The inclusion of theory errors in PDF fitting.

The NNPDF4.0MHOU PDFs set

A. Barontini on behalf of the NNPDF collaboration

University of Milan and INFN Milan

QCD@LHC2023

04/09/2023

Outline.

INTRODUCTION

- What are theory errors?
- How can we estimate them?
- Why is it relevant to include them in a PDF fit?

METHODOLOGY AND VALIDATION

- How can we include MHOU in a PDF fit?
- Can we validate our estimation?

RESULTS

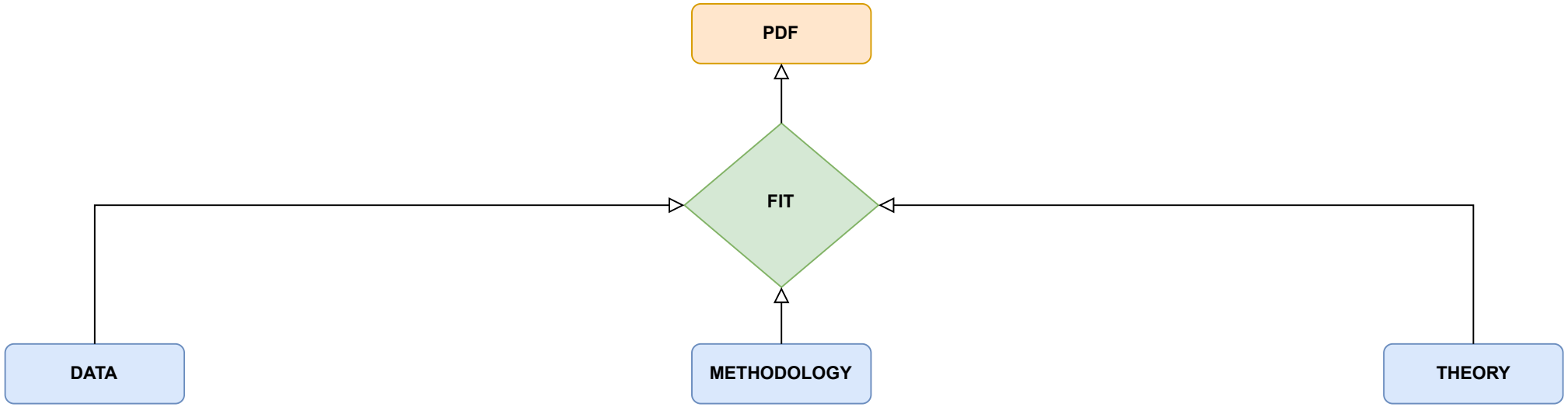
- What is the impact on the PDFs at NLO and NNLO?
- What is the impact on the phenomenology?

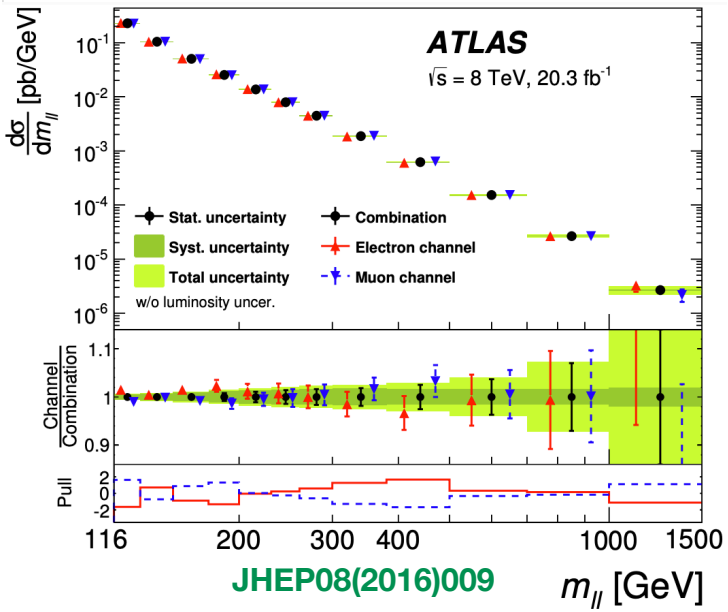
INTRODUCTION

- What are theory errors?
- How can we estimate them?
- Why is it relevant to include them in a PDF fit?

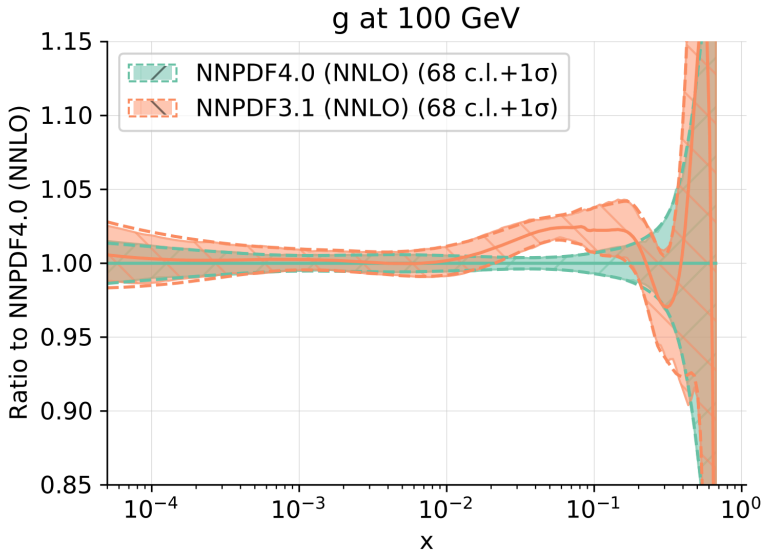
“We are not strangers, only the introduction is missing”
(Jesus Apolinaris)

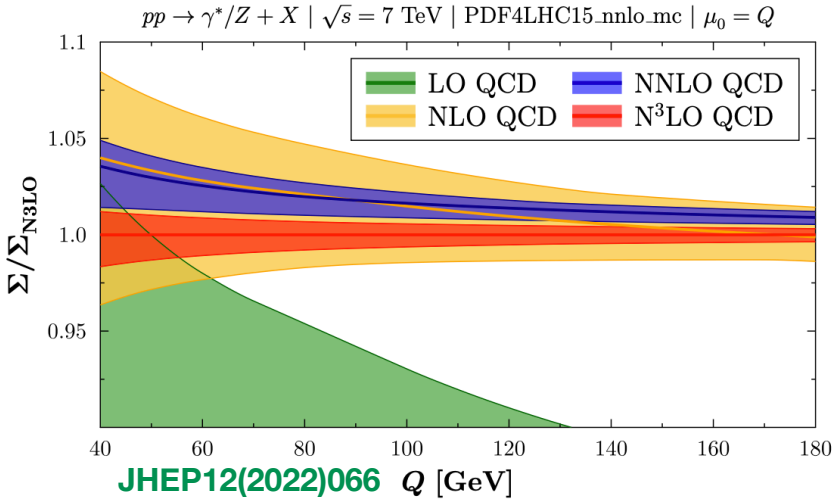
Motivation.





