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RECENT UPDATES FROM NNPDF

LHC EW WG GENERAL MEETING - CERN

11 TH JULY 2024

OUTLINE

➡ Part I: Highlights of recent progress from the NNPDF collaboration

➡ Part II: The precision vs accuracy challenge: a road-map to robustly test accuracy

PART I: RECENT PROGRESS FROM NNPDF

THE NNPDF TIMESCALE

- ☑ Sep 2021: **NNPDF4.0 (paper & open-source code)**
- ☑ Aug 2022: **Intrinsic charm**
- ☑ Sept 2022: **PDFs & BSM searches** (A_{FB} high-mass)
- ☑ Nov 2023: **IC asymmetry** study

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- ☑ Jan 2024: NNPDF4.0 **QED**
- ☑ Jan 2024: NNPDF4.0 **MHOUs**
- ☑ Feb 2024: NNPDF4.0 **aN3LO**
- ☑ June 2024: NNPDF4.0 **aN3LO & QED & MHOU**
- ☑ June 2024: NNPDF4.0 for MC event generators

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- ☑ June 2024: NNPDF4.0 for MC event generators

- **WIP**: Implications of NNPDF4.0 for LHC processes
- **WIP**: Closure test with inconsistent experimental data
- **WIP**: Towards NNPDF4.1

THE NNPDF TIMESCALE

- ➡ Beyond neural networks: PDFs from Bayesian inference [Candido et al 2404.07573, Costantini et al 2404.10056]
- ➡ Improved ML hyper-parameter optimisation from parallel replica training on GPUs [WIP]
- ➡ Fixed functional forms for Hessian fits in NNPDF [WIP]
- ➡ Determination of strong coupling simultaneously with PDFs at aN^{3}LO [WIP]
- ➡ Determination of higher twist corrections [WIP]
- ➡ Updated NNPDF polarised fits and EIC projections [WIP]
- ➡ Simultaneous SMEFT and PDF fits [Costantini et al 2402.03308] [Iranipour, MU 2201.07240]
- ➡ Study of possible BSM contamination effects in PDF fits [Hammou et al 2307.10370]
- ➡ ...

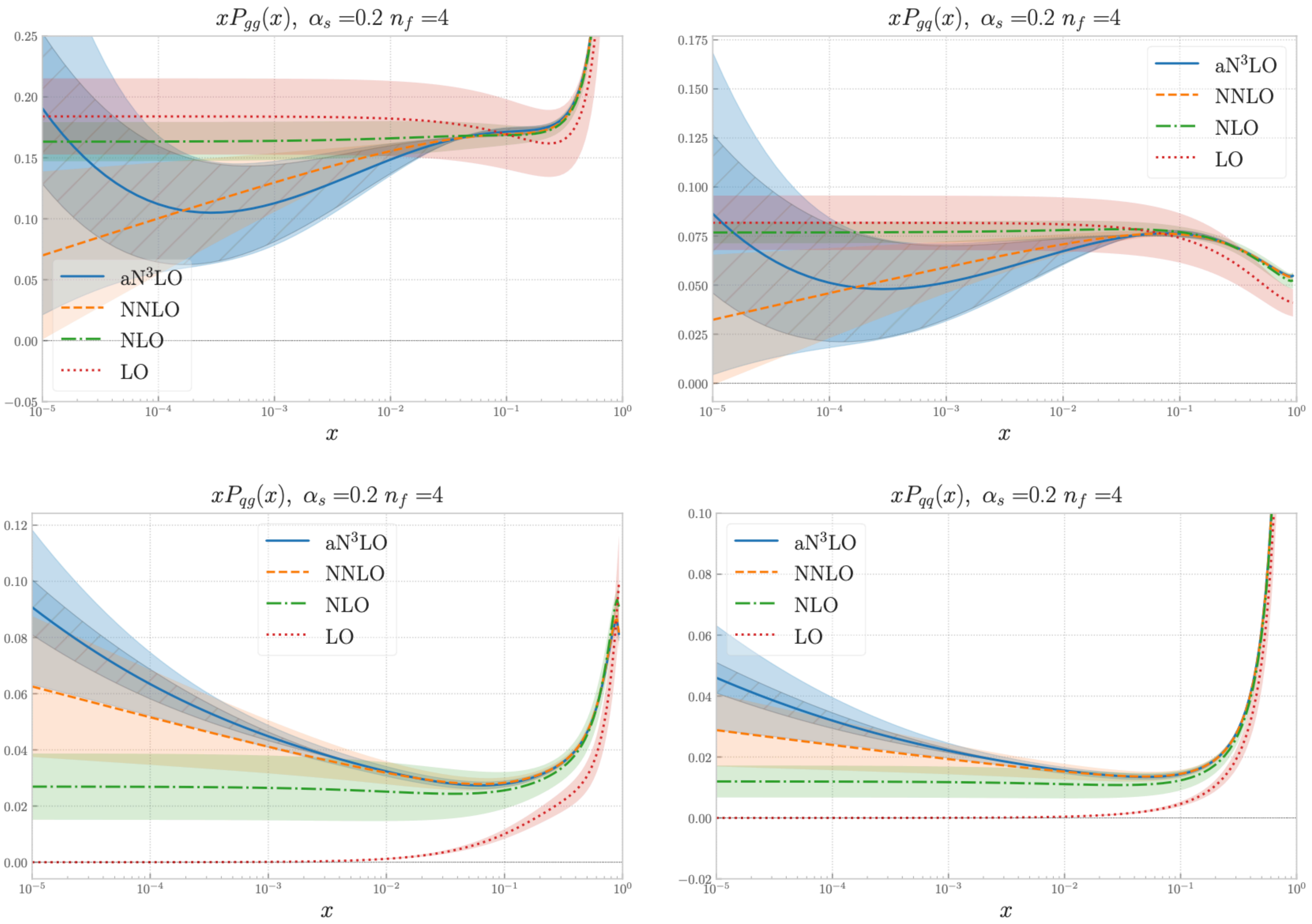
WIP: Implications of NNPDF4.0 for LHC processes

WIP: Closure test with inconsistent experimental data

WIP: Towards NNPDF4.1

NNPDF40 AN3LO: SPLITTING FUNCTIONS

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



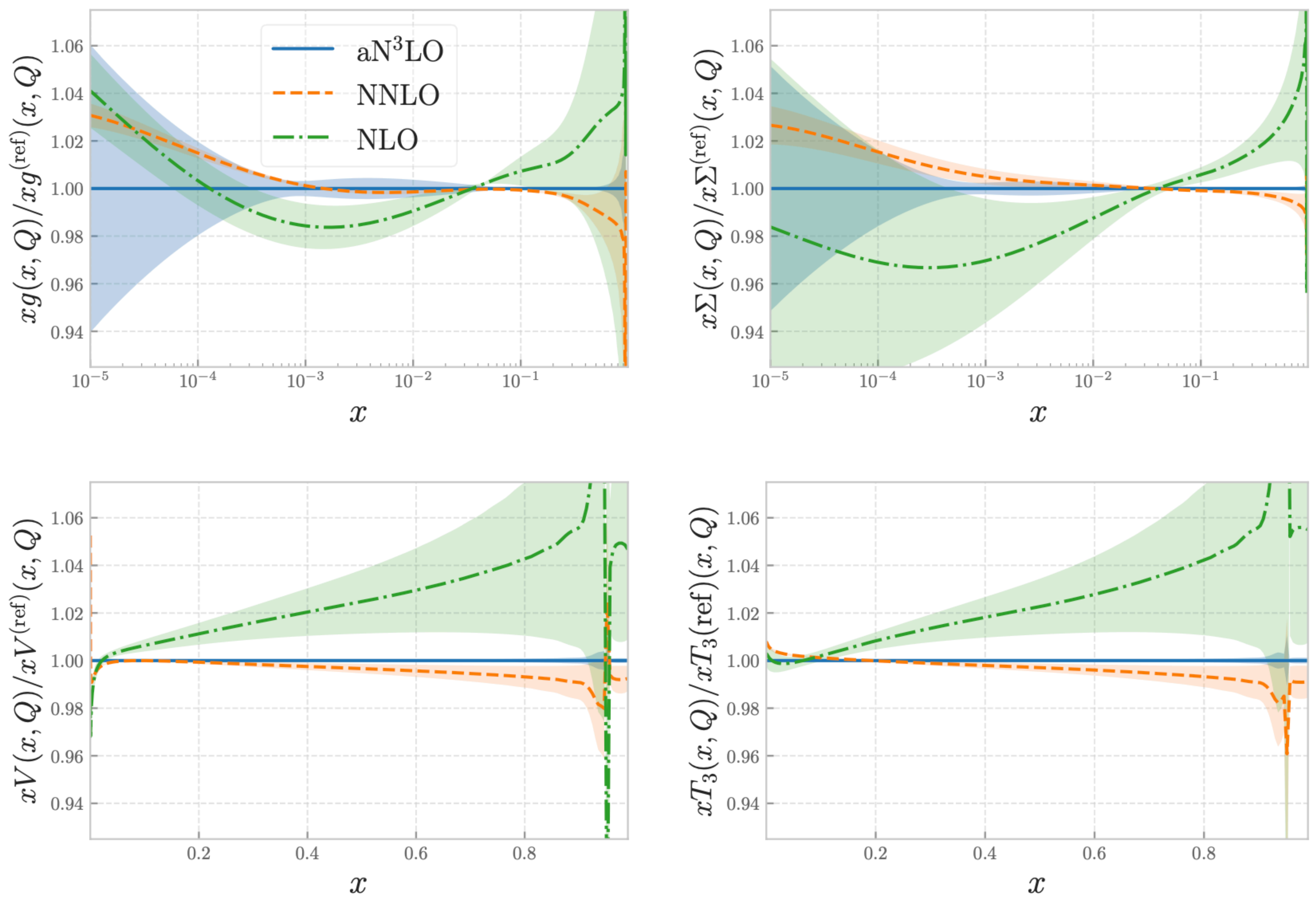
LO, NLO, NNLO: MHOU (μ_F)

N³LO: MHOU (μ_F) + IHOUs (dark)

- Estimate **Incomplete Higher Order Uncertainties** (IHOUs) by varying interpolating functions connecting known limits
- WIP: dedicated LH benchmark paper on N3LO splitting functions and PDFs

Good perturbative consistency within uncertainties

NNPDF40 AN3LO: IMPACT ON PDF EVOLUTION



- Effects of N3LO 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

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

NNPDF40 AN3LO: 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)

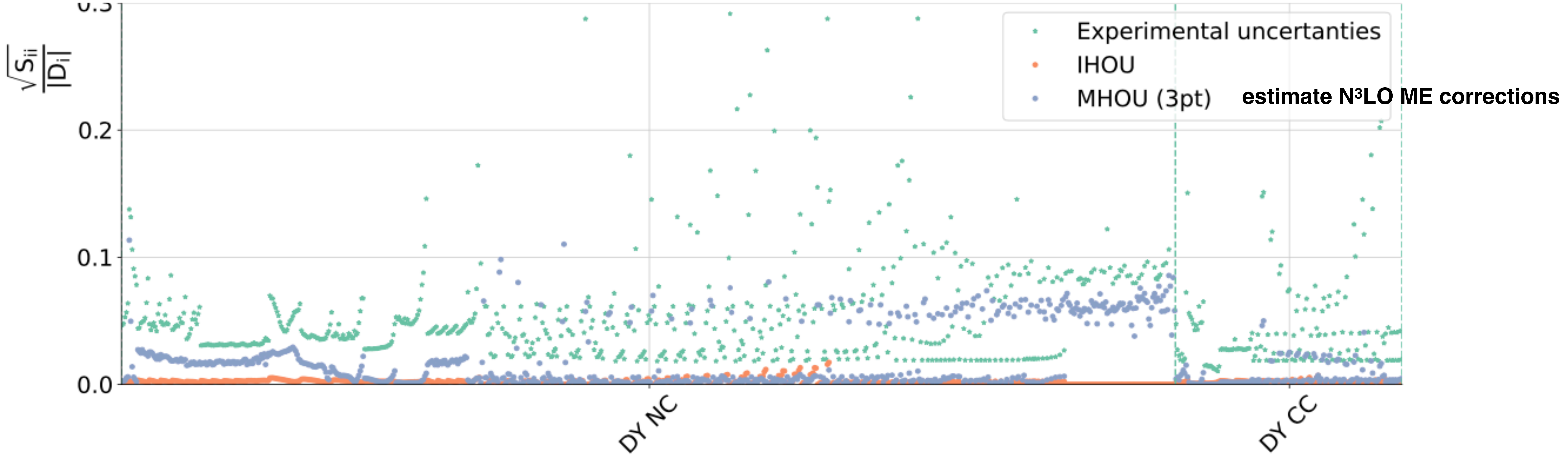
$$\Delta_i(\rho_f,\rho_r) \equiv T_i(\rho_f,\rho_r) - T_i(0,0),$$

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

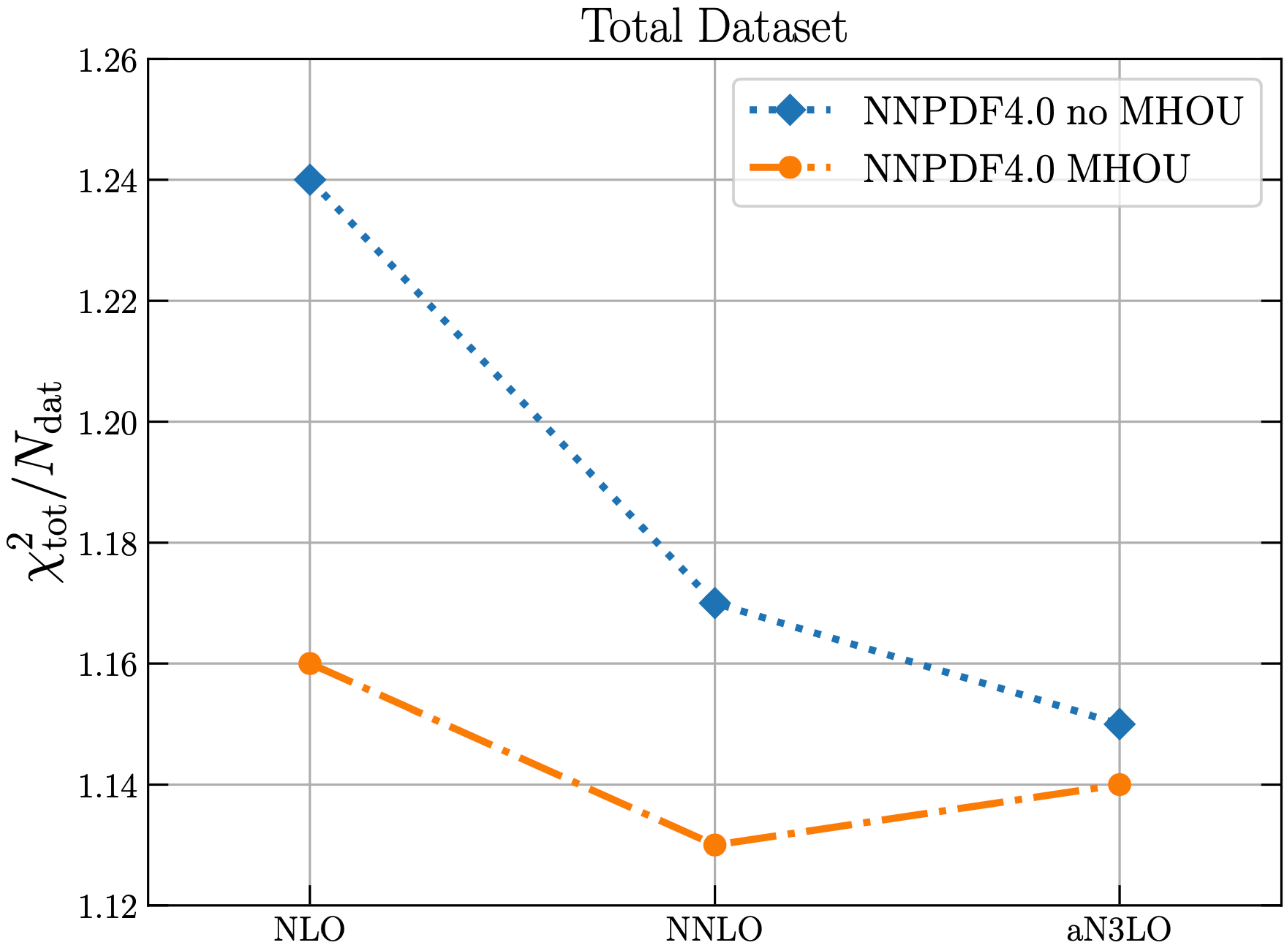
$$S_{ij} = n_m \sum_{V_m} \Delta_i(\rho_f,\rho_{r_i})\Delta_j(\rho_f,\rho_{r_j}),$$

