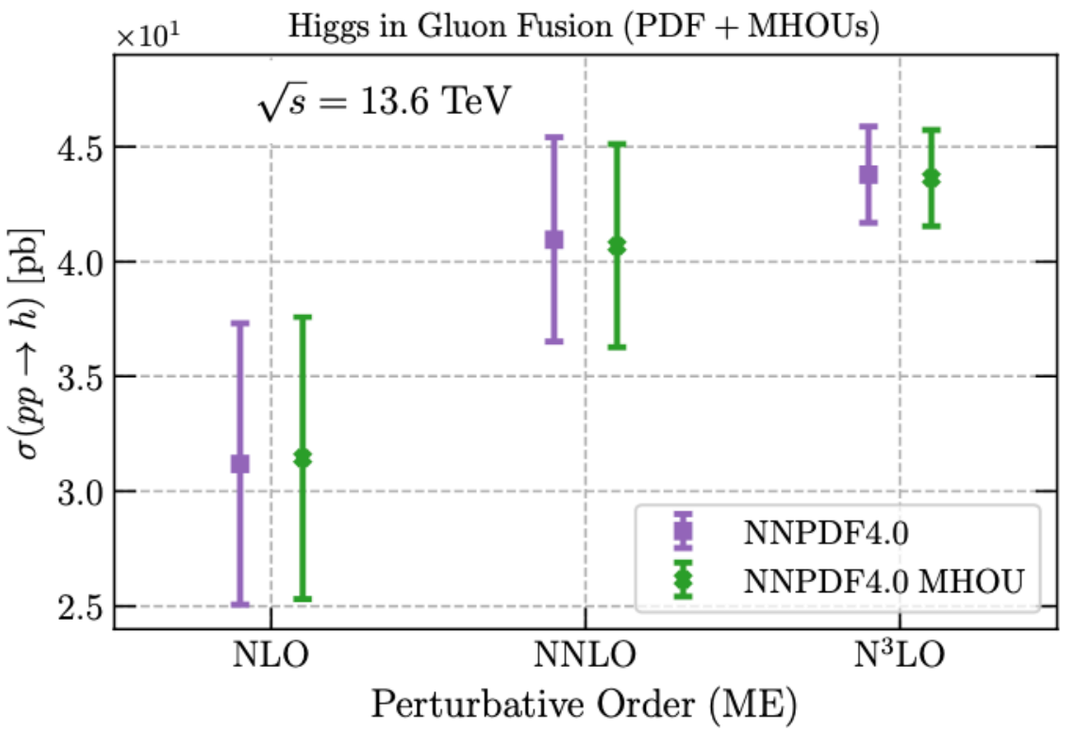
NNPDF progress and the path to N³LO PDFs

Juan Rojo, VU Amsterdam & Nikhef



DIS2024, Grenoble, 9th April 2024

Motivation I

Reducing PDF uncertainties entering LHC predictions requires an **in-depth understanding of the differences and similarities between PDF analysis**

ATLAS strong coupling extraction from Z p_T data at 8 TeV

	PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
baseline	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

$$\Delta_{\mathrm{PDF}}\left(\mathrm{MSHT20\ only}\right) = 0.34\,\%$$

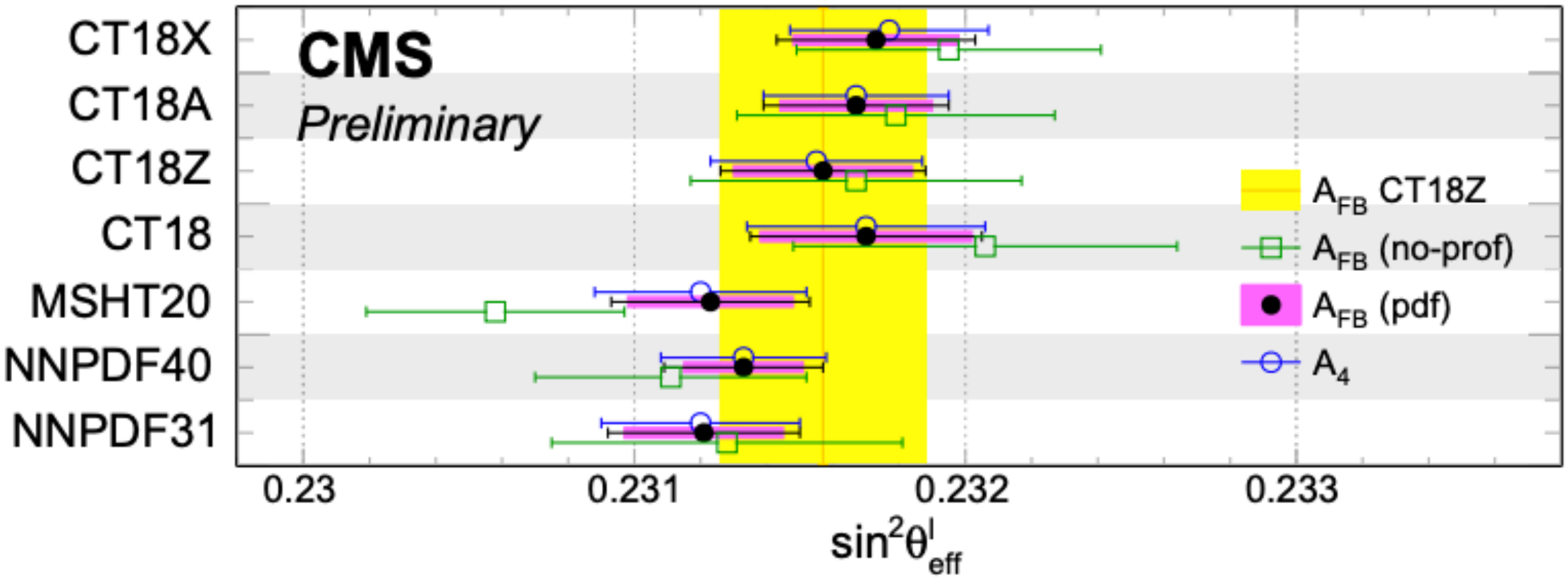
$$\Delta_{\mathrm{PDF}}\left(\mathrm{NNPDF4.0} - \mathrm{CT18A}\right) = 1.6\,\%$$

What is the ``true PDF uncertainty'' that should be associated to this measurement?

Motivation II

Reducing PDF uncertainties entering LHC predictions requires an **in-depth understanding of the differences and similarities between PDF analysis**

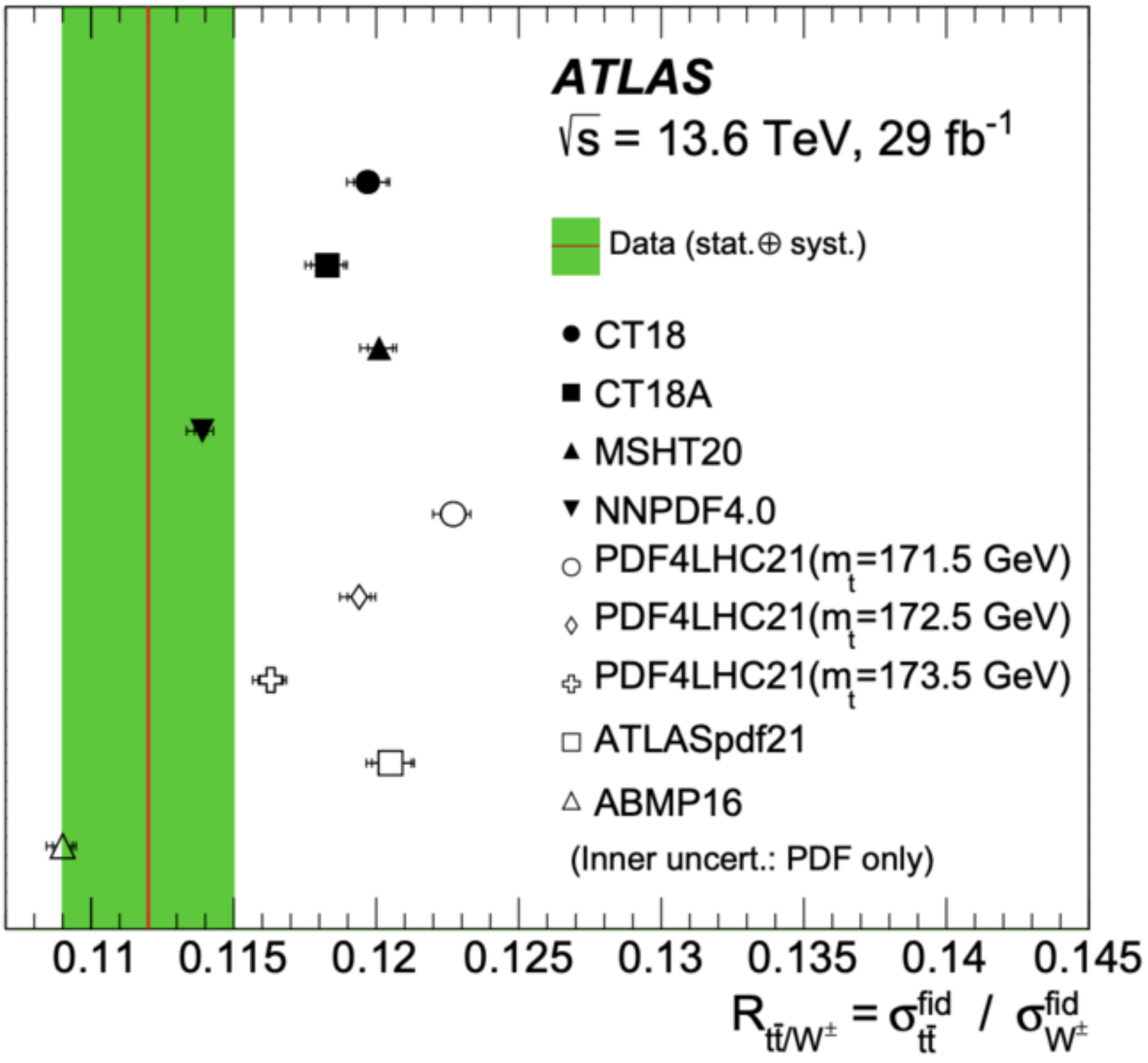
CMS determination of the weak mixing angle at 13 TeV



What is the ``true PDF uncertainty'' that should be associated to this measurement?