JHEP08(2016)009





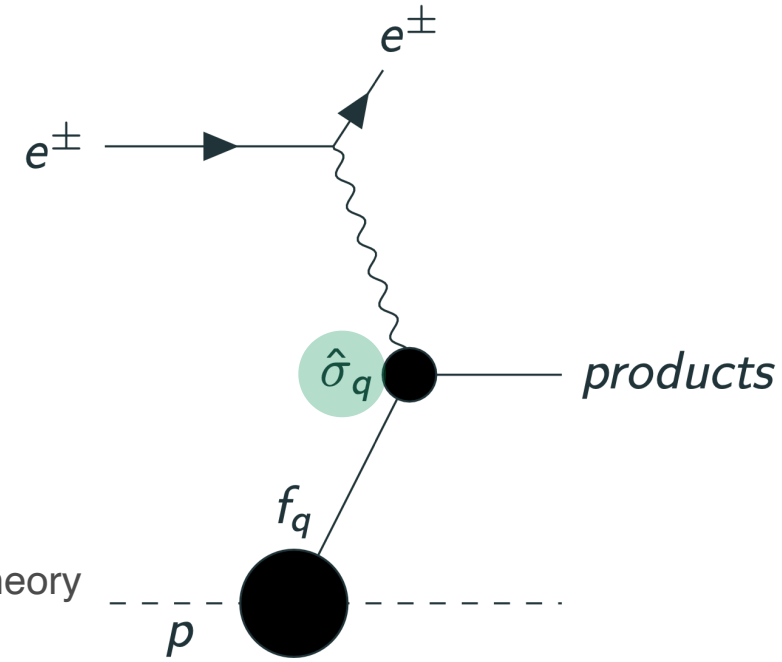
JHEP12(2022)066

Definition of the problem.

$$F(Q) = \hat{\sigma}(Q) \otimes U(Q, Q_0) \otimes f(Q_0)$$

- ***Partonic cross sections*** are computed in perturbation theory
- ***DGLAP evolution operator*** evolves the *PDFs* from Q_0 to Q
- ***Anomalous dimensions*** inside DGLAP operator are computed in perturbation theory

Deep Inelastic Scattering (DIS)



$$\hat{\sigma}^{NLO} = \hat{\sigma}^{(0)} + \alpha_s \hat{\sigma}^{(1)} + \mathcal{O}(\alpha_s^2)$$

$$\gamma^{NLO} = \alpha_s \gamma^{(0)} + \alpha_s^2 \gamma^{(1)} + \mathcal{O}(\alpha_s^3)$$

MHOU

(Missing Higher Order Uncertainties)

How can we estimate them?

Theory errors: estimation.

Scale Variations

$$\overline{F}^{NLO}(\mu_f = \kappa_f Q, \mu_r = \kappa_r Q) - F^{NLO}(\mu_f = Q, \mu_r = Q) = \mathcal{O}(NNLO)$$

Factorization scale

Estimates MHOU of anomalous dimensions

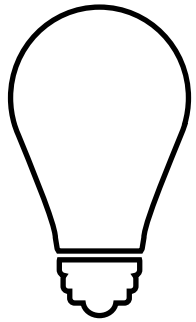
$$U^{NLO}(Q, Q_0) \to \overline{U}^{NLO}(Q, Q_0, \kappa_f)$$

Renormalization scale

Estimates MHOU of partonic cross sections

$$\hat{\sigma}^{NLO}(Q) \to \overline{\hat{\sigma}}(Q, \kappa_r)$$

$\kappa_f, \kappa_r \in (0.5, 2.0)$ is the most common choice



METHODOLOGY AND VALIDATION

- How can we include MHOU in a PDF fit?
- Can we validate our estimation?

“Truth has nothing to do with the conclusion, and everything to do with the methodology”
(Stefan Molyneux)

MHOU in a PDF fit: the *theory covmat*.

➜ **Minimization** of a *loss function* depending on
- Datapoints D
- Predictions T
- Exp. Covmat C

Also, for a NNPDF fit…

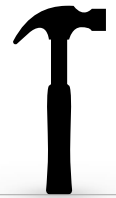
➜ Fit through a ***Neural Network***

➜ Delivery of a Montecarlo sample of fits on *replicas*

How to use it

FIT WITHOUT THEORY ERRORS		FIT WITH THEORY ERRORS
$\chi^2 \propto (D_i - T_i)C_{ij}^{-1}(D_j - T_j)$	⟶	$\chi^2 \propto (D_i - T_i)(C+S)_{ij}^{-1}(D_j - T_j)$
Pseudodata replica $\propto C$	⟶	*Pseudodata replica* $\propto C + S$

MHOU in a PDF fit: the *theory covmat*.