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 aN^{3}LO evolution and NNLO matrix elements**, supplemented by MHOUs associated to μ_R variations to account for missing K-factors

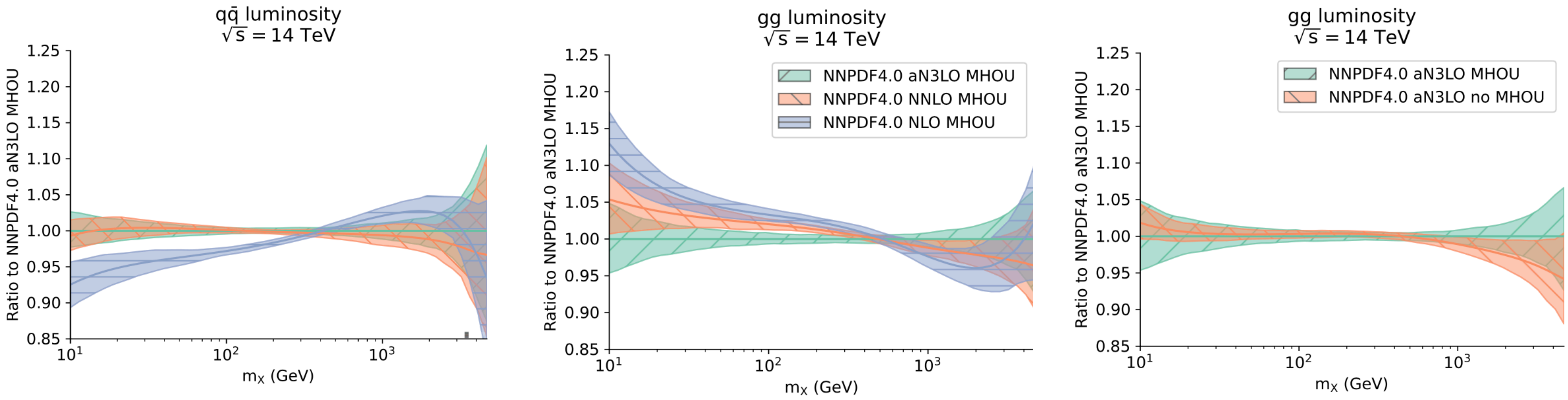


NNPDF40 AN3LO: FIT QUALITY



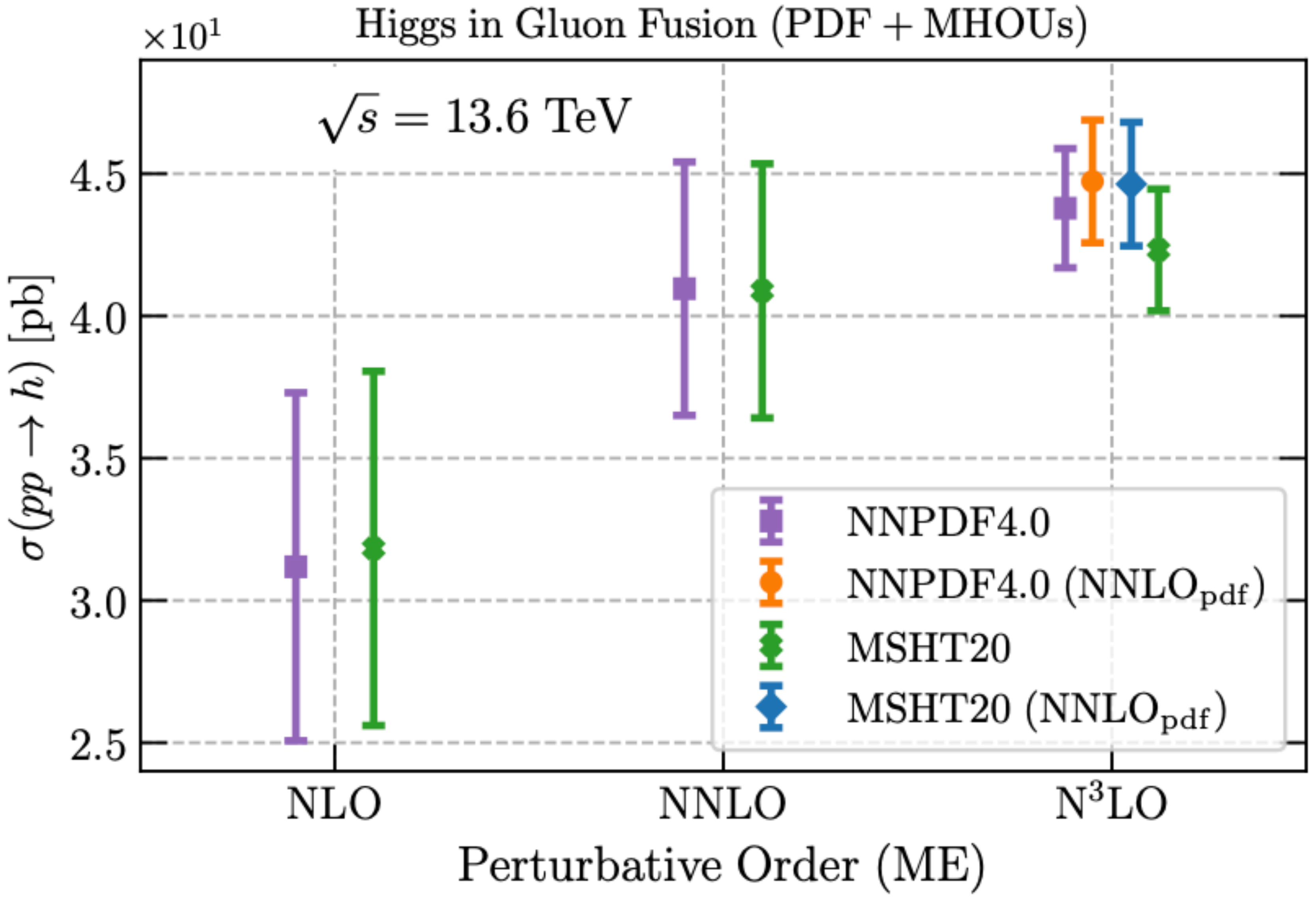
- Without MHOUs, the **χ^2 improves with the perturbative accuracy** of the PDF fit
- With MHOUs, the **χ^2** becomes **feebly dependent on the perturbative accuracy**
- At aN^{3}LO impact of MHOUs is small (also at PDF level) but non negligible
- **N^{3}LO corrections** required for perturbative convergence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

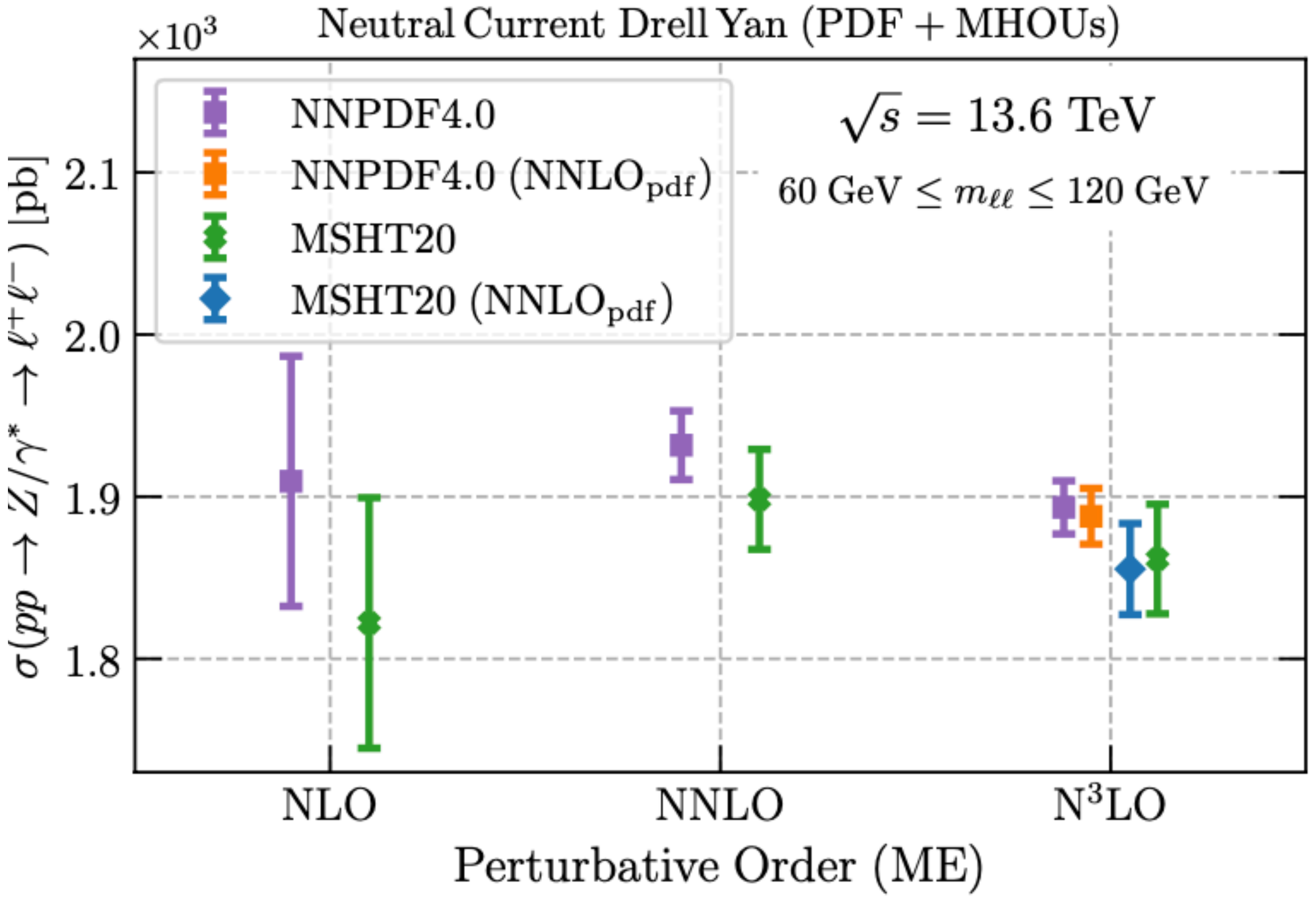
PERTURBATIVE CONVERGENCE AND MHOUS

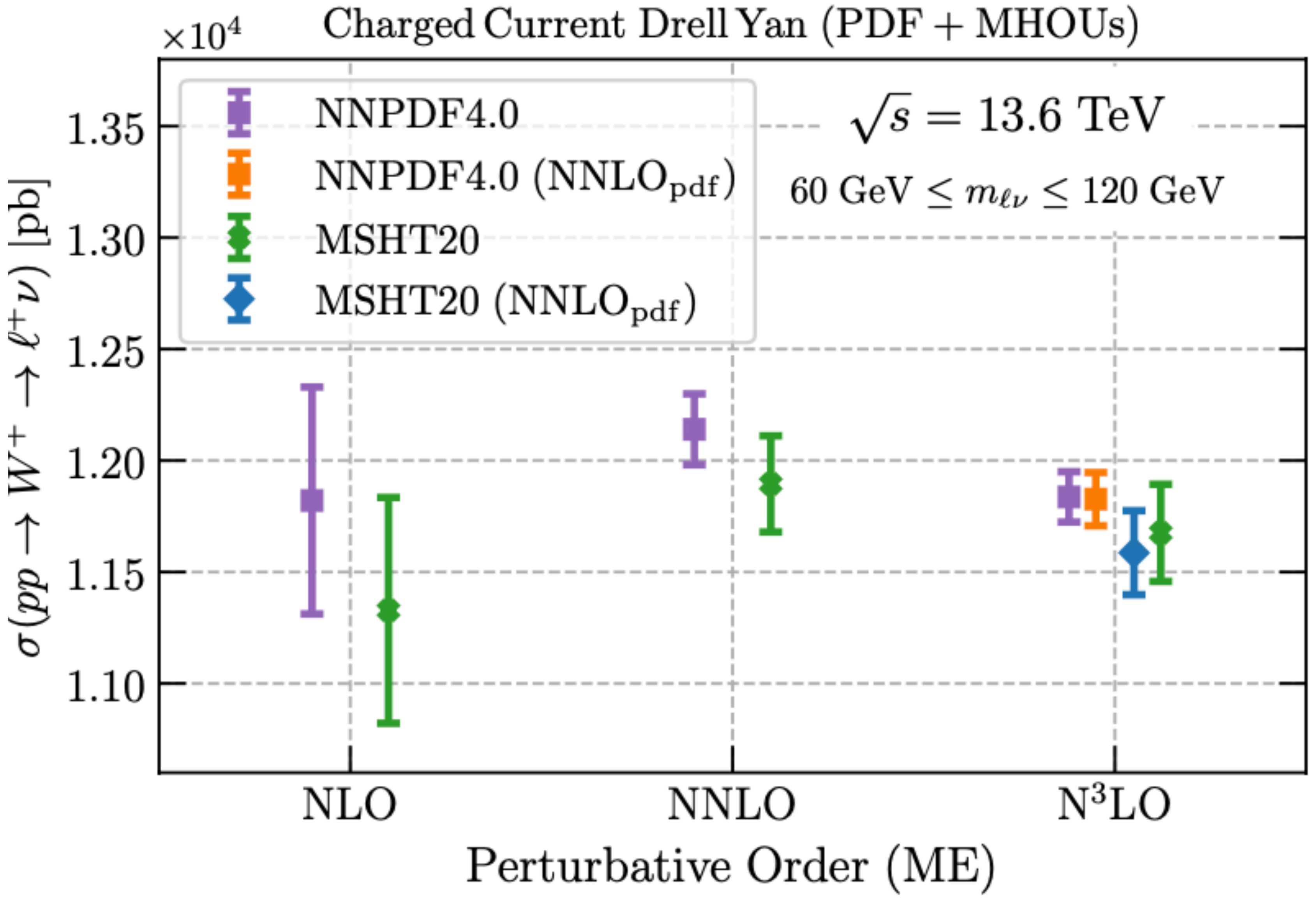


- **Good perturbative convergence**
- Impact of N^{3}LO corrections moderate, specially for the quark luminosities
- For the gluon-gluon luminosity, NNPDF4.0 finds a **small suppression** around Higgs mass (2% effects
- Impact of **MHOUs is not negligible** even at N^{3}LO, both in terms of central values and uncertainties
- Motivates inclusion of **exact N^{3}LO calculations** for hadronic processes in global PDF fits (*e.g.* Drell-Yan production, already available)