Is **in-situ profiling of PDFs** always justified? Back-reaction in other experiments?

Motivation III



- LHC precision measurements provide **discrimination power …**

- … but only their **combination into a consistent global analysis** can provide a coherent picture of the overall data vs theory comparison

- The **interpretation of precision LHC measurements** is a challenging effort pushing the limits of both theory calculations and methodological approaches

demands strong cross-talk between theory and experiment & dedicated benchmark exercises

NNPDF Timeline

NNPDF timescale

☑ Sep 2021: **NNPDF4.0 (paper & code)**

☑ Sept 2022: **PDFs & BSM searches** (A_{FB} high-mass)

☑ Aug 2022: **Intrinsic charm**

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☑ Nov 2023: **IC**

asymmetry study

☑ Feb 2024: NNPDF4.0

aN3LO

☑ Jan 2024: NNPDF4.0

MHOUs & QED

NNPDF timescale

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📌 **WIP**: Implications of NNPDF4.0 for LHC processes

📌 **WIP**: NNPDF4.0 aN3LO & QED & MHOU

📌 **WIP**: NNPDF4.0 for MC event generators

📌 **WIP**: Towards NNPDF4.1

NNPDF timescale

- Beyond neural networks: PDFs from Bayesian inference
- Improved ML hyper-parameter optimisation from parallel replica training on GPUs
- Fixed functional forms for Hessian fits in NNPDF
- Determination of strong coupling at aN^{3}LO
- Determination of higher twist corrections
- Updated NNPDF polarised fits and EIC projections
- ……..

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Many new results presented here at DIS2024!

- **WIP**: Implications of NNPDF4.0 for LHC processes
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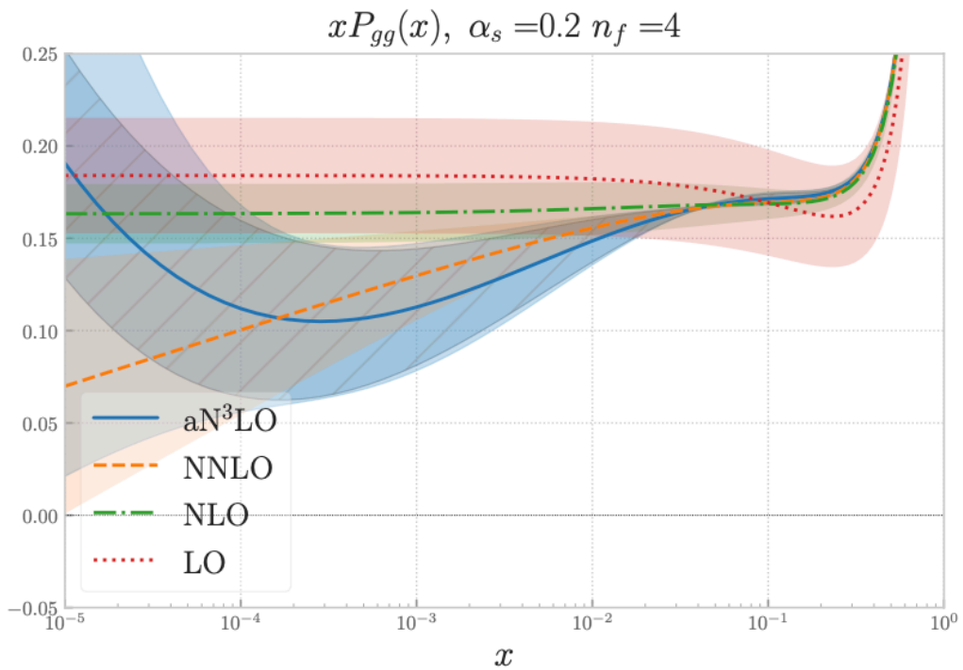
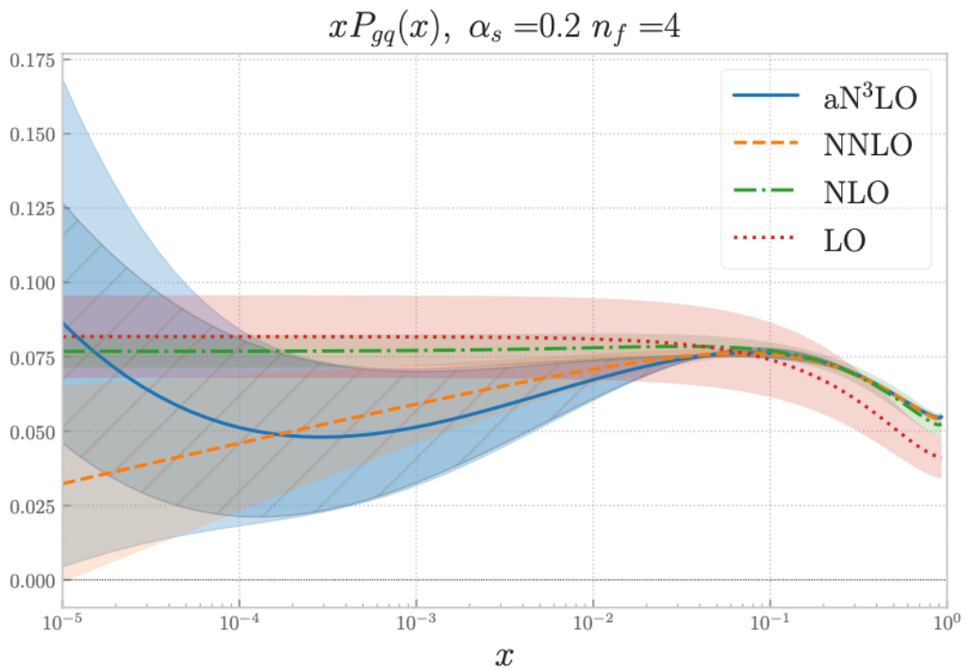
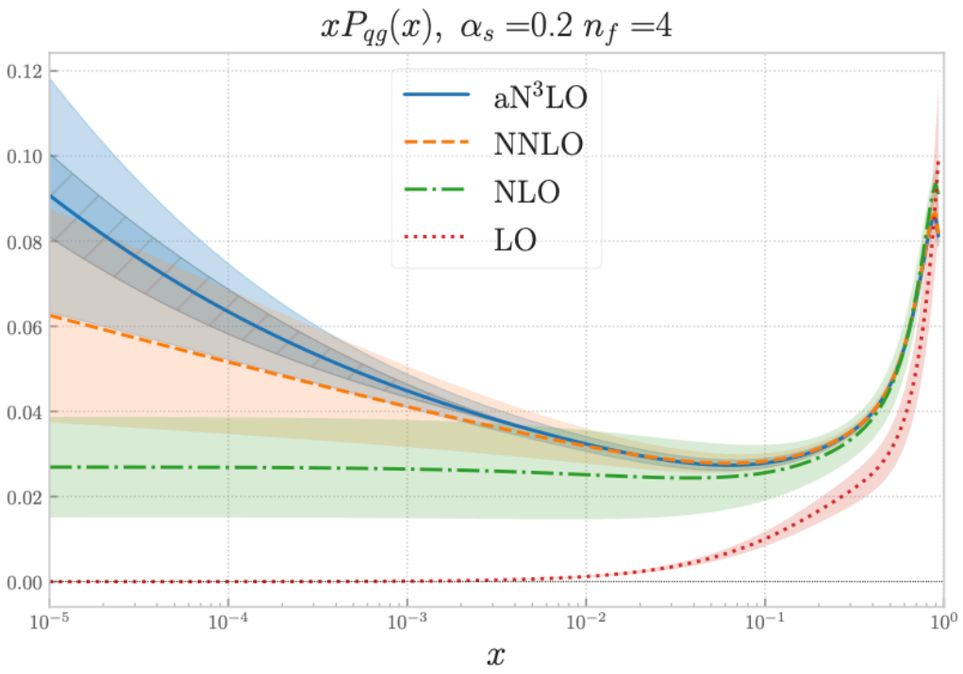
The Path to PDFs at N^{3}LO

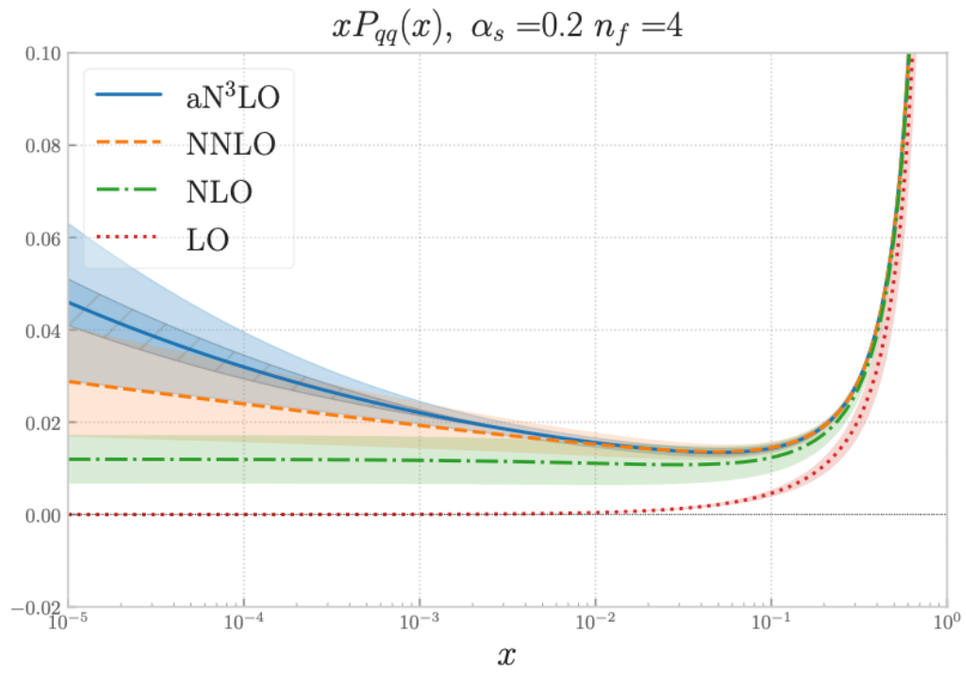
aN³LO splitting functions

- Approximate parametrisation for the N³LO splitting functions satisfying known **exact results and limits**









