Recent Progress on PDF Determination: NNPDF4.0 Updates

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On behalf of the **NNPDF Collaboration**

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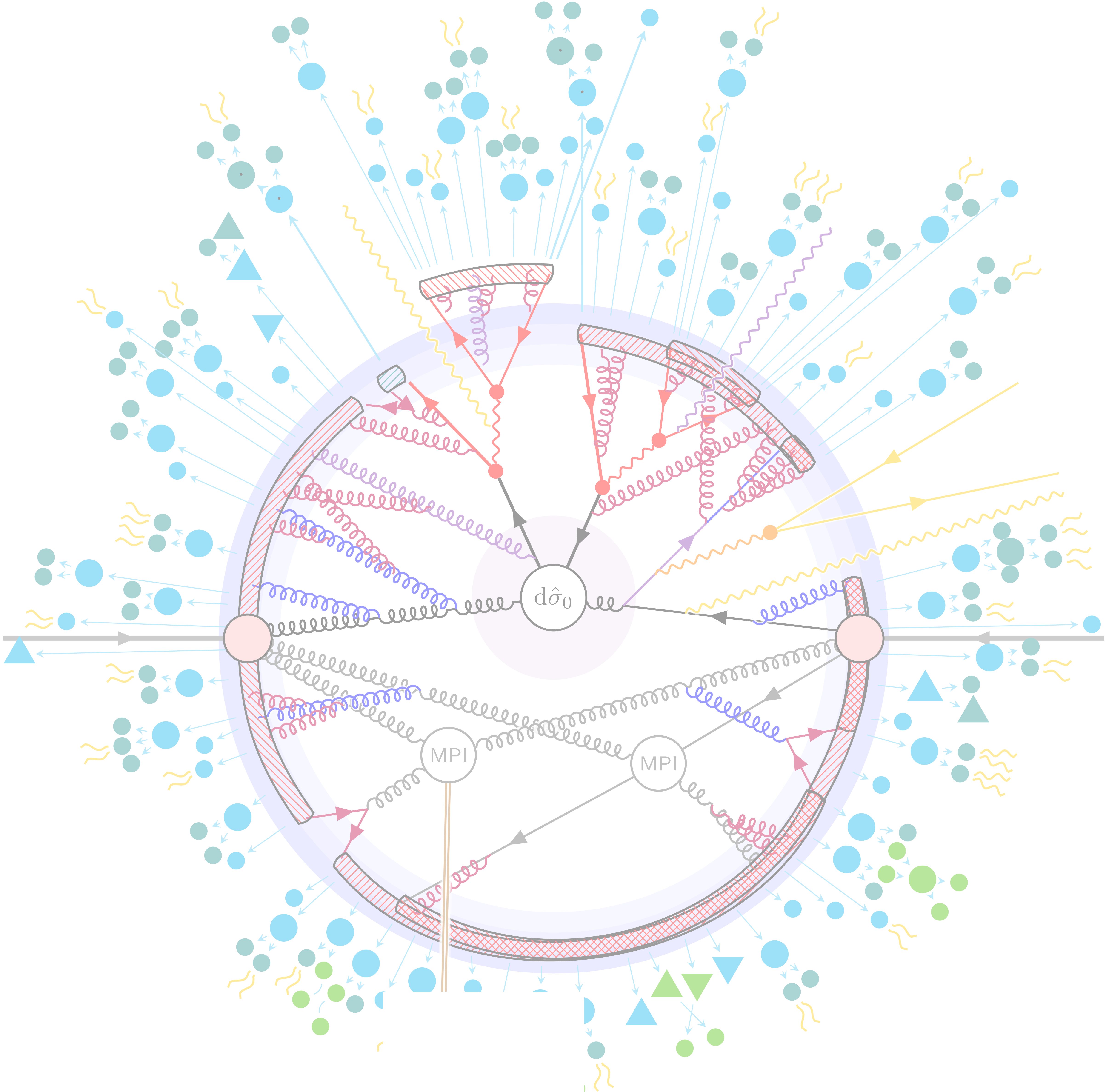
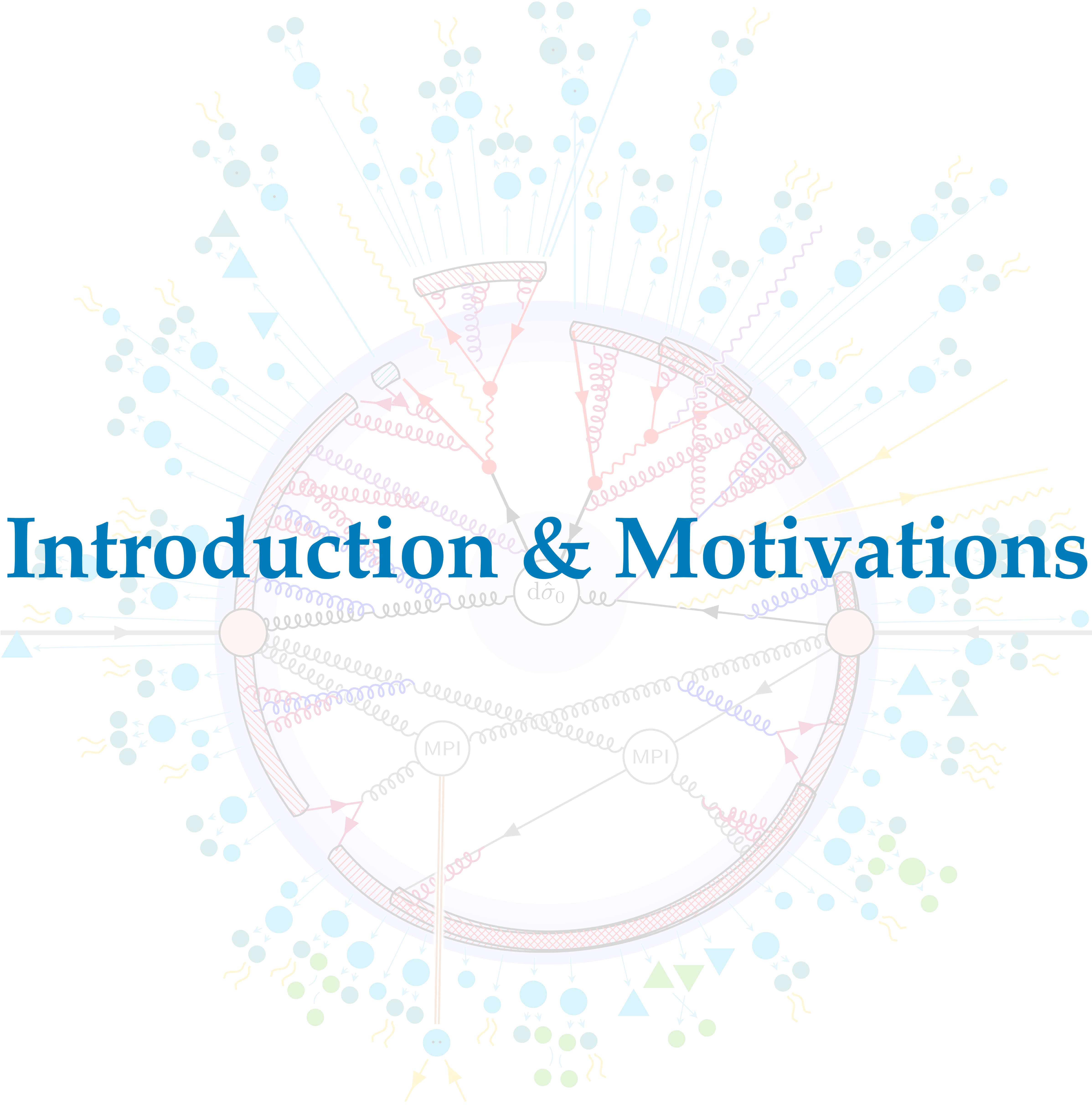
OUTLINE OF THE TALK:

1. Introduction & Motivations
2. Approximate N3LO (aN3LO) PDFs
3. Theory Uncertainties in PDF Determination
4. PDF Determination with QED Corrections
5. Conclusions & Outlook



Introduction & Motivations



Introduction: NNPDF Landscape

Significant improvements on all 3 FRONTS for NNPDF4.0:

- **Experiments:** contains $\mathcal{O}(4500)$ datapoints, abundant LHC data from Run II, probe more processes and channels.
- **Methodology:** SGD for NN minimisation, Automated Optimisation of Hyperparameters, Methodology validation using **Closure Tests/ Future Tests/Parametrisation Basis independence**.
- **Theory:** NNLO QCD with **Electroweak** corrections and Nuclear Unc.

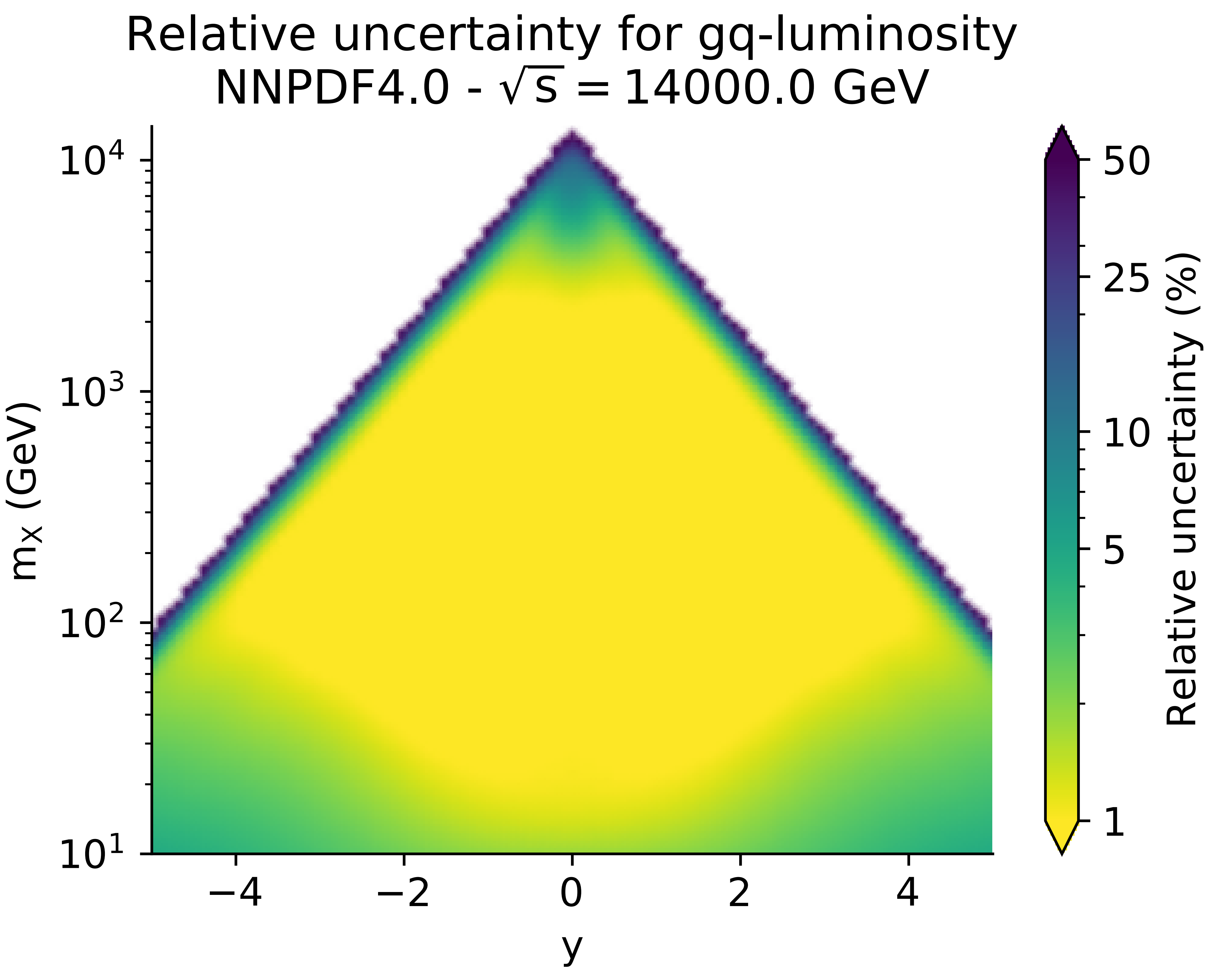
NNPDF

Tests passing | DOI 10.5281/zenodo.7554886

NNPDF: An open-source machine learning framework for global analyses of parton distributions

The NNPDF collaboration determines the structure of the proton using Machine Learning methods. This is the main repository of the fitting and analysis frameworks. In particular it contains all the necessary tools to reproduce the NNPDF4.0 PDF determinations.

https://github.com/NNPDF/nnpdf

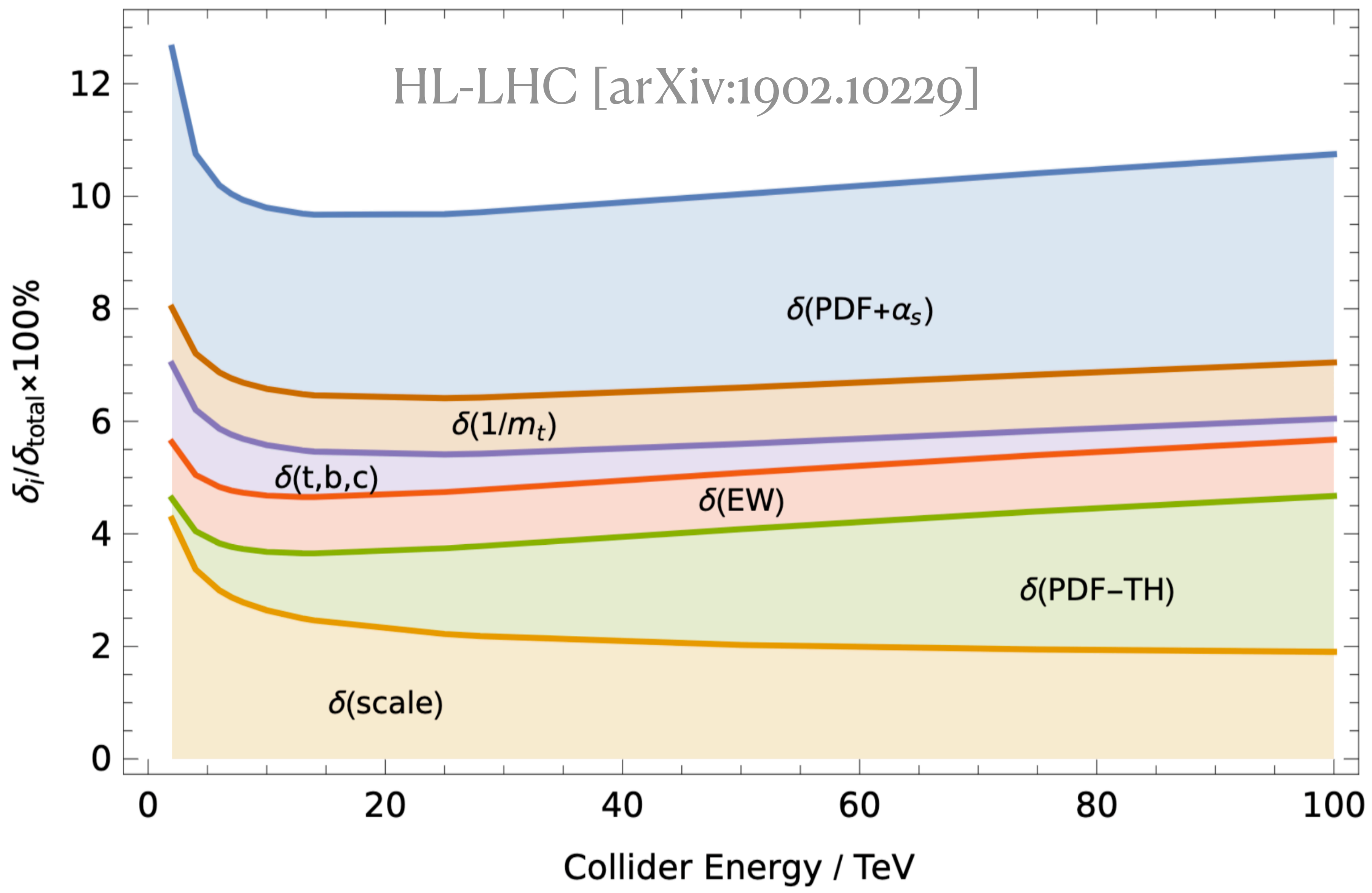


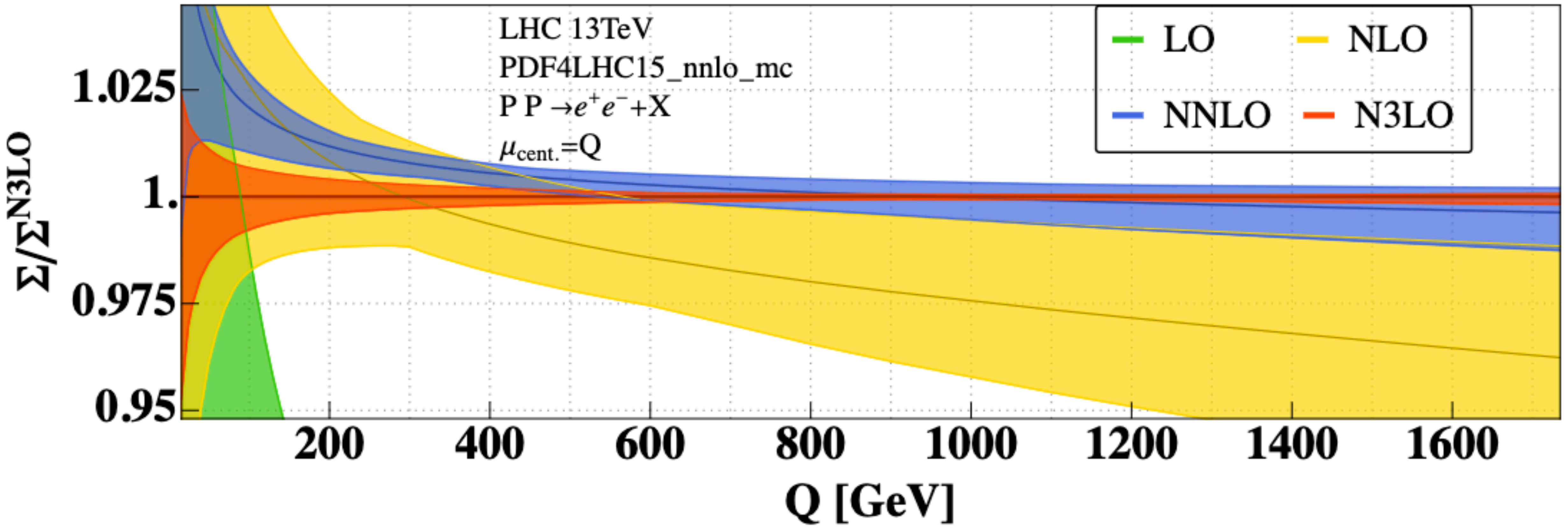
NNPDF [arXiv:2109.02653]

Achieves $\mathcal{O}(1\%)$ accuracy across a Wide range of Kinematics

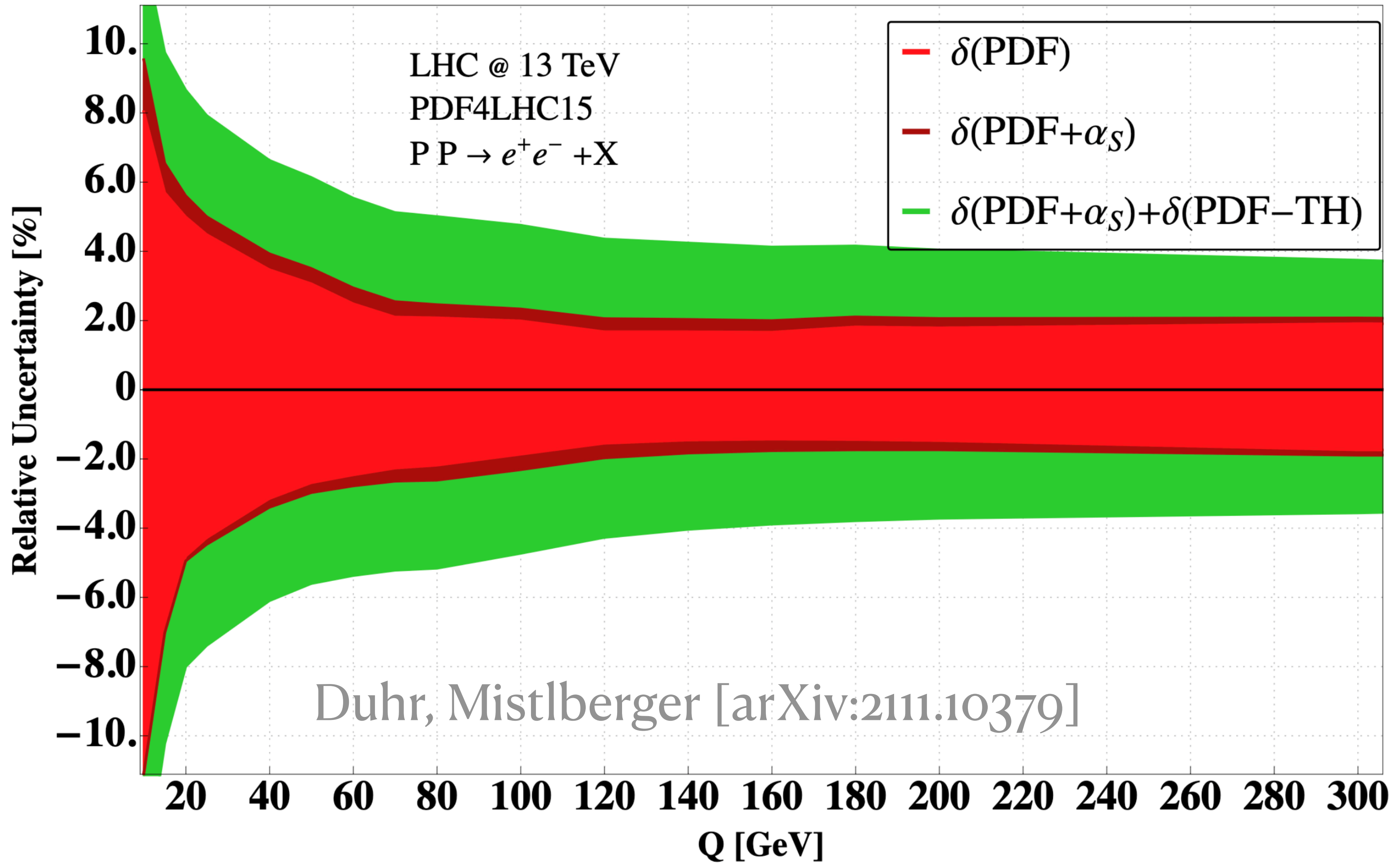
Introduction: Challenges

- **PDFs are becoming a bottleneck for LHC precision calculations** with the largest uncertainties along with the incomplete knowledge of α_s.
- **Progress on N3LO calculations** for Higgs (ggF, VBF, VH) & NC/CC DY processes requires **N3LO PDFs**.
- **QED effects in PDFs** are **no longer negligible** as experimental measurements become more precise and determination of parton densities more accurate.
- **Theoretical uncertainties** on PDFs are crucial to assess accuracy/uncertainties on MHOUs & IHOUs.





Duhr, Mistlberger [arXiv:2111.10379]



Approximate N3LO (aN3LO) PDFs

What do we need for N3LO PDFs?

