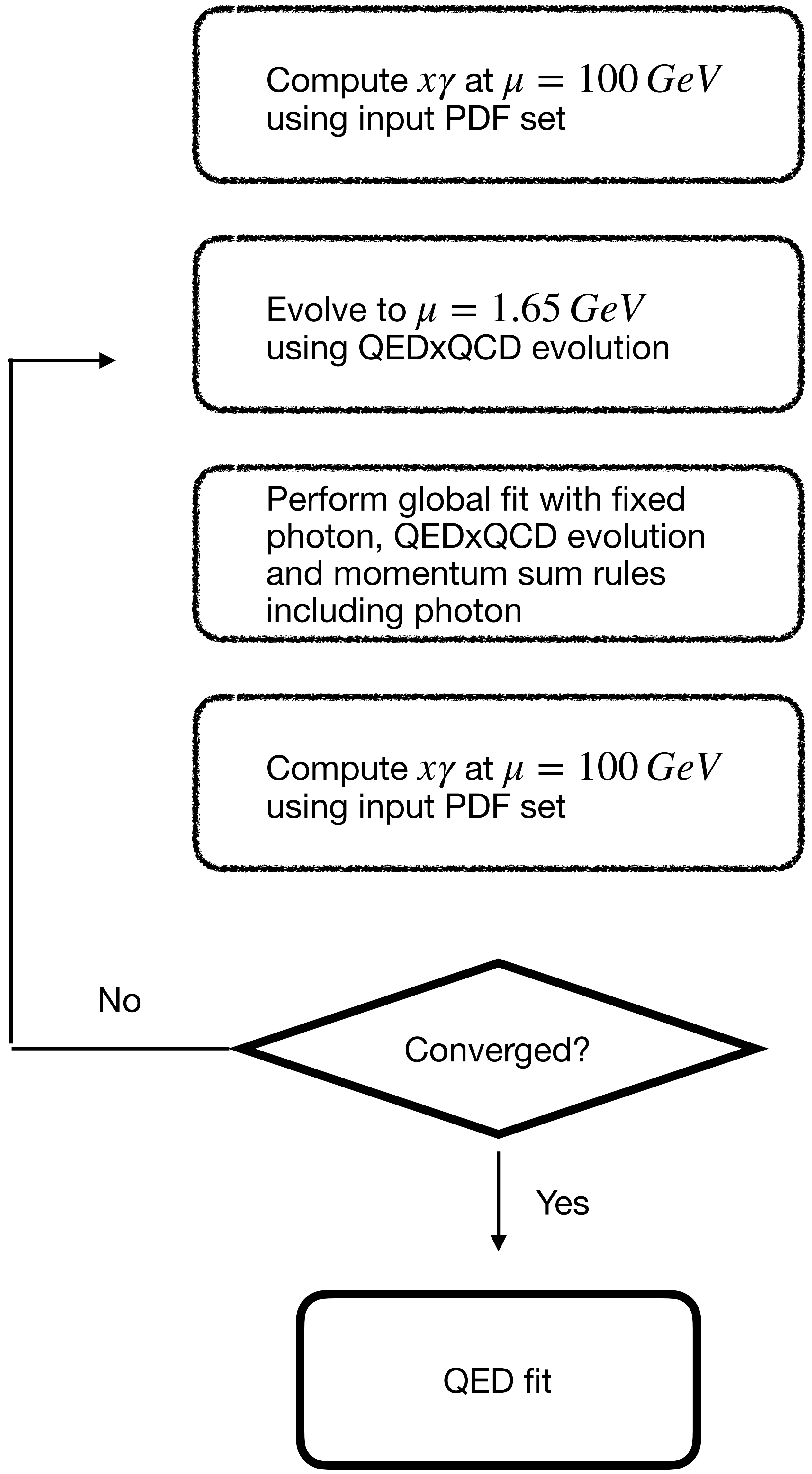
  - combined QEDxQCD evolution

  - photon PDF determined using the LuxQED formalism

$$x\gamma\left(x,\mu^2\right) = \frac{2}{a_{em}(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{m_p^2x^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} a_{em}^2(Q^2)\left[\left(zP_{\gamma q(z)} + \frac{2x^2m_p^2}{Q^2}\right)F_2 - z^2F_L\right] - a_{em}^2(\mu^2)z^2F_2\right\}$$