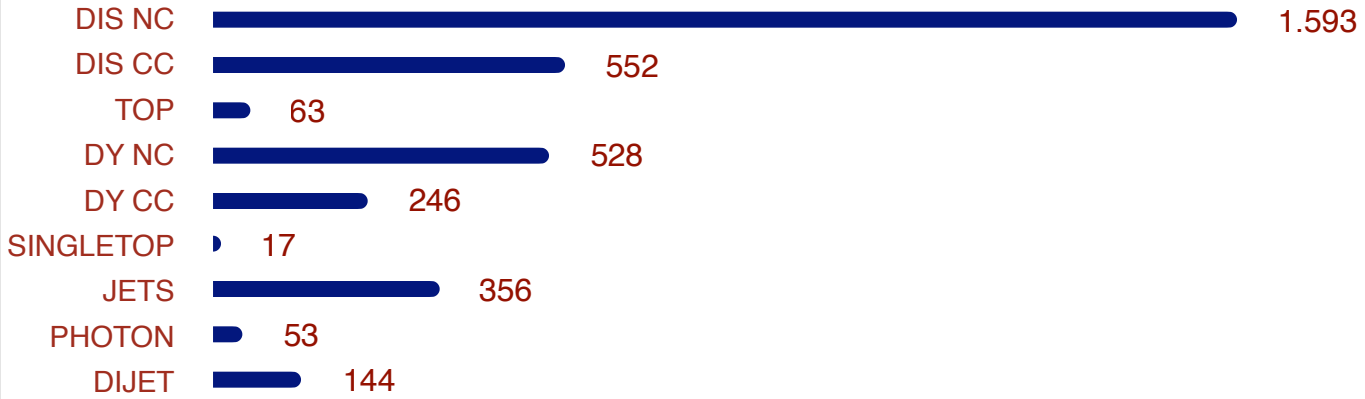


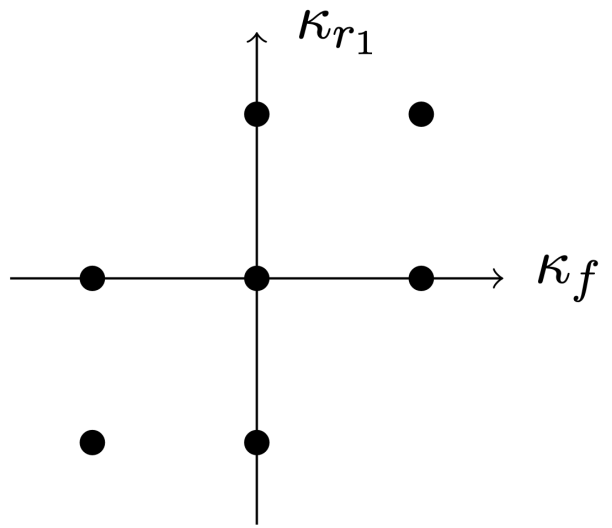
$$S_{ij} = n_m \sum_{V_m} \left(\overline{F}(\kappa_f, \kappa_{r_a}) - F \right)_{i_a} \left(\overline{F}(\kappa_f, \kappa_{r_b}) - F \right)_{j_b}$$

How to construct it

→ *Factorization scale* **correlates** all the points

→ *Renormalization scale* **correlates** points belonging to the same process

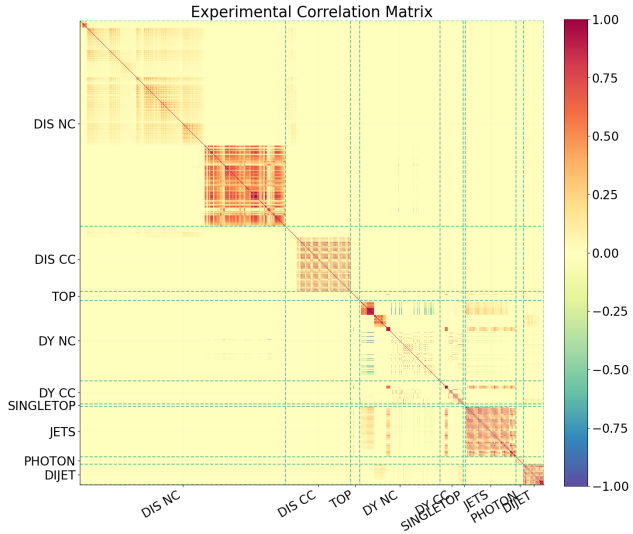


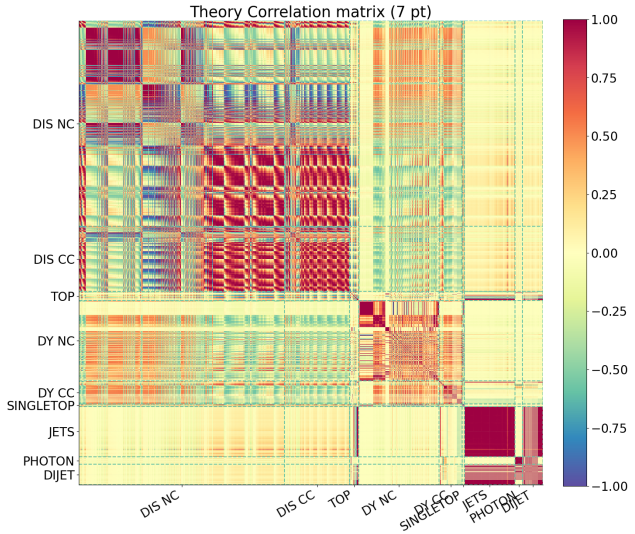


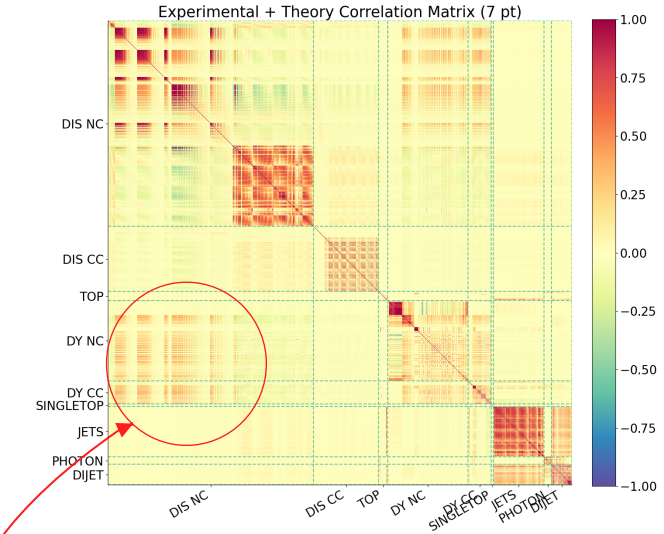
How do they look like?