Several theory ingredients are required to achieve N3LO PDF fits:

- **Splitting Functions/Anomalous Dimensions (AD)** to evolve PDFs through the DGLAP equation

$$\gamma(\alpha_s) = \alpha_s \gamma^{(0)} + \alpha_s^2 \gamma^{(1)} + \alpha_s^3 \gamma^{(2)} + \boxed{\alpha_s^4 \gamma^{(3)}} + \cdots$$

- **Matching Conditions/Transition Matrix Elements** to change number of PDF flavours at **heavy-quark matching scales**

$$f_\alpha^{n_f+1}(x, Q^2) = \boxed{\mathrm{A}_{\alpha\beta}^{(n_f)}(x, Q^2/m_h^2)} \otimes f_\beta^{n_f}(x, Q^2)$$

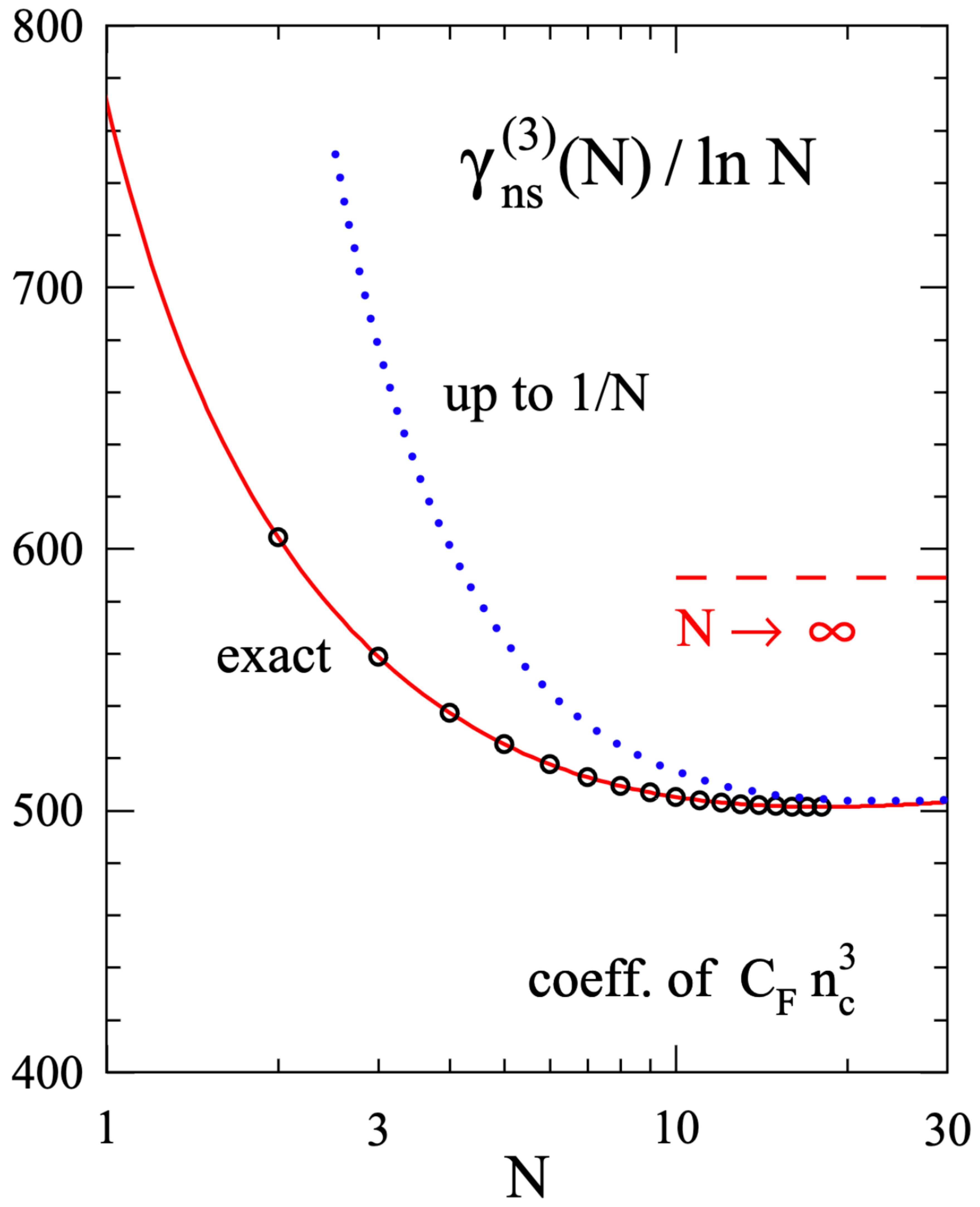
- **DIS Coefficient Functions** to compute structure functions

$$F_\alpha(x, Q^2) = \sum_{\beta,\eta} \mathscr{C}_{\alpha,\beta,\eta}^{n_f+1}(x, Q^2) \otimes \mathrm{A}_{\eta\xi}^{(n_f)}(x, Q^2/m_h^2) \otimes f_\xi^{n_f}(x, Q^2)$$

- **Hadronic Cross-Section k-factors**

$$\Sigma(x) = \Sigma_0(x) + \Sigma_1(x) + \Sigma_2(x) + \boxed{\Sigma_3(x)} + \cdots$$

Several Pieces are still missing⟶Need Reliable Approximations



Moch, Ruijl, Ueda, Vermaseren, Vogt [arXiv:1707.08315]

What do we know about 4-Loop Non-Singlet AD?

The complete N3LO Anomalous Dimensions are not known yet, but a lot of information is already available.

- The case of **NON-SINGLET** sector:
  - $\mathcal{O}(n_f^2)$ and $\mathcal{O}(n_f^3)$ terms are known **analytically** Davies, Vogt, Ruijl, Ueda, Vermaseren [arXiv:1610.07477]
  - $\mathcal{O}(n_f^0)$ and $\mathcal{O}(n_f)$ terms are known in the **Large-N_c** limit Moch, Ruijl, Ueda, Vermaseren, Vogt [arXiv:1707.08315]
  - **Small-N limit:** coefficients of logarithms at pole $N = 0$ are known numerically Davies, Kom, Moch, Vogt [arXiv:2202.10362]

$$P_{\rm ns}(x) \supset \sum_{k=1}^{6} c_k \ln^k(1/x)$$

  - **Large-N limit:** some coefficients and constant terms are known Henn, Korchemsky, Mistlberger [arXiv:1911:10174]; Duhr, Mistlberger, Vita [arXiv:2205:04493]

$$\gamma_{\rm ns}^{(3)}(N) \approx A_4 S_1(N) - B_4^+ C_4 \frac{S_1(N)}{N} - D_4 \frac{1}{N}$$

  - Results for **Even/Odd Mellin Moments** are known Moch, Ruijl, Ueda, Vermaseren, Vogt [arXiv:1707.08315]

The dependence of $\gamma_{ij}^{(3)}$ on the number of active flavours can be expressed as follows:

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

	n_f^0	n_f^1	n_f^2	n_f^3
$\gamma_{ns,-}^{(3)}$	✓	✓	✓	✓
$\gamma_{ns,+}^{(3)}$	✓	✓	✓	✓
$\gamma_{ns,s}^{(3)}$		✓	✓	

What do we know about 4-Loop Singlet AD?

The complete N3LO Anomalous Dimensions are not known yet, but a lot of information is already available.

- The case of **SINGLET** sector:
  - **Leading Large-n_f** contributions to $\mathcal{O}(n_f^3)$ terms are known **analytically** Davies, Vogt, Ruijl, Ueda, Vermaseren [arXiv:1610.07477]
  - **Small-N limit:** BFKL limits of $\gamma_{qg}^{(3)}$ and $\gamma_{gg}^{(3)}$ are known up to LL and NLL, respectively. Coefficients of logarithms at pole $N=1$ are known numerically Bonvini and Marzani [arXiv:1805.06460]; Davies, Kom, Moch, Vogt [arXiv:2202.10362]

$$P_{\rm ns}(x) \supset \sum_{k=0}^{3} c_k \frac{\ln^k(1/x)}{x}$$

  - **Large-N limit:** Diagonal $(\gamma_{gg}^{(3)}, \gamma_{qq,\rm ps}^{(3)})$ and Off-diagonal $(\gamma_{qg}^{(3)}, \gamma_{gq}^{(3)})$ need to be treated separately. Their coefficients in the expansion $1/N$ are known numerically Duhr, Mistlberger, Vita [arXiv:2205.04493]; Henn, Korchemsky, Mistlberger [arXiv:1911.10174]; Soar, Moch, Vermaseren, Vogt [arXiv:0912.0369]
  - Results for **Even Mellin Moments** are known Falcioni, Herzog, Moch, Vogt [arXiv:2302.07593]-[arXiv:2307.04158]; Moch, Ruijl, Ueda, Vermaseren, Vogt [arXiv:2111.15561]

The dependence of $\gamma_{ij}^{(3)}$ on the number of active flavours can be expressed as follows:

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

	n_f^0	n_f^1	n_f^2	n_f^3
$\gamma_{gg}^{(3)}$	✓	✓	✓	✓
$\gamma_{gq}^{(3)}$	✓	✓	✓	✓
$\gamma_{qg}^{(3)}$		✓	✓	✓
$\gamma_{qq,ps}^{(3)}$		✓	✓	✓

Approximating N3LO Anomalous Dimensions

The approximation to the full $\gamma_{ij}^{(3)}$ is done in Mellin space for each power of n_f **independently** with the following steps:

- Select a basis function $G_1(N)$ for **leading** large-N contributions
- Select a basis function $G_2(N)$ for **leading** small-N contributions
- Select two basis functions $G_1(N), G_2(N)$ for **subleading** small- and large-N contributions
- Varying **subleading** G_ℓ bases to produce Candidates $\longrightarrow$ **IHOUs**

Provided with the known ingredients, we can approximate $\gamma_{ij}^{(3)}$ (for a given n_f^α) by parametrising the missing $\tilde{\gamma}_{ij}^{(3)}$ as follows:

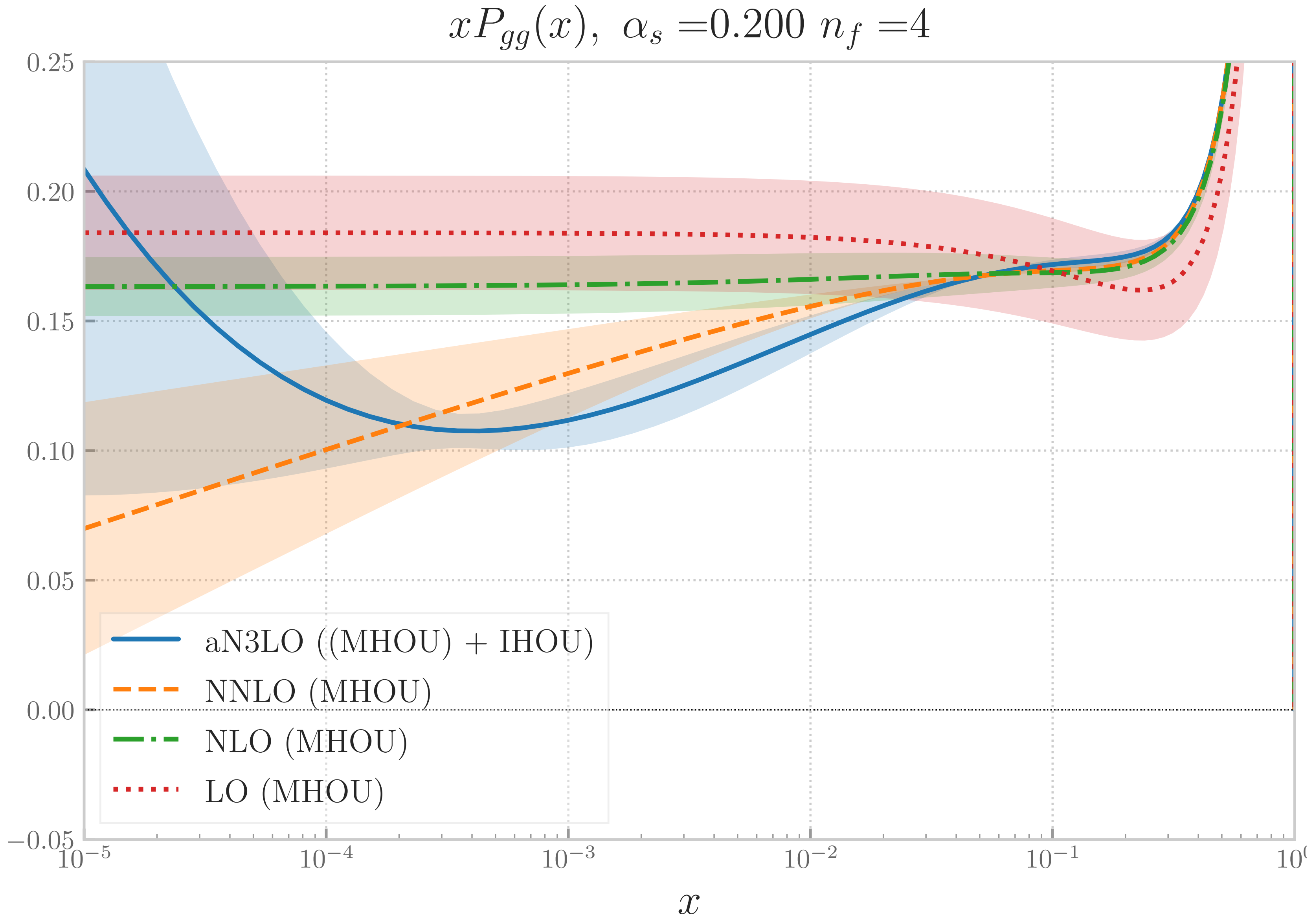
$$\gamma_{ij}^{(3)} = \gamma_{ij,n_f}^{(3)} + \gamma_{ij,N\to\infty}^{(3)} + \gamma_{ij,N\to 0}^{(3)} + \tilde{\gamma}_{ij}^{(3)}$$

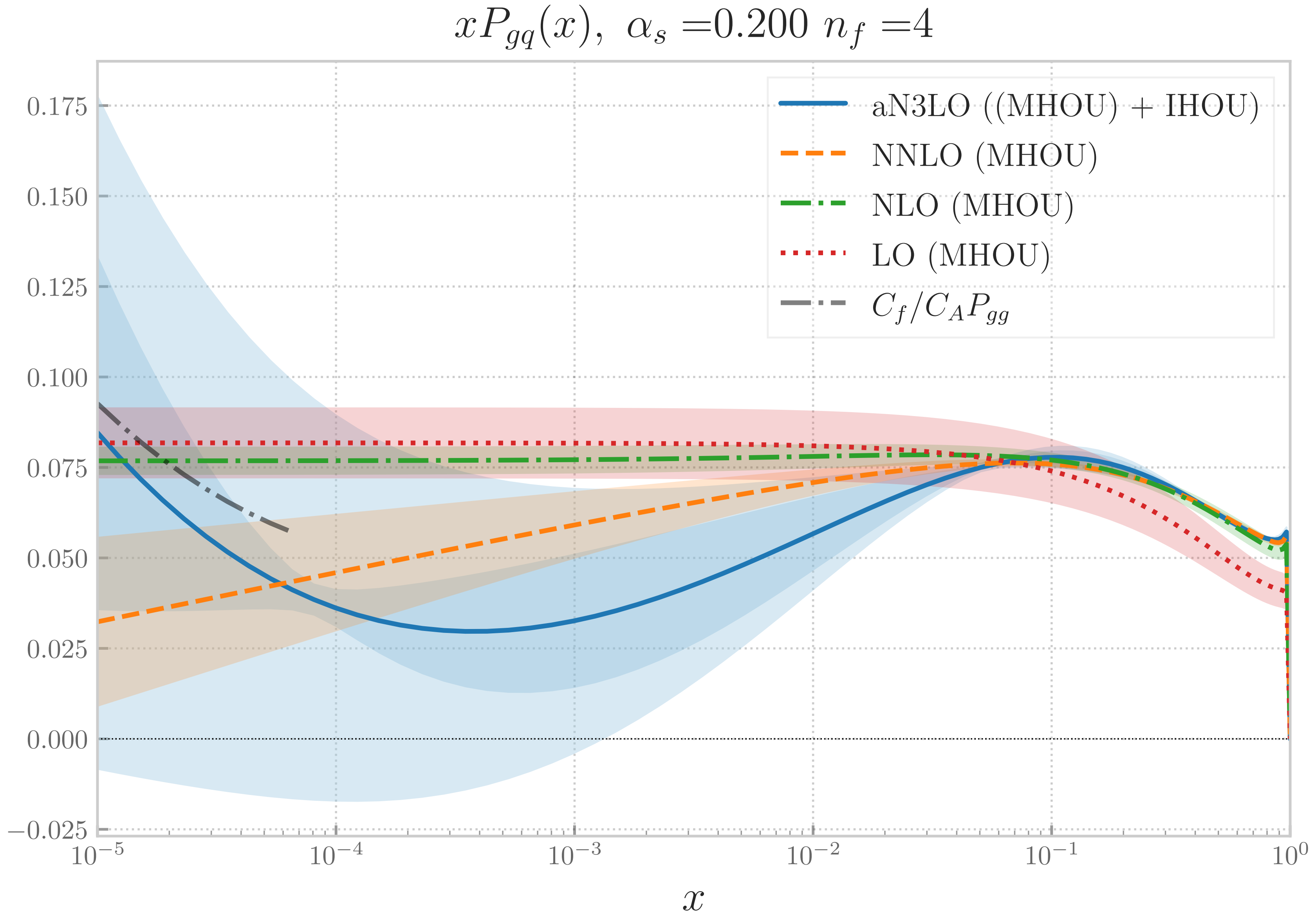
With $\tilde{\gamma}_{ij}^{(3)}$ expressed as a linear combination of interpolating functions

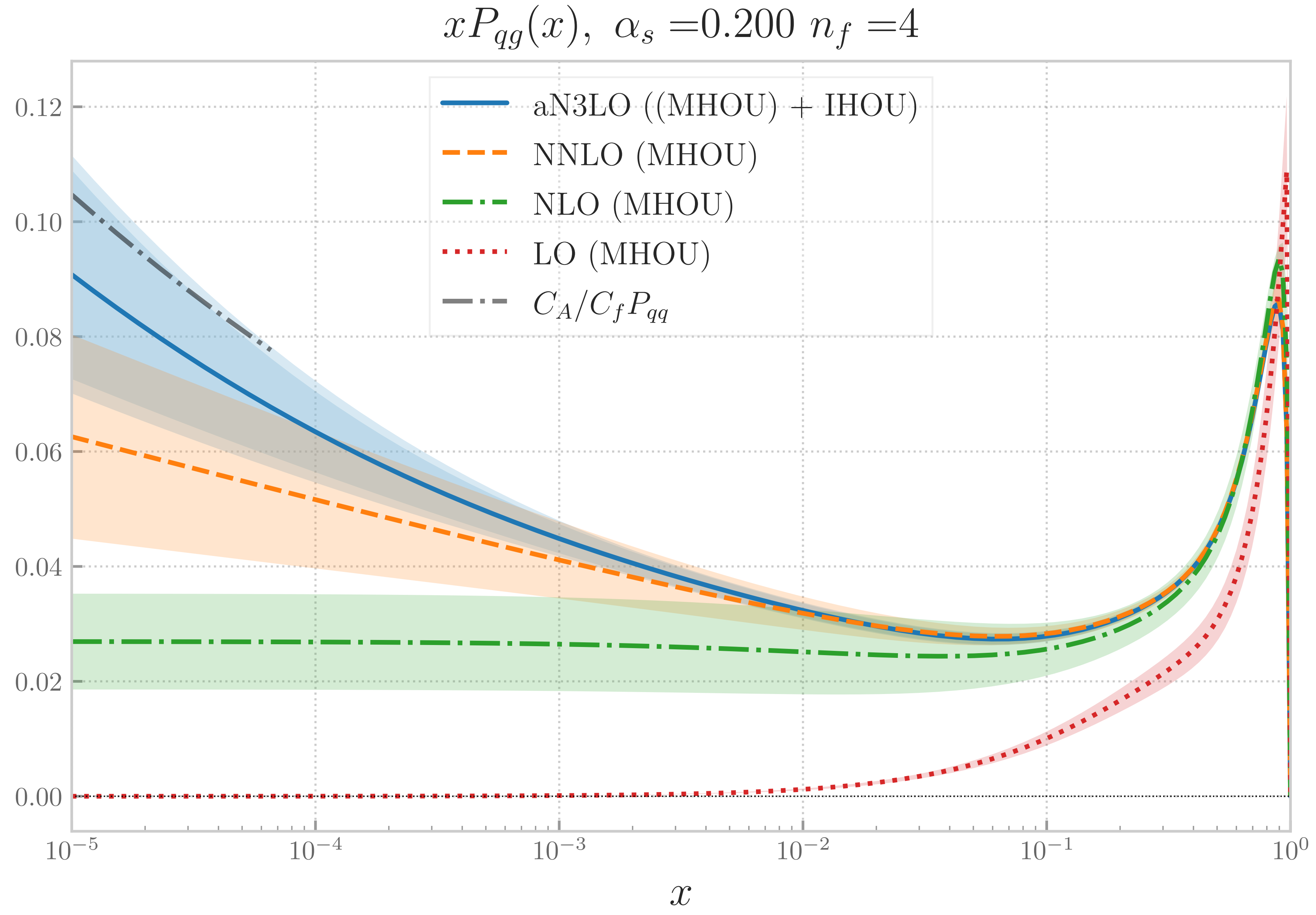
$$\tilde{\gamma}_{ij}^{(3)}(N) = \sum_{\ell=1}^{n_\ell} a_\ell^{ij} G_\ell(N)$$

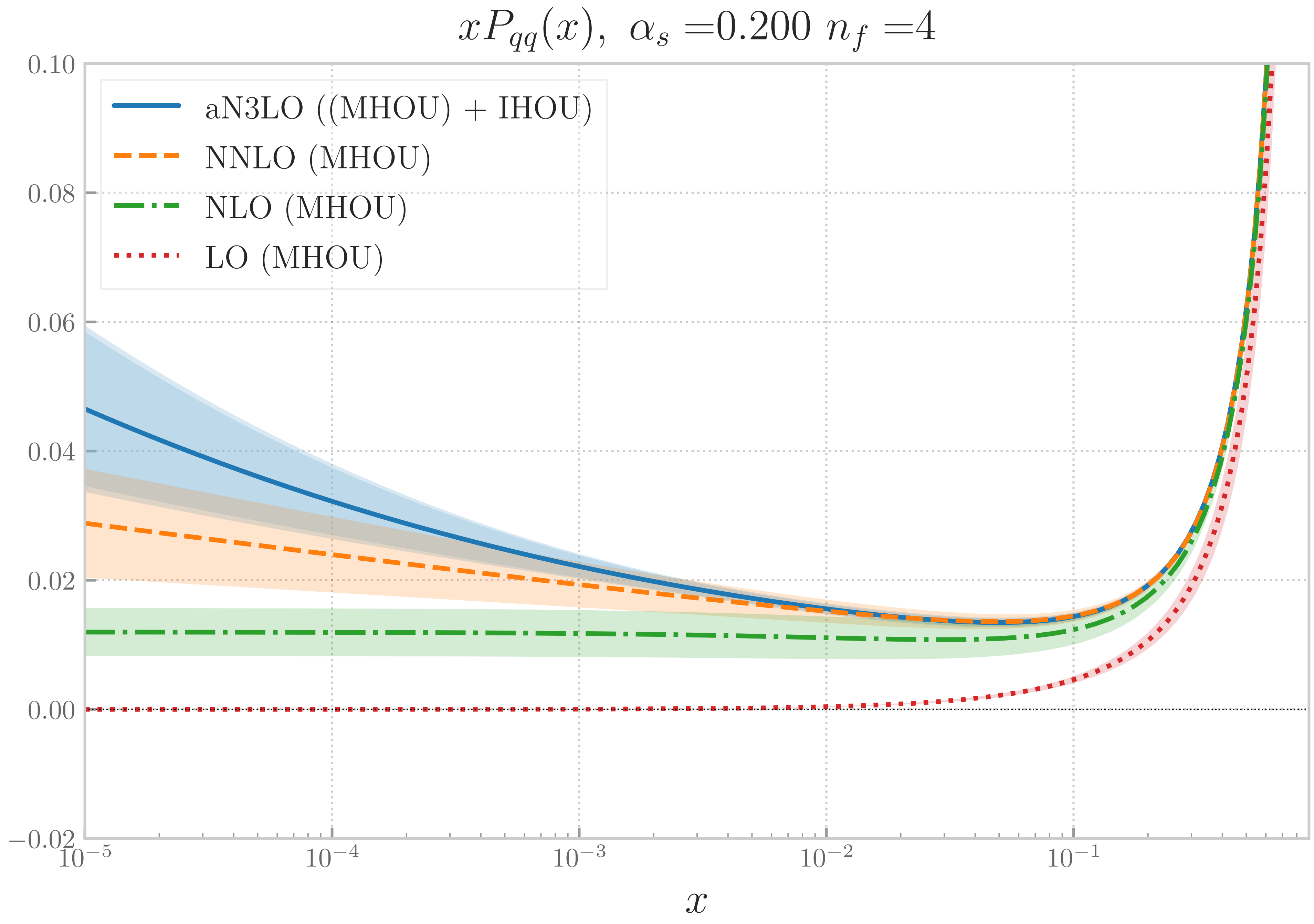
$\gamma_{qq,\mathrm{ps}}^{(3)}(N)$	$G_1(N)$	$\mathcal{M}[(1-x)\ln^2(1-x)]$
	$G_2(N)$	$-\frac{1}{(N-1)^2} + \frac{1}{N^2}$
	$G_3(N)$	$\frac{1}{N^4},\ \frac{1}{N^3},\ \mathcal{M}[(1-x)\ln(1-x)]$ $\mathcal{M}[(1-x)^2\ln(1-x)^2],\ \frac{1}{N-1}-\frac{1}{N},\ \mathcal{M}[(1-x)\ln(x)]$
	$G_4(N)$	$\mathcal{M}[(1-x)(1+2x)],\ \mathcal{M}[(1-x)x^2],$ $\mathcal{M}[(1-x)x(1+x)],\ \mathcal{M}[(1-x)]$