LO, NLO, NNLO:
MHOU (μ_F)

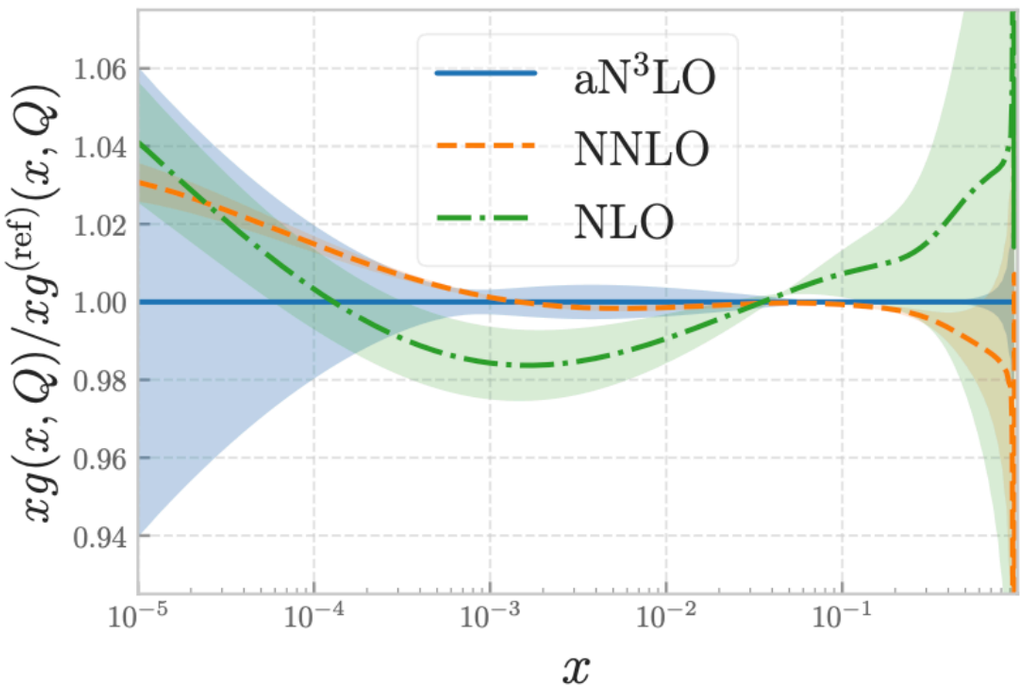
N³LO: **MHOU (μ_F)**
+ IHOUs (dark)

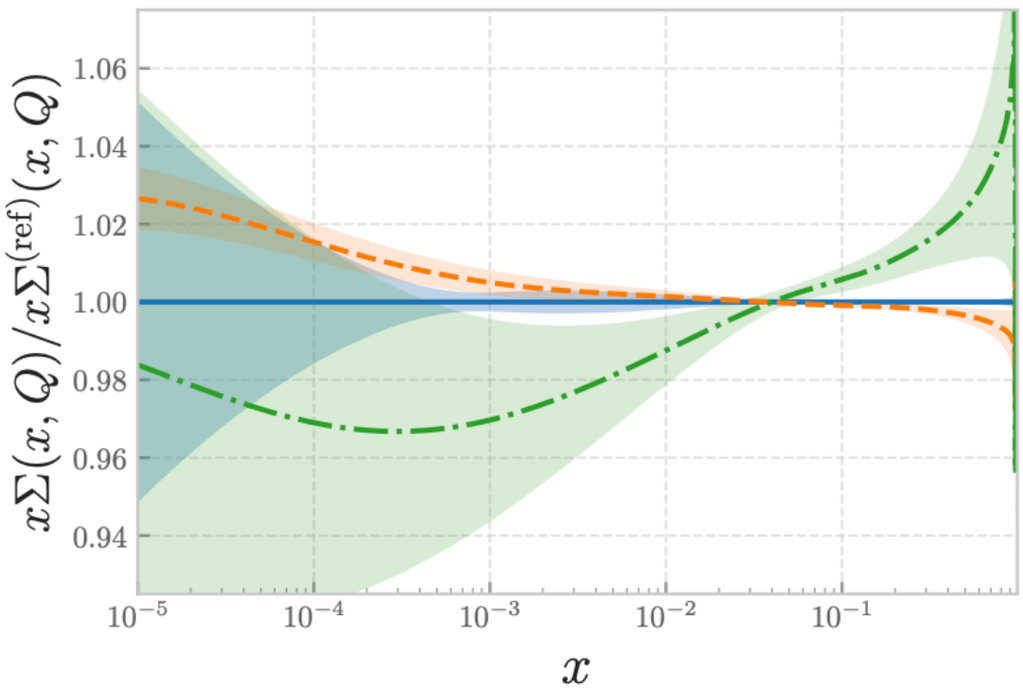
Estimate **Incomplete Higher Order Uncertainties** (IHOUs) by varying interpolating functions connecting known limits

Good perturbative consistency within uncertainties

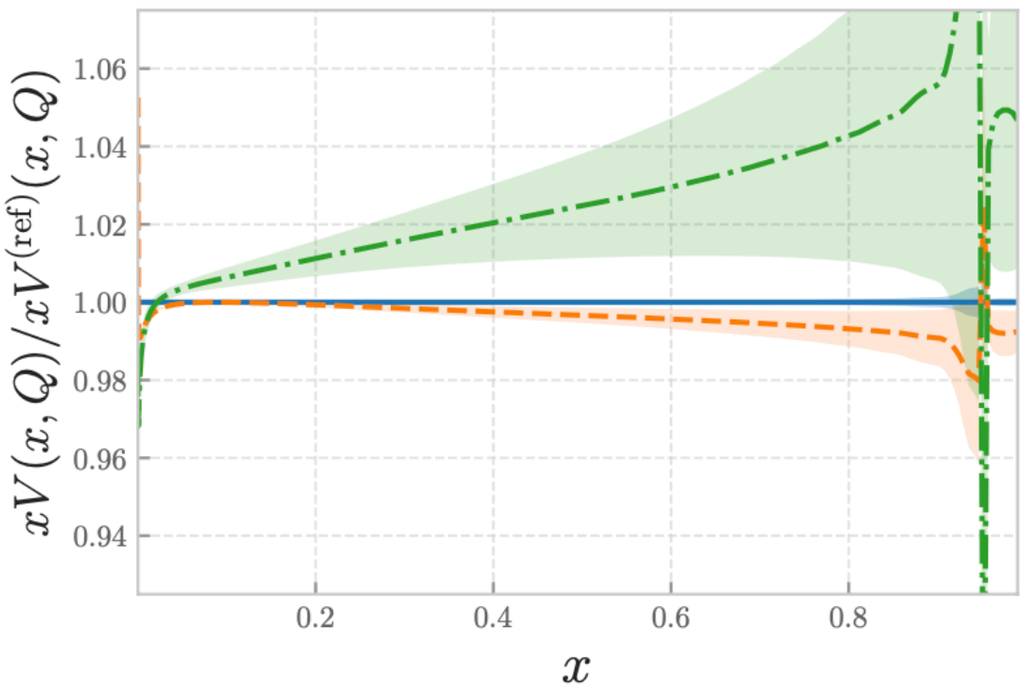
***WIP**: dedicated LH **benchmark paper** on N³LO splitting functions and PDFs (Robert's talk)*