C S $C + S$

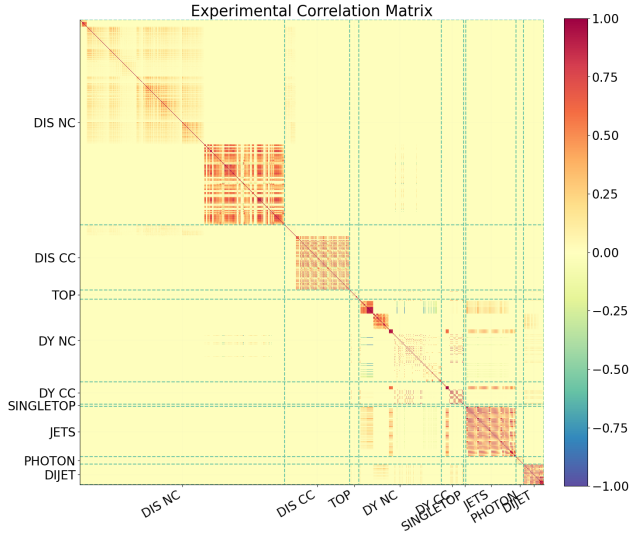
→ *NLO*

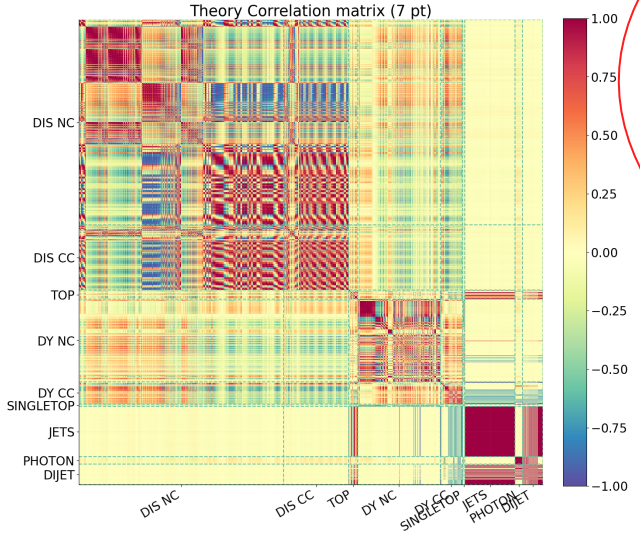


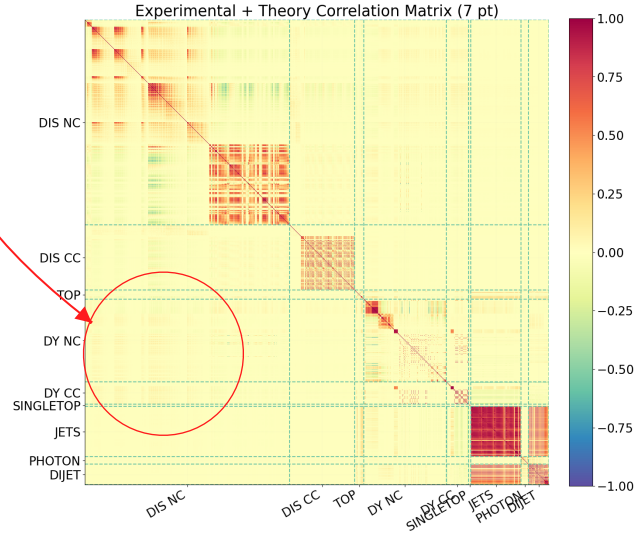




→ *NNLO*

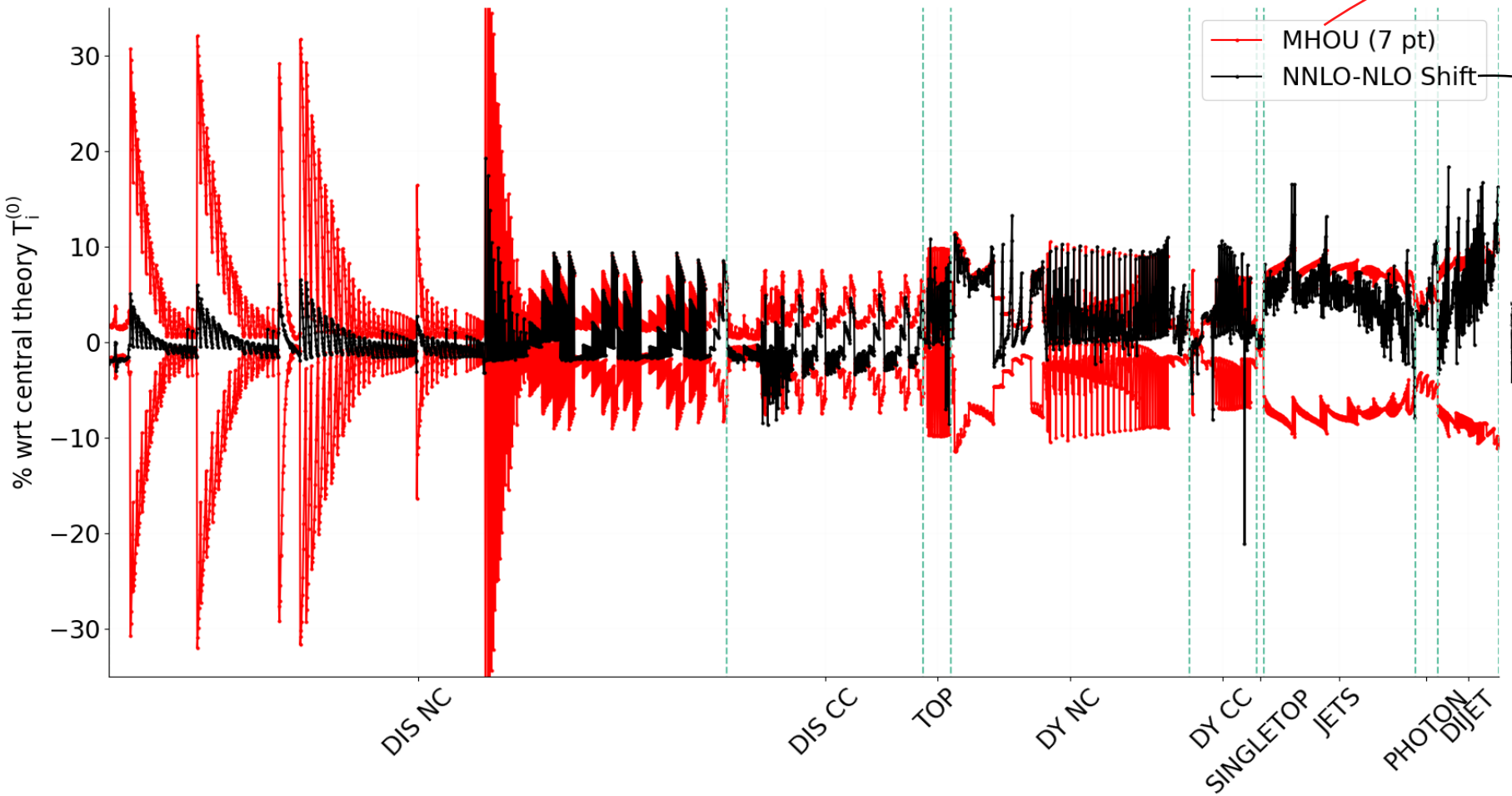






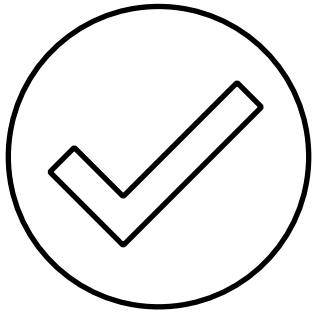
Validation: is it reproducing the known MHOU?

Most of the predictions are currently known up to $\mathcal{O}(NNLO)$:
we can test the NLO MHOU !



$$\left(\frac{\sqrt{S_{ii}^{NLO}}}{F_i^{NLO}}\right) \times 100$$