NNPDF40 AN3LO: PHENOMENOLOGICAL IMPACT







- N^{3}LO PDF corrections to **Higgs in gluon fusion small,** with a 1.5% suppression wrt NNLO PDFs
- Good perturbative convergence at N^{3}LO also for **quark-initiated processes**

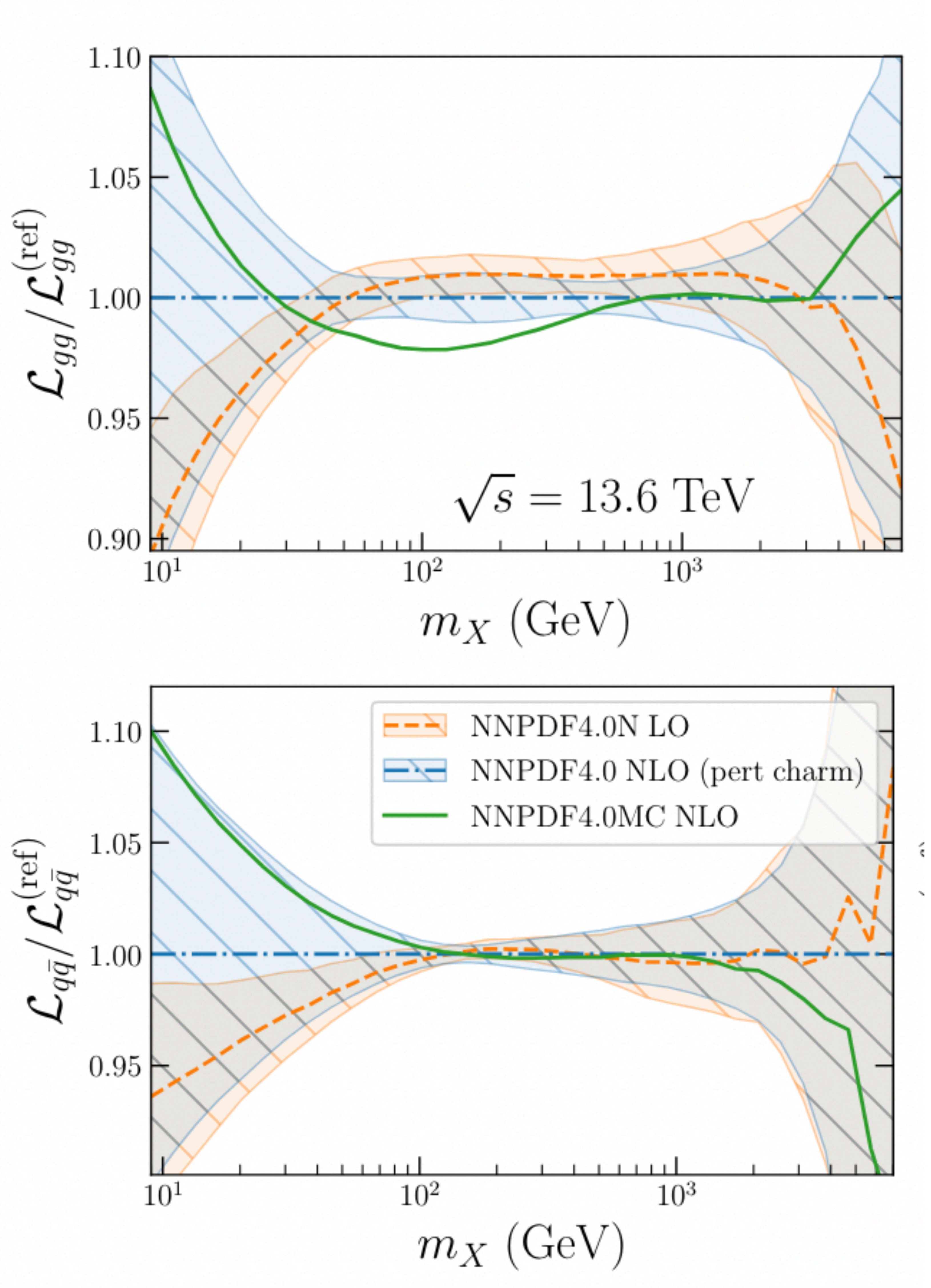
NEW: COMBINED NNPDF AN3LO + MHOU +QED PDF SETS

Fit ID	Perturbative accuracy	Theory cov. mat.
NNPDF40_nnlo_as_01180_qed_mhou	$\mathrm{NNLO_{QCD}} \otimes \mathrm{NLO_{QED}}$	$\mathrm{MHOU_{7pt}}$
NNPDF40_an3lo_as_01180_qed	$\mathrm{aN^3LO_{QCD}} \otimes \mathrm{NLO_{QED}}$	$\mathrm{IHOU+MHOU_{3pt}}$
NNPDF40_an3lo_as_01180_qed_mhou	$\mathrm{aN^3LO_{QCD}} \otimes \mathrm{NLO_{QED}}$	$\mathrm{IHOU+MHOU_{7pt}}$

- Qualitative impact of QED corrections on quark and gluon is the same in the NNLO and aN3LO fits.
- Largest impact associated to the gluon, where QED effects lead to overall decrease of ~1%
- For the quark PDFs, the impact of QED effects in the aN3LO fit is small but consistent with the results the corresponding NNLO fits

Barontini et al arXiv:2406.01779

NEW: NNPDF40 LO, NLO AND NNLO SETS FOR MC EVENT GENERATORS



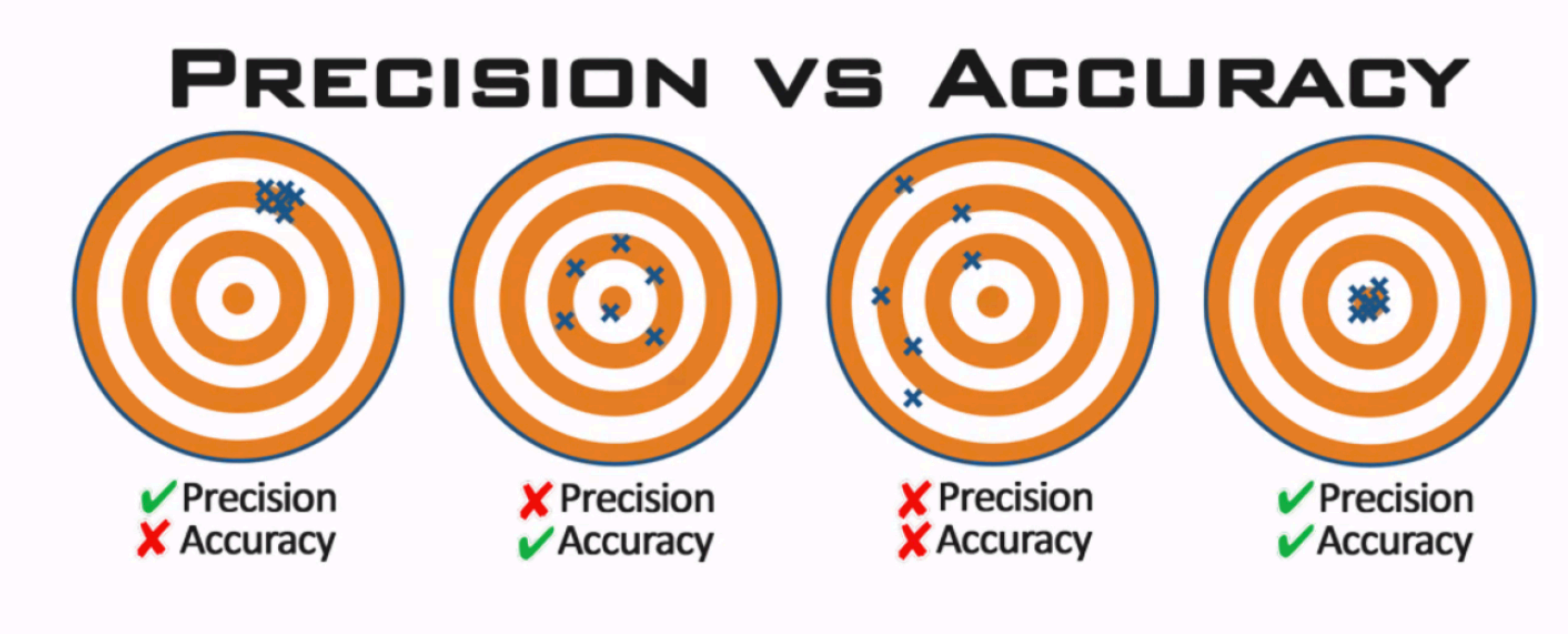
- NNPDF4.0MC PDFs satisfy the requirements of event generators (non-negative down to Q ~ 1 GeV, smooth extrapolation to very small-x and Q, fast growing gluon at small-x, photon PDF included and perturbatively generated heavy quark PDFs) at LO, NLO, NNLO.
- Available with various settings to be matched to different Monte Carlo event generators

NNPDF23_lo_as_0130_qed	[27]	$\mathrm{QCD_{LO}}\otimes\mathrm{QED_{LO}}$ TRN (1.0 GeV)	$g, q_i, \bar{q}_i > 0$ (1 GeV)	0.130	pert.
NNPDF40_lo_as_01180	[32]	$\mathrm{QCD_{LO}}$ TRN (1.65 GeV)	$g, q_i, \bar{q}_i > 0$ (1.65 GeV)	0.118	fitted
NNPDF40_lo_pch_as_01180	[32]	$\mathrm{QCD_{LO}}$ TRN (1.65 GeV)	$g, q_i, \bar{q}_i > 0$ (1 GeV)	0.118	pert.
NNPDF40MC_lo_as_01180	t.w.	$\mathrm{QCD_{LO}}$ TRN (1.0 GeV)	$g, q_i, \bar{q}_i > 0$ (1 GeV)	0.118	pert.
NNPDF40MC_lo_as_01180_qed	t.w.	$\mathrm{QCD_{LO}}\otimes\mathrm{QED_{LO}}$ EXA (1.0 GeV)	$g, q_i, \bar{q}_i > 0$ (1 GeV)	0.118	pert.
NNPDF40_nlo_as_01180	[32]	$\mathrm{QCD_{NLO}}$ TRN (1.65 GeV)	$g, q_i, \bar{q}_i > 0$ ($\sqrt{5}$ GeV)	0.118	fitted
NNPDF40_nlo_pch_as_01180	[32]	$\mathrm{QCD_{NLO}}$ TRN (1 GeV)	$g, q_i, \bar{q}_i > 0$ ($\sqrt{5}$ GeV)	0.118	pert.
NNPDF40MC_nlo_as_01180	t.w.	$\mathrm{QCD_{NLO}}$ TRN (1 GeV)	$g, \Sigma > 0$ (1 GeV) $q_i, \bar{q}_i > 0$ ($\sqrt{5}$ GeV)	0.118	pert.

J. Cruz-Martines et al arXiv:2406.12961

PART II: A ROADMAP TO TEST ACCURACY

THE PRECISION VERSUS ACCURACY CHALLENGE



Challenges

- Inconsistency or tension in data of experimental origin (underestimate of systematics…)
- Deficiencies in fitting methodology (data-driven parametrisation change, optimisation issues, overfitting…)
- Inaccuracy in theoretical framework
  - ➡ Missing higher order uncertainties (QCD, EW)
  - ➡ Other corrections (nuclear, higher-twist, non-perturbative effects…)
- Fitting away possible BSM signals

CLOSURE TEST: A TOOL TO TEST METHODOLOGY AND THEORY

- Closure tests for **data region**: imagine we knew the law of Nature f: is our fitting methodology able to reproduce it? Is the uncertainty faithful? Statistical validation of PDF uncertainties can be performed via closure tests.