Approximating N3LO Anomalous Dimensions





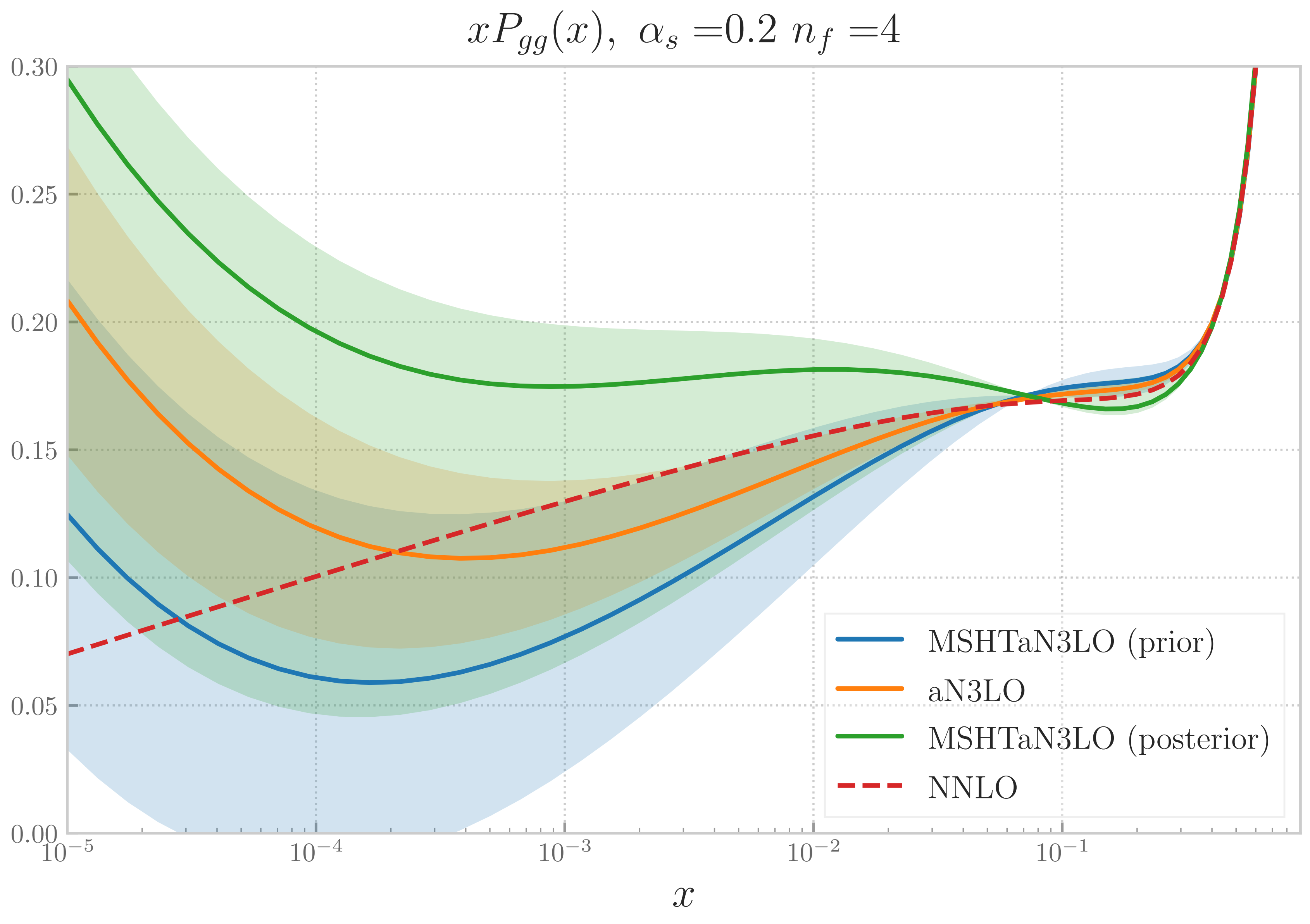


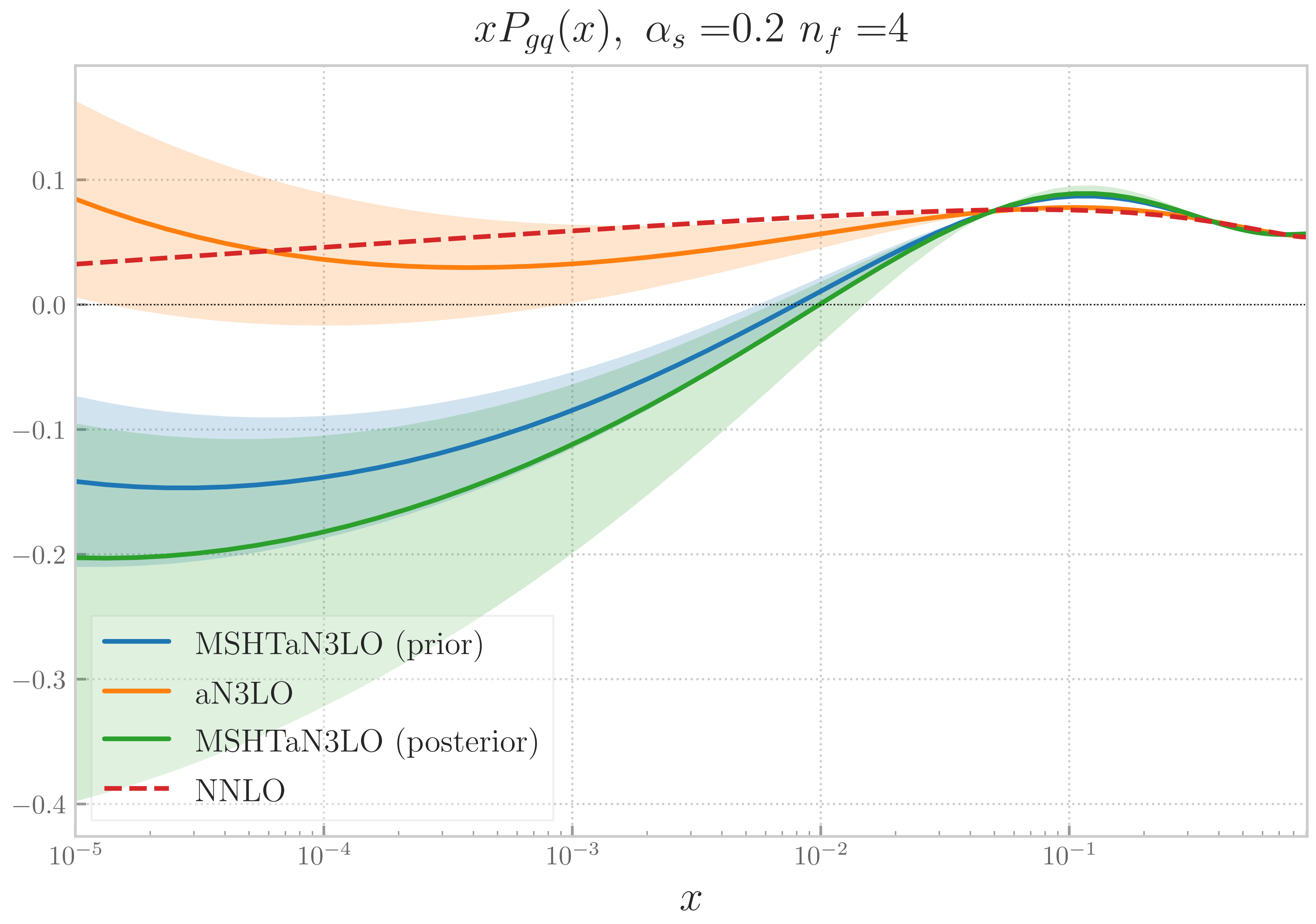


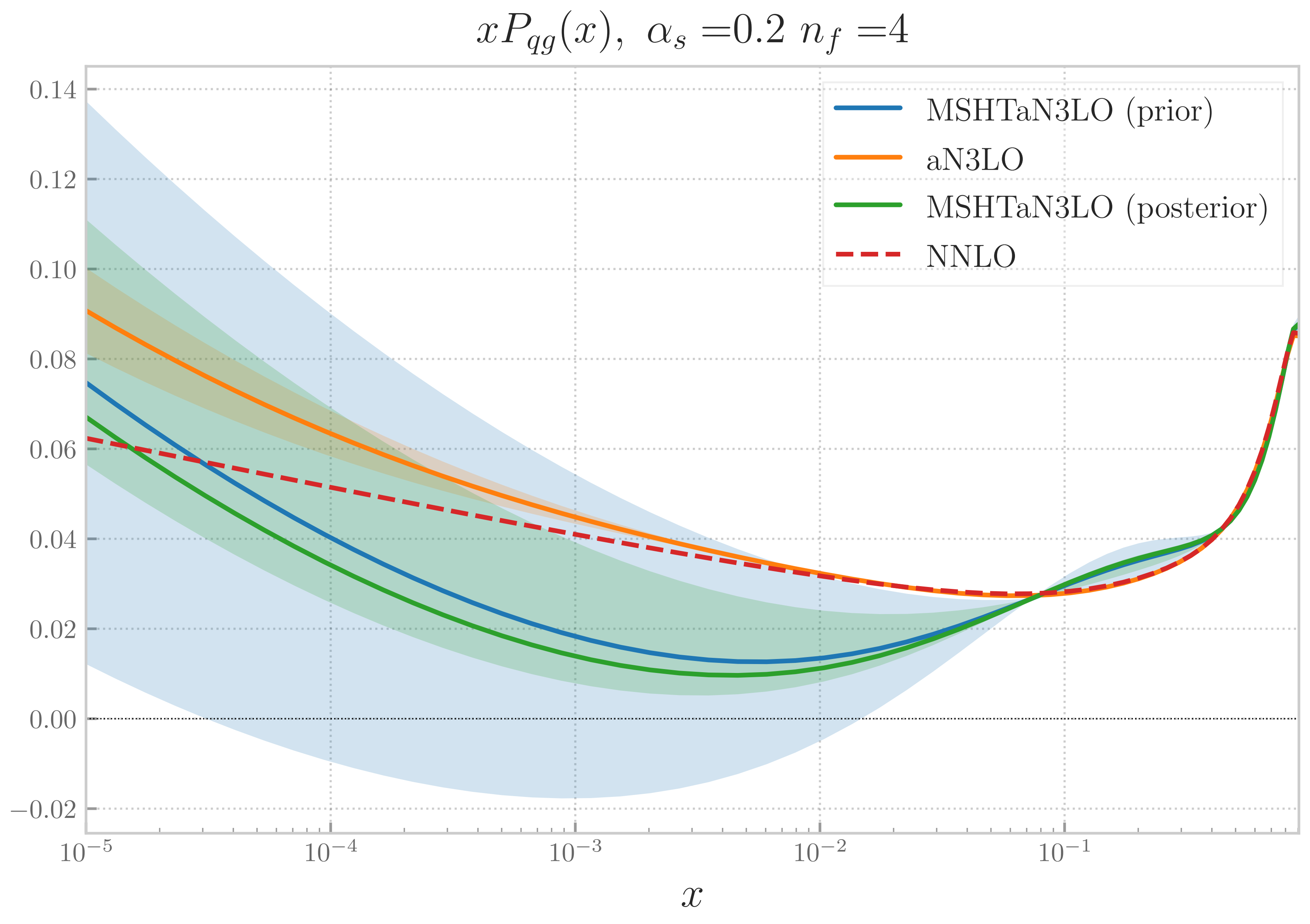
- Good agreement between different perturbative orders at large-x
- Pronounced effect of $\ln^k x/x$ behaviour ($k = 1{,}2$) at small-x
- Large **IHOUs** for **non-diagonal components** due to limited information $\Longleftrightarrow$ **MHOUs** only are not enough
- **IHOU** effects become negligible as more perturbative information are available (additional moments for $P_{qq}(x) = \mathscr{M}^{-1}(\gamma_{qq}(N)), P_{qq}(x)$

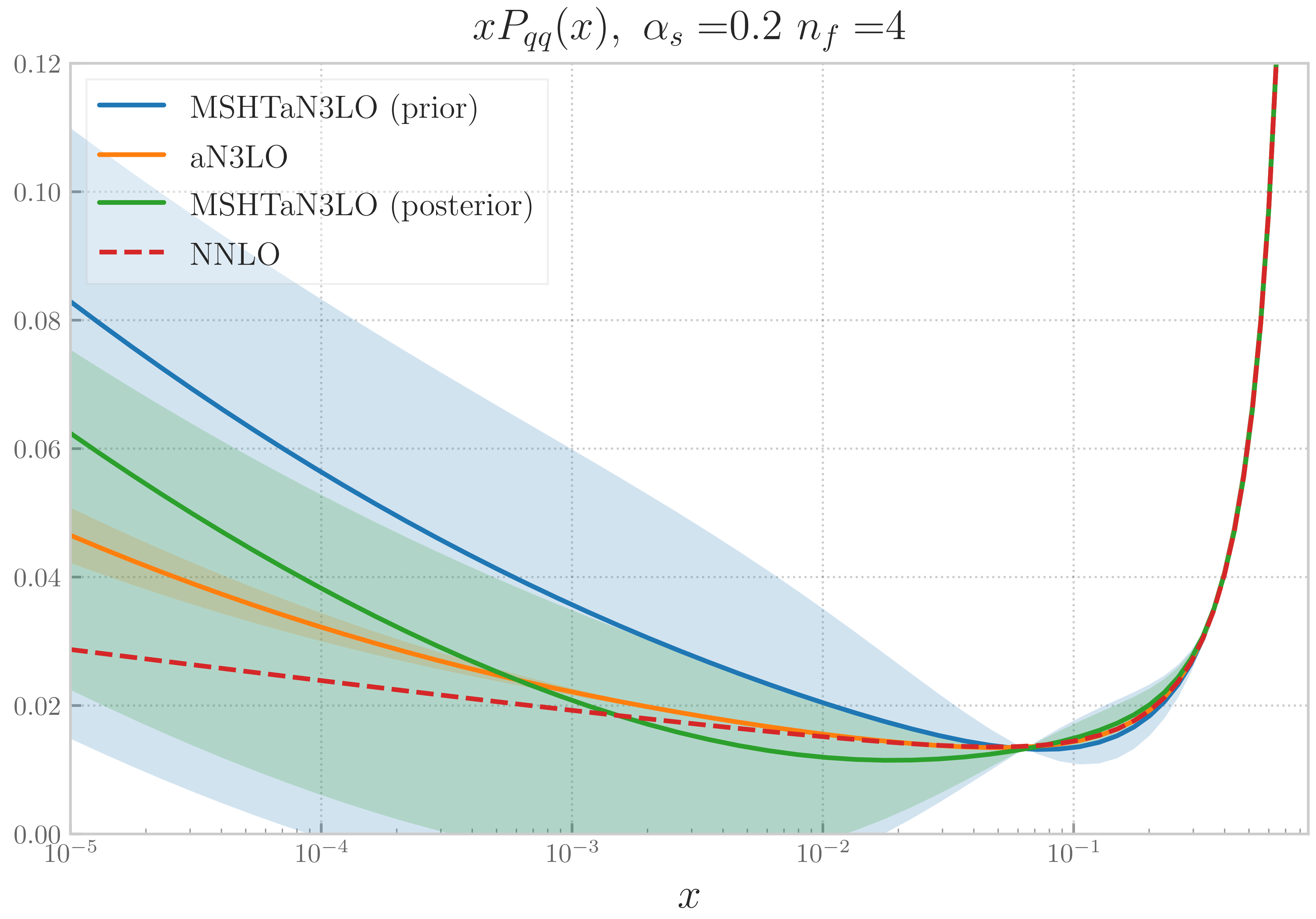
[NNPDF] G. Magni

Comparisons with MSHTaN3LO









- **MSHTaN3LO posterior uncertainties** are constrained by experimental data.
- In NNPDF4.0, uncertainties associated with **IHO** are encoded in the covariance matrix to avoid fitting nuisance parameters.
- Both approximations **agree within uncertainties** with the exception of $P_{gq}(x) = \mathscr{M}^{-1}(\gamma_{gq}(N))$ where **MSHTaN3LO saturate** at small-x.

[NNPDF] G. Magni

N3LO DIS Coefficient Functions

Some of the perturbative ingredients to produce N3LO structure functions are not yet known.

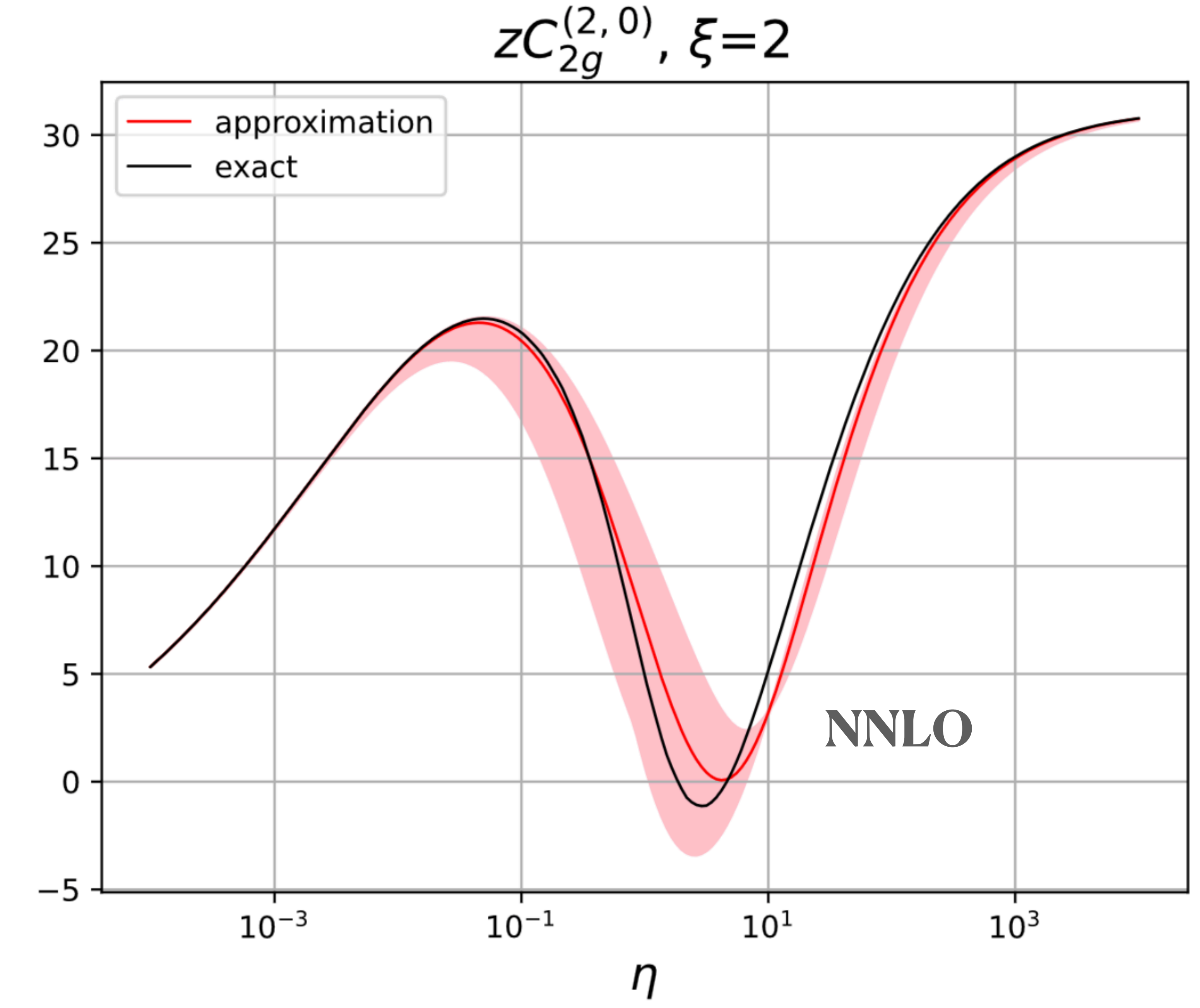
- All **Light Flavour Coefficient Functions** both for **NC** and **CC** are **known exactly** Larin, Nogueira, Van Ritbergen, Vermaseren[arxiv:9605317]; Moch, Vermaseren, Vogt [arxiv:0411112], [arxiv:0504242]

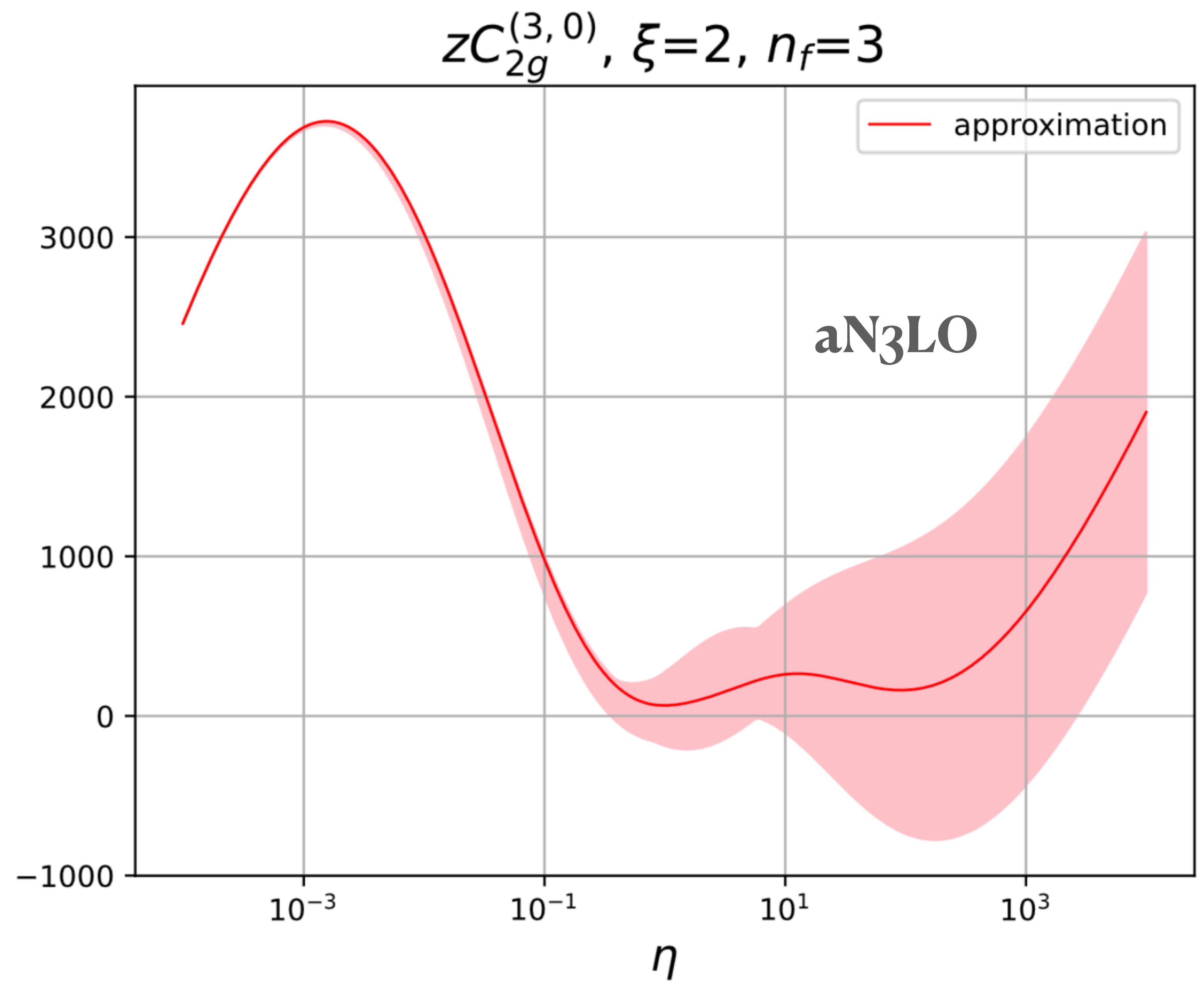
- Some parts needed for the construction of **Heavy Flavour Coefficient Functions** are missing. Take the quark & gluon coefficient functions:

$$\mathscr{C}_i^{(3)} = \mathscr{C}_i^{(3,0)} + \mathscr{C}_i^{(3,1)} \ln\left(\frac{\mu^2}{m^2}\right) + \mathscr{C}_i^{(3,2)} \ln^2\left(\frac{\mu^2}{m^2}\right)$$

While $C_i^{(3,1)}$ and $C_i^{(3,2)}$ are known exactly $C_i^{(3,0)}$ can be constructed by combining known limits with some **matching functions** $f_1(x)$ **and** $f_2(z)$ that interpolate between the two limits:

$$\mathscr{C}_{i,\mathrm{approx}}^{(3,0)}(z) = \mathscr{C}_{i,z\to 0}^{(3,0)}(z) f_1(z) + \mathscr{C}_{i,z\to z_{\max}}^{(3,0)}(z) f_2(z)$$





N. Laurenti et. Al [github:Adani]

Matching Conditions & GM-VFNS

Predictions for structure valid for all Q^2 require matching Mass effects in the Machine Scheme with Log resummation in the Massless scheme.