$$\left(\frac{F_i^{NNLO} - F_i^{NLO}}{F_i^{NLO}}\right) \times 100$$



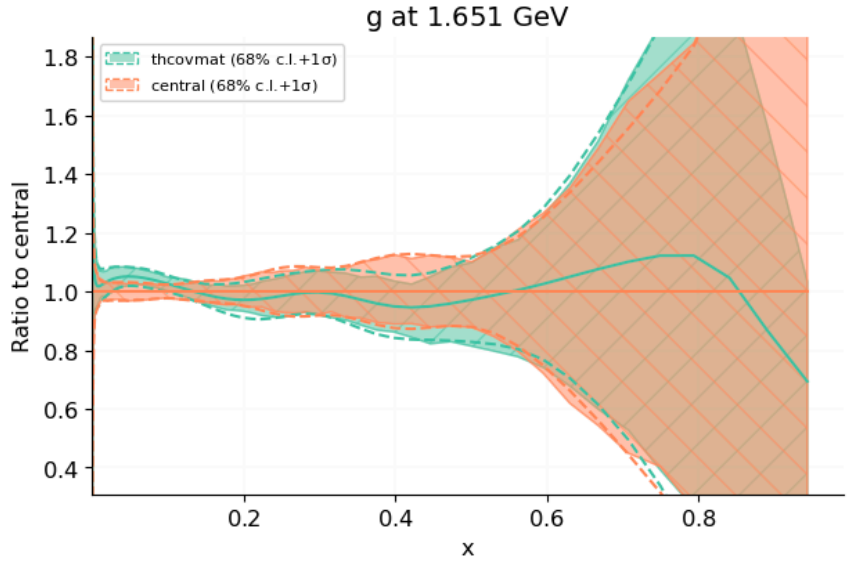
RESULTS

- What is the impact on the PDFs at NLO and NNLO?
- What is the impact on the phenomenology?

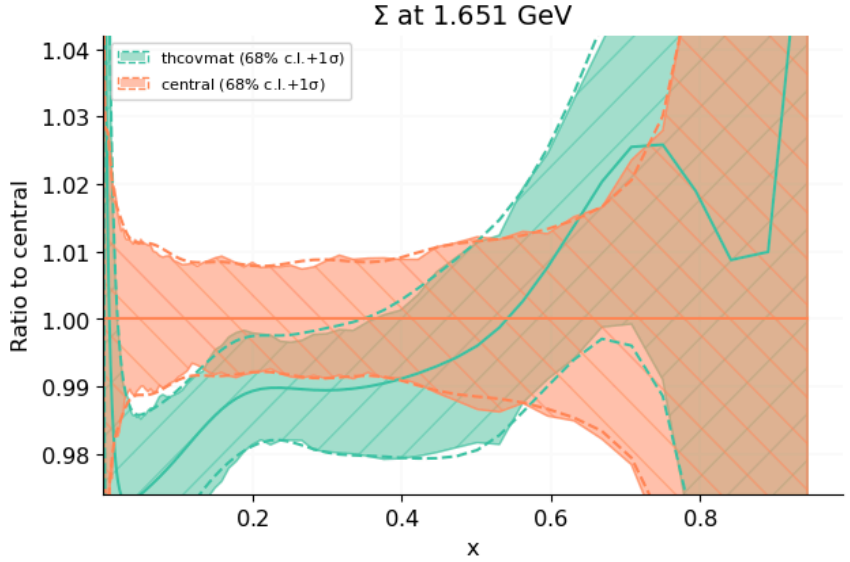
“We're always, by the way, in fundamental physics, always trying to investigate those things in which we don't understand the conclusions. After we've checked them enough, we're okay”
(Richard P. Feynman)

PDF central values change: NLO.