L0 pseudo-data

$$y_0 = f + \eta$$

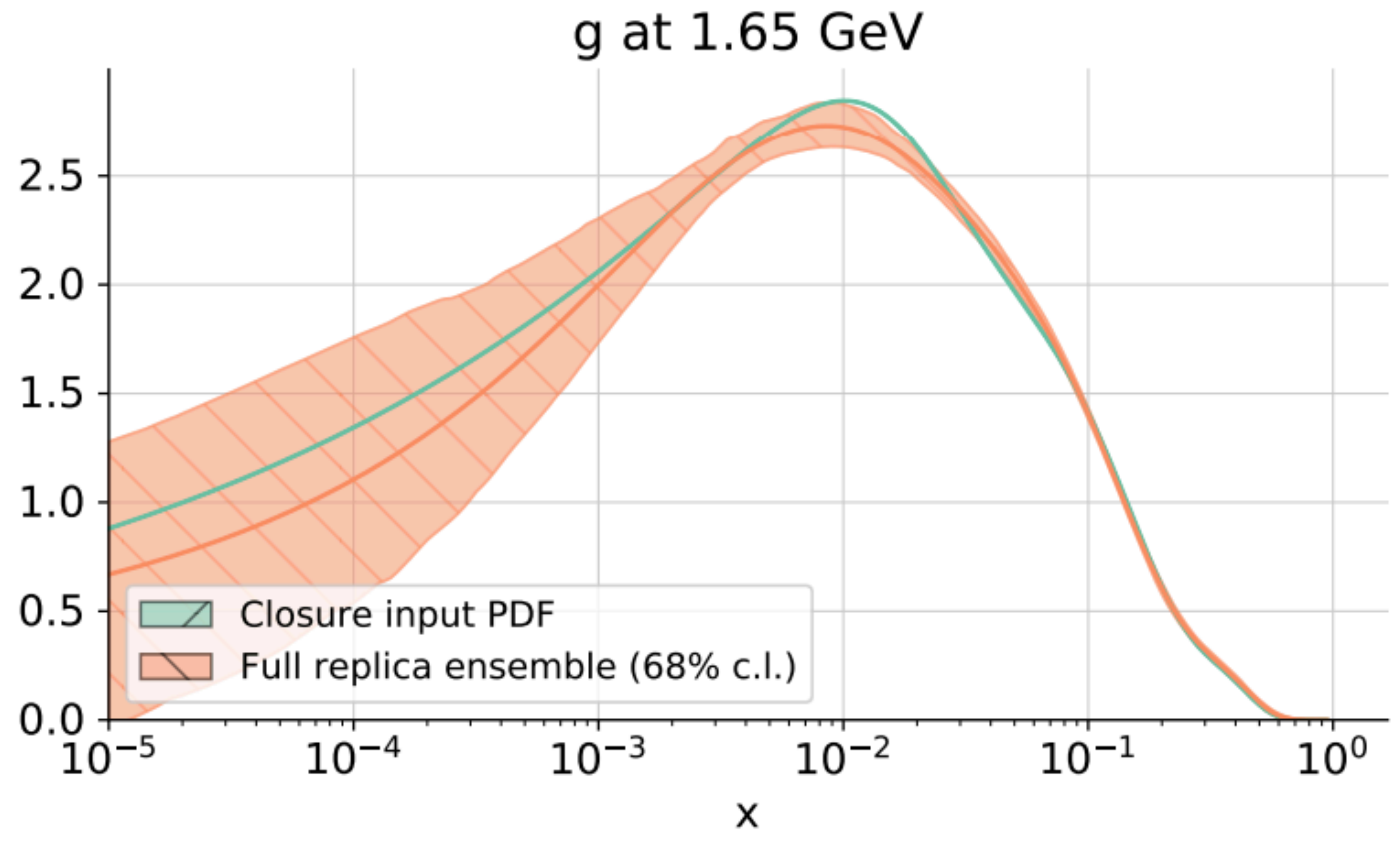
Experimental noise

Law of Nature

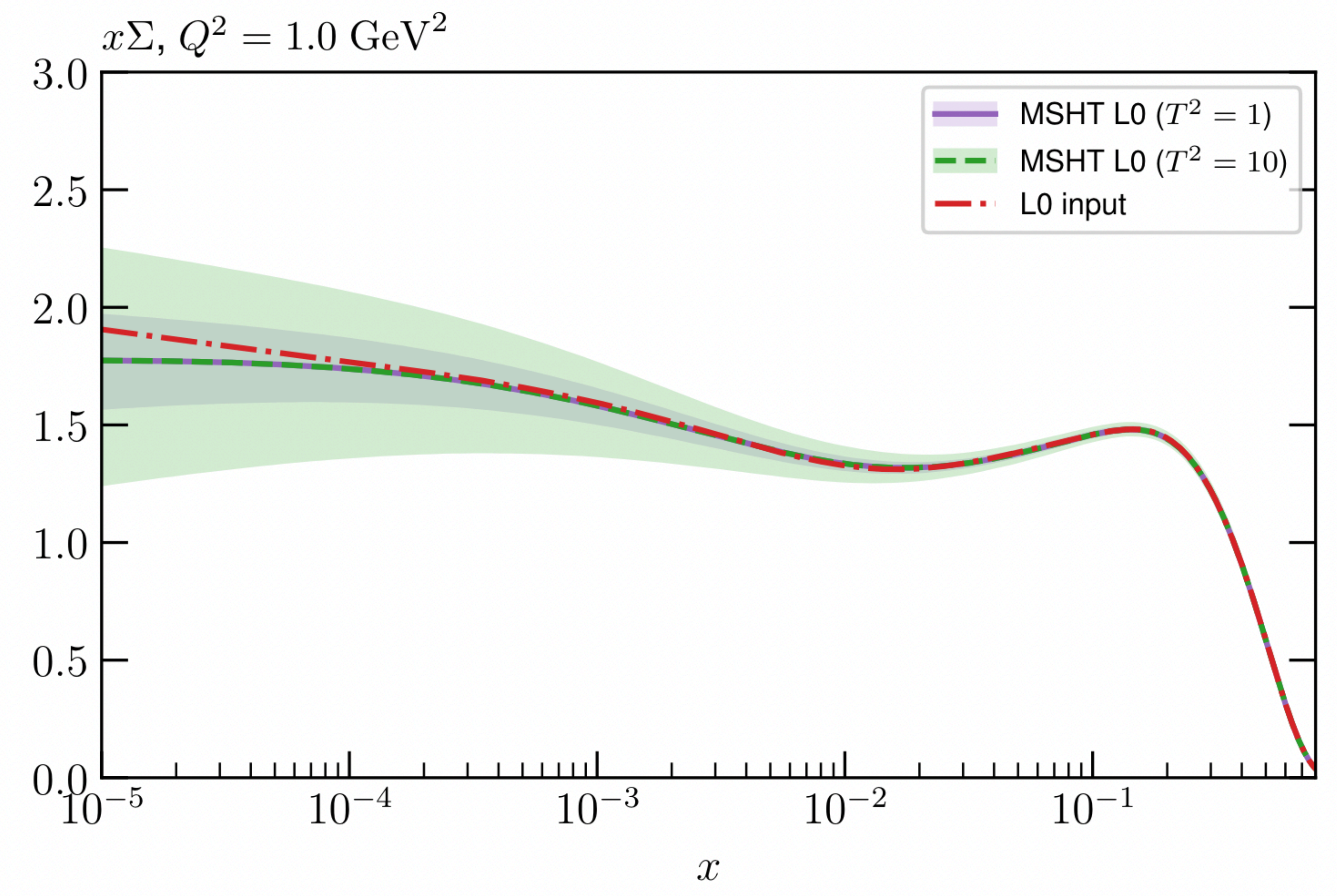
$$\hat{\sigma}_{\rm NNLO} \otimes (f \otimes f)_{\text{“true” PDF}}$$

Test fitting methodology with consistent data (by construction)

Del Debbio et al, [arXiv: 2111.05787]



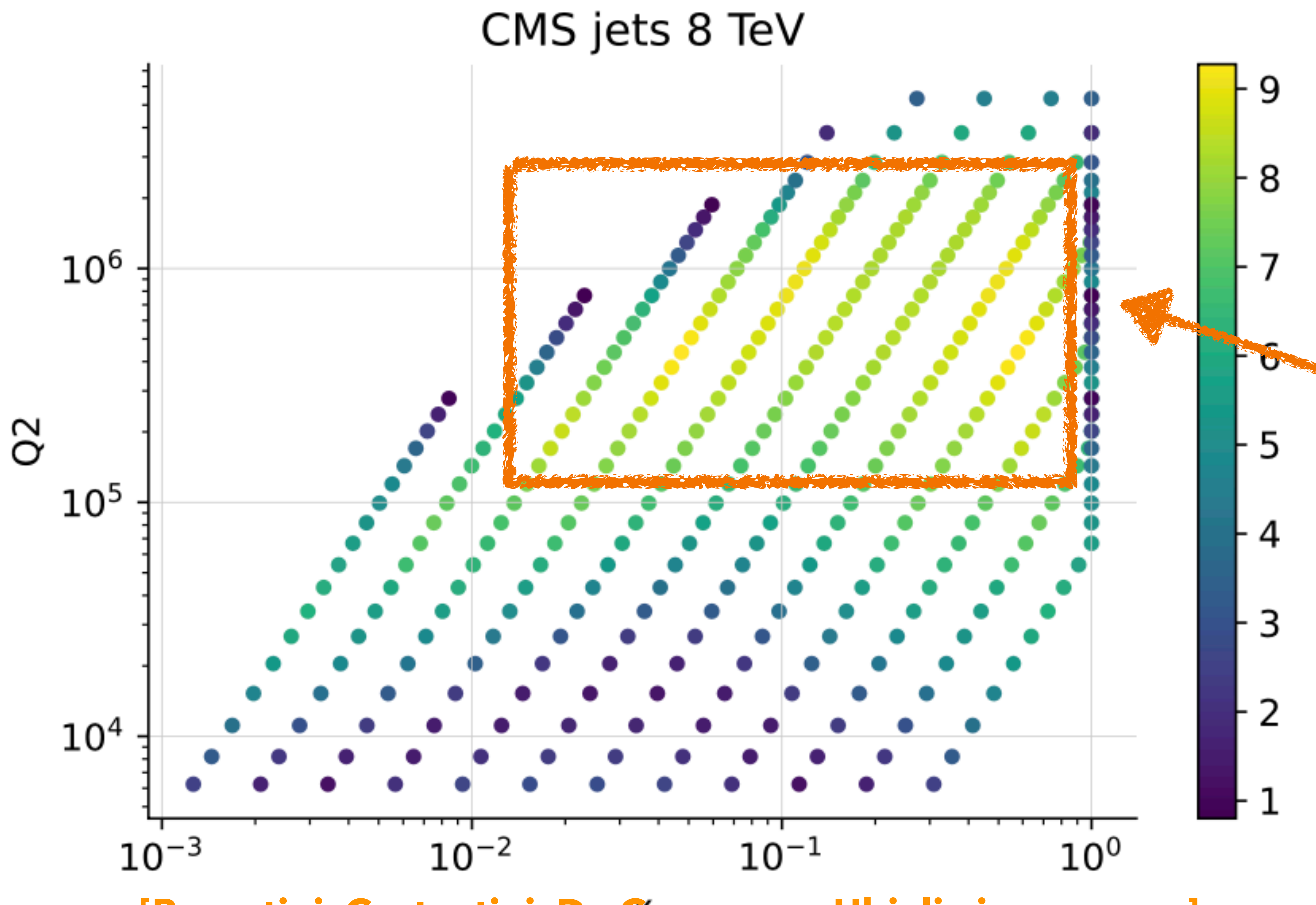
L. Harland Lang, DIS 2024



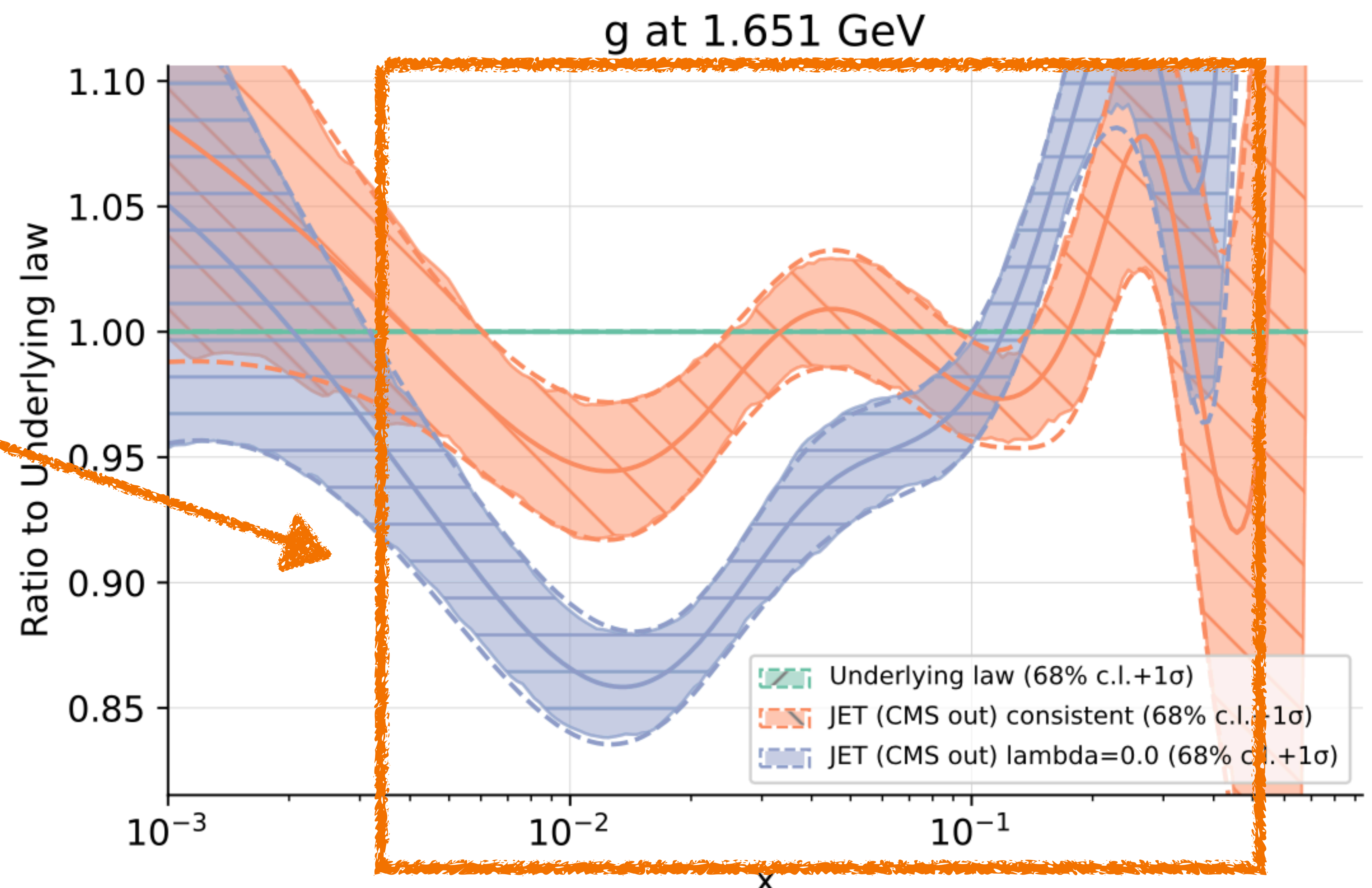
CLOSURE TEST: A TOOL TO TEST METHODOLOGY AND THEORY

- Closure tests for <u>data region</u>: imagine we knew the law of Nature **f**: is our fitting methodology able to reproduce it? Is the uncertainty faithful? Statistical validation of PDF uncertainties can be performed via closure tests.
- What happens if experimentalists underestimated some systematics? Example: Build in the closure test an complete underestimate of ATLAS jets systematics, check effects on CMS jets observables (if out-of-sample) and gluon PDFs

Diagnostic tools: determine statistical indicators such as ratio bias-variance of under (>1) or over (<1) estimated uncertainties allow to check effect of experimental inconsistencies on datasets included and on the PDFs



NNPDF methodology robust under inconsistencies in data, closure test estimators would enable to spot data inconsistency



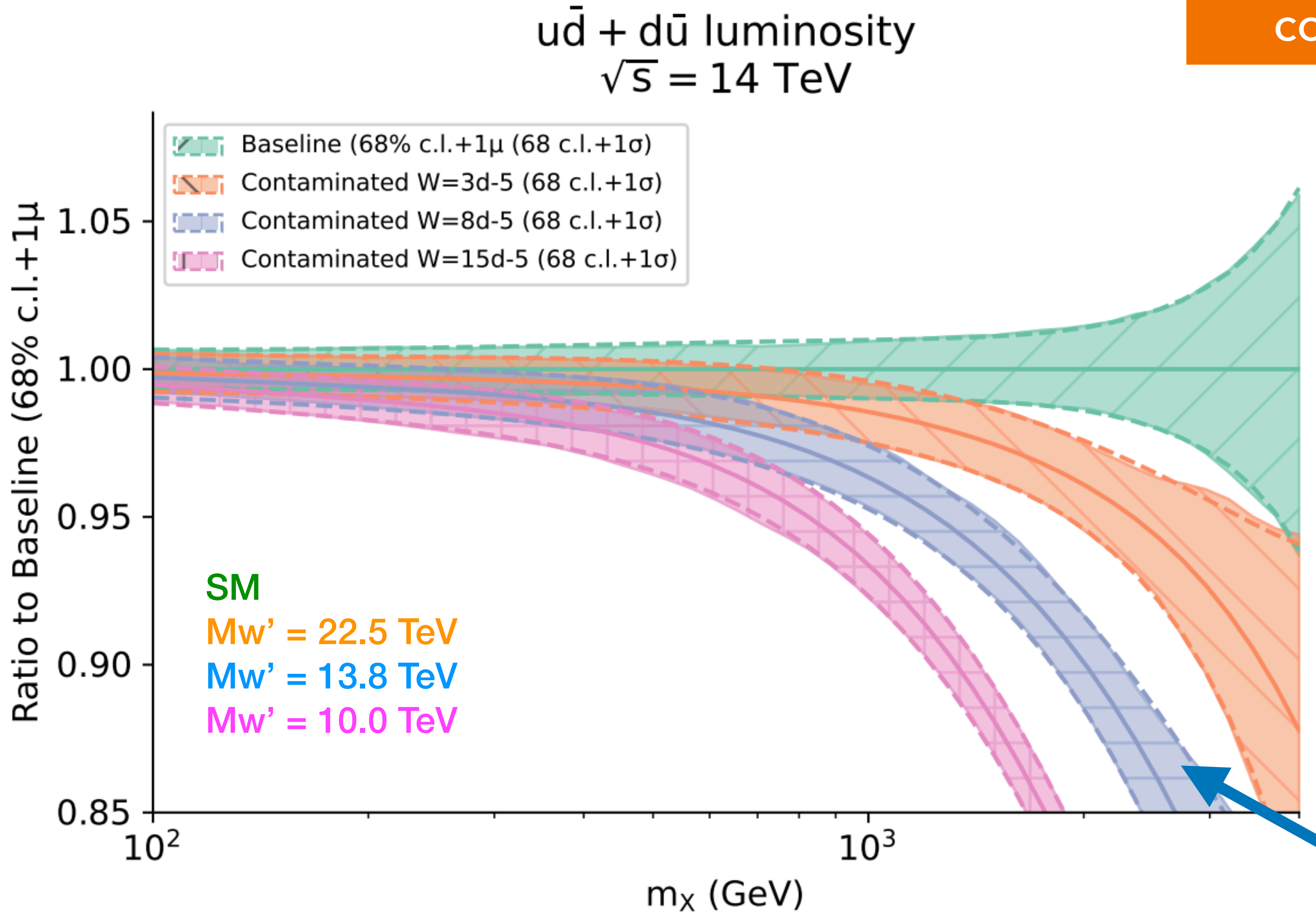
[Barontini, Costantini, De Crescenzo, Ubiali - in progress]