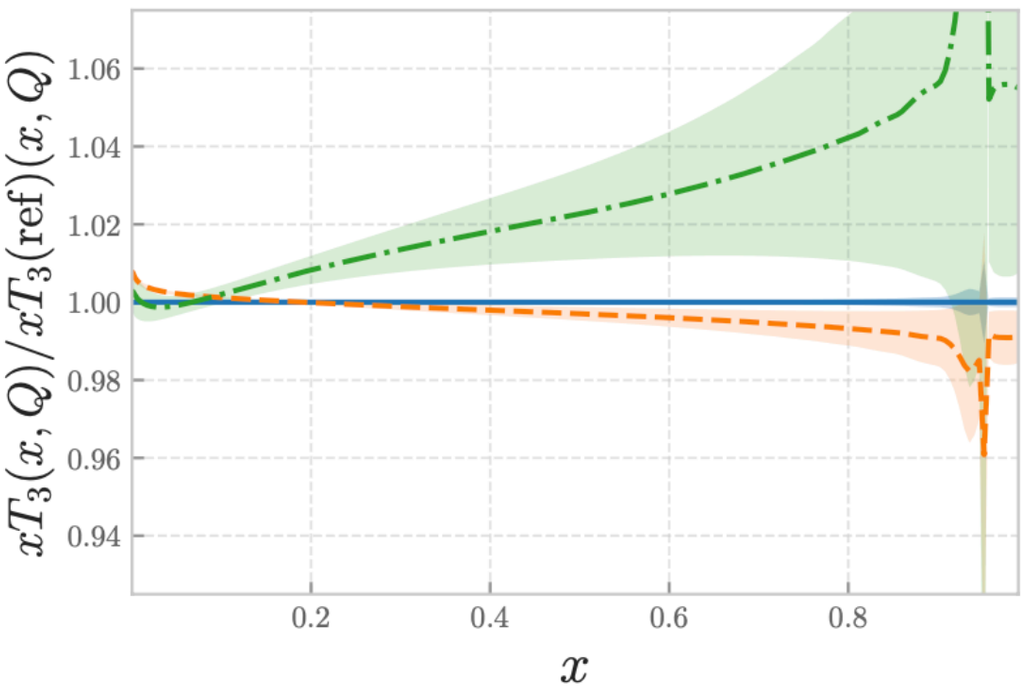
Impact on PDF evolution





evolution of fixed PDF boundary condition from Q=1.65 GeV to Q=100 GeV





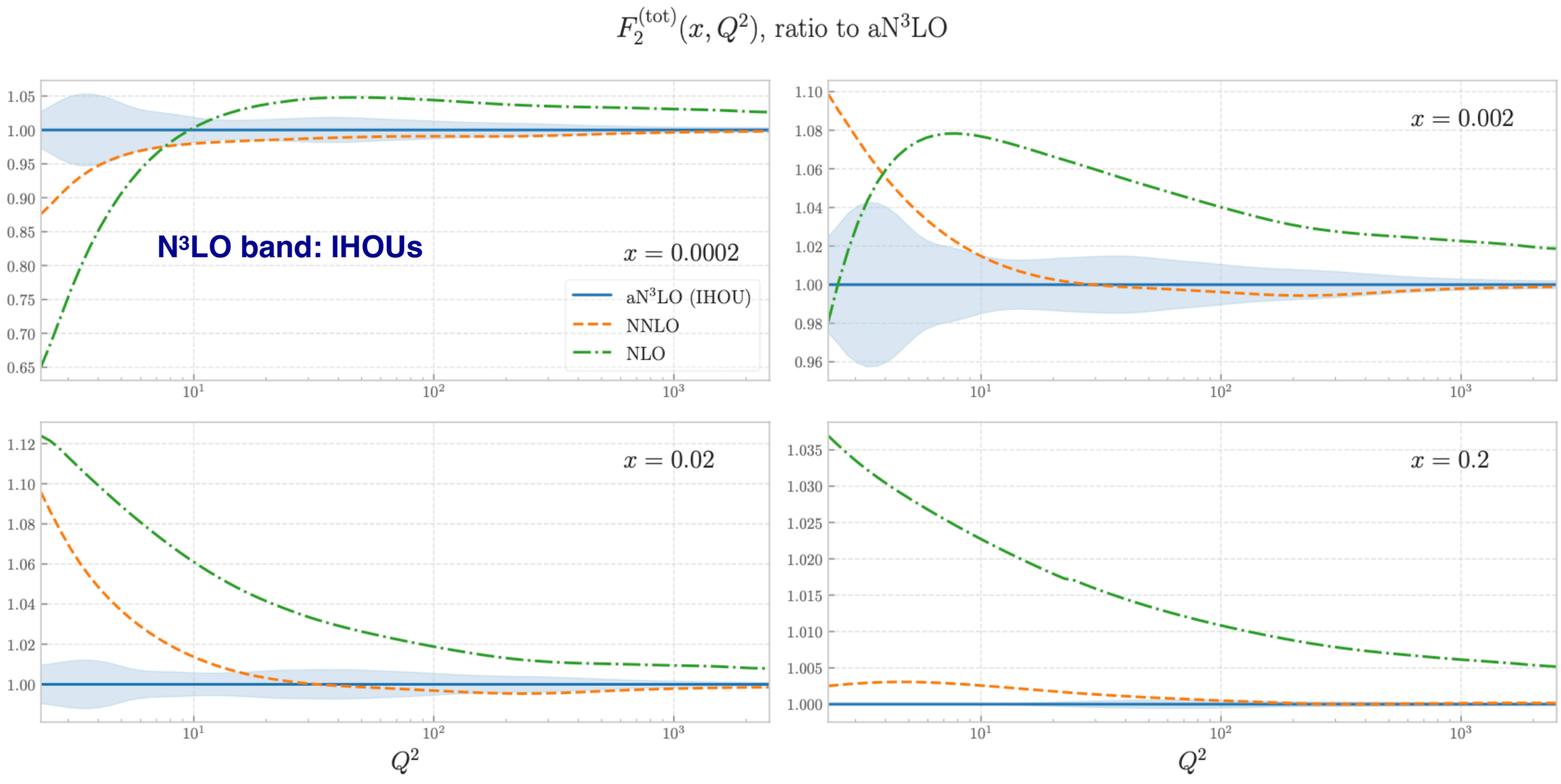
Effects of N^{3}LO corrections to DGLAP evolution **< 1%** except at small-*x* and large-*x*

Excellent **perturbative convergence of PDF evolution**, may be improved with small-*x* or large-*x* resummations

Structure functions

- Exact (approximate) massless (massive) deep-inelastic coefficient functions at N³LO accuracy & extension of the **FONLL general -mass scheme at N³LO**

- Relies on parametrisation of massive DIS coefficients reproducing known results



- **N³LO corrections to** DIS inclusive structure functions become significant at low-Q

- IHOUs associated to **N³LO massive coefficient functions** deweight the impact of HERA low-Q data

Fit settings

- Same methodology, dataset, and **pipeline for theory calculations** as in NNPDF4.0 MHOU & QED sets
- Produce fit variants with and without theory uncertainties (using the theory covariance matrix)

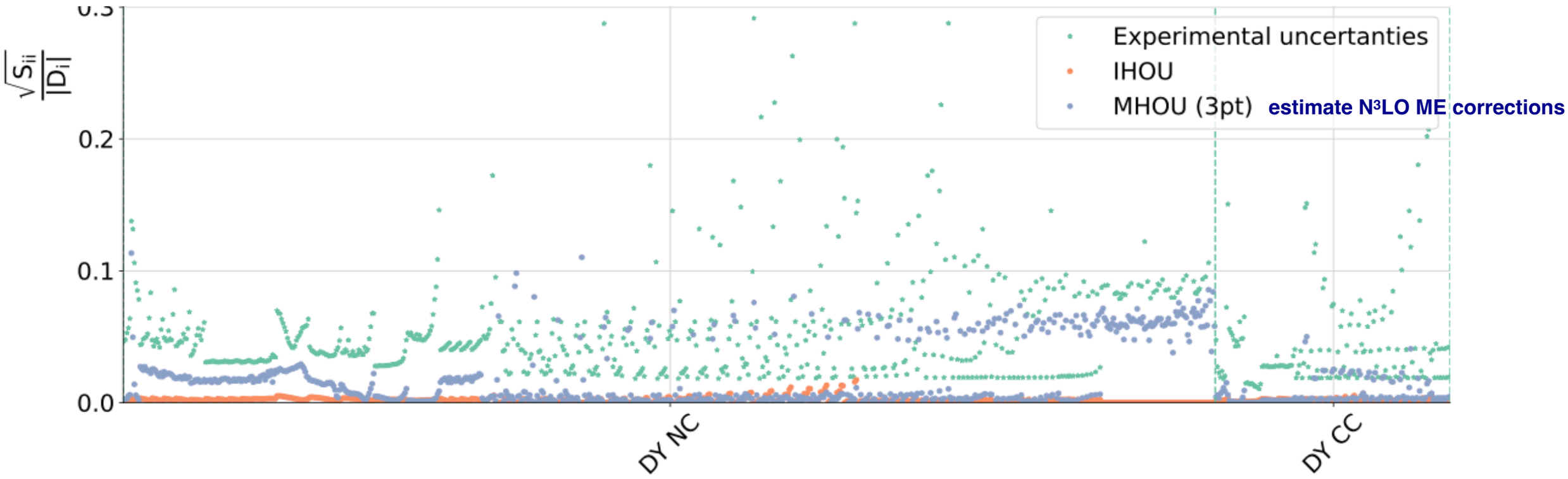
$$\Delta_i(\rho_f, \rho_r) \equiv T_i(\rho_f, \rho_r) - T_i(0,0),$$

Shift wrt central theory on the physical observables due to theory variations (e.g. scales)

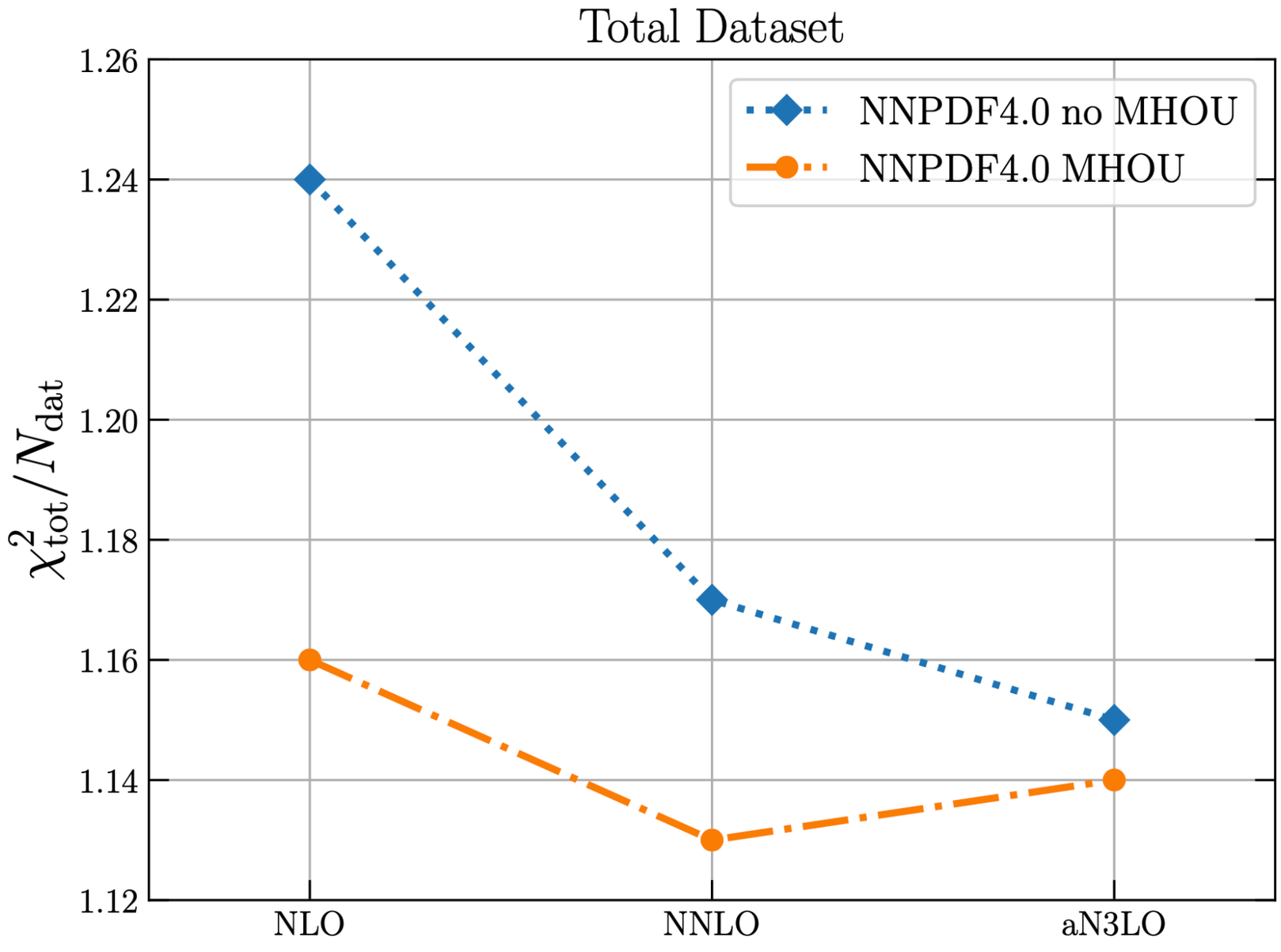
$$S_{ij} = n_m \sum_{V_m} \Delta_i(\rho_f, \rho_{r_i}) \Delta_j(\rho_f, \rho_{r_j}),$$