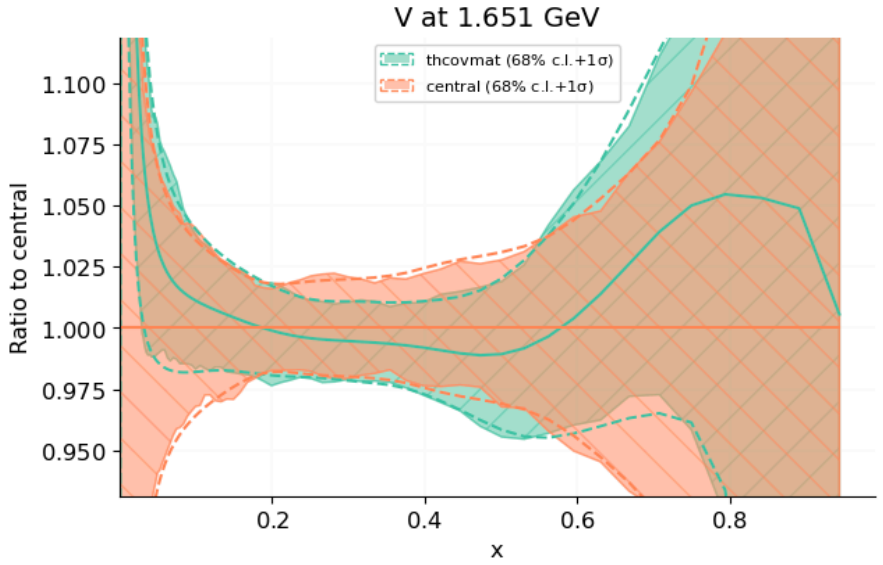
g



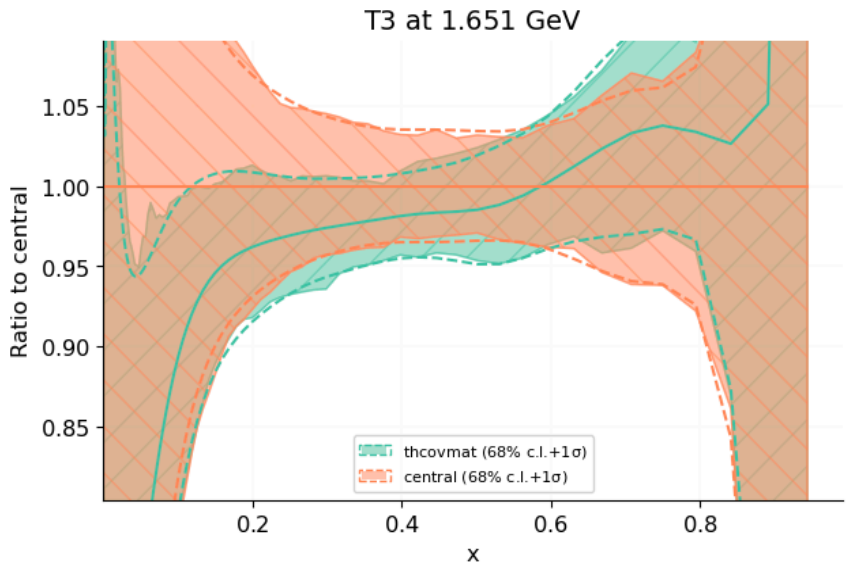
Σ



V

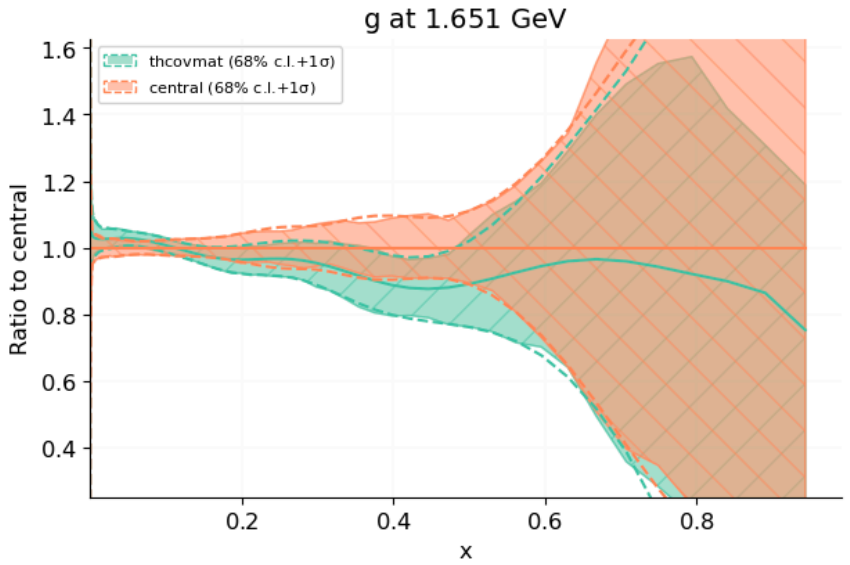


$T3$

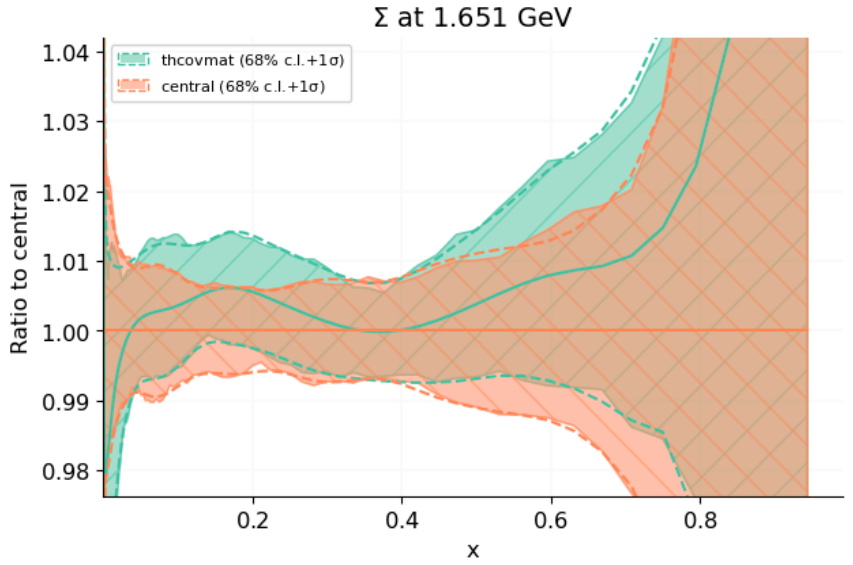


PDF central values change: NNLO.