CLOSURE TEST: A TOOL TO TEST METHODOLOGY AND THEORY

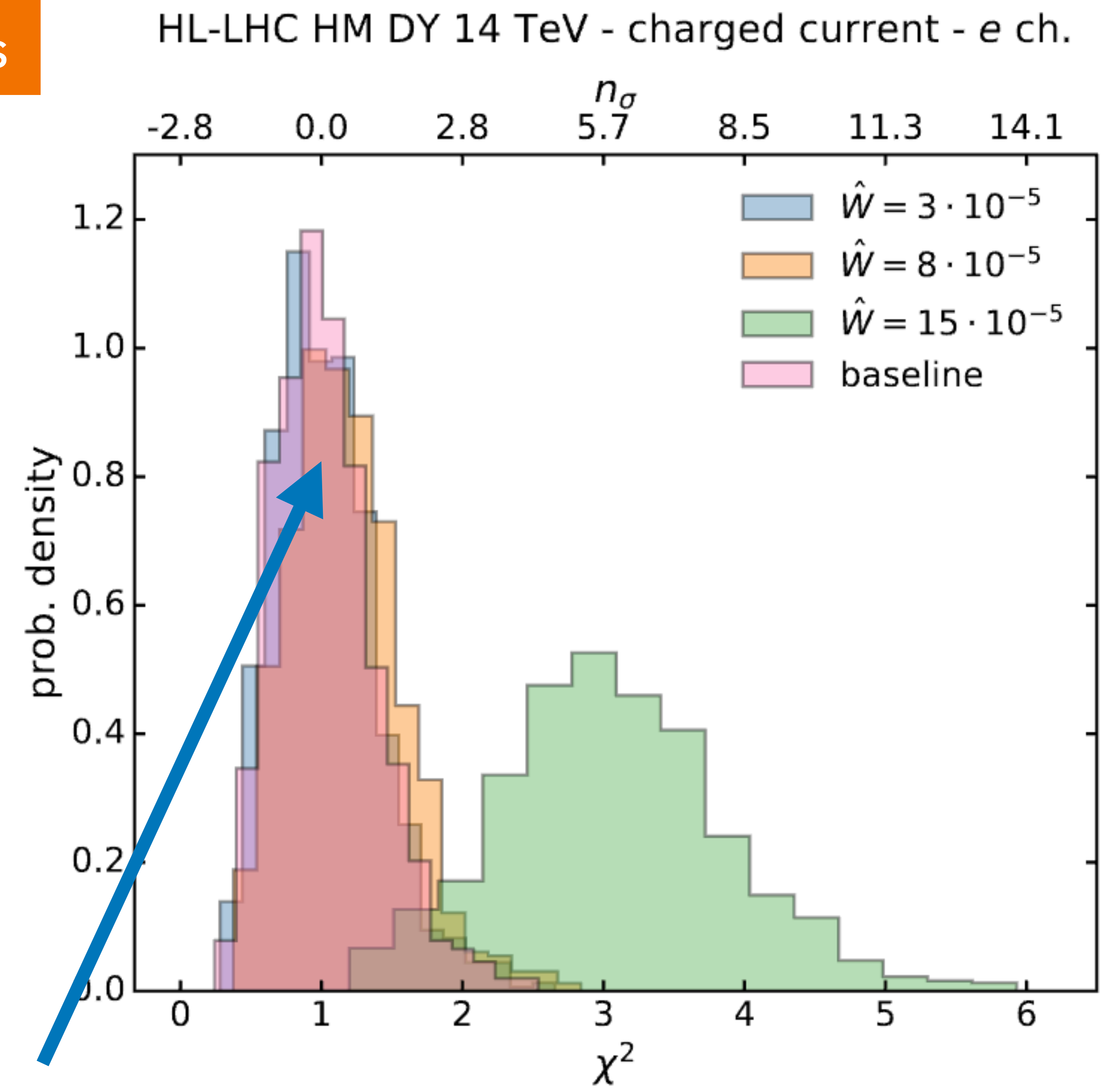
- Imagine that on top of the “true” PDFs one inject the “true” NP model in the pseudo-data
- Generate HL-LHC pseudo-data assuming
  “true” law of nature = “true” PDFs + “true” UV model
- Fit PDFs assuming SM
- Can PDFs absorb signs of new physics?

Z'	W'
Selection test: ✗	Selection test: ✓
➡ Excluded from PDF fit	➡ Included in PDF fit
No impact on PDFs	**PDFs contaminated**

Test possible New Physics contamination in PDF fits



Max contamination allowed by global fit Without spoiling χ^2



Hammou, Madigan, Mangano, Mantani, Moore, Morales, MU 2307.10370

TEST GENERALISATION OF PDF AND EXTRAPOLATION

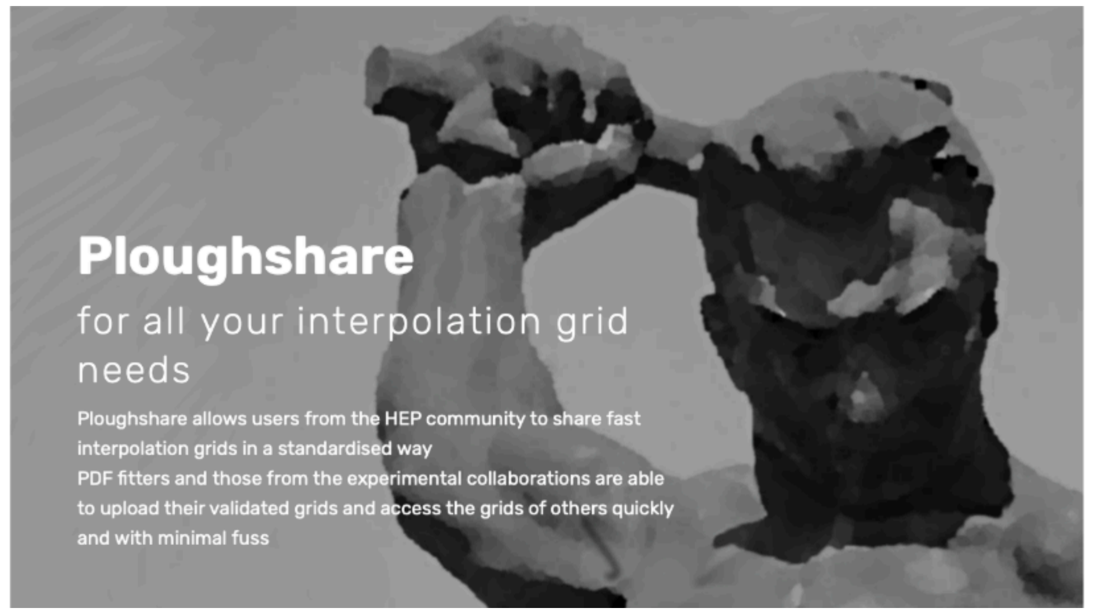
- Future tests help to discriminate among PDF sets [J. Cruz-Martinez et al, Acta Phys.Polon.B 52 (2021) 243 - on Run I] [Chiefa et al, in progress]: test all global PDF sets agains new precise data from LHC Run I and Run II data & DIS HERA jets data. How well do various PDF sets describe data that are not yet included in the fit?

- Remarks:
  - ➡ All results are NNLO (no k-factor approximation) thanks to PineAPPL, NNLOJET, MATRIX and Ploughshare

PineAPPL

Carrazza et al: 2008.12789

Gehrmann-De Ridder et al: 1507.02850, 1605.04295…



MATRIX

Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
Automates qT-subtraction and Resummation to Integrate X-sections

Grazzini et al: 1711.06631

  - ➡ NNLO PDF sets considered: PDF4LHC15, PDF4LHC21, ABMP16, CT18, CT18A, CT18Z, MSHT20, NNPDF3.1, NNPDF4.0
  - ➡ The computation of χ^2 is always shown considering as uncertainties either (exp) or (exp + mho) or (exp + mho + pdf) and over the entire dataset / HEPdata entry

$$\chi^2 = \sum_{i,j=1}^{N_{\mathrm{dat}}} \left(T_i^{(0)} - D_i\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(T_j^{(0)} - D_j\right)$$

$$\begin{aligned} \chi^2_{\mathrm{exp}} &\leftrightarrow \mathrm{cov} = \mathrm{cov}_{\mathrm{exp}} \\ \chi^2_{\mathrm{exp+mho}} &\leftrightarrow \mathrm{cov} = \mathrm{cov}_{\mathrm{exp}} + \mathrm{cov}_{\mathrm{mho}} \\ \chi^2_{\mathrm{exp+mho+pdf}} &\leftrightarrow \mathrm{cov} = \mathrm{cov}_{\mathrm{exp}} + \mathrm{cov}_{\mathrm{mho}} + \mathrm{cov}_{\mathrm{pdf}} \end{aligned}$$

THE EXPERIMENTAL DATA IN THE TEST SET

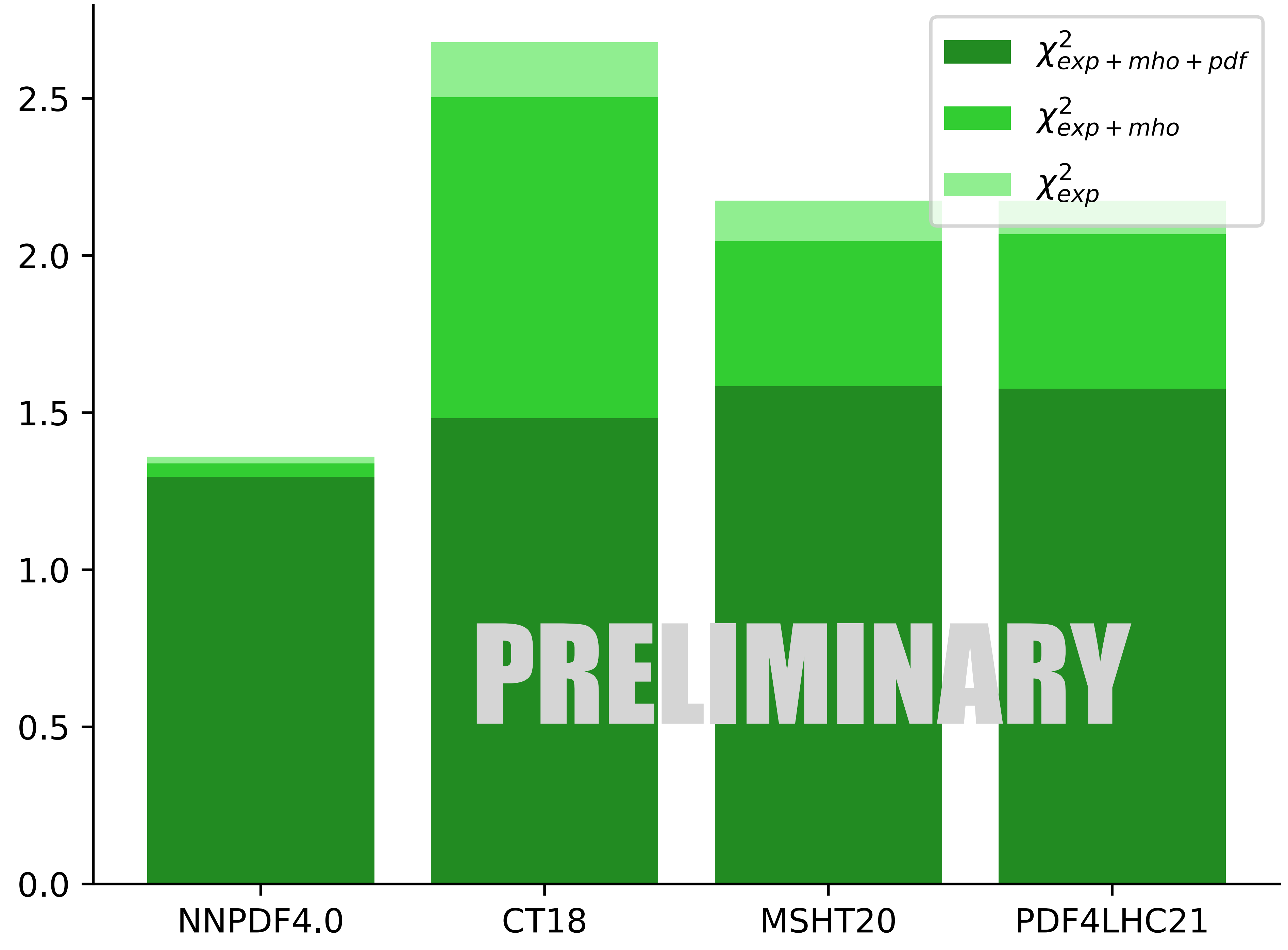
Sector	Exp.	$\sqrt{s}$ (TeV)	Channel	Observable	$\mathcal{L}$ (fb^{-1})	N$_{\text{dat}}$
W, Z	ATLAS	13	Z p_T spectrum	$\frac{d\sigma}{dp_T^Z}$	36.1	10
	ATLAS	8	Z incl. prod.	$\frac{d\sigma}{d\|y_{ll}\|}$	20.2	7
	CMS	8	W incl. prod.	$\frac{d\sigma_{W\pm}}{d\eta_l}$	35.9	36
	LHCb	13	Z incl. forward prod.	$\frac{d\sigma_Z}{dy_Z}$	5.1	17
top	ATLAS	13	hadronic	$\left(\frac{1}{\sigma}\right)\frac{d\sigma}{dm_{t\bar{t}}}, \frac{d\sigma}{d\|y_{t\bar{t}}\|}, \frac{d^2\sigma}{d\|y_{t\bar{t}}\|dm_{t\bar{t}}}$	36.1	9, 12, 11
	ATLAS	13	ℓ+jets	$\left(\frac{1}{\sigma}\right)\frac{d\sigma}{dm_{t\bar{t}}}, \frac{d\sigma}{dp_{T,t}}, \frac{d\sigma}{d\|y_t\|}, \frac{d^2\sigma}{d\|y_{t\bar{t}}\|}$	36.1	9, 8, 5, 7
	CMS	13	ℓ+jets	$\left(\frac{1}{\sigma}\right)\frac{d\sigma}{dm_{t\bar{t}}}, \frac{d\sigma}{dp_{T,t}}, \frac{d\sigma}{d\|y_{t\bar{t}}\|}, \frac{d\sigma}{d\|y_t\|}, \frac{d^2\sigma}{d\|y_{t\bar{t}}\|dm_{t\bar{t}}}$	137	15, 16, 10, 11, 35
jets	ATLAS	13	incl. jet R=0.4, 0.7	$\frac{d^2\sigma}{dp_{T,j}d\|y_j\|}$	3.2	177
	ATLAS	13	di-jets R=0.4	$\frac{d^2\sigma}{dm_{jj}d\Delta y}$	3.2	136
	CMS	13	incl. jets R=0.4, 0.7	$\frac{d^2\sigma}{dp_{T,j}d\|y_j\|}$	3.2	78
DIS jets	H1	0.319	incl. jet (low q^2)	$\frac{d^2\sigma}{dq^2dpT}$	0.29	48
	H1	0.319	di-jets (low q^2)	$\frac{d^2\sigma}{dq^2d\langle pT\rangle}$	0.29	48
	H1	0.319	incl. jet (high q^2)	$\frac{d^2\sigma}{dq^2dpT}$	0.351	24
	H1	0.319	di-jets (high q^2)	$\frac{d^2\sigma}{dq^2d\langle pT\rangle}$	0.351	24
	ZEUS	0.3	incl. jet	$\frac{d^2\sigma}{dE_Tdq^2}$	0.038	30
	ZEUS	0.319	incl. jet	$\frac{d^2\sigma}{dE_Tdq^2}$	0.082	30
	ZEUS	0.319	d-jets	$\frac{d^2\sigma}{dE_Tdq^2}$	0.374	22