Theory covariance matrix: combine all shifts, keeping into account their correlations

- The theory covariance matrix includes contributions from **MHOUs** (μ_F and μ_R variations) and **IHOUs**
- Hadronic data is fitted **using aN³LO evolution and NNLO matrix elements**, supplemented by MHOUs associated to μ_R variations to account for missing K-factors



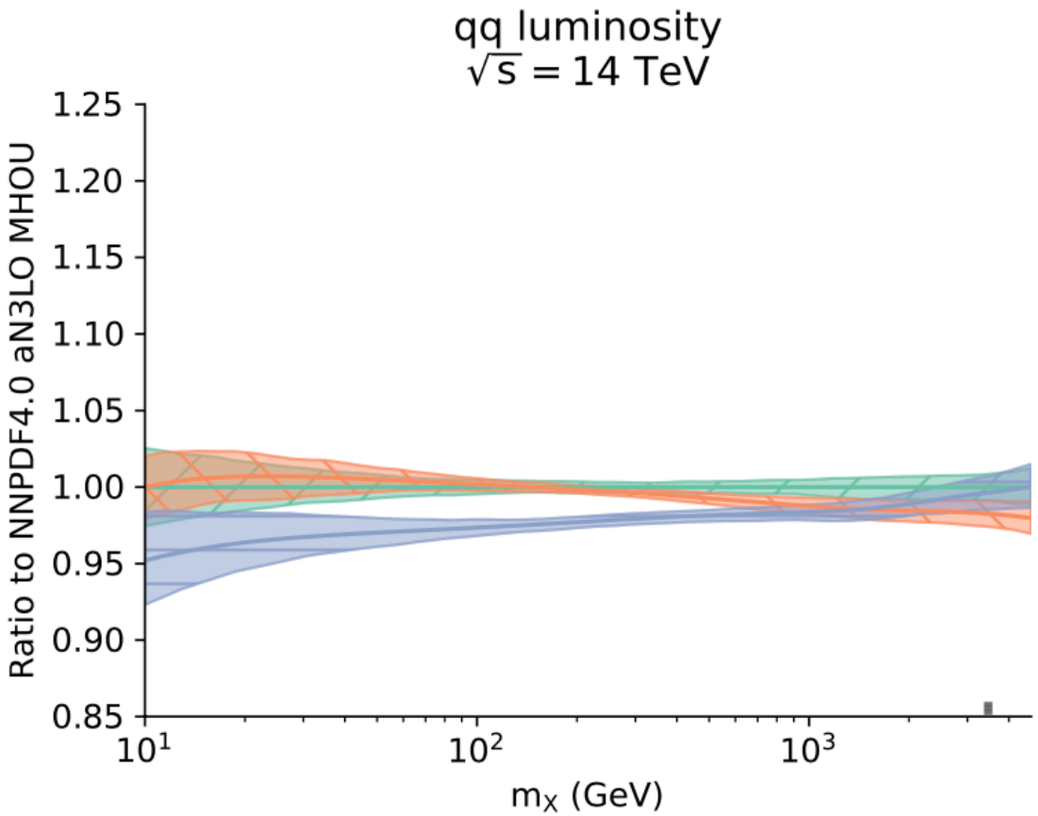
Results: Fit quality

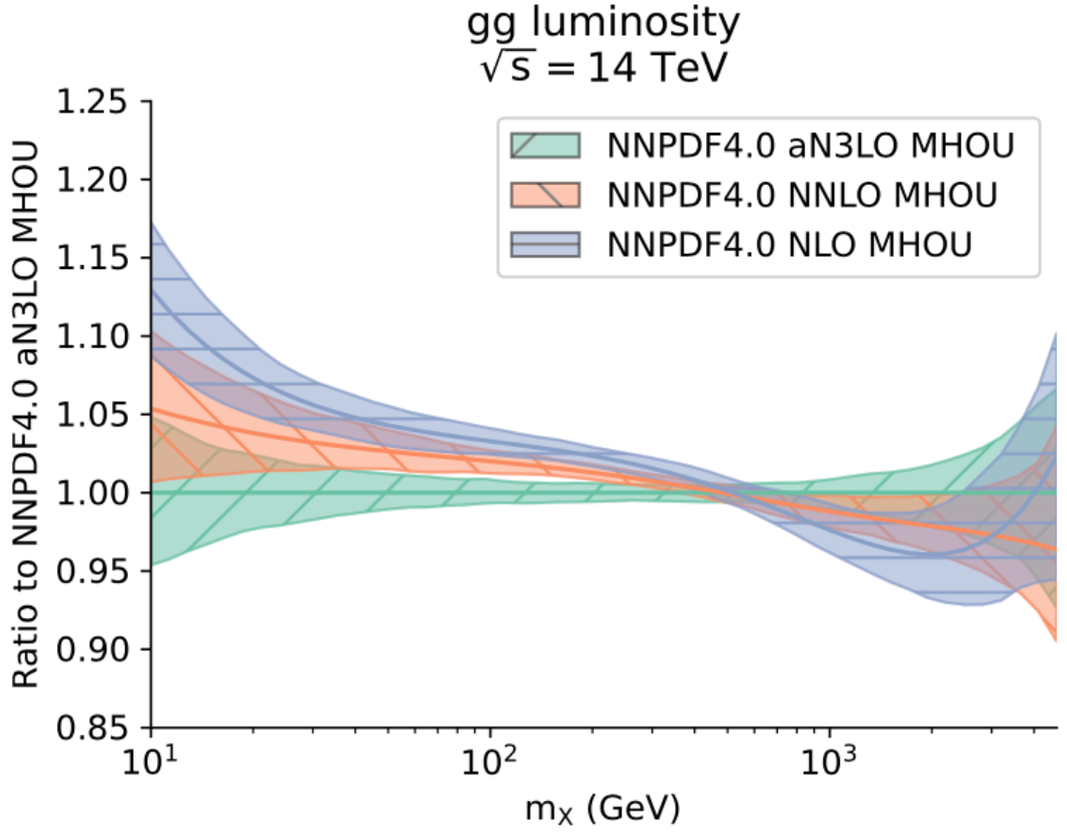


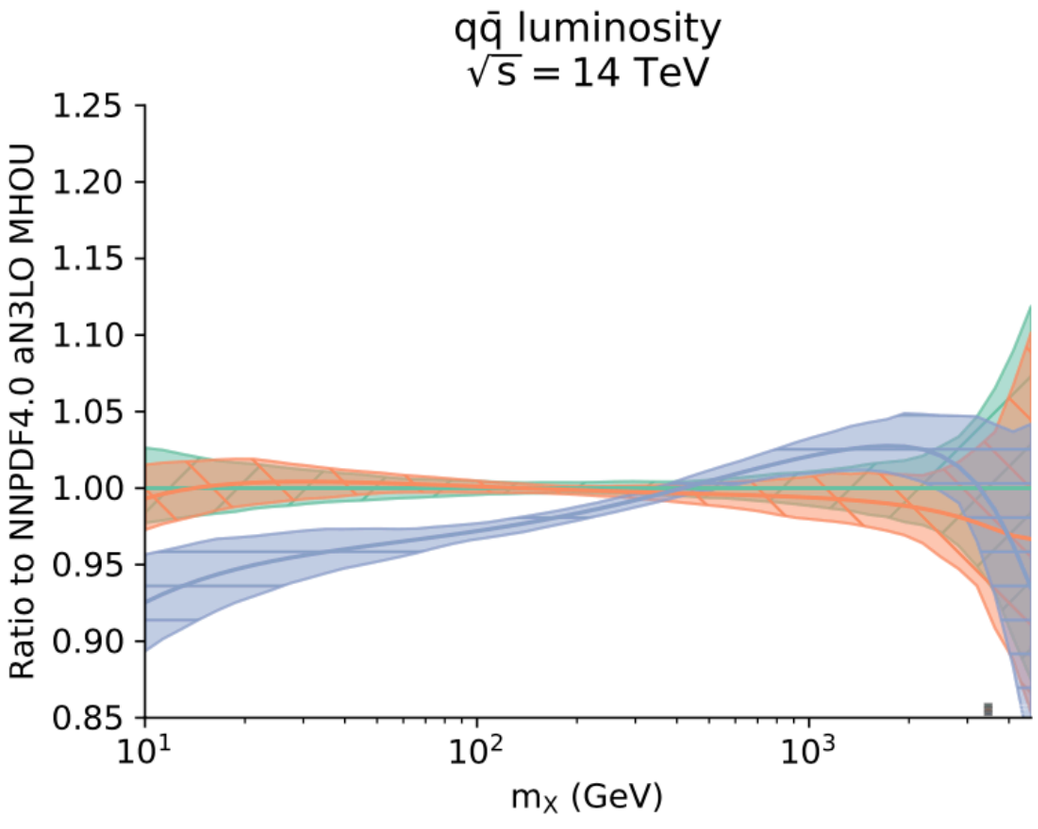
- Without MHOUs, the **χ^2 improves with the perturbative accuracy** of the PDF fit
- With MHOUs, the **χ^2** becomes **feebly dependent on the perturbative accuracy**
- At aN^{3}LO impact of MHOUs is small (also at PDF level) but non negligible

N^{3}LO corrections required for perturbative convergence at the PDF fit level!