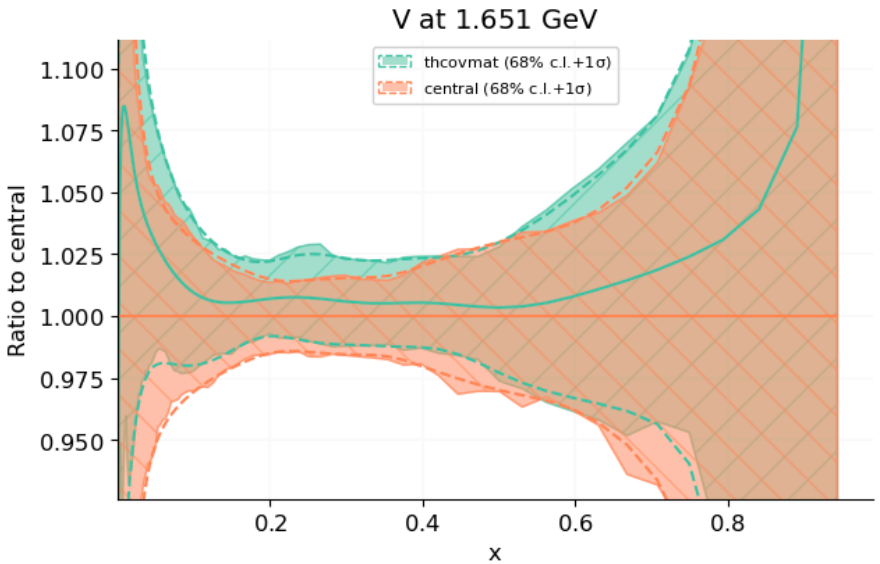
g



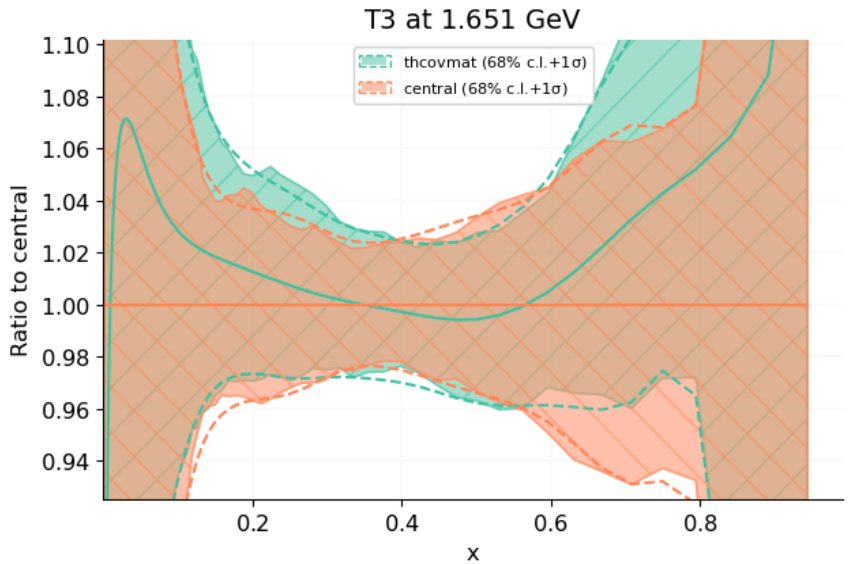
Σ



V

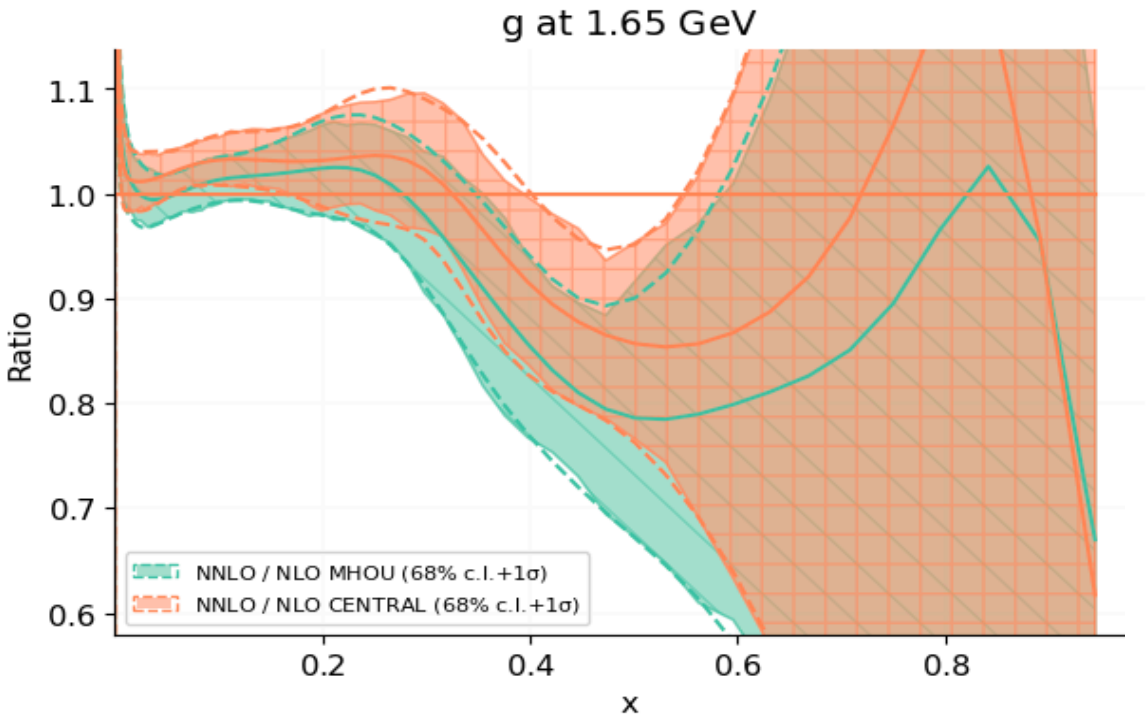


$T3$

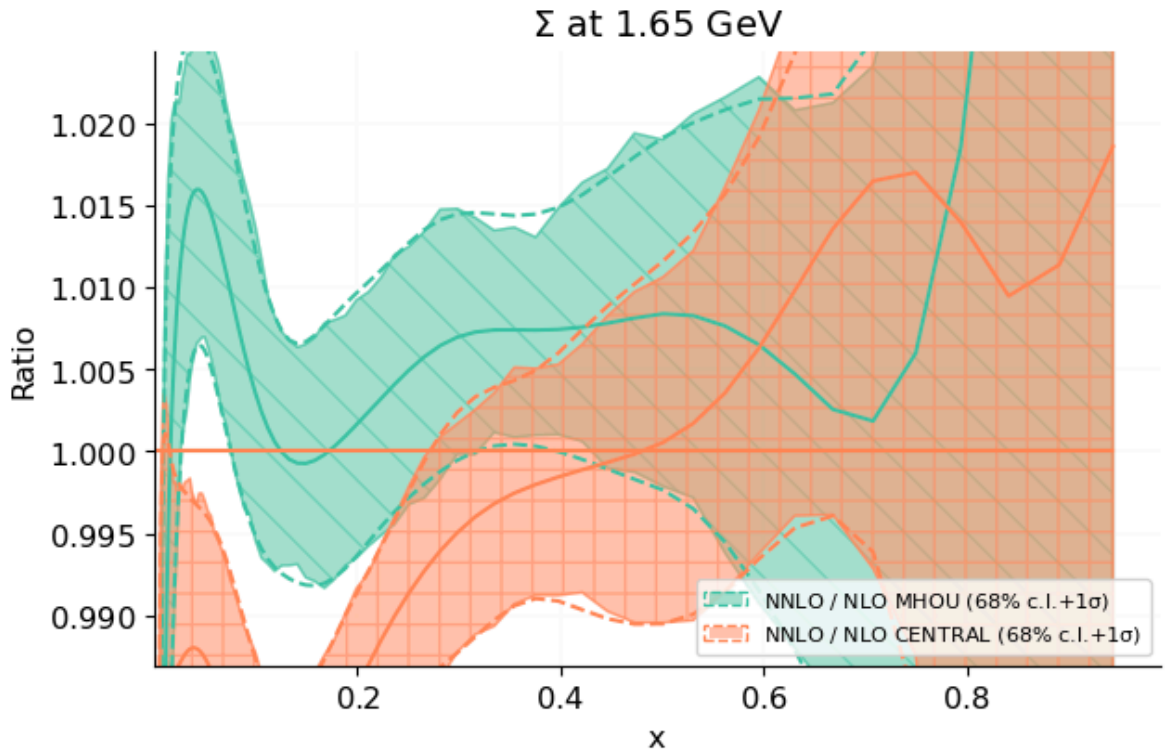


The perturbative convergence : NLO vs NNLO.

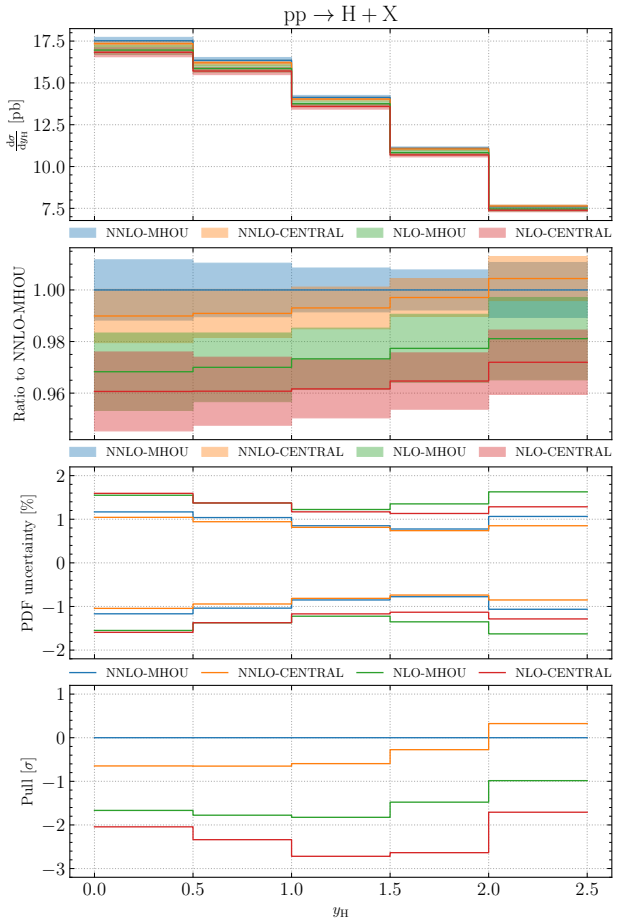
g



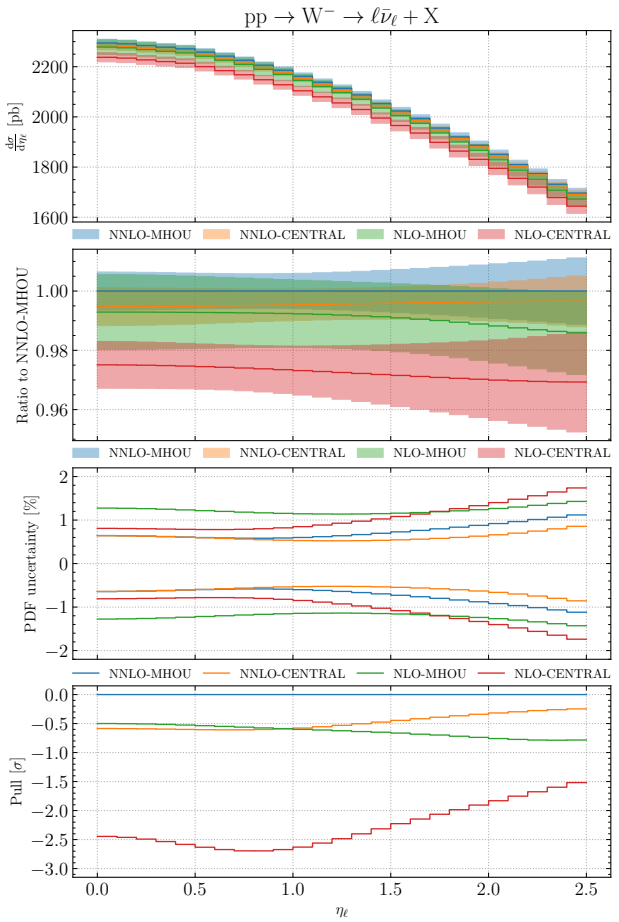
Σ



PDFs comparison in phenomenology.



NLO-MHOU is closer to NNLO than NLO-CENTRAL!



Using these MHOU PDF sets still requires the addition of the usual MHOU in the partonic cross sections

Conclusions.

- Thanks to *scale variations* it is possible to estimate MHOU while, thanks to the theory covmat formalism, it is possible to include such estimation in a PDF fit
- Including MHOU in a PDF fit is necessary to have faithful uncertainties and central values
- The perturbative convergence from NLO to NNLO improves once theory errors are accounted for

Thanks for your attention!