Chiefa et al, in progress

THE TOP SECTOR

ATLAS top pair production at 13 TeV, l+jet channel, (36.1fb^{-1})

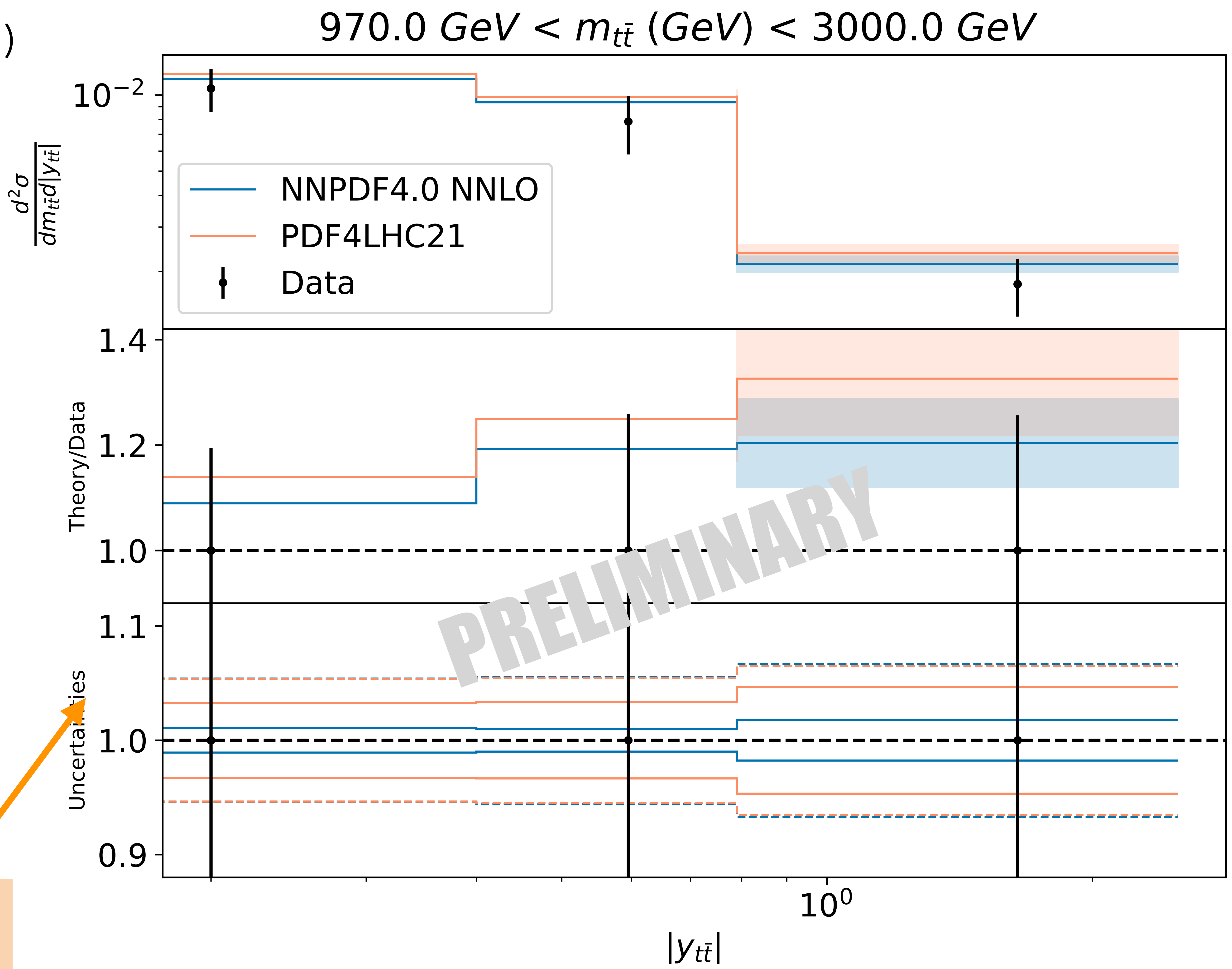
ATLAS collaboration [arXiv:1908.07305]



	$\chi^2_{exp+mho+pdf}$	$\chi^2_{exp+mho}$
ABMP16	0.832	(0.835)
CT18	1.483	(2.504)
CT18A	1.489	(2.347)
MSHT20	1.585	(2.046)
NNPDF3.1	1.200	(1.244)
NNPDF4.0	1.297	(1.338)
PDF4LHC15	1.298	(2.088)
PDF4LHC21	1.577	(2.068)

Absolute comparison, normalized & size of PDF (solid) and dashed (MHO) **Δ** compared to data **Δ**.

Shaded band includes MHO (9 pts variation) and PDF uncertainties added in quadrature.



Chiefa et al, in progress

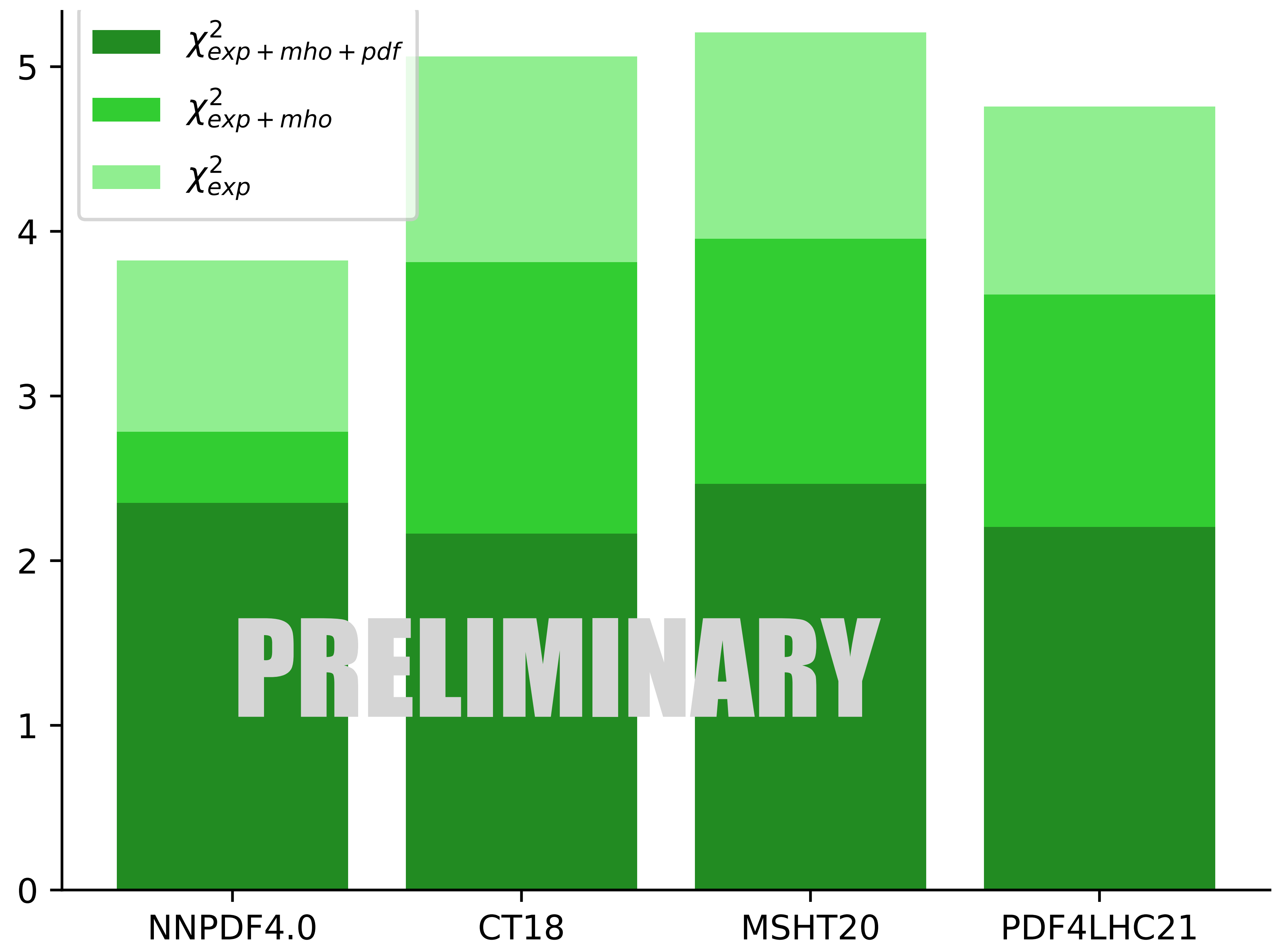
Predictions: MATRIX

Hepdata: 10.17182/hepdata.95758

THE JET SECTOR

CMS inclusive jet cross-sections at 13 TeV (33.5fb-1) anti-kT, R=0.7

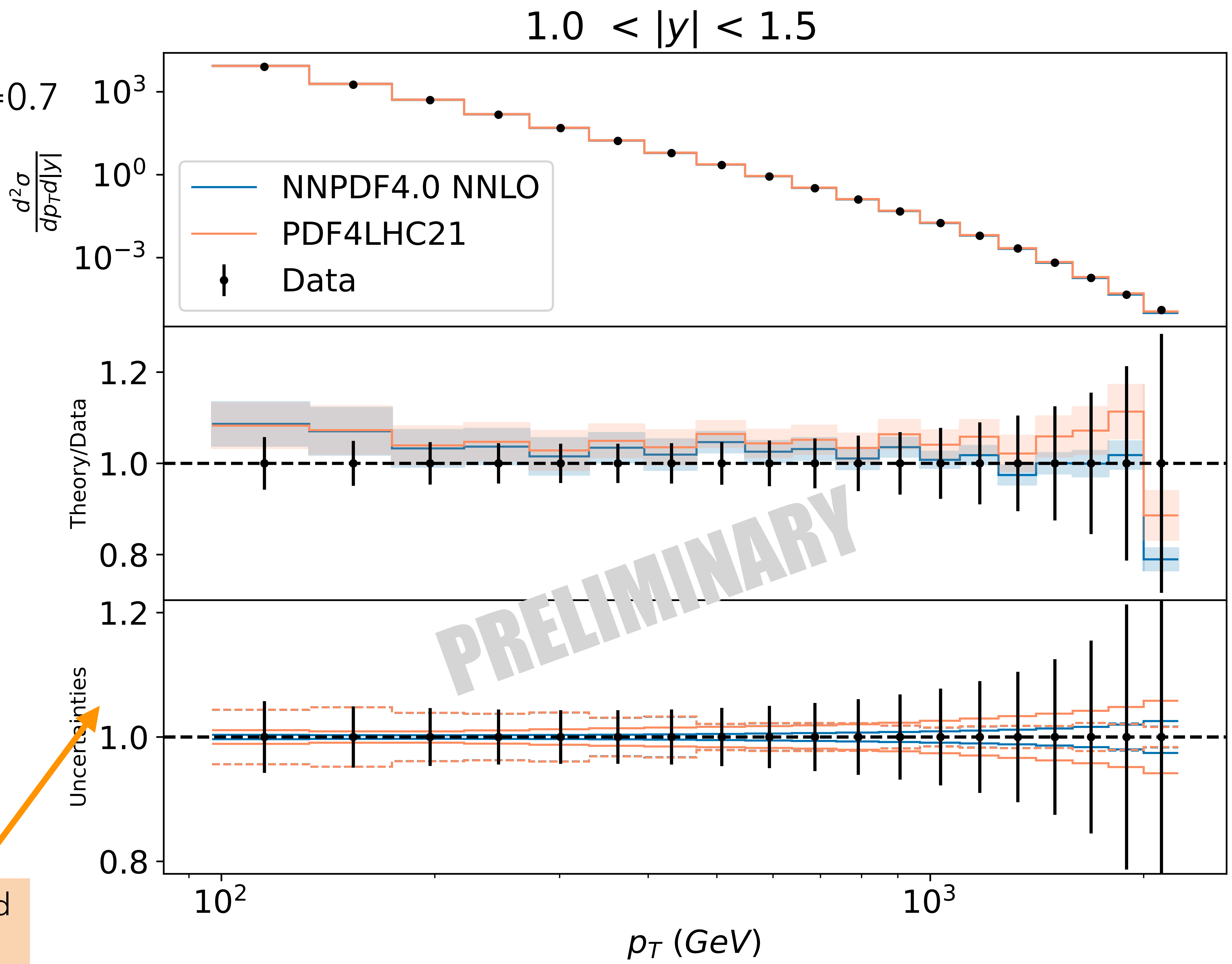
CMS collaboration [arXiv:2111.10431]



	$\chi^2_{exp+mho+pdf}$	($\chi^2_{exp+mho}$)
ABMP16	2.77	(3.71)
CT18	2.16	(3.81)
CT18A	2.16	(3.77)
CT18Z	**2.06**	(3.34)
MSHT20	2.47	(3.96)
‘ NNPDF3.1	2.52	(3.88)
NNPDF4.0	2.35	(**2.78**)
PDF4LHC15	2.15	(3.80)
PDF4LHC21	2.21	(3.62)

Absolute comparison, normalized & size of PDF (solid) and dashed (MHO) **Δ** compared to data **Δ**.

Shaded band includes MHO (9 pts variation) and PDF uncertainties added in quadrature.