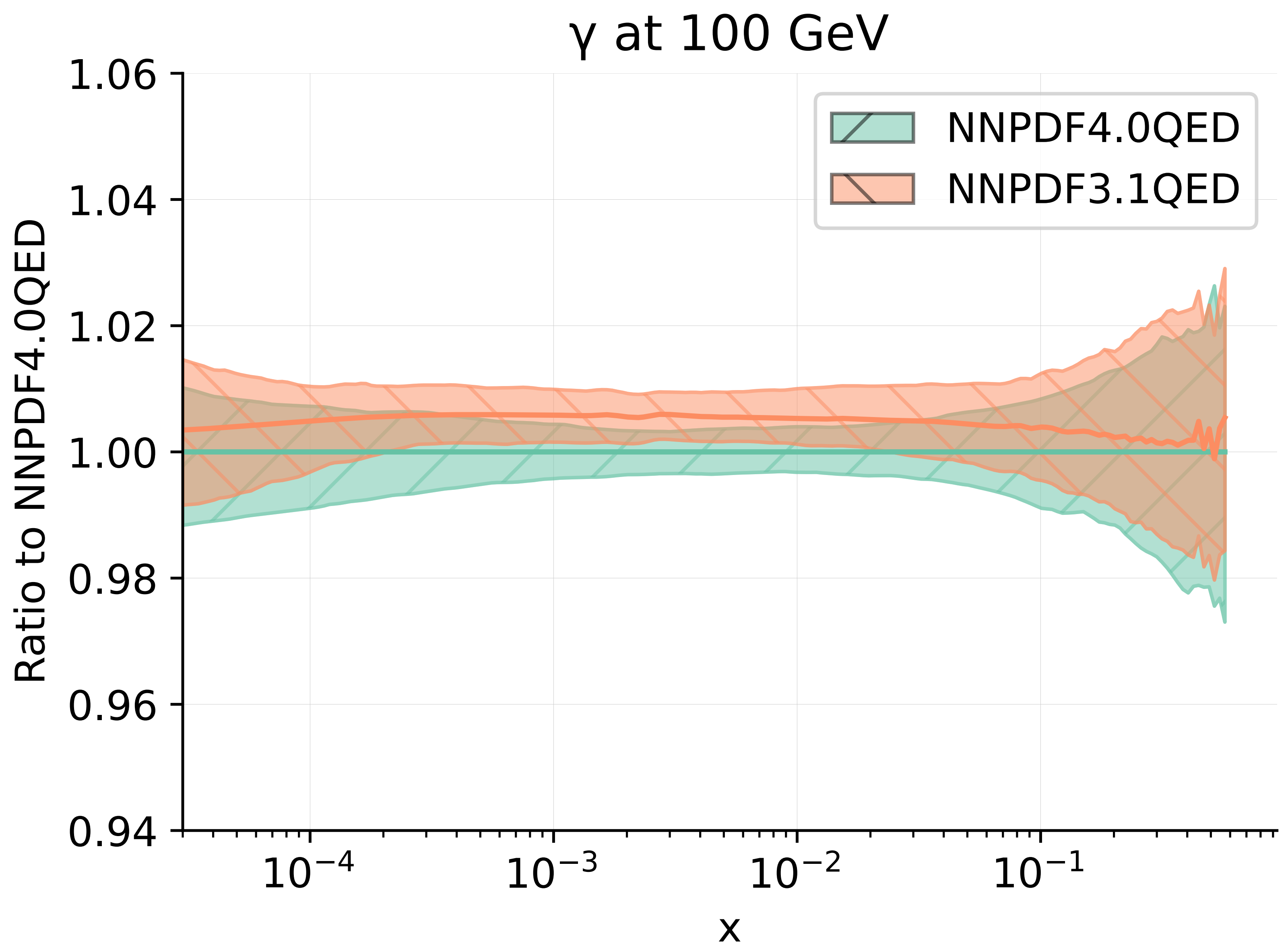
  - pure QCD for theory predictions. In particular no photon induced contributions (future work)