Results: perturbative convergence

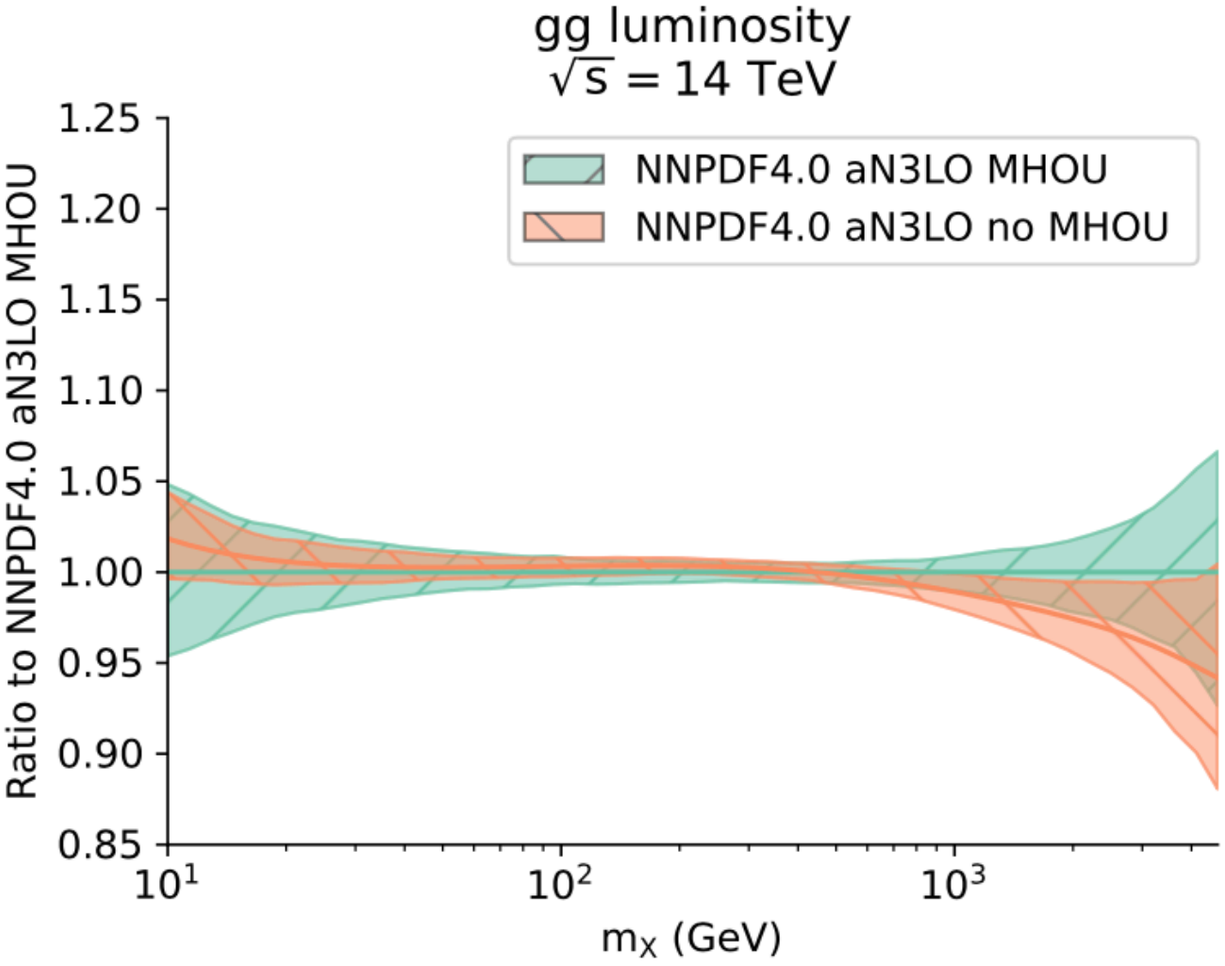


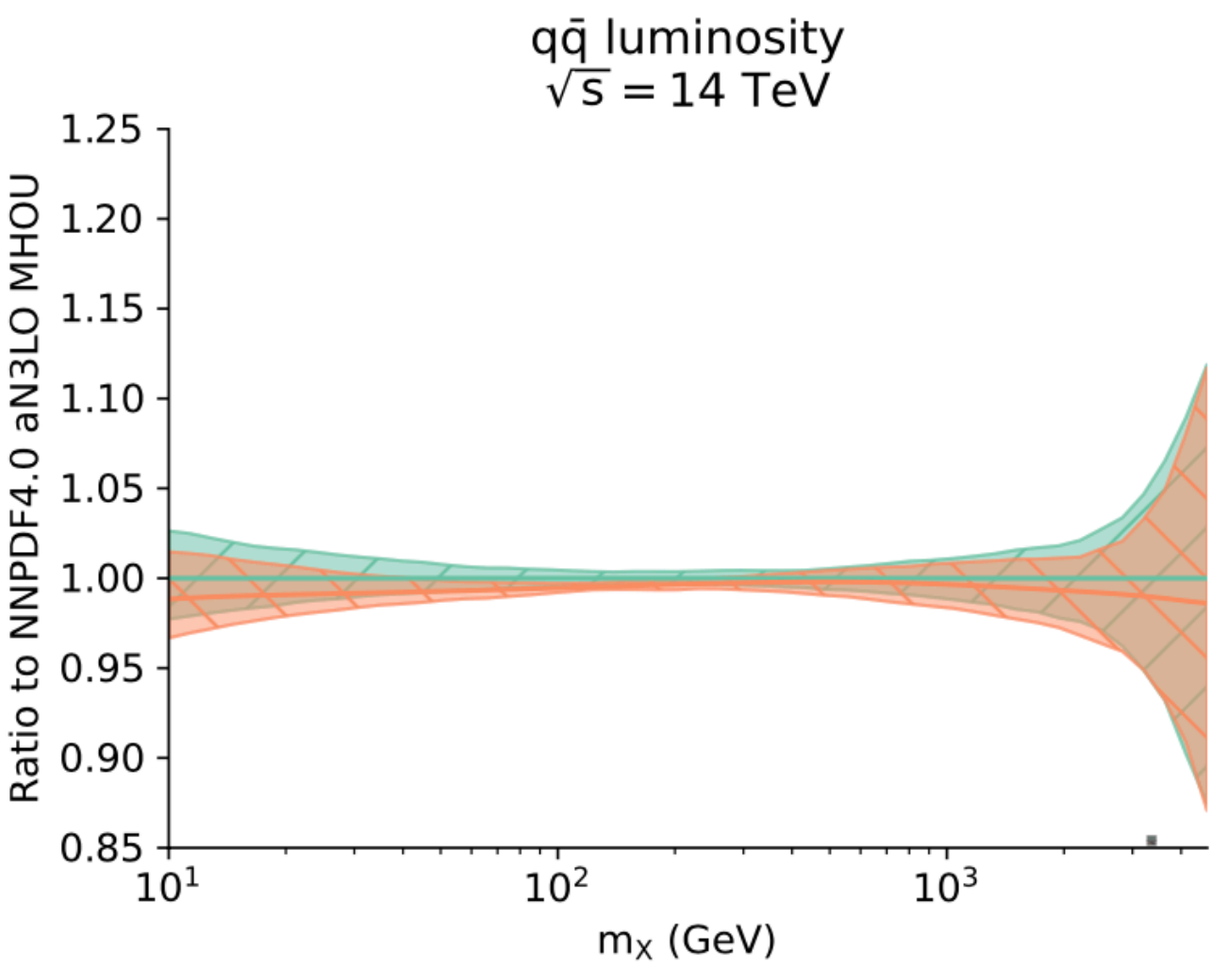




- **Good perturbative convergence**
- Impact of N^{3}LO corrections moderate, specially for the quark luminosities
- For the gluon-gluon luminosity, NNPDF4.0 finds a **small suppression** around Higgs mass (2% effect)