Chiefa et al, in progress

Leading color NNLO correction

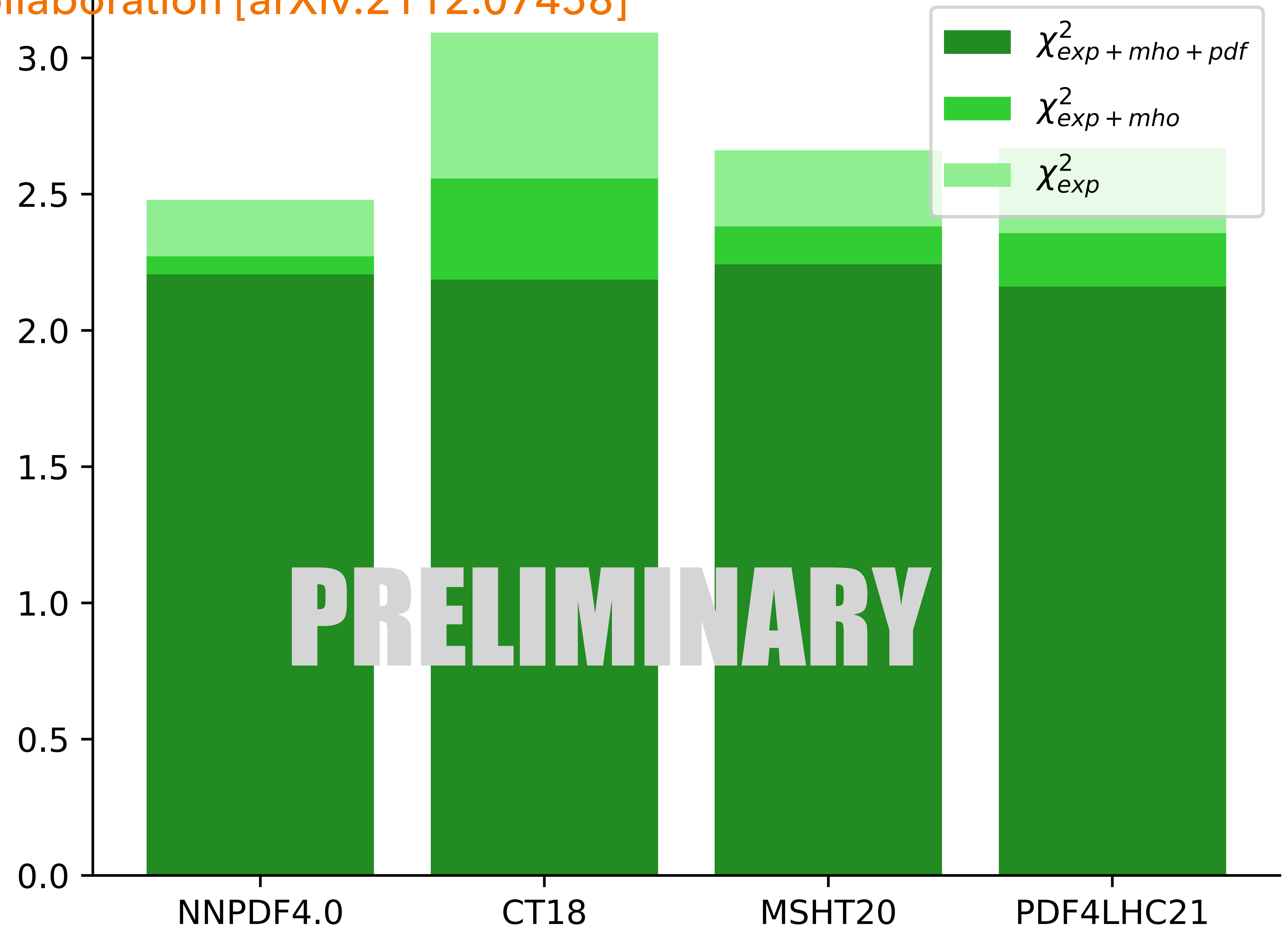
Predictions: NNLOJET (plougshare)

Hepdata: 10.17182/hepdata.115022.v2

THE DRELL-YAN SECTOR

LHCb Z forward production at 13 TeV (5.1fb-1)

LHCb collaboration [arXiv:2112.07458]

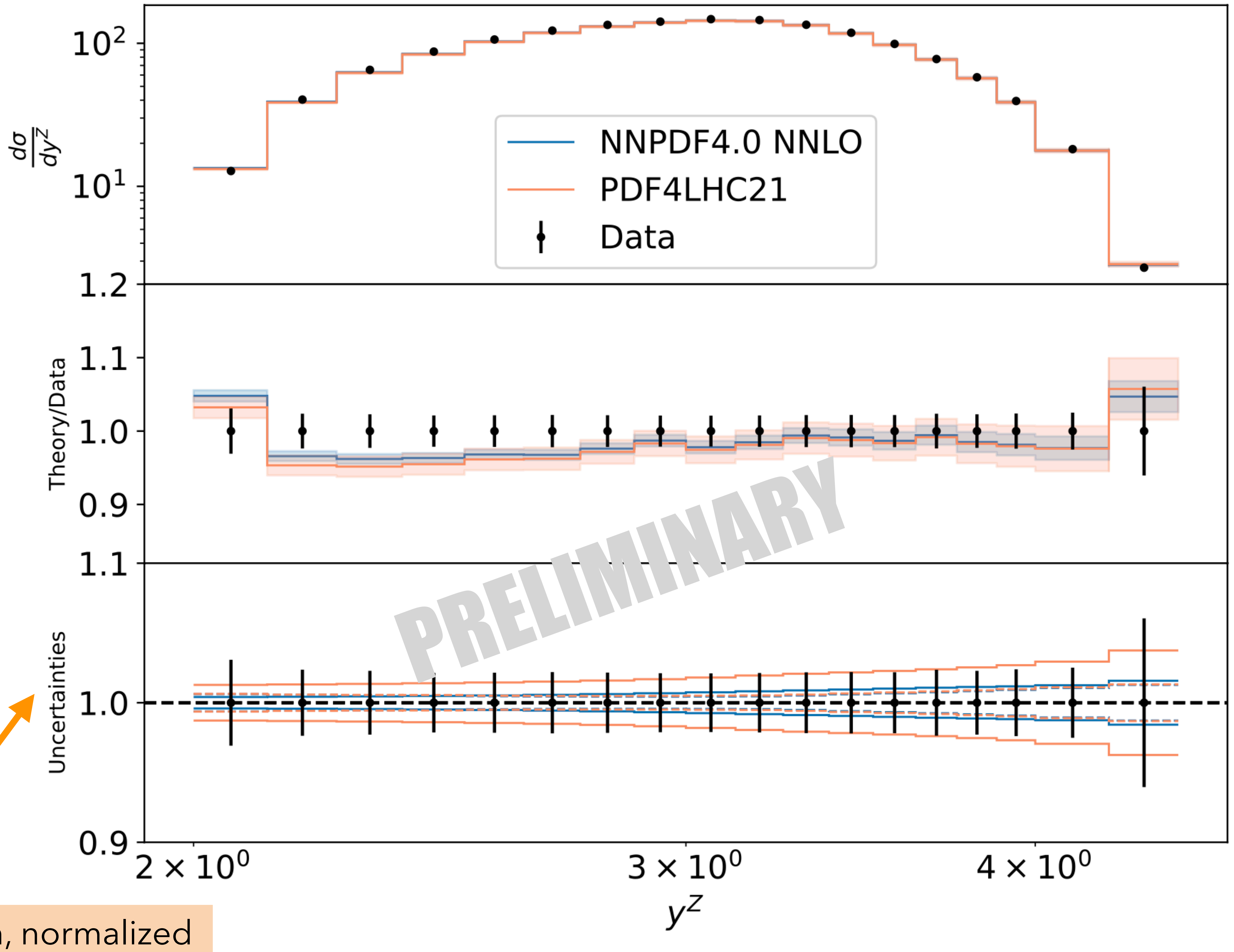


	$\chi^2_{exp+mho+pdf}$ ($\chi^2_{exp+mho}$)
ABMP16	2.22 (**2.26**)
CT18	2.19 (2.56)
CT18A	2.25 (2.49)
MSHT20	2.24 (2.38)
NNPDF3.1	2.49 (2.73)
NNPDF4.0	2.21 (2.27)
PDF4LHC15	2.17 (2.59)
PDF4LHC21	**2.16** (2.36)

Absolute comparison, normalized & size of PDF (solid) and dashed (MHO) **Δ** compared to data **Δ**.

Shaded band includes MHO (9 pts variation) and PDF uncertainties added in quadrature.

LHCb $Z \to \mu\mu$



Chiefa et al, in progress

Predictions: MATRIX

Hepdata: 10.17182/hepdata.102956

CONCLUSIONS AND OUTLOOK

- In an era of precision at LHC, need precise and accurate PDFs

- NNPDF: lots of progress in several main and side projects, NNPDF4.0 aN3LO, NNPDF4.0 MHOU, NNPDF4.0 QED, NNPDF4.0 for MC event generators, methodological studies, EW corrections, more data towards NNPDF4.1. Stay tuned!

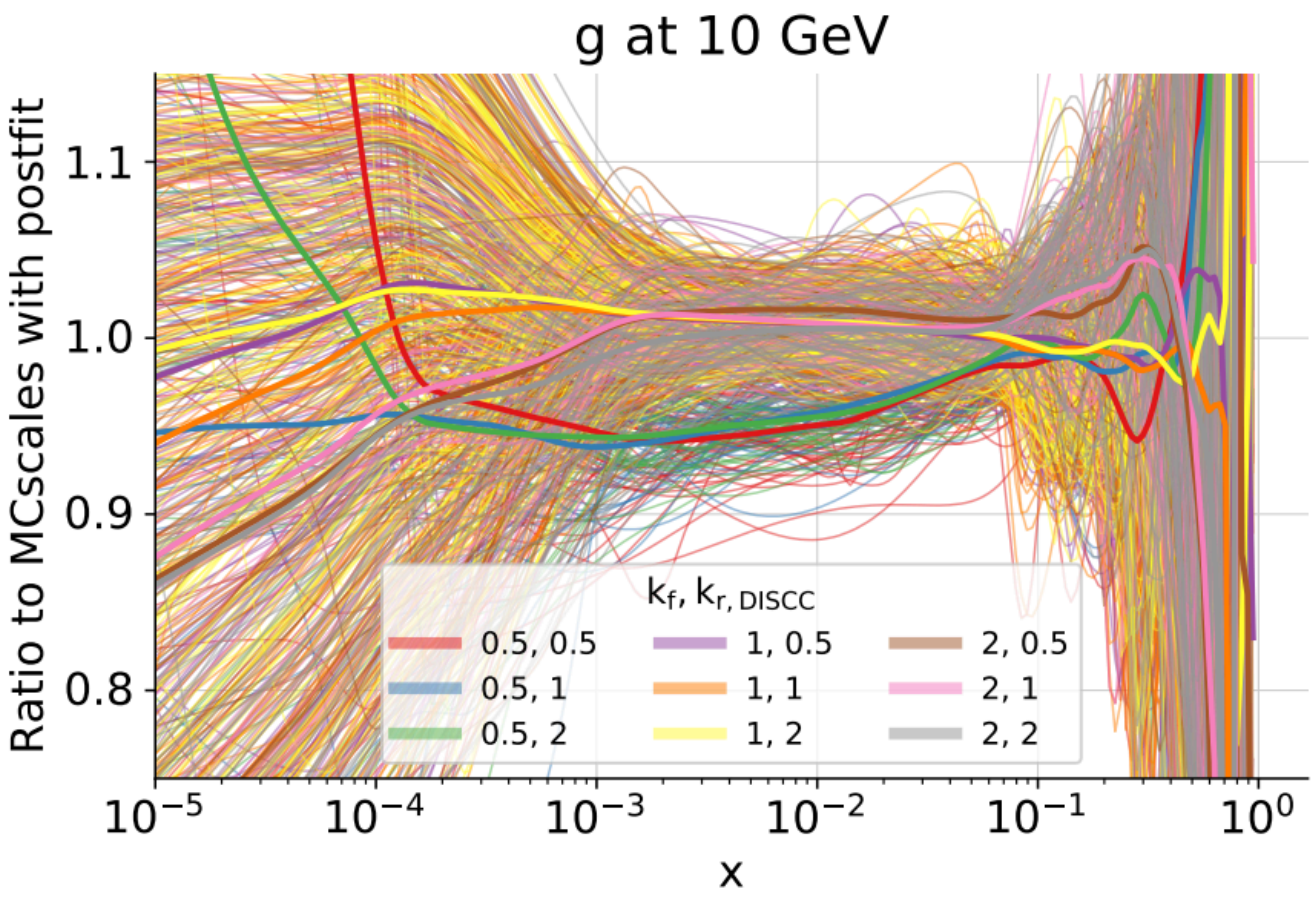
- How to make progress on the precision vs accuracy challenge?

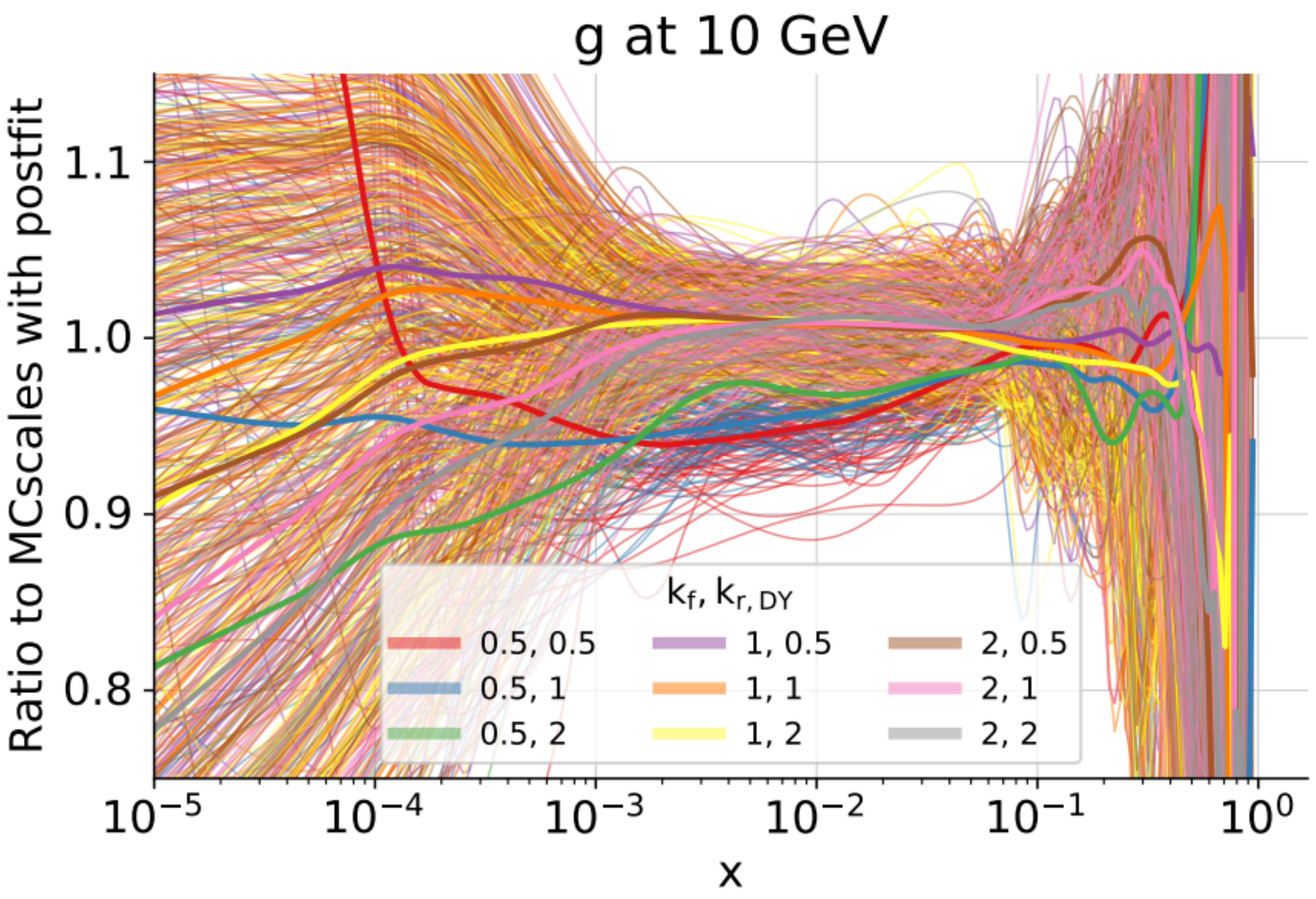
  1. Public codes ensure reproducibility
  2. Closure tests (now explored also by MSHT collaboration): a coordinated effort of PDF fitting collaboration should help converging on agreed set of tests (Level 0, Level 1, Ratio Bias to Variance). These would assess faithfulness of central values and uncertainties of each PDF fits.
  3. Tests on comprehensive set of data not yet in the global PDF fits are only possible discriminant of generalisation and extrapolation of PDFs.
  4. Effects of possible experimental inconsistencies and even possible effects of new physics in the high energy tails, definition of conservative PDF sets, simultaneous PDFs and SM parameter fits the new frontiers that should be explored from multiple angles