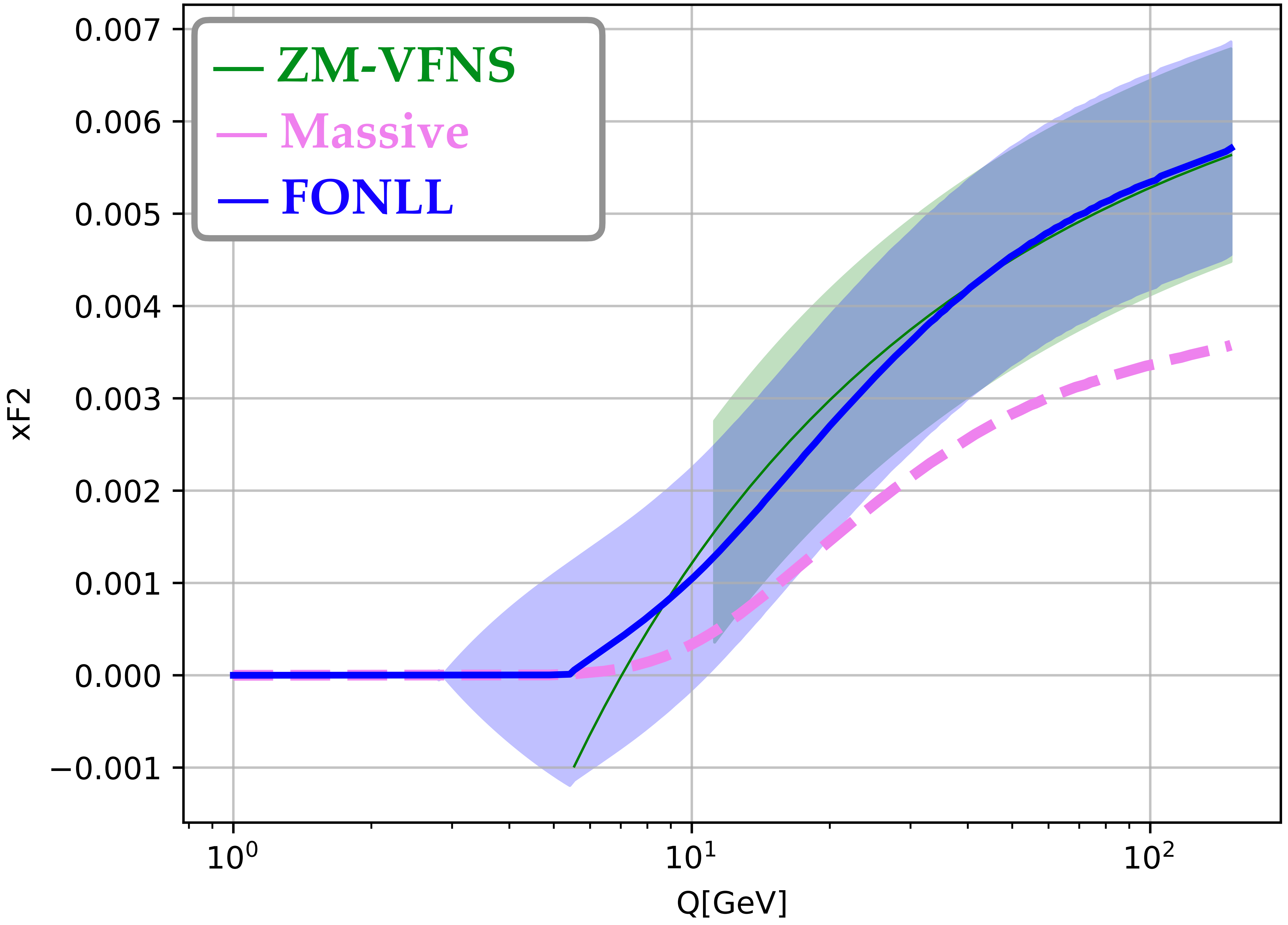
In NNPDF, DIS structure functions are computed using the **FONLL method**:

$$\tilde{F}_{\alpha}(x,Q^2) = F_{\alpha}^{(n_f+1)}(x,Q^2) - F_{\alpha}^{(n_f,0)}(x,Q^2) + F_{\alpha}^{(n_f)}(x,Q^2)$$

PDFs defined in (n_f+1) and (n_f) are related via **Matching Conditions**:

$$f_{\alpha}^{n_f+1}(x,Q^2) = \mathrm{A}_{\alpha i}^{(n_f)}(x,Q^2/m_h^2) \otimes f_i^{n_f}(x,Q^2)$$

The **full entries** of the Matching Condition matrix elements are **almost** completely known except for $a_{H,g}^{(3)}$ Ablinger, Behring, Blümlein, De Freitas, Goedicke, von Manteuffel, Schonwald [arXiv:2211.0546]; Ablinger, Behring, Blümlein, De Freitas, Hasselhuhn, von Manteuffel, Round, Schneider, Wißbrock. [arXiv:1406.4654]; Bierenbaum, Blümlein, Klein [arXiv:0904.3563]

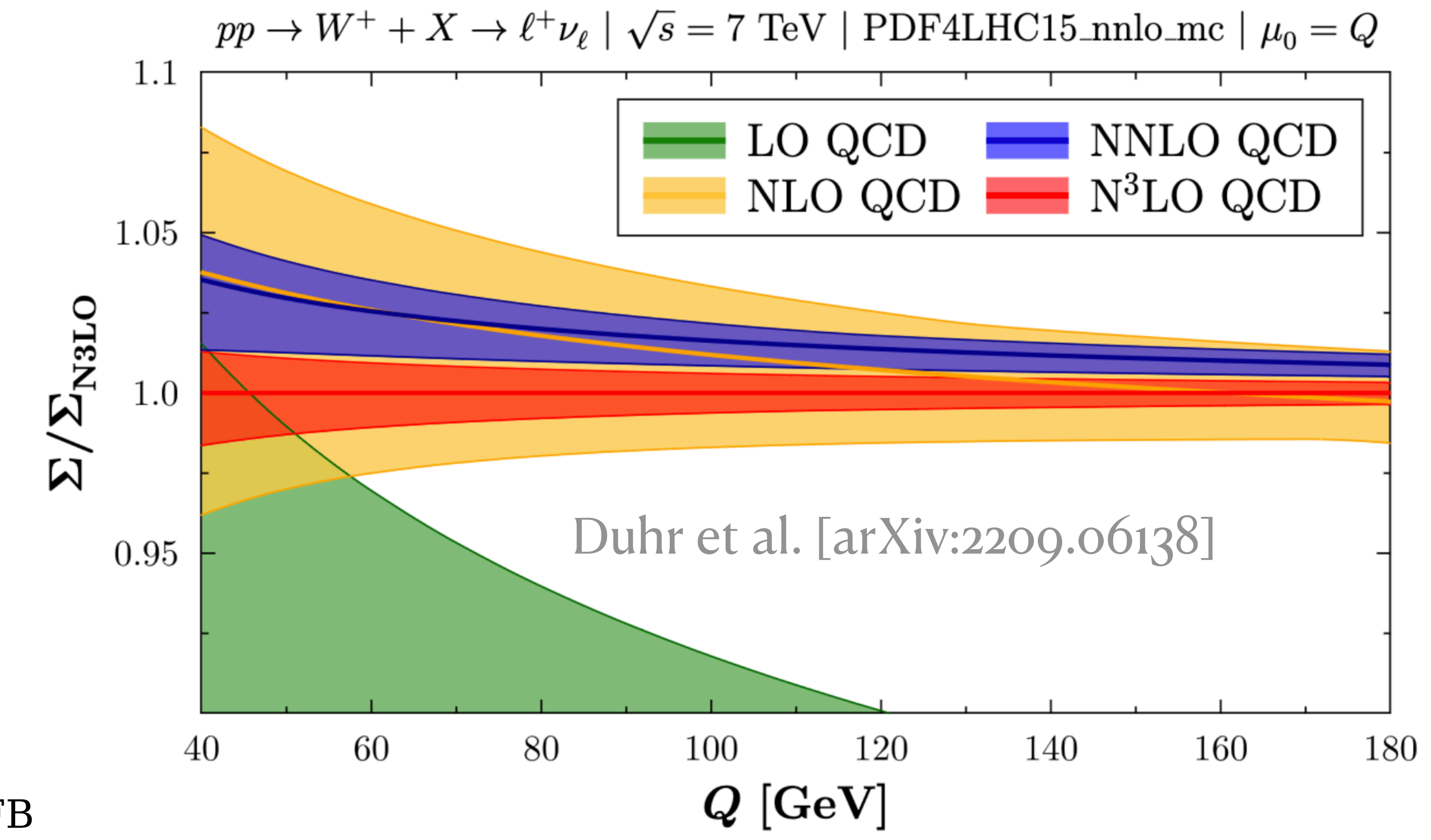


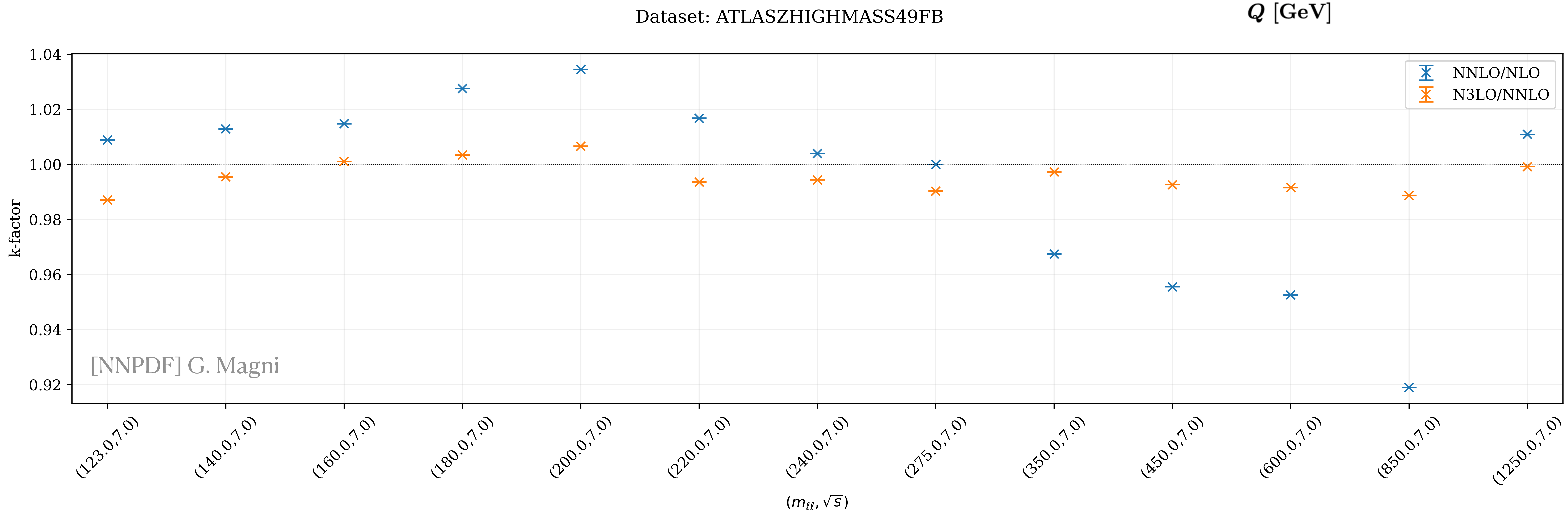
[NNPDF] G. Magni, A. Barontini

Hadronic K-factors

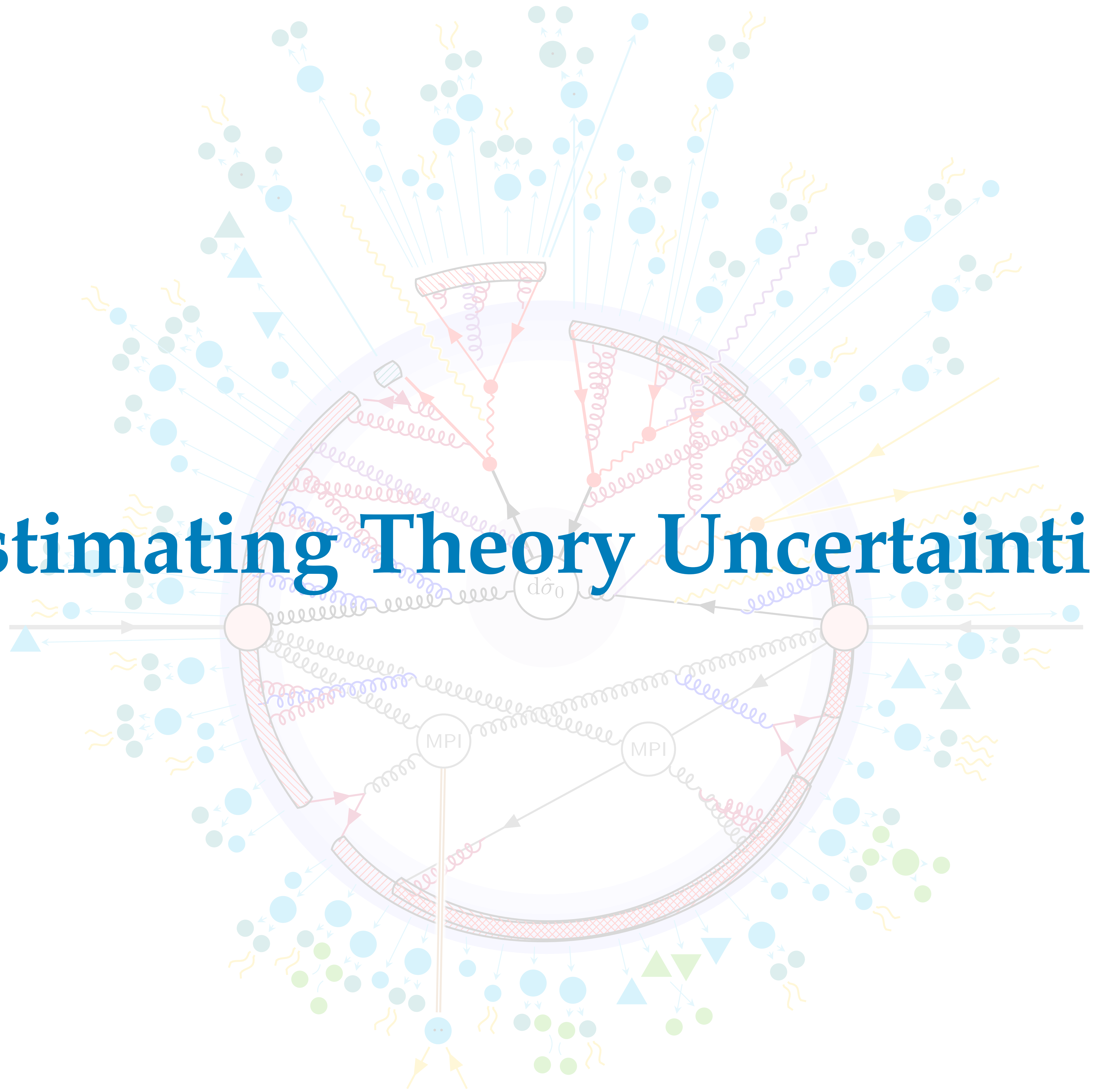
https://github.com/jubaglio/n3loxs

- **Double Hadronic K-factors** are **much less known** than the other ingredients needed for (a)N3LO
- Various calculations are available at **N3LO** but **not useful for PDF fits**: Higgs (ggF, VBF, VH) B. Mistlberger [arXiv:1802.00833]; A. Dreyer, A. Karlberg [arXiv:1606.00840], J. Baglio, C. Duhr, B. Mistlberger, R. Szafron [arXiv:2209.06138], Top N. Kidonakis, M. Guzzi, A. Toreno [arXiv: 2306.06166]
- In NNPDF, hadronic K-factors are computed using **n3loxs** for all NC/CC DY J. Baglio, C. Duhr, B. Mistlberger, R. Szafron [arXiv:2209.06138]:





Estimating Theory Uncertainties



IHOUs from N3LO Splitting Functions

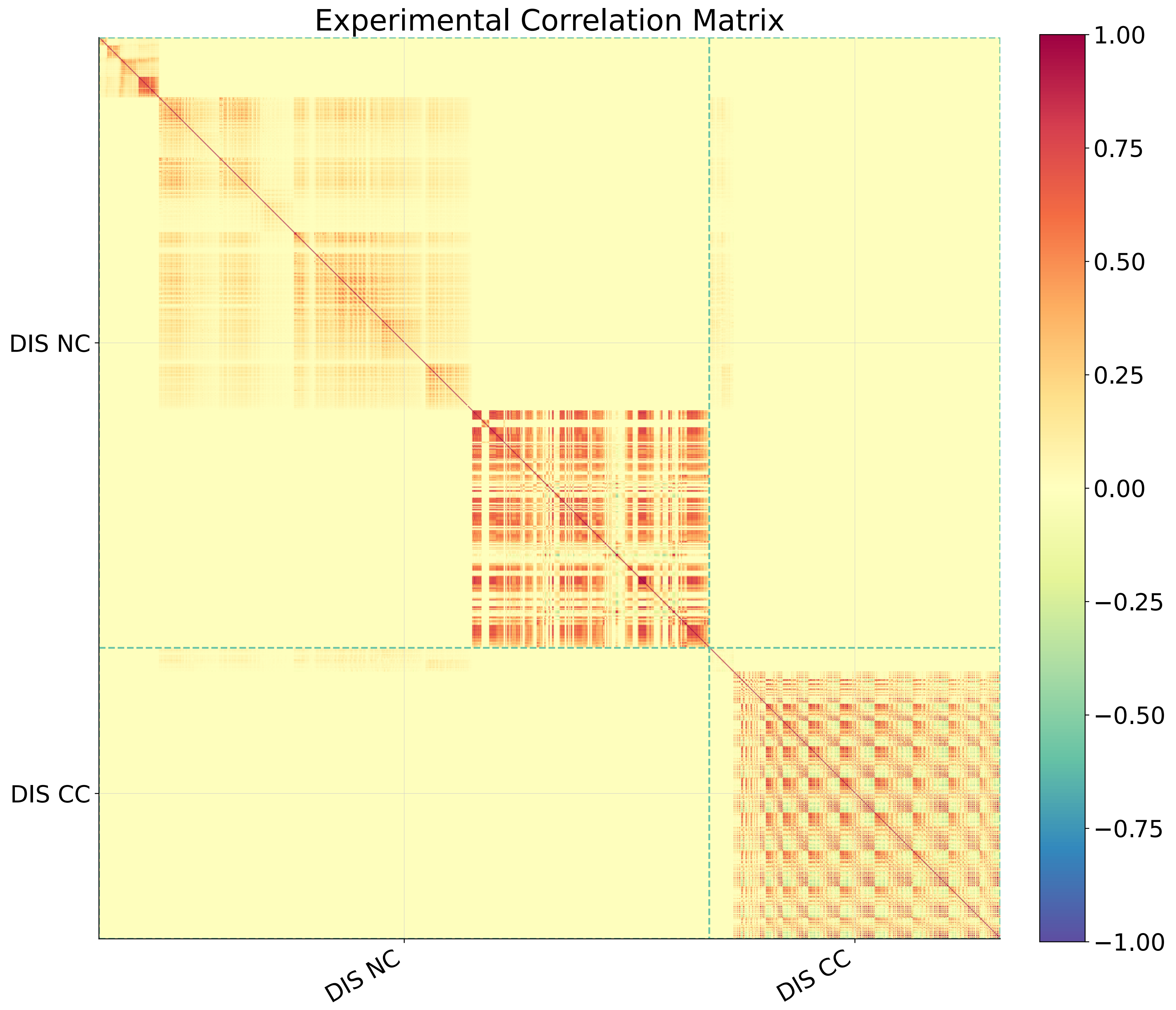
How are higher-order uncertainties arising from the approximation of N3LO splitting functions propagated into the PDF Fit?

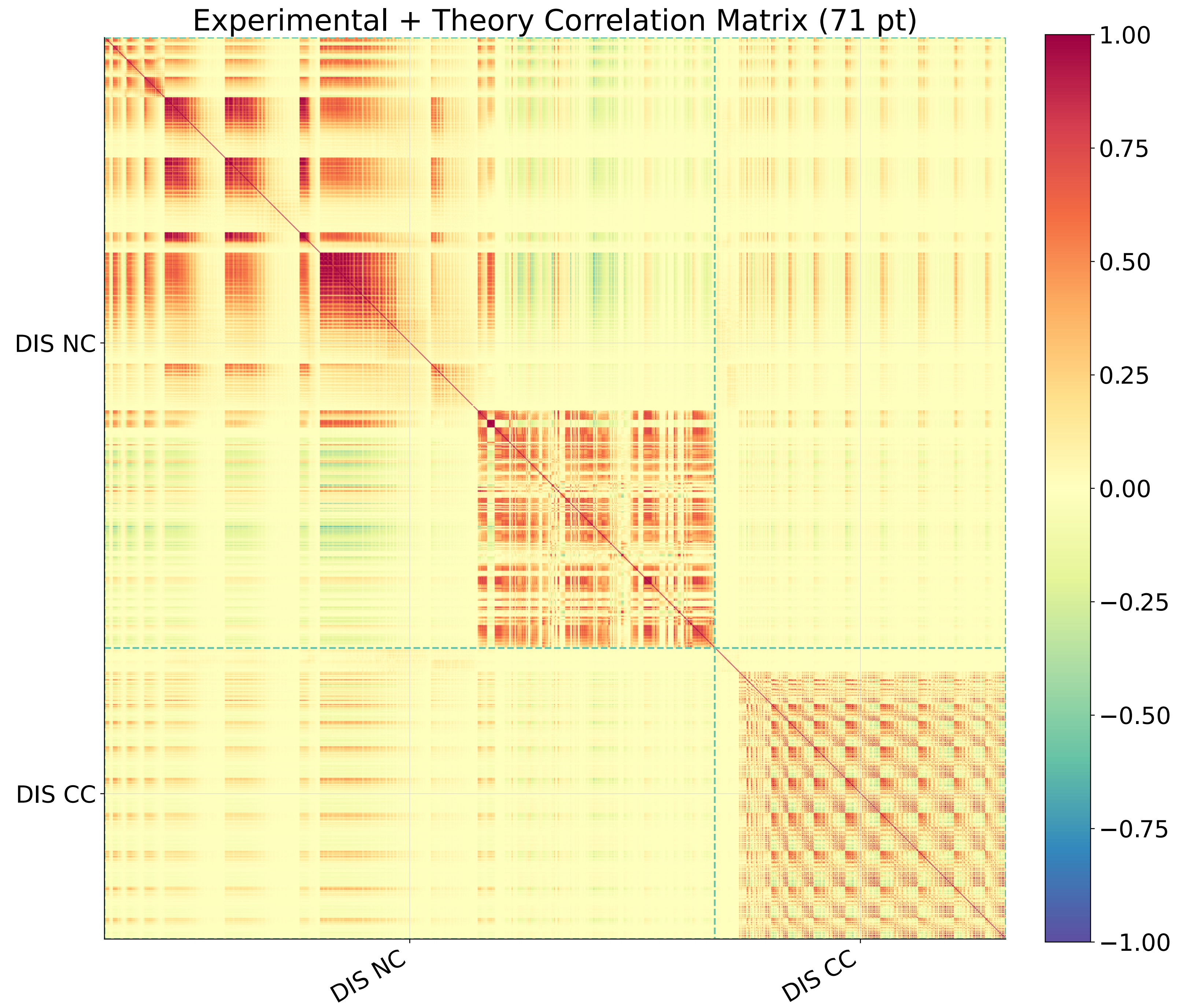
Variation of the Basis functions used to parametrise $\widetilde{\gamma}_{ij}$ generate N_γ variations. The spread of variation w.r.t. the Central Predictions is used to define a **Covariance Matrix**:

$$\mathrm{Cov}^{\mathrm{IHOU}}_{i,j} = \frac{1}{N_{\mathrm{var}} - 1} \sum_{k=1}^{N_{\mathrm{var}}} \left(T_{i,k} - \bar{T}_i\right)\left(T_{j,k} - \bar{T}_j\right)$$

Since theory uncertainties resulting from **IHOUs** are **independent** from experimental uncertainties, the two contributions can be added in Quadrature:

$$\mathrm{Cov}_{i,j} = \mathrm{Cov}^{\mathrm{exp}}_{i,j} + \mathrm{Cov}^{\mathrm{IHOU}}_{i,j}$$

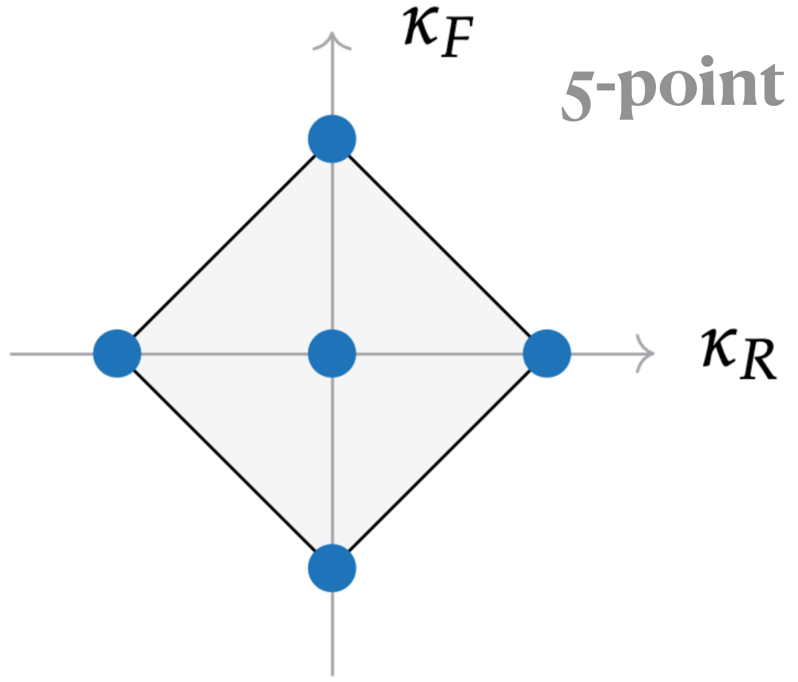




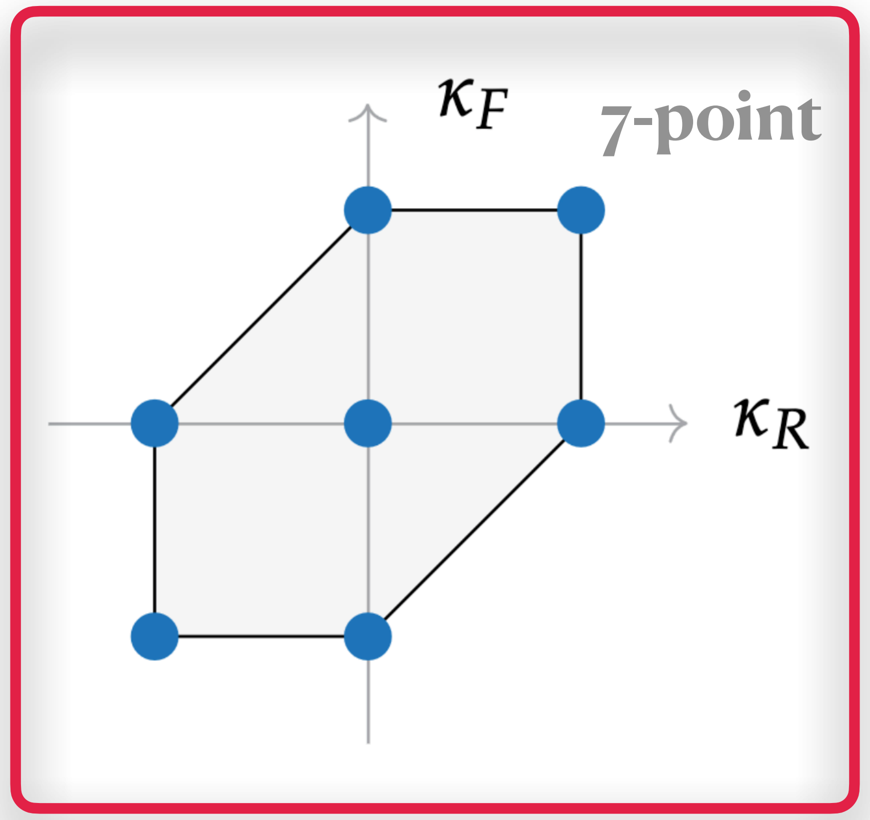
Missing Higher Order Uncertainties (MHOUs)