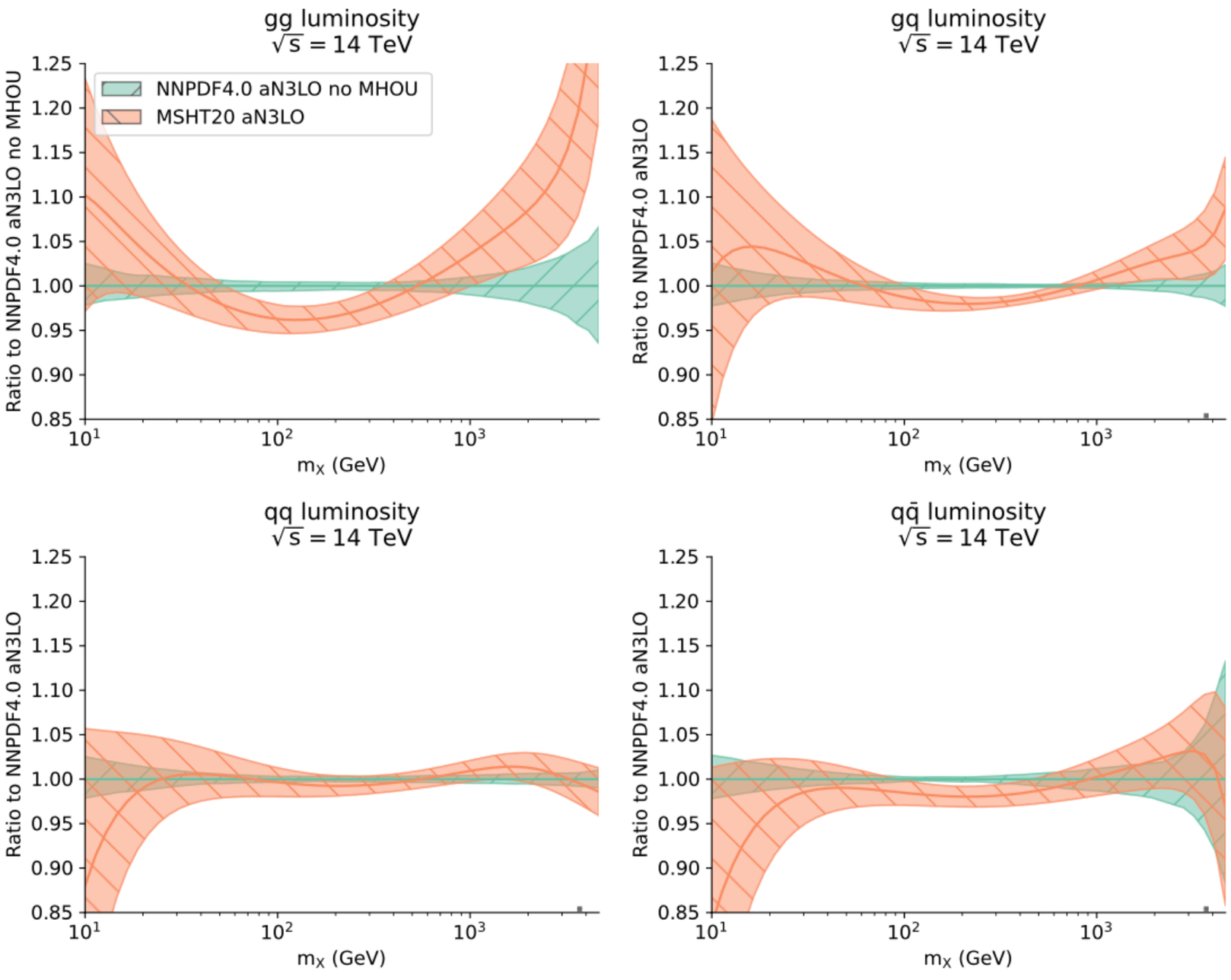
Results: impact of MHOUs at N³LO





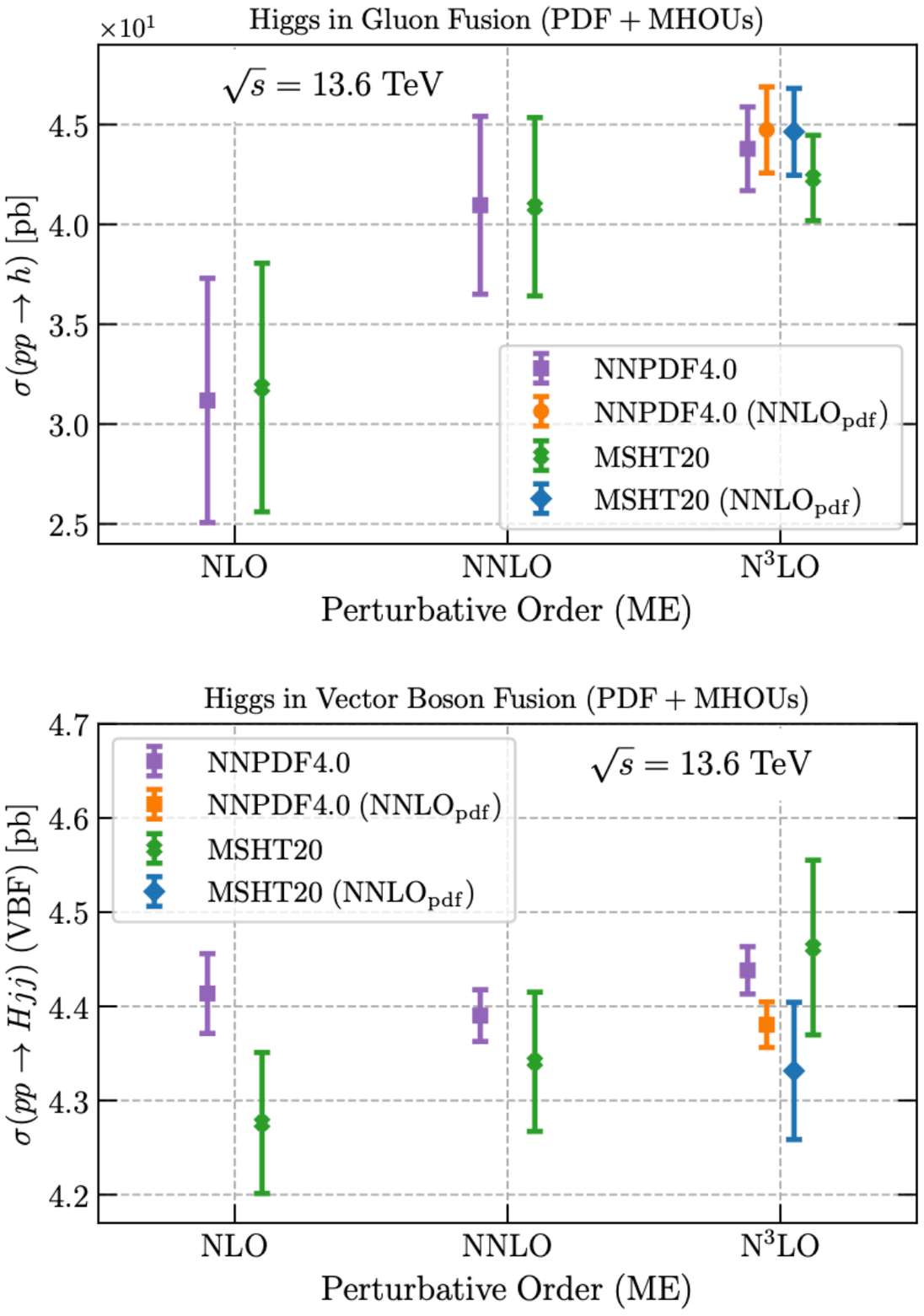
- Impact of **MHOUs is not negligible** even at N³LO, both in terms of central values and uncertainties
- Motivates inclusion of **exact N³LO calculations** for hadronic processes in the global PDF fit (*e.g.* Drell-Yan production, which is already available)
- Further highlights the relevance of MHOUs also for NNLO and NLO fits

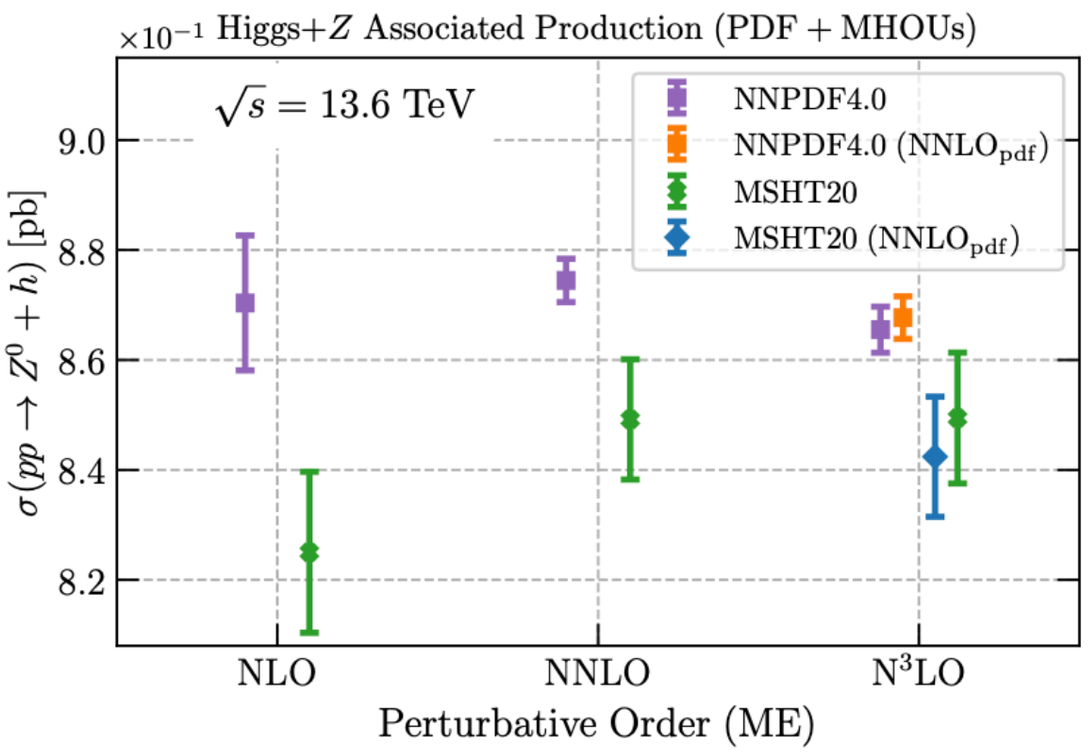
Results: comparison with MSHT20



- **Good agreement** with MSHT20 for the quark luminosities
- Likewise for the gluon luminosities, except **around the Higgs mass** and for $m_X > 3$ **TeV**
- Ongoing benchmark exercise to understand the differences
- In general, agreement between NNPDF4.0 and MSHT20 tends to **improve in the N³LO fits**