THANK YOU FOR YOUR ATTENTION

EXTRA MATERIAL

THE MCSCALES APPROACH





- ✓ Main idea of MCscales: the renormalisation and factorisation scales are free parameters of the fixed-order theory, that induce an uncertainty on the theory predictions included in a PDF fit & need to be propagated
- ✓ Joint sampling of experimental uncertainty (propagated to PDF uncertainty by MC sampling) by specifying a suitable prior probability distribution of all possible scale choices & a-posteriori criterion based on agreement with the data.

$$P\left(k_f = \xi_f, k_{r_1} = \xi_1, \ldots, k_{r_{N_\mathrm{p}}} = \xi_{N_\mathrm{p}}\right) = P(\omega)$$

with $\omega \in \Omega = \{(\xi_f, \xi_1, \ldots, \xi_{N_\mathrm{p}})\ \forall\ \xi_f, \xi_1, \ldots, \xi_{N_\mathrm{p}} \in \Xi\}$

3^{1+N_p} elements, with N_p = 5, p=DIS NC, DIS CC, DY, JET, TOP

Choose prior = choose P($\boldsymbol{\omega}$)

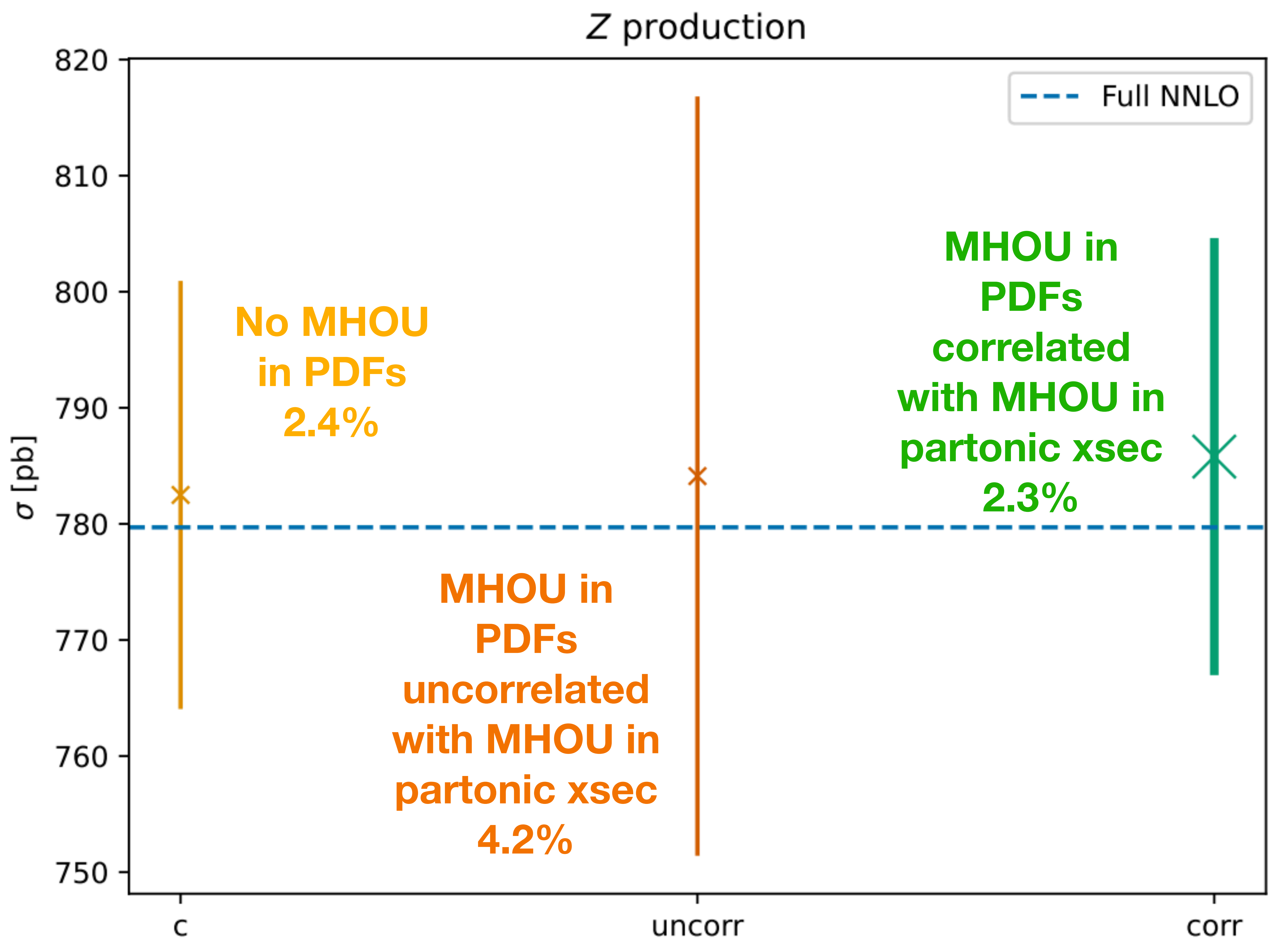
Posterior

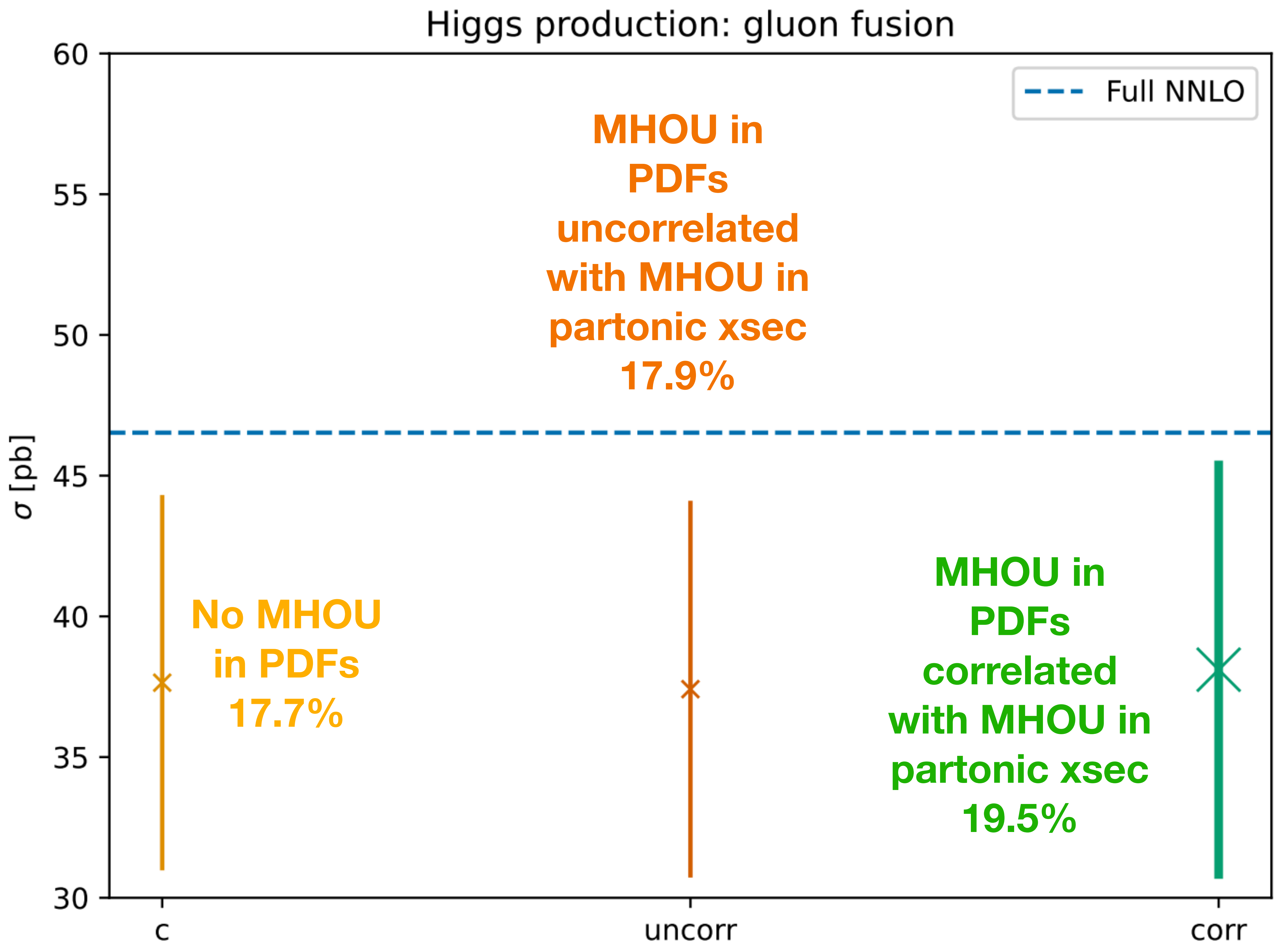
$$\chi^2_n > \langle \chi^2 \rangle_{n\,|\,\omega^{(n)}=\{1,\ldots,1\}} + 4\,\mathrm{std}(\chi^2)_{n\,|\,\omega^{(n)}=\{1,\ldots,1\}}$$

THE MCSCALES APPROACH

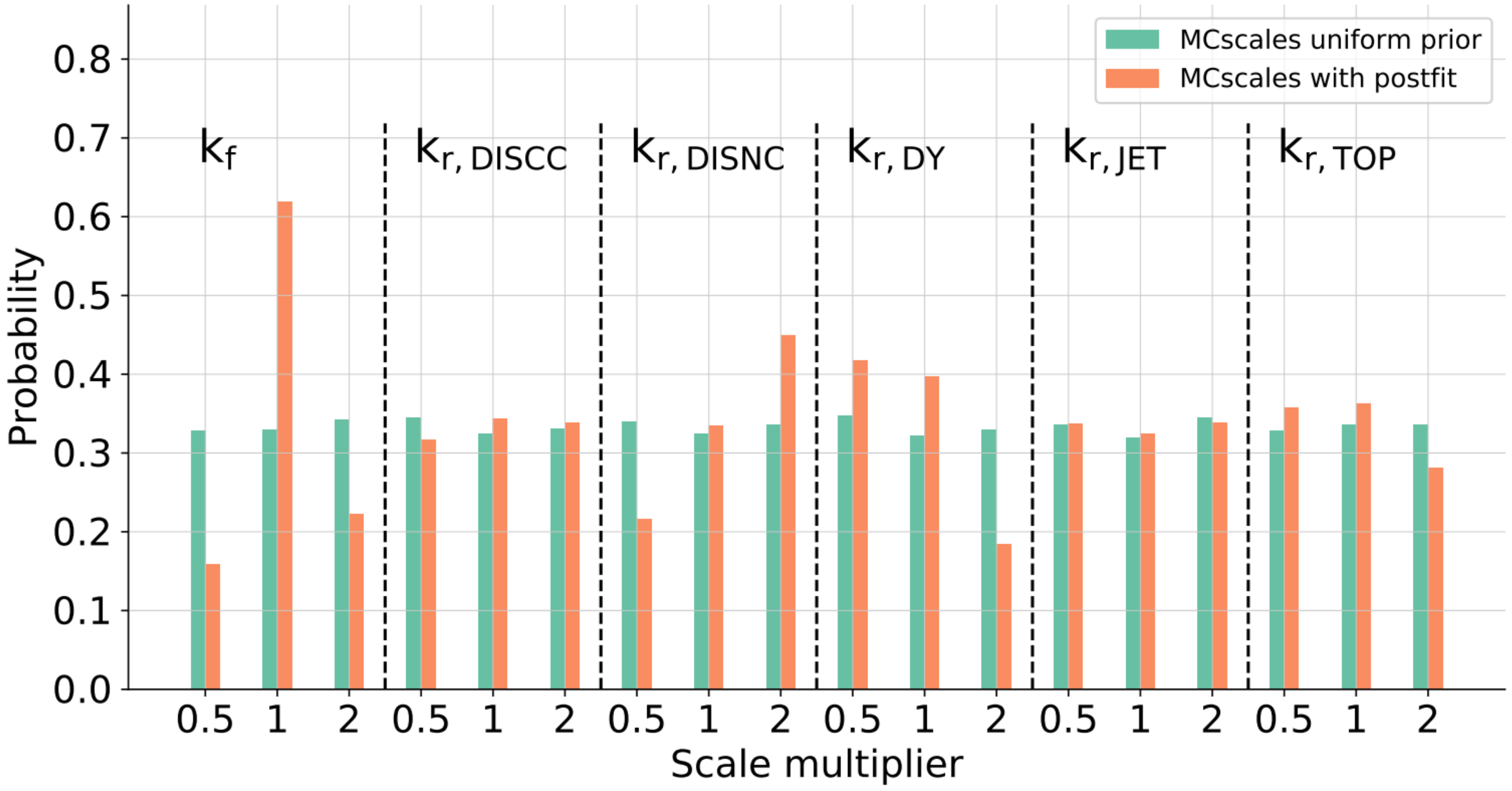
√Can compute full PDF+SCALE uncertainty in cross sections at NLO by matching the scales in the hard cross section computation with the scales in the MCscale PDF set: correlation fully taken into account

$$\left\{\sigma_n = \hat{\sigma}_p(k_f^{(n)}, k_{r_p}^{(n)}) \otimes f_n(k_f^{(n)}, k_{r_p}^{(n)}) \ \ \forall n = 1, \ldots, N\right\}$$





THE MCSCALES APPROACH



- ✓ Can look at the distribution of each of the scales over replicas.
- ✓ Flat distribution for the MCscales uniform prior.
- ✓ After applying postfit observe preference for central factorisation scale.
- ✓ Each process affected in a different way.

Scale multipliers	Process	Preferred values
(k_f, k_r)	DIS CC	$(1, 1)$
	DIS NC	$(1, 2)$
	DY	$(1, 1)$
	Jets	$(1, \frac{1}{2})$
	Top	$(1, 1)$