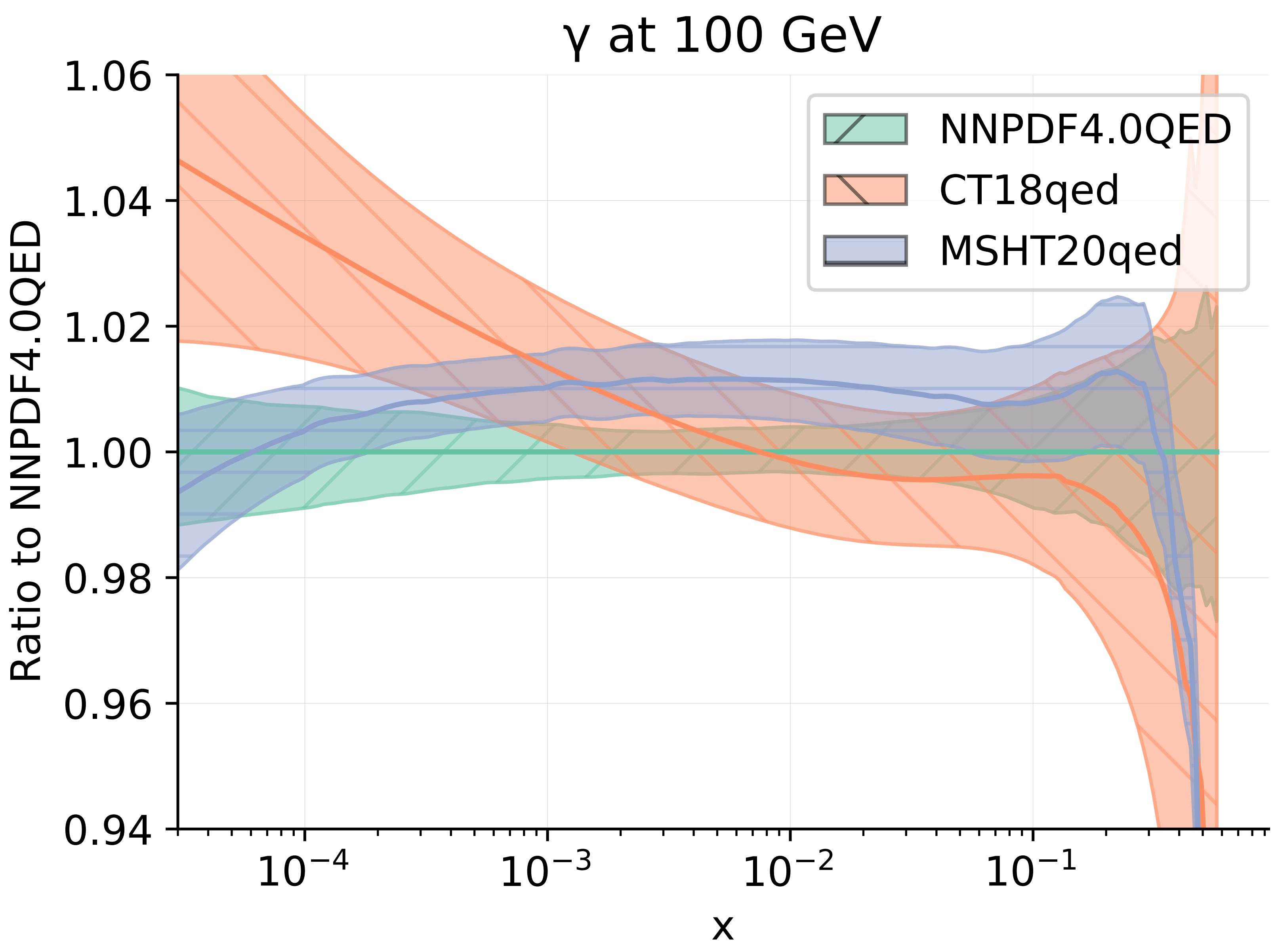


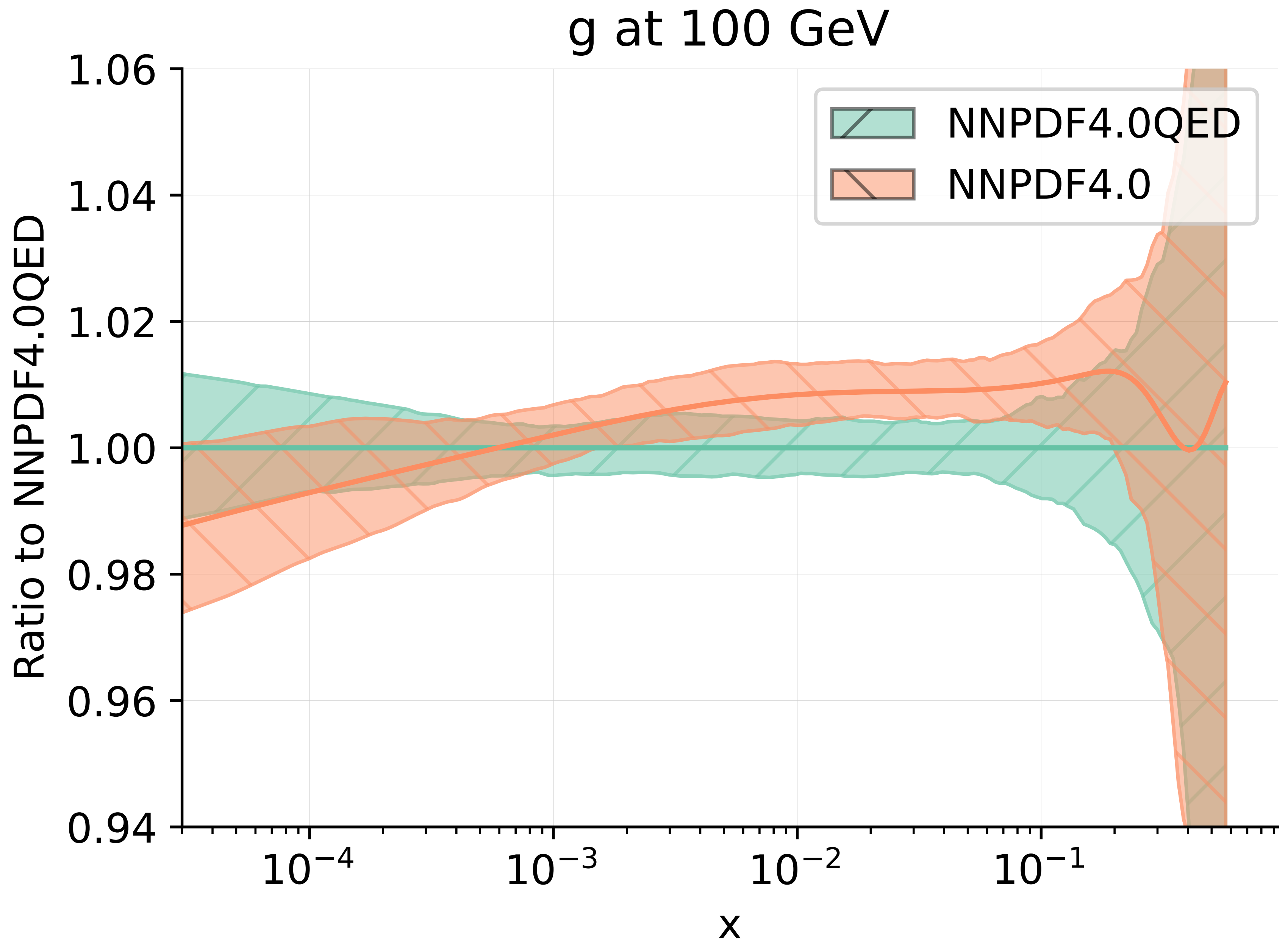


Good agreement with previous NNPDF determination…

…and with determinations by other groups