For a given observable $\mathcal{O}$, **MHOUs** are commonly estimated by **varying the unphysical scales** in the **Parton evolutions** and in the **partonic cross-sections**:

$$\mathcal{O}\left(\alpha_s\left(\mu^2\right), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right) = \mathcal{L}\left(\alpha_s\left(\mu_F^2\right), \frac{Q^2}{\mu_F^2}\right) \mathcal{O}\left(\alpha_s\left(\mu_R^2\right), \frac{Q^2}{\mu_R^2}\right)$$

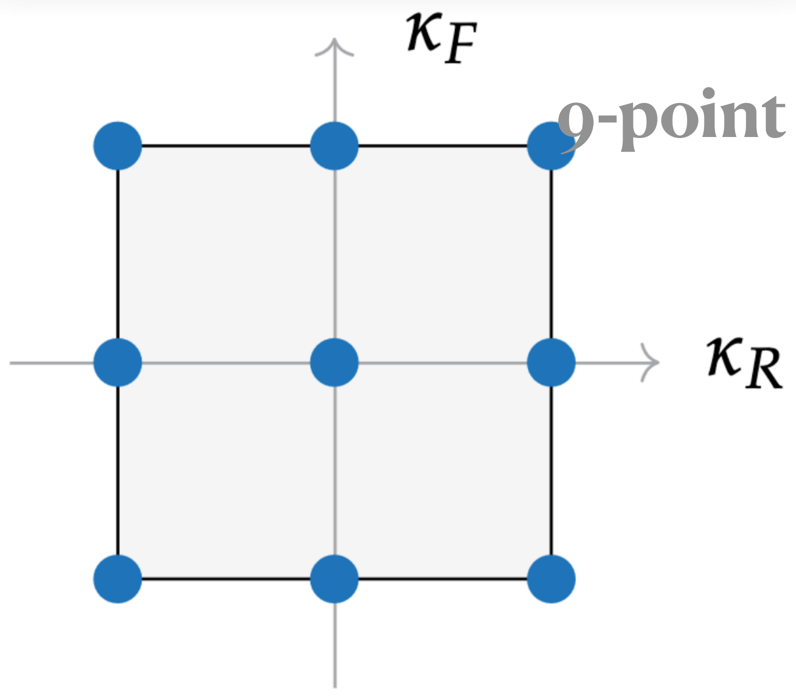


Variation of **Factorisation Scale** $\kappa_F = Q^2/\mu_R^2$ estimates MHOUs from Anomalous Dimensions in the evolution while variation of **Renormalisation Scale** $\kappa_R = Q^2/\mu_R^2$ estimates MHOUs from partonic cross-sections.



Similar to **IHOUs**, **MHOUs** can be added as a nuisance parameter to the Covariance Matrix NNPDF [arxiv:1906.10698], [arxiv:2105.05114]

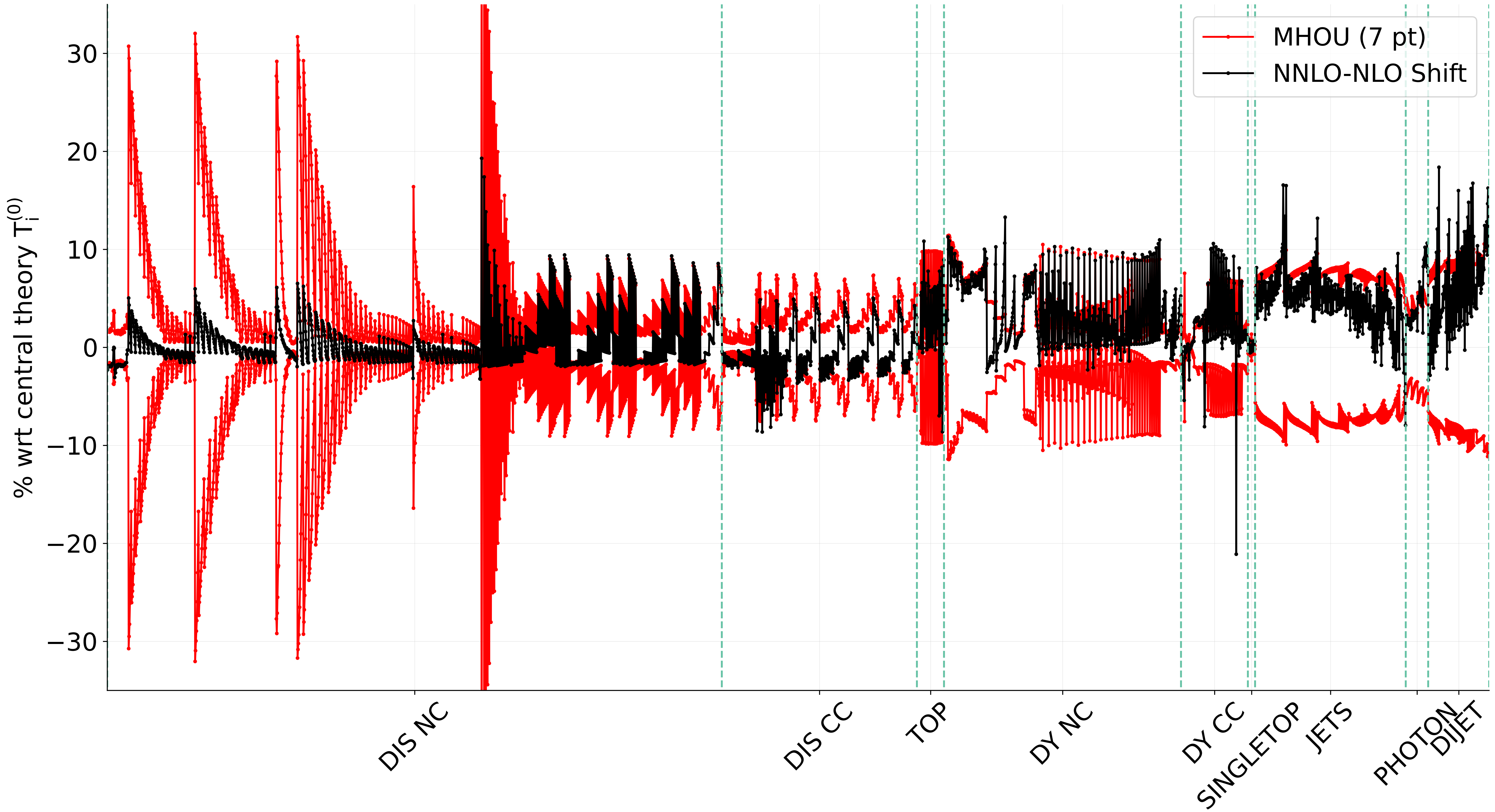
$$\mathrm{Cov}_{i,j} = \mathrm{Cov}_{i,j}^{\mathrm{exp}} + \mathrm{Cov}_{i,j}^{\mathrm{MHOU}}, \quad \mathrm{Cov}_{i,j}^{\mathrm{MHOU}} = \frac{1}{N_{\mathrm{var}} - 1} \sum_{k=1}^{N_{\mathrm{var}}} \left(S_{i,k} - \bar{S}_i\right)\left(S_{j,k} - \bar{S}_j\right)$$



7-point scale variation prescription is used. Points belonging to the same process are CORRELATED by κ_R-variation while κ_F correlates all the points.

Missing Higher Order Uncertainties (MHOUs)

We can check that the MHOU is Working by looking at the <u>Diagonal Entries</u>.



$$\left(\frac{\sqrt{\mathrm{Cov}^{MHOU}_{ii,\mathrm{NLO}}}}{\mathcal{O}_i^{\mathrm{MHOU}}}\right) \times 100$$

$$\left(\frac{\mathcal{O}_i^{\mathrm{NNLO}} - \mathcal{O}_i^{\mathrm{NLO}}}{\mathcal{O}_i^{\mathrm{NLO}}}\right) \times 100$$

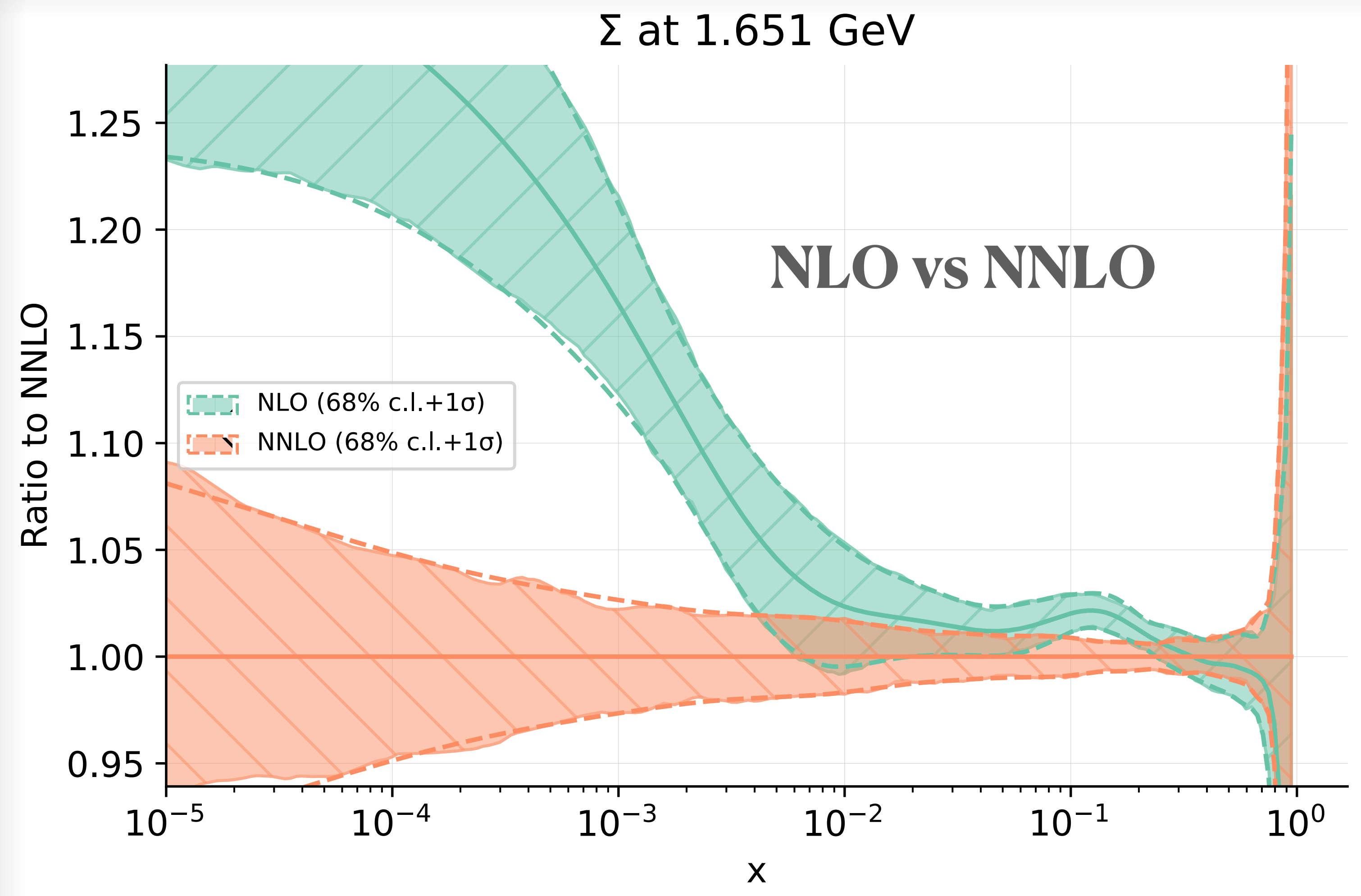
Good consistency between MHOUs & NNLO-NLO Shifts

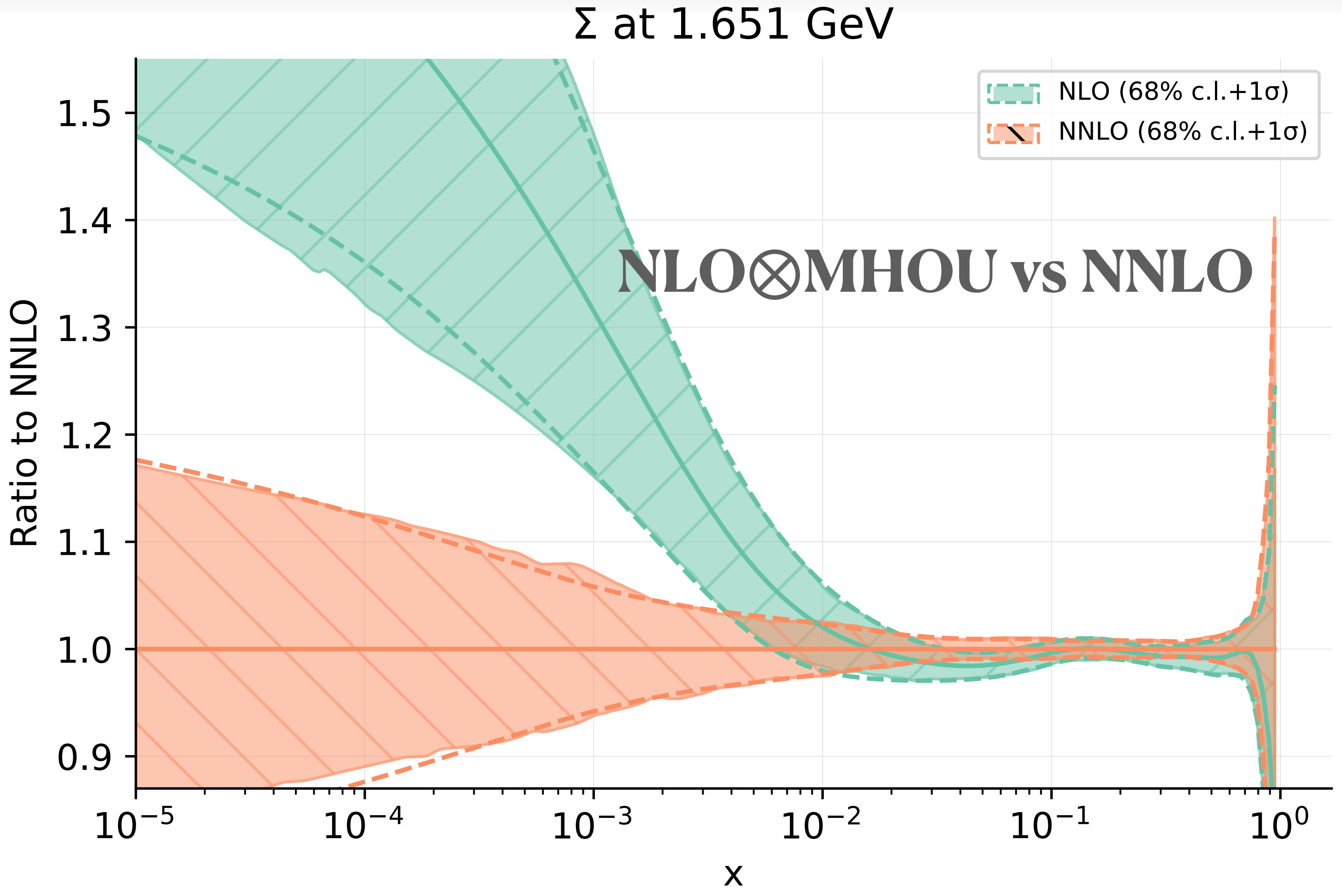
NNLO MHOU Correlation Matrices

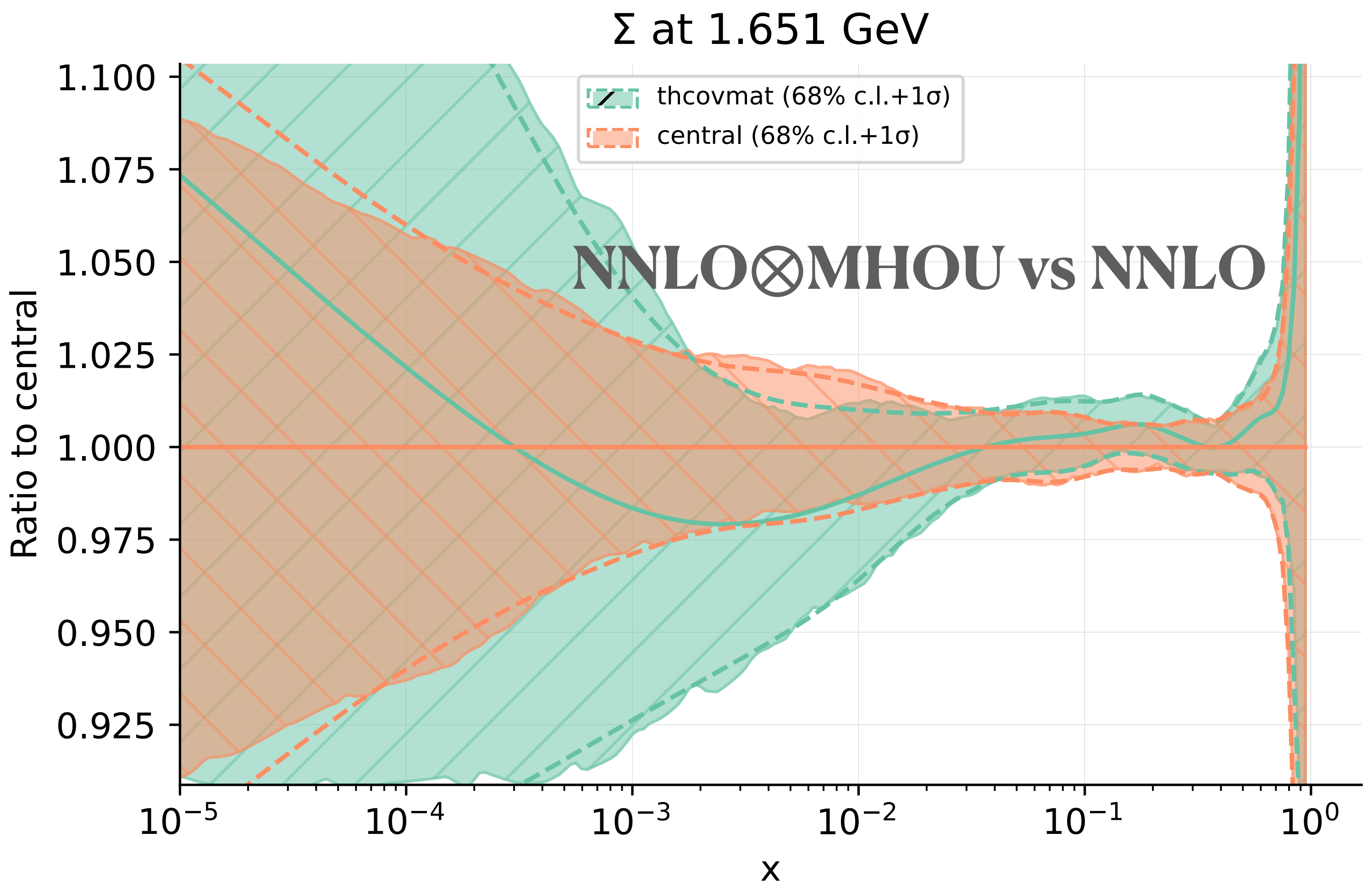
- First ever NNLO PDF determination with MHO Uncertainties
- MHOUs add CORRELATION between process not taken into account by experimental Covariance Matrix

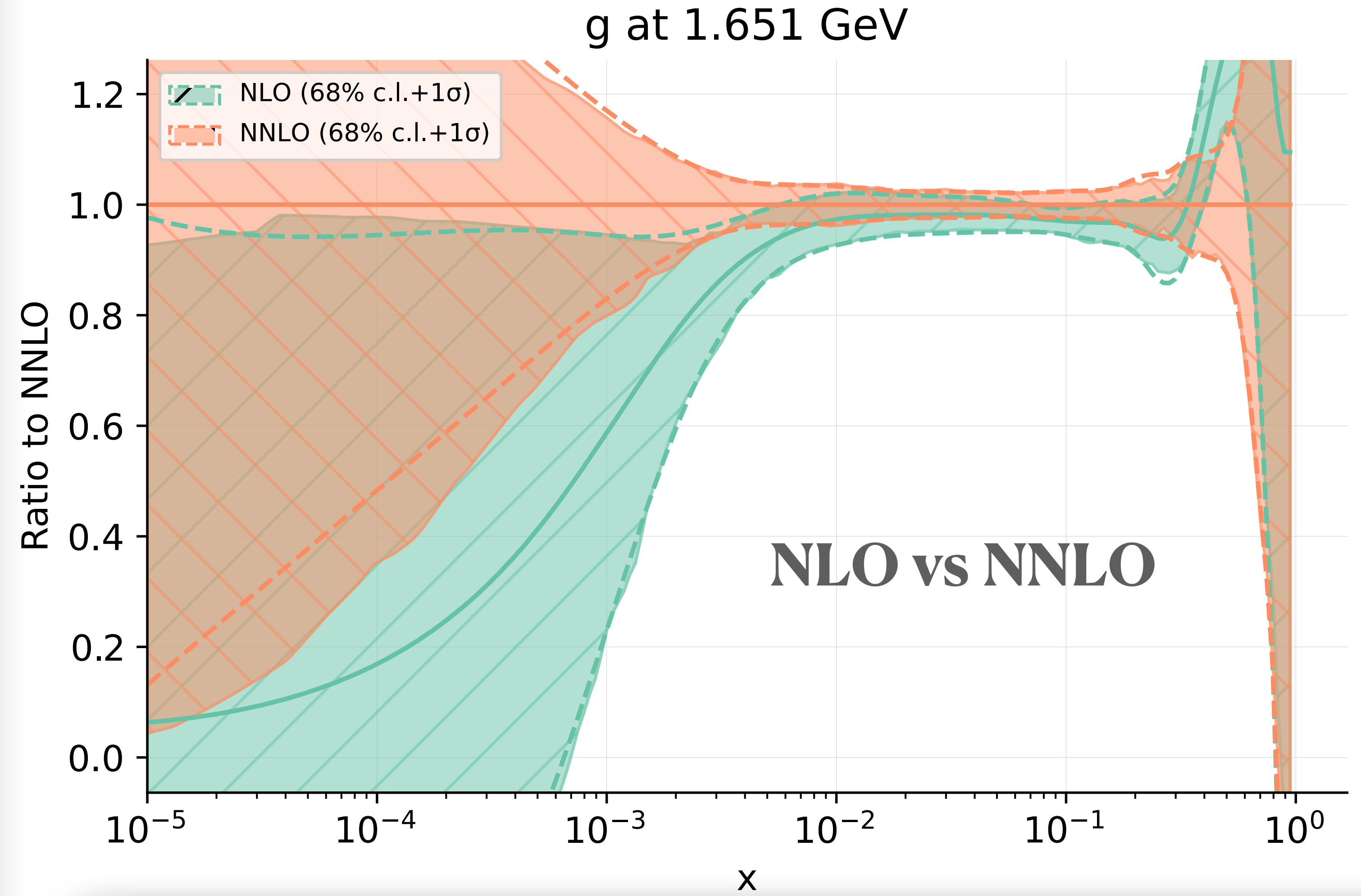
$$\rho_{ij} = \frac{\mathrm{Cov}_{ij}}{\sqrt{\mathrm{Cov}_{ii}}\sqrt{\mathrm{Cov}_{jj}}}$$