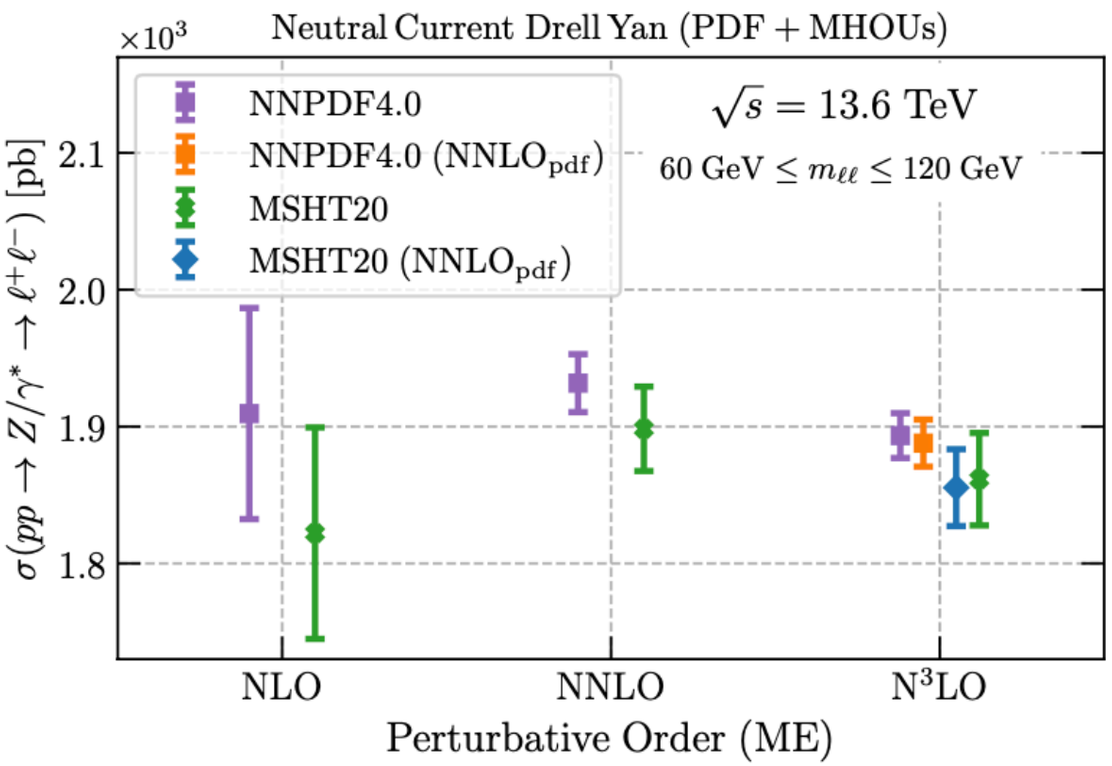
LHC phenomenology: Higgs production

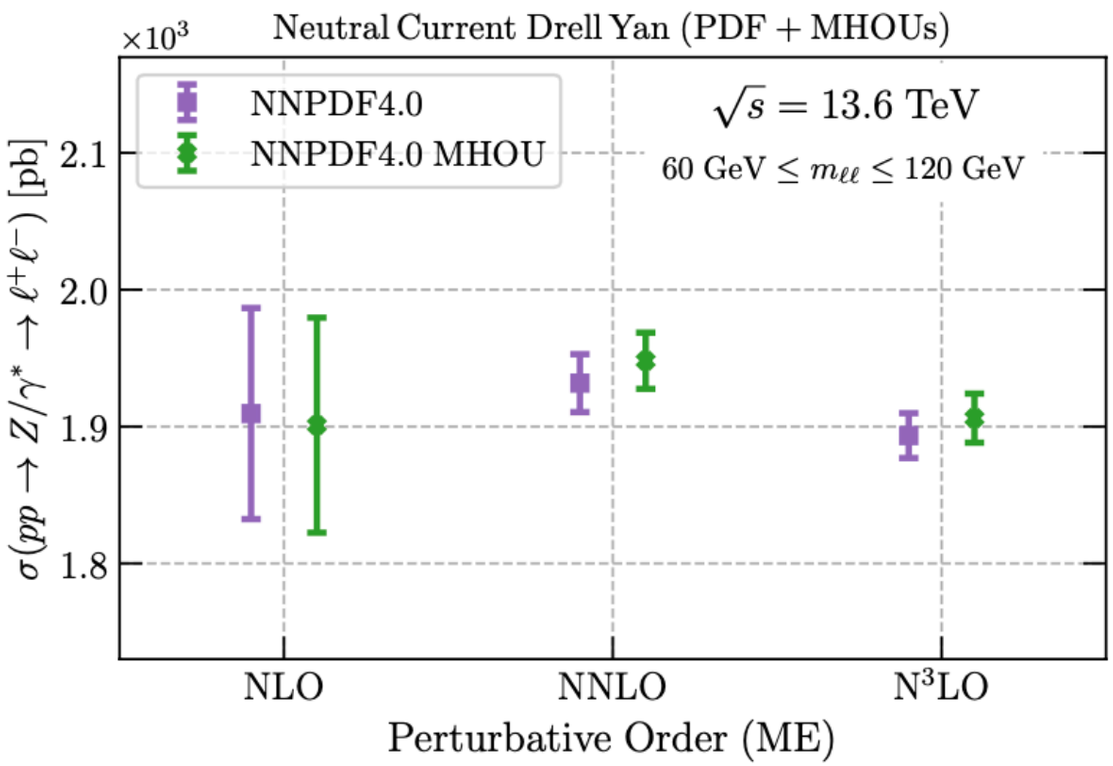


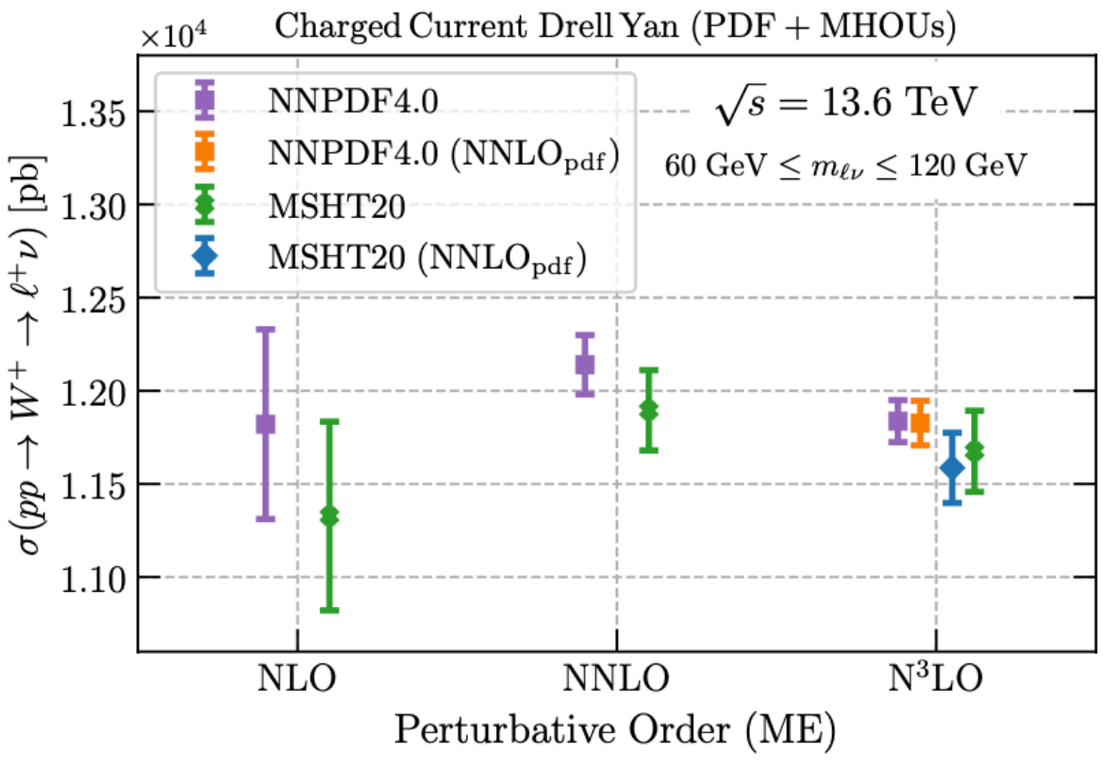


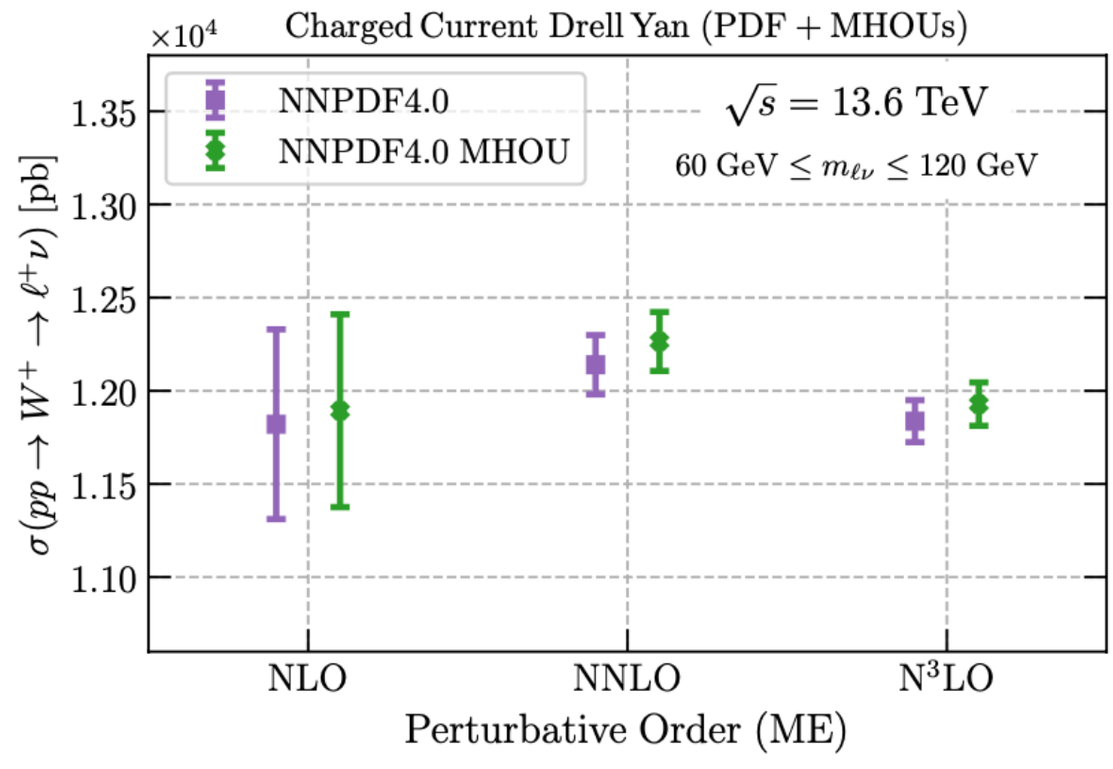
- N^{3}LO PDF corrections to **Higgs in gluon fusion small,** with a 1.5% suppression wrt NNLO PDFs
- N^{3}LO corrections improve agreement between NNPDF4.0 and MSHT20 for ***hZ***
- **Higgs VBF** perturbatively stable

LHC phenomenology: Drell-Yan









Good perturbative convergence at N^{3}LO also for **quark-initiated processes**

Summary and outlook

☑ A key ingredient to **LHC phenomenology at 1% precision** are N^{3}LO PDFs which account for all sources of theory uncertainties

☑ The new NNPDF4.0 aN^{3}LO determination enables **consistent N^{3}LO calculations** of LHC cross-sections. An initial study suggests good perturbative convergence for inclusive **Higgs** and **Drell-Yan production**

☑ Work in progress aims to **combine aN^{3}LO PDFs with QED and MHOU** effects, study the phenomenological implications of the NNPDF4.0 family, and **determine precision SM parameters** such as the strong coupling constant

☑ Also steady progress in the implementation of new datasets and updated theory calculations (based on NNLO grid technology) **aiming to NNPDF4.1**

☑ Lots of progress in related projects, such as NNPDF4.0 for MC event generators and methodological studies. Stay tuned!

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Thanks for your attention