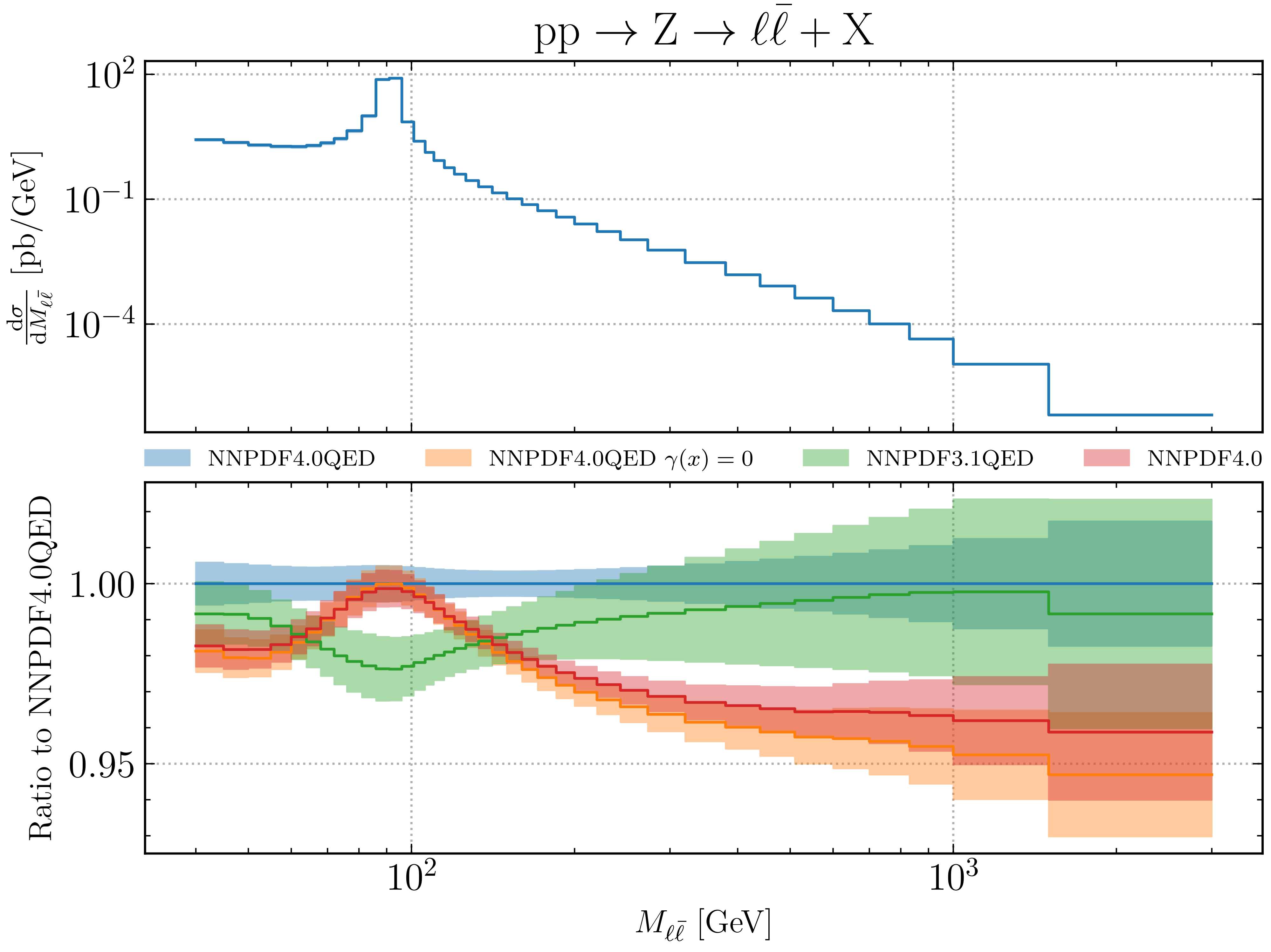




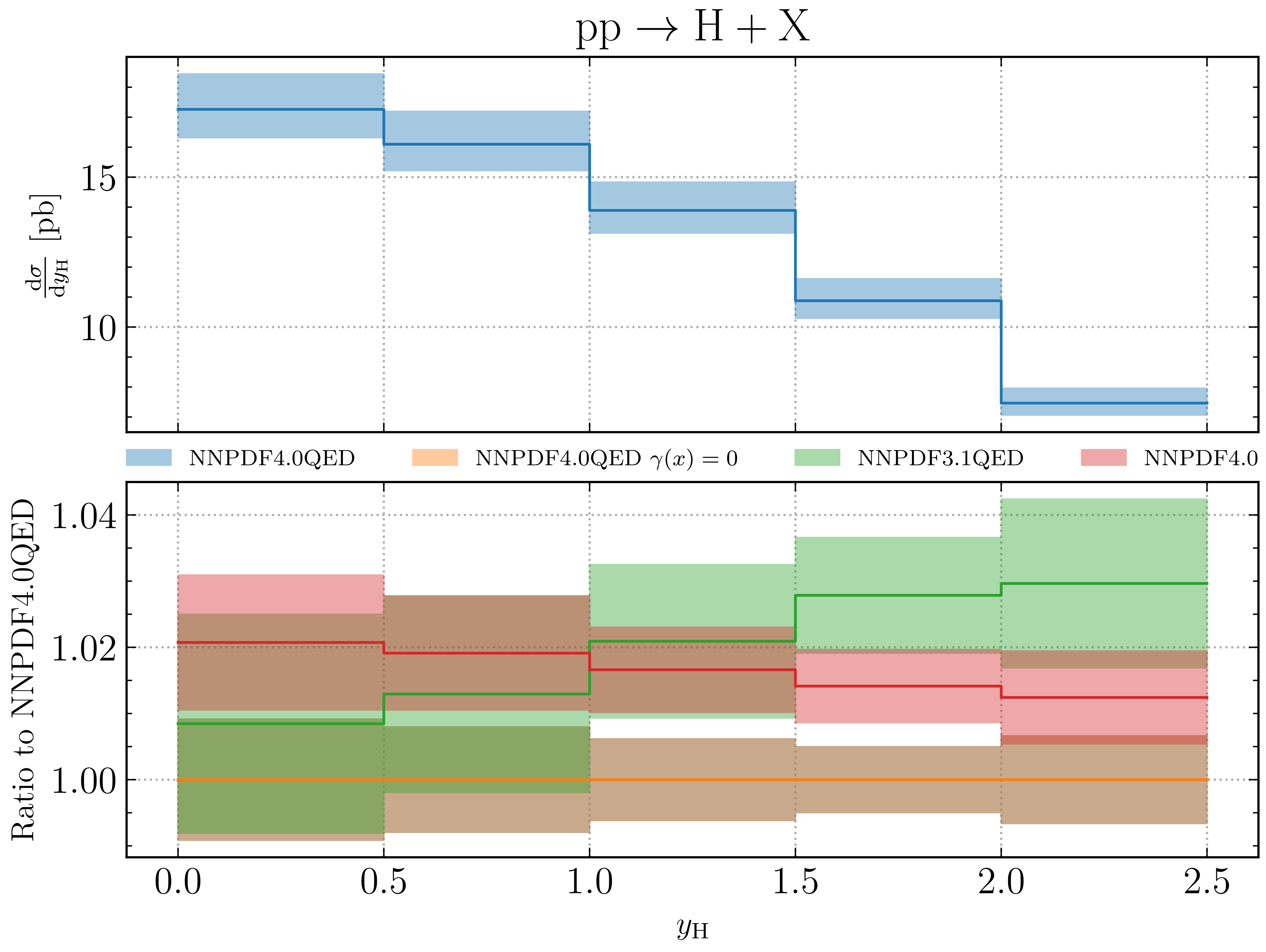
The impact of the photon on the other PDFs is very moderate. Largest effects are seen in the gluon (suppressed according to momentum sum rule)

Implications for LHC phenomenology (only NLO accuracy)

NC DY: Enhancement of cross section due to photon-induced contributions (up to $\sim 5\,\%$)



Higgs production in gluon fusion: Suppression due to suppression of gluon PDF (up to $\sim 2\,\%$) and unimportance of photon induced contributions



QED corrections important for precision phenomenology at the percent level