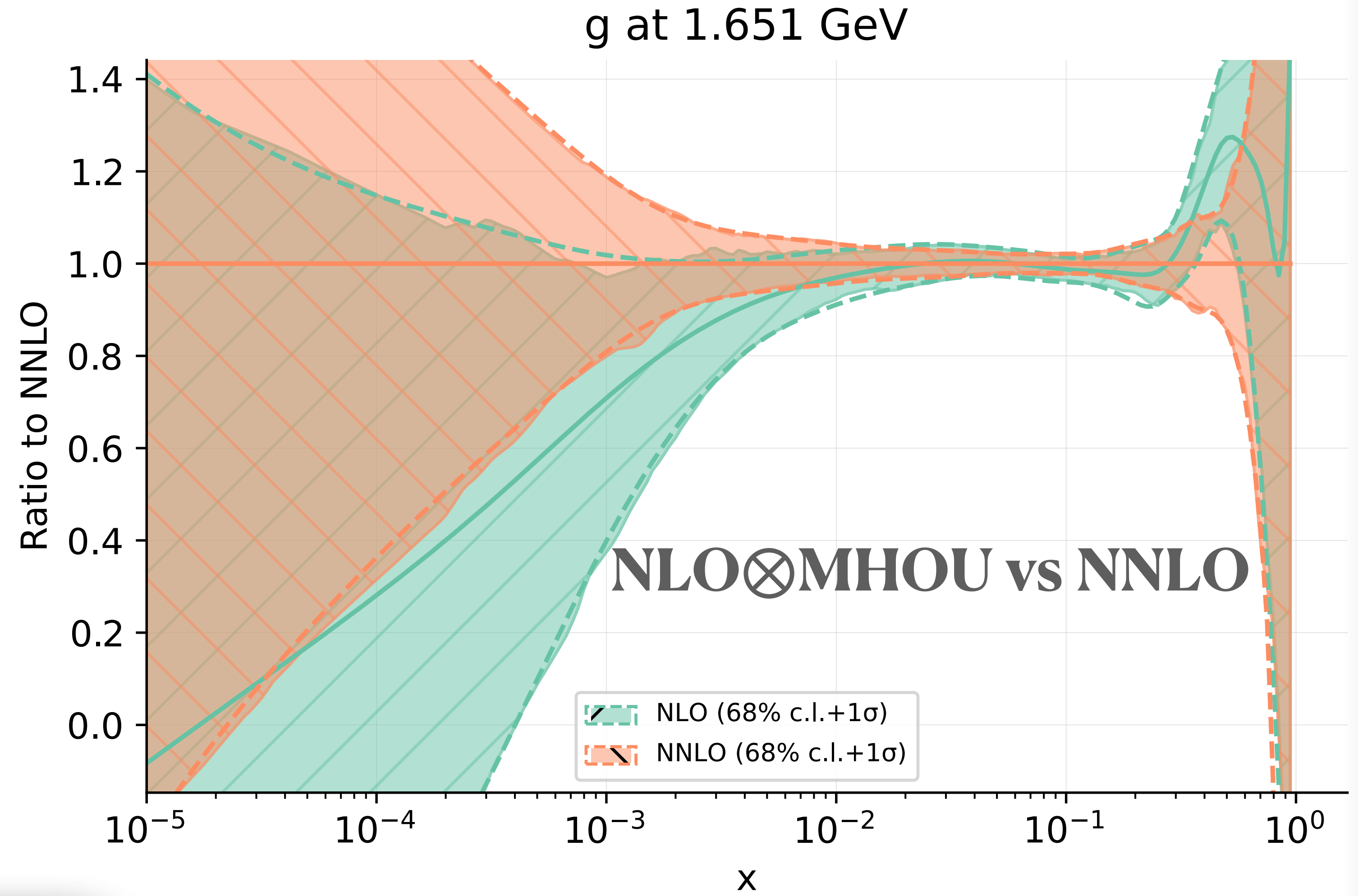
Impacts of MHOUs on PDFs

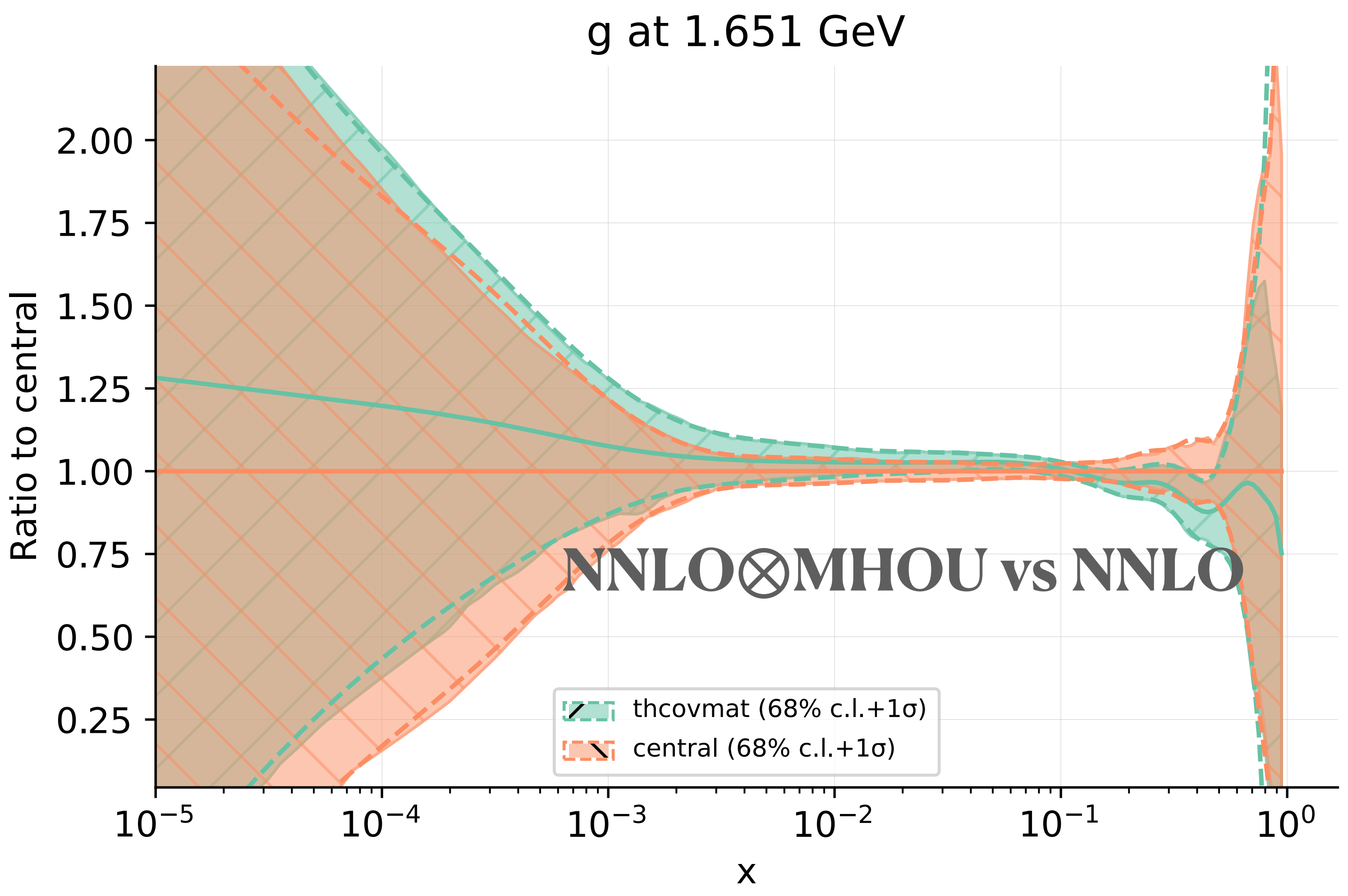






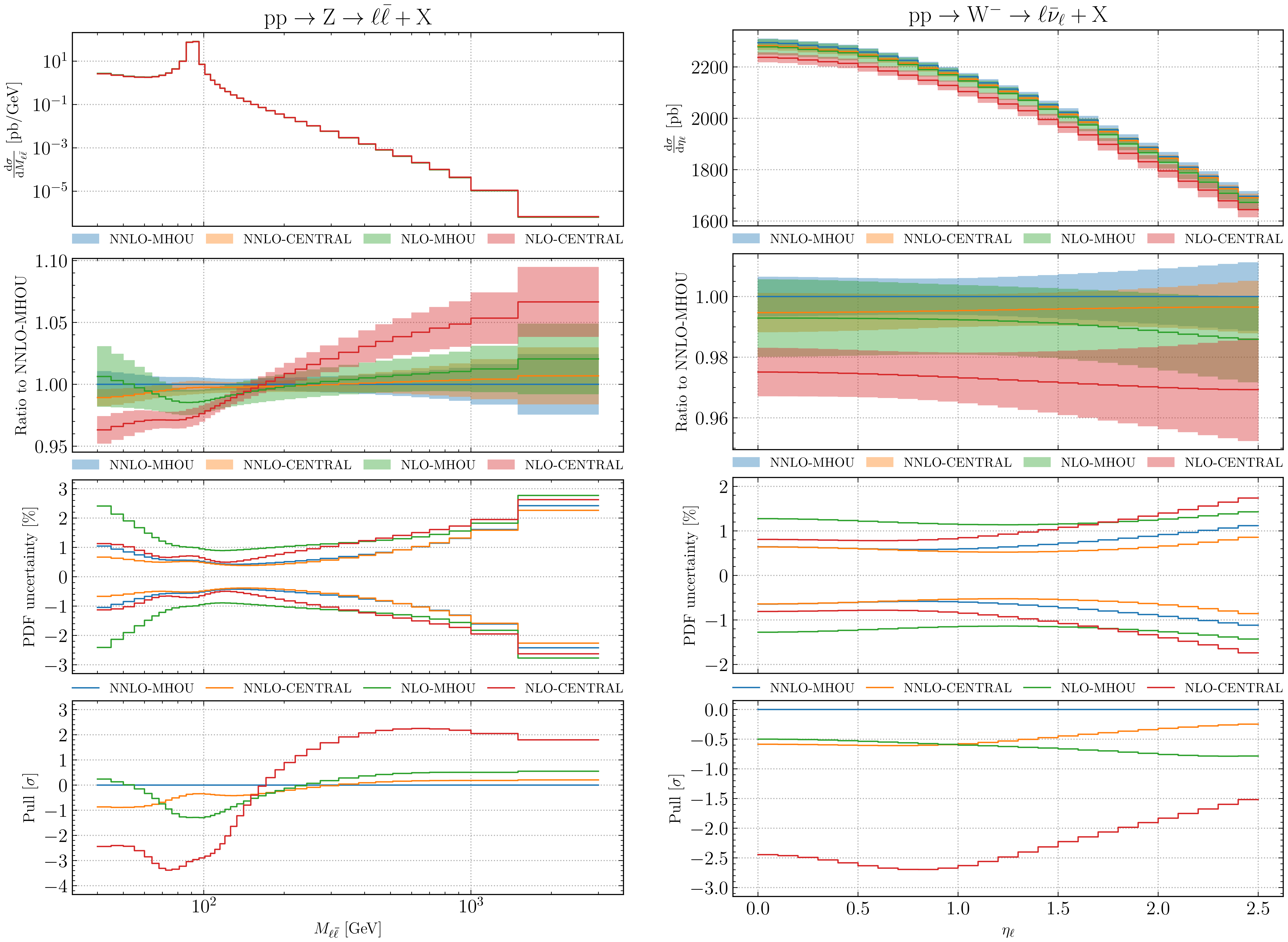






Compare Perturbative Convergence

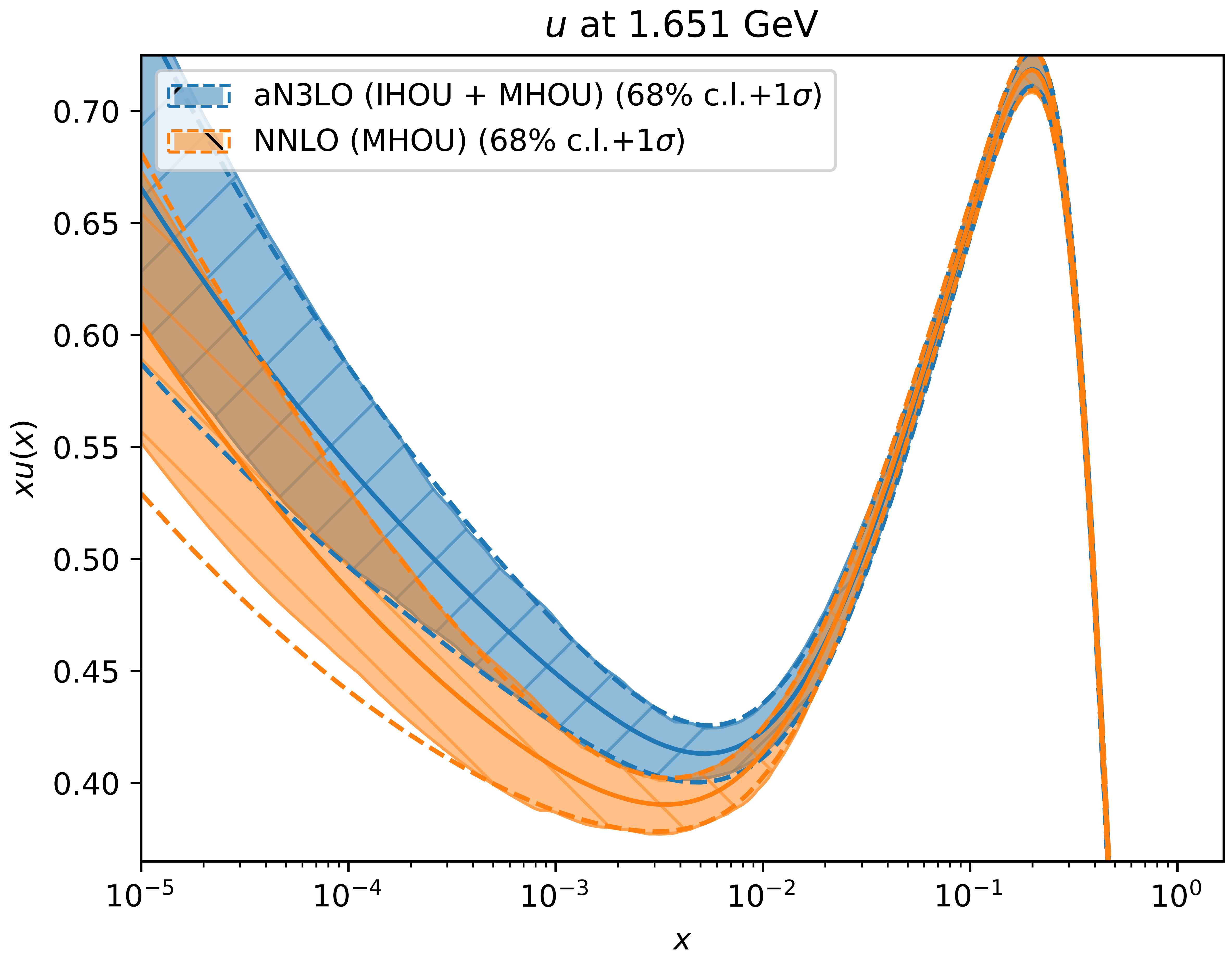
Phenomenological Impacts of MHOUs



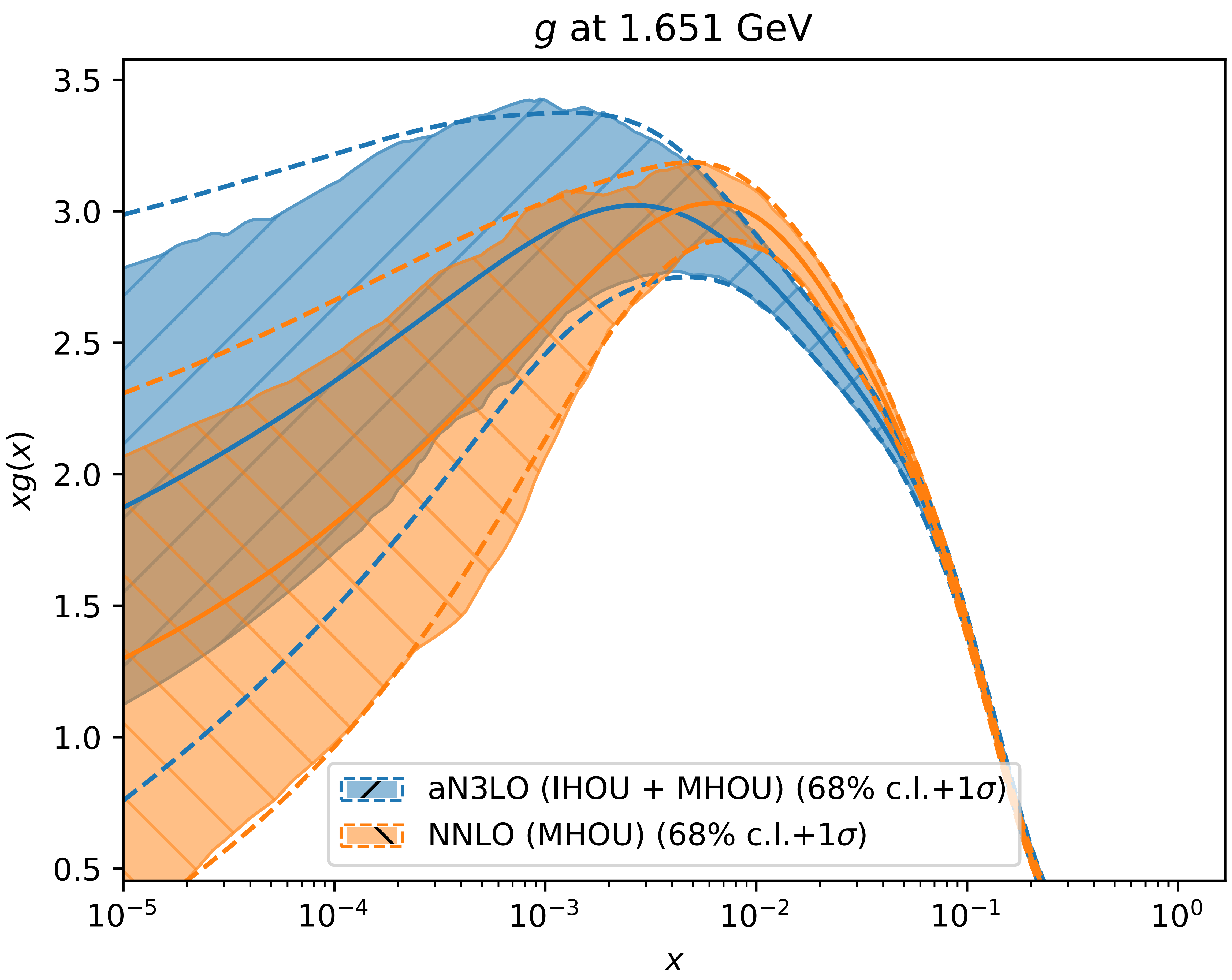
- **NLO-MHOU** predictions are closer to **NNLO** than pure **NLO**.
- Very good agreement between **NNLO** and **NNLO-MHOU**.
- MHOUs **improve perturbative convergence** from **NLO** to **NNLO**.
- **NLO** vs. **NNLO** exhibit the **largest Uncertainty Pull**.

[NNPDF] C. Schwan & A. Barontini

NNPDF4.0 @ aN3LO PDFs with MHOUs



- Very good agreement at large-x
- Noticeable discrepancies at small-x, nevertheless results are compatible within uncertainties



PDF Determination with QED

PDF Fits with QED Effects

- Photon PDF $\gamma(x, Q^2)$ can no longer be neglected as determination of parton densities become more accurate $\alpha \sim \mathcal{O}(\alpha_s^2) \sim \mathcal{O}(1\%)$.
- **LuxQED**: γ-PDF can be computed perturbatively using as inputs structure functions A.V. Manohar, P. Nason, G.P. Salam, G. Zanderighi [arXiv:1607.04266]—[arXiv:1708.01256]; NNPDF3.1 [arXiv:1712.07053]; MSHT20 [arXiv: 2111.05357]

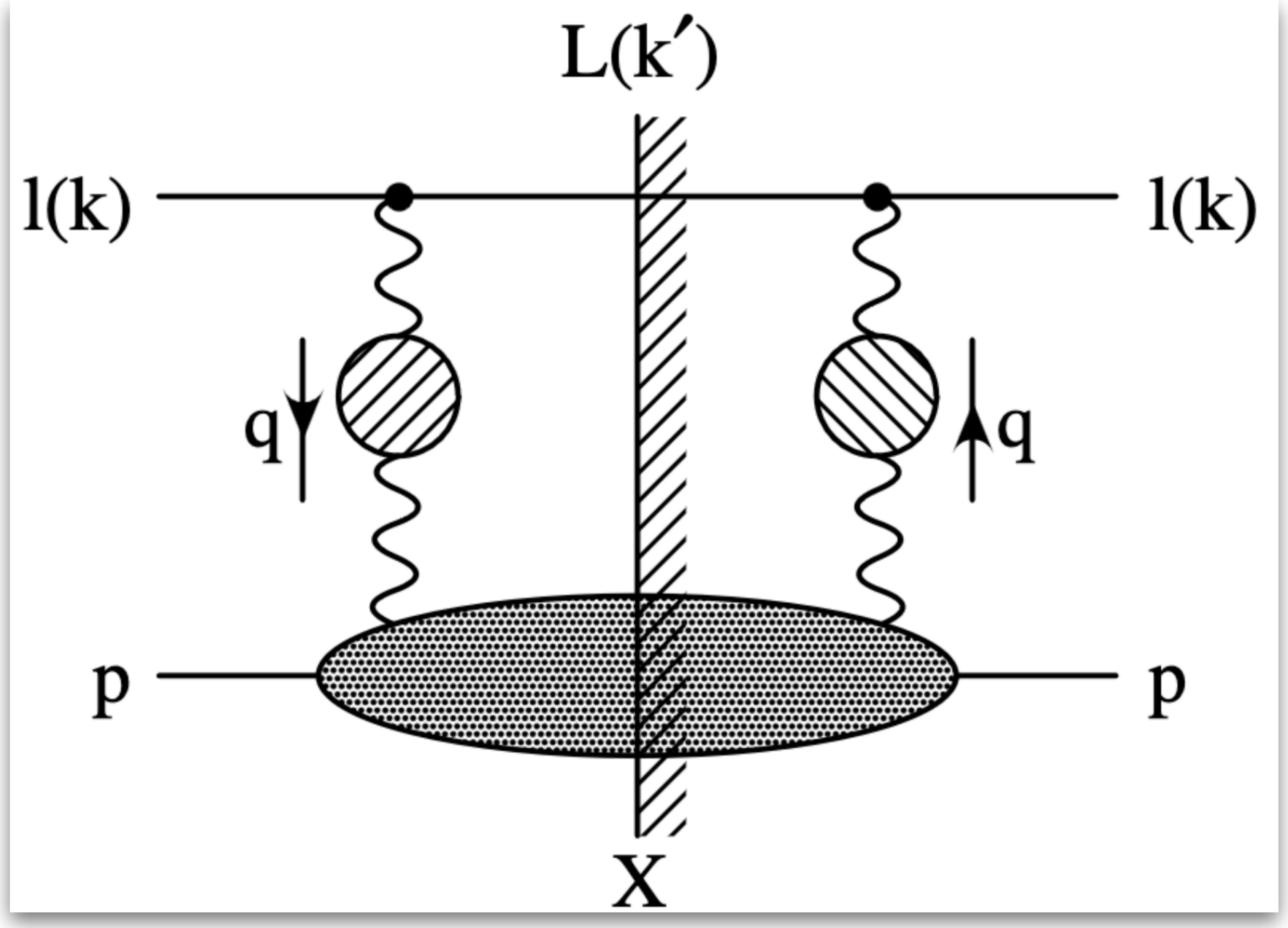
Two main changes are required to account for QED effects in PDF fits:

- **Modified QCD ⊗ QED DGLAP Evolution:**

$$\mu^2 \frac{df_i\left(N,\mu^2\right)}{d\mu^2} = \sum_j \gamma_{ij}\left(N, \alpha_s\left(\mu^2\right), \alpha\left(\mu^2\right)\right) f_j\left(N,\mu^2\right)$$

- **Mixed QCD ⊗ QED Sum Rules:**

$$\int_0^1 dx\left(x\Sigma + xg + x\gamma\right) = 1$$



LO	$\alpha_s^1\alpha^0$	$\alpha_s^0\alpha^1$	
NLO	$\alpha_s^2\alpha^0$	$\alpha_s^1\alpha^1$	$\alpha_s^0\alpha^2$
NNLO	$\alpha_s^3\alpha^0$	$\alpha_s^2\alpha^1$	....

★ Orders Included ★ Orders Not Included

Determination of γ PDF

Parton density functions and γ-PDF are determined such that they satisfy the following Sum Rule:

$$\int_0^1 dx \left(x\Sigma\left(x, Q^2\right) + xg\left(x, Q^2\right) + x\gamma\left(x, Q^2\right)\right) = 1$$

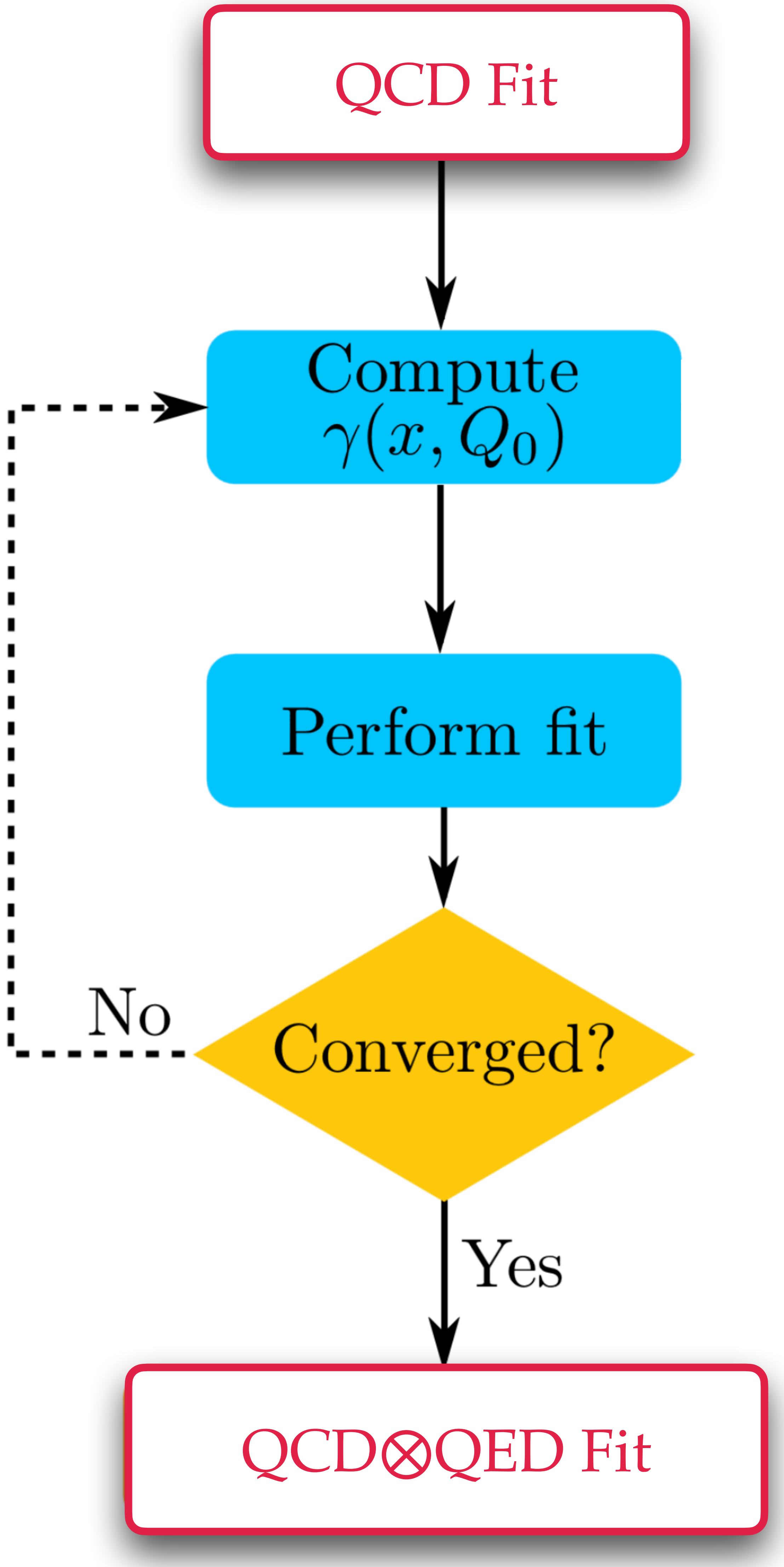
$$a_{em} = \alpha/(4\pi)$$

$$F_{2,L} = \mathscr{C}^i_{2,L} \otimes f_i$$

Where $\gamma(x, Q^2)$ is computed iteratively during the fit using structure function inputs:

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

While $\gamma(x, Q^2)$ depends on the PDFs through the structure functions, it affects their determination.



NNPDF [arXiv:1712.07053]

Mixed QCD ⊗ QED Evolution

Because photons couple differently to **up-like** and **down-like** quarks

$\Longleftrightarrow$

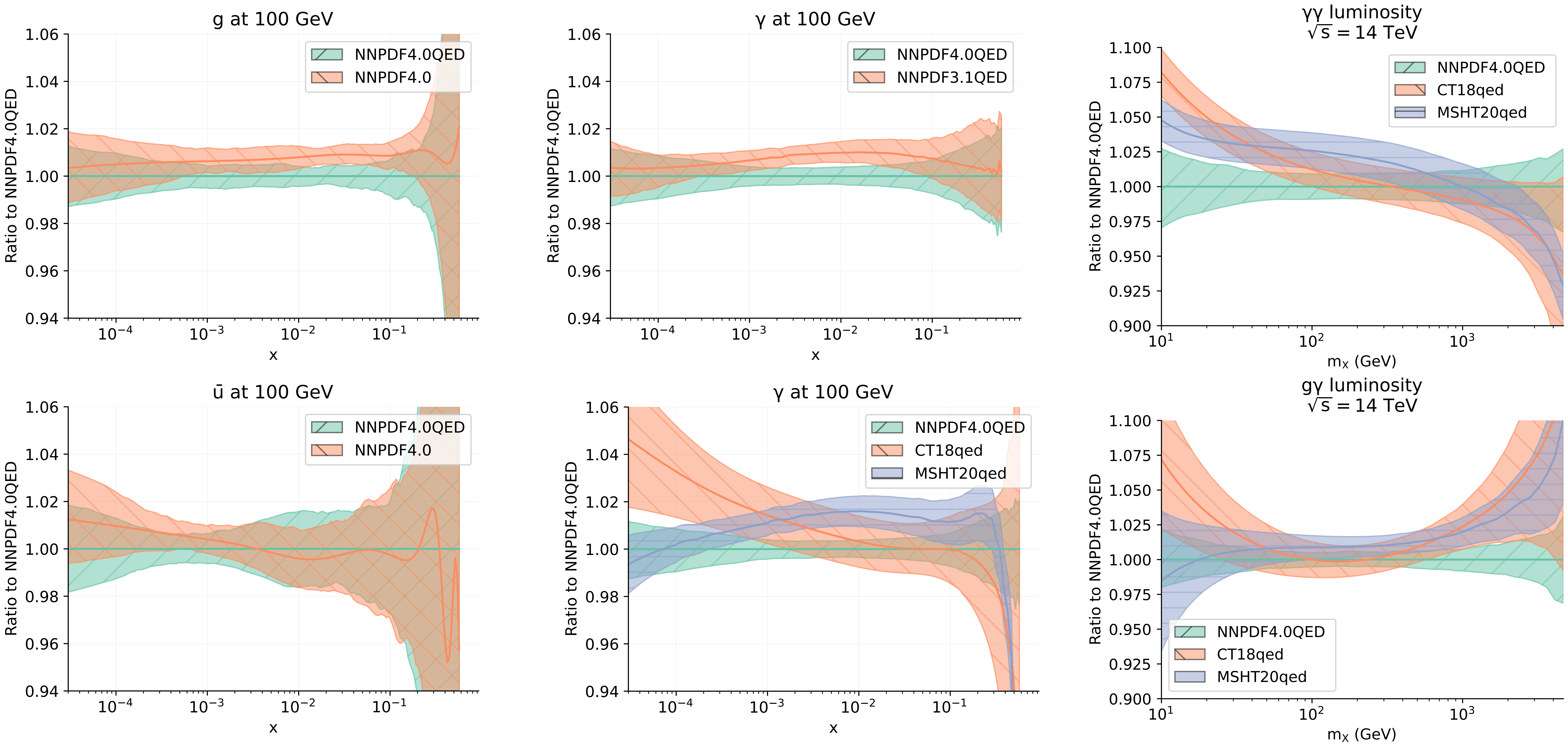
QCD⊗QED Evolution is **more difficult to Diagonalise**

NNPDF4.0QED uses a so called **Unified Evolution Basis** n_f active quarks are split into n_u and n_f flavors $(n_f = n_u + n_d)$

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Sigma_\Delta \end{pmatrix} = -\boldsymbol{\Gamma}_s \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Sigma_\Delta \end{pmatrix}, \quad \mu^2 \frac{d}{d\mu^2} \begin{pmatrix} V \\ V_\Delta \end{pmatrix} = \boldsymbol{\Gamma}_V \begin{pmatrix} V \\ V_\Delta \end{pmatrix}, \quad \mu^2 \frac{d}{d\mu^2} f^{u/d}_{ns,\pm} = \left(\gamma_{ns,\pm} + \tilde{\gamma}^{u/d}_{ns,\pm}\right) f^{u/d}_{ns,\pm}$$

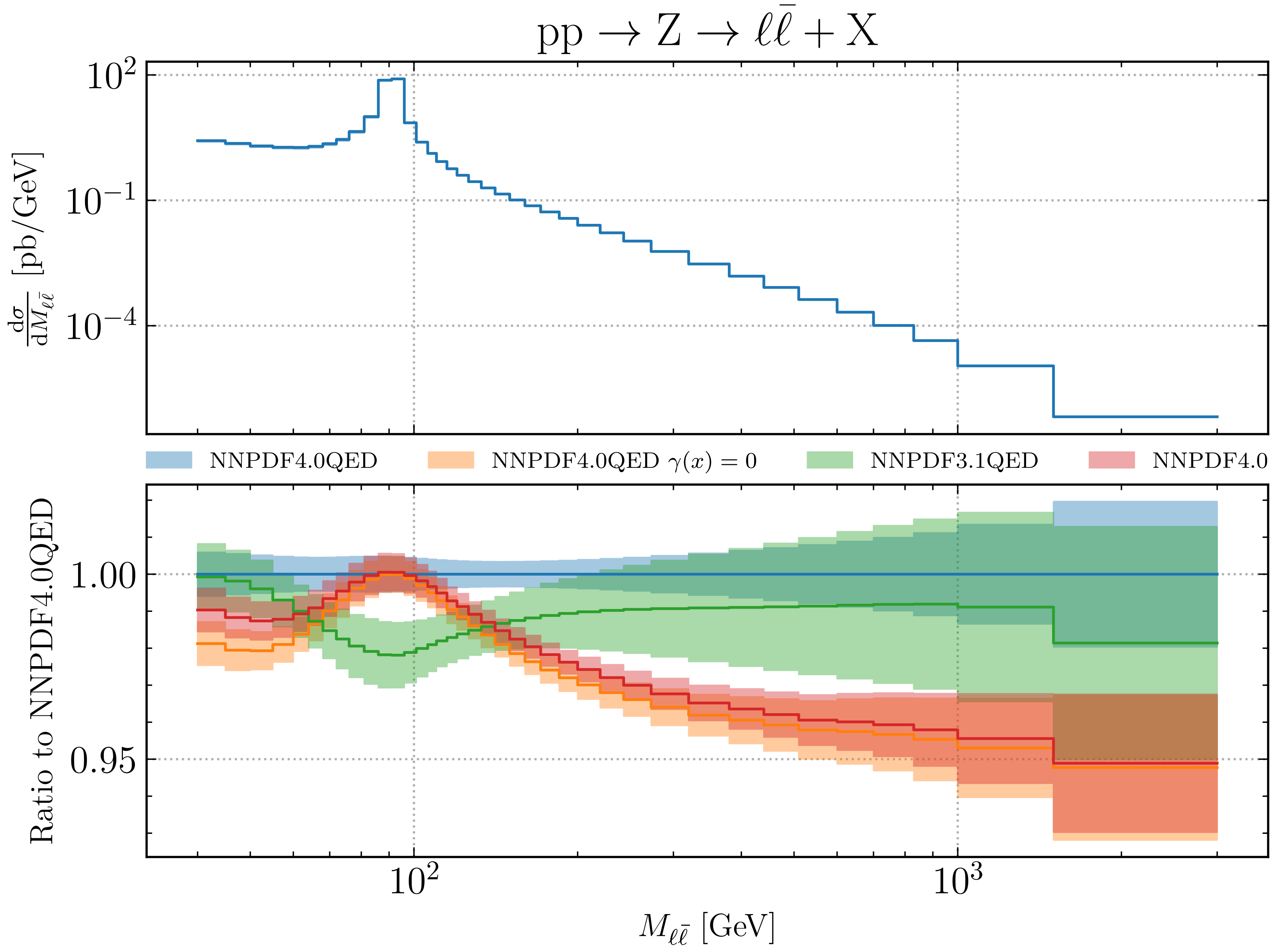
$$f^u_{ns,\pm} = \begin{cases} u^\pm - c^\pm \\ u^\pm + c^\pm - 2t^\pm \end{cases}, \quad f^d_{ns,\pm} = \begin{cases} d^\pm - s^\pm \\ d^\pm + s^\pm - 2b^\pm \end{cases}, \quad \Sigma_\Delta = \frac{n_d}{n_u} \sum_{i=1}^{n_u} u_i^+ - \sum_{i=1}^{n_d} d_i^+ \quad V_\Delta = \frac{n_d}{n_u} \sum_{i=1}^{n_u} u_i^- - \sum_{i=1}^{n_d} d_i^-$$

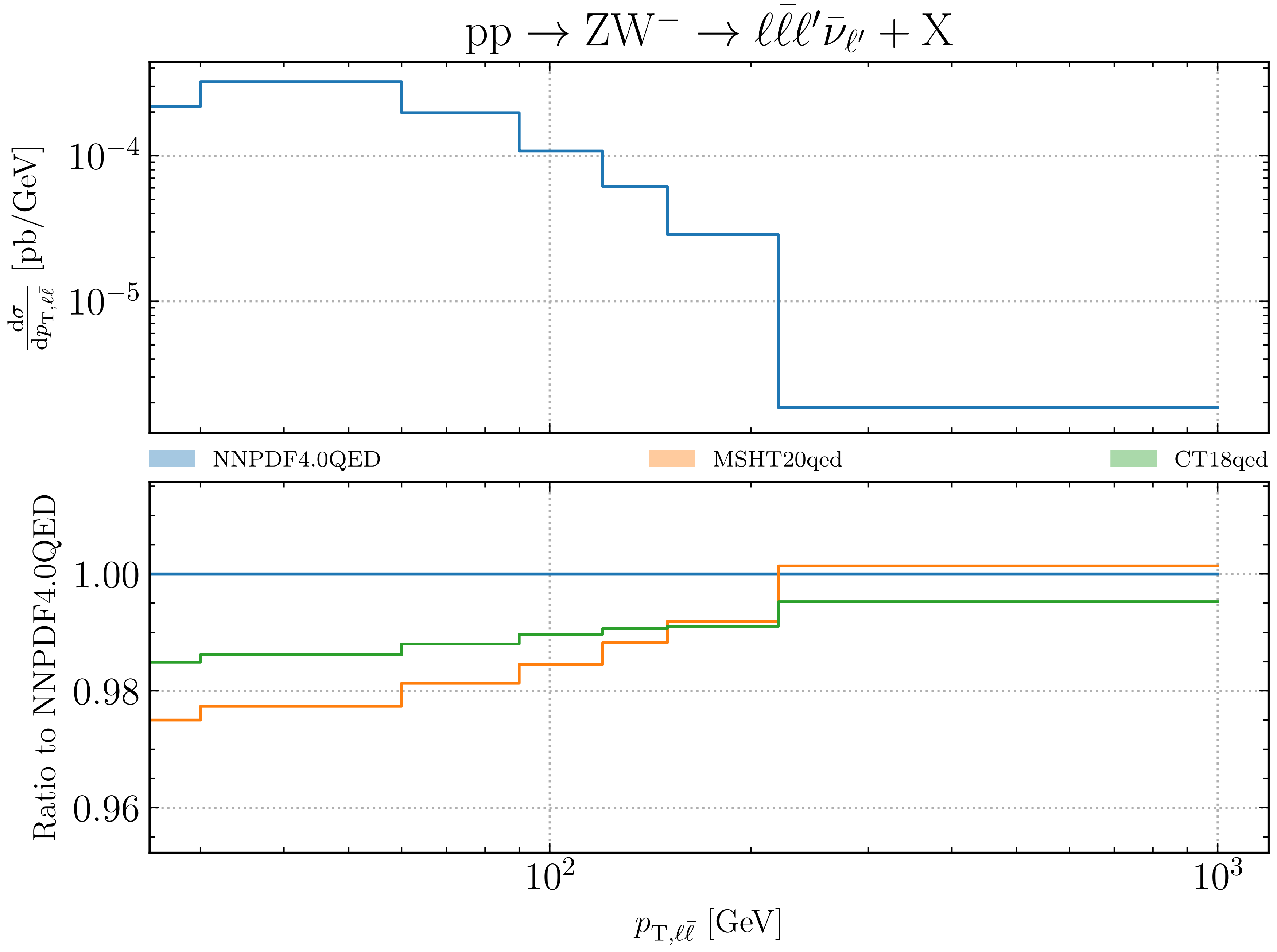
NNLO QCD ⊗ QED PDFs

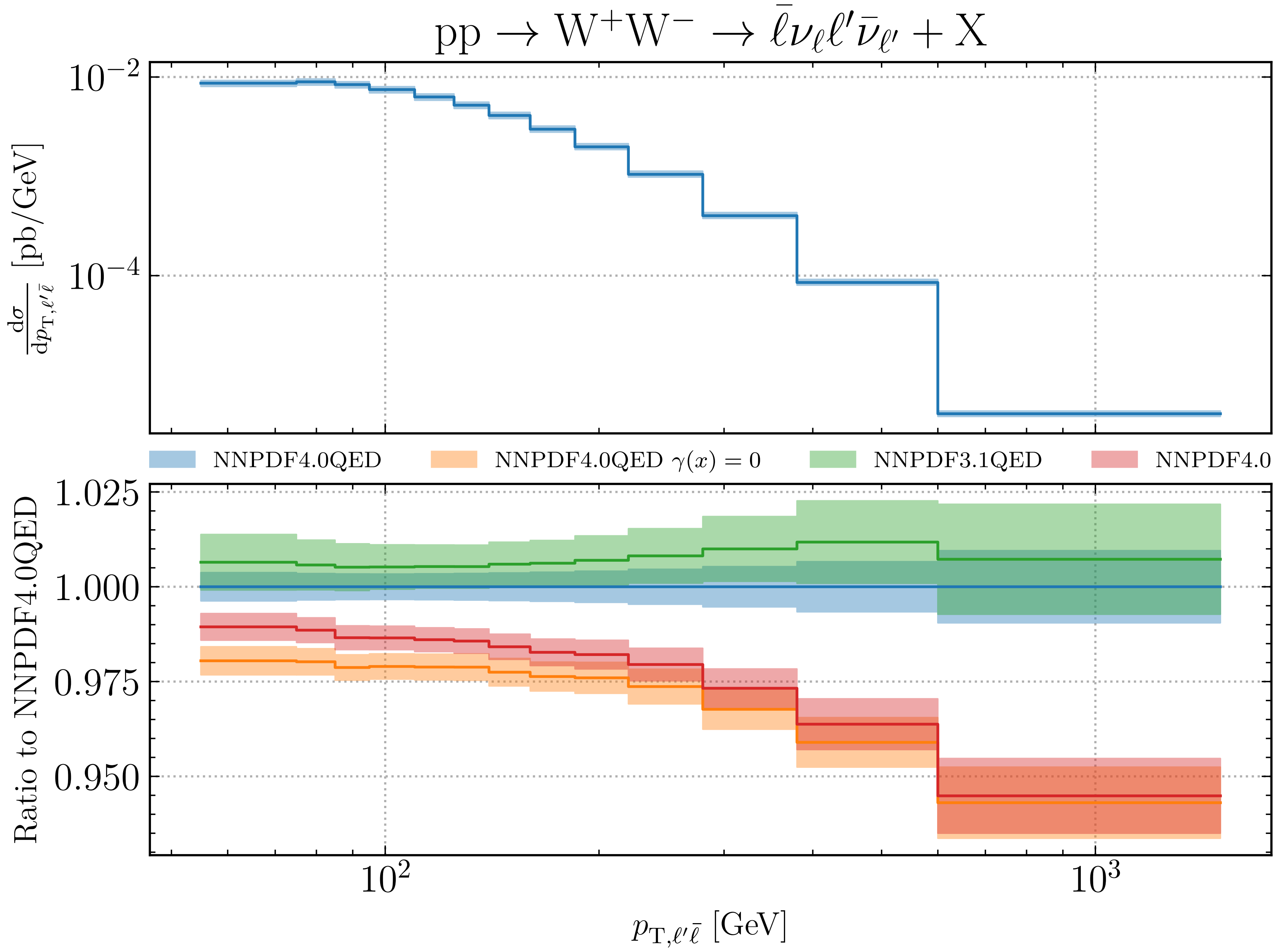


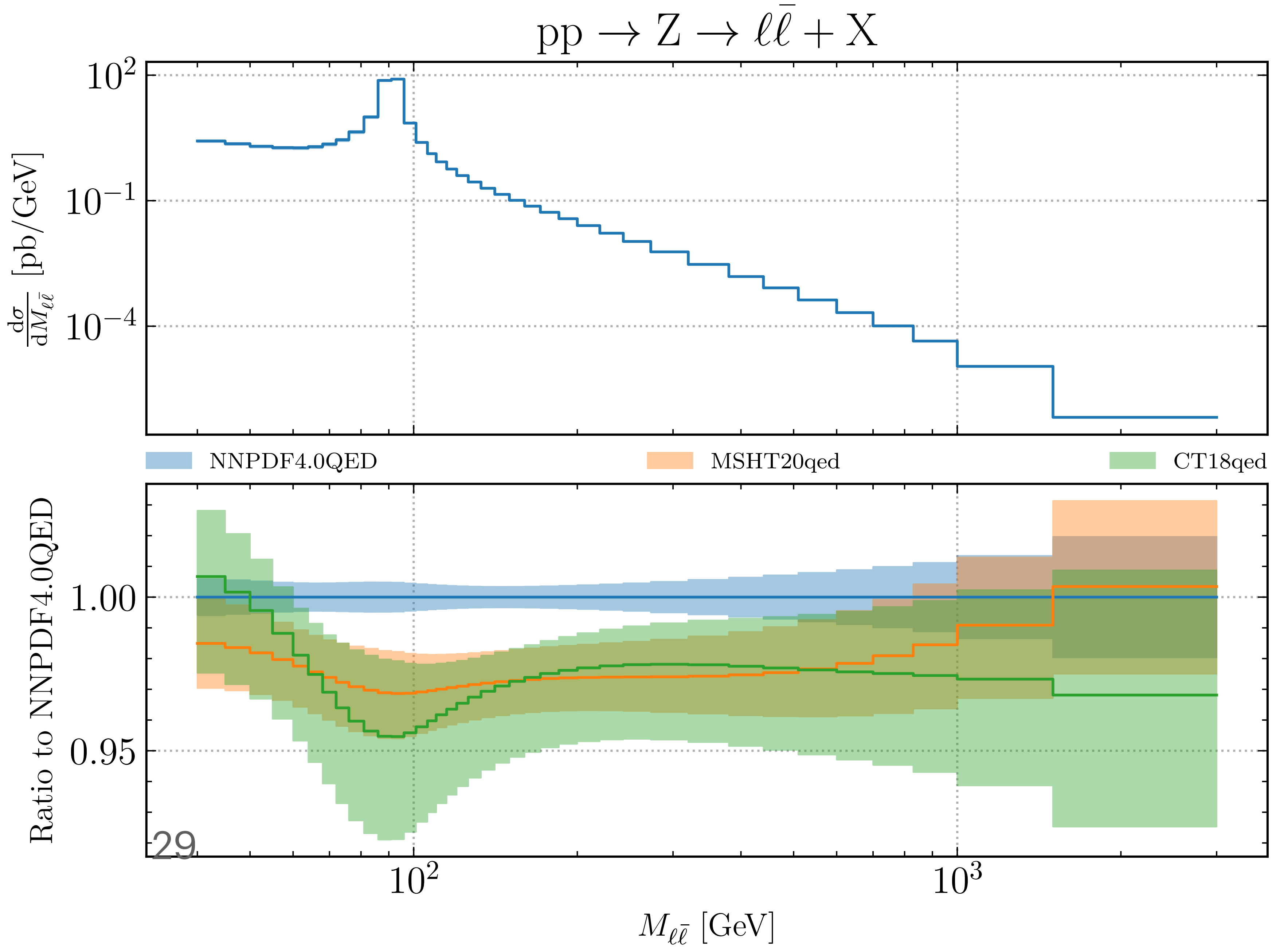
[NNPDF] E. Nocera

Phenomenological Impacts of QCD ⊗ QED PDFs









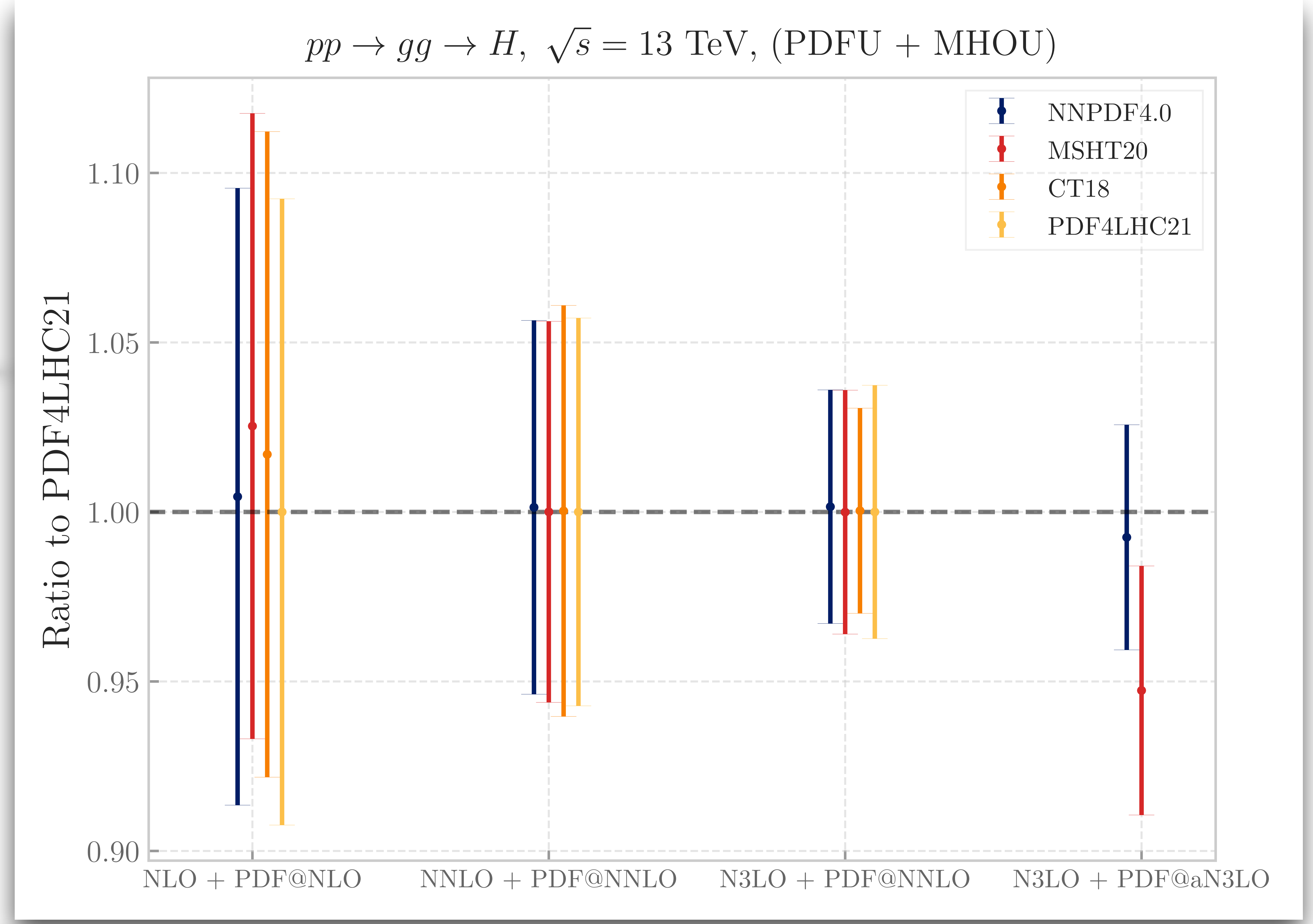
Non-negligible corrections in high-invariant mass and high-p_T regions

[NNPDF] C. Schwan & N. Laurenti

Conclusions & Outlook

Conclusions & Outlook

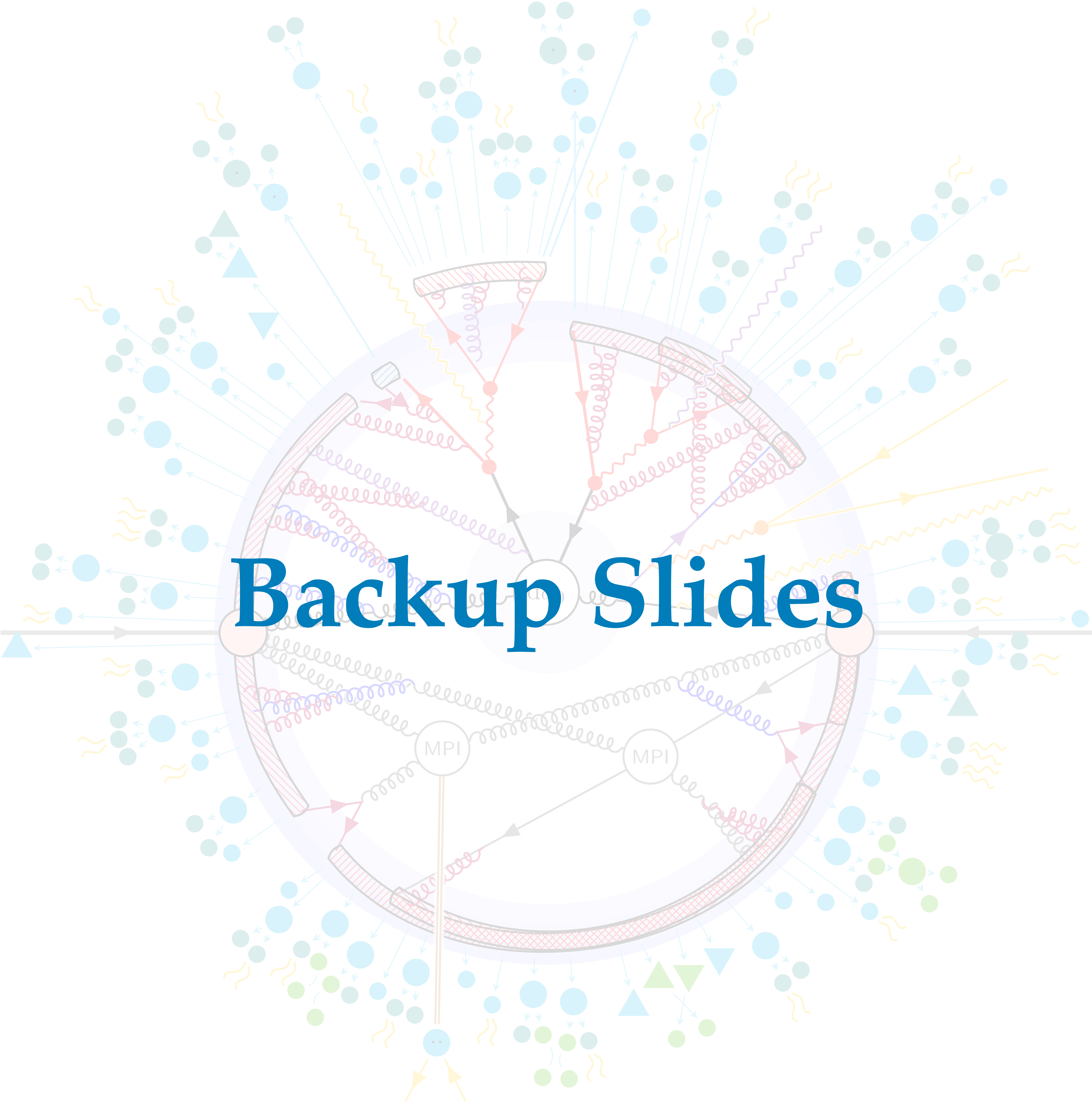
- More **precise** and **accurate** **PDF central values AND uncertainties** are vital for precision and beyond the Standard Model Physics.
- Inclusion of **Electroweak corrections** is becoming more relevant $\Leftarrow$ **QED corrections & photon γ-PDF**



Stay tuned for new NNPDF4.0 releases:

- NNLO PDFs with Faithful estimation of MHO uncertainties $\Longrightarrow$ **NNPDF4.0 MHOU**
- PDF determination with QED $\Longrightarrow$ **NNPDF4.0 QED**
- Approximate N3LO PDF determination $\Longrightarrow$ **NNPDF4.0 aN3LO**

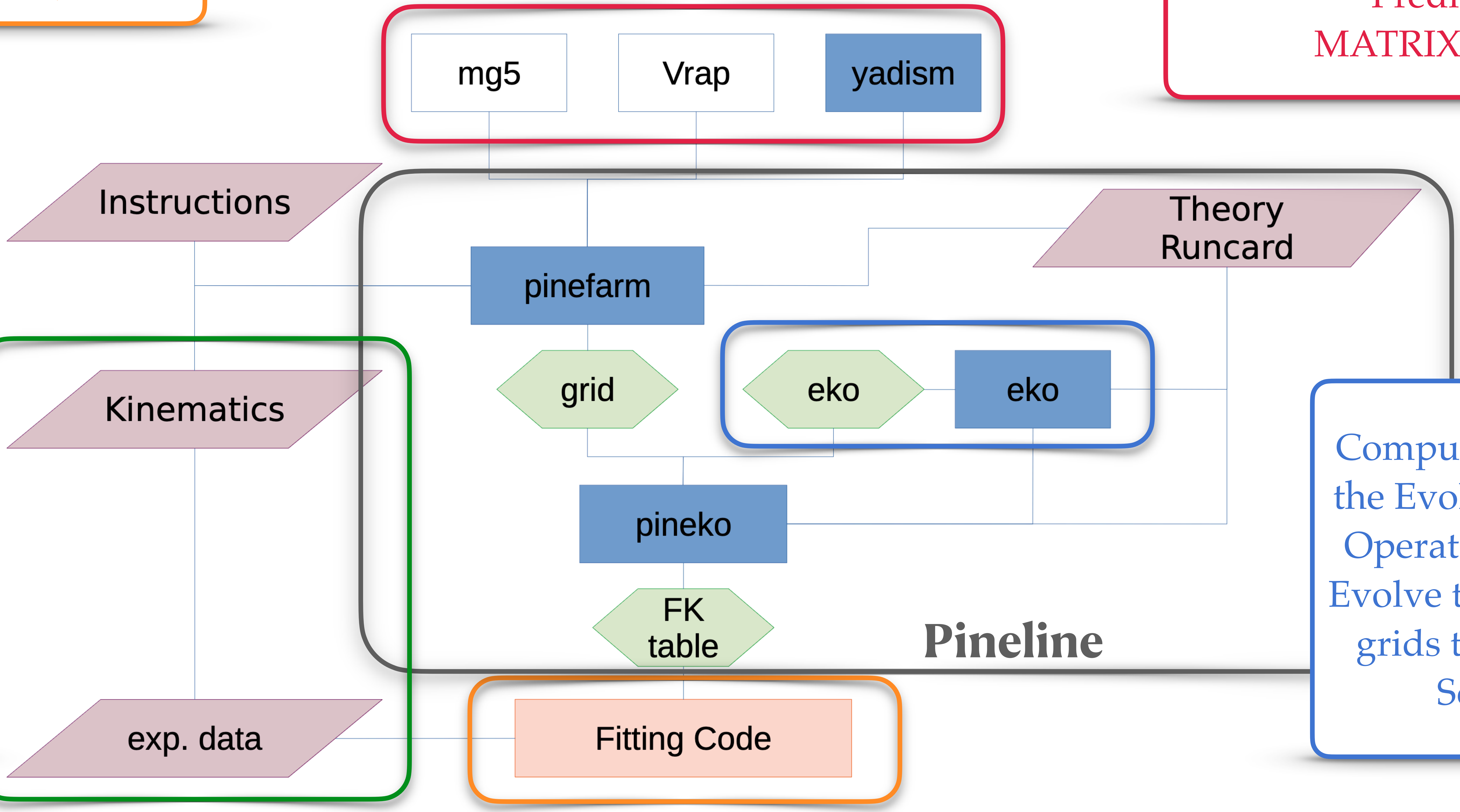
Backup Slides



A new Toolchain for PDF predictions

Fitting Code can be anything:
NNPDF, CTEQ, MSHT, etc.

Generators providing Theory Predictions
MATRIX, MCFM?

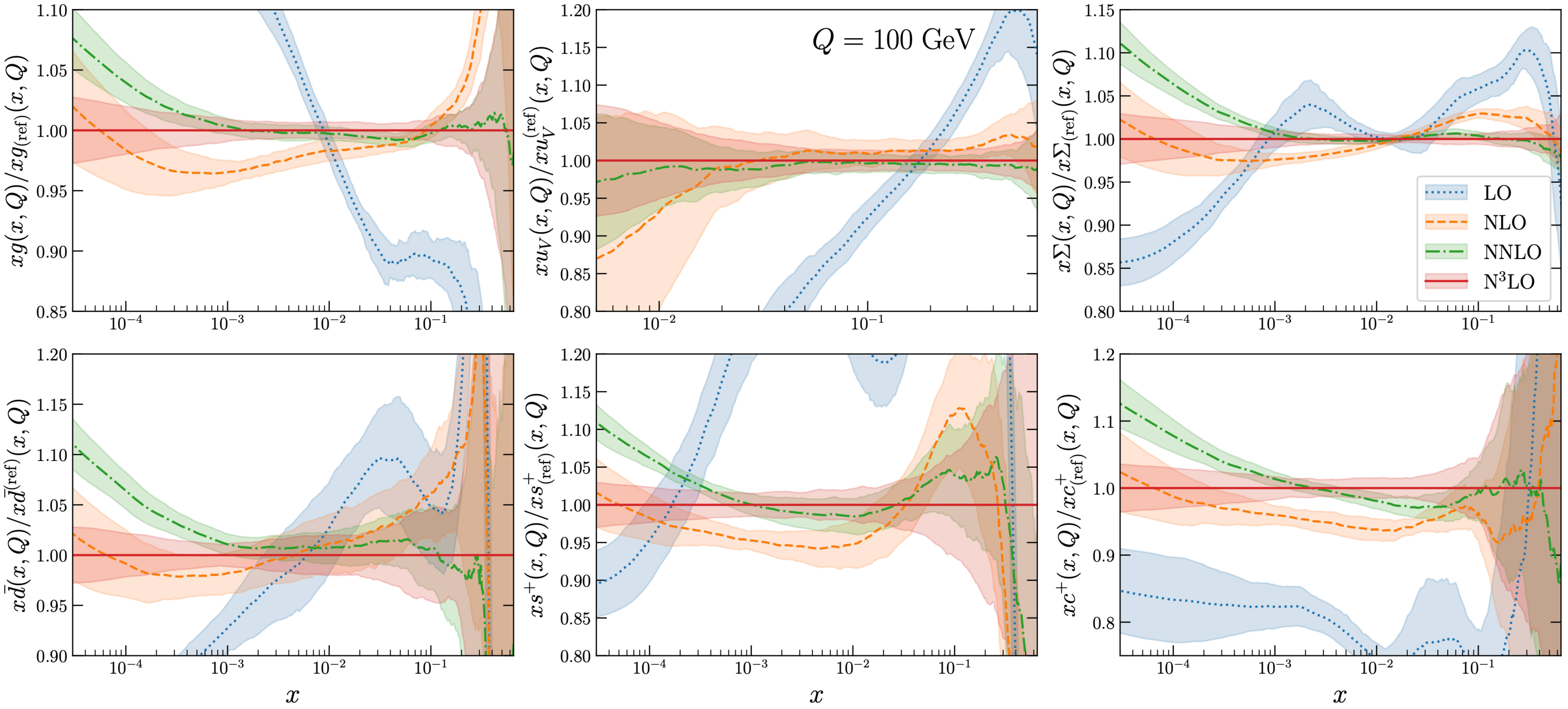


Experimental Inputs that provides the kinematics and the corresponding central values

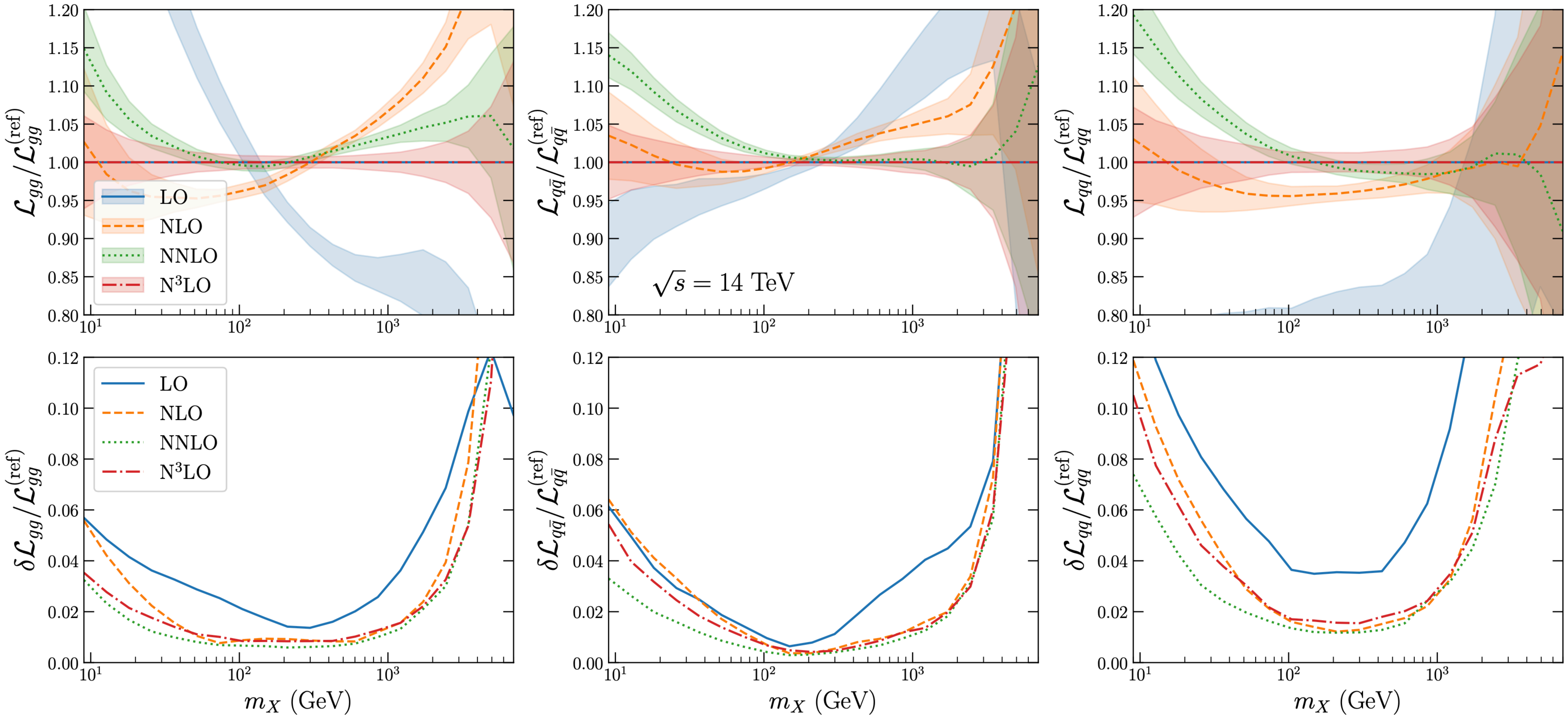
Computes/Provides the Evolution Kernel Operators (EKO) to Evolve the PineAPPL grids to the fitting Scale Q_0

arXiv:2302.12124

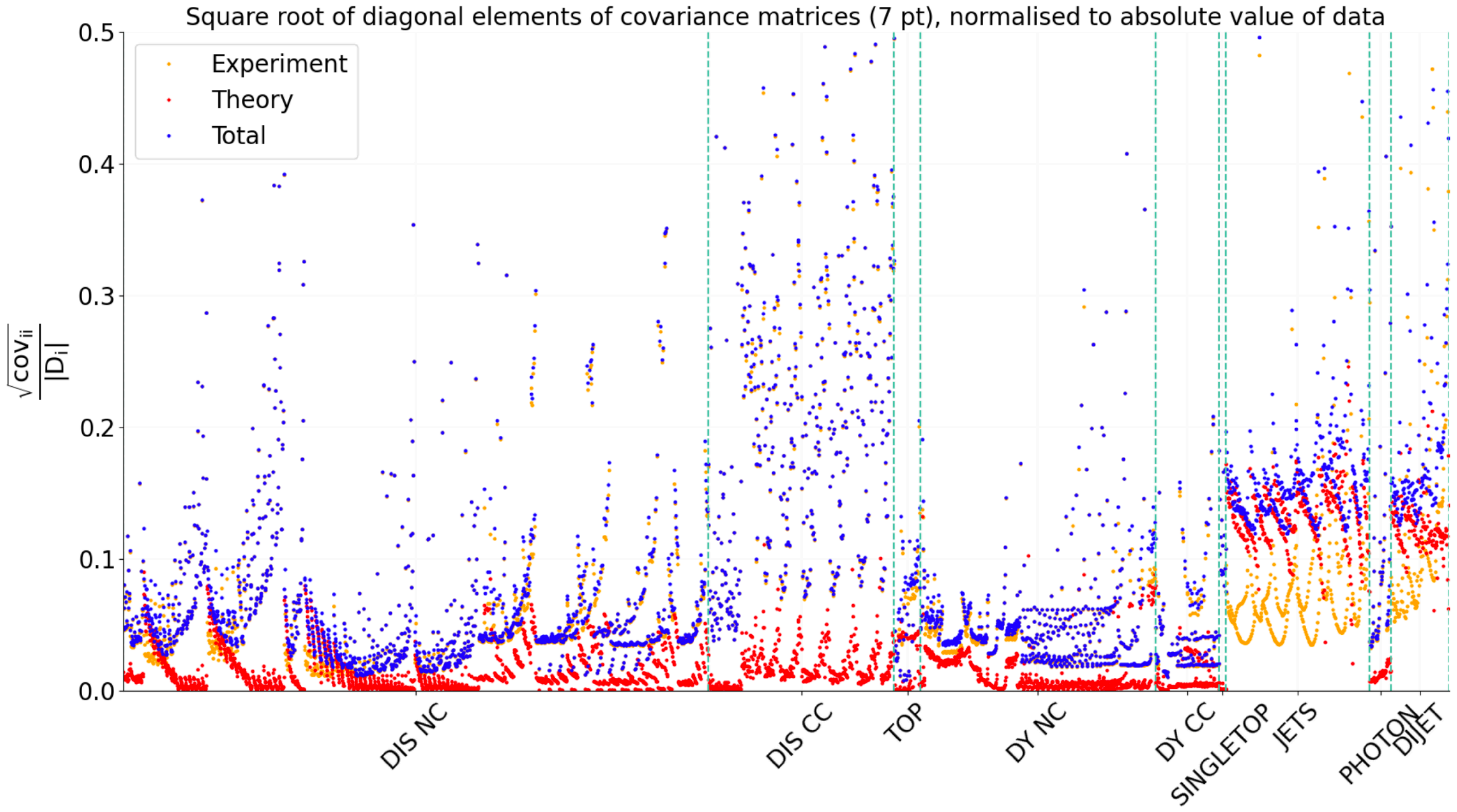
aN3LO PDFs: Perturbative Stability



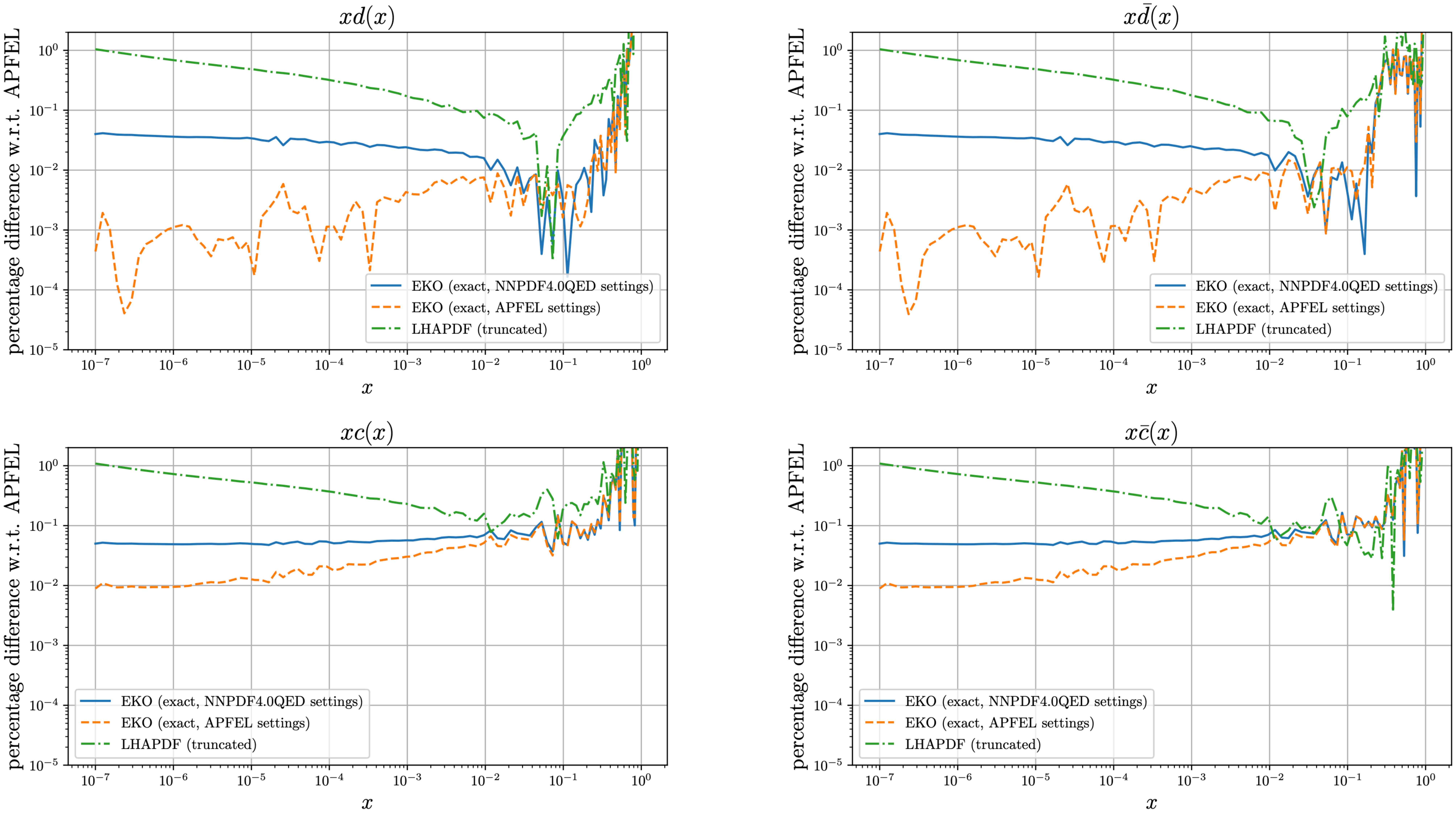
aN3LO PDFs: Luminosities



MHOUs: closer look at CovMat



QCD⊗QED Evolution



Scale Dependence of γ